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Temperature dependence of the Hall coefficient of sensitive layer materials considered for DEMO Hall sensors

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ABSTRACT

The Hall sensors as a part of the DEMO magnetic diagnostics will perform an absolute measurement of the steady-state magnetic field. However, the magnitude of the Hall coefficients generally depends on the temperature. The paper presents an evaluation of the temperature dependencies of the Hall coefficients of materials considered for the DEMO Hall sensors from room temperature up to 550 °C. The results show that tantalum or molybdenum sensors would be the best in terms of the low temperature dependence of their Hall coefficient. Bismuth and antimony offer a Hall coefficient several orders of magnitude higher than other considered materials, but strongly temperature-dependent, while usability of bismuth is limited by its melting temperature of 271.4 °C. The gold, copper and platinum sensors feature modest temperature dependence of their Hall coefficients which might result in the necessity of dedicated temperature monitoring of these sensors in order to achieve sufficient measurement accuracy, similarly to bismuth and antimony.

1. Introduction

Future fusion power reactors will operate in a continuous mode, and the magnetic field of these reactors will be steady-state. The applicability of the magnetic coil-based diagnostic for the measurement of the steady-state magnetic field under fusion power reactor conditions is limited by drifts of signal integrators [1–3]. A dedicated diagnostic of the steady-state magnetic field will, therefore, be an important part of the diagnostic set of fusion power reactors including the DEMO fusion power reactor prototype [3].

The ITER reactor will be equipped with steady-state magnetic diagnostics based on Hall sensors with a bismuth sensitive layer. Bismuth provides high radiation resistance of the sensors as well as a relatively high output signal. The bismuth-based Hall sensor manufacturing process was elaborated in detail, and the sensors were extensively tested [4–11]. The bismuth sensors were approved by the expert committee within the ITER final design review, and their production was launched by Institute of the Plasma Physics of the CAS in Prague (IPP).

At present, the Hall sensors are proposed as a part of DEMO magnetic diagnostics performing an absolute measurement of the steady-state magnetic field. The Hall sensors will contribute to the measurement of the plasma current, plasma-wall clearance, and local perturbations of the magnetic flux surfaces near the wall. Overall, 240 in-vessel Hall sensors should be installed between the blanket or divertor cassettes and vacuum vessel, and 552 ex-vessel Hall sensors on the outer skin of the vacuum vessel [12,13]. On that account, the in-vessel sensors operating temperature range is in the order of 300 − 520 °C in the case of the helium-cooled blanket [14], 280 − 330 °C in the case of the water-cooled blanket [15], and 180 − 210 °C in the case of divertor cassette area [16]. The ex-vessel sensors operating temperature range is in the order of 190 − 200 °C [15].

The higher ambient temperature at some sensor locations on DEMO compared to ITER (up to 520 °C) limits the applicability of the bismuth sensors only to the divertor area and ex-vessel locations, as it melts at 271.4 °C. Therefore, several candidate materials offering higher operational temperatures compared to bismuth were assessed. The main requirements for the sensor's sensitive layer material include:

- Radiation stability up to neutron fluence of 6.1×10^{25} n/m^2 [17].
- Operating temperatures up to 520 °C [14].
- High magnitude of the Hall coefficient.
- Minimum temperature dependence of the Hall coefficient.

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Such a material that meets all of the above requirements is currently unknown and the candidate materials fulfil the requirements partially.

An assessment of the radiation stability of candidate materials can be found in [17]. This paper evaluates the operating temperatures, magnitude and temperature dependency of the Hall coefficients of sensitive layer materials of bismuth (Bi), antimony (Sb), molybdenum (Mo), tantalum (Ta), gold (Au), copper (Cu), and platinum (Pt). Additional candidate materials are mentioned in [18]. However, their experimental investigation is still ongoing, and assessment of their applicability for the DEMO steady-state magnetic diagnostics is subject to future studies.

The Hall sensors with the sensitive layer made of gold and platinum were not tested in this study and data from [19–21] were used for the comparison with other candidate materials. The gold sensors for fusion reactor application were developed at the Magnetic sensor laboratory of Lviv Polytechnic National University, Ukraine, (MSL) and manufactured at the University of Wisconsin's Center for Applied Microelectronics, USA [19].

2. Hall coefficient

The Hall coefficient is one of the main parameters of any sensitive material considered for Hall sensors. The Hall voltage is proportional to a component of the magnetic field B normal to the sensitive layer:

$$V_H = R_H(T, B)\frac{I}{t}B_N, \tag{1}$$

where R_H denotes the Hall coefficient as a function of temperature T and magnetic field B, I is the sensor supply current, B_N is the normal component of the magnetic field, and t is the sensitive layer thickness. The magnitude of the Hall coefficient is always a function of temperature [22].

