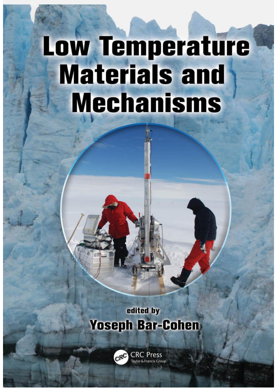

Low Temperature Materials and Mechanisms

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12

Low Temperature Electronics

Nathan Valentine and Patrick McCluskey

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12.1 Introduction to Low Temperature Environments and Applications

Low temperature technology has allowed scientists and engineers to delve into a new realm of material science and physics, advancing material capabilities and system functionality. It first received prominence during World War II when it was discovered that metals that had been subjected to extremely low temperatures were more resistant to wear.

Since that time the field of low temperature physics has expanded into many fields such as electronics where low temperatures are used to produce high-efficiency electronic systems. The present chapter is a discussion of the physics and applications of electronics subjected to low temperatures, beginning with a background discussion, followed by information on the performance of electronics at low temperatures, and finally a discussion of both device- and circuit-level packaging.

12.1.1 Definition of Low Temperature and Motivation to Study Low Temperature Electronics

There are several reasons to study the effects of low temperature on electronics. Operation at low temperatures can improve the performance of devices. At lower temperatures, there is less thermal noise and thus semiconductors with lower energy band gap can be used, thereby increasing efficiency. Another reason to operate at low temperatures is because it is necessary to integrate electronics into systems that experience these low temperatures. Finally, low temperature electronics are studied to observe and use phenomena such as the Josephson effect and superconductivity and to better understand negative effects such as charge trapping.

Military standards limit the operating temperature for conventional electronics ranges from –55°C to 125°C. The scope of this chapter is to discuss electronics and their operation at temperatures colder than this range. There are three classes of low temperature generally defined by the mechanism by which they are achieved. The first are those systems that are cooled by liquid nitrogen; thus, they are operated at temperatures of approximately 77 K (or –196°C). The second are those that are achieved by mechanical cooling and can be operated at temperatures around 20 K (or –253°C). The final are those that operate around the temperature of liquid helium, 4.2 K (or –269°C) [Kirschman, 1986]. Applications in this range are generally limited to research purposes; thus, the scope of this chapter will be focused on practical applications in extreme exploration such as polar and space, as well as cryogenic computing. These applications generally experience temperatures in the range of the first two classes.

12.1.2 Polar Exploration

Polar exploration has long been of human interest. The extreme weather conditions in the area have made it difficult and, in many instances, impossible to explore via direct-on-surface methods. The average daily temperature in August for the American Amundsen-Scott station at the South Pole is –60°C, making it difficult for exploration by humans.

Due to the increasing interest in mitigating and monitoring the effects of climate change on Earth, several organizations have been studying the polar regions. One example of a polar exploration robot is NASA's Greenland Rover or Goddard Remotely Operated Vehicle for Exploration and Research (GROVER) (Figure 12.1), used to gather snow accumulation data using a ground-penetrating radar during its 5-week, 18-mile mission [Trisca et al., 2013]. The rover was exposed to temperatures of –30°C during its mission. However, temperatures in Greenland can reach as low as –60°C; therefore, the rover had to be designed with the proper circuitry and materials to withstand these worst-case operating conditions.

Another robotic application in a polar system is the Yeti (Figure 12.2). Originally designed by engineers at Dartmouth College for operation in Greenland, Yeti is a lightweight autonomous robot outfitted with a ground-penetrating radar sensor designed to detect crevasses masked by snow [Trautmann et al., 2009]. Yeti drives ahead of convoys

FIGURE 12.1
NASA GROVER during its mission in Greenland. (Courtesy of NASA.)

FIGURE 12.2
Yeti crevasse sensing autonomous. (Courtesy of Laura E. Ray, professor of engineering at Dartmouth College and Yeti project leader.)

that deliver essential supplies to outposts in remote regions of the polar ice caps, and identifies these gorges allowing the convoys to reroute avoiding costly and potentially life-threatening situations. The original design was to withstand sustained temperatures of −40°C in up to 60 mph winds. After a successful launch in Greenland, the Yeti is now being used in Antarctica, where the conditions are harsher still [Oskin, 2013].

12.1.3 Space Exploration

Often referred to as the final frontier, space exploration and the associated technology provide a challenge to engineers, as they must design systems to operate under extreme conditions on both ends of the temperature scale. Systems studying permanently shadowed lunar regions, other moons in the solar system, and comets can be expected to experience temperatures as low as 3–90 K [Cressler and Mantooth, 2012]. In addition to ensuring functionality at extreme low temperatures, systems such as the space station and other orbiting satellites must be able to withstand a large temperature cycling range. For example, the International Space Station experiences temperatures oscillating between –157°C and 121°C [Price et al., 2001].

Satellites with infrared imagers, which will operate at low temperatures, such as the James Webb telescope (Figure 12.3), are becoming essential tools as scientists look for further knowledge of the formation of the universe following the Big Bang. James Webb is designed to have infrared sensors that operate at temperatures as low as 7 K to provide low-noise, high-resolution images [NASA, 2014a]. To achieve such temperatures, new technologies such as advanced radiation heat shielding and cryocoolers have been implemented. Other infrared telescopes have been developed such as the European Space Agency's Planck Space Observatory and Herschel Space Observatory, which are designed to operate at temperatures as low as 0.1 and 1.4 K, respectively [ESA, 2014].

Other space exploration units such as NASA's Voyager spacecraft, must also endure low temperatures [NASA, 2012]. Systems still operate on both of these craft, although, due to their distance from the sun, their power source can no longer operate subsystems such as heaters. Consequently Voyager 1, which was originally designed to operate at a temperature of –35°C, is now operating at –79°C.

12.1.4 Cryogenic Computing

While polar and space exploration technologies experience low temperatures by their inherent environmental conditions, fields such as cryogenic supercomputing exploit the more advantageous phenomena of low temperature environments to improve system performance. Current technologies use enhancements to traditional semiconductor technologies to achieve higher speeds in high-performance computing applications [Top500, 2014].

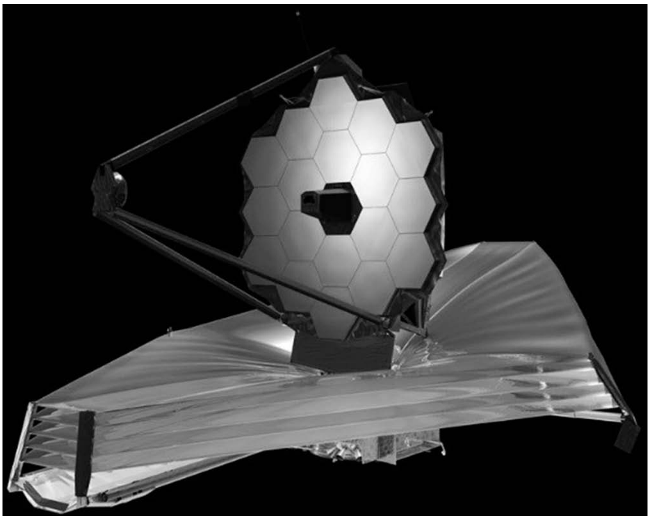

FIGURE 12.3
Artist's depiction of James Webb telescope [NASA, 2014b]. (Courtesy of NASA.)

As cryogenic technology becomes more affordable, it is expected that future supercomputers will be based on superconducting phenomena.

To achieve higher computing speeds in complementary metal-oxide semiconductor (CMOS)–based computers, a decrease in distance that the signals must travel and increased trace density are required; thus, such systems attempt to minimize the length and size of signal conductors. However, this has the adverse effect of increasing the RC delay for the system, as resistance is inversely proportional to area [Keyes et al., 1970]. At low temperatures, crystalline structures experience less lattice vibrations from thermal excitation; consequently, metals experience a decrease in resistivity when they are used at lower temperatures. Properties such as these can mitigate the increase in RC delay, thus allowing for a reduction in system size and an increase in the system speed [Keyes et al., 1970]. Decreasing the temperature also reduces thermal noise, allowing for the use of narrow band gap semiconductors, increasing system efficiency and speed. Due to their abundance and inert nature, liquid nitrogen and helium remain the most commonly used coolants in cryogenic supercomputers. One example of a cryogenic supercomputer is the ETA Systems Inc. ETA-10. This computer was first available in 1987 and was designed to operate at 90 K using liquid nitrogen in its internal cooling system [Carlson et al., 1989].

New cooling technologies are being developed to replace supercooled baths for cryogenic computers, such as quantum well on-chip cooling. Quantum well on-chip cooling has been shown to reduce chip temperature to 45 K [Anthony, 2014]. Due to the extreme costs and limited efficiency gains of cooling traditional CMOS systems, the Intelligence Advanced Research Projects Agency started a 5-year program called Cryogenic Computing Complexity designed to research superconducting technologies for use in supercomputers. Such a technology could provide a lower cost alternative to CMOS technologies in terms of cooling requirements [Manheimer, 2015].

12.2 Low Temperature Electronic Devices

To facilitate the operation of systems at extreme temperatures, extensive research on the operation of electronic devices in these environments has been documented by many groups. In many instances, traditional systems such as silicon CMOS experience performance gains when decreasing the temperature to approximately 77 K. Here, for silicon CMOS, benefits of decreased temperature tend to level off and phenomena such as freeze-out begin to deteriorate the system performance. The following section provides a brief overview of the many differing types of electronics that have been found or designed to operate in low temperature environments.

