УДК 537.622

ЭКСТРАОРДИНАРНЫЙ И ПЛАНАРНЫЙ ЭФФЕКТЫ ХОЛЛА В ТОНКИХ ПЛЕНКАХ ПЕРМАЛЛОЯ

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Изучены петли гистерезиса холловского сопротивления в тонких (d = 80–280 нм) магнитоупорядоченных пленках пермаллоя ($Ni_{0,8}Fe_{0,2}$) при T = 300 К, и разных углах (φ = 0–360°) между плоскостью пленки и направлением магнитного поля (экстраординарный и обычный эффекты Холла), и разных углах (θ = 0–90°) между направлением магнитного поля и протекающим током (планарный эффект Холла при φ = 0°) в магнитном поле с индукцией до B = 1,25 Тл. Пленки получены на ситалловой подложке методом ионно-лучевого распыления. Как в экстраординарном, так и планарном эффекте Холла при перемагничивании наблюдаются резкие пики холловского сопротивления, обусловленные изменением при перемагничивании анизотропии сопротивления магнитоупорядоченной среды. В экстраординарном эффекте Холла положение и ширина пика на полувысоте определяются углом между направлением магнитного поля и плоскостью пленки. Показано, что при приближении направления внешнего магнитного поля к направлению спонтанной намагниченности пленки магнитное поле положения $B_п$ и полуширина пика $\Delta B_п$ увеличиваются. В интервале углов φ = 0–90° $B_п$ и $\Delta B_п$ пика холловского сопротивления изменяются в близких интервалах ($\Delta B \approx$ 0,2–5,0 мТл). Обнаружена немонотонная зависимость холловского сопротивления и положения его пика в планарном эффекте Холла от угла между протекающим током и направлением

Образец цитирования:
Головчук ВИ, Лукашевич МГ. Экстраординарный и планарный эффекты Холла в тонких пленках пермаллоя. *Журнал Белорусского государственного университета. Физика.* 2021;2:53–60 (на англ.).
https://doi.org/10.33581/2520-2243-2021-2-53-60

For citation:
Halauchuk VI, Lukashevich MG. Exstraordinary and planar Hall effects in thin permalloy films. *Journal of the Belarusian State University. Physics.* 2021;2:53–60.
https://doi.org/10.33581/2520-2243-2021-2-53-60

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магнитного поля, обусловленная изменением продольной и поперечной компонент сопротивления магнитоупорядоченной среды внешним магнитным полем. Определены величины обычного и экстраординарного коэффициентов Холла: $R_{H_0} = 6 \cdot 10^{-9}$ м^3/Кл и $R_{H_1} = 3{,}2 \cdot 10^{-8}$ м^3/Кл соответственно.

Ключевые слова: пермаллой; экстраординарный эффект Холла; планарный эффект Холла; подложка; пленка; магнитное упорядочение.

EXSTRAORDINARY AND PLANAR HALL EFFECTS IN THIN PERMALLOY FILMS

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The Hall resistance hysteresis loops in thin (d = 80–280 nm) magnetically ordered permalloy films ($Ni_{0.8}Fe_{0.2}$) were studied at room temperature at different angles between the film plane and the magnetic field direction (φ = 0–360°) (extraordinary and ordinary Hall effects), at different angles (θ = 0–90°) between the magnetic field direction and the flowing current (planar Hall effect at φ = 0°) in a magnetic field up to B = 1.25 T. The thin films were obtained on sitall dielectric substrate by ion beam sputtering. Sharp peaks of the Hall resistance were observed in the extraordinary and planar Hall effects during the magnetisation reversal of the films due to a change of the magnetisation direction with respect to the sampling current direction. In the extraordinary Hall effect the position and full width at half maximum of a peak is determined by the angle between the magnetic field direction and the film plane. It has been shown that as the direction of the external magnetic field approaches the spontaneous magnetisation direction, both the peak magnetic field position B_p and the full width at half maximum of the peak ΔB_p increase. In the angles range of φ = 0–90° B_p and ΔB_p varies in the magnetic field range from $\Delta B \approx 0.2$ to 5.0 mT. A non-monotonic dependence of the planar Hall resistance and its peak position on the angle between the flowing current and the magnetic field direction was detected. It is related to the change of the longitudinal and transverse components the resistance of the magnetically ordered solids by an external magnetic field. The values of the ordinary and extraordinary Hall effects coefficients have been determined: $R_{H_0} = 6 \cdot 10^{-9}$ m^3/C and $R_{H_1} = 3.2 \cdot 10^{-8}$ m^3/C, respectively.

