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Spontaneous and field-induced magnetic configurations in a Fe/Si/Fe trilayer with ferromagnetic interlayer exchange

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Abstract
Magnetization reversal of a Fe/Si/Fe trilayer having a ferromagnetic bilinear and biquadratic exchange is investigated at 10 and 300 K. The experiments were performed using the magneto-optical Kerr effect technique and a SQUID magnetometer. The type of stable magnetic configuration is determined for both temperatures of the study. The hysteresis loops contain jumps in magnetization, which could be associated with the overcoming of the energy barriers related to the uniaxial anisotropy hard axes in the two iron layers. The analysis of the experimental results was performed in the framework of a model in which the ferromagnetic bilinear and biquadratic exchange between two magnetic layers separated by a nonmagnetic spacer and the cubic and uniaxial anisotropy were taken into account. Good qualitative agreement is obtained between the experimental and calculated field dependences of the magnetization.

1. Introduction

The study of the noncollinear magnetic structures in layered Fe/Si films has been a topic of interest during recent years because of the variety of the steady configurations and the phase transitions between them [1–7]. This variety is determined by the competition between the bilinear and biquadratic exchange between the layers of iron, and the competition between the exchange and anisotropy. The bilinear exchange tends to bring the magnetic layered system into collinear (parallel or antiparallel, depending upon the sign of the bilinear exchange constant) ordering, while the biquadratic exchange aligns the magnetic moments of adjacent Fe layers in perpendicular pairs. Already, the magnetization-reversal process in Fe/Si films with antiferromagnetic bilinear exchange has been investigated in detail. The system with ferromagnetic bilinear and biquadratic exchange interactions has, however, almost not been studied at all until now. Against this background, our attention was attracted by the paper [8] in which the layered Fe/Si/Fe system was studied by means of ferromagnetic resonance (FMR). The analysis of the experiments performed demonstrates the presence of ferromagnetic and biquadratic exchange in the structure at room and helium temperatures. The aim of our work was the investigation of magnetic structures in the Fe/Si/Fe sandwich studied early on by means of FMR and the elucidation of the magnetization-reversal process in this system.

2. Experiment

The Fe30/Si14/Fe30 Å film studied was prepared by dc magnetron sputtering. A single-crystal GaAs plate of (001) orientation was used as the substrate. The substrate was at room temperature during the film fabrication. The sample has been covered with a protective Si layer of thickness about 50 Å. The thickness of the layers was determined by quartz monitoring and later controlled by an x-ray fluorescence method. As was shown in [8], cubic anisotropy and uniaxial in-plane anisotropy are present in the system. The uniaxial anisotropy has different directions of the easy axis in the two Fe layers. The anisotropy constants in the Fe layers have different temperature dependences related to the difference in thermal expansion coefficient between Fe, Si and GaAs.

The magnetization reversal was studied using a longitudinal magneto-optical Kerr effect set-up and a commercial SQUID magnetometer (MPMS-5 Quantum Design) at 300 and 10 K. During magneto-optical experiments, a He–Ne laser ($\lambda = 633$ nm) was used as a light source. The magnetic field was applied in different directions in the film plane and always in the plane of light incidence. The magnetic field dependences of the angle of rotation Φ of the polarization plane of the reflected light have been obtained for different directions of the magnetic field in the film plane. The value of Φ was proportional to the projection M of the system magnetization on the field direction in the geometry of the experiment. During SQUID measurements the magnetic field was also applied in the film plane. The magnetic field dependences of the projection M of the magnetization of the system on the field direction have been obtained. The magneto-optical and magnetic experimental curves were normalized to Φ_S, the value of the angle of rotation of the plane of polarization in the saturated state, and to M_S, the saturation magnetization, respectively.

Figure 1 shows typical curves of the field dependences of M/M_S and Φ/Φ_S. The field dependences of the magnetization measured at 300 and 10 K are represented by points. The field dependences of the angle of rotation of the polarization plane measured at 300 K are represented by lines. The angle α characterizes the direction of the external magnetic field in relation to the [100] direction in the (001) plane. Jumps of the magnetization in the magnetic field, which are accompanied by local hystereses, were observed in the magnetization-reversal loops. Different numbers of the jumps take place depending on the direction of the magnetic field in the film plane. It was also revealed that the magnetic field at which the jump appears changes its value with temperature. The number of jumps can change with temperature for some directions of magnetic field.

