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STATE OF THE ART AND OUTLOOK FOR DEVELOPMENT OF HALL EFFECT SENSORS FOR ELECTRONIC DEVICES

The fast development of solid electronics is contingent on the fast development of sensor electronics, including Hall sensors for different applications. The objective of this paper is to review classical and modern approaches to designing Hall sensors from bulk structure to quantum dimensions. Practical applications, advantages and disadvantages of Hall sensors are presented. In order to establish a theoretical basis for the development of Hall sensors, the study presents an overview of the mathematical models for Hall effects in semiconductor materials. Based on the analysis of the presented mathematical models, the authors offer recommendations for selecting the optimal material for Hall sensors with the highest sensitivity. This paper concludes with the discussion of future prospects for the development of sensors based on the Hall effect.

Keywords: Hall sensors, Hall effect, semiconductor materials for Hall sensors.

The Hall effect plays a key role in the development of modern electronic and sensor technologies. This physical phenomenon, which involves the emergence of an electric voltage perpendicular to the direction of current and magnetic field in a conductor, has a wide range of applications from macroscopic systems to quantum nanodevices. Due to its ability to provide highly accurate measurements of magnetic fields and changes in material conductivity, the Hall effect is used in many fields of science and technology, including the creation of sensors, magnetic data storage devices, identification systems, and in the study of fundamental physical phenomena at the micro- and nano-levels.

The relevance of researching the application of the Hall effect in various devices is driven by the need for further technological advancements to enhance the accuracy, sensitivity, and energy efficiency of electronic systems. In the context of rapidly increasing computational power and the miniaturization of electronic components, studying this effect on macro-, micro-, nano-, and quantum scales is crucial for developing innovative solutions in modern technologies.

The aim of this work is to review and summarize current achievements and mathematical models applied to the Hall effect in sensor devices for various scales: from bulk to macroscopic and quantum, as well as to identify promising semiconductor materials and Hall sensor designs.

Hall Effects — History and Development

The ordinary Hall effect (**OHE**), discovered by Edwin Hall in 1879, is one of the fundamental phenomena in the physics of semiconductors and magnetism. This effect occurs when an electric current flows through a conductor (or semiconductor) in the presence of a perpendicular magnetic field. As a result, a transverse voltage, known as the Hall voltage, is created, which is perpendicular to both the direction of the current and the magnetic field [1].

When current passes through a conductor, free charge carriers (electrons or holes) move in the direction of the electric field. In the presence of a magnetic field, these charge carriers are deflected by the Lorentz force, leading to the accumulation of charges on one side of the conductor. This accumulation creates an additional electric field that opposes the Lorentz force. In equilibrium, the Hall voltage that develops across the conductor is proportional to the current, the magnetic field, and the nature of the charge carriers [2].

The anomalous Hall effect (**AHE**) differs from the ordinary Hall effect in that it arises not only due to the action of the magnetic field on the charge carriers in the conductor but also due to the internal structure of the material, particularly the spin of the electrons. This phenomenon depends on the spin polarization of the electrons and can be significantly stronger than the OHE in materials with a high degree of spin polarization [3].

The anomalous Hall effect was first observed in the 1880s by Edwin Herbert Hall, but its "anomalous" aspects became the subject of detailed study much later when physicists began to understand the role of quantum properties of materials, particularly electron spin. The modern understanding of the anomalous Hall effect is closely tied to the development of quantum mechanics and solid-state physics in the 20th century [4].

The aforementioned Hall effects were discovered and applied at the macro level, while other Hall effects were identified at the micro level many years later. Among these is the planar Hall effect (**PHE**), discovered in the 1960s. This variation of the traditional Hall effect is observed in thin films or two-dimensional materials when a magnetic field is applied parallel to the plane of the sample, rather than perpendicular as in the classical Hall effect. This phenomenon reveals the dependence of the electric field intensity on the direction of the magnetic field within the plane of the sample, unlike the usual Hall effect where the field intensity depends on the perpendicular magnetic field [5].

The planar Hall effect is closely related to the phenomenon of anisotropic magnetoresistance, where the material's resistance changes depending on the angle between the magnetic field direction and the electric current direction. In many cases, the PHE can be enhanced or modulated through spin-dependent interactions in the material, making it significant for research in the field of spintronics [6].

Theoretically, the PHE can be explained by the dependence of charge carrier mobility on the magnetic field and the anisotropy of scattering in the material. These effects influence the distribution of charge carriers in the sample and induce a transverse field intensity similar to the classical Hall effect but with an additional dependence on the orientation of the magnetic field [7, 8].

In 1971, the foundations for the spin Hall effect (**SHE**) were laid. This quantum-mechanical phenomenon enables the generation of spin current in semiconductors and other materials without the use of external magnetic fields. Much later, in 2004, with the development of highly sensitive methods for measuring spin currents, the effect was confirmed experimentally. The SHE arises due to spin-orbit interaction in the material. When an electric current flows through the material, electrons with different spin orientations are deflected in opposite directions due to the interaction of their spins with the internal electric field of the crystal lattice. This deflection creates a redistribution of spins, leading to the emergence of a spin current perpendicular to the primary electric current [9].

