THE AMERICAN OIL & GAS REPORTER®
NOVEMBER 2005
The "Better Business" Publication Serving the Exploration / Drilling / Production Industry

New Paradigm In Electronics Needed To Take The Heat Of Deep Gas Drilling

By John D. Rogers, Bruce Ohme and Randy Normann

MORGANTOWN, WV–The absence of high-temperature electronics poses an obstacle to developing the United States' vast untapped deep gas resources. Enormous amounts of unconventional natural gas are trapped in deep or tight formations, shales, and coal seams in places such as the Gulf of Mexico, the Rocky Mountains, the Mid-Continent region and the Appalachian Basin. Of these reserves, a considerable portion exists in reservoirs 15,000 feet and deeper.

Although domestic natural gas producers have begun to tap this resource, economic and technical hurdles remain before significant quantities can be categorized as economically recoverable reserves.

Deep gas drilling is done in harsh environments. Pressures can surpass 20,000 psi and temperatures can easily exceed 200 degrees Celsius. As the drill bit reaches increasing depths, it also becomes correspondingly important but difficult to monitor downhole conditions. Furthermore, because conventional, off-the-shelf electronic components cannot adapt to high-temperature conditions, new technologies must be developed.

Step One

The U.S. Department of Energy indicates that high-temperature electronics are necessary to develop deep gas resources. Most oil and gas wells are drilled in environments cooler than 200 degrees C, and therefore under the temperature limitations of a typical semiconductor. Commercial silicon integrated circuits (ICs) are rarely specified to operate at temperatures greater than 125 degrees C. Downhole tool providers often create equipment that can withstand temperatures as hot as 175 degrees C by screening electronic parts designed for lower temperatures. However, the screening process is expensive and using components intended for lower temperatures compromises system reliability.

Drilling to greater depths requires a different electronics paradigm. Operators using logging while drilling and measurement while drilling tools, logging tools, and smart well applications must be confident that their electronic components can withstand high temperatures for extended periods.

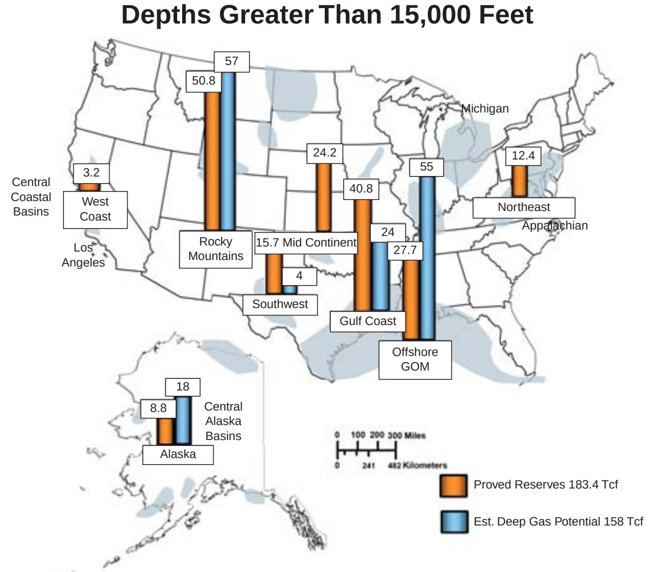
The trend in the oil and gas industry is for sensors and devices that can reliably explore, drill, and produce oil and gas at temperatures above 190 degrees C. A number of major, national, and independent operators have or are developing plans for deep gas wells like the Blackbeard deep well. That partnership of several major oil companies is drilling toward a target deeper than 30,000 feet along the Gulf of Mexico's continental shelf.

At the High-Temperature Electronics Conference in June 2000, the market potential for high-temperature directional drilling services was estimated at $1 billion to $3 billion a year. Relatively low current demand, uncertain projections for return-on-investment, and the fact that high-temperature components are not a core business for electronics manufacturers prevent that industry from striving to widen operating temperature ranges. Nevertheless, the size of the prize waiting below 15,000 feet suggests great potential for electronics capable of taking the heat (Figure 1).

Unfortunately, the components to build the tools for deep well drilling are needed before the market can grow. This historical conundrum slows deep drilling advancements and prevents significant resources from being classified as economically recoverable reserves (Figure 2).

