DOI 10.5162/EUROSENSORSXXXVI/OT4.86

Hall-effect sensors for extreme temperature applications

Semir El-Ahmar[1], Jakub Jankowski[1], Paweł Czaja[1], Wiktoria Reddig[1], Marta Przychodnia[1], Jan Raczyński[1], Wojciech Koczorowski[1]
[1] Institute of Physics, Poznan University of Technology, 61-138 Poznan, Poland

semir.el-ahmar@put.poznan.pl

Summary:

This work is focused on developing magnetic field sensors that rely on the Hall effect and can operate stably in extreme temperatures. We have achieved this by creating a Hall effect structure using indium antimonide and a housing that can withstand an extremely wide range of operating temperatures. Our device has been tested and proven to operate stably at high temperatures up to 350°C, as well as in the cryogenic range using liquid helium. This is a significant milestone as no other magnetic field sensor has been able to perform in such extreme temperature conditions.

Keywords: Hall effect, cryogenics, high-temperature electronics, magnetic field sensors, thermal stability

Motivation and state of the art

Magnetic field detection devices are highly valuable in many industries, thanks to the fact that they can measure various quantities such as position, movement, direction, and rotational speed. Nowadays, there is a high demand for electronics that can function reliably in harsh environments[1], including those that can withstand extreme temperatures [2]. By the term "extreme", we mean mostly temperatures extremely high for electronics, in a mid-wide temperature range from room temperature up to high temperatures (above 200 °C), or extremely high reaching 500 °C [3]. Traditional electronics design often requires active or passive cooling, but this may not always be practical or effective. Hence, there is an increasing need for extreme environment electronics, particularly in the automotive, defense, and energy industries. [4,5]. Magnetic field sensors have great potential in high-temperature electronics. However, it's also important to consider their performance in low and cryogenic temperatures. A sensor that can provide precise magnetic diagnostics in a wide range of temperatures, from cryogenic temperatures up to liquid helium (LHe), through room temperature, and up to high temperatures, would be highly valuable in the market. This kind of sensor could be particularly useful for space research vehicles that need to travel through hot environments. A sensor that can operate accurately in a wide temperature range would offer new possibilities for diagnostic devices in space.

We have found that research on semiconductor-based Hall sensors operating in extreme conditions is limited to a temperature range from liquid nitrogen (LN) up to 350 °C [4]. On the other hand, alternative solutions based on monolayer graphene have been tested in the LN – 500 °C range in a magnetic field below 1 T. Our research explores the potential of using classic semiconductor thin-film material) as an active layer for a Hall effect sensor capable of measuring magnetic fields in extreme temperature ranges from liquid helium (LHe) temperatures up to 350 °C. We have verified the usability, thermal stability of our device and the linearity of its signal in the magnetic field range above 1 T. Additionally, we have proposed a solution for the sensor package suitable for an extremely wide range of work. We have developed a complete magnetic field sensor that can meet industrial requirements, manufactured using almost exclusively the academic infrastructure of the Poznan University of Technology. Our findings represent a significant step forward in the development of magnetic diagnostic devices that can operate in a broadly defined extreme environment.

Construction of a Hall sensor

The sensor consists of a Hall structure and an extreme temperature housing. Fig. 1 shows a real view of the series of fabricated devices. The Hall structure itself is placed under the white cover visible in Fig. 1, inside a ceramic casing. The Hall structure inside is made of a thin film of indium antimonide (InSb) doped with tin donor in the process of flash evaporation method. Details about the exact fabrication technology of the Hall structure are included in Ref. [6].

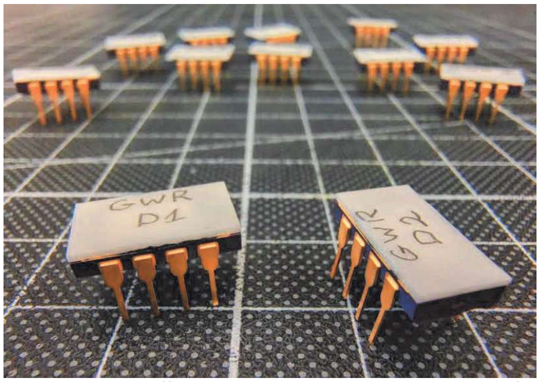

Fig. 1. Hall effect sensors in housings, ready for use at liquid helium temperatures, fabricated at Poznan University of Technology. The square scale under the sensors has a side of 10 mm.

