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Magnetic Moment Transformation in a Heterophase Nanomagnet GdFeCo|IrMn in the Vicinity of the Ferrimagnet Compensation Point

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Ta|Pt|GdFeCo|IrMn|Pt multilayer structure with perpendicular magnetic anisotropy in vicinity of the ferrimagnet compensation temperature T_K has been carried out. It has been established that the distribution of the magnetic moment in the GdFeCo ferrimagnetic film exchange-coupled to the IrMn antiferromagnet is largely determined by the magnitude and orientation of both the field applied during cooling from room temperature to $T = 2\,\mathrm{K}$ and the testing field over the entire temperature range. It is shown that the direction of the domain wall moving changes to the opposite one at a fixed value of the amplitude of the magnetic field pulse when the temperature passes through the T_K.

Keywords: ferrimagnets, heterostructures, perpendicular magnetic anisotropy, magnetic moment, compensation temperature, domain wall.

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1. Introduction

Studies of magnetic heterostructures with perpendicular anisotropy providing ultra-rapid magnetization switching by femtosecond laser pulses have recently become widespread. The most promising for use in ultra-fast elements of spintronics are intermetallic ferrimagnet (FM) films „rare earths|transition metal“. At the same time, studies of GdFeCo [1] films have been most developed. Less studied are ferrimagnetic films exchange-coupled to an antiferromagnetic (AFM) layer [2]. Exchange interaction at the interface between layers with different magnetic order forms a fundamentally new ground state of a heterophase magnetic, radically changes the behavior of spins in the external magnetic field and leads to the emergence of a number of unusual phenomena. In such heterostructures, the orientation of the spins of the ferrimagnetic layer near the interface is fixed by the distribution of the spins in the antiferrimagnet, thus forming a unidirectional (exchange) anisotropy, which is characterized by the appearance of an exchange bias field H_{Ex} of hysteresis loop along the magnetic field H axis and increase in coercive force H_c. The most realistic model describing the microscopic mechanism of the occurrence of the exchange anisotropy has been proposed for the heterostructures „ferrimagnetic|antiferrimagnet“ in paper [3]. An important feature of such materials is that the thickness of the magnetic layers in them does not exceed the width of the domain wall. Experimental [4–6] and theoretical [3,7] studies have shown that by switching the ferrimagnetic layer of such a heterostructure in its AFM layer near the interfacial surface, along the normal to the film, an inhomogeneous magnetization distribution characterized by spin rotation in adjacent atomic planes will be formed. This means that the entire remagnetization process of such a heterostructure from the ground state is accompanied by the nucleation and evolution of a partial domain wall — an exchange spin spiral (spring) in the AFM layer parallel to the film surface. The most commonly used antiferrimagnet in such systems is the polycrystalline IrMn with a texture of $\langle 111 \rangle$, possessing a magnetic anisotropy constant of $\sim 10^6\,\mathrm{erg/cm^3}$ [8,9]. This material is technologically interesting and has a higher thermal stability.

The temperature dependence of hysteresis characteristics in such heterostructures is largely determined by the transformation of the domain structure of the ferrimagnetic layer, which has a strong temperature dependence of magnetization and, as a rule, compensation temperature T_K. In this case, the spin dynamics near T_K depends on both the distribution of magnetic moments in the heterostructure layers, and the domain structure in them and its transformation when magnetized by the nucleation of domains of a new phase and the movement of domain walls (DW). The results of an experimental study of the influence of cooling/heating conditions of the GdFeCo ferrimagnetic film, exchange-coupled to the IrMn antiferrimagnet, on magnetization in a wide temperature range, are given in the present paper as well as investigating the dynamic properties of domain walls near the compensation temperature.

