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Single spin ensemble model for the change of unidirectional anisotropy constant by annealing on polycrystalline ferromagnetic/antiferromagnetic bilayers

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A model for the exchange coupled polycrystalline ferromagnetic/antiferromagnetic (F/AF) bilayers is proposed in order to discuss the mechanism of the change of the unidirectional anisotropy constant (J_K) of the bilayers by thermal annealing. The AF layer is treated as an aggregation of the AF grains whose magnetic anisotropy axes lay in the film plane with two-dimensionally random distribution. Two stable states concerning the direction of the AF spins are calculated for the AF grain. Determining the populations of the AF grains in each state in thermal equilibrium, total energy of the system is obtained, which provides the magnetization curves and the magnetic torque curves of the F/AF bilayers. The calculated results show the reduction of J_K with increasing the equilibrium temperature, which is due to the changes of the probability functions for the respective spin alignments of the AF grain. We conclude that the changes in J_K do not necessarily need any changes of the microstructure and the intrinsic physical quantities of the F/AF bilayers. [S0021-8979(00)36408-8]

I. INTRODUCTION

The control of the unidirectional anisotropy constant (J_K) of the ferromagnetic (F) layer pinned by the adjacent antiferromagnetic (AF) layer is the key to the performance of spin valves.[1] The disordered AF alloys such as FeMn and Mn–Ir are widely used for the AF layer, because they induce the unidirectional anisotropy on the F layer even in the as-deposited state. However, J_K of the F/AF bilayers such as Ni–Fe/FeMn[2,3] and Ni–Fe/Mn–Ir[4,5] are generally changed by the annealing even when the external field is applied during the annealing along the easy direction of the anisotropy of the as-deposited state. These changes are not simple; the enhancement and/or the reduction of J_K are both reported.[6–9] Although the modification of the F/AF interface by the interdiffusion effect[7] or the change of the mechanical strain of the AF layer[9] is accounted the cause for, the mechanism of the change of J_K is not fully understood. What seems to be lacking for understanding of the mechanism is the difference in the AF spin alignments between the as-deposited bilayers and the annealed ones. The microstructure and the magnetic anisotropy of the AF layer in the actual bilayers are the most important factors, because they strongly correlate with the AF spin alignment. Recently, through magnetic torque analysis on the Ni–Fe/Mn–Ir bilayers,[10] we clarified that the polycrystalline F/AF bilayer system, which has a blocking temperature, should be treated as the aggregation of the individual AF grains exchange-coupled with the F layer, and the magnetic anisotropy axes of the AF grains lay in the film plane with two-dimensionally random distribution (hereafter, ''single spin ensemble model'').[11] In the present study, based on the single spin ensemble model, we demonstrate theoretically the changes of J_K without any changes of the microstructure and the intrinsic physical quantities of the polycrystalline F/AF bilayers.

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II. CALCULATION MODEL

Figure 1 shows the schematic view of the calculation model.[11] The magnetization of the F layer is treated as a single spin. The AF layer is regarded as an aggregation of the AF grains whose magnetocrystalline anisotropy has uniaxial symmetry. The anisotropy axes of the AF grains lay in the film plane with two-dimensionally random distribution. The intergranular magnetic coupling of the AF grains is neglected. The simple model proposed by Meiklejohn (hereafter, ''single spin model'')[12,13] is applied between the F layer and each AF grain.

III. RESULTS AND DISCUSSION

A. Energy of an AF grain

In order to calculate the magnetization processes of the system, we first consider the energy of an AF grain per unit area of the film plane

$$tE_{AF}=K_{AF}d_{AF}\sin^2(\alpha-\varphi)-J\cos(\alpha-\beta), \quad (1)$$

where, $K_{AF}d_{AF}$ is the magnetocrystalline anisotropy energy of the AF grain per unit area of the film plane; J is the coupling energy per unit area of the F/AF interface; angle φ

