DOI 10.5162/sensor2017/A1.3

Using Magnetoresistive Sensors in High Temperature Applications

Dr. Rolf Slatter, Dipl.-Ing (FH) Rene Buß
Sensitec GmbH, Georg-Ohm-Straße 11, 35633 Lahnau, Germany
rolf.slatter@sensitec.com

Abstract

The proliferation of sensors means that they are increasingly used in harsh environments. A "harsh" environment refers to extremes of temperature, pressure, shock, radiation and chemical attack. Sensing in harsh environments enables real-time monitoring of combustion processes, subsurface properties, space environments, and critical machine components. In the industrial and automotive fields, the trend to higher power density for motors and actuators is leading to higher operating temperatures for the sensors used to measure position and speed. In addition to this trend there are new applications in the oil- and gas-industry that also require sensors capable of operating at higher temperatures, typically up to 250 °C. There is therefore a need for sensor and packaging technologies that can survive these new requirements.

Key words: high temperature, harsh environment, magnetic sensors, position measurement

More sensing in "harsh" environments

High temperature electronics is a continuously growing market in constant need of new technologies and concepts. Sensors, in particular, are being implemented in increasingly severe operating environments to enable better process monitoring as well as process control in a wide range of industries [1]. There is an additional trend in the field of power electronics to higher power density, which is also resulting in more demanding requirements for sensors regarding permissible operating temperatures [2]. Furthermore, new sensor applications in the automotive [3] and aerospace markets [4] are pushing operating temperatures beyond 150 °C, which was the upper operating limit for many sensor technologies to date.

Accordingly new sensor technologies are required that can survive such demanding operating conditions.

Magnetoresistive (MR) sensors are well known for their robustness, as demonstrated by applications in space, e.g. on the Mars-Rover "Curiosity", where most of the moving mechanisms are controlled using MR sensors. In terrestrial applications in a number of different fields there is a trend to higher operating temperatures and this paper explains why MR sensors are particularly well suited to such applications and describes some of the special precautions necessary to ensure reliable operation in harsh environments.

Magnetoresistive sensors for high temperature applications

Magnetoresistive (MR) sensors are firmly established in automobiles, mobile telephones, medical devices, wind turbines, machine tools or industrial robots: be it for the measurement of path, angle or electrical current, or as an electronic compass. Originally developed for data storage applications, the different MR effects open up new measurement possibilities for sensors, not only in terrestrial applications, but also in space applications.

MR sensors are robust, reliable, precise and miniaturized. This combination of features is leading to continuous growth in the application field of MR sensors. The extremely low power consumption of MR sensors makes them ideal for wireless, autonomous sensor applications. They present the developers of many different types of mechanism or instrument with completely new possibilities to measure angle, path, electrical currents or magnetic fields.

DOI 10.5162/sensor2017/A1.3

The magnetoresistive effect has been known for more than 150 years. The British physicist William Thomson, later known as Lord Kelvin, discovered that the electrical resistance of a conductor changed under the influence of a magnetic field. However, this effect could first be used industrially more than 120 years later, during the late 1970s, in combination with thin-film technologies derived from the semiconductor industry. The intelligent arrangement of thin-film structures within a sensor enabled the development of many different sensor types for measuring the angle, strength or gradient of a magnetic field. The effect discovered by Thomson was named the “anisotropic magnetoresistive effect” (AMR) and resulted in a resistance change of just a few percent. Nevertheless this effect was used million-fold in the production of read-heads for hard discs. At the end of the 1980s the “giant magnetoresistive effect” (GMR) was discovered independently by Prof. Grünberg at the Forschungszentrum Jülich in Germany and by Prof. Fert at the University of Paris in France. Here the resistance change was more than 50%, which opened up even more applications for MR sensors. This discovery was awarded the Nobel Prize for Physics in 2007.

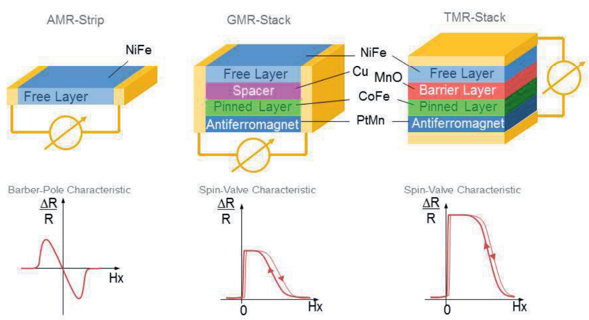

Fig.1: Comparison of MR technologies

In the meantime the read-heads of hard discs are almost exclusively based on the “tunnel magnetoresistive effect” (TMR), which can exhibit a resistance change of several hundred percent under laboratory conditions. This technology has additional features that are not only interesting for storage technology, but also for sensors. For example, TMR-based sensors have an extremely high sensitivity and a very low power consumption. Fig.1 shows a schematic comparison of the different MR layer structures. For sensor applications the AMR, GMR and TMR effects are complementary, each offering specific advantages that can be of benefit in different applications 0[6].