There are two main types of the SHE: intrinsic and extrinsic. The intrinsic SHE arises directly from spin-orbit interaction in the crystal lattice of the material. The efficiency of this process depends on the symmetry of the crystal and the electronic structure of the material. The extrinsic SHE is caused by the scattering of electrons on defects, impurity atoms, or interfaces. This effect depends on the interaction between the spins of the electrons and the atoms on which they scatter [10].

Later, in 1980, the integer quantum Hall effect (**IQHE**) was discovered — a quantum mechanical phenomenon observed in two-dimensional electron systems at low temperatures and under the influence of a strong magnetic field. IQHE is characterized by the quantization of transverse (Hall) resistance and zero longitudinal resistance. The effect was first observed by Klaus von Klitzing during experiments that demonstrated the quantization of Hall resistance with extraordinary precision, allowing IQHE to be used as a standard for measuring electrical resistance. The theoretical explanation of IQHE is based on the concept of Landau levels and quantum mechanics. In a strong magnetic field, electron orbits are quantized, forming Landau levels. Electrons fill these levels, and the Hall resistance becomes quantized [11, 12].

In 1982, the fractional quantum Hall effect (**FQHE**) was discovered — one of the most remarkable phenomena in condensed matter physics, observed in two-dimensional electron systems at very low temperatures and under strong magnetic fields. Discovered by Daniel Tsui and Horst Störmer, this phenomenon demonstrates the quantization of Hall resistance not only at integer values, as in the IQHE, but also at fractional values.

Unlike IQHE, which can be directly explained through independent electrons, FQHE arises due to strong correlations between electrons, forming complex many-body states. FQHE was first observed in experiments with two-dimensional electron gases in heterostructures based on gallium arsenide (GaAs) [13]. The discovery was made during the study of the integer quantum Hall effect when it was noticed that Hall resistance plateaus occurred at fractional fillings of Landau levels [14].

Although direct practical applications of the FQHE have not yet been found, research into this phenomenon deepens our understanding of quantum mechanics, quantum electrodynamics, and the potential for creating quantum computers based on qubits that utilize states characteristic of the FQHE.

The inverse spin Hall effect (**ISHE**) was first theoretically predicted in 1971. However, experimental confirmation of the ISHE was obtained much later, in 2006, by the group led by Eiji Saitoh in Japan [15].

The ISHE is a fundamental phenomenon in spintronics, which allows the conversion of spin current back into charge current. This phenomenon is the reverse of the SHE, where an electrical current through spin-orbit interaction generates a spin current, separating electrons with different spin orientations to opposite edges of the sample [16, 17].

ISHE is crucial for the development of spintronics because it enables the electrical detection of spin currents without using ferromagnetic materials. This can be utilized in various devices such as spin transistors, spin logic devices, and sensors. Moreover, ISHE plays a key role in studying spin phenomena and developing new technologies for controlling spin states at the microscopic level. ISHE has been investigated in a variety of materials, including semiconductors, metals, and insulators. Recent research focuses on finding materials with a high spin

Hall angle to enhance conversion efficiency and develop high-performance spintronic devices [18, 19].

The quantum spin Hall effect (**QSHE**) is one of the key phenomena in modern condensed matter physics. QSHE is observed in so-called topological insulators — materials that behave as insulators in their bulk but have conductive edge states where electrons can move without energy loss. Electrons moving along different edges of the sample have opposite spin polarizations, allowing for the creation of spin currents without the use of external magnetic fields. QSHE can be viewed as a variant of the quantum Hall effect, but without the need for an external magnetic field [20].

The QSHE was theoretically predicted in 2005 by physicists Charles Kane and Eugene Mele, who developed a model describing this phenomenon in graphene. The first experimental observation of QSHE was made in 2007 in mercury telluride (HgTe) based heterostructures [21].

Theoretically, QSHE is explained by the presence of unusual topology in the electronic bands of the material, leading to the formation of edge states that are topologically protected. These edge states cannot be localized or scattered by ordinary defects or inhomogeneities in the material, making them ideal for dissipationless electron transport [22].

The Bernevig – Hughes – Zhang model is one of the main theoretical models describing QSHE. It was developed for a system based on HgTe/CdTe quantum wells and shows how quantum wells with band inversion can lead to the emergence of edge states exhibiting QSHE [23].

The quantum anomalous Hall effect (**QAHE**) combines the QHE and the AHE without the need for an external magnetic field. The QAHE is characterized by a quantized value of the transverse electrical resistance in the absolute absence of an external magnetic field, resulting from internal magnetic orientation and strong spin-orbit interaction in the material. The first theoretical prediction of the QAHE was made in the 1980s, but experimental observation was achieved only in 2013 in systems based on thin films of Cr-doped $(Bi,Sb)_2Te_3$, which are topological insulators [24].

The valley Hall effect (**VHE**) is a phenomenon in solid-state physics that occurs in two-dimensional materials with hexagonal symmetry, such as graphene and transition metal dichalcogenides (TMDCs). The VHE is characterized by the separation of charge carriers belonging to different valleys of the energy spectrum along opposite edges of the sample under the influence of an electric field, without the application of an external magnetic field. The VHE was theoretically predicted and later experimentally observed in various two-dimensional materials. One of the first materials where the VHE was observed was graphene, followed by similar effects being found in TMDCs such as MoS_2, WSe_2, and others [25].

