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Correlation between electrical, galvanomagnetic and magnetic properties of nanocrystalline iron films obtained by ion assisted deposition

© V.I. Halauchuk[1], Y.A. Bumai[2], M.G. Lukashevich[1], N.M. Lyadov[3], I.A. Faizrakhmanov[3], R.I. Khaibullin[3]

[1] Belarusian State University,
Minsk, Republic of Belarus
[2] Belarusian National Technical University,
Minsk, Belarus
[3] Zavoisky Physical-Technical Institute, FRC Kazan Scientific Center of RAS,
Kazan, Russia

E-mail: Golovchuk@bsu.by

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Here we present the measurements of the temperature dependence of resistance, transverse and longitudinal magnetoresistance (MR) in nanocrystalline iron films in the temperature range 2–300 K and the sweep of the magnetic field up to 8 T. Thin nanocrystalline films of α-iron phase with 80 nm thickness were obtained by ion-beam assisted deposition on a silicon substrate. In addition to the shape anisotropy, the obtained iron films exhibited perpendicular magnetic anisotropy (PMA), which disappeared after annealing the films at a temperature of 450°C in a vacuum. The effect of PMA on the sign and magnitude of the MR of iron films, as well as on the magnetic field dependences of the magnetoresistive effect, recorded at different orientations of the external magnetic field with respect to the film plane and current direction, is experimentally shown. The results obtained are discussed in the framework of modern views on the processes of charge transfer in a weakly disordered ferromagnetic films with different magnetic anisotropy and domain structure when a weak (less than the saturation field of magnetization) or strong (higher than the saturation field) external magnetic field is applied.

Keywords: nanocrystalline iron films, perpendicular magnetic anisotropy, magnetoresistance, anisotropic magnetoresistance, magnon magnetoresistance, percolation, weak localization.

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1. Introduction

Wide application of thin magnetic films and multi-layer heterostructures with various type of magnetic ordering in layers in magnetoelectronics and spintronics stimulates unfailing interest to searching for a correlation between magnetic microstructure of study object and its electrical, galvanomagnetic and magnetoelectrical characteristics [1]. Dimensional features of nanostructured magnetic systems (for instance, crystallite size, layers thickness, etc.) can be comparable (or even less) with correlation length of magnetic ordering and spatial characteristics of electron transport, such as free length, jump distance or length of electron wave function phase failure. Therefore even at insignificant variation of structure parameters of nanostructured system the significant change of its magnetic and magnetotransport properties can be expected. Usually in nanostructured systems the spin-dependent processes of carriers (electrons) scattering or tunneling play a critical role in establishing the dependencies of electrical resistance on value of external magnetic field (i.e. magnetoresistance, MR). At the same time, the value of MR significantly depends not only on electron transport mechanism, but also on angle between magnetization vector and current flow direction. However, along with classical effects of anisotropic magnetoresistance (AMR) [2] or Lorentz magnetoresistance (LMR) [3], the electrons scattering on domain walls or electron-magnon interaction (magnon scattering) can also significantly influence the MR [4,5]. It should be noted, that currently there are no fixed notions not just on influence of domain walls types on transport characteristics of magnetic material, but also on contribution of domain walls displacement process during system remagnetization to sign and value of the observed MR. All abovementioned mechanisms of electrons scattering are spin-dependent processes, can result in various types of magnetic field dependence of electrical resistance and define sign and value of magnetoresistance effect, and, therefore, should be considered at development of new spintronic devices based on nanostructured magnetic systems [6].

The purpose of this work is to find a correlation between electrical (electron transport mechanism), galvanomagnetic (sign, value and type of MR magnetic field dependence) and magnetic (magnetic microstructure, magnetization direction) characteristics of thin iron films depending on direction of external electrical and magnetic fields and measurement geometry for searching for the optimal ways to control the galvanomagnetic characteristics by means of purposeful change of electron transport mechanism, film magnetic state and appearance of geometric and size effects both in galvanomagnetic and magnetic characteristics.

2. Microstructure and magnetic properties

Thin (thickness $d = 80$ nm) nanocrystalline iron films, obtained on silicon substrate by ion-beam assisted deposition method, were the study objects. The detailed description of films obtaining conditions and results of their microstructure study, magnetic phase composition and magnetic properties were presented earlier in the works [7,8]. The obtained iron films were nanostructured magnetic material, consisting of compositions of nanoscale

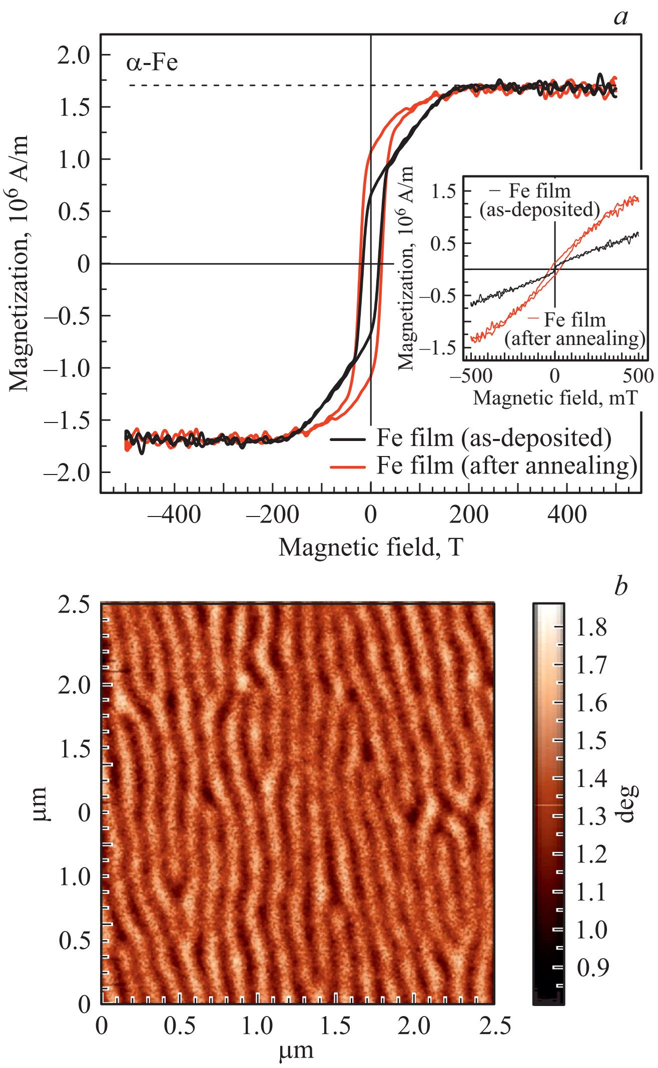

Figure 1. *a*) curves of magnetization of as-deposited and successively annealed iron films at room temperature and magnetic field scanning in film plane. Figure insert shows the curves of magnetization for the same films at magnetic field scanning perpendicular to the film plane; *b*) image of stripe domain structure, obtained using magnetic-force scanning microscopy, in as-deposited nanocrystalline iron film.