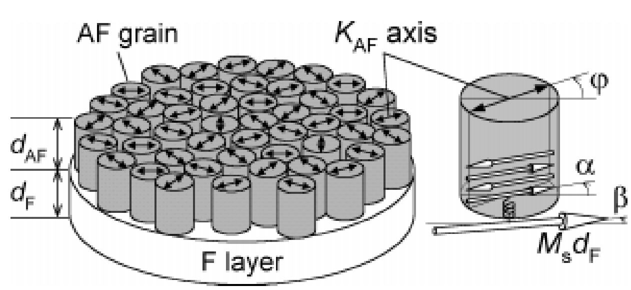

FIG. 1. A schematic model of the F/AF bilayer for calculation. The spin configuration in the F layer and in the AF grain, and the angular relations of them are indicated (right).

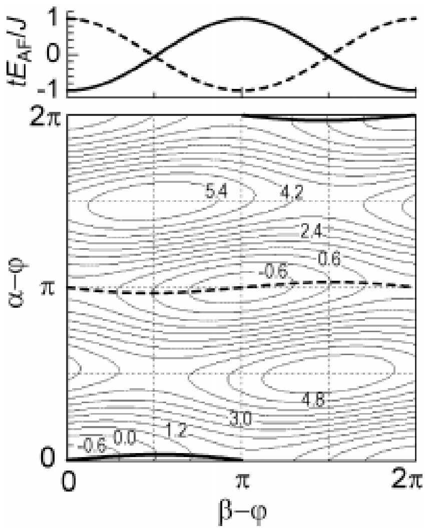

FIG. 2. A contour map of the AF grain's energy as functions of deviation angles α-φ, and β-φ, calculated for the case of $K_{AF}d_{AF}/J=5.0$. The contour lines indicate the reduced energy, tE_{AF}/J. The upper part shows the changes of tE_{AF}/J along the thick lines in the contour map.

is the direction of the anisotropy axis of the AF grain, which is defined in the range from $-\pi/2$ to $\pi/2$; angles α and β are the directions of the axis of the AF spins and the magnetization of the F layer, respectively. From the partial derivation of Eq. (1) with α, we obtain the energy minimum equations, which determine the angle α under certain values of β and φ.

Figure 2 shows a contour map of the AF grain's energy as functions of deviation angles α-φ and β-φ, calculated with Eq. (1) for the case of $K_{AF}d_{AF}/J=5.0$. The reduced energy, tE_{AF}/J, is indicated by contour lines. We can see two values of α-φ which satisfying the energy minimum equations, for the respective values of β-φ. The thick solid line and the dashed one in the map indicate the loci of these values of α-φ when the angle β-φ continuously changes; they always remain near α-$\varphi=0$ and π. This result means that the direction of the AF spins is adhered to the anisotropy axis of the AF grain when the F layer magnetization rotates round and that the AF grain has two stable states concerning the direction of the AF spins. Hereafter, we call the state corresponding with the thick solid line as "+state" and that with the dashed line as "− state," respectively. The changes of the reduced energy, tE_{AF}/J, along the respective loci are shown with the same line forms in the upper part of Fig. 2, as a function of the angle β-φ. We find that the energy of the AF grain changes reversibly for a round rotation of the F layer magnetization with one-fold symmetry.

B. Population in the respective AF spin state

In order to calculate the total energy of the system, we should know the populations of both the + state AF grain and the − state one for the respective φ values under $\beta=0$. Figure 3 shows the reduced energy, tE_{AF}/J, as a function of the angle α when $\varphi=0.2\pi$ for the case of $K_{AF}d_{AF}/J=5.0$. There are potential barriers between the + state located at $\alpha=0.18\pi$ and the − state at $\alpha=1.22\pi$. Here we are concerned with the thermal equilibrium of the

