CrossMark

REVIEW

A review of high-temperature electronics technology and applications

Jeff Watson[1] · Gustavo Castro[1]

Abstract Electronics that must operate at extreme temperatures present a unique set of challenges that must be carefully addressed. We review the applications that are calling for high temperature electronics, discuss some of the underlying problems with standard technology, and examine the established and emerging technologies that provide solutions to engineers who wish to design high-temperature electronic systems.

1 Introduction

Many industries are calling for electronics that can operate reliably in harsh environments, including extremely high temperatures. Traditionally, engineers had to rely on active or passive cooling when designing electronics that must function outside of normal temperature ranges, but in some applications, cooling may not be possible—or it may be more appealing for the electronics to operate hot to improve system reliability or reduce cost. Operating electronic components above their specified temperature range presents challenges that affect many aspects of the electronic system, including the semiconductor devices, packaging, qualification methodology, and design techniques. In this paper we will review the applications that require high temperature electronics and the state-of-the-art technology that enable these systems, with a focus on semiconductor devices and the supporting system components.

✉ Jeff Watson
jeffrey.watson@analog.com

Gustavo Castro
gustavo.castro@analog.com

[1] Analog Devices, Inc., Wilmington, MA, USA

The definition of "high temperature" can vary widely. For this discussion we will define high temperature, or "HT", as *ambient* temperatures >150 °C. We choose ambient rather than junction because for the majority of these systems the dominant heat source is from the environment rather than from self-heating, and therefore we see the negative effects even on small signal devices. However, for systems with high power dissipation or very dense packing we must, of course, take into account the self-heating effects added to the ambient temperature. We choose 150 °C as our reference because that is a typical inflection point where performance degradation, assembly methods and device reliability force us to use methods different from the industry norm for standard temperature electronics. On the high end of the scale, we will learn that commercially available components (rated for operation at elevated temperature) are in the range of 210–225 °C maximum. For this reason we will focus on the enabling technologies in this temperature range but also touch on the emerging technologies that may allow us to push beyond this limit in the future.

The field of HT electronics is not new, there has been work in the field for the past several decades. A similar review paper from over 20 years ago [1] summarizes many of the same challenges we still face today in the industry and makes an important point: operating electronics at high temperature cannot be solved by any one component of the system, it is a whole system problem. The passive components, circuit board, solder, connector, battery, etc. need to be robust or it will severely limit the market for such systems. 20 years ago there were extremely few commercially available solutions to these problems. However, today there is an increasing focus on HT systems and, while it is still a niche market by most standards, there are many more options available for designers in high-temperature applications.

2 Applications

HT electronics tend to be used in applications where cooling is not practical or there is some other motivation for the electronics to operate in the hot environment, such as improved system reliability or better efficiency in the form of decreased size, weight or power [2]. Some of these applications have been driving the need for HT electronics for years, and other are emerging as the HT technology becomes commercially available.

The oldest user of high-temperature electronics is the down-hole oil and gas industry. In this application, the operating temperature is a function of the underground depth of the well. Worldwide, the typical geothermal gradient is 25 °C/km depth, but in some areas, it is greater. In the past, drilling operations have reached their limit at temperatures of 150–175 °C, but advancing technology has made it feasible for the oil industry to drill deeper, as well as in regions of the world with a higher geothermal gradient. Temperatures in these hostile wells can exceed 200 °C, with pressures >25 kpsi. Active cooling is not efficient in this harsh environment, and passive cooling techniques are not effective when the heating is not confined to the electronics. The applications for high-temperature electronics in the downhole industry can be quite complex. First, during a drilling operation, electronics and sensors steer the drilling equipment and monitor its health. With the advent of directional drilling technology, high-performance geosteering instrumentation must guide the borehole path to an exact geologic target. While drilling, or soon thereafter, sophisticated downhole instruments acquire data about the surrounding geologic formations. This practice, known as well logging, measures resistivity, radioactivity, acoustic travel time, magnetic resonance, and other properties to determine characteristics of the formation, such as lithology, porosity, permeability, and water/hydrocarbon saturation. This data allows the geologist to make judgments about the types of rock in the formation, the types of fluids present and their location, and whether adequate amounts of hydrocarbons can actually be extracted from fluid-bearing zones. Finally, during the completion and production phases, electronic systems monitor pressure, temperature, vibration, and multiphase flow—and actively control valves. Meeting these needs requires a complete signal chain of high-performance components (Fig. 1). System reliability is of utmost importance, as the cost of downtime due to equipment failure can be quite severe. For example, by some estimates a failed electronics assembly on a drill string operating miles underground can take more than a day to retrieve and replace—and the rate for operating a complex deep-water offshore rig can be as high as $1M per day.
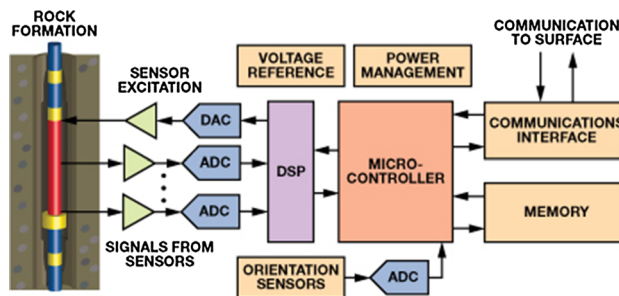