12.2.1 SiGe Transistors and Diodes

Traditional silicon-based CMOS devices experience increased transconductance, increased charge carrier mobility, decreased turn-on times, and reduced thermal noise when operating at decreased temperatures as low as 77 K; however, at lower temperatures, impurity freeze-out begins to decrease carrier concentrations and increase threshold voltages appreciably [Kirschman, 1986]. As such it is necessary to find a switching device that can operate stably at temperatures lower than 77 K. Silicon-based bipolar transistors were found to have very poor electrical characteristics in cryogenic regions, primarily due to low emitter-base injection efficiency [Lengeler, 1974]. Early research focused on finding a heterojunction bipolar transistor (HBT) with promising results. Heterojunction bipolar transistors are bipolar transistors that have different semiconductor materials in the emitter-base region than the rest of the transistor.

Silicon germanium HBTs have developed as the leading candidate for transistors in low temperature operation. The devices show increased performance down to sub-Kelvin temperatures [Cressler and Mantooth, 2012]. Current gain, transconductance, cutoff frequency, and switching frequency all show improved characteristics when cooled to cryogenic temperatures. Figure 12.4 shows peak cutoff frequency and peak current gain performance with varying temperature. In each of the formulations for these properties, the kT term favorably affects the overall parameter at decreasing temperature [Cressler and Mantooth, 2012]. The use of a silicon–germanium alloy, which has a smaller energy band gap, in the base region reduces the potential barrier between the emitter-base regions, thus amplifying the collector current. The exact band gap of the base region depends on the relative concentration of germanium and silicon in the alloy and is often graded within the device; the energy band gap of the SiGe layer will be between 0.67 and 1.1 eV, the intrinsic band gaps of the respective materials [Streetman and Banerjee, 1995].

In addition to their performance at cryogenic temperatures, SiGe HBTs have been shown to operate with minimal performance degradation at high temperatures and in radiation-intense environments. SiGe has been called a temperature-invariant material. These characteristics make SiGe ideal for applications such as space exploration in which systems can experience extreme temperature swings. As such SiGe is the leading candidate for extreme environment systems [Cressler and Mantooth, 2012].

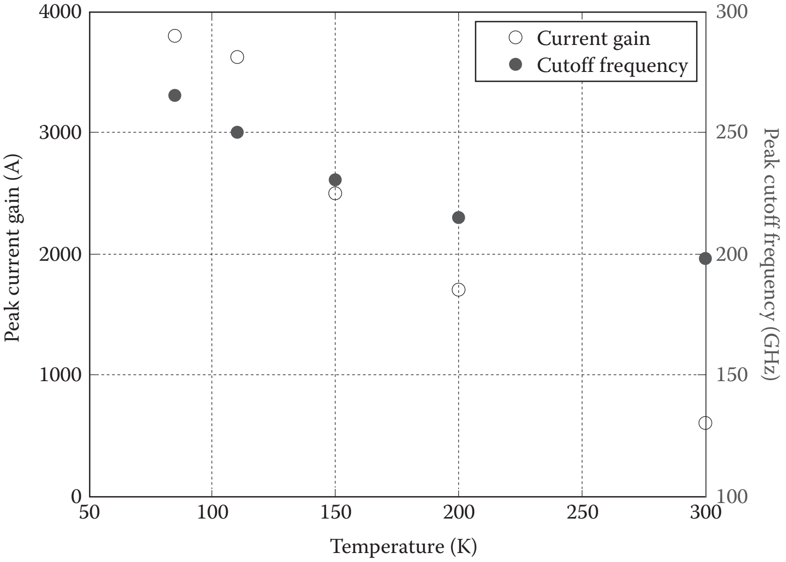

FIGURE 12.4
Peak current gain and peak frequency versus temperature for third-generation SiGe HBT. (Data from Cressler, J.D. and Mantooth, H.A. (Eds.), *Extreme Environment Electronics*, CRC Press, London, NY, 2012.)

12.2.2 Other Low-Bandgap Transistors and Diodes

Many other materials have been investigated for use in semiconductor junctions in low-temperature environments [Kelm, 1968; Forrest and Sanders, 1978; Lo and Leskovar, 1984; Prance et al., 1982; Keyes, 1977a, 1977b]. III–V semiconductors, namely InAs and InSb, are the most useful in low temperature applications due to their relatively small band gap; at room temperature, their operation can be dominated by intrinsic carriers. An important quality of high-speed bipolar transistors is that they have both high electron mobilities and high hole mobilities. While InAs and InSb have very high electron mobilities, they have very poor hole mobilities (Table 12.1), limiting their performance in high-speed applications. The reduction in noise and increase in mobility due to decreased lattice scattering have made GaAs an attractive material for preamplifiers that operate at cryogenic temperatures [Lo and Leskovar, 1984; Prance et al., 1982].

Early research also investigated the use of germanium in low temperature applications [Kelm, 1968; Keyes, 1977a]. Germanium has an intrinsic mobility that is five times that of silicon due to its small band gap (0.67 eV), which gives germanium a lower thermal voltage (Figure 12.5). Because of this property, germanium was of high interest during the search for a high-speed transistor in the 1960s. Germanium also showed excellent electrical characteristics in cryogenic applications, avoiding carrier freeze-out, which had been affecting silicon devices, due to its relatively low thermal voltage. Additionally, a lower thermal voltage allows for decreased voltage requirements when operating a germanium device, reducing the power dissipation. However, low-band-gap materials need to be properly cooled to ensure that the intrinsic behavior of the semiconductor does not dominate its operating characteristics. High-speed devices also needed to be contained in small packages to minimize signal propagation time. Small package sizes also make it difficult to remove heat. Ultimately, silicon remained the dominant material of choice for high-speed transistors [Keyes, 1977a].

12.2.3 Optical Devices

Optical devices such as light-emitting diodes (LEDs), optocouplers, and solid-state lasers are essential for modern signal transmission. While GaAs semiconductors did not become dominant for low temperature applications, variants of GaAs have become prevalent in infrared LEDs. The spectral power density (SPD) of an AlGaAs infrared LED at 300 and 77 K is shown in Figure 12.6 [Camin, 2006]. Several key conclusions can be made by analyzing this graph. First and most prevalent is that the output power of the LED is increased by a factor of 10. This observation can be explained by an increase in the quantum efficiency of the semiconductor at lower temperatures. Another observation is

TABLE 12.1

Energy Gap, Dielectric Constant, and Mobilities of Semiconductors at 77 K

Quantity	Si	Ge	GaAs	InAs	InSb	GaN	4H-SiC
E_g (eV)	1.15	0.73	1.5	0.4	0.23	3.4	3.3
μ_n	1.2	4	25	12	100	1	0.95
μ_n (doped 10^{17})	0.1	0.4	1	2	5	0.4	0.11
μ_p	0.6	4	0.4	0.4	1	0.2	0.9
μ_p (doped 10^{17})	0.05	0.4	0.1	0.05	0.2	0.11	0.6

Sources: From Keyes, R., *Comments on Solid State Physics*, 8(2), 37–46, 1977b; Lutz, J. et al., *Semiconductor Power Devices*, 17–75, 2011; Gaskill, D.K. et al., *Properties of Group III Nitrides*, Edgar, J. (Ed.), *EMIS Data Reviews Series, N11*, Wiley, pp. 101–116, 1995; Shatter, W.J. et al., *Institute of Physics Conference Series*, 137, 155, 1994.

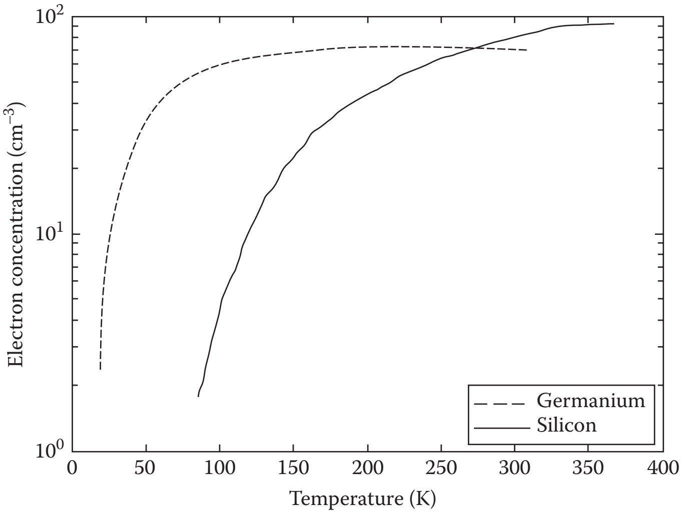

FIGURE 12.5
Difference between the trapping of electrons on donors in germanium and silicon. Specimens contain ~10^{17} donor impurities. (Based on Keyes, R., *Comments on Solid State Physics*, 8(3), 47–53, 1977a.)

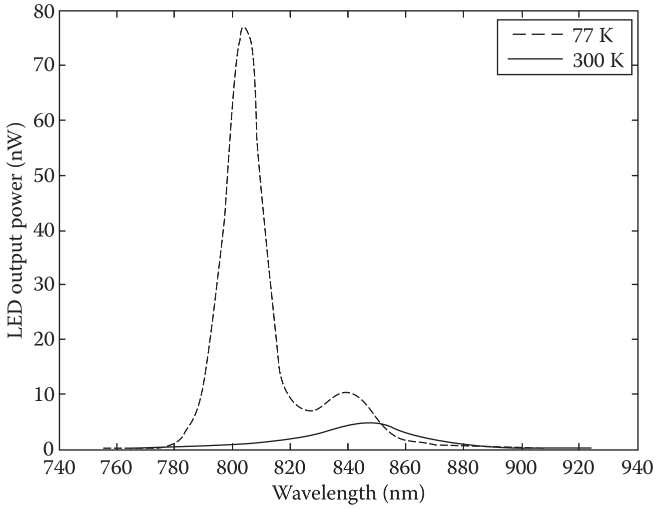

FIGURE 12.6
Spectral power density of AlGaAs LED under 1 mA bias. (Based on Camin, D., *IEEE Transactions on Nuclear Science*, 53(6), 3929–3933, 2006.)

that the peak wavelength has shifted to a shorter more energetic wavelength. As temperature decreases, the band gap of the semiconductor increases as described by the Varshni equation [O'Donnell and Chen, 1991]. A second peak appears when the LED is cooled; this is expected due to the presence of impurities. Finally, the full-width half-maximum for the cooled peaks is less than the 300 K peak, which can also be predicted by the Varshni equation [Camin, 2006]. The same AlGaAs study showed an increase in the turn on forward voltage drop, which is to be expected as temperature and forward voltage drop have a negative correlation [Hambley et al., 2008]. The observations found in Camin [2006] have also been observed in other studies [Cao and LeBoeuf, 2007; Carr, 1965; Wauters et al., 2009].

