25 YEARS OF SEMICONDUCTORS

PART 2

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POWER DEVICES, PHOTO DEVICES AND INTEGRATED CIRCUITS

THE first article described the types of transistor and small-signal diode available. This article considers power devices, photo devices using, or emitting light, and the most revolutionary semiconductor device of all—the integrated circuit.

POWER DIODES

The amount of power that can be handled by a semiconductor diode is limited by the junction temperature. Provided the heat dissipated within the device can be conducted away so that the maximum permissible junction temperature is not exceeded, the diode will operate satisfactorily. Therefore a power diode should have as large a junction area as possible, and a low thermal resistance to the case. The cooling area can be increased by mounting the diode on a suitably shaped heatsink.

Germanium power diodes were developed using these techniques, and could carry currents of approximately 10A and withstand peak inverse voltages of up to 600V. The introduction of silicon, however, led to their replacement during the 1960's by silicon diodes with junctions alloyed or diffused with aluminium.

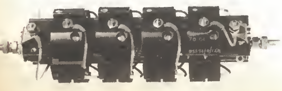
AVALANCHE DIODES

As the reverse voltage across a junction diode is increased, a voltage is reached where avalanche breakdown occurs, marked by a sudden increase of current. Provided the diode can withstand the current at breakdown, it will recover when the reverse voltage is decreased below the breakdown value. Avalanche diodes are designed to withstand such breakdown currents, and so can be used safely in applications where voltage transients are likely to be encountered.

By the end of the 1960's other protection devices such as high-speed fuses had been developed so that semiconductor-diode rectifier systems were firmly established in such applications as battery chargers, electroplating and electrolysis processes, and electric furnace supplies. These semiconductor systems occupied less space than the existing systems, had a higher rectifier efficiency, and for the first time presented power engineers with a device that had no wear-out effects.

A high-voltage rectifier stack is shown in the photograph of Fig. 8. Diodes are mounted on heatsinks around a central fixing stud. Such stacks can be cooled by natural convection, or for higher currents by forced-air cooling or immersion in an oil bath.

Fig. 8 High-voltage rectifier stack operating at 12kV and 5A with natural convection cooling (length approximately 10in)



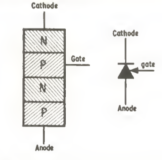


Fig. 9 Structure and circuit symbol of thyristor

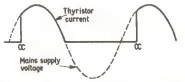


Fig. 10 Phase control using thyristor

THYRISTORS

The thyristor or controlled silicon rectifier was developed for power control in parallel with the silicon rectifier diode. The rectifier action of the thyristor allows a current to flow in one direction only, but in addition current can only flow when the thyristor has been triggered.

In form, the thyristor is a four-layer *pnpn* device, as shown in Fig. 9. The circuit symbol is also shown in this figure. If the anode is positive with respect to the cathode, and a positive voltage is applied to the gate, the thyristor conducts. Once conduction has been established, the gate voltage can be removed.

Therefore the thyristor can be triggered by a pulse provided the duration is sufficient to allow the current to be established. The thyristor is made non-conducting by reducing the current to below a holding value.

The method of power control with thyristors is shown by the waveforms in Fig. 10. By varying the trigger angle within the half-cycle (α), the amplitude of the current pulses passed by the thyristor, and hence the power delivered to the load, can be varied. This control technique is called phase control.

A second method of control is burst triggering, used for loads with a high thermal inertia such as furnaces. In this method, complete half-cycles of the mains supply are passed by the thyristor, the ratio of half-cycles passed to those blocked determining the power to the load.

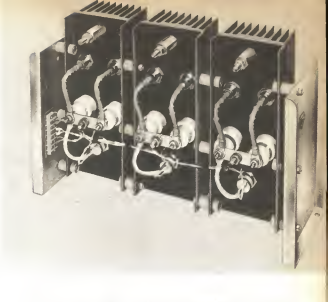


Fig. 12 Thyristor stack for operation on 440V three-phase mains to control 110A per phase

TRIACS

Another device for power control similar to the thyristor is the triac or bidirectional thyristor. This device is equivalent to two thyristors connected in inverse-parallel with a common gate connection. The circuit symbol for a triac is shown in Fig. 11. A current will flow through the device when the gate is sufficiently positive or negative with respect to terminal mt1, the direction of current flow depending on the relative polarities of mt1 and mt2.