FIGURE 1

U.S. Gas Reserves and Potential at Depths Greater Than 15,000 Feet



The Technology Hurdle

Typically, ICs are designed to perform reliably at temperatures as high as 70 degrees C for commercial grade electronics, 85 degrees C for industrial grade, and 125 degrees C for military grade. Above these design limits, semiconductors fail to meet circuit parameters and permanent changes may cause the circuit to fail.

Wireline surveying and logging tools–if even available for high temperature conditions–may require substantial downtime and carry the risk of well bore instability during deployment. Conventional MWD, LWD and their associated telemetry systems are limited primarily because of temperature constraints on the tools' electronic components.

The cost of imprecise drilling or inaccurate geologic information ranges from deficient productivity to the complete loss of a well. Even small productivity losses can translate into unrecoverable resources worth millions of dollars. More crucial yet is the risk to human life created by technological limitations that cannot provide accurate, real time drilling data and well control.

Fortunately, technology exists to develop reliable high-temperature electronics, and efforts to extend the capabilities and reliability of LWD, MWD, conventional logging tools and other smart-well tools have been under way for some time.

In the late 1990s, the National Energy Technology Laboratory entered into partnership projects with Maurer Engineering Inc., Sperry-Sun, and Halliburton Energy Services. The goal was to adapt what were then considered high-temperature LWD and MWD tools. The teams strove to increase the temperature at which LWD tools would function reliability from 140 degrees C to 175 degrees C, with survivability to 200 degrees C. They also sought to extend the tolerance of the MWD suite of tools from 175 degrees C to 195 degrees C.

The projects offered significant lessons and led to more robust MWD and LWD tools that operate at 175 degrees C and below. However, the projects never reached their ultimate goal of crafting tools that function long and reliably at 200 degrees C and hotter. NETL and its partners came to realize that conventional, off-the-shelf electronics cannot provide the building blocks to produce tools for deep well environments.

It was time to start from scratch.

The Building Blocks

Transistor density and speed define the performance and cost of a digital device. A metal-oxide semiconductor (MOS) tran-

FIGURE 2

Resource to Reserves

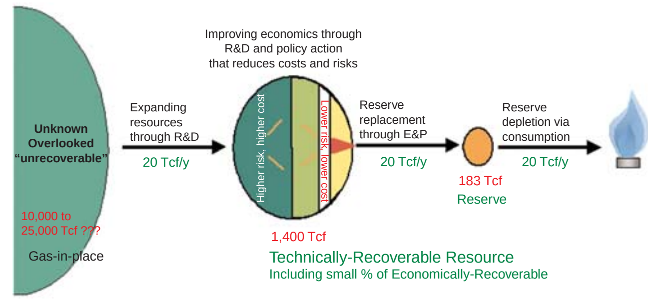


FIGURE 3
Cross Section of a Typical MOS Transistor on Silicon Substrate (Showing a Possible High Temperature Leakage Path)

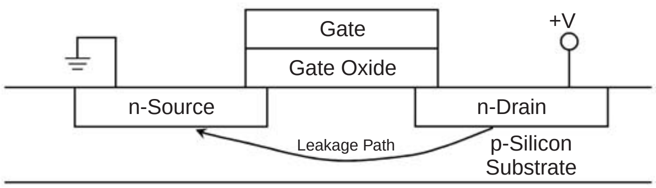
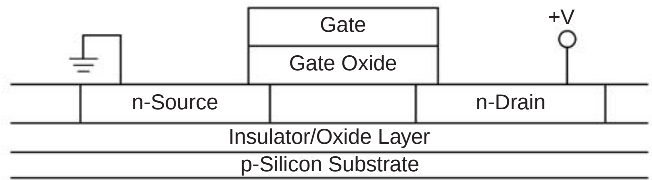


FIGURE 4
Cross Section of a MOS Transistor with SOI Technology



sistor is an electronic switch that consists of three basic elements: the source, the gate, and the drain. Figure 3 is a simplified sketch of a MOS transistor.

The source and drain are regions of silicon that have been implanted with a very small percentage of dopant atoms, such as boron or phosphorous, which change the silicon's conductive properties. The silicon region between the source and drain is doped with a different species, creating a junction with an inherent electrostatic conduction barrier.