(~ 10 nm) crystallites of α-phase of Fe with large share (up to 40%) of iron amorphous stage inclusions and dividing ultrathin (less than 1 nm) oxide layer of ($Fe_{1-x}O$ or Fe_3O_4). It was shown, that at certain modes of ion-beam assisted deposition the nanocrystalline (nanocomposite in iron phases) films at room temperature exhibit perpendicular magnetic anisotropy (PMA), which value is defined by film deposition rate [8]. It was established, that the nature of PMA is related to microstresses (magnetoelastic effect) in nanocrystalline iron phase, appearing during films growth due to presence of amorphous iron phase and oxide layer ($Fe_{1-x}O$) in the film. After thermal annealing of the obtained iron films at temperature of $T = 450^\circ$C for 15 min under vacuum (10^{-2} Pa) the average size of crystallites of α-phase of Fe increased to 20−30 nm due to crystallization of amorphous phase, microstresses were removed and PMA in nanocrystalline iron films completely disappeared [7,8].

In this work for revealing the PMA influence on magnetotransport properties of nanocrystalline iron films we used two film types with various magnetic anisotropy. Specifically, as-deposited iron films, exhibiting PMA with anisotropy field of $B_a \cong 180$ mT, and similar films after additional thermal annealing in vacuum, without PMA. PMA presence in as-deposited nanocrystalline iron films is indicated by transcritically-shaped magnetic hysteresis loop, registered at magnetic field scanning in the film plane (see Fig. 1, *a*, curve *1*), as well as observance of stripe domain structure, presented in Fig. 1, *b*, where light and dark strips correspond to perpendicular magnetization components in domain, directed in opposite directions. Unlike as-deposited nanocrystalline iron film, the annealed sample of the same film exhibits magnetic hysteresis loop, typical for polycrystalline iron films (Fig. 1, *a*, curve *2*). It should be noted, that for both types of iron films (with PMA and without) at magnetization curves registration along normal to the film plane (see insert to Fig. 1, *a*) the dominant influence on films magnetization process is exerted by shape anisotropy due to high value of spontaneous magnetization of α-phase of Fe.

3. Electrical and magnetic resistance measurement technique

Ohmic contacts to nanostructured iron films were made by ultrasonic soldering of copper wires. Hysteresis loops of transverse and longitudinal MR were measured at linear section of volt-ampere characteristic at magnetic field scanning to 8 T in two directions without preliminary sample demagnetization before each measurement. Measurements were performed in temperature range from 2 to 300°K with heating of samples, pre-cooled in zero magnetic field to liquid helium temperatures. Transverse magnetoresistance effect was measured at two values of angle between magnetic field vector direction and film plane, specifically: $\varphi = 0$ and $\varphi = 90^\circ$, while longitudinal — at $\varphi = 0^\circ$. For determination of the dominant mechanism of electrons transport in various temperature ranges the measurements of electrical resistance temperature dependencies were performed. All measurements were performed in current stabilization mode for current, flowing in iron film plane.

4. Results and discussion

As was noted before, the synthesized films are nanostructured material, in which nanocrystallites of α-iron with diameter of ~ 10 nm are divided with disordered layers of amorphous and oxide iron phases. After annealing the crystallites sizes increase to 20−30 nm, while disordered layer almost disappears. In such films the domination of various electron transport mechanisms with temperature change can be expected. In high temperature region the activation or percolation mechanisms can be the most important ones, while in low temperature region — diffusion mechanism, processes of tunneling or low localization depending on structural perfection. Temperature dependencies of resistance of as-deposited and annealed films are shown in Fig. 2, *a* and *b*.

Resistance of as-deposited and annealed films increases in the beginning with temperature lowering, reaches maximum value at temperature of $T_{max} \approx 150$ and 260 K respectively and then decreases, reflecting domination of diffusion mechanism of electrons transport, characteristic for metals.

At $T > T_{max}$ in as-deposited and annealed films, as it seen in Fig. 2, the temperature dependence of resistance is not described with activation dependence, thus indicating the dominance of percolation processes over random resistance grating of metal nanocrystalline islands of iron and its amorphous layers and oxides. The latter have negative temperature resistance coefficient, defining temperature dependence of resistance in region of $T > T_{max}$. At lower temperatures the diffusion mechanism of electrons transport along iron nanocrystallites starts to dominate. Annealing, resulting in improving of structural perfection, homogeneity of film and metal percolation channels, displaces the resistance maximum into the high temperature region (Fig. 2, *b*) and expands the region of domination of metal nature of transport until $T = 2$ K.

Increase of resistance of as-deposited films at $T \leq 35$ K (Fig. 2, *a*) can be caused by processes of weak electron localization [9], tunneling between metal crystallites [10], or reflect presence of magnetic phase transition. The performed analysis showed, that within temperature interval of $T = 35-5$ K the resistance of as-deposited films is interpolated well with logarithmic dependence, characteristics for thin poorly disordered metal films (insert in Fig. 2, *a*), i.e. defined with processes of weak localization. Deviation from logarithmic dependence at lower temperatures can be related to influence of spin-orbital interaction on electron transport processes.

