Low temperature Electronics for Space Exploration

Space exploration requires a wide range of temperatures in which it is desirable to operate electronics for control, sensing, communications and actuations. In the equatorial region of the Moon, the temperature varies from -180 °C (night) to 120 °C (day), while in the permanently shadowed craters the temperature remains at -230 °C. The Table.1 gives the variations in the temperature for space exploration.

Space exploration needs electronics to be capable of operating under low temperature, have high reliability, higher system efficiency and longer life time.

The term Low Temperature Electronics (LTE) means operating the electronics well below the temperature of “traditional” range of −55 °C to +125 °C essentially down to absolute zero (0 K). The lower limits defined for the electronic components are -40 °C for commercial usages and -55 °C for military / space applications. These limits are defined by the materials used in the manufacturing and the techniques used in the design and process of these components. The various characteristics of the devices and circuits may improve / degrade upon cooling to lower temperatures.

For astronomical/planetary observations, many sensors (such as X ray and γ ray detectors) need to be operated at very low temperature to have high resolution data. For example, Gamma Ray Spectrometer (GRS) onboard Selene/KAGUYA used High Purity Ge detector for detection of γ rays and this detector was cooled to below 77 K using Stirling cryocooler.

At the same time, to achieve the required performance and reduce the noise from these cooled sensors, front end electronics should also be placed as close to the detectors as possible, which eventually needs electronics also to be operated at lower temperatures.

The operation of electronics at lower temperature depends upon many parameters like component type, its material, bonding between two different types of material etc. The cooling to lower temperature improves many parameters for electronic components, like for MOSFETs – gain, latch up, speed, parasitic resistances and capacitances values are improved. The cooling of amplifiers reduces the noise and cooling of transistors reduces the thermal noise.

Availability of Parts:
Parts availability to operate at such lower temperatures is a critical issue. The options available are: either have custom fabrication of the parts or select from the available resources. The selection between these options involves a number of factors like performance requirements, budget available, expected operating life of the design and application criticality. Each of these options has its own advantages and drawbacks.

Option1:
Custom parts can be designed to meet the lower temperature requirements, but this needs both time and expense. As the manufacturing of these components can take a longer time for the intended applications and at the same time this may need a lot of budget. The number of manufacturers, willing to undertake this job is also limited. Moreover, these organizations can change their area of business and discontinue the service.

Option2:
Selection of the components from the available resources is less expensive and can be faster than the other option. In this option, the procedure followed is to buy batches of the parts, test for the intended functionality and reli-

Table 1: Variations in the temperature with distance from the SUN. (Credit: John D. cressler, “Low temperature electronics”, 6th International planetary probe workshop – short course, 6/21/08).

<table>
<thead>
<tr>
<th>PLANET</th>
<th>Solar Intensity (W/m²)</th>
<th>Surface Temp (K)</th>
<th>Spacecraft Temp (K) (Internal power = 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>9149</td>
<td>100-700</td>
<td>448</td>
</tr>
<tr>
<td>Venus</td>
<td>2620</td>
<td>740</td>
<td>328</td>
</tr>
<tr>
<td>Earth</td>
<td>1371</td>
<td>288-293</td>
<td>279</td>
</tr>
<tr>
<td>Mars</td>
<td>591</td>
<td>140-300</td>
<td>226</td>
</tr>
<tr>
<td>Jupiter</td>
<td>51</td>
<td>165</td>
<td>122</td>
</tr>
<tr>
<td>Saturn</td>
<td>15</td>
<td>134</td>
<td>90</td>
</tr>
<tr>
<td>Uranus</td>
<td>3.7</td>
<td>76</td>
<td>64</td>
</tr>
<tr>
<td>Neptune</td>
<td>1.5</td>
<td>72</td>
<td>51</td>
</tr>
<tr>
<td>Pluto (dwarf planet)</td>
<td>0.9</td>
<td>40</td>
<td>44</td>
</tr>
</tbody>
</table>
ability for the operating conditions of the intended applications. Finding of the suitable parts involves lots of trial and error. These components can’t be used directly for the temperature outside of their specified operating temperature range and consequently the problem often encountered is that manufacturer may change the fabrication process of the components such as it still meets the specifications for conventional use but their characteristics at low temperature are again unpredictable.

These conventional temperature range electronics can be used in such lower temperature scenario by use of insulation and/or heating mechanism for the components. There are two ways for heating: Passive heating or Active heating.

