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Exchange coupling and enhanced coercivity in $Fe_{50}Mn_{50}$/permalloy bilayers

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Abstract
We have determined the dependence of the exchange coupling on both the thickness of the antiferromagnetic (AF) layer (t_{AF}) and that of the ferromagnetic (FM) layer (t_{FM}) in a $Fe_{50}Mn_{50}$/permalloy bilayer, where the thickness of the FeMn layer varies from 0.5 to 32 nm with a fixed permalloy layer of 30 nm, and that of the permalloy layer varies from 3.5 to 45 nm with the uniform FeMn layer fixed at 10 nm. For $t_{AF} > 3$ nm, the exchange field H_{ex} varies as $1/t_{AF}^{0.3}$ at both 80 and 300 K, whereas the coercivity does not vary with t_{AF}. The dependence of H_{ex} on t_{FM} displays a behaviour varying as $1/t_{FM}^{0.9}$, and H_C a behaviour varying as $1/t_{FM}^{1.7}$ which is close to the theoretical prediction based on a random field at the interface of a FM/AF bilayer.

1. Introduction

Exchange coupling is a very important property of the magnetic interaction at an interface between a ferromagnet (FM) and an antiferromagnet (AF) in an FM/AF bilayer; it was first discovered as a new type of magnetic anisotropy in partially oxidized Co fine particles [1, 2]. After a FM/AF bilayer is field cooled across the Néel temperature (T_N) of the AF layer, exchange coupling causes a unidirectional anisotropy which results in a shift of the hysteresis loop of the FM layer away from the original location of that for a single FM layer, characterized by an exchange field (H_{ex}), with an enhanced coercivity (H_C) [1–10]. Because of its important role in applications in spin-valve magnetoresistance devices [8–10], much attention has been focused on the exchange coupling between a ferromagnetic layer and an antiferromagnetic layer. Experimentally, it has been shown that the FM/AF interface and the AF ordering play important roles in the exchange coupling, and that the values of both H_{ex} and H_C depend on

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the constituent materials. Also, it has been established that H_{ex} is inversely proportional to the thickness of the FM layer (t_{FM}) [4, 10], and that H_{ex} decreases with increase of the temperature and vanishes at the so-called blocking temperature (T_B), which is below (e.g., for NiO and FeMn) or close to (e.g., for CoO) T_N for the AF layer.

In efforts to understand the mechanism of the exchange coupling, several models with both uncompensated [11] and compensated interfacial spin structures [12] as well as random fields at the interfaces of FM/AF bilayers [13, 14] have been proposed. However, few models reproduce the dependence of H_{ex} on the AF layer thickness (t_{AF}). On the other hand, some key dependences of the exchange coupling remain to be unequivocally established experimentally. Among these are the dependence of the exchange coupling on the AF layer thickness (t_{AF}) and the enhancement of H_C with increasing FM layer thickness (t_{FM}). Although some experimenters noted the effect of t_{AF} [4, 9, 15, 16], few systematic studies have established a clear relationship between H_{ex} and t_{AF}. It is very interesting that a dependence of H_{ex} on t_{AF} in CoO/permalloy bilayers has been revealed, with the behaviour of H_{ex} varying approximately as $1/t_{AF}$ [17].

In this paper, we report the dependence of H_{ex} on both t_{AF} and t_{FM}, as well as the enhancement of H_C with increasing t_{FM}, in exchange-coupled FeMn/permalloy bilayers.

2. Experiments

Multilayered samples of Si(100)/Cu/$Fe_{50}Mn_{50}$/permalloy/Cu were fabricated by a computer-controlled magnetron sputtering system using bulk solid targets of Cu, permalloy ($Ni_{81}Fe_{19}$), and $Fe_{50}Mn_{50}$. The Cu underlayer was used to grow the fcc AF FeMn layer with a [111] orientation [4, 18] and the Cu cap layer was present for protective purposes. During deposition of the permalloy layer, a dc field of about 200 Oe was applied in the plane of the layer to induce a uniaxial anisotropy. To facilitate the observation of the layer thickness effect, a wedge-shaped layer was prepared to enable us to examine the different layer thickness dependences of H_{ex} and H_C in the samples. The compositions of the constituent layers were verified by electron microprobe analysis. The thickness dependences of H_{ex} and H_C were measured using many small pieces cut from the large multilayered sample along the wedge layer direction, so that t_{AF} or t_{FM} is the only variable. Magnetic measurements were made by a vibrating-sample magnetometer (VSM) with field cooling (FC). The FC was performed by cooling the samples from above the Néel temperature $T_N = 425$ K of the FeMn layer down to room temperature in a dc field of 10 kOe applied in the same direction as that of the dc field during the permalloy layer deposition.