Another type of optical device is solid-state lasers, which have several advantages at cryogenic temperatures. The first is that at low temperatures, the laser threshold is decreased, meaning that the device can operate at more efficient voltages [Fan et al., 2007]. Another is that early diode-pumped solid-state lasers simply needed to be cooled to cryogenic temperatures to operate [Keyes and Quist, 1964]. In addition to the first two advantages, thermo-optic effects are reduced at cryogenic temperatures [Fan et al., 2007].

LEDs are one critical part of optocouplers, the second being a sensing mechanism, often a photodiode. Photodiodes showed a wider variety of behaviors depending on the device type. Standard Si p-n photodiodes experienced a decrease in responsivity at lower temperatures, which can be explained by a decrease in carrier concentration (Figure 12.7) [Camin, 2006]. Contrary to the standard Si p-n photodiode, Si p-i-n photodiodes exhibited increased or consistent performance at low temperatures. A Si p-i-n diode was tested at 300 and 77 K, and it was determined that the responsivity of the photodiode to an LED remained consistent (Figure 12.7). The consistent behavior can be explained by the large intrinsic region that remained unaffected by the decrease in temperatures. Furthermore, for both devices the noise of the photodiodes was reduced due to a decrease in dark current at cryogenic temperatures [Camin, 2006]. Again, the findings in Camin [2006] were consistent with other studies [Zhang et al., 1997; Wauters et al., 2009].

12.2.4 Timing Devices

As with the previous types of electronics, oscillators show improvements in performance when operated at cryogenic temperatures [Luiten et al., 1995; Giles et al., 1989]. For crystal oscillators, sapphire appears to be the dominant crystal. Research in the field has shown that cryogenic oscillators are more stable than atomic clocks in short-term applications. Specifically liquid helium cooled superconducting cavity masers have been shown to yield high quality factors, ~10^9 while outputting high power, 10^{-9} W relative to other oscillators that have shown a quality factor of 10^8 and output power of 10^{-12} W [Wang, 1988].

Superconducting cavity masers inherently have the requirement that they be cooled to liquid helium temperatures for operation. While these devices may be superior to others

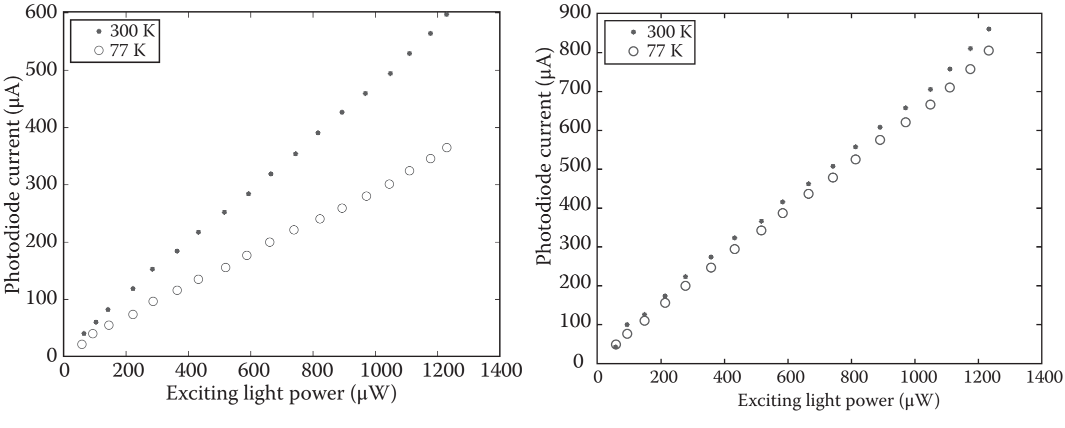

FIGURE 12.7
Responsivity of Si p-n diode (left) and responsivity of Si p-i-n photodiode (right) at 300 and 77 K. (Data from Camin, D., *IEEE Transactions on Nuclear Science*, 53(6), 3929–3933, 2006.)

at this temperature, systems used at low temperature but not necessarily below 4 K need to utilize other devices. GaAs FETs are widely used for clocks in 1–10 GHz applications due to their relatively low noise in a range of temperatures below 300 K [Kirschman 1986; Lo and Leskovar, 1984].

12.2.5 MEMS and Sensor Devices

Micro-electromechanical systems (MEMS) have rapidly achieved market integration by the application of fabrication techniques developed for processing silicon for electrical circuitry to mechanical designs [Kovacs, 1998]. These devices are superior to their conventional counterparts in terms of their size and per unit cost [Kovacs, 1998]. Nonetheless, operation of MEMS devices at cryogenic temperatures is largely unstudied [Attar et al., 2011]. Early research in the area of cryogenic RF switching MEMS found an increase in the required actuation voltage with decreasing temperatures, following the conventional wisdom of mechanical stiffening at low temperatures [Noelet al., 2008; Goldsmith and Forehand, 2005]. However, a later study [Attar et al., 2011] showed that the actuation voltage was more dependent on the mechanical structure of the device, and in fact, it is possible to get a positive or negative correlation with a decrease in temperature if the proper structure is selected.

Other applications of MEMS are microcantilevers, which are used in atomic force microscopy (AFM) and chemical sensing devices. Operating the AFM microcantilevers at cryogenic temperatures increases the resolution, as it reduces thermal noise and overcomes issues related with tissue softness at room temperature [Park et al., 2007]. To increase the range of measurable parameters for cryogenic temperatures, heated microcantilevers can be used in AFM. Using these cantilevers would allow for measurements of local heating on freezing processes, studying low temperature calorimetry, and other similar metrics [Park et al., 2007]. It is important to note when designing such a system that electrical resistance of the heated microcantilevers increases with decreasing temperature (Figure 12.8).

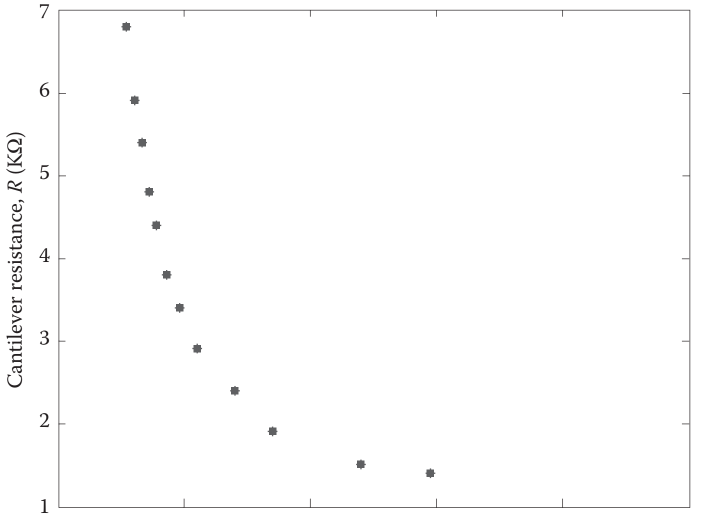

FIGURE 12.8
Heated cantilever electrical resistance versus temperature. (Data from Park, K. et al., *Journal of Applied Physics*, 101(9), 094504.)

In terms of sensing, infrared detectors experience similar characteristics to the photodiodes discussed in Section 12.2.3. That is, p-i-n diode infrared detectors experience a reduction in dark currents from thermal noise [Camin, 2006]. This is essential on telescopes such as the James Webb telescope, which use infrared detectors to observe faint infrared signatures to gather data on the beginning of the universe [NASA, 2014a].

12.3 Low Temperature Device Packaging

The packaging of the electronics within a system is essential to ensure the integrity and operation of the circuitry. For low temperature device packaging, perhaps the most prominent difficulty, due to the large difference in processing and operating temperatures, is matching the coefficient of thermal expansions (CTEs) of the materials making up the system [Cressler and Mantooth, 2012]. As materials of discrete devices are in intimate contact, systems that are not made up of materials with similar thermal expansion coefficients are prone to warping fracture and fatigue (Figure 12.9). The following sections discuss the various issues and potential solutions related to the selection of components of device packaging by examining several case studies [Shapiro et al., 2010; Sivaswamy et al., 2008; Tudryn et al., 2006].

