KAPITEL 3 / *CHAPTER 3* [3]
MAGNETORESISTORS AND HALL SENSORS IN MAGNETOMETRY

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Introduction

In the modern era of scientific and technological progress, sensor technologies have become an integral part of intelligent systems. Sensors provide feedback between equipment and the environment. One of the important elements of such sensor systems is magnetoresistors and Hall sensors. Magnetoresistors are devices that change their electrical resistance under the influence of an external magnetic field. Hall sensors are devices that generate an EMF (electric voltage) under the influence of an external magnetic field. The principle of their operation is based on the physical Hall effect. This effect has become the basis for the creation of a whole class of sensors that are widely used today in the automotive industry, automation and security systems, measuring equipment, etc. Despite the relative simplicity of these sensors at first glance, these physical phenomena are based on complex interactions of various electrophysical processes [1-5,12].

The relevance of research in this area is due not only to the wide range of practical applications of these sensors, but also to the active development of new types of materials, nanostructures, and technologies that allow improving the characteristics and expanding the scope of their application. The purpose of this work is to reveal the principles of operation of these measuring transducers, analyze their main types, describe the designs and materials used, consider the key technical parameters and main characteristics of the sensors developed by us, and outline the prospects for their further development in the context of modern science and technology.

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3.1. Physical basis of the magnetoresistive effect and main types

The magnetoresistive effect is a physical phenomenon in which the electrical resistance of a material changes under the influence of an external magnetic field. The basis of this effect is a change in the trajectory of electrons in a conductor or semiconductor under the influence of the Lorentz force. This force changes the direction of movement of charge carriers, which affects the effective resistance of the conductive material.

Magnetoresistive effects are divided into several types depending on the nature of the underlying physical processes, as well as on the type of material and structure of the device. The most famous among them are: anisotropic magnetoresistive effect (AMR), giant magnetoresistive effect (GMR), tunnel magnetoresistive effect (TMR) [1, 4-8].

At the microscopic level, electrons in a metal move in random directions, and collisions with lattice defects or other electrons create resistance. When a magnetic field is applied, the trajectory of these electrons changes, and the number of collisions increases or decreases, which directly affects the resistance. In some materials, this effect can be negligible (0.1-5%), as in the case of the classical anisotropic magnetoresistance (AMR) effect, or very pronounced - up to 200% or more, as in the tunnel magnetoresistance (TMR) effect.

The anisotropic magnetoresistive effect is the simplest and was discovered in the 19th century. It is observed in magnetic metals, such as nickel and iron, and consists in the fact that the electrical resistance depends on the angle between the direction of electric current and the direction of magnetization (Fig. 1). This effect is usually manifested as a slight change in resistance of up to 5%, but it is widely used in industry due to its simplicity and stability.

The giant magnetoresistive effect was discovered in 1988 and was a breakthrough in solid state physics. It occurs in multilayer structures consisting of alternating thin ferromagnetic and nonmagnetic layers. When the magnetic layers are aligned in parallel, spin-conserved electrons pass through the device more easily than when they

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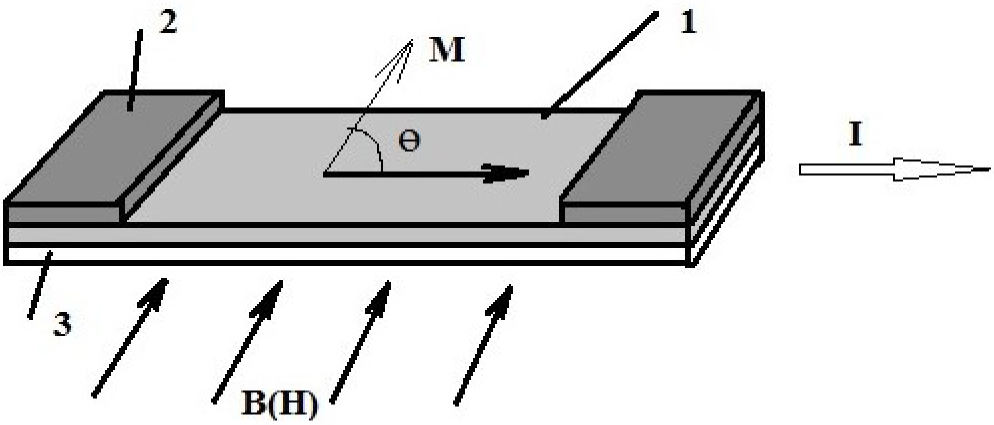

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Fig. 1. Schematic representation of a magnetoresistor based on the anisotropic magnetoresistive effect. 1 - permalloy thin film, 2 - metal contacts, 3 - substrate, I - current, B - external magnetic field.

are oriented antiparallel. This effect allows changing the resistance by tens of percent and was the basis for creating the first ultra-sensitive reading heads in hard disks [6-8].