The results of the experiments performed in the absence of an external magnetic field are re-plotted in figure 2. This figure presents the change of the normalized projection of the magnetization (M_R/M_S) and the normalized angle of rotation of the polarization plane (Φ_R/Φ_S), both measured in magnetic field $H = 0$ (M_R and Φ_R are remanent magnetization and remanent rotation, respectively). There are also the dependences of M_R/M_S on the angle α at 300 K (●) and at 10 K (○) and the dependence of Φ_R/Φ_S (▲) on the angle α at 300 K. According to a theoretical model [9, 10], which is successfully applied to the description of the layered magnetic structure [5, 6], we consider that the magnetic moments inside the iron layers are ordered ferromagnetically, as in the common case of bulk iron. In this situation the

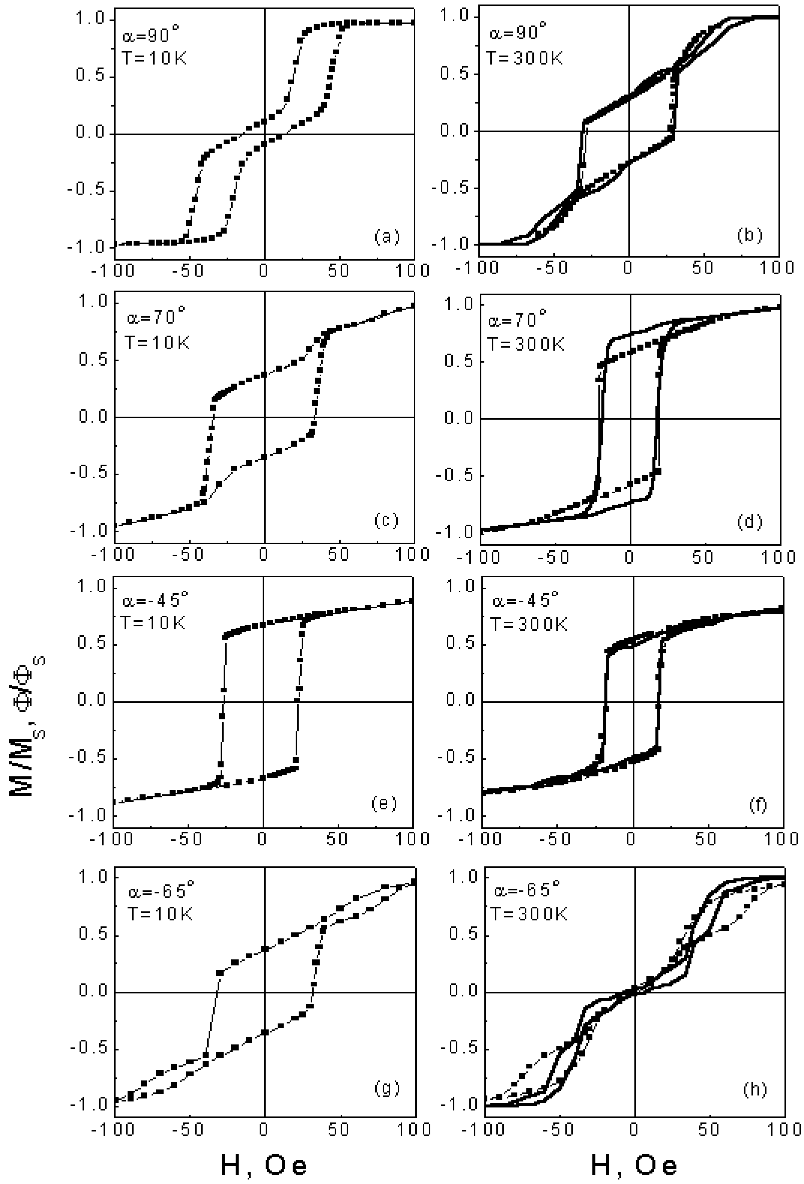

Figure 1. Experimental magnetic field dependences of the projection of the magnetization on the field direction (points) and of the angle of rotation of the plane of the reflected light polarization (lines). (a), (c), (e), (g) 10 K; (b), (d), (f), (h) 300 K; (a), (b) $\alpha = 90°$; (c), (d) $\alpha = 70°$; (e), (f) $\alpha = -45°$; (g), (h) $\alpha = -65°$.