It should be noted, that in iron films, containing nanometric islands [11], the observed increase of resistance at low temperatures was caused by appearance of heterogeneous

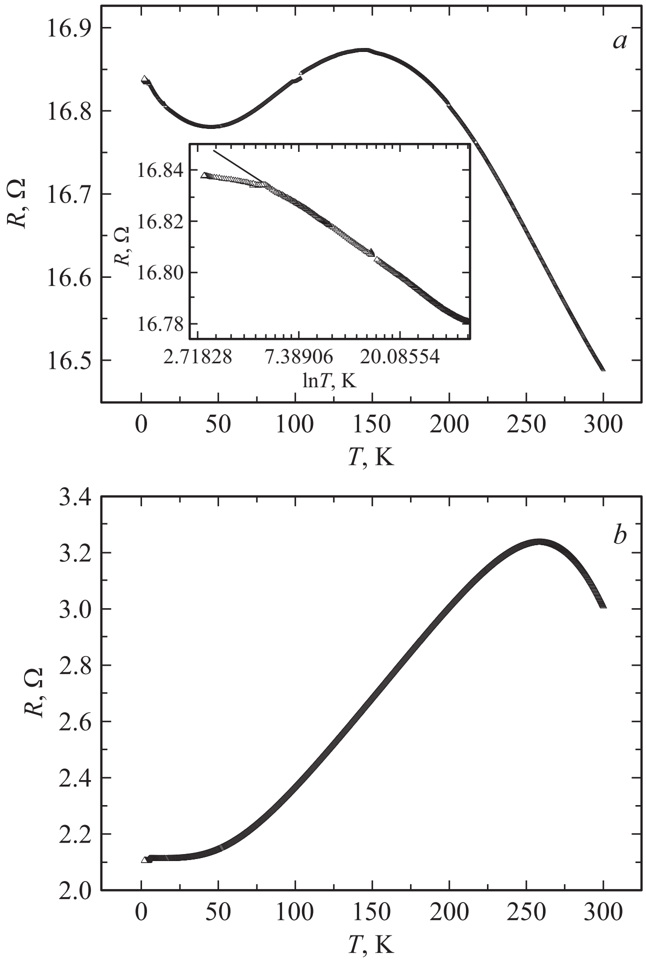

Figure 2. Temperature dependence of resistance of *a*) as-deposited and *b*) annealed iron film. Inserts show the dependence in interval of $T = 35-2$ K in logarithmic scale.

magnetization of the film at temperature lowering due to freezing of spin directions at islands boundaries and, as a result, increase of spin-dependent scattering.

Fig. 3−5 shows hysteresis loops of transverse (Figs 3, 4) and longitudinal (Fig. 5) MR of as-deposited film, measured at parallel ($\varphi = 0°$; Fig. 3) and perpendicular ($\varphi = 90°$; Fig. 4) orientations of direction of magnetic field−film plane and various temperatures.

It is seen, that hysteresis loops of transverse MR at $\varphi = 0°$ and longitudinal effects (Figs 3 and 5), i.e. when magnetic field is parallel to the film plane, regardless of direction and value of magnetic field, are well correlated by sign, value and type of magnetic field dependence. Value of longitudinal MR at $T \leq 100$ K is even a bit higher. Such correlation confirms the dominance of percolation mechanism of electrons transport at near room temperatures, when ratio of current flow perpendicular and parallel to magnetic field is almost the same and MR linearly depends on the field [12,13]. Magnetic field orientation change from $\varphi = 0$ to $\varphi = 90°$ (Figs 3 and 4) results in drastic changes of sign and value and type of magnetic field dependence of

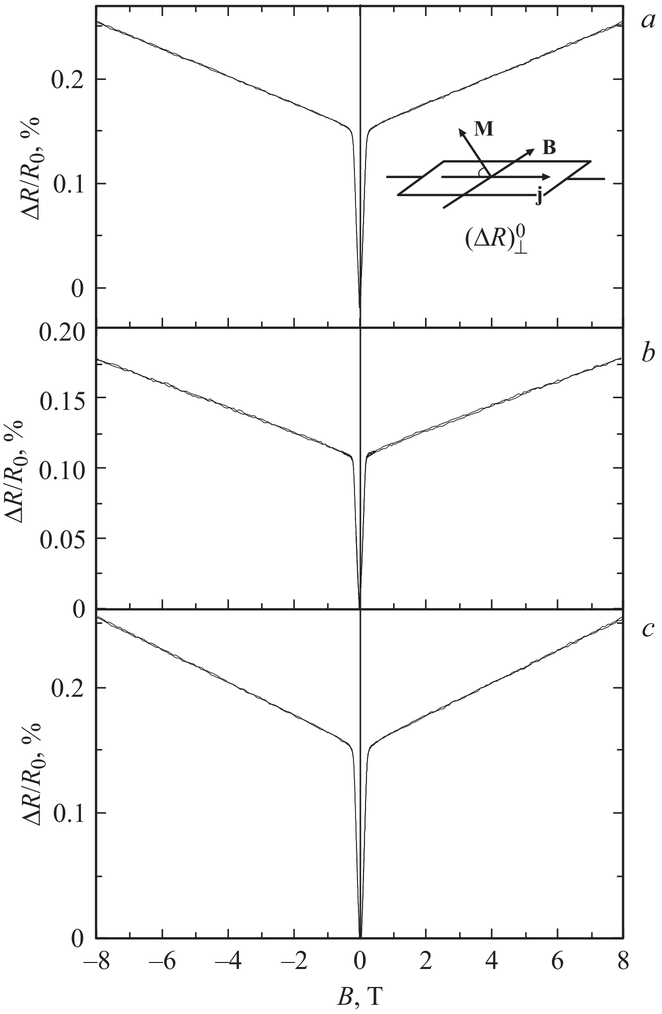

Figure 3. Hysteresis loops of transverse magnetoresistance of as-deposited iron film at $\varphi = 0^\circ$, measured at various temperatures: *a*) — 300 K; *b*) — 100 K; *c*) — 2 K.

transverse MR, while temperature lowering to $T = 2$ K only insignificantly changes the effect value, except for $\varphi = 90^\circ$ (Fig. 4, *c*), when at $T = 2$ K MR sign changes from negative to positive.

Three characteristic regions can be separated at MR of as-deposited samples, measured at various φ and temperatures. Since for diffusion mechanism of electrons transport the longitudinal LMR is equal to zero, and transverse is very small and quadratically depends on magnetic field [3], the conclusion can be made, that the main contribution to the measured effect can be made by the following components: anisotropy of resistance of magnetic ordered environment [2,14], magnon magnetoresistance (MMR) [5], giant magnetoresistive effect (GME) [15,16] and influence of magnetic field on processes of weak percolation [12,13] or weak localization of electrons in the low temperature region [9].

Let's examine the peculiarities of MR transformation of as-deposited films depending on geometry of measurement and temperature based on phenomenological theory of anisotropy of resistance of magnetic ordered environment [2] and influence of magnetic field on transport processes considering the abovementioned mechanisms of electron transport and mechanisms of magnetoresistance effect appearance. As known, value of ferromagnet resistance is higher if current direction is parallel to magnetization. In this case the external magnetic field results in resistance increase (positive MR, PMR), while at mutual perpendicular orientation — to its reduction (negative MR, NMR). Upon reaching the saturation magnetization (strong fields region) the further field increase can result in increase or decrease of resistance of magnetic ordered environment, i.e. to PMR or NMR depending on dominant conduction mechanism.