Magnetoresistive sensors are well suited to high temperature applications for the following reasons:

- The solid-state, thin-film metal construction (see Fig. 2) allows operation in a vacuum or under radiation as well as operation at both high and low temperatures
- The contactless magnetic measurement principle makes MR sensors robust with respect to contamination
- Information transmission through a medium and high sensitivity allow large gaps between measurement scale and electronics and permits hermetic sealing of the electronics
- The miniaturized sensor design allows the use of robust assembly technology for housings
- Special design features enable functionally safe applications (ASIL-D and SIL-3)

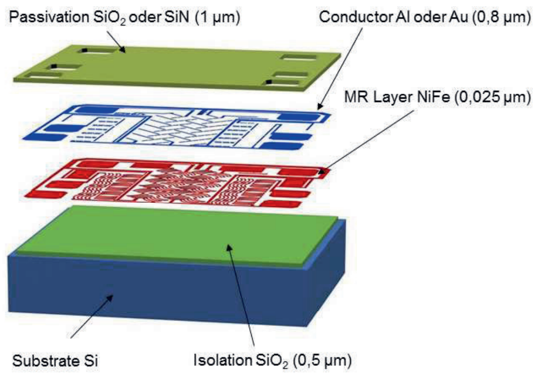

Fig. 2: Basic construction of AMR sensor chip

Sensitec has undertaken extensive tests in order to better understand the effects of high temperature operation on key performance characteristics of MR sensors. Some typical test results are shown in Fig. 3. An AMR angle sensor (Type AA746) was subjected to extremely high temperature (280 °C) for 96 hours and measurements were taken of key signal characteristics.

As can be seen from Fig. 3, the internal resistance of the sensor changed only marginally (< 3 %) under this demanding test. Similarly, the signal offset changed by only 0.6 mV/V and the signal amplitude also only dropped by less than 3 %. Beyond the 96 hours of the initial test the further change in properties was minimal, indicating that the sensor chip itself can withstand operating temperatures in excess of 250 °C.

DOI 10.5162/sensor2017/A1.3

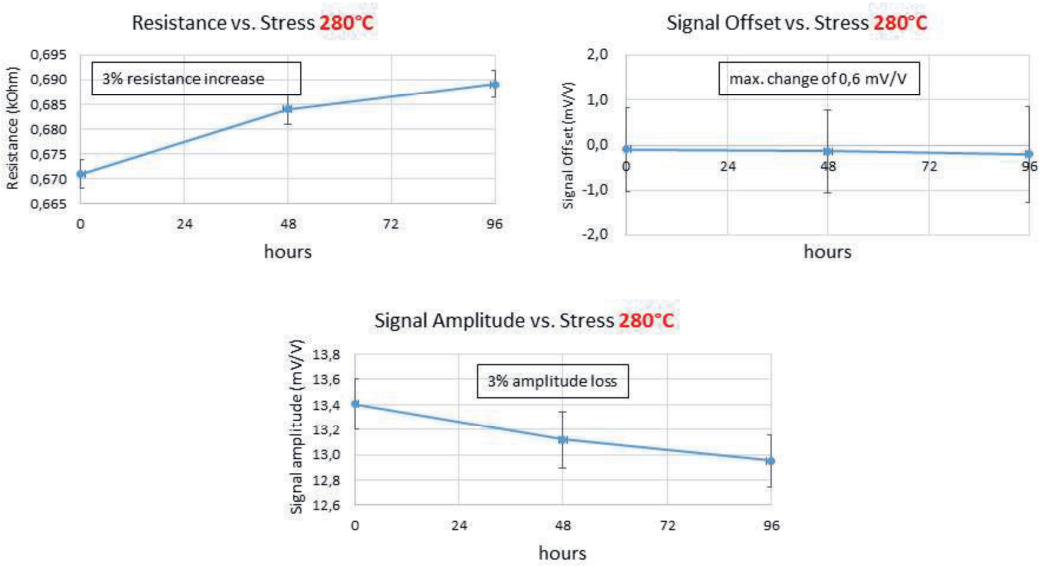

Fig. 3: Typical stress test results for AMR angle sensor chip (Type: AA746)

Packaging requirements for high temperature sensors

The sensor chip itself is not the only limiting factor in high temperature applications. Particular attention must also be paid to the packaging and interconnection technologies.