The photo-induced Hall effect (**PIHE**) is a phenomenon where optical illumination of a material leads to the emergence or modification of the Hall effect. This phenomenon demonstrates how light can influence the electronic properties of materials, particularly their ability to conduct electric current in the presence of a magnetic field [26].

Under the influence of light, charge carriers (electrons and holes) can be generated in the material, altering the distribution of electrons across energy levels and affecting electronic conductivity. Optical radiation can change the characteristics of the Hall effect in a material, such as increasing or decreasing the Hall resistance [27] or even affecting the magnetic properties of the material [28]. PIHE offers the possibility to control the electronic properties of materials directly through radiation, which can be used in optoelectronics and quantum computing. PIHE has been investigated in various materials, including semiconductors [29], films [30], perovskites [31], and two-dimensional materials [32].

Fig. 1 shows the timeline of the discovery of Hall effects and **Fig. 2** demonstrates the basic principles of Hall effects including power sources, magnetic inductance and Hall voltages.

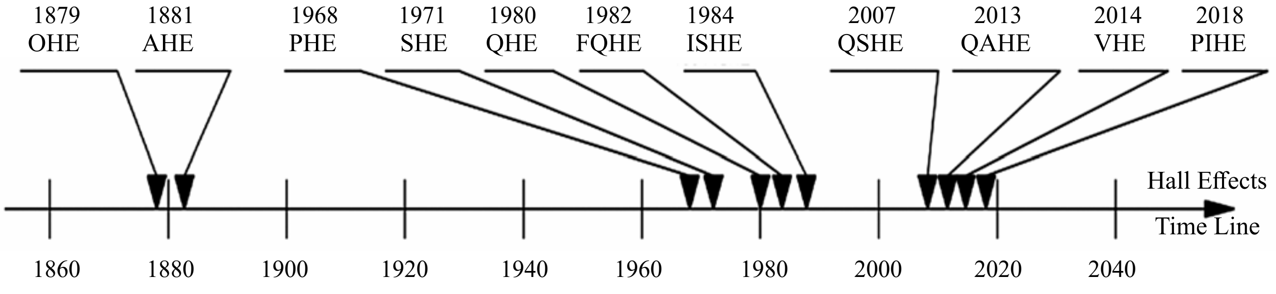

Fig. 1. Timeline of discovery of Hall effects:
OHE — ordinary; AHE — anomalous; PHE — planar; SHE — spin; IQHE — integer quantum; FQHE — fractional quantum; ISHE — inverse spin; QSHE — quantum spin; QAHE — quantum anomalous; VHE — valley; PIHE — photo-induced