3. Results and discussions

3.1. Sample structures

Before preparing the FeMn/permalloy exchange-coupled bilayer, a sample of Cu(30 nm)/FeMn(30 nm) was prepared for structural observation, performed using XRD. The XRD pattern of the sample is shown in figure 1. It is clear that the FeMn layer is matched well to the structure of the Cu sublayer with Cu(111) texture, which is very different from the case for a FeMn monolayer deposited on a Si(100) substrate directly. Figure 2 shows a cross section micrograph of a Si(100)/Cu/FeMn/permalloy sample. The image displays a clear multilayered structure with a somewhat rough interface between the FeMn and permalloy in the bilayer. This indicates that there is interdiffusion at the interface, and so it is difficult to obtain an ideal compensated or uncompensated spin structure at the interface in these sputtered samples. In other words, the behaviour of the exchange coupling displayed in this system may originate from the random spin configuration at the interface, which leads to a net uncompensated spin alignment contributing to the exchange coupling.

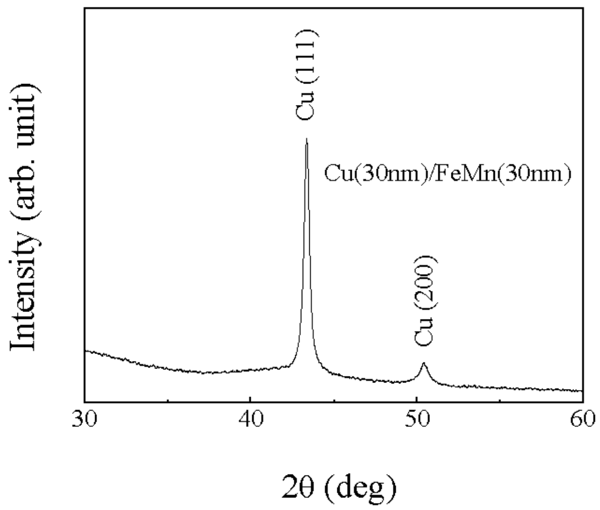

Figure 1. The XRD pattern of the Cu (30 nm)/FeMn (30 nm) sample.

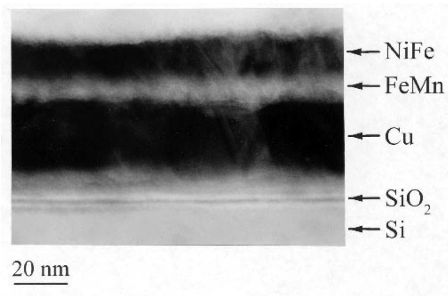

Figure 2. A cross section micrograph of the Si(100)/Cu (30 nm)/FeMn (10 nm)/permalloy (20 nm) sample.

3.2. Dependence of the exchange field (H_{ex}) on t_{AF}

To facilitate the observation of the AF layer thickness effect, a wedge-shaped FeMn layer with thickness varying from 0.5 to 32 nm was prepared, whereas the permalloy layer and both Cu layers had a uniform thickness of 30 nm.

Figure 3 shows H_{ex} as a function of t_{AF} for the samples, measured at both 300 and 80 K with FC. It is clear that H_{ex} shows a strong dependence on t_{AF}. In both cases, except for small t_{AF}, H_{ex} varies as $1/t_{AF}^{\lambda}$, with the value of $\lambda = 0.3$ for the results obtained at 300 K, and $\lambda = 0.31$ for the results obtained at 80 K. For these samples, where the AF layers retain their bulk T_N-values, H_{ex} varies as $1/t_{AF}^{\lambda}$. As shown in figure 3, for small t_{AF}-values ($t_{AF} < 7.3$ nm and $t_{AF} < 3$ nm for the data at 300 and 80 K respectively), H_{ex} shows a deviation from the power-law behaviour, which is due to the finite-size scaling of T_N [19].