The housing itself was made in accordance with the descriptions in [4], introducing a modification regarding the pins to simplify integration with the measuring holder for a helium cryostat.

Results in a nutshell

The effects of work on a Hall effect sensor that can function in extreme temperature conditions were verified through a series of Hall effect measurements utilizing three independent measurement systems. For high-temperature tests, a Linseis HCS 1 analyzer equipped with a 0.65 T permanent magnet was used. This was supported by a galvanomagnetic effects measurement system equipped with an electromagnet that enabled a smooth transition in the range of 0-0.65 T. These tests were previously described in Ref. [4]. The purpose of the new experiment was to measure the Hall effect at low temperatures and in very strong magnetic fields. The International Laboratory of Strong Magnetic Fields and Low Temperatures, which belongs to the Institute of Low Temperatures and Structural Research Polish Academy of Sciences, provided the necessary infrastructure for the experiment. Bitter electromagnets were used to generate a uniform, constant magnetic field in the range of 0 - 15 T. The Bitter magnet design allows the use of a liquid helium cryostat insert. The results of the experiment showed that the sensor signal (Hall voltage, UH) depended linearly on the magnetic field induction in the range of 0 - 1.2 T at a temperature of approximately 5 K. The linear nature of the dependence at extremely low temperatures was confirmed by the results, together with the research presented in Ref. [4]. The study will be further supplemented with the results of Hall effect measurements in a magnetic field above 10 T, both at room temperature and at liquid helium temperature.

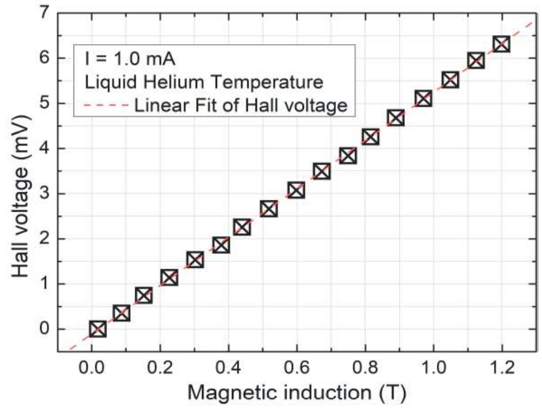

Fig. 2. Dependence of the Hall sensor signal on the magnetic field induction at the temperature of liquid helium.

The usefulness of the modified housing for applications in extreme environments was confirmed, making our sensor the first Hall sensor capable of stable operation in the temperature range from approximately -268 °C to 350 °C.

The research has received funding from the National Centre for Research and Development under Grant Agreement No. LIDER/8/0021/L-11/19/NCBR/2020 for project MAGSET and partly from the Ministry of Education and Science (Poland) under Project No. 0512/SBAD/2420.

References

[1] S. Eswarappa Prameela et al., Materials for extreme environments, *Nature Reviews Materials*, 8, 2, 81–88, 2023, doi: 10.1038/s41578-022-00496-z

[2] B. T. Schaefer et al., Magnetic field detection limits for ultraclean graphene Hall sensors, *Nature Communications*, 11, 4163 (2020), doi: 10.1038/s41467-020-18007-5

[3] T. Ciuk et al., High-Temperature Hall Effect Sensor Based on Epitaxial Graphene on High-Purity Semiinsulating 4H-SiC, *IEEE Transactions on Electron Devices*, 66, 7, 3134–3138 (2019), doi: 10.1109/TED.2019.2915632

[4] S. El-Ahmar et al., Magnetic Field Sensor Operating From Cryogenics to Elevated Temperatures, *IEEE Sensors Letters*, 7, 8, 1–4, article no. 2501904 (2023), doi: 10.1038/s41578-022-00496-z

[5] H. S. Alpert et al., Sensitivity of 2DEG-based Hall-effect sensors at high tempera- tures, *Rev. Sci. Instrum.*, 91, 2, 1–6, article no. 025003. (2023), doi: 10.1063/1.5139911

[6] M. Oszwaldowski et al., High temperature Hall sensors, *Sens. Actuators A Phys.*, 136, 234–237, (2007), doi: 10.1016/j.sna.2006.11