Extreme Design: Developing integrated circuits for -55 degC to +250 degC

What Honeywell did to meet the challenge of designing analog silicon ICs for aerospace and deep-drilling applications

(*Editor's note:* This is the next in our series of "Extreme Design" stories, where a project is focused largely on one overwhelming priority. www.planetanalog.com)

In addition to being key to consumer-electronic devices which have opened up so many mass-market applications, semiconductors are essential to systems which are much less glamorous and friendly. Industrial environments can be extremely severe and commercial electronics will not survive. However, there continues to be the need to add electronics to mechanical devices to increase the functionality and extend performance.

Certain applications have to operate beyond the melting point of many materials used in commercial electronics. These include aircraft and turbine engine controls, as well as monitors and down-hole well-drilling tools for energy exploration, **Figure 1**. These environments have extreme temperatures, vibration, pressures and moisture levels, among other stressful factors.

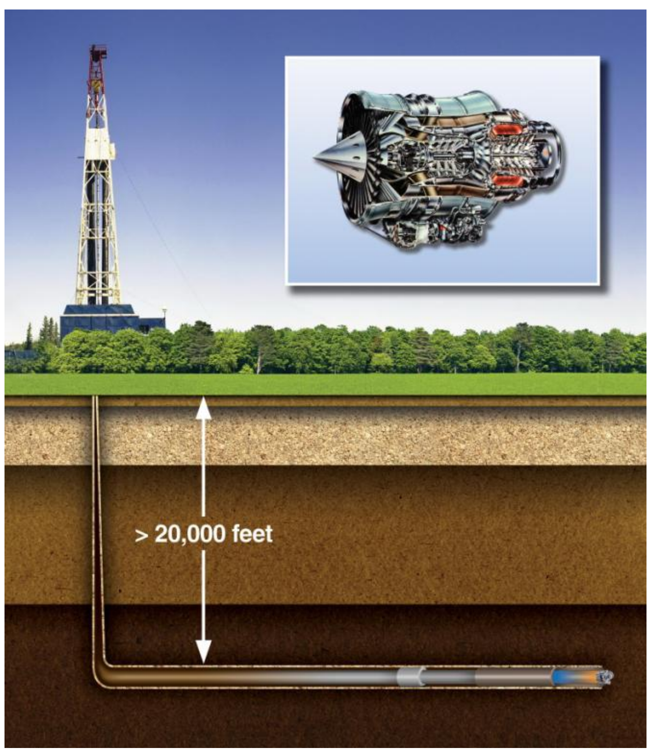

Figure 1: High temperature applications: Down-hole drilling and jet engine controls

Conventional electronics built for consumer products have amazing functionality but cannot withstand these rugged industrial environments. Manufacturing semiconductors for these environments presents a number of challenges. As the temperature goes above 175°C, many aspects of silicon processes, material properties, and design constraints change, and the availability of companion components is severely limited. Several of these challenges and their solutions will be addressed.

Technology for high-temperature electronics
Honeywell has created an integrated circuit (IC) technology which can operate in these harsh environments for long periods of time (five years at 225°C). The silicon on insulator (SOI) CMOS technology is used because of its characteristic of low leakage current at high temperatures (HT), allowing operation from -55°C to above 225°C. The high-temperature performance, and several design and manufacturing techniques, set these electronics apart from conventional wide-range ICs, **Figure 2**. SOI CMOS extends that range to a practical limit of approximately 300°C.

