WTEC Panel Report on

EUROPEAN RESEARCH AND DEVELOPMENT IN HYBRID FLEXIBLE ELECTRONICS

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The increasing miniaturization and complexity of emerging electronics products and systems brings many technical challenges but also excellent promise for improving capabilities and reducing costs through printing-like manufacturing processes and through combining of functionalities in what are called hybrid flexible electronics systems. Important application areas include energy, consumer electronics, healthcare, communications, and national defense. This report is a review of hybrid flexible electronics research and development activities in Western Europe, conducted by a panel of leading U.S. experts in the field, as a window to view what opportunities and challenges exist for U.S. researchers, educators, and manufacturers in this highly interdisciplinary field. The report covers materials development, device challenges, systems opportunities, and processing and manufacturing topics. It also includes a section that reviews several of the large European innovation centers that are bringing a multidisciplinary and practical commercial focus to R&D in the field. The report details the strengths of the basic research being conducted in Europe and the vitality of the close partnerships between university groups, basic research laboratories, industry, and innovation centers, sustained by sizeable research grants that specifically promote such interactions and efficiently support development. Appendix C summarizes the results of the WTEC bibliometric study of world research in hybrid flexible electronics, 1994?2008, which includes a view of the status of R&D in this field in Asia as well as in Europe and the United States.

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WTEC PANEL ON HYBRID FLEXIBLE ELECTRONICS

Sponsored by the National Science Foundation (NSF) and the Office of Naval Research (ONR).

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WTEC Mission

WTEC provides assessments of international research and development in selected technologies under awards from the National Science Foundation (NSF), the Office of Naval Research (ONR), and other agencies. Formerly part of Loyola College, WTEC is now a separate nonprofit research institute. Michael Reischman, Deputy Assistant Director for Engineering, is NSF Program Director for WTEC. Sponsors interested in international technology assessments and related studies can provide support for the program through NSF or directly through separate grants or GSA task orders to WTEC.

WTEC's mission is to inform U.S. scientists, engineers, and policymakers of global trends in science and technology. WTEC assessments cover basic research, advanced development, and applications. Panels of typically six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in their labs.

The WTEC staff helps select topics, recruits expert panelists, arranges study visits to foreign laboratories, organizes workshop presentations, and finally, edits and publishes the final reports. See http://wtec.org for more information about WTEC and for access to reports and information about specific studies. Dr. R. D. Shelton, President, is the WTEC point of contact: telephone 410-467-9832 or email Shelton@ScienceUS.org.

WTEC Panel Report on

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FINAL REPORT

July 2010

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ABSTRACT

The increasing miniaturization and complexity of emerging electronics products and systems brings many technical challenges but also excellent promise for improving capabilities and reducing costs through printing-like manufacturing processes and through combining of functionalities in what are called hybrid flexible electronics systems. Important application areas include energy, consumer electronics, healthcare, communications, and national defense. This report is a review of hybrid flexible electronics research and development activities in Western Europe, conducted by a panel of leading U.S. experts in the field, as a window to view what opportunities and challenges exist for U.S. researchers, educators, and manufacturers in this highly interdisciplinary field. The report covers materials development, device challenges, systems opportunities, and processing and manufacturing topics. It also includes a section that reviews several of the large European innovation centers that are bringing a multidisciplinary and practical commercial focus to R&D in the field. The report details the strengths of the basic research being conducted in Europe and the vitality of the close partnerships between university groups, basic research laboratories, industry, and innovation centers, sustained by sizeable research grants that specifically promote such interactions and efficiently support development. Appendix C summarizes the results of the WTEC bibliometric study of world research in hybrid flexible electronics, 1994–2008, which includes a view of the status of R&D in this field in Asia as well as in Europe and the United States.

ACKNOWLEDGMENTS

We at WTEC wish to acknowledge and thank all the panelists for their valuable insights and their dedicated work in conducting this international benchmarking study of hybrid flexible electronics, and also to thank all the site visit hosts for so generously sharing their time, expertise, and facilities with us. For their sponsorship of this important study, our sincere thanks go to National Science Foundation and the Office of Naval Research. We also appreciate the support provided by Joycelyn Harrison and Shaochen Chen of the NSF Division of Civil, Mechanical, and Manufacturing Innovation. Finally, our deep personal thanks go to Dr. Usha Varshney, NSF Program Director for Electrical, Communications, and Cyber Systems (ECCS); Pradeep Fulay, also of ECCS; Khershed Cooper of the Naval Research Laboratory, and Ralph Wachter at the Office of Naval Research for their interest in and vital support of this study.

R. D. Shelton
President, WTEC

WORLD TECHNOLOGY EVALUATION CENTER, INC. (WTEC)

FOREWORD

> We have come to know that our ability to survive and grow as a nation to a very large degree depends upon our scientific progress. Moreover, it is not enough simply to keep abreast of the rest of the world in scientific matters. We must maintain our leadership.[1]

President Harry Truman spoke those words in 1950, in the aftermath of World War II and in the midst of the Cold War. Indeed, the scientific and engineering leadership of the United States and its allies in the twentieth century played key roles in the successful outcomes of both World War II and the Cold War, sparing the world the twin horrors of fascism and totalitarian communism, and fueling the economic prosperity that followed. Today, as the United States and its allies once again find themselves at war, President Truman's words ring as true as they did a half-century ago. The goal set out in the Truman Administration of maintaining leadership in science has remained the policy of the U.S. Government to this day: the current NSF strategic plan lists as its first goal, "Foster research that will advance the frontiers of knowledge, emphasizing areas of greatest opportunity and potential benefit and establishing the nation as a global leader in fundamental and transformational science and engineering."[2]

The United States needs metrics for measuring its success in meeting this goal of maintaining leadership in science and technology. That is one of the reasons that the National Science Foundation (NSF) and many other agencies of the U.S. Government have supported the World Technology Evaluation Center (WTEC) and its predecessor programs for the past 20 years. While other programs have attempted to measure the international competitiveness of U.S. research by comparing funding amounts, publication statistics, or patent activity, WTEC has been the most significant public domain effort in the U.S. Government to use peer review to evaluate the status of U.S. efforts in comparison to those abroad. Since 1983, WTEC has conducted over 60 such assessments in a wide variety of fields, from advanced computing, to nanoscience and technology, to biotechnology.

The results have been extremely useful to NSF and other agencies in evaluating ongoing research programs, and in setting objectives for the future. WTEC studies also have been important in establishing new lines of communication and identifying opportunities for cooperation between U.S. researchers and their colleagues abroad, thus helping to accelerate the progress of science and technology generally within the international community. WTEC is an excellent example of cooperation and coordination among the many agencies of the U.S. Government that are involved in funding research and development: almost every WTEC study has been supported by a coalition of agencies with interests related to the particular subject at hand.

As President Truman said over 50 years ago, our very survival depends upon continued leadership in science and technology. WTEC plays a key role in determining whether the United States is meeting that challenge, and in promoting that leadership.

Michael Reischman
Deputy Assistant Director for Engineering
National Science Foundation

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[1] Remarks by the President on May 10, 1950, on the occasion of the signing of the law that created the National Science Foundation. *Public Papers of the Presidents* 120:338.

[2] *NSF Investing in America's Future: Strategic Plan FY 2006–2011.* Washington, DC: National Science Foundation, NSF-0648, October, 2006.

PREFACE

Organic/polymeric and inorganic flexible devices integrated to intrinsic and hybridized systems represent a highly promising interdisciplinary area of technology that will provide greatly increased functionality and potential to meet future challenges of scalability, flexibility, low power consumption, light weight, and reduced cost. Continued advances in electronics, photonics, and magnetic systems are critically important in sustaining the nation's economic growth, particularly in the areas of telecommunications, information technology, wearable microprocessors, organic memories, efficient solid-state lighting, alternate power generation sources, and healthcare engineering (such as the use of conductive polymers as artificial muscles and in nerve-tissue replacement). Further applications include foldable electronic newspapers, flexible large-area imaging and display systems, low-cost thin-film transistors and integrated circuits, photovoltaic devices, organic batteries and fuel cells, injection lasers, electrochromic camouflage coatings, organic microelectromechanical systems, and sensors.

The creation of a strong scientific and technological base ranging from synthetic chemistry to device engineering, and from circuit design and systems to manufacturing has become increasingly important to advancing the frontiers of hybrid flexible electronics. This interdisciplinary field fosters interaction among various disciplines that will impact the fields of organic/polymeric electronics, photonics, and magnetics, thereby resulting in heretofore unanticipated breakthroughs and enabling technologies. The anticipated market is very large, expected to grow from $0.65 billion in 2005 to $250 billion by 2025,[3] and research advances promise breakthroughs that can have a pervasive impact on technological development. Consequently, there is a need to address scientific issues and challenges associated with the underpinnings of hybrid flexible electronics. This study will enhance scientific understanding of key phenomena in flexible electronics, photonics and magnetics, and will accelerate applications in industry and society in order to promote economic growth. The goal is to explore and establish the basic science and technology needs in order to utilize and advance new concepts in flexible electronics.

This study by the World Technology Evaluation Center (WTEC), Inc., was carried out with the objective of identifying new concepts and approaches stimulated by the interaction of diverse disciplines and novel stand-alone concepts and breakthrough ideas; it focuses on critical, enabling engineering technologies for long-term growth. The study includes concepts for theoretical and experimental aspects of charge transport and device physics, processing techniques and manufacturing technologies, interface engineering, device design, circuits and packaging, metrology and diagnostic tools, architectures, and systems engineering. The study bridges science and technology by introducing new concepts, and it has as its intent the promotion of evolution of thought and techniques that address issues ranging from fundamentals to applications. The goal of the study was to identify for researchers, educators, and manufacturers practicing in the field opportunities and challenges that are underpinning the next-generation advances in hybrid flexible electronics, resulting in reduced cost and new functionalities, in addition to identifying new opportunities for international collaboration.

The National Science Foundation (NSF) in conjunction with the Office of Naval Research (ONR) commissioned this worldwide study of the status of hybrid flexible electronics with particular emphasis on the United States and Europe. The study was conducted by WTEC utilizing a panel of six experts from United States universities and industry, and observers from Federal government agencies. The panel consisted of Prof. Ananth Dodabalapur, Dr. Ana Claudia Arias, Prof. C. Daniel Frisbie, Dr. Daniel Gamota, Prof. Tobin J. Marks, and Dr. Colin Wood, and was supported by

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[3] Raghu Das and Peter Harrop. 2005. Printed, organic & flexible electronics forecasts: Players & opportunities 2005-2015. Cambridge MA: IDTechEx. Available online: http://www.idtechex.com/research/?catflag=P

participants from NSF, ONR, and the Naval Research Laboratory. Prof. Dodabalapur chaired the study. Not only did the panel compile a comprehensive literature survey and analysis, but it conducted numerous interviews and team site visits to some thirty universities, industries, and government laboratories in Europe.

The panel summarizes its broad conclusions in the Executive Summary, addressing the vitality of European research as well as the scientific and technological strength of U.S. research in the field of hybrid flexible electronics. It is noted in the study that Asian countries are ahead in manufacturing, publication records for leading European countries are similar to those of the United States, and Europe is heavily involved in basic research and has extensive availability of infrastructure facilities for prototyping and pilot-scale manufacturing. The United States leads in basic research and advanced systems research and development, but lags behind in manufacturing. It was also noted that undergraduates in Europe are better trained than in the United States; however, PhD programs in the United States are well regarded as compared to those in the European countries. The close connection between universities and the venture capital community in the United States was well recognized in promoting innovation and transition of technologies from academic laboratories to societal applications.

This focused study identifies novel engineering concepts in flexible electronics and its applications and addresses major advances in the state-of-the-art in hybrid flexible electronics with the goal of producing significant benefits to society. The study provides outcomes under six broadly defined chapters, as detailed below:

In Chapter 1, Prof. Ananth Dodabalapur introduces the background and scope of the study, sites visited, and approaches involved.

In Chapter 2, Prof. Dr. C. Daniel Frisbie and Dr. Colin Wood provide an enlightening account of innovation centers in European countries, including ones in Austria, Belgium, Germany, Italy, the Netherlands, Sweden, and the United Kingdom. The goal of these centers is to mitigate financial risk by sharing costs among commercial enterprises by leveraging substantial government funding at both at the national and European Union levels. The focus of these centers is to expedite the commercialization of flexible electronics systems by leveraging technical expertise and financial resources of multiple companies, academic laboratories, and government funding agencies.

In Chapter 3, Prof. Tobin J. Marks discusses materials synthesis and development activities for substrates, devices, and contacts for hybrid flexible electronics. The chapter addresses materials issues related to molecular engineering of hybrid organic and inorganic materials, surfaces, interfaces (organic/organic, organic/metal, organic/dielectric), structures, and nanocomposites; control of structural, magnetic, and optical properties of hybrids; novel functionality, such as light emission; thermal, chemical, and mechanical sensitivity; approaches to reduce quenching mechanisms of electroluminescence; doping and charge accumulation at hybrid interfaces; stability; and operational lifetimes. In addition, it notes novel polymerization and processing techniques to prepare hybrid structures together with molecular and supramolecular templating to create complex yet functional hierarchical structures.

In Chapter 4, Dr. Ana Claudia Arias and Prof. Ananth Dodabalapur provide a concise account of the state of the art of devices and discuss goals, challenges, and needs. The chapter elucidates device characteristics and performance of polymer-organic light-emitting diodes (P-OLEDs), organic photovoltaics (OPV), and organic field-effect transistors (OFETs), which are the building blocks of organic flexible electronics. The chapter further addresses specific issues relating to charge generation, injection, transport and collection, grain-boundary effects, crystallinity, room temperature carrier mobility, cycling stress effects, long-time-scale relaxation effects, carrier diffusivity, recombination, quenching, trapping and annihilation rates of excitons, quantum and conversion efficiencies, photodegradation and device lifetimes, and device reliability.

In Chapter 5, Dr. Ana Claudia Arias and Dr. Daniel Gamota identify systems opportunities relating to hybrid flexible electronics and review activities in organic light-emitting diodes, organic photovoltaics, reflective displays, field-effect transistor-based components including matrix backplanes, biosensors, RFIDs, and memories, among other circuits and systems. The chapter details device architectures involving integrated intrinsic and hybridized organic electronics, photonics, and magnetic systems for futuristic applications that can provide greatly increased functionality and potential to meet future challenges of scalability, flexibility, light weight, and low power consumption.

In Chapter 6, Dr. Daniel Gamota and Dr. Colin Woods detail the status of processes involved in manufacturing of hybrid flexible electronics products. The chapter highlights advances in both solution and vacuum processing techniques that lead to improvement in material properties and high-volume manufacturing methodologies scalable to both micro- and macro- levels at high throughput and compatible with organic semiconductors and devices. The chapter details patterning techniques, large area and moisture-resistant encapsulation of electronics and photonics, roll-to-roll processing, and innovative printing techniques. The chapter further discusses quality assurance and environmental testing and life-testing tools. It identifies the needs for new and improved diagnostic techniques to image and characterize morphology and chemical, structural, electronic, optical, and magnetic properties of materials, interfaces, buried layers, and structures with nanometer-scale resolution for quality assurance; measurements and new nondestructive methods for probing organic and inorganic interfaces requiring atomic-level resolution; innovative techniques to evaluate device encapsulation and performance; and higher-resolution printing tools.

Each chapter of this report is supported by a comprehensive list of references, which in total cover all aspects of organic and inorganic hybrid flexible electronics in the United States and Europe. Other highlights of this study are to be found in the appendices, which present biographical information on the WTEC panel members and authors in Appendix A, and the site reports of the panel's visits in Europe in Appendix B—I can attest to the wealth of information that is contained in these site-visit reports. Of equal interest to the reader should be Appendix C that presents highlights of the Bibliometric Study of World Research in Hybrid Flexible Electronic activities complied by Dr. Grant Lewison. This details the evolution of the numbers of published papers in hybrid flexible electronics—and citations of those papers—by country and region. A glossary of technical terms and acronyms is provided in Appendix D.

I continue to be impressed by the quality and insight of the panel members and the high regard in which they are held by members of the worldwide flexible-electronics community. We are deeply grateful to all of those European institutions and the many individuals who so generously shared their work and their insights with the panel.

My thanks go to Dr. Robert J. Trew, Division Director for Electrical Communications and Cyber Systems (ECCS) at the National Science Foundation (NSF), Dr. Khershed Cooper of the Naval Research Laboratory, and Dr. Ralph Wachter at the Office of Naval Research, for their excellent and continuous support of and participation in the WTEC study of Hybrid Flexible Electronics in the United States and Europe. Also, I wish to acknowledge my colleagues at NSF, in particular Dr. Michael Reischman, Deputy Assistant Director for Engineering; Dr. Pradeep Fulay, Program Director for ECCS; and Drs. Joycelyn Harrison and Shaochen Chen, Program Directors for Civil, Mechanical, and Manufacturing Innovation, who gave generously of their time and effort to make the Hybrid Flexible Electronics study the great success that it has been. Finally, I would like to thank Dr. Russell J. Churchill of the American Research Corporation of Virginia for technical discussions.

The WTEC study on hybrid flexible electronics could not have been successfully conducted without the expertise and attentiveness of WTEC President Dr. Robert D. Shelton. I acknowledge the WTEC team with special thanks to Dr. Michael DeHaemer (Executive Vice-President of

WTEC), Dr. David Nelson (Vice-President for Development) and Dr. V. J. (Ben) Benokraitis (Vice-President for Operations), who have worked diligently from the initiation of the study two years ago. My thanks go also to Mr. Grant Lewison (Evaluametrics, Ltd.) for arranging the site visits in Europe, Dr. Ben Benokraitis for coordinating the report activity, and Ms. Patricia M. H. Johnson for providing editing support.

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EXECUTIVE SUMMARY

This study on hybrid flexible electronics was designed to investigate what opportunities and challenges exist for U.S. researchers, educators, and manufacturers in what is a highly interdisciplinary field. It is an important topic. Application areas impacted by flexible electronics include *energy* (e.g., photovoltaic energy conversion systems and energy-efficient lighting), *consumer electronics* (e.g., portable flexible displays, sensors, and actuators), *healthcare* (e.g., low-cost personal health monitoring systems), *communications* (e.g., radio-frequency identification systems), and *national defense* (e.g., networked sensing, intelligent and autonomous systems, and enhancement of individual warfighter capabilities). Commonalities across all applications are the required coordination of the knowledge and skills of practitioners in multiple areas of expertise, and the increasing miniaturization and complexity of emerging products and systems. There is excellent promise in all these applications for reducing costs through manufacturing processes that utilize printing and lithography methodologies and through combining of multiple functionalities.

This international assessment of European R&D in hybrid flexible electronics was sponsored by the National Science Foundation (NSF) and the Office of Naval Research (ONR) and organized by the World Technology Evaluation Center (WTEC). In visiting or talking with leaders of over 30 foremost European institutions and laboratories engaged in R&D for hybrid flexible electronics, the key questions that the study panel considered were:

1. What is the vitality of European research in this field?
2. What are the strengths of the United States research effort in this field, according to the Europeans?
3. How can the United States improve its competitive position in the field of hybrid flexible electronics?
4. What is needed in the U.S. national science infrastructure and in agency policies to transform the early promise of this field to an area of U.S. scientific and technological strength?

Along the way, the panel also looked to identify opportunities for synergies and collaborations and to learn how research and education in this complex, interdisciplinary field are handled by some of the best-known institutions in the world.

There were consistent themes and points that emerged during the panel's site visits in Europe and its compilation of this report; these are summarized below. It should be noted that Asia is emerging as a vital and important region for the development of the field, particularly in manufacturing. While the panel did not visit laboratories in Asia for this study, references to Asian efforts are made throughout this report, and all countries were included in the bibliometric study (Appendix C) to provide perspective on Asian activities in the area of hybrid flexible electronics.

European Vitality in this Field

The growth in scientific publication output in the field of hybrid flexible electronics for leading European countries is similar to that of the United States. The Europeans are doing well as far as basic research is concerned. There is also a close partnership between university groups and basic research laboratories with industry and innovation centers. This is encouraged and sustained by research grants that specifically undergird such interactions. Another noticeable feature of activities in Europe is the existence of large research projects across Europe involving multiple university groups with strengths in complementary areas. A feature noted in many of the countries visited is the availability of infrastructure facilities for prototyping and pilot-scale manufacture at the innovation centers. These innovation centers interact with both university groups and small companies to efficiently help promote development.

Principal strengths of Europe's efforts that the panel observed are as follows:

- This has been EU-level priority R&D area for about a decade
- Europeans have a long-term view of the field
- Strong research groups have existed for many years
- There is close industry-university-innovation center cooperation in precompetitive research
- Industry and universities have access to specialized fabrication/prototyping facilities
- Multi-organization R&D centers are dispersed across many countries

U.S. Strengths in this Field, as Perceived by European Scientists

The European groups were nearly unanimous in praising the quality of the leading U.S. research universities but also pointed out that undergraduate students in Europe often receive better training than their U.S. counterparts. The close connections between university groups and the venture community in the United States also came in for praise as a well-developed process for moving innovation out from the academic laboratory. However, it was troubling that few of the groups the panel visited actually considered the United States as a threat in any sense, reserving that for Asian countries, particularly Korea and Japan, and organizations and companies based in these countries.

Principal strengths of U.S. efforts, as perceived by European scientists are as follows:

- Strong research universities with well-regarded PhD programs
- A well-developed venture capital infrastructure that is more advanced than what exists in most other countries
- Practical knowledge in creating start-up companies
- Ability to attract talent from everywhere
- Strong support from Federal agencies such as NSF, ONR, Department of Defense, Department of Energy, etc.

Implications for the U.S. Competitive Position

What the panel discerned from this study is that the relatively low prevalence of actual manufacturing and advanced systems research and development in the United States has led to an incomplete hybrid flexible electronics R&D scenario for this country: it is strong in basic research and in innovation but weak in advanced development for manufacturing, mirroring trends in some other sectors as well. Although the United States may be doing what it does best, manufacturing is moving to regions of the world that provide greater investment and commitment to product development. It then becomes questionable as to whether this approach is a healthy one and can be sustained in the long term.

It is hoped that this report will stir debate in appropriate circles as to what we should do about this. It is particularly noteworthy that some of the organizations outside the United States that are strong in manufacturing also have developed good in-house research efforts and arrangements with research universities. We must add that there are some commendable efforts in manufacturing in U.S. corporations that also are backed up by strong research efforts; a noteworthy example is General Electric in the area of flexible organic-based solid-state lighting. The panel maintains that more such efforts, more cross-disciplinary and cross-sector cooperative interactions, and longer-term investment strategies will greatly help the United States improve its overall position in the field of hybrid flexible electronics, with commensurate benefits to the U.S. economy.

CHAPTER 1

INTRODUCTION

Ananth Dodabalapur

BACKGROUND

There is a clear understanding among U.S. leaders that in order to maintain economic competitiveness in the world, the United States must also maintain scientific and technological competitiveness in all fields of science and technology (S&T). Indeed, President Obama has charged the nation's top science agencies with preserving America’s place as the world leader in S&T (Holdren 2009). As Michael Reischman points out in the Foreword, the NSF strategic plan lists as its first goal, "foster research that will advance the frontiers of knowledge, emphasizing areas of greatest opportunity and potential benefit and establishing the nation as a global leader in fundamental and transformational science and engineering" (NSF 2006). This leadership is not a given. Those who assess the quality of research abroad often find centers of excellence that challenge U.S. science leadership. So it is with electronics. Those who buy electronic gadgets know that most of them are made abroad—even though U.S. scientists made many of the basic discoveries that make those products possible. One area in the worldwide electronics industry where American scientists and engineers continue to be leaders is in basic research and innovation, particularly in emerging areas like hybrid flexible electronics. Yet the international scientific interest in this field is vigorous and intensifying.

There is a growing demand worldwide for electronic circuits and systems on flexible substrates. This trend matches the spread of electronic functionality everywhere and the emergence of new materials, systems, device architectures, and fabrication processes to create new types of electronic circuits. At the heart of this trend is the functional integration of many types of materials—inorganic, organic, and even biological materials. Such integration permits new functionality and enhanced performance of devices and systems. Some successful examples of past research in this area include the development of flexible backplanes based on organic semiconductor transistors for electronic paper (Dodabalapur 2006; Rogers et al. 2001). Such transistors are inherently more easily printable, and their performance levels are adequate for a wide variety of applications.

As requirements for components in flexible/printable circuits and systems grow more complex, investigations are continuing into new material systems—including inorganic semiconductors, organic single crystals, nanotubes, and advanced wiring—and related processing techniques. Equally important is the integration of multiple functionalities within systems by combining various components such as sensors and actuators with interface electronics—for example, for antennae systems. Other examples of such integrated systems include low-cost printed radio frequency identification tags (RFID) for such diverse uses as inventory management, e-toll collection, and animal tracking (Cantatore et al. 2007); optoelectronic circuits and systems that integrate light emitters, photodetectors, electronic transistors, and sensors, and yet are produced by conventional photolithography and inkjet printing (Someya et al. 2005; Noguchi, Sekitani, and Someya 2006); and Braille e-book readers that are portable, mechanically flexible, lightweight, shock-resistant, and potentially inexpensive to manufacture (Kato et al. 2007).

U.S. excellence in these emerging areas offers an opportunity to restore U.S. competitiveness in electronics generally, but doing so also requires detailed knowledge of research and development trends abroad. At the same time, science advancement is an inherently cooperative process that can benefit all citizens of the world. In the spirit of both competition and cooperation, the National Science Foundation (NSF) and the Office of Naval Research (ONR) of the U.S. Navy sponsored this review of the status and trends in hybrid flexible electronics research and development in Europe. The study was managed by the World Technology Evaluation Center, Inc. (WTEC).

SCOPE OF THE STUDY

The objectives of this study are to compare research underway in Europe with that in the United States, to identify opportunities for collaboration, and to suggest ways to refine the thrust of U.S. research programs. While the study sought information about new and emerging electronics devices specifically, the NSF and ONR sponsors were more broadly interested in the full ranges of technologies necessary to make successful applications: materials, devices, interfaces, circuits and systems, and manufacturing. Of additional interest were European infrastructure and policies to promote these new technologies, and educational resources and funding levels in Europe. The study also sought the Europeans' perspectives on the strengths of the United States in the area of hybrid flexible electronics. While an effort was made to include visits to as many of the leading laboratories as possible, logistic constraints made this difficult. Thus, while all the laboratories the study panel visited are leading centers of research in Europe in the field we are studying, there are others that we have not been able to visit that are also outstanding.

Asia is emerging as a vital and important region for the development of the field, particularly in manufacturing. While the panel did not visit laboratories in Asia for this study, numerous references to Asian efforts made throughout the book, and the inclusion of all countries in the bibliometric study reported in Appendix C, provide a broad perspective.

WTEC CREDENTIALS

With core funding and management from the NSF Directorate for Engineering, WTEC has conducted over 60 international technology assessments. Other U.S. Federal agencies have also provided funding for various WTEC studies: Air Force Office of Scientific Research (AFOSR), Army Research Office (ARO), Defense Advanced Research Projects Agency (DARPA), the Departments of Energy and Commerce, National Aeronautics and Space Administration (NASA), other NSF directorates, and ONR. Recently, panels of experts assembled by WTEC have assessed Asian and European R&D in nanotechnology, spin electronics, carbon nanotube manufacturing and applications, brain-computer interfaces, catalysis by nanostructured materials, and simulation-based engineering and science. Full text versions of the final reports are available at http://wtec.org. WTEC personnel also compile cross-cutting findings from WTEC studies to help evaluate national positions in S&T; a recent example, "The race for world leadership of science and technology: Status and forecasts," was completed by Shelton and Foland in 2009.

STUDY APPROACH

NSF and ONR defined the scope of the study in meetings in late 2008. WTEC then recruited a panel of U.S. experts, chaired by Ananth Dodabalapur, the Ashley H. Priddy Centennial Professor in Engineering at the University of Texas at Austin. The panel members are listed in Table 1.1, along with others who accompanied the panel on its site visits in Europe. Short biographies of the panelists and authors are provided in Appendix A.

The study was initiated at a kickoff meeting held in Arlington, VA, on December 3, 2008. Initial funding provided for only four expert panelists, but additional funds from offices at NSF and from ONR permitted two additional panelists to be added in the spring of 2009. Sponsors and panelists jointly planned the study tour and reviewed the status of U.S. research in the field to serve as a baseline for the study's evaluation of European R&D. During May 9–15, 2009, the delegation divided into two teams to visit the sites shown in Table 1.2 and Figure 1.1, with advance work provided by Grant Lewison of Evaluametrics, Inc.

Table 1.1. Delegation Members

Delegate	Affiliation
Ananth Dodabalapur	University of Texas at Austin (Panel Chair)
Ana C. Arias	Palo Alto Research Center (Panelist)
C. Daniel Frisbie	University of Minnesota (Panelist)
Daniel Gamota	Printovate, Inc. (Panelist)
Tobin J. Marks	Northwestern University (Panelist)
Colin E. C. Wood	Texas State University San Marcos (Panelist)
Pradeep Fulay	National Science Foundation (Sponsor)
Khershed Cooper	Office of Naval Research (Sponsor)
Grant Lewison	Evaluametrics (Advance Contractor for WTEC)

Table 1.2. Sites Visited in Europe

#	Country	Site	#	Country	Site
1	Austria	Johannes Kepler University, Linz Institute for Organic Solar Cells, Linz	15	Italy	CNR, Institute for the Study of Nanostructured Materials (ISMN), Bologna + other CNR hosts
2	Austria	Konarka Technologies, Inc., Linz	16	Italy	University of Bari, Department of Chemistry, co-host in Bologna
3	Austria	Plastic Electronic GmbH, Linz	17	Italy	University of Bologna Department of Chemistry, Bologna
4	Belgium	IMEC (Inter-University MicroElectronics Center), Leuven	18	Netherlands	Holst Centre, Eindhoven
5	Germany	Institute for Applied Photophysics, Technical University of Dresden	19	Netherlands	Philips Research, Eindhoven
6	Germany	Heliatek GmbH, Dresden	20	Netherlands	Polymer Vision, Ltd., Eindhoven
7	Germany	Novaled AG, Dresden	21 22	Sweden	University of Linköping, Centre for Organic Bioelectronics, Norrköping, and Acreo AB
8	Germany	Fraunhofer Institute for Photonic Microsystems (IPMS), Dresden	23 24	United Kingdom	University of Cambridge Department of Engineering, Cambridge Integrated Knowledge Centre, Ctr. for Advanced Photonics and Electronics, Cambridge
9	Germany	University of Erlangen-Nürnberg Institute of Polymeric Materials, Erlangen	25	United Kingdom	University of Cambridge Department of Physics, Cavendish Laboratory Optoelectronics Group, Cambridge
10	Germany	BASF, Ludwigshafen am Rhein	26	United Kingdom	Plastic Logic, Ltd., Cambridge
11	Germany	Max Planck Institute for Solid State Research, Organic Electronics Group, Stuttgart	27	United Kingdom	Cambridge Display Technology (CDT), Cambridge
12 13	Germany	PolyIC GmbH & Co. KG, Fürth, and interview with Board Chairman of Organic Electronics Association	28 29 30	United Kingdom	Imperial College London, Departments of Physics (Blackett Laboratory), Chemistry, and Materials, London
14	Germany	University of Stuttgart Display Technology Laboratory, Stuttgart	31	United Kingdom	London Centre for Nanotechnology (University College London and Imperial College London)

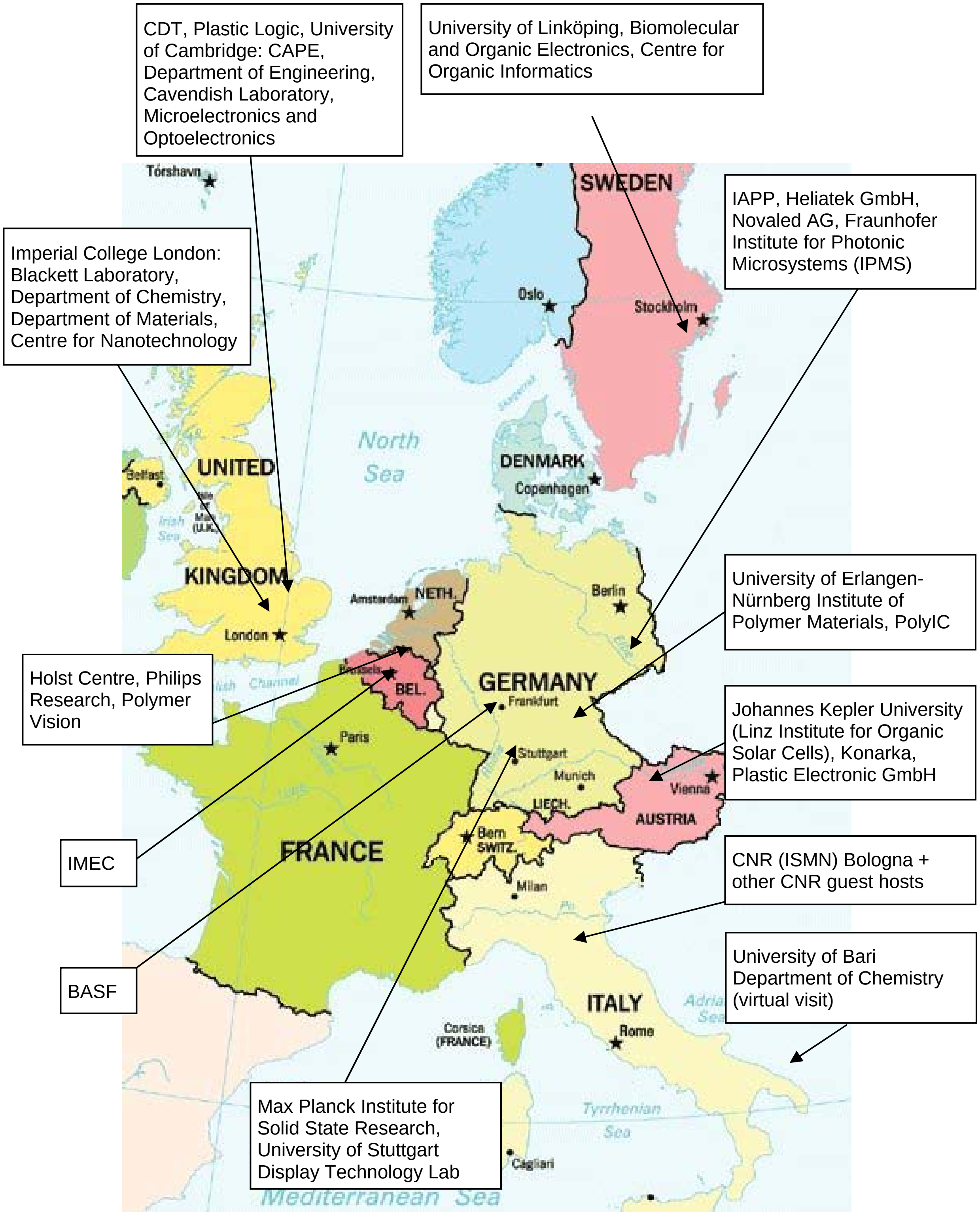

Figure 1.1. Sites visited in Europe.

Panelists visited (or met with leaders of) over 30 research groups and labs, in some cases by dividing into teams to hold separate meetings at one site. Appendix B contains detailed site reports from each location the team visited. This material was reviewed for accuracy by the individual hosts before inclusion in this report.

The panel held a day-long workshop at NSF in Arlington, VA, on June 30, 2009, to present its findings publicly. More than 50 people attended, including representatives of the leading U.S. universities, Federal agencies, and companies involved in this field. Slide presentations from the workshop are posted in the workshop proceedings at http://wtec.org/flex/.

ACKNOWLEDGEMENTS

This study would not have been possible without the sustained support from several U.S. Government offices. Usha Varshney, at the NSF Division of Electrical, Communications, and Cyber Systems (ECCS), suggested this study several years ago. Pradeep Fulay, also of ECCS, helped organize the study. To cover the all-important manufacturing aspects, support was provided by Joycelyn Harrison and Shaochen Chen of the NSF Division of Civil, Mechanical, and Manufacturing Innovation, plus Ralph Wachter and Khershed Cooper of the Office of Naval Research. Michael Reischman, Deputy Assistant Director for Engineering, added the support to make a six-person panel possible.

Our foreign hosts were consistently hospitable and generous in sharing their research results. We owe them a deep debt of gratitude—and reciprocal hospitality. As chair, I would like to express my appreciation for the willingness of the expert panelists to devote significant amounts of their time and energy in this project. The study tour was grueling, but we learned a great deal, and I know this made their participation worthwhile.

REFERENCES

Cantatore, E., T.C.T. Geuns, G.H. Gelinck, E. van Veenendaal, A.F.A. Gruijthuijsen, L. Schrijnemakers, S. Drews, and D.M. de Leeuw. 2007. A 13.56-MHz RFID system based on organic transponders. *IEEE Journal of Solid-State Circuits* 42(1):84–92.

Dodabalapur, A. 2006. Organic and polymer transistors for electronics. *Materials Today* 9:24-30.

Holdren, J. 2009. The President's plan for science and innovation: Doubling funding for key basic research agencies in the 2010 budget. Available online: http://whitehouse.gov/galleries/budget/doubling.pdf.

Kato, Y., T. Sekitani, M. Takamiya, M. Doi, K. Asaka, T. Sakurai, and T. Someya. 2007. Sheet-type Braille displays by integrating organic field-effect transistors and polymeric actuators. *IEEE Trans. on Electron Devices* 54(2):202–209.

National Science Foundation (NSF). 2006. *Investing in America's future: Strategic plan 2006–2011*. Arlington, VA: NSF 06-48. Available online: http://www.nsf.gov/pubs/2006/nsf0648/nsf0648.jsp.

Noguchi, Y., T. Sekitani, and T. Someya. 2006. Organic-transistor-based flexible pressure sensors using ink-jet-printed electrodes and gate dielectric layers. *Appl. Phys. Lett.* 89(25): 253507.

Rogers, J.A., Z. Bao, K. Baldwin, A. Dodabalapur, B. Crone, V.R. Raju, V. Kuck, H. Katz, K. Amundson, J. Ewing, and P. Drzaic. 2001. Paper-like electronic displays: Large-area rubber-stamped plastic sheets of electronics and microencapsulated electrophoretic inks. *Proceedings of the National Academy of Sciences of the United States of America* 98:4835–4840.

Shelton, R. D., and P. Foland. 2009. The race for world leadership of science and technology: Status and forecasts. In *Proceedings of the 12th International Conference on Scientometrics and Informetrics*, Rio de Janeiro, July, 2009, B. Larsen and J. Leta, eds., 369–380. Leuven, Belgium: International Society for Scientometrics and Informetrics. Available online: http://itri2.org/Rpaper/.

Someya, T., Y. Kato, S. Iba, H. Kawaguchi, and T. Sakurai. 2005. Integration of organic field-effect transistors with organic photodiodes for a large-area, flexible, and lightweight sheet image scanner. *IEEE Trans. Electron Devices* 52(11):2502–2511.

CHAPTER 2

INNOVATION CENTERS IN EUROPE

C. Daniel Frisbie and Colin Wood

INTRODUCTION

One of the central observations of the panel's fact-finding tour was that in Europe there is a very strong emphasis on innovation centers that foster the development of flexible electronics systems and manufacturing methods. The goal of these centers is to speed the commercialization of flexible electronics by leveraging the technical expertise and financial resources of multiple companies, academic laboratories, and government funding agencies. In addition to substantial technical challenges, the cost of research and development in the flexible electronics area is perceived as a significant risk to individual companies, many of which have core expertise in only a subset of required competencies (e.g., circuit/systems design, coating, printing, and materials). European innovation centers mitigate the financial risk by sharing costs among multiple commercial enterprises and by leveraging substantial government funding at both the national and European Union (EU) levels. On the technical front, the centers foster a highly synergistic and interdisciplinary environment in which the complementary expertise of industrial, government, and academic scientists is combined to achieve new systems design goals (e.g., ultra-low-power systems in foil), enhanced device performance, broader materials choices, and practical, low-cost manufacturing approaches.

Flexible electronics innovation centers are spread throughout many countries in Europe; this chapter describes the eight centers that the WTEC panel visited. They are presented roughly in order of size (largest first), as judged by the number of staff working in the hybrid flexible electronics area and their annual budgets. In general, these centers share a set of common characteristics:

- Substantial industrial and government support
- Multiple industrial members
- Synergistic, open-innovation, precompetitive environments with a 5–10 year research horizon
- Significant educational components, including opportunities for graduate student and postdoctoral training

Additional information on these centers and their host institutions and departments may be found in the corresponding site reports in Appendix B.

HOLST CENTRE (EINDHOVEN, THE NETHERLANDS)

http://www.holstcentre.com/

The Holst Centre is a large, government- and industry-supported innovation center that develops novel technology in the flexible and hybrid electronics area. The Holst Centre staff consists of approximately 130 persons, which includes ~20 PhD students from several universities and ~40 resident researchers from industry. The Centre plans to expand to 220 staff persons in 2010. The Holst Centre is a joint initiative of the Dutch Research Foundation TNO and IMEC, a major microelectronics centre in Belgium (also visited by the WTEC panel and described below).

The Centre focuses its research on products and fabrication processes that are 3–10 years from market introduction. A central aspect of the Holst Centre is that it implements a "shared research and development" model: substantial support from the Dutch Government is leveraged by annual participation fees from ~20 member companies. This model has been motivated by the general problem that R&D costs are growing faster than revenues. In addition, a typical member company often has a core technology that it seeks to exploit in a new or perceived electronics market, but it lacks sufficient experience or R&D capabilities to realize its end goal. Holst brings these companies together in a precompetitive environment to develop new technologies and manufacturing capabilities.

The Centre is located on the High Tech Campus in Eindhoven (Figure 2.1), formerly Philips Research Laboratories, which is currently the home of a number of small companies, including spin-offs from Philips. Research projects in the Centre take advantage of extensive cleanroom/microfabrication facilities and characterization instrumentation on campus, which are available on a fee-for-use basis. It was clear to the panel that the rapid buildup of the Holst Centre (for example, in terms of industry participation) since its founding in 2005 is attributable in large part to the excellent research facilities that are in place on the High Tech Campus.

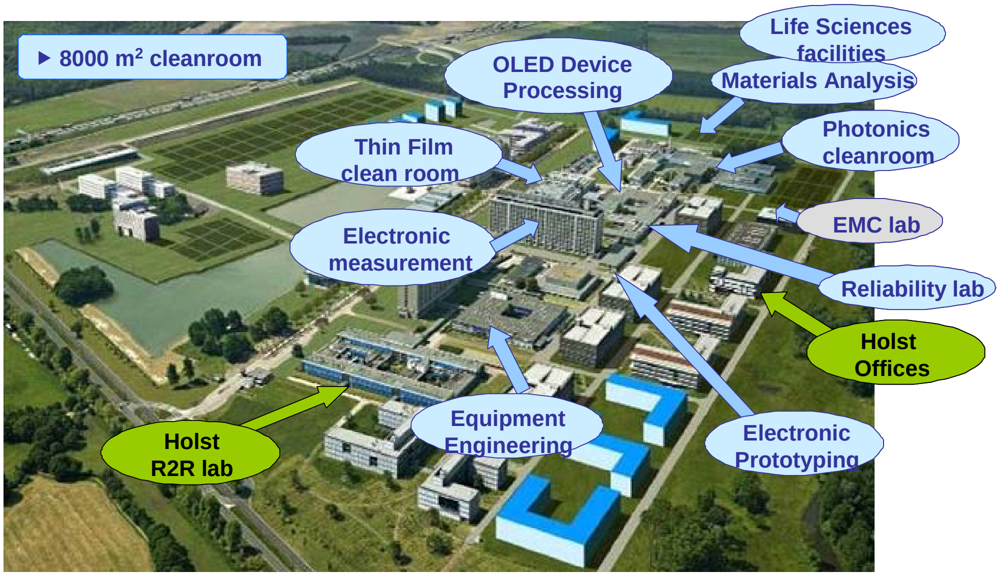

Figure 2.1. Aerial view of the High Tech Campus in Eindhoven, Netherlands, which contains the Holst Center, Philips Research, and a number of start-up companies (courtesy of the Holst Centre).

