



KAPITEL 5 / CHAPTER 5 ⁵

APPLICATION OF MAGNETIC FIELDS IN MODERN TECHNOLOGY AND MEANS OF THEIR CONTROL

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Introduction

The study of magnetic fields is one of the fundamental tasks of modern physics, since magnetic fields are important in many areas of science and practice: medicine, geology, astronomy, electrical engineering, superconducting systems engineering, etc. High accuracy in measuring magnetic fields makes it possible to study the structure of the Earth's crust, predict geophysical phenomena, create modern devices with high accuracy of measurement of other physical quantities, diagnose the state of the human body in medicine, diagnose and control electrical installations, including superconducting ones. Technologies for measuring magnetic fields are constantly evolving and achieving new successes. With the advent of new highly sensitive devices, it has become possible to make accurate measurements not only at the level of terrestrial but also cosmic magnetic fields. The application of these technologies opens up new opportunities in creating accurate navigation systems, security systems, and diagnostic medical devices such as magnetic resonance imaging (MRI) and others. Modern tools allow for measurements in a wide range of temperatures and magnetic fields [1-7].

Technologies for measuring and controlling magnetic fields are responding to the needs of science, medicine, industry, and other sectors. Increasing accuracy, miniaturization, reliability, and expanding the ability to work in extreme conditions are the main trends in the improvement of magnetic sensors and measuring devices.

In modern electronics, there is a need to reduce the size of any sensor, in particular for use in portable devices and integration into smartphones. Miniature magnetometers can significantly expand the capabilities of personal devices, for example, provide navigation, work with augmented reality, and even conduct basic scientific research.

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Also, miniature magnetic sensors are actively used in medicine, for example, in microscopic devices for intra-body research [10-16].

Nanotechnology opens up new perspectives in measuring magnetic fields by enabling the creation of ultra-small and ultra-sensitive sensors. For example, nanowires and nanoparticles with magnetoresistive properties can serve as the basis for innovative magnetic sensors in medicine, including the measurement of magnetic fields at the molecular level. This can significantly improve the accuracy of research in biology and chemistry, allowing to work with extremely small objects and reactions, such as biomolecules and cells.

The purpose of our study is to review the current literature in the field of magnetic fields in science, technology, industry, and medicine and to familiarize ourselves with modern means and methods of measuring and controlling magnetic fields, as well as to present the known experimental results of the study of modern magnetic field measurement devices.

5.1. Magnetic fields

A magnetic field is known to be created by moving electric charges and magnetic moments of elementary particles. It is described by characteristics such as magnetic field strength H , magnetic field induction B , and magnetic flux F . The main sources of magnetic fields are natural and artificial sources. The Earth's magnetic field, which is created by processes in the planet's core, as well as the magnetic fields of stars and cosmic bodies, are natural. Artificial magnetic fields include those created by electric current or electromagnets. They are widely used in industry, science, medicine, transportation, and other fields.

Various methods are used to measure magnetic fields, which can be divided into two main groups: direct and indirect. Direct methods measure magnetic quantities directly, while indirect methods involve obtaining parameters related to the magnetic field, which are subsequently used to determine the magnitude of induction or magnetic



field strength.

5.2. Existing means of measuring and controlling the magnetic field.

Devices that allow measuring the strength of a magnetic field through the interaction of a magnetic field with an electric current passing through a conductor are called galvanometers. The principle of operation of galvanometers is based on the Ampere effect, when a conductor with an electric current interacts with a magnetic field, creating a force that deflects the instrument's arrow. Galvanometers are widely used in laboratories, but have limited sensitivity for measuring weak fields.

One of the most common types of devices for measuring magnetic fields are magnetometers. They include different types of devices. Proton magnetometer: based on the phenomenon of nuclear magnetic resonance and used to measure weak fields, such as the Earth's magnetic field. The principle of operation is to measure the resonance frequency of protons in a magnetic field. A quantum magnetometer uses the quantum properties of atoms to measure magnetic fields with high accuracy. These devices are highly sensitive and can detect weak magnetic fields, for example, in studies of human biomagnetic fields.