Figures 6, *a–c* shows the same dependencies in the region of weak magnetic fields at temperature of $T = 100$ K, demonstrating peculiarities of MR sign change.

In geometry measurement of $\varphi = 0^\circ$ both transverse and longitudinal MR change sign from negative to positive (Fig. 6, *a* and *c*), and at $\varphi = 90^\circ$ (Fig. 6, *b*) the very small

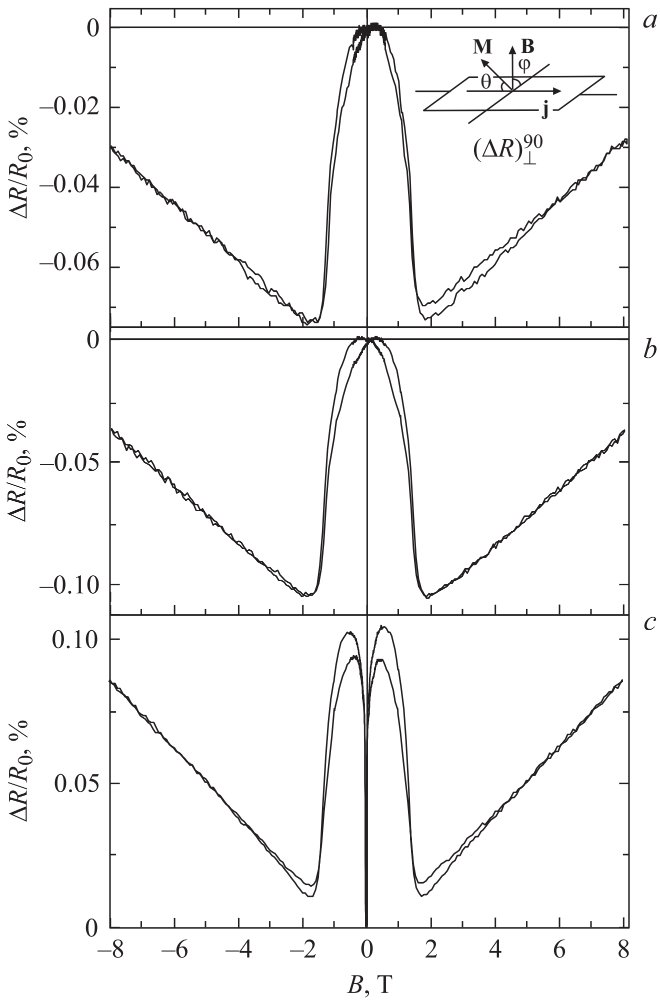

Figure 4. Hysteresis loops of transverse magnetoresistance of as-deposited iron film at $\varphi = 90^\circ$, measured at various temperatures: *a*) — 300 K; *b*) — 100 K; *c*) — 2 K.

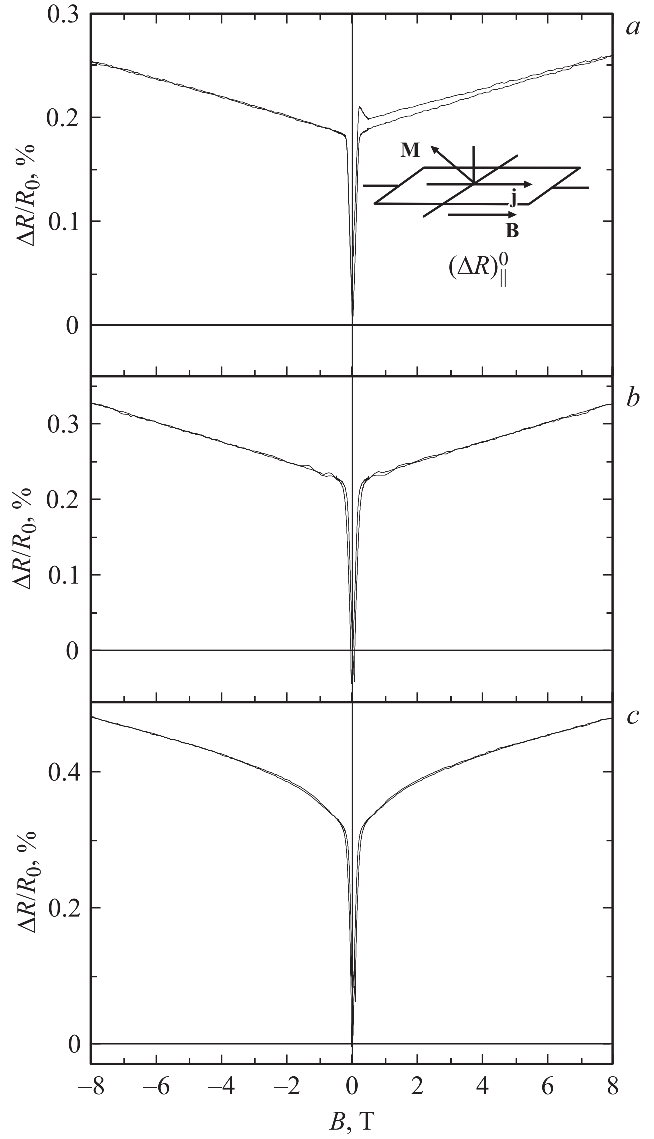

Figure 5. Longitudinal magnetoresistance hysteresis loops, measured at various temperatures: *a*) — 300 K; *b*) — 100 K; *c*) — 2 K.

transverse PMR is observed only at magnetic field reduction from maximum value to zero at $B \approx 0,\ 3\,\mathrm{T}$. Field change direction in Fig. 6 is showed with arrows. Such dependencies, when in magnetized state the sample resistance is higher, are not characteristic for regular GME [15,16], but characteristic for inverse GME, observed in magnetic heterogeneous environment [17], i.e. in environment, where one of magnetic phases has larger electrons conductivity with spin downward direction than conductivity with spin upward direction. This allows to define a coercitive force, and AMR independence of filed in a field, larger than magnetization saturation field — to define its value. Values of coercitive force and magnetization saturation field at $T = 300\,\mathrm{K}$, obtained from measurements of hysteresis loops of magnetization [7,8] and MR of as-deposited and annealed films at various angles φ are presented in the table and are in good agreement.

Temperature reduction to $T = 2\,\mathrm{K}$ results in dominance of processes of weak localization and/or electron-electron interaction [9] in as-deposited films, confirming the logarithmic dependence of resistance on temperature at $T < 35\,\mathrm{K}$. At the same time, the hysteresis phenomena and MR sign change, characteristic for temperatures above $T > 100\,\mathrm{K}$, are not observed in weak field. When magnetic field is in the film plane, both transverse and longitudinal MR in weak and strong field have positive sign and are close to linear dependence on magnetic field, caused by dominance of AMR positive component in weak field and field influence on percolation processes in strong field.