In the simplest model of exchange coupling assuming an ideal interface [1,2], H_{ex} can be expressed as

$$H_{ex} = nJS_{FM}S_{AF}/M_{FM}t_{FM} \qquad (1)$$

where S_{FM} and S_{AF} are the expectation values of the spins of the FM and AF magnetic moments at the interface respectively, M_{FM} is the magnetization, t_{FM} is the layer thickness

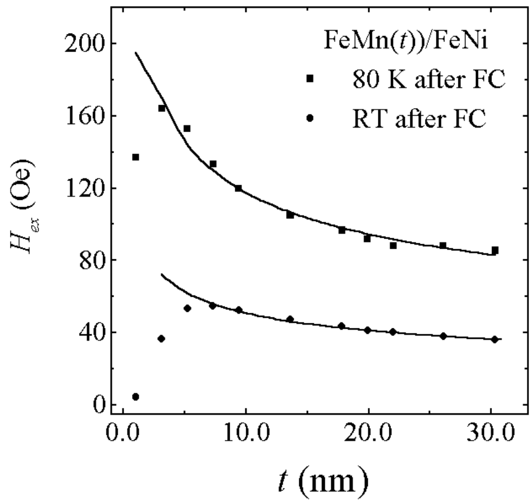

Figure 3. The dependence of the exchange field H_{ex} on the thickness of the FeMn layer t_{AF} in the FeMn (t_{AF} nm)/permalloy (30 nm) bilayer, at both 80 and 300 K with FC. The solid curves are the best fits of the results with $1/t_{AF}^{0.3}$.

of the FM layer, J is the strength of the interaction between S_{FM} and S_{AF}, and n is the number of such interactions per unit area. While the dependence on t_{FM} is explicit, t_{AF} does not appear at all. The fact that H_{ex} varies as $1/t_{AF}^{\lambda}$ indicates that the exchange coupling involves not only the interfacial spins, but also the spin configuration and the domain structures in the AF layer. It is also noted that the exponent $\lambda = 0.3$ for the FeMn/permalloy bilayer is smaller than that, $\lambda \approx 1.0$, for the permalloy/CoO bilayer [17]. The difference between the exponents λ for the two AFs (FeMn and CoO) may be a reflection of the more complex AF spin structure at the interface in the FeMn/permalloy bilayer as compared to the simple one in the CoO/permalloy bilayer.

Figure 4 shows that H_{ex} decrease monotonically with temperature for representative FeMn/permalloy samples with t_{AF} spanning from 1 to 30 nm. For the samples with $t_{AF} > 10$ nm, H_{ex} decreases to zero at $T_B = 400$ K, which is close to, but lower than, the Néel temperature $T_N = 425$ K for the FeMn films. For the samples with $t_{AF} < 10$ nm, due to finite-size scaling, the values of T_N (and hence T_B) decrease significantly as t_{AF} reduces, as shown in the inset of figure 4.

3.3. Dependence of the exchange field (H_{ex}) on t_{FM}

To observe the FM layer thickness effect in a FeMn/permalloy bilayer, the samples were prepared using the technique described above, but a wedge-shaped permalloy layer was also prepared. After depositing the Cu underlayer, the uniform FeMn layer with the thickness of 10 nm was deposited, and this was followed by a wedge-shaped permalloy layer with thickness varying from 1.5 to 45 nm, whereas both Cu layers had the uniform thickness of 30 nm.

Experimentally, it has been shown that the exchange field H_{ex} in FeMn/permalloy bilayers varies roughly as $1/t_{FM}$ in the region of FM layer thickness from 25 to 400 nm and deviates from this behaviour in the very thin region [4]. Tsang *et al* [4] suggested that the deviation from the variation as $1/t_{FM}$ is due to very small grain size and the less well crystallized structure in a very thin permalloy layer, resulting in only weak magnetic coupling across the interface.

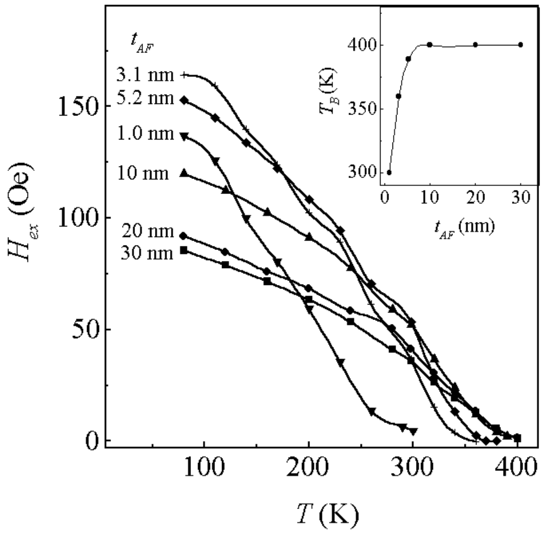

Figure 4. Temperature dependences of the exchange field H_{ex} for samples of the FeMn (t_{AF} nm)/ permalloy (30 nm) bilayer with the FeMn layer thickness varying from 1 to 30 nm. The inset shows T_B as a function of t_{AF}.