Ferromagnetic probes. They are used to determine the magnetic field strength in ferromagnetic materials. Ferromagnetic probes are placed in a field and, depending on changes in magnetization, determine the field characteristics. This method is often used to detect and analyze local magnetic anomalies.

Indirect measurement methods include induction methods. The basis of induction methods is Faraday's law of electromagnetic induction, according to which an electric current appears in a conductor under the influence of an alternating magnetic field. Induction coils are a classic example of this approach, and they are used to measure alternating magnetic fields. In high-frequency fields, this method is particularly convenient and effective.

There are also measurement methods using the magnetoresistive effect:



$$M = \Delta\rho/(\rho_0\Delta B) \quad (1),$$

where $\Delta\rho$ is the change in resistivity when the magnetic field changes by ΔB , ρ_0 is the initial resistivity.

The change in electrical resistance of materials under the influence of a magnetic field is used in many modern devices. This phenomenon is known as the magnetoresistive effect and is the basis for the operation of devices such as giant magnetoresistive sensors (GMRs), spin-valve magnetoresistors. They are used to measure weak magnetic fields in high-precision electronics and sensors.

There is also a type of magnetoresistors that are sometimes divided into film and monolithic. In general, the operating principle of these magnetoresistors also consists of changing the electrical resistance of the conductive material when it is placed in a magnetic field. When manufacturing monolithic magnetoresistors, semiconductor materials with high carrier mobility are usually used. Such materials include indium antimonide, gallium arsenide, and others.

The magnetoresistor's film magnetoresistor's magnetosensitive element is made from ferrimagnetic material films. Such films have an anisotropic magnetoresistive effect.

Sensors based on the Hall effect are widely used to measure magnetic fields in a wide range of temperatures (from cryogenic to climatic intervals). Modern Hall sensors are mainly made on the basis of semiconductor films on insulating substrates. Using modern microelectronics technologies, the sensing elements of Hall sensors are formed from the film using the photolithography process. The most commonly used materials for their manufacture are indium antimonide, gallium arsenide, silicon, etc. The main advantages of such sensors are their ease of use and small size, which are achieved by using modern microelectronics technologies. Such sensors also have a fairly high sensitivity at relatively low supply currents (at the level of 1000 mV/T), low temperature dependence of the main parameters, etc. [7-10].

Optical effects are also used. The use of optical methods to measure magnetic fields is based on the Faraday effect, which is a change in the polarization of light passing through a material under the influence of a magnetic field. Optical



magnetometers have high sensitivity and are used in systems where electrical interference must be avoided, for example, in biomedical research.

Proton magnetometer. A proton magnetometer is based on the phenomenon of nuclear magnetic resonance (NMR) of protons in a magnetic field. The protons of hydrogen atoms begin to precess (rotate) around magnetic force lines with a certain frequency proportional to the magnitude of the magnetic field. From the measured resonance frequency, the field induction can be accurately calculated. Proton magnetometers are highly accurate and stable, making them useful for measuring weak fields, such as the earth's magnetic field. However, they are less sensitive to rapid field changes, so they are not suitable for high-frequency measurements. They are most often used in geophysical research and archeology to study the Earth's magnetic anomalies, as well as in navigation systems.

Quantum magnetometer. Quantum magnetometers use quantum effects, such as the resonance properties of cesium or rubidium atoms that interact with a magnetic field. In the presence of a magnetic field, the atoms change their state, which can be detected using special optical or radio frequency systems. They are extremely sensitive to weak magnetic fields, which allows them to be used in the most complex scientific research, such as biomagnetic field studies, astronomy, and quantum physics. They are used in medicine for magnetocardiography (MCG) and magnetoencephalography (MEG), where it is necessary to record the magnetic fields of the brain and heart, as well as in aerospace and fundamental physics.