The gate sits between the source and the drain atop a thin insulating layer of silicon dioxide. When sufficient charge or voltage is applied to the gate (referred to as the threshold voltage, or V_T), the electrostatic conduction barrier is overcome, establishing a conducting channel in the silicon region directly beneath the gate. In such a case, current can flow from the source to the drain through the silicon substrate.

When the gate voltage is below threshold, the silicon substrate acts as an insulator, and when the gate voltage is above threshold, the substrate acts as a conductor. However, regardless of gate voltages, a small amount of current can leak into the substrate even at conventional temperatures. As temperatures increase, the leakage currents rise dramatically.

Furthermore, the threshold voltage varies according to temperature. Depending on the processing details, such as the thickness of the insulator under the gate and the doping levels in the substrate, the threshold voltage may stand at zero in high temperatures, making it difficult to use the gate terminal as a means to control conduction.

The other basic effects that occur in material as temperature increases are:

- Increased electrical resistance of interconnection materials and contacts;
- Decreased electrical resistance of insulating materials and increased charge leakage;
- Decreased thermal conduction for good conductors;
- Increased thermal conduction for poor conductors;
- Increased thermal expansion coefficients; and
- Increased chemical and metallurgical activity and interactions within and between materials.

Controlling these effects is essential for ICs in devices needed to operate at high temperatures. Additionally, operating life and dependability can be critical, as high temperatures often shorten lifetimes and degrade reliability.

Silicon On Insulator Technology

Silicon on insulator (SOI) technologies greatly reduce junction current leakage between the source or drain and the substrate. The MOS transistors are isolated by a SiO_2 dielectric layer, as shown in Figure 4. SOI limits appear to be 300 degrees C, the point at which junction leakage currents become theoretically prohibitive, but there have been reports of success with operations as hot as 400 degrees C.

Semiconductor processes employed for conventional commercial electronics are incapable of producing components that operate reliably at high temperatures. The upper limit of operation for conventional silicon devices is 200 degrees C, during which their operating life may be measured in a matter of weeks and their functionality may prove erratic. Operating at 300 degrees C for deep gas resources calls for different materials.

These materials could include gallium nitride (GaN), diamond, gallium arsinide (GaAs), or silicon on sapphire (SOS). However, GaN and diamond are less technologically mature than silicon and are difficult to work with. GaAs offers a slight temperature advantage over SOI but lacks SOI's design flexibility. Finally, the cost of growing a layer of silicon on a single crystal of sapphire substrate limits SOS technology.

SOI and silicon carbide (SiC) appear to be the best choices at this time. SiC has found a home for power electronics with the ability to handle severe voltages, currents and temperatures.

SOI and SiC are also complementary technologies. SOI provides the brains, taking measurements, processing data, and making decisions, while SiC supplies the power to turn the motor or open the valve. In 2004, such power transistors became commercially available.

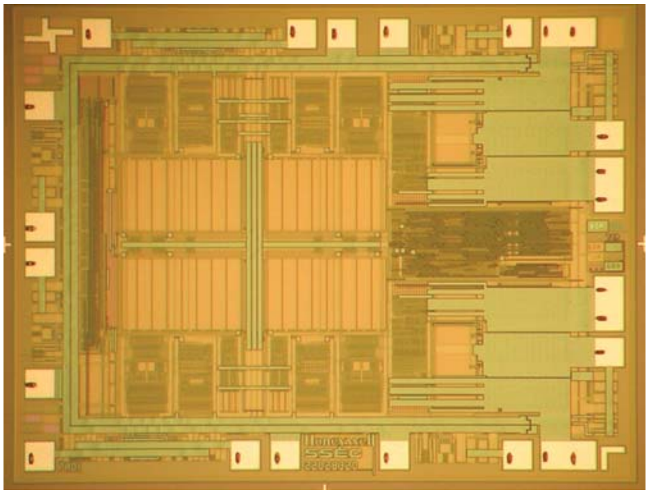
The other materials have not drawn sufficient market or generated the commercial devices to justify process development. The material selected depends on the temperature range and bandwidth needed. Even for high-temperature SOI technology, IC manufacturing is difficult and only a few companies have the foundry capable of making the high quality, high-temperature SOI devices. SOI technology, though not highly employed, is well understood and can produce devices that function in temperatures as high as 300 degrees C.

