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Recent Advancements in High-Temperature, High-Reliability Electronics Will Alter Geothermal Exploration

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ABSTRACT

New high-temperature semiconductors that were being studied in the universities ten years ago are now becoming a commercial reality. SiC (Silicon-Carbide) micro-machine (MEM) pressure sensors are already commercial. This technology can easily operate up to 500°C (752°F). Another high-temperature semiconductor process called Silicon-On-Insulator (SOI) has been used to build microprocessor data acquisition systems. These systems can operate up to 300°C within a logging tool WITHOUT any heat shielding. Already, high-temperature electronic sensor systems can continuously monitor deep within a geothermal well at up to 225°C. Future systems will operate hotter and last longer. This paper looks at the future of geothermal logging, drilling and reservoir monitoring equipment. Future control systems could actually guide drilling and control production while never leaving the well. Examples of how aerospace requirements are driving the development of new high-temperature electronics and sensors are given.

1. INTRODUCTION

Unshielded electronic control and measurement systems that can operate for many years at 300°C (572°F) are technically achievable. High temperature (HT) semiconductor technology has reached the point of operating at these temperatures. There are two principle HT semiconductor technologies, SOI (Silicon-On-Insulator) and SiC (Silicon-Carbide). The majority of the HT components available today are fabricated using SOI technology. SOI technology is designed for a 5 year operating life at 225°C with most components continuing to operate up to 300°C for hundreds for hours, e.g. Swenson and Ohme, (1996). SiC is being utilized in extreme temperature applications. With SiC semiconductor technology, reliable operation at temperatures in excess of 500°C (752°F) is possible!

Clearly, high temperature electronics is an enabling technology in all aspects of future geothermal developments. However, one of the first and most important applications of high temperature electronics will be tools designed to help keep geothermal power plants on-line, Henfling and Normann (2002). High temperature tools can impact this trend almost immediately by giving operators the ability to monitor reservoir characteristics on a much more frequent basis, or in the case of a downhole reservoir monitoring system, continuous real-time data is achieved. This is the area in which new tools will immediately benefit the industry through improvements in production, re-injection and well maintenance strategies.

Future applications will enhance production and reduce the cost of drilling. For example, MWD (Measurement-While-Drilling) tools used within the oil patch are already being designed for +225°C. These tools can steer the bit to the geothermal production zones. But how will the drillers know where the production zones are located?

In areas of micro-quakes, seismic sensors installed deep into the hot formation will clearly identify fault zones with accuracies never before seen by surface instrumentation. SiC MEM seismic sensors permanently monitoring deep within competent rock will have several orders of magnitude of seismic signal over surface sensors. This results in higher seismic frequencies, improving location determination. Where surface sensors can detect micro-quakes to within ~1000 ft, these deep sensors can improve accuracy to <100 ft.

In areas lacking naturally occurring micro-quakes, seismic while drilling sensors will look ahead of the drill bit. Again, SiC MEM sensors cannot only operate at very high temperatures but they can handle the shock and vibration of drilling. Not only is SiC a very robust material on its own, a SiC MEM device can easily be designed for both vibration sensitivity and shock tolerant. For example, a 2 G MEM vibration sensor from Silicon Designs is rated for 2000G shock. [Silicon Designs www.silicondesigns.com model 1010 MEM Accelerometer]

Based on SOI technology originally developed for aircraft engine controls [1], Sandia has developed and field-tested a PT (Pressure/Temperature) logging tool and three reservoir monitoring tools. After a brief discussion on Sandia's approach to high temperature electronics and a look at the next generation HT components (both SOI and SiC), the remainder of this paper will elaborate on the high temperature downhole reservoir monitoring system.

2. APPROACH

The Sandia approach is simple: "Adapt and expand high-temperature electronics technology to downhole applications". For example, the aircraft industry has been the driving force for most commercial HT electronic components. The components needed for electronic aircraft engine controllers are nearly identical to the components needed for a simple logging tool. So, when Sandia demonstrates a high-temperature logging or drilling tool, we are helping the industry develop dual-uses, helping to increase production and helping to keep costs low.

Most geothermal applications will require features and components not required for aircraft. For example, special batteries and narrow tubular packaging must be developed for unshielded geothermal logging tools, e.g. Normann and Guidotti (1996). Once new high temperature designs are demonstrated for geothermal wellbore applications, the geothermal industry will gain never-before-realized instrumentation capabilities that will lead to new approaches in well logging and reservoir characterization.