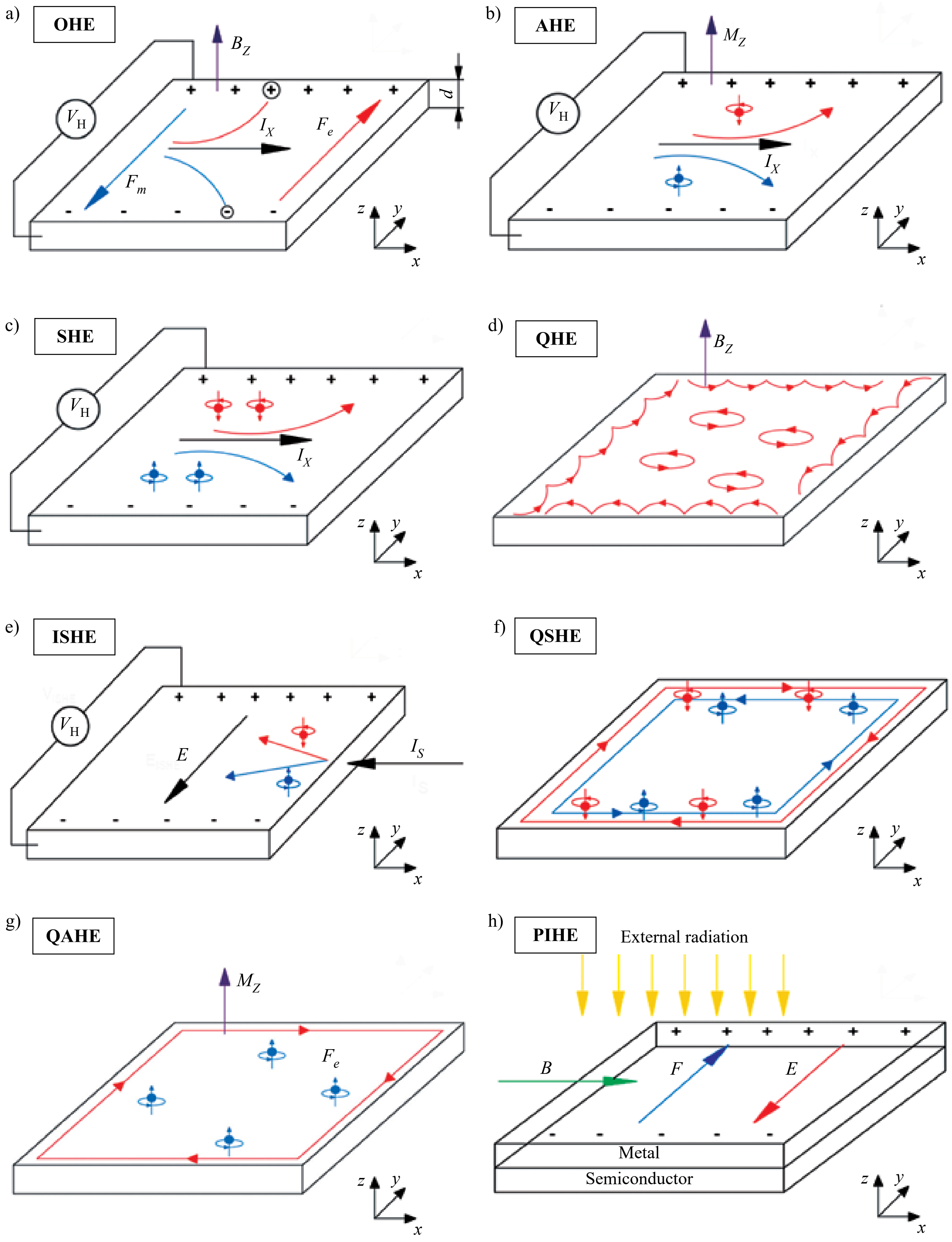

Fig. 2. Overview of the basic principles of Hall effects:

V_H — Hall voltage; I_X, I_S — electric current direction; B, B_Z — magnetic field inductance direction; F_e — Lorentz's force; E — electric field; M_Z — spontaneous magnetization due to spin-orbit coupling

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Integration of Hall Effects

Examining the application of Hall effects at macro-, micro-, and nanoscale levels reveals the growing interest researchers have in this field. Over the past seven decades, various Hall effect-based devices have been extensively studied. In addition to classical textbooks published several decades ago [33], which predominantly focus on the ordinary Hall effect, books and articles dedicated to quantum Hall effects — QHE [34–36] and QSHE [37] — have emerged in the early twenty-first century.

Following the attempts to incorporate the Hall effect into devices and circuits, several structured books [38, 39], industrial handbooks [40], and review articles [41, 42] have been published. In the 1990s and early 21st century, partial reviews in specific areas, such as the application of giant magnetoresistance in electrical current measurement [43], were conducted. However, those reviews were limited in scope, and the described devices are now outdated and have been replaced by digital solutions. Therefore, a modern review covering all areas is timely and relevant.

Evidence from previous publications indicates the utility of Hall effects in various applications. Among macro devices, one can find insulators, converters, circulators, phase detectors, and magnetometers. Several decades ago, Honeywell, a leader in the sensor industry, introduced specialized measuring devices [40]. These devices included Hall effect-based sensors for measuring flow velocity, current, temperature, pressure, speed, angle, revolutions per minute, position, and more. Applications include sensors for office machines, magnetic card readers, brushless DC motor sensors, piston position detectors, and others (**Fig. 3**).

Advantages and Disadvantages of Hall Sensors

Hall sensors are widely used in various industrial applications due to their ability to measure magnetic fields without direct contact. Here are some key advantages and disadvantages of Hall sensors.

Advantages

Non-contact measurement: Hall sensors measure magnetic fields without physical contact, which reduces wear and extends the sensor's lifespan.

Reliability: these sensors are generally reliable and durable, capable of operating in diverse environments without performance degradation.

Versatility: Hall sensors can be used in a wide range of applications, including speed detection, position sensing, and current measurement.

Galvanic isolation: they provide electrical isolation between the measurement circuit and the current, protecting against grounding potential differences and enhancing safety.

Cost-effectiveness: Hall sensors typically offer a good price-to-performance ratio and require minimal maintenance over their operational lifetime.

Disadvantages

Sensitivity to external magnetic fields: Hall sensors require relatively strong magnetic fields to operate, which can limit their sensitivity and accuracy in some applications. They may also be affected by external magnetic fields and electrical noise, leading to measurement errors. Sensitivity depends on sensor dimensions and material properties that requires different sensors for different applications (i.e. for weak and strong magnetic fields).