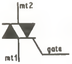


Fig. 11 Circuit symbol for triac

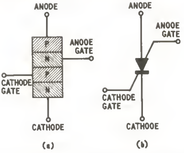


Fig. 14 Structure and circuit symbol for silicon controlled switch

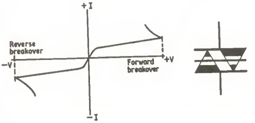


Fig. 13 Breakdown characteristic and circuit symbol for diac

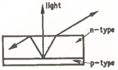


Fig. 15 Diagram showing construction of a typical light emitting diode

The currents that could be handled by thyristors, and the inverse voltages they could withstand, increased during the 1960's as the manufacturing techniques were improved. Present-day thyristors can handle currents up to 1000A and withstand inverse voltages of over 2kV. Protection devices have been developed as with rectifier diodes to ensure reliable operation under practical conditions.

A typical thyristor stack with thyristors connected in a bridge configuration for the control of power to a load is shown in Fig. 12. The thyristors are mounted on heatsinks.

THE DIAC

The diac, or bidirectional diode thyristor, is a useful trigger device for thyristors and triacs. It uses avalanche breakdown, but as the characteristic in Fig. 13 shows, the voltage decreases after breakdown so that the gate circuit is not overloaded on triggering.

SILICON CONTROLLED SWITCH

Another four-layer *pnpn* device is the silicon controlled switch or SCS. Unlike the thyristor and triac, both intermediate layers of the SCS are accessible making it a four-terminal device. The structure and circuit symbol are shown in Fig. 14.

The SCS (like the thyristor) has two stable states: conducting and non-conducting. The SCS can be used in two circuit configurations. In one, the load is connected in the anode gate circuit so that the SCS operates as a four-terminal device. In the other, the load is in the anode circuit and the anode gate is not connected. The SCS then acts as a low-power thyristor or three-terminal device.

PHOTOTRANSISTORS AND PHOTODIODES

Light falling on a junction in a semiconductor diode or transistor affects the current through the device. The energy of the light dislodges electrons and so increases the number of carriers available at the junction.

Constructive use of this effect is made in photodiodes and phototransistors where the change in current with light can be used in such applications as light meters and alarm systems.

Other semiconductor materials exhibit a change of resistance with light, and this effect is used in photoconductive cells (or light-dependent resistors). The choice of semiconductor material determines which part of the spectrum the device responds to, for example cadmium sulphide responds to visible light while lead sulphide is used for infrared detectors.

LIGHT EMITTING DIODES

Another type of photodevice is the electroluminescent or light-emitting diode (Fig. 15). This device is made from gallium arsenide or gallium arsenide phosphide, and when a sufficiently high current (a few milliamperes) is passed through, light is emitted. Such diodes can be used as indicator lights directly coupled into, for example, computing systems.

INTEGRATED CIRCUITS

Of all the semiconductor devices that followed the invention of the transistor, the most revolutionary both in reducing the size of equipment and improving reliability is the integrated circuit.

The problems of manufacturing different circuit elements on the same silicon chip were overcome so that integrated circuits that were both practicable and economic became available by the mid-1960's.

Today two types of integrated circuit (i.c.) are available, the bipolar and MOS, each with their advantages and disadvantages for particular applications.

BIPOLAR I.C.

The bipolar i.c., as the name implies, uses bipolar transistors manufactured by the planar process. Diodes are formed by a single diffusion, capacitors by using a reverse-biased diode junction, and resistors by a single diffusion like a stretched-out diode with connections at both ends. The main problem with the manufacture of bipolar i.c.s is isolation between components.

MOS INTEGRATED CIRCUITS

The transistor used in MOS i.c.s is a field-effect transistor, the MOSFET or MOST. Because MOS i.c.s are almost exclusively used in digital applications, an MOST can form the load for another MOST, the transistors are directly coupled, and the capacitances on which information is stored are formed by the gate capacitances of the MOSTs themselves. Thus only transistors and connections need to be formed on the chip.

One advantage of MOS i.c.s over the bipolar type already mentioned, is the fact that no isolating diffusion is needed on the chip. In addition, an MOST is smaller than the equivalent bipolar transistor. Both these reasons lead to a higher packing density being achieved with MOS i.c.s. On the other hand, bipolar i.c.s have a higher operating speed, and can drive higher current and capacitive loads which MOS i.c.s cannot do without interface circuits.

Thus the choice of MOS or bipolar i.c. may well depend on the requirements of the application rather than any clear-cut advantage of a particular type.