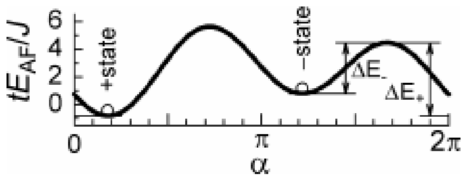

FIG. 3. Change of the reduced energy, tE_{AF}/J as a function of the angle of the AF spin axis, α, calculated for the case of $K_{AF}d_{AF}/J=5.0$, $\beta=0$, and $\varphi=0.2\pi$.

system. Under the thermal equilibrium, the transition velocity from the +state to the − state and that from the − state to the + state are equalized

$$p_+\exp(-\Delta E_+/kT)=p_-\exp(-\Delta E_-/kT), \tag{2}$$

where p_+ and p_- are the probabilities of the AF spins to be the + state and the − state, respectively; ΔE_+ and ΔE_- are the heights of the lower potential barrier measured from the + state and the − state, respectively; and T is the equilibrium temperature. Taking into account $p_++p_-=1$, we obtain

$$p_+=1/[1+\exp\{(\Delta E_--\Delta E_+)/kT\}], \tag{3}$$

for the respective φ values. Figure 4 shows $p_+(\varphi)$ for the case of $K_{AF}d_{AF}/J=5.0$. We find that $p_+(\varphi)$ becomes flat by decreasing the calculation parameter, JS/kT, where S is the contacting area of the AF grain with the F layer. This result means that when the thermal energy (kT) becomes large compared with the coupling energy between the AF grain and the F layer (JS), the difference between the populations in the + state and in the − state becomes small.

Here, we assume the immutability of the probability functions p_+ and p_- during the magnetization process; in other words, the sufficiently longer time constant for the transition between both states, compared with the measuring time in the laboratory.

C. Total energy of the system

By using the geometrical distribution function of the anisotropy axes of the AF grains, $w(\varphi)$, the summation of the AF grain's energy per unit area of the film plane is given as a function of β:

$$tE_{AF}^{\text{total}}(\beta)=\int_{-\pi/2}^{\pi/2}[tE_{AF}^{+}(\beta-\varphi)p_+(\varphi) + tE_{AF}^{-}(\beta-\varphi)p_-(\varphi)]w(\varphi)d\varphi, \tag{4}$$

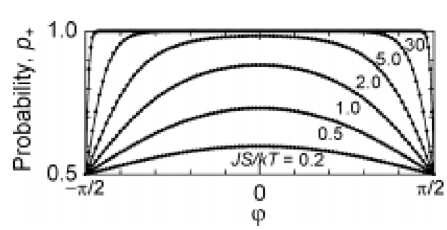

FIG. 4. Probability function, $p_+(\varphi)$, calculated for various values of JS/kT in the case of $\beta=0$ and $K_{AF}d_{AF}/J=5.0$.

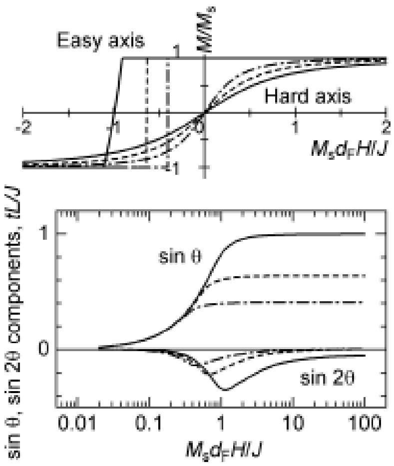

FIG. 5. Calculated MH loops (top) and the magnitudes of sin θ and sin 2θ components of the calculated torque curves as a function of the reduced applied field (bottom) for the case of $K_{\mathrm{AF}}d_{\mathrm{AF}}/J=5.0$. Calculations were performed based on the single spin model (solid lines) and the single spin ensemble model with $JS/kT=\infty$ (dashed lines) and $JS/kT=1.0$ (one dotted-dashed lines).

