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Elimination of Heat-Shielding for Geothermal Tools

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ABSTRACT

This report focuses on Sandia National Laboratories' effort to create high-temperature logging tools for geothermal applications without the need for heat-shielding. Presently, tool electronics can operate up to 300°C with a few limiting components operating to only 250°C. An actual well log to 240°C without shielding is discussed. The first prototype high-temperature tool measures pressure and temperature using a wire-line for power and communication. The tool is based around the HT83C51 processor. The HT83C51 processor with 32K RAM has been tested in excess of 300°C within the lab environment.

This development is being made possible through the development of Silicon-On-Insulator (SOI) electronics. This new category of electronics allows for manufacturers to qualify silicon electronic components to 225°C for continuous operation with reduced performance and life at 300°C. There is presently a short fall of available SOI components for tool building. Only recently, an SOI analog-to-digital inverter became available. Thus, designing circuits using only SOI components has limited function. In the future, additional components should become available, which will increase design functionality.

At temperatures above 225°C there is a loss of performance or accuracy compared to conventional Dewared logging tools. To increase accuracy at temperatures above 225°C will require the creation of second generation electronics for key components. For example, the analog-to-digital conversion can be no better than the voltage reference used. At present, the SOI voltage reference has increased error over 225°C and failure at about 270°C. A second-generation device made from wide-band-gap semiconductors at silicon carbide (SiC) is needed.

To power new unshielded tools and instruments downhole will require the development of high-temperature batteries. At Sandia National Laboratories, we are working to develop a new battery using molten salt technology. These batteries, often called thermal batteries, require a minimum temperature to activate the battery. At Sandia National Laboratories, we have developed usable thermal batteries, which start operating below 200°C and continue to operate up to 250-300°C.

Introduction

In the past 30 years, electronics have been qualified for operating within three temperature ranges: commercial, industrial, and military. New higher temperature applications for commercial and military aircraft have pushed for the development of high-temperature electronics, creating a new 225°C standard. Table 1 provides the aforementioned temperature ranges in degrees Celsius and Fahrenheit.

Table 1 Temperature for Various Grades of Electronics.

Grade	Operating Temperature Range
Commercial	0 to +70°C (0 to +158°F)
Industrial	-25 to +85°C (-13 to +185°F)
Military	-25 to +125°C (-25 to +257°F)
High Temperature	-25 to +225°C (-25 to +225°F)

These new high-temperature components are based primarily on Silicon-on-Insulator (SOI) technology. Figure 1 shows a CMOS transistor pair which was constructed using common bulk silicon and SOI. The buried oxide layer in the SOI forms a non-conducting layer wherein the N-substrate common to lower temperature electronics is a semi-conductor material. This buried oxide layer reduces leakage current by a factor approaching 100X, [1].

Obviously, the benefit of this new technology is the possibility of displacing, or at least reducing, the heat-shield (Dewar). Presently, the Dewared flask is one of the most costly components in any geothermal logging tool, [2]. There are numerous benefits to replacing the Dewar flask with high-temperature electronics. Following is a list of advantages of Dewared and non-Dewared tools.

Advantages of high-temperature electronics over Dewared tools:

- Unlimited time downhole, whereas the Dewar flask provides only 8-12 hours in most applications

- Reduced outer dimension of tool. The flask adds 50-100mm to the outer dimension.
 - Lower cost by reducing possible downhole damage to tool from overheating or replacing the expensive Dewar flask
- Advantages of using Dewared tools over new high-temperature electronics:

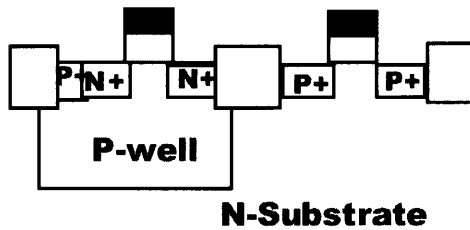
- There is a broader range of electronic components from which to choose when designing a logging tool;
- There is usually a higher degree of accuracy in measurements due to greater component selection and reduced operating temperature range.