In general, it can be said that small scale integration (SSI) is rarely economical with MOS i.c.s so that gate packs and flip-flops will use bipolar i.c.s.

Large scale integration (LSI) for such devices as random-access memories (RAMs) and read-only memories (ROMs) will use MOS i.c.s. The choice for medium scale integration (MSI) will depend on the application.

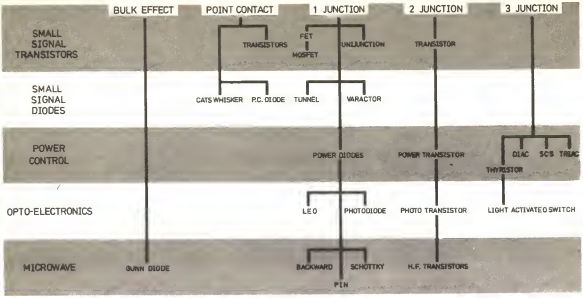
COMPLEMENTARY MOS

A limitation on the use of MOS i.c.s occurs through the use of field-effect transistors. The current-carrying channel for the transistor is formed in the substrate, and so normally only *p*-channel or *n*-channel devices but not both can be formed on any one i.c.

To overcome this, a technique called complementary symmetry MOS or CMOS has been developed. Areas of *p*-material are diffused into an *n*-type substrate so that both *n*-channel and *p*-channel MOSTs can be formed.

More diffusions are required for CMOS than with normal MOS i.c.s, and a lower packing density results. On the other hand, there are considerable advantages for the user, particularly higher operating speeds and lower dissipation.

Fig. 16 Integrated circuit chip compared with ordinary sewing needle, the chip being 1·5 × 3mm



FAMILY TREE OF SEMICONDUCTOR DEVICES

LINEAR I.C.s

The i.c.s described above are digital circuits. Later in the 1960's linear i.c.s were developed. In terms of the number of devices contained, these i.c.s are more complex than the equivalent discrete stages they replace, although cheaper and with better performance. Today a wide range of linear i.c.s is available covering r.f. and i.f. amplifiers, operational amplifiers, TV signal-processing circuits and audio amplifiers with output powers up to several watts.

The reduction in size possible with an i.c. is impressive, typified by such photographs as that in Fig. 16 showing a silicon chip containing over 120 devices passing through the eye of an ordinary sewing needle.

COLLECTOR DIFFUSION ISOLATION

Another process which overcomes many of the disadvantages of conventional bipolar i.c.s has been developed by Ferranti from an American idea. Known as the collector diffusion isolation (CDI) process, it makes use of thin epitaxial layers but needs only five masking processes making it comparable to MOS technology in simplicity.

Fig. 17 shows the structure of a CDI transistor. The process uses a *p*-type substrate into which buried low resistivity $n+$ areas are diffused where each resistor, transistor or diode is to be formed. A thin epitaxial *p*-type layer is then diffused. The collector diffusion is then made producing low resistivity $n+$ channels round each component. This diffusion serves three purposes: to make contact with the buried $n+$ area which forms the collector; to provide isolation between components; and to define base and resistor areas.

A shallow *p*-type layer is diffused over the whole slice to define resistor values. A shallow emitter diffusion then follows.

The CDI process reduces transistor areas by up to a third and also enables digital and linear circuits to be combined on one slice. The main disadvantage is that there is no *pnp* transistor available, though

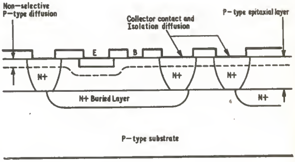


Fig. 17 Structure of a CDI transistor (*Ferranti*)

a *p*-channel f.e.t. under development should overcome this difficulty.

CONCLUSIONS

From the original low-power low-frequency transistor have developed transistors capable of operating high in the radio frequencies, transistors handling powers of over 100W, transistors capable of switching wave-forms with rise times of 1ns. Signal diodes operating in the microwave freqencies have been developed, and diodes and thyristors capable of operating on high-voltage supplies controlling powers measured in megawatts. Devices reacting to and producing light are available, and devices containing a complete computer processing system on a chip only 3·5mm square.

Although the transistor was the fore-runner, the most revolutionary device may well be the integrated circuit which has brought a new concept into electronic circuit design. The thermionic valve (apart from its more specialised forms such as klystrons and magnetrons) had a commercial life of about 35 years. It may well be that the discrete transistor apart from more specialised forms like photodevices will have a shorter life. ★