There is a number of critical aspects for the sensor packaging at higher temperatures:

- It is important to avoid a mismatch of the coefficient of thermal expansion (CTE) of the different materials (Si-chip, substrate, housing and encapsulant) as far as possible. Otherwise mechanical stress can lead to delamination and cracks.
- Care should be taken to avoid diffusion in the contact areas. Kirkendall-voids in Au/Al- wire bonds and solder joints can lead to reduced reliability and higher joint resistance.
- Solder interconnects should be carefully selected to avoid creeping (T_H = T/T_m > 0.4). Otherwise work hardening can lead to cracks and reduced fatigue life.
- Ageing of organic materials can lead to a loss of flexibility, which in turn can lead to cracks and/or delamination

These requirements lead to a special selection of materials for high temperature applications as shown in Tab. 1 below.

Tab. 1: High temperature sensor packaging requirements

Materials	**Industrial Standard Application** (< 125 °C)	**High Temperature Application** (> 125 °C)
Chip with MR-Structures and Bond pads	Au, Al, SAC-Flip-Chip-Bump	Au, Al
Die-Attach-Adhesive	Filled Epoxy	High temperature adhesive, solder
Bonding wire	Au, Al	Au, Al, Pd -> monometallic bonded to the bond pads
Substrate	HT-FR4	Ceramic, low CTE organic substrate
Magnet	e.g. NdFeB, SmCo	e.g. AlNiCu, SmCo
Housing / Sealing	Filled Epoxy	Hermetic package, high temp. organic materials
Signal processing (e.g. ASIC, passives)	Near to the sensor element	Separated from the “Hot-Spot”, T_{max} = 150°C

DOI 10.5162/sensor2017/A1.3

Application Examples

The capabilities of magnetoresistive sensors in high temperature applications can be demonstrated by the following practical application examples.

Speed sensor for Formula 1 engine development

During the development of high performance engines for Formula 1 cars there is a requirement for robust sensors for measuring the angle and speed of fast rotating shafts, such as the crankshaft and camshaft. The sensor must be applicable to a range of different gear wheels with different tooth pitches (2 to 8 mm) and also be able to allow a large air gap between sensor and gear wheel (up to 5 mm). For this application a special AMR-based gear tooth sensor has been developed incorporating an AMR sensor and bias magnet (Fig. 4). The bias magnet locally magnetizes the ferromagnetic material of the gear wheel. The sensor also incorporates a PT1000 temperature sensor and both digital and analogue speed signals are available as sensor output. To allow the sensor to be used in a fired engine the housing and encapsulant for the sensor electronics have been carefully selected to allow continuous operation at up to 150 °C.

Fig. 4: Speed Sensor based on AMR technology

Valve lift sensor for valve travel analysis in fired internal combustion engines

GMR sensors can also be used in high temperature applications: A valve lift sensor developed by Sensitec can measure the valve movement (lift and rotation) in a fired engine (environmental temperature approx. 175 °C). Currently these sensors are used in motor test-stands. The requirements on the sensor performance are quite challenging: a contactless measurement principle with a resolution below 10 µm suited for the measurement of linear speed above 100 m/s. All of these requirements can be met with a GLM Tooth Sensor Module which detects the deformation of the magnetic field caused by a tooth structure in the valve (see Fig. 5). The measurement is not even affected by oil contamination.

The VLS sensors are used in the development phase of gasoline engines to measure dynamic effects and to detect errors in the valve train. In the very near future these sensors will not only be applied to test-stands but also to racing cars to improve the engine control and thus the performance of the car.

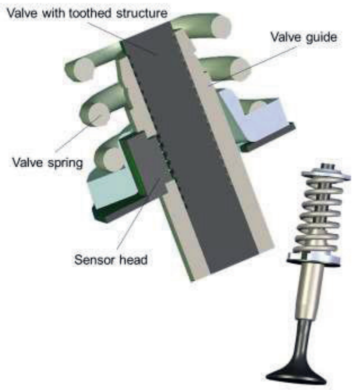

Fig. 5: Operating principle of VLS sensor

Wheel speed sensor for ABS- and ESP-systems in passenger cars

There are several high temperature applications of MR sensors in production vehicles. One of the high volume applications is a wheel speed sensor based on AMR sensor chips. A very important requirement is the extremely high reliability (< 0.1 ppm field return rate) despite high operating temperatures of up to 195 °C. The complete sensor assembly and the injection molded MR sensor device are depicted in Figure 6. More than 150 million Sensitec AMR sensor chips have been delivered for this application without a single field return caused by the MR technology.

