Synthesis of the Physical Structure of Adjustable-Range Ferromagnetic Current Converters in Electrical Engineering and Improvement of Their Designs

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Abstract. In this article, the relevance of synthesizing the physical structure of ferromagnetic current converters with an adjustable range and improving their designs in the context of the rapid development of modern information technologies is substantiated. The study investigates how the creation of an automated bank of physical effects underlying measuring converters enables the effective synthesis of new structural principles for such devices. It is also highlighted that the application of chains of physical effects ensures an innovative approach in the design of technical devices. At the same time, in the research conducted within the framework of the article, the operating principles of ferromagnetic converters, the sequence of physical effects, and the methods for improving structural solutions were scientifically substantiated and analyzed.

INTRODUCTION

Due to the rapid development of information technologies related to the accumulation of knowledge, great attention is currently being paid to creating an automated database of the physical effects underlying the design principles of technical devices, including measuring transducers, and to developing methods for synthesizing new physical design principles for measuring transducers based on these effects. These methods are considered one of the most effective tools of engineering creativity. Based on the application of these methods, the synthesis of the physical structural principles of technical devices is carried out by representing physical effects in the form of a sequential chain [1-3].

SYNTHESIS OF THE PHYSICAL STRUCTURE PRINCIPLES OF ADJUSTABLE-RANGE FERROMAGNETIC CURRENT CONVERTERS

A comparative analysis of existing automated synthesis methods for the physical design principles of measuring transducers has shown that the most efficient among them is the energy-information method (Table 1).

This method is based on the apparatus of energy-information models and parametric structural schemes of chains with various physical natures, and it stands out due to the following capabilities:

- the processes in measuring transducers are mathematically described using equations of the same form, regardless of the differences in their physical nature;

- the possibility of taking into account physical effects and phenomena that are not within the strict scope of the model;

- the possibility of describing the physical construction principles of measuring transducers using block diagrams.

TABLE 1. Comparative analysis of automated synthesis methods of measuring transducers based on physical structure principles

№	Characteristics	Name of the method			
		«Sapfit»	«Edison»	«Koller»	Energy-information method
1.	Universal or specialized	universal	universal	universal	Special
2.	The nature of describing a physical-technical effect in a database	Verbal	formal	Verbal	verbal-formal
3.	The availability of operational characteristics in the database	It does not exist	It can be included	It does not exist	Available
4.	Calculation of operational characteristics	It does not exist	It can be added	It does not exist	Available
5.	The specification of the principle length of the synthesized physical structure (the number of physical-technical effects)	Up to 4	Up to 20	As you wish	Up to 6
6.	Selection of physical structure options based on operational characteristics	It does not exist	It can be added	It does not exist	Available
7.	Generating constructive variants based on morphological matrices	It does not exist	It does not exist	It does not exist	Available
8.	Quantitative evaluation of constructive options	It does not exist	It does not exist	It does not exist	Available
9.	Graphical representation of skeletal structures	It does not exist	It does not exist	It does not exist	Available