2. Experimental procedure

Heterostructure Ta(3 nm)|Pt(3 nm)|$Gd_{21.6}Fe_{67.8}Co_{10.5}$ (20 nm)|$Ir_{20}Mn_{80}$(7 nm)|Pt(5 nm) was grown by magnetron sputtering on a glass substrate. Induced Ta|Pt texture (111) in the ferrimagnetic amorphous layer formed a perpendicular magnetic anisotropy. Macroscopic hysteresis loops and magnetization $\mathbf{M}$ dependences on temperature were obtained by the SQUID magnetometer MPMS 5XL Quantum Design at temperature T from 2 to 300 K in the range of magnetic fields $\mathbf{H}$ from -10 to $+10$ kOe, oriented parallel to the axis of unidirectional anisotropy [10]. Of all the dependencies $\mathbf{M}(\mathbf{H})$ when measuring loops, the contribution from the diamagnetic substrate was deducted. The dependence of magnetic moment $M(T)$ of the sample on temperature was measured at $H_{\text{Test}} = \pm 200$ Oe along the easy magnetization axis and performed at a temperature increase from $T = 2$ K after pre-cooling either in the absence or in the absence, or in the presence of an external magnetic field H_{Cold}, which was withdrawn at $T = 2$ K. Fields H_{Test} and H_{Cold} were oriented perpendicular to the sample surface. Microscopic measurements of magnetization reversal of samples in the pulse magnetic field from -2.5 to $+2.5$ kOe were made using the polarization microscope and magnetooptic (MO) Kerr effect in optical cryostat in temperature range of 80–300 K. Images of the domain structure of the sample were recorded by the CCD camera.

3. Experimental results and discussion

The hysteresis properties of the heterostructure were obtained by measuring magnetization dependencies on the external magnetic field over a wide temperature range. Fig. 1 shows the hysteresis loops of Ta|Pt|GdFeCo|IrMn|Pt sample measured at a temperature above ($T = 300$ K) and below ($T = 20$ K) the compensation point in a magnetic field applied perpendicular to the sample surface, along the easy magnetization axis. The dependence $M(T)$, obtained from the hysteresis loops (Fig. 2, curve *1*), was linearly dependent on temperature in almost the entire measurement range. The magnetic properties of heterostructure are due to the ratio of contributions of anti-parallel directed magnetic moments in sublattices of rare earth and transition metals. The magnetization value M decreases with temperature decrease, because at high values T in this GdFeCo ferrimagnet the magnetization of $3d$-metals prevails, whereas with temperature reduction, the anti-parallel magnetization of $4f$-rare earth gadolinium increases faster. At the compensation temperature of $T_K = 120$ K the sign of the net magnetic moment changes. Due to the exchange interaction of the ferrimagnet and antiferrimagnet spins on the interface, the hysteresis loop parameters of the samples differed significantly at different temperatures. The dependence of coercive force $H_c = (H_{c2} - H_{c1})/2$ and exchange shift field $H_{\text{Ex}} = (H_{c2} + H_{c1})/2$ on temperature are given in Fig. 2 (curves *2* and *3*, respectively). With temperature decrease, the value of H_c and the absolute value of H_{Ex} increased, reaching their maximum values near the compensation point and dramatically changing at $T = T_K$. At $T < T_K$ the value

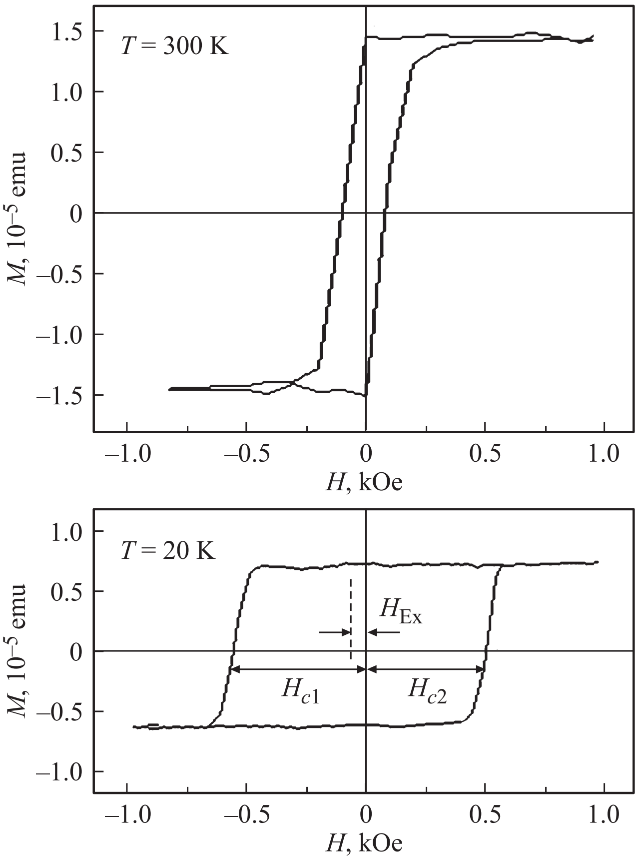

Figure 1. Hysteresis loops measured above ($T = 300$ K) and below ($T = 20$ K) the compensation points ($T_K = 120$ K) of the ferrimagnet.