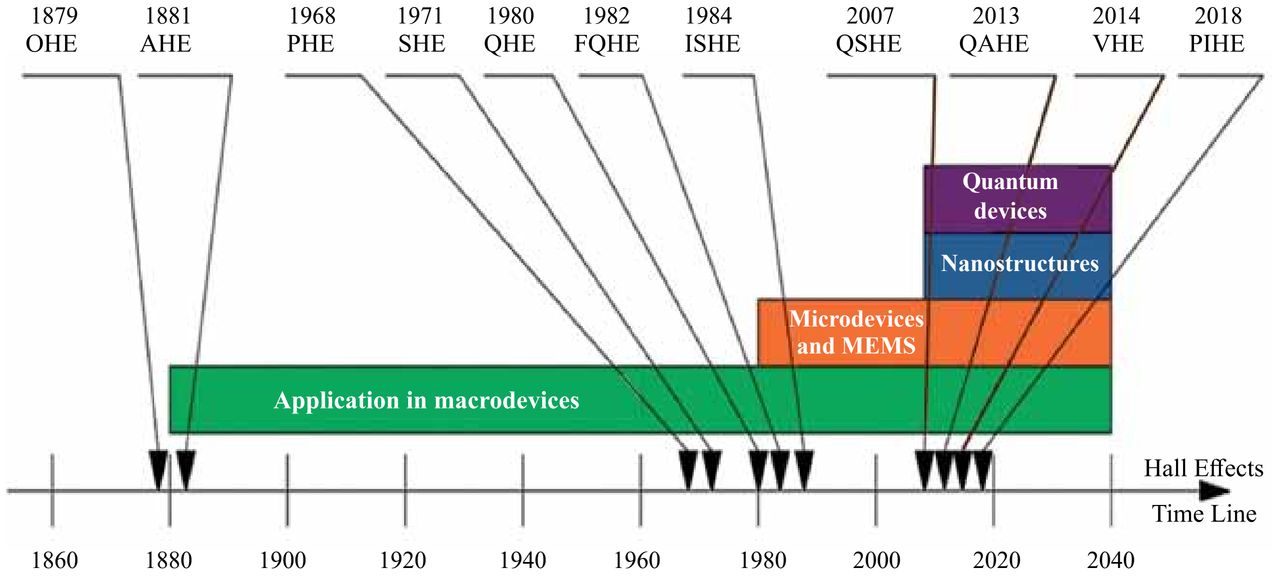

Fig. 3. Hall effects and their applications in electronic devices

Frequency range: Hall sensors have a limited frequency range and can be more expensive compared to other types of sensors, such as those based on resistive, capacitive or inductive principles.

Need for external magnets: some types of Hall sensors require an external magnet to operate, which can complicate integration into existing systems.

Despite these limitations, the advantages of Hall sensors often outweigh their disadvantages, making them a preferred choice for various applications, including automotive, aerospace, and industrial sectors. Their ability to detect and measure magnetic fields without direct contact is crucial in applications where mechanical wear and environmental conditions might impact sensor performance.

Overview of Hall Effect Mathematical Models

Classical Hall Effect Model

A model that describes the ordinary Hall effect is shown in Fig. 2, *a*, where classical approach to the Hall effect is based on a well-known set of assumptions and equations. Let's assume that free charge carriers in semiconductor (conductor) are in a state of equilibrium. The essence of the galvanomagnetic Hall effect can be explained as follows: if an electric current I_x is passed through a relatively long plate (where $l>>d$), made from a semiconductor, such as one with *n*-type conductivity, and the plate is placed in a magnetic field, then each electron moving inside the plate experiences a Lorentz force.

Assuming that the magnetic induction vector $\boldsymbol{B}$ is directed perpendicular to the plane of the plate, i.e., along the *z*-axis, the Lorentz force is given by

$$F_l=e_0 vB, \tag{1}$$

where e_0 — charge of an electron;
v — average velocity of charge carriers in the direction of the current I_x.

Under the influence of this force, electrons will be deflected toward one of the longitudinal edges of the plate, leading to an increase in their concentration at that edge and a decrease at the opposite edge. This results in a spatial separation of charges and the development of a potential difference between the edges, which gives rise to a transverse component of the electric field, known as the Hall field intensity. As a result, in addition to the Lorentz force, an electric interaction force begins to act on the electrons, which can be defined as

$$F_2=e_0 E_y. \tag{2}$$

The accumulation of charges at the longitudinal edges of the plate will continue until the action of the Hall electric field on the charges is balanced by the Lorentz force. The equilibrium condition will be expressed as

$$E_y=vB. \tag{3}$$

Since the current I_x flowing through a rectangular plate of cross-sectional area $b\times d$ is related to the average drift velocity of the charge carriers by the following relation:

$$v=\frac{I_x}{e_0 nbd}\ , \tag{4}$$

the expression for electric field E_y will be

$$E_y=\frac{I_x}{e_0 nbd}B\,. \tag{5}$$

From equation (5) it is now possible to get the Hall voltage:

$$e_h=E_y b=\frac{I_x B}{e_0 nd}=\frac{R_h}{d}IB\ , \tag{6}$$

where R_h — Hall coefficient, which depends on the nature of the material of the sensing element, $R_h=1/e_0 n$;
n — electron concentration per unit volume (if they are main charge carriers).

Hall coefficient R_h usually can be experimentally measured by Van-der-Pauw method that allows to determine the electrical conductivity, resistivity, charge carrier concentration and the charge carrier mobility of materials (bulk and thin films) as well.

Magnetoresistance Hall Model

To describe this model, the Drude model is used. This approach allows for the assessment of the change in resistance of a sample and is also applied in cases where the scattering mechanism of carriers is unknown or not important [46]. The equation of motion for the momentum of a free carrier is

$$\frac{d\vec{p}}{dt}=-\frac{\vec{p}}{\tau}+\vec{F}\ , \tag{7}$$

where $\vec{p}$ — momentum of each free carrier;
τ — mean free time of the carrier;
$\vec{F}$ — external force.

The velocity $\vec{v}$ of free charge carriers in 3D material is

$$\vec{v}=v_x\hat{x}+v_y\hat{y}+v_z\hat{z}, \tag{8}$$

resulting electric field is

$$\vec{E}=E_x\hat{x}+E_y\hat{y}, \tag{9}$$

magnetic field directed along *z*-axis is

$$\vec{B}=B_z\hat{z}, \tag{10}$$

then equation (7) can be expressed as the equation of motion

$$m_e\left(\frac{d}{dt}+\frac{1}{\tau}\right)\vec{v}=q(\vec{E}+\vec{v}\times\vec{B}), \tag{11}$$

where m_e — effective mass of the free charge carrier;
q — charge of the carrier (positive for holes, negative for electrons).