12.3.1 Wire Bonding

For wire bonding in cryogenic applications, the material most often chosen is gold wire, bonded using a thermosonic bonding method [Sivaswamy et al., 2008; Shapiro et al., 2010; Tudryn et al, 2006]. The industry standard for military and space applications are 1-mil-diameter wires. Several commercial industries have switched to 0.7-mil wires to reduce cost; however, this size produces reliability concerns [Shapiro et al., 2010]. Additionally, wire bonds greater than 2 mil show fatigue failures at the ball bonds [Shapiro et al., 2010]. There are a wide range of results for wire bonds suggesting that

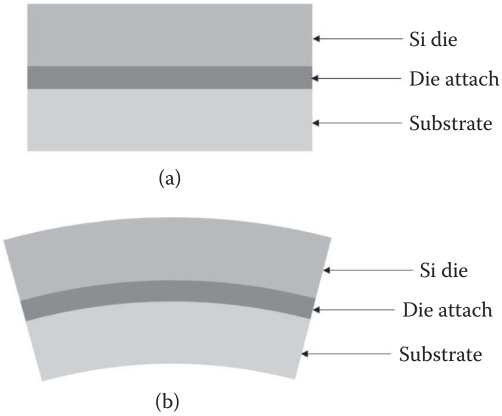

FIGURE 12.9
Exaggeration of warpage due to differing CTE. (a) The temperature is the bonding temperature, (b) after cooldown. The CTE of the Si die is less than that of the substrate. (Based on Cressler, J.D. and Mantooth, H.A. (Eds.), *Extreme Environment Electronics*, London, NY: CRC Press, 2012.)

their reliability in cryogenic operation may be application specific. Sivaswamy et al. have reported a case study of a system-in-package device to be thermal cycled from –180°C to 120°C that uses Au wire bonds. Early finite element analysis (FEA) showed that the wire bonds were relatively low stress and their reliability was of low concern [Sivaswamy et al., 2008]. Shapiro et al. also created a device with Au wire bonds that was thermal cycled from –180°C to 120°C; however, this study showed that wire bonds were the primary failure mechanism and, because of this, recommended flip chip for low temperature applications [Shapiro et al., 2010]. Tudryn et al. created a device very similar to that of Shapiro et al.; however, several of their bonds were aluminum. They also found that the wire bonds caused all observed failures, and in cases where the wire bonds had not failed, they showed strong evidence of stress [Tudryn et al, 2006]. Interestingly, although all bonds appeared stressed, the Au wire bonds failed before the Al ones. Therefore, the reliability of wire bonds at low temperatures exhibit varying results, although Al bonds may somewhat enhance reliability. Flip chip packaging appears to be a more reliable alternative.

12.3.2 Flip Chip

Due to the potential reliability issues associated with wire bond interconnections, flip chip is a leading candidate for the transmission of signals from the package to the die in reliable high thermal cycle cryogenic devices [Sivaswamy et al., 2008; Shapiro et al., 2010; Tudryn et al., 2006]. Of primary interest when investigating flip chip assemblies are the solder bumps used to connect the die to the substrate. Sivaswamy et al. employed a flip chip assembly using a In50Pb50 high-compliance solder [Sivaswamy et al., 2008]. A SiGe die was used with a Si substrate, materials that have highly similar CTE. The high-compliance solder in combination with the thermal expansion match of the die and substrate leads the authors to use no underfill (Figure 12.10). Previous studies had shown that the thermal expansion properties of the underfill are not desirable at low temperatures and can even increase stress in the system [Rahim et al., 2005].

Ulrich et al. and Yamamoto et al. separately designed microprocessors in multichip module packages using a flip chip assembly that can reliably be immersed in liquid nitrogen for performance enhancement at cryogenic temperatures [Ulrich and Rajan, 1996; Yamamoto, 1991]. Ulrich et al. used a silicon die joined with conductive epoxy-based solder bumps to the device's substrate. Yamamoto et al. used a GaAs die attached via an indium-based solder to a multilayer ceramic substrate to be described in Section 12.3.4.

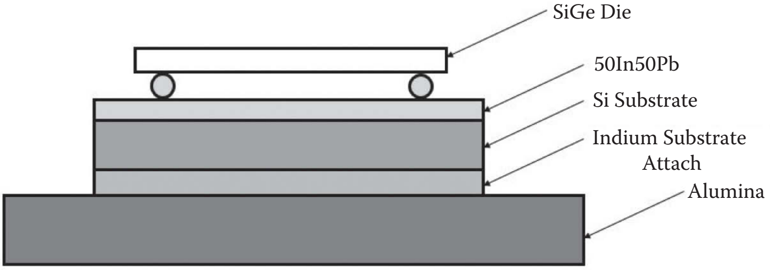

FIGURE 12.10
Schematic of flip chip assembly. (Based on Sivaswamy, S. et al., *Electronic Components and Technology Conference, 2008 (ECTC 2008)*, 58, 2044–2050, 2008.)

12.3.3 Die Attach

The use of several different types of die attach materials has been studied for cryogenic applications including solders, silicones, and epoxies [Kirschman et al., 1999; Rahim et al., 2005; Shapiro et al., 2004, 2010; Sivaswamy et al., 2008; Tudryn et al., 2006; Yamamoto, 1991]. Several considerations should be made when selecting a solder for die attach. The solder should have no phase transitions in the expected operating temperature range. The solder should be highly compliant to help reduce thermo-mechanical stresses. Finally, the solder should have minimal intermetallic growth with the metals used in traces or wire bonds of the device [Shapiro et al., 2004].

Indium solder exhibits many of these traits and has been used both as a die attach in wire bond assemblies and a substrate attach. As mentioned previously, an indium–lead alloy has been used for flip chip solder bumps. Indium remains malleable even at low temperatures, which can reduce residual stresses [Sivaswamy et al., 2008]. Additionally, indium does not experience a phase shift in the expected operating region for these devices, –180°C to 120°C, and indium is somewhat resistant to intermetallic growth with gold, which can cause failure [Shapiro et al., 2010]. Although Sivaswamy et al. used a pure indium solder, Tudryn et al. recommend the use of In80Pb15Ag5 [Tudryn et al., 2006]. Shapiro et al. [2010] provided a comprehensive list of so-called "soft" solders, which are primarily indium and lead based, and "hard" solders, which are primarily gold based [Kirschman et al., 1999]. Although the hard solders are not as compliant, they have the lowest melting temperature, which gives them the lowest "zero-stress" temperature, reducing the overall stress as the temperature is decreased. One concern with using these solders is that due to their relatively low melting points, efforts must be made to ensure that additional processing to the assembly does not reflow the solder.

In addition to studying solders, Shapiro et al. investigated the use of a silver-filled epoxy and a silicone-based adhesive [Shapiro et al., 2004]. Here it was observed that all samples that used a combination of silver-filled epoxy die attach with a low temperature co-fired ceramic (LTCC) were able to survive their stress test of 1500 thermal cycles between –180°C to 120°C. The silicone-based die attach also survived the stress test, although it should be noted that all samples prepared with a parylene survived the stress test, suggesting that the encapsulant material is of greater importance in determining reliability. Furthermore, only wire bonds were used here and they were the primary failure mode in this study, further suggesting that there is a strong dependence between reliability and the encapsulant [Shapiro et al., 2004].

12.3.4 Substrates and Leadframes

The selection of substrates and leadframes is highly dependent on the thermal expansion properties of the materials within the device. AlN is an ideal substrate material, as it has a CTE between silicon and many ceramics used for encapsulation AlN acts as a buffer layer between the Si die and an Al_2O_3 ceramic encapsulant. Sivaswamy et al. conducted an FEA analysis on both combinations mentioned and found that the interface between the substrate and the package was lifetime limiting (Figure 12.10) [Sivaswamy et al., 2008]. This is likely due to the fact that the substrate and package have a larger contact area than the substrate and die; therefore, this interface will also have the portion of attach that is furthest from the neutral point, giving it the largest strain. Another example of a good match is between Si and Si_3N_4, which has a CTE that also matches very well with a SiGe die and thus would make a good candidate for cryogenic applications [Sivaswamy et al., 2008].

Shapiro et al. tested a variety of other substrate materials such as polyimide, alumina, and LTCC. Polyimide was tested, as it is currently the most common space flight circuit board material. Alumina has been widely used in noncryogenic applications, so it was selected to determine its properties at low temperatures. The results of the –180°C to 120°C test showed failures in polyimide and alumina substrates. All samples prepared with an LTCC substrate and silver-filled epoxy attach survived the thermal cycle testing, which was expected after an FEA analysis showed that this combination of materials had the lowest stress [Shapiro et al., 2004]. The results from this study were confirmed in Tudryn et al. [2006].

Yamamoto et al. chose a GaAs die that has a CTE twice that of silicon and consequently had to fabricate a multilayer ceramic substrate to match this CTE [Yamamoto, 1991]. The authors sintered a zirconia powder with a borosilicate glass using an alumina film in between to prevent the zirconia from reacting with the glass at 1000°C. This produced a substrate with a CTE within 10% of GaAs. Thermal simulations of the die and substrate were performed to compare the maximum stresses using both alumina and the multilayer ceramic. It was found that the multilayer ceramic had a maximum stress of only 6.7 N/mm^2 compared to the alumina substrate, which had a maximum stress of 50 N/mm^2.

12.3.5 Encapsulants

Encapsulants have a large effect on the reliability of cryogenic devices. Due to the fact that at lower temperatures, materials become more brittle, plastic encapsulants are generally replaced with ceramics, which are more resistant to property changes due to thermal variations, thus improving device reliability [Cressler and Mantooth, 2012]. The most common ceramic used for packaging is alumina [Sivaswamy et al., 2008].

Another key consideration when designing discrete cryogenic ceramic electronics is the fill or encapsulation inside the ceramic housing. Shapiro et al. studied the use of an epoxy, a silicone, and parylene for such a function [Shapiro et al., 2004]. The epoxy and silicone provide a glob-top-like protection. Parylene is a thin-film covering that is deposited via a vapor deposition processing step. Interestingly, the parylene showed the best performance under thermal cycling, as all samples prepared with parylene survived the thermal stress test. One possible explanation for this is that the two glob-top-style encapsulants could have embrittled at cryogenic temperatures affecting the wire bonds in the sample [Shapiro et al., 2004]. While it would seem that parylene should then be used, it should also be noted that due to its thin-film nature, parylene does not provide mechanical support to the wire bonds. Thus, a tradeoff must be made and the application of the device should be considered when selecting an encapsulant.

12.4 Low Temperature Circuit Packaging

Once the design of the individual components has been completed, the next logical step is to design a board that can facilitate the interactions between multiple discrete devices as well as communicate with systems external to those on the board. The following sections are discussions of the various issues and potential solutions related to the selection of materials and components for board or so-called second-level packaging.