At the time of the WTEC panel's visit, the Holst Centre had two main focus areas: (1) Wireless Autonomous Microsystems and (2) Systems in Foils. Plans were in place to add programs in Flexible Photovoltaics and Smart Packaging in 2010. The Autonomous Microsystems program aims to develop ultra-low-power, wireless sensors that can be integrated into clothing, packaging, or medical bandages, among other applications. The emphasis of the Systems-in-Foils program is to prepare electronically functional foils (e.g., sensor tapes) using high-throughput printing and lithography processes and to achieve system integration by laminating functional foils together. Collectively, the emphasis of the two programs is less on novel materials development (member companies typically supply key materials), and more on systems design and fabrication methods.

Designs take advantage of both conventional semiconductors (e.g., silicon) and novel organic materials. The technology areas that they aim to impact are summarized in Figure 2.2.

A key aspect of the Holst Centre is that the member companies share intellectual property (IP). An initial membership fee is required of prospective companies; this fee increases as the IP portfolio matures. In addition, there is an annual membership fee. There appears to be provision for exclusive licensing of technology developed at Holst; the panel's hosts indicated that this component of industrial relations may increase over time.

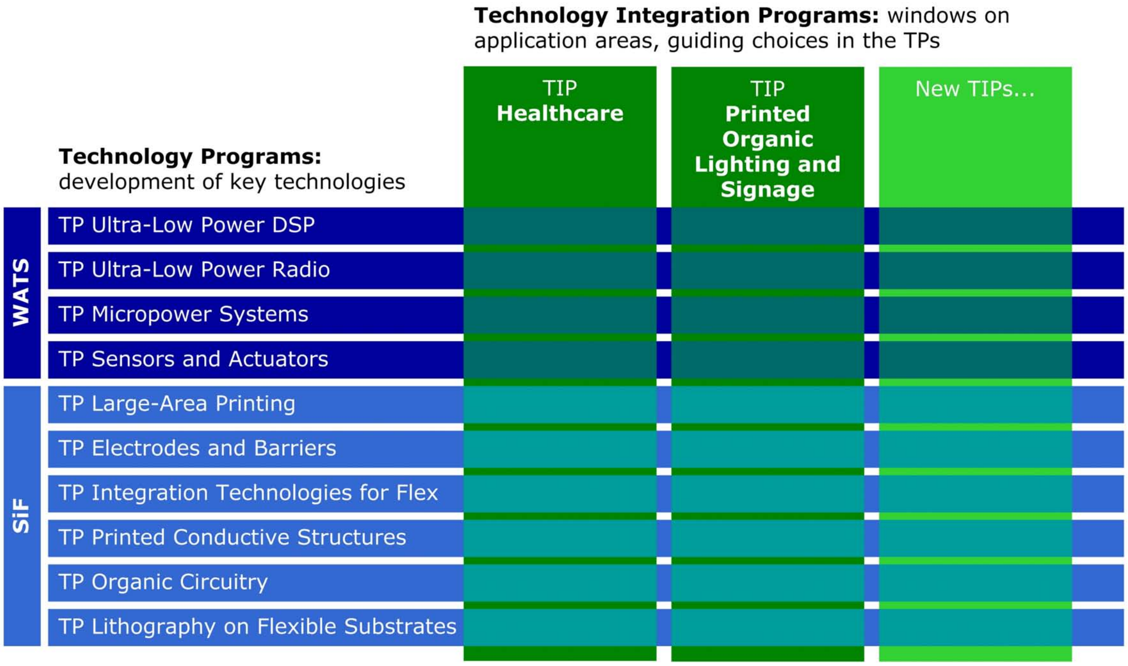

Figure 2.2. Program matrix used at the Holst Centre to summarize development activities. Technology programs shown on the left are organized into two main areas, Wireless Autonomous Microsystems (WATS) and Systems in Foil (SIF). The general markets that the center currently hopes to impact are shown in green, namely Healthcare and Lighting/Signage; other markets (Technology Integration Programs) may be added later (courtesy of the Holst Center).

IMEC (LEUVEN, BELGIUM)

http://www2.imec.be/imec_com/imec_com_homepage.php

IMEC is a very large and well-established international microelectronics research center (Figure 2.3) that was founded in 1984 with an initial government investment of EUR 62 million. It is a nonprofit organization, and all revenues are reinvested in research programs and facilities. Annual review of the center assesses the following performance criteria (1) overall excellence (as judged by contract revenue, publications), (2) excellence in exploratory work (number of PhD students and publications with universities), and (3) impact on local industry (spin-offs and collaborations). IMEC has generated 25 spin-off companies since its inception.

The annual budget of IMEC is approximately EUR 250 million, and it has a staff of 1500. The center focuses principally on issues in silicon microelectronics, but it has a small yet very visible program in organic electronics that is closely allied with the Holst Center in Eindhoven (only 100 km away), which is why it is listed second in this chapter. The organic electronics staff consists of 23 personnel in organic circuits and 11 in organic photovoltaics. This research staff includes graduate students from the Catholic University in Leuven.

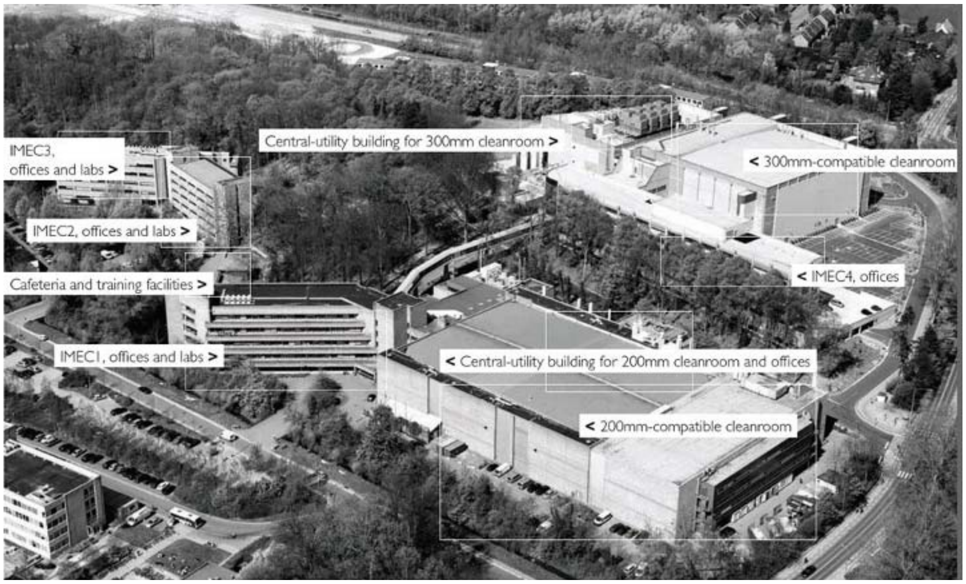

Figure 2.3. The IMEC campus in Leuven, Belgium (courtesy of IMEC).

IMEC and the Holst Centre are similar in that they both follow a shared research and development model and aim to fill the technology transfer gap between universities and industry. Member companies pay annual fees to participate in IMEC core program areas; these fees account for nearly 85% of the center's annual revenue. Benefits to companies include sharing of R&D costs, risks, and resources. This partnership accelerates the timescale of product inception to market introduction in technology areas where development costs are escalating. Intellectual property issues are resolved using protocols developed over the 25 years since IMEC was founded. The environment is heavily interdisciplinary and multicultural. Approximately 350 industrial fellows work and reside at IMEC; many of these are foreign nationals—approximately 50 different nationalities are represented across the center. In addition, IMEC has close collaborations with a number of universities. A number of staff members have joint appointments with universities, and there are approximately 150 PhD students carrying out their dissertation research on the campus.

The organic and hybrid electronics group focuses on organic circuitry (e.g., all organic RFIDs and sensor tapes) and organic photovoltaics. The organic circuitry work aims at demonstrating high levels of integration (hundreds to thousands of transistors) processed on wafer-supported plastic sheets (the plastic sheets are separated from the support after fabrication). Conventional lithographic methods are used. Particularly noteworthy achievements include a 64-bit RFID tag operating at 800 bps that includes a 13.56 MHz transponder. Key to this demonstration was the development of organic-based diodes that can rectify current at this frequency (Myny et al. 2008). As mentioned, the organic circuitry group also is an active partner in the large area electronics on foil and smart packaging efforts at the Holst Center in Eindhoven.

The IMEC photovoltaics effort aims to achieve high-performance organic-based cells (small molecules or polymers) that can deliver power at less than EUR 0.50/Wp, where Wp is peak power in Watts. The program focuses on efficiency, technology, and lifetime, with the goal of achieving 10% record efficiency (average efficiency of 7%) and 5-year lifetimes. The IMEC researchers believe that silicon will not likely be able to match such low cost/watt ratios, though it will approach EUR 1/Wp with continued development. Materials for the photovoltaic (PV) effort are supplied by partner companies. Processing methods for PVs include inkjet printing, spray coating, thermal evaporation, and organic vapor phase deposition. The organic circuitry and photovoltaics efforts utilize dedicated laboratory space (~2000 square feet) with a variety of deposition tools, inert atmosphere boxes, and measurement equipment. In addition, this group uses lithography and deposition tools, which are available in the cleanroom originally used to process 150 mm Si wafers (Figure 2.4).

Figure 2.4. IMEC has two state-of-the-art-cleanroom facilities (courtesy of IMEC).

FRAUNHOFER INSTITUTE FOR PHOTONIC MICROSYSTEMS (DRESDEN, GERMANY)

http://www.ipms.fraunhofer.de/en/

The Institute for Photonic Microsystems (IPMS) is one of 11 nonprofit Fraunhofer institutes that address the area of microelectronics. The overall mission of the Fraunhofer institutes is to help drive technological innovation by performing contract research and development work in support of industry and government agencies. The annual budget for the IPMS is EUR 24 million, with 40% generated from industrial contract research. The location of IPMS in Dresden is strategic, because the city has a long tradition of excellence in microelectronics dating to before reunification in the early 1990s. There is also a growing industrial presence in organic optoelectronics in Dresden—the Dresden area is viewed as an emerging "organics valley" in the middle of Europe.

Within IPMS, the Center for Organic Materials and Electronic Devices (COMED) carries out development research in organic light-emitting diodes (OLEDs) for lighting (see Figure 2.5), signage, and displays.

Figure 2.5. IPMS technician with an OLED lighting panel.

COMED is also increasingly focused on organic photovoltaics (OPV). This center involves approximately 60 personnel, has an annual budget of ~EUR 6 million/year, and has vast and impressive facilities for processing OLED displays and OPV cells on glass and stainless steel. The focus is primarily on vapor-deposited small-molecule organic semiconductors. As is characteristic of Fraunhofer institutes, much of the work at COMED is motivated by the commercial interests of nearby companies in the OLED and OPV industry, such as Novaled and Heliatek. There are also close interactions with the Technical University of Dresden, which is the home of world-class academic experts in organic optoelectronics.

CAMBRIDGE INTEGRATED KNOWLEDGE CENTRE (CAMBRIDGE, UK)

http://www-g.eng.cam.ac.uk/CIKC/

The Cambridge Integrated Knowledge Centre (CIKC) is a venture started in 2007 at the University of Cambridge that combines flexible electronics expertise at the Cavendish Laboratory (Physics Department) and the Engineering Division of the University with market and manufacturing expertise in the Judge Business School. The CIKC focuses on (1) flexible electronics manufacturing; (2) integrated systems using polymers, liquid crystals, and nanostructures; and (3) biosensors. It is funded at $15 million over 5 years from the UK Engineering and Physical Sciences Research Council (EPSRC), with additional support from the University of Cambridge, member companies, and trade organizations totaling ~$20 million over 5 years.

The CIKC leverages substantial faculty expertise at Cambridge in the areas of semiconducting, polymers, liquid crystals, amorphous silicon, zinc oxide, and carbon nanotubes. Projects appear to be awarded competitively to faculty investigators who are members of the center. These projects are well documented on the CIKC website. A central feature of the CIKC is its access to the ~7000 sq. ft. Electrical Engineering Division cleanroom and the equipment it operates there (Figure 2.6), dedicated to processing devices and systems on flexible substrates.

Figure 2.6. CIKC cleanroom facility.

The multimaterials approach to flexible circuitry and systems appears to be a particular strength of the CIKC and positions it well for future commercial developments in flexible electronics. The center also builds off of the excellent track record of many of the faculty in generating spin-off companies. The City of Cambridge is an acknowledged leader in organic semiconductor start-up companies (e.g., Plastic Logic and Cambridge Display Technology).

LONDON CENTRE FOR NANOTECHNOLOGY (LONDON, UK)

http://www.london-nano.com/

The London Centre for Nanotechnology (LCN) is a multi-investigator center formed jointly by Imperial College and the University College London (UCL) in 2003. It has core competencies in simulation and design (nanoCAD), nanofabrication, nanocharacterization, and nanosystems (e.g., sensors). Its main mission is to produce excellent science in three main areas: Health Care, Planet Care (energy and the environment), and Information Technology. The Centre is similar in design to a U.S. National Science Foundation (NSF) Materials Research Science and Engineering Centers (MRSECs), in which faculty are organized into interdisciplinary research groups focused on particular problems. Efforts in flexible electronics are mainly in the health care and information technology areas, where example projects include the integration of amorphous or nanocrystalline silicon transistors into large-area arrays on plastic for displays and medical imaging purposes, and the development and characterization of new organic semiconductor materials. There is also ongoing work with oxides (e.g., ZnO) for thin-film electronics and semiconductor nanowires. For this work, LCN has established 2,500 square feet of combined cleanroom space at its two locations in London: Gordon Street (UCL) and South Kensington (Imperial).

The LCN is led by approximately 30 faculty members from multiple departments within University College London and Imperial College; in all there are 250 personnel, including all faculty, staff, students, and post docs. The annual budget is £10 million/year, largely from the UK EPSRC and the European Commission. Industrial funding is actively sought and growing. The budget is used to support students and postdocs, and most members of the faculty have 50% appointments at the LCN. Thus, a large portion of the budget is appropriated for faculty salaries.

DOCTORAL TRAINING CENTRE FOR PLASTIC ELECTRONICS (LONDON, UK)

http://www3.imperial.ac.uk/plasticelectronics

Three institutions in London—Imperial College, Queen Mary University of London, and University College London—have joined forces to develop the Doctoral Training Centre (DTC) for the Science and Application of Plastic Electronics. This center is part of a large network of DTCs in many subject areas that are funded by the UK EPSRC. The plastic electronics DTC in London leverages the large concentration of faculty working in this field. Imperial College alone, for example, has ~15 faculty members working on different aspects of organic semiconductors and flexible electronics. The DTCs are focused on graduate education and typically fund 10 PhD students per year for five years. Of course, the DTC is but one component of flexible electronics support at Imperial College, Queen Mary, and UCL. UCL has a nanotechnology center, described above, that supports some aspects of flexible electronics research. Imperial estimates it has approximately 50 postdoctoral fellows and 70 graduate students working on plastic electronics projects in the Physics, Chemistry, and Materials Science departments.

ACREO RESEARCH INSTITUTE (LINKÖPING, SWEDEN)

http://www.acreo.se/

Acreo is an incorporated “Fraunhofer-style” research institute tightly connected with the organic electronics program at the University of Linköping (LiU). Its printed electronics division has ~30 employees, and its mission is to develop commercial applications through contract research. Acreo follows the long tradition in Sweden of industry-sponsored research institutes closely connected with universities. Acreo obtains 50% of its funding from industry; the remaining 50% comes from a combination of Swedish government and EU funding.

The Swedish government and the pulp and paper industry are very interested in supporting the development of printed electronics technology. Sweden has commercial strength in paper production and packaging. Printed electronics, smart labels, ultra-low-cost sensors, and displays are seen as key to maintaining the strength of these industries in the future. Collaborating academic research groups at Linköping have a long track record in the development of new organic semiconductor materials and their characterization in devices. Acreo maintains a printing laboratory within a few hundred meters of LiU academic laboratories, in the Norrköping Campus. The printing lab houses industrial-sized screen printers, dryers, roll-to-roll printers capable of flexographic and gravure printing on 10-inch-wide paper or plastic substrates at 30 m/s (Figure 2.7), ink jet printers, and another roll-to-roll coater for dry patterning of materials, such as metal lines for antennas and interconnects. LiU PhD students routinely use these printers for their research. The overall emphasis is to develop low-cost, solution-processed materials for novel applications in biological sensing, solar energy conversion, and flexible electronics. Acreo has several patented products, including a low-voltage electrochromic display called PaperDisplay^{TM}, which is available for license.

Figure 2.7. A roll-to-roll printing machine in Acreo's Printed Electronics Laboratory.

ITALIAN NATIONAL RESEARCH COUNCIL (BOLOGNA, ITALY)

http://www.cnr.it and http://www.bo.ismn.cnr.it/research.php

The Italian National Research Council in Bologna (Consiglio Nazionale delle Ricerche, or CNR, Bologna) is a large, multi-institute national research laboratory that has a substantial research effort in organic and hybrid electronics (see Figure 2.8 for a broad view of the CNR campus). These efforts fall largely under the Institute for Nanostructured Materials (ISMN) within CNR Bologna. Particularly active areas of research for the CNR team include organic spintronics and organic light-emitting transistors. While the emphasis has been on basic research, there have been recent thrusts to establish manufacturing technologies and also to create start-up companies from technologies originating within CNR.

The CNR researchers indicated to WTEC panelists that there is flexibility in terms of the time spent on research in CNR versus time spent in the start-up company. Researchers are able to work for a significant time-share for the start-ups for a few years and then return to research at CNR. These start-ups are housed in the same building, which facilitates interaction with researchers as well as provides facilities to the start-ups that would otherwise be very difficult to obtain. In this regard, there are similarities with the charters of the NSF–funded National Nanotechnology Infrastructure Network (NNIN) university-based program established to encourage start-up companies to use university facilities.

One Italian start-up company (E.T.C. srl, in conjunction with Saes Getters S.p.A.) focuses on the development and commercialization of advanced materials and of organic light-emitting transistors (OLETs; see Figure 2.9); it has evolved from fundamental research conducted by CNR in this area. Some of the start-up companies that have been created include Advanced Polymer Materials, Mediteknology, Organic Spintronics, Lipinutragen, and Scriba Nanotecnologie. Government agencies encourage the formation of these start-up companies because they facilitate job creation and economic growth.

Figure 2.8. CNR campus in Bologna, Italy (courtesy of CNR).

Figure 2.9. CNR facility for the fabrication, encapsulation, and characterization of OLET devices.

REFERENCES

Myny, K., S. Steudel, P. Vicca, J. Genoe, and P. Heremans. 2008. An integrated double half-wave organic Schottky diode rectifier on foil operating at 13.56 MHz. *Appl. Phys. Lett*. 93:093305.

Muccini, M. 2006. A bright future for organic field-effect transistors. *Nature Mater*. 5:605–613. DOI:10.1038/nmat1699

CHAPTER 3

MATERIALS DEVELOPMENT

Tobin J. Marks

INTRODUCTION

Materials are truly "the stuff that dreams are made of"; for hybrid flexible electronics, the accessibility, tunability, and durability of materials constrain what can be invented, fabricated, and ultimately, manufactured. For maximum productivity, all electronic materials synthesis and development efforts should be closely coupled to processing, fabrication, and device-testing capabilities. Indeed, this coupling was observed in most of the European organizations that the WTEC team visited, although the nature and strength of the coupling varied considerably.

In discussing the materials aspects of this study of hybrid flexible electronics in Europe, two important factors should be recognized. First, the materials and material properties of interest for hybrid flexible electronics are highly unconventional and not straightforwardly predictable. Thus, trivial extensions of existing materials and their properties are not, in general, adequate strategies to pursue for materials development in this field. Labor-intensive empiricism is frequently required, combined with novel processing methodologies, to achieved desired performance. Secondly, the exact identities of many materials currently under development at European laboratories are frequently regarded as proprietary; hence they were not made available to the WTEC visiting teams. Nevertheless, strategies and overall progress were provided so that it is possible to summarize efforts at the various sites the panelists visited. The materials presentation here is organized by device technology to parallel the discussion in Chapter 4, which reviews the predominant hybrid flexible electronics systems.

ORGANIC LIGHT-EMITTING DIODES

Figure 3.1 outlines general structures and materials types that are incorporated in current-generation small-molecule and polymer organic light-emitting diodes (SM-OLEDs and P-OLEDs) (Martin 2006). Specific materials are needed in OLEDs for hole and electron transport, emission (frequently a dopant), charge injection, and for blocking undesired carriers from reaching an electrode or other device region. For small-molecule OLEDs, important criteria are volatility, thermal stability, and purity of the small-molecule components, because almost all such devices are fabricated by equipment-intensive vacuum deposition techniques. Matched and reasonably large-hole and electron mobilities of the hole and electron transport materials are necessary for efficient device function.

To maximize luminous efficiency, it is usually necessary to include heavy metal–containing triplet-emitting luminophores—usually iridium (Ir) or platinum (Pt) complexes, of which thousands have now been reported—to harvest, via intersystem crossing, the maximum percentage of emissive excitons, and also to achieve the desired CIE color coordinates (Baldo, Thompson, and Forrest 2000).

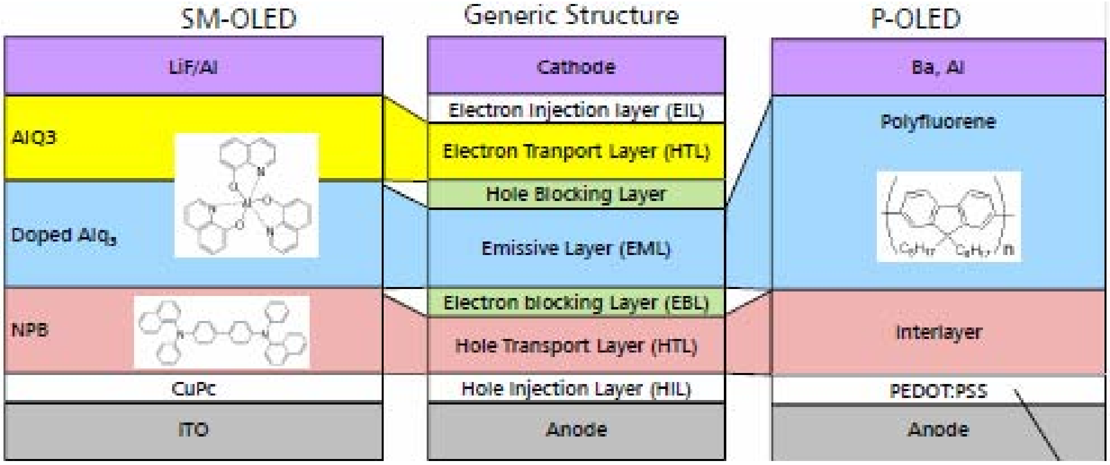

Figure 3.1. General structures of organic light-emitting diodes showing component materials and functional layers (courtesy of Dr. Jonathan Halls of CDT).

While luminophore lifetimes are now acceptable for red and green colors (10^5–10^7 hours), blue luminophores still present a challenge because of the large bandgap and/or high photon energies. Novaled (http://www.novaled.com/), a spin-off from the IAPP (Institut für Angewandte Photophysik of the Technical University of Dresden), devotes much research effort to evaluating, purifying, and down-selecting acceptable OLED luminophores, relying on both in-house and outside (e.g., Ciba Specialty Chemicals) materials sources. Recent IAPP accomplishments[4] include all-phosphorescent (different Ir luminophore materials for red, green, and blue) top-emitting OLEDs with efficiencies as high as 90–120 lumens/watt. Efforts are also underway at IAPP to understand luminophore degradation mechanisms, some of which appear to involve ligand exchange and displacement.

Another OLED company, Cambridge Display Technology (CDT), Ltd. (http://www.cdtltd.co.uk/), which has a large laboratory with approximately 40 chemists involved in OLED materials synthesis, focuses on a variety of transport and emissive materials. Figure 3.2 shows schematics of several of the P-OLED (polymer-OLED) materials that CDT is developing.

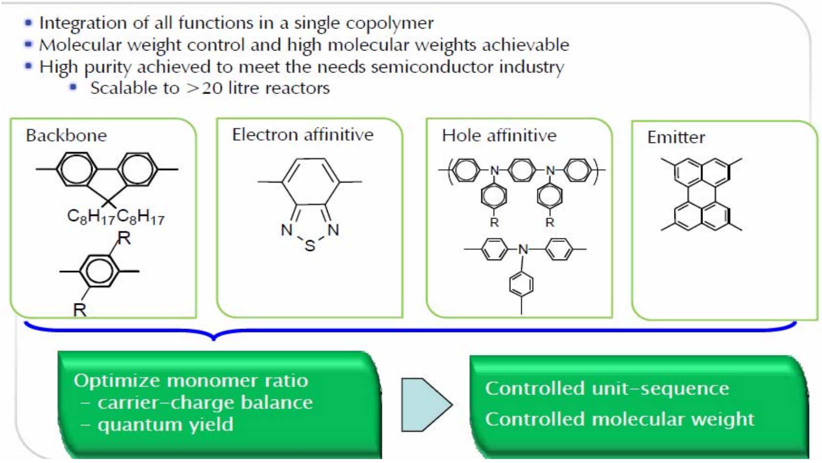

Figure 3.2. Examples of polymer active layer materials under development at CDT for polymer light-emitting diodes (courtesy of Dr. Jonathan Halls of CDT).

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[4] For more details and illustrations, see the Novaled websites http://www.novaled.com/oledcompetence/overview.html and http://www.novaled.com/oledcompetence/advantage_overview.html.

Among the laboratories that the WTEC team visited, there was not a general consensus on the merits of vacuum-deposited versus solution-deposited fabrication processes. The former offers high purity and layer thickness control but is capital intensive, whereas the latter offers simpler fabrication by printing, but control of purity and layer structures is more challenging. In terms of commercialization, OLEDs manufactured by vacuum deposition are far ahead of those manufactured by solution deposition.

Another important OLED materials component is interfacial layers, which serve the purpose of interfacing the electrodes with the active layers, enhancing charge injection, and blocking leakage of incorrect charges to incorrect electrodes, that is, blocking electrons from reaching the anode and blocking holes from reaching the cathode. Novaled frequently uses doped hole or electron transport materials, respectively, for this function (Walzer et al. 2007), whereas CDT uses other materials, as shown in Figure 3.1. Self-assembled silane (Huang et al. 2005 and 2007) or phosphonate (Sharma et al. 2009) structures that covalently bond to the ITO (tin-doped indium oxide) anode have been shown to be very effective in this charge injection/blocking function, and also in enhancing electrode-organic cohesion, important for device thermal durability (Huang et al. 2005 and 2007). There is a general consensus that the acidic/corrosive, structurally/electrically inhomogeneous polythiophene derivative PEDOT:PSS is not an ideal interfacial layer and should be replaced if at all possible (Sharma et al. 2009). There was also a general consensus among the WTEC team's hosts that it would be desirable to replace the current transparent oxide anode material ITO with a material that contains less expensive indium and is more electrically conductive (Ni et al. 2005).

Materials for encapsulating environmentally sensitive OLED materials are also important; for flexible devices, much progress has been made in fabricating barrier structures comprised of inorganic/polymer multilayers (Dameron et al. 2008). Note that the barrier material demands are significantly greater than for food packaging material demands; thus, new materials must be developed. Ultimately it is hoped that HOMO and LUMO energies (highest and lowest occupied molecular orbitals) can be lowered to the point where reaction with O_2 and/or H_2O is kinetically insignificant. There is good reason to believe from thin-film transistor (TFT) results (see below) that this is a viable strategy.

Choice of plastic substrate materials is another issue: polyesters such as polyethylene terephthalate (PET) or more expensive but more thermally robust polyethylene naphthalenate (PEN) currently are favored. Also a concern is the dimensional stability and smoothness of plastic substrates.

There was a general consensus among the WTEC hosts that OLED displays, which are now appearing on the market in MP3 players, cell phones, and televisions, will continue to grow in importance. Recent demonstrations of flexible active matrix OLED cell phone displays by Samsung and Kyocera (Engadget/Weblogs, Inc. 2009a and 2009b) represent intriguing prototypes of what can be accomplished with current-generation flexible electronics (e.g., see Figure 3.3). Also, the use of white OLEDs for efficient indoor lighting has enormous potential and is being vigorously developed by Novaled, the Fraunhofer Institute, and many Asian companies (Reineke, Luessem, and Leo 2009; Hatwar and Spindler 2008).

Figure 3.3. Folding cell phone by Kyocera with a flexible OLED display (http://www.inhabitat.com/).

ORGANIC PHOTOVOLTAICS

Organic photovoltaic (OPV) cells share many materials features, strategies, and challenges in common with OLEDs. In OPVs, incident sunlight creates excitons, which undergo scission at a donor-acceptor interface to create holes and electrons that then must efficiently transport through the active materials and cross the organic-electrode interface for collection as solar electricity (Kippelen and Bredas 2009; Günes, Neugebauer, and Sariciftci 2007). Much like OLEDs, the two general approaches that are being pursued for OPVs are vacuum-deposited small-molecule devices and solution-processed small-molecule or polymer devices. The attraction of the former is the rigorous purity and control of layer architecture that is possible, whereas the attraction of the latter is that it is more amenable to large-area printing and related coating techniques. In all cases, the limited exciton diffusion lengths in these organic materials mean that scission to holes and electrons must take place at a nearby donor-acceptor interface, usually achieved via a phase-separated bulk-heterojunction (BHJ) architecture (Kim et al. 2007). The general consensus is that power conversion efficiencies near 10% and temporal stability are necessary for market entry.

Heliatek (an IAPP spin-off; http://www.heliatek.com/en/page/index.php) and the Fraunhofer Institute for Photonic Microsystems (http://www.ipms.fraunhofer.de/en/) are pursuing vapor-deposited "P-i-N" devices (anode/p-doped hole transport material/BHJ active layer/n-doped electron transport layer/cathode). The function of doping the interfacial layers is to enhance ohmic contact with the electrodes while blocking undesired carriers. The active layers are typically a mixture of a metallo-phthalocyanine donor combined with a fullerene acceptor. Hole-transport-layer (HTL) dopants are strong acceptors such as tetrafluoro-TCNQ (tetracyanoquinodimethane), and electron-transport-layer (ETL) dopants may be alkali metals. OPV performance is dependent on a number of growth parameters, with maximum certified power conversion efficiencies to date of 6.07 +/-0.2% for small-molecule tandem solar cells on 2 cm^2 (Green et al. 2010) and 7.7% for small-molecule tandem solar cells on 1 cm^2 (6 April 2010 press release, http://www.heliatek.com). The IAPP materials development includes collaborations with Bäuerle's group at the University of Ulm, which is developing new polythiophenes. Figure 3.4 shows some common small molecule device structures and materials.

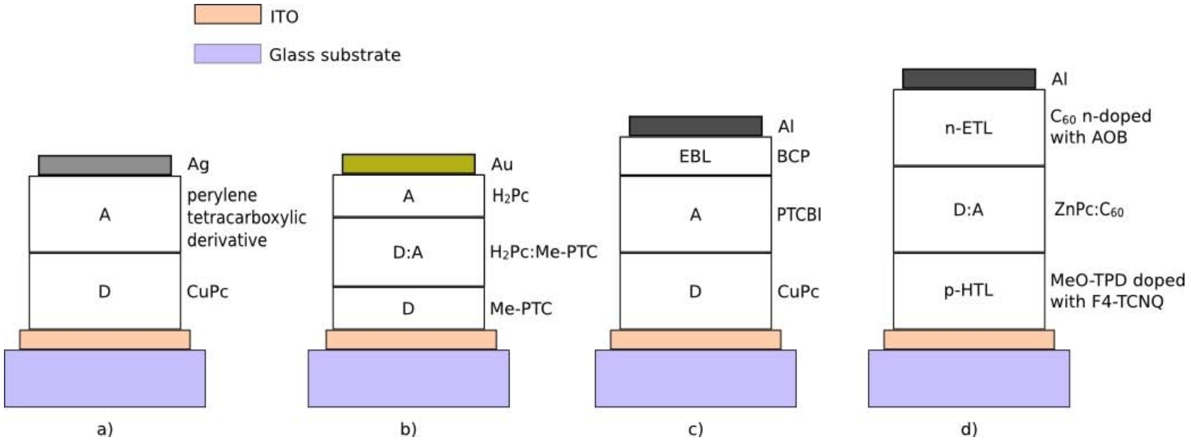

Figure 3.4. Small-molecule organic photovoltaic cell device structures (courtesy of Dr. Moritz Riede, Technical University of Dresden).

Solution-processed OPVs generally consist of donor polymers (usually a polythiophene derivative) and fullerene acceptors in a BHJ motif, as shown in Figure 3.5. Power conversion efficiencies as high as 6% have been recently reported for single-device (as opposed to tandem) cells (Liang et al. 2009). Konarka in the United States and Austria, and the Carbon Trust, University of Cambridge, and Imperial College in the UK are all active in this area. Solarmer, Plextronics, and Polyera are examples of U.S. companies developing polymer BHJ cell materials.

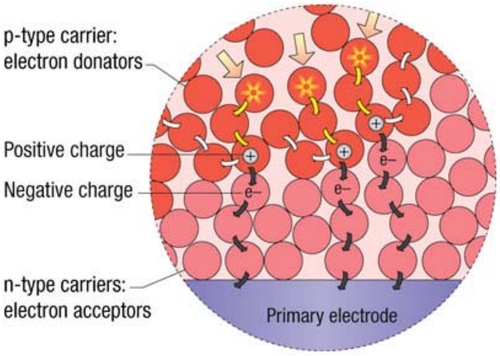

Figure 3.5. Schematic of a polymer bulk heterojunction solar cell (courtesy of R. Gaudiana and C. Brabec, Konarka Corp.).

The public power conversion efficiency record (as of late 2009) is 6.1% (see Figure 3.6), from the Yu group at the University of Chicago collaborating with Solarmer Corporation (Liang et al. 2009), whereas the highest certified value is 7.9 +/-0.3% for an unpublished single-junction polymer solar cell on 4 mm^2 (Green et al. 2010). Another intriguing option is solution-processed small-molecule BHJ OPVs, with the attraction being that small molecules are monodisperse and easier to purify and/or modify than polymers. Several groups in the United States, some with Italian collaboration, have pushed efficiencies of small-molecule BHJ devices to near 3.0% using oligothiophene, squaraine, or arylacetylene donors combined with fullerene acceptors (Tamayo et al. 2008; Silvestri et al. 2008). Unlike the vacuum-deposition methods discussed above, solution-deposition methods are challenged by the difficulty of fabricating multilayer structures without layer depositions risking the dissolution or swelling of previous layers. Useful tactics are orthogonal solvents (e.g., aqueous vs. organic) or layers that crosslink, hence become insoluble, after deposition.

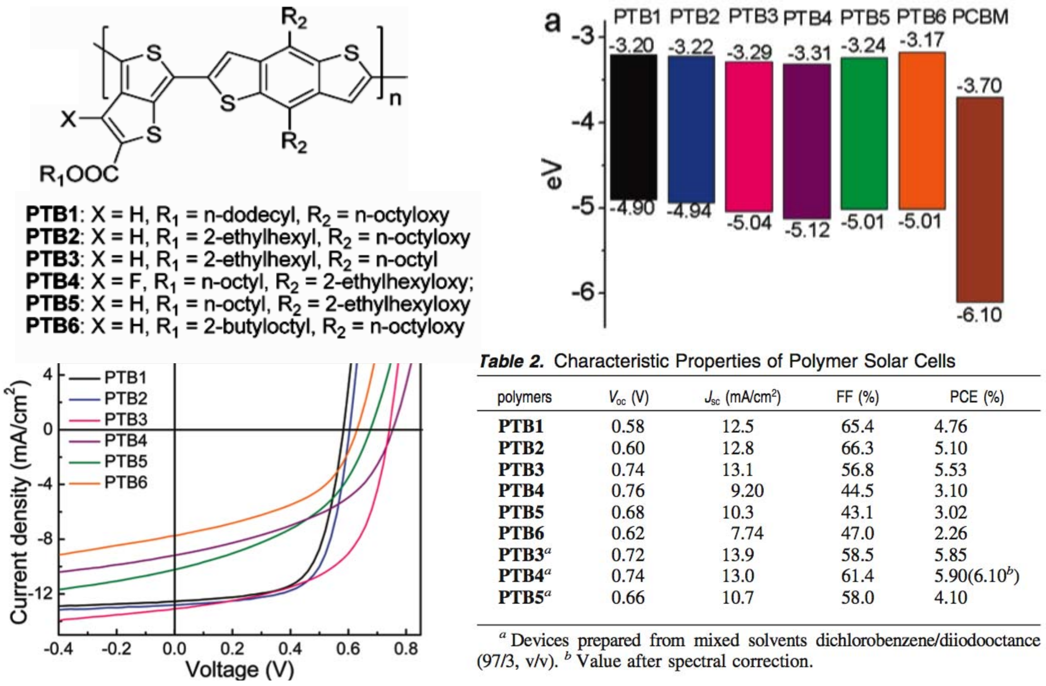

Table 2. Characteristic Properties of Polymer Solar Cells

polymers	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	PCE (%)
PTB1	0.58	12.5	65.4	4.76
PTB2	0.60	12.8	66.3	5.10
PTB3	0.74	13.1	56.8	5.53
PTB4	0.76	9.20	44.5	3.10
PTB5	0.68	10.3	43.1	3.02
PTB6	0.62	7.74	47.0	2.26
PTB3^a	0.72	13.9	58.5	5.85
PTB4^a	0.74	13.0	61.4	5.90(6.10^b)
PTB5^a	0.66	10.7	58.0	4.10

^{a} Devices prepared from mixed solvents dichlorobenzene/diiodooctance (97/3, v/v). ^{b} Value after spectral correction.

Figure 3.6. Polymer bulk-heterojunction solar cells designed to capture a large portion of the solar spectrum and exhibiting high power conversion efficiency (from Liang et al. 2009).

Major active layer materials development goals for all OPVs are to

- maximize the capture of solar photons by broadening the optical absorption profile (primarily by decreasing the optical band gap)
- increase the open circuit voltage, which scales approximately as the difference between the donor HOMO and the acceptor LUMO
- maximize the efficiency of exciton splitting without using too great a donor LUMO-acceptor LUMO driving force (which would waste energy)
- provide sufficient carrier mobility to transport holes and electrons rapidly away from the donor-acceptor interface
- provide a means, through the active regions, for the correct carriers to cross the organic-electrode interface for collection while blocking incorrect carriers

Although much has been recently learned about BHJ microstructure, electrical, and optical properties (Dennler et al. 2008; Ohkita et al. 2008), the community is nowhere near having the capability to rationally design optimum materials. Much of the industrial effort in this materials development area is highly proprietary.

As with OLEDs, there is a need in all OPVs for interfacial layers that enhance charge extraction, block undesired carriers, and prevent exciton quenching at the electrodes. PEDOT:PSS is used as an anode interfacial layer in most solution-processed OPVs, despite its many limitations (see above), and there is much consensus that there must be some better material. Recent results indicate that either self-assembled organosilane-based cross-linking polymer blends (Hains and Marks 2008; Hains et al. 2009) or vapor-deposited p-type metal oxides such as NiO (Irwin et al. 2008) are superior interfacial layers. The former gives comparable or superior OPV performance compared to PEDOT:PSS, but greater thermal stability. The latter gives power conversion efficiencies as high as 5.2%.

In regard to ITO as the transparent conducting anode material, there was a general consensus among the WTEC team's European hosts that something cheaper (containing less In) and more conductive would be highly desirable. The IAPP group showed that thin metal layers (e.g., of silver) could be used to replace ITO (Meiss, Riede, and Leo 2009). Other options that are being pursued include oxide materials such as Al-doped ZnO (AZO), and transparent conducting oxide multilayers, e.g., highly conductive In-doped CdO covered with a thin layer of ITO (Liu et al. 2009).

As with OLEDs, materials for encapsulating environmentally sensitive OPV materials are also important; for flexible devices, significant progress has been made in fabricating inorganic/polymer multilayer barrier structures (Dennler et al. 2006). The requirements are more stringent than for food packaging. As noted in the OLED discussion above, there is good reason to believe that sufficient lowering of the HOMO and LUMO energies should significantly enhance stability to O_2 and/or H_2O intrusion. Note that OPV stability issues are even more demanding than for OLEDs, because many solar cell products must be stable on illuminated roof tops for many years to be able to compete with inorganic photovoltaic (PV) materials.

The choice of plastic substrate materials is another relevant issue for OPVs, with transparent polyesters such as PET or more expensive but more thermally robust PEN currently most favored.

There was a general consensus among the European specialists visited by the WTEC team that if OPV efficiencies can be increased and stabilities improved, the possibility of roll-to-roll manufacturing should make OPV production prices lower than for inorganic photovoltaic materials. Furthermore, organic PV materials should be nontoxic (unlike cadmium telluride, CdTe), and all components should be abundantly available in the earth (unlike some forecasts for In and Te supplies). The future of OPVs will depend heavily on successful materials development efforts.

ORGANIC AND HYBRID ORGANIC-INORGANIC FIELD-EFFECT TRANSISTORS

Materials components essential to optimum organic field-effect transistor (OFET) performance include the semiconductor; the gate dielectric; the source, drain, and gate contacts; and the substrate (Facchetti 2007; Murphy and Frechet 2007). Figure 3.7 shows diagrams of the common types of organic transistors.

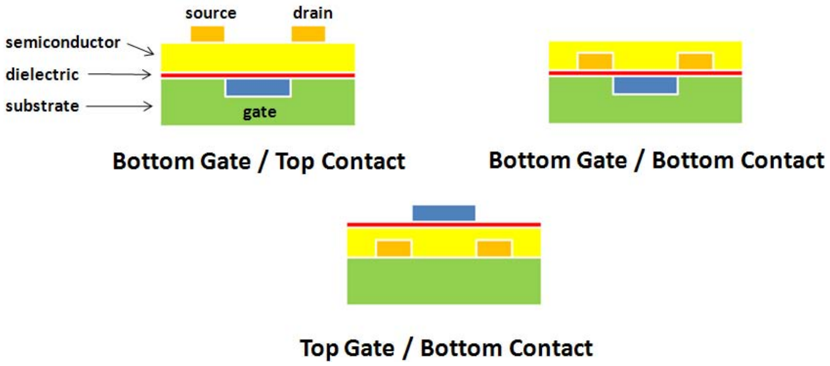

Figure 3.7. Some common types of transistor structures used in hybrid flexible electronics.

The attraction of organic materials is their innate compatibility with plastics and inks for printing; however, there was a general consensus within the laboratories the WTEC team visited that inorganic materials would also be acceptable if they could be processed and printed with good efficiency. While researchers at those laboratories generally agree that the first applications for OFETs will likely be as display backplanes driving electronics, radio-frequency identification (RFID) devices, and various types of smart cards and sensors, it is also likely that what is learned about the relationships between molecular-scale architecture, film-formation/microstructure, environmental stabilization, and transport properties will simultaneously advance the development of useful OLED and OPV materials.

Semiconductor Materials

In regard to organic semiconductors, both small-molecule and polymeric systems are under active investigation all over the world. Major efforts are in progress at the University of Cambridge, the Max Planck Institute in Stuttgart, Erlangen University, Imperial College, Plastic Logic, BASF, Philips, and the Holst Center, to name a few institutions and companies. The European effort is impressively well integrated. When vapor-deposited under optimum high-vacuum conditions and with appropriate gate dielectrics (see below), small-molecule materials can yield films with mobilities as high as ~5 cm^2/Vs—considerably in excess of the mobility of amorphous silicon (~0.5–1.0 cm^2/Vs). As single crystals, organic semiconductor mobilities can be as high as ~20 cm^2/Vs. However, for printing and other coating technologies used in device fabrication, solution-phase film growth is generally believed necessary (Sirringhaus 2009; Friend 2009; Sirringhaus and Ando 2008). Although the mobilities of solution-processed films are usually lower than for vapor-deposited films, due to less controlled overall order and intergrain growth, progress has been made in understanding and controlling these factors. Successful growth tactics include optimizing the solvent, deposition temperature, substrate/gate surface chemistry and morphology, and thermal or solvent annealing conditions.

Advances have also been made in increasing the mobilities of polymeric organic semiconductors by creating more structurally regular and defect-free architectures, substituted with extended organic side-chains to optimize solubility and self-organization, yet allow close interchain π-π packing to maximize charge transport. By implementing these approaches, solution-cast polymer film mobilities as high as ~1 cm^2/Vs have been achieved (Smits et al. 2008; Yan et al. 2009; Usta et al. 2009).