SOI devices are reliable even at high temperatures. The major factors limiting the life of IC conductors and contacts operating at elevated temperatures are electromigration and corrosion accelerated by the high temperatures.

Trekking Deep

At one Houston energy forum, a panel of operators and service companies recognized that the absence of reliable, high-temperature electronic components prevented the development of vast untapped energy resources, including deep oil and gas. Overcoming this obstacle is the cornerstone of DOE's Deep Trek program to develop technologies for deep natural gas drilling systems.

Since 2002, Deep Trek has funded a technically diverse portfolio of projects addressing technical issues in materials, ce-



NETL-funded tests of the op amp by Sandia National Laboratories have demonstrated that high temperature silicon on insulator technology can perform well at temperatures higher than 300 degrees C. After more than 1,000 hours at 300 degrees C, the tests show a maximum of only 20µV offset voltage.

ments, drilling fluids, deep well completion and drilling methodologies, as well as downhole sensors and communication tools. Its objective is to dramatically reduce the cost and risk of drilling to depths of 20,000 feet and below.

The Deep Trek high-temperature electronics program seeks to overcome the economic and technical barriers to technology development by investing in high-temperature IC technology and infrastructure, while developing electronic components applicable to a wide range of downhole tools and instruments. The program is administered by DOE's Office of Natural Gas through NETL.

Through the NETL gas program, DOE initiated a project in 2003 to accelerate SOI technology development for the oil and gas industry. Partnering with Honeywell International Inc.'s Solid State Electronics Center in Plymouth, Mn., is a joint industry partnership organized to direct the project and share its cost.

Joining DOE to cofund the JIP are major service companies Baker Hughes and Schlumberger, smaller technology developers and service providers Quartzdyne and NOVATEK, major oil and gas operator BP, and aerospace company Goodrich Corporation Aerospace Engine Systems. Additional membership is needed to continue this basic development, preferably by oil and gas operators, who will ultimately benefit the most from more reliable tools.

DOE provides $6.7 million in funding, while the JIP and Honeywell shoulder a $2.9 million cost share. The JIP members recommended and prioritized more than two dozen components. The highest ranking components recommended by the JIP members that fit the allocated budget were:

- Electrically erasable programmable read-only memory (EEPROM);
- Reprogrammable field programmable gate arrays (FPGA);
- Precision amplifiers;
- Sigma-delta analog-to-digital converters; and
- An electronic designer's tool kit for creating custom "system-on-a-chip" SOI ICs.

Unfortunately, intellectual property rights and subsequent upgrading to SOI technology made a state-of-the-art microprocessor prohibitively expensive for the current project. The custom "system-on-a-chip" capability allows engineers to mix analog and digital circuits in one SOI IC. The result is a small and powerful application-specific device.

The JIP partners' top priority is a user-programmable memory product capable of holding data or program despite power interruptions, a requirement for systems that contain FPGA. User-programmable memory is also critical to a system that uses a microprocessor where such nonvolatile memory commonly stores application-specific instruction code. Finally, this type of memory is useful in any type of data acquisition system where sensors are characterized and sensor-specific calibration coefficients are stored and employed to improve system accuracy.

High-temperature SOI designed for five years of life at 225 degrees C will improve the components' reliability and lower tool costs by allowing tool reuse and reconfigurations. JIP members enjoy exclusive market access to the components until project completion and rights to discounted component prices for two years thereafter.

The project is already bearing fruit with the completion of the op amp. Wafer-level testing yielded 11,000 good op amp die, which are integrated circuit chips. Accomplishing this in one pass with a first design that requires no modifications to meet the required specifications is considered a good yield by semiconductor manufacturing standards. The initial lot of packaged devices were tested over the full specified operating temperature range, and showed no fall-out during high-temperature operation. The amplifier was stable to 250 degrees C. Fifty die were packaged and delivered to the JIP members for evaluation.

NETL has funded Sandia National Laboratories to do limited lifetime testing of the op amp, which has thus far demonstrated that high-temperature SOI can work well at temperatures greater than 300 degrees C. After more than 1,000 hours at 300 degrees C, the tests show a maximum of only 20µV offset voltage, a level approximately 100 times better than existing technology. Although the high noise levels and large voltage offsets of high-temperature amplifiers previously impeded the development of high-temperature logging and drilling tools, an accurate solution now offers low frequency measurements of strain, pressure, temperature, inclination and azimuth.