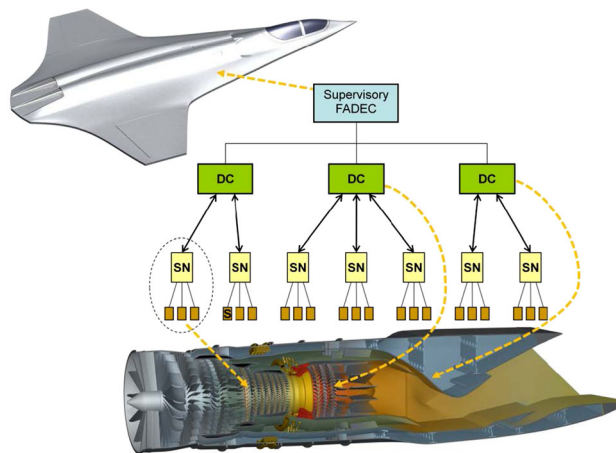Fig. 1 Typical downhole tool signal chain

Fig. 2 Avionics distributed engine control architecture [5]

Another application driving HT electronics is avionics and aerospace. In this industry engine monitoring and control is traditionally a centralized architecture managed by a computer system called a Full Authority Digital Engine Controller (FADEC). There are many sensors and actuators in close proximity to the hot engine, all of which must be hard-wired to the FADEC with long, heavy wire harnesses with hundreds of conductors and multiple connector interfaces. Moving to a distributed control scheme places the engine controls closer to the engine (Fig. 2), reducing the complexity of the interconnections by a factor of 10, saving hundreds of pounds of aircraft weight [3] and increasing the reliability of the system (estimated in part as a function of connector pin count per MIL-HDBK-217F [4]). One of the proposed distributed architectures being evaluated by an industry working group has sensors and actuators connected to smart nodes in close proximity to the engine. Within the smart node the sensor signal conditioning and simple processing occurs, allowing data to be transmitted on a shared digital data bus back to a simplified FADEC computer. This has the benefits of dramatically reducing the complexity of the wire harness, simplifying maintenance of the engine, and easing adoption of new sensor technology in the industry. However, such smart nodes require the sensor/actuator and signal conditioning electronics to be co-located in the hot

environment, thus fueling the demand for HT electronics. Although electronics can be cooled in this application, it is undesirable for two reasons: cooling adds cost and weight to the aircraft, and, most importantly, failure of the cooling system could lead to failure of the electronics that control critical systems.

In addition to engine monitoring, there is a desire to put sensors and instrumentation on other hot areas of the aircraft, such as landing gear and braking systems. Also, the trend toward more electric aircraft calls for a replacement of hydraulic, pneumatic and mechanical systems with electronics. These electronics may need to be in high ambient temperature sections of the craft or require densely packed power electronics [6]. If these power electronics could run without cooling it would significantly simplify the environmental control system (ECS), improve reliability and decrease weight.

The automotive industry provides another emerging application for use of high-temperature electronics. As with avionics, the auto industry is migrating from purely mechanical and hydraulic systems to electromechanical or mechatronic systems [7]. This requires locating sensors, signal conditioning, and control electronics closer to heat sources. For example [8] describes a mechatronic system consisting of a transmission controller co-located on the mechanical transmission assembly that must operate at 150 °C ambient. There are other potential HT electronics applications under the hood, on wheel sensors, and in the exhaust, as shown in Fig. 3.

3 Limitations of standard devices at high temperatures

The negative effects of increased temperature on both the performance and reliability of semiconductor devices are well understood and documented [1]. Some of the most important and ubiquitous are listed below in Table 1.
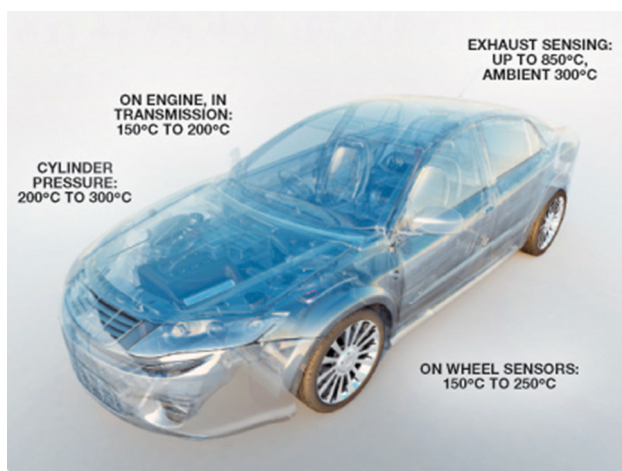

Fig. 3 Typical automotive temperature ranges for HT electronics [8]

Table 1 Primary limiting physical effects of semiconductor device performance and reliability at elevated temperature

