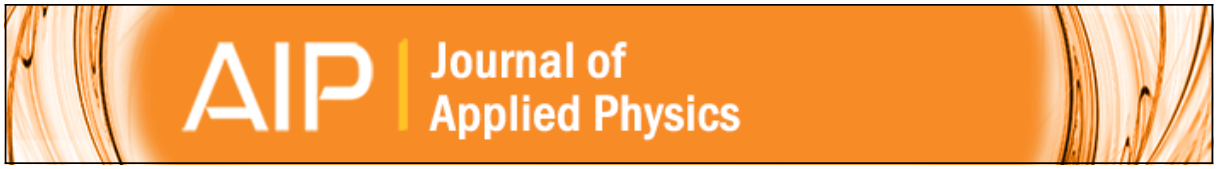

Coercive mechanism and training effect in Fe-Au/Ni-Fe bilayer films

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Citation: Journal of Applied Physics **109**, 07E148 (2011); doi: 10.1063/1.3562903
View online: http://dx.doi.org/10.1063/1.3562903
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Coercive mechanism and training effect in Fe-Au/Ni-Fe bilayer films

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(Presented 15 November 2010; received 23 September 2010; accepted 1 December 2010; published online 8 April 2011)

Exchange bias effect in spin glass/ferromagnetic systems has been studied recently. Here, we report the coercive mechanism and training effect in Fe-Au/Ni-Fe films. Experimental results indicate that the coercivity (H_c) mainly originates from direct coupling between Fe-Au and Ni-Fe layers at temperatures (T) well below the blocking point (T_b). At T near T_b, H_c comes from spin-flop coupling and defects in the Ni-Fe layer. The findings confirm the validity of our spin structure model. Additionally, irreversible rearrangement of Fe-Au spins from the field cooling state was indicated by the training effect of both Fe-Au/Ni-Fe and Fe-Au powder samples. The results are discussed in detail. © *2011 American Institute of Physics*. [doi:10.1063/1.3562903]

The exchange bias (EB) effect, a crucial physical phenomenon widely applied in the design of various modern spintronic devices, has resulted in rapid advancements in technology. A most significant case is the invention of the spin valve structure, which led to a breakthrough in areal density in magnetic recording devices. Exchange bias has been extensively studied in many different systems such as thin films, particles, composite materials, and even materials with inhomogeneous magnetism; however, a comprehensive understanding is still needed. Among the explanations for the origin of EB phenomena, glassy behavior-disorder and frustration-is accepted as an important aspect based on studies in a variety of systems including antiferromagnet/ferromagnet (AFM/FM) compensated and uncompensated interfaces,[1,2] interface roughnesses,[1,3] and single-crystal or polycrystalline systems.[4,5] Since systems exhibiting features of disorder show significant EB phenomena, studying the interaction between a fully random system, spin glass, and a ferromagnetic layer may provide useful information for the understanding of exchange bias triggered by spin freezing. A recent study first reported the EB in spin glass CuMn/Co bilayer films.[6] At temperatures well below the glassy point (T_g), normal EB, similar to that observed in AFM/FM systems, was obtained. When temperature approached T_g, the unique temperature dependence, a sign change of EB was discovered. A Ruderman–Kittel–Kasuya–Yoshida (RKKY) model has been proposed to explain this abnormal behavior.[6] Our previous work has further confirmed this nature of inverse EB in Fe-Au/Ni-Fe system.[7] We have proposed a spin dynamic model to interpret the mechanism of inverse EB based on the spin refreezing effect which could be evidence for the reversible rotation of interfacial magnetic moment in the spin glass layer.[7] In this study, we further investigate the coercive mechanism and training effect in Fe-Au/Ni-Fe films to further clarify the role of magnetization dynamic processes at the interface of spin glass and ferromagnetic layers.

Fe-Au/Ni-Fe thin films were prepared by radio frequency (RF) magnetron sputtering. The films were deposited at room temperature (RT) with a base pressure better than 3×10^{-7} Torr and argon working pressure of 10 mTorr. A composite target consisting of a gold disk overlain with Fe foils was used. The binary composition of Fe-Au was controlled by adjusting the number of Fe foils. The chemical composition was analyzed with calibrated energy dispersive spectroscopy (EDS) to be Fe(9.6 at. % Au). Because the magnetic moment of a spin glass is very small, magnetic properties of Fe-Au were measured using Fe-Au powder collected by removing the RT-sputter-deposited thick films from the glass substrates. The weight of the powder sample was 22.7 mg. The glassy temperature T_g was 54.2 K, as described previously.[7] After deposition of the Fe-Au layer, a 5 nm Ni-Fe layer was then deposited. A 2 nm Au top layer was finally deposited to prevent oxidation. The thickness of the Fe-Au layer (t_{sg}) is varied from 5 nm to 100 nm.