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In the case of direct current along x-axis

$$F_x = m_e\left(\frac{d}{dt}+\frac{1}{\tau}\right)v_x = q(E_x + v_y B_z). \tag{12}$$

In the stationary state equation (12) can describe the charges velocity behavior:

$$\frac{m_e v_x}{\tau} = q\left(E_x + v_y B_z\right) \rightarrow v_x = \frac{q\tau E_x}{m_e} + \omega_c v_y \tau; \tag{13}$$

$$\frac{m_e v_y}{\tau} = q\left(E_y + v_x B_z\right) \rightarrow v_y = \frac{q\tau E_y}{m_e} - \omega_c v_y \tau, \tag{14}$$

where ω_c — cyclotron frequency (in Hertz), which is defined as

$$\omega_c = \frac{qB_z}{m_e}. \tag{15}$$

For the stationary state and $v_y=0$ in the presence of a magnetic field, the resistance tensor ρ, electric field E and electric current j are defined thus:

$$(E_x, E_y)=[\rho_{xx}, \rho_{xy}, \rho_{yx}, \rho_{yy}](j_x, j_y). \tag{16}$$

Equation (16) shows that magnetoresistance highly dependent on the isotropic properties of materials and the direction of the magnetic field.

Dynamic Magneto-Conductivity Model for Charge Carriers

In the case of a variable (oscillating) magnetic field, the model requires a new approach. In this case, the Drude model is combined with perturbation theory. The quantum Hall effect is only noticeable in strong magnetic fields; however, it is not considered in this particular model. In this instance, equation (11) is modified as follows:

$$m_e\left(\frac{d\vec{v}}{dt}+\frac{\vec{v}}{t}\right) = q(\vec{E}+\vec{v}\times\vec{B}), \tag{17}$$

where the value of the carrier velocity is

$$\vec{v} = \vec{v}_0 + \varepsilon\vec{v}_1 + \varepsilon^2\vec{v}_2; \tag{18}$$

$$\varepsilon = \frac{\|\vec{v}_0\|\|\vec{B}\|}{\|\vec{E}\|} \ll 1, \tag{19}$$

where ε — the term that defines the magnetic field perturbation;
v_1, v_2 — the first and second terms that define the carrier velocity, respectively;
v_0 — the term that is unrelated to the perturbation (expresses the carrier velocity without the application of the magnetic field);
ε, ε^2 — the first and second orders of the carrier velocity perturbation, respectively.

For the case of zero approximation ε^0 (absence of magnetic field), equation (17) is

$$m_e\left(\frac{d\vec{v}_0}{dt}+\frac{\vec{v}_0}{t}\right)v_0 = q\vec{E}. \tag{20}$$

Assuming $\vec{E}$ is constant, we get $d\vec{v}_0 / dt = 0$ and $\vec{v}_0 = \mu_e\vec{E}$, where μ_e — effective mobility of free carriers.

For the current density $\vec{J} = qn\vec{v}$ we can transform equation (20) thus:

$$\vec{J}_0 = \frac{nq^2\tau}{m_e}\vec{E} = \sigma_0 E. \tag{21}$$

For the first-order approximation, equation (17) takes the following form:

$$m_e\left(\frac{d\vec{v}_1}{dt}+\frac{\vec{v}_1}{t}\right)q\vec{v}\times\vec{B}, \tag{22}$$

where $\vec{B}(t) = \vec{B}_0\exp(-i\omega t)$ and $\vec{v}_1(t) = \vec{v}_{10}\exp(-i\omega t)$.

Then from equation (22) we can find the velocity $\vec{v}_{10}$:

$$\vec{v}_{10} = \frac{\mu_e^2\vec{E}\times\vec{B}_0}{1-iwt}. \tag{23}$$

Finally, equation (21) for current density $\vec{J}_{10}$ is defined through the tensor:

$$\vec{J}_{10} = \left|\frac{\sigma_0\mu_e\vec{B}_0}{1-i\omega t}\right|\times\vec{E}. \tag{24}$$

The second-order approximation is defined in a similar manner. Thus, equations (17)–(24) show that the current density for a variable magnetic field is a complex value and must be taken into account in experimental measurements. Equations (1)–(24) are fundamental to the design of macro and micro Hall sensors and help to find the most suitable semiconductor materials.

Devices Based on the Hall Effect

Macro-Devices

Currently, there is a large number of devices and applications for the Hall effect, awaiting their classification. The devices are divided into three categories: macro-sized (> 1 mm), micro-sized (> 1 μm), and nano-sized and quantum (< 100 nm). Let us first examine macro-devices, given that they were the first to emerge in this field.

PHE sensors are increasingly used in the biomedical field, particularly in magnetic biosensor platforms for detecting magnetically labeled biomolecules and cells. The advantages of PHE sensors, such as their ability to operate without external magnetic fields, make them suitable for portable and cost-effective on-site testing devices. For example, they have been used to detect beta-amyloid biomarkers, a key factor in Alzheimer's disease research, where their high sensitivity and low noise level enable effective detection of low concentrations of biomarkers [48, 49].