Related Projects

In addition to the JIP, DOE is pursuing other technologies to enable quick and economic exploration and development of high-temperature, high-pressure gas resources. Six projects on electronics have been funded under Deep Trek to develop high-temperature downhole tools. The projects' objectives are:

- A wireless electromagnetic telemetry system by E-Spectrum for use in drilling applications below 20,000 feet and in temperatures of 200 degrees C. The system is being designed to facilitate MWD operations in deep drilling environments.
- A permanently installed pressure and temperature MWD tool that operates at 225 degrees C using SOI technology. In a collaborative development and testing effort by Sandia National Laboratory and NETL, the tool is intended to demonstrate both logging and smart well electronic circuit technology in high-temperature geothermal wells, and fulfill the industry's need for tools that can drill below 20,000 feet. Additionally, the collaboration will test the components developed in the Honeywell project and design a battery system that can operate at 225 degrees C, which also is critical for deep, high-temperature gas wells.
- A high-temperature, high-pressure MWD tool by Schlumberger. Designed to be retrievable and reseatable with real-time continuous inclination, vibration detection, annular pressure, and gamma ray detection, the tool's main purpose is to improve deep drilling economics by improving the overall rate-of-penetration and accurate well placement in deep hostile environ-

ments. Specific research is required in the areas of high-temperature and high-pressure sensors, electronics, packaging, materials, and pressure housings.

- A solid-state gamma-ray detector suitable for use in harsh environment downhole gas and oil exploration by GE Global Research. This advanced detector will employ wide bandgap semiconductor technology to extend detector temperature capability and provide ruggedness and reliability that exceed the photomultiplier tube-based designs. The project tasks will focus on developing a silicon carbide avalanche photodiode that can perform at 200 degrees C and a matched scintillator. Such developments could enable a 40 percent increase in drilling depth.
- A microprocessor system and associated peripheral devices based on SOS that performs at 275 degrees C by Oklahoma State University. The downhole microcomputer system will permit the use of embedded microcomputer control techniques in deep drilling bit controls, MWD assemblies, and well logging instruments. The proposed systems will be based on the Motorola 68HC11 single chip microcomputer and its associated peripherals. The high-temperature version of the 68HC11 chip will use SOS and SOI technology.
- A high-temperature downhole electric generator by Dexter Magnetics and Noble Wellbore Technologies. This will provide a downhole power source that will allow the subsequent design of intelligent drilling and logging tools. The new high-temperature turbine generator (HTTG) will build on the design of a conventional pressure/temperature generator. The new HTTG will avoid the use of rotary seals by driving the generator by a synchronous coaxial magnetic coupling, which allows electrical components to be separated from the drilling fluid in a pressure barrel that relies only on static seals. The advanced HTTG will be versatile and easily adapted to address different industry needs.

One of the most critical components missing from high-temperature tools–especially for powered devices such as valves, switches, and generators–is a high-temperature capacitor. Although service companies employ creative ways to work around this void, such approaches are not as efficient and do not reduce the risk as much as would components designed to meet the required environmental specifications.

Potential Benefits

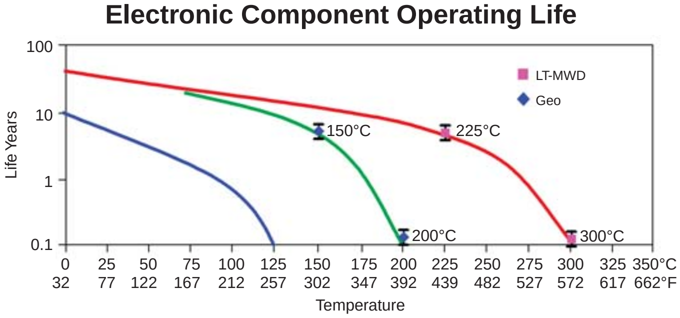
Despite significant progress, technical hurdles still prevent vast deep resources from being categorized as economically recoverable reserves. Without high-temperature electronics, it is impossible to monitor the downhole environments and geosteer a well during drilling operations. High-temperature electronics are an enabling technology to safely and economically recover deep, high-pressure, high-temperature natural gas.