Keywords: permalloy; exstraordinary Hall effect; planar Hall effect; substrate; film; magnetic ordering.

Introduction

Finding the correlation between the magnetic and galvanomagnetic characteristics of thin films and multilayer structures with different types of magnetic ordering and magnetic anisotropy, alternating magnetic and non-magnetic layers with different electron transfer mechanisms has been the subject of active experimental and theoretical investigations due to the promising prospects in the solid-state electronics [1; 2]. The last two decades have been characterised by a rapid transition from the use of resistance anisotropy effects in magnetically ordered solids to the use of giant and tunneling magnetoresistive effects [3–6]. Of a great interest is the study the influence of domain walls on the magnitude of the resistance and its change during magnetisation reversals in thin films and multi-layer structures and, in particular, when the layer thicknesses are close to the characteristic lengths of magnetic interactions or the electron transport [7–9]. The change of the sign of the magnetoresistive effect was observed in bilayer superconductor or ferromagnet structures at a change of the type of the domain structure in a ferromagnet [10], as well as in a thin film permalloy Corbino disk [11] at a magnetisation reversal in the direction perpendicular to the disk plane. The aim of this work was to study the features of the extraordinary Hall effect (EHE) and the planar Hall effect (PHE) hysteresis in thin permalloy films and the transition from the ordinary Hall effect (OHE) and the EHE to the PHE, as well as the dependency of this effect on the angle between the flowing current and the magnetic field direction.

Experimental methods

The permalloy thin films ($Ni_{0.8}Fe_{0.2}$) were obtained by ion-beam sputtering of a target onto a sitall dielectric substrate in an external magnetic field with the induction of B = 0.01 T. The thickness of the films was varied in the range of d = 80–280 nm. The surface morphology and the magnetic microstructure of the films were presented in [11]. The samples in the form of a rectangular parallelepiped were prepared by photolithography and etching. In order to avoid the short-circuiting effect of the current contacts on the Hall voltage, the ratio of the sample length to its width was at least three and varied in the range from 3 to 5. No dependence of the effects on the film thickness and the length-to-width ratio was observed.

Ohmic contacts were formed by a deposition of low-melting solder on the film surface, to which copper wires were soldered. The Hall effect was measured at $T = 300$ K in the field of an electromagnet with the induction up to $B = 1.25$ T and a Helmholtz coil with the induction up to 10 mT when scanning the field in positive and negative directions. The measurements were carried out at different angles (φ) between the magnetic field direction and sample plane as well as different angles (θ) between the sampling current and the external magnetic field direction when measuring the PHE. Since the processes of magnetisation reversal depend on the initial magnetic state, all measurements were carried out with a sequential increase in the magnetic field to a maximum value in two scaning directions at least four times. The Hall resistance $R_{yx} = \frac{U_y}{I_x}$ is defined as a ratio of the potential difference measured between the Hall contacts to the sampling current. The magnetic field induction measurement error did not exceed 1.5 %, and the angle setting error between the magnetic field and plane of the sample direction did not exceed ±1°. The angle setting error between the flowing current and the magnetic field direction when measuring the PHE did not exceed ±3°. The estimation of the current and the voltage measurement errors showed that they did not exceed 0.008 and 0.1 %, respectively.