High-resolution magnetometry is another important area where PHE sensors are used. Arrays of elliptical PHE sensors have been developed to achieve exceptionally low equivalent magnetic noise, making them ideal for detecting subtle variations in magnetic fields. This capability is crucial for applications requiring precise magnetic field measurements, such as geological and archaeological research or specific types of industrial equipment monitoring [50].

PHE sensors are increasingly being explored for their applications in robotics, particularly in the fields of localization and tracking. These sensors are used in magnetic capsule endoscopy, where their ability to accurately track the position of capsules within the body is essential for diagnostic purposes. They are a vital component in the development of magnetic tracking systems that assist in precise navigation and manipulation of robots, especially in complex and constrained environments [51].

Micro-Devices

CMOS Hall effect sensors are widely used across various fields due to their versatility, integration capabilities, and cost-effectiveness. These sensors are typically used for current sensing, position detection, and non-contact switching. Their integration into CMOS technology ensures high performance with low energy consumption, making them particularly suitable for compact devices.

In the automotive industry, CMOS Hall effect sensors are used for position and speed measurements and are incorporated in systems such as anti-lock braking systems and engine synchronization. Such sensors are also notably used in consumer electronics, such as smartphones, for detecting magnetic fields and assisting in navigation [52, 53].

A notable example of this is the linear 3D Hall effect sensors from Texas Instruments designed for high integration with built-in angle computation capabilities. This integration simplifies system design by reducing the need for complex external processing, which in turn accelerates development time and enhances system performance, providing high sampling rates and low latency for real-time control [54].

The use of graphene Hall effect sensors is growing in various industries due to their unique properties, including ultra-high sensitivity and resistance to environmental factors such as radiation and temperature. These sensors are used in high-temperature power electronics, electric machines, and drives, particularly in the aerospace sector. Their ability to reliably operate at temperatures up to 230°C allows them to be integrated directly into machines or power modules, enhancing design flexibility and performance [55].

Nano- and Quantum Devices

Nano-sized Hall effect sensors are being researched and utilized in several cutting-edge programs due to their high sensitivity and compact size. They are particularly important for the development of biomedical devices, where their ability to measure magnetic fields with high precision is crucial. These sensors are integrated into medical braces to monitor forces applied to the body, aiding in the treatment of musculoskeletal disorders. This approach not only helps understand the interaction between the device and human skin but also allows for the customization of medical treatments to improve patient outcomes [56].

Additionally, these nanoscale sensors play a key role in the development of next-generation electronic devices, leveraging their small size and sensitivity to enhance the functionality of compact systems. They are designed for integration into various electronic applications, including high-speed switches and sensor arrays, where traditional Hall sensors may be unsuitable due to size constraints [57].

While Hall effect sensors are well-known, there are less familiar components based on the same effect, such as amplifiers. Recently, a new nanoscale device component called HAND (Hall effect nano-device) has been developed and modeled. HAND is based on the well-known Hall effect and may enable circuits to operate at very high frequencies (tens of terahertz). Further precise analytical models have been developed to support the understanding of the device's functionality, including addressing specific phenomena such as heat transfer and the potential application of mega-magnets within integrated circuits. This new device, combining both the Hall effect and nanoscale dimensions, has the potential to revolutionize computation speeds in the world of microelectronics [58].

Material Selection for Hall Sensors

Choosing the right material for Hall sensors is crucial as it directly impacts their performance, sensitivity, durability, and suitability for specific applications.

The selected material should have good electrical conductivity to ensure effective charge carrier flow, which is vital for generating Hall voltage. High carrier mobility is desirable as it enhances the sensor’s sensitivity to magnetic fields. Stability under operating conditions such as temperature, humidity, and exposure to chemicals or radiation is essential for ensuring long-term reliability. Economic factors, such as the cost and availability of materials, also play a significant role in material selection, especially for industrial production.

Commonly used materials include:

silicon — the most prevalent material for Hall sensors due to its excellent semiconductor properties, wide availability, and well-established processing technologies. Silicon sensors can be easily integrated into various electronic circuits [59, 60];

indium antimonide (InSb) — known for its high electron mobility, making it very sensitive and suitable for precise Hall sensors. However, it is less common than silicon due to its high cost and more complex production process [61];

gallium arsenide (GaAs) — provides higher electron mobility than silicon and better stability at high frequencies and temperatures. It is used in