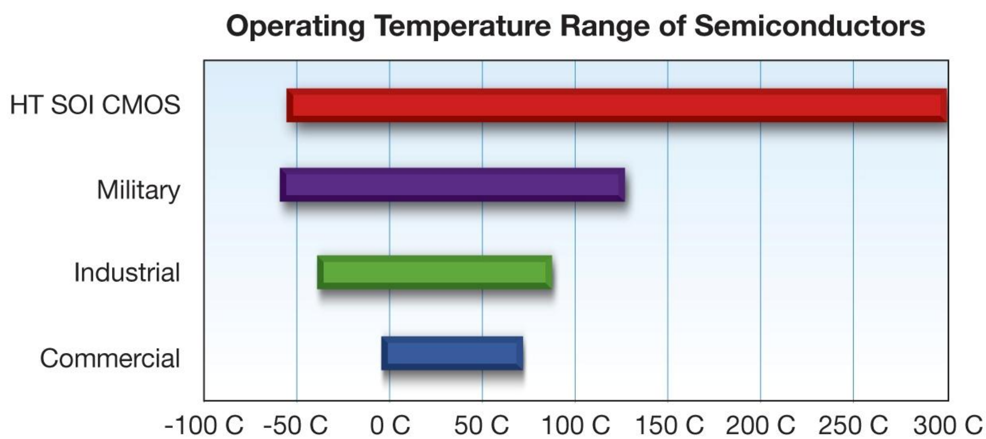

Figure 2: Semiconductor temperature ranges

A broad range of ICs have been developed using this SOI CMOS technology, for aircraft engines, turbine power-generation engines, and down-hole drilling tools that measure pressures, vibrations, chemical parameters, stress, and similar parameters. The ICs perform the same basic functions as today's commercial electronics, including digital, analog and mixed signals devices. The products allow electronic systems to be developed and implemented in environments that cannot be supported by commercial electronics. ICs are packaged in ceramic through-hole packages to survive the rugged environment, **Figure 3**.

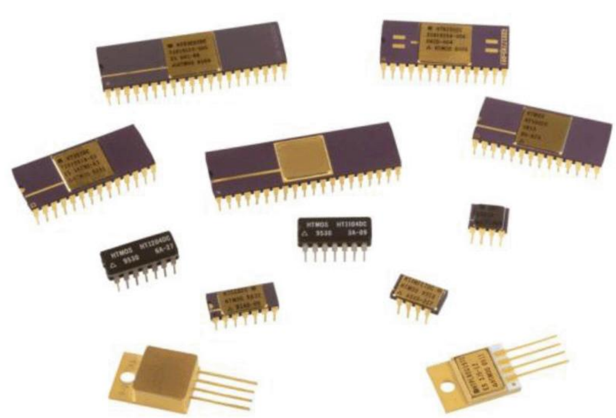

Figure 3: High-temperature IC products

Leakage current
At high temperatures, the overriding limitation for semiconductors is leakage current of the individual transistors. The largest part of the solution comes from the use of a SOI CMOS in place of bulk CMOS. SOI greatly reduces the amount of leakage current in the IC, which impacts all types of designs. In digital designs, the large number of devices on an IC can create excessive power consumption and reduce performance. Analog designs will tend to lose resolution for measuring and controlling very small signals. Devices such as an HTOP01 require stable references to support input offset currents of less than 1 nA and input offset drift of less than 0.2 μV/°C.

There are two main leakage paths to address: the larger one is leakage from the drain to the silicon substrate, and there is a smaller component of leakage from the drain to the source.

With bulk CMOS, there is a large area directly from the drain to the source. This leakage path is eliminated when using SOI CMOS. The silicon dioxide (SiO_2) insulates the drain from the bulk substrate. The difference is illustrated in **Figure 4**.

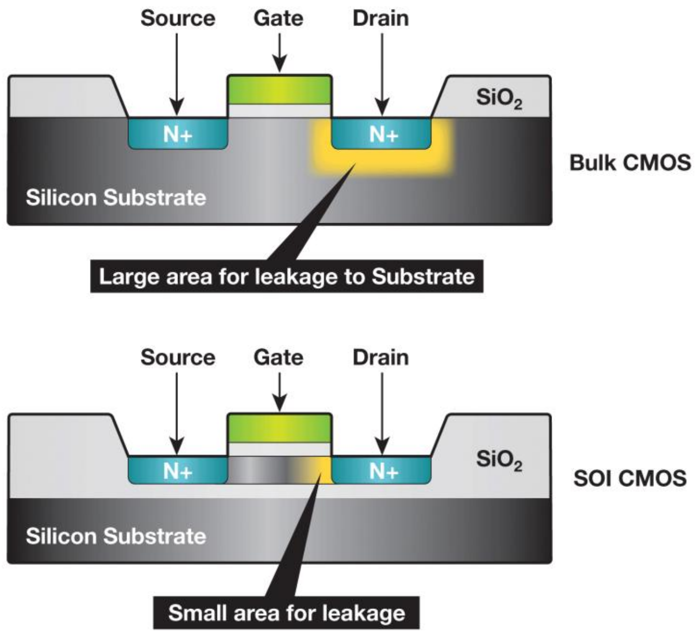

Figure 4: Comparison of leakage-current paths of bulk CMOS and SOI CMOS.

