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ОСОБЕННОСТИ НИЗКОТЕМПЕРАТУРНОГО МАГНИТОСОПРОТИВЛЕНИЯ В ДИСКЕ КОРБИНО С МАГНИТНЫМ УПОРЯДОЧЕНИЕМ

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В условиях снижения температуры от 300 до 2 К изучены петли гистерезиса поперечного магнитосопротивления (МС) в диске Корбино с магнитным упорядочением при параллельной ($\varphi = 0°$) и перпендикулярной ($\varphi = 90°$) ориентациях магнитное поле – плоскость диска. Индукция магнитного поля не превышала 1 Тл. Диск Корбино изготовлен из тонкой пленки пермаллоя, полученной на ситалловой подложке методом ионно-лучевого распыления. Независимо от температуры и геометрии измерений МС в области слабых магнитных полей (меньше поля насыщения намагниченности) наблюдаются резкие пики отрицательного МС, обусловленные движением доменных стенок при перемагничивании образца. Положение пика в магнитном поле определяется углом между направлением магнитного поля и плоскостью диска, а также температурой. Установлено, что при уменьшении температуры от 300 до 2 К положение пика в магнитном поле изменяется от 0,2 до 6,0 мТл (при $\varphi = 0°$) и от 8 до 22 мТл (при $\varphi = 90°$). При температуре 2 К и переориентации магнитное поле – плоскость диска от параллельной до перпендикулярной положение пика в магнитном поле изменяется от 6 до 22 мТл. В области сильных магнитных полей, бóльших поля насыщения намагниченности, при $\varphi = 0°$ положительная компонента МС имеет линейную ненасыщающуюся до температур $T \approx 40–50$ К зависимость МС, обусловленную магнонным механизмом, а при

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T = 2 K магниторезистивный эффект отсутствует из-за вымораживания магнонов. При φ = 90° в слабых полях знак эффекта изменяется с положительного на отрицательный вследствие ориентации намагниченности диска перпендикулярно линиям тока и доминирования отрицательного анизотропного МС, а в сильном поле – из-за доминирования лоренцевского МС.

Ключевые слова: пермаллой; магнитосопротивление; подложка; пленка; диск Корбино; магнитное упорядочение.

PECULIARITY OF THE LOW TEMPERATURE MAGNETORESISTIVE EFFECT IN THE CORBINO DISK WITH MAGNETIC ORDERING

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The transverse magnetoresistance (MR) hysteresis loops of a magnetically ordered Corbino disk have been studied in the temperature range 300–2 K in an external magnetic field with induction up to 1 T oriented in the plane of the disk (φ = 0°) and perpendicularly to its plane (φ = 90°). The Corbino disk is made of a thin permalloy film obtained on an insulating sitall substrate by ion-beam sputtering. Independently of the temperature and measurement geometry, the field dependences of MR in the range of weak magnetic fields up to the magnetisation saturation exhibit sharp peaks of the negative MR caused by the domain walls motion during the magnetisation reversal of the sample. The position of the peak in the magnetic field (B_p) is determined by the temperature as well as the angle between magnetic field direction and the disk plane. It was found that a temperature change in the range of T = 300–2 K leads to a change in its position in the range of 0.2–6.0 mT and 8–22 mT at φ = 0° and φ = 90°, respectively. The magnetic field direction reorientation from in-plane to out-of-pane at T = 2 K leads to the B_p change from 6 to 22 mT. In the range of strong magnetic fields above the magnetisation saturation field at φ = 0° the positive MR component decreases with induction and has a linear non-saturable dependence down to $T \approx$ 40–50 K due to the magnon MR component dominance. The complete freezing of magnons at T = 2 K leads to the absence of high-field magnetoresistive effect. At φ = 90° in weak fields, the MR changes its sign from positive to negative due to the anisotropic MR component dominance because of the disk magnetisation reorientation perpendicular to the current lines. In a strong field it changes the slope due to the saturation of negative anisotropic MR component, as well as possible additional contribution of the positive geometric Lorentzian MR.