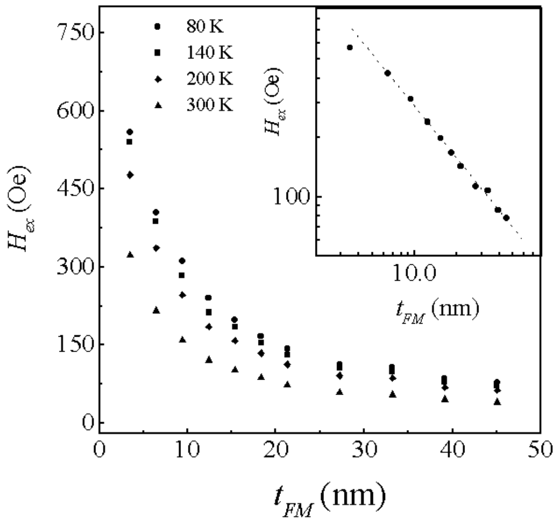

Figure 5. The dependence of H_{ex} on t_{FM} for FeMn (10 nm)/permalloy (t_{FM} nm) bilayer samples at different temperature. The inset shows the best fit with $1/t_{FM}^{0.9}$ for the results obtained at 80 K.

Figure 5 shows our experimental results on the dependence of H_{ex} on the thickness of the permalloy layer in the FeMn/permalloy bilayer measured at different temperatures. It shows that the dependence of H_{ex} on t_{FM} has a similar monotonic behaviour below $T = 200$ K and tends to remain unchanged as temperature varies except for $t_{FM} < 20$ nm. The results obtained at room temperature show that the exchange coupling across the interface is slightly weaker than that below $T = 200$ K. This indicates that the spin configuration at the interface between the AF and FM layers in the bilayer is closely related to temperature, and thus influences the

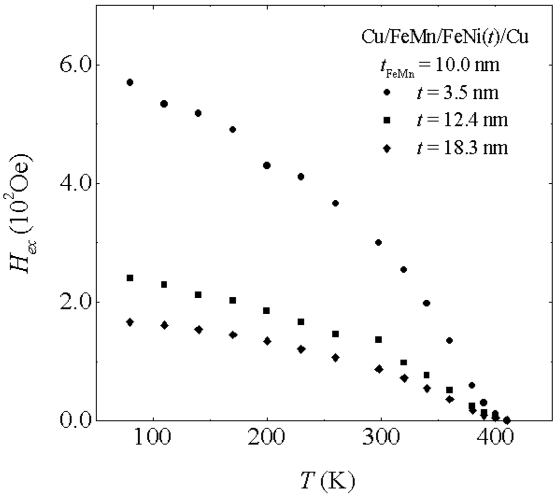

Figure 6. The temperature dependence of H_{ex} for different values of t_{FM} in the FeMn/permalloy bilayer.

domain structure in the FM layer as the thickness of the FM layer decreases (t_{FM} < 20 nm). Fitting the data obtained at 80 K as shown in figure 5, the H_{ex}-dependence on t_{FM} is seen to display a rough power law: $1/t_{FM}^{0.9}$, as shown in the inset of figure 5, deviating from $1/t_{FM}$ slightly. One can see that H_{ex} deviates from the behaviour described by the power law for t_{FM} < 5 nm, which may be due to the layer structure with pinholes leading to much weaker magnetic coupling across the interface. According to the simple model of an ideal interface between the AF and FM layers in the bilayer, H_{ex} should display a behaviour like that described by equation (1). In fact, H_{ex} depends not only on t_{FM} but also on t_{AF}, as discussed above. Also, the influence of the AF layer upon the FM layer for a very thin FM layer (t_{FM} < 45 nm) may lead to the spin configuration at the interface playing a very important role, resulting in the slight deviation of H_{ex} from the variation as $1/t_{FM}$.

Figure 6 shows the temperature dependence of H_{ex} for different FM layer thicknesses in the FeMn/permalloy bilayer. It is clearly seen that H_{ex} decreases monotonically with increase of the temperature and goes towards zero at T_B = 400 K (<T_N = 425 K). For the t_{FM} = 12.4 and 18.3 nm samples, H_{ex} varies almost linearly with temperature below T = 300 K, and gradually goes to zero as the temperature rises to T_B, unlike that for the t_{FM} = 3.5 nm sample. It can also be seen that the temperature dependence of H_{ex} deviates from the linear relation for thinner FM layers and H_{ex} reduces more quickly for t_{FM} = 3.5 nm than for thicker FM layers as the temperature rises.

