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INTERFACE ELECTRONICS FOR SMART SENSORS
IN
LOW-TEMPERATURE AND HIGH-TEMPERATURE ENVIRONMENTS

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The applications of sensors are continually expanding into new areas which expose them to hostile environments. The particular hostile factor considered here is temperature, specifically environments that are considerably outside the conventional "room-temperature" range—either above or below. There are many examples of sensors in such "extended-temperature" environments, including sensors for temperature, pressure, radiation, fluid flow, and position; they are used in automobiles, aircraft, spacecraft, particle accelerators, cryogenic systems, processing equipment, and well-logging probes.

These applications may subject a sensor to temperatures nearly as low as absolute zero (–273°C) or to over +300°C. This presents a challenge for the sensor, but, in addition, it is often desirable to improve system performance by closely coupling interface electronics to the sensor, to realize a smarter sensor. Co-locating this electronics in the same extended-temperature environment presents a serious challenge for the designer, since electronic components are usually rated only for temperatures between –55°C and +125°C at best.

Fortunately there is information and experience to draw upon—electronics has been used at the extremes of temperature mentioned above. This tutorial is intended to overview the status of such electronics for environments outside the "conventional" temperature range, both colder and hotter. Topics include the reasons for extending the temperature range of electronics, temperature capabilities of electronics, basic component characteristics, and design considerations for extended-temperature operation, with a number of examples to illustrate the concepts. The focus here is electronics for sensors, but the concepts apply also to actuators.

I. NEEDS AND APPLICATIONS

Reasons for co-locating electronics with sensors in a cold or hot environment include

(1) The data-gathering system needs to operate autonomously or semi-autonomously,

(2) The sensor output signal is weak and requires immediate preamplification or buffering,

(3) There are many sensors so that multiplexing is required,

(4) Smart sensors are needed in a distributed monitoring and control system.

Figure 1 – A DS2 probe: the larger part (center) remains on the surface while the cylindrical part (lower right) penetrates up to about a meter into the Martian soil. Both parts contain low-temperature electronics. In the foreground is a quarter for size reference. (Courtesy of NASA/JPL/California Institute of Technology.)

The exploration of our Solar System affords a good illustration of reason (1) above. Environmental temperatures can be extreme. For example, on Mars the surface temperature may dip to around –100°C, and on Venus surface temperatures exceed +400°C. Extended-temperature electronics is being explored by NASA as an alternative to temperature control systems that are typically used to keep electronics within the conventional temperature range [1]. The recent (December 1999) DS2 (Deep Space 2) mission to Mars included two small surface probes with electronics qualified for –120°C (Figure 1) [2].

A high-temperature example of reasons (1) and (2) is provided by well-logging—gathering data by lowering a probe, or *sonde*, deep into a bore hole for a petroleum or geothermal well where temperatures can reach +300°C. These probes may contain complete electronics systems for signal processing, data transmission and power conditioning (Figure 2).

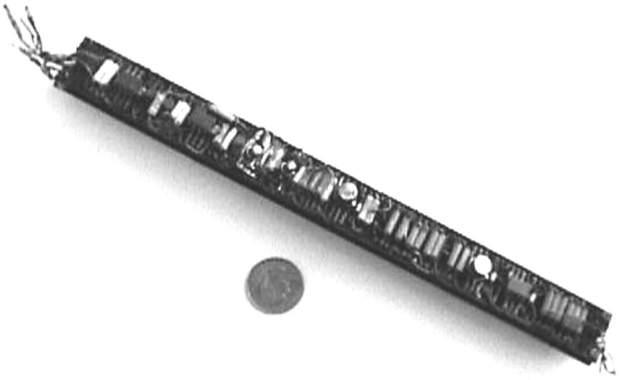

Figure 2 – Complete electronics for a well-logging probe used for pressure measurement in bore holes. This electronics operates to 275°C and with reduced life to 315°C. Below the electronics is a quarter for size reference. (Courtesy of Linear Measurements Inc.) [3]

Returning to spacecraft as an example, scientific satellites have been a major user of low-temperature electronics for reason (2) above. These satellites carry sensors, such as infrared detectors, that must operate at very low temperatures to attain the desired performance. The low-level output signals from these sensors must be strengthened before being sent to “conventional-temperature” electronics outside the low-temperature environment.

As an example, the XRS detector array for the ASTRO-E X-ray astronomy satellite uses an array of 32 micro-calorimeters operating at approximately 65 mK (approximately –273°C). Preamplification takes place by silicon transistors cooled to about 120 K (about –150°C) (Figure 3) [4].

