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Magnetic-Field Sensors Based on Anisotropic Magnetoresistive Thin-Film Structures for Operation in a Wide Temperature Range

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Abstract—The results of studies on the fabrication and optimization of the configuration of magnetic-field sensors based on anisotropic magnetoresistive thin-film structures are described. Magnetic-field sensors with an odd characteristic and a sensitivity to 23.7 (mV/V)/(kA/m) and a 180° angle-rotation sensor with a signal amplitude of 15 mV/V are obtained. Based on the performed thermal tests, the possibility of applying the developed sensors in extreme environments in the temperature range from –60 to +150°C is shown, and the temperature-sensitivity coefficient amounts to –0.35%/°C. The obtained sensors are tested in angle, speed, and phase sensors in the automobile industry. The characteristics of the developed sensors correspond to the analogues of leading world firms.

Keywords: anisotropic magnetoresistance (AMR) effect, magnetic-field sensor, magnetic films, angular-position sensor, rotation-angle sensor, phase sensor.

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INTRODUCTION

The fabrication of devices for magnetic-field measurement based on thin magnetic films is of great interest. The effect of a variation in the resistance of metals, in particular, iron and nickel, in a magnetic field was discovered quite long ago; however, this phenomenon was barely used in engineering for a rather long time. The development of technology for the deposition of thin metal films and the discovery of the effect of magnetoresistance in films of iron–nickel and nickel–cobalt alloys opened up the possibility for the fabrication of efficient devices (based on these films) for measuring magnetic fields. High sensitivity to magnetic fields stimulated interest in them first as detectors of cylindrical magnetic domains (CMDs) in memory devices, then, as the basis for the construction of heads for reading information from magnetic carriers. The first direction did not undergo development in association with the end of work on the fabrication of CMD devices, the second direction developed mainly as a result of utilizing the giant magnetoresistance effect (GMR effect) [1].

There exists a variant of the magnetoresistance effect, which is called the anisotropic magnetoresistance effect (AMR effect), which is now used as the basis for constructing highly efficient devices for magnetic-field measurement. This effect is observed in anisotropic magnetic films, and the value of the resistance variation amounts to from 1.5 to 3.9% depending on the material of the thin magnetic film [2–4]. Sensors based on the AMR effect are made up of one layer of resistive material, whereas sensors based on the GMR effect assume the presence of several magnetic layers with different properties [5]. Recently, reports have appeared on the fabrication of new sensors consisting of periodically alternating nanoisland layers of magnetoresistors, in particular, $(FeNi–Co)_N$, where N is the number of pair layers, which are capable of detecting ultraweak magnetic fields of $\sim 10^{-6}$ Oe [6, 7] at the same value of the magnetoresistance of 2–3%. All this testifies to the great potential possibilities of similar sensors [8].

CHARACTERISTICS OF THIN PERMALLOY FILMS

At the Scientific–Technological center "Nano- and microsystem technology" MIET, thin permalloy (80% Ni, 20% Fe alloy) films with a magnetoresistance effect of ~2.2% [9, 10] were obtained. The coercive force of the films amounts to ~80 A/m and the anisotropy field is ~400 A/m. The permalloy films are obtained by magnetron sputtering, and their magnetoresistive effect amounts to ~1.0% after deposition. Vacuum annealing in a magnetic field of 12 kA/m for 3 h enabled us to decrease the film resistance and

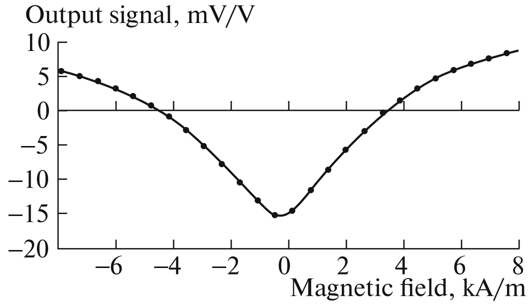

Fig. 1. Even transfer characteristic of the sensor.

increase the magnetoresistance effect to 2.2% without greatly affecting the magnetic parameters of the film.

Based on the obtained films, magnetic-field sensors with even and odd transfer characteristics are developed. The structures represent four magnetoresistors connected in a bridge circuit. Such an arrangement of magnetoresistors enables us to obtain the output signal amounting to tens of millivolts against the background of the feed voltage of the order of several volts and to minimize the negative effect of the ambient-temperature variation.

SENSORS WITH AN EVEN TRANSFER CHARACTERISTIC

The sensor with an even transfer characteristic consists of four magnetoresistors in the form of a strip of thin magnetic film 0.03 μm thick with contact platforms made from aluminum of ~0.6 μm thick. The magnetoresistors on different shoulders of the bridge are turned 90° from each other, as a result of which a variation in the resistance of all resistors is provided under the action of a planar magnetic field. The transfer characteristic of such a sensor is shown in Fig. 1. A prominent feature of this sensor consists in the almost total absence of linear portions. The sensors have a high output signal (~20 mV/V); however, their characteristic is nonlinear, which provides serious difficulties when measuring magnetic fields and prevents determining the magnetic-field polarity.