Keywords: permalloy; magnetoresistance; substrate; film; Corbino disk; magnetic ordering.

Introduction

Basic studies of galvanomagnetic phenomena in both diamagnetic and magnetically ordered solids with different mechanisms of charge carrier transfer are focused on investigating their properties in thin and multilayer structures, nanowires and ensembles of magnetic nanoparticles in insulating or conducting matrices and looking for correlations between their electric, galvanomagnetic and magnetic characteristics [1–4]. In magnetically ordered substances, much attention is paid to establishing the contribution of domain walls to the resistivity, sign and magnitude of galvanomagnetic coefficients (magnetoresistance (MR) and Hall resistance) during their motion induced by an external field or current [5–9], since the displacement of domain walls in a weak field can lead to significantly greater changes in the kinetic coefficients, than the effects associated with an anisotropic MR (AMR) [10; 11] or magnon MR (MMR) in a strong field [12]. An active interest in the low-temperature investigations in magnetically ordered thin films and structures is primarily determined by the possibility for the electron transport mechanism to change from diffusion to processes of weak or strong localisation in different temperature ranges, as well as the main magnetic characteristics. This seems to be effective for optimising the sign and values of the galvanomagnetic and magnetic characteristics, since the basic principles of spintronics are determined by the value of the kinetic coefficient and the ability to fix and easily control the magnetisation direction.

Earlier [13], we have studied at T = 300 K the magnetic microstructure and transverse MR hysteresis loops of a permalloy thin film in the Corbino disk form at different angles between the magnetic field direction and the disk plane. In weak magnetic fields up to technical magnetisation saturation field the MR, a peak caused by the rearrangement of the domain structure and the peak sign change were found. In a magnetic field greater than the saturation magnetic field linear negative MR was observed independent of the measurements geometry. It was of interest to study these dependences in the low-temperature region, in particular, in the magnons freeze-out region, and to establish the dependences of the MR peak position on the temperature and the angle between the magnetic field and the disk plane. Therefore, the aim of this work was to study the peculiarity of the MR hysteresis loops in a magnetically ordered Corbino disk at low temperatures in the cases of in-plane and out-of-plane magnetisation reversal.

Experimental methods

The permalloy thin films ($Ni_{0.8}Fe_{0.2}$) were obtained by ion-beam sputtering off a target onto a sitall dielectric substrate in an external magnetic field with induction $B = 0.01$ T. The direction of the induction vector of the external magnetic field in the close proximity to the surface of the growing film was perpendicular to its surface. The thickness of the films was varied in the range of $d = 80–280$ nm. The sample preparation technique, their magnetic microstructure, and the measurement technique are presented in [13]. To establish the electron transfer mechanism the disk resistance temperature dependence was studied in the range of 2–300 K. The hysteresis loops of the transverse magnetoresistive effect were measured in the current generator mode without the sample demagnetising at sequential increases in temperature from 2 to 300 K in a magnetic field of up to $B = 1$ T. The measurements were carried out at parallel ($\varphi = 0°$, in-plane) and perpendicular ($\varphi = 90°$, out-of-plane) orientations of the disk plane with respect to the magnetic field direction.

Results and discussion

The study of the resistance temperature dependence (see fig. 1, *a*, inset) showed that in the temperature range from 300 to 2 K for the films under investigation the resistance temperature coefficient is positive, i. e. the diffusion or metallic mechanism of the electrons transfer dominates. This allows us to conclude, that the MR components contributing to the measured effect can be: a) the resistance anisotropy of a magnetically ordered substance [11] in a weak magnetic field up to the technical saturation magnetisation field; b) usual positive Lorentzian MR (PMR) in a strong field greater than the saturation magnetisation field [14]; c) negative MR (NMR) component caused by scattering of electrons at domain walls [5; 6] or by magnon scattering [12].