The Hall coefficient has a fundamental influence on the sensitivity of the sensors to the magnetic field S_H:

$$S_H = \frac{R_H(T, B)}{t}, \tag{2}$$

The higher Hall coefficient is a prerequisite for higher sensor sensitivity, which is a prerequisite for the higher sensor output signal. In the fusion reactor environment, the magnitude of the output signal is critical to achieving sufficient measurement accuracy and noise immunity.

3. Experimental setup

The tests were performed in the Hall sensors laboratory of IPP. A stainless steel high-vacuum chamber was equipped with a miniature ceramic resistive heater with a power of 40 W. The test magnetic field was created by a pair of strong permanent magnets providing a stable magnetic field of 270 mT at the sensor location.

The tested sensors were manufactured using existing technologies developed for the ITER steady-state sensors [6]. Direct bond copper (DBC) aluminum nitride substrates with dimensions of 6.4 mm × 6.4 mm were used. The DBC substrates with a thickness of 630 μm were metallized on both sides by a copper layer with a thickness of about 127 μm, and copper contact pads were etched on one side of the substrate. The symmetrical cross sensitive layer with a thickness of about 1 μm made of the tested material was deposited on the substrate by magnetron sputtering. Fig. 1 shows the sensor design before encapsulation.

A sensor output signal was processed by a Hall sensor controller for an ultra-low sensor signal on the nanovolt level, which was developed in IPP based on the ITER Hall sensor controller prototype [11]. The tested sensors were supplied by an AC current of 4 mA.

4. Results

The magnitude of the Hall coefficients and their temperature dependencies are shown in Fig. 2 on a logarithmic scale. The highest Hall coefficient provided by bismuth is followed by antimony and then by molybdenum, tantalum, gold, copper, and platinum. For example, the Hall coefficient of antimony is from 300 to 45 times higher than the Hall coefficient of gold in the range from room temperature to 500 °C.

The bismuth sensors of the ITER production pre-series IPP00 produced by IPP were successfully tested up to temperature 265 °C. As a result, the limit for application of bismuth Hall sensors, including some modest safety margin, lays around 250 °C. The behaviour of the bismuth sensitive layer corresponds to the previously identified exponential dependence of the Hall coefficient on temperature [9].

Antimony offers sufficient temperature resistance due to its melting temperature of 630.6 °C and, at the same time, its output signal is by a few orders of magnitude higher than that of the other considered materials excluding bismuth [12]. In this test, the antimony sensors of the series IPPS2 were successfully tested at temperatures up to 550 °C. The Hall coefficient of antimony decreases with temperature similarly as in the case of bismuth, but the dependence is much more linear. In compliance with earlier findings, the antimony Hall coefficient is approximately 25 times smaller than the bismuth Hall coefficient [12].

Molybdenum is another promising material for the Hall sensor's sensitive layer. Molybdenum is compatible with an extremely high temperature operation (melts at 2623 °C). However, it provides a very low output signal similar to other classical metals. The molybdenum sensors of the series IPPM2 with a sensitive layer thickness of 750 nm were successfully tested at temperatures up to 550 °C, the sensors of the series IPPM4 with a sensitive layer thickness of 190 nm were successfully tested up to 240 °C. The molybdenum sensor features a very weak dependence of the Hall coefficient on temperature. The Hall coefficient of molybdenum is low, approximately 100 times lower than that of antimony at room temperature. However, due to the significant drop of the antimony Hall coefficient with temperature, the difference is only by a factor of 10 at 500 °C.

A certain problem was experienced in the manufacturing process of the molybdenum sensors. The sensitive layer of molybdenum requires annealing at a very high temperature approaching the melting temperature of molybdenum of 2623 °C which is significantly above the maximum allowed temperature of used DBC substrates. As a result, it was not possible to anneal the sensitive layer properly, and the instability of the layer caused errors in the measurement.

The same annealing issue applied to the tantalum sensitive layer. Attractive features of tantalum as candidate material are very high melting temperature (3017 °C) combined with very low dependence of sensor sensitivity on temperature. Unfortunately, the sensor output signal is very low, half of that of molybdenum. Preliminary results for tantalum sensors of the series IPPT1 were obtained up to a temperature of 360 °C. The technology of tantalum Hall sensors preparation is also subject to further development.

The gold sensors provide several orders of magnitude weaker output signal than bismuth sensors, the gold Hall coefficient is also less than that of molybdenum and tantalum. However, gold allows rather straightforward preparation of golden nanolayers and, thereby, further increase the sensor output signal by reduction of sensitive layer thickness to a few tens of nanometres. Data from [19] and [20] were used for the comparison with other candidate materials. However, while according to [19] the absolute value of the Hall coefficient is slightly decreasing with temperature, according to [20] it is slightly increasing with temperature; therefore, a further detailed experimental investigation is necessary.