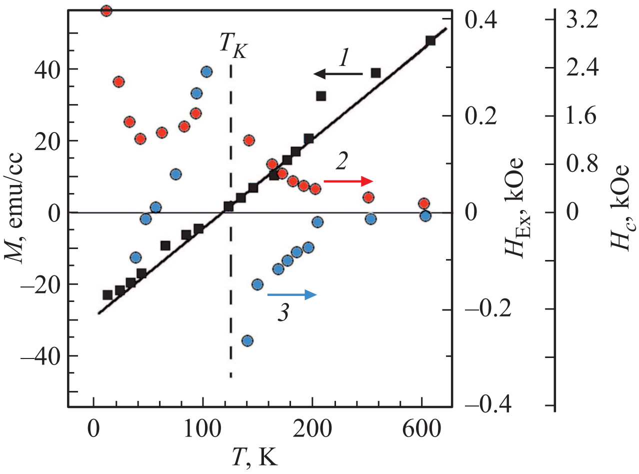

Figure 2. Temperature dependence of magnetization (curve *1*), coercivity field (curve *2*) and exchange shift field (curve *3*) of the sample obtained from measurements of the hysteresis loops.

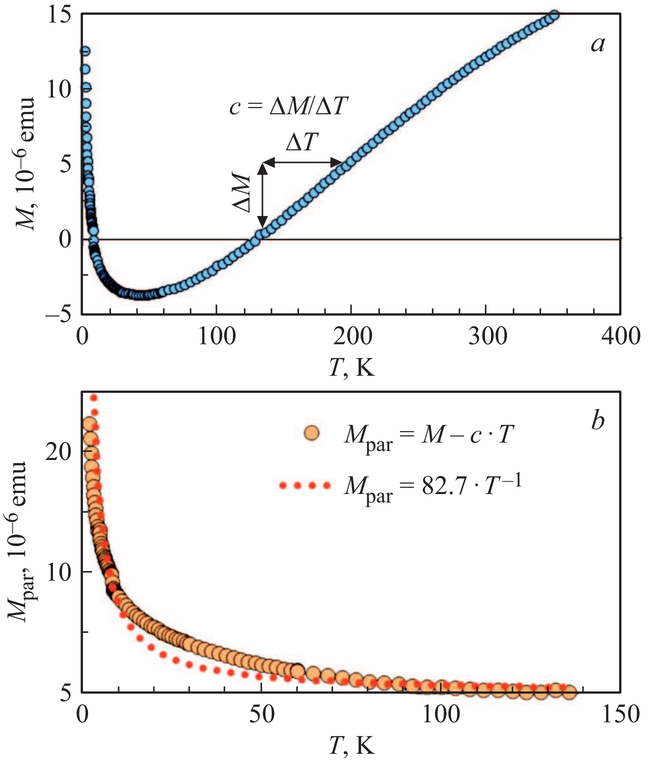

Figure 3. *a*) Temperature dependence of magnetization obtained by direct measurement after pre-cooling in the zero field. *b*) Low temperature dependence of paramagnetic magnetization component and adjustment curve to it.

of H_c decreased with temperature, while H_{Ex} changed the sign and also decreased. At temperatures approaching zero, the hysteresis loops were superimposed on the magnetic moment component increasing linearly with the field, which is characteristic of the paramagnetic dependence of $M_{\text{par}}(H)$. Thus, at $T = 10\,\text{K}$ the susceptibility of the paramagnetic component $\chi = \Delta M_{\text{par}}/\Delta H$ was 0.034, and at $T = 2\,\text{K}$ it increased by more than 6 times. The paramagnetic contribution to $\mathbf{M}(\mathbf{H})$ dependence could be given by the spin of atoms Pt and Ta.