As seen from fig. 1 and 2, which show the transverse MR hysteresis loops of the Corbino disk with a thickness of $d = 120$ nm at T is equal 100; 50; 2 K for in-plane ($\varphi = 0°$ (see fig. 1)) and out-of-plane measurements ($\varphi = 90°$ (see fig. 2)), a temperature decrease leads to significant changes in the MR magnitude and the form of the magnetic-field dependence in comparison to $T = 300$ K [13], when the NMR component dominates regardless of the measurement geometry. Furthermore, at $T = 300$ K, independently of the temperature and measurement geometry, in weak fields sharp peaks of the NMR are observed. These peaks are caused by the electron scattering because of the rearrangement of the domain structure upon the magnetisation reversal of the disk.

One can see that at $T = 100$ K and $\varphi = 0°$ in a strong magnetic field above the magnetic saturation field ($B_s = 20$ mT at the temperature 100 K) the MR effect positive and linearly decreases with the increase of the magnetic field. The in-plane magnetisation hysteresis loop at $T = 2$ K is shown as inset in fig. 1, *c*. The decrease of the PMR is related to the contributions of the negative MMR components. Indeed, a further decrease of the temperature, leading the magnons to freeze, causes a decrease in the negative MMR and to a smaller change in the positive component (see fig. 1, *a* and *b*). As a result of the complete freezing of magnons at $T = 2$ K, there is no magnetoresistive effect at $B > 0.25$ T (see fig. 1, *c*). The dominance of the linear non-saturable negative MR due to the magnons scattering (MMR) was predicted theoretically and experimentally confirmed for the negative longitudinal MR of iron-group metal films in a magnetic field up to $B = 40$ T [12].

A characteristic feature of the current flow in the Corbino disk is its spreading from the central electrode to the peripheral one. In this case, the longitudinal MR measurement in a «pure» form is impossible regardless of disk orientation in a magnetic field. Nevertheless, a linear decrease in the positive MR in a strong magnetic field is caused by the negative MMR, since at the transition point from weak to strong fields ($B = B_s$) positive AMR riches the maximum value and a further MR change may be due to the contributions of the negative MMR components. It should be noted that for in-plane measurements the magnetic saturation field changes from 15 to 25 mT at the temperature 300 and 2 K, respectively. These values are in a good agreement with the saturation field MR data in the temperature range from 300 to about 50 K, while at $T = 2$ K the MR data indicate the saturation field to be one order of magnitude grater. However, the MR curve measured at 2 K demonstrates a complex step-like shape with a plateau in the low-field range close to B_s value of the corresponding magnetisation curve, and a subsequent MR increase in $B = 0.20–0.25$ T accompanied by a complete signal saturation at higher fields. A sharp increase in the positive MR in the range of magnetic fields 0.20–0.25 T could be associated with the dominance of the positive AMR component increasing abruptly due to aligning the majority of magnetic moments of the film in its plane along the field direction only at this magnetic induction value. The latter peculiarity of the MR(B) dependence at 2 K indicates a possible change in the domain structure and (or) dominating anisotropy of the film.

Thus, the magnon freezing temperature in a Corbino permalloy disk is about 40–45 K, i. e. it is close to the temperature at which the disk resistance loses its dependence on temperature (see fig. 1, *a*, inset) and is determined by the structural defects only. It can be noted also, that the magnon freeze-out temperature, estimated from the negative longitudinal MMR measurements of iron and nickel films, is significantly higher and reaches about 160 K [12].