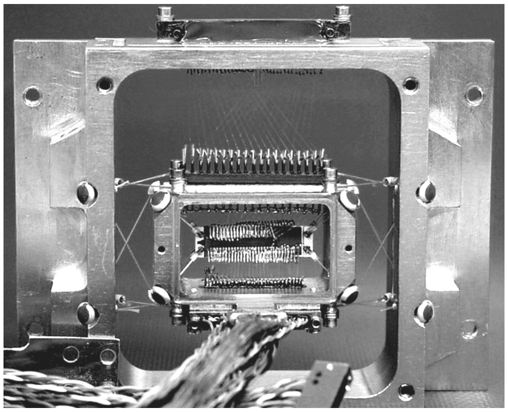

Figure 3 – A preamplifier assembly for X-ray detectors on the ASTRO-E satellite. The temperature of the outer frame is about 1.2 K (–272°C); of the innermost part carrying eight transistors about 120 K (–153°C). (Courtesy of NASA Goddard.) [4]

If there are a large number of sensors, multiplexing must also be performed in the low- or high-temperature environment, as indicated in reason (3) above. A good example of this is the combination of an infrared detector array chip and a signal-processing (readout) chip such as illustrated in Figure 4. Arrays of this type, which operate at very low temperatures, are used for astronomy, surveillance and tracking and may have as many as 10^6 or more detector elements. The readout chip preamplifies, scans, and multiplexes signals from the detector array, with both chips operating at temperatures as low as a few degrees above absolute zero (about –270°C).

As an illustration of reason (4), aircraft designers want to co-locate more interface electronics with the numerous sensors and actuators in remote locations on an aircraft, to implement a more distributed system. In a “fly-by-wire” or “fly-by-light” aircraft, the various sensors and actuators, by means of their interface electronics, communicate digitally with a central monitoring and control system through a common wire or optical fiber rather than by dedicated wiring to each unit. A similar idea—“drive-by-wire”—is being considered for automobiles.

Since many of these sensors and actuators would be on engines or in other hot environments, it would be advantageous to operate their associated electronics in the same high-temperature environments. Envisioned temperatures are in the range +200 to +300°C.

But why not use standard electronics for the applications described above, and maintain its temperature within the conventional range by thermal control? Passive and active thermal control in the form of insulation, heat absorbers, refrigeration or heating is an alternative approach that has often been used. However, in many situations this approach may be impractical, undesirable or inefficient. Which path to follow becomes a question of trade-offs and engineering judgement—with the factor of temperature taking on greater importance and latitude. For many situations, extending the temperature range of the electronics has been the preferred path.

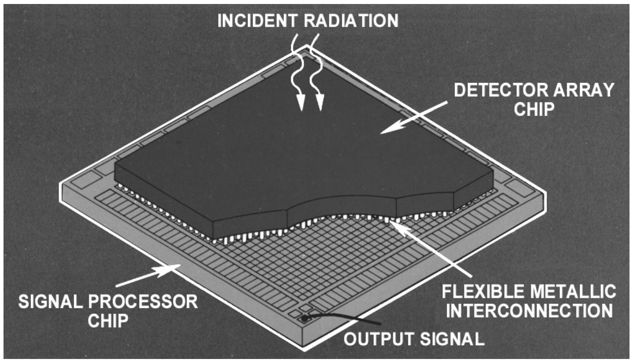

Figure 4 – Illustration of an infrared detector array and readout chip combination. The two chips are joined by bump bonds, one for each cell in the array. The operating temperature may be as low as a few K (around –270°C) (Courtesy of Boeing).

II. DESIGN FACTORS

Choosing components, designing the circuits, and assembling the electronics for low- or high-temperature instrumentation involves the following factors:

Temperature and temperature range: Will the electronics need to operate over a wide range, or only within a narrow range or at a single temperature? Extreme temperatures or wider ranges are more difficult because of the changes in semiconductor device parameters and to a lesser extent passive component parameters.

Required reliability and lifetime: These are important factors for high-temperature operation because of the generally increased rate of deterioration and aging of components. If a high level of reliability or long operating life are not needed, then implementation is easier.

Circuit complexity and integration level: Will a simple one-stage preamplifier suffice, or is an entire complex signal-processing system required? Simpler circuits can accommodate more extreme temperatures and can take advantage of more exotic technologies, such as silicon-carbide transistors. More complex systems or even moderately integrated circuits limit the choices to conventional technologies, namely silicon-based, or possibly gallium-arsenide-based, since these are the only technologies that are sufficiently mature.

Circuit type: Is the circuitry analog or digital, or a mixture? Digital circuitry is generally more tolerant of extreme temperatures and temperature variations.