Historically, p-type organic semiconductors (hole majority carriers) were developed first, and there was even some question as to whether n-type materials (electron majority carriers) could be made with acceptable mobilities and environmental stability. The special value of n-type organic semiconductors is in organic CMOS devices, which would require both p- and n-type semiconductors for complementary circuits, but which would provide higher OFET modulation speeds and lower power consumption (Jones et al. 2007; Letizia et al. 2008; Cai et al. 2006). Considerable experimental and theoretical progress has been made in this area, for both n-type small-molecule and polymeric semiconductors, by appending electron-withdrawing substituents (e.g., fluoroalkyl, fluoroacyl, carbonyl, dicyanomethylene, etc.) to the conjugated molecular cores to lower the HOMO and LUMO energies, hence to stabilize the charge carriers from reaction with ambient O_2 and/or H_2O (Jones et al. 2007; Letizia et al. 2008; Cai et al. 2006). Combined with molecular and macromolecular structure designs that facilitate close π-π stacking, the net result is processable and printable, indefinitely ambient-stable n-type organic semiconductors with mobilities as high as ~1 cm^2/Vs (Yan et al. 2009, Jones et al. 2007; Letizia et al. 2008; Cai et al. 2006). Several generations of complementary logic devices such as ring oscillators and inverters have been printed with these materials (Yoo et al. 2007; Klauk et al. 2007).

Inorganic semiconductors have also been investigated for flexible electronics. For room-temperature vapor-deposited oxides such as In_2O_3, mobilities on glass/ITO substrates are as high as ~120 cm^2/Vs (with a self-assembled organic gate dielectric), and the resulting TFTs are optically transparent (Wang et al. 2006; Fortunato et al. 2008; Nomura et al. 2004). This performance level falls somewhat on PET/ITO substrates to ~20 cm^2/Vs for flexible, transparent devices (Wang et al. 2007). Solution-processed inorganic chalcogenide and oxide semiconductor films have not yet advanced to this level. A major challenge has been to lower the annealing temperatures of the inorganic films to those compatible with plastic substrates. Annealing is required to crystallize the film microstructures and enhance intergrain connectivity for maximum mobility. Recently, aqueous solution-processed amorphous In-Sn-O films were reported to exhibit mobilities of ~10–20 cm^2/Vs after annealing at 250 °C (in combination with a self-assembled organic gate dielectric) (Kim et al. 2009). TFTs can also be fabricated at room temperature from aqueous suspensions of oxide nanowires, and arsenic (As)–doped In_2O_3 nanowires exhibit mobilities as large as ~2000 cm^2/Vs (Chen et al. 2009). It is then possible to fabricate transparent monochrome active-matrix OLED displays driven entirely by nanowire TFTs (Chen et al. 2009; Ju et al. 2008; Sun, Peterson, and Sirringhaus 2007). Major activities in the flexible, transparent inorganic TFT area are centered in Japan, Portugal, and the United States.

Gate Dielectric Materials

Gate dielectrics are essential components of TFTs (Figure 3.7) and modulate the current flow. The equations describing TFT drain current are given in equations 3.1 (linear regime) and 3.2 (saturation regime), where μ is the field-effect carrier mobility of the semiconductor, W the channel width, L the channel length, C the capacitance per unit area of dielectric layer, VT the threshold voltage, VSD the drain voltage, and VG the gate voltage. Note that C scales as κ/thickness.

$$(3.1) \qquad \left(I_{\mathrm{SD}}\right)_{lin} = \left(\frac{W}{L}\right)\mu C\left(\mathrm{V_G} - \mathrm{V_T} - \frac{\mathrm{V_{SD}}}{2}\right)\mathrm{V_{SD}}$$

$$(3.2) \qquad \left(I_{\mathrm{SD}}\right)_{sat} = \left(\frac{W}{2L}\right)\mu C\left(\mathrm{V_G} - \mathrm{V_T}\right)^2$$

In conventional Si electronics, recent advances include substituting high dielectric constant (high-κ) doped HfO_2 for SiO_2, resulting in lower electrical leakage/tunneling through the dielectric and lower operating voltages (DiBenedetto et al. 2009; Veres et al. 2004). For organic and related inorganic TFTs, higher κ gate dielectrics significantly reduce the device operating voltage, which can be important when mobility is modest. In addition, it has been shown by Friend et al. at the University of Cambridge that surface hydroxyl (-OH) groups on the dielectric surface can react with and/or trap the electrons of n-type organic semiconductors electrons, thereby compromising performance. Removal of the –OH groups by silylation and/or using semiconductors with very low LUMO energies can suppress this effect (Chua et al. 2005; Yoon et al. 2006). It can be seen from the above relationships that increasing κ and minimizing the dielectric layer thickness can be beneficial as long as current does not leak/tunnel through the thin dielectric layer.

The Vuillaume (Lenfant et al. 2003) and Klauk (Halik et al. 2004) groups in France and Germany pioneered the use of self-assembled monolayers (SAMs) based on organosilane and organophosphonic acid reagents as low-leakage gate dielectrics; these conformal coatings can be applied by solution deposition techniques. Another approach to organic gate dielectrics (Figure 3.8) utilizes a modular, layer-by-layer wet self-assembly of σ- and π- building blocks to make self-assembled nanodielectrics (SANDs), which exhibit substantial κ values, very low leakage, high breakdown fields, and high thermal stability (DiBenedetto et al. 2009; Veres et al. 2004; Yoon, Facchetti, and Marks 2005).

These gate dielectrics are compatible with a wide variety of organic and inorganic semiconductors and enhance TFT performance by a combination of suppressing trapped charge at the semiconductor-dielectric interface and providing a favorable surface for semiconductor crystallization. Yet another successful strategy from Frisbie et al. at the University of Minnesota has employed high- ion-conducting gels as gate dielectrics. This clever approach offers high performance, materials tunability, and printability, although the response may be slow under some conditions (Lee et al. 2009; Cho, Lee, and Xia 2008; Herlogsson, Noh, and Zhao 2008).

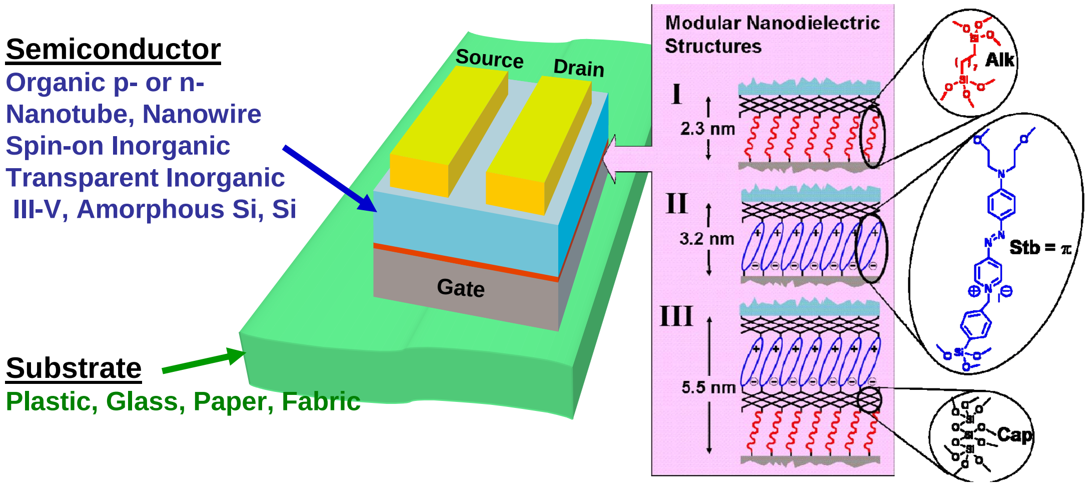

Figure 3.8. Structures of self-assembled nanodielectrics used in organic and inorganic TFTs.

Contact Materials

Also important in all TFT structures are the conductive materials used for source, drain, and gate electrodes. Key contact electronic issues include matching the work functions of metallic contacts to the semiconductors HOMO or LUMO energies for efficient p- or n-channel conduction, respectively. How the metallic surfaces are prepared for subsequent organic semiconductor deposition has also been shown to influence charge injection/extraction efficiency. The reasons appear to be a combination of matching surface energies for good wetting and/or more ordered nucleation and growth, to passivation for preventing reaction between the semiconductor and the metallic electrodes, to creating surface dipoles to aid charge transport across the electrode-organic interface. For example, self-assembled thiol monolayers are commonly used to treat gold and other noble metal electrodes for various combinations of these reasons (Dholakia 2006). In contrast, vapor deposition of metals on organic films, where a metal surface is not exposed to ambient contaminants, is thought to create cleaner, more regular interfaces. Other materials that have been used as contacts include carbon nanotubes and other conductive carbons, and conducting polymers such as PEDOT:PSS and polyaniline (Yan 2009; Facchetti 2007).

Deposition techniques for contact materials depend on the type of device structure (see Figure 3.7 above). For bottom contacts, it may be desirable, and it has been possible, to pattern the contacts using conventional photolithographic approaches, especially when very close dimensional tolerances are required. Alternatively, for both bottom and top contact structures, metallic contacts can be deposited by vapor deposition with shadow masks or by printing nanoparticle-based inks using inkjet, gravure, and other techniques. The inks are then sometimes thermally annealed to drive off the organic binder and sinter the metal nanoparticles to more contiguous and conductive microstructures. For carbon and organic contact materials, printing techniques are widely used. Much of the printing research activity in this area is centered in Germany and Asia.

Substrate Materials

Conventional substrate materials such as doped silicon with a native oxide coating are routinely used for exploratory investigations of TFT materials properties such as microstructure and interfaces, and how they can be optimized via processing conditions. For transparent electronics, glass has been used with ITO as a bottom gate material (Nomura et al. 2004; Wang et al. 2006; Wang et al. 2007). However, the substrates of greatest interest for hybrid flexible electronics are, of course, low-cost plastics. The limitations of most low-cost polymeric materials for this application are thermal—both low glass transition temperatures and coefficients of thermal expansion that may not be well matched. If optically transparent hybrid flexible electronics are desired, then there are additional restrictions on the polymeric substrate material. Nevertheless, much progress has been made in this area, including using heat-shrunk PET, PEN, and various high-temperature polyimides. In regard to both organic and inorganic semiconductors, much progress has been made in reducing film growth and annealing temperatures for solution-processed materials (Yan et al. 2009; Kim et al. 2009; Jeong et al. 2010). Major activity in this area is centered in Asia and the United States.

ORGANIC LIGHT-EMITTING TRANSISTORS

By combining the functions of organic transistors (hole and electron injection) with emission, devices can be fabricated that combine electrical switching and electroluminescent display properties (see Figures 3.9 and 3.10). Muccini’s group in the CNR laboratories in Bologna is a world leader in this area (Muccini 2006; Capelli et al. 2010), with a substantial, complementary effort by Sirringhaus in the Cavendish laboratories in Cambridge (Gwinner et al. 2009; Zaumseil et al. 2008). Muccini’s group recently demonstrated that the efficiency of organic light-emitting transistors (OLETs) out-performs the equivalent OLEDs (Capelli et al. 2010). Key materials challenges for OLETs are good and matched hole and electron mobilities, and efficient, compatible emission for red, green, and blue. The attractions of such devices are high efficiency, high brightness, high switching speeds, longer device lifetimes arising from better control of charge flow, relatively easy integration with silicon, and easier fabrication than conventional OLED and electronics fabrication/integration.

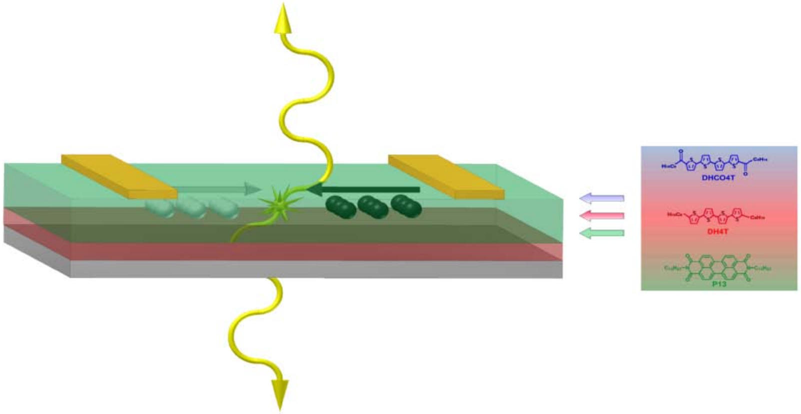

Figure 3.9. Organic light-emitting transistor structure and function (courtesy of M. Muccini, CNR Bologna).

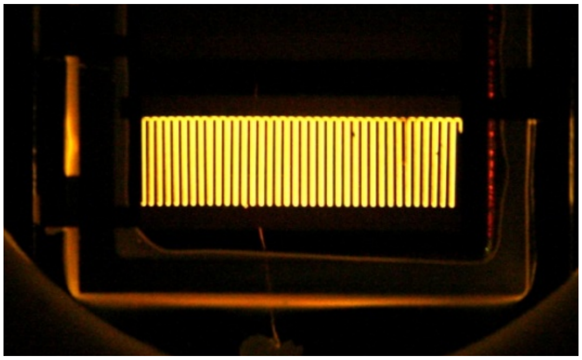

Figure 3.10. Picture of an OLET with interdigitated source and drain structure (courtesy of M. Muccini, CNR Bologna).

CONCLUSIONS

Materials development, materials evaluation, device engineering, and the transition to manufacturable devices are well integrated in Europe. There are far stronger connections between universities, government laboratories, and industrial efforts, as well as a longer-term commitment to being leaders in this field. Impressive examples are found in the UK, Germany, Austria, the Netherlands, and Italy, many of which are undergirded by large EU programs. Many individual academic, government, and corporate groups in the United States are carrying out innovative materials research in diverse areas of hybrid flexible electronics, but their efforts are in general not coordinated, nor is it clear that there is long-term Federal commitment to progress in this field.

REFERENCES

Baldo, M.A., M.E. Thompson, and S.R. Forrest. 2000. High-efficiency fluorescent organic light-emitting devices using a phosphorescent sensitizer. *Nature* 403:750-753. DOI:10.1038/35001541.

Cai, X.Y., M.W. Burand, C.R. Newman, D.A. da Silva Filho, T.M. Pappenfus, M.M. Bader, J.-L. Brédas, K.R. Mann, and C.D. Frisbie. 2006. N- and p-channel transport behavior in thin film transistors based on tricyanovinyl-capped oligothiophenes. *J. Phys. Chem. B* 110:14590-14597. DOI:10.1021/jp061168v

Capelli, R., S. Toffanin, G. Generali, H. Husta, A. Facchetti, and M. Muccini, 2010. Organic light-emitting transistors with an efficiency that out-perfroms that of the equivalent light-emitting diodes *Nature Mater.* 9:496–503. DOI:10.1038/nmat2751

Chen, P.-C., G. Shen, H. Chen, Y.-G. Ha, C. Wu, S. Sukcharoenchoke, Y. Fu, J. Liu, A. Facchetti, T.J. Marks, M.E. Thompson, and C. Zhou. 2009. High-performance single-crystalline arsenic-doped indium oxide nanowires for transparent thin-film transistors and active matrix organic light-emitting diode displays. *ACS Nano* 3(11):3383–3390. DOI:10.1021/nn900704c

Cho, J.H., J. Lee, Y. Xia, B.S. Kim, Y. He, M.J. Renn, T.P. Lodge, and C.D. Frisbie. 2008. Printable ion-gel gate dielectrics for low-voltage polymer thin-film transistors on plastic. *Nature Mater.* 7:900-906. DOI:10.1038/nmat2291

Chua, L.L., J. Zaumseil, J.-F. Chang, E.C.-W. Ou, P.K.-H. Ho, H. Sirringhaus, and R.H. Friend. 2005. General observation of n-type field-effect behaviour in organic semiconductors. *Nature* 434:194-199. DOI:10.1038/nature03376

Dameron, A.A., S.D. Davidson, B.B. Burton, P.F. Carcia, R.S. McLean, and S.M. George. 2008. Gas diffusion barriers on polymers using multilayers fabricated by Al_2O_3 and rapid SiO_2 atomic layer deposition. *J. Phys. Chem. C* 112:4573-4580.

Dennler, G., C. Lungenschmied, H. Neugebauer, N.S. Sariciftci, M. Latrèche, G. Czeremuszkin, and M.R. Wertheimer. 2006. A new encapsulation solution for flexible organic solar cells. *Thin Solid Films* 511-512:349-353. DOI:10.1016/j.tsf.2005.12.091

Dennler, G., M.C. Scharber, T. Ameri, P. Denk, K. Forberich, C. Waldauf, and C.J. Brabec. 2008. Design rules for donors in bulk-heterojunction tandem solar cells: Towards 15% energy-conversion efficiency. *Adv. Mater.* 20(3):579-583.

DiBenedetto, S.A., A. Facchetti, M.A. Ratner, and T.J. Marks. 2009. Molecular self-assembled monolayers and multilayers for organic and unconventional inorganic thin-film transistor applications. *Advan. Mater.* 21:1407-1433. DOI:10.1002/adma.200803267

Dholakia, G.R., M. Meyyappan, A. Facchetti, and T.J. Marks. 2006. Monolayer to multilayer nanostructural growth transition in n-type oligothiophenes and implications for electronic transport. *Nano Letters* 6:2447-2455, and references cited therein.

Dinelli, F., R. Capelli, M.A. Loi, M. Murgia, M. Muccini, A. Facchetti, and T.J. Marks. 2006. High-mobility ambipolar transport in organic light-emitting transistors. *Advan. Mater.* 18:1416-1425. DOI:10.1002/adma.200502164

Engadget/Weblogs, Inc. 2009a (Jan. 9). OLED Association and Samsung show flexible screen. http://www.engadget.com/2009/01/09/oled-association-and-samsung-show-flexible-screen/.

———. 2009b (April 16). Kyocera shows off preposterous, beautiful EOS folding OLED phone concept. http://www.engadget.com/2009/04/16/kyocera-shows-off-preposterous-beautiful-eos-folding-oled-phone/.

Facchetti, A. 2007. Semiconductors for organic transistors. *Mater. Today* 10(3):28-37.

Fortunato, E.M.C., L.M.N. Pereira, P.M.C. Barquinha, A.M. Botelho do Rego, G. Gonçalves, A. Vilà, J.R. Morante, and R.F.P. Martins. 2008. High mobility indium free amorphous oxide thin film transistors. *Appl. Phys. Lett.* 92:222103. DOI:10.1063/1.2937473

Friend, R. 2009. Organic materials for large area electronics. *Materials Science Forum* 608:159-179. DOI:10.4028/www.scientific.net/MSF.608.159

Green, M., K. Emery, Y. Hishikawa, and W. Warta, 2010. Solar cell efficiency tables (version 35). *Prog. Photovolt: Res. Appl.* 18:144-150. DOI:10.1002/pip.974

Günes, S., H. Neugebauer, and N.S. Sariciftci. 2007. Conjugated polymer-based organic solar cells. *Chem. Rev.* 107:1324-1338.

Gwinner M.C., S. Khodabakhsh, H. Giessen, and H. Sirringhaus. 2009. Simultaneous optimization of light gain and charge transport in ambipolar light-emitting polymer field-effect transistors. *Chem. Mater.* 21:4425-4433. DOI:10.1021/cm900982a

Hains, A.W., A.B.F. Martinson, J. Liu, M.D. Irwin, and T.J. Marks. 2009. Anode interfacial tuning via electron-blocking/hole-transport layers and indium tin oxide surface treatment in bulk-heterojunction organic photovoltaic cells. *Advan. Funct. Mater.* DOI:10.1002/adfm.200901045.

Hains, A.W., and T.J. Marks. 2008. High-efficiency hole extraction/electron-blocking layer to replace poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) in bulk-heterojunction polymer solar cells. *Appl. Phys. Lett.* 92:023504-1-3. DOI:10.1063/1.2834697.

Halik, M., H. Klauk, U. Zschieschang, G. Schmid, C. Dehm, M. Schuitz, S.C. Maisch, F. Effenberger, M Brunnbauer, and F. Stellacci. 2004. Low-voltage organic transistors with an amorphous molecular gate dielectric. *Nature* 43l:963-966. DOI:10.1038/nature02987

Hatwar, T.K., and J. Spindler. 2008. Development of white OLED technology for application in full-color displays and solid-state lighting. Chapter 4 in *Luminescent materials and applications*, A. Kitai, ed., 111-159. DOI:10.1002/9780470985687

Herlogsson, L., Y.Y. Noh, N. Zhao, X. Crispin, H. Sirringhaus, and M. Berggren. 2008. Downscaling of organic field-effect transistors with a polyelectrolyte gate insulator. *Advan. Mater.* 20:4708-4714. DOI:10.1002/adma.200801756

Huang, Q., G.A. Evmenenko, P. Dutta, P. Lee, N.R. Armstrong, and T.J. Marks. 2005. Covalently bound hole-injecting nanostructures. Systematics of molecular architecture, thickness, saturation, and electron-blocking characteristics on organic light-emitting diode luminance, turn-on voltage, and quantum efficiency *J. Am. Chem. Soc.* 127:10227-10242.

Huang, Q., G.A. Evmenenko, J. Lee, P. Dutta, and T.J. Marks. 2007. Triarylamine siloxane anode functionalization/hole injection layers in high efficiency/high luminance small-molecule green-and blue-emitting organic light-emitting diodes. A systematic investigation. *J. Appl. Phys*. 101:093101.

Irwin, M.D., D.B. Buchholz, A.W. Hains, R.P.H. Chang, and T.J. Marks. 2008. p-Type semiconducting nickel oxide as an efficiency-enhancing anode interfacial layer in polymer bulk-heterojunction solar cells. *Proc. Natl. Acad. Sci*. 105:2783-2787. DOI:10.1073/pnas.0711990105

Jeong, S., Y.-G. Ha, J. Moon, A. Facchetti, and T.J. Marks. 2010. Thin-film transistors based on solution-processed low-temperature annealed Ga-doped amorphous oxide semiconductor films. *Advanced Materials* (in press).

Jones, B.A., A. Facchetti, M.R. Wasielewski, and T.J. Marks. 2007. Tuning orbital energetics in arylene diimide semiconductors. Materials design for ambient stability of n-type charge transport. *J. Am. Chem. Soc*. 129:15259-15278. DOI:10.1021/ja075242e

Ju, S., J. Li, J. Liu, P.-C. Chen, Y.-G. Ha, C. Zhou, A. Facchetti, D.B. Janes, and T.J. Marks. 2008. Transparent active matrix organic light-emitting diode displays driven by nanowire transistor circuitry. *Nano Lett*. 8:997-1004. DOI:10.1021/nl072538+

Kim, H.S., M.-G. Kim, Y.-G. Ha, M. Kanatzidis, T.J. Marks, and A. Facchetti. 2009. Low-temperature solution-processed amorphous indium tin oxide field-effect transistors. *J. Am. Chem. Soc*. 131:10826-10827. DOI:10.1021/ja903886r

Kim, J.Y., K. Lee, N.E. Coates, D. Moses, T.-Q. Nguyen, M. Dante, and A.J. Heeger. 2007. Efficient tandem polymer solar cells fabricated by all-solution processing. *Science* 317:222-225. DOI:10.1126/science.1141711

Kippelen, B., and J.L. Bredas. 2009. Organic photovoltaics. *Energy Environ. Sci*. 2:251-261.

Klauk, H., G. Schmid, W. Radlik, W. Weber, L. Zhou, C.D. Sheraw, J.A. Nichols, and T.N. Jackson, T. N. 2003. Contact resistance in organic thin film transistors. *Solid-State Electron.* 47:297-301. DOI:10.1016/S0038-1101(02)00210-1

Klauk, H., U. Zschieschang, J. Pflaum, and M. Halik. 2007. Ultralow-power organic complementary circuits. *Nature* 445:745-748. DOI:10.1038/nature05533

Lee, J., L.G. Kaake, J.H. Cho, X.-Y. Zhu, T.P. Lodge, and C.D. Frisbie. 2009. Ion gel-gated polymer thin-film transistors: Operating mechanism and characterization of gate dielectric capacitance, switching speed, and stability. *J. Phys. Chem. C* 113:8972-8981. DOI:10.1021/jp901426e

Lenfant, S., C. Krzeminski, C. Delerue, G. Allan, and D. Vuillaume. 2003. Molecular rectifying diodes from self-assembly on silicon. *Nano Lett*. 3(6):3741-3746. DOI:10.1021/nl034162f

Letizia, J.A., M.R. Salata, C.M. Tribout, A. Facchetti, M.A. Ratner, and T.J. Marks. 2008. n-Channel polymers by design: Optimizing the interplay of solubilizing substituents, crystal packing, and field-effect transistor characteristics in polymeric bithiophene-imide semiconductors. *J. Am. Chem. Soc*. 130:9679-9694. DOI:10.1021/ja710815a

Liang, Y., D. Feng, Y. Wu, S.-T. Tsai, G. Li, C. Ray, and L. Yu. 2009. Highly efficient solar cell polymers developed via fine-tuning of structural and electronic properties. *J. Am. Chem. Soc*. 131:7792-7799. DOI:10.1021/ja901545q

Liu, J., A. Hains, J. Servaites, M. Ratner, and T.J. Marks. 2009. Highly conductive bilayer transparent conducting oxide thin films for large-area organic photovoltaic cells. *Chem. Mater*. 21(21):5258-5263. DOI:10.1021/cm902265n

Martin, G. 2006. Chapter 1 in *Handbook of optoelectronics*, Vol. II, J.P. Dakin and R.G.W. Brown, eds. Boca Raton, Fl: CRC Press.

Meiss, J., M.K. Riede, and K. Leo. 2009. Optimizing the morphology of metal multilayer films for indium tin oxide (ITO)-free inverted organic solar cells. *J. Appl. Phys*. 105:063108. DOI:10.1063/1.3100039

Muccini, M. 2006. A bright future for organic field-effect transistors. *Nature Mater*. 5:605-613. DOI:10.1038/nmat1699

Murphy, A.R., and J.M.J. Frechet. 2007. Organic semiconducting oligomers for use in thin film transistors. *Chem. Rev*. 107:1066-1096.

Ni, J., H. Yan, A. Wang, Y. Yang, C.L. Stern, A.W. Metz, S. Jin, L. Wang, T.J. Marks, J. Ireland, and C.R. Kannewurf. 2005. MOCVD-derived highly transparent, conductive zinc- and tin-doped indium oxide thin films: Precursor synthesis, metastable phase film growth and characterization, and application as anodes in polymer light-emitting diodes. *J. Am. Chem. Soc*. 127:5613-5624.

Nomura K., H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono. 2004. Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors. *Nature* 432:488-492. DOI:10.1038/nature03090

Ohkita, H., S. Cook, Y. Astuti, W. Duffy, S. Tierney, W. Zhang, M. Heeney, I. McCulloch, J. Nelson, D.D.C. Bradley, and J.R. Durrant. 2008. Charge carrier formation in polythiophene/fullerene blend films studied by transient absorption spectroscopy. *J. Am. Chem. Soc*. 130(10):3030-3042. DOI:10.1021/ja076568q

Reineke, S., B. Luessem, and K. Leo. 2009. Organische leuchtdioden: Zeit für eine neue lichtquelle (Organic light emitting diodes: Time for a new light source). *Physik in Unserer Zeit* 40:170-171.

Riede, M., T. Mueller, W. Tress, R. Schueppel, and K. Leo. 2008. Small-molecule solar cells—Status and perspectives. *Nanotechnology* 19:424001. DOI: 10.1088/0957-4484/19/42/424001

Sharma, A., A. Haldi, P.J. Hotchkiss, S.R. Marder, and B. Kippelen. 2009. Effect of phosphonic acid surface modifiers on the work function of indium tin oxide and on the charge injection barrier into organic single-layer diodes. *J. Appl. Phys*. 105(7):074511. DOI:10.1063/1.3095490

Silvestri, F., M.D. Irwin, L. Beverina, A. Facchetti, G.A. Pagani, and T.J. Marks. 2008. Efficient squaraine-based solution processable bulk-heterojunction solar cells. *J. Am. Chem. Soc*. 130:17640-17641. DOI:10.1021/ja8067879

Sirringhaus, H. 2009. Materials and applications for solution-processed organic field-effect transistors. *Proc. IEEE* 97(9):1570-1579. DOI:10.1109/JPROC.2009.2021680

Sirringhaus, H., and M. Ando. 2008. Materials challenges and applications of solution-processed organic field-effect transistors. *MRS Bull*. 33:676-682.

Smits, E.C.P., S.G. Mathijssen, P.A. van Hal, S. Setayesh, T.C. Geuns, K.A. Mutsaers, E. Cantatore, H.J. Wondergem, O. Werzer, R. Resel, M. Kemerink, S. Kirchmeyer, A.M. Muzafarov, S.A. Ponomarenko, B. de Boer, P.W. Blom, and D.M. de Leeuw. 2008. Bottom-up organic integrated circuits. *Nature* 455:956-959. DOI:10.1038/nature07320

Sun, B.Q., R.L. Peterson, and H. Sirringhaus. 2007. Low-temperature sintering of in-plane self-assembled ZnO nanorods for solution-processed high-performance thin film transistors. *J. Phys. Chem. C* 111:18831-18835.

Tamayo, A.B., X.D. Dang, B. Walker, J. Seo, T. Kent, and T.Q. Nguyen. 2008. A low band gap, solution processable oligothiophene with a dialkylated diketopyrrolopyrrole chromophore for use in bulk heterojunction solar cells. *Appl. Phys. Lett*. 94:103301. DOI:10.1063/1.3086897

Usta, H., C. Risko, Z.M. Wang, H. Huang, M.K. Deliomeroglu, A. Zhukhovitskiy, A. Facchetti, and T.J. Marks. 2009. Design, synthesis, and characterization of ladder-type molecules and polymers. Air-stable, solution-processable n-channel and ambipolar semiconductors for thin-film transistors via experiment and theory. *J. Amer. Chem. Soc.* 131:5586-5608. DOI:10.1021/ja809555c

Veres, J., S. Ogier, and G. Lloyd Dago de Leeuw. 2004. Gate insulators in organic field-effect transistors. *Chem. Mater.* 16(23):4543-4555. DOI:10.1021/cm049598q

Walzer, K., B. Maennig, M. Pfeiffer, and K. Leo. 2007. Highly efficient organic devices based on electrically doped transport layers. *Chem. Rev*. 107(4):1233–1271. DOI:10.1021/cr050156n.

Wang, L., M.-H. Yoon, A. Facchetti, and T.J. Marks. 2007. Flexible inorganic/organic hybrid thin-film transistors using all-transparent component materials. *Advan. Mater*. 19:3252-3256. DOI:10.1002/adma.200700393

Wang, L., M.-H. Yoon, G. Lu, A. Facchetti, Y. Yang, and T.J. Marks. 2006. High-performance transparent inorganic–organic hybrid thin-film n-type transistors. *Nature Mater*. 5:893-900. DOI:10.1038/nmat1755

Yan, H., Z.H. Chen, Y. Zheng, C. Newman, J.R. Quinn, F. Dötz, M. Kastler, and A. Facchetti. 2009. A high-mobility electron-transporting polymer for printed transistors. *Nature* 457:679-687. DOI:10.1038/nature07727

Yoo, B., B.A. Jones, D. Basu, D. Fine, T. Jung, S. Mohapatra, A. Facchetti, K. Dimmler, M.R. Wasielewski, T.J. Marks, and A. Dodabalapur. 2007. High-performance solution-deposited n-channel organic transistors and their complementary circuits. *Advan. Mater*. 19:4028-4032. DOI:10.1002/adma.200601969

Yoon, M.-H., A. Facchetti, and T.J. Marks. 2005. -π molecular dielectric multilayers for low-voltage organic thin-film transistors. *Proc. Nat. Acad. Sci.* 102:4678-4682. DOI:10.1073/pnas.0501027102

Yoon, M.-H., C. Kim, A. Facchetti, and T.J. Marks. 2006. Gate dielectric chemical structure–organic field-effect transistor performance correlations for electron, hole, and ambipolar organic semiconductors *J. Am. Chem. Soc*. 128:12851-12869. DOI:10.1021/ja063290d

Zaumseil, J., C.R. McNeill, M. Bird, D.L. Smith, P.P. Ruden, M. Roberts, M.J. McKiernan, R.H. Friend, and H. Sirringhaus. 2008. Quantum efficiency of ambipolar light-emitting polymer field-effect transistors. *J. Appl. Phys.* 103:064517. DOI:10.1063/1.2894723

CHAPTER 4

DEVICE CHALLENGES

Ana Claudia Arias and Ananth Dodabalapur

INTRODUCTION

In the field of organic electronics, many new materials have been synthesized in order to increase luminescence or achieve a specific color in a light-emitting diode, to improve charge generation and light absorption in solar cells, or to improve charge mobility in a thin film transistor (TFT). There are many types of electronic, optoelectronic, optical, and other varieties of thin-film devices that can be formed on flexible substrates. The materials systems used in the construction of these devices include purely organic materials, purely inorganic materials, and combinations of organic and inorganic materials along with metals for contacts. In reviewing the progress that the WTEC panel observed in Europe with respect to device fabrication, this chapter discusses the needs and challenges for each of three categories of devices: (1) organic light-emitting diodes (OLEDs), (2) organic photovoltaic devices (OPVs), and (3) thin-film transistors (TFTs). The general geometry of these devices is shown schematically in Figure 4.1. A fourth, emerging category of devices (not discussed here) is bioelectronic devices. The discussion in this chapter is focused on organic-based devices because most of the groups the WTEC panel visited work on such devices, although many of them have now begun to also study printable inorganic materials (semiconductors and dielectrics).[5]

It is in a device structure that interfaces between semiconductors, conductors, and insulators are studied and optimized. In each category of devices there are specific challenges that need to be overcome, but goals of long lifetimes and high performance are shared for all types of devices. All materials used in OLEDs and photovoltaic devices must show long lifetimes, because these devices will be applied to televisions and displays that are used for years.

ORGANIC LIGHT-EMITTING DIODES

The discovery in 1990 at the Cavendish Laboratory at the University of Cambridge that the conjugated polymer poly(para-phenylene vinylene) (PPV) could be used in electroluminescent devices (Burroughes et al. 1990) became the starting point of a new area in conjugated polymer science. Soon after the initial report, a number of other conjugated polymers were successfully used in electroluminescent devices; today several companies are interested in commercializing displays based on these devices. Electroluminescence is defined as the emissive recombination of electrons and holes where these are injected from separate electrodes, as compared to photoluminescence, where the electron and hole are created when a photon is absorbed.

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[5] For more information on these device types, the reader is referred to Müllen and Scherf 2006; Geffroy, Roy, and Prat 2006; Hoppe and Sariciftci 2004; Forrest 2005; Horowitz 1998; and Sirringhaus 2005.

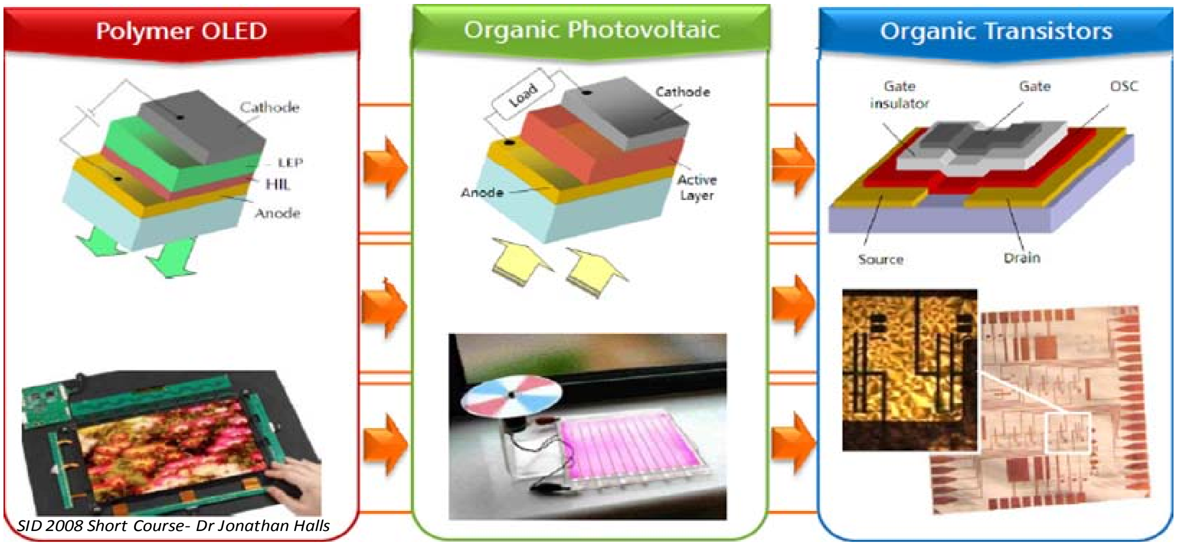

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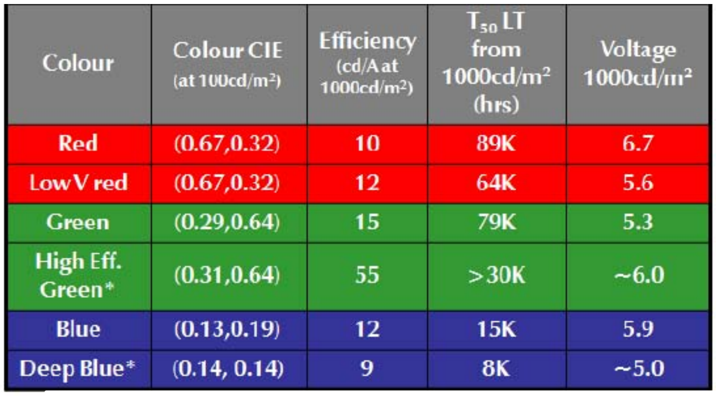
Figure 4.1. Schematic representation of light-emitting diodes, photovoltaic devices, and thin-film transistors. These three types of devices represent the building blocks of organic-based flexible electronics (courtesy of Dr Jonathan Halls, CDT).

The usual way of arranging electrodes in polymer light-emitting diodes is to use a sandwich-type of structure having a low-work-function material injecting electrons from one side and an electrode with higher work function on the other side to inject holes, as shown in Figure 4.2. Organic small-molecule-based OLEDs, which were first reported by Tang and coworkers at Kodak (Tang and Van Slyke 1987), are fabricated using the same generic structure used for polymer-based OLEDs. Small-molecule-based OLEDs show higher efficiencies when a hole-transporting layer is deposited between the anode and the emissive layer, and an electron-transporting layer is placed between the cathode and the emissive layer (see Figure 3.1 in Chapter 3).

Indium tin oxide (ITO) thin films are commonly used as the transparent electrodes in OLEDs, and careful processing conditions are used in order to control the work function, roughness, and transparency of the electrode before deposition of the subsequent layer (Kim et al. 1998). poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) is sometimes used in polymer-based OLEDs in order to better match the work function of the transparent electrode with the semiconducting material. Flexible arrays of polymer-based OLEDs using PEDOT:PSS as transparent electrodes were demonstrated by Linköping University in 1995 (Granström and Inganäs 1995).

Cambridge Display Technology (CDT) is a pioneer in the development of polymer-based organic light-emitting diodes (P-OLEDs). CDT was founded in 1998 as a spin-off company from the Cavendish Laboratory. Since then, CDT has demonstrated P-OLEDs with high efficiency in the whole color spectrum, as shown in Figure 4.2. The blue emission has proven to be the hardest to achieve true color and good lifetimes. The table in Figure 4.2 summarizes efficiency, lifetime, and operation voltage for red, green, and blue P-OLEDs fabricated by CDT. CDT has demonstrated printed full-color displays using P-OLEDs processed from solution that show good film formation and high luminescence (see Figure 4.3)



Colour	Colour CIE (at 100cd/m²)	Efficiency (cd/A at 1000cd/m²)	T_{50} LT from 1000cd/m² (hrs)	Voltage 1000cd/m²
Red	(0.67,0.32)	10	89K	6.7
Low V red	(0.67,0.32)	12	64K	5.6
Green	(0.29,0.64)	15	79K	5.3
High Eff. Green*	(0.31,0.64)	55	>30K	~6.0
Blue	(0.13,0.19)	12	15K	5.9
Deep Blue*	(0.14, 0.14)	9	8K	~5.0

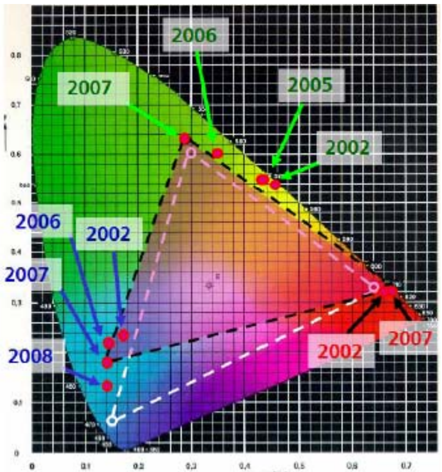


Figure 4.2. (*Left*) Table describing characteristics of red, green, and blue pOLEDs developed by Cambridge Display Technology, and (*right*) CIE color space diagram showing the year CDT achieved each specific color milestone (courtesy of Dr. Jonathan Halls, CDT).

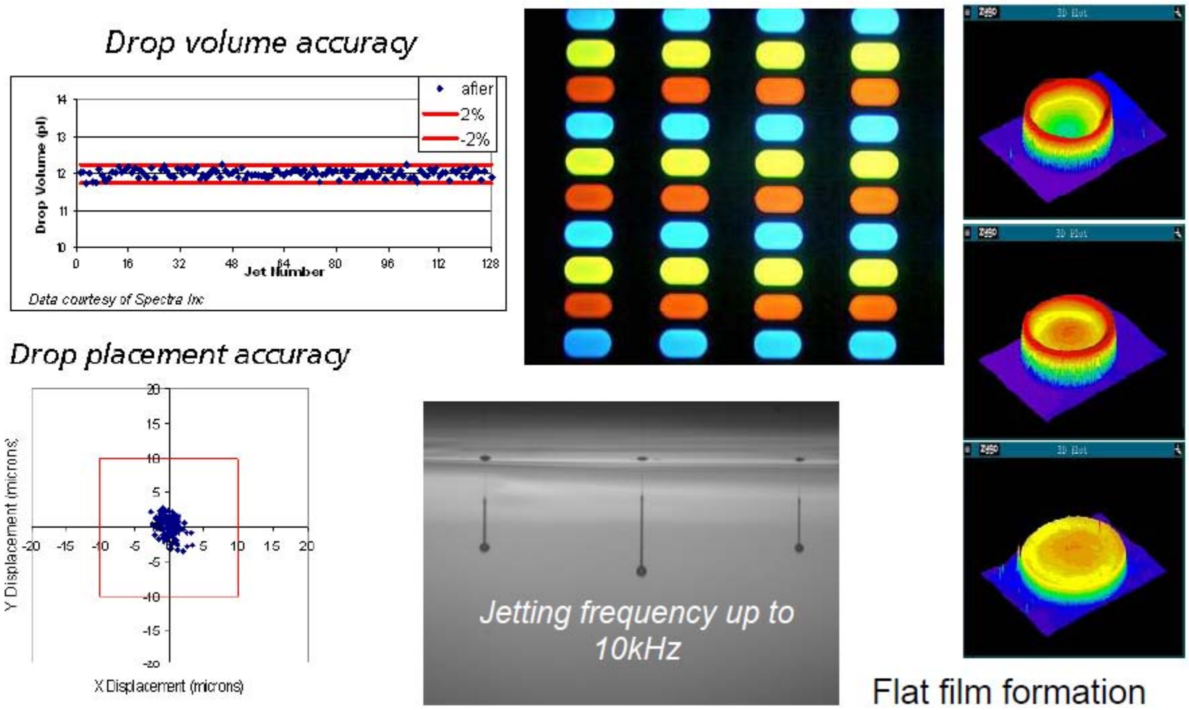


Figure 4.3. Polymer-based OLEDs are processed from solution, allowing inkjet printing to be used as a deposition and patterning technique. The inkjet process shows a drop volume of 12 pl with drop placement accuracy better than 5 μm when using inkjet frequency up to 10 kHz (courtesy of Dr. Jonathan Halls, CDT).