The tunneling magnetoresistive effect is based on the quantum tunneling of electrons through a thin insulating layer between two ferromagnetic layers. Depending on the relative orientation of the magnetization of the layers - parallel or antiparallel - the tunneling probability changes significantly, leading to large changes in resistance. TMR structures make it possible to achieve resistance changes of more than 200%.

Each of these types of effects opens up new possibilities in the development of electronic components and sensors, providing a variety of solutions for the modern technology industry.

3.2. Design features of magnetoresistors, their characteristics

The design of a magnetoresistor is determined by both the principle of operation and the scope of its application. Simple devices based on the AMR effect are usually made in the form of thin films of magnetic material that are applied to a substrate. These films can be shaped like a coil or a lattice, which allows for increased sensitivity and adaptation of the structure to the specific geometry of the electrical circuit.

More complex structures, such as GMR and TMR elements, have a multilayer architecture. For example, in GMR modules, the structure looks like an alternation of a ferromagnetic layer (e.g., cobalt) and a non-magnetic layer (e.g., copper). In TMR structures, the insulating layer is several nanometers thick and acts as a barrier to tunneling current. It is very important that the thickness of the layers is controlled with high precision, so such elements are made using molecular beam epitaxy, magnetron sputtering, or chemical vapor deposition methods.

Magnetoresistors can also include additional elements for temperature compensation, surge protection, or be integrated into hybrid chips. In many cases, the design includes integration with analog-to-digital converters or logic circuits, which provides digital signal output and increased measurement accuracy.

Among the most common magnetic materials for the AMR effect are permalloy (nickel-iron alloy, NiFe), cobalt, and cobalt alloys with other metals. Permalloy is characterized by high magnetic permeability and stability of properties, so it is widely used in position and current sensors. To improve thermal stability, molybdenum or chromium impurities are often added to reduce the impact of temperature fluctuations.

In devices based on the GMR effect, multilayer structures based on cobalt, iron, nickel, and a non-magnetic layer of copper or silver play a key role. The creation of such structures requires extremely high precision in controlling the thickness of the layers, because even a change in thickness by a few atoms can significantly affect the efficiency of the device.

In recent years, new materials have been actively studied, such as topological insulators, graphene, and hybrid compounds based on 2D materials. The use of such materials can potentially achieve extreme sensitivity with minimal power consumption, which is critical in portable and medical electronics.

The main parameters of magnetoresistors are: magnetoresistance ratio (MR), sensitivity, magnetic field operating range, temperature stability, speed, power consumption, and device size.

Magnetoresistance (MR) is defined as the percentage change in resistance when

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a magnetic field is applied. In AMR sensors, it is usually 1-5%, in GMR - up to 50%, and in TMR it can exceed 200%, which makes the latter extremely effective for accurate information reading.

The sensitivity characterizes the change in the output signal per unit change in the magnetic field and is critical for applications in weak fields, such as biomedical devices or navigation. In some TMR structures, the sensitivity can reach tens of mV/ohm.

Many modern magnetoresistors have integrated temperature compensation circuits that allow them to operate in the range of -40 to +125°C.

3.3. Application of magnetoresistors in various industries and development prospects

Magnetoresistors are versatile components that are used in a wide range of modern technologies. Due to their high sensitivity to magnetic fields, stability, and compactness, they have become indispensable in electronics, automotive, medicine, energy, industry, and even space technology.

In medicine, magnetoresistive sensors are used to detect weak magnetic fields emitted by biological tissues, for example, in magnetocardiography. They are also integrated into portable devices for monitoring physiological parameters where miniaturization and energy efficiency are required. Some next-generation biosensors use magnetic nanoparticles and TMR structures for ultra-precise detection of biomarkers in body fluids.

In industrial control and automation systems, magnetoresistors enable precise detection of the position of moving parts, speeds, currents, and voltages, which is especially important in robotics and production lines. They provide contactless operation, which reduces wear and tear and increases system reliability.