The presence of a paramagnetic component at low temperatures was also obtained by direct measurement of the magnetization dependence on temperature. Fig. 3 shows the $M(T)$ dependence obtained by cooling in the zero field. This relationship also decreases linearly with the decrease in temperature in the high and medium range. At low temperatures, however, the magnetic moment increases dramatically. If we assume that the dependence $M(T)$ is linear over the entire temperature range, as in the case shown in Fig. 2 (curve *1*), then we can, by extrapolating this dependence with coefficient $c = \Delta M/\Delta T$ (Fig. 3, *a*) to the low temperature range and extracting the calculated dependence cT from the experimental curve $M(T)$, obtain the magnetization $M_{\text{par}}(T) = M(T) - cT$ (Fig. 3, *b*). Adjusting the trend lines (shown by dots in the inset of Fig. 3, *b*) to the curve $M_{\text{par}}(T)$ by power law gives the dependence $M_{\text{par}}(T) = 82.7T^{-1.0}$, whose inverse dependence on T also corresponds to the paramagnetic component of magnetic moment. Susceptibility calculation $\chi = M_{\text{par}}/H$ at $T = 10\,\text{K}$ gives the value of 0.118. In order of magnitude it is the same as in the previous case, and the difference of ~ 2 times can be explained by the accuracy of measurement with a strong dependence of $M(T)$ in the area of very low temperatures. Since it is obvious that the strong growth of $M(T)$ in low temperatures is due to the paramagnetic component of $M(T)$ dependence, it will not be taken into account in future experiments.

The dependence of the magnetic moment $\mathbf{M}$ of the GdFeCo|IrMn biphase film on temperature depends largely on both the value and orientation of the magnetic field during the sample H_{Cold} cooling and on the test field H_{Test}, which is necessary in measurements using the SQUID magnetometer. Fig. 4 shows dependencies of $M(T)$ sample after it has cooled into H_{Cold}, equal to 0.5, 1.0 and 10 kOe (curves *1, 2* and *3*, respectively). The dependence $M(T)$ obtained by cooling the heterostructure in a small field (curve *1* in Fig. 4) is slightly different from the dependence obtained at $H_{\text{Cold}} = 0\,\text{Oe}$ (Fig. 3, *a*), whereas the dependencies obtained when cooled in higher fields (curves *2* and *3* in Fig. 4), differ radically. Apart from the paramagnetic component of magnetization, it is noteworthy that at T, close to 0 K, the orientation $\mathbf{M}$ at high values of H_{Cold} coincides with the direction of this field, whereas at cooling in $H_{\text{Cold}} \leq 0.5\,\text{kOe}$ fields inversion of the original magnetization occurs. In all cases, however, the dependence is nearly linear in the compensation temperature region $T_K = 120\,\text{K}$, regardless of the field H_{Cold} in which the cooling occurred. In this case, the signs $dM(T)/dT$ when cooled in low (curve *1*) and high (curves *2* and *3*) fields H_{Cold} are opposite. In the case of $H_{\text{Cold}} \geq 1\,\text{kOe}$ at temperature rise $M(T)$ reached the minimum at $T \approx 180\,\text{K}$, where the sign $dM(T)/dT$ changed to the opposite, resulting in the magnetization starting to the original state. It is worth noting, that the nonlinear

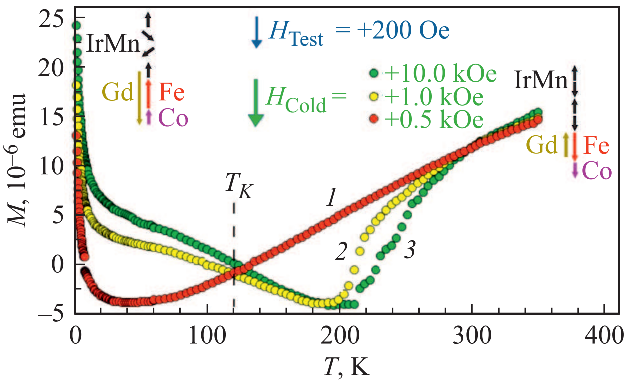

Figure 4. Temperature magnetization dependences obtained at a constant field of measurement $H_{\text{Test}} = +200\,\text{Oe}$ and cooling in the field H_{Cold}, equal to +0.5 (curve *1*), +1.0 (curve *2*) and +10.0 kOe (curve *3*).