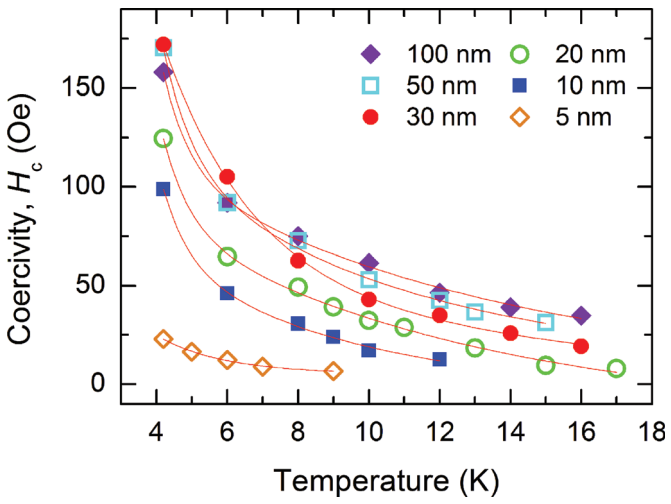

FIG. 1. (Color online) Dependence of coercivity on temperature for the Fe-Au/Ni-Fe samples with different Fe-Au layer thickness of 5, 10, 20, 30, 50, 100 nm. Solid lines are the fitting curve of second-order exponential decay.

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Magnetic properties were measured by a superconducting quantum interference device (SQUID) magnetometer. Before measurements were performed, the samples were cooled from RT to 4.2 K at external magnetic field of 5 kOe. Care was taken to zero the residual magnetic field before magnetic measurements.

Figure 1 shows the dependence of coercivity (H_c) on temperature (T) for the Fe-Au/Ni-Fe films with different t_{sg}. H_c decreases with rising T. The data can be perfectly fitted by an exponential decay function with extremely high R^2 (goodness-of-fit) value ranging from 0.981 to 0.998, as shown by the solid lines. Additionally, H_c is as a function of t_{sg}. At low T, H_c increases with increasing t_{sg} from 25 Oe to a saturation value of 175 Oe at $t_{sg} = 30$ nm. But at higher T ($\geq$ 8 K), H_c increases with increasing t_{sg}, without saturation. The temperature dependence of H_c obtained in this study is distinct from reported results for the CuMn/Co system where H_c takes a maximum near the blocking point T_b, the temperature where exchange bias disappears.[6] A theoretical prediction for antiferromagnetic/ferromagnetic (AFM/FM) system by Hu *et al.*[8] can be used to partially explain the presented temperature dependence of H_c. The interface coupling in the study includes two contributions from direct coupling and spin-flop coupling, and the original distribution of the easy axis of AFM grains after field cooling was considered. The assumptions seem valid for the spin glass layer. The decrement of H_c at T well below the Neel point matches well with our results, suggesting that the interface coupling of Fe-Au/Ni-Fe at low T dominates by direct coupling. The result is consistent with the model we proposed previously.[7] When T approaches the Neel point, a peak of H_c was predicted due to the domination of spin-flop coupling. This feature is not observed in our case, since spin glass is a disorder system the frustration of which caused by spin-flop coupling would not result in significant increase in H_c.

In order to understand magnetic properties of spin glass layer, hysteresis loops of Fe-Au powder sample were measured at T ranging from 4.2 to 30 K. Before the measurement, the sample was field cooled from RT to 4.2 K. The results are shown in Figs. 2(a) and 2(b). It is clear that an applied field of 5 T is not sufficient to saturate Fe-Au spin glass. Dependence of H_c is plotted in Fig. 2(c), showing decreased H_c with increasing T due to thermal agitation. The decrement of H_c from 1220 to 22 Oe perfectly fits the exponential decay function ($R^2 = 0.9996$), which is consistent with the variation in Fe-Au/Ni-Fe films. The difference in H_c between Fe-Au powder and Fe-Au/Ni-Fe thin films with $t_{sg} = 100$ nm (ΔH_c) is displayed in Fig. 2(d). ΔH_c exponentially decreases from 1025 to 130 Oe with increasing T from 4.2 K to 16 K. Large ΔH_c indicates that the spins of Fe-Au at interface of the bilayer are stable at low T. With increasing T, reduced ΔH_c reveals that the rotation of Fe-Au spins induced by magnetic reversal of the Ni-Fe layer becomes easier. The results confirm the coercive mechanism of Fe-Au/Ni-Fe: at low T, H_c of the Ni-Fe layer is mainly determined by direct coupling of Fe-Au interfacial spins; at higher T, it chiefly comes from extensive reversible rotation of interfacial spins of Fe-Au and defects in the Ni-Fe layer.