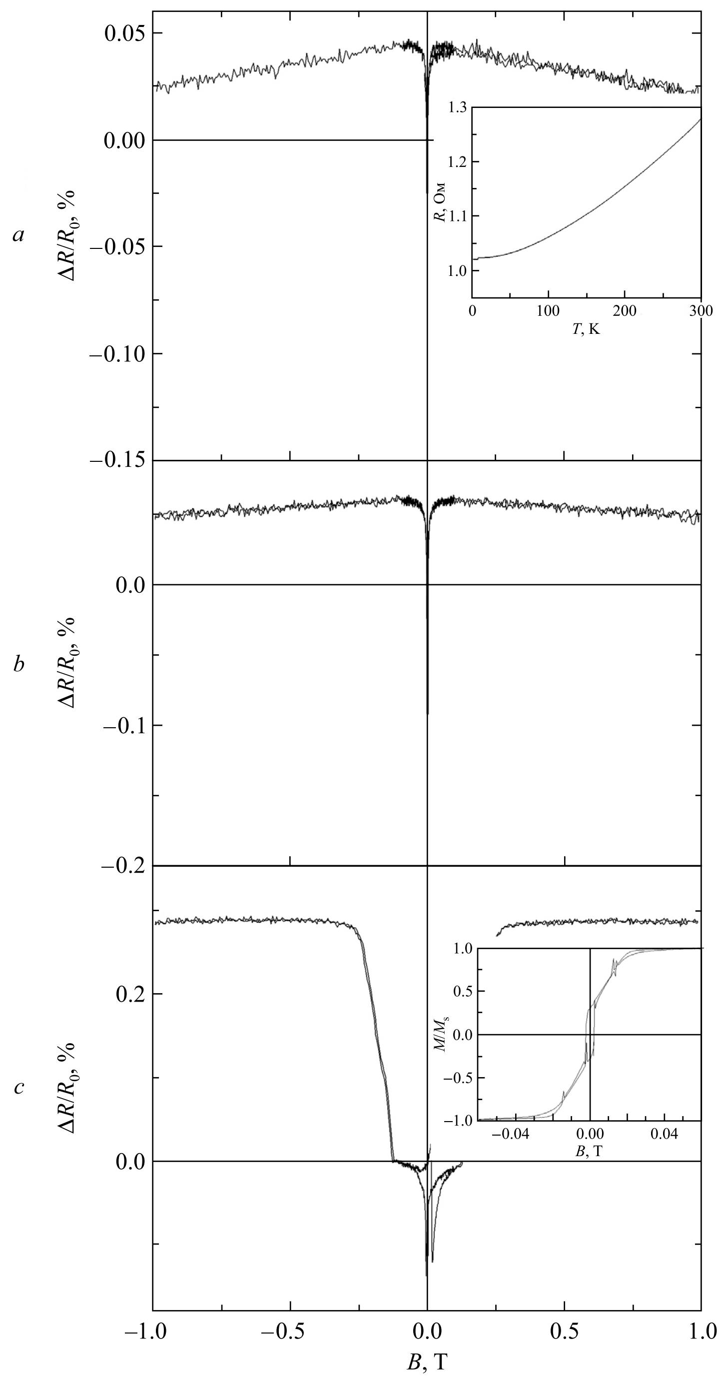

Fig. 1. Magnetoresistance hysteresis loops of the Corbino permalloy disk at φ = 0°, measured at different temperatures: *a* – 100 K; *b* – 50 K; *c* – 2 K (the inset in figure *a* shows the temperature dependence of the disk resistance, and in figure *c* – the magnetisation hysteresis loop at T = 2 K)