Integration with intelligent systems based on artificial intelligence allows you to create sensors that not only detect field changes but also automatically analyze data to adapt to environmental changes. This opens the way to the full use of magnetoresistors in autonomous vehicles, smart homes, security systems, and automated manufacturing

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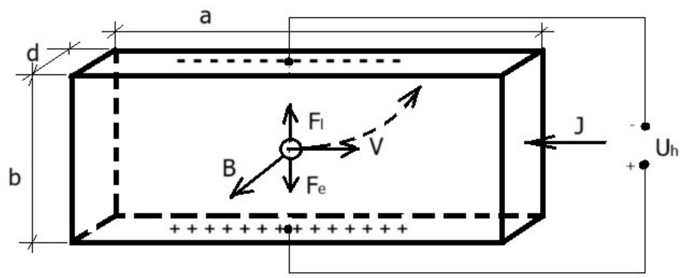
[3-5].

3.4. The Hall effect and Hall sensors

The reason for the Hall effect (the appearance of the Hall voltage) is the deviation of the motion of charged particles (electrons, holes) under the action of the Lorentz force from a straight line (dashed line in Fig. 2). As a result, the concentration of free carriers increases on one of the side faces. Despite the fact that the direction of the Lorentz force acting on both electrons and holes is the same, more carriers with higher concentrations are deflected to one of the faces.

Fig. 2 shows a diagram of the Hall voltage. The case of a donor (electronic n-type) semiconductor is shown. A current flows in the semiconductor plate and the current carriers move with a speed V. In the magnetic field B, the Lorentz force F_l acts on them and deflects the carriers to one of the plate faces. Thus, the charges are redistributed, and a transverse electric field with intensity E_h appears, which prevents further redistribution of charges by acting on them with a force F_e.



Source: Built by the authors on the basis of [1-3,12].

Fig. 2. A conductive plate with an electric current J and a diagram of the Hall voltage U_h in a magnetic field B. V is the direction of the velocity of the current carriers, F_l is the Lorentz force, F_e is the force due to the occurrence of the Hall electric field E_h.

This transverse electric field creates a potential difference U_h between the sides of the conductor, which is called the Hall voltage. Its value depends on the strength of the magnetic field, the current, and the type of material.

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The Hall emf (Hall voltage U_h) is defined by the expression:

$$E_h \approx U_h = (1/ne) \cdot (IB/d) \qquad (1),$$

where $1/ne = R$ is the Hall constant, which for semiconductors can be from 10 to 10^5 cm^3/Cl, I is the supply current, B is the magnetic field induction, and d is the thickness of the Hall sensor's sensing element.

The Hall effect allows you to determine the sign of charge carriers (electrons or holes), their concentration, and speed of movement. Thanks to these properties, the Hall effect is widely used in science and technology. It is used to create sensors - Hall sensors - that can respond to changes in the magnetic field [1,2,4,14].

In the sensor, the Hall voltage (electrical signal) is used for further processing. If there is no magnetic field, the Hall voltage is zero. When a magnetic field appears or changes, a measurable signal is generated. Thus, the Hall sensor allows you to detect the presence of a magnetic field, determine its direction and change in magnitude.

3.5. Design, types and characteristics of Hall sensors

A Hall sensor (detector) usually consists of several components. The main element of the sensor (sensing element) can be made of different materials, such as silicon, gallium arsenide, or other semiconductors. An electric current flows in this material, creating the movement of charged particles (electrons or holes). Under the influence of a magnetic field, the charged particles deviate from their trajectory, which leads to the accumulation of charges on opposite faces of the sensor and the formation of a Hall voltage. This voltage is proportional to the magnetic field, current strength, and material characteristics. A change in the magnetic field causes a change in the magnitude of the Hall voltage, which allows the sensor to measure magnetic fields. To apply electric current and measure the resulting transverse voltage, special electrical contacts are created on the sensor edges [9-14].

There are several types of industrial Hall sensors that differ in their operating principle, design, and application. For example, analog Hall sensors measure the Hall voltage, which varies in proportion to the magnetic field. This type of sensor produces a continuous output signal that can be used to measure magnetic induction, rotational speed, object position, and more. The output voltage is directly proportional to the magnitude of the magnetic field.

Integrated Hall sensors. These are compact modules that incorporate not only the Hall sensor itself but also electronics for signal processing. Such sensors are often used in automotive electronics, household appliances, and various measuring devices.