To further reduce the leakage current, modifications are made to the transistors to shift the threshold voltage (V_T). By increasing the V_T, the transistor stays in its "off state" and reduces leakage at high temperatures until a higher voltage is applied. With the combination of SOI CMOS and shifting V_T, designers can achieve a reduction in leakage current of three orders of magnitude (1000x less current) compared to standard bulk CMOS at 250°C, **Figure 5**. Another benefit for digital circuits is the "on to off" current ratio of more than five orders of magnitude is maintained at 250°C. For the analog circuits, it improves the stability of linearity over temperature.

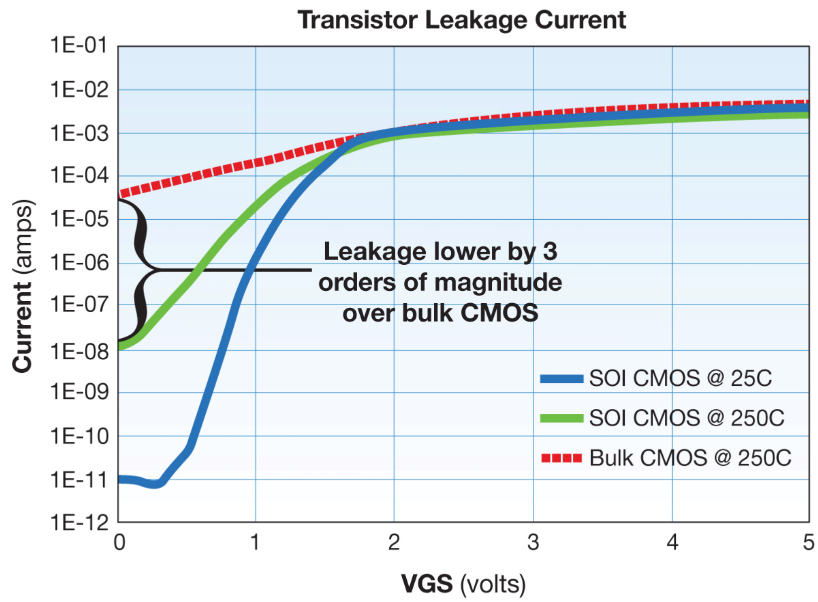

Figure 5: Comparison of transistor leakage current between SOI CMOS and bulk CMOS

IC design

A number of IC design challenges must be addressed for high-temperature applications. This begins with the modeling of the transistors and other devices over temperature. In general, the modeling is straightforward with minor modifications. Temperature coefficients are non-linear and the performance curves are generated by empirical methods. For digital applications, the standard BSIM3 models for simulation are adequate.

However, more complex transistor models are created for the analog domain due to the differences in performance needs. Other components used for IC design include MIM (Metal-Insulator-Metal) capacitors and CrSi alloy thin-film resistors. These are required to operate within tight margins over the broad temperature range but are stable and predictable at high temperatures.

Another technique used to improve performance and reduce leakage current is to balance the P-channel and N-channel devices, relative to leakage current. The objective is to match the values and minimize the net current. This is easy and beneficial when working with semiconductors. When working with analog circuits, a key element to maintaining linearity of the circuits is to temperature-compensate the reference bias circuits. Temperature stability and matching components is crucial to op amps, regulators, and ADCs.

System design

As you build the high-temperature IC into a full design, external factors bring new constraints. The designer must address three main factors:

What are the temperature zones of the system?

What functions are required in each zone?

Do components exist to support the design?