Sandia realizes that many factors are stifling the development of high temperature tools by the geothermal service companies. Some of these factors include: 1) lack of SOI devices to complete the SOI component set available from Honeywell; 2) a means to reduce the learning curve required to develop a downhole tool; 3) identifying and testing components and sensors needed to build a complete system; 4) development of high temperature (250-300°C) batteries, e.g. Normann and Guidotti (1996); and 5) fabrication issues such as the development of better solders and fluxes.

Sandia has been working to solve the above issues, and has designed a custom ASIC (Application Specific Integrated Circuit) to complement the SOI components available from Honeywell. The ASIC design was fabricated at Honeywell using their SOI technology. Sandia and Honeywell have arranged make this SOI device available to geothermal tool builders. The part number for this device is HT83SNL00. Sandia has designed and assembled "learning kits" to decrease the development time of designing tools. Under the DOE sponsored Sandia High-Temperature Electronics program, we have an ongoing testing and evaluation program to identify and qualify suitable high temperature components and sensors. Geothermal service companies can utilize Sandia component information without restriction, which will result in reduced cost to develop high temperature Dewarless tools that were not possible even a short time ago, e.g. Normann and Henfling (2000).

As more and more HT tools are successfully fielded, the need for HT electronics will increase. The proven reliability of SOI and SiC technologies has helped to spark ideas for many additional HT applications. Agencies such as NASA, JPL, USAF and NETL now have active HT programs. The components that are developed for these programs will enhance the capabilities of all HT applications. Geothermal temperature requirements are comparable to the aforementioned programs; by providing input during the development stage of these components, many will be suited for future downhole reservoir monitoring and drilling tools. A list of sources for new HT technology follows:

3. LIST OF NEW HT APPLICATIONS DRIVING FUTURE DEVELOPMENT

3.1 NASA-Glenn Research Center

NASA is an active supporter of the HT electronics industry. NASA has several planned, unmanned missions to Venus and Jupiter. The expected temperature of Jupiter probes is 350°C and Venus's surface temperature is a hot 460°C! As such, NASA has invested in SiC semiconductor technology.

Sandia will be receiving a SiC MEM pressure sensor designed for 600°C (1112°F) operation from the Glenn Research Center. This technology has considerable potential for long-term wellbore pressure monitoring within geothermal wells. Sienna Technologies, Inc is making the pressure sensor commercial. They have already identified a number of industrial applications including potential for geothermal well logging and permanent monitoring.

Sandia will test the pressure sensor for measurement drift and hydrogen degradation at 320°C (608°F) for permanent deployment applications within geothermal wells. We expect this sensor to pass laboratory testing and move on to actual wellbore deployment in 2005.

NASA–Glenn is supportive of producing SiC MEM sensors for space missions and making simple changes to enhance the commercial applications. This way, they can create commercial support for the technology. This commercial support is important as space missions are separated by many years.

3.2 Jet Propulsion Laboratory

The Jet Propulsion Laboratory (JPL) is starting a HT University Consortium to develop new components needed to support upcoming missions to Venus. One of the first components being considered for development is a SiC seismic sensor system. A SiC seismic sensor will enable seismic signatures to be measured on Venus by NASA probes. Such a seismic system could also be used for long term monitoring of natural micro-earthquakes and hydro fracturing deep within the geothermal reservoir.

3.3 US Air Force

The USAF is a major player in the development of new high-temperature components. The USAF has a program to develop the More Electric Aircraft (MEA). In the MEA, a distributed electric power system will displace heavy hydraulic systems. Naturally, high-temperature electronics components and sensors must be highly reliable, operating without failure for many years. The expected temperature ranges are from 200°C to 300°C.

The USAF feels that they can reduce weight, reduce system complexity and reduce maintenance. Overall the cost savings is in the billions of USD each year, [May 20, 2004: HiTEC 2004, Joseph Weimer, AFRL presentation titled "High-Temperature Power Electronics for the More Electric Aircraft"]. Commercial airline engine manufacturers are also looking at electronic engine controls to reduce weight and increase reliability.

One of the components needed for the MEA program is a SiC power transistor. Power transistors for aircraft engine controls have already been demonstrated and are now becoming commercially available from SemiSouth Laboratories. Sandia has already received eight test samples for evaluation. These transistors are rated for 6 amperes, 200-600 volts at 300°C. Future devices are planned for 100 amperes.