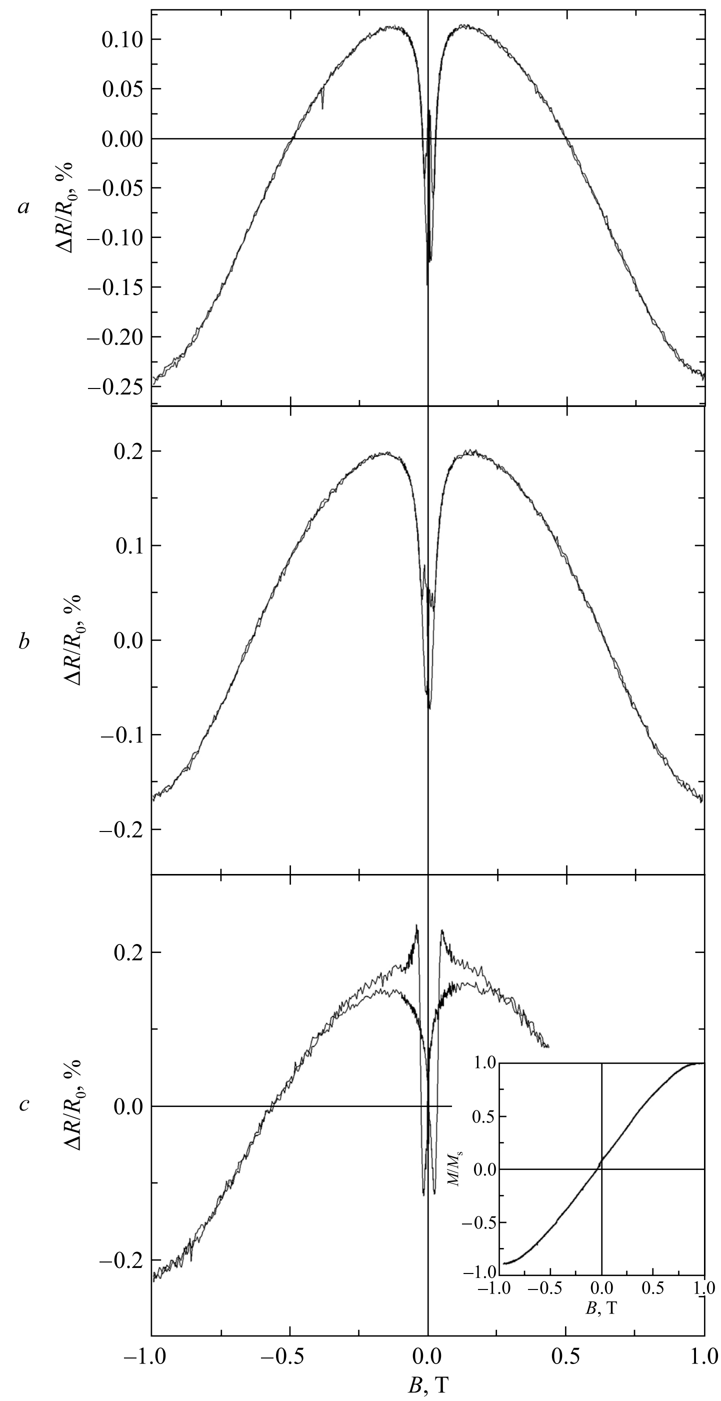

Fig. 2. Magnetoresistance hysteresis loops of the Corbino permalloy disk at φ = 90°, measured at different temperatures: *a* – 100 K; *b* – 50 K; *c* – 2 K (the inset in figure *c* shows the magnetisation hysteresis loop at $T = 2$ K)

A change of the external magnetic field direction from in-plane to out-of-plane leads to an increase in the magnetisation saturation fields, which change from 0.75 to 0.83 T at the temperature 300 and 2 K, respectively, suggesting the expansion of the weak magnetic field and AMR dominance areas. The inset in fig. 2, *c*, shows the out-of-plane magnetisation hysteresis loops at $T = 2$ K. As a result, in a weak field the negative AMR component begins to dominate due to the reorientation of the disk magnetisation direction to the direction perpendicular to the current lines. It is well known that in this case the AMR is negative [11]. One can see in addition that the MR dependence exhibits a change of its slope in a strong magnetic field. Moreover, the fields at which the slope change is observed increases upon a decrease of temperature. The observation of the slope change at $T = 2$ K (see fig. 2, *c*) can be caused by saturation of negative AMR component in a strong field as well as due to an additional contribution of the PMR component. Indeed, in the out-of-plane geometry the PMR geometric effect in the Corbino disk is the greatest [15; 16]. It can also be noted that an increase of the NMR slope variation upon a decrease of temperature correlates with the temperature change the saturation magnetisation field.