Needs for Flexible OLEDs

Below are listed some of the R&D needs for flexible OLEDs that were identified by the leading researchers the WTEC team visited:

- Continued development of high-performance emitting materials
- Continued development of high-performance flexible active matrix backplanes

- Development of solution-processed high-performance materials to simplify processing of large area displays
- Development of “display grade” flexible substrates that provide an adequate barrier to moisture without compromising flexibility and performance
- Development of processing tools capable of handling flexible substrates
- Development and qualification of scalable high-volume production equipment and processes to realize cost benefits due to economies of scale
- Development of gang-testing tools to assess OLED module performance during accelerated life testing
- Continued development of improved barrier materials and device structures to increase OLED product longevity

Advanced White OLEDs

Solid-state lighting has emerged as a major application area for organic LEDs, and several groups worldwide have reported power efficiencies in excess of 50 lumens/W. This is much larger than that of incandescent lamps (~15 Lumens/W) and comparable to fluorescent lamps (50-100 lumens/W). There are also significant efforts to commercialize white OLED-based lighting technology (Service 2005). The WTEC team visited Novaled AG in Dresden, which is a spin-off from the Institute for Applied Photophysics (IAPP) of the Technical University of Dresden, as well as visiting the IAPP itself. For the realization of high-efficiency white OLEDs, complex multilayer structures are employed that possess multiple emission layers in addition to the hole and electron transporting and exciton blocking layers. For white light emission, there are typically three emission zones for blue, green, and orange/red photons. The thicknesses of these emission zone layers as well as other interlayers and transport layers needed for optimal operation are precisely controlled. For this reason, vacuum sublimation is believed to be advantageous because multiyear doped films with precisely controlled thicknesses (in the nm range) can be achieved. In an organic LED, the external power efficiency is given by the equation

$$\eta_E = \chi \gamma \beta \phi_L \frac{\varepsilon_p}{eV} \tag{4.1}$$

where χ is the out-coupling factor, γ is the charge balance factor, β is the probability of producing an emissive exciton, ϕ_L is the quantum yield of the emitter, ε_p is the energy of the emitted photon and V is the applied voltage. The out-coupling factor is typically 0.2 in organic LEDs and is the largest loss mechanism. It is due to the large fraction of light unable to escape from the device due to total internal reflection in the layers comprising the device, anode, and substrate. The IAPP group increases the out-coupling factor by three methods: (1) use of high index substrates, (2) use of hemispheres, and (3) patterned surfaces that randomize the emission direction of photons.

These approaches substantially increase the value of χ from the ~0.2 that is typical for organic LEDs. The high-efficiency white OLEDS reported by the IAPP group (see Figure 4.4) use three emission zones, each with a phosphorescent dopant (Reineke et al. 2009). Phosphorescent dopants result in very high quantum yields because nearly all the excitons formed are triplet excitons, which decay radiatively with good efficiency. For comparison, in fluorescent dopants, nearly 75% of the excitons are non-emissive triplets. Additional improvements to device performance are obtained by employing doped semiconductor layers with relatively high conductivity at the interfaces with the anode and cathode. This serves to reduce the operating voltage. The IAPP group pioneered the use of such conducting layers to obtain high-performance devices.

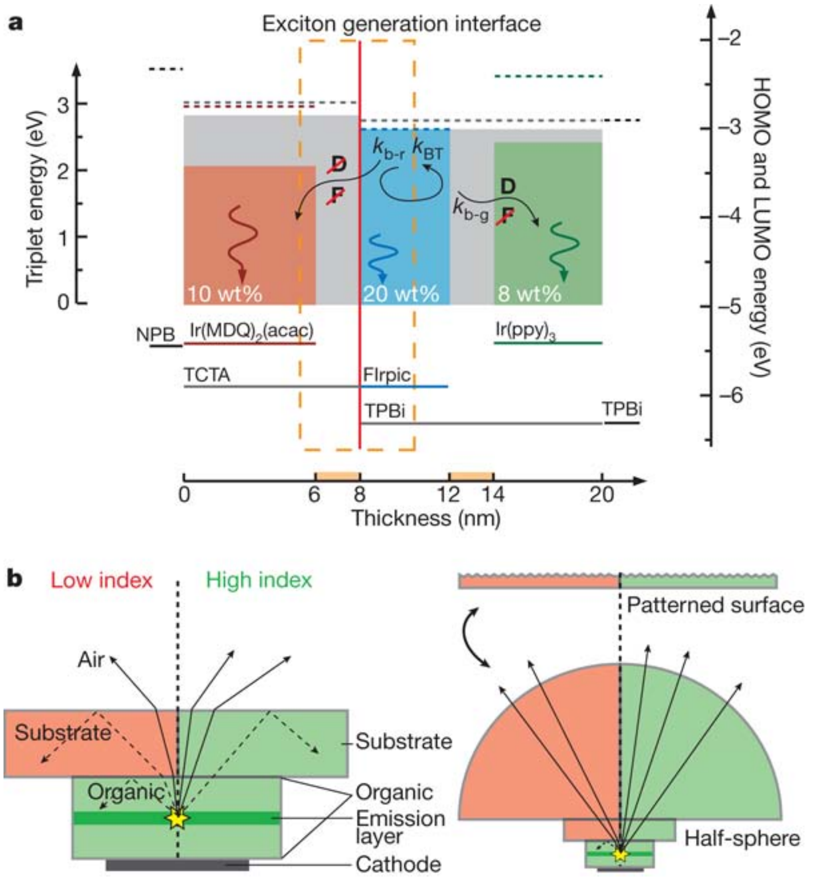


Figure 4.4. Illustration of the operation of the very efficient white OLED from the group of Karl Leo and coworkers at IAPP, Dresden: (a) schematic layer structure and exciton formation pathways; (b) illustration of methods to increase out-coupling efficiency including the use of half-spheres, patterned surfaces, and high index substrates (from Reineke et al. 2009).

ORGANIC PHOTOVOLTAICS

There are many types of device architectures that have been employed to fabricate OPV cells. Two of the successful architectures are the bulk heterojunction (illustrated in Figure 4.5) and multilayer sublimed semiconductor device with small molecule-based active layers (Peumans, Yakimov, and Forrest 2003). In bulk heterojunction solar cells, the absorption layer consists of a pair of materials with offset energy levels to facilitate photoinduced charge transfer, which dissociates excitons at interfaces between the two semiconductor materials that constitute the bulk heterojunction. Bulk heterojunction solar cells have been made mainly with solution-processable materials, although it is also possible to realize such devices with sublimed small molecule pairs (Xue et al. 2005). The solution-processed materials include a pair of polymers, small-molecule polymer pairs, and small-molecule pairs and inorganic-organic pairs. Many of the institutions the WTEC panel visited—including Cambridge University, Imperial College, University of Linköping, Johannes Kepler University, and Konarka—had active research programs in this area.

Sublimed small-molecule-based solar cells are also promising for commercial applications. The layers next to the contacts can be doped to increase conductivities, which will lower the contact resistance and improve fill factors and efficiencies. The doping technology originated at IAPP Dresden and is being further investigated at Heliatek. Interestingly, according to the WTEC panel's hosts at Heliatek, these vacuum-processed devices are not much more expensive to fabricate than solution-processed solar cells, (see site report in Appendix B).

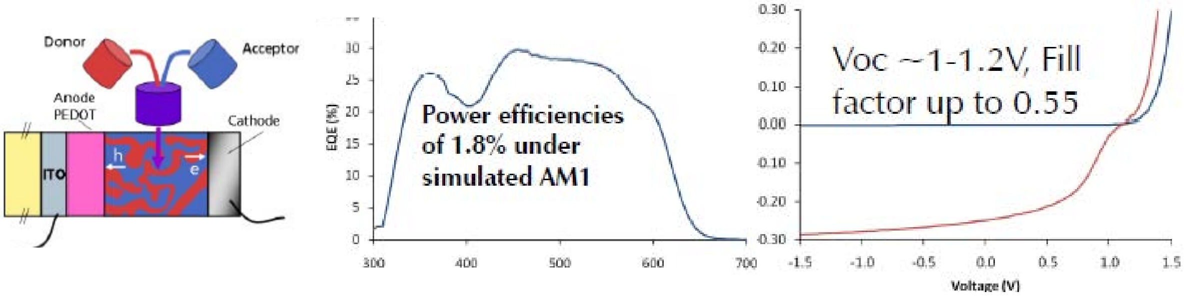


Figure 4.5. (*Left*) Schematic device structure of an organic solar cell based on polymer blends, (*center*) the external quantum efficiency performance, and (*left*) current X voltage characteristics of such a device.

The year 2009 saw a significant reduction in the costs of silicon solar cells—both crystalline and multicrystalline. This is mainly due to significant increases in the capacity of bulk silicon material production and refinement. There have also been improvements in the economics of thin-film solar technologies such as CdTe and a-Si solar cells. To be competitive, the operating lifetimes of organic solar cells need to be significantly increased, along with increasing power conversion efficiency, which for modules is currently below 5%. This needs to approach 10% for OPV to compete in non-niche applications. If the efficiencies and operating lifetimes of organic-based solar cells increase to acceptable levels (>10% and >15 years, respectively), then huge markets will open up, because of the inherently low OPV production costs.

Needs for Flexible OPVs

Below are listed some of the technological needs for flexible OPVs that the WTEC team's hosts identified:

- Continued development of improved barrier/packaging materials to increase PV module longevity
- Continued development of higher-performance materials and novel cell structures
- Development of cell modules that optimize light capture
- Further research on improving the fill factor by reducing series resistance and increasing shunt resistance
- Development of design tools to model system layout and to identify optimal architecture, e.g., modular versus integrated
- Expansion of existing standards and development of new standards, e.g., PV interoperability with the power grid
- Establishment of industry association groups to promote products and to engage end-customers

THIN FILM TRANSISTORS

There has been a lot of progress in several of the laboratories in Europe in developing organic- and polymer-based semiconductor transistors for several applications, such as electronic paper backplanes, RFID tags, labels, etc. The structure of a bottom-gate, bottom-contact transistor and a top gate transistor are shown in Figure 4.6. Much of the emphasis in recent years is on developing materials (both semiconductor and insulator) that are easily printed. With such solution-processed materials, Merck reported a field-effect mobility of ~4 cm^2/V-s, which is among the highest reported for solution-based organic transistors (Heckmeier 2009).

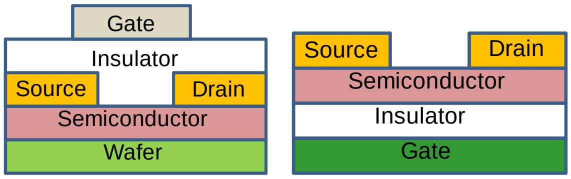


Figure 4.6. Schematic diagrams of a bottom-gate (*left*) and a top-gate thin film transistor (*right*).

The top-gate structure is also used by PolyIC in its basic device structure for RFID tags (Clemens et al. 2004). PolyIC typically employs poly(3-hexylthiophene) as the semiconductor, due to the low cost and wide availability of this material. The gate insulator used by PolyIC also serves as a protection layer. While most of the circuits reported to date are based on p-channel FETs, complementary transistors have been recently used as well.

The bottom contact geometry has been used by researchers at the Max Planck Institute in Stuttgart to fabricate complementary circuits with very low operating voltages (Klauk et al. 2007). The bottom gate geometry is also typically employed in display drivers such as electronic paper backplanes. The channel length is a key parameter in devices, and the value of the channel length depends on fabrication method.

PolyIC also uses a range of other fabrication methods, including photolithography as lab process, desktop printing for process development, and high-speed roll-to-roll printing for production. With photolithography, channel lengths in the few micron range are easily obtained. With printing, the channel lengths depend on the printing method, materials, and various other details such as surface treatments.

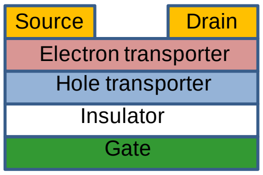


Figure 4.7. Schematic representation of bilayer ambipolar light-emitting transistor.

When the active semiconductor layer can transport both carrier types, ambipolar transistors can be created. Such transistors are useful in logic and light emission. In light-emitting ambipolar organic transistors, the active semiconductor is often a single material, but it can also be a bilayer of two semiconductors: one an electron transporter and the other a hole transporter (Dinelli et al. 2006). The schematics of two types of light-emitting transistor are shown in Figures 4.7 and 4.8. The advantages of light-emitting transistors is that balanced electron and hole injection and transport can be obtained. The efficiencies typically obtained to date with light-emitting transistors (~5%) are lower than those of OLEDs, for which external quantum efficiencies of >20% are regularly reported.

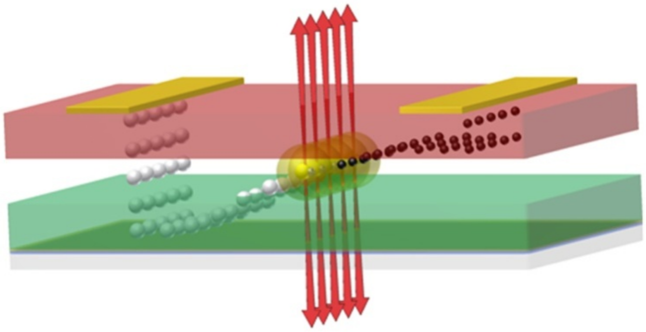


Figure 4.8. Schematic representation of the tri-layer OLET developed at CNR (courtesy of M. Muccini, CNR Bologna).

Light-emitting transistor research is being carried out in many universities and institutes, including the University of Cambridge and CNR Bologna, where a startup (E.T.C. srl, with participation from Saes Getters S.p.A.) has been set up to develop and commercialize these devices. Recent results by CNR, Polyera, and others have demonstrated that organic light-emitting transistors (Figure 4.8) can be fabricated with an efficiency that out-performs that of the equivalent light-emitting diodes (Capelli et al. 2010).

The basic bottom-gated organic transistor device also functions as a chemical sensor. The active semiconductor device is exposed to the ambient, which contains the analyte molecules. The interaction between the analyte molecules and the semiconductor produces a change in the semiconducting properties, which manifests as a measurable change in device properties (such as current, threshold voltage, etc.). Figure 4.9 illustrates the basic device structure of an organic thin-film transistor (OTFT) sensor.

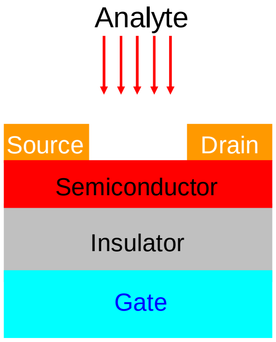


Figure 4.9. Illustration of an OTFT chemical vapor sensor. The semiconductor is exposed to the ambient containing analyte molecules.

The addition of receptor molecules adds additional selectivity and sensitivity to the process. The University of Bari group of Luisa Torsi and coworkers (see site report in Appendix B) has been engaged in this research for more than a decade. Some of the highlights of their research include the ability to discriminate very similar molecules that differ only in their chirality (Torsi et al. 2008).

Needs for Field-Effect-Based Components

Below are listed some of the needs for field-effect-based components that the WTEC team's hosts identified:

- Establishment of an open database comprising NMOS, PMOS, and CMOS device operating parameters for product designers using a statistically significant number of devices; mastery of device parametric curves
- Development of design tools that are offered to the public to help proliferate the technology
- Continued development of improved p-type and n-type materials to increase product opportunities
- Organization of groups to discuss interoperability standards for hybrid systems

CONCLUSION

A variety of hybrid flexible electronics products are in early commercialization with a greater number in final stages of product development.

REFERENCES

Burroughes, J.H., D.D.C. Bradley, A.R. Brown, R.N. Marks, K. Mackay, R.H. Friend, P.L. Burns, and A.B. Holmes. 1990. Light-emitting-diodes based on conjugated polymers. *Nature* 347:539–541.

Capelli, R., S. Toffanin, G. Generali, H. Husta, A. Facchetti, and M. Muccini, 2010. Organic light-emitting transistors with an efficiency that out-performs that of the equivalent light-emitting diodes. *Nature Mater.* 9:496–503. DOI:10.1038/nmat2751

Clemens, W., W. Fix, J. Ficker, A. Knoblock, and A. Ullman. 2004. From polymer transistors toward printed electronics. *Journal of Materials Research* 19(7):1963-1973.

Dinelli. F., R. Capelli, M.A. Loi, M. Murgia, M. Muccini, A. Facchetti, and T.J. Marks. 2006. High-mobility ambipolar transport in organic light-emitting transistors. *Adv. Mater.* 18(11):1416-1420.

Forrest, S. R. 2005. The limits to organic photovoltaic cell efficiency. *MRS Bull.* 30:28–32.

Geffroy, B., P. Roy, and C. Prat. 2006. Organic light-emitting diode (OLED) technology: Materials, devices and display technologies. *Polymer International* 55(6): 572-582.

Granström, M., and O. Inganäs. 1995. Flexible arrays of submicrometer-sized polymeric light emitting diodes. *Adv. Mater.* 7(12):1012–1014.

Heckmeier, M. 2009. Status and roadmap of functional materials for printed electronics. Plenary Talk, International Workshop on Flexible and Printed Electronics, Muju, Korea, November 2009.

Hoppe, H., and N.S. Sariciftci. 2004. Organic solar cells: An overview. *J. Mater. Res.* 19(7):1924–1945.

Horowitz. G. 1998. Organic field-effect transistors. *Adv. Mater.* 10(5):365–377.

Kim, J.S., M. Granström, R.H. Friend, N. Johansson, W.R. Salaneck, R. Daik, W.J. Feast, and F.J. Cacialli. 1998. Indium-tin oxide treatments for single- and double-layer polymeric light-emitting diodes: The relation between the anode physical, chemical, and morphological properties and the device performance. *J. Appl. Phys.* 84(12):6859–6870.

Klauk, H., U. Zschieschang, J. Pflaum, and M. Halik. 2007. Ultralow-power organic complementary circuits. *Nature* 445:745-748.

Müllen, K., and U. Scherf, eds. 2006. Organic light emitting devices: Synthesis, properties and applications. Weinheim: Wiley-VCH.

Peumans, P., A. Yakimov, and S.R. Forrest. 2003. Small molecular weight organic thin-film photodetectors and solar cells. *J. Appl. Phys.* 93(7):3693–3723.

Reineke, S., F. Lindner, G. Schwartz, N. Seidler, K. Walzer, B. Lüssem, and K. Leo. 2009. White organic light-emitting diodes with fluorescent tube efficiency. *Nature* 459:234–238.

Service, R.F. 2005. Organic LEDs look forward to a bright, white future. *Science* 310(5755):1762–1763.

Sirringhaus, H. 2005. Device physics of solution-processed organic field-effect transistors. *Adv. Mater.* 17:2411–2425.

Tang, C.W., and S.A. Van Slyke. 1987. Organic electroluminescent diodes. *Appl. Phys. Lett.* 51:913–915.

Torsi, L., G.M. Farinola, F. Marinelli, M.C. Tanese, O.H. Omar, L. Valli, F. Babudri, F. Palmisano, P.G. Zambonini, and F. Naso. 2008. A sensitivity-enhanced field-effect chiral sensor. *Nat. Mater.* 7:412–417.

Xue, J., B.P. Rand, S. Uchida, and S.R. Forrest. 2005. Mixed donor-acceptor molecular heterojunctions for photovoltaic applications. II. Device performance. *J. Appl. Phys.* 98(12):124903.

CHAPTER 5

SYSTEMS OPPORTUNITIES

Ana Claudia Arias and Daniel Gamota

INTRODUCTION

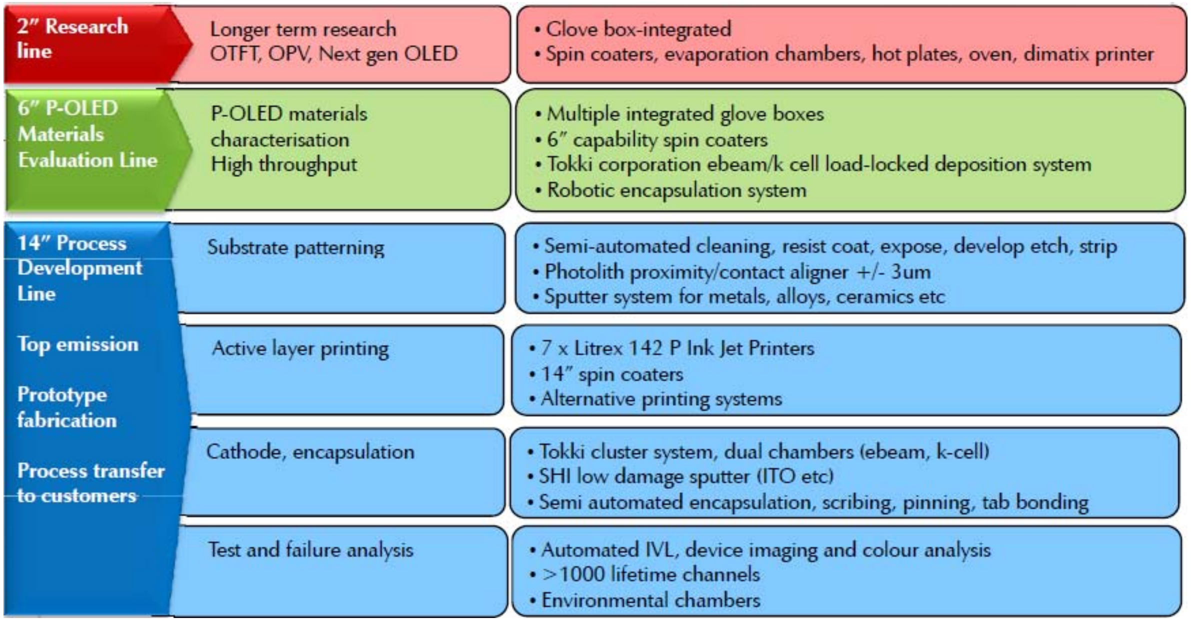
A driving force for research in the area of hybrid flexible electronics is the need for high-performance electronics that can be fabricated using less-expensive processes capable of delivering large-area, conformal, foldable, and lightweight devices. In order to achieve flexible devices, researchers have taken many different processing approaches. Some groups have processed conventional silicon devices to be very thin and subsequently detached from the substrate to form flexible circuits when placed onto flexible substrates (Ahn et al. 2007; Yoon et al. 2008). Other groups have developed fabrication approaches based on changing the processing temperatures of silicon and conventional dielectric layers to allow deposition of these materials onto flexible polymeric substrates (Ng et al. 2009; Gleskova and Wagner 1999; Wagner et al. 2000). Another approach observed in this field of research is the use of organic semiconductors that can be deposited by sputtering or solution processing. These approaches are likely to open new manufacturing opportunities (Burroughes et al. 1990; Halls et al. 1995; Sirringhaus et al. 1999; Sirringhaus, Tessler, and Friend 1998).

This chapter reviews systems and products the WTEC panel observed during its site visits in Europe. These use a number of the approaches noted above, which can be broadly classified into five general groups:

1. Organic light-emitting diodes (OLED)
2. Organic photovoltaics (OPV)
3. Reflective displays
4. Field-effect-transistor (FET)–based components: active matrix backplanes for displays, biosensors, RFID, memory, etc.
5. Other systems and products: capacitive array structures, microfluidic components for diagnostics, resistor structures for heaters, etc.

ORGANIC LIGHT-EMITTING DIODES

Cambridge Display Technology (CDT; http://www.cdtltd.co.uk/) is a pioneer in the development of polymer-based light-emitting diodes (PLEDs). CDT was founded in 1992 and bought by Sumitomo Chemical Group in 2007. The research and development activities of CDT involve materials and ink development, device architecture, and prototypes based on inkjet-deposited polymer semiconductors. CDT has three lines of research and development for OLEDs, including 900 m^2 of cleanroom, test, and metrology labs: a 2-inch research line, a 6-inch P-OLED materials evaluation line, and a 14-inch process development line. The focus and capabilities of each of these research and development lines are summarized in Figure 5.1.



2″ Research line	Longer term research OTFT, OPV, Next gen OLED	• Glove box-integrated • Spin coaters, evaporation chambers, hot plates, oven, dimatix printer
6″ P-OLED Materials Evaluation Line	P-OLED materials characterisation High throughput	• Multiple integrated glove boxes • 6″ capability spin coaters • Tokki corporation ebeam/k cell load-locked deposition system • Robotic encapsulation system
14″ Process Development Line **Top emission** **Prototype fabrication** **Process transfer to customers**	Substrate patterning	• Semi-automated cleaning, resist coat, expose, develop etch, strip • Photolith proximity/contact aligner +/- 3um • Sputter system for metals, alloys, ceramics etc
	Active layer printing	• 7 x Litrex 142 P Ink Jet Printers • 14″ spin coaters • Alternative printing systems
	Cathode, encapsulation	• Tokki cluster system, dual chambers (ebeam, k-cell) • SHI low damage sputter (ITO etc) • Semi automated encapsulation, scribing, pinning, tab bonding
	Test and failure analysis	• Automated IVL, device imaging and colour analysis • >1000 lifetime channels • Environmental chambers

Figure 5.1. Summary of research and development lines created at CDT to synthesize and optimize polymer materials, print display prototypes, and transfer manufacturing processes to customers (courtesy of Dr. Jonathan Halls, CDT).

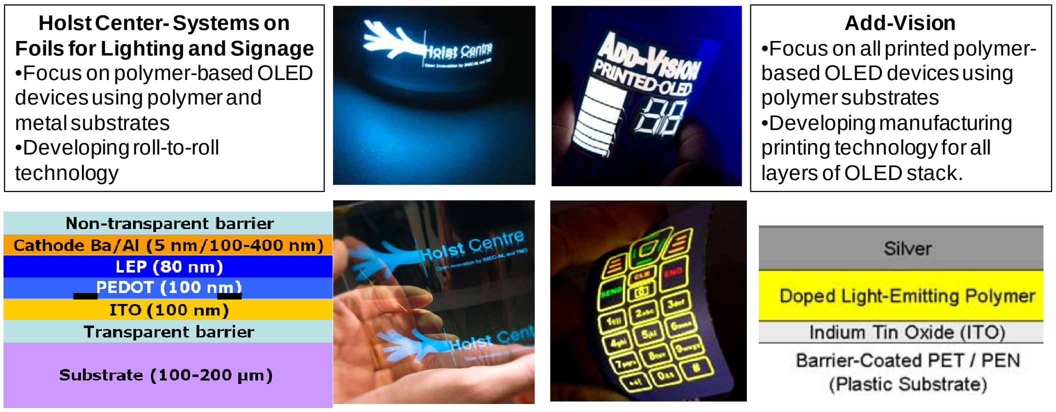
Throughout the years CDT has demonstrated several display prototypes based on printed polymer semiconductors that operate at video rate (Figure 5.2). Active matrix displays have a circuit defined in each pixel that maintains the pixel in ON state for the full frame period. Typically a two-TFT-per-pixel design is used (TFT is a thin-film transistor), where a switch transistor charges a storage capacitor during addressing. The capacitor holds the drive transistor ON, driving the OLED until new data is written in the capacitor at the next select period. Most of active matrix backplanes are based on large-area thin-film silicon technologies, amorphous silicon (a-Si), or polysilicon, due to the high current requirements to drive an OLED. The examples shown in Figure 5.2 are both based on a-Si-on-glass technology.

Figure 5.2. Display prototypes printed at CDT to demonstrate PLED manufacturing capabilities.

The development of flexible OLED displays is dependent upon the development of high-current/high-stability flexible TFT backplanes. Most of the flexible backplanes currently available are suited for e-paper applications where the media does not need current to switch; examples are shown later in this chapter. Samsung and Universal Display Corporation (UDC) have demonstrated prototypes of flexible OLED displays using low-temperature-polysilicon (LTPS)–based backplanes processed on stainless steel sheets.

Several OLED displays currently in production are addressed by passive matrix, due to their simple display architectures. The pixel is formed by the overlap between cathode and anode and addressed by selecting each row and driving the cathode columns while the image is built by scanning the anode rows. The simpler configuration of passive matrix addressing facilitates the integration of OLEDs to flexible substrates.

The Holst Center (http://www.holstcentre.com/), based in the Netherlands, and Add-Vision (http://www.add-vision.com/), based in the United States, have demonstrated flexible displays based on PLEDs for both lighting and signage; examples of such displays are shown in Figure 5.3 (Mackenzie et al. 2009; http://www.holstcentre.com/). The main differences between the Add-Vision and Holst approaches are that the Add-Vision process is fully printed and uses doping of the semiconducting layer to improve injection, and it uses a more stable printable cathode (Mackenzie et al. 2009; http://www.add-vision.com/), whereas the Holst Center process is compatible with roll-to-roll manufacturing using sputtering for the metal layers. A cross-section of devices fabricated by Add-Vision and Holst Center is shown in Figure 5.3. Both companies are working with manufacturing partners in order to transfer the flexible OLED technology. The main partner for the Holst Center is Philips, and Add-Vision has licensed its technology to Alps and Toppan Forms; both are based in Japan.



Holst Center- Systems on Foils for Lighting and Signage
- Focus on polymer-based OLED devices using polymer and metal substrates
- Developing roll-to-roll technology

Add-Vision
- Focus on all printed polymer-based OLED devices using polymer substrates
- Developing manufacturing printing technology for all layers of OLED stack.

Figure 5.3. Processes used by Holst Center and Add-Vision to fabricate flexible-polymer-based OLED displays (http://www.holstcentre.com/; http://www.add-vision.com/).

Novaled (http://www.novaled.com/) is commercializing OLED material suites that enable design of a variety of display and lighting products (Figure 5.4). The materials offer higher performance (e.g., green OLED with more than 120 lm/W at 1,000 cd/m^2) and greater lifetimes (e.g., red top emission over 1,000,000 h at 1,000 cd/m^2) compared to other commercially available OLED materials. Novaled's product offerings leverage its rich intellectual assets, including its PIN OLED® technology, which combines device architecture with the PIN OLED structure. In addition, its products benefit from higher-performance doping and transport materials.

Figure 5.4. Large-area white OLED panels for lighting applications (courtesy of Novaled).

The Novaled sublimed OLEDs have significantly higher power efficiencies compared to solution-processed OLEDs, which is a critical attribute necessary for lighting applications. Also, these products can be fabricated in roll-to-roll formats using flexible substrates (e.g., steel) to realize high-value novel form factor products. In addition to developing and qualifying processes, the company has well-staffed efforts to develop novel doped transport layers with adequate conductivity (up to 10^{-5} S/cm) that facilitates quasi-ohmic contacts and provides greater freedom for the selection of electrode materials (e.g., material work-function).

Needs for Flexible OLEDs

Below are listed some of the technology needs for flexible OLEDs that the WTEC panel's hosts identified:

- Continued development of high-performance emitting materials
- Continued development of high-performance flexible active matrix backplanes
- Development of solution-processed high-performance materials to simplify processing of large-area displays
- Development of "display-grade" flexible substrates that provide an adequate barrier without compromising flexibility and performance
- Development of processing tools capable of handling flexible substrates
- Development and qualification of scalable high-volume production equipment and processes to realize cost benefits due to economies of scale
- Development of gang-testing tools to assess OLED module performance during accelerated life testing
- Continued development of improved barrier materials and device structures to increase OLED product longevity

ORGANIC PHOTOVOLTAICS

There are several groups in Europe focusing their research on organic photovoltaic (OPV) systems and devices. The Cavendish Laboratory in the UK (http://www.phy.cam.ac.uk/) has started a start-up company incubator called Carbon Trust to develop printed organic solar cells. It is at an early stage of development and has the goal of establishing a low-temperature, roll-to-roll process to fabricate high-performance, at least 10% efficient, flexible solar cells. The Smart Systems and Energy Group of IMEC (http://www2.imec.be/be_en/education/phd/smart-systems-energy-technology.html) has an organic solar cells program that focuses on efficiency, technology, and lifetime with goals of achieving 7% efficiency and 5 years of lifetime. Although the program is at an early stage, it benefits from approximately 2000 square feet of labs with deposition tools and testing and patterning equipment. Imperial College (http://www3.imperial.ac.uk/solar/research) in London has many faculty members focusing their research on organic solar cells ranging from material synthesis and film characterization to device fabrication. While these groups are at the early stages of research and development, others have demonstrated manufacturing capabilities and products.

Heliatek (http://www.heliatek.com/en/page/index.php) is developing a high-conversion-efficiency (8 to 10%) organic tandem and triple-junction vacuum-deposited solar cell product by establishing a strong mature technology platform and by partnering with Fraunhofer Institute for Photonic Microsystems (IMPS) to develop a scalable mass production line. The solar cells technology is based on several differentiated attributes: novel tailor-made materials, proprietary absorber materials (green, red, and infrared absorber), unique p- and n-doped solar cell structures, triplet harvesting materials, and patented tandem and triple cell technology. These attributes enabled the Heliatek solar cell (Figure 5.5) to achieve the following key performance differentiators: high-power-efficiency tandem cells, excellent transport and contact properties due to controlled doping, and extended cell operating lifetimes as a result of ultra-pure organic materials.

Figure 5.5. Flexible organic solar cell on metal foil (courtesy of Heliatek).

Presently, Heliatek is developing photovoltaic (PV) systems for two markets: (1) large area, flexible or non-flexible modules for angled roofs, flat roofs, and outdoor installations, and (2) modules of different sizes for portable systems, tents, outdoor electronics, and teaching materials. To achieve the product platform commercialization goals, the company is organized into three groups, each of which have specific efforts: the *R&D Physics Group* has efforts to develop new materials, optimize the stacks, develop tandem cells architectures, and improve the PV cell lifetime; the *R&D Chemistry Group* is actively developing new absorber and transport materials, and scaling-up the synthesis routes; and the *Production Group* is developing large-scale modules by teaming with the Fraunhofer IPMS to establish a scalable roll-to-roll production scheme.

Figure 5.6. Konarka flexible organic photovoltaic cells manufactured via a roll-to-roll process (courtesy of Konarka).

Konarka (http://www.konarka.com/) is commercializing a third-generation solar technology product, “Power Plastic,” based on solution-processed organic materials deposited on flexible plastic substrates (Figure 5.6). Power Plastic is comprised of several thin layers: a photo-reactive printed layer, a transparent electrode layer, a plastic substrate, and a protective packaging layer. The Power Plastic product platform leverages three key Konarka strengths: (1) materials development, e.g., unique families of conducting organic polymer materials; (2) device architectures, e.g., flexible PV devices with performance parameters for integration into a range of applications; and (3) process development, e.g., printing technologies that reduce the production process and cost.

Konarka researchers have investigated a variety of systems: dye-sensitized titania solar cells, organic photovoltaics, tandem cells, and materials that generate multiple electron-hole pairs, including novel combinations of these approaches. The company’s products can be organized into four categories: microelectronics, portable power, remote power, and building integrated applications (BIPV). Some of the applications for the Konarka solar module technology are:

- portable battery chargers for laptops, cell phones, and lanterns
- microelectronics for sensors, smart cards, and remote starters
- personal care devices for electric trimmers and toothbrushes
- camping equipment for tents and backpacks that can power portable electronics and lighting

- emergency power generators for police, military, and first responders to maintain communications
- carport covers for trickle-charging electric cars
- window shades and integrated window panels for both office and residential use

In addition to the Power Plastic product portfolio, Konarka is developing power fibers, bifacial cells, and tandem architectures that could substantially raise conversion efficiency and create new products for high-growth markets. Power Fiber™ was developed using proprietary chemistries to expand the possible form factors available for PV, with an ultimate goal of integration into woven textiles. The efforts to develop bifacial cells will allow light to reach the active material from both sides, enabling the design of transparent PV systems that can be placed on windows unobtrusively to capture both indoor and outdoor light. A third area of development is novel tandem architectures that could lead to flexible OPV with conversion efficiency approaching 15%.

The University of Linköping in Sweden (https://cms.ifm.liu.se/applphys/biorgel/) is working in collaboration with ACREO (http://www.acreo.se/) to develop screen-printed organic solar cells. Members of this group have characterized several polymer semiconductors that are synthesized by Prof. Mats Andersson from the Chalmers University of Technology in Gothenburg. They have studied the gain of efficiency due to multiple light reflections when a flexible solar cell is folded to form a "V" or a "W." They have demonstrated tandem cells with the folding approach and also have improved the absorption range of devices (Tvingstedt et al. 2007; Figure 5.7). By connecting four cells in series, they have demonstrated an open-circuit voltage of 3.65 V; the folded polymer solar cell showed power conversion efficiency enhancement of 62% when compared to planar cells (Zhou et al. 2008).

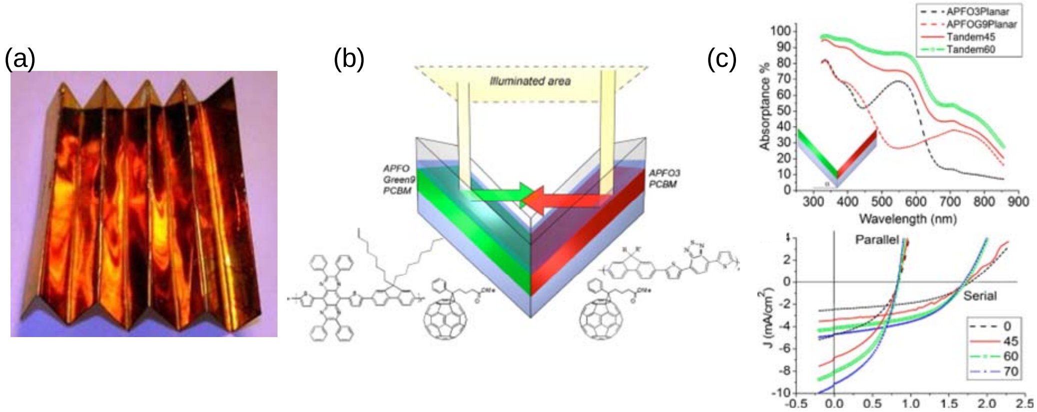


Figure 5.7. (a) W-shaped organic solar cell based on polymer semiconductor; multiple light reflections enhance overall efficiency of cells. (b) Sketch of the folded tandem cell and the chemical structures of the alternating polyfluorenes APFO3, APFO Green-9, and the acceptor molecule PCBM. (c) Measured absorbance and IV characteristics from a folded tandem cell with APFO3/PCBM on one side and APFO-Green9/PCBM on the other (Tvingstedt et al. 2007; Zhou et al. 2008).

Needs for Flexible OPVs

Below are listed some of the technology needs for flexible OPVs that the WTEC panel's hosts identified:

- Continued development of improved barrier/packaging materials to increase PV module longevity
- Continued development of higher-performance materials and novel cell structures

- Development of cell modules that optimize light capture
- Development of design tools to model system layout and to identify optimal architecture, e.g., modular versus integrated
- Expansion of existing standards and develop new standards, e.g., PV interoperability with grid
- Establishment of industry association groups to promote products and to engage end-customers

REFLECTIVE DISPLAYS

Reflective displays have several advantages compared to emissive displays. Low power consumption is one of the key motivators for the development of such displays. The human interaction factor is also very important. Reflective displays are easier to read because they require only the same reading conditions that are used when one reads a paper; light is reflected from the display.

E Ink Corporation (http://www.eink.com/) has been the main provider of reflective media for commercially available e-readers such as Kindle, Sony Reader, and Plastic Logic's "Que." Its initial technology, developed at the Massachusetts Institute of Technology (MIT), uses electrophoretic ink based on a microencapsulated electrophoretic medium that shows intrinsic bistability, exhibits extremely low power, uses dc field-addressing and is capable of high contrast and reflectivity (Comiskey et al. 1998).

Today, there are several electronic book readers available in the market; some of them are shown in Figure 5.8. The Kindle™ commercialized by Amazon has been very well received by the public, and today sales of e-books represent 10% of the revenue that Amazon gets from books sales (35% of new title sales). The display media used in all the products shown in Figure 5.8 is flexible; however, the backplanes are based on a-Si processed on glass, leading to final products that are rigid. There have been several laboratory demonstrators of flexible backplanes integrated with e-ink, but no flexible product is currently available. E-ink media does not require high-current drivers because the electrophoretic media is dc-field-driven. This feature enables the use of organic-based TFT backplanes that are flexible and fabricated with nonconventional processes, such as printing and non-vacuum deposition, which lead to new display form factors at lower fabrication cost (Rogers et al. 2001; Huitema et al. 2001; Burns et al. 2002).

Sony PRS505

Sony PRS700 (touch)

Hanlin V3

iRex DR1000s (touch & wifi)

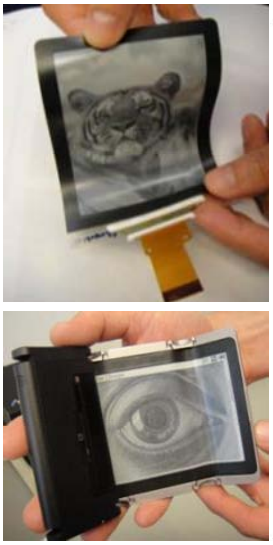
iRex iLiad (touch & wifi)

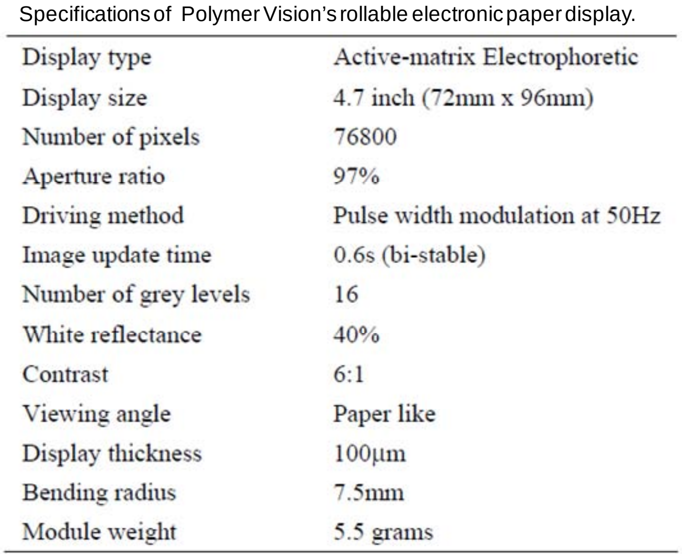
Bookeen Cybook gen 3

Amazon Kindle

Figure 5.8. Pictures of examples of electronic book readers available in the market.

The two leading companies driving the commercialization of flexible organic-based TFT backplanes are Plastic Logic and Polymer Vision. Polymer Vision's product, Readius® (http://www.readius.com/pocket-ereader/specifications), represents the first demonstration of rollable displays. Readius® was designed to address the consumer demand for larger displays in small sized mobile devices. When closed, Readius® is 50 mm wide and provides a 160 mm-wide display when the device is open.[23] The display contains 240 rows and 320 columns with a pixel size of 300 μm^2. The minimum feature size is 5 μm, TFT channel length, and the pixel optical aperture ratio is 97%. The displays are fabricated in a batch process using PEN (polyethylene naphthalate) as the substrate (Huitema et al. 2008). The specifications of Polymer Vision's product are displayed in Figure 5.9, along with a picture of the flexible display module and the final product.





Specifications of Polymer Vision's rollable electronic paper display.

Display type	Active-matrix Electrophoretic
Display size	4.7 inch (72mm x 96mm)
Number of pixels	76800
Aperture ratio	97%
Driving method	Pulse width modulation at 50Hz
Image update time	0.6s (bi-stable)
Number of grey levels	16
White reflectance	40%
Contrast	6:1
Viewing angle	Paper like
Display thickness	100μm
Bending radius	7.5mm
Module weight	5.5 grams

Figure 5.9. Picture of flexible backplane/e-ink laminated module and picture of Readius® (product prototype) from Polymer Vision. The table displays its specifications Huitema et al. 2008).

Polymer Vision's organic TFT devices, based on solution-processed pentacene, show an average field effect mobility of 0.15 cm^2/Vs, threshold voltage close to 5 V and ION/IOFF ratio of 106 (Huitema et al. 2008). Polymer Vision was founded in 1998 by Philips, which has announced that it will not commercialize the Readius®; it is offering its intellectual property and know-how to other companies interested in the technology.

Plastic Logic (http://www.plasticlogic.com/) is a spin-off company from the Cavendish Laboratory that has been developing technology and products to commercialize flexible electronics for the past ten years. Plastic Logic's eReader, shown in Figure 5.10, is considerably thinner and larger than the Amazon Kindle™, and it is robust (no glass), lightweight, and glare-free. Plastic Logic's eReader is 8.5 x 11 inches, equivalent of A4 paper size, and incorporates touch-screen technology to improve navigation and annotation. The display has 1280 x 960 pixels, with resolution of 150 ppi, and is fabricated on PET substrates using a sheet-to-sheet process. TFTs are based on polyfluorene semiconductors and show field effect mobility of 0.03 cm^2/Vs, threshold voltage between -5V and -10 V and ION/IOFF ratio of 106 (Burns et al. 2006). There were several announcements in 2009 of Plastic Logic partnering with content providers in order to offer magazines, books, blogs, and newspapers together with its eReader.