Sandia National Laboratories is working to demonstrate designs for operating tools at temperatures up to 300°C and to encourage the continued development of electronic devices which would regain the accuracy of measurements at such elevated temperatures. This report discusses Sandia's ongoing activities regarding high-temperature issues.

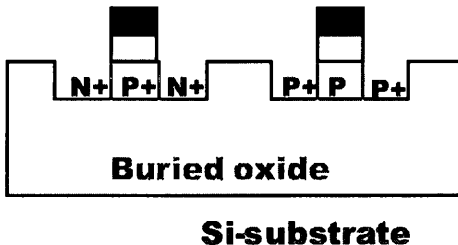
For purposes of this discussion, a very simple block diagram indicating the elements needed in most downhole instruments is illustrated in Figure 2.

Looking up from the base of Figure 2, note that the sensors measure wellbore information and convert it to an electrical voltage or frequency. These changes in voltage or frequency are conditioned by analog circuits in a form acceptable for conversion from analog to digits. Once in digital form, the microprocessor can store the result in memory or transmit them to the surface.

An electronic circuit needs power, usually DC voltage and current. Power can be sent downhole via an e-line or it may be contained within the tool by use of high-temperature batteries.



A: Cross-section of bulk CMOS inverter



B: Cross-section of a SOI CMOS inverter

Figure 1. Comparing standard bulk silicon and SOI construction for CMOS. CMOS is a type of digital logic gate made from two transistors. The buried oxide layer of SOI prevents loss of leakage current from the CMOS inverter

Sensors

High-temperature sensors can be categorized in three sections: readily available, soon to be available, may never be available.

Readily Available: Many geothermal sensors are already available for high-temperature applications. Some sensors have always been in direct contact with the wellbore environment in conventional logging tools. Recently additional new pressure sensors and accelerometers have become available for new high-temperature applications.

Soon to be Available: We are aware of several companies currently working on high-accuracy, high-temperature pressure and inclination sensors. There is reasonable evidence that magnetometers and collar counters can be produced to perform at 300°C. In this case, the use of high-temperature materials can lead to new high-temperature sensors, which are based on older designs.

May Never be Available: Sensors such as Sodium Iodide [NaI(Tl)] using photon multipliers are used for gamma spectroscopy. This sensor will require a technology breakthrough in order to operate above 200°C.

Analog Circuits

In the recent past, the main obstacle to developing high-temperature instrumentation (>200°C) has been the lack of analog devices, which are used to amplify, filter, buffer, or otherwise interface sensor signals to digital converters. Any inaccuracies in an analog device can ripple through as a sensor

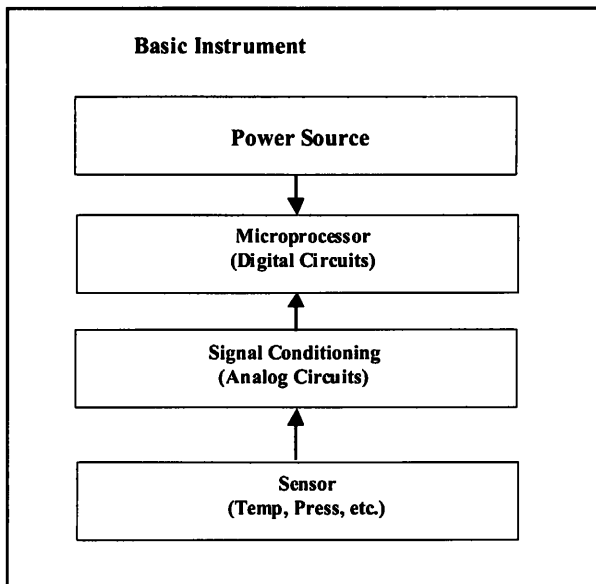


Figure 2. Basic block diagram of a downhole instrument. The sensor information is processed first by analog circuits and then by digital circuits.