USAF projects motor control systems as large as 50kW. Sandia has supplied high-temperature SOI digital circuits to two private companies hoping to couple SOI digital circuits with SiC power devices for a host of power control applications.

In fact, the idea of driving large electric drilling motors downhole has caught the attention of the oil patch. Here electric DC current would be cabled down the drill pipe and used by motor controller electronics to power a 3-phase, 100kW motor used to rotate the drilling bit. This is made possible because SiC power devices can handle 6 times the power of silicon devices for the same given space.

3.5 Sandia National Laboratories

Clearly, Sandia is a supporter of new high-temperature component development for the geothermal industry as already described. Most of Sandia effort is in filling in the missing pieces to enable building new high-temperature drilling and logging tools from the components being developed within the aerospace industries listed above. Much of Sandia's efforts have been with SOI (Silicon-On-Insulator). This technology is coming from Honeywell. It has been proven for an operating life of 225°C (430°F) for five years without failure. Sandia tested digital (microprocessors, logic, and memory devices) have continued to operate up to 300°C (572°F) for hundreds of hours.

Sandia development activities directly support high-temperature geothermal drilling and logging tool development. In particular, Sandia is working with Silicon Designs and Diamond Research and Development to develop a 225°C steering tool sensor for directionally guiding the bit while drilling.

Sandia is also working with companies like General Atomics to develop a new type ceramic high-temperature battery. These batteries can supply power at temperatures as high as 500°C.

However the major Sandia project is to build a drilling diagnostic tool for detecting and correcting drilling problem before rig time is lost. This project is called the DWD or Diagnostics While Drilling project. This tool will be rated for 225°C operation and survivable to 250°C.

One last but important Sandia project is the demonstration of high-temperature electronics and sensors for long-term monitoring of geothermal wells. These demonstrations are designed to build confidence within the geothermal industry and support component manufacturers with a means for actual wellbore testing. One such long-term test has been highly successful and is described in the following section.

4. RESERVOIR MONITORING SYSTEM DEMONSTRATION

To date, three reservoir monitoring systems have been successfully deployed. The first two systems were funded by the USGS to help in their work in reliably predicting volcanic unrest. Several examples of pre-eruptive groundwater pressure changes show that fluid pressure monitoring can be a valuable tool for detecting volcanic unrest. Subsurface magma movement affects fluid pressure by deforming the earth's crust and heating subsurface fluids. Moreover, intriguing interactions between earthquakes and volcanic unrest are believed to be mediated by fluid-pressure effects. By monitoring downhole pressure and temperature with very high resolution, and interpreting the resulting data in the context of crustal deformation, seismicity, and gas emission, valuable volcanic information may be gained from these tools. The two systems are currently installed in moderate temperature wells located near Mammoth Lakes, CA. One of these tools will be redeployed this summer in a moderate temperature well located in Hawaii.

The third system was deployed in a Coso Naval Test Range well. The tool has been installed within the well at 3100 ft using wire in tubing. At this point the nominal temperature is 192°C (379°F). This is the hottest location within the well. Prior to the tool going into the well, the tool was oven tested for one month at temperatures between 180 and 200°C. The purpose of this field test is to demonstrate the increased reliability gained when using manufacturer-qualified high-temperature electronic components. Sandia is working with a large number of manufacturers to build a complete logging tool using only commercially available components. We hope to continue this test for the next two years. At the time of this report, this system has been deployed for approximately 260 days. Combining the oven tests prior to deployment with the ongoing field test, the tool is approaching 6500 hours at elevated temperatures.