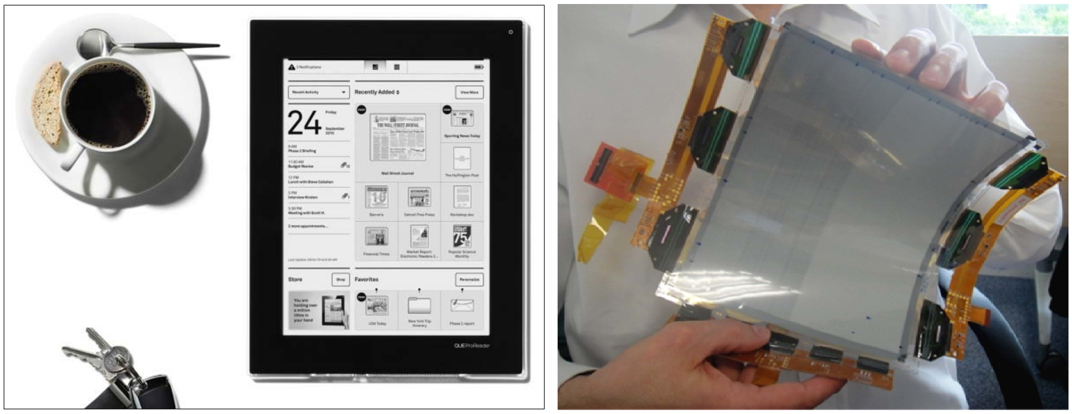


Figure 5.10. Plastic Logic’s QUE ProReader (e-reader) and a flexible backplane/e-ink laminated module.

Needs for Reflective Displays

Below are listed some of the technology needs for reflective displays that the WTEC panel’s hosts identified:

- Continued development of manufacturing equipment and tooling
- Continued development of higher-performance materials and novel display structures
- Continued development of color displays (e.g., non-filter-based displays)
- Improved display media response time
- Improved longevity of display media (electrophoretic ink)

FIELD-EFFECT-TRANSISTOR (FET)–BASED COMPONENTS

(Active Matrix Backplanes for Displays, Biosensors, RFID, Memory)

PolyIC (http://www.polyic.com/) is developing printed-electronics-based products that transmit information via radio frequency waves and provide the following three attributes: (1) a novel method for simple, electronic identification and authentication of goods (e.g., electronic brand protection on item-level goods); (2) a disruptive technology for cost-effective tracking and tracing in the supply chain for producers and retail businesses; and (3) a new possibility to enhance safety and security for consumer designs. To deliver these benefits to the customer, PolyIC is designing, developing, and manufacturing two product platforms that leverage the attributes of printed electronic technology (see also Figure 5.11):

- POLYID®: Printed radio frequency identification tags (RFID): the long-term product offering is an EPC-compliant printed RFID tag.
- POLYLOGO®: Printed smart objects (combinations of printed components): the long-term product offering is a smart card (intelligent sensor) that combines sensor devices (temperature, humidity) with RF transmission/reception functionality.

These platforms leverage the economies of scale and merits of high-volume manufacturing using wide-web equipment in non-cleanroom environments. The products are multilayer structures that are fabricated using solution-processed materials (conductive, dielectric, and semiconductive), patterned films (conductive and dielectric), and flexible plastic substrates. Each product platform has a well articulated “go-to-market” strategy that consists of near-term, mid-term, and long-term product offerings. Both product platforms will be part of larger systems that combine traditional silicon-based integrated circuit (IC) technology where appropriate.

Figure 5.11. (*Left*) POLYLOGO® product platform, a VIP ticket for a pop concert. (*Right*) PolyID® product platform, an electronic brand protection application (courtesy of PolyIC).

As an example, POLYID® will be based on printed electronics technologies (solution-processable materials and non-cleanroom processing), and the reader device will be designed using silicon-based IC technology. By following this approach, PolyIC leaders feel that this system design methodology will enable operation/functionality metrics and total system cost parameters to be met.

In an effort to support the commercialization of future product offerings within these platforms, PolyIC has programs for the fabrication of organic-semiconductor-based devices and circuits. The effort has resulted in the company achieving several industry milestones within the field of organic electronics: 125 kHz circuit functionality in 2004; 600 kHz circuit functionality in 2005; 13.56 MHz circuit functionality in 2006; 32/64-bit prototype operating at 13.56 MHz; and first printed CMOS (complementary metal-oxide semiconductor) in 2008. In 2007, PolyIC presented the first printed RFID tag produced in roll-to-toll production, working at the standardized frequency of 13.56 MHz. The majority of these milestones were achieved using well-characterized material systems and a stable proven process for top-gate OFET device architecture (insulating polymer dielectric, conjugated polymer semiconductor, and polyester film substrate).

Needs for Field-Effect–Based Components

Below are listed some of the technology needs for FETs that the WTEC panel’s hosts identified:

- Establishment of an open database comprising NMOS (negative-channel metal-oxide semiconductor), PMOS (positive-channel metal-oxide semiconductor), and CMOS device operating parameters for product designers using a statistically significant number of devices; master device parametric curves
- Development and offering to the public of design tools to help proliferate the technology
- Continued development of improved p-type and n-type materials to increase product opportunities
- Organization of groups to discuss interoperability standards for hybrid systems

OTHER SYSTEMS AND PRODUCTS

(Capacitive Array Structures, Microfluidic Components for Diagnostics, Resistor Structures for Heaters)

Plastic Electronic (http://www.plastic-electronic.com/) is developing products and systems based on capacitive sensor technology that provide near-term revenue streams. As an example, it is presently developing a novel product that combines large-area multilayer flexible plastic films that have embedded capacitive technology with a software platform to enable a “smart shelf”

(Figure 5.12). This product provides weight sensing, object recognition, and position recognition functionality that can be used in several markets: consumer goods, retail products, and electronics. In addition to the Smart Shelf, Plastic Electronic researchers are developing “smart blister” packaging and human-machine interface components that combine demonstrated technologies with novel product final assembly processes (Figure 5.12). As an example of leveraging a demonstrated technology, the human-machine interface is a back-injection-molded capacitive-device–based touch panel for system control and operation. The Plastic Electronic business plan articulates a strategy that identifies near-term product opportunities that are based on passive devices and mid-term products (greater than 3 years) that will offer functionality that requires both passive and active devices.

The near-term products such as the Smart Shelf are fabricated using well-established large-area-format manufacturing processes such as screen printing, laminating/bonding, and laser cutting/trimming. The Smart Shelf is designed with capacitive devices having feature sizes of 100 microns and can be manufactured in a high-volume manufacturing environment using existing equipment. Final product testing will leverage commercially available equipment and QC/QA (quality control/quality assurance) protocols.

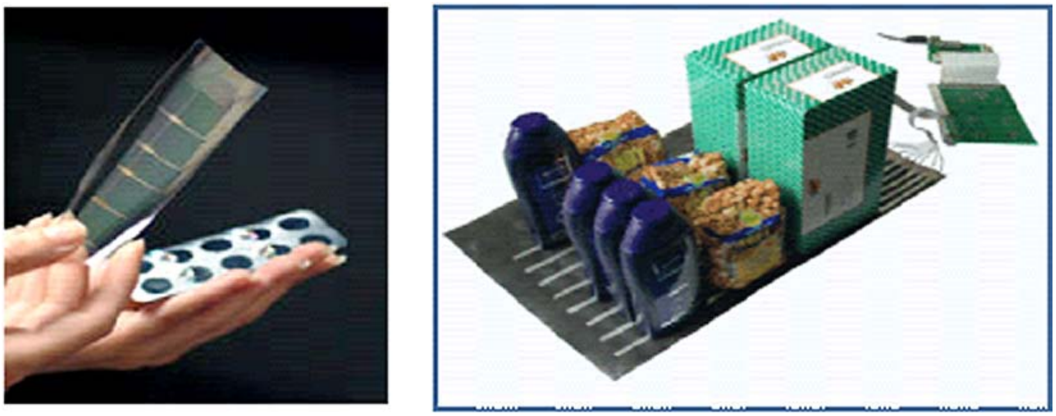


Figure 5.12. (*Left*) Smart blister packaging. (*Right*) Smart Shelf system that has capacitive embedded film to sense the presence and location of products (courtesy of Plastic Electronic).

Acreo (http://www.acreo.se/) is a pioneer in printed electrochromic displays that are printed on paper, as shown in Figure 5.13. The displays are very simple and consist of only two components: a conducting p-doped polymer poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) and an electrolyte. In the reduced state, PEDOT exhibits semiconducting properties characterized by strong optical absorption in the visible wavelength region and low electrical conductivity (Andersson et al. 2002). The displays are patterned by printing PEDOT and the electrolyte on low-cost substrates. Acreo also assembles microchips to printed electronic components in order to enhance performance.

Figure 5.13. Electrochromic displays printed on paper and an integrated system with pressure switches, printed battery, and printed display.

PolyIC (http://www.polyic.com/en/index.php) also is active in transparent conductive films, suitable for many applications such as touch panels; in addition, it develops printed memories.

Needs for Systems and Products

Below are listed some of the systems and product needs that the WTEC panel's hosts identified:

- Development of scalable wide-web processing tools with enhanced process control
- Design and commercialization of equipment with integrated final product operation testing hardware/software
- Development of higher-toughness films for ease of integration to enable additional product form factors
- Establishment of user groups to educate engineers, designers, and marketing talent to support growth of the printed electronics industry

CONCLUSION

A variety of hybrid flexible electronics products are in early commercialization with a greater number in final stages of product development.

REFERENCES

Ahn, J.-H., H.-S. Kim, E. Menard, K.J. Lee, Z. Zhu, D.-H. Kim, R.G. Nuzzo, J.A. Rogers, I. Amlani, V. Kushner, S.G. Thomas, and T. Duenas. 2007. Bendable integrated circuits on plastic substrates by use of printed ribbons of single-crystalline silicon. *Appl. Phys. Lett.* 90(21):213501. DOI:10.1063/1.2742294

Andersson, P., D. Nilsson, P.-O. Svensson, M. Chen, A. Malmström, T. Remonen, T. Kugler, and M. Berggren. 2002. Active matrix displays based on all-organic electrochemical smart pixels printed on paper. *Advanced Materials* 14(20):1460–1464. DOI:10.1002/1521-4095

Burns, S.E., C. Kuhn, N. Stone, D. Wilson, A.C. Arias, T. Brown, P. Cain, P. Devine, K. Jacobs, N. Murton, J.D. MacKenzie, J. Mills, and H. Sirringhaus. 2002. Inkjet printed polymer thin film transistors for active-matrix display applications. Paper 43.1 in *SID 2002 international symposium digest of technical papers* 33(1):1193–1195. Campbell, CA: Society for Information Display.

Burns, S.E., W. Reeves, B. H. Pui, K. Jacobs, S. Siddique, K. Reynolds, M. Banach, D. Barclay, K. Chalmers, N. Cousins, P. Cain, L. Dassas, M. Etchells, C. Hayton, S. Markham, et al. 2006. A flexible plastic SVGA e-paper display. Paper 7.4 in *SID 2006 international symposium digest of technical papers* 37(1):74–76. Campbell, CA: Society for Information Display.

Burroughes, J.H., D.D.C. Bradley, A.R. Brown, R.N. Marks, K. Mackay, R.H. Friend, P.L. Burns, and A.B. Holmes. 1990, Light-emitting diodes based on conjugated polymers. *Nature* 347:539–541. DOI:10.1038/347539a0

Comiskey, B., J.D. Albert, H. Yoshizawa, and J. Jacobson. 1998. An electrophoretic ink for all-printed reflective electronic displays. *Nature* 394(6690):253–255. DOI:10.1038/28349

Gleskova, H., and S. Wagner. 1999. Amorphous silicon thin-film transistors on compliant polyimide foil substrates. *IEEE Electron Device Letters* 20(9):473–475. DOI:10.1109/55.784456

Halls, J.J.M., C.A. Walsh, N.C. Greenham, E.A. Marseglia, R.H. Friend, S.C. Moratti, and A.B. Holmes. 1995. Efficient photodiodes from interpenetrating polymer networks. *Nature* 376:498–500. DOI:10.1038/376498a0

Huitema, E., E. van Veenendaal, N. van Aerle, F. Touwslager, J. Hamers, and P. van Lieshout. 2008. Rollable displays: A technology development enabling breakthrough mobile devices. Paper 60.4 in *SID 2008 international symposium digest of technical papers* 39(1):927–930. Campbell, CA: Society for Information Display.

Huitema, H.E.A., G.H. Gelinck, J.B.P.H. van der Putten, K.E. Kuijk, C.M. Hart, E. Cantatore, P.T. Herwig, A.J.J.M. van Breemen, and D.M. de Leeuw. 2001. Plastic transistors in active-matrix displays. *Nature* 414(6864):599–600. DOI:10.1038/414599a

Mackenzie, J.D., J. Breeden, J. Chen, P. Hinkle, E. Jones, A. Menon, Y. Nakazawa, J. Shin, V. Vo, M. Wilkinson, Y. Yoshioka, and J. Zhang. 2009. Printed doped flexible P-OLED displays. Paper 4.3 in *SID 2009 international symposium digest of technical papers* 40(1):20–24. Campbell, CA: Society for Information Display.

Ng, T.N., W.S. Wong, R.A. Lujan, and R.A. Street. 2009. Characterization of charge collection in photodiodes under mechanical strain: Comparison between organic bulk heterojunction and amorphous silicon. *Advanced Materials* 21(18):1855–1859.

Rogers, J.A., Z. Bao, K. Baldwin, A. Dodabalapur, B. Crone, V.R. Raju, V. Kuck, H. Katz, K. Amundson, J. Ewing, and P. Drzaic. 2001. Paper-like electronic displays: Large-area rubber-stamped plastic sheets of electronics and microencapsulated electrophoretic inks. *Proc. Nat. Acad. Sci*. 98(9):4835–4840. DOI:10.1073/pnas.091588098

Sirringhaus, H., N. Tessler, and R.H. Friend. 1998. Integrated optoelectronic devices based on conjugated polymers. *Science* 1998, 280(5370):1741–1744. DOI:10.1126/science.280.5370.1741

Sirringhaus, H., P.J. Brown, R.H. Friend, M.M. Nielsen, K. Bechgaard, B.M.W. Langeveld-Voss, A.J.H. Spiering, R.A.J. Janssen, E.W. Meijer, P. Herwig, and D.M. De Leeuw. 1999. Two-dimensional charge transport in self-organized, high-mobility conjugated polymers. *Nature* 401(6754):685–688. DOI:10.1038/44359

Tvingstedt, K., V. Andersson, F. Zhang, and O. Inganäs. 2007. Folder reflective tandem polymer solar cell doubles efficiency. *Appl. Phys. Lett.* 91(12):123514.

Wagner, S., H. Gleskova, J.C. Sturm, and Z. Suo. 2000. Novel processing technology for macroelectronics. In *Technology and applications of hydrogenated amorphous silicon,* ed. A.A. Street, 222–251. New York: Springer Series in Materials Science, 37.

Yoon, J., A.J. Baca, S. Park, P. Elvikis, J.B.I. Geddes, L. Li, R.H. Kim, J. Xiao, S. Wang, T.-H. Kim, M.J. Motala, B.Y. Ahn, E.B. Duoss, J.A. Lewis, R.G. Nuzzo, P.M. Ferreira, Y. Huang, A. Rockett, and J.A. Rogers. 2008. Ultrathin silicon solar microcells for semitransparent, mechanically flexible and microconcentrator module designs. *Nature Materials* 7:907–915. DOI:10.1038/nmat2287

Zhou, Y., F. Zhang, K. Tvingstedt, W. Tian, and O. Inganas. 2008. Multifolded polymer solar cells on flexible substrates. *Appl. Phys. Lett*. 93:033302. DOI:10.1063/1.2957995

CHAPTER 6

PROCESSING AND MANUFACTURING

Daniel Gamota and Colin Wood

INTRODUCTION

The topic of manufacturing and processing for hybrid flexible electronics can be subdivided into two categories based on the environments in which product manufacturing is performed and the processes required to deposit the materials:

1. Solution processing
2. Vacuum processing

These categories can be further subdivided based on the substrate (rigid or flexible), which can further determine the type of process: batch or roll-to-roll (Figure 6.1).

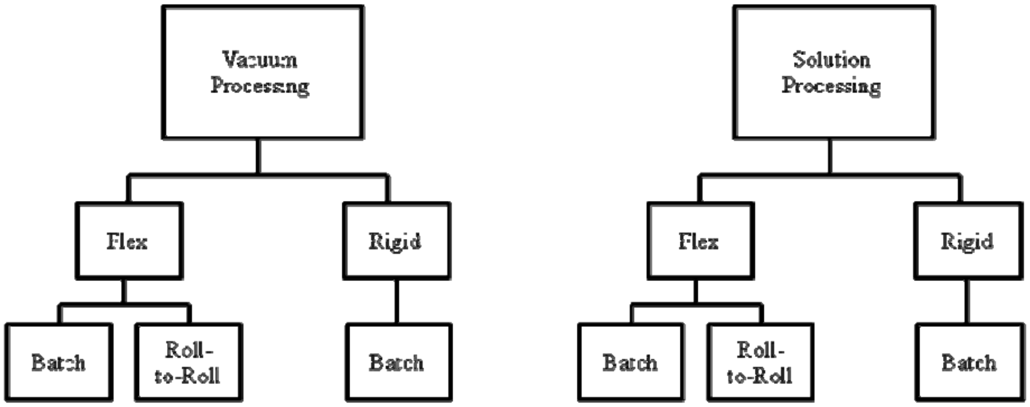


Figure 6.1. Hierarchy of manufacturing and processing for hybrid flexible electronics.

PRODUCTS

Several hybrid flexible electronics products are in varying stages of manufacturing maturity: R&D, pilot scale, and volume manufacturing. These products can be assigned into four general groups:

- Organic light-emitting diodes (OLED)
- Organic photovoltaics (OPV)
- Field-effect-transistor (FET)–based components: active matrix backplanes for electrophoretic and other displays, biosensors, radio frequency identification (RFID) systems, memory, etc.
- Other systems and products: capacitive array structures, batteries, on-off switches, sensors, microfluidic components for diagnostics, resistor structures for heaters, etc.

Various shapes and sizes of products are primarily dependent on the manufacturing technologies and final assembly equipment being used, as well as on the required product dimensions.

Table 6.1 classifies the stages of manufacturing maturity of institutions WTEC panel members visited, in terms of whether they are at the *R&D*, *pilot-scale*, or *volume manufacturing* stage of developing hybrid flexible electronics products. In some cases, the institutions and their respective business plans/missions have enabled them to do R&D, pilot-scale, and volume manufacturing without diluting efforts for first-product commercialization. Where business plans articulated outsourcing (asset light) models, investment in volume manufacturing equipment was limited.

MANUFACTURING PLATFORMS AND PROCESS DEVELOPMENT

In general, the institutions listed in Table 6.1 have access to the necessary equipment and tools to support their various stages of manufacturing maturity. As expected, the institutions approaching commercialization have the equipment and processing platforms in-house to ensure high-yield final product assembly, whereas those institutions active in R&D have established strong collaboration partners that provide access to the necessary equipment and tools.

Open-innovation centers and incubator centers are available in Europe for developing manufacturing platforms and processes (see also Chapter 2). The Holst Center is an open-innovation center that receives donations of equipment and tooling (e.g., for semiconductor processing, lithography, and testing) from Philips Research Laboratories and that is accessible for use by members (membership is fee-based) during the development of materials, equipment, and products and systems. Once these technologies approach maturity, they can be transferred to the member's own production facilities. Examples of incubator centers that provide manufacturing support are IMEC in Leuven, Belgium, and the Center for Organic Materials and Electronic Devices Dresden (COMEDD) within the Fraunhofer IPMS in Dresden, Germany, both of which have the capabilities to develop a broad range of manufacturing technologies required for hybrid flexible electronics product prototypes.

In addition to the innovation centers mentioned earlier, many universities provide support, directly or in partnership with other entities, to start-up businesses and small companies for process and product development, usually in exchange for student support, fellowships, and the like. Most notable among these are the High Technology Campus of the University of Eindhoven's MiPlaza (Microsystems Plaza); Johannes Kepler University in Linz, Austria; the Technical University of Dresden Institute for Applied Photophysics (IAPP) in Germany; and Imperial College and the University of Cambridge Department of Engineering in the UK.

EQUIPMENT FOR SOLUTION PROCESSING

A variety of solution-processing platforms are being used at the various hybrid flexible electronics centers in the EU. The platforms can be divided into two general categories: (1) contact and (2) non-contact systems. Examples of contact systems are screen, gravure, and flexography; examples of non-contact systems are curtain coating, ink-jet, and micro-dispensing.

Research & Development

The equipment used for solution-processing R&D tends to have minimal automation options. Thus, manual set-up is usually required, together with adjustment during operation. In general, R&D types of equipment have limited processing areas/dimensions and do not have the capability for scalability or integration into a manufacturing line. Their value is to provide a well-controlled platform for performing design-of-experiments (DoEs) for a variety of purposes such as testing of new materials and assessment of deposition technologies, interfacial compatibility, deposited feature dimension repeatability, minimal achievable resolution, and registration tolerance. Lab bench ink-jet, screen printing, gravure, stencil, and flexography systems are most often used at this stage of manufacturing development. A benefit of using lab-bench systems is the smaller material volume (milliliters) required for conducting experiments as compared to the larger volumes required for pilot and volume manufacturing (liters).

Table 6.1. Manufacturing Maturity of Institutions Visited by the WTEC Panel

INSTITUTION	STAGE of MANUFACTURING
Organic Light Emitting Diodes (OLED)	
Display Fabrication Facility, University of Stuttgart	R&D, Pilot Scale (displays – OLEDS, electrophoretic LCDs)
Consiglio Nazionale delle Ricerche (CNR)	R&D (lighting)
Technical University of Dresden, Institute for Applied Photophysics (IAPP)	R&D (lighting)
Novaled AG	R&D, Pilot Scale (displays and lighting)
Fraunhofer Institute for Photonic Microsystems	R&D, Pilot Scale, Volume Manufacturing (OLED modules)
Cambridge Display Technology	Pilot Scale (polymer-OLED modules; production at Sumitomo)
Holst Center	R&D (P-OLEDs on R2R)
IMEC (Inter-University MicroElectronics Center, Belgium)	R&D (O-LEDS on flex substrates)
Philips Research	Pilot Scale (LED lighting, signage, and displays)
Organic Photovoltaics (OPV)	
Konarka	R&D, Pilot Scale, Volume Manufacturing (OPV modules)
Heliatek GmbH	R&D, Pilot Scale (OPV modules)
Johannes Kepler University	R&D (OPV devices)
Consiglio Nazionale delle Ricerche (CNR)	R&D (OPV devices)
Technical University of Dresden, Institute for Applied Photophysics (IAPP)	R&D (OPV devices)
Fraunhofer Institute for Photonic Microsystems	R&D, Pilot Scale, Volume Manufacturing (OPV modules)
Cambridge Display Technology	R&D (OPV devices)
Holst Center	R&D (R2R OPV detectors, and OPV devices)
Imperial College	R&D (OPV polymer dielectrics)
Field-Effect-Transistor (FET)–Based Components	
PolyIC GmbH	R&D, Pilot Scale, Volume Manufacturing
Plastic Logic	R&D, Pilot Scale, Volume Manufacturing (active-matrix backplanes for reflective displays)
Max Planck Institute for Solid State Research	R&D (FET-based circuitry)
University of Erlangen-Nürnberg	R&D (FETs)
University of Bari	R&D (biosensors)
Polymer Vision	R&D, Pilot Scale, Volume Manufacturing (electrophoretic roll-out displays)
CIKC (University of Cambridge Dept. of Engineering)	R&D (RFID, flex displays, sensors)
CAPE (University of Cambridge Dept. of Engineering)	R&D (low-temperature ZnO for plastic displays)
Holst Center	R&D (organic TFT and organic back planes, RFID, logic, memory, displays, and signage)
Other Systems and Products	
Plastic Electronic GmbH	Pilot Scale, Volume Manufacturing
University of Linköping	R&D, Pilot Scale (R2R paper systems, pilot production batteries, displays, memory, and logic)
Holst Centre (w/ MiPlaza)	R&D (R2R coating, printing, lithography on flex substrates, smart foils integration – systems in foil)
IMEC Leuven	R&D (plastic electronics products in cooperation with Holst Center)

Pilot Scale

The biggest differentiators between R&D and pilot-scale stages of manufacturing are processing area (substrate size), manufacturing speed, semi-automated versus automated tooling, and the establishment of standard operating procedures (SOPs) to ensure high final product yield. The pilot scale stage is the most critical stage when transitioning applied R&D results to product realization. Process windows are established on larger-sized equipment that must reproduce the manual operations that are performed by well-trained and highly-skilled personnel at the R&D stage. Also, materials are used that have demonstrated performance, have achieved a high level of supplier quality assurance for batch-to-batch consistency, and are available in mid-sized volume.

Several pilot-scale manufacturing lines are modular in nature and combine different equipment platforms—automated, semi-automated, and manual. As an example, commercially available semi-automated screen printing tools are used at the Plastic Electronic company to fabricate capacitive array-based products in sheet format (Figure 6.2). These tools can achieve high yield manufacturing of passive devices at high speeds and/or volumes with features of less than 100 micron and thickness of 10 to 150 micron. Ultimately, when transitioning to volume production, a roll-to-roll (R2R) process is envisioned using possibly a rotary screen printing tool with the appropriate hardware and software for in-processing correction.

The WTEC panel observed other examples of pilot-scale manufacturing tools at the Cambridge Display Technology (CDT) facility, which has a well-equipped cleanroom that has multiple polymer-based organic light-emitting diode (P-OLED) processing platforms and the necessary module testing equipment (Figure 6.3). A few pilot-scale lines have automated tooling during the front-end processes but switch to manual tooling during the back-end processing (final product assembly). In several labs the WTEC team visited, this approach was chosen to enable electrical testing to minimize the yield loss.

Figure 6.2. Screen printing equipment for large feature devices (courtesy of Plastic Electronic GmbH).

Figure 6.3. P-OLED product and process testing cleanroom (courtesy of CDT).

In development at various locations in Sweden, including Acreo (Figures 6.4 and 6.5), are prototyping R2R systems using paper and flexible plastic substrates for products such as thin film batteries, random number generators, displays, RFIDs, and large-area under-floor resistive heating. These systems are slightly modified, commercially available label-printing R2R systems; as an example, Acreo makes modifications to accommodate curing of the electronic materials.

Figure 6.4. Roll-to-roll process prototyping platform developed from a commercial label printer (courtesy of ACREO).

Figure 6.5. Flexible RFID tag fabrication by R2R label printer (courtesy of ACREO).

In addition to pilot-scale platform development taking place in Sweden, the University of Linköping in that country has established programs to develop new products in collaboration with commercial companies throughout Europe. These materials are developed with intrinsic properties that enable high-volume production on a variety of R2R and sheet-fed platforms.

Volume Manufacturing

A few European companies are bringing volume manufacturing online. Their manufacturing flow is batch or R2R, highly automated, and they leverage equipment platforms based on manufacturing technologies used in the printing, electronics assembly, and semiconductor industries. As an example, the Plastic Logic manufacturing site in Dresden, Germany, houses a $100-million, 4000-square-meter cleanroom that has automated batch manufacturing equipment for production of electrophoretic flexible display-based e-books (Figure 6.6). The base technologies used for production were developed at Plastic Logic laboratories in Cambridge, UK, before transfer to the Dresden facility for volume production.

Figure 6.6. Plastic Logic’s volume manufacturing facility (courtesy of Plastic Logic).

The Plastic Logic facility in Dresden uses a combination of batch processing tools leveraged from display, printing, and semiconductor manufacturing. The facility combines highly automated tooling with well-established processes that are used to fabricate arrays of active matrix backplanes in panel format on a rigidizer. The fabrication process uses ink-jet technology for solution processing of the organic semiconductor material.

An example of a R2R manufacturing process has been built by PolyIC (Figure 6.7). The company is leveraging R2R processing equipment to benefit from the economies of scale to offer price-competitive products in high-growth markets. PolyIC is using a variety of printing technologies (e.g., flexography, gravure, and screen) to fabricate the different layers of the circuitry.

Figure 6.7. Wide-web roll-to-roll solution processing manufacturing platform (courtesy of PolyIC).

Needs for Solution-Processing Equipment

Several equipment development needs were mentioned by the WTEC teams' European hosts; those identified as critical are listed below:

- Stronger appreciation for fundamental relationships between material rheological properties and printing technologies to provide tight control of printed features
- Printing technologies and printing consumables that provide higher-resolution as-printed features
- Processing technologies that have greater flexibility in the materials they can process (e.g., a wider range of rheological properties) and the printed features they can achieve (e.g., in terms of thickness, uniformity, and surface roughness)
- Hardware/software systems to enable automated in-line registration correction
- Novel, high-speed, integrated optical, electrical, and mechanical quality-assurance tooling

EQUIPMENT FOR VACUUM PROCESSING

The most common vacuum-processing equipment that the WTEC panel observed during its visits to European institutions enabled batch processing of rigid substrates and flexible substrates laminated to rigid backing. An example of rigid-backed flexible substrate vacuum processing is that employed by Polymer Vision in its Southampton, UK, facility. At the time of the WTEC visit, a roll-to-roll vacuum processing system was in development at the Fraunhofer IPMS Center for Organic Materials and Electronic Devices Dresden (COMEDD).

Research and Development

The R&D processing platforms observed during the WTEC panel's visits were either self-built or procured from commercial vendors. Both types of systems accepted substrates of minimal area and were designed for low-volume output. Self-built systems tended to offer a greater flexibility for materials selection, *in situ* characterization, and processing parameters. Additional equipment co-located in the laboratories, such as those used for photolithography, etching, deposition, etc., are well known in the semiconductor and display industries.

Pilot Scale

The greatest differentiators between the R&D and pilot-scale equipment are (1) available processing area, (2) degree of automation, and (3) degree of flexibility. Several pilot-scale batch manufacturing platforms are available in Europe for hybrid flexible electronics fabrication. As an example, the Fraunhofer Institute for Photonic Microsystems (IPMS) has a system designed by Sunic System, Ltd. (Korea), that is used for pilot-scale production of passive matrix and active matrix OLED displays on glass substrates (200 mm x 200 mm, thickness 0.7 to 1.1 mm) and silicon wafers (150 mm and 200 mm diameters, thickness 0.6 to 0.8 mm). The system has a total of 7 process chambers, 12 organic sources, 5 inorganic sources, and 2 physical vapor deposition (PVD) sources and cells to provide Ar/O_2 plasma activation and encapsulation (Figure 6.8).

Figure 6.8. Pilot-scale vacuum-processing manufacturing platform (courtesy of Fraunhofer IPMS).

Another example of a facility that provides pilot-scale manufacturing capabilities for hybrid flexible electronics is the Display Technology Fabrication Lab at the University of Stuttgart. The facility houses a class 10/100 cleanroom that is 480 m^2. It houses both prototype and production-scale manufacturing equipment to build and assemble the necessary components for a display system (backplane, front plane, and drive electronics). In addition, to commercially available equipment, the facility houses novel platforms that were developed by students for processing and characterization.

Volume Manufacturing

Batch and R2R volume vacuum manufacturing types of equipment are prominently displayed at the COMEDD within the Fraunhofer IPMS. COMEDD is the best-equipped facility that the WTEC panel visited for providing support during transition from prototype to pilot and/or volume manufacturing. The equipment located in the Class 10 (900 m^2) cleanroom is scalable and can be used for high-volume manufacturing. COMEDD has state-of-the-art automated pilot-volume equipment for fabrication of advanced devices and system architectures based on vacuum-processed organic electronic materials. This equipment can handle rigid substrates (glass, 200 mm x 200 mm) offering a cycle time of 120 minutes, rigid/flexible substrates (glass or laminated foils, 370 mm x 470 mm) offering a cycle time of 3 minutes, and a R2R line (metal foils, 300 mm width). When completed, the R2R line will consist of substrate patterning equipment, a deposition tool for both OLED and OPV, and a thin-film encapsulation tool. Figure 6.9 shows an example of a scalable batch manufacturing platform located at COMEDD.

Figure 6.9. Vacuum processing manufacturing platform (courtesy of Fraunhofer IPMS).

For its rollable displays, Polymer Vision uses a batch process with 150-mm-diameter silicon substrates. These rigid carriers allow accurate backplane alignment for fabricating the active matrix stacks, followed by lamination of the electrophoretic imaging film. After the display assembly is completed, the finished modules are delaminated from the silicon carrier substrates.

Needs for Vacuum Processing Equipment

Below are listed some of the equipment development needs identified by the different groups that the WTEC panel visited:

- Establishment and publication of Design for Manufacturing protocols to help strengthen the hybrid flexible electronics equipment supplier infrastructure
- Development of web-based equipment with wider web capacity and with in-plane substrate deformation correction, integrated automated metrology tools, and defect recognition
- Strengthening of the equipment supplier base with multiple tool providers
- Development of tools to provide real-time or near-real-time manufacturing metrics
- Performing a sufficient number of volume product builds to determine equipment operational specifications such as mean-time-to-repair, mean-time-to-failure, and preventative maintenance schedules

FINAL ASSEMBLY SYSTEM PRODUCTION

Most of the systems observed or mentioned during the WTEC visits were commercially available and have demonstrated production scalability. Systems such as those used for large-area lamination, integration of components—that is, pick and place of traditional microelectronic components such as display driver ICs, resistors, and capacitors—and packaging (barriers against humidity) are well established. It did not appear that new equipment platforms were in development in Europe at the time of the WTEC visits.

Needs for Final Assembly Production

Although the hybrid flexible electronics field today is leveraging various types of existing final assembly production-level equipment, several needs were identified by WTEC hosts for development of new assembly production equipment platforms designed specifically for hybrid flexible electronics applications:

- Development of scalable equipment that offers a larger processing area for both batch (substrate size) and roll-to-roll (web width) processing
- Development of scalable automated tooling for integration of hybrid electronics in traditional non-electronics-based products (e.g., smart walls and smart ceilings) to reduce the requirement for operator intervention
- Establishment of interoperability standards for product designers to build hybrid flexible electronics integrated with traditional electronics

CHARACTERIZATION AND OPERATION TESTING TOOLS

In general, characterization (electrical, metrology, optical) and product operation testing tools were categorized in Europe as either: (1) quality assurance tools or (2) environmental testing and life-testing tools.

Quality assurance tools were discussed at the sites the WTEC panel visited in terms of off-line characterization tools and in-line characterization tools. Off-line tools required a skilled operator to prepare the sample and to perform the testing. In-line tools were automated with feedback loops for real-time data capture for the product, and they required minimal operator oversight. The in-line tools typically performed contact measurements (resistance, capacitance) or optical inspection (pinholes, surface roughness). Off-line tools were commercially available from large electronics and materials testing equipment suppliers, whereas in-line tools seemed to have been developed in-house and were proprietary.

Environmental testing and life-testing tools, in general, consisted of commercially available equipment used in the microelectronics and electronic products industries: burn-in, temperature cycling, and humidity and temperature testing chambers. WTEC panelists observed minimal hardware modifications to the equipment; however, the software used to perform and monitor the samples during testing was self-developed in an effort to minimize the time for testing as well as to allow greater numbers of samples to be tested (i.e., increased throughput). One example of a special noncommercial tool that was developed to perform *in situ* electrical characterization of active matrix backplanes was built at the Display Technology Fabrication Lab at the University of Stuttgart. This tool gang-probed the individual devices of an active matrix display backplane to provide data on device electrical characteristics during operation while under environmental conditioning (on-current, threshold shift, on/off ratio).

Needs for Characterization and Operation Testing Tools

The WTEC panel's hosts named several tools needed to help continue the development and commercialization of hybrid flexible electronic products:

- Design of scalable testing solutions to accommodate speed/volume/product pulse rates
- Establishment of testing and performance metrics (via standards bodies)

- Development of equipment for *in situ* electrical and product operation testing during mechanical flexure
- Establishment of a database of product and device performances as functions of environmental conditioning to help designers build circuits and products
- Development of first-order models for failure mechanisms
- Development of novel equipment for greater throughput characterization of thin/thick films, e.g., of their thickness, porosity, resistance, and capacitance

FUNDING

Several funded precompetitive programs have been sponsored by the EU and individual countries' departments of science, education, industry, etc., to develop a stronger appreciation of materials, processes, and manufacturing of hybrid flexible electronics. *PolyApply* is an example of a completed EU 6th Framework Programme to establish an organic electronics technology platform. During the program (2004 to 2008), team members investigated various materials systems, processes, manufacturing platforms, and designs to enable products with radio-frequency functionality—RFIDs and sensors. All-solution-processing, all-vacuum-processing, and hybrid processing routes were developed to move the technologies closer to commercialization.

A program established to develop a stronger appreciation for R2R processing and manufacturing is named the "Rollex" project. The Fraunhofer IPMS, Dresden IAPP, Novaled, and others are members of this project, which was funded starting in 2007 by Germany's Federal Ministry of Education and Research for the development of R2R production of highly efficient light-emitting diodes on flexible substrates. At the conclusion of the program, the members will have established a stronger fundamental appreciation for processing and manufacturing using R2R equipment.

CONCLUSIONS

In general, the WTEC panel members felt that the individuals at the different sites visited in Europe have a strong appreciation for manufacturing and processing for hybrid flexible electronics. The approaches they are taking have nuances that differentiate them, but as a group they share the vision of roll-to-roll large-area processing platforms for the manufacture of novel hybrid flexible electronics–based products. Nuances such as processing technology, ink jet versus gravure printing, manufacturing environment, and cleanroom versus non-cleanroom, were repeatedly discussed. Each group had a rigorous set of processing parameters that led it to its outlined process flow and equipment selection.

Independent of specific process and equipment technology, engineers in Europe have outlined strategies for transitioning from sample prototyping to product commercialization. These strategies highlight the necessary manufacturing and processing milestones that must be achieved and the related equipment and tooling specifications necessary to meet these milestones. The needs and gaps for successful high-volume manufacturing are being addressed. Engineers are working with equipment suppliers to educate them in this emerging technology and to provide them with equipment specifications. This partnering and teaming appears to have led to success in delivering manufacturing-capable tools. The development of a strong infrastructure with multiple suppliers of manufacturing-capable equipment is necessary to enable the establishment of a new market. Provided these activities continue in Europe, the panel feels that several volume manufacturing platforms will be offered in the near-term that will facilitate hybrid flexible electronics–based product commercialization.

REFERENCES

Websites of companies, institutions, and government-funded programs involved in development of improved manufacturing and processing capabilities for hybrid flexible electronic products[6]

ACREO	http://www.acreo.se/
CDT	http://www.cdtltd.co.uk/
CAPE	http://www.cape.eng.cam.ac.uk/
CIKC	http://www-g.eng.cam.ac.uk/CIKC/
CNR Bologna	http://www.bo.ismn.cnr.it/ and http://www.cnr.it
Holst Center	http://www.holstcentre.com/
Heliatek	http://www.heliatek.com/
IAPP	http://www.iapp.de
IMEC	http://www2.imec.be/
IPMS	http://www.ipms.fraunhofer.de/en/
Imperial College	http://www.imperial.ac.uk
Johannes Kepler University/LIOS	http://www.ipc.uni-linz.ac.at/
Konarka	http://www.konarka.com/index.php
Linköping University	http://www.norrkopingsciencepark.com
MiPlaza	http://www.miplaza.com/
Novaled	http://www.novaled.com/
Philips Research	http://www.philips.com/global/index.page
Plastic Logic	http://www.plasticlogic.com/
Plastic Electronic	http://www.plastic-electronic.com/
PolyIC	http://www.polyic.com/
PolyApply	http://www.vdivde-it.de/portale/polyapply/home.html
Polymer Vision	http://www.readius.com/
Rollex	http://www.feast.org/articles/?ID=549/ (ROLLEX project: BMBF FKZ 13N8857)
FlexiDis	http://www.ist-world.org/ProjectDetails.aspx?ProjectId=0f0f3aff6a864f17add71f93ef2c611b
University of Bari	http://www.chimica.uniba.it
University of Stuttgart Display Technology Fabrication Lab	http://www.lfb.uni-stuttgart.de/forschung/labor.en.html

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[6] Many of these sites were visited by the WTEC panel; site reports of those visits are provided in Appendix B.

APPENDIX A. BIOGRAPHIES OF PANELISTS AND AUTHORS

Ananth Dodabalapur, PhD (Panel Chair)

BS in Electrical Engineering, Indian Institute of Technology, Madras
MS and PhD in Electrical Engineering, The University of Texas at Austin

Ananth Dodabalapur is the Ashley H. Priddy Centennial Professor in Engineering at the University of Texas at Austin. Between 1990 and 2001 he was with Bell Laboratories, Murray Hill, NJ. Since 1992 he has investigated various aspects of the physics and technology of organic and polymer semiconductor devices. He has published over 100 articles in refereed journals and has more than 30 U.S. patents issued or pending office action. His research on organic transistor circuits and injection lasers was cited as one of the top ten scientific breakthroughs for 2000 by *Science* magazine. He is a co-recipient of the 2002 Award for Team Innovation of the American Chemical Society and a co-recipient of an R&D 100 award for 2001. Since September 2001, he has been with The University of Texas at Austin where he is a professor in the Department of Electrical and Computer Engineering and holds the June and Gene Gillis Endowed Faculty Fellowship. Dr. Dodabalapur's teaching interests are in the areas of electronic circuits (undergraduate), organic and polymer semiconductors (graduate), and charge transport in organic semiconductors (graduate). His current research interests include organic transistors, organic-based chemical and biological sensors, and organic-based laser physics and optics.

Ana Claudia Arias, PhD

BS and MS in Physics, Federal University of Paraná, Brazil
PhD in Physics, Cambridge University, UK

Ana Claudia Arias is currently a member of the research staff and manager of the Printed Electronic Devices Area at PARC Inc., formerly Xerox-PARC, in Palo Alto, CA. At PARC she uses inkjet printing techniques to fabricate organic active matrix display backplanes, flexible electronics, and sensors. She also serves as principal investigator for PARC's DARPA sensor-tape program. She came to PARC from Plastic Logic in Cambridge, UK, where she led the semiconductor group. She completed her PhD on semiconducting polymer blends for photovoltaic devices at the University of Cambridge, UK. Her research work in Brazil focused on the use of semiconducting polymers for light emitting diodes. Ana Claudia is the author of numerous publications and patents on the field of polymer-based electronics and optoelectronics.

C. Daniel Frisbie, PhD

BA in Chemistry, Carleton College
PhD in Physical Chemistry, Massachusetts Institute of Technology

C. Daniel Frisbie is Professor of Chemical Engineering and Materials Science at the University of Minnesota, where he has been since 1994. Prior to Minnesota, he was an NSF Postdoctoral Fellow at Harvard. His research focuses on structure and electronic properties of organic semiconductor thin films for applications in transistors and solar cells. He is particularly interested in the dependence of electron and hole transport on molecular structure, crystal packing, intermolecular bonding, and defects in organic crystals and films. His research themes include the synthesis and characterization of novel organic semiconductor materials, structure property relationships in organic semiconductor devices, and the application of scanning probe microscopy techniques to electrical characterization. A major research focus is the use of polymer electrolytes as high capacitance gate dielectrics in organic thin film transistors to boost output currents and lower drive voltages. Frisbie currently leads a multi-investigator effort, Organic Optoelectronic Interfaces, at the University of Minnesota, sponsored by the Materials Research Science and Engineering Center (MRSEC) program of the National Science Foundation. He also serves as Director of Graduate Studies for Materials Science and Engineering at the University of Minnesota. He has published approximately 100 papers.

Daniel Gamota, PhD

MBA, Northwestern University, J.L. Kellogg Graduate School of Management
PhD in Engineering, the University of Michigan

Daniel Gamota is co-founder and president of Printovate, Inc., which has developed clean-tech, large-area electronics manufacturing technology for point-of-care diagnostics, lighting, and renewable energy applications. Previously at Motorola in the role of director, he was responsible for all administrative, technical, and product development activities within the Large Area Electronics Department. Dan's leadership led to his department receiving a 2007 "R&D 100 Award" for commercialization of a printed electronics–enabled product manufactured using electrically functional inks (organic and inorganic semiconducting materials) and large–area non-cleanroom manufacturing platforms. In 2008, his department was internationally recognized for having fabricated the first all-printed active matrix flexible display module using conventional graphic arts printing technologies. Dan chairs several international groups that are developing standards for large-area flexible electronics and nanotechnology (IEEE) and that are publishing large-area flexible electronics roadmaps (International Electronics Manufacturing Initiative, Inc., iNEMI). He has been granted 38 patents, has published 27 articles in peer-reviewed journals, has co-authored three book chapters, and has co-edited the first book that combined the fields of graphic arts printing, microelectronics, organic semiconductors, and nanotechnology. Dan was elevated to IEEE Fellow for his contributions to the field of printed electronics and nanotechnology.