magnetic state of this layered system is characterized by the directions of the magnetization in two Fe layers. These directions are determined by the angles θ_1 and θ_2 (figure 3(a)). The experimental angular dependences are well described by the function $a\cos(\alpha - \beta)$ (dotted curves in figure 2), where a is the maximum value of the curve and β is the value of the angle where the maximum occurs. For 300 K, $a = 0.99$, $\beta = 25°$, while for 10 K, $a = 0.99$, $\beta = 7°$. This means that the experimental points correspond to just one steady noncollinear

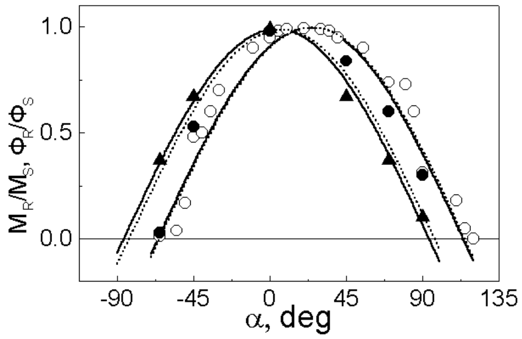

Figure 2. ▲: the experimental angle dependence of Φ_R/Φ_S at 300 K; ● and ○: experimental angle dependences of M_R/M_S at 300 and 10 K; dotted curves: approximation of the experimental results by the $a\cos(\alpha-\beta)$ function; solid curves: calculated angle dependences of the projection of the magnetization of the layered system studied on the magnetic field direction.

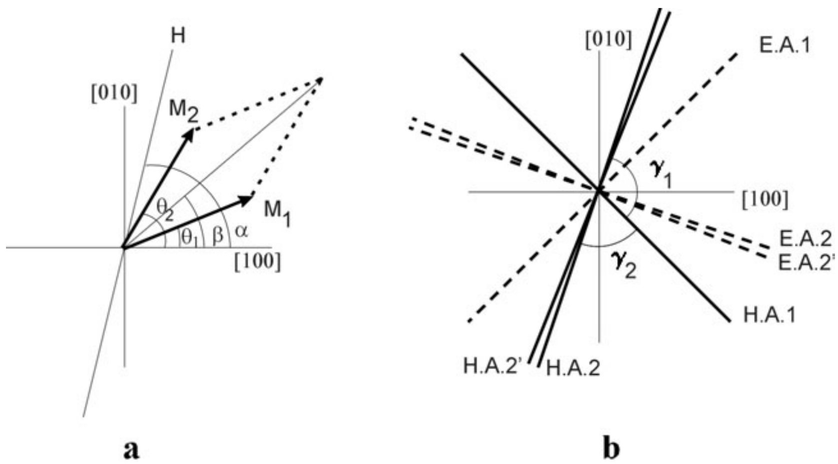

Figure 3. (a) Magnetic moments in two iron layers. (b) Easy (EA1 and EA2) and hard (HA1 and HA2) axes of uniaxial anisotropy in the two iron layers. EA2′ and HA2′: directions for low temperature.

configuration. Generally, in the layered system studied one of several stable or metastable configurations can exist in the absence of the magnetic field [4]. Which one it is depends on the magnetic prehistory of the system. The angular dependence of the projection of the magnetization would not be described by the $a\cos(\alpha-\beta)$ function in the case of the existence of several magnetic configurations in the film studied.

The steady noncollinear configuration in the layered system studied could be described by the couple of angles θ_1 and θ_2 (figure 3(a)). These angles determine the directions of magnetic moments in two iron layers. For 300 K $(\theta_1+\theta_2)/2=\beta=25°$ and for 10 K $(\theta_1+\theta_2)/2=\beta=7°$. Thus it is possible to conclude from the experimental results that with the temperature decrease the stable noncollinear configuration rotates by an angle of 18° in the (001) plane.

Table 1. Values of constants used in the calculations.

