Sensors for data logging during deep drilling

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Piezoresistive Wheatstone bridges allow acquisition of a variety of data in extreme environments.

Geothermal power is one of the most important sources of energy worldwide.\textsuperscript{1} However, to meet the increasing needs for alternative energy supplies, geothermal economic efficiency must be increased. In particular, the technical reliability of the drilling systems must be improved and bore costs reduced. To achieve these goals, modern drilling systems have been equipped with sensor technologies for measurements while drilling (MWD). These sensors have a variety of functions that include process monitoring, early identification of faults, and timely response to critical situations, for example, detecting vibrations caused by interactions between the chisel and rock formation. The severe environmental conditions expected in geothermal energy projects—such as temperatures up to 300°C and bore depths up to 10,000m—make heavy demands on the materials and electronics used. Here, we describe our progress in developing sensors capable of operating at high temperatures for MWD.

Piezoresistive silicon sensors are widely used for sensitive measurements in a variety of applications, from household appliances and the automotive industry to biomedical devices.\textsuperscript{3} In general, they consist of a mass and n-doped silicon cantilever with integrated p-type resistors connected to a full Wheatstone bridge. When an external load deflects the cantilever, the resulting stress changes the resistance and unbalances the Wheatstone bridge. This in turn produces a voltage that can be measured. Unfortunately, commercial piezoresistive sensors cannot be used in deep drilling because they only operate at temperatures less than ~175°C. This limitation at higher temperatures is caused by the supply current of the bridge flowing through both the p-doped resistors and n-doped substrate, rather than just the resistor. That is, an undesirable p/n junction forms, which causes current to ‘leak,’ thus reducing the voltage through the bridge and skewing measurements. A common remedy for this involves embedding

![Figure 1.](image)

the resistors in the top layer of silicon-on-insulator (SOI) materials, which expands the operational temperature range.\textsuperscript{4} SOIs

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Figure 2. Temperature behavior of p-SOI etched Wheatstone bridges compared to bridges of n-silicon (n-Si) and n-SOI.

are ‘sandwich’ structured, where a thin oxide layer electrically insulates the resistors and bridge from the silicon substrate. Despite this improvement, the maximum temperature before current leaks is ~200°C. To expand the field of operation for piezoresistive sensors, we used SOIs where the p-type resistors and interconnects were etched down on the insulating oxide layer.

We fabricated the Wheatstone bridges using a bulk micromachining process. First, we improved contact formation to the p-type silicon top layer by boron diffusion, which decreased both the contact resistance and resistance of the interconnects by a factor of 10. We found that a resistor p-type doping concentration of $5 \times 10^{18}$ acceptor atoms/cm$^3$ was important for achieving the lowest temperature coefficient of resistance (TCR), which minimized the bridge voltage drift under temperature loading. We next fabricated the electrical contact to the resistors using high-temperature-stable metallization. We produced contact layers of titanium/palladium/gold or titanium/titanium nitride/gold by electron-beam evaporation and reactive sputtering, respectively. We defined and electrically insulated the resistors and interconnects of the top device layer using cryogenic reactive-ion etching with sulfur hexafluoride and oxygen. The etching was material-selective, i.e., the process automatically stopped at the oxide layer. We used chromium masks to produce the structures with high process accuracy (±100nm), with an offset of 0.1mV/V (see Figure 1).

To assess the quality of our p-SOI Wheatstone bridges, we measured thermal noise using an instrumentation amplifier in a high-precision climate chamber. We found that very low thermal noise ($5.5 \times 10^{-9} \text{V}/\sqrt{\text{Hz}}$ at 20°C) dominated down to a corner frequency of 3.5Hz. That is, flicker noise (1/f noise) in these electronic devices only occurs at very low frequencies. Additionally, we compared the temperature behavior of our etched p-SOI Wheatstone bridges to those made of n-type silicon and n-type SOIs with p-diffused resistors. Our Wheatstone bridges endured higher temperatures than the other bridge types (see Figure 2). The TCR for our bridges was as low as $2.6 \pm 0.1 \mu \text{V/K}$ up to 400°C. We also tested our bridges under temperature cycling (see Figure 3). Even after more than 400 cycles—up to 250°C for 120h—the signal remained unchanged. Thus, the current leakage typically found in piezoresistive sensors was completely suppressed by etching down the material layers.

In summary, we have shown the high-temperature suitability of our etched p-SOI Wheatstone bridges. They can be adapted for a variety of sensors—such as pressure, inclination, and acceleration—and enable MWD at temperatures of at least 250°C. In future work, we will test complete sensor systems for harsh environmental applications.

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