As one addresses these three questions, partitions and communication interfaces become apparent. The designer must match function, performance and component availability to an application, **Figure 6**. Basic elements for a design of a commercial product may not exist for high-temperature applications. System partitions are strongly driven by component availability for each temperature zone. The IC designer must be aware of these factors so he can design into the IC the needed functions or be sure a supplier is identified.

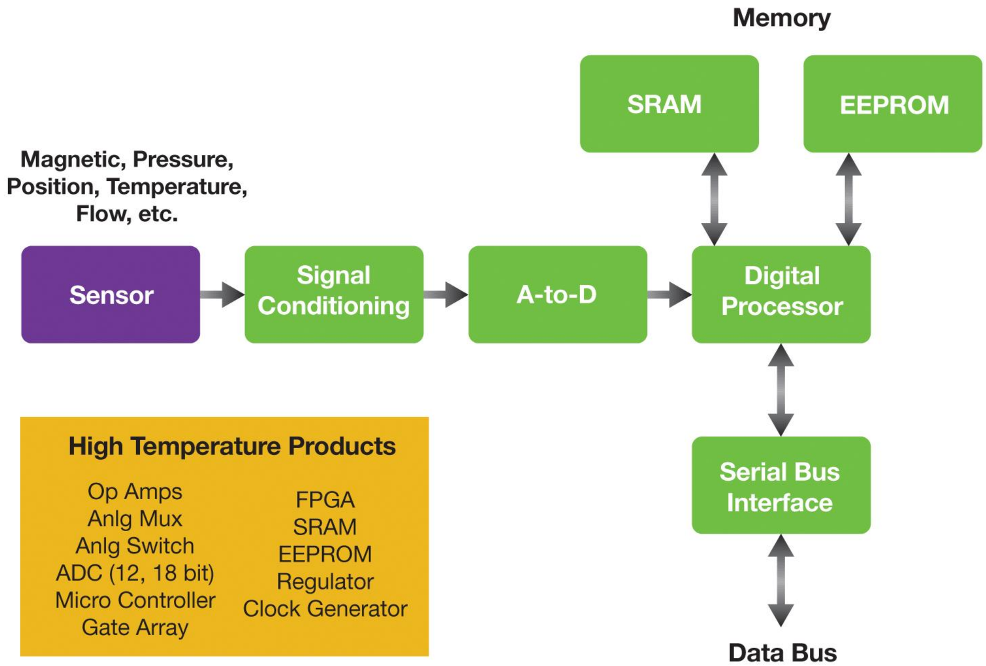

Figure 6: Data acquisition block diagram

Materials and packaging

Continuous operation at temperatures above 150°C places a number of unique constraints on the materials commonly used for assembling and packaging a high temperature IC. Some of the specific items are that must be managed are:

Consideration of interconnect conductors: Different materials are used within the IC are based on resistivity and electromigration. Aluminum is used on IC interconnect traces and tungsten on vias.

Decreased electrical resistance of insulation materials causing additional leakage: The leakage current between pins of ceramic packages at temperatures below 150°C are usually negligible. At higher temperatures, the levels can become significant. They can become high enough to become issues with sensitive analog inputs. Special effort has been made to characterize various material compositions and ceramic suppliers to ensure the resistance is sufficiently high.

Increased chemical and metallurgical activity within and between materials: One of the main areas of focus here is the gold and aluminum interface. Over time and high temperature, the inter-metallic bond changes characteristics. Most of the ICs have aluminum pads and the packages have gold pads. The selection of the wire joining the two is crucial to operation at high temperatures. Both electrical resistance and bond strength are two factors. It was determined that aluminum wire bonds are preferred. This gives a monometallic bond at the IC (Al-to-Al) and an Al-Au intermetallic bond at the package. The reliability of the Al-to-Au bond at the package has been successfully verified with over 10,000 hours of operation at 225°C.

Stability of adhesives: Traditional die attach adhesives such as epoxies are not stable at temperatures above approximately 150°C. Alternative high-temperature adhesives, such as Cyanate Esters, must be qualified and used in high temperature applications.

Reliability
High-temperature, long-life operation is defined by Honeywell as five years at 225°C. Operation at even higher temperatures is possible, but for a reduced period of time. Many applications have a lower nominal temperature, with brief excursions to high levels. **Figure 7** illustrates the lifetime versus temperature for SOI and commercial bulk silicon.