T (K)	K_{C1} (erg cm^{-3})	K_{C2} (erg cm^{-3})	K_{U1} (erg cm^{-3})	K_{U2} (erg cm^{-3})	I_1 (erg cm^{-2})	I_2 (erg cm^{-2})	φ_1 (deg)	φ_2 (deg)
300	53 000	12 000	282 000	110 000	−0.3	0.003	45	−22
4.2	80 000	107 000	268 000	304 000	−0.31	0.008	45	−25

3. Calculation and discussion

The analysis of the experimental results was performed in the framework of a theoretical model [9, 10] taking into account the bilinear and biquadratic exchange interactions between two magnetic layers of iron separated by a nonmagnetic spacer and the cubic and uniaxial anisotropy in the iron layers. The magnetic moments within the magnetic layers are ordered ferromagnetically and the magnetization of each Fe layer makes angles of θ_1 and θ_2 with the direction [100].

The energy of the system can be written as

$$E = I_1 \cos(\theta_1 - \theta_2) + I_2 \cos^2(\theta_1 - \theta_2) + K_{C1} d \cos^2\theta_1 \sin^2\theta_1 + K_{C2} d \cos^2\theta_2 \sin^2\theta_2 + K_{U1} d \sin^2(\theta_1 - \varphi_1) + K_{U2} d \sin^2(\theta_2 - \varphi_2) - HMd[\cos(\theta_1 - \alpha) + \cos(\theta_2 - \alpha)], \qquad (1)$$

where I_1 and I_2 are the bilinear and biquadratic exchange constants, respectively, K_{C1} and K_{C2} are the cubic anisotropy constants of the iron layers, K_{U1} and K_{U2} are the uniaxial anisotropy constants of both layers, H is the external magnetic field, M is the saturation magnetization, d is the thickness of each Fe layer, φ_1 and φ_2 determine the positions of the uniaxial anisotropy easy axes in both Fe layers (the angles are related to the [100] direction). During our calculation we used the values of the constants determined in [8] as a result of FMR curve analysis.

The main peculiarity of our theoretical consideration is the ferromagnetic character of the bilinear interlayer exchange interaction ($I_1 < 0$). In the condition of relatively weak biquadratic exchange (see table 1), the competition between ferromagnetic interlayer exchange and anisotropy basically determines the direction of the magnetization in the iron layers. The weak biquadratic interlayer exchange causes inclination from the collinear ferromagnetic structure. The other peculiarity is that the uniaxial anisotropy has different directions of easy axis in the two Fe layers and that the anisotropy constants of the Fe layers have individual temperature dependences [8]. The noncollinearity of the uniaxial anisotropy in the two iron layers is reflected in the complicated shape of the magnetization-reversal loops, because magnetization reversal is associated with the overcoming of the energy barriers related to the hard axes in two layers.

To determine the stable magnetic configurations of the system in the absence of a magnetic field we performed a numerical analysis of equation (1) under the condition $H = 0$. The constants used in the calculations are presented in table 1. There are two different stable magnetic configurations for 300 and 4.2 K. These configurations, C1 and C2, are described by the following angles θ_1 and θ_2, which determine the directions of the magnetic moments in the Fe layers: for 300 K, $\theta_1 = 27°$ and $\theta_2 = 21°$ (accordingly $\beta = (\theta_1 + \theta_2)/2 = 24°$, $\delta = \theta_1 - \theta_2 = 6°$); for 4.2 K, $\theta_1 = 10°$ and $\theta_2 = -2°$ (accordingly $\beta = (\theta_1 + \theta_2)/2 = 4°$, $\delta = \theta_1 - \theta_2 = 12°$); see figure 4. Thus, our calculation demonstrated that in the system studied the rotation of the stable configuration in the (001) plane and the increase of the angle δ between magnetic moments take place with temperature decrease. Generally the variation of the angle δ is determined by the change in the relationship between the energies of the exchange and the anisotropy. In the present experiment the main reason for this variation is the

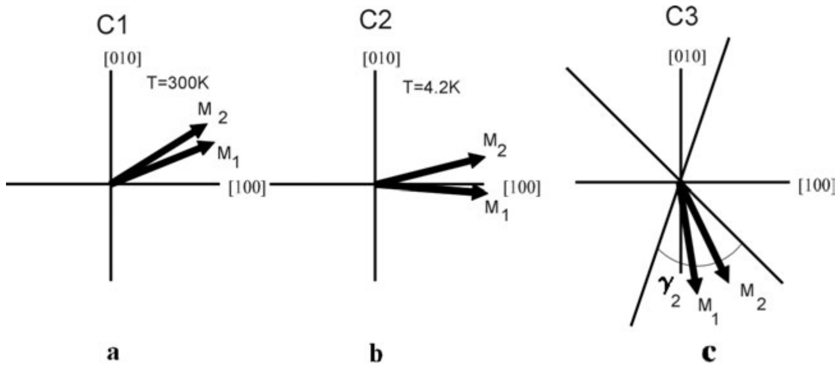

Figure 4. (a), (b) Stable magnetic configurations for 300 K (C1) and for 4.2 K (C2). (c) The magnetic configuration C3 that exists in a magnetic field when magnetic field is directed in the γ_2-angle sector.