12.4.1 Boards and Flex Circuits

The printed circuit board (PCB) provides a mechanical structure for mounting of discrete packages, and facilitates the electrical connection between the devices and any external systems. Fink et al. completed a comprehensive mechanical strength study on the various materials used to make PCBs: testing PCB 2301 Multilayer Board (MLB) with epoxy glass, which is an FR-4-type material, PCB thermount, and PCB 2302 MLB polyimide glass [Fink et al., 2008]. In the study, samples were tested at room temperature, liquid nitrogen, and liquid helium for mechanical properties such as Young's modulus, yield strength, elongation at rupture, and ultimate tensile strength. Select results of the study are shown in Figure 12.11 for comparison. The 2301 MLB epoxy glass was determined to be the superior material for cryogenic PCBs, clearly showing the strongest ultimate and yield strengths. The Thermount PCB showed the weakest strengths for all categories.

In addition to testing PCB materials, Fink et al. studied various conformal coatings to determine their mechanical properties at low temperatures [Fink et al., 2008]. It was determined that there was a general trend among all of the seven different coatings tested that there is an increase in strength and modulus. Failure analysis of the coatings showed a

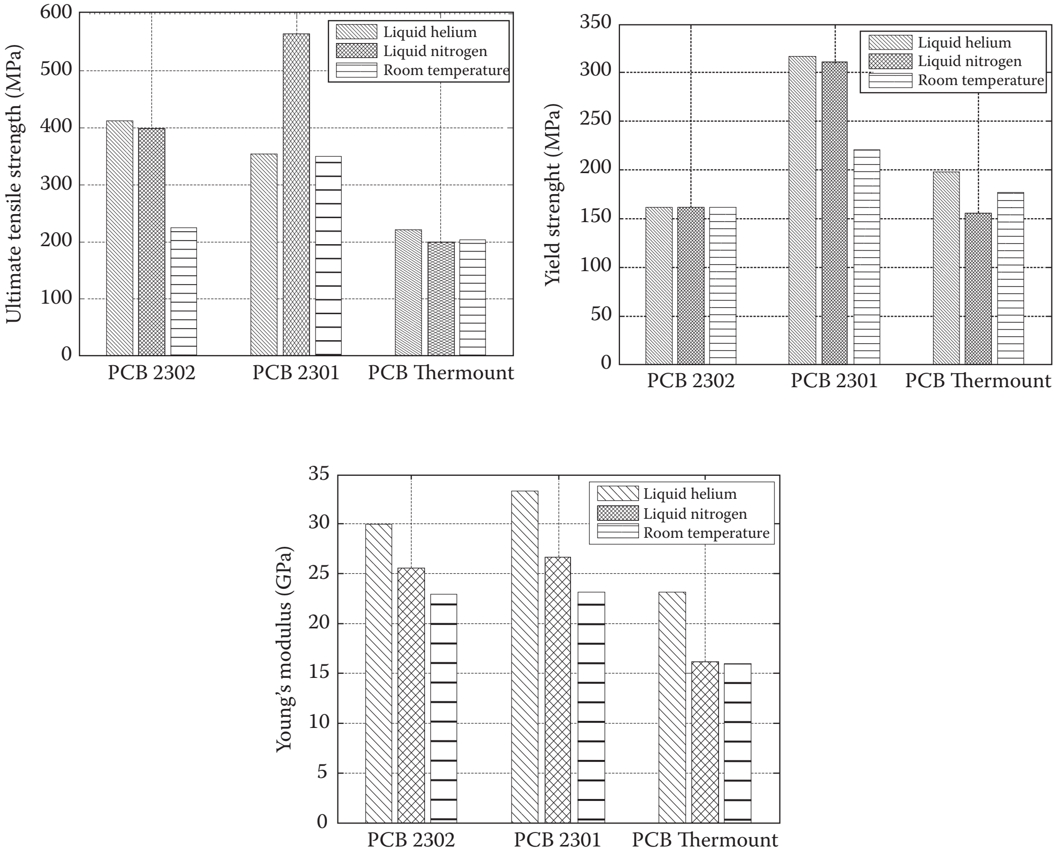

FIGURE 12.11
(Top left) Ultimate tensile strength, (top right) yield strength, and (bottom) Young's modulus of tested PCB materials. (Based on data from Fink, M. et al., *Cryogenics*, 48(11), 497–510, 2008.)

strong decrease in elongation. It is expected that due to the wide range of coatings tested, these characteristics can be extrapolated to most coatings. Fink et al. found that while the differences were minimal, Solithane 113 was superior in terms of its mechanical characteristics [Fink et al., 2008].

12.4.2 Solders

To facilitate a connection between the board and the component at cryogenic temperatures, a solder with the desired characteristics needs to be identified. The desired characteristics are likely application dependent. A general rule to follow would be to use a solder that remains soft at low temperatures to allow for compliance. In their study, Fink et al. tested a large variety of solders: 63Sn37Pb, 62Sn36Pb2Ag, 96Sn4Ag, 50In50Pb, 70Pb30In, 96.8Pb1.5Ag1.7Sn, and 96.5Sn3Ag0.5Cu [Fink et al., 2008]. The results of their testing are shown in Figure 12.12.

Lead-free tin-based solders did not perform well at low temperatures, showing a decrease in all strength parameters. Additionally, these components showed a drastic increase in

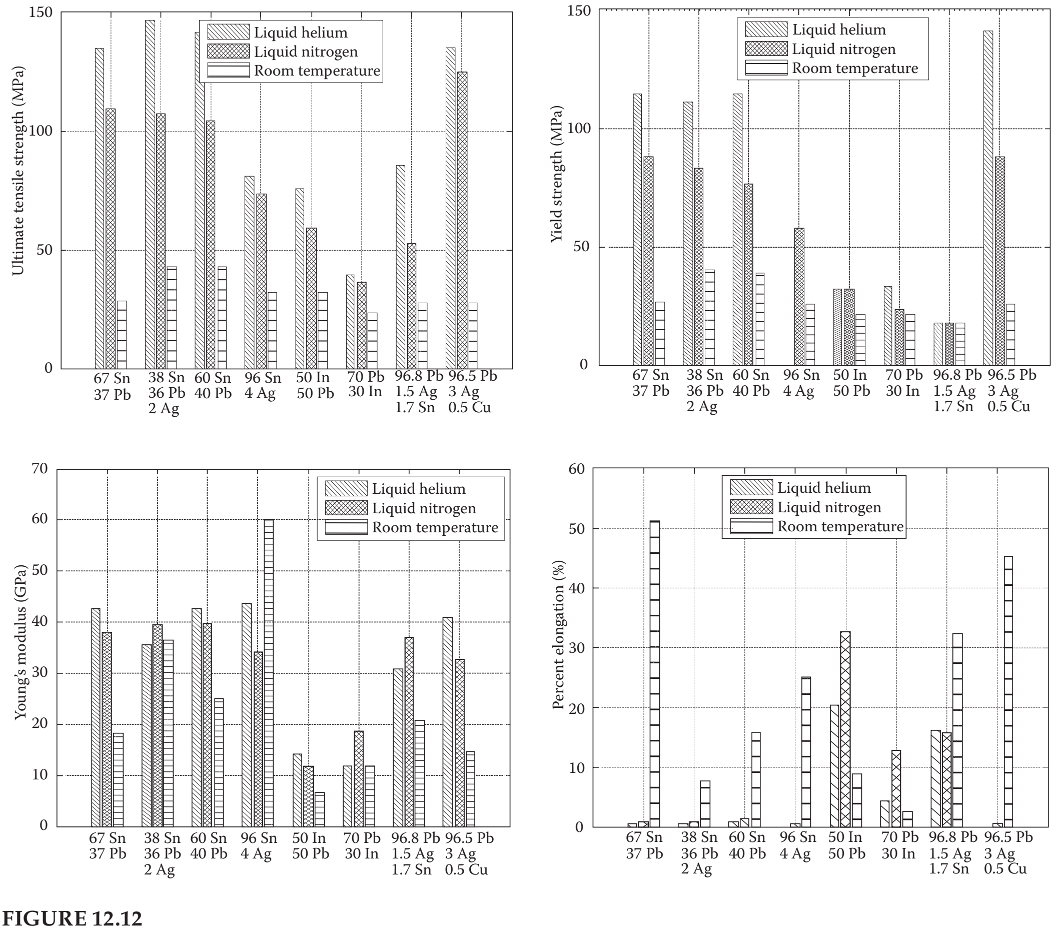

FIGURE 12.12
(Top left) Ultimate tensile strength, (top right) yield strength, (bottom left) Young's modulus, and (bottom right) percent elongation at failure of tested solder alloys. (Based on data obtained from Fink, M. et al., *Cryogenics*, 48(11), 497–510, 2008.)

brittle behavior, failing with very little elongation. This presents a difficulty when dealing with restrictions such as the restriction on the use of hazardous substances (RoHS), which attempts to remove substances such as lead from electronics. Many industries such as aerospace and military have temporary exemptions to this policy, and a significant development of lead-free solders will need to take place before such a restriction can be placed on these industries.

Lead- and indium-based solders perform very well in cryogenic testing. While these solders tend to show low yield strengths, they allow for elongation at cryogenic temperatures unlike the lead-free solders, which were highly brittle. Generally speaking, the ability to deform is desirable at low temperatures, allowing for compliance between materials of differing CTEs. One difficultly with using indium in solder is that its low melting temperature makes it susceptible to forming intermetallic compounds [Shapiro et al., 2010].