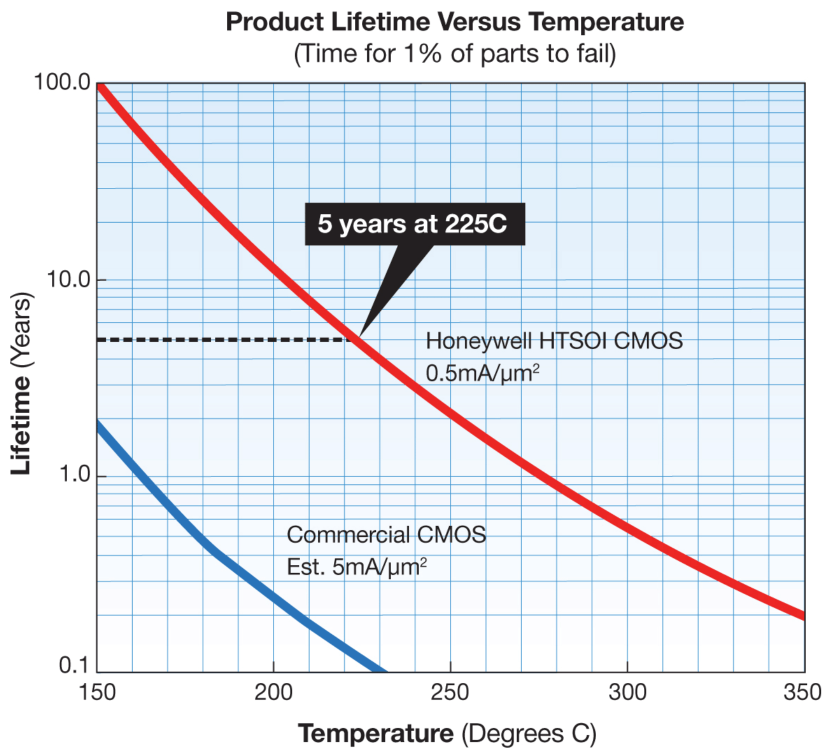

Figure 7: Semiconductor lifetime based on electromigration

There are a number of reliability characteristics which need to be addressed to achieve this performance. The high temperature impacts the lifetime of materials and changes their characteristics. These are associated the current in the conductors (electromigration) and voltage applied to insulators (gate oxide). These include:

Electromigration: This phenomenon is the actual moving of atoms to the point where open circuits can occur due to the current in the traces. Adequate conduction material in the interconnect is used to compensate for the inevitable atomic migration during the lifetime of the circuit. Barrier metal is also used between metal and silicon to slow the migration. Refractory materials can be used to replace the common soft metal, aluminum, used for interconnects. However, these materials usually have a higher resistivity and are definitely unsuited to be used in bonding pads. Therefore, trade-offs are made to use the best materials and for high-temperature devices.

Time-Dependent Dielectric Breakdown (TDDB): This is a long-term failure mechanism in the gate oxide of MOSFETs. It is a result of long-time application of relatively low electric field (as opposite to immediate breakdown, which is caused by ESD). It is accelerated by high temperature. Although this does not require a specific modification to the process, special screening processes are implemented to be sure processing impurities do not impact long term reliability.

Conclusion
Using the base SOI CMOS technology and implementing a number of design, screening and reliability techniques, ICs such as Honeywell's HTOP01 and HTADC12 are enabling high-temperature analog and digital signal processing. The main objective is to broaden the portfolio of highly reliable, extreme-temperature ICs and expand electronic system capabilities for temperatures of -55°C to 250°C.

About the author
Thomas Romanko is an Electrical Engineer who has been with Honeywell for 25 years. He has an extensive background in integrated circuits for radiation-hardened space applications, high-temperature, and wireless communications.
He is currently the Business Development Group as Technical Customer Interface and Applications Engineer for High Temperature and Radiation Hardened products, which serves both commercial and aerospace applications. He is located at Honeywell Aerospace in Plymouth, MN which is a Silicon On Insulator (SOI) CMOS foundry.

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