1. Increasing intrinsic carrier density (doping becomes ineffective)
2. Exponentially increasing junction leakage current (degrades performance, increases power consumption)
3. Increased electromigration in conductors (lower reliability, shorter lifetime)
4. Decreased dielectric breakdown strengths
5. Mechanical stress due to coefficient of thermal expansion (CTE) mismatch
6. Variation in device parameters

The temperature dependence of semiconductor device parameters have a profound effect in the operation of semiconductor devices. For example, with higher thermal excitation there is a decrease in carrier mobility and velocity saturation due to increased scattering [9]. Lower mobility reduces the base transport in bipolar transistors, thus lowering the current gain (beta). For short-channel CMOS devices that operate in velocity saturation regimes, lower velocity saturation translates directly into lower transconductance. Therefore, it is crucial to manage semiconductor doping levels and other key device characteristics for successful, high-performance operation at elevated temperatures. Unfortunately, simulation models for most processes deviate from reality at extreme temperatures, thus making it difficult for IC designers to take these variations into account.

Despite these limitations, in the past high-temperature electronics designers were compelled to use standard-temperature components well above their rated specification due to the unavailability of high-temperature rated ICs. This process is sometimes called 'up-rating' or 'self-certifying' [10]. Some standard-temperature components, including ICs, will indeed work at elevated temperatures, but it is an arduous and risky endeavor to use them. For example, engineers must identify potential candidates, completely test and characterize performance over temperature, and qualify the reliability of the part over a long period of time. Performance and lifetime of the part are often substantially derated. This is a challenging, expensive, and time-consuming process, for a multitude of reasons:

1. Qualifying components requires testing in a lab oven with a high-temperature printed-circuit board (PCB) and fixtures, for at least as long as the mission profile requires. It is difficult to accelerate testing because new failure mechanisms may be encountered. Failures during testing require another iteration of component selection and long-term test, delaying project timelines.
2. Operation outside of data sheet specifications is not guaranteed, and performance may vary between

component lots. In particular, semiconductor process shifts can result in unexpected failures at temperature extremes. Moreover, plastic packages are only robust up to about 175 °C—with a specialized material set and reduced operating life. Near this temperature limit, it can be difficult to distinguish between a packaging-related failure and silicon-related failure without costly and time-consuming laboratory failure analysis.

3. Availability of standard components in hermetic packages, which tend not to degrade as much at high temperature, are scarce in today's market. In addition, components used in harsh environments often must survive not only high temperature but also severe shock and vibration. Many engineers prefer to use packages with leads, such as a DIP or a gull-wing SMT, because they provide a more robust attachment to the PCB and give more compliance to the solder joint over temperature cycling. This further limits device selection, as other industries trend toward smaller, leadless packages.

4. For custom packaging solutions it is desirable to obtain parts in die form, especially if a component is otherwise only available in a plastic package. The die can then be repackaged in a high-temperature compliant hermetic package or multichip module. However, of the few components that will work at elevated temperature, yet a smaller subset is readily available as tested dice.

5. Due to time constraints and test-equipment limitations, engineers in the industry may tend to restrict qualification of a device to a specific application circuit, without covering all key device parameters, thus limiting component reuse for other projects without further testing.

6. Key device properties for reliable HT operation, such as current density in metal interconnects, are not normally specified in the datasheet.

It is then clear that with the inherent limitations in standard silicon, and the challenges in trying to work around them, there is a great need for electronics that are designed with high temperature operation in mind and leverage circuit design, fabrication process, and package assembly techniques to yield high performance and reliability. Fortunately, in recent years there has been much work in this area and we are now seeing an increasing number of commercial off-the-shelf components designed and rated for HT operation.

4 Process technology for HT

One of the most fundamental requirements to manufacture robust integrated circuits is an adequate semiconductor manufacturing process that can guarantee consistent
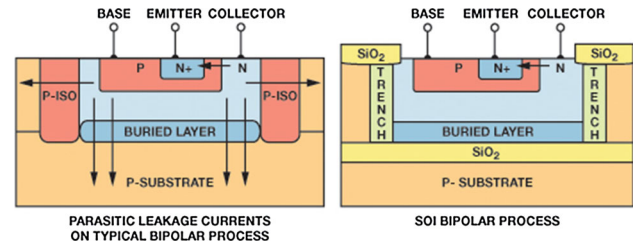

Fig. 4 Junction leakage mechanisms in bulk silicon and SOI compared

operation of semiconductor devices over wide temperature ranges. Fortunately, the same advances in semiconductor fabrication that have increased density, speed, and power efficiency, have also produced devices that can operate reliably at elevated temperatures.

One of the most important and well-known challenges in ICs is posed by increased substrate leakage due to lowering of semiconductor band-gap energy as temperature increases [11]. To provide electrical isolation between multiple transistors, traditional fabrication processes rely solely on junction isolation. This technique consists in biasing the substrate and the field region (area between active regions or transistors) with the lowest potential available on the IC. The result is the equivalent of having multiple reversed-bias diodes, which double their leakage current for every 10 °C increase in temperature. Although ICs fabricated with this standard silicon process can operate well beyond the military requirement of 125 °C [12], this fundamental leakage becomes unacceptable for many precision applications. The leakage paths are shown schematically on the left panel of Fig. 4.