12.4.3 Passives Components: Capacitors, Inductors, and Resistors

Passive components are used in circuitry to condition signals, removing noise and helping to extract relevant information. A significant amount of research exists for capacitors at cryogenic temperatures [Teyssandier and Prêle, 2010; Patterson et al., 1998; Teverovsky, 2006]. Commercially available capacitors are often categorized into three classes: class 1, class 2, and class 3, which describe how the capacitance of the components changes with temperature or the tolerance of the temperature within a specified temperature range. Class 1 capacitors are typically the most robust in their performance and show linear trends with temperature. More information can be found on the classes of capacitors in Pan and Clive [2010]. A chart of the performance of capacitors at cryogenic temperatures is shown in Figure 12.13. Not surprisingly NP0-type capacitors showed little to no change in capacitance even at 4 K and thus should be strongly considered for systems that must show temperature invariance.

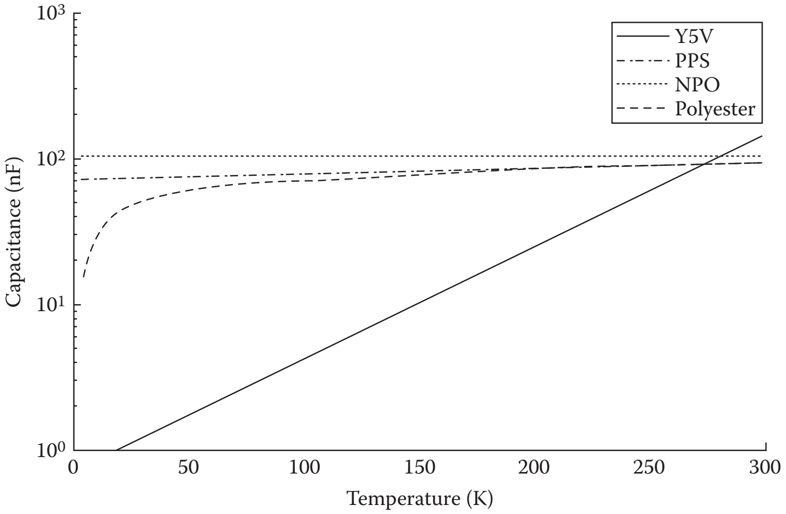

FIGURE 12.13
Performance of various classes of ceramic capacitors at cryogenic temperatures. (Data from Teyssandier, F. and Prêle, D., *Ninth International Workshop on Low Temperature Electronics (WOLTE9)*, 2010.)

For tantalum capacitors, a reduction in capacitance and an increase in equivalent series resistance were observed at 77 K [Teverovsky, 2006]. Additionally, the breakdown voltage was increased at low temperatures; however, for step surge tests, the breakdown voltage decreases, suggesting an increase in reliability for high-impedance cryogenic applications but a decrease in reliability for low-impedance cryogenic applications [Teverovsky, 2006]. Work completed by Patterson et al. suggests that polypropylene, polycarbonate, and mica-based capacitors show excellent stability at 77 K; however, tantalum capacitors showed an increase in dielectric loss, confirming the results in Teverovsky [2006] and Patterson et al. [1998].

Gerber et al. studied an array of cores used for inductors in switch mode power supplies (SMPS) [Gerber, 2004]. They tested four types of cores: three powered cores, molypermalloy cores (MPCs), high-flux cores (HFCs), and Kool Mu cores (KMCs), as well as a solid ferrite cores. The results of the study are shown in Figure 12.14. MPC showed the greatest stability in both frequency and temperature variation. HFC also showed consistent behavior across frequency and temperature; however, there were slight variations with temperature. Both the ferrite and KMC showed decreases in inductance with increasing temperature but showed stable inductance with frequency variation.

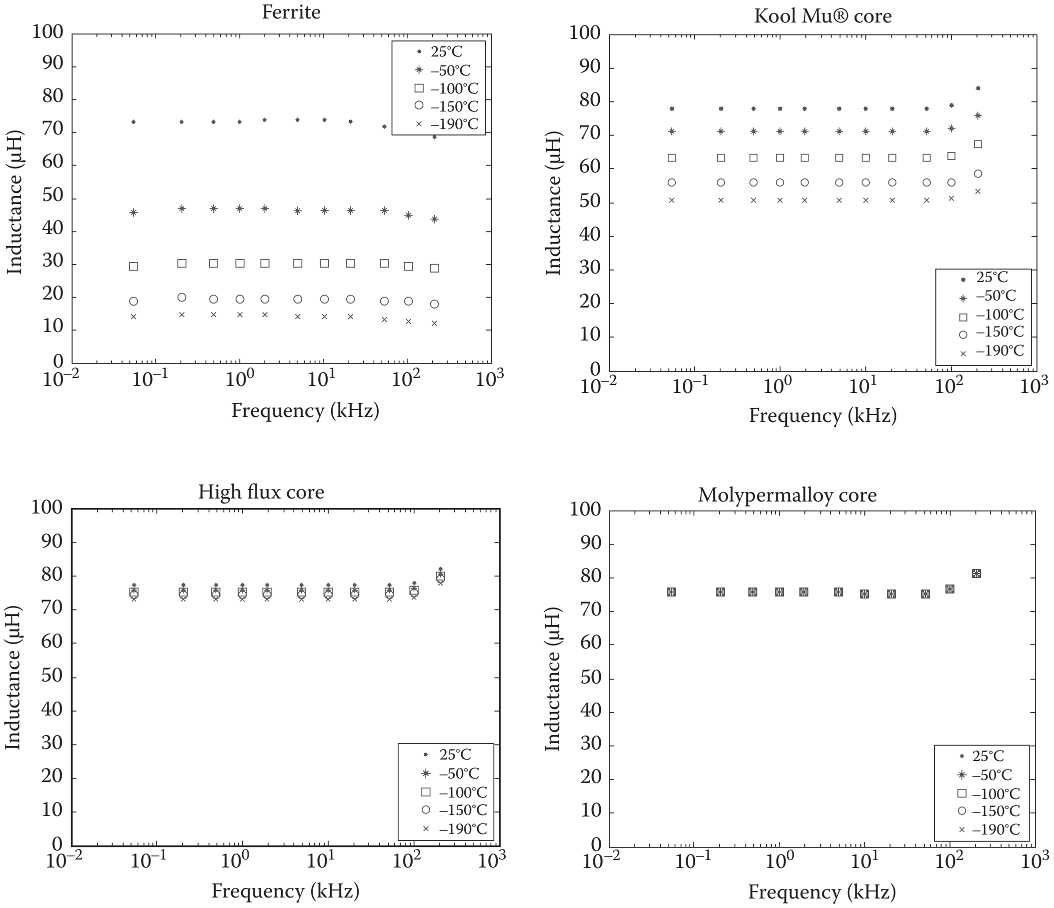

FIGURE 12.14
Core inductances at varying temperatures and frequencies. (Data from Gerber, S.S., *IECEC'02. 2002 37th Intersociety IEEE Energy Conversion Engineering Conference*, 249–254, 2004.)

TABLE 12.2

Performance of Resistors at Cryogenic Temperature [Patterson et al., 2001]

Type	Value (Ω)	Resistance (Ω) at 25°C	Resistance (Ω) at –190°C	Change in Resistance (%) at –190°C
Metal film	10	10.00	9.99	0.0
	1 K	999.15	1001.86	0.3
Wirewound	10	9.70	9.62	–0.9
	1 K	984.80	979.31	–0.6
Thin film	33	33.07	34.32	3.8
	1 K	995.41	1007.88	1.3
Thick film	100	99.99	105.42	5.4
	1 K	998.70	1003.22	0.5
Carbon film	10	9.96	10.46	5.1
	1 K	980.30	1035.83	5.7
Carbon composition	15	14.65	16.34	11.6
	1 K	1013.29	1296.54	28.0
Ceramic composition	10	9.49	10.99	15.8
	1 K	993.09	1167.51	17.6
Polymer film	10	10.00	10.48	4.9
	1 K	996.20	1037.06	4.1

Resistors are the final major passive component to be considered for second-level packaging. Patterson et al. studied the behavior of a wide variety of resistor types at 25°C and –190°C for electrical characterization in planetary exploration [Patterson et al., 2001]. The results of their study are shown in Table 12.2. Key findings from the research suggest that metal film, wirewound, thin-film, and thick-film resistors all showed temperature-independent results. Carbon film, carbon composition, ceramic composition, and polymer film all showed significant increases in resistance as temperature was decreased.

12.5 Low Temperature Housing

In this final section, third-level packaging will be considered. Again, CTE is of great importance; however, considering many cryogenic operations involve space flight, weight will be of paramount importance. Maximizing the strength to weight ratio of materials is one of NASA's key research areas [NASA, 2002]. The following sections very generally discuss issues and potential solutions related to the selection of materials for electronics housings or so-called third-level packaging.

12.5.1 Housings

Materials used for housing cryogenic electronics must be able to withstand low temperatures without producing large stresses. For space applications, these materials must also be as light and strong as possible to reduce costs. Using modern technology, it costs approximately $10,000 to put a pound of material into Earth orbit [NASA, 2014c]. Missions going further distances, such as to Mars and beyond can be expected to cost significantly more.

One category of low-density material being researched is metal matrix composites, which are materials composed of two distinct materials, one of which must be a metal [Rawal, 2001; Zweben, 1992; Ibrahim et al., 1991]. Metal–matrix composites can be used to tailor a material to attain properties that are otherwise not attainable by a pure substance. For example, an Al/B metal matrix composite has a higher ultimate tensile strength at approximately 1100 MPa, than titanium, which has a strength of 950 MPa, while having approximately half the density: 2.7 g/cc for Al/B, 4.4 g/cc for titanium.

For structures that must be kept thermally isolated from the environment, such as the interior of the International Space Station, which must maintain a livable temperature in both –160°C and 120°C conditions, thermal blankets called multilayer insulation (MLI) are employed (Figure 12.15). These are commonly composed of layers of either Kapton® or Mylar® separated by thin polyester netting. The Kapton and Mylar prevent radiation heat transfer, and the thin netting prevents conduction between the layers of the blanket [Savage, 2003].