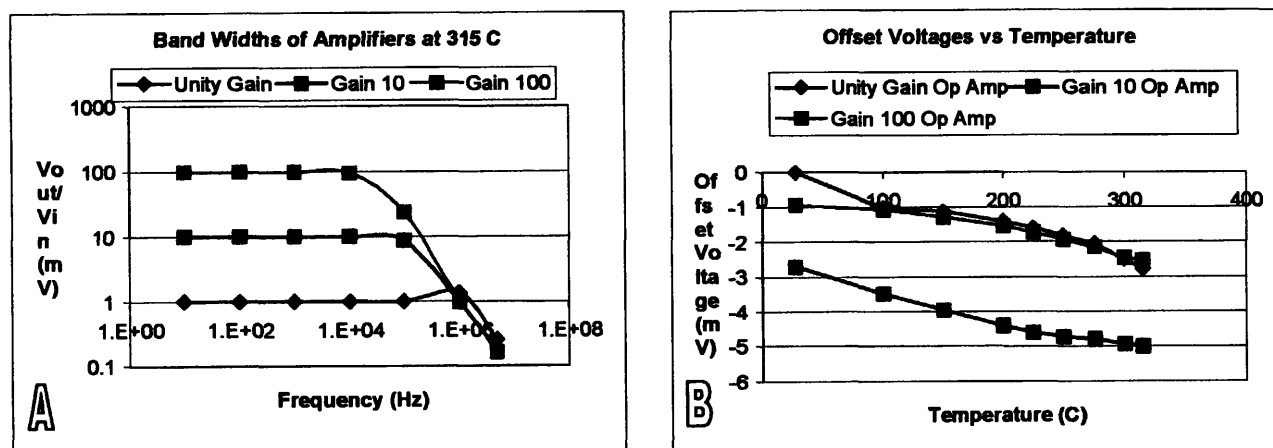


Figure 3. Several operational amplifiers were tested with three different gains, unity, X10, and X100. A) Shows the bandwidth of the amplifiers at 315°C. The unity gain bandwidth is over 100KHz. B) Shows the offset (DC Error) as a function of temperature..

error. By nature, analog integrated circuits are sensitive to leakage currents caused by elevated temperatures. This is where SOI has the greatest impact. SOI technology reduces leakage currents. As such, testing of Honeywell's HTMOS™ quad operational amplifier (HT1104) shows real promise. Figures 3A and 3B represent actual test data taken from SOI operational amplifiers. Although insufficient component testing was performed to qualify these devices for 300°C operation, the measured results are extremely positive, showing useful device performance up to 315°C.

The frequency response is good enough for most sensors such as accelerometers, pressure transducers, low frequency acoustics, and others. However, DC offset voltage error is a problem for DC-dependent sensors such as strain and inclination. In phone conversations with people who are responsible for this device at Honeywell's Solid State Electronics Center, we have learned that second generation devices reducing offset voltages will be available soon.

Other devices, as the analog-to-digital (A/D) HT574 operates up to 280°C, see Figure 4. Researchers at Sandia National Laboratories believe that this is the first demonstration of a commercially available A/D converter to operate at these temperatures.

This is an important development because A/D converters are complex devices. These devices must capture sensitive analog signals coming from various sensors and perform the conversion to digital where the information can be retrieved and save by the microprocessor for later consumption by the human operator.

As a result of this one device, a sample and hold, D/A converter, voltage reference and success approximation comparator circuits have been demonstrated. The circuit limiting temperature operation was the voltage reference. The other circuits continued to operate up to 300°C without failure. At that point, testing was terminated. More follow on testing is to be performed, however, these early results are very encouraging.

Other devices, such as linear voltage regulators, have also functioned at very high temperatures (>250°C). The limiting

factor for the A/D and linear voltage regulator is the voltage reference, which is a common electronic component needed in virtually all instrumentation.

In the future, Sandia National Laboratories hope to have a program for developing a voltage reference from wide band-gap semi-conductors. These new voltage references will not only improve the operating range of linear voltage regulators, but will also increase the overall measurements accuracy of the instrumentation. With this improvement, the new high-temperature electronics may provide room temperature measurement accuracy.