Trench isolation, silicon-on-insulator (SOI), and other variations on the standard silicon process can greatly decrease leakage and enable high-performance operation to well above 200 °C. The right panel on Fig. 4 illustrates how a SOI bipolar process reduces the leakage area by adding an insulating layer of SiO_2 around the substrate. There are other SOI processes that have been proven for HT operation based on CMOS in the marketplace. Some also use alternative interconnect metallization such as tungsten due to its higher electromigration activation energy, but at the expense of much higher resistance and a tendency for corrosion. Ohmic contacts between metal interconnects and silicon are also a potential failure point at high temperature which is typically prevented with a diffusion barrier layer [13].

SOI is an attractive solution because it helps solve the leakage problems and leverages existing, mature process technologies. However, it does not solve some of the other fundamental limitations of Si and therefore device operation will be inherently limited to lower than 300 °C. New semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN) hold much promise for high
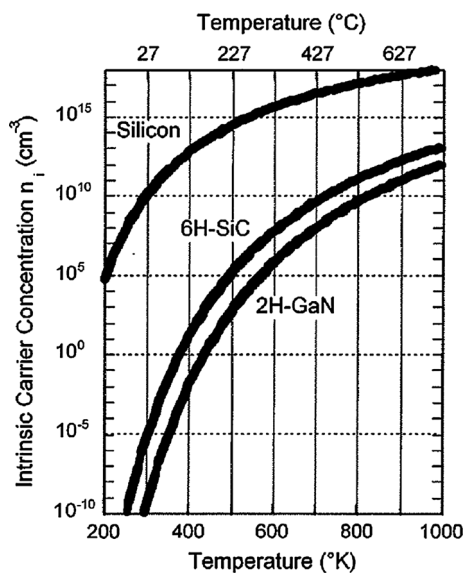
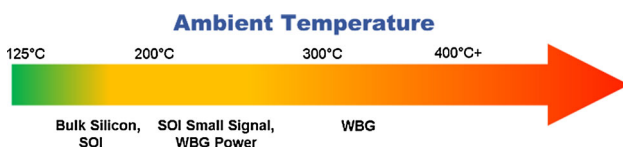Fig. 5 Intrinsic carrier density in Si, SiC and GaN versus temperature [16]

Fig. 6 Semiconductor device and process type versus temperature

temperature operation because they are "wide-bandgap" (WBG) semiconductors, i.e. having a much larger bandgap energy than silicon. These materials inherently have a lower intrinsic carrier density (as shown in Fig. 5) and thus the effects of leakage are orders of magnitudes less. Lab demonstrations have shown simple devices and ICs operating above 500 °C for short periods of time. For example, [14] describes the characterization of SiC MOSFET devices to 650 °C, and [15] describes the operation of SiC JFETs and simple circuits for thousands of hours. However, unlike silicon, fabrication processes based on these materials are relatively new and commercialization is being driven by simple devices leveraging large-volume applications such as power switches and LEDs in standard temperature ranges. Work is ongoing to optimize performance for HT applications and increase device count and performance to make viable higher-integration devices.

As we look to the future, it is clear that both SOI and WBG semiconductors will play a role. The component types fabricated on the different process technologies will largely depend on the temperature range where they will be used and the self-heating of the device. A possible, rough division of these regions is shown in Fig. 6, where we have bulk silicon and some SOI used up to 150–175 °C, SOI
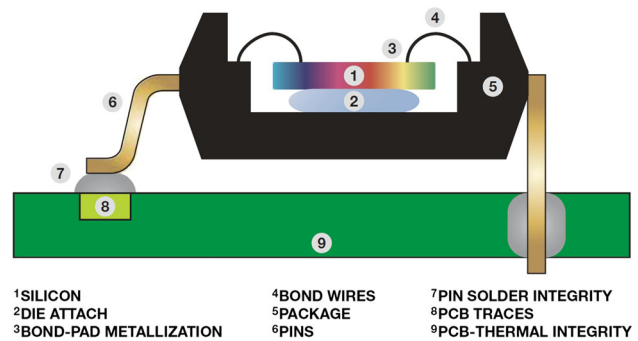

Fig. 7 Elements of IC packaging and mounting

small signal and WBG power used between 175 and 300 °C, and WBG exclusively used above 300 °C.

5 High temperature packaging considerations

Once high-temperature functional semiconductor devices are in hand, the battle is only half won. Packaging the die, and then attaching the package to the PCB, is not trivial at high temperatures. Many factors affect package integrity at temperature (Fig. 7).

The die-attach material secures the silicon to the package or substrate. Many materials proven for use in standard temperature ranges have a low glass transition temperature (T_G) and are not suitable for high-temperature operation. Particular attention needs to be paid to matching the coefficient of thermal expansion (CTE) between the die, die-attach, and substrate—so that the die is not stressed or fractured over cycles of wide temperature span. Even slight mechanical stress on the die can cause electrical parameters to shift to unacceptable levels for precision applications. For power devices that require good thermal and electrical connection to the package substrate, metallic die-attach materials may be necessary, such as hard solders or sintered silver. Specialized die coatings can help to provide a buffer from mechanical stress and also improve the thermal conductivity. For instance gel coatings can help absorb stress induced from CTE mismatch, and specialized coatings can improve thermal transport to the package so that the die temperature stays closer to ambient.