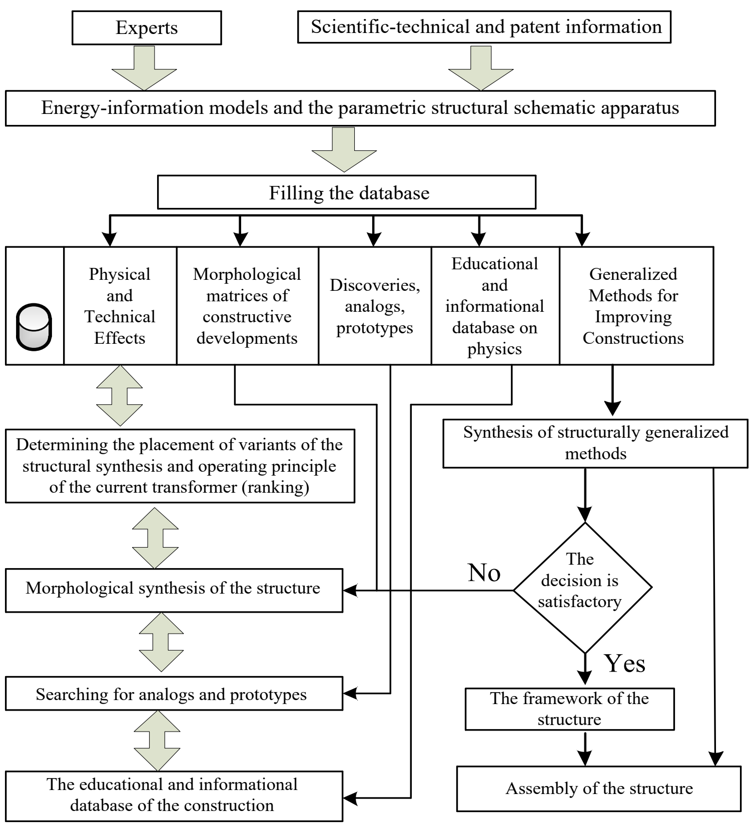


FIGURE 1. The main stages of synthesizing new technical devices based on the energy-information method of technical creativity

The initial design process of measuring transducers requires the design engineer not only to make maximum use of the bank of physical and technical effects, but also to solve the following tasks, which are labor- and timeintensive (Fig.1) [4-8]:

- structural synthesis for the purpose of identifying the principle of a new physical structure;
- to compare several technical solutions and choose the best one;
- to carry out the morphological synthesis of each physical-technical effect involved in the selected physical structure principle.

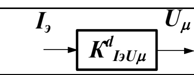
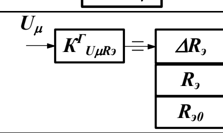
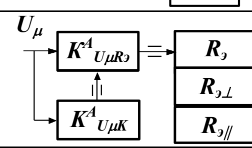
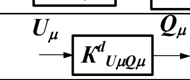
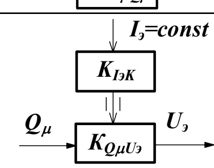
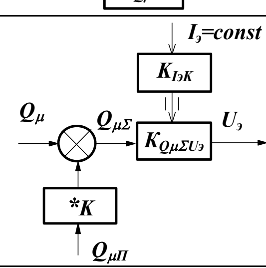
As seen from the main stages of synthesizing new technical devices based on the energy-information method in Figure 1, knowledge of creators and experts in the fields of scientific-technical data, reference (handbook) and patent information, as well as measurement transducers, is analyzed and systematized according to the energy-information method and stored in the corresponding databases. Later, these databases will be used in software for synthesizing new technical solutions, morphological synthesis, and other stages.

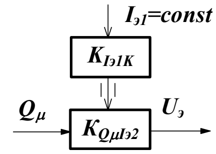
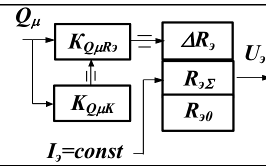
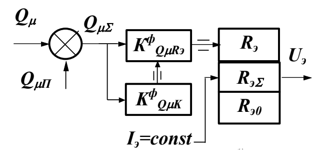
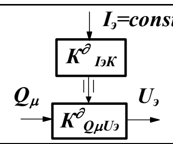
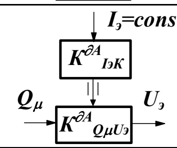
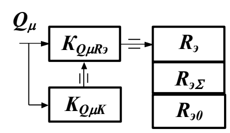
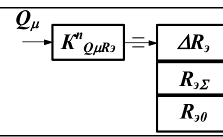
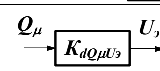
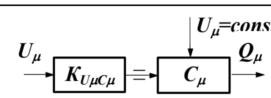
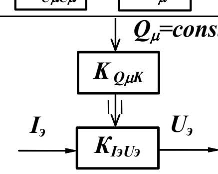
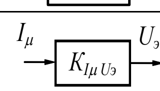
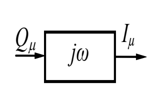
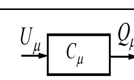
It should be noted that during the stage of searching for the physical design principle of a new measuring transducer, it is necessary to maximize the number of possible variants: the greater the number of variants, the higher the probability of selecting those with the best operational characteristics [9-14].