As mentioned above, independently of the temperature and measurement geometry, the MR magnetic field dependence in the region of weak fields exhibits sharp peaks in the NMR. Figures 3 and 4 show in-plane and out-of-plane MR hysteresis loops in a weak magnetic field at $T = 2$ K. The arrows show the field scanning direction. At approximately the same MR peak magnitudes for both measured geometries, the peaks magnetic field positions differ significantly. Regardless of the temperature, the out-of-plane MR peak position is always greater. It reflects the much more difficult rearrangement of the domain structure in the direction perpendicular to the disk plane because of the very strong demagnetising factor in this direction. We also note the difference in the peak position during the Corbino disk magnetisation reversal in the directions conventionally designated as B_+ and B_-. It can differ by up to three times and, moreover, a greater difference was always observed for in-plane MR. Such a difference is believed to indicate the different domain structure formation upon the magnetisation reversal and requires a more detailed investigation. It should be noted that for low-temperature out-of-plane measurements, in contradiction to $T = 300$ K [13], there are no sharp MR oscillations. The MR peak at $T = 2$ K changes sign from negative to positive in a rather smooth manner without any oscillation.

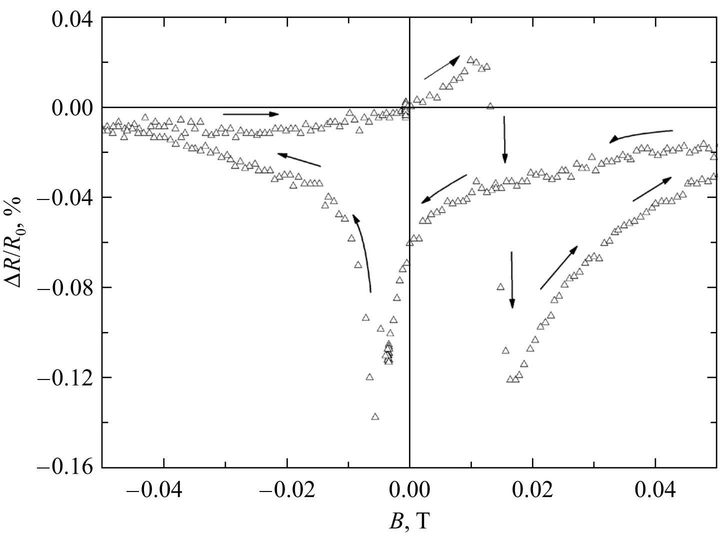

Fig. 3. Magnetoresistance hysteresis loop for the Corbino permalloy disk in a weak magnetic field at $\varphi = 0°$ and $T = 2$ K

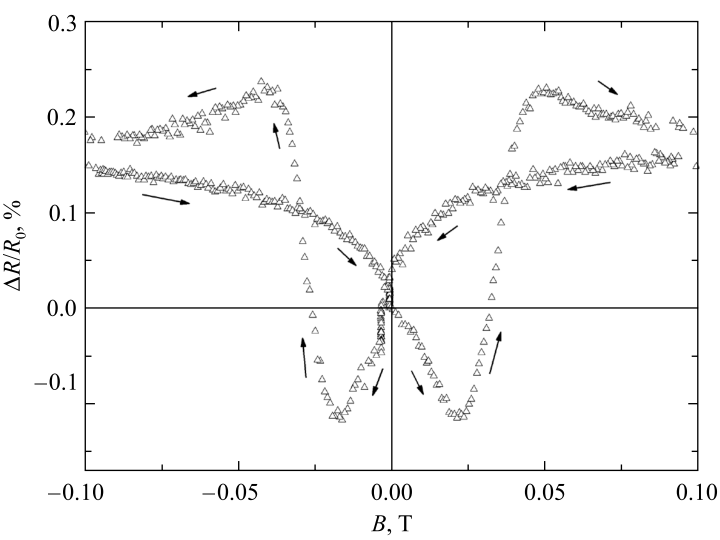

Fig. 4. Magnetoresistance hysteresis loop for the Corbino permalloy disk in a weak magnetic field at $\varphi = 90°$ and $T = 2$ K