When considering wire bond reliability at elevated temperatures, the compatibility of the metals used for the wire and bond-pad metallization is of major concern. Failures related to poor compatibility of bonding metals are twofold: intermetallic compound (IMC) growth at the interface, which creates a brittle bond; and diffusion (Kirkendall effect), which creates voids at the interface, weakening the bond's strength and increasing its resistance. Unfortunately, one of the most popular metal combinations in industry—gold wire and aluminum bond-pad
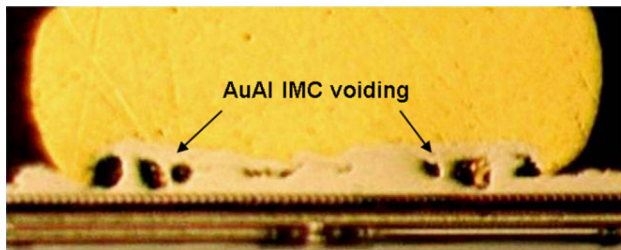
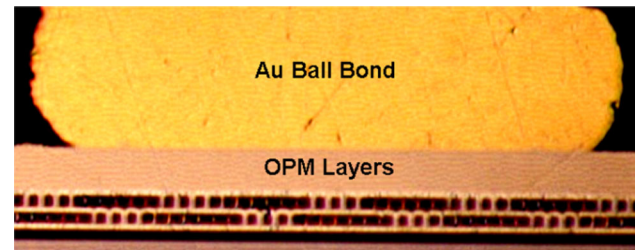Fig. 8 Au ball bond on Al pad, post 500 h at 195 °C

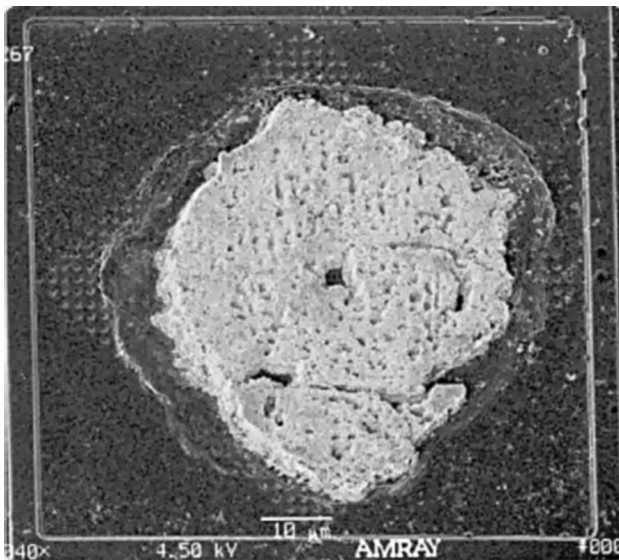Fig. 10 Au ball bond on OPM post 6000 h at 195 °C (No IMC) [2]

Fig. 9 Intermetallic growth with voids [2]

metallization—is prone to these phenomena at elevated temperatures. Figure 8, a section through an Au/Al bond, shows IMC growth, which is compromising bond integrity after 500 h at high temperature (references for Figs. 8, 9, 10 added).

Figure 9 shows substantial Au/Al intermetallic growth and Kirkendall voids after bond failure at high temperature. To make matters worse, halogens such as bromine and chlorine—sometimes found in molding compounds—can cause corrosion at the boundary interface at elevated temperature, accelerating the time to failure (although fortunately, the industry is shifting to "green" halogen-free molding compounds).

Thus, there is a strong incentive to use the same metal for the bond wire and bond pad (a monometallic bond) to avoid these negative effects. An option for Au/Al systems is to use an over pad metallization process (OPM), a stack-up of barrier metals, to create a gold pad surface for the gold bond wire. This monometallic interface has shown to not form IMCs after over 6000 h at 195 °C, as shown in Fig. 10. If it is not possible to have a monometallic system, engineers should select metals that have slow enough IMC growth and diffusion rates to be reliable over the required lifetime.

The IC package must also withstand stresses imposed by harsh environments. Plastic packages, although the industry standard, have historically only been rated to 150 °C for sustained use. With recent interest in high-temperature applications, investigations have shown that this rating can stretch to 175 °C but only for relatively short durations and with a specialized bill of materials. Depending on package construction, 175 °C is the point at which some materials, such as the molding compound, exceed the glass-transition temperature. Operating above T_G can cause significant mechanical changes in key parameters, such as CTE and flexural modulus, and lead to failures such as delamination and cracking from the increased thermal strain [17].

For this reason, hermetic ceramic packages are often preferred for high-temperature applications. The hermetic seal provides a barrier to the moisture and contamination ingresses that cause corrosion. Unfortunately, hermetic packages are normally larger, heavier, and significantly more expensive than their plastic counterparts. In applications with less extreme temperature requirements (<175 °C), plastic packages may be preferred to conserve PCB area, reduce cost, or provide better vibration compliance. For systems requiring hermetic packaging and high component density, high-temperature multichip modules (MCM) may be an appropriate solution, and there are many MCM solutions that have been proven robust up to 300 °C.