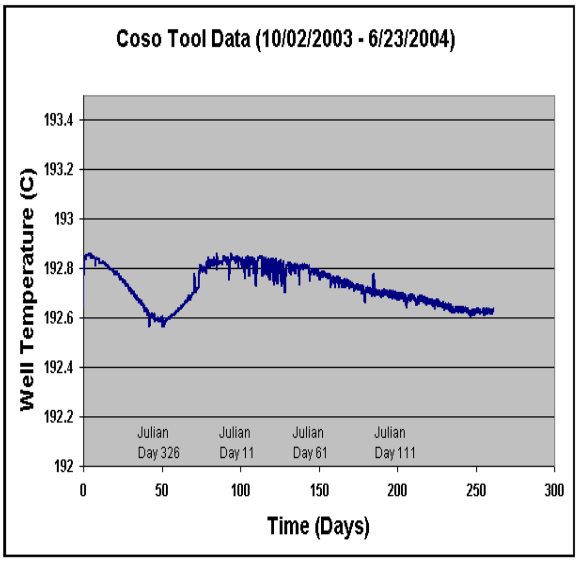

Figure 1A: Well temperature data for the first 260 days

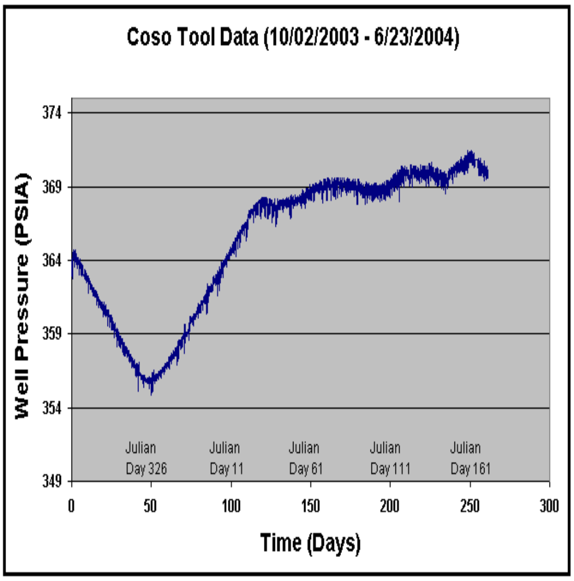

Figure 1B: Well pressure readings the first 260 days. There has been no correction for earth tides.

The charts shown in Figures 1A and 1B show the temperature and pressure measurements we have made thus far at the Navy well.

The Sandia tool used in this experiment, uses a Sandia designed SOI chip from Honeywell. Utilizing, the chip (part number HT83SNL00), we were able to design and build a reservoir monitoring tool capable of sustained operation at 240°C. The Navy tool utilizes a subset of the HT83SNL00 capabilities that include 3 bridge type measurements, 13 additional analog measurements, 2 precision frequency measurements, and 3 low resolution frequency measurements. We currently have a Quartzdyne pressure transducer and a RTD temperature sensor installed in the tool. We are making additional measurements such as downhole voltage to help monitor the status of the electronics. Quartzdyne, Inc. has performed extensive life testing to 225°C and is capable of resolving better than .008 psi and a temperature measurement better that .008°C. The tool was designed to enable additional sensors to be installed as they become available. This approach also lends itself to "customizing" the tool to meet a particular application without a complete redesign.

The tool is 7 feet long and less than two inches in diameter. The tool can be deployed using a standard logging cable or wired tubing.

The data is transmitted uphole using FSK (Frequency Shift Key) data encoding. The carrier frequency chosen for this tool is approximately 70kHz. This data transmission scheme is ideal for transmitting through long wires and has been used by Sandia for many years at wire lengths up to 15,000 feet (the length of our logging truck's cable), although not limited to this distance. The data is transmitted every 3 seconds. This rather lengthy time interval is needed for the Quartzdyne transducer. Since the Quartzdyne sensors are frequency based, sufficient gate time is needed to maximize the resolution of the pressure and temperature sensor. The acquisition time interval for the tool is determined based on the application and the sensors required.

5. CONCLUSIONS

The time is right to exploit the use of high temperature electronics based on SOI and SiC technology. Sandia has achieved a barefoot logging tool for accurate pressure and temperature (PT) measurements without heat-shielding. A natural progression from the PT Tool was the reservoir monitoring system. The benefit from this type of system is threefold. The data in itself is important and additionally, the system is a test bed for newly developed high temperature sensors and is a testimonial for the reliability of tools designed with new high-temperature electronic components and sensors.

Sandia is working to "seed" the geothermal service companies to excite new development. By providing an inexpensive learning kit to service companies, the time it takes to develop a high temperature tool is greatly reduced. This approach will help move this technology into the field more quickly and will in turn raise the industry standard on high temperature drilling and well logging.

Lab and field-testing is essential when developing high temperature tools. By lab and field-testing tools and components, pitfalls can be identified early and strategies can be made to eliminate them.

As more and more HT tools are successfully fielded, the need for HT electronics will increase. The proven reliability of SOI and SiC technologies has helped to spark ideas for many additional HT applications. The components that are developed for these applications will enhance the capabilities of all HT applications.

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