The benefits of high-temperature electronics can have a broader impact. Because temperature dramatically affects solid state devices, silicon-on-insulator technology can significantly increase longevity, reliability, and reduce costs even at lower operating temperatures (Figure 5). Low-temperature products using high-temperature electronic components function more reliably and last longer. Whereas high-temperature components and their tools achieve a life expectancy of five years of continuous duty at 225 degrees C, continuous operation may continue for 10-15 years at 175 degrees C and 15-20 years at 150 degrees C.

Other industries will benefit from the commercial availability of high-temperature electronics as well. High-temperature components improve safety, reliability, and maintainability at lower cost. Potential applications include long-life automobiles with higher fuel efficiency, chemical processes with ultra-precise control and minimal waste, distributed controls for avionics, and high-speed commercial and military aircraft. Despite the range of possible applications, the market alone is insufficient to sustain the research and process development needed to manufacture the components. ❒

FIGURE 5

Qualitative Comparison of Electronic Component Operating Life



JOHN D. ROGERS *is research group coordinator and group leader for the SCNGO research activities within the Office of Science and Engineering Research at the U.S. DOE National Energy Technology Laboratory and is the DOE project manager for the Honeywell HT Electronics Project. His area of emphasis is in advanced drilling and completions technology, primarily high-pressure, high-temperature deep gas drilling and production applications. Rogers holds an M.S. in petroleum engineering from Texas Tech University and a B.S. and Ph.D. in chemical engineering from New Mexico State University.*

BRUCE OHME *is project leader in the mixed-signal design group at Honeywell's Defense and Space Electronics Systems facility in Plymouth, Mn., and is the technical director for the Deep Trek high-temperature electronics program. Ohme has worked in SOI high-temperature electronics since 1993, and led the design group that developed 225 degrees C integrated circuits for the U.S. Department of Defense HiTEC program. Ohme holds a B.S.E.E. from the University of Minnesota.*

RANDY NORMANN *has an M.S.E.E. from the University of New Mexico. He has more than 20 years of experience designing telemetry systems at Sandia National Laboratories, with a focus during the past 10 years on designing high-temperature electronics. Normann is the technical chair for the High-Temperature Electronic Conference and co-chair for SAE - AE7 High-Temperature Electronic Products.*

Honeywell's HTMOS™ High Temperature Electronics

Technology and Product Features

- Complete oxide isolation of all transistors
- TiW barrier layer on all metals and contacts
- Variable width oxide trench
- Twin well technology
- CrSi thin film resistors available
- N+poly to N+silicon linear capacitor
- 0.8 micron 5 volt digital capability
- Designed for 50,000 hours of 225ºC operation
- Final test at 225ºC ambient
- Burn-in at 250ºC

High Temperature Electronics

Product Family Description

Honeywell has developed a revolutionary family of High Temperature electronic components, the HTMOS™ family, that use Silicon On Insulator (SOI) technology to provide extraordinary value in high temperature applications. Designed to continuously operate for at least 5 years at 225 degrees Centigrade, the HTMOS™ standard electronic product family is targeted at sensor signal conditioning, data acquisition, and control applications in hostile environments. These products have significant reliability and performance advantages over traditional silicon integrated circuits when the operating temperatures are greater than 150 degrees Centigrade.

Applications

The HTMOS™ product line has been developed for high temperature operation in instrumentation and distributed control applications such as:

- Down Hole Petroleum and Geothermal Exploration and Production
- Gas Turbine Engines (Aircraft Propulsion and Power Generation)
- Diesel Engine (Propulsion and Power Generation)

Products

HT1104	High Temperature Quad Operational Amplifier
HT1204	High Temperature Quad Analog Switch
HT83C51	High Temperature 83C51 Microcontroller
HT506/HT507	High Temperature Analog Multiplexors 16-Channel Single/8-Channel Dual
HTPLREG	High Temperature Positive Linear Regulator
HT6256	High Temperature 32K x 8 Static RAM
HTNFET	High Temperature N-Channel Power FET

Find out more

For more information on Honeywell's High Temperature Electronics visit us online at www.ssec.honeywell.com/hightemp, or contact us at 800-323-8295 or 763-954-2474. Customer Service Email: ssec.customer.service@honeywell.com.

Honeywell International Inc.
12001 Highway 55
Plymouth, MN 55441
Tel: 800-323-8295
www.honeywell.com

January 2006

Honeywell