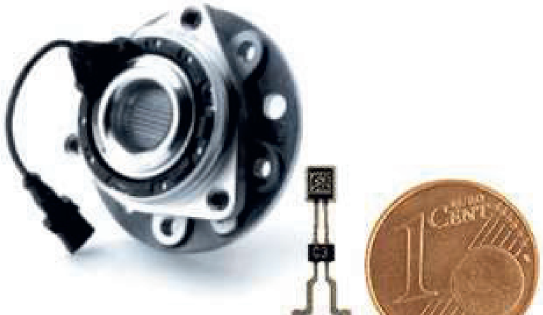

Fig. 6: AMR based wheel speed sensor for automotive applications (source: Continental AG)

Angle sensor for borehole caliper in oil- and gas-industry applications

Another example for high operating temperatures in combination with high pressure is the use of MR sensors in calipers (open hole tools) for borehole diameter measurement. Antares Datensysteme GmbH uses Sensitec AMR sensors in 4-arm calipers. Since 2005 several thousand systems have been fabricated; the field-return rate is extremely low. The 4-arm caliper measurements provide diameter data of the borehole in two directions. The measurements are used to

- describe the shape of the borehole, in particular washout and restrictions in 2 directions
- provide information on the build-up of mudcake
- calculate borehole and cement volumes (in respect to casing size)
- correct parameters of other logs.

The caliper is specified for operation up to 175 °C (350 °F) and 140 MPa (20.000 psi); the sensor system is specified for temperatures up to 205 °C. Figure 7 shows a schematic of the 4-arm caliper. A detailed view of the sensor seat can be seen in fig. 8.

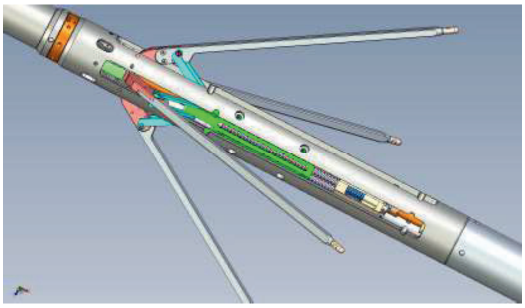

Fig. 7: Schematic of the Antares 4-arm caliper (source: ANTARES Datensysteme GmbH)

Fig. 8: Detail of the sensor position in the 4-arm caliper (source: ANTARES Datensysteme GmbH)

Outlook

Magnetoresistive sensors have proven their capabilities under high operating temperatures in a wide range of applications, ranging from industrial automation, through automotive to the oil- and gas-industries [7].

The increasing availability of high temperature signal processing ASICs [1], as well as new packaging and interconnection technologies for high temperature operation [8] will mean that the range of applications is likely to increase significantly in the coming years as market pull is increasingly matched by technology push.

Sensitec is actively involved in a number of state-funded R&D projects in order to better understand the thermal limits of magnetoresistive sensors.

References

[1] Goehlich, A. & Kappert, H.; "SOI Based High Temperature Sensor Devices and Electronics", Proc. of Fraunhofer IMS Workshop „High Temperature Electronics", Duisburg, 2016

[2] Schletz, A.; "Power Modules for Power Electronics – Electrical and Lifetime Specifics", Proc. of Fraunhofer IMS Workshop „High Temperature Electronics", Duisburg, 2016

[3] Trageser, H.; "Interconnection Technologies and Substrates for Automotive Electronics", Proc. of Fraunhofer IMS Workshop „High Temperature Electronics", Duisburg, 2016

[4] Meurat, R.; "High Temperature Motor Drive for Aeronautic Application", Proc. of Fraunhofer IMS Workshop „High Temperature Electronics", Duisburg, 2016

[5] Doms, M. et al; "AMR vs. GMR vs. TMR – Eigenschaften, Unterschiede, Anwendungen", Proc. of 5. Mikrosystemkongress, Aachen, 2013

[6] Slatter, R.; "Magnetische Mikrosysteme in Industrie-, Automobil- und Raumfahrtanwendungen", Proc. of 4. Mikrosystemtechnikkongress, Darmstadt, 2011

[7] Slatter, R., Doms, M., "Energy efficient magnetoresistive sensors for low-power and wireless applications", Proc. of Smart Systems Integration Conference, Vienna, 2014

[8] Wickham, M.; "Characterisation of High Temperature Interconnect Materials", Proc. of Fraunhofer IMS Workshop „High Temperature Electronics", Duisburg, 2016