Results and discussion

Figure 1 shows the Hall resistance hysteresis loops of the permalloy film at different angles between the magnetic field direction and the sample plane. The sample has the form of a rectangular parallelepiped of 2 × 8 mm and a thickness of $d = 120$ nm. Despite the fact that at φ = 0 the voltage measured between the Hall contacts strictly speaking is not related to the Hall effect, we will use the well-established terms PHE when the magnetic field is parallel to the film plane and EHE as well as OHE measured at arbitrary angles φ. As can be seen, an increase in the field leads to a rather sharp increase in the Hall resistance due to the dominance of the EHE because of the spontaneous magnetisation of the sample. Upon reaching the magnetisation saturation ($B > 0.7$ T), the slope of the Hall resistance is reduced and is determined by the action of the Lorentz force on the moving electrons, i. e. the OHE. The inset in fig. 1 shows the magnetisation hysteresis loop at φ = 90°. One can see the value of magnetisation saturation field corresponds the change of the Hall resistance slope.

An increase in the angle φ leads to an expected increase in the value of the Hall resistance due to its dependence on the magnetic field component normal to the sample plane, and an increase in the slope in the region of a weak magnetic field where the EHE dominates. Moreover, one can see the asymmetry in the value of the Hall resistance when the direction of the magnetic field changes to the opposite. The lack of the Hall resistance symmetry upon a change of the magnetic field direction is most clearly manifested when measuring the EHE and the PHE (see fig. 1, curves *1* and *3*, respectively). The asymmetry of the Hall resistance is typical for magnetic solids. It is related to the non-symmetric location of the Hall contacts and changes in the longitudinal and transverse components of the resistance anisotropy [12].

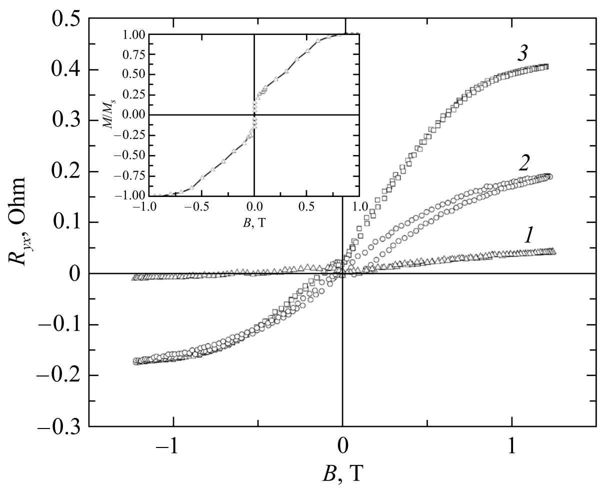

Fig. 1. The Hall resistance hysteresis loops of the permalloy film at different angles between the magnetic field direction and the sample plane φ: *1* – 0°; *2* – 45°; *3* – 90°. The inset shows the magnetisation hysteresis loop at φ = 90°

It should be noted, that the value of the Hall resistance depends not only on the normal magnetic field component, but also on the manifestation of the sample resistance anisotropy induced by the external magnetic field and the presence of the resistance anisotropy, i. e. the ordinary or the so-called Lorenz magnetoresistance (OMR), or the anisotropic magnetoresistive effect (AMR). It should also be noted, that with a change in the measurement geometry one can expect the appearance of the size effect contributions. It is well known, that OMR reaches the maximum value when the ratio of the sample length to its size in the direction perpendicular to the electric and magnetic field is small [13]. It corresponds to the ratio of the length of a sample to its width $\varphi = 90°$ and the ratio of the length to its thickness at $\varphi = 0°$.

In addition one can see a sharp peak of the Hall resistance in the region of a very weak magnetic fields $B < 10$ mT, observed with the field increase in both field directions. The low field Hall resistance hysteresis loops at different φ is shown in fig. 2, *a* – *c*. The direction of the magnetic field change is shown by arrows. The peak amplitude weakly depends on the angle, while the peak position and it's full width at half maximum (FWHM) depends significantly on the measurement geometry.

The Hall coefficient of diamagnets depends on the charge currier scattering mechanism, characterised through the Hall factor, which in metals equals to unity [14]. Consequently, the peaks of the EHE resistance are due to a change in the magnitude and direction of the film magnetisation during the magnetisation reversal and, as a consequence, due to a change in the longitudinal and transverse components of the AMR.