Parameters of some semiconductor materials

Semiconductor	Band gap, eV	Effective mass		Refractive index	Lattice constant. nm	Mobility, $\frac{m^2}{V \cdot s} \cdot 10^{-4}$	
		m_e^*	m_h^*			μ_e	μ_h
Silicon (Si)	1.11	0.98(∥) 0.19(⊥⊥)	0.52	3.44	0.543	1350	480
Germanium (Ge)	0.67	1.58(∥) 0.08(⊥⊥)	0.3	4	0.566	3900	1900
Selenium (Se)	1.74	—	0.12	5.56(∥) 3.72(⊥⊥)	—	1	—
Tellurium (Te)	0.32	0.038(⊥⊥)	0.26(∥) 0.1(⊥⊥)	3.07(∥) 2.68(⊥⊥)	—	1100	—
Gallium Nitride (GaN)	3.5	0.2	—	2.4	a 0.318 c 0.516	150	—
Gallium Arsenide (GaAs)	1.43	0.07	0.5	3.4	0.5653	8600	400
Indium Antimonide (InSb)	0.17	0.0133	0.18	3.75	0.64787	76000	5000 (78000)
Indium Arsenide (InAs)	0.36	0.028	0.33	3.42	0.6058	30000	240
Zinc Selenide (ZnSe)	2.58	0.17	—	2.89	0.5667	100	—
Cadmium Sulfide (CdS)	2.53	0.2	0.7(⊥⊥) 5(∥)	2.5	a 0.4136 c 0.6713	210	—
Cadmium Selenide (CdSe)	1.74	0.13	2.5(∥) 0.4(⊥⊥)	—	a 0.4299 c 0.701	500	—
Cadmium Telluride (CdTe)	1.5	0.11	0.35	2.75	0.6477	600	—
Mercury Selenide (HgSe)	–0.15	0.045	—	—	0.6085	5500	—
Mercury Telluride (HgTe)	0.14	0.029	0.3	3.7	0.642	22000	100 (20000)
Indium Phosphide (InP)	1.28	0.07	0.4	3.37	0.586	4000	650
Graphene	0	0.01	—	2.6	2.46	200000	—
Zinc Oxide (ZnO)	3.37	0.24	—	2.0	4.6	200	—
CuInGaSe	1.04	—	—	2.7	5.78	100	—
InGaAs	0.74	0.041	—	3.51	5.87	12000	—

applications requiring very high sensitivity and fast response times [62];

graphene — a new material in Hall sensor technology due to its exceptional electron mobility and sensitivity. It can operate over a wide temperature range and is highly resistant to environmental factors. Graphene-based sensors are particularly promising for advanced applications in quantum and molecular electronics [63].

Materials such as aluminum gallium nitride (AlGaN) and indium phosphide (InP) are used in specialized applications where high performance is needed under extreme conditions. Integrating magnetic nanoparticles or quantum dots into traditional semiconductor matrices can enhance magnetic sensitivity and tuning capabilities of Hall sensors. Organic materials are being explored for wearable flexible sensors, thus opening new possibilities for medical electronics [64].

The parameters of semiconductors commonly used in various devices, as well as some photo-conductive semiconductors, are listed in **Table 1**.

The parameters of semiconductor materials presented in Table 1 and the Hall effect mathematical model show that the best decision to maximize sensor sensitivity is to apply thin semiconductor materials with a higher electron mobility μ_e and a lower hole mobility μ_h. While graphene is a highly promising material, the 2D electron gas behavior, which is common in the presence of quantum effects, must be taken into consideration.

Conclusions

Analytical review of Hall effects has shown their extensive applications in a variety of sensor devices, ranging from macro to nano and quantum. Conducted theoretical research has shown, that simple miniaturization and the application of new materials alone will not satisfy all current and future demands. A promising solution would be to use different combinations of semiconductor materials and modify their parameters (conductivity, charge carrier concentration) by applying external irradiation (e.g. photo-induced Hall effect) or another form of influence.

A review of existing technological solutions has shown that the Hall effect has wide applications in macroscopic devices, such as magnetic sensors and measurement systems. These devices are key elements in various industries, including automotive, aerospace, identification, and energy.

Examining the use of the Hall effect at the micro- and nano-levels showed that this phenomenon serves here as the basis for the development of highly sensitive sensors capable of detecting extremely small changes in magnetic fields and electrical parameters of materials. It would be rather challenging to design a new, universal wide-range Hall sensor that can operate in both weak and strong magnetic fields, as well as being suitable for miniaturisation and integration into new electronic devices, such as smartphones and medical devices.

The prospects for applying the Hall effect in sensors for quantum devices, including quantum computing systems and sensors, were explored. The integration of the Hall effect into quantum systems can significantly improve the accuracy of measurements and the stability of calculations in quantum processors, which is critically important for the further development of quantum technologies.

These research findings are essential for future studies of the Hall sensor that operates under external light radiation aimed at improving its sensitivity and minimizing common disadvantages in comparison to other types of Hall sensors.

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СТАН ТА ПЕРСПЕКТИВИ РОЗВИТКУ СЕНСОРІВ ХОЛЛА ДЛЯ ЕЛЕКТРОННИХ ПРИЛАДІВ

Стрімкий розвиток твердотільної електроніки вимагає швидкого розвитку сенсорної електроніки, зокрема сенсорів Холла, для різних практичних застосувань. У статті наведено огляд класичних і сучасних підходів до проєктування сенсорів Холла різного масштабу — від макроскопічних систем до квантових нанопристроїв, їх практичне застосування, переваги та недоліки. Представлено також огляд математичних моделей ефектів Холла в напівпровідникових матеріалах, на основі аналізу яких надано рекомендації щодо вибору матеріалу для сенсора Холла із заданими параметрами чутливості до магнітного поля, а також визначено перспективні напрямки подальших досліджень і технологічних розробок на основі ефекту Холла.

Ключові слова: сенсори Холла, ефект Холла, напівпровідникові матеріали для сенсорів Холла.

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