SENSORS WITH AN ODD TRANSFER CHARACTERISTIC

Magnetic-field sensors with an odd transfer characteristic have wider possibilities; the general view of such a sensor is shown in Fig. 2a. The structure represents a strip of magnetic film 0.03 μm thick on which thin strips of high-conductivity material (aluminum) are located at an angle of 45° to the magnetic-film axis. It enables us to linearize the characteristic and to make it odd (Fig. 2b). By virtue of these circumstances, sensors with an odd transfer characteristic have received greater circulation in comparison with conventional Hall sensors.

The developed sensors have various configurations, in particular, a different magnetic-layer width and sizes of strips and distances between them. As a result of the performed investigations, we established an unambiguous relationship between the structure configuration and its sensitivity. The sensor sensitivity is determined as the ratio of the output-signal value (the bridge-misbalance voltage under the action of magnetic field) to the magnetic-field value at which the measurements were carried out on a linear portion of the characteristic. The output-signal value is usually taken as the ratio to the supply voltage of the structure. The investigated structures have a wide spectrum of sensitivity values from 3.4 to 9.7 (mV/V)/(kA/m). It is established that sensors with a magnetic-strip (permalloy) width of 30 and 40 μm and a distance between aluminum strips of 6 and 10 μm have the highest sensitivity (Fig. 2b). The graphs in Fig. 2b are measured in a magnetization field (along a permalloy strip) of 1 kA/m, which is necessary for suppressing the hyster-

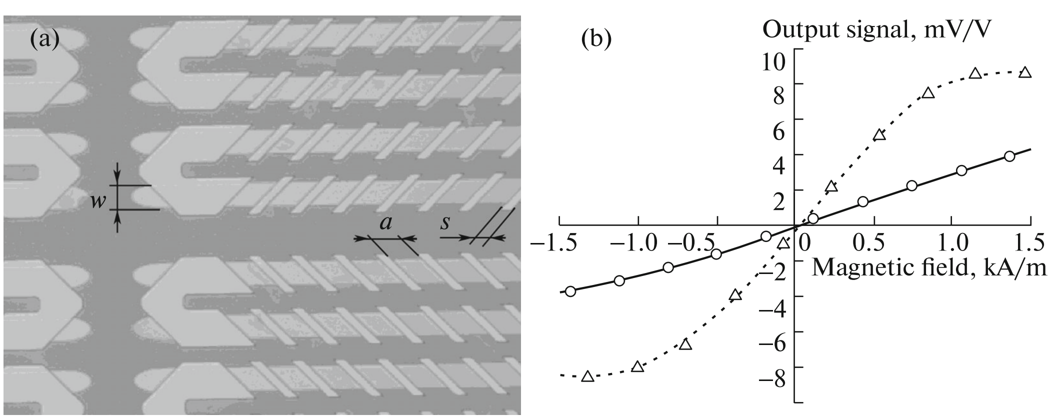

Fig. 2. (a) Fragment of topology of the sensor with an odd transfer characteristic and (b) its transfer characteristic: — sensitivity 3.4 (mV/V)/(kA/m) (w = 10 μm, a = 15 μm, s = 6 μm); · · · · · sensitivity 9.7 (mV/V)/(kA/m) (w = 40 μm, a = 6 μm, s = 6 μm).

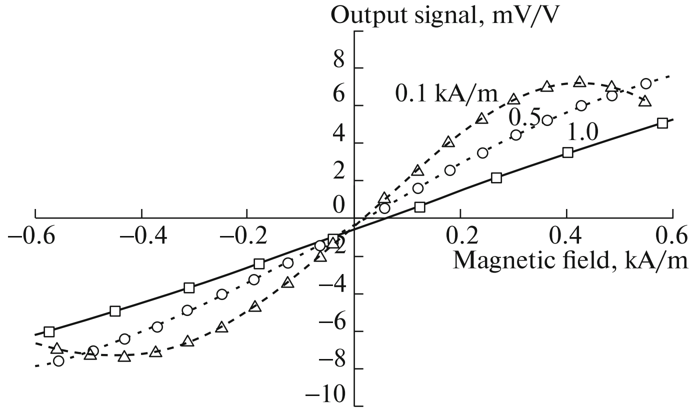

Fig. 3. Transfer characteristic as a factor of the magnetization field: — sensitivity of 9.7 (mV/V)/(kA/m); ····· sensitivity of 15.0 (mV/V)/(kA/m); – – – sensitivity of 23.7 (mV/V)/(kA/m).

