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Temperature-dependence of interlayer exchange bias coupling in NiO/Cu/NiFe

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The trilayers 10 nm NiO(AF)/X Cu/10 nm NiFe(FM) were prepared for the study on the temperature effect in interlayer exchange bias coupling. The characteristic behavior of the interlayer exchange bias coupling as a function the spacer thickness was shown to strongly depend on the temperature. A monotonic decrease of the exchange bias field with increasing Cu spacer layer was observed at low temperature around 20 K. At higher temperatures (about 145 K), a clear oscillatory evolution of the exchange bias field with the Cu thickness was found even without background subtraction. The temperature-dependent feature of the interlayer exchange bias coupling was also found to vary significantly with different Cu thickness.
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The long-range magnetic coupling between magnetic layers across a conductive spacer is one of the most important discoveries in low dimensional magnetic systems in recent years. The interlayer coupling between two ferromagnetic layers behaves oscillatory with the spacer thickness and alternates between ferromagnetic (FM) and antiferromagnetic (AF) coupling;[1,2] this result has been successfully described in a model based on Ruderman–Kittel–(Kasuya)–Yosida (RKKY) approach.[3,4] The interlayer coupling for the exchange bias trilayer system (AF/spacer/FM) was first reported by Gökemeijer and co-workers.[5] They observed a long-range interaction between the AF and FM layers through the conductive metal spacer layer, extending several tens of Å. Although the FM layer may also correlate with the AF layer via the conduction electrons across the nonmagnetic conductive (NM) layer, an oscillatory exchange bias field with the spacer thickness as expected in the RKKY approach for the FM/NM/FM system, was, however, not found in this work. In contrast to the finding in Ref. 5, nonmonotonic and even oscillatory variation of the exchange bias field with the NM spacer thickness was recently reported by Mewes and co-workers.[6] These contradictory results indicate a complicated physical mechanism for determining the interlayer exchange bias coupling, as compared to the FM/NM/FM system.

In order to clarify these points, we investigated the temperature effect on the interlayer exchange bias coupling for various spacer thickness.

The magnetron sputtering system with a base pressure lower than 3×10^{-7} Torr was used in 2 mTorr Ar working pressure for deposition of the FM layers (100 Å NiFe), Cu layers and AF (100 Å NiO) layers on the Si(110) substrate, using dc and rf power sources for conductive and nonconductive layers, respectively. The thickness of the layers was carefully calibrated by quartz thickness monitor and Detak surface texture probing system, and could be, in particular for the Cu spacer, well controlled within 10% deviation of the desired value for each deposition. This thickness control excludes also the uncertainty of the T_N or the blocking temperature due to the finite size effect.

The magnetic hysteresis loops were obtained by superconducting quantum interference device magnetometry. Prior to each magnetic measurement, the sample was cooled from 300 K under an external field H_f 1 kOe or 50 kOe down to the measurement temperature, below the Neél temperature T_N. The T_N of 100 Å NiO (<200 K) is much lower than the room temperature due to the finite size effect.[7] Following this procedure, each measurement at a given temperature is independent of the measurements at other temperatures.

Figure 1 shows the representative examples of the hysteresis loops taken at 20 K for the 100 Å NiO/X Cu/100 Å NiFe with Cu spacer layer thickness X=3, 8, 10, and 28 Å for $H_f=1$ kOe. A significant shift in all hysteresis loops from the H=0 is observed, clearly indicating the presence of exchange bias coupling. The exchange bias coupling decreases with increasing spacer layer thickness, and behaves as a long-range interaction (see also Fig. 2). The hysteresis loops for the samples at other Cu thickness reveal the similar feature, except the changes in coercivity and bias field, as shown in Fig. 2.

Figures 2(a) and 2(b) show the values of the coercivity field H_c and the exchange bias field H_e of 100 Å NiO/Cu/100 Å NiFe as a function of the Cu thickness for different temperatures. For $H_f=1$ kOe, the H_e measured at 20 K decreases monotonically with increasing Cu thickness and vanishes above 25 Å. These results agree well with the previous finding in Py/Cu/CoO systems.[5] However, the monotonic decaying of the interlayer exchange bias coupling can only be observed at low temperatures. Increasing the temperature, the interlayer exchange bias coupling become oscillatory with the Cu thickness. The Cu-thickness dependence of the H_e changes with the temperature. At 70 K, H_e becomes os-

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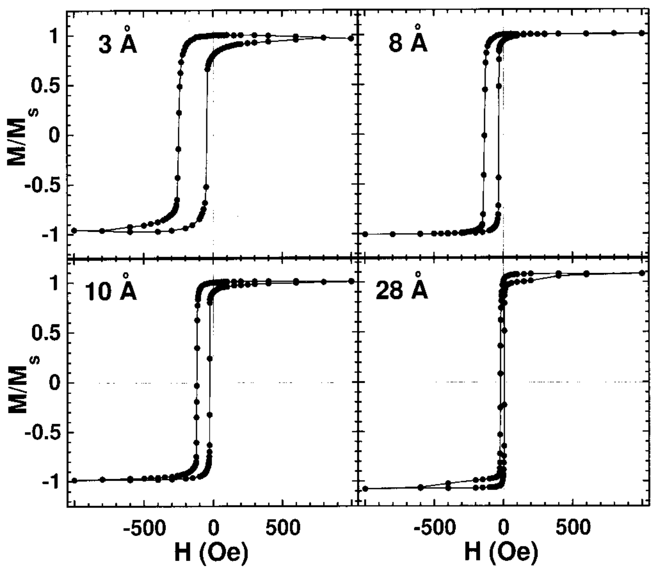