SQUID magnetometer and its principle of operation: SQUID (Superconducting Quantum Interference Detector) magnetometers work based on the properties of superconductors. SQUID magnetometers use the quantum interference effect to detect small changes in the magnetic field even at the picotesla level (10^{-12} T). This is one of the most sensitive types of magnetometers, capable of detecting the smallest changes in the magnetic field. To operate, SQUID magnetometers require cooling to cryogenic temperatures (liquid helium or nitrogen), which limits their application. They are used in biomedical research to detect neuromagnetic fields, in physical laboratories to study the magnetic properties of materials, as well as in the search for mineral resources and



in geophysical research.

Vector magnetometer. Vector magnetometers measure all three components of the magnetic field vector (x, y, z axes) simultaneously. For this purpose, various types of sensors are used that can accurately determine the direction and magnitude of each component of the field. They provide a complete picture of the magnetic field, which allows for more accurate research and measurements. Their main advantage is the ability to measure both the amplitude and direction of the field. They are used in space research to study the magnetic fields of the planets and the Sun, as well as in navigation systems and instrumentation.

Magnetometers for smartphones. Most modern smartphones use miniature magnetoresistive or Hall sensors that can determine the magnetic field and orientation of the device in space. Although such magnetometers are not ultra-precise and have limited sensitivity, they provide sufficient accuracy for spatial orientation, navigation, and compass work in everyday life. They are used in everyday navigation applications, augmented reality (AR), and in some scientific research where mobility and compactness are crucial.

5.3. Main applications of magnetic measuring devices.

The study of the Earth's magnetic field is important for understanding its internal structure and dynamic processes in the subsurface. By measuring the magnetic field, it is possible to study the structure of the Earth's crust, to detect anomalies that indicate the presence of minerals such as iron, copper, nickel, and other metals. Proton magnetometers are widely used in geophysical expeditions to search for minerals and investigate magnetic anomalies. Magnetic methods are effective, especially in hard-to-reach areas where the use of other methods is limited.

Medicine. Magnetic resonance imaging (MRI). MRI is one of the most important methods of visualization of internal organs, allowing to obtain high-precision images of body tissues. This method is based on the principles of nuclear magnetic resonance



and allows to diagnose diseases, neoplasms and other pathological changes. MRI is widely used in oncology, neurology, cardiology, and orthopedics.

Magnetocardiography (MCG). MCG allows you to track the magnetic fields created by the electrical activity of the heart. It is used to diagnose various heart diseases and heart rhythm disorders. Magnetocardiography provides an opportunity to obtain information about the work of the heart non-invasively.

Table 1 - Comparative analysis of modern methods and means of measuring magnetic fields.

Type of magnetometer	How it works	Accuracy / Sensitivity	Features	Application area
Proton magnetometer	Nuclear magnetic resonance	High	Weak field measurements	Geophysics, archaeology
Quantum magnetometer	Quantum effects of atoms	Very high	Sensitive to the slightest changes	Medicine, fundamental physics
SQUID magnetometer	Superconducting properties	Extremely high	Requires cryogenic cooling	Biomedical research, geophysics
Induction coils	Electromagnetic induction	Average	For variable fields	Industry, quality control
Magnetoresistive sensors	Magnetoresistive effect	High	Compact, integration into electronics	Electronics, mobile devices
Optical magnetometers	Faraday effect	Very high	No electrical interference	Biomedicine, brain research

Source: compiled and summarized by the authors based on [1-6, 8, 11-16].

Exploration of outer space. Measuring the magnetic field in space helps to study the magnetic properties of planets, stars and other celestial bodies. For example, space probes equipped with magnetometers study the magnetosphere of the Earth and other planets in the Solar System, and determine magnetic fields in the interstellar medium. Navigation in space. Magnetometers can be used to orient spacecraft in space, as they help determine their position relative to the magnetic fields of celestial bodies such as



the Earth or Mars. This significantly improves the accuracy of space navigation and allows for the successful completion of complex missions.

Industry. Quality control and flaw detection. In industry, magnetic field measurements help detect defects in metals and other materials. Magnetic flaw detection methods help to identify cracks, cavities, and other anomalies in materials without damaging their structure, which is important for ensuring product quality. Magnetic sensors are widely used in production lines to control processes, measure the speed, position and rotation of objects. This allows automating processes and increasing their accuracy [2,6,13].