The dependence of the Hall resistance peak position on the φ for two magnetic field directions B_+ and B_- is shown in fig. 3. It can be seen that an increase in the angle φ leads to a peak position shift to the region of stronger fields. The most significant change is observed at $\varphi > 45°$. Maximum value of the magnetic field peak position B_p is reached at $\varphi \approx 75°$. In the range of angles $\varphi \approx 75–80°$, the peak was practically not observed. A further increase in the angle to $\varphi = 180°$ leads to a decrease in the peak field position to a value close to its position at $\varphi = 0°$. The angular dependence of the peak position in the angle range of 180–360° is similar to this dependence for the angles ranging in the interval of $\varphi = 0–180°$. The absence of this feature in the range of angles of $\varphi = 90–180°$ indicates that the magnetisation reversal of the film does not occur in the direction of the heavy axis, but corresponds to a change in the magnetisation direction to the opposite.

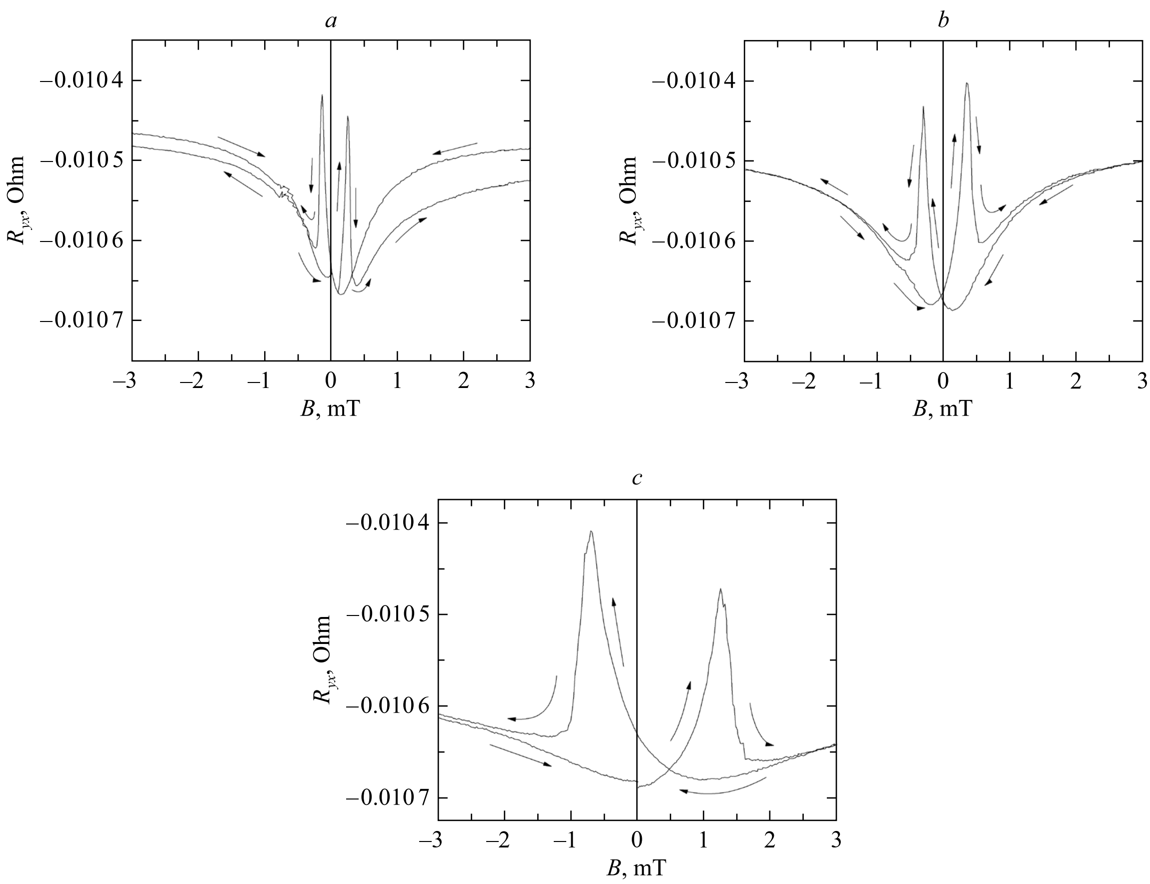

Fig. 2. Hysteresis loops of the Hall resistance of a permalloy film at different angles between magnetic field direction and the film plane in the region of low field φ:
1 – 0°; *2* – 45°; *3* – 90°