In this article, ferromagnetic current converters operating on the principle of galvanomagnetic and transformer physical structures were synthesized using the energy-information method, where the input quantity I_e is the electric current, and the output quantity U_e is the voltage.

As a result of the synthesis, 24 variants of the physical structure principle of a ferromagnetic current converter, based on galvanomagnetic and electromagnetic induction effects, were generated. Table 2 presents brief information on the physical and technical effects used in the synthesis process, including the name of the physical-technical effect, its equation, and the schematic of its parametric structure.

TABLE 2. Brief information on the physical and technical effects used in the synthesis of galvanomagnetic and transformer ferromagnetic current converters

№	Name of the physical-technical effect	Equation of the physical-technical effect	Parametric structure diagram
1	Ampere's loop effect	$U_\mu = K^{d}_{I_e U_\mu} I_e$	
2	Giant magnetoresistive effect	$R_e = К^{Г}{}_{U_\mu R_e} U_\mu$	
3	Anisotropic magnetoresistive effect	$K^{A}{}_{U_\mu R_e} = K^{A}{}_{U_\mu K} U_\mu,$ $R_e = K^{A}{}_{U_\mu R_e} U_\mu + R_e \perp,$ $R_e = K^{A}{}_{U_\mu K} U_\mu^2 + R_e \perp.$	
4	Wiegand effect	$Q_\mu = K^{d}_{I_e U_\mu} \cdot U_\mu$	
5	Hall effect of an electric conductor	$U_e = K_{Q_\mu U_e} \cdot Q_\mu,$ $K_{Q_\mu U_e} = K_{I_e K} \cdot I_e,$ $I_e = const$	
6	Hall effect in ferromagnetics	$U_e = K_{Q_\mu U_e} \cdot Q_{\mu\Sigma},$ $Q_{\mu\Sigma} = Q_\mu + K \cdot Q_{\mu п},$ $K_{Q_\mu U_e} = K_{I_e K} \cdot I_e,$ $U_e = K_{I_e K} \cdot I_e (Q_\mu + K \cdot Q_{\mu п}),$ $I_e = const$	

Continuation of Table 2			
7	The Hall effect (electric current effect)	$I_e = K_{\mu I_e 2} \cdot Q_\mu,$ $K_{Q\mu Ie2} = K_{Ie1K} \cdot I_{e1},$ $I_{e1} = const$	
8	The planar Hall effect in ferromagnetic materials	$U_e = R_e \cdot I_e,$ $R_e = K_{Q_\mu R_e} Q_\mu,$ $K_{Q_\mu R_e} = K_{Q_\mu K} \cdot Q_\mu,$ $U_e = K_{Q_\mu K} \cdot I_e \cdot Q_\mu^2,$ $I_e = const$	
9	The Planar Hall Effect	$U_e = R_e \cdot I_e,$ $R_e = K^{\Phi}_{Q_\mu R_e} Q_{\mu\Sigma},$ $K^{\Phi}_{Q_\mu R_e} = K^{\Phi}_{Q_\mu K} \cdot Q_{\mu\Sigma},$ $U_e = K^{\Phi}_{Q_\mu K} \cdot I_e \cdot Q_{\mu\Sigma}^2,$ $I_e = const$	
10	Quantum Hall effect	$U_e = K^{\partial}_{Q_\mu U_e} \cdot Q_\mu,$ $K^{\partial}_{Q_\mu U_e} = K^{\partial}_{I_e K} \cdot I_e,$ $I_e = const$	
11	Fractional Quantum Hall Effect	$U_e = K^{\partial A}_{Q_\mu U_e} \cdot Q_\mu,$ $K^{\partial A}_{Q_\mu U_e} = K^{\partial A}_{I_\mu K} \cdot I_e,$ $I_e = const$	
12	Magnetoresistive effect	$K_{Q_\mu R_e} = K_{Q_\mu K} Q_\mu,$ $R_e = K_{Q_\mu R_e} Q_\mu,$ $R_e = K_{Q_\mu K} Q_\mu^2$	
13	Magnetoconcentration effect	$\Delta R_e = K^{n}_{Q_\mu R_e} Q_\mu$	
14	Magnetodiode effect	$U_e = K_{d Q_\mu U_e} \cdot Q_\mu,$	
15	Magnetic modulation effect	$Q_\mu = K_{U_\mu C_\mu} U_\mu^2$	
16	Hall effect (current-controlled)	$U_e = K_{I_e U_e} \cdot I_e,$ $K_{I_e U_e} = K_{Q_\mu K} \cdot Q_\mu,$ $Q_\mu = const$	
17	The effect of electromagnetic induction	$U_e = K_{I_\mu U_e} I_\mu$	
18	The effect between Q_μ and I_μ	$I_\mu = j\omega Q_\mu$	
19	Magnetic permeability parameter	$Q_\mu = C_\mu U_\mu$	