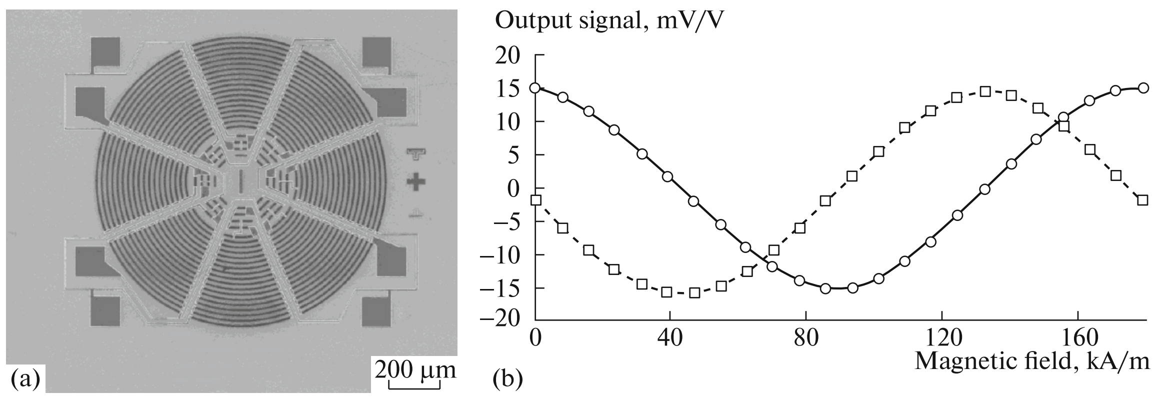

Fig. 4. General view of (a) the rotation-angle sensor and (b) its transfer characteristic.

esis phenomenon in the transfer characteristic. However, the application of such a field renders also a negative effect; it results in a decrease in sensitivity.

The measurements were carried out at various magnetization-field values; their results are shown in Fig. 3. From the figure it can be seen that a sensitivity of 23.7 (mV/V)/(kA/m) can be attained with a decrease in a magnetization field to 0.1 kA/m for the same sensor, which initially had a sensitivity of 9.7 (mV/V)/(kA/m) in a magnetization field of 1 kA/m. In other words, the sensitivity of a structure of the same configuration can be varied within rather wide limits by means of the magnetization field. An important circumstance is the fact that the hysteresis does not exceed 1% at a bias field of only 0.3 kA/m. Sensors with such sensitivity can be used in very different fields from detecting magnetic fields to constructing various sensors on their basis, for example, sensors of current, rotation, linear and angular displacements, etc. Sensors with a high sensitivity of 23.7 (mV/V)/(kA/m)

Comparison between the developed magnetic-field sensor with odd characteristic and foreign and domestic analogues

Sensor	Sensitivity, (mV/V)/(kA/m)	Working field, kA/m	References
MPC10H (developed)	23.7	±0.10	–
HMC1001(Honeywell)	40	±0.16	[12]
KMZ10A1(Philips)	22.0	±0.05	[13]
MRChE237 (OAO “NPO IT”, Korolev)	6.3	±1.6	[14]
AMRP on the basis of FeNi (NPK “Technological center”, Moscow)	8.8	±0.25	[15]

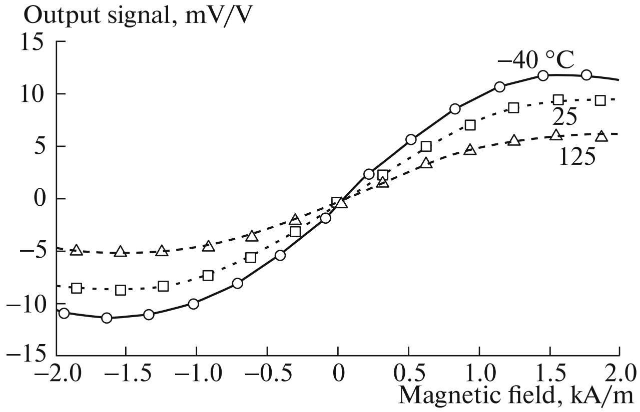

Fig. 5. Transfer characteristic of the sensor with an odd transfer characteristic as a factor of the temperature.

are suitable for constructing magnetometric sensors on their basis capable of measuring the Earth's magnetic field and having characteristics corresponding to similar sensors of leading world firms (see the table) [11–15].

ROTATION-ANGLE SENSORS

Based on anisotropic magnetoresistive structures, we developed a rotation-angle sensor. It should be noted that the described structure can also be used as such a sensor. However, this structure can provide measurement of an angle only in the range of 0°–90° (±45°), which is insufficient in most cases. Therefore, we developed a sensor representing two magnetoresistive bridges turned 45° from each other (Fig. 4a). The transfer characteristic of this sensor represents two sine wave signals shifted by 45° (Fig. 4b). Further processing of these signals using a microprocessor enables us to obtain the linear function of the dependence of the sensor output signal on the angle of magnetic-field rotation.

The significant interest represents the Investigation of the operation of anisotropic magnetoresistive sensors in a wide range of temperatures and under extreme conditions is of significant interest. The transfer characteristic of anisotropic sensors with an odd transfer characteristic is measured in the temperature range from –40 to +150°C. The results of the measurements are shown in Fig. 5. With increasing temperature, the sensor sensitivity decreases, whereas it increases with a decrease in temperature. The change in sensitivity amounts to –0.35%/°C, which enables us to draw a conclusion concerning the possibility of using the structures under the most extreme operating conditions both in automobile electronics and in systems of special purpose. Extension of the operating-temperature range to +170°C is possible; however, it is limited by the material of the structure casing.

CONCLUSIONS

The results presented in this study (see table) give grounds to consider that the developed magnetoresistive sensors can be used as magnetic-field sensors in very different fields of application including the automobile electronics, etc.

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