3.4. Dependence of the enhanced coercivity (H_C) on t_{FM}

From the above discussion, one can see that the exchange field H_{ex} in a FeMn/permalloy bilayer depends closely on both t_{AF} and t_{FM}. As is well known, experimentally, the coercivity H_C of a FM layer in an exchange-coupled FM/AF bilayer is found to be much larger than that of an uncoupled FM layer regardless of the exchange field H_{ex}. In most theoretical investigations of exchange-coupled FM/AF systems, only H_{ex} has been addressed, and the enhanced coercivity is still an unresolved theoretical issue. It is interesting that Zhang *et al* [20] have recently proposed a theoretical model based on a random field at the interface of a FM/AF bilayer in

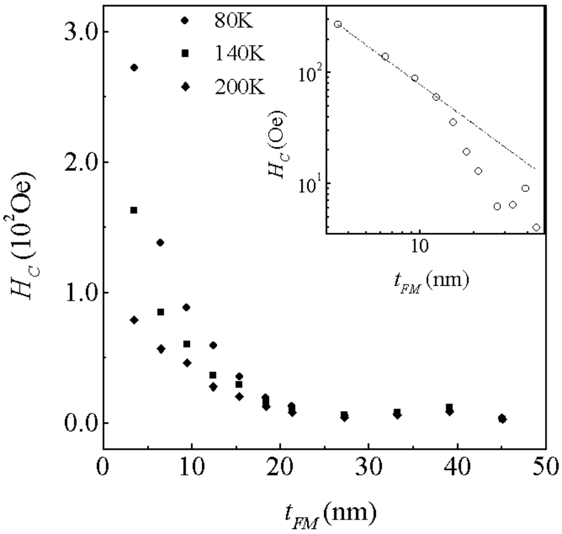

Figure 7. H_C as a function of t_{FM} measured at different temperatures in the FeMn/permalloy bilayer with a log–log linear fit of the result measured at 80 K shown in the inset.

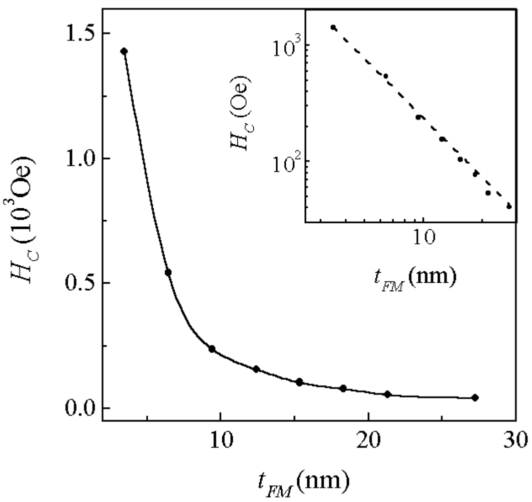

Figure 8. H_C as a function of t_{FM} measured at 15 K. The inset shows the best fit of the result with $1/t_{FM}^{1.7}$.

an effort to explain the enhanced coercivity H_C in exchange-coupled FM/AF bilayers; this predicts that H_C varies as

$$H_C = (\alpha/M_F)(1/t_{FM})^{3/2} \quad (2)$$

where the factor α involves the exchange coupling strength of the magnetic moments both in the layers and at the interface.

Figure 7 shows H_C in a FeMn/permalloy bilayer as a function of t_{FM} measured at different temperatures. One can see that H_C rapidly increases as t_{FM} decreases for $t_{FM} < 15$ nm. For $t_{FM} > 15$ nm, H_C tends to remain unchanged as temperature varies and is much smaller than that for the thinner FM layer. Shown in the inset of figure 7 is the dependence of H_C on t_{FM}