Digital Circuits

Advanced CMOS military specification electronic devices often continue to operate as high as 300°C without the added benefit of SOI technology. Even so, SOI digital circuits have the advantage of keeping supply currents considerably lower at elevated temperatures, thus reducing downhole power requirements. More importantly, SOI devices are tested and qualified for high-temperature applications at the factory, resulting in greater dependability downhole.

At Sandia, we have tested complete microprocessor designs using SOI microprocessors and memory. Other required digital interface logic came from the advanced CMOS family 54ACXXXX from National Semiconductor Inc., [Figure 3]. These devices continue working above 270°C but bias currents increase significantly and component life is greatly shortened.

The microprocessor circuit is the basic building block for our new high-temperature logging tool. This circuit was tested to 300°C and above with several hundred operating hours at temperatures between 200°-300°C. Future plans include incorporating all digital logic to SOI by developing an SOI ASIC (Application Specific Integrated Circuit), See Figure 4. This ASIC will increase functionality and allow memory addressing up to 500K bytes for data storage.

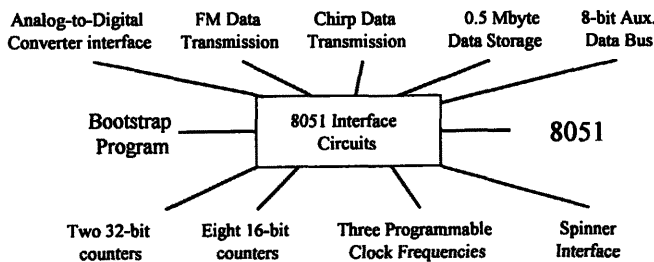


Figure 4. This is the proposed high-temperature digital ASIC design. This new ASIC will reduce component count while reducing circuit size and increasing functionality. This device is being funded by DOE Geothermal Research Program and will be made commercially available.

Power Sources

A downhole tool has two sources for power: wire-lines or batteries. Both have concerns at 300°C. High-temperature wire-lines are expensive and have a limited life at temperatures approaching 300°C. Commercially available batteries have limited operation up to 200°C.

At Sandia, the development of thermal batteries is considered the best option. Thermal batteries use molten salt technology. At room temperature, thermal batteries are inactive. Only until the battery salts have been melted will the battery become active. Most thermal batteries become active at temperatures above 300°C.

Our battery development effort is aimed at closing the gap between the starting temperature of thermal batteries and the upper limitation of conventional batteries. Work is ongoing to develop a thermal battery with useful power production below 200°C and upper temperature limitation above 300°C. Such batteries give the tool designer the option of using them in

memory tools, which can be deployed on slick-line cable or conventional wire-line.

Sandia's First Pressure/Temperature Dewarless Tool

Two prototype electronic packages were built. One used a machinable ceramic board for mounting the electronic devices. Device interconnects were done by hardwiring and then spot welding to ensure reliable performance up to and above 300°C. The second used a more conventional approach. Electronic devices were mounted on polyimide board with high-temperature solder used for electrical connections. This second package has a temperature limitation of ~250°C. It was the second prototype system was used in an actual geothermal well, logging pressure and temperature.

The tool successfully logged a 240°C/12000 foot geothermal well. It operated within the well for more than 56 continuous hours at temperatures between 225-240°C. While the prototype tool was designed more for high-temperature functionality than absolute accuracy, it did provide a favorable well temperature/pressure profile. Figure 5 shows the high-temperature data plotted against a conventional Dewared tool. Here the temperature profiles of both tools were within 2% of each other. The high-temperature tool has the potential of having accuracy's very nearly the same as conventional Dewared tools.

However, there is an accuracy loss in the pressure measurement. The Dewared pressure sensor is based on crystal oscillator technology, where the high-temperature pressure sensor uses strain gage technology. This leads to an accuracy loss in pressure measurement. The Dewared tool having +/-0.02% accuracy sensor while the high-temperature sensor is +/- 4%. The high-temperature tool was also less linear in it's response as can be seen in Figure 5.