where tE_{AF}^{+} and tE_{AF}^{-} are the energies of the + state AF grain and − state one, corresponding to the solid line and to the dashed one in Fig. 2, respectively. In the present study, $w(\varphi)=1/\pi$ was used for the calculation, because of the two-dimensionally random distribution of the anisotropy axes of the AF grains. The total energy of the system per unit area is thus obtained as functions of the strength (H) and the direction (θ) of the external applied field

$$tE^{\mathrm{total}}(H,\theta)=tE_{\mathrm{AF}}^{\mathrm{total}}(\beta)-M_s d_{\mathrm{F}}H\cos(\theta-\beta), \tag{5}$$

where $M_s d_{\mathrm{F}}$ is the saturation magnetization of the F layer per unit area of the film plane. The direction of the F layer magnetization, β, is determined numerically to minimize Eq. (5) for certain values of H and θ; consequently, we can calculate the magnetization processes of the F/AF bilayer.

D. Unidirectional anisotropy constant

Figure 5 shows the calculated results for the case of $K_{\mathrm{AF}}d_{\mathrm{AF}}/J=5.0$: MH loops along both the easy and the hard magnetization axes, and the sin θ and the sin 2θ components of the torque curve as a function of the reduced applied field, $M_s d_{\mathrm{F}}H/J$. The magnitudes of the sin θ and the sin 2θ components of the torque curve were determined from Fourier analysis. No hysteresis was found in the torque curves, corresponding well with the experimental results.[10] In Fig. 5, we find the shift of the MH loops along the easy axis (without hysteresis) and the persistence of the sin θ components at the high field, which mean the existence of unidirectional anisotropy. Comparing these results with those based on the single spin model (solid lines in Fig. 5), one can say that the present single spin ensemble model gives qualitatively similar results with the single spin model in the MH loops and the magnetic torque curves. The only difference is the value of the unidirectional anisotropy constant, J_{K}, which is defined as $M_s d_{\mathrm{F}} H_{\mathrm{ex}}$ or the saturated value of the sin θ component, tL, at the high field. Here, H_{ex} is the shifting field of the MH loop along the easy axis. Figure 6 shows the reduced unidirectional anisotropy constant, J_{K}/J, as a function of JS/kT. In the case of $K_{\mathrm{AF}}d_{\mathrm{AF}}/J=5.0$, J_{K}/J, which is 0.1 at $JS/kT=0.2$, increases gradually with increasing JS/kT, and tends to saturate beyond $JS/kT=5.0$. In the other $K_{\mathrm{AF}}d_{\mathrm{AF}}/J$ cases, J_{K}/J changes similarly against JS/kT, except for the small difference in the saturated values. Assuming the constant JS, one can finally say that J_{K} reduces by increasing the equilibrium temperature of the system. Taking into account that the F/AF bilayers are not generally in the thermal equilibrium in the as-deposited state and that the annealing procedure tends to bring them into equilibrium, we conclude that Fig. 6 shows the mechanism of the changes of J_{K} by thermal annealing. It is due to the changes of the probability functions for the respective spin alignments of the AF grain, $p_{+}(\varphi)$ and $p_{-}(\varphi)$. The important point to be noticed is that the changes of the unidirectional anisotropy constant of the polycrystalline F/AF bilayers do not need any microstructural changes of the AF layer and the changes of the intrinsic physical quantities such as K_{AF} and J.

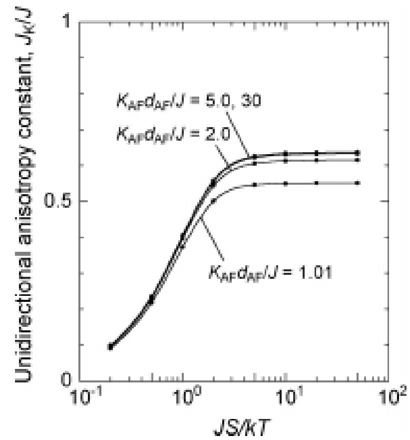

FIG. 6. Reduced unidirectional anisotropy constant, J_{K}/J, as a function of JS/kT, calculated for various $K_{\mathrm{AF}}d_{\mathrm{AF}}/J$ values.

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