Package lead configuration and metallization must also be evaluated. Surface-mount components depend solely on the bond pad area and quality of the adhesive between the copper layer and the pre-impregnated material (pre-preg). On the other hand, the through-hole DIP configuration, one of the most proven and reliable packages in industry, provides robust shock and vibration performance. In extreme cases, attachment strength can be improved further by bending the pins on the bottom side of the board to "staple" it to the PCB, but the through-hole pinout does not allow component population of the bottom side of the board—possibly a major concern for applications such as downhole instruments, which have tight space constraints.

Gull-wing SMT lead configuration is a viable alternative in many cases, but leadless SMT may not be robust enough under high shock and vibration conditions encountered in

many high temperature environments. When using SMT components, the designer should consider their height and mass. The application of high-temperature epoxies will improve attachment robustness but increase manufacturing costs and limit the ability to perform repairs. A longer, bent lead also provides compliance to the joint and can help to alleviate stress from temperature cycles. In all cases, the lead metallization must be compatible with high-temperature solders.

Traditionally, the most popular standard solder alloys have melting points below 200 °C. This has changed recently with the introduction of newer lead free solders, many of which have melting points in the 210–220 °C range. For high temp ranges, there are some readily available alloys that fall within the category of "high melting point" (HMP), with melting points well above 250 °C. Even in such cases, the maximum recommended operating temperature for any solder subjected to stress is about 40 °C below its melting point. For example, the standard HMP solder alloy composition of 5 % tin, 93.5 % lead, and 1.5 % silver has a melting point of 294 °C but is recommended for use only up to about 255 °C.

Finally, the PCB itself is a potential source of failure. Standard FR4 reaches glass transition anywhere from 130 to 180 °C, depending on the specific composition. If used above this temperature—for even short time durations—it can expand and delaminate. A good proven alternative is polyimide, the same material used in Kapton, which has TG as high as 250 °C, depending on composition. However, polyimide suffers from very high moisture absorption, which can quickly lead to failure of the PCB by a variety of mechanisms, so it is important to control moisture exposure. In recent years, industry has introduced exotic laminates that absorb less moisture and maintain integrity at high temperatures. It is well known in industry that there are interactions between the surface finish of the PCB metallization and lead finish of the component that can cause poor reliability, such as gold embrittlement. The effects of these interactions are almost always exacerbated at high temperatures, so it is important to choose these materials according to industry best practices. Substrates used in MCMs are typically ceramic or other materials that closely match the CTE of the attached devices, such as AlN for SiC.

6 Passive components

Over the last few years, there have been several advances around passive components for high reliability and high-temperature operation. There have been numerous studies on the performance of existing materials and standard components at high temperature and for extended periods of time [18]. While temperature dependence is the first concern, understanding long-term parametric shift is key to ensure reliability and accuracy over lifetime. Published results have motivated the development of new technologies and optimization strategies for high reliability.

6.1 Capacitors

In many electronic systems, capacitors tend to be the least reliable of all the passive components. Because they are essential in power conversion, bypassing, filtering, signal coupling, and in many other applications, they also are ubiquitous. Standard ceramic capacitors such as X7R experience dramatic drops in their capacitance value, typically in the order of 50 % at 200 °C [19]. This makes them unsuitable in most signal processing applications. In contrast, C0G/NP0 capacitors maintain their more or less linear temperature coefficient of 30 ppm/°C up to 250 °C. Nonetheless, insulation resistance normally drops by several orders of magnitude for both ceramic types. Designers of high-temperature equipment need to take this into consideration, and make the proper selection.

Moreover, multi-layer ceramic capacitors (MLCC) that operate in conditions of shock and vibration, are more prone to cracks that can result in catastrophic failure. Surface mount MLCCs are available for temperatures to 250 °C and beyond. Nonetheless, through-hole components such as radial molded ceramic components are also available to help alleviate the stress created by these conditions. In addition, some studies presented by capacitor manufacturers [20], C0G capacitors exhibit a modulus of rupture that is more than twice that of X7R capacitors, thereby increasing system reliability.

New materials and fabrication technologies are emerging to provide options beyond traditional ceramic dielectrics, such as silicon capacitors. While still in early stages, these devices exhibit promising characteristics up to 250 °C [19].

In applications that require higher capacitance density, tantalum capacitors are also available for high temperature operation, and modern advances have made them available in hermetic packages that reach as high as 230 °C. However, as with most tantalum capacitors, the working voltage must be derated by as much as 80 % to achieve high reliability at extreme temperatures. Just as there has been steady advances in semiconductor technology for extreme temperature, so has there been for capacitors. Table 2 summarizes commercially available capacitor types by maximum temperature.