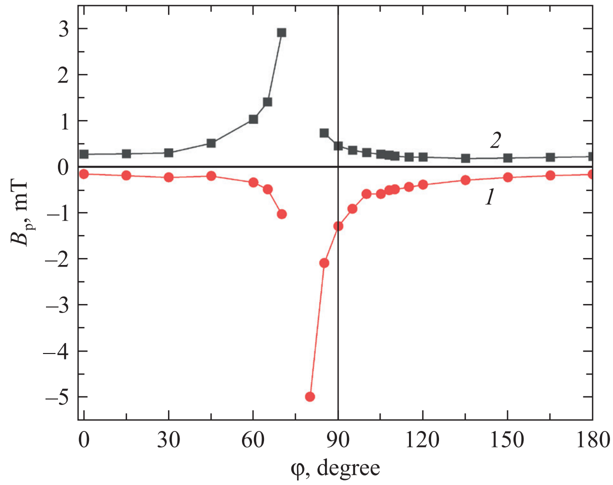

Fig. 3. Angular dependence of the position of the Hall resistance peak for two magnetic field directions B_+ (*1*) and B_- (*2*)

The Hall resistance peak and its angular dependence are caused by the rearrangement of the domain structure during the magnetisation reversal upon a change of φ. This indicates that the direction of the spontaneous magnetisation of the film is close to φ ≈ 75–80° with respect to the film plane. This correlates with the stripe domain structure of the films under study [11].

However, the Hall resistance of magnetic solids can be approximated with a good accuracy by the additive contribution of the ordinary or extraordinary Hall coefficients by the expression [13; 15]:

$$R_{yx} = R_{\mathrm{H}_0} H_{\mathrm{int}} + R_{\mathrm{H}_1} M,$$

where R_{H_0} is the ordinary Hall coefficient; R_{H_1} is the so-called extraordinary Hall coefficient, which is determined by the R_{H_0} and spontaneous (R_{H_s}) Hall coefficients: $R_{\mathrm{H}_1} = R_{\mathrm{H}_0} + R_{\mathrm{H}_s}$. H_{int} is the internal magnetic field strength in the sample, and M is the magnetisation. Values of the ordinary and extraordinary Hall coefficients calculated from the experimental data (see fig. 1) are: $R_{\mathrm{H}_0} = 6 \cdot 10^{-9}$ m^3/C and $R_{\mathrm{H}_1} = 3.2 \cdot 10^{-8}$ m^3/C. They are in a good agreement with the values for the permalloy films of a similar composition [12].

The amplitude of the Hall resistance peak weakly depends on φ, while its FWHM increases significantly as the direction of the external magnetic field approaches to φ ≈ 75–80°. This dependence is shown in fig. 4. One can see that it correlates well with the angular dependence of the peak position (see fig. 3 and 4). Such an angular dependence of the position of the Hall resistance peak and its FWHM is due to the significantly higher value of the film demagnetising factor in the direction perpendicular to the plane of the film. It leads to a greater value of the external magnetic field that is required to achieve an irreversible rearrangement of the sample domain structure and a magnetisation saturation for larger φ values.