Let's discuss the reasons for transverse MR sign change in as-deposited films at reorientation of magnetic field direction relating to film plane from $\varphi = 0$ to $\varphi = 90°$. As seen from comparison of Figs 3 and 5 with Fig. 4, regardless of the measured effect (transverse or longitudinal), the change of φ results in MR sign change from positive to negative at $T > 10\,\mathrm{K}$. In weak localization mode MR is only positive and demonstrates the sharp increase or decrease almost to zero at $B \approx 2\,\mathrm{T}$ and linear growth in the stronger field. Since AMR has negative sign at mutually perpendicular direction of flowing current and sample magnetization, such change of MR sign indicates the presence of perpendicular magnetic anisotropy in as-deposited films when measuring the transverse MR and at $\varphi = 90°$. Indeed, in this case the increase of magnetic field, perpendicular to film plane, results in final turn of magnetization to direction, perpendicular to the flowing current, i.e. domination of negative component of AMR. As per Mössbauer spectroscopy data, magnetization in as-deposited films is oriented at angle of about 75° to film plane.

As was mentioned earlier, samples annealing results not only to change of dominant conductivity mechanism in various temperature ranges, but also to magnetization

Values of coercitive force B_c and magnetization saturation field B_s at $T = 300\,\mathrm{K}$, obtained from measurements of hysteresis loops of magnetization and magnetoresistance effect in as-defined and annealed films at various angles between film plane and magnetic field direction

	Sample	As-deposited		Annealed	
Angle φ, deg	Characteristic	B_c, T	B_s, T	B_c, T	B_s, T
0	M(0)	15	0.2	7	0.1
	$(\Delta R)^0_{\perp}$	16	0.2	13	1
90	M(90)	5	1.25	6	2
	$(\Delta R)^{90}_{\perp}$	–	1.7	–	2
0	M(0)	15	0.2	7	0.1
	$(\Delta R)^0_{\parallel}$	19	0.2	12	1

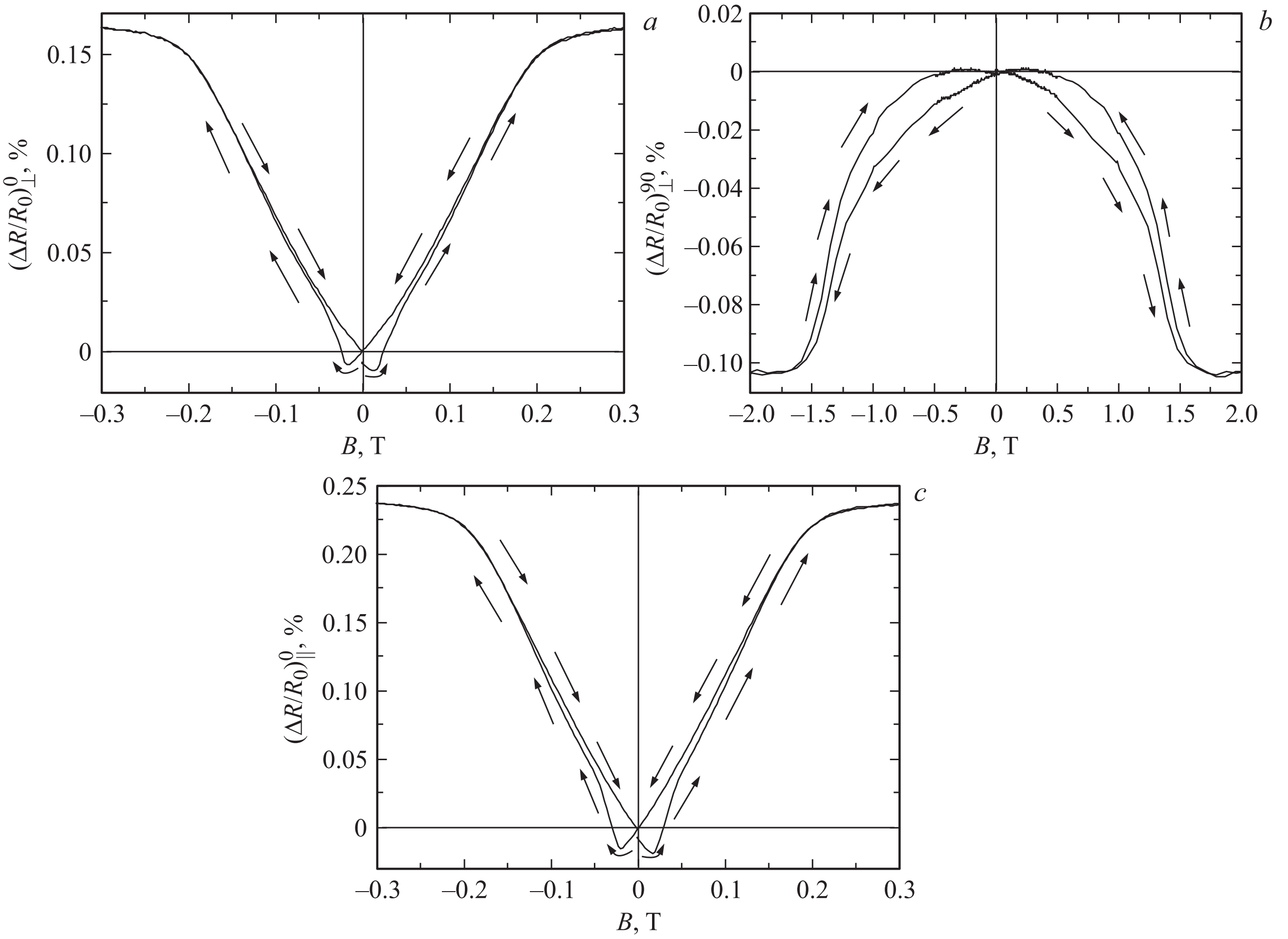

Figure 6. Hysteresis loop of transverse — *a*) $\varphi = 0$ and *b*) $\varphi = 90^\circ$ — and *c*) longitudinal magnetoresistance, at $T = 100$ K of as-deposited iron film in weak magnetic field.

dominance in film plane and, as a result, to drastic changes of MR. These changes appear the most at temperature lowering. Figures 7–9 show hysteresis loops of transverse (Figs 7, 8) and longitudinal (Fig. 9) MR of annealed film, measured at parallel (Figs 7, 9) and perpendicular (Fig. 8) orientations of direction of magnetic field — film plane.