6.2 Resistors

Resistors are fundamental components in the design of electronic circuits, where they perform numerous different functions, such as protection, ballasting, current sensing,

Table 2 Commercially available HT capacitor technologies

Construction	Max temp (°C)	Common package	Comments
MLCC (ceramic) C0G/NP0	260	SMT-chip, stacked gull-wing, encapsulated through-hole	Low TC, recommended for signal processing
MLCC (ceramic) X7R	260	SMT-chip, stacked gull-wing, encapsulated through-hole	Higher capacitance density than COG/NP0 but poor stability above 175 °C
Electrolytic wet tantalum	200	Axial through-hole	High capacitance values, mostly through-hole
Solid tantalum	230	SMT and through-hole	High capacitance values. Derate voltage by 60–80 % at maximum temperature

Table 3 Commercially available HT resistor technologies

Construction	Max temp (°C)	Common package	Comments
Wire-wound	350	Through-hole	High surge capability, precision power
Metal foil	240	Through-hole, SMD-chip, flip-chip	High precision
Metal oxide	275	Through-hole	General purpose, power resistors, better frequency characteristics than wire-wound
Thick film	300	SMD-chip, flip-chip	General purpose, wide resistance range
Thin film	275	SMD-chip, flip-chip	Compact, low TC, high stability, resistor arrays available

feedback, signal attenuation, etc. As with other components in high-temperature applications, reliability is extremely important, but for signal processing, precision resistors are required to be both reliable and stable over time and temperature. Resistor manufacturers have been pushing the load life tests to 2000 h at the rated operating temperature, and making new developments to improve package reliability and resistance value stability over time. Table 3 summarizes resistor types currently available for very high temperatures.

Very often, resistors used in the signal path, together with the voltage reference, are the main contributors to gain uncertainty. Moreover, in many high-temperature applications, calibration is not an option throughout the life of the instruments. Therefore, their thermal and life stability have a direct impact on system accuracy over wide temperature ranges and long operation cycles. For this reason, it is important to consider parametric shifts to ensure that the circuit tolerance at end-of-life remains within acceptable levels.

Thin-film chip resistors, such as those based on deposited Ni–Cr alloys, are widely popular for being relatively economical, small size, and having good performance. Many of these are also available for high temperature operation, and are appropriate for moderate precision applications where they are not exposed to overload conditions. In contrast, thick-film resistors are more reliable upon overload conditions [21], but their stability is inferior and they generate excess noise. They are good general purpose devices but generally not recommended for precision applications.

Thanks to their construction, metal foil resistors offer high reliability and precision in harsh conditions, surpassing thin film based resistors. They also tend to be larger and more expensive, so their application is sometimes limited to key areas. These devices are also available as bondable chip for 240 °C operation in aluminum and gold bond wire options.

Some circuits such as differential amplifiers and gain/attenuation networks, demand well-matched resistors with low tracking temperature coefficients. The best way to ensure matching and tracking is by employing resistor arrays and networks.

6.3 Inductors and transformers

Magnetic components also face challenges and new failure modes at high temperature. Many ferrite materials have Curie temperatures below 200 °C. Above their Curie temperature, the commonly used soft-magnetic cores become paramagnetic, and inductors and transformers built with these materials lose their magnetic properties. Moreover, many of these components tend to be used in power conversion applications, where core and IR losses further increase their temperature, and thermal dissipation is limited. For these reasons, ferrite materials need to have high Curie temperatures for harsh environments. Ferrites with Curie temperatures of 350 °C have been developed [22] and devices that can operate reliably up to 250 °C are commercially available.

There are mechanical aspects that limit the reliability of standard magnetic components at high temperatures, such as plastic bobbins and their wire wound construction. Modern developments such as low temperature co-fired ceramic (LTCC) ferrites overcome some of these challenges by integrating the solenoids into the magnetic material, and eliminating the need for a separate bobbin and additional soldered windings.

7 Testing and reliability qualification

Verification of high-temperature components in the laboratory is not a trivial task, as it requires engineers to incorporate all the aforementioned techniques to test performance at temperature extremes. In addition to using special materials in the construction of the test fixture, test engineers must operate the environmental chambers carefully, allowing the system to adjust to the required temperature changes. Due to the mismatch in expansion coefficients, fast temperature changes can result in damage to the solder joints on the PC board, warping, and ultimately, premature system failure. A guideline employed in the industry is to maintain the temperature rate of change below 3 °C/min.

To accelerate testing of life and reliability, an accepted practice for electronic components is to perform the tests at a stress temperature T_s above the expected operating temperature during use T_a. This introduces an acceleration factor, α, defined by the Arrhenius equation:

$$\alpha = \frac{E_a}{e^k}\left(\frac{1}{T_a} - \frac{1}{T_s}\right)$$

where E_a is the activation energy, k is the Boltzmann's constant. The acceleration factor introduced by the difference between the stress temperature and the use temperature reduces the duration of life and reliability tests to a few weeks or months, which would otherwise take several years. Although accelerated life testing works well for standard temperature ranges, the acceleration factor goes to unity when the intended operating temperature is near the rated temperature. It is not possible to increase the stress temperature very far above the rated temperature because this may introduce new failure mechanisms and yield inaccurate results. This phenomenon is problematic for HT systems where there is little headroom to increase the stress temperature due to the breakdown of other pieces of the system. Statistical techniques for increasing the success rate of life prediction include accurately oversizing the test sample to add a margin of error for premature system failures not caused by a DUT (device under test) failure. In all cases, a good understanding of the mission profile of the specific application is necessary to ensure that the test regime is appropriate.