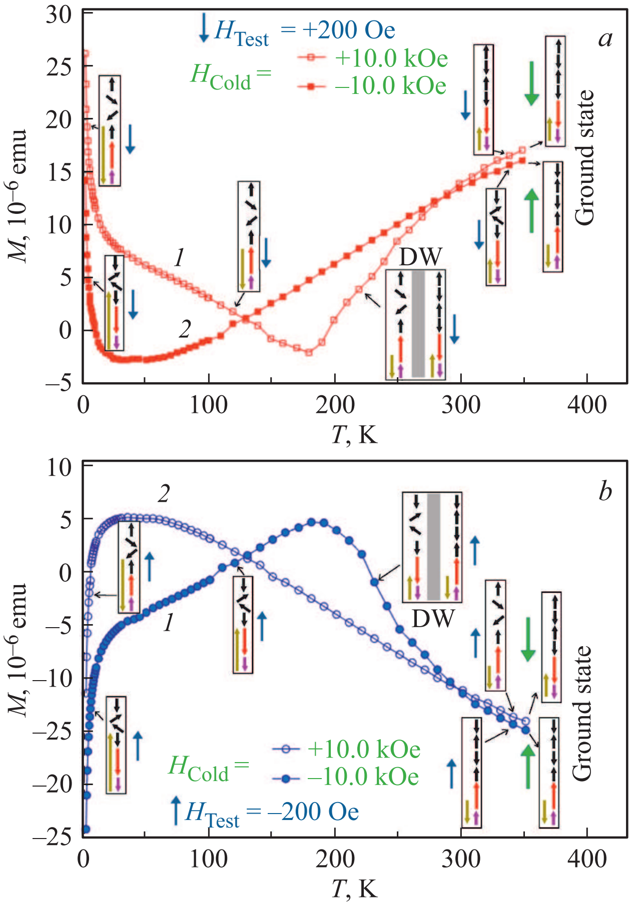

Figure 5. Temperature magnetization dependences obtained in the field of measurement *a*) $H_{\text{Test}} = +200$ Oe and *b*) $H_{\text{Test}} = -200$ Oe. The dependences *1* and *2* were obtained at H_{Cold} field cooling equal to $+10.0$ and -10.0 kOe, respectively. DW is the domain wall.

dependence $M(T)$ shown in Fig. 4 was obtained when the signs of the fields H_{Cold} and H_{Test} were positive.

Fig. 5 shows the dependences of magnetization on temperature at the field $H_{\text{Cold}} = \pm 10$ kOe and $H_{\text{Test}} = +200$ Oe (Fig. 5,*a*) and $H_{\text{Test}} = -200$ Oe (Fig. 5,*b*). It turned out that the nonlinear dependence $M(T)$ at large values of H_{Cold} was always observed when the directions of the cooling and measuring fields coincided (curves *1* in 5,*a* and *b*), regardless of their sign. At the same time, linear dependence of M on T was always observed when the directions of H_{Cold} and H_{Test} fields were opposite (curves *2* in 5,*a* and*b*).

The identified differences in the character of $M(T)$ dependences are due to the redistribution of spins in the FM sublattice and in the AFM layer when the temperature changes. As it follows from the results of temperature measurements under the conditions of application of H_{Cold} field saturating the sample (Fig. 5), in each case, when the sample cooled below T_K, an orientation phase transition resulted in the inversion of magnetization in the FM layer. At the same time, the magnetic structure in the AFM layer remained unchanged, but near the interface an inversion **M** in the FM layer formed an exchange spin spring. Insets in Fig. 5, schematically show the spin distribution in the heterostructure in the ground state, final after cooling and removal of H_{Cold} field (in the left part of the graphs) and in the intermediate and final states as a result of warming the sample. Under conditions of a weak test field H_{Test}, when its direction coincided with that of H_{Cold}, it also coincided with **M** at $T < T_K$. With $T > T_K$, the magnetization was inverted and became anti-parallel to the H_{Test} field, resulting in an increase in the Zeeman energy. Since the coercive field near T_K is large, the resulting metastable state cannot be resolved until $H_c(T)$, gradually decreasing with temperature increase (Fig. 2, curve *2*) does not reach the H_{Test} value. It follows from analysis of MO-measurements of magnetization distribution with temperature change, that in the temperature range from ~ 190 to ~ 250 K the magnetization switching occurs due to a non-uniform nucleation of new phase domains and movement of their borders under the action of the H_{Test} field. This heterogeneity is associated with $H_c(T)$ heterogeneity along the surface of the sample. At the nucleation of domains, unwinding of the spin spring occurs, and as a result, at room temperature, the sample comes to its ground state [5].