Frequency range/speed: If microwave frequencies or extremely fast switching are involved, this limits the types of devices that can be used and often rules out silicon. Frequency range and speed generally degrade as temperature increases.

Power dissipation: Allowable power dissipation may be restricted because heat removal is often more difficult for extended-temperature electronics. At low temperatures the capacity of refrigeration systems may be small or excess heat may disturb the sensors. At high temperatures the thermal conductivity of materials and the efficiency of electronic components usually decrease. Conversely, the higher the power dissipation of a component, the more limited its temperature capability will be.

Electronic noise: Noise in analog circuits is frequently of concern because of the desire to extract feeble signals and obtain the best performance from sensors. True thermal noise is roughly proportional to environmental temperature, but for the frequencies involved in many instrumentation applications (below a few MHz), the relevant noise is non-thermal or "excess" noise whose behavior with temperature often cannot be predicted. Noise margins in digital circuits generally decrease as temperature increases.

Time, effort, and expense: How much can be expended on a particular application must also be considered. Does the situation warrant special devices and circuits purpose-designed and fabricated to obtain the best performance for a particular application, or must a compromise be accepted by relying on standard, readily available components?

Additional environmental stresses: In addition to the temperature, components may be exposed to acceleration, radiation, or other stresses. Such added stresses will interact with the temperature effects, often in a complex manner.

The above factors need to be considered in designing electronics for extended-temperature environments. The basic design approach is much the same as for conventional electronics but with a greater emphasis on temperature and its effects.

III. ELECTRONICS CAPABILITIES

Although it is not universal, electronic devices and circuits can be made to work over a wide range of temperatures. How far can electronics be pushed to low or high temperatures? There is no simple answer, and it depends on the factors discussed above, but some general guidelines follow.

The primary difficulties for very low-temperature operation are "freeze-out" and charge trapping, both consequences of a lack of thermal energy. On the other hand, at high temperatures, an excess of thermal energy leads to greatly increased leakage as well as physical degradation.

As with "room-temperature" electronics, "extended-temperature" electronics has nearly always been based on familiar types of semiconductor devices. These are primarily of silicon or gallium arsenide (and other III-V materials), although more advanced materials such as silicon carbide are being developed for high temperatures. The rule is that the further the temperature is from the conventional range the narrower the choice of component types.

On the low-temperature side, many conventional silicon-based semiconductor devices and circuits can operate satisfactorily down to about –200°C (about 70 K). This generally requires field-effect transistors (JFETs, MOSFETs and CMOS). In order for bipolar transistors to operate to low temperatures, heterojunction bipolars or other special types are required. Si MOSFETs (including CMOS) can operate below 70 K, but they are subject to idiosyncrasies of operation. An alternative is to switch to another material, the most common being GaAs. Devices based on GaAs or other III-V semiconductors can operate to the lowest temperatures, essentially to absolute zero (–273°C). An example of a custom low-temperature GaAs IC is shown in Figure 5 [5]. Another possible material is Ge. Operation of electronic devices to temperatures within a few degrees of absolute zero is not unusual.

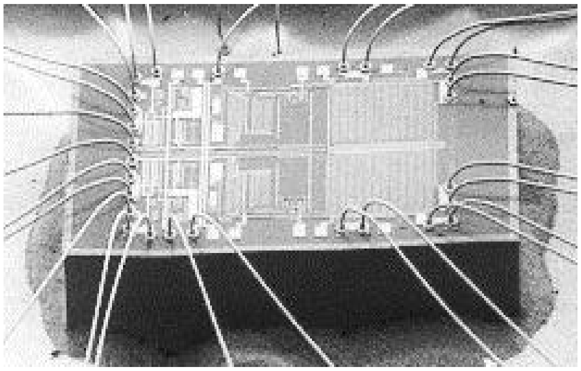

Figure 5 – A GaAs preamplifier IC for use in particle physics instrumentation. The die is 2.5 mm × 1.5 mm. This circuit can operate at temperatures down to within a few degrees of absolute zero. (Courtesy of the University of Milan.) [5]

Operating electronics to high temperatures is more difficult, and there is no natural limit to the high end of the temperature scale as there is at the low end. Some silicon-based devices can operate fairly comfortably to +300°C. For higher temperatures, devices based on GaAs and other medium-bandgap semiconductor materials could go to perhaps +500°C. Higher temperatures would require exotic large-bandgap semiconductor materials such as silicon carbide, in which only basic devices are available so far. Device operation to temperatures as high as +700°C has been reported; however, this is for a very few devices and short times in the laboratory.