First of all, change of sign of transverse at $\varphi = 0^\circ$ and longitudinal MR from positive to negative at $T = 300$ K at annealing should be noted (Figs 3 and 5; 7 and 9). Temperature lowering to $T = 100$ K also results in drastic changes of sign and type of magnetic field dependence of transverse at $\varphi = 0^\circ$ and longitudinal effects, particularly to the effect sign change from negative to positive. At $\varphi = 90^\circ$ the effect sign remains negative, but in strong field the slope of magnetic field dependence changes from negative to positive (Fig. 8, *a* and *b*), reflecting dominance of positive component of percolation MR in strong field.

Linear dependence of NMR of magnetic ordered environments in the region of strong magnetic fields is caused by dominance of magnon scattering, that is theoretically predicted and experimentally confirmed for 3*d*-metals [5]. As expected, decrease of magnon number with temperature lowering results in dominance of field influence in percolation processes and, as a result, to close values of positive transverse and longitudinal MR (Figs 7 and 9, *b*), as well as dominance of positive component of MR at negative sign of transverse MR at $\varphi = 90^\circ$ in strong magnetic field $B > 2$ T (Fig. 8, *b*). It should be noted, that magnons freezing temperature, evaluated as per results of measurement of linear non-saturated longitudinal negative MMR of iron films in the field of up to 40 T, is about 160 K [5].

Exponential factor of magnetic field dependence of MR ($\Delta R \sim B^\alpha$) at $T = 100$ K is a bit higher, that in as-deposited samples ($\alpha = 1$, Figs 3 and 5, *b*), but less than characteristic for positive LMR ($\alpha = 2$) [3], thus reflecting the best structural perfection of annealed films and lesser influence of percolation processes on MR. At that temperature MR is rather well extrapolated with power dependence with $\alpha \approx 1.5$.

Dominance of pure metallic nature of electrons transport in annealed films at $T = 2$ K allows to separate two MR components at that temperature: AMR in the region of weak magnetic fields before magnetization saturation field and positive component with close-to-linear dependence in

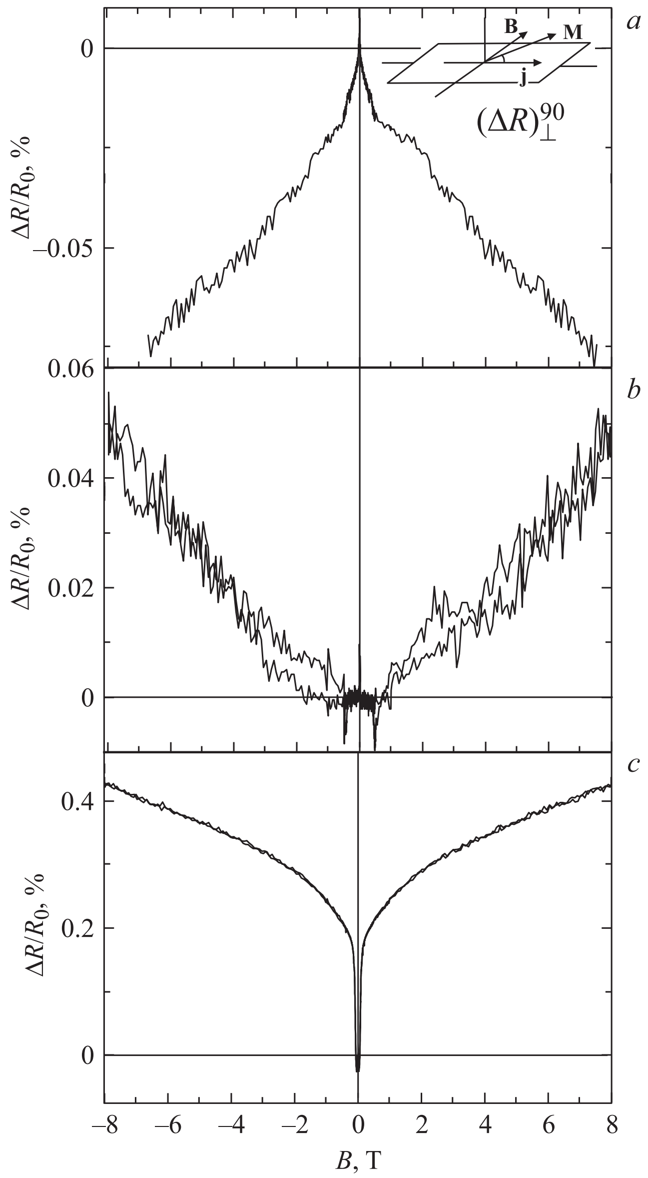

Figure 7. Hysteresis loops of transverse magnetoresistance of annealed iron film at $\varphi = 0°$, measured at various temperatures: *a*) — 300 K; *b*) — 100 K; *c*) — 2 K.

strong field regardless of measurement geometry. As in as-deposited samples, in strong field the transverse and longitudinal effects insignificantly differ by value and have close-to-linear dependence on field (Figs 7–9 (*c*)), thus indicating the dominance of percolation mechanism of electrons transport at low temperatures.

Note the appearance of noises as sharp peaks of MR in annealed films in magnetic field of up to $B \approx 0.5$ T at $T < 100$ K, caused by domain walls movement [4–19]. These peaks appear most clearly at mutual perpendicular orientation of field —film plane at room temperature already (Fig. 8, *a*) and are not observed at $T = 2$ K regardless of angle (Fig. 8). Figure 10, *a*–*c* shows the same dependencies at $T = 100$ K in the region of magnetic fields of up to $B = 2$ T. Arrows indicate direction of magnetic field change. It is seen, that unlike as-deposited films, the resistance of annealed films in magnetized state is less (see Figs 6 and 10), i.e. as a result of annealing not just a structure, but also magnetic homogeneity of the film was improved, and presence of sharp peaks of MR indicated the multi-domain structure of crystallites.