The different nature of $M(T)$ dependence was observed when H_{Cold} and H_{Test} fields had different signs. After the H_{Cold} field was removed, the direction of the test field H_{Test} did not coincide with direction **M** at $T < T_K$, i.e., created a metastable sample state. Since at these temperatures $H_c(T)$ far exceeds the field H_{Test}, remagnetization of the FM layer was impossible. At $T > T_K$, when the magnetization inverted and became parallel to the field H_{Test}, on the contrary, the state became energetically stable, and the magnetization changed linearly with temperature up to room temperature. At the same time, the spin spiral in the AFM-layer should have survived.

To find out the mechanism of remagnetization of heterostructures near T_K, the magnetization transformation in a pulsed magnetic field of an amplitude of $H = 2.5$ kOe and duration 10 ms (Fig. 6) at temperatures below and above T_K was studied using the Kerr effect. Fig. 6,*a*–*c* and *d*–*f* represents the remagnetization process of a section of a ferrimagnetic film at $T = 130$ K and $T = 105$ K, respectively. As can be seen, the magnetization process occurs by shifting domain walls. Two important conclusions can be drawn from this data. First, under the action of the same impulses, the DW field shifts in opposite directions at $T > T_K$ and $T < T_K$, which corresponds to a change in the magnetization sign of the sample due to an increase in the magnetization of Gd with a decrease of T. Second, the Kerr effect, which is determined by the contribution of the transition metal atoms [11], and the domain structure throughout the studied temperature range, including T_K, remain constant, meaning that the spin distribution in IrMn and Fe–Co is constant. The independence of the Kerr effect from the temperature near the compensation point indicates that the orientation of

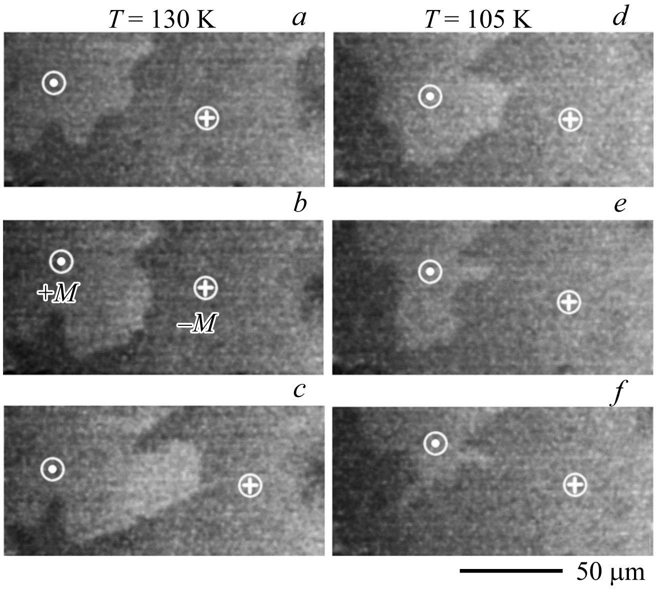

Figure 6. MO images of domain wall shift in the sample at a temperature higher than (130 K) and lower than (105 K) compensation temperature $T_K = 120$ K. The images *b–c* and *e–f* show the DW positions after successive applications of magnetic field pulses.

the magnetic moments of the transition metals at these temperatures remains constant, i.e., there are no significant deviations of magnetization in the ferrimagnet from the axis of the unidirectional anisotropy induced. It follows from this fact that the canted (angular) phases of the magnetic moments of the ferrimagnet near T_K, which are possible, as predicted theoretically for uniaxial anisotropic ferrimagnets [12], are not observed. Through exchange interaction on the interface, the antiferrimagnet stabilizes the magnetic structure of the ferrimagnet at temperatures close to T_K.

4. Conclusion

The direct experimental study of multilayer heterostructures with perpendicular magnetic anisotropy revealed the non-monotonic nature of temperature dependencies of magnetization, coercive force and exchange displacement in the ferrimagnetic film of GdFeCo, exchange-coupled to antiferromagnetic IrMn. It was discovered that the $H_{\mathrm{Ex}}(T)$ dependence changes the sign and undergoes a break at the temperature of compensation of magnetic moments of GdGd and FeCo ions $T_K \approx 120$ K. It is shown that the value of coercive field $H_c(T)$ when the temperature approaches the compensation point T_K from both low and high temperatures increases dramatically. It was found that mutual orientation of the H_{Cold} and H_{Test} fields dramatically affects the nature of $M(T)$ dependence, causing the transformation of spins at the interface and changing the kinetics of the domain structure near the compensation point.

Conflict of interest

The authors declare that they have no conflict of interest.

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