Tobin J. Marks, PhD

BS in Chemistry, University of Maryland
PhD in Chemistry, Massachusetts Institute of Technology

Tobin J. Marks is Charles E. and Emma H. Morrison Professor of Chemistry, Vladimir N. Ipatieff Professor of Catalytic Chemistry, and Professor of Materials Science and Engineering at

Northwestern University. Professor Marks was awarded the 2005 Presidential Medal of Science by President Bush, and he is a member of the U.S. National Academy of Sciences and the German National Academy of Sciences. He has published 950 professional papers, holds 95 U.S. patents, and has received many prestigious awards. These include the American Institute of Chemists Gold Medal (2002); the Karl Ziegler Prize, Gesellschaft Deutscher Chemiker (2003); the Sir Edward Frankland Prize, Royal Society of Chemistry (2004); American Chemical Society Awards for Organometallic Chemistry (1989), Inorganic Chemistry (1994), Chemistry of Materials (2000), and Distinguished Service in the Advancement of Inorganic Chemistry (2008); the Principe de Asturias Prize for Technical and Scientific Research (Spain, 2008), and the von Hippel Medal of the Materials Research Society (2009). His research group is divided into five parts: organometallics and catalysis, photonics, MOCVD, molecular electronics, and solar energy.

Colin E. C. Wood, PhD

BS, MS, North Lancashire University, UK
PhD in Electrical Engineering, Nottingham University, UK
Doctorate of Science, Nottingham University, UK

Colin E. C. Wood is a Research Professor at Texas State University San Marcos. He came to Texas State University from the Office of Naval Research (ONR), where he served as a Program Officer for over 18 years. He was awarded the Patterson Medal from the United Kingdom Institute of Physics, and he is a Fellow of the American Institute of Physics. Dr. Wood has made many paradigm-changing advances in Group III-V science and technology over his career. His work considered RHEED intensity oscillations, delta and predeposition doping, planar-doped barrier and transistor, low temperature GaAs, dopant incorporation, non-alloyed ohmic contacts, antimonides and alloy ordering, and structures for infrared detectors. He has published over a hundred professional papers in his field.

Grant Lewison, PhD (WTEC Bibliometrics Consultant)

BA, University of Cambridge
PhD, Mechanical Engineering, University of Cambridge

Dr. Grant Lewison was trained as a mechanical engineer and experimental hydrodynamicist at the University of Cambridge and spent a number of years as a scientist in the British civil service. His own research has focused on bibliometrics. In 1993 Dr. Lewison joined the Wellcome Trust to design and manage its Research Outputs Database (ROD). Since then he has carried out many consultancy assignments in bibliometrics and has written about 70 papers. At the end of 2000, the ROD was transferred to The City University on contract from the Trust, and he moved with it as visiting professor in the Information Science Department. Dr. Lewison left City University at the end of 2005 to set up his own consultancy company in Richmond (UK), Evaluametrics, Ltd., which undertakes research evaluation through publication metrics. He has been appointed a Senior Research Fellow at University College, London. His particular interest is in presentation of research to the public through the mass media and policy documents, and its evaluation by these means.

Site: **BASF Future Business GmbH**
BFB-Z025
6703 Ludwigshafen, Germany
http://www.basf-futurebusiness.com/en.html

Date Visited: May 11, 2009

WTEC Attendees: Tobin J. Marks (report author), Ananth Dodabalapur, Dan Gamota

Host: Dr. Peter Eckerle, Project Manager, BASF Future Business
Tel: +49(0)621 60 42611, Email: peter.eckerle@basf.com

GROUP SIZE

There is a core group of more than 10 dedicated BASF researchers in Ludwigshafen and Singapore in areas related to flexible electronics; in addition there are several part-time participants, and a number of external partners. The April 2009 acquisition of Ciba added several more people to the effort.

SUPPORT

Support is primarily provided by BASF, but some funds come from the EU and German government

DISCUSSION

Dr. Eckerle is primarily involved in the project “Printed Electronics,” largely focused on OFET-based applications. Besides printed electronics, BASF is involved in two other projects addressing organic photovoltaics (OPVs) and organic light-emitting diodes (OLEDs; for lighting) within an “energy management cluster.” The polymeric printed electronics effort overlaps the organic photovoltaic activity. The drivers for BASF in this field are the consumer (low-cost packaging solutions), energy (OPV, OLED), and display (e.g., Kindle-type products) markets. Dr. Eckerle feels the commercialization of early generations of OPVs and electrophoretic displays most likely will be realized within 5 years. He is also optimistic regarding low-complexity RFID (radio-frequency identification) tags but doesn’t expect that there will be EPC-compliant RFID tags (probably requiring CMOS circuits) or large OLED displays with printed backplanes within the next ten years. Although BASF is still primarily a commodity chemical company, Eckerle sees printed electronics as having a large potential market and a place as an important business in the company.

Comparing organic, inorganic, or hybrid organic-inorganic active materials, Dr. Eckerle feels that performance is most important, and that as long as the processing temperatures for inorganic materials are sufficiently low (130–150 °C desired; 180–200 °C for polyethylene naphthalate/ PEN), with good flexibility and printability, inorganic materials could be acceptable. In addition to p-type P3HT, which has low performance but low cost, he expects many organic materials with much better performance. CMOS is seen as prerequisite for long-term development of printed electronics. Based on current research progress, Dr. Eckerle is optimistic that n-types will emerge within 10 years that match p-types in performance and lifetime.

Comparing solution- and vapor-phase processing, Eckerle feels that the former is essential for traditional printing processes, but that low-cost/high-throughput evaporation processes could in principal be important. For hybrid organic-inorganic materials, these deposition processes may be more complex. As for interconnects, he feels that current-generation conductive polymers are insufficiently conductive and that metals, deposited by photolithography or laser ablation, will be used. He feels that good research in this area requires more than materials development alone.

In regard to continued EU support, he feels that Europe is committed to keeping research and manufacturing in this area strong. Furthermore, more and more PhDs are being produced who are trained in this area of research. He sees collaborations as very important in this area, and collaborations between large and small companies can offer the best of both worlds.

BASF has set up a fully functional research laboratory in Singapore that focuses on two areas: OPV and organic TFT (thin-film transistor) research. The scientific staff is mainly from Asian countries, which offer BASF a large talent pool. There is collaboration between BASF and the Institute of Materials Research and Engineering (IMRE), a Singapore government research institute, in the area of organic photovoltaics.

Site: **Cambridge Display Technology (CDT), Ltd.**
Building 2020
Cambourne Business Park
Cambridgeshire
CB23 6DW, UK
http://www.cdtltd.co.uk/

Date Visited: May 13, 2009

WTEC Attendees: Ana C. Arias (report author), C. Daniel Frisbie, Colin Wood, Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts: Dr. Jeremy Burroughes, Chief Technical Officer
Tel: +44 (0)1954 713600
Fax: +44 (0)1954 713620
Email: jburroughes@cdtltd.co.uk

Dr. Jonathan Halls, Group Leader, Strategic Innovations
(later, Chief Technical Officer of Solar Press)

GROUP SIZE

Cambridge Display Technology (CDT), Ltd., employs approximately 140 personnel.

SUPPORT

CDT is wholly owned by Sumitomo Chemical Group.

DISCUSSION

CDT makes full color active matrix OLED displays using solution-processed organic semiconductors. The company was founded in 1992 as a spin-off from Cambridge University's Cavendish Laboratory. It was purchased by Sumitomo Chemical Group in 2007 for $285 million. The company remains in a start-up phase and employs approximately 140 people in Cambridge. Dr. Burroughes is one of the primary authors of the original P-OLED (polymer organic light-emitting diode) patent and was the lead author on a 1990 paper in *Nature* that described electroluminescence from polymer semiconductors.

CDT has numerous full-color, active matrix prototype displays working at video rates. The active OLED materials are synthesized in house by ~40 working chemists or are supplied by the parent company (Sumitomo). All final display development work is carried out in Japan. The Cambridge facility focuses on research and development. CDT emphasizes solution-processing approaches to OLED display fabrication. Functional inks are formulated from proprietary materials and are printed on glass substrates using multi-nozzle production ink jet printers. Each pixel in the display consists of red, green, and blue emitters; the lifetimes of the red and green emitters exceeding 50,000 hours at 1000 candelas/m^2, and the lifetimes of the blue emitters are 10,000 hours at 1000 cd/m^2. Current research aims to develop alternative active matrix backplanes based on solution-processed TFTs and so-called top-emission structures.

Site: **CNR Bologna**
Via P. Gobetti n. 101
1-40129 Bologna, Italy
http://www.cnr.it
http://www.bo.cnr.it/
http://www.bo.ismn.cnr.it/

Date: May 14, 2009

WTEC Attendees: Dan Gamota (report author), Ananth Dodabalapur, Tobin J. Marks

Host: Dr. Michele Muccini, Head of Organic and Hybrid Electronics Division
Institute for the Study of Nanostructured Materials (ISNM)
Tel: +39 051 639 8521; Email: mmuccini@bo.ismn.cnr.it

GROUP SIZE

The CNR Bologna research area has a total of 600 personnel, including 350 CNR employees and 250 collaborators. CNR Bologna's Institute for the Study of Nanostructured Materials (Instituto per lo Studio dei Materiali Nanostrutturati, ISMN) has about 60 research employees, of which 30 are CRN employees.

SUPPORT

CNR-ISMN Bologna's annual budget for research, excluding staff salaries and running costs, is about EUR 4 million. The total CNR annual budget (for 107 research institutes) is EUR 1 billion, 60% of which comes from government resources and 40% from external resources.

DISCUSSION

CNR (Consiglio Nazionale delle Ricerche) is the National Research Council of Italy. Its mission is to create, by research, knowledge for the technological, economic, and social development of the country. Some 92 research projects are underway within 11 CNR departments.

CNR-ISMN Bologna hosted a symposium to provide the WTEC visiting team with a brief overview of activities related to hybrid flexible electronics at CNR facilities at the University of Bari and the University of Bologna. Also, a presentation was given by the corporate R&D manager at Saes Getters S.P.A,. a strategic partner for the CNR spin-off E.T.C. srl aimed at developing advanced materials and commercializing organic electroluminescence (OLET) technology. During the presentations given at the symposium (see agenda below), the importance of collaborating was stressed several times: "collaboration is critical for transforming science to innovation."

The WTEC panel's hosts organized a tour of the CNR facilities, including several labs. The CNR labs have tools for processing active and passive thin films for characterizing their electrical/optical-structure properties, as well as for electronic, optoelectronic, and photonic device fabrication.

CNR has an appropriate infrastructure to spin out new companies. Several start-up companies have been founded based on technologies nurtured at CNR: Advanced Polymer Materials (http://www.apmpolymers.com/), Mediteknology (http://www.mediteknology.it/), Organic Spintronics (http://www.organic-spintronics.com/), Lipinutragen (http://www.lipinutragen.it/), and Scriba Nanotecnologie (http://www.scriba-nanotec.com/).

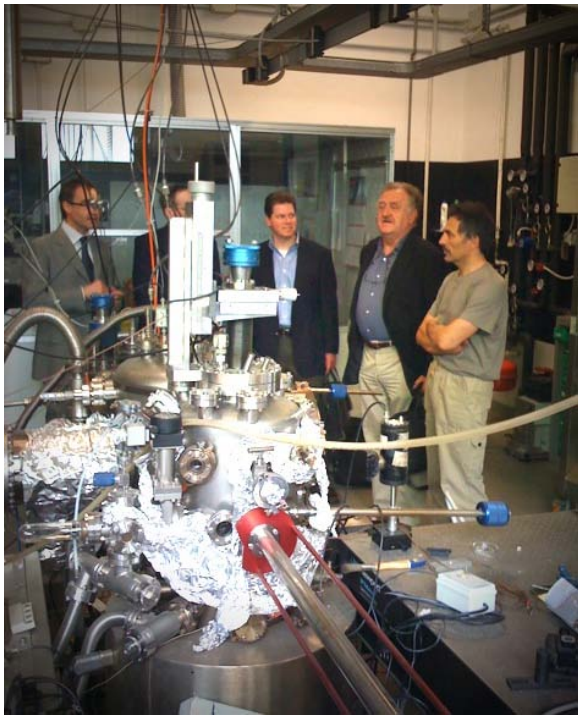

Figure B.1. (*Left)* Dan Gamota (photo center) of the WTEC visiting team listening to details about a vacuum system from Dr. Carlo Taliani (second from right) of CNR; (*right*) Dr. Michele Muccini of CNR.

Prior to its visit, the WTEC panel provided a list of questions to the host for review by the scientists and engineers active in the field of hybrid flexible electronics. The responses by those individuals are captured below. The importance of various focal areas and/or technologies was ranked from 5 (high) to 1 (low).

Table B.1. CNR Responses to WTEC Panel Questionnaire

Question	Brief Comment	Mark 1–5
GENERAL		
How strategic do you consider flexible electronics for your group's activities?	Flexible electronics is considered one of the most relevant platforms for future strategic development.	4
What major development do you expect in the field of flexible electronics in ten years?	Biosensing RFID Loco-regional drug-delivery with built-in monitoring Displays Lightings	
How important do you consider collaboration between groups in Europe?	Very Important	5
How would you define your IP strategy?	It is becoming more and more systematic starting from the last 3-5 years	4
How related is your research to the industrial needs?	The research activity normally targets long term applications. It does not necessarily take into account from the beginning the present industrial needs. If required of a number we would consider our research related to industrial needs at a 25% level.	
How integrated do you consider the universities/research centers systems?	Medium: there is certainly room for improvement.	3
How adequate do you consider the supply	Fair	4

Question	Brief Comment	Mark 1–5
of talents?		
How appropriate do you consider EU or National policies in the field of FE?	Appropriate in the case of EU. Poor in the case of national policies.	4 2
How advanced do you consider the research in the US in the field of FE?	It is considered to be well advanced with respect to the state of the art	4
How advanced do you consider U.S. industrial R&D in the field of FE?	We consider it to be at a fair to advanced level.	3
MATERIALS & DEVICES		
What materials do you work with?	Polymers, molecular systems, oxides, metals.	
What is the potential for a major discovery in the materials area for the field?	Medium to high potential for a breakthrough discovery	4
What are the devices you work with?	Field Effect Transistors Sensors, photovoltaic cells, spin valves, tunnel junctions.	
How important do you consider in depth understanding of the device physics?	Very important	5
DEVICE FABRICATION		
What deposition methods do you use?	Vacuum sublimation, solution processing, channel spark, stamp-assisted self-organisation; microfluidics	
How important do you consider cleanroom conditions?	Crucial for further development from the current stand-point.	4
How important is the issue of reproducibility in device fabrication?	Very important	5
What are the patterning methods you use?	Advanced *in situ* masking, photo- and EB lithography, unconventional lithography, soft printing, imprinting, screen printing, laser irradiation.	
CIRCUITS AND SYSTEMS		
How relevant is system integration for your activity?	Low now; it is expected to become important in few years from now	3
Do you perform circuit/system design in-house or through collaborations?	This activity, when it is performed, is typically done through collaborations	2
How strong is interaction with medical institutions for work in the field of flexible electronics?	Strong and rather extended	4
MANUFACTURING		
What manufacturing facilities are in place?	Advanced deposition machines with in-situ transfer and *in situ* masking, reel-to-reel (in spin off), lift-off, soft printing, and imprinting	
What future investment would be necessary to match your manufacturing targets?	Investments are required for screen printing, R2R, high-resolution patterning, and cleanroom facilities.	4
What do you consider as the major manufacturing-related hurdles?	Alignment, multicomponent devices, metal electrodes and vias. Maintaining in the manufacturing process the quality of in-situ prepared interfaces.	
APPLICATIONS		
What are the most important commercial opportunities in the field?	Disposable diagnostic devices, High throughput screening, Lighting, Wearable electronics, photovoltaics	
What are in your opinion the most important markets for flexible electronics?	Health, ICT, energy, military	

SYMPOSIUM AT CNR BOLOGNA

Dr. Muccini organized a symposium that presented highlights of technical and entrepreneurial activities in Bologna and Bari related to hybrid flexible electronics. The agenda is given below.

Meeting at CNR Bologna, May 14, 2009

9:00-9:10	Introduction and welcome (M. Muccini)
9:10-9:25	The role of the Italian Agency for Diffusion of Technologies: Do we have chances in plastic electronics? (Prof. R. Ugo, President of National Agency for Technologies and Innovation)
9:25-9:40	Scope of the NSF visit, methodology (Prof. Ananth Dodabalapur, Chairman of the Evaluation Panel on Hybrid Flexible Electronics – U.S. NSF)
9:40-9:55	The strategic initiatives of Regione Emilia Romagna (Dr. P. Bonaretti, Director of ASTER)
9:55-10:10	The research agenda of CNR on hybrid flexible electronics (Dr. G. Padeletti, Director of the CNR-ISMN—the Institute of Nanostructured Materials—representing CNR's Department of Molecular Design)
Session 1	**Activities at CNR**
10:10-10:25	Technologies for lighting and photovoltaics (Dr. M. Muccini, Head of Organic and Hybrid Electronics Division of CNR-ISMN)
10:25-10:40	Industrial partnership: The vision of SAES Getters S.p.A. (Dr. R. Giannantonio, Corporate Innovation Manager, Saes Getters)
10:40-10:50	Technologies for organic electronic biosensors (Prof. L. Torsi, Department of Chemistry, University of Bari)
10:50-11:00	Design and tailoring of organic and hybrid materials (Dr. M. Melucci, CNR-ISOF)
11:00-11:20	Break with coffee and tea
11:20-11:30	Nanofabrication and nanotechnology of multifunctional materials (Dr. F. Biscarini, Head of Nanotechnology of Multifunctional Materials Division of CNR-ISMN)
11:30-11:40	Organic and hybrid spintronics (Dr. V. Dediu, Head of Organic Spintronics Division of CNR- ISMN)
11:40-11:50	The silk technological platform: An across-the-sea initiative (Dr. R. Zamboni, CNR-ISMN, Leader of CNR National Project on Organic and Hybrid Electronics and Optoelectronics)
11:50-12:30	Discussion
12:30-13:30	Lunch
Session 2	**Activities at University of Bologna**
13:30-13:45	Multicomponent molecular systems for optoelectronics (Prof. P. Ceroni, University of Bologna, Department of Chemistry)
13:45-14:00	Modeling and simulations (Prof. C. Zannoni, Director of the Department of Physical and Inorganic Chemistry, University of Bologna)
14:00-14:30	Discussion
14:30-14:45	Concluding remarks, followed by a visit to the CNR facilities

Site: **Fraunhofer Institute for Photonic Microsystems (IPMS)**
Maria-Reiche-Strasse 2
1109 Dresden, Germany
http://www.ipms.fraunhofer.de/en/

Date: May 15, 2009

WTEC Attendees: Dan Gamota (report author), Ananth Dodabalapur, Tobin J. Marks

Hosts: Prof. Dr. Hubert Lakner, Executive Director
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Mr. Jörg Amelung
Email: joerg.amelung@ipms.fraunhofer.de
Dr. Christian May
Email: christian.may@ipms.fraunhofer.de

GROUP SIZE

There are 240 personnel at the Fraunhofer-Institut für Photonische Mikrosysteme (Fraunhofer IPMS) facility (80% employees, 20% scientific assistants). Approximately 60 individuals are involved in the field of organic electronics.

SUPPORT

The annual research budget of Fraunhofer IPMS is EUR 24 million, of which more than 40% is generated via contract research. In 2008, IMPS was awarded EUR 1.8 million in EU projects. The total research budget for R&D at all Fraunhofer Institutes is EUR 1.3 billion (basic-focused 30%, public-focused 30%, and industry-focused 40%).

DISCUSSION

Fraunhofer IPMS is one of 60 Fraunhofer institutes throughout Germany and one of the 11 Fraunhofer institutes that are active in the field of microelectronics. IPMS was established in 2003, and its technical facilities (cleanrooms) were modernized in 2007. IPMS is a well-equipped and well-staffed institute that has the ability to provide product concept generation, product development, process development, and pilot fabrication development services to scientists and engineers throughout the world. Two cleanroom facilities are located at IPMS: (1) 1500 m^2 Class 1 and (2) 900m^2 Class 10. The Class-1 cleanroom (6-inch wafer tools) is used for silicon-based devices development (e.g., MEMS), and the Class-10 cleanroom has tooling for organic-based electronics devices and systems fabrication.

The Class-10 cleanroom is part of a world-class center dedicated to the research, development, and pilot-production of organic-materials-based devices and systems that was opened in October 2008: the *Center for Organic Materials and Electronic Devices (COMEDD)*. In addition to the cleanroom, COMEDD has labs for device/system electrical characterization, materials, and device/system reliability operation. The mission of COMEDD is to provide services supporting the following 3 applications: (1) OLED-based lighting and signage, (2) organic-based photovoltaics, and (3) OLED-on-CMOS applications.

COMEDD is well equipped with state-of-the-art lab-scale, prototype-scale, and pilot-volume-scale equipment for customer- and applications-specific research, development, and pilot fabrication of advanced devices and system architectures based on vacuum-processed organic electronic materials. The following lines are available: (1) a prototype line for rigid substrates (glass, 200 x 200 mm^2) offering a cycle time of 120 minutes, (2) a pilot line for rigid/flexible substrates (glass or laminated foils, 370 X 470 mm^2 – Gen2) offering a cycle time of 3 minutes, (3) a pilot line for OLED-on-CMOS for silicon/CMOS wafers (150-200 mm diameter) offering a cycle time of 60 minutes, and (4) a roll-to-roll line (metal foils, 300 mm width).

Based on interaction with customers, IPMS personnel predict that organic-based displays will be commercialized first, followed by lighting, and then OPV. There is strong belief at IPMS that several businesses (both product platforms and services) will be established based on these technologies.

IPMS is a member of German- and EU-funded programs that advance the state-of-the art for organic-based devices and systems manufacturing/assembly. As an example, IPMS is a member of the Rollex project funded by the Federal Ministry of Education and Research for the development of roll-to-roll production of highly efficient light-emitting diodes on flexible substrates. The goal is to provide a highly efficient, low-cost alternative to conventional lighting.

Figure B.2. Organic-based device processed at COMEDD on one of its pilot lines.

Site: **Heliatek GmbH**
Leibigstrasse 26
D-01187 Dresden, Germany
Tel: +49-(0)351-21303430; Email: office@heliatek.de
http://www.heliatek.com/en/page/index.php

Date: 15 May, 2009

WTEC Attendees: Ananth Dodabalapur (report author), Dan Gamota, Tobin J. Marks.

Principal Hosts: Dr. Martin Pfeiffer, CTO (not in attendance on day of visit)
Email: martin.pfeiffer@heliatek.com
Dr. Karsten Walzer, Project Manager
Dr. Christian Ulrich

GROUP SIZE

The Heliatek group consists of 27 staff scientists, including 10 chemists and 17 from other disciplines

SUPPORT

Seed-financing of EUR 600,000 was from the German "High-Tech-Gründerfonds" (HTGF – fund founder) and a “business angel.” Second-round financing (ca EUR 4 million) closed in June 2007 with the investors BASF Venture Group, Bosch GmbH, Wellington Partners (VC), and the HTGF. There is close cooperation between Heliatek and BASF for materials for OPV, and between Heliatek and Bosch for process and production technology.

DISCUSSION

Dr. Pfeiffer was away on travel on the day of the WTEC team’s visit, but the team met with Drs. Walzer and Ulrich, who gave a presentation and tour.

Heliatek specializes in organic-based photovoltaics; it was founded in July 2006 as a spin-off of the Institute of Applied Photo Physics (IAPP) of the University of Technology, Dresden, and the University of Ulm, based on successful interdisciplinary scientific cooperation. The goal of the company is to realize 0.5-1 Euro/peak watt solar cells based on sublimed organic semiconductors. Heliatek has been one of the companies believing in the commercial viability of vacuum-processed organic-based devices. The WTEC team’s hosts maintained that cleanrooms are less critical for vacuum sublimed systems and that commercial availability of linear sublimation sources of up to 1 meter width is a major advantage for manufacturing solar cells based on vacuum sublimed materials. The company has achieved efficiencies similar to those of the best solution-based organic/polymer solar cells (6% power conversion efficiency). They mentioned that solar cells are less sensitive to non-uniformities than LEDs, in which non-uniformities are easily spotted.

Heliatek has achieved 6% power conversion efficiencies in individual tandem cells and module efficiencies of 4.4% for modules of 15 cm x 15 cm in size with an open circuit voltage > 15 V. These figures are as good as any reported for organic-based solar cells and modules. The Heliatek technology involves several innovations, including in absorber materials, doping of materials to achieve improved electrical performance, and low series resistance. The stability figures that Drs. Walzer and Ulrich reported were T80 = 34,000 hours (at an intensity of 2 suns) for ZnPc-based solar cells.

They maintained that collaboration is the key to achieving good results. They have extensive interactions with IAPP and with the Fraunhofer Institute in Dresden, as with several other institutions. They also emphasized the need for public funding of such companies.

The Heliatek scientists shared their vision for the future of organic solar cells. They saw 2011 as the year products will come out. They said that building integration is a key niche, and the light weight of organic solar cells will be a plus and will facilitate building integration. They also said that the deployment of low-costs cells in developing countries is an important area.

Site: **Holst Centre**
Building 31, P.O. Box 8550
5605 KN Eindhoven, The Netherlands
http://www.holstcentre.com/en

Date: May 11, 2009

WTEC Attendees: C. Daniel Frisbie (report author), Ana C. Arias,
Colin Wood, Khershed Cooper, Pradeep Fulay,

Host: Dr. Paul Blom, Scientific Director
Tel: +31 40 277 4000
Email: p.blom@tno.nl

GROUP SIZE

The Holst Centre employs approximately 130 staff members, which number currently includes about 20 PhD students from several universities and approximately 40 resident researchers from industry. Expansion to 220 staff members is planned in 2010.

SUPPORT

The target for distribution of financial support for the center is 50% from the Dutch Government and 50% from industry through annual participation/membership fees. Currently, the funding contribution of the Dutch government is greater than 50%.

DISCUSSION

The Holst Centre is a government- and industry-supported innovation center that develops novel technology in the area of flexible and hybrid electronics. It was founded in 2005 by IMEC (http://www.imec.be) and TNO (http://www.tno.nl/index.cfm), with support from the governments of the Netherlands and Flanders. The center focuses its research on products and fabrication processes that are 3–10 years from market introduction. A unique aspect of the Holst Centre is that it implements a “shared research and development” model: substantial support from the Dutch Government (currently more than 50% of the budget) is leveraged by annual participation fees from ~20 member companies. The motive for this model has been the general problem that R&D costs are growing faster than revenues. In addition, while typical member companies often have core technologies that they seek to exploit in a new or perceived electronics market, they lack sufficient experience or R&D capabilities to realize their end goals. Holst brings these companies together in a precompetitive environment to develop new technologies and manufacturing capabilities. (For more information, see http://www.holstcentre.com/en/AboutHolstCentre/Nutshell.aspx.)

The Holst Centre is located on the High Tech Campus in Eindhoven, formerly Philips Research Laboratories, which is currently the home of a number of small companies, including spin-offs from Philips. Research projects in the center take advantage of extensive cleanroom/microfabrication facilities and characterization instrumentation on campus, which are available on a fee-for-use basis. It was clear to the WTEC panelists that the rapid build-up of the Holst Centre (for example, in terms of industry participation) since its founding is attributable in large part to the excellent research facilities that are in place on the High Tech Campus.

Currently, the Holst Centre has two main focus areas: (1) Autonomous Microsystems and (2) Systems in Foils. Plans are in place to add programs in 2010 in Flexible Photovoltaics and Smart Packaging. The Autonomous Microsystems program aims to develop ultra-low-power, wireless sensors that can be integrated into, for example, clothing, packaging, or medical bandages. The emphasis of Systems in Foils is to prepare electronically functional foils (e.g., lighting foils and sensor tapes) using high-throughput printing and lithography processes and to achieve system integration by laminating functional foils together. Collectively, the focus of the two programs is less on novel materials development (member companies typically supply key materials) and more on systems design and fabrication methods. Designs take advantage of both conventional semiconductors (e.g., silicon) and novel organic materials supplied by industrial and faculty participants.

Site: **IMEC (**Inter-University
MicroElectronics Center)
Kapeldreef 75
B-3001 Leuven, Belgium
http://www2.imec.be/

Date: May 12, 2009

WTEC Attendees: C. Daniel Frisbie (report author), Ana C. Arias, Colin Wood, Khershed Cooper, Pradeep Fulay, Grant Lewison

Principal Host: Dr. ir. Paul Heremans, IMEC Fellow, Professor at K.U. Leuven, Holst Centre Program Manager, Organic Circuits; Director, Large-Area Electronics
Tel: + 3216281521; Email: heremans@imec.be

GROUP SIZE

There are 1,650 staff members at IMEC; approximately 50% of these are in silicon CMOS development, the other 50% are in Smart Systems and Energy, which includes photovoltaics, large area electronics, nanobioelectronics, wireless, etc. Of the IMEC staff members, some 350 are industrial residents and 150 are PhD students. At the time of the WTEC visit there were 23 personnel in organic circuits and 11 in organic photovoltaics.

SUPPORT

About sixteen percent of IMEC's total budget (EUR 270 million in 2008) comes from the Government of Flanders (EUR 44 million in 2008); the balance (EUR 226 million in 2008) is provided by industrial partners and EC contracts. Approximately 50 industrial partners pay annual participation/membership fees.

DISCUSSION

IMEC and the Holst Centre are similar in that they both follow a shared research and development model and aim to fill the technology transfer gap between universities and industry. Member companies pay annual fees to participate in IMEC core program areas; these fees account for nearly 85% of the Center's annual revenue. Benefits to companies include sharing of R&D costs, risks and resources. This partnership accelerates the timeframe from product inception to market introduction in technology areas where development costs are escalating. Intellectual property issues are resolved using protocols developed over the 25 years since IMEC was founded in 1984 (initial government investment was EUR 62 million). The environment is heavily interdisciplinary and multicultural. Approximately 350 industrial fellows work and reside at IMEC; many of these are foreign nationals, and approximately 60 different nationalities are represented across the Center. In addition, IMEC has close collaborations with a number of universities. A number of staff members have joint appointments with universities (e.g., Dr. Heremans), and there are approximately 150 PhD students carrying out their dissertation research on the campus.

IMEC is a nonprofit organization and all revenues are reinvested in research programs and facilities. Annual review of the Center assesses the following performance criteria: (1) overall excellence (as judged by contract revenue, publications), (2) excellence in exploratory work (number of PhD students and publications with universities, and (3) impact on local industry (spin-offs and collaborations). IMEC has generated 25 spin-off companies since its inception.

IMEC is largely silicon-focused, with approximately 50% of its staff working on CMOS-related development issues. Most of the silicon-based work is carried out in a state-of-the-art cleanroom facility that processes 300 mm wafers. This silicon knowledge base is an advantage for the large-area, organic electronics effort in that development is targeted to take advantage of aspects of organic and hybrid electronics that cannot easily be achieved with conventional silicon CMOS.

Heremans oversees an organic and hybrid electronics group that focuses on organic circuitry (e.g., all organic RFIDs and sensor tapes) and organic photovoltaics. The organic circuitry work aims at demonstrating high levels of integration (hundreds to thousands of transistors) processed on wafer-supported plastic sheets. (The plastic sheets are separated from the support after fabrication). Conventional lithographic methods are used. Particularly noteworthy achievements include a 64 bit RFID tag operating at 800 bps that includes a 13.56 MHz transponder. Key to this demonstration was the development of organic-based diodes that can rectify current at this frequency. Heremans' organic circuitry group also is an active partner in the Large-Area Electronics on foil and smart packaging efforts at the Holst Center in Eindhoven. Heremans spends one day a week at Holst to facilitate interaction.

The photovoltaics (PV) effort aims to achieve high-performance organic-based cells (small molecules or polymers) that can deliver power at less than EUR 0.5/Wp, where Wp is peak power in watts. The program focuses on efficiency, technology, and lifetime with the goal of achieving 10 % record efficiency (average efficiency of 7 %) and 5-year lifetimes. The IMEC rationale is that silicon will not likely be able to match such low cost/watt ratios, though it will approach EUR 1/Wp with continued development. Materials for the PV effort are supplied by partner companies. Processing methods for PVs include inkjet printing, spray coating, thermal evaporation, and organic vapor phase deposition. The organic circuitry and photovoltaics efforts utilize dedicated laboratory space with a variety of deposition tools, inert atmosphere boxes, and measurement equipment (~2000 sq. ft.). In addition, this group uses lithography and deposition tools in a second, older cleanroom that was originally used to process 150 mm wafers.

REFERENCES

IMEC. 2009. *08 annual report*. Leuven, Belgium: IMEC. Available: http://www2.imec.be/

Site: **Imperial College London**
South Kensington Campus
London, SW7 2AZ, UK
http://www3.imperial.ac.uk/

Date: May 14, 2009

WTEC Attendees: C. Daniel Frisbie & Colin Wood (report authors), Ana C. Arias, Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts: Dr. Donal Bradley, Professor and Head,
Dept. of Physics
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Dr. Iain McCulloch, Chair in Polymer Materials
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GROUP SIZE

Imperial College London has a group of 15 faculty members collaborating in organic/flexible electronics. The members are affiliated with three different departments: Physics (total faculty of 126), Chemistry (total faculty of 55), and Materials Science (total faculty of 35). There are 50 postdocs and 70 graduate students involved in the area of flexible/organic electronics.

SUPPORT

Fifteen faculty members share $32 million. They have raised funds from many sources, primarily from the UK Engineering and Physical Sciences Research Council (EPSRC), Cooperative Awards in Science and Engineering (CASE). The Royal Society provides research funding in addition to support from the College "Center of Excellence in Displays and Lighting," and BP Solar and other industrial partners. The UK government Energy Futures Initiative is also providing funds for organic PV research.

DISCUSSION

Starting in the late 1990s, the Physics Department at Imperial made a strategic decision to expand efforts in organic semiconductors. This resulted in several new faculty hires. The Chemistry Department made a similar decision, and a strong synergy between the two departments has developed in this area. Recent new hires in the Materials Department have expanded further the number of faculty working on organic electronics. The *Center for Plastic Electronics* was created at Imperial and encompasses the work of the 15 faculty.

Research efforts concentrate on the synthesis of new organic semiconductor materials, the phase behavior and processability of these materials, their photophysical properties, and their incorporation into devices such as solar cells, transistors, LEDs, and organic lasers. Currently, efforts in organic photovoltaics are growing rapidly. There is also interest in other low-temperature processable semiconductors such as ZnO (zinc oxide). A cleanroom located in the Physics Department (Blackett Laboratory) is available for processing and characterization of devices. This facility also has some printing equipment, including a lab-scale gravure printer. Individual investigator laboratories are well equipped for device preparation and characterization, and for examining photophysical properties.

Site: **Institute for Applied Photophysics (IAPP)**
Technical University of Dresden
George-Bähr-Straße 1
01062 Dresden
http://www.iapp.de/iapp/index.php?order=4&lan=en

Date: 15 May 2009

WTEC Attendees: Dan Gamota (report author), Ananth Dodabalapur, Tobin J. Marks

Hosts: Professor Dr. Karl Leo; Email: karl.leo@iapp.de
Dr. Moritz Riede; Email: moritz.riede@iapp.de
Dr. Björn Lüssem; Email: bjoern.luessem@iapp.de
Dr. Dominik Gronarz; Email: gronarz@oes-net.de

GROUP SIZE

The Institut für Angewandte Photophysik (IAPP, the Institute for Applied Photophysics) at the Technical University of Dresden has approximately 130 people on staff. Professor Karl Leo and a colleague are responsible for managerial, technical, and financial operations at IAPP.

SUPPORT

Support for the institute comes from a combination of sources, including government subsidies and competitive research awards.

DISCUSSION

The IAPP serves as a critical element of the organic electronics ecosystem in Europe, having strong ties to national laboratories, start-ups, and large companies. IAPP has a rich history in developing and commercializing photographic technology that dates back to 1908. Today IAPP is known for providing the fundamental underpinnings for organic photovoltaic (OPV) and organic light emitting diode (OLED) theory, materials, and devices. In addition, to housing well-equipped laboratories for performing studies of OPV and OLED technology, the IAPP serves as an "incubator." Due to the flexibility of the IAPP, individuals are given the opportunity to reside at the IAPP as "incubators" for a period of 6 to 12 months, during which time they can prepare for venture launch via prototype and applications development, business plan creation, etc.

The OPV team at IAPP is led by Dr. Moritz Riede. His team of 15 PhD and 5 post-doctoral students are investigating OPV topics ranging from basic science to prototype applications. Several programs addressing critical photophysical and technical issues are underway: charge-separation at the donor-acceptor heterojunction, tandem solar cell device physics, device optimization using charge transport layer (CTL), morphology of the bulk heterojunction, degradation, increased conversion efficiency via novel materials, and device structure features for capping layers and electrodes.

The OLED team at IAPP is led by Dr. Björn Lüssem. His team consists of 10 PhD and 5 post-doctoral students and focuses much of its work on improving the in-operation performance of white OLED (top and bottom emission). Similar to the OPV team, specific efforts within the OLED team mainly address technical/physical issues (degradation mechanisms, material stability, device architectures, power efficiency l m/W). Team members conduct their studies using small-format OLED devices (2.5 cm x 2.5 cm) with either rigid (90%) or flexible substrates (10%).

Dr. Dominik Gronarz is the business manager of Organic Electronics Saxony Management GmbH (OES; http://www.oes-net.de/en/home.html). During the meeting he provided an overview of the organic electronics environment in Saxony (German federal state, of which Dresden is the principal city) and the OES mission to establish the leading cluster in this emerging field. The organic electronics footprint in Saxony will span several market elements: R&D, materials, tools/equipment, products, and manufacturing.

Attendees of the meeting with WTEC panel members were in general agreement about the business opportunity that OPV and OLED offer. Some specific comments follow:

- It is difficult for OLED to compete with LCD unless flexible OLED is offered as a differentiator.
- OPV must achieve 8% conversion efficiency at module level (12% in lab) with a 20-year lifetime to address several growth markets (Building-Applied PV, Building-Integrated PV and integrated photovoltaics—BAPV, BIPV, and IPV).
- Stable blue OLED is needed.
- Several opportunities exist today to offer solar products providing a range of efficiency and lifetime values; therefore, it is important to select the process (vacuum or solution) to achieve the desired product/application attributes, e.g., lower efficiency and lower lifetime solar product for wireless product recharging versus high-efficiency and high-lifetime solar product for building applied photovoltaics. Processes, device performance, product attributes, and price are interdependent.
- Roll-to-roll *in situ* monitoring equipment is needed. Dual-use equipment for both vacuum and solution processing platforms is preferred.
- A “bridge” between university and industry is critical for successful product commercialization. One good example of such a “bridge” is the Fraunhofer Institute for Photonic Microsystems (IPMS). The IPMS enables the IAPP to scale-up its technology in a well-controlled environment.

Site: **Johannes Kepler University Linz**
Linz Institute for Organic Solar Cells (LIOS)
Institute of Physical Chemistry
Altenberger Straße 69
A-4040 Linz, Austria
http://www.ipc.uni-linz.ac.at/

Date: May 13, 2009

WTEC Attendees: Ananth Dodabalapur (report author), Dan Gamota, Tobin J. Marks

Hosts: Prof. Dr. Niyazi Serdar Sariciftci
Tel: +43-732-2468-8753; Email: serdar.sariciftci@jku.at

GROUP SIZE

The Linz Institute for Organic Solar Cells (LIOS) at Johannes Kepler University Linz has ~5 full-time university-paid staff and additional externally funded researchers (total: 27 to 30).

SUPPORT

Most of the research at LIOS is externally funded. The 2008 annual report of the institute lists that the total support received is in excess of EUR 1 million.

DISCUSSION

This institute is very well known as one of the early centers for research in the area of donor-acceptor solar cells. It also conducts work on organic FETs and sensors, along with basic science and photophysics of organic and polymeric semiconductor materials. The institute is a successful academic research center with an active research program as well as being the source for several spin-off companies. In terms of publications, more than 20 publications were listed in the annual report for 2008.

Linz is one of the more industrialized areas of Austria, and the city and suburbs have numerous companies. Research from the LIOS Institute has resulted in 6 spin-off companies over the years. These include QSEL, a solar cell spin-off that entered into a stock swap merger with Konarka a few years ago, resulting in Prof. Dr. Sariciftci joining the scientific advisory board of Konarka. Konarka has a research location within the same building that houses LIOS (please see Konarka site report). Another spin-off in the area of plastic electronics is the company Plastic Electronic (please see Plastic Electronic site report). Yet another recent spin-off in the area of energy harvesting is a company working in the area of homogeneous catalytic methanol production from sunlight and CO_2 (Solar Fuel GmbH; http://www.solar-fuel.com). A Tech2B (technology to business) program has been set up by the local government to facilitate the transfer of technology from the university. Members of the Tech2B select ideas, and those chosen subsequently receive $100 thousand to assist during the “incubation/creation phase.” Although the Tech2B has provided some assistance for new ventures, in general the spin-outs from LIOS required significant involvement by Professor Sariciftci, who served as founder and individually performed several of the other functions required for a startup.

The funding of research in European universities has two principal sources: government agency and private industry. According to Prof. Sariciftci, industry has good funding schemes. He feels that the future of organic photovoltaics depends on oil prices and how they change over the next several years. Organic FETs will be useful in display drivers and backplanes for systems such as electronic paper; the field of flexible biosensors will be slowed down by the numerous approvals required by agencies such as the FDA. He also feels that the biosensor field is very competitive. He is optimistic regarding the prospects of solid-state lighting based on organic/flexible electronics—described as the "Second Edison Evolution." Prof. Sariciftci is inspired by Silicon Valley and the U.S. academic-industrial research complex model. He feels that from an industrial perspective, Japan and Korea are key players for the future in the field of flexible electronics and photonics.

REFERENCES

LIOS Annual Report 2008. 2009. Available online: http://www.ipc.uni-linz.ac.at/AnnualReports/Annual08/.

Site: **Konarka Technologies, Inc.**
Johannes Kepler University Linz
Altenbergerstrasse 69
4040 Linz, Austria
http://www.konarka.com/index.php

Date: May 13, 2009

WTEC Attendees: Tobin J. Marks (report author), Ananth Dodabalapur, Dan Gamota

Host: Dr. Christoph Brabec, Vice President and Chief Technical Officer
Tel: +43 732 2468 5118; Email: cbrabec@konarka.com

GROUP SIZE

The Konarka Technologies R&D facility includes 12 people at Johannes Kepler University; 12 R&D people in Nuremberg (Nürnberg), Germany; 55 administrative and research people in Lowell, MA (USA); and 20 manufacturing people in New Bedford, MA (USA).

SUPPORT

Support is provided primarily by venture capital and by Austrian, German, and U.S. government funds.

DISCUSSION

Konarka's primary focus is on the development and manufacture of flexible organic photovoltaics. In regard to promising applications for hybrid flexible electronics in general, Dr. Brabec listed four major areas:

1. Energy and energy savings, OPV
2. Displays
3. Organic lighting (very promising)
4. Active packaging

In regard to the prospects for inorganic versus organic materials sets, Dr. Brabec felt that solution-processed inorganic materials might be a significant competitor to organics for organic electronics in the mid-term to long-term. Solutions based on metal oxide nanoparticles are developing rapidly; however, dealing with the surface passivating layers remains challenging. For large-area lighting, the strength of organics as the enablers of white OLEDs is particularly attractive. In regard to printed versus vapor-deposited films, Brabec noted that roll-to-roll high-throughput vacuum flash evaporation of metal films is well-developed; however, it is difficult to smooth uniform films on plastic substrates, so here, printing techniques appear to have an advantage. In regard to small-molecule versus polymeric materials, Brabec noted that small molecules are cheaper, easier to purify, and generally more stable. While solution processing is more complex, companies such as BASF and Mitsubishi Chemicals are working on small-molecule solution processes with some success. He also pointed out that vapor deposition processes with shadow masking are difficult for large areas but still attractive for OLED displays.