Hysteresis loops of transverse at $\varphi = 0°$ and longitudinal MR in the region of weak magnetic fields are shown in inserts of Fig. 10, *a* and *c*. It is seen, that regardless of transverse or longitudinal MR change, when magnetic field is in the film plane, MR peaks at $B \approx 0.5$ T have negative sign and are observed at magnetic field reduction from maximum

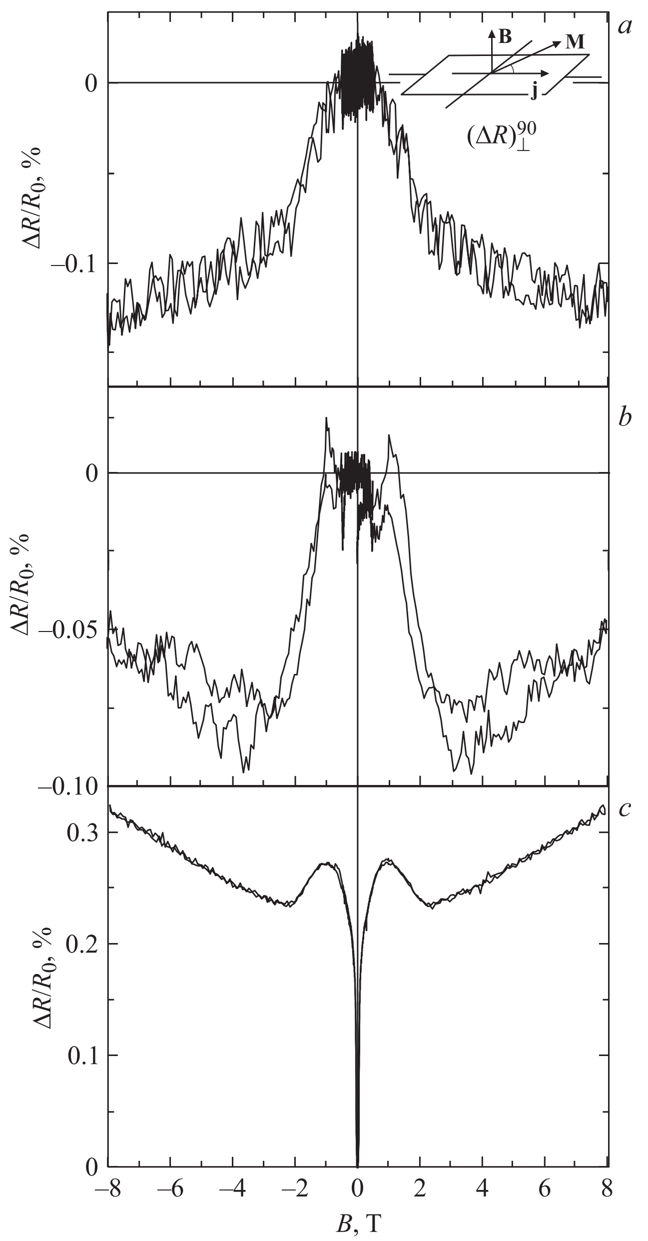

Figure 8. Hysteresis loops of transverse magnetoresistance of annealed iron film at $\varphi = 90°$, measured at various temperatures: *a*) — 300 K; *b*) — 100 K; *c*) — 2 K.

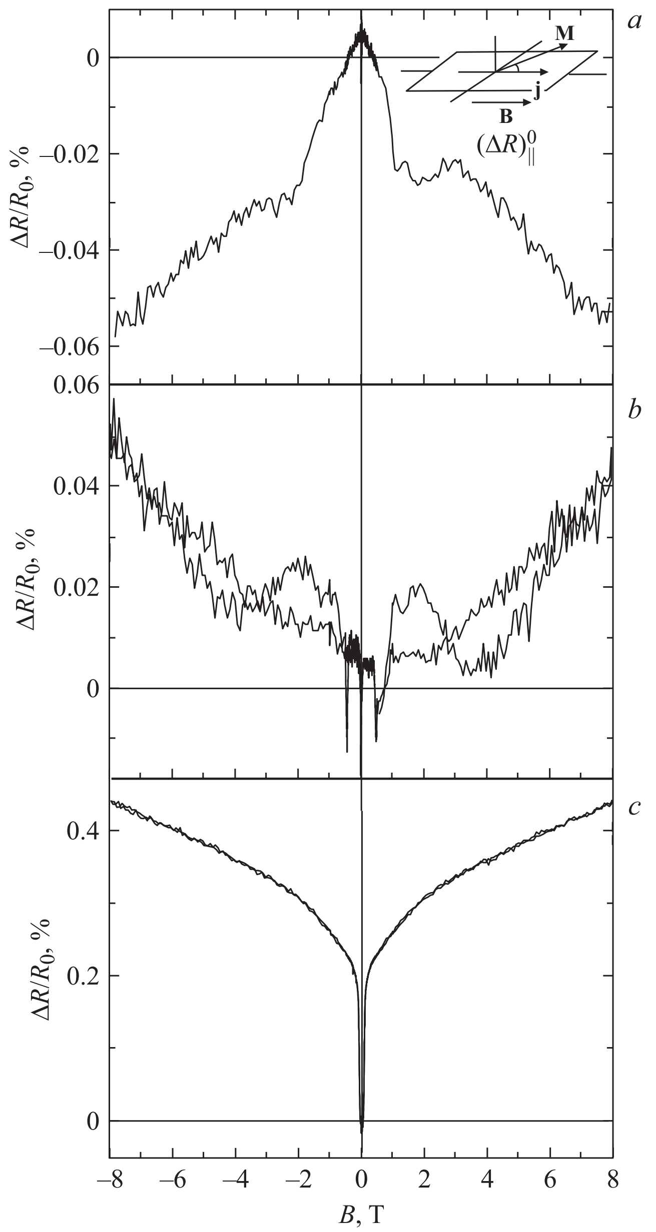

Figure 9. Hysteresis loops of longitudinal magnetoresistance of annealed iron film, measured at various temperatures: *a*) — 300 K; *b*) — 100 K; *c*) — 2 K.

value to zero, i.e. at magnetization reduction. These peaks position is well correlated with sharp (almost without field change) jump of magnetization in case of loop measurement only at $\varphi = 90^\circ$, that may be caused by a change of domain magnetization direction of one of the phases to the opposite one. It should be noted, that MR peaks at $B \approx 0.5\,\mathrm{T}$ are also observed at sample remagnetization to the opposite direction, but their amplitude is much less.

Sharp peaks of NMR at demagnetization are also observed in weak field ($B \approx 14{-}35\,\mathrm{mT}$, insert in Fig. 10, *c*) at longitudinal MR measurement. At transverse MR measurement at $\varphi = 0^\circ$, i.e. when the field, as in the longitudinal effect in the film plane, these peaks are observed in much smaller field ($B \approx 12\,\mathrm{mT}$, insert in Fig. 10, *a*), have positive sign and are characteristic only for sample remagnetization in the opposite direction. In transverse MR in geometry of $\varphi = 90^\circ$ MR peaks were not singled out due to strong noises.