Both of these pressure errors will be improved in next generation tool designs. Better high-temperature pressure sensors

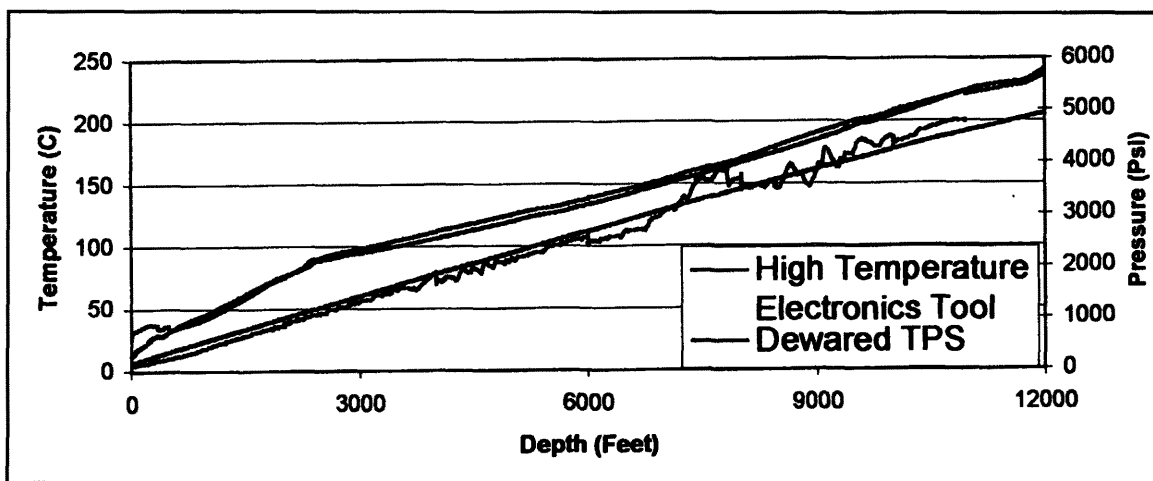


Figure 5. High-temperature tool operating without a heat-shielding flask (Dewar) is compared with the reading from a conventional Dewared logging tool. The upper pair of traces are temperature, the lower pair are of pressure. The temperature readings compare favorably while the pressure reads are tracking rising pressure but suffer from nonlinear increments. The next generation high-temperature tool will use a 12bit analog-to-digital converter for pressure measurement. This converter was not available at the time of the test. The new converter should greatly improve the pressure readings.

are being designed and an analog-to-digital converter is now commercially available from Honeywell. We feel confident that the A/D converter will significantly improve the tools performance.

The Future is Beyond 300°C

Silicon-on-insulator technology is limited to approximately 300°C. This is particularly true for instrumentation-quality electronics. As stated previously, there are efforts to improve the performance of a few temperature-limiting components. For example, the SOI voltage reference has stability problems above 270°C. Research to create a stable voltage reference from wide-band gap semiconductor materials is ongoing. The same can be said with regards to the clock oscillator circuit.

One of the principal semiconductor material technologies is SiC. SiC devices have proven operational at temperatures that exceed 350°C. SiC has the unique advantage of both high temperature operation and great chemical stability, making it a desirable material for micro-machine technology. Thus, future SiC devices may contain electronics and sensors on a single chip.

The fundamental problem with SiC is the cost of production. Ideally, new SiC components, supplementing SOI for improved performance, will develop new markets for high-temperature wide-band gap materials. These first simple devices can pave the way to greater commercial acceptance of the technology, resulting in increased demand and eventually lower costs.

Conclusion

Silicon-on-Insulator (SOI) technology for high-temperature electronics is becoming commercially available. This new technology is pushing the operation temperature of downhole tool

electronics to 225°C and higher. Thus, there is a possibility of eliminating the Dewar flask used on most geothermal tools. The advantages of a Dewarless tool include its slimmer design, unlimited wellbore exposure, and lower cost.

Work at Sandia National Laboratories has proved that simple data logging tools can be designed for temperatures as high as 300°C. However, there is a trade-off in measurement accuracy. Continuing development of second generation high-temperature electronics with supplemental wide-band gap (SiC) devices will improve high-temperature measurement accuracy while eventually extending the operating range of high-temperature electronics to 350°C or more.

Acknowledgments

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