General needs for organic photovoltaic development have included more time for development of products and more funding than originally planned, i.e., managing public expectations. In terms of technical needs, Brabec identified two areas. First, there is an unsatisfactory materials situation in that materials having the attributes of poly-3-hexylthiophene are needed but with greater absorption of the solar spectrum, lower-lying highest occupied molecular orbitals (HOMOs) and lowest unoccupied molecular orbitals (LUMOs), and greater stability. The community must finalize on the materials set. The major technical need is to better develop the science of functional printing to achieve higher speeds; it will be necessary to move from 0.1 meter/min which is too slow to 1.0 meter/min.

In comparing and contrasting U.S. versus European research cultures, Drs. Brabec and Sariciftci (see also the Johannes Kepler University – LIOS site report) felt that U.S. researchers enjoy problem solving, are more innovative, more willing to take risks, and less afraid of failure. Europeans are more fearful of failure and enjoy working on problems. Importantly, European efforts are more sustained, and there is a tradition of developing centers of expertise and long-term attitudes toward the solving of important problems. Europeans are very conservative investors, and generally, employees are not anxious to work in risky companies. Europeans are less mobile, especially when it comes to changing the country of workplace. However, young people realize that the picture is changing and that they can no longer expect lifetime employment in one company or to remain in one location. In general it was felt that European undergraduates are better trained than their U.S. counterparts, but that U.S. graduate students were more capable. There is difficulty in Europe in getting employees with the right skills in organic electronics, especially for organic photovoltaics. However, recent U.S. visa policies have attracted many qualified Asian scientists to Europe.

Regarding start-up companies, the WTEC visiting team's host noted that 85% of venture capital money spent worldwide flows to the east coast and west coast of the United States. However, in Europe, large companies successfully lobby for large government research programs, and small companies can get public funding from the EU, national, and local governments.

Site: **London Centre for Nanotechnology**
17-19 Gordon Street
London WC1HOAH, UK
http://www.london-nano.com

Date: May 12, 2009

WTEC Attendees: C. Daniel Frisbie (report author), Ana C. Arias, Colin Wood, Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts:

Dr. Gabriel Aeppli, LCN Director, Quain Professor of Physics, University College London
Tel: +44 (0)20 7679 3448, Fax +44 (0)20 7679 7145/1360
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GROUP SIZE

The London Centre for Nanotechnology (LCN) is formed by approximately 30 faculty members from multiple departments within University College London (UCL) and Imperial College. It has 250 personnel, counting all faculty, staff, students, and post-docs.

SUPPORT

LCN's annual budget is £10 million, largely from the UK Engineering and Physical Sciences Research Council (EPSRC) and the EC. Industrial funding is actively sought and growing. The budget is used to support students and postdocs, and most members of the faculty have 50% appointments at LCN. Thus, a large portion of the budget is appropriated for faculty salaries.

DISCUSSION

LCN is a multi-investigator center formed jointly in 2003 by Imperial College and University College London (UCL). It has core competencies in simulation and design (nanoCAD), nanofabrication, nanocharacterization, and nanosystems (e.g., sensors). Its main mission is to produce excellent science in three main areas: Health Care, Planet Care (energy and the environment), and Information Technology. The center is similar in design to an NSF Materials Research Science and Engineering Center (MRSEC), in which faculty are organized into interdisciplinary research groups focused on particular problems. Efforts in flexible electronics are mainly in the Health Care and Information Technology areas, where example projects include the integration of amorphous or nanocrystalline silicon transistors into large-area arrays on plastic for displays and medical-imaging purposes, and the development and characterization of new organic semiconductor materials. There is also ongoing work with oxides (e.g., ZnO) for thin-film electronics and semiconductor nanowires. For this work, LCN has established 2,500 square feet of combined cleanroom space at its two locations in London: Gordon Street (at UCL) and South Kensington (at Imperial College).

Site: **Max Planck Institute for Solid State Research**
Organic Electronics Group
Heisenbergstrasse 1
70569 Stuttgart, Germany
http://www.fkf.mpg.de/start.html

Date: May 11, 2009

WTEC Attendees: Ananth Dodabalapur (report author), Dan Gamota, Tobin J. Marks

Host: Dr. Hagen Klauk, Head, Junior Independent Group on Organic Electronics
Tel: +49 (0)711 689-1401, Email: h.klauk@fkf.mpg.de

GROUP SIZE

The organic electronics group at Max Planck Institut für Festkörperforschung (Institute for Solid State Research) is composed of 3 PhD students, 1 MS student, and 2 senior scientists (Dr. Klauk and Dr. Ute Zschieschang).

SUPPORT

Annual support is provided by the Max Planck Institute (MPI). Funding from sources external to MPI is optional. Institutional facilities are good and are supported as well.

DISCUSSION

This group is focused on predominantly experimental (not synthetic) and publication-oriented basic research. Most of the research conducted is published in the open literature. Some invention disclosures have been filed as well. Dr. Klauk's group is engaged in unfettered applied scientific research. Some of the important research topics include high-performance organic thin film transistors, carbon nanotube field-effect transistors, inorganic nanowire field-effect transistors, and low-power circuits based on these transistors.

Dr. Klauk believes that small, highly efficient collaborative groups are important in his line of research. He collaborates with both Max Planck Institute (MPI) colleagues and other groups in Europe, the United States, and Japan. His vision for the field of hybrid flexible electronics is that over the next five years, applications such as displays and basic sensors (such as impact sensors) will be important, while in the longer term, photovoltaics will become very important, particularly in off-grid systems.

The WTEC visiting team discussed the merits of vacuum-deposited versus solution-deposited active materials with Dr. Klauk. In a field where much of the effort is devoted to developing printing methods and solution-based active materials, he is of the opinion that high-performance vacuum-sublimable materials are important because of their better performance characteristics, and that the reproducibility, uniformity, and manufacturing throughput of systems based on such materials can be high (as exemplified by amorphous silicon growth processes). Most systems need not be flexible; trying to make them flexible could lead to performance and yield problems.

Dr. Klauk stressed the importance of cleanrooms in improving reliability and yield in organic electronics, particularly in the fabrication of circuits with thin gate dielectrics. The quality of the results is critically dependent on the particulate count and size. This is also likely to be the case in manufacturing.

Figure B.3. (*Left to right*): Tobin Marks, Ananth Dodabalapur, and Dan Gamota in the MPI cleanroom.

Figure B.4. Dr. Ute Zschieschang and Dr. Hagen Klauk in the MPI cleanroom.

Site:	**Novaled AG** Tatzberg 49 01307 Dresden, Germany http://www.novaled.com/
Date:	May 15, 2009
WTEC Attendees:	Ananth Dodabalapur (report author), Dan Gamota, Tobin J. Marks
Host:	Dr. Jan Blochwitz-Nimoth, Chief Scientific Officer Email: jan.blochwitz-nimoth@novaled.com

GROUP SIZE

Novaled has more than 90 employees based in Dresden and 1 employee based in Tokyo.

SUPPORT

Total venture funding received so far is EUR 28.5 million. The company has an intellectual property portfolio of more than 400 patents (issued and pending).

DISCUSSION

Novaled was founded in 2001 by Karl Leo and colleagues. It is a spin-off from the research conducted at the Technische Universität Dresden, Institute für Angewandte Photophysik (IAPP, the Institute of Applied Photophysics at the Technical University of Dresden) and a cooperation with the Fraunhofer Society (through its Dresden-based Institute for Photonic Microsystems—see site report). The main goals of the company are to develop novel materials and technology for organic light-emitting diodes, particularly doped transport layers that provide adequate conductivity (up to 10^{-5} S/cm) to facilitate quasi-ohmic contacts and provide some freedom for the work functions of the electrode materials. The company has an agreement with CIBA (now part of BASF) for mass production of the materials developed by Novaled. The company also is collaborating with several companies, including steel manufacturer ArcelorMittal to develop flexible OLEDs on steel substrates.

In collaboration with Philips and others in the European-funded project OLLA (http://www.hitech-projects.com/euprojects/olla/) then ended in June 2008, Novaled has achieved OLEDs with 100,000 hours operating lifetimes at 35-50 Lumens/W. Very recently, in collaboration with the IAPP, a paper was published in *Nature* on white LEDs with more than 120 Lumens/W (Reineke et al. 2009). A lot of the research of Novaled is conducted as part of consortia. Some of the European projects that involve Novaled include large-area OLEDs for lighting. Additionally, the company finds that Fraunhofer-type institutions are very helpful in product development and support. Novaled interacts very closely with the Fraunhofer IPMS (see Fraunhofer trip report) to develop prototyping and manufacturing processes for OLED lighting systems.

Novaled management feels that sublimed OLEDs will have significantly higher power efficiencies compared to solution-processed OLEDs and that these will dominate in lighting applications. However, sublimed OLED materials are compatible with flexible substrates such as steel, as has been demonstrated by the company. Additionally, roll-to-roll processing is compatible with vacuum processing.

In the lighting field, approximately 20% of the value is the lamp and 80% in the luminaire (housing and fixtures). OLED-based lighting offers the possibility to combine the lamp and the luminaire in creative and attractive ways for greater value. Because an OLED light panel is much more a luminaire already than any other light source (lamp type), the 20/80 split will move dramatically; this is likely to shake up the market.

The preeminence and vibrancy of Dresden, described as the “Silicon Valley” of plastic electronics in Europe, helps attract new talent to the area. There is a large pool of existing talent in the area.

REFERENCES

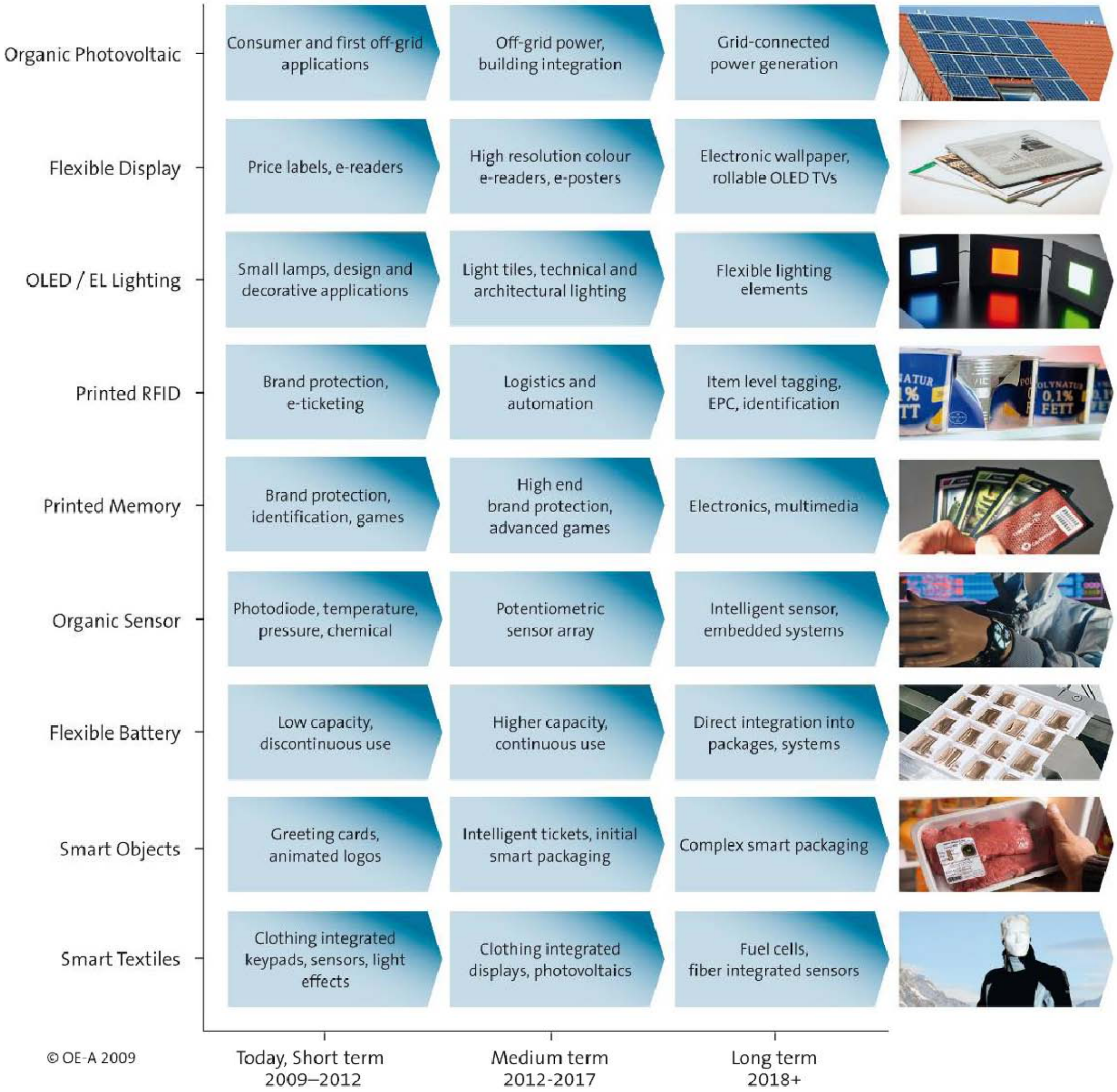
Reineke, S., F. Lindner, G. Schwartz, N. Seidler, K. Walzer, B. Lüssem, and K. Leo. 2009. White organic light-emitting diodes with fluorescent tube efficiency. *Nature* 459:234–238. DOI:10.1038/nature08003.

Site:	**Organic Electronics Association (OE-A)** Lyoner Strasse 18 60528 Frankfurt am Main, Germany http://www.vdma.org/oe-a
Date:	May 12, 2009 (interview with the chairman of the board; not actually visited)
WTEC Attendees:	Ananth Dodabalapur (report author), Dan Gamota, Tobin J. Marks
Host:	Mr. Wolfgang Mildner, Chairman of the Board, OE-A and Managing Director of PolyIC GmbH&Co. KG Tel: +49 911 20 249-8115; Email: wolfgang.mildner@polyic.com

DISCUSSION

Mr. Mildner, the elected head of the Organic Electronics Association (OE-A)—a working group within the German Engineering Federation (VDMA)—explained the purpose of the OE-A during the WTEC panelists' visit to PolyIC. The OE-A is an industry association representing the interests of organic electronics activities. At the early stages, it had mainly European members. At the time of the WTEC visit to Europe, it had 90 members from Europe, 13 from the United States, and 6 from Asia. As of November 2009, OE-A had 128 members, of whom 106 were from the EU, 15 from North America, and 6 from Asia. OE-A maintains a North American Office.

The OE-A organizes periodic meetings of its members where scientific, technology, and application information is exchanged. Additionally, OE-A publishes roadmaps for organic and printed electronics that are widely used by various European agencies in helping decide funding priorities. There are two versions of the roadmap, one of which is publicly available from the OE-A website, and a second, more detailed report that is intended for members. The report details the expected development schedules and market penetration of several organic/flexible electronics applications. It also contains performance metrics and discussions of "red brick walls" that are likely to be encountered. Figure B.5 on the next page shows a summary roadmap of the OE-A (release 3). The complete version can be found in the OE-A website http://www.vdma.org/oe-a (see "Projects & Initiatives").



	Today, Short term 2009–2012	Medium term 2012-2017	Long term 2018+
Organic Photovoltaic	Consumer and first off-grid applications	Off-grid power, building integration	Grid-connected power generation
Flexible Display	Price labels, e-readers	High resolution colour e-readers, e-posters	Electronic wallpaper, rollable OLED TVs
OLED / EL Lighting	Small lamps, design and decorative applications	Light tiles, technical and architectural lighting	Flexible lighting elements
Printed RFID	Brand protection, e-ticketing	Logistics and automation	Item level tagging, EPC, identification
Printed Memory	Brand protection, identification, games	High end brand protection, advanced games	Electronics, multimedia
Organic Sensor	Photodiode, temperature, pressure, chemical	Potentiometric sensor array	Intelligent sensor, embedded systems
Flexible Battery	Low capacity, discontinuous use	Higher capacity, continuous use	Direct integration into packages, systems
Smart Objects	Greeting cards, animated logos	Intelligent tickets, initial smart packaging	Complex smart packaging
Smart Textiles	Clothing integrated keypads, sensors, light effects	Clothing integrated displays, photovoltaics	Fuel cells, fiber integrated sensors

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Figure B.5. The 2009 OE-A roadmap for organic and printed electronics applications; forecast for market entry in large volumes (general availability) for the different applications (http://www.vdma.org/oe-a).

Site: **Philips Research Eindhoven**
Building TFC34, Room 1065
High Tech Campus 34 / PO Box WB 01
5656 AE Eindhoven, The Netherlands
http://www.research.philips.com/

Date: May 11, 2009

WTEC Attendees: Ana C. Arias and Colin Wood (report authors), Daniel Frisbie, Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts: Dr. Eliav I. Haskal, Director,
Strategic Partnerships Technology Program
Philips Research
Tel: +31 40 27 47888, Email: eliav.haskal@philips.com

Dr. Dago de Leeuw, Research Fellow
Email: dago.de.leeuw@philips.com

DISCUSSION

The WTEC visiting team's hosts provided a general overview of Philips business and its three main generic product and business lines: (1) lighting, (2) healthcare products (at home and hospitals) and medical equipment (in and around the body), and (3) consumer products such as domestic appliances and televisions. Philips targets market shares of over EUR 100 million; it enjoys being a (fast) technology follower in consumer products, yet its research is focused on being a field leader in its growth businesses (for example, lighting systems, medical devices, and imaging) when it comes to defining research activities or processes. Philips is involved in several European and national programs that focus on flexible electronics. These programs normally have from five to fifteen collaborating institutions and a cost-share model.

According to Philips management, if (sufficiently-performing) printed electronics can reduce the cost of devices to a target where the volume can be manufactured and all of it sold with a profit, this will revolutionize the industry of device fabrication. Textiles (and body-compatible large-area foils) will provide new applications in medical and lifestyle domains. If the organic semiconductor TFT cost structure is indeed lower than inorganic TFTs, then the market revenue (and application possibilities) will be larger for organic thin-film transistors (OTFTs) than for silicon inorganic thin film transistors (iTFTs). This depends on materials costs and fabrication equipment development. And what was once flat and fragile will become rounded and robust… where it's needed or where it's cheaper.

The research efforts on flexible electronics at Philips are moving forward with different solutions. Its researchers are using plastic foil and textile substrates with the goal of achieving robustness/flexibility, body compatibility, and low cost. The research group watches upcoming areas of research in flexible electronics very closely, and is always looking for a match to an immediate product line of Philips. One of the major foci of Philips in the field of organic electronics is OLEDs for lighting. In the past, Philips management decided not to invest further in the display business, and the core technology developed in Research Fellow Dago de Leeuw's laboratory was spun off into Polymer Vision. Philips also used its EPLAR (Electronics on Plastic by Laser Release) process to fabricate flexible amorphous silicon (a-Si) and low-temperature polysilicone (LTPS) backplanes and demonstrated e-reader prototypes with Prime View International (http://www.pvi.com.tw) and IRex (http://www.irextechnologies.com/). The group is interested in organic electronics due to low-temperature process, being able to spray/jet, and low cost per area. The WTEC team's hosts predicted that there will be an explosion in roll-to-roll processing for display and solar cell applications.

The High Tech Campus in Eindhoven was created when Philips decided to combine its independent R&D organizations in one location and create an atmosphere of open innovation between Philips and other companies and institutes located on the campus. Amortizing the annual costs of a significant infrastructure in an open innovation environment meant that it was useful to find customers/users for its R&D facilities. The campus has extensive cleanroom/microfabrication facilities and characterization instrumentation available, with full staffing, on a fee-for-use basis to several companies and universities. The campus is now home to a number of small companies, including spin-offs from Philips such as Polymer Vision. The Holst Centre is also located on the High Tech Campus, and it was clear to the panel that the rapid start of the Holst Centre could largely be attributed to the infrastructure already in place on the High Tech Campus.

Site: **Plastic Electronic GmbH**
Rappetsederweg 28
4040 Linz, Austria
http://www.plastic-electronic.com

Date: May 13, 2009

WTEC Attendees: Dan Gamota (report author), Ananth Dodabalapur, Tobin J. Marks

Hosts: Philipp Weissel, CEO and Managing Director
Email: philip.weissel@plastic-electronic.com
Dipl.-Ing. Mag. Andreas Tanda
Email: andreas.tanda@plastic-electronic.com
Dr. ir. Niyazi Serdar Sariciftci
Email: serdar.sariciftci@jku.at

GROUP SIZE

There are 10 business, technical, and administrative employees at Plastic Electronic.

SUPPORT

Plastic Electronic receives funding from the regional government and private investors.

DISCUSSION

Plastic Electronic company was spun-out in 2006 from the Johannes Kepler Universität Linz, Linzer Institut für Organische Solarzellen (LIOS, Linz Institute for Organic Solarcells). The business model is to develop and commercialize products based on capacitive sensor technology that provide revenue streams in less than two years. As an example, Plastic Electronic researchers are currently developing a novel product that combines flexible large-area multilayer films having embedded capacitive technology with a software platform to enable a "Smart Shelf" (Figure B.6). This product provides weight sensing, object recognition, and position recognition functionality that can be used in several markets: consumer products goods, retail, and electronics. In addition, to the Smart Shelf they are developing smart packaging and human-machine interface components that combine demonstrated technologies with novel product final assembly processes such as back-injection-molded capacitive-device-based touch panels for system control and operation. Near-term product opportunities will be based on passive devices, while mid-term products (greater than 3years) will offer functionality that requires both passive and active devices.

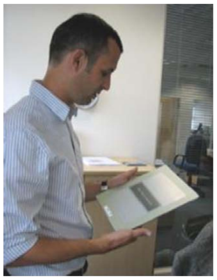
Plastic Electronic is housed in an 800 m^2 facility that includes space for offices, product development, and small-scale prototyping. The large-volume prototyping and manufacturing is conducted at the facilities of Plastic Electronic's strategic partner, Hueck Folien (http://www.hueck-folien.at/). Its core competencies are large-area passive device/circuit design and development, software design for sensing & recognition, and final product development. Today the company uses well-established large-area-format manufacturing processes such as screen printing, laminating/bonding, and laser cutting/trimming. The Smart Shelf product can be manufactured in a high-volume manufacturing environment using existing equipment, since it is designed with capacitive devices having feature sizes of 100 microns. Final product testing will leverage commercially available equipment and QC/QA (quality control/quality assurance) protocols. The ability to manufacture the mid-term products will require further development of the manufacturing equipment and tooling, e.g., multilayer flexible film handling, precision large-area vacuum laminating, fine registration/resolution materials deposition tooling, in-line testing, high speed singulating hardware, and final product assembly hardware and test.

Plastic Electronic is an active member of the Holst Centre and is a founding member of the industry trade association, Organic Electronics Association (OE-A), that is developing the ecosystem. Philipp Weissel serves on the board of the OE-A. It is also is the parent company of green-lama (http://www.green-lama.com/), an online platform for printed electronics.

Figure B.6. Smart Shelf product prototype of Plastic Electronic company: A capacitive embedded film to sense the presence and location of products.

Site: **Plastic Logic, Ltd.**
34 Cambridge Science Park
Milton Road
Cambridge CB4 0WD, UK
http://www.plasticlogic.com/

Date: May13, 2009



WTEC Attendees: Ana C. Arias (report author),
C. Daniel Frisbie, Colin Wood,
Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts: Dr. Martin Jackson, Vice President of Technology
Email: martin.jackson@plasticlogic.com
Dr. Timothy von Werne, Director of Research (at the time of the WTEC visit)

GROUP SIZE

Plastic Logic has approximately 300 employees worldwide; of these, around 75 are in Cambridge, 35 of whom are directly working in the OTFT process research, development, and operations, and 10 of whom are working on flexible display applications.

SUPPORT

Over the years Plastic Logic has received funding from such investors as Intel, Oak Investment Partners, Tudor Investment Corp., Bank of America, Polytechnos, Dow, BASF, Morningside Asia, Nanotech Partners, Siemens, and Yasuda.

DISCUSSION

Plastic Logic is a spin-off company from the Cavendish Laboratory (University of Cambridge) that is developing technology and products to commercialize flexible electronics. The main product is a so-called e-reader, a black-and-white electrophoretic active matrix display. This e-reader has some similarities to the Kindle (Amazon) but is considerably thinner and is A4 paper size (210 × 297 mm, or about 8.3 x 11.7 inches). Plastic Logic's activities are divided among three sites: Manufacturing Pilot Line in Germany, and Research & Development in Cambridge, UK, and Mountain View, CA (USA). The WTEC panel visited the R&D facilities located in Cambridge.

The Plastic Logic research activities in Cambridge are focused on introducing color capability to displays and on reducing the amount of external electronics in the system. In order to achieve that, gate and data drivers would be integrated into the backplane. Plastic Logic is also looking for applications where flexible distributed electronics are needed. The backplane is fabricated on PET (polyethylene terephthalate), which is attached to glass sheets during the fabrication process. The semiconductor and gate dielectric used in the process are based on organic materials. The electrodes and addressing lines are based on conventionally deposited metals. The fabrication process is a sheet-to-sheet process with 9 displays/sheet (each display is 150 ppi with a resolution of 1280 by 960). The display media is provided by E-ink. The goal of the manufacturing facility is to fabricate around 500,000 units per year. The product will be brought to market via trials and piloting with partners and key customers. Plastic Logic's reader will have an open standard where most file formats can be loaded.

Site: **PolyIC GmbH & Co. KG**
Tucherstrasse 2
90763 Fürth, Germany
http://www.polyic.com

Date: May 12, 2009

WTEC Attendees: Dan Gamota (report author), Ananth Dodabalapur, Tobin J. Marks.

Hosts: Mr. Wolfgang Mildner, Managing Director
Email: wolfgang.mildner@polyic.com
Dr. Wolfgang Clemens, Head of Applications
Email: wolfgang.clemens@polyic.com

SUPPORT

PolyIC receives support from Kurz and Siemens as well as various other EU and German sources.

DISCUSSION

PolyIC is a joint venture between Leonhard Kurz Stiftung & Co. KG (51%) and Siemens AG (49%) that was established in November 2003. Its core competency is the design, development, and manufacture of printed electronic products comprising active and passive elements and the required components e.g., power and display. It follows a well-structured 3-tier strategy/approach to bring products to market. Specific efforts are performed within each of the 3 tiers that are critical to establishing the materials systems, processes, and manufacturing methodologies necessary for taking concept through R&D to commercialization. Its three tiers have the following specific goals:

1. *Cleanroom* (spin coating and photolithography): Development of chip design and materials
2. *Lab printing* (including lab platform gravure, flexography, and screen): Identifying and testing formulations for printing
3. *Roll-to-roll* (including large format gravure, flexography, and screen): Delivering low-cost, high-volume products

PolyIC has achieved several industry milestones within the field of organic electronics: 125 kHz circuit functionality in 2004; 600 kHz circuit functionality in 2005; 13.56 MHz circuit functionality in 2006; first printed RFID tag working at 13.56 MHz in 2007, 32/64 Bit prototype operating at 13.56 MHz; and first printable CMOS in 2008. In 2007, PolyIC presented the first printed RFID tag produced in roll-to-roll production, working at the standardized frequency of 13.56 MHz. The majority of these milestones were achieved using a well characterized material system and a stable proven process for top-gate OFET device architecture (insulating polymer dielectric, conjugated polymer semiconductor, polyester film substrate).

Currently, PolyIC has two product platforms that leverage the merits of high-volume manufacturing using wide web equipment in non-cleanroom environments: (1) PolyID® and (2) PolyLogo®. Each product platform has a well articulated "go-to-market" strategy that consists of near-term, mid-term, and long-term product offerings. The PolyID® long-term product offering is an EPC-compliant printed RFID tag; the PolyLogo® long-term product offering is smart packaging that combines display elements and sensors (temperature, humidity) with RF transmission/reception functionality. Besides this, PolyIC is active in the field of components like printed memories and transparent conductive films.

PolyIC has been actively involved in several EU and German consortia (e.g., the MADRIX, project of the German Federal Ministry for Education and Research [BMBF] for the development of new materials for next-generation printed RFID, PolyApply for ubiquitous microsystems with communications and sensing functionality, and PRISMA for printed smart labels) as well as in industry trade associations (e.g., the Organic Electronics Association, OE-A) that are developing the ecosystem. Wolfgang Mildner serves as the chairman of the OE-A.

In collaboration with Kurz and strategic suppliers, PolyIC is actively developing solutions to the key technical issues for product commercialization: materials performance and stability, substrate handling, in-line characterization tooling, and QA/QC equipment.

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Figure B.7. Dr. Wolfgang Clemens demonstrates the use of a PolyIC® product integrated with a coffee/latte/cappuccino vending machine.

REFERENCES

Clemens, W., W. Fix, J. Ficker, A. Knobloch, and A. Ullman. 2004. From polymer transistors toward printed electronics. *Journal of Materials Research* 19(7):1963-1973.

Site: **Polymer Vision, Ltd.**
High Tech Campus 48
5656AE Eindhoven, The Netherlands
http://www.readius.com

Date: May 11, 2009

WTEC Attendees: Ana C. Arias (report author), C. Daniel Frisbie, Colin Wood, Khershed Cooper, Pradeep Fulay, Grant Lewison

Host: Dr. Nick A.J.M. van Aerle
Manager, Technology R&D
Email: nick.van.aerle@polymervision.com

GROUP SIZE

Polymer Vision, Ltd., employs approximately 80 staff members.

SUPPORT

Initial technology was developed at Philips Research with internal funding. After spinning off, Polymer Vision, Ltd., was funded by Technology Capital SA.

DISCUSSION

Polymer Vision, Ltd., is a start-up company that spun off from Philips to develop and commercialize rollable displays and devices such as e-readers. The R&D facility of Polymer Vision, located in Eindhoven, is divided into four development streams: Technology R&D, Display R&D, Product Development, and Quality & Reliability. The company decided to use existing deposition and patterning techniques to accelerate product development and to enable easy transfer to mass manufacturing. Photolithography is used to pattern pentacene-based active-matrix TFT backplanes on flexible substrates. DuPont Teijin is the PEN (polyethylene naphthalate) substrate provider. The current process is a batch process of 24 wafers, where the flexible substrate is attached to a silicon wafer throughout the deposition and patterning steps. Each batch is completed in a week, and at the time of the WTEC team's visit, the production capacity of the R&D site is approximately 3000 units per year.

TFTs with bottom gate, bottom contact are fabricated using gold as source, drain and gate electrodes, an organic gate dielectric (unspecified), and a solution-processed pentacene precursor as the active semiconductor. The gate dielectric and semiconducting layers are deposited by spin-coating and subsequently patterned by photolithography. A passivation layer is deposited between the metal pixel pad electrode and the TFTs in order to shield the gate and data lines from the display medium and to give an aperture ratio (active pixel area/total pixel area) of about 95%. The backplanes are integrated with electrophoretic display media developed by E-Ink. Silicon gate and data drivers are bonded on the display edge, and the final first-generation display is QVGA (240 x 320 pixels) with a resolution of 85 dpi. The total display thickness is ~100 μm. The displays are rollable (0.5 cm minimum radius) with the mechanically weakest layers placed in the neutral plane.

Several prototypes are available, including a high-resolution 254 dpi black-and-white and a 127 dpi color display that was achieved by adding color filters to each pixel of the display. The first product, a black-and-white pocket mobile phone/e-reader named Readius®, is scheduled to be launched in early 2010.

Site: **University of Bari Department of Chemistry**
Via Orabona, 4
70126 Bari - Italy
http://www.uniba.it/
http://www.chimica.uniba.it

Date: May 14, 2009

WTEC Attendees: Ananth Dodabalapur (report author), Dan Gamota, Tobin J. Marks

Host: Prof.ssa Luisa Torsi (met WTEC panel at CNR in Bologna)
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BACKGROUND

The group of Professor Luisa Torsi has been very active at the European and international levels in the areas of organic transistor-based chemical and biological sensing. The group was represented in the meeting with members of the WTEC team by Professor Torsi. Her team includes two postdoctoral researchers, one of whom is Dr. Maria Cristina Tanese, an experienced researcher in the field of organic electronics and sensors. The group also has several PhD students in the general area of analytical chemistry. Prof. Torsi is presently the coordinator of the Marie Curie Initial Training Network, granted by the European Commission, involving nine partners from academia and industry. Activities involve training 21 students in the field of hybrid, very-low-cost, ultra-low-power olfaction systems based on a bioreceptor and implemented on a flexible substrate system, intended to be compatible with wireless read-out, and setting the ground for the future development of smart sensing RFID tags. Organizationally, the group of Prof. Luisa Torsi shares facilities at the Department of Chemistry with other full professors Prof. Luigia Sabbatini and Prof. Francesco Palmisano and their groups.

DISCUSSION

Professor Torsi gave the WTEC team a presentation at CNR on the work being done by her group. The group's main activities are in the areas of (1) new organic semiconductors for chemical vapor sensing (some of the semiconductors, including polymeric semiconductors, are synthesized by collaborating organic chemistry groups), (2) implementation of receptor molecules for use in chemical vapor sensors, and (3) the detection of chirally asymmetric analytes through the use of engineered receptors. The last area is a very important area of recent research that was published in *Nature Materials*.

The group of Prof. Torsi collaborates with the group of Prof. Subbodh Mhaisalkar of Nanyang Technological University in Singapore in the area of sensors. They have recently reported work on toxic gas (NOx) sensors based on organic semiconductors. There is an exchange of postdocs and graduate students, with two Bari PhD students spending significant time in Singapore. The group also had and still has collaborations with The University of Texas at Austin and groups in Europe, including the Berggren group (Linköping, Sweden), the group of Prof. Gilles Horowitz at The University of Paris Diderot (Paris 7), and the group of Prof. Annalisa Bonfiglio in Cagliari, Sardinia, Italy.

The work in the biosensors area employs conjugated polymers with side groups engineered to chemically interact with specific moieties. The detection mechanism is the change in threshold voltage and/or field-effect mobility in the transistor-based sensor.

Site: **University of Bologna Department of Chemistry**
Via Zamboni
33 - 40126 Bologna, Italy
http://www.eng.unibo.it/PortaleEn/default.htm

Date: May 14, 2009

WTEC Attendees: Tobin J. Marks (report author), Ananth Dodabalapur, Daniel Gamota

Hosts:

Prof. Vincenzo Balzani
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Prof. Paola Ceroni
Dipartimento di Chimica "G. Ciamician"
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Prof. Claudio Zannoni
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DISCUSSION

The group of Professor Vincenzo Balzani has a major international presence in the area of molecular devices and machines and their chemical/photophysical/photochemical and electrochemical properties. The group was represented at the meeting with WTEC panelists by Professor Paola Ceroni. She briefly described projects on rotaxanes, dendrimers, molecular logic gates, and chemical computing. In many cases, desired molecular phenomena were driven by using pH to modulate metal complexation and decomplexation with optical readout. She also described Grätzel dye-sensitized solar cells in which the dyes were multiple metal complexes with optical absorption maxima designed to cover a large portion of the solar spectrum.

Professor Claudio Zannoni leads a group of 12 postdoctoral students and researchers focusing on the modeling and simulation of soft materials. The focus is to go from atomistic computation on individual molecules to predicting the properties of very large systems. Projects described included predicting the order parameters, dielectric constants, and densities of liquid crystal systems and their alignment near interfaces. Systems include hexathiophene and phthalocyanine mesogenic phases and computation of charge hopping through arrays of these molecules. The group has also worked on describing the growth and disorder of organic semiconductors on the surfaces of glassy polymers. Zannoni's vision is to ultimately be able to choose a molecular formula, compute single-molecule properties, and from these parameters simulate bulk morphologies, mesophases, and ultimately, a working device.

Site: **University of Cambridge**
Department of Engineering
Electrical Engineering Division
Cambridge Integrated Knowledge Centre
Centre for Advanced Photonics & Electronics
9 JJ Thomson Avenue
Cambridge CB3 0FA, UK
http://www-g.eng.cam.ac.uk/CIKC/
http://www-cape.eng.cam.ac.uk/

Date Visited: May 13, 2009

WTEC Attendees: C. Daniel Frisbie (report author), Ana C. Arias, Colin Wood, Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts: Dr. Bill Milne, FREng, Head of Electrical Engineering and Director of CAPE
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GROUP SIZE

The University of Cambridge's Electrical Engineering Division consists of 20 academic staff, 62 postdocs, 168 PhD students. These personnel work in three main areas: Solid State Electronics, Energy, and Photonics/Optoelectronics. Within these three main areas, there is a focus on flexible electronics; this program constitutes about 20% of the division, involving 20 PhDs and 8–10 postdocs.

SUPPORT

The Division has a total budget of about £33.7 million over 3 years. Of this, £7.1 million (25%) currently comes from industry, £4 million (12%) from the EU. Based on this and the work effort described above, the panel estimates that support for flexible electronics research is approximately £6.7 million. The flexible electronics work of the division is funded largely by two umbrella organizations, the Centre for Advanced Photonics and Electronics (CAPE) and the Cambridge Integrated Knowledge Centre (CIKC). Funding for CAPE is ~£10 million over 5 years, supplied largely by major industrial partners. Funding for CIKC is ~ £15 million over 5 years, provided by the UK Engineering and Physical Sciences Research Council (£7 million), the University of Cambridge, local government, and industry.

DISCUSSION

The Electrical Engineering Division of the Department of Engineering at Cambridge has a long history of working in thin-film electronics and displays. It is a world-leading academic center for research in amorphous and nanocrystalline silicon for applications in active-matrix backplanes and sensors. It also has impressive expertise in liquid crystalline materials for displays and other technologies, including tunable antennas. The unit's device research efforts employ both inorganic and organic thin-film materials, including carbon nanotubes, silicon nanowires, metal oxides, polymers, and nanocomposites. The WTEC team's hosts estimate that their division's materials emphasis is approximately 80/20 inorganic versus organic, and they believe that future thin-film electronics technologies are likely to employ a diverse array of materials such as the ones that are included in their program. The unit is now clearly interested in alternative thin-film electronic materials and liquid phase processing. New or recent efforts include solution-processed ZnO, carbon nanotube transistors, and amorphous silicon-based biosensors. The effort in flexible or plastic electronics involves many of the materials mentioned above and is probably 20% of the division effort (noted above in the Support section).

CIKC is a multidisciplinary "Fraunhofer-style" organization that includes investigators from Physics (the Cavendish Laboratory), Chemistry, and the business school. Business school members are interested in assessing market opportunities for flexible electronics. CAPE is a partnership between Cambridge University and several global electronics and photonics industries companies such as Alps Electric and Dow Corning that is dedicated to state-of-the-art multidisciplinary research, development, and commercialization in the convergence of photonic and electronic technology platforms.

Electrical Engineering has its own building next to the Cavendish Laboratory and houses a very impressive ~7000 sq. ft. cleanroom facility equipped with standard semiconductor processing equipment as well as a variety of printing machines (screen, ink jet, roll-to-roll, nano-imprint, laminators) for processing devices on flexible plastic substrates. The emphasis on flexible electronics is readily apparent. The Electrical Engineering Division also has an impressive track record in generating spin-off companies, with 9–10 companies formed over the last decade. Perceived commercial opportunities in flexible electronics include RFID, photovoltaics, displays, electroactive foils, and sensors.

Site: **University of Cambridge Department of Physics**
Cavendish Laboratory Optoelectronics Group
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Cambridge CB3 0HE, UK
http://www.phy.cam.ac.uk/

Date Visited: May 13, 2009

WTEC Attendees: Ana C. Arias (report author), C. Daniel Frisbie, Colin Wood, Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts: Prof. Sir Richard Friend, Optoelectronics Group
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Prof. Henning Sirringhaus, Head of Microelectronics and Optoelectronics
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Prof. Neil Greenham, Optoelectronics Group
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GROUP SIZE

There are 60 professors and 750 graduate students working in the Cavendish Laboratory. The optoelectronics group is formed by 3 professors who together represent more than 10 percent of lab activities and funding.

SUPPORT

The group receives support from many sources, including the European Commission, the UK EPSRC (Engineering and Physical Sciences Research Council), and industry.

DISCUSSION

The optoelectronics group in the Cavendish Lab is a world leader in organic electronics research. The core mission of the group is to pursue first-rate science pertaining to optoelectronic phenomena in organic semiconductors. Basic topics of interest include the role of electronic localization versus delocalization in polymers, understanding of charge transport mechanisms and understanding of charge separation phenomena. The group also focuses on devices such as solar cells, transistors, and LEDs.

There is a new effort on learning how to print solar cells. This activity is supported by the Carbon Trust, a government-owned not-for-profit organization. The goal of the project is to establish a low-temperature roll-to-roll process to fabricate flexible solar cells with efficiency of at least 10 percent. Current development is concentrating on device geometry and batch-processed cells on glass. Patterning and deposition equipment for a roll-to-roll system were being purchased at the time of the WTEC panel's visit.

This group has a track record of spinning out companies: both Plastic Logic and Cambridge Display Technology originated from the Cavendish Optoelectronics Group. According to the panel's hosts, this can only happen because they have the freedom to simultaneously hold positions at companies and at the university. There is open flow of information and intellectual property between the group and the companies; in addition, the university has a discovery fund that supports researchers to make prototypes in order to raise money from private investors. Cambridge Enterprise works with technology transfer from university to small businesses, and on identifying space for start-up efforts. The university will support new ideas, pay for the first patent filling, and through the Challenge Fund, support the creation of new businesses. The city of Cambridge has positioned itself to be a center for advanced technology, with over a thousand companies offering 40,000 high-tech jobs.

The Cambridge Integrated Knowledge Center (CIKC; http://www-g.eng.cam.ac.uk/CIKC/) has been created to facilitate collaboration between the Departments of Physics (Cavendish Lab) and Engineering (especially the Centre for Advanced Photonics and Electronics) to accelerate the creation of new businesses focused on advanced manufacturing technologies for photonics and electronics. The Judge Business School, the Institute for Manufacturing (IfM), and the Centre for Business Research of Cambridge University are part of the center and help with technology transfer, businesses studies, and market analysis.

Site: **University of Erlangen-Nürnberg**
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http://www.omd.uni-erlangen.de/

Date: May 12, 2009

WTEC Attendees: Tobin J. Marks (report author), Ananth Dodabalapur, Dan Gamota

Host: Prof. Dr. Marcus Halik, Chair of Polymeric Materials,
Department of Materials Science
Tel: 49-9131-852-7732; Email: marcus.halik@ww.uni-erlangen.de

GROUP SIZE

The group includes 5 PhD students and one senior scientist (Prof. Dr. Halik).

SUPPORT

In addition to the usual DFG (German Research Foundation) support for students and consumables, Prof. Halik is involved in a new German federal government-funded center of excellence grant at Erlangen entitled “Engineering of Advanced Materials.” His overall funding is EUR 2.0 million over 5 years to support students and to purchase equipment; the indirect cost rate (overhead rate) is 20%. He has good institutional facilities and support (cleanroom, chemical computational center; circuit design help in the Electrical Engineering Department), as well as network collaborations with MIT, Georgia Tech, Siemens, Starck, and Osram.

DISCUSSION

Professor Halik’s research focus is on materials properties, function, and materials applications in organic electronic devices. The applications include TFTs, nonvolatile memories, capacitors, and memory cells. He is not a materials synthesis specialist but has collaborators who provide materials. Self-assembly processes (predominantly self-assembled monolayers) to create hierarchically ordered structures are a major focus of his research, with some activity on printing using micro-contact techniques, and vapor deposition for film formation. He feels that self-assembly is more precise than printing. He is presently using an organic-inorganic hybrid approach with ZnO for integration on flexible substrates. Almost all of his group is working on flexible electronics, with approximately 80% doing experiments (as opposed to theory). He is able to select from the best graduate students because many are interested in the projects his group works on.

Professor Halik feels that in the short-term, displays will continue to grow in importance, especially those where large areas provide an advantage. For RFID tags, the reading distance must be solved. He also feels that organic photovoltaics will grow in importance and that some of the importance will be politically driven even if power conversion efficiencies are low. Because of aging populations around the world, cheap medical electronics/diagnostics will be important, hence the need for effective printed biosensors (e.g., for blood sugar testing). For his research, intra-European collaborations are essential because the problems are so interdisciplinary. However, he finds the administrative effort involved in such projects is prodigious, and small interdisciplinary teams involving only a few local researchers are frequently more productive. Industrial partners are also essential; most productive German groups typically have at least one major corporate partner.