While density and thermal insulation are priorities in housing space electronics, another key consideration in design is communications. Some internal electronics systems may need to communicate wirelessly to external systems; the housing should be designed to facilitate these communications while at the same time blocking noise from external sources.

12.5.2 Wires and Cables

Metal conductors used for wiring exhibit several phenomena at low temperatures. The general trends for a variety of metals are shown in Figure 12.16 [NIST, 2015]. Several distinct regions arise when observing this graph. First, it is seen that above 150 K all metals

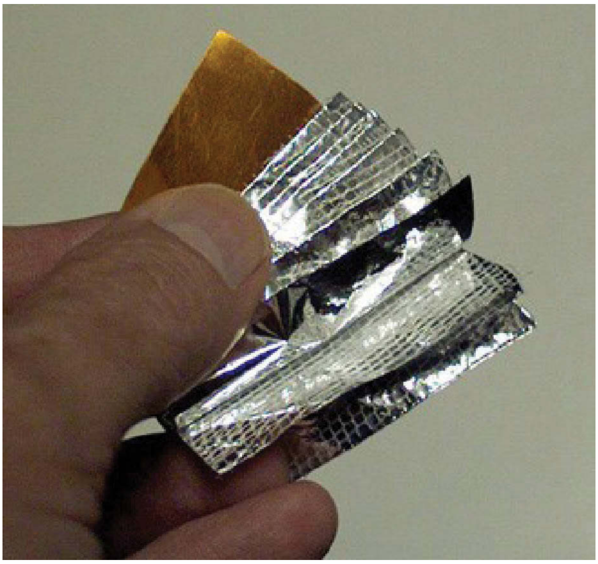

FIGURE 12.15
Multilayer insulation "opened" to see various internal layering [Rossie, 2015]. (Courtesy of John Paul Rossie, Director, Aerospace Educational Development Program.)

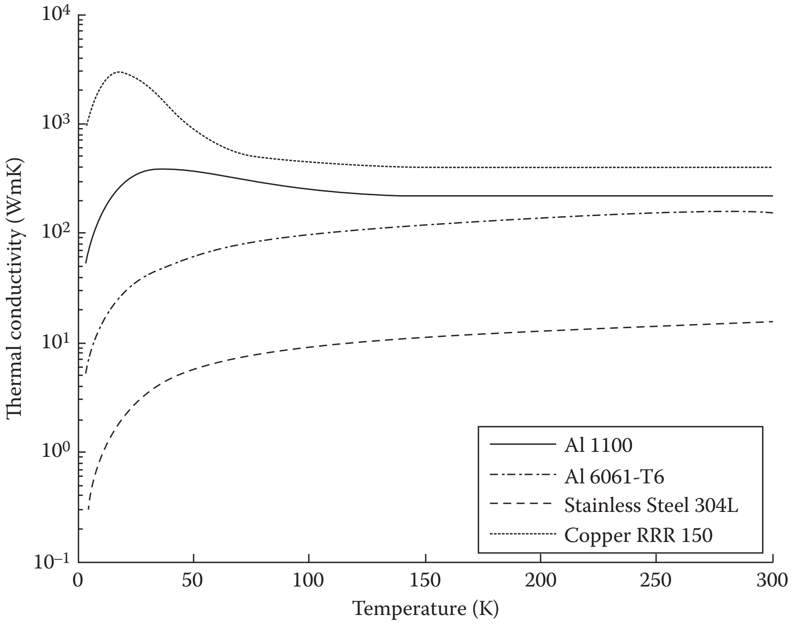

FIGURE 12.16
Thermal conductivity versus temperature for selected metals. (Data obtained from NIST, Material Properties, NIST Material Measurement Laboratory, Cryogenic Technologies Group, 2015.)

shown exhibit fairly constant thermal conductivity. The second key observation is the enhanced thermal conductivity that many metals exhibit around 20 K. As the thermal conductivity of a metal is mostly due to the transport of electrons through the metal, the reduced scattering at these temperatures allows the electrons to move most freely, increasing the thermal conductivity of the material. Finally, the conductivities of all metals approaches 0 at 0 K; this is due to electrons no longer being able to move at these low temperatures.

Metals also exhibit increased hardness, yield strength, tensile strength, modulus of elasticity, and fatigue resistance when temperature is lowered [Hurlich, 1968]. Where metals differ at low temperature is their failure signatures. Some metals lose their ductility properties at low temperatures and experience brittle failure. Other metals can remain soft at low temperatures and exhibit ductility in failure. Therefore, the choice of a metal is application dependent and may ultimately come down to which type of failure is more acceptable.

12.5.3 Connectors

Minimal research exists on the topic of electrical connectors at cryogenic temperatures. Several patents exist on the topic but these do not have much detail regarding the physical nature of connectors at low temperatures [Tighe, 2000; Otte and Fischer, 1973]. Connectors are likely to be made up of similar materials as those found in Section 12.5.2, and readers are referred to that section for metallic material considerations. In cryogenic applications, there appear to be two key considerations for connector design: electrical connection and thermal connection. Electrical connection is the more obvious and trivial of the two. Thermal connection is important for systems that must be cooled to extremely low temperatures. A designer must note the ability of the connector to participate in heat transfer. A design should strive to minimize the transfer of heat to these systems using adequate materials.

12.6 Summary

Low temperature applications for electronics systems are growing with continued space and polar exploration in addition to supercomputing technologies. Many types of electronic devices were shown to have improved operating characteristics such as transistors, LEDs, and oscillators. However, electronics engineers need to design electronics systems with packages that can reliably operate in cryogenic environments. Systems in low temperature environments should utilize small band gap semiconductors such as SiGe or germanium. Efforts should be made to match the CTEs of the materials used in the device packaging to reduce thermo-mechanical stresses. Flip chip provides the most reliable die to substrate bonding. Gold is the most reliable metal for applications that require wire bonding. Compliant "soft" indium- or lead-based solders and die attaches should be utilized to minimize residual stresses at cryogenic temperatures. Finally, due to their brittle nature at low temperatures, plastic encapsulants should be avoided where possible, in favor of ceramic packages.

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References

Anthony S. Cryogenic on-chip quantum electron cooling leads towards computers that consume 10x less power. Extreme Tech, 2014. Available at: http://www.extremetech.com/extreme/189999-on-chip-quantum-wells-create-cryogenic-electrons-computers-that-consume-10x-less-power.

Attar S. S., S. Setoodeh, R. Al-Dahleh, and R. R. Mansour. Cryogenic performance of gold-based and niobium-based RF MEMS devices. In *European Microwave Integrated Circuits Conference (EuMIC)*, 2011, Manchester, United Kingdom, October 2011, pp. 672–675. *IEEE*, 2011.

Camin D. Cryogenic behavior of optoelectrionic devices for the transmission of analog signals via fiber optics. *IEEE Transactions on Nuclear Science* 53, no. 6 (2006): 3929–3933.

Cao X. A. and S. F. LeBoeuf. Current and temperature dependent characteristics of deep-ultraviolet light-emitting diodes. *IEEE Transactions on Electron Devices* 54, no. 12 (2007): 3414–3417.

Carlson D. M., D. C. Sullivan, R. E. Bach, and D. R. Resnick. The ETA 10 liquid-nitrogen-cooled supercomputer system. *IEEE Transactions on Electron Devices* 36, no. 8 (1989): 1404–1413.

Carr W. N. Characteristics of a GaAs spontaneous infrared source with 40 percent efficiency. *IEEE Transactions on Electron Devices* 12, no. 10 (1965): 531–535.

Cressler, J. D. and H. A. Mantooth (Eds.). *Extreme Environment Electronics*. London, NY: CRC Press, 2012.

ESA. Space Science/Our Activities/ESA. European Space Agency (ESA), 2014.

Fan T. Y., D. J. Ripin, R. L. Aggarwal, J. R. Ochoa, B. Chann, M. Tilleman, and J. Spitzberg, Cryogenic Yb 3+-doped solid-state lasers. *IEEE Journal of Selected Topics in Quantum Electronics* 13, no. 3 (2007): 448–459.

Fink M., T. Fabing, M. Scheerer, E. Semerad, and B. Dunn. Measurement of mechanical properties of electronic materials at temperatures down to 4.2 K. *Cryogenics* 48, no. 11 (2008): 497–510.

Forrest, S. R. and T. M. Sanders Jr. GaAs junction field effect transistors for low-temperature environments. *Review of Scientific Instruments* 49, no. 11 (1978): 1603–1604.

Gaskill, D. K., L. B. Rowland, and K. Doverspike. Electrical transport properties of A1N, GaN and AlGaN. In *Properties of Group III Nitrides*, Edgar J. (Ed.). *EMIS Data Reviews Series, N11*. INSPEC, The Institution of Electrical Engineers, London, 1995, pp. 101–116.

Gerber S. S. Performance of high-frequency high-flux magnetic cores at cryogenic temperatures. In *IECEC'02. 2002 37th Intersociety IEEE Energy Conversion Engineering Conference*. 2004, Washington, WA, USA, July 2004, pp. 249–254.

Giles A. J., S. K. Jones, D. G. Blair, and M. J. Buckingham. A high stability microwave oscillator based on a sapphire loaded superconducting cavity. In *Proceedings of the 43rd Annual Symposium on Frequency Control, IEEE* (1989): 89–93.

Goldsmith C. L. and D. I. Forehand. Temperature variation of actuation voltage in capacitive MEMS switches. *IEEE Microwave and Wireless Components Letters* 15, no. 10 (2005): 718–720.

Hambley A. R., N. Kumar, and A. R. Kulkarni. *Electrical Engineering: Principles and Applications*. Upper Saddle River, NJ: Pearson Prentice Hall, 2008.