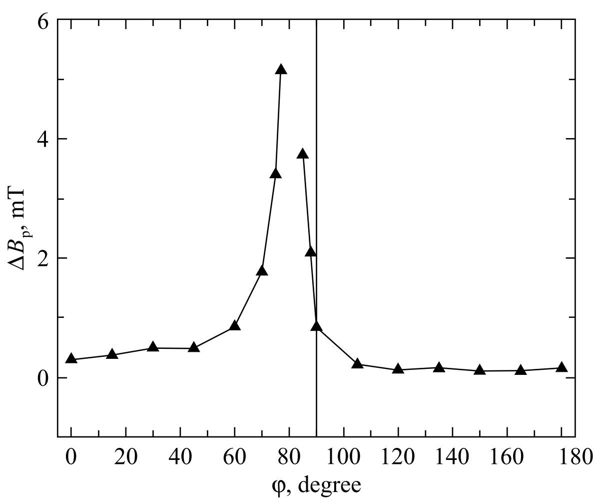

Fig. 4. The dependence of the FWHM of the Hall resistance peak on the angle between magnetic field direction and the film plane

The PHE in diamagnets is caused by the resistance anisotropy induced by the external magnetic field. It is determined by the angle between the magnetic field and the sample current directions and has maximum at $\theta = 45°$ [16]. In a magnetically ordered films, the angular dependence of the PHE is determined not only by the OMR, but also by the AMR. The longitudinal and transverse components of the AMR have different values and moreover have different slopes in an external magnetic field. Typical for a magnetically ordered solid is an increase in the longitudinal component of the resistance and a decrease in the transverse one in an external magnetic field [17]. In this case the electrical field of the PHE is given by the relation [15]:

$$E_{\mathrm{pl}} = j\left(\rho_{\parallel} - \rho_{\perp}\right)\cos\theta\sin\theta,$$

where $\rho_{\parallel}$ and $\rho_{\perp}$ are specific resistance of the longitudinal and transverse components; j is the current density, and θ is the angle between the magnetic and electric fields. This means that the observed effect is determined not only by the angle between the current direction and the external magnetic field, but also by the difference between the magnetic fields influence on the longitudinal and transverse the components of the resistance. Figure 5 shows the dependence of the resistance of the PHE on the angle between the direction of the magnetic field and the sample current, when the EHE ($B = 0.25$ T, curve *1*) and OHE ($B = 1$ T, curve *2*) dominate.

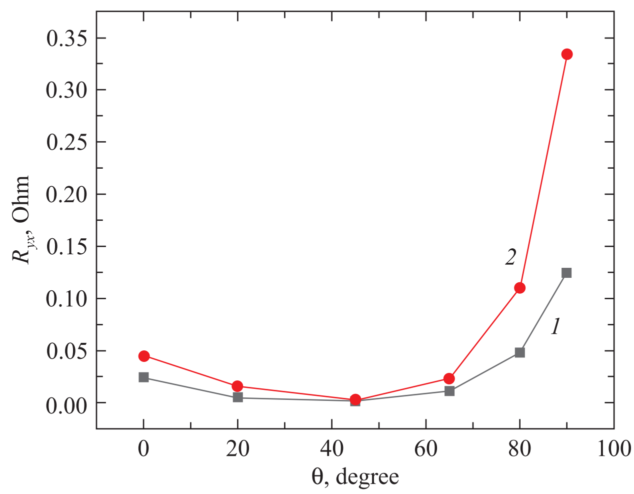

Fig. 5. Dependence of the PHE resistance on the angle between the magnetic field and the sampling current direction in a weak and strong magnetic fields: $B = 0.5$ T (*1*); $B = 1$ T (*2*)

An increase of the angle θ leads to a decrease in the PHE resistance, which reaches a minimum value at $\theta \approx 45°$. When $\theta > 45°$ the PHE resistance increases rather sharply. As noted above, the transverse component of resistance in magnetic solids in a magnetic field decreases. Therefore, the decrease of the PHE resistance in the angle range of $\theta \approx 0–45°$ can be due to the rotation of the initial direction of the film magnetisation to the direction parallel the sampling current. At $\theta > 45°$, a reverse process is presumably observed, i. e. a rotation of the magnetisation direction perpendicular to the sampling current. It should be noted, that there is a slight decrease in the demagnetising factor of the film in the angle range of $\theta = 0–45°$ and a corresponding increase at large angles. It correlates with the angular dependence of the PHE. However, the change in the demagnetising factor in this case is insignificant. In our opinion, it's related to a change in the longitudinal and transverse components the resistance of magnetically ordered solids in an external magnetic field. Therefore the change demagnetising factor this effect is not very important.