The topogram shown in Figure 2 displays the options of ferromagnetic current converters based on the synthesis results. Some of their solutions have been confirmed by patents invented by the authors [15-21].

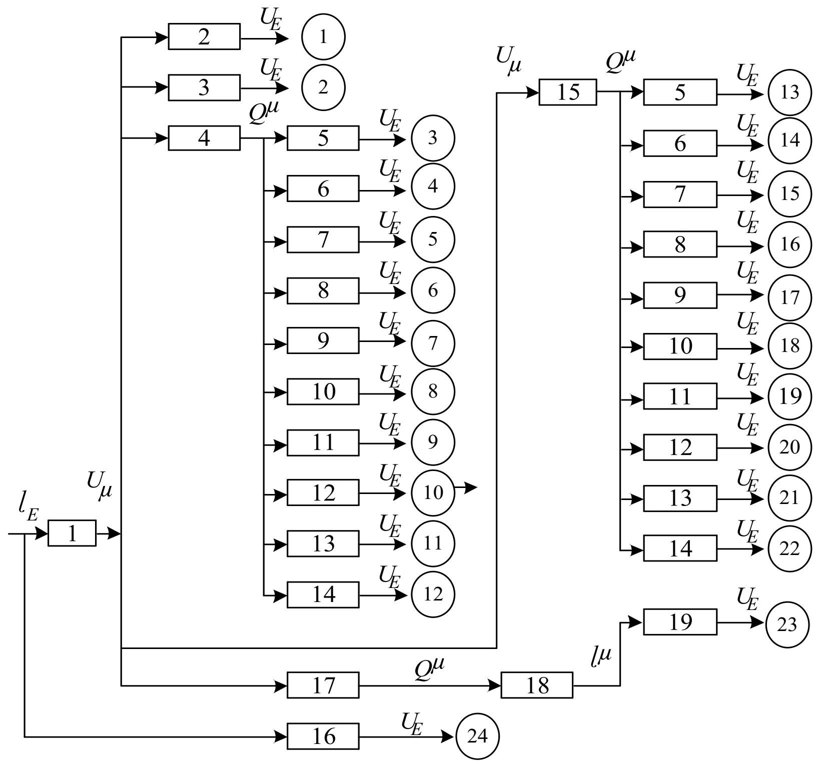


FIGURE 2. Topogram of the synthesis results of ferromagnetic current converters based on the principles of physical structure, galvanomagnetic, and transformer effects

The presence of patented designs among the 24 variants produced as a result of the synthesis demonstrates the effectiveness of the energy-information method. Furthermore, as a result of the conducted synthesis, there are also new designs protected by patents, invented with the participation of the authors [22-28].

When the 24 variants obtained as a result of the synthesis are evaluated according to their sensitivity operational characteristics, variant 1 is considered the most efficient for changing the direct current, while variant 23 is considered the most efficient for changing the alternating current.

GENERALIZED METHODS FOR IMPROVING THE DESIGNS OF RANGE-ADJUSTABLE FERROMAGNETIC CURRENT TRANSFORMERS

As a result of analyzing, according to the methodology developed by Professor M.F.Zaripov, titled "Determining and Applying Generalized Methods to Improve the Main Characteristics of Measuring Transformers", the designs presented in patents and scientific-technical literature registered over the past 50-60 years in leading countries such as the Russian Federation, Germany, Japan, France, the USA, China, the United Kingdom, and other leading European countries, as well as in Uzbekistan, for the creation and production of ferromagnetic current transformers, 57 generalized methods were identified. Thirty-eight of them are devoted to improving the magnetic systems of ferromagnetic current converters, while nineteen focus on the enhancement of Hall elements within them.