FIG. 1. Hysteresis loops taken at 20 K for the 100 Å NiO/X Cu/100 Å NiFe with X = 3, 8, 10, and 28 Å with 1 kOe cooling field.

cillatory with Cu thickness. This tendency increases with increasing temperature. Without background subtraction, an significant oscillation of the H_e is observed at 145 K within the thickness range 3 and 14 Å. The period of the oscillation is about 11 Å, which is consistent with the one in FM/Cu/FM system, such as Co/Cu/Co and Fe/Cu/Fe.[8,9] This implies that the oscillatory behavior observed has the same physical origin as that in FM/NM/FM systems. At 200 K, the H_e vanishes for all Cu thicknesses investigated.

The finding that the characteristic behavior of the interlayer exchange bias coupling depends on the temperature may clarify the contradiction in the previous studies mentioned above.[5,6] The absence of the H_e oscillation for Py/Cu/CoO in the previous work[5] may be due to the reduced measurement temperature. It (80 K) could be too low with respect to the T_N (290 K) of the CoO AF layer. Temperature plays thus a crucial role in determining the interlayer exchange bias coupling.

The insert in Fig. 2(b) shows the value of the H_e as a function of the Cu thickness with H_f=50 kOe for different temperatures. The feature of the characteristic behavior of the H_e as well as the temperature effect is almost the same as that with H_f=1 kOe. This indicates that the 1 kOe cooling field is high enough to well order the AF spin, giving the saturated values of the H_e.

As shown in Fig. 2(a), the H_c evolution with the Cu thickness reveals a similar behavior like the H_e one. At higher temperature around 145 K, the H_e oscillates with the Cu thickness. The location of the maximal point of the H_c is, however, not exactly the same as that for the H_e. The value of the H_c may be strongly affected by the detailed AF and FM spin configuration or domain structure at interface with different mechanism from that for the H_e.

Figure 2 has shown a strong temperature influence on the characteristic behavior of the interlayer exchange bias coupling with the spacer thickness. It is also interesting to monitor the temperature dependence of the interlayer exchange bias coupling for different Cu thickness. The interlayer exchange bias coupling strength $[H_e(T)/H_e(20\ \mathrm{K})]$ is depicted as a function of temperature in Fig. 3 for various characteristic Cu thickness. 3 and 14 Å are the Cu thickness with a minimal value of the oscillatory interlayer exchange bias field, while 8 Å is the maximal point. 5 Å is the one between those with the maximal and minimal bias field. The temperature evolution curves for both 3 and 8 Å have almost the same concave feature. The feature changes with the characteristic Cu thickness (5 Å), and become nearly linear for 8 Å. This finding indicates that the temperature dependent behavior of the H_e is determined by the Cu thickness with corresponding phase position of the oscillation.

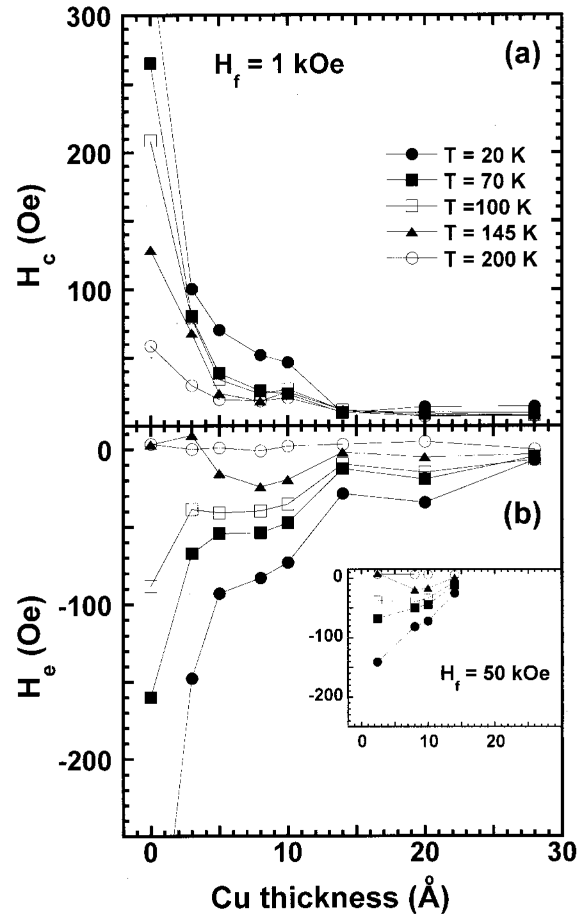

FIG. 2. The H_c (a) and H_e (b) values for 100 Å NiO/Cu/100 Å NiFe as a function of the Cu thickness at various temperatures of 20, 70, 100, 145, and 200 K. The cooling field H_f is 1 kOe. The insert in (b) shows the H_e values for H_f = 5O kOe. Both data for different H_f are nearly the same.