When the magnetic field direction is parallel to the film plane, the classical size effect manifestation in the positive component of the OMR can be excluded, since this effect is minimal due to the low thickness of the film [13]. However, a possibility of an increase of the positive OMR component cannot be ruled out, since a change of θ in the range of $\theta = 0–90°$ leads to a transition from the longitudinal to the transverse OMR effect. The transverse OMR is greater than the longitudinal one and can contribute to the OMR effect at $\theta > 45°$. As one can see, this is especially pronounced in a strong magnetic field (see fig. 5, curve *2*).

The Hall resistance peaks were observed also in PHE measurements. The amplitude of the PHE peaks was somewhat smaller. Since the peak position is determined by the magnetic field due to the rearrangement of the domain structure, the observed effects depend on the demagnetising factor of the sample. It was of interest to establish, how the position of the peak changes during the film magnetisation reversal in plane, i. e. when measuring the PHE as a function of the angle between the magnetic field and the sampling current direction.

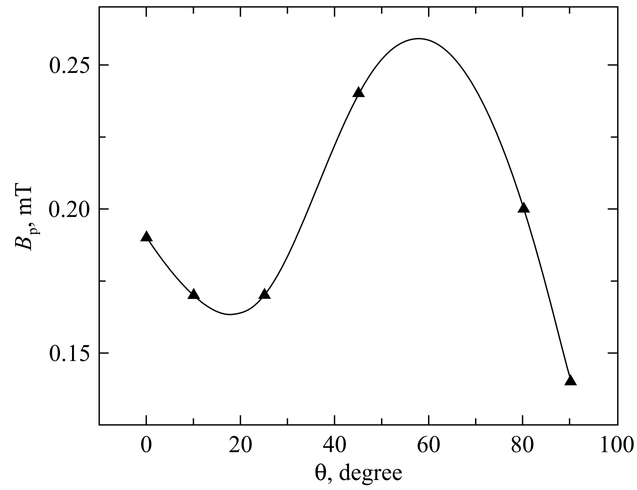

Fig. 6. The dependence of the planar Hall resistance peak position on the angle between the magnetic field and sampling current direction

The corresponding dependence is shown in fig. 6. The change of the peak position can be associated with a change of the demagnetising factor of the rectangular parallelepiped when the magnetic field rotates in plane. In this case the demagnetising factor decreases when the magnetic field direction approaches the diagonal of the parallelepiped and increases when the field moves away from it. However, as it was mentioned above, this change is insignificant, and does not correlate with the observed decrease in the peak position at $\theta > 60°$, which may be related to the peculiarity of the in-plane remagnetisation of thin films with a perpendicular magnetic anisotropy.

Conclusion

The sharp peak in the EHE and PHE resistance was observed in thin permalloy films obtained by means of ion beam sputtering onto a dielectric substrate. This peak is caused by the domain structure rearrangement upon the magnetisation reversal of the film. The peak position of the Hall resistance and its FWHM of the EHE and PHE is determined by the angle between the magnetic field and the film plane direction, as well as by the angle between the sampling current and the external magnetic field. The position of the Hall resistance peak and its FWHM in the EHE both change in the range of $\Delta B \approx 0.2–5.0$ mT, when the angle between the film plane and the magnetic field direction changes in the range of $\varphi = 0–90°$. The magnitudes of the ordinary and extraordinary Hall coefficients determined from the experimental data are: $R_{H_0} = 6 \cdot 10^{-9}$ m^3/C and $R_{H_1} = 3.2 \cdot 10^{-8}$ m^3/C, respectively. Non-monotonic dependences of the planar Hall resistance and its peak position are related to the change in the longitudinal and transverse components of the anisotropic resistance in magnetically ordered solids.

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Received 03.11.2020 / revised 14.04.2021 / accepted 14.04.2021.