There are numerous studies dedicated to systematizing generalized methods for improving the magnetic systems of ferromagnetic current transformers and analyzing them. Therefore, in this article, we limit ourselves to presenting the identified generalized methods for improving magnetic systems and focus on analyzing the generalized methods aimed at enhancing the characteristics of Hall elements used in ferromagnetic current converters. The identified generalized methods are classified into the following three categories: constructive, technological, and the use of new materials [29-33].

CONSTRUCTIVELY GENERALIZED METHODS

The reduction of the shunting effect of electrodes. The following expression has been derived to calculate the shunting effect of Hall element current electrodes:

$$\frac{U_{X.meas.}}{U_X} = 1 - \frac{16}{\pi^2} \cdot e^{-\frac{\pi a}{2b}} \cdot \left(1 - \frac{8}{9} \cdot e^{-\frac{\pi a}{b}}\right) \cdot \left(1 - \frac{\theta^2}{3}\right) \quad (1)$$

Here, U_X, $U_{X.meas.}$ – the Hall electric conductive force and its measured value; a, b – the corresponding length and width of the sample; θ – Hall angle.

The calculations show that when $\frac{a}{b} > 3$ and the Hall contacts are located in the middle of the sample edges, $U_{X.meas.} = U_X$, can be assumed [34-35].

Selecting the optimal version of contact forms. From the point of view of not affecting the distribution of the electric field generated in the Hall sample, point or blade-like contacts (Figures 3a and 3b) are considered ideal. However, making such contacts with low resistance, moderate characteristics, and minimal noise is considered very difficult. The analysis of the Hall contact shapes shown in Figure 3 indicates that the trapezoidal Hall contact (Figure 3d) is considered the most optimal [36-37].

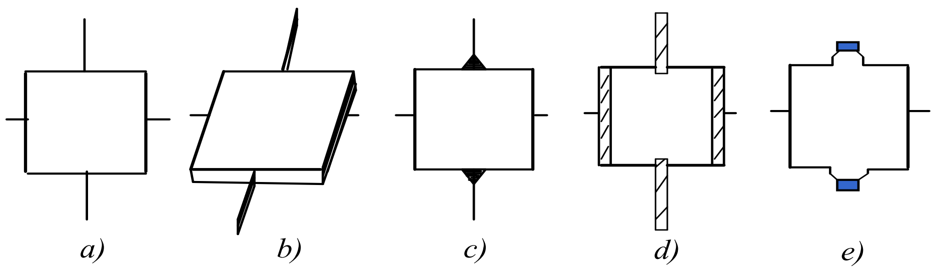


FIGURE 3. The shapes of Hall contacts:
a – point-shaped; b – blade-shaped; c, d – contacts with enlarged surface; e – trapezoidal

Connecting Hall elements in a differential circuit. If two identical Hall elements are fabricated on a single substrate using planar technology and connected in a differential circuit, and the corresponding measurements are carried out, the measurement accuracy significantly increases [38-39].

The principle of "rotating" the magnetic field. The working current is supplied through contacts positioned opposite each other, while the Hall voltage is taken from contacts located perpendicular to them. In this case, the measurement direction gradually rotates by 45^0 at a frequency of 200 Hz during the measurement process, resulting in higher measurement accuracy (Fig. 4).

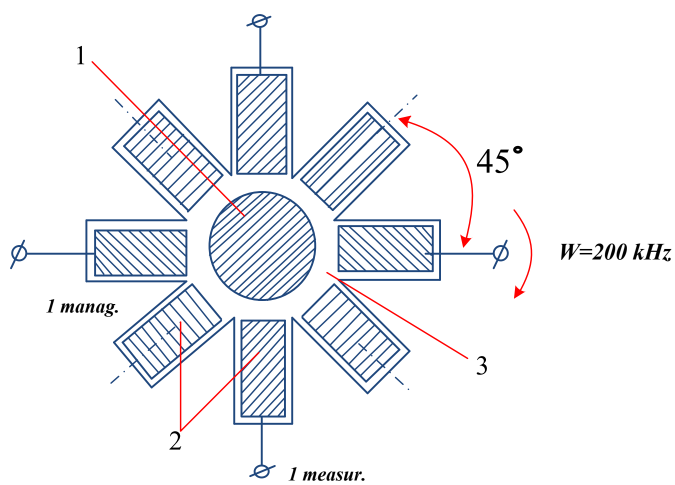


FIGURE 4. The principle of "rotating" the magnetic field:
1 - shutter; 2 - mutually cross-arranged contacts; 3 - base