Hurlich A. Low temperature metals. In *1968 Summer Study on Superconducting Devices and Accelerators*. Upton, NY: Brookhaven National Laboratory, June-July, 1968.

Ibrahim I. A., F. A. Mohamed, and E. J. Lavernia. Particulate reinforced metal matrix composites—A review. *Journal of Materials Science* 26, no. 5 (1991): 1137–1156.

Kelm E. C. Operation of a germanium FET at low temperatures, *Review of Scientific Instruments* 39 (1968): 775–776.

Keyes R. Semiconductor devices at low temperatures. *Comments on Solid State Physics* 8, no. 3 (1977a): 47–53.

Keyes R. Low temperature high mobility transistor materials. *Comments on Solid State Physics* 8, no. 2 (1977b): 37–46.

Keyes R. J. and T. M. Quist, Injection luminescent pumping of CaF2: U3+ with GaAs diode lasers. *Applied Physics Letters* 4, no. 3 (1964): 50–52.

Keyes, R. W., E. P. Harris, and K. L. Konnerth. The role of low temperatures in the operation of logic circuitry. *Proceedings of the IEEE* 58, no. 12 (1970): 1914–1932.

Kirschman R. K. *Low-Temperature Electronics*. New York, NY: IEEE Press, 1986, p. 500. No individual items are abstracted in this volume.

Kirschman R. K., W. M. Sokolowski, and E. A. Kolawa, Die attachment for –120 C to +20 C thermal cycling of microelectronics for future Mars Rovers: An overview. In *ASME International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems* (InterPACK), Maui, Hawaii, June 1999.

Kovacs G. T. A. *Micromachined Transducers Sourcebook*. New York, NY: WCB/McGraw-Hill, 1998.

Lengeler B. Semiconductor devices suitable for use in cryogenic environments. *Cryogenics* 14, no. 8 (1974): 439–447.

Lo C. C. and B. Leskovar. Cryogenically cooled broad-band GaAs field-effect transistor preamplifier. *IEEE Transactions on Nuclear Science* 31, no. 1 (1984): 474–479.

Luiten A. N., A. G. Mann, M. E. Costa, and D. G. Blair. Power stabilized cryogenic sapphire oscillator. *IEEE Transactions on Instrumentation and Measurement* 44, no. 2 (1995): 132–135.

Lutz J., H. Schlangenotto, U. Scheuermann, and R. Doncker. Semiconductor properties. *Semiconductor Power Devices* (2011): 17–75.

Manheimer M. Cryogenic Computing Complexity. Intelligence Advanced Research Projects Activity (IARPA). http://www.iarpa.gov/index.php/research-programs/c3, visited July 1, 2015.

NASA. The Right Stuff for Super Spaceships, NASA, www.NASA.gov, 2002.

NASA. Voyager Instrument Cooling After Heater Turned Off. NASA, http://www.jpl.nasa.gov/news/news.php?release=2012-017, 2012.

NASA. The James Webb Space Telescope—About the Webb., http://jwst.nasa.gov/about.html, 2014a.

NASA. The James Webb Space Telescope—Images of the Spacecraft, http://jwst.nasa.gov/images.html, 2014b.

NASA. Advanced Space Transportation Program Fact Sheet, NASA, www.NASA.gov, 2014c.

NIST. Material Properties, NIST Material Measurement Laboratory, Cryogenic Technologies Group, http://www.nist.gov/mml/acmd/structural_materials/cryogenicmatprop.cfm, 2015.

Noel J. G., A. Bogozi, Y. A. Vlasov, and G. L. Larkins. Cryogenic pull-down voltage of microelectromechanical switches. *Journal of Microelectromechanical Systems* 17, no. 2 (2008): 351–355.

O'Donnell K. P. and X. Chen. Temperature dependence of semiconductor band gaps. *Applied Physics Letters* 58, no. 25 (1991): 2924–2926.

Oskin B. Yeti Robot Finds Cracks in Antarctic Ice. Discovery News. Discovery Communications, LLC (2013).

Otte R. F. and C. L. Fischer. Cryogenic Connection Method and Means. U.S. Patent 3,740,839, June 26, 1973.

Pan Ming-Jen and Clive A. Randall. A brief introduction to ceramic capacitors. *IEEE Electrical Insulation Magazine* 26, no. 3 (2010): 44–50.

Park K., A. Marchenkov, Z. M. Zhang, and W. P. King. Low temperature characterization of heated microcantilevers. *Journal of Applied Physics* 101, no. 9 (2007): 094504.

Patterson R., A. Hammoud, and S. Gerber, Performance of various types of resistors at low temperatures. NASA Glenn Res. Center, Cleveland, OH: GESS Rep. NAS3-00142 (2001).

Patterson R. L., A. Hammond, and S. S. Gerber. Evaluation of capacitors at cryogenic temperatures for space applications. Conference Record of the 1998 IEEE International Symposium on Electrical Insulation, vol. 2, (1998) pp. 468–471. *IEEE*, 1998.

Prance, R. J., A. P. Long, T. D. Clark, and F. Goodall. UHF ultra-low noise cryogenic FET preamplifier. *Journal of Physics E: Scientific Instruments* 15, no. 1 (1982): 101.

Price S., T. Phillips, and G. Knier. Staying Cool on the ISS. NASA Science, March 21, 2001.

Rahim M. K., J. C. Suhling, D. S. Copeland, M. S. Islam, R. C. Jaeger, P. Lall, and R. W. Johnson. Die stress characterization in flip chip on laminate assemblies. *IEEE Transactions on Components and Packaging Technologies* 28, no. 3 (2005): 415–429.

Rawal S. P. Metal-matrix composites for space applications. *Journal of Materials* 53, no. 4 (2001): 14–17.

Rossie. Multi-Layer Insulation for Satellites and Other Spacecraft Image. http://www.rossie.com/mli.htm, visited July 1, 2015.

Savage C. J. Thermal control of spacecraft. In *Spacecraft Systems Engineering*, 4th edition (2003), Hoboken, N.J.: Wiley,: 357–394.

Shapiro A. A., S. X. Ling, S. Ganesan, R. S. Cozy, D. J. Hunter, D. V. Schatzel, M. M. Mojarradi, and E. A. Kolawa. Electronic packaging for extended mars surface missions. *Proceedings of the 2004 IEEE Aerospace Conference* vol. 4, pp. 2515–2527. IEEE, 2004.

Shapiro A. A., C. Tudryn, D. Schatzel, and S. Tseng. Electronic packaging materials for extreme, low temperature, fatigue environments. *IEEE Transactions on Advanced Packaging* 33, no. 2 (2010): 408–420.

Shatter, W. J., H. S. Kong, G. H. Negley, J. W. Palmour, *Institute of Physics Conference Series* 137 (1994): 155.

Sivaswamy S., R. Wu, C. Ellis, M. Palmer, R. W. Johnson, P. McCluskey, and K. Petrarca. System-in-package for extreme environments. In *Electronic Components and Technology Conference, 2008* (ECTC 2008). 58, pp. 2044–2050. *IEEE*, 2008.

Streetman B. G. and S. Banerjee. Solid state electronic devices. Vol. 2. Englewood Cliffs, NJ: Prentice-Hall, 1995.

Teverovsky A. Performance and reliability of solid tantalum capacitors at cryogenic conditions, Greenbelt, MD: NASA Goddard Space Flight Center, 2006.

Teyssandier F. and D. Prêle. Commercially available capacitors at cryogenic temperatures. In Ninth International Workshop on Low Temperature Electronics (WOLTE9), Guaruja, Brazil, June 2010.

Tighe T. S. Flex cable connector for cryogenic application. U.S. Patent 6,045,396, issued April 4, 2000.

TOP500 Lists November 2014. Toplist 500—November 2014. Top 500, Nov. 2014.

Trautmann E., L. Ray, and J. Lever. Development of an autonomous robot for ground penetrating radar surveys of polar ice. In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 1685–1690. *IEEE*, 2009.

Trisca G. O., M. E. Robertson, H. Marshall, L. Koenig, and M. A. Comberiate. GROVER: An autonomous vehicle for ice sheet research. In *AGU Fall Meeting Abstracts*, vol. 1, p. 0691, San Francisco, California, December 2013.

Tudryn C. D., B. Blalock, G. Burke, Y. Chen, S. Cozy, R. Ghaffarian, D. Hunter, M. Johnson, E. Kolawa, M. Mojarradi, D. Schatzel, and A. Shapiro. Low temperature thermal cycle survivability and reliability study for brushless motor drive electronics. *IEEE Aerospace Conference*, 2006 p. 37. *IEEE*, 2006.

Ulrich R. K. and S. Rajan. Thermal performance of an MCM flip-chip assembly in liquid nitrogen. IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part A 19, no. 4 (1996): 451–457.

Wang R. T. Operational Parameters for the Superconducting Cavity Maser. Pasadena, CA: California Institute of Technology, 1988.

Wauters F., I. S. Kraev, M. Tandecki, E. Traykov, S. Van Gorp, D. Zákoucký, and N. Severijns. Performance of silicon PIN photodiodes at low temperatures and in high magnetic fields. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 604, no. 3 (2009): 563–567.

Yamamoto H. Multichip module packaging for cryogenic computers. IEEE International Sympoisum on Circuits and Systems, pp. 2296–2299. *IEEE*, 1991.

Zhang, Y. M., V. Borzenets, N. Dubash, T. Reynolds, Y. G. Wey, and J. Bowers. Cryogenic performance of a high-speed GaInAs/InP pin photodiode. *Journal of Lightwave Technology* 15, no. 3 (1997): 529–533.

Zweben C. Metal-matrix composites for electronic packaging. *Journal the Minerals, Metals & Materials Society* 44, no. 7 (1992): 15–23.