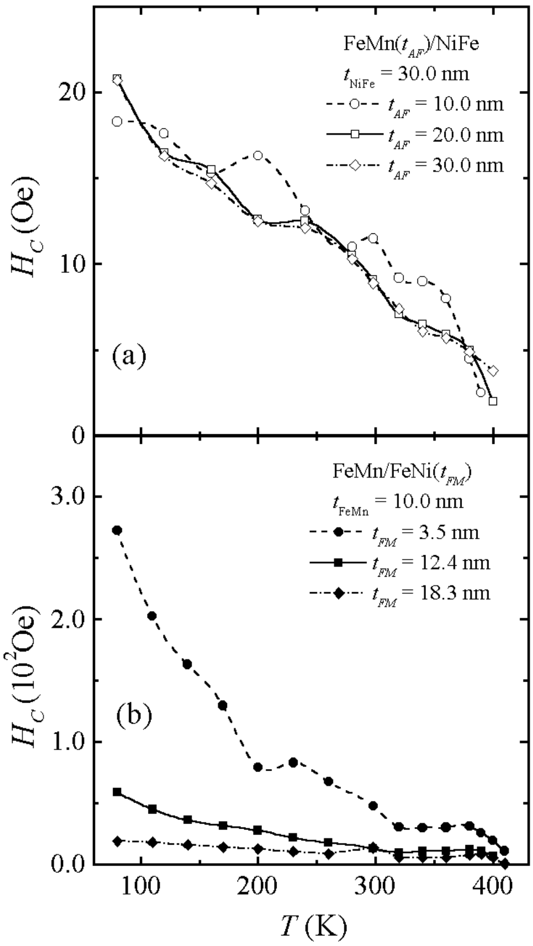

Figure 9. The temperature dependence of H_C with different values of t_{AF} (a) and with different values of t_{FM} (b). The curves are drawn to guide the eyes.

measured at 80 K. It is clear that only a few data points are located on the log–log linear fitting line ($H_C \sim t_{FM}^{-1.2}$) for $t_{FM} < 15$ nm. After the sample had cooled down to a lower temperature fixed at $T = 15$ K, H_C increased to about 1500 Oe for the thinnest FM layer of 3.5 nm and to about 50 Oe for the FM layer of 20 nm, as shown in figure 8. This behaviour is very different from that observed in a permalloy/CoO/Si system (at 80 K), but similar to that observed in a $Ni_{0.5}Co_{0.5}O$/permalloy/MgO system (at 10 K) [20]. Fitting these data points to $H_C \sim t_{FM}^{-\lambda}$ using the least-squares fitting method, we obtained a dependence of H_C on t_{FM}, as shown in the inset of figure 8, with the exponent $\lambda = 1.70 \pm 0.04$ which is close to, but slightly larger than, the theoretical prediction $\lambda = 3/2$.

The temperature dependences of H_C with different values of t_{FM} and t_{AF} have been obtained, as shown in figure 9. In figure 9(a), H_C shows a quasi-linear dependence on temperature for different values of t_{AF} for a fixed t_{FM} of 30 nm with a small fluctuation, and H_C decreases from about 20 Oe to a few Oe as the temperature rises—considerably smaller than those of permalloy/CoO bilayers [17]. On the other hand, it is clear that H_C remains almost unchanged with change of t_{AF} with temperature varying for fixed t_{FM}, indicating that enhancement of H_C originates just from spin pinning at the interface of a FM/AF bilayer. However, H_C displays different temperature dependences for values of t_{FM} with t_{AF} fixed at 10 nm, as shown in figure 9(b). For $t_{FM} > 12$ nm, the behaviour of H_C displays a linear dependence on T. For the thinnest FM layer, the behaviour of H_C apparently deviates from the linear temperature dependence and rapidly decreases as temperature rises in the range of temperature from 80 to 400 K. This may be due to the FM layer becoming discontinuous when t_{FM} decreases to a critical size and the pinholes appear. In this case, the FM layer may display a discontinuous granular structure rather than being a uniform film. Therefore a different theoretical prediction for this system is expected.

4. Summary

In summary, we have established that H_{ex} in exchange-coupled FeMn/permalloy bilayers varies as $1/t_{AF}^{0.3}$, and the exponent $\lambda = 0.3$ is significantly different from $\lambda = 1$ observed for permalloy/CoO bilayers. The dependence of H_{ex} on t_{FM} varies as $1/t_{FM}^{0.9}$. The results deviate from some present theoretical predictions and are different from those for other systems such as CoC/permalloy bilayers, indicating that the AF spin configuration at the interface in a FeMn/permalloy bilayer is more complex than that in a CoO/permalloy bilayer. The coercivity H_C in this system is closely related to the thickness of the FM layer, and varies as $1/t_{FM}^{1.7}$ at low temperature ($T = 15$ K); the exponent here is close to, but slightly larger than, the theoretical prediction $\lambda = 3/2$, whereas the value of H_C does not vary significantly with t_{AF} and displays a quasi-linear temperature dependence.

Acknowledgments

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