One of the key parameters is sensitivity, which is the ability of the sensor to respond to changes in magnetic induction, i.e. how much the output voltage changes when the magnetic field changes.

The output voltage depends on the type of sensor: in analog models, it changes smoothly depending on the field, while digital sensors have fixed signal levels that switch when a certain threshold is reached.

Power supply parameters, such as voltage and current consumption, are also important. Many modern sensors have minimal power consumption, which allows them to be used in portable devices.

The linearity of the output signal ensures accuracy in current or position measurement tasks. For digital sensors, hysteresis - the difference between the response level when the magnetic field increases and decreases - is also important, which helps to avoid false switching.

3.6. Applications

Hall sensors are used in a wide range of engineering and electronics applications due to their high reliability, compact size, and ability to accurately detect the presence or change in a magnetic field. The most common use is in the automotive industry, where such sensors are used to determine the position of the camshaft or crankshaft, monitor wheel speed, ABS systems, speed sensors, and pedal position.

In household appliances, Hall sensors are used in washing machines, refrigerators, induction cookers, and fans, for example, to control the position of doors or the speed of motors.

In electronics and instrumentation, Hall sensors are widely used for non-contact control, and in robotics, they perform the functions of positioning, determining the angle of rotation or moving parts of mechanisms.

Among the main advantages is the non-contact operation of the sensors, the absence of mechanical friction ensures durability and wear resistance. The sensors do not require sealing on the magnet side. Small size and ease of integration into microelectronic systems. A wide temperature range allows the sensors to be used in the cryogenic range, in extreme conditions, as well as in automotive and industrial equipment.

The disadvantages include the need for a power supply, which can somewhat complicate the design of autonomous systems. The temperature dependence of the characteristics sometimes requires additional measures to improve measurement accuracy.

3.7. Some modern experimental developments and their characteristics

Although the Hall effect was discovered quite a long time ago, its practical application for measuring magnetic fields also began quite a long time ago, nevertheless, these devices are constantly being improved due to new requirements for measurement accuracy, miniaturization of automation systems, emergence of new technologies, etc. If we analyze the formula (1), which determines the value of the Hall voltage, it becomes clear that to increase this voltage, and, accordingly, the sensitivity of the sensor, it is first of all necessary to use materials with the highest possible mobility of current carriers. Such materials include, for example, indium antimonide (InSb) and gallium arsenide (GaAs) semiconductors. Therefore, these materials are most widely used for the manufacture of Hall sensors. At the same time, other requirements are sometimes important and must be taken into account, such as the magnitude of the supply currents and heat dissipation, respectively, the temperature range of the sensor, economic feasibility, etc. Therefore, taking into account the whole range of requirements, other materials are used to manufacture the sensing elements of

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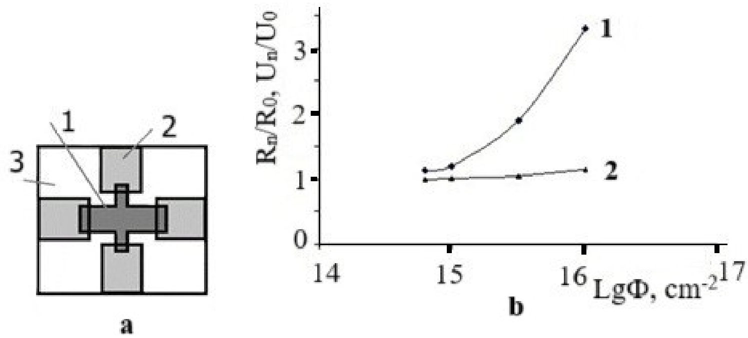
Hall sensors, for example, silicon (Si), germanium (Ge), indium phosphide (InP), etc.

For the research and development of Hall sensors, we used different thicknesses of GaAs films on an insulating substrate of the corresponding gallium arsenide. The thickness of the films d, as can be seen from formula (1), affects the technical characteristics of the sensor through the corresponding dimensions, the permissible current value, etc. The design of the sensor sensing element and its shape are shown in Fig. 3a. The dimensions were 1.0x1.0x0.4 mm^3 [11-14].



Source: Built by the authors on the basis of [9,12-14].