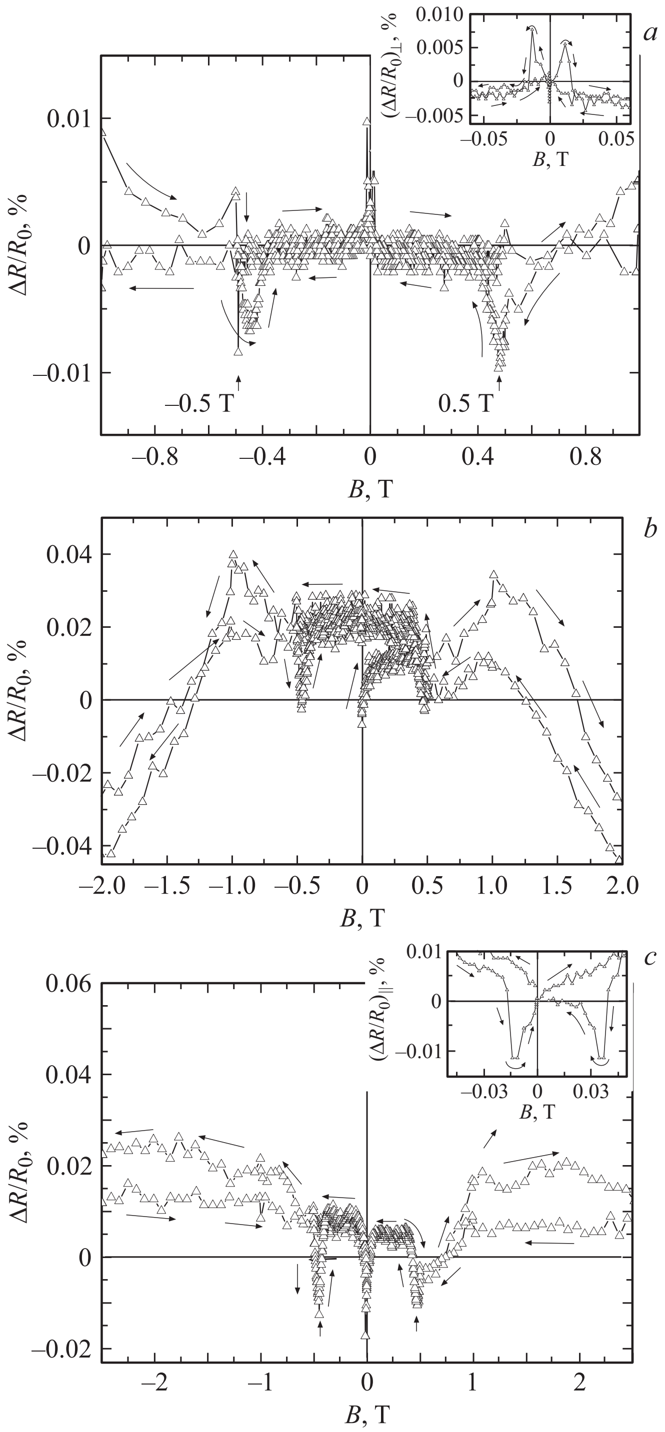

Figure 10. Hysteresis loop of transverse magnetoresistance at $T = 100\,\mathrm{K}$ of annealed iron film in magnetic field of up to $B = 2.5\,\mathrm{T}$ at *a*) $\varphi = 0^\circ$; *b*) $\varphi = 90^\circ$; and longitudinal *c*). Inserts of Fig. 10, *a* and *c* show loops in weak fields region.

Sharp peaks of MR, observed regardless of measurement geometry in magnetic field of $B \approx 0.5$ T, correspond to the beginning of irreversible reconfiguration of domain structure (domain walls movement) of one magnetic phase, while in weak field — of another (or movement of domain walls of other type). In magnetic films with thickness of $d < 20-30$ nm the Neel walls dominate, while in thicker films — Bloch walls [20]. In films with intermediate thickness of up to $d \approx 120$ nm the presence of both wall types is possible — so called walls with bonding or walls of more complicated type. It can be assumed, that different nature of magnetization direction change in walls of Bloch or Neel types at various geometries of MR measurement results in resistance changes with opposite sign, i.e. to peaks of positive and negative MR. However, the further studies are required for a definite statement on influence of domain walls types and their reconfiguration in magnetic field on MR.

5. Conclusion

In as-deposited and annealed nanocrystalline iron films with various type of magnetic anisotropy, obtained by ion-beam assisted deposition method on silicon substrates, the dependence of sign, value and type of magnetic field dependence of magnetoresistance effect in the region of magnetic fields before magnetization saturation on type of magnetic anisotropy, angle between magnetic field direction and film plane, and measurement temperature is revealed, caused by a presence of film spontaneous magnetization and change of electrons transport mechanism at temperature lowering and annealing from percolation in room temperature region to weak localization mode at low temperatures through dominance of metal transfer at intermediate temperatures.

It was established, that in as-deposited films with perpendicular magnetic anisotropy in temperature range of percolation conductivity dominance until magnetization saturation field the change of transverse and longitudinal MR sign at $\varphi = 0^\circ$ from positive to negative is observed at magnetic field direction change from parallel to film plane to perpendicular, due to dominance of anisotropic component of negative MR, when current direction is perpendicular to magnetization. In strong field the reduction of negative MR value is caused by dominance of positive component of percolation MR. In weak field in transverse and longitudinal effects at $\varphi = 0^\circ$ the inverted giant magnetoresistive effect is observed, caused by films magnetic heterogeneity.

In annealed films with anisotropy in the plane at $T = 300$ K, regardless of measurement geometry, in the region of weak magnetic fields the component of anisotropic MR dominates, while in the region of strong fields — the linear non-saturated negative magnon MR. Change of sign of transverse and longitudinal effects from negative to positive at $\varphi = 0^\circ$ and temperature lowering due to magnons freezing, as well as at $\varphi = 0^\circ$ and $T = 100$ K the linear reduction of negative MR in strong field due to dominance of positive component of Lorentz MR and sharp peaks of MR increase and decrease, caused by domain walls movement at remagnetization and demagnetization of films, are revealed.

It is demonstrated, that characteristic fields of MR magnetic field dependence sign and type change at various measurement geometries are in good agreement with characteristic fields of magnetization hysteresis loops, specifically: coercitive force and magnetization saturation field, measured at $\varphi = 0$ and $\varphi = 90^\circ$.

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Conflict of interest

The authors declare that they have no conflict of interest.

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