dramatic changes of the uniaxial and cubic anisotropy with temperature under the condition of different directions of the easy axis in the two iron layers.

To compare the results of the experiments and the calculations for the case of $H = 0$, the angular dependences of the projection of the magnetization for the layered system studied have been constructed in figure 2 (solid curves) using the expression $(\cos(\alpha-\theta_1)+\cos(\alpha-\theta_2))/2$. For low temperature, the results of the experiments performed at 10 K have been compared with the results of the calculation done for 4.2 K, because the constants necessary for our calculations were obtained in [8] only for 4.2 and 300 K.

It should be noted that we could determine from experiments only the value of $\beta = (\theta_1+\theta_2)/2$, and not the values of θ_1 and θ_2. The value of β defines the position of the maximum of the $a\cos(\alpha-\beta)$ line. In this situation the comparison of the maximum value of the $a\cos(\alpha-\beta)$ function obtained from experiment and calculation has a special meaning, because in the observed situation this maximum value is determined by the value $\delta = \theta_1 - \theta_2$. Generally, the calculation can indicate the noncollinear configuration for which β would be close to the experimental value but δ would not be close to the experimental value. This would be reflected in the amplitude of the $a\cos(\alpha-\beta)$ line and would mean that the experimental and calculated values of θ_1 and θ_2 differ. The proximity of the angular dependences obtained from the experiments to those from the calculations (the position and the value of the maximum) (figure 2) attests to the structure of the stable noncollinear configuration in the system being really close to the structures which were obtained as a result of the calculation. The experimentally observed rotation of the noncollinear structure and change in the angle between magnetic moments with temperature have been also reflected in the results of calculations.

We also performed calculations of the field dependences of the magnetization for our system. The values of the angles θ_1 and θ_2 in the stable configurations were calculated for different values of H. Then, knowing θ_1 and θ_2, we determined the projection of the magnetization on the direction of the external magnetic field. The calculated field dependences of the magnetization are presented in figure 5 for different directions of the magnetic field for 300 and 4.2 K.

The comparison of the experimental and the calculated field dependences of the magnetization was performed taking into account the complex system of the anisotropy in the structure studied. As was shown in the work [8], where the constants of the cubic and uniaxial anisotropy were determined, the uniaxial anisotropy dominates in both magnetic layers and establishes the anisotropy of the whole system. The easy and hard directions of the uniaxial