Fig. 3. a - Design and shape of the sensing element of the Hall sensor based on GaAs films. 1 - gallium arsenide film, 2 - metal contacts, 3 - insulating base (substrate). b - Dependence of the relative change of the input resistance R_n/R_0 (1) (where R_n is the value of the resistance after irradiation, R_0 is the initial resistance) and the initial output signal U_n/U_0 (2) (where U_n is the value of the output signal after irradiation, U_0 is the initial output signal) of the magnetic field measuring transducer on the value of neutron flux irradiation.

We also studied sensors based on indium antimonide films, the sensing elements (chips) of which were ordered from third-party organizations.

Table 1 shows the main characteristics of the experimental sensors.

On the basis of the developed sensors, a three-component magnetic field sensor was created, which generally consists of a base in the form of a cube with a side of 7 mm, on three opposite faces of which single-component Hall sensors (HS) are placed. The characteristics of such a sensor are presented in Table 2.

Table 1: Main technical characteristics of experimental Hall sensors.

Material	GaAs	InSb
Active zone, μm	100x100	100x100
Input/output impedance, Ohm	1000	1,5
Rated supply current at 300K, mA	7	100
Sensitivity μV/Gs	50	10
Initial offset voltage, mV	<± 3	<± 0,1
Operating temperature range, K	4,2-425	4,2-425

Source: compiled and summarized by the authors based on [9,12-14].

The developed sensors were also tested for the effect of radiation on their main characteristics. The results are shown in Fig. 3-b.

The characteristics of the sensors were measured at a temperature of 300 K before irradiation and after irradiation with neutron fluxes Φ from 8·1014 cm-2 to 1·1017 cm-2. The temperature during the measurements was stabilized to within 0.1 K. The neutron energy was 1 MeV and the flux intensity was (2-4)·108 fl/s [14].

Fig. 3-b shows the dependence of the relative change in the input resistance of the magnetic field transducers (Hall sensors) on the value of the neutron flux Φ. The input impedance of the sensors is 1.1 kΩ, the initial output signal is no more than 4.5 mV, and the sensitivity is 350 mV/T.

Resistance changes begin at fluxes of $1 \cdot 10^{15}$ cm^{-2} and amount to 15-20%, and at $1 \cdot 10^{16}$ cm^{-2} the resistance increases by 3.3 times. At the same time, the initial output signal at a constant supply voltage of 4.5 V changed by no more than 15%, which is equivalent to the effect of a magnetic field of up to 1 mT. At a constant supply voltage, the sensitivity after irradiation decreased by about 1.4 times. After irradiation with fluxes of $1 \cdot 10^{17}$ cm^{-2}, the resistance of the sensors increases to infinity.

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Table 2: Main technical characteristics of a three-component magnetic field transducer based on Hall sensors.

Base size	Cube with a side of 7 mm
Accuracy of determination of spatial and angular coordinates of single-component DCs	0.5 μm, 0.1 angular degree
Rated supply current	30 mA
Temperature stabilization accuracy in the range of ±60 °C	±0.05 °C
Absolute sensitivity after signal processing	<1 mGs

Source: compiled and summarized by the authors based on [9,12-14].

Studies show that the sensors can be used up to quite significant neutron irradiations, up to about $1 \cdot 10^{15}$ cm^{-2}. A slight change in the characteristics can be taken into account and compensated for in various ways.

Conclusions

Magnetoresistors have opened up new possibilities in the field of magnetic field measurement. Thanks to a variety of magnetoresistive effects (AMR, GMR, TMR, CMR), a wide range of materials, and the possibility of nanostructuring, they have found application in numerous industries, from computer technology to medicine, from industrial automation to space.

These sensors are compact, energy efficient, highly sensitive and reliable. Compared to alternative technologies, magnetoresistors offer a good balance between performance and cost. Their prospects are particularly promising due to the development of spintronics, new materials, and smart sensor systems.

The structure, principle of operation, types, and main characteristics of Hall sensors are analyzed, as well as their numerous applications, ranging from automotive to household appliances, medical devices, and energy.

We present some experimental results of studying the technical characteristics of

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our Hall sensors based on gallium arsenide films.

The main advantages of this technique, such as reliability, high accuracy, small size, and low power consumption, are identified. Their prospects for application and development are significant, in particular due to miniaturization, integration with microprocessor systems, and improvement of materials.

Thus, solid-state magnetic field sensors such as magnetoresistors and Hall sensors are not only an important part of modern electronics, but also open the way to even newer approaches to collecting, analyzing, and processing information. Their further improvement will play a key role in the development of the high-tech society of the future.

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