Unfortunately, in practice, there is no technology base for temperatures above +300°C. This is because of limitations of the on-chip metallizations and packaging of the devices; even at 200°C, most standard devices suffer rapid degradation. Moreover, the present market forces to develop higher-temperature technology are weak.

IV. PASSIVE COMPONENTS, INTERCONNECTIONS AND PACKAGING

Semiconductor devices are the vital ingredients, but instrumentation also requires many types of additional components such as resistors, capacitors, inductors, and perhaps batteries, as well as interconnections and packaging. Fortunately, with careful selection and design, electronic components and assembly techniques can meet the extra demands of operation at low and high temperatures.

Finding passive components for extended-temperature use is not as difficult as finding active devices. The shift in their parameters with temperature will generally be an extrapolation of trends over the "conventional" range. The exceptions are components whose operation involves atomic or molecular motion, such as high-dielectric-constant ceramic capacitors, electrolytic capacitors, and batteries. Such motion is very temperature sensitive and particularly at low temperatures the properties of these components will change drastically.

At low temperatures most conventional assembly and packaging materials and techniques are useable. At the other extreme, as temperatures increase above the conventional range, there are fewer choices of materials for assembly and packaging. In both cases thermal expansion mismatches become more of an issue and materials with large thermal expansion coefficients can be troublesome.

Particularly for high temperatures, materials and techniques for assembly and packaging need to be carefully selected and many commonly used materials and techniques will not be suitable. Many plastics as well as epoxies used for component attachment cannot tolerate elevated temperatures well; likewise standard solders with melting points about +200°C cannot be used; wirebonds between dissimilar metals can cause problems. Alternatives must be adopted: ceramics, high-temperature plastics, and special solders and attachment materials.

V. PRACTICAL CONSIDERATIONS

Two approaches can be taken to obtain semiconductor devices and other components for extended-temperature electronics: (1) selection and adaptation of conventional commercial devices, or (2) purpose-designed-and-built devices.

Applications with limited resources have typically taken the first approach, relying on commercially available components even though they are nearly always specified for operation only as low as –55°C or as high as +125°C at best. Although many commercial devices do not function at very low temperatures because of their design and the physics of semiconductor materials or deteriorate rapidly at high temperatures, many requirements can be satisfied by skillful choices from among available devices and technologies. In this first approach, trial-and-error, persistence and luck play a large role in obtaining suitable components. Because of this, the second approach is preferred for critical applications that can afford it, such as military and space systems.

There is sometimes a third approach: using commercially available components that are specified for extended-temperature use. However, such components are rare. Few manufacturers wish to address this development-intensive and so far limited market.

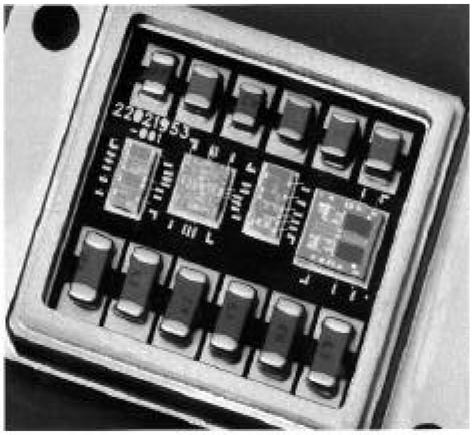

Figure 6 – A sensor interface circuit specified for several years operation at 225°C. It includes two silicon-on-insulator ICs, two resistor chips and 12 capacitors. (Courtesy of Honeywell Solid State Electronics Center.) [6]

For low temperatures there are very few components available commercially; these usually use standard parts selected for low-temperature use. Fortunately, as described earlier, is it easier to find standard components that will work down to very low temperatures.

For high temperatures there is a limited selection of commercially available active components, all silicon-based, for the +200°C to +300°C range. An example is the 225°C MCM in Figure 6, developed for a jet aircraft engine [6]. Some passive components for high temperatures are likewise available commercially. For anything more, one must adapt or develop one's own components and technology.

VI. SUPERCONDUCTOR ELECTRONICS?

With few exceptions, low-temperature electronics has so far been based on semiconductor devices rather than superconductor devices. This is because of the much more advanced state of development and broad technology base of semiconductor electronics, as well as its ability to operate over a much wider temperature range.

However, in recent years superconductor-based circuits have evolved to the point that they are available for instrumentation, specifically preamplification. An example of a commercial circuit, a preamplifier, is shown in Figure 7 [7].