The temperature dependence of the NMR peak position for in-plane and out-of-plane measurements is shown in fig. 5. As expected, the freezing of the magnetic moment directions and wall positions of individual domains leads to an increase in the magnetic field of the domain structure rearrangement and, as a consequence, to a change in the MR peak position. One can see that the most significant change of the MR peak position is observed at temperatures below 50 K, i. e. below the magnon freezing temperature.

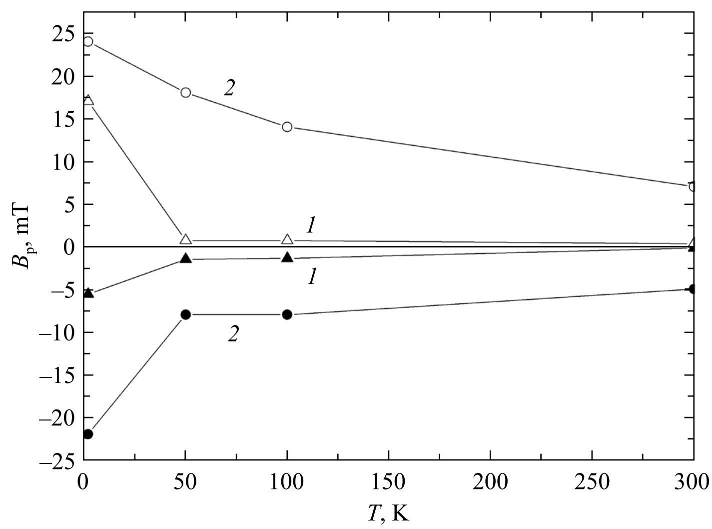

Fig. 5. Temperature dependence of the NMR peak position for in-plane (*1*) and out-of-plane (*2*) measurements for two directions of the magnetic field B_+ and B_-

Finally, it should be noted that the sign and the magnitude of MR in a magnetically ordered Corbino disk in the region of the peak can be determined not only by the magnitude of the AMR or MMR, but also by the number, type, and size of the domain walls crossed by the charge carriers. For example, in magnetic films thinner than 20–30 nm, the Neel walls are stable, while for larger thicknesses the Bloch walls play the major role [17]. In films with thickness in the range of 30–120 nm, the transition between the Bloch and Neel walls, as well as vortex domain walls or more complex types can be observed. However, the above-mentioned question is currently a topic of further intensive theoretical and experimental research.

Conclusions

In Corbino thin-film permalloy disks with magnetic ordering in the temperature range of 300–2 K, sharp peaks of negative magnetoresistance due to the domain walls motion are observed. The magnetic field peak position is determined by the temperature and the angle between the magnetic field and the plane of the disk. The temperature decrease in the range of 300–2 K leads to a change in the peak position in the range of 0.2–6.0 and 8–22 mT for in-plane and out-of-plane measurements, respectively. A transition from in-plane to out-of-plane measurements at $T = 2$ K leads to change of the peak position in the range of 5–22 mT. A linear NMR at $T = 300$ K and a decreasing PMR at the temperatures of down to 40–45 K in a strong magnetic field is related to the magnon magnetoresistive effect. It was found that the magnon freezing temperature is about 40–45 K. The change of the slope of the MR dependence for out-of-plane measurements is related to the saturation of negative AMR and possible additional contribution of the positive geometric Lorentzian component to the Corbino disk MR.

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