Passive heating has a limited lifetime which may not be sufficient for the desired application. Active heating technique requires additional resources like power and other subsystems. Warm electronics boxes are used on the rovers to keep the electronics warm in their specified temperature limits. All these passive & active techniques add weight, complexity to the system and this also limits the operating life of the system, which may be less acceptable or less practical. This technique also needs lots of test and debug prior to launch.

In subsequent sections, the effect of thermal, mechanical and electrical properties of the materials used in the electronic components, which decide the ultimate achievability of LTE are discussed, with scope for future developments in this important field.

Operation of the electronic system:
Electronic systems usually have combination of passive (resistor, capacitor and inductor) and active (diodes, transistors, MOSFETs, integrated circuits etc.) components for the desired applications. The challenge comes when any of these components change behavior at the lower temperatures. The general behavior of the components on decreasing the operating temperature is as follow:

- Thermal conductivity of metals, ceramics and silicon increases, and for metal alloys it decreases
- Coefficient of thermal expansion decreases, while young’s modulus and yield strength increases
- Electric resistivity decreases, while dielectric constant of printed circuit material nearly remains constant

The operating temperature limits of a semiconductor device depend on a number of factors:

Problems in testing electronics at low temperature:
While testing the circuit operations at lower temperatures, suitable test setups are required to be designed. The problem of operating these electronics at lower temperature is the repeatability factor. If a LTE breaks down, the repair process require heating the circuit back to room temperature, fixing the problem, and then cooling the circuit back down to low temperature. This process involves extra time and at the same time this is far more complex than repairing a circuit at room temperature.

To deal with this issue, two methods can be proposed. The first method is prevention – take the proper time and resources needed to ensure that the circuit will function correctly. The second is redundancy – if one component is weak, put another in parallel such that if one breaks down the other is still available.

Both solutions, however, are expensive. The first method is not only costly at the ensuring stage but also if the circuit (unluckily) breaks down, more capital would be required doing repairs. The second method may not be feasible, as reproducing and storing an entire component in such low temperature conditions may be even costlier.

Increasing the operating temperature capability of the electronic components is more suitable, which can increase the operating life of the overall system and will reduce the size, weight and complexity.

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The properties of the basic semiconductor material (Si, GaAs, SiC)

The type of device (diode, bipolar transistor, field-effect transistor)

The design of the device (materials, geometry and dimensions)

The materials and designs of the contacts and interconnections

The assembly and packaging techniques and materials

How long the device needs to operate at low temperature.

Change in the characteristics of electronic components:

There are many atomic, ionic and electronic processes taking place in a component. Some of these determine the characteristics at conventional temperatures, but there are many which come into play at lower temperatures. For example, Si freeze-out occurs at -230 °C which causes major changes in operation of Si devices below this temperature. The capacitance of electrolytic capacitors and ceramic capacitors degrade at lower temperatures, as their operation depends on the movement of ions. The variations caused by temperature in the various parameters of different materials are explained below:

Energy band gap:
The energy band gap between conduction and valence bands (also known as forbidden gap) varies with the materials and with the combination of materials.

From Fig. 1, band gap energy depends upon the percentage of the materials, and at the same time, this band gap energy increases, with the decreasing temperature (Fig. 2). To operate components / devices at certain temperatures both of these parameters should be taken into account to achieve the required results.

Mobility:

Mobility is defined as the drift velocity of a particle under an applied electric field. MOSFET mobility depends on four scattering parameters: Phonon scattering, surface roughness scattering, bulk charge columbic scattering, and interface charge columbic scattering. The variation in the mobility with temperature is shown in Fig. 3.

As temperature decreases, the mobility of electrons and holes increases due to reduction in the atomic lattice vibrations, but this is also dependent on the doping concentration of the MOSFETs.

Interconnect resistance:
The number of free carriers in the material does not increase, with the decrease in temperature. At room

Figure 2: Variations in the energy band gap with the temperature. (credit: David Wolpert et al., “Temperature Effects in semiconductors”, http://www.springer.com/cda/content/document/cda_downloaddocument/9781461407478-c1.pdf)

Figure 3: Carrier mobility versus temperature (credit: David Wolpert et al., “Temperature Effects in semiconductors”, http://www.springer.com/cda/content/document/cda_downloaddocument/9781461407478-c1.pdf)
temperature conditions, a conductor’s DC resistance depends on the dimensions of the contact. As the temperature is lowered, DC resistance starts decreasing and hence conductivity of the metal increases. When this resistance becomes zero, the phenomena is called “superconductor”. So the metals used for the interconnections in the semiconductor, show decrease in the resistance values with the decrease in the temperatures.