Table 1 shows a comparative analysis of some modern methods and means of measuring magnetic fields, based on the literature used.

5.4. Some results of experimental studies of Hall sensors

We [3,7,8] conducted experimental studies of the main technical characteristics of experimental semiconductor magnetic field sensors based on the Hall effect. The sensors are made on the basis of thin films of gallium arsenide (GaAs). The films are deposited on semi-insulating gallium arsenide and used to form the sensing elements of the sensors using photolithography technology. Due to the high mobility of current carriers in gallium arsenide, they produce relatively large values of the electromotive force (EMF) E_x .

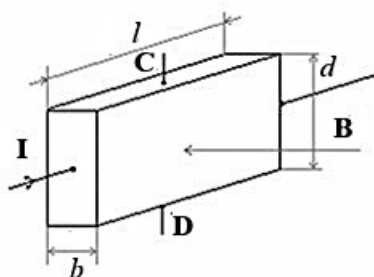


Figure 1 - A plate conducting electric current I placed in a magnetic field B .

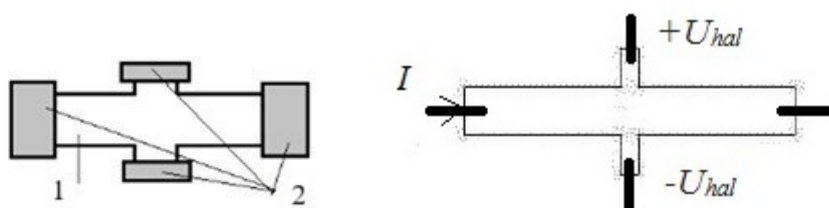
l - plate length, b - thickness, d - width, CD - Hall contacts.



The Hall effect is that if an electric current I is passed along a conducting plate and a magnetic field B is created perpendicular to the plane of the plate, then an electric field called the Hall field will arise on the lateral planes of the plate in the direction CD. Let's assume that the sample has the shape of a rectangular plate of length l , width d , thickness b (see Fig. 1). In practice, as a rule, the Hall field is characterized by the potential difference, which is measured between symmetric points C and D on the lateral surface of the sample. This potential difference is called the Hall potential difference U_h or Hall EMF E_h . In the classical theory of conductivity, the Hall effect is explained by the fact that in a magnetic field, the Lorentz force acts on moving electric charges, the magnitude and direction of which are determined by the corresponding vector equation. Using this theory, we can obtain an expression (formula) for the Hall EMF (Hall voltage U_x):

$$E_h \approx U_h = R \cdot IB/b \quad (2),$$

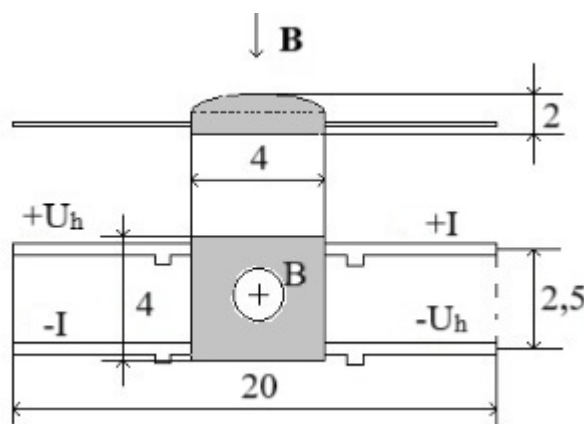
where $R = 1/ne$ is the Hall constant, which for semiconductors can have a value from 10 to $10^5 \text{ cm}^3 / \text{C}$, I is the supply current, B is the magnetic field induction, and b is the thickness of the Hall sensor sensing element.



Source: [3,7,8]

Figure 2 - Typical shapes of the Hall sensor sensing element. 1 - semiconductor film, 2 - contact pads.