Using concentrators of the working magnetic field. To increase the sensitivity of current transducers using the galvanomagnetic effect, a Hall-element-based microchip is placed in special grooves of magnetic concentrators made from electrical steel, permalloy, or soft magnetic ferrites. In such constructions, placing ultra-thin Hall elements, with dimensions not exceeding 150 μm, in an air gap allows for a sharp increase in the sensitivity of the transducer.

Improving heat dissipation. To protect against external mechanical influences, the Hall element is often placed inside a ceramic casing, which simultaneously serves as a conductor to dissipate the heat generated in the Hall element to the surroundings [39-40].

Protection from external mechanical impacts. The Hall element magnetic concentrator, after being placed in the air gap, is coated with epoxy resin.

Protection from other external influences. In order to improve the reliability of Hall-effect magnetic sensor integrated circuits under high-humidity operating conditions, their package is coated with a three-layer 'UR-231' grade varnish [41-42].

Loss of non-equilibrium electric conducting forces. When Hall contacts are asymmetrically positioned, an error occurs during measurement due to the transverse electromotive force generated in the sample even in the absence of a magnetic field. To reduce this error, it is necessary to place the Hall contacts on a single equipotential, select a uniform sample, and prevent the occurrence of a temperature gradient. The asymmetry voltage caused by the asymmetric placement of Hall contacts is eliminated with the help of compensation circuits (Fig. 5) [40-43].

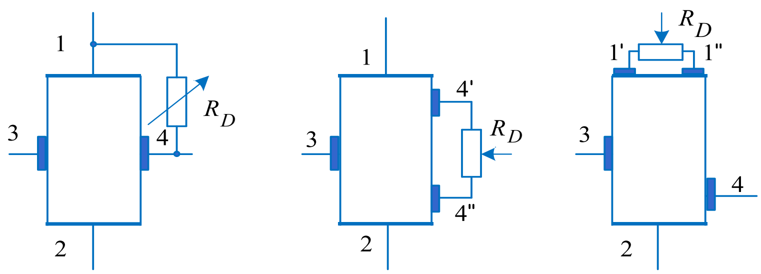


FIGURE 5. Asymmetry voltage compensation circuits: 1 and 2, and 3 and 4 are the input and output electrodes, respectively; R_d is the compensating resistor

Thermal stabilization. The most effective way to reduce the temperature error of a Hall element is to thermally stabilize it. This method is not aimed at negatively affecting the temperature output signal, but rather at eliminating the source that causes this error. The circuits for compensating the temperature of a Hall element are diverse, and the most effective and widely used of these is the circuit that adjusts the Hall element's temperature by varying the input current [43-44].

Reducing hysteresis. The generalized method provides high sensitivity, but it reduces accuracy, resulting in an error of up to 3-5%. The decrease in the working gap of the magnetic concentrator leads to an increase in the error caused by the hysteresis loop. *For example*, in a K10×6×2-type ferrite core with a 3000 NM rating, the error arising from magnetic hysteresis can reach up to ±2.8% [45-46].

Reducing the thickness of the active area of the Hall element. The use of an SOI ("silicon on insulator") structure is considered preferable when fabricating a thin-film Hall element. In this case, a dielectric is used instead of an *n-p* junction. Firstly, this makes it possible to form a thin active region of the Hall element, which leads to an increase in its magnetic sensitivity; secondly, the use of dielectric insulation in the element expands its operating temperature range. Measurements carried out on a Hall element fabricated from a silicon sample placed in an insulator showed that, with an active area of 50×50 μm^2 and a current of 1 mA, its magnetic sensitivity exceeds 200 V/(A·T).