8 Summary

Many applications, both established and emerging, require components that function in very high-temperature environments. In the past, it was challenging to design such systems reliably due to the lack of devices rated for these kinds of harsh environments. Now, discrete semiconductor devices, ICs, and supporting components designed and qualified to operate in these environments are available, saving engineering time and lowering the risk of failure. Leveraging this new technology and following high-temperature design practices will enable high-performance systems to operate reliably in even more extreme environments than were previously feasible.

References

1. P. Dreike, D. Fleetwood, D. King, D. Sprauer, T. Zipperian, An overview of high temperature electronic device technologies and potential applications. IEEE Trans. Compon. Packag. Manuf. Technol. **17**(4), 594–609 (1993)
2. J. Watson, G. Castro, High temperature electronics pose design and reliability challenges. Analog Dialogue **46**(2), 3–9 (2012)
3. R. Norman, *First High Temperature Electronics Product Survey 2005 SAND2006-1580* (Sandia National Labrotories, Albuequeque, 2006)
4. A.I. Medhi, K. Brockschmidt, A Case for High Temperature Electronics for Aerospace, in *International Conference on High Temperature Electronics (HiTEC)*, (Albuequeque, 2006)
5. A. Behbani, B. Wood, D. Bendon, A. Berner, B. Hegwood, J. Dejager, W. Rhoden, B. Ohme, J. Sloat, C. Harmon, Technology Requirements and Development for Affordable High-Temperature Distributed Engine Controls, in *58th Internatnation Instrumentation Symposium* (San Diego, 2012)
6. K. Reinhardt, M.A. Marciniak, Wide Bandgap Power Electronics for the More Electric Aircraft, in *International High Temperature Electronics Conference (HiTEC)* (Albuquerque, 1996)
7. M.A. Huque, S.K. Islam, B.J. Blalock, C. Su, R. Vijayaraghavan, L.M. Tolbert, Silicon-on-Insulator Based High Temperature Electronics for Automotive Applications, in *IEEE International Symposium on Industrial Electronics* (Cambridge, 2008)
8. R. Johnson, J. Evans, P. Jacobsen, J. Thompson, M. Christopher, The changing automotive environment: high temperature electronics. IEEE Trans. Electron. Packag. Manuf. **27**(3), 164–176 (2004)
9. S.M. Sze, K. Ng, *Physics of Semiconductor Devices* (Wiley, Hoboken, 2007)
10. D. Das, M. Pecht, N. Pendse, *Rating and Uprating of Electronic Products* (CALCE EPSC Press, University of Maryland, College Park, 2004)
11. Y. Varshni, Temperature dependence of the energy gap in semiconductors. Physica **34**(1), 149–154 (1967)
12. National Research Council, *Materials for High Temperature Semiconductor Devices* (The National Academic Press, Washington DC, 1995)
13. J. Goetz, Sensors that Can Take The Heat Part 1: Opening the High Temperature Toolbox. Sensors **17**(6), 20–38 (2000)
14. J.W. Palmour, H.S. Kong, R.F. Davis, Characterization of device parameters in high-temperature metal-oxide-semiconductor field-

effect transistors in B-SiC thin films. Appl. Phys. Lett. **64**(4), 2168–2177 (1988)

15. P.G. Neudeck, D.J. Spry, L.Y. Chen, G.M. Beheim, R.S. Okojie, C.W. Chang, R.D. Meredith, T.L. Ferrier, L.J. Evans, M.J. Krasowski, N.F. Prokop, Stable electrical operation of 6H–SiC JFETs and ICs for thousands of hours at 500C. IEEE Electron Device Lett. **29**(5), 456–459 (2008)

16. P. Neudeck, R.S. Okojie, L.Y. Chen, High temperature electronics—a role for wide bandgap semiconductors? Proc. IEEE **90**(6), 1065–1076 (2002)

17. P. McCluskey, R. Grzybowski, T. Podlesak, *High Temperature Electronics* (CRC Press, New York, 1997)

18. R. Gryzbowski, High temperature passive components for commercial and military applications, in *Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference*, vol. 1, no. 1, pp. 699–704, 1997

19. C. Bunel, L. Lengignon, Silicon Capacitors with Extremely High Stability and Reliability Ideal for High Temperature Applications," in *International Conference on High Temperature Electronics (HiTEC 2012)* (Albuquerque, 2012)

20. R. Phillips, *High Temperature Ceramic Capacitors for Deep Well Applications* (CARTS International, Houston, 2013)

21. Y. Hernik, Strength and Weaknesses of Common Resistor Types. 31 May 2010. http://www.eetimes.com/document.asp?doc_id=1256482. Accessed 1-2-2015

22. J. Galipeau, G. Slama, Reliability Testing on a Multilayer Chip Inductor Fabricated from a Ferrite with 350C Curie Point, in *International Conference on High Temperature Electronics (HiTEN)* (Oxford, 2011)