**Latchup:**
The latchup occurs when the electrons follow a path, which was not intended. Latchup can occur by capacitive coupling during switching, current / voltage spikes etc. In MOSFETs, when the current supply by the power supply is lower than the holding current, latchup does not occur. As the temperature decreases, the holding current increases, which reduces the possibility of latchup.

**Passive devices:**
There have been measurements on the performance of passive components like resistors and capacitors. The effects of temperature on electrical characteristics of commercially available resistors and capacitors are shown below: The resistors and NPO capacitors, show not much change in the values with the decreasing temperature. However for X7R, capacitance values decrease with the decreasing temperature. The following figure shows the comparison between 3 types of capacitors with the temperature variations. The Mica capacitors show excellent stability with temperature, while tantalum electrolytic capacitors show significant decrease in capacitance value, when operated below -20°C.

**Batteries:**
Energy storage in power system for space applications is a very important parameter. There should be sufficient

![Figure 4: Resistance as a function of temperature for Susumu Co., Ltd. High precision, RR series, 0.1%, 1/10W thin film resistors (data for 19 resistors)](image1)

![Figure 5: Resistance as a function of temperature for Yageo America precision thick film chip resistors, 1%, 1/8W (data for 19 resistors)](image2)
efforts for energy storage for low temperature applications. Lithium based batteries are considered to be good for low temperature applications for short term space missions. The following figure shows the variations in the current – voltage characteristics of lithium battery. The above characteristics are taken at various loads at a given test temperature. The above figure shows that battery underwent a drop in its voltage / current performance with decreasing temperature.

Solders: The solder materials (PbSn, InSn and InPb alloy etc.) have melting point temperature from 150 to 300 °C. Usually these solder materials should be able to operate at lower temperatures, compared to higher temperatures (> 300 °C). But challenge comes in play, when at lower temperatures these solders tend to relax and multiple temperature cycle leads to failure. These solders (usually called soft solder), typically show increase in strength with decreasing temperatures but at the same time their ductility decreases. This requires appropriate selection of solder material for the lower temperature applications. Pb rich PbSn shows a good stability in ductility down to cryogenic temperature, but as Sn content increases (> 40%), this solder material becomes brittle. People have experienced that small amount of Sb to Sn rich solders, avoids the problem of low ductility at lower temperatures.

Packaging technology: Packaging provides the electrical interconnections between different devices; this also provides the mechanical and environmental protection for the device. For low temperature applications changes in the mechanical properties of the packaging materials should be considered, before selecting the appropriate material. There are many materials which are flexible and compliant at room temperatures (such as silicone encapsulant), but become very much rigid at cryogenic temperatures. The design should be made in such a way that packaging is minimal. Coefficient of thermal expansion (CTE) should be chosen appropriately, so that the differences are as low as possible. When these two differing materials are connected, they are usually caused by the different reactions due to the difference in their CTEs and with decrease in temperature, thermal stress increases.

There are many other parameters as well as, which change their behaviour at lower temperatures. So before selecting some devices / components for operation at non-conventional temperatures, all these parameters are needed to be looked into.

New devices for Low temperature: It is true that for the space exploration, new devices have to be developed which can work at LN (77 K) temperature or even at lower temperatures. New device technologies...
There are many other devices as well which are able to work in such low temperature scenarios. But most of these developments are still under research field. Once these devices are proven to work at such low temperatures and they come into large productions, then the development of instruments for exploring the various planets will overcome the other heating/cooling systems. This will finally reduce the weight, power and other requirements and will improve the performance of the overall system.

Although future development in electronics are difficult to predict, it is likely that low temperature electronics will continue when ultimate performance and operation in extreme environments is needed from devices, circuits, and systems.

Further Reading:

Figure 9: Forward voltage – current characteristics of SiGe diodes as a function of temperature

Figure 10: DC gain (Ic/Ib) as a function of temperature for a SiGe HBT (Hetero junction bipolar transistor) (Fig. 9 & 10 – credit: Richard L Patterson et. al., “Electronic components for use in extreme temperature aerospace applications”, 12th international components for military and space electronics conference, San Diego, CA, Feb. 11-14, 2008)

such as silicon-on-insulator, silicon-germanium, silicon carbide and gallium nitride have been developed, which are making possible electronics capable of operating over very wide temperature ranges. Few results are shown here:

Fig. 9 shows that for SiGe diodes, knee voltage changes from ~0.4 V (at +85°C) to ~0.8 V (at -196°C), while Fig. 10 shows the change in the current gain for SiGe HBT. By using such devices, extra temperature control units can be avoided.

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