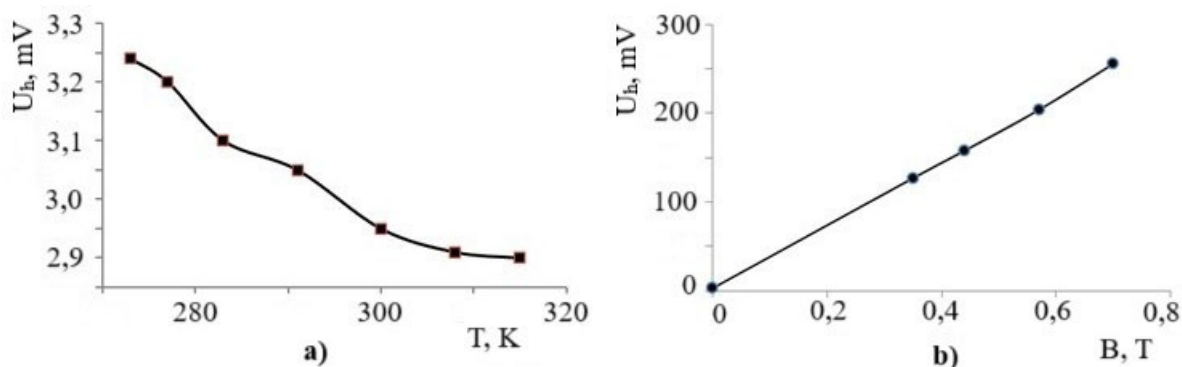
Sketches of the shapes of sensitive elements of modern Hall sensors are shown in Fig. 2. The dimensions of the sensor without an external housing can be $1.0 \times 1.0 \times 0.3 \text{ mm}^3$, although modern microelectronic technologies make it possible to achieve smaller dimensions. The general typical design and dimensions of industrial Hall sensors are shown in Fig. 3.



Source: [8]

Figure 3 - Typical design of a Hall sensor.

The temperature dependence of the output signal U_x of the sensor in the range of room temperatures (Fig. 4-a) and the dependence of the output signal on the magnitude of the magnetic field B (Fig. 4-b) were investigated, and the sensitivity to the magnetic field γ was determined. $\gamma = \Delta u_h / \Delta B \approx 345 \text{ mV/T}$.



Source: Built by the authors on the basis of [3,8].

Fig. 4. a) - Dependence of the initial output signal of the Hall sensor U_x on the temperature in the room temperature range. The supply current $I = 5 \text{ mA}$, b) - Dependence of the output signal of the Hall sensor U_x on the magnetic field induction B . The induction vector is directed perpendicular to the plane of the sensor's sensing element.

A reference Hall sensor was used to determine the magnitude of the magnetic fields, and a special ceramic thermostat with an electric heater was used to study the



temperature dependence. The results are shown in the corresponding figures. The analysis of the experimental results indicates a slight temperature dependence of the output signal (approximately no more than 10 $\mu\text{V/K}$) compared to the dependence of the signal on the magnetic field. The deviation from the linearity of the output signal versus the magnetic field does not exceed 1%. The sensors are promising for use in measuring and controlling magnetic fields in a wide temperature range in various electromagnetic devices and systems. In particular, in electromagnetic systems operating in a wide temperature range, automated process control systems, etc.

Conclusions

Magnetic fields and their properties are widely used in the national economy. To date, the means of measuring and controlling magnetic fields have achieved significant development, which allows solving complex scientific and engineering problems. The main directions of modern research and development are related to improving accuracy, miniaturization, expanding the ability to work in extreme conditions, and integration with digital technologies, such as artificial intelligence. Magnetic measurement and control are important today for science, industry, medicine, ecology, and navigation systems. This is confirmed by the topics of scientific and technical research, conferences, and publications in various scientific journals. Magnetic field sensors based on the Hall effect are already widely used and show promise for use in scientific research, in various industries related to electrical devices and systems where it is necessary to measure and control magnetic fields, in automation systems, cryogenic electromagnetic installations, etc.