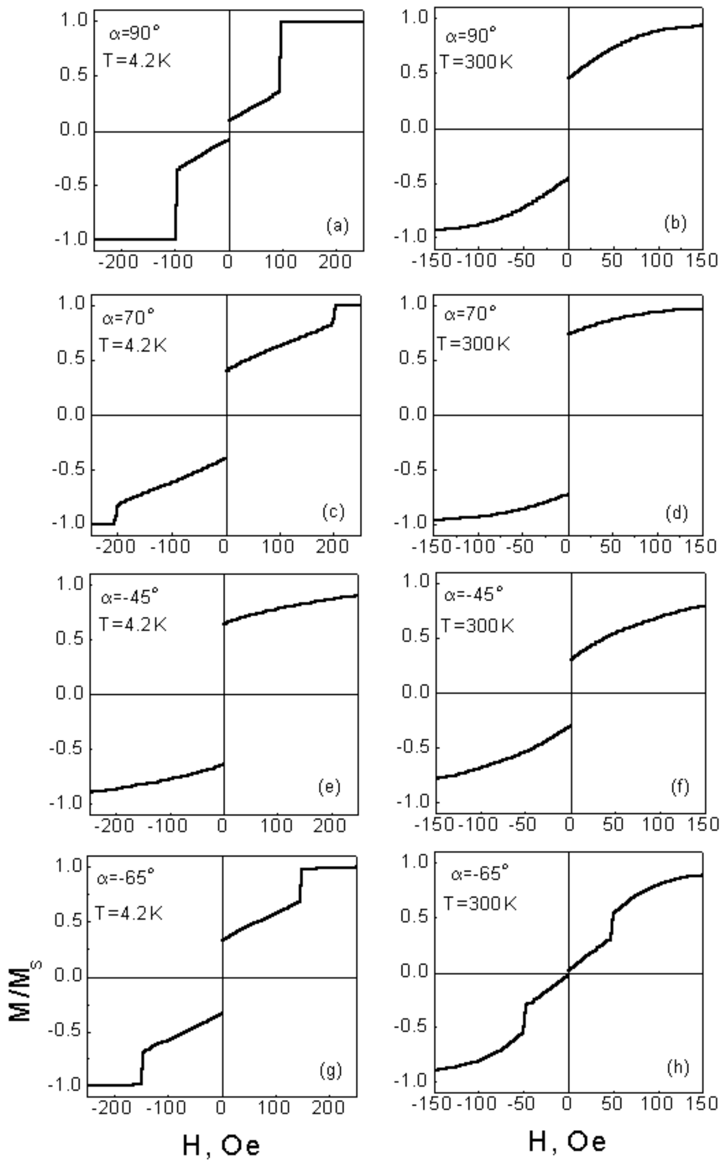

Figure 5. Calculated field dependences of the projection of the magnetization on the magnetic field direction. (a), (c), (e), (g) 10 K; (b), (d), (f), (h) 300 K; (a), (b) $\alpha = 90°$; (c), (d) $\alpha = 70°$; (e), (f) $\alpha = -45°$; (g), (h) $\alpha = -65°$.

anisotropy in the two iron layers are demonstrated schematically in figure 3(b). The values of the angles determining the directions of the easy axis of the layers are presented in table 1. The shape of the hysteresis curves is determined in particular by the direction of the magnetic field in relation to the directions of the hard axes in the layers. It is possible to select two sectors in the (001) plane marked by γ_1 and γ_2 (figure 3(b)). The stable noncollinear configurations C1 and C2 presented in figure 4 belong to the sector γ_1. When the magnetic field is directed in the sector γ_1, the magnetization-reversal process is associated with a jump between the configurations of C1 type for room temperature and between the configurations of C2 type for low temperature. If the magnetic field is directed in the sector γ_2, the magnetization reversal would be associated also with the overcoming of the energy barriers related to the hard axes in the layers HA1 and HA2 (or HA2′ for low temperature). In this case an additional jump to a configuration of C3 type should be observed in the hysteresis loop.

Let us now examine the results of our calculation taking into account the factors mentioned above. The real values of the sector in the (001) plane, where two jumps are observed in the hysteresis loop, depend on the relation between the values of the anisotropy constants in the layers and the values of the exchange constants. Let us consider first the results of calculations for temperature 4.2 K. There are two possible shapes of the hysteresis loop. When the external magnetic field is directed in the angle sector −60° to 68° (or −112° to 120°), the first-order phase transition between C2-type configurations in zero magnetic field take place. The rotation of the magnetization into the saturation condition appears after the transition (see figure 5(e) for an example). When the external magnetic field is directed in the angle sector −60° to −112° (or 68° to 120°), the additional first-order phase transition between C2-type and C3-type configurations is observed (see figures 5(a), (e), (g)). The observed phase transitions were identified experimentally as first-order phase transitions, because these transitions appear as fairly sharp jumps and are followed by clearly expressed local hysteresis.

For temperature 300 K the situation is more complicated. The calculations demonstrate the second jump in the hysteresis loop only when the magnetic field is applied in the angle sector 114° to 130° (or −50° to −66°) (see figure 5(h)). This means that overcoming the energy barrier related to the hard axis in the first layer, HA1, is accompanied by a first-order phase transition and by a jump of magnetization, while overcoming that related to the hard axis in the second layer, HA2, is not. Varying the value of the anisotropy and the exchange constants, we found that the shape of the hysteresis loop is very sensitive to the relation between these constants. To observe a jump of the magnetization associated with the overcoming of the energy barrier related to the hard axis in the second layer, HA2, it is necessary to increase the ration K_{U2}/K_{U1} or to weaken the exchange interaction between the iron layers.