Copper (Cu) is a native material for electronics and sensors. Platinum (Pt) offers a high melting temperature (1768 °C). Both of these metals are well processable, but of the metals considered herein, they have the lowest Hall coefficients significantly increasing with

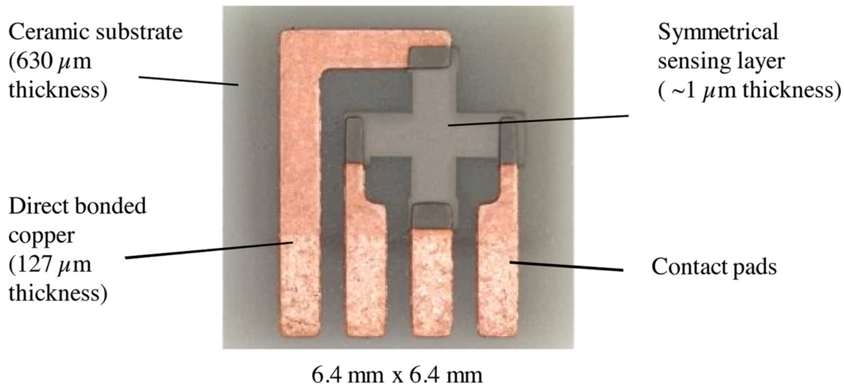

Fig. 1. Design of the tested Hall sensors.

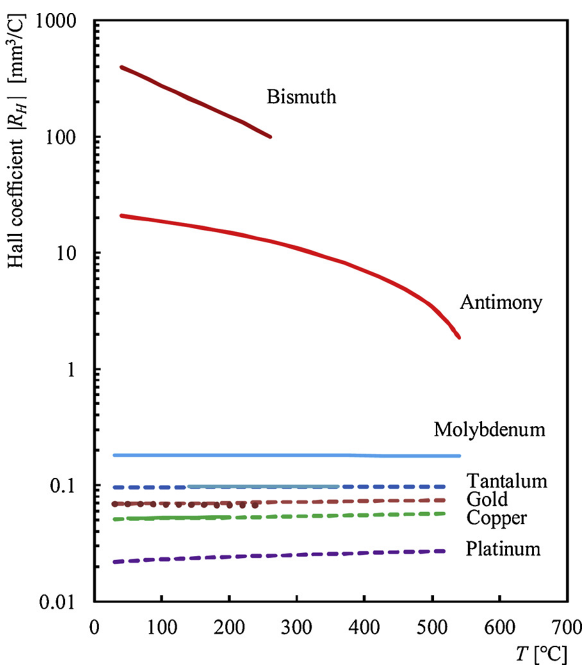

Fig. 2. Comparison of all listed Hall coefficients in logarithmic scale (dotted line [19], dashed lines [20,21]).

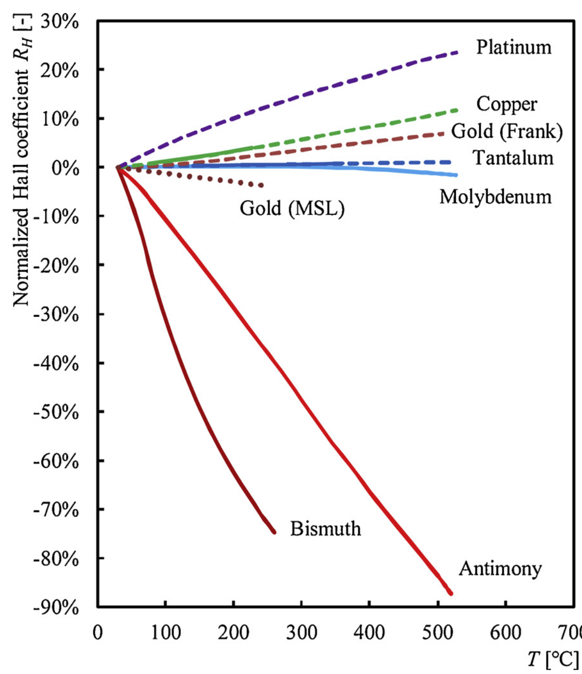

Fig. 3. Relative change of the Hall coefficients in the operating temperature range (dotted line [19], dashed lines [20,21]).

temperature.

5. Discussion

The temperature dependence of the Hall coefficient of these most considered materials poses a challenge for the realization of DEMO magnetic diagnostics, as the temperature measurement by the thermocouples requires two additional wires for each magnetic sensor (or a pair of sensors in the case of use of an ITER-like sensor unit incorporating the tangential and normal Hall sensor) increasing the wiring volume. Moreover, the accuracy of the magnetic measurement may depend on the temperature measurement accuracy, which is generally limited to a fraction of Kelvin for the best commercial thermocouples.