GENERALIZED TECHNOLOGICAL METHODS

Assembly using the hybrid-module method. The widespread use of electronic circuits built on integrated technologies has created the opportunity to develop unified functional circuits consisting of a Hall element and electronic components placed on a single common substrate. Magnetic-sensitive integrated circuits equipped with a Hall element have the following advantages over electronic circuits consisting of a discrete Hall element combined with an associated integrated circuit:

- Since there are no intermediate connections, it has high reliability;

- The large magnitude of the output signal makes it possible to use it without special amplifiers;
- high stability against temperature variations;
- Since the Hall element and the integrated circuit connected to it are placed on a single substrate, there is no need for interconnecting wires between them, which prevents the induction of various interference signals.

Formation of high mobility of charge carriers in a thin-thickness sample. The thickness of a planar-epitaxial technology film is equal to that of a Hall element with a film, but the mobility of charge carriers allows the creation of Hall elements whose charge carrier mobility is equal to that of monocrystalline materials. For example, a Hall element is presented with an antimony-indium thin active layer of 5-7 μm thickness, grown epitaxially on a gallium-arsenide semi-insulating substrate with a Hall element thickness of approximately 400 μm. Thus, in a sample with a small thickness, the formation of high carrier mobility makes it possible to create a Hall element with very high sensitivity.

Precision machining. The promising direction for the development of Hall elements is the utilization of recent advancements in precision microfabrication and manufacturing of miniature, including thin-film, components to produce Hall elements with high sensitivity [45-47].

Reducing quadrature disturbances. In an unshielded Hall element, external varying magnetic fields induce a voltage in the contour formed by the relevant section of the Hall plate, called a quadrature disturbance, which adds to the useful signal. Therefore, to reduce the error caused by this interfering voltage, an effort is made to minimize the dimensions of the circuit as much as possible; for example, one of the Hall electrodes is brought out to the surface of the Hall element and twisted together with a second lead outside the plate boundary, and after the Hall element is completed, it is coated with a protective varnish [47-48].

USING NEW MATERIALS

Use of highly porous materials. Ultrathin Hall elements possess extremely high sensitivity and are formed by the repeated alternation of small and large blocking zones within ultrathin heterostructure layers. Such Hall elements, using MDS (Metal-Dielectric-Semiconductor) technology, are integrated with an electronic circuit on a single chip, resulting in an intelligent magnetic sensor integrated circuit with high accuracy and sensitivity [48-52].

Application of heterostructures. The best characteristics were obtained for a Hall element grown on an InP semi-insulating substrate and fabricated based on a III-V heterostructure. Such Hall elements are distinguished by their low noise level and relatively small TCS (Telecommunication Channel Sensitivity), with a comparative sensitivity of 1000 V/(A·T) corresponding to 0.01%/degree for the first structure.

Use of ferromagnetic materials. Using ferromagnetic materials in Hall elements allows for a tenfold increase in sensitivity compared to semiconductor materials. In measuring transducers, including galvanomagnetic ferromagnetic current transducers, soft magnetic thin magnetic sheets are widely used in practice [51-54].

Based on the energy-information method briefly described above, new design schemes of galvanomagnetic and transformer ferromagnetic current transducers, developed with the participation of the authors and protected by patents, have been created [55-57].

CONCLUSION

Based on the study of the article on “Synthesis of the Physical Structure and Improvement of the Designs of Ferromagnetic Variable-Range Current Transformers in the Field of Electrical Engineering,” the following conclusions have been drawn:

- A comparative analysis of existing methods for the automated synthesis of measuring transducers has shown that the energy-information method is the most efficient, due to its capabilities to calculate operational characteristics from a database, select options for physical structure principles based on these characteristics, generate design variants using morphological matrices, numerically evaluate the design variants, and graphically represent skeletal structures;
- Based on the galvanomagnetic and transformer effects, 24 variants of current-measuring transducers were synthesized using the energy-information method. When these were ranked by sensitivity, it was determined that for measuring direct current, the galvanomagnetic transducer based on the giant magnetoresistive effect, and for measuring alternating current, the transformer transducer based on the electromagnetic induction effect, exhibit the highest sensitivity.

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