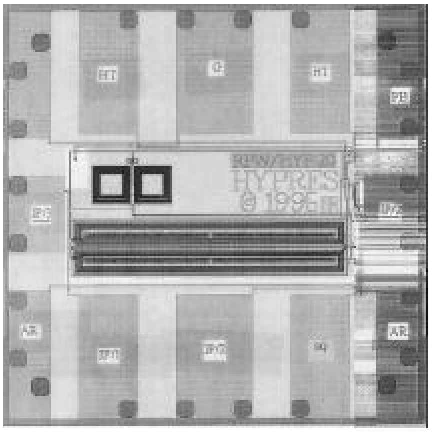

Figure 7 – A preamplifier based on superconductors and Josephson junctions. This die is 5 mm × 5 mm and operates at about 5 K (–268°C). (Courtesy of Hypres, Inc.) [7]

Superconductor-based preamplifiers are the most sensitive available, and are suited to low-impedance (current) output sensors. On the other hand, operation of these circuits is more complicated than that of semiconductor preamplifiers and their operation cannot be "checked" at ordinary (or even low) temperatures. Since they use "low-temperature" superconductor materials they must be cooled to around 5 K (–268°C). Although there are materials that are superconductors to over 120 K (–153°C) electronic devices based on them are still in a rudimentary state.

VII. SUMMARY/CONCLUSION

As sensor technology becomes more widely used, there is every reason to expect increased use of sensors at low and high temperatures considerably beyond the customary range. Often, co-locating some interface electronics in the same environment can improve performance and simplify design of the overall system. With care in their design and implementation, electronic components and circuits can operate down to a few degrees above absolute zero (–273°C) or up to +300°C. Such "extended-temperature" electronics has been successfully used with sensors of many types in a variety of practical instrumentation situations at both low and high temperatures.

There is a great deal more to the subject of extended-temperature electronics than can be covered in this tutorial—resources for further information are given below.

VIII. FOR FURTHER INFORMATION

Low-temperature electronics: There is a book on this subject, although it is dated:

> R. K. Kirschman, ed., *Low-Temperature Electronics*, IEEE Press, 1986.

Another book on this subject is expected shortly from IEEE Press.

The Electrochemical Society has held a Symposium on this subject as part of its spring of fall meeting in odd years, and WOLTE (European Workshop on Low Temperature Electronics) has been held in Europe in even years since 1994. Proceedings from the former appear as *Electrochemical Society Proceedings* vols. 88-9, 91-14, 93-22, 95-9 and 97-2 (no proceedings for the 1999 Symposium); proceedings from the latter appear as *Journal de Physique* vol. 4, col. 6, Suppl. JP III, no. 6, and vol. 6, col. 3, Suppl. JP III, no. 4, and *Journal de Physique IV* vol. 8, Pr3.

High-temperature electronics: There are three recent books on this subject:

> R. K. Kirschman, ed., *High-Temperature Electronics*, IEEE Press, 1998.

F. P. McCluskey, R. Grzybowski and T. Podlesak, eds., *High Temperature Electronics*, CRC Press: Boca Raton, 1997.

M. Willander and H. L. Hartnagel, eds., *High Temperature Electronics*, London: Chapman & Hall, 1997.

Two principal organizations are

The (European) High Temperature Electronics Network of Excellence (HITEN):

HITEN
Building 552
AEA Technology
Didcot, Oxfordshire
United Kingdom OX11 0RA
Tel: +44-1235-435541, Fax: +44-1235-432697
http://www.hiten.com

The CALCE Electronic Packaging Research Center (EPRC):

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http://www.calce.umd.edu

HITEN generally holds a meeting in Europe in odd years and there has been a HiTEC (High Temperature Electronics Conference) in the USA in even years. Proceedings from a number of these meetings and others have appeared as separate publications. For details see my book, Part I - Introduction, Table 2 (page 7).

General: There was a Conference on Electronics for Extreme Environments, covering both low and high temperatures, organized by JPL in February 1999 (http://extremeelectronics.jpl.nasa.gov/conference/main.html).

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Also http://nmp.jpl.nasa.gov/ds2/

[3] http://www.linearmeasurements.com/

[4] (Astro-E mission) http://lheawww.gsfc.nasa.gov/docs/xray/astroe/ae/fea.html

[5] G. Battistoni, D. V. Camin, N. Fedyakin, G. Pessina, M. Sironi, "Cryogenic performance of monolithic MESFET preamplifiers for LAr calorimetry," *Nuclear Instruments & Methods in Physics Research A*, vol.A395, no.1, pp.134-140, 1 Aug. 1997.

[6] http://www.ssec.honeywell.com/products/hightemp_index.html

[7] http://www.hypres.com/squidamp.html

THE INSTRUCTOR

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