Now let us compare the experimental and calculated hysteresis loops (figures 1 and 5). As was mentioned above, the results of the experiments obtained at 10 K were compared with the results of calculations done for 4.2 K, because the constants which we used in the calculations were obtained in [8] only for temperatures of 4.2 and 300 K. For low temperature, these results are in good qualitative agreement. For $\alpha = -45°$ (figure 1(e)) a jump of the magnetization accompanied by hysteresis is observed in the experimental loop. This feature in the vicinity of zero magnetic field is associated, accordingly to our calculation (figure 5(e)), with the phase transition between configurations of C2 type. For $\alpha = -65°$ (figure 1(g)) there are two jumps and two local hysteresis loops. The second jump is not so sharp as the first one, but the existence of local hysteresis suggests that the first-order phase transition to a phase of C3 type, predicted by the calculation (figure 5(g)), takes place here. For $\alpha = 90°$ the jump of magnetization and the local hysteresis related to the phase transition between the configurations of C2 and C3 types is more clearly expressed than the jump between the configurations of C2 type in the vicinity of zero magnetic field. A possible reason for this feature is the small value of M_R/M_S for this direction of magnetic field and the closeness of the magnetic field values for which these two phase transitions appear. The experimental hysteresis loop for $\alpha = 70°$ (figure 1(c)) is similar in general to the hysteresis loop for $\alpha = 90°$. It is also possible to assign here two local hystereses as related to two phase transitions. Under the conditions of a relatively large value of M_R/M_S for $\alpha = 70°$, the second jump of magnetization is not so pronounced as for $\alpha = 90°$.

For 300 K the shapes of the experimental loops are qualitatively in agreement with the results of the calculations for 70°, −45° and −65° (figures 1(d), (f), (h) and 5(d), (f), (h) respectively). For −45° there is only one jump of magnetization, related to the phase transition between configurations of C1 type. For −65° there are two jumps of magnetization, related to phase transitions between configurations of C1 type and between configurations of C1 and C3 types. The calculated curves for 70° and 90° (figures 5(b), (d)) do not contain the second jump. The calculations performed for temperature 300 K, in comparison with those for low temperature, do not give the jump related to the overcoming of the energy barriers associated with the hard axis HA2 in the second layer. Being in agreement with the experimental results for 70°, the results of the calculation are in some disagreement with the experiment for 90° (figure 1(a)): the small local hysteresis in the vicinity of 70 Oe, observed in the experimental loop, could be considered as reflecting a first-order phase transition from a configuration of C1 type to a configuration of C3 type. Good quantitative agreement was observed for all hysteresis loops in the calculated and experimental values of the ratio M_R/M_S, while agreement of the calculated and experimental values of the magnetic fields at which the phase transitions took place could not be achieved. Quantitative agreement could be achieved by variation of the relation between the constants of exchange and anisotropy, but in the present investigations we adhered to using the constants obtained independently in FMR studies of the film.

4. Conclusions

In this paper, experimental investigations of a magnetization-reversal process have been performed on the Fe/Si/Fe sandwich structure, in which bilinear ferromagnetic and biquadratic exchanges coexist with a complex system of cubic and uniaxial anisotropies. Numerical calculations of stable magnetic configurations and field dependences of the magnetization were performed on the basis of a model in which the variation of the constants of the exchange and the anisotropy with temperature was taken into account. The values of the constants of the exchange and the anisotropy and also information about the directions of the anisotropy axes in the iron layers, which were used in the calculations, were taken from independent FMR investigations of the same Fe/Si/Fe film [8]. Good agreement of the results of the experiments and the calculations for the case of absence of an external magnetic field was obtained. This permitted us to conclude that in the absence of a magnetic field, a noncollinear magnetic structure in which the angle between the directions of the magnetizations in the layers and the easy axis direction of the structure both change with temperature exists in the sandwich system studied. The comparison of the experimental and the calculated field dependences of the magnetization demonstrated that the presence of strong uniaxial anisotropy with different easy directions in the iron layers governs the existence of different noncollinear configurations in the system in the presence of a magnetic field and the field-induced phase transitions between them. The types of the magnetic configurations and the transitions between them are defined by the competition between the exchange and anisotropy.

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