To evaluate the effect of temperature dependence on measurement accuracy, it is appropriate to normalize the Hall coefficients at room temperature (Fig. 3). Assuming the operational temperature variability of ± 5 °C during the reactor pulse period, Table 1 shows that the temperature variation causes a change in the Hall coefficient and thus a different result in the sensor output voltage lower than 0.1 % in the cases of tantalum and molybdenum. The limit of 0.1 % is based on the maximum allowable magnetic field measurement error of a few mT at

Table 1
Average Hall coefficients relative change per 10 °C in the range from room temperature to 550 °C, respectively 250 °C in the case of gold (MSL) and 265 °C in the case of bismuth.

Material	Hall coefficient relative change
Tantalum	0.02 % / 10 °C
Molybdenum	0.03 % / 10 °C
Gold (Frank)	0.15 % / 10 °C
Gold (MSL)	0.17 % / 10 °C
Copper	0.24 % / 10 °C
Platinum	0.48 % / 10 °C
Antimony	1.82 % / 10 °C
Bismuth	3.40 % / 10 °C

the measurement range of several Tesla [5]. For other materials, the impact of temperature change is higher and may compromise the accuracy of magnetic field measurement. At the first approximation, this may result in the need to measure the temperature of the Hall sensors by dedicated embedded temperature sensors.

In addition to the Hall coefficient, the sensor sensitivity is also influenced by the thickness of the sensitive layer (see Eq. (2)). The manufacturing of thin sensitive layers is a technologically demanding

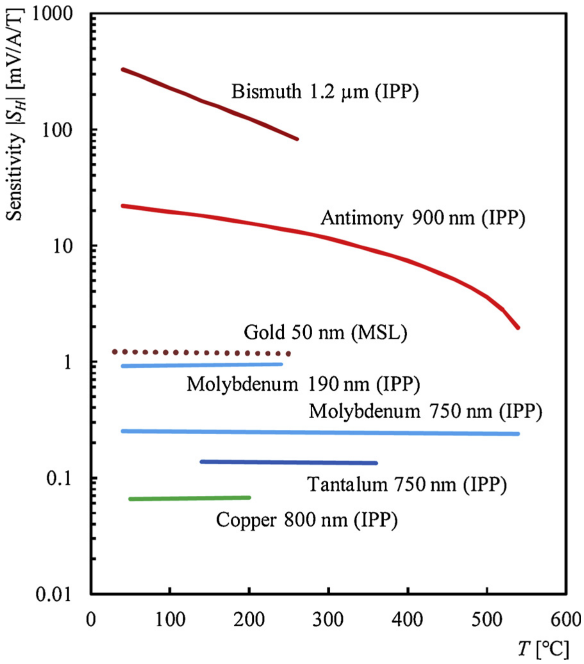

Fig. 4. Sensitivity of the Hall sensors tested within the DEMO project in logarithmic scale (dotted line [19]).

process, and the achievable thickness of the layer depends on a number of factors, in particular, the substrate surface and the manner in which the layer is formed.

The sensitivities of the presently available sensors are shown in Fig. 4. The gold sensors developed by MSL have relatively high sensitivity due to the very thin sensitive layer of 50 nm [19] compared to the other tested sensors. Two presented sensitivities of the molybdenum sensors correspond to the different sensitive layer thickness of 190 nm and 750 nm, respectively.

6. Conclusion

The temperature dependencies of several materials proposed for the Hall sensors of the DEMO reactor are presented in this paper. Bismuth and antimony offer relatively high Hall coefficient by several orders of magnitude higher than other candidate materials, but these coefficients are highly temperature-dependent and their implementation requires measurement of the temperature of the sensors with the dedicated sensors. The Hall coefficients of molybdenum and tantalum are almost independent of temperature. For other materials considered here, the pronounced temperature dependence of the Hall coefficient may require temperature measurement similar to that needed in the case of bismuth and antimony.

The results show that bismuth and antimony are the best in terms of the magnitude of sensor sensitivity and that tantalum and molybdenum would be the best in terms of the output signal temperature stability. However, due to insufficient neutron radiation resistance, tantalum is not suitable for the DEMO project [17]. The use of molybdenum nanolayers could be a promising solution, although the preparation of such sensors still requires further demanding development.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Slavomir Entler: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Ivan Duran:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Karel Kovarik:** Methodology, Resources, Writing - review & editing. **Petr Sladek:** Methodology, Resources. **Ondrej Grover:** Formal analysis. **Monika Vilemova:** Resources. **Dominik Najman:** Investigation, Resources. **Michal Kohout:** Investigation, Resources. **Josef Sebek:** Methodology, Writing - review & editing. **Karel Vyborny:** Resources. **Zbynek Soban:** Investigation, Resources.

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