As noted above, Professor Halik works on both organic and inorganic materials. His activity in the latter area is about 30% of his effort. He has recently demonstrated the low temperature conversion of zinc oxide nanoparticles to films at 100°C; these films have impressive mobilities as high as 2 cm/Vs. Halik only uses a cleanroom on occasion, because his results are more focused on demonstrating new principals rather than on fabrication yield. For deposition, his group uses evaporation, spin-coating, self-assembly, and atomic layer deposition (ALD). In regard to the issue of solution versus vapor phase deposition processes, Halik feels that printing has been over-emphasized and is not as cheap or reliable as might be imagined, noting that 1 m x 1 m white OLEDs have been fabricated by vapor deposition in Japan. However, he does feel that solution processes may be best for large-area photovoltaic cells where small feature sizes are not required. In regard to printing RFID tags for mass retail packaging, Halik believes this technology may be too expensive and complex (five layers are required, and there seems to be no way to avoid a metallic electrode). For more expensive items and pallets, he feels that silicon-based RFID tags are a simpler solution. The area of biosensors/diagnostics, as noted above, offers promise and may bring in additional revenue for organic electronics companies.

Halik feels strongly that much of EU success in organic electronics comes from the size of the programs, the industrial interest, and the better continuity of research funding in Europe compared to that in the United States.

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Acreo AB
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Date: May 15, 2009

WTEC Attendees: C. Daniel Frisbie (report author), Ana C. Arias, Colin Wood, Khershed Cooper, Pradeep Fulay, Grant Lewison

Hosts: Professor Magnus Berggren, Organic Electronics Group
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Professor Olle Inganäs, Soft Condensed Matter Physics
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Leif Ljungqvist, Vice President, Acreo AB
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GROUP SIZE

There are two principal academic organic electronics groups at the University of Linköping. The host site at the Norrköping campus is the home of Magnus Berggren's research group. He has approximately 25 students and postdoctoral researchers working on organic electronics and bioelectronics, and he serves as the Director of the Center for Organic Bioelectronics, which also involves the Karolinska Institute in Stockholm. Prof. Olle Inganäs is located on the main campus in Linköping. His group consists of approximately 10 researchers in organic photovoltaics and organic bioelectronics. Prof. Inganäs is also the head of the Center of Organic Electronics (COE) on the Linköping campus.

Acreo is an incorporated research institute in Norrköping tightly connected with the organic electronics program at Linköping. It has 30 employees; its mission is to develop commercial applications of printed electronics. Acreo follows the long tradition in Sweden of industry-sponsored research institutes closely connected with universities.

SUPPORT

Acreo obtains 50% of its funding from industry; the remaining 50% comes from a combination of Swedish government and EC funding. Support for the Center for Organic Bioelectronics is EUR 0.8 million per year. Berggren and Acreo activities in printing are also supported at EUR 0.8 million per year. Additional funding for Berggren and Inganäs in the area of solid state organic electronics and photovoltaics totals approximately EUR 1.2 million per year.

DISCUSSION

The Swedish government and the pulp and paper industry are very interested in supporting the development of printed electronics technology. Sweden has commercial strength in paper production and packaging. Printed electronics, smart labels, ultra-low-cost sensors and displays are seen as key to maintaining the strength of these industries in the future. The groups of Berggren and Inganäs have a long track record in the development of new organic semiconductor materials and their characterization in devices. Current work emphasizes organic solar cells, transistors, biosensors, and printing methodologies.

Regarding the printing work, Berggren has an exceptionally close link with the Swedish research institute Acreo. Acreo is dedicated to developing printed electronics and is supported by a combination of funding from the Swedish government, the EC, and industry. Acreo maintains a printing laboratory within a few hundred meters of Berggren’s laboratories in Norrköping. The printing lab houses industrial sized screen printers, dryers, roll-to-roll printers capable of flexographic and gravure printing on 10-inch-wide paper or plastic substrates at 30 m/s, ink jet printers, and another roll-to-roll coater for dry patterning of materials (e.g., metal lines for antennas and interconnects). Students in Berggren’s group routinely use these printers for their research.

The overall emphasis of the Linköping group is to develop low-cost, solution-processed materials for novel applications in biological sensing, solar energy conversion, and flexible electronics. The tight collaboration with Acreo provides a good connection with industry. There is an increasing effort in biological applications of printed electronics, for example in sensing and drug delivery.

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http://www.lfb.uni-stuttgart.de/index.en.html
http://www.lfb.uni-stuttgart.de/forschung/labor.en.html

Date: May 11, 2009

WTEC Attendees: Dan Gamota (report author), Ananth Dodabalapur, Tobin J. Marks

Hosts: Prof. Dr.-Ing Norbert Fruehauf, Director, Chair of Display Technology
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GROUP SIZE

The University of Stuttgart Display Technology Laboratory group is composed of 13 graduate students, 1 faculty member, 2 senior technicians, and 1 administrative assistant.

SUPPORT

The university provides support for 4 personnel (faculty, technician, and administrative assistant). The balance of the group is supported by external funding from industry and government.

DISCUSSION

Professor Fruehauf is the director overseeing all administrative and technical activities conducted at the display module fabrication laboratory. The facility houses a class-10/100 cleanroom and was built in the late 1980s when German officials observed large investments being made internationally (Asia, United States) in the emerging field of active matrix display technology. This was a strategic move by Germany to become a strong player in the potentially high-revenue market. The laboratory is one of four cleanroom facilities located on the University of Stuttgart campus. The value of the 480 m^2 facility when built was approximately \$50 million; it houses prototype and production-scale manufacturing equipment to build and assemble the necessary components for a display system (backplane, frontplane, and drive electronics). In addition, to commercially available equipment, the facility houses novel platforms that have been developed by students, such as an automated tool for electrical characterization of backplane devices during environmental conditioning.

The group is focused on applied research with strong foundations in materials, process, and display component/system development. Efforts in the 1980s and 1990s were geared towards developing a deep appreciation for amorphous silicon-based active matrix display systems on rigid substrates. Since 1995, the scientists/engineers in the group have broadened their research scope to include display systems fabricated on flexible substrates. Also, since establishing a stable and highly disciplined approach for amorphous silicon-based systems, they have moved to establish a strong understanding for low-temperature polysilicon-based systems on rigid and flexible substrates.

Since 2003, the group has been establishing a strong foundation for R&D of organic and carbon-nanotube-based thin film transistors. This initiative has led them to design and build novel equipment (a multichamber environmentally controlled glove box) and new tools (metrology and electrical characterization) to enable the fabrication of organic light-emitting diode–based applications and organic thin film transistor–based circuitry.

Professor Fruehauf, who succeeded Professor Ernst Lueder (the founder and first director of the group), considers “collaboration as the cornerstone of success.” He has been involved in consortia (funded by Germany and the EU) to assess the merits of novel display-related technologies, and he is actively engaged with industrial partners (Novaled) in developing next-generation display technologies. He believes that there is a market for hybrid flexible electronics but is unsure what will be the first product—possibly a low-content display product. He considers the biggest technical issue to successfully fabricating electronic devices (3 to 10 micron features) on flexible substrates to be the ability to design for and control the mechanical properties of the flexible substrates during processing.

The lab's graduate students have the opportunity to conduct research on a variety of frontplane technologies (OLED, PDLC, twisted nematic, electrophoretic), different driving schemes, novel dielectrics, and electrode materials (e.g., carbon nanotubes). It seems that the students are highly sought-after because upon graduation they already have exceptional hands-on, real-life display development experience.

APPENDIX C. BIBLIOMETRIC STUDY OF WORLD RESEARCH IN HYBRID FLEXIBLE ELECTRONICS, 1994–2008

This study was carried out by Dr. Grant Lewison of Evaluametrics, Ltd., at the request of the World Technology Evaluation Center. It is intended to inform and complement the WTEC Panel Report on European Research and Development in Hybrid Flexible Electronics.

SUMMARY OF FINDINGS

1. This study examined the research outputs in hybrid flexible electronics, as recorded in the Web of Science for the 15 years 1994–2008. The objectives were to compare the outputs of the leading countries in terms of both quantity and impact, and also to list leading research institutions in Western Europe with a view to assisting the WTEC evaluation panel in its selection of sites to visit. The papers were identified by means of a complex filter based on journals and title words; it had a precision of 0.87 and a recall of 0.71. The analysis file contained 36,852 papers. After allowance for the lack of recall of the filter, the annual output was just over 3000 papers.
2. Over the 15-year period, the output of papers in hybrid flexible electronics grew strongly, by about 10% per year, compared with just over 3% for physics and for science overall. For most of the period, the USA had the largest output, averaging 20% of the world total on a fractional count basis, but it was overtaken by China in 2008. Most countries shared in the strong growth of the subject, particularly ones in East Asia (China, Japan, Korea, Singapore, Taiwan). Within Europe, the leaders were Germany, the UK, France, Italy, the Netherlands, Spain, and Sweden.
3. Citation counts, both potential (based on all papers in the journals used) and actual, can give an indication of the impact of the research. Overall, the leading countries on the basis of mean counts over 5 years, and of fractional counts of addresses, were the Netherlands and Austria, followed by the USA, Switzerland, and the UK. The same ranking occurred in terms of percentages of papers in the top centiles (e.g., those in the top 1% that received 129 or more cites). A new indicator of esteem, the percentage of reviews, showed Israel and Austria, followed by the USA, Belgium, and Australia, in the leading positions.
4. Lists were prepared of the leading institutions carrying out research on hybrid flexible electronics in 10 countries of Western Europe, with at least 50 papers over the last eight years. The names of the institutions were complemented with the names of their leading researchers and estimates of their mean citation scores for their papers published in 2001–2004.

INTRODUCTION

Study Objectives

The purpose of this study was two-fold:

- to compare the research outputs of the United States and other leading countries in this field over the 15 years 1994–2008 during which the subject has been developing
- to identify the leading laboratories in Europe, and their principal scientists, with a view to the provision of information on sites that would be useful to visit during the panel's European tour

The subject area was defined as follows:

> Hybrid flexible electronics covers organic and polymeric electronics, and optoelectronics and thin-film electronics using inorganic materials, provided they permit use of flexible substrates, particularly if printing or solution processing is involved. It also includes flexible or potentially flexible sensors and actuators. It is multidisciplinary and may involve chemistry, engineering, materials science, or physics.

The papers were to be identified within the Web of Science (WoS) by means of a “filter,” described below, and the analysis was intended to provide the following information:

- the numbers of papers per year, worldwide, and a comparison with the numbers in the field of physics
- the outputs of 26 leading countries in the three five-year periods, 1994–1998, 1999–2003, and 2004–2008, selected from North America, Europe, and Asia and East Asia
- the mean potential citation impact of papers from these countries, based on the average number of citations to papers in the journals in which they were published
- the mean actual citation impact of papers from these countries
- the identities of the leading research organizations (based on numbers of papers in 2001–2008) in the western European countries of potential interest to the panel

METHODOLOGY

Filter Development and Paper Downloads

The method for defining a “filter” has been described earlier (Lewison 1996; Lewison 1999; Lewison et al. 2007). It involves a partnership between a bibliometrician (Grant Lewison) and an expert in the subject (Professor Ananth Dodabalapur). A filter normally comprises lists of specialist or semi-specialist journals and of title words, combined together in various ways in order to include relevant papers and also to exclude those deemed outside the subject area. It is developed iteratively, with calibrations to check its precision and recall, based on the marking of lists of papers by the nominated expert. After several rounds of filter development, a final version was agreed (and coded as FLECT). This was applied to the Web of Science (Science Citation Index – SCI – only) for publication years 1994–2008, and only articles, notes, and reviews were retained. Their bibliographic details were downloaded to a MS Excel file, containing six fields:

- authors
- title
- document type
- source (journal, year, volume, issue, pages)
- addresses
- language

It was, however, necessary to transform the data from the downloading process to the format previously used for downloads from the SCI on CD-ROM so that Excel macros used for analysis (and written by Philip Roe) could also be used for this study.

In parallel with the downloads of the bibliographic data from the selected papers, citation analyses were also carried out, and the numbers of citations, year by year, were also downloaded to file and processed by other macros written by Philip Roe. These enabled the five-year citation scores (actual citation impact, ACI) for papers from 1994–2004 to be determined and for them to be carried across to the main bibliometric file.

For comparison of the amount of research in hybrid flexible electronics and its growth with time, data were also obtained from the WoS on the numbers of papers (again, articles, notes, and reviews) in the topic “physics,” defined by sets of journals in the physics subfields. (However the numbers rose sharply in the early 1990s from a low level, and so data were only retained for use from the years 1996 onwards.)

The filter was estimated to have a precision, *p*, of 0.87 and a recall, *r*, of 0.71. The final Excel file contained details of 36,852 papers, but because the lack of recall is greater than the lack of precision, the true number would have been approximately 45,157 papers.

Addresses: Integer and Fractional Counts

Another special macro was used to analyze the addresses on each of the downloaded papers, and the fractional count of each of 26 countries was calculated and tabulated in a separate column of the spreadsheet. (A paper with two U.S. addresses and one French address would count unity for each country on an integer count basis, but 0.67 and 0.33 respectively on a fractional count basis, which gives a fairer view of each country's contribution to the research.) These countries were as listed in Table C.1, where ISO digraph codes have been shown—they also are used in the subsequent tables and figures. These are the leading countries in terms of output over the 15-year study period, based on fractional counts.

Table C.1. List of 26 countries used for the analysis of hybrid flexible electronics research, with ISO digraph codes

Codes for the 11 Member States of the European Union, plus Switzerland, are shown in bold.

Code	Country	Code	Country	Code	Country
AT	Austria	FR	France	RU	Russia
AU	Australia	GR	Greece	SE	Sweden
BE	Belgium	IL	Israel	SG	Singapore
BR	Brazil	IN	India	TR	Turkey
CA	Canada	IT	Italy	TW	Taiwan
CH	Switzerland	JP	Japan	UA	Ukraine
CN	China (PR)	KR	Korea (S)	UK	United Kingdom
DE	Germany	NL	Netherlands	US	United States
ES	Spain	PL	Poland		

Classification of Journals by Potential Citation Impact (PCI)

The large majority of the journals used for the hybrid flexible electronics papers were classified in terms of the average number of citations received from papers in SCI journals by papers published in a given year during the year of publication and four subsequent years, *i.e.*, in a five-year citation window. For papers from 1994 to 2002, the data were obtained directly from Thomson Reuters, the publishers of the WoS, or its predecessors; for papers in 2004, the values for the leading journals were obtained directly from the WoS.[7] These five-year citation scores are, of course, much higher than the frequently-cited "journal impact factors" but give a more accurate picture of the influence of the journal. Some examples of PCI values for journals commonly used for hybrid flexible electronics research papers are shown in Table C.2.

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[7] These values were for citations to articles and reviews only; for earlier years, Thomson Reuters gave data for all citations but with the denominator equal to the numbers of articles, notes and reviews. For some journals, the difference is appreciable because some of the citations would have been to other document types.

Table C.2. Examples of journals used for hybrid flexible electronics papers with their potential citation impact (PCI) values for 2004

Journal	PCI	Journal	PCI
Nature Materials	76.2	Solar Energy Materials and Solar Cells	13.8
Nano Letters	46.9	Chemical Physics Letters	10.2
Advanced Materials	36.6	Thin Solid Films	7.0
Physical Review Letters	28.0	Electronics Letters	4.6
Journal of Materials Chemistry	20.3	IEICE Transactions on Electronics	2.2

Classification of Papers by Potential and Actual Citation Impact (ACI)

This was possible only for papers published in 2004 and earlier years because the count of citations in the WoS for 2009 was not complete. Mean values were obtained for the world and each of the 26 selected countries on both an integer and a fractional count basis. The latter is fairer, as some of the most highly cited papers are international, and so the contribution of a given country may be quite small. Consequently, for nearly all countries, mean values of PCI or ACI are lower when fractional counts are used for the apportionment of credit.

It is of interest also to determine how many of a country's papers are cited highly enough for them to be in the top 1%, top 2%, top 5%, top 10%, top 20%, or top 50% of the world's papers. These percentages can be compared with the corresponding values for the world. (These are usually slightly more than the nominal values because citation numbers are integers; thus, 2079 papers [rather than 2000] received 33 cites, enough to put them in the top 10%.) The ratios of the percentages, multiplied by 100, are termed "world-scale" values, by analogy with tanker charter rates (see Lewison et al. 2007). For example, out of 1324 German papers (fractional count basis) with citation scores, 73.3 received 53 cites or more, enough to put them in the top 5%. The world-scale value at this centile was (73.3 / 1020) / (1324 / 19996) x 100 = 108.5, which is a little above the average value of 100.

Percentage of Reviews—A New Measure of Esteem

Recently (Lewison 2009), it has been suggested that, because reviews are usually invited or commissioned from senior researchers with an established reputation, the number of reviews contributed by a country provides a measure of the esteem with which its senior researchers are held. Although this indicator is found to correlate positively with potential and actual citations measures, it is by no means the same, and it can provide additional information about the quality of research taking place in a country (or other geographical unit). In physics, there tend to be relatively few reviews compared with the situation in chemistry or biomedicine, but it is still worth examining each of the selected countries' outputs in order to calculate this indicator, the world average value being only 2.16%, although this percentage rose from 1.7% in 1994–1998 to 2.4% in 2004–2008.

Identification of Leading European Research Institutions

In the WoS, the first item in each address is the name of the parent institution carrying out the research; it is often followed by a departmental or unit name, and then by the name of the city, with the province or state and postcode, and the country name given last, thus:

UNIV-MASSACHUSETTS, DEPT POLYMER SCI & ENGN, AMHERST, MA 01003, USA

The first elements in the addresses of each western European country in turn (see Table C.1: the ISO digraphs in bold, except for Greece and Poland) were listed in descending order of frequency of occurrence. However, some institutions had variant name forms (*e.g.*, UNIV-COLL-LONDON, UCL, UNIV-LONDON-UNIV-COLL), and some unification of these forms was needed in order to prepare more accurate tallies of papers so that the leading institutions in each of the 10 countries could be determined.

RESULTS

World Output of Papers in Hybrid Flexible Electronics

Figure C.1 shows that there has been a rapid growth in the numbers of papers, from 1400 per year in 1994–1995 to over 4400 per year in 2007–2008, with an annual average percentage growth (AAPG) of almost 10%. By contrast, the output of papers in the topic area "physics" has increased by much less, with an AAPG of 3.2%. Table C.3 shows the percentages of papers from each of the 26 selected countries.

There have been some major changes in the relative positions of the leading countries over the 15-year period. Table C.4 shows the actual outputs (fractional counts) of the 15 leading countries in five three-year periods. Japan, whose output was almost equal to that of the USA in 1994–1996, dropped to fourth position in 2008, just behind South Korea, and in that year China (PRC) overtook the USA in output for the first time. The rise in output from the East Asian countries has inevitably depressed the world share of U.S. and European papers (except for Spain); India, however, has maintained its percentage presence and has recently overtaken the UK in output.

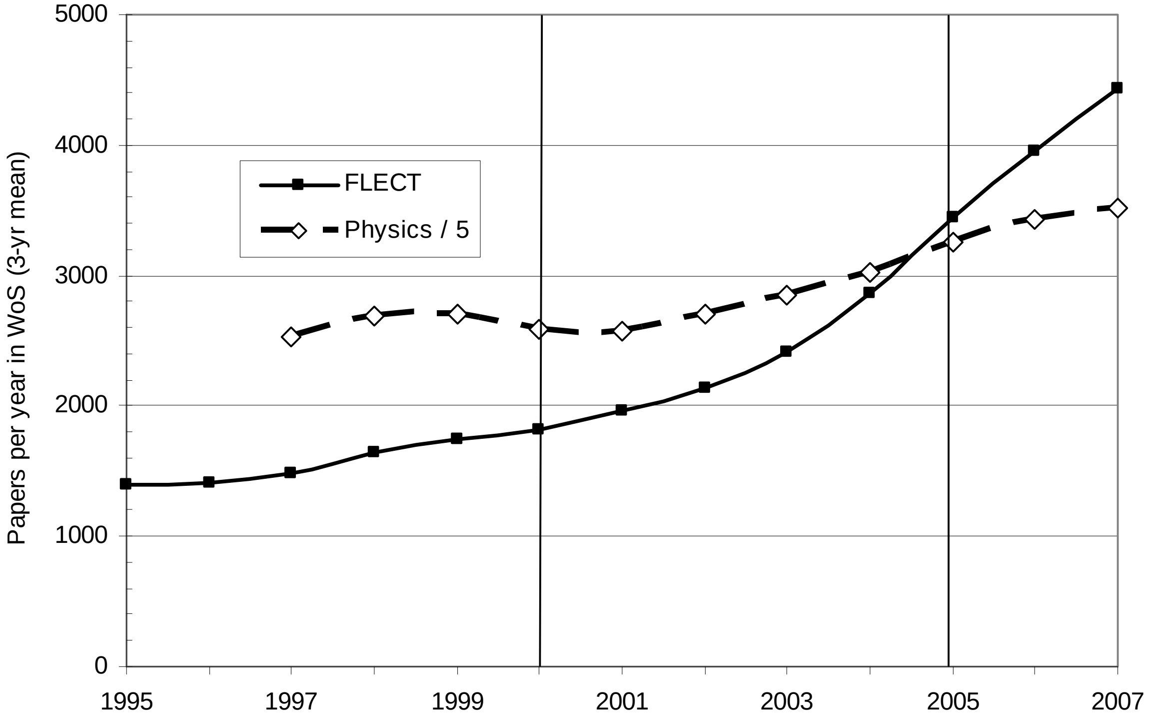

Figure C.1. Growth in the annual output of hybrid flexible electronics papers and of "physics" papers in the WoS (not corrected for calibration factor), 1994–2008, three-year running means.

Table C.3. Outputs of the 26 selected countries* in hybrid flexible electronics, 1994-2008, on both integer (INT) and fractional (FR) count basis, percentages of world total (36,852 papers)

	INT %	FR %			INT %	FR %			INT %	FR %
US	23.36	19.92		RU	3.61	2.87		PL	1.27	0.86
JP	15.17	13.68		IT	3.12	2.35		AU	1.10	0.86
CN	13.41	12.27		CA	2.47	1.90		TR	0.86	0.75
KR	7.29	6.61		NL	2.33	1.75		BE	1.30	0.75
DE	8.26	6.06		ES	2.13	1.50		UA	0.91	0.67
UK	5.75	4.25		SE	1.64	1.14		IL	0.88	0.66
TW	4.21	3.92		SG	1.34	1.09		AT	1.02	0.59
IN	4.28	3.86		BR	1.22	0.96		GR	0.81	0.56
FR	4.70	3.32		RU	3.61	2.87				

* See codes in Table C.1

Languages Used

As expected, virtually all (almost 98%) of the papers were in English. Other languages used were Chinese, 384 papers; Russian, 164; Japanese, 91; German, 40; Korean, 25; French, 20; Spanish and Ukrainian, 10. Eight other languages were also used but had fewer than 10 papers in any one.

Table C.4. Outputs of the world and 15 leading countries in hybrid flexible electronics research in five three-year periods in 1994-2008, fractional counts

Country	1994-96	1997-99	2000-02	2003-05	2006-08
World	4023	4888	5916	8580	13445
US*	825	1016	1211	1766	2489
JP	789	801	813	1149	1467
CN	193	359	589	1114	2244
KR	105	181	307	592	1238
DE	269	353	372	498	733
UK	182	217	306	379	475
TW	90	106	168	324	749
IN	149	205	231	334	499
FR	213	234	223	225	323
RU	208	209	191	193	252
IT	112	134	135	201	282
CA	99	87	105	173	233
NL	52	82	130	192	187
ES	60	59	92	120	219
SE	58	62	75	96	127

* Some 28 papers published by J.H. Schon in the years 1998–2002 have subsequently been queried because of doubts about their correctness; almost all were from the USA, but they have not been removed from the U.S. total in the above table or in the rest of the analysis.

Potential and Actual Citation Impact

Over the ten years 1994–2003, the field has become not only larger by a factor of three, but it has also become much better cited. This has occurred in terms of both potential citations (based on all papers in the journals used for its publications) and actual citations during a constant five-year window 2004–2008 (see Figure C.2.) The latter have effectively doubled, from 9 to almost 20 citations in the five-year window. This variation has to be borne in mind when the citation performance of different countries is considered: it will give an undue advantage to those countries whose output has increased rapidly in recent years, particularly those in East Asia. It is also noticeable that hybrid flexible electronics papers normally receive more citations than the average for papers in the journals in which they are published. This would make them attractive to journal editors, who are constantly striving to increase the impact factors of their journals.

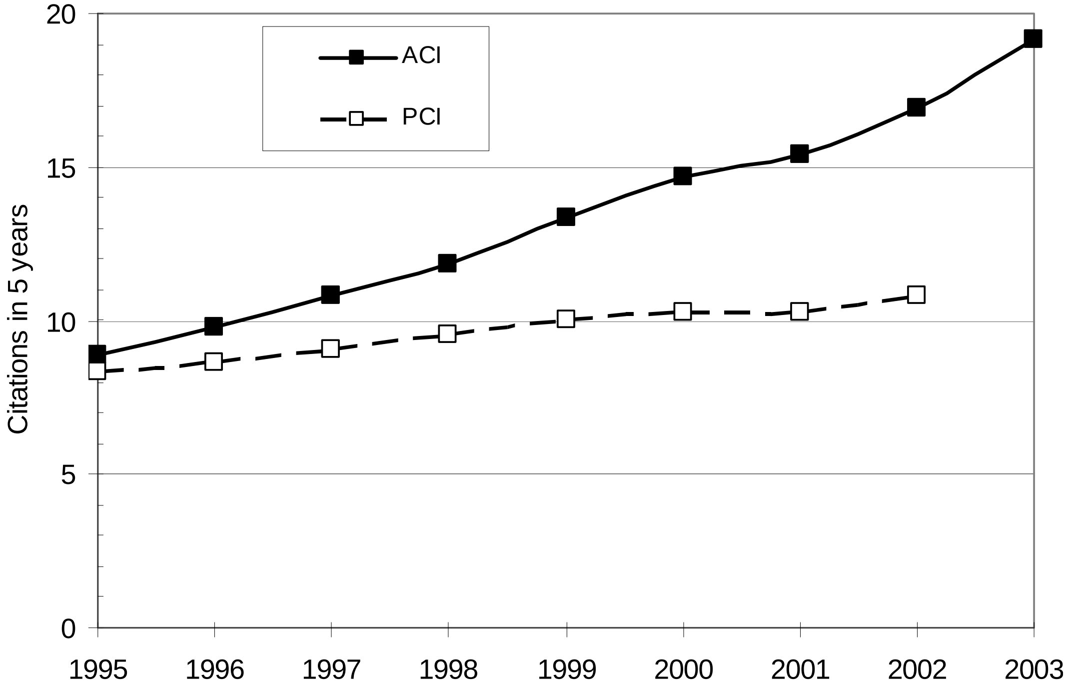

Figure C.2. Variation of actual citation impact (ACI) and potential citation impact (PCI) of hybrid flexible electronics papers with time, three-year running means (based on five-year citation data; papers were cited 2004 through 2008).

Figure C.3 shows the citation performance of 16 leading countries with both potential and actual citation mean scores shown on a fractional count basis. Two European countries, the Netherlands and Austria, lead in terms of actual citation counts, with the USA third, followed by three other European countries, all of whose papers are better cited than the world mean. The East Asia countries' papers are not well cited, and the effect of their rapid increase in output will be to make the comparison even worse.

Citation of Papers in the Top Centiles

The tendency of world-scale scores is for them to approach 100, the mean level, as the centile number increases. That is, countries with a superior citation performance will show to strong advantage in the top centiles, and rather less so in the lower ones; conversely, those with an inferior performance will have relatively very few papers in the top centiles but a more nearly average score at, for example, the 50th centile. This is illustrated in Figure C.4 for five countries (the Netherlands and the USA, with superior performance; Canada, with average performance; and Taiwan and Brazil, with below-average citation performance).

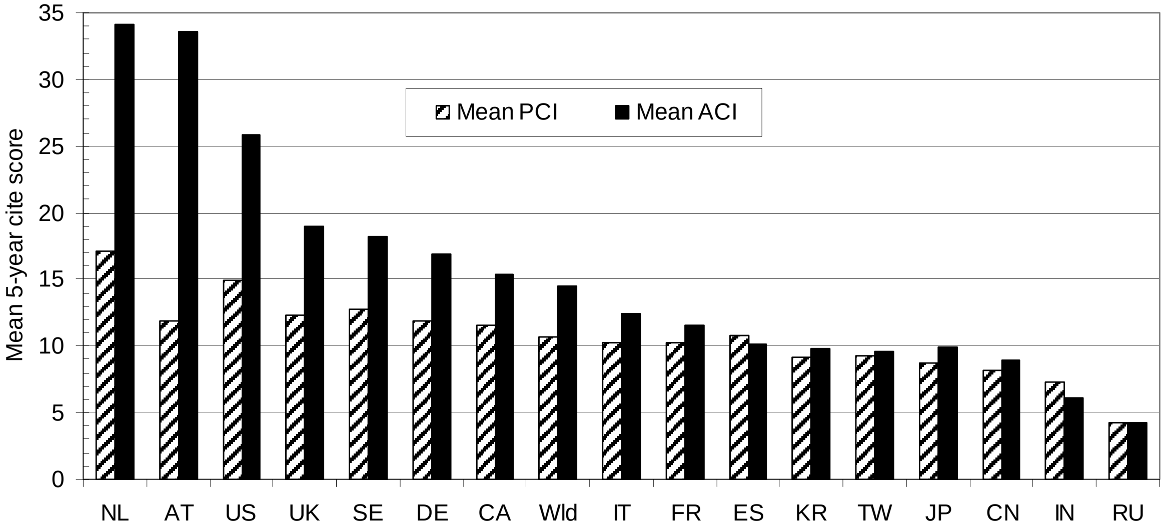

Figure C.3. Mean potential (PCI) and actual (ACI) five-year citation counts of hybrid flexible electronics papers from 16 leading countries, 1994–2004; fractional count basis.

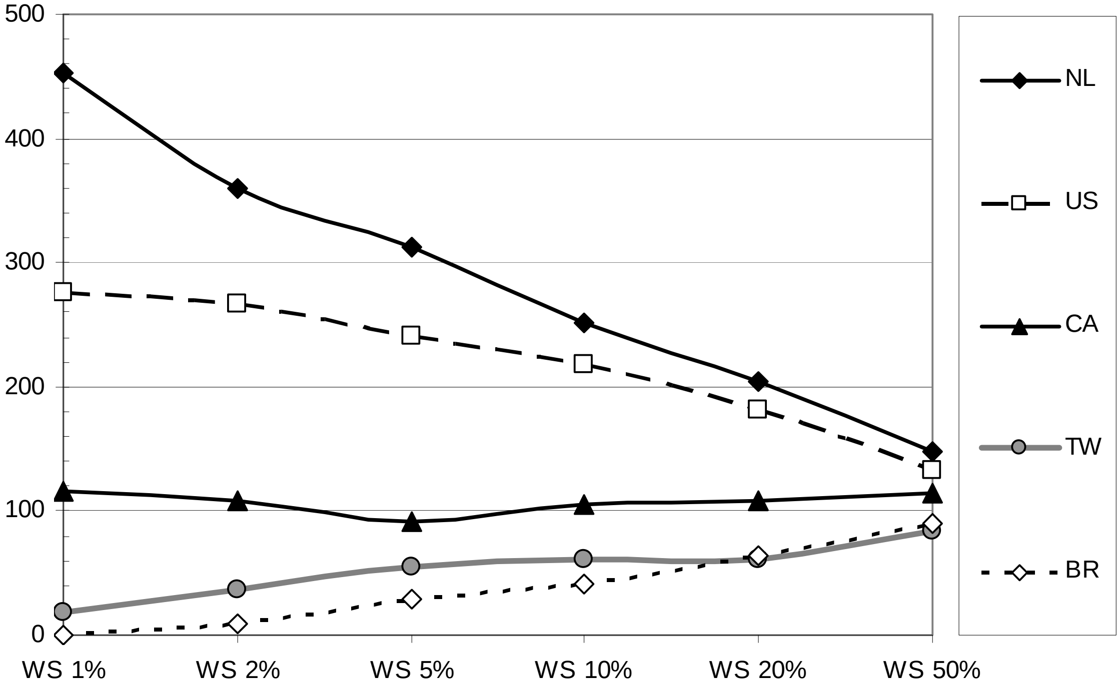

Figure C.4. The regression of world-scale (WS) values to the mean as centile number increases. Values for the Netherlands, the USA, Canada, Taiwan, and Brazil papers in hybrid flexible electronics, 1994-2004, at six centiles (qualifying five-year citation scores: 129, 89, 53, 33, 19, and 6 cites).

The actual world-scale values for 26 leading countries are shown in Table C.5. It is striking that the same five countries head the list as in the analysis of mean actual citation counts (Figure C.3; Switzerland would have been in fourth place), but the differences in values are rather more extreme, particularly at the higher centiles. Seven of the 26 countries had no papers in the top-cited 1%, with 129 cites or more in five years.

Percentage of Reviews from Different Countries

The percentages are shown in Table C.6 for all years together. This table also gives a small advantage to the East Asian countries, which have expanded their output rapidly in the last few years, but they are still far down the list. Strikingly, Israel tops the list, although with only 18 reviews (compared with an expected number, based on the world average of 2.16%, of 7). Nevertheless, this difference is statistically significant at <0.01%. Somewhat surprisingly, the UK appears rather low in the list, although it is normally top, at least in biomedical subject areas.

Table C.5 World-scale (WS) five-year actual citation scores at six centiles for hybrid flexible electronics papers, 1994–2004; fractional count basis

All world-scale values are to be compared with 100, the mean value at all centiles.

Country		WS 1%	WS 2%	WS 5%	WS 10%	WS 20%	WS 50%
Cites:		129	89	53	33	19	6
NL	Netherlands	453	360	313	252	205	147
AT	Austria	532	323	214	189	167	125
US	United States	276	266	241	218	181	132
CH	Switzerland	46	153	245	214	204	141
UK	United Kingdom	104	136	152	151	133	120
IL	Israel	148	150	110	98	141	126
SE	Sweden	120	90	128	131	141	124
DE	Germany	95	104	109	122	135	122
CA	Canada	116	108	92	105	109	114
BE	Belgium	82	69	115	126	116	109
Wld	World	100	100	100	100	100	100
FR	France	64	40	56	65	85	99
IT	Italy	13	56	63	65	87	112
JP	Japan	40	45	43	54	66	85
TW	Taiwan	19	37	54	61	61	83
SG	Singapore	24	12	40	58	73	101
KR	Korea (S)	11	10	43	58	70	91
ES	Spain	0	23	40	48	68	104
AU	Australia	0	0	15	60	78	103
CN	China (PR)	9	22	34	44	65	80
GR	Greece	0	50	36	23	48	90
BR	Brazil	0	9	28	41	64	90
IN	India	29	21	13	13	26	62
PL	Poland	0	6	15	19	37	73
TR	Turkey	0	0	5	14	45	84
RU	Russia	7	11	8	7	11	37
UA	Ukraine	0	0	0	8	19	46

Table C.6. Percentage of reviews in hybrid flexible electronics research, 1994–2008, in the output of the world and 26 leading countries (for codes, see Table X.1)

Codes for European countries are shown in **bold.**

ISO	% revs		ISO	% revs		ISO	% revs		ISO	% revs
IL	5.57		DE	2.97		SE	2.33		JP	1.42
AT	4.02		IT	2.79		World	2.16		SG	1.22
US	3.56		CH	2.63		UA	2.09		TW	0.91
BE	3.37		PL	2.57		BR	2.02		KR	0.90
AU	3.21		FR	2.56		CA	1.98		CN	0.85
ES	3.07		RU	2.42		GR	1.69		TR	0.63
NL	3.05		UK	2.37		IN	1.46			

LISTING OF LEADING WESTERN EUROPEAN RESEARCH INSTITUTIONS

Each of the 10 selected western European countries' papers during the last eight years (2001–2008) was separately transferred to individual files so that the addresses in each country could be listed. Once the leading institutions had been identified, with unification of the addresses as needed, they were given trigraph codes and the papers in the file marked with a "1" in the relevant column of the spreadsheet. For each institution, the leading authors were then listed, and a check made that they were, in fact, at that institution in the latest years. The mean ACI value for papers published from 2001–2004 from the institution was also determined as a rough indicator of their impact, albeit only for the first four years of the period. The results are given in Table C.7.

The panel's selection of sites to visit was informed by an earlier version of this bibliometric study than what is indicated here, with a much simpler filter. However, the results from the present analysis are not very different in terms of country performance, although the later filter identified far more papers. In Table C.7, the sites visited by the panel are shown in **bold**. As may be seen, they were all significant contributors to the research literature. In addition, a number of industrial companies were visited. Many of these appeared among the addresses of papers in the analysis, but with one exception (Philips nv in Eindhoven), they were not among the leading contributors.

REFERENCES

Lewison, G. 1996. The definition of biomedical research subfields with title keywords and application to the analysis of research outputs. *Research Evaluation* 6(1):25-36.

Lewison, G. 1999. The definition and calibration of biomedical subfields. *Scientometrics* 46(3):529-537.

Lewison, G., G. Thornicroft, G. Szmukler, and M. Tansella. 2007. Fair assessment of the merits of psychiatric research. *British Journal of Psychiatry* 190:314-318.

Lewison, G. 2009. The percentage of reviews in research output: A simple measure of research esteem. *Research Evaluation* 18(1):25-37.

Table C.7. Leading Western European institutions carrying out research in hybrid flexible electronics, ranked by the number of their papers in 2001–2008 (N), with mean ACI value for 2001-04 papers and the names of their leading researchers, with corresponding numbers of papers

ISO	Institution	N	ACI	Researchers
AT	Johannes Kepler Univ., Linz	117	75.9	Sariciftci-NS 95; Neugebauer-H 26
AT	Karl Franzens Univ. Technol., Graz	79	33.1	List-EJW 30; Scherf-U 20
BE	IMEC, Leuven	79	16.8	Heremans-P 40
BE	Katholieke Univ., Leuven	70	21.4	Heremans-P 26
CH	Ecole Polytech Fed., Lausanne	145	34.8	Gratzel-M 60; Zakeeruddin-SM 34
CH	ETH, Zurich	112	21.6	
DE	Max Planck Inst., Mainz	136	35.1	Mullen-K 76
DE	Tech Univ., Dresden	92	30.6	Leo-K 55; Pfeiffer-M 31
DE	Univ. Munich	90	31.8	Feldmann-J 17; Lupton-JM 14
DE	Max Planck Inst., Stuttgart	85	24.0	Burghard-M 17; Roth-S 17
DE	Univ. Erlangen-Nürnberg	78	20.5	Guldi-DM 25
DE	Univ. Marburg	65	18.0	Bassler-H 48
ES	CSIC, Madrid	79	8.1	
ES	CSIC, Barcelona	54	11.4	Canadell-E 15
FR	CNRS, Paris	146	13.9	
FR	Univ. Grenoble 1	57	14.4	Pron-A 15
IT	CNR, Bologna	128	21.0	Barbarella-G 19; Camaioni-N 18
IT	Univ. Bologna	55	11.3	
IT	Politecn., Milan	54	14.7	Lanzani-G 17
NL	Eindhoven Univ. Technol.	182	30.8	Janssen-RAJ 71
NL	Univ. Groningen	167	51.7	Blom-PWM 73; Hummelen-JC 46
NL	Delft Univ. Technol.	130	50.4	Siebbeles-LDA 34; Warman-JM 19
NL	Philips nv	127	50.8	deLeeuw-DM 58; Blom-PWM 27
SE	Univ. Linkoping	135	20.0	Inganas-O 62; Andersson-MR 33; Berggren-M 25
SE	Univ. Uppsala	81	13.9	Hagfeldt-A 21
SE	Chalmers Inst. Technol., Goteborg	76	27.1	Andersson-MR 41; Inganas-O 29
SE	Royal Inst. Technol., Stockholm	61	12.3	Hagfeldt-A 14
UK	Univ. Cambridge	293	35.4	Friend-RH 97; Sirringhaus-H 49
UK	Imperial College, London	204	21.7	Bradley-DDC 79; Durrant-JR 46
UK	Univ. Durham	104	16.8	Monkman-AP 42; Bryce-MR 29
UK	Univ. Sheffield	84	16.8	Lidzey-DG 23; Grell-M 20
UK	Univ. Oxford	75	20.0	Burn-PL 26; Samuel-IDW 24
UK	University College, London	68	17.8	

APPENDIX D. LIST OF ACRONYMS

ALD	atomic layer deposition
BAPV	building-applied photovoltaics
BHJ	bulk-heterojunction
BIPV	building-integrated photovoltaics
CIE	International Commission on Illumination: mathematically defined RGB and XYZ "color spaces"
CMOS	complementary metal-oxide–semiconductor (standard integrated circuit technology)
CNR	Consiglio Nazionale delle Ricerche, the National Research Council of Italy
COMEDD	Center for Organic Materials and Electronic Devices at the Fraunhofer Institute for Photonic Microsystems (IPMS)
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)
EPC	Electronic Product Code, created by a global consortium of corporations and university labs
EPSRC	Engineering and Physical Sciences Research Council (UK)
ETL	electron-transporting layer
FET	field-effect transistor
HOMOs	highest occupied molecular orbitals
HTL	hole-transporting layer
IAPP	Institut für Angewandte Photophysik (Institute for Applied Photophysics) of the Technical University of Dresden
IMEC	Inter-University MicroElectronics Center, Belgium
IP	intellectual property
IPMS	Fraunhofer Institute for Photonic Microsystems
IPV	integrated photovoltaics
ISMN	CNR Bologna's Institute for the Study of Nanostructured Materials (Instituto per lo Studio dei Materiali Nanostrutturati)
iTFTs	(silicon) inorganic thin film transistors
LCD	liquid crystal display
LED	light-emitting diode
LUMOs	lowest unoccupied molecular orbitals
MEMS	microelectromechanical systems
OFET	organic FET
OLA	organic large-area
OLEDs	organic light-emitting diodes
OLET	organic light-emitting transistor
OPV	organic photovoltaics
OTFT	organic thin-film transistor
PEDOT:PSS	p-doped polymer poly(3,4-ethylenedioxythiophene):poly (styrenesulfonate)
PDLC	polymer dispersed liquid crystal
PEN	polyethylene naphthalate
PET	polyethylene terephthalate
PLED	polymer light-emitting diode
P-OLED	polymer -based organic light-emitting diode
PPV	polymer poly(para-phenylene vinylene)
PV	photovoltaic(s)
QC/QA	quality control/quality assurance
QVGA	quarter video graphics array
R2R	roll-to-roll
RF	radio frequency
RFID	radio-frequency identification (devices, tags, etc.)
SAM	self-assembled monolayer
SAND	self-assembled nanodielectrics
TFT	thin-film transistor
UCL	University College London
VDMA	German Engineering Federation
Wp	Watt-peak

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Nanotechnology: Societal implications. Mihail Roco and William Bainbridge (Eds.) Springer, 2006. Two volumes.

Biosensing: International research and development. J. Shultz (Ed.) Springer, 2006.

Spin electronics. D.D. Awschalom et al. (Eds.) Kluwer Academic Publishers, 2004.

Converging technologies for improving human performance: Nanotechnology, biotechnology, information technology and cognitive science. Mihail Roco and William Brainbridge (Eds.) Kluwer Academic Publishers, 2004.

Tissue engineering research. Larry McIntire (Ed.) Academic Press, 2003.

Applying molecular and materials modeling. Phillip Westmoreland (Ed.) Kluwer Academic Publishers, 2002

Societal implications of nanoscience and nanotechnology. Mihail Roco and William Brainbridge (Eds.) Kluwer Academic Publishers, 2001.

Nanotechnology research directions. M.C. Roco, R.S. Williams, and P. Alivisatos (Eds.) Kluwer Academic Publishers, 1999. Russian version available.

Nanostructure science and technology: R & D status and trends in nanoparticles, nanostructured materials and nanodevices. R.S. Siegel, E. Hu, and M.C. Roco (Eds.) Kluwer Academic Publishers, 2000.

Advanced software applications in Japan. E. Feigenbaum et al. (Eds.) Noyes Data Corporation, 1995.

Flat-panel display technologies. L.E. Tannas, et al. (Eds.) Noyes Publications, 1995.

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