HITEN Semiconductors Overview

Summary of High Temperature Electronic Devices & Technologies

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Beyond 125°C

Table 1 illustrates the operational temperature ranges for most **commercially available** electronic components. Very few electronic devices are specified for operation beyond an ambient temperature of 125°C, apart from sensors and some series of discrete power transistors and ICs.

Increasing ambient temperatures are almost invariably associated with increased demands of other environmental parameters such as corrosion, vibrations, and mechanical shock.

The upper limit of 125°C is largely set by commercial considerations. Technically, it is has long been established that silicon devices can perform well beyond 125°C. However, so far the demand has not justified the development effort required to characterise the wide range of devices that is required to enable new subsystem designs.

At present, devices specified beyond 125°C can mostly be obtained only on a custom basis. A few standard parts are available rated up to 150°C, and even to 200°C, at considerable expense, mainly for military and space applications.

However, **many off-the-shelf devices display only small changes in characteristics from 25-250°C**. Due to the limited availability of high temperature devices, some users purchase commercially available standard components, and specify them in-house for high temperature operation up to 200°C and beyond, for incorporation into systems.

This is time-consuming and expensive. Typically it is only of interest for high-performance, technology-driven, low volume, applications, such as electronic braking systems for aircraft, and well-logging equipment. Sandia National Laboratories, for example, has described a wide class of commercial CMOS devices which have been successfully operated at 200°C.

In-house qualification of devices for high temperature operation is not feasible for larger volume, and more price-sensitive, applications.

Devices required to operate at high temperatures

The greater the extent to which controlling electronics can be placed in proximity to the sensing element, the greater the benefits that can be realised. The devices under consideration include **sensors and their controlling electronics** for precision control, data acquisition, data processing and high power systems.

System partitioning is a key consideration, determined by price-performance trade-offs. Initial applications incorporate amplifiers with the sensors in the hostile environment. The development of **smart sensors**, chips that contain the functions of sensing, signal conditioning, A/D conversion, and a bus output, is a major area of investigation.

Another key research goal is to develop high temperature (200°C) electronic subsystems incorporating sensors, amplifiers, A-to-D converters, microcontrollers, D-to-A converters, and power amplifiers. Such systems could, for example, enable the elimination of cooling requirements in rack-mounted avionics in aircraft.

Some manufacturers of well logging equipment have already developed systems which can tolerate temperatures up to 250°C for short periods of time, but the demands of the aerospace environment are much more severe.

Temperature ranges

For most applications device operation up to 300°C ambient environments will be sufficient, and operation up to 200°C is expected to account for the majority of needs.

Above 300°C, several specialist applications can be identified, but a significant development effort is required before they can materialise.

A critical requirement in many applications is not only steady state operation at high temperatures, but also the ability of components to operate reliably over **wide temperature ranges**. Failures resulting from thermal cycling are as much a problem, if not more so, than failures due to sustained high temperature operation.

Semiconductors for high temperature electronics

Over the next 10 years silicon devices are expected to dominate demand for high temperature electronics.

Initially WBS (wide bandgap semiconductors) are expected to make a more immediate impact on the sensor market. A considerable development effort is still required before they contribute significantly to active electronics.

These materials are being developed for a range of high performance applications and not just for high temperature operation.

Silicon

It is well established that silicon devices can potentially operate at temperatures much higher than their current maximum temperature ratings. Si is also by far the most mature and lowest cost semiconductor technology and is expected to dominate applications up to 250-300°C, which accounts for most of the market.

At elevated temperatures silicon devices show an increase in leakage currents. However bulk silicon processes such as modifications of CMOS and integrated injection logic, are being developed to address this and other issues for high temperature operation.

Leakage currents can be virtually eliminated by using silicon-on-insulator (SOI). The term SOI includes any technology using a silicon monocrystalline film on top of an insulating layer.

Of the various types of SOI technology, there are three which are currently considered manufacturable: SIMOX (Separation by Implantation of Oxygen), SOS (Silicon-On-Sapphire) and BESOI (Bonded and Etched Back SOI).

SOI is under development at many companies worldwide, especially for small signal applications (SOI is less suited to power devices). Synergistic areas of development for SOI include radiation hardness, high speed, and low power applications.

GaAs

The bandgap of GaAs is 1.43 eV, compared to 1.1 eV for Si, lending it to higher temperature operation. GaAs is currently the dominant technology for high power microwave applications.

Mainstream GaAs technology is based on MESFETs, fabricated on semi-insulating (SI) substrates. A key problem is that the SI property, and hence device isolation, is reduced at higher temperatures, although GaAs MESFETs have been demonstrated up to 350°C ambient.

Heterojunction GaAs, using wide bandgap material systems such as AlGaAs, can potentially resolve the problems associated with the use of bulk substrates, although these systems are less mature and more expensive.

Intelligent AlGaAs sensors have been demonstrated up to 500°C, and large volumes of GaAs Hall Effect sensors are used in the automotive industry.

The companies developing GaAs for high temperature markets tend to be those with vertically integrated interests in aerospace and military systems, such as Honeywell and Hughes.

Wide Bandgap Semiconductors

A range of WBS are under development for high temperature including SiC, diamond, GaN and c-BN. Of these, SiC is the leading candidate as it is the only one available both in single crystal form and in good quality heteroepitaxy, and it can easily be doped both n- and p-type.

SiC

The bandgap of SiC is in the region of 3eV (varies according to the polytype). Its operating characteristics are, in theory, far superior to Si or GaAs, and devices should be able to function up to at least 600-700°C.

Although it is progressing rapidly, SiC technology to-day is where GaAs electronics was roughly 25-30 years ago. Discrete power transistors fabricated on 1-inch substrates have been widely demonstrated by several organisations.

The main driver for SiC is **high power** devices, and for niche high ambient temperature applications beyond 300°C. SiC electronic devices could start to be designed-in to systems within the next 3-4 years (SiC optoelectronic devices - blue LEDs - are already in relatively high volume production).

Diamond

The figures of merit for diamond are superior to those of all other semiconductors and diamond devices could theoretically demonstrate outstanding performance. The main obstacles to realising diamond electronics are the lack of: low activation energy dopants, large area single crystal substrates, a native oxide, and suitable process technologies.

However over the past few years considerable excitement has been generated from studies of working transistors fabricated on single crystal diamond.

The performance of these devices varies greatly according to device structure, starting material, doping technique and device processing technologies.

Only very recently have the first devices showing high temperature operation, saturation, and complete pinch-off of the active channel been reported, as well as demonstration of the first diamond digital logic circuits (operating up to 400°C). Overall, diamond lags behind SiC for active electronic applications, although intensive efforts from some key groups could yet close the gap.

Passive diamond devices should impact the market much earlier.

For example, diamond thermistors with fast response times, low heat capacity and high thermal conductivity could be available shortly.

Group III-Nitrides

The wide bandgap nitrides, especially GaN and c-BN, have outstanding characteristics, exceeding those even of SiC, and are under development for several applications including high temperature.

These materials are at very early stages in their development and are expected to play only a minor commercial role in high temperature electronics over the next 10 years.

A summary of the status of these semiconductor technologies for high temperature electronics is shown in Table 2.

Other key development issues

Extending the operational temperature range of semiconductors is just the starting point. As mentioned above, advances are also required in the high temperature capability of die attachment materials, wirebonding, packaging, passive devices, printed circuit boards, interconnection, and advanced thermal management (such as multi-chip modules). **The prime failures in high temperature electronics usually arise from these factors, not the semiconductor**.

Various individual aspects of the technology have been addressed, but the information has only recently started to be consolidated into a form suitable for applications.