Extending Koon's model[10] to the trilayer system, a simple picture may qualitatively explain the findings extracted from Figs. 2 and 3. The behavior of the exchange bias field is often traced back to the spin configuration or microstructure at interface, which may be temperature dependent.[11] Nevertheless, different from the AF/FM bilayer, the spin configuration at interface of the FM/NM/AF trilayer is not only determined by the AF coupling or intrinsic spin structure within AF layers, but also affected by the long-range interlayer interaction across the spacer with the

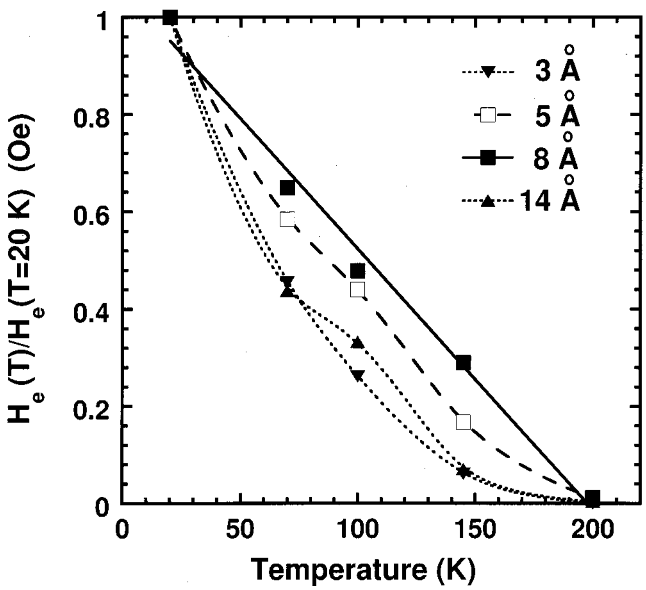

FIG. 3. The exchange bias field as a function of temperature for the samples with 3, 5, 8, and 14 Å Cu spacer. The data for 8 Å are fitted linearly. The solid lines for other thickness serves as eye guide only.

FM layer. The characteristic behavior as well as the temperature dependence of the exchange bias field should be thus attributed to both AF and interlayer couplings. We may express the energy E_b of the exchange bias system as

$$E_b(T,d)=J_{\mathrm{inter}}(T,d)S_{\mathrm{FM}}S_{\mathrm{AF},i}+J_{\mathrm{AF}}(T)S_{\mathrm{AF},i}S_{\mathrm{AF}},$$

where S_{FM} is the spin of the FM layer, $S_{\mathrm{AF},i}$ the effective uncompensated spin at interface, which participates in the exchange bias interaction with the FM layer, S_{AF} the neighbor spin within the AF layer, J_{inter} the effective interlayer coupling between the FM and AF interface layers (i.e., S_{FM} and $S_{\mathrm{AF},i}$), $J_{\mathrm{AF}}(T)$ the antiferromagnetic coupling between $S_{\mathrm{AF},i}$ and S_{AF}. $J_{\mathrm{inter}}(T,d)$, a long-range coupling, depends on the temperature T and the spacer thickness d. $J_{\mathrm{AF}}(T)$ is a function of the temperature. Based on this picture, the interlayer exchange bias field would be determined by the total effect of the $J_{\mathrm{inter}}(T,d)$ and $J_{\mathrm{AF}}(T)$. The J_{inter} may decay slowly with the temperature. At low temperatures, the J_{AF} is dominant, and the oscillatory behavior due to the RKKY-like J_{inter} is suppressed. At higher temperatures close to the T_N, the RKKY-like interlayer interaction may overcome the J_{AF} coupling, resulting thus in oscillation of the H_e.

The different features of the H_e temperature dependence at various characteristic Cu thickness d can be also easily understood in this simple picture. Since the d determines the oscillation amplitude of the periodic term in the J_{inter}, the J_{inter} at various d gives, therefore, different contribution to the E_b, leading to the different T dependence of the interlayer exchange bias coupling, as shown above in Fig. 3. This makes also the T dependence of the interlayer exchange bias coupling more complicated as compared to the interlayer coupling in FM/NM/FM systems, and still requires further theoretical input for a quantitative understanding.

In conclusion, a strong temperature effect on the characteristic behavior of the interlayer exchange bias coupling was observed in the NiO/Cu/NiFe trilayer system. At low temperature, the exchange bias field decreased monotonically with the Cu spacer thickness. Increasing the temperature close to the Neél temperature, the interlayer exchange bias field became oscillatory with the Cu spacer thickness. The temperature-dependence feature of the interlayer exchange bias coupling also changed significantly with characteristic Cu thickness. These findings may be attributed to a mechanism in which the RKKY-like interlayer coupling *temperature*-dependently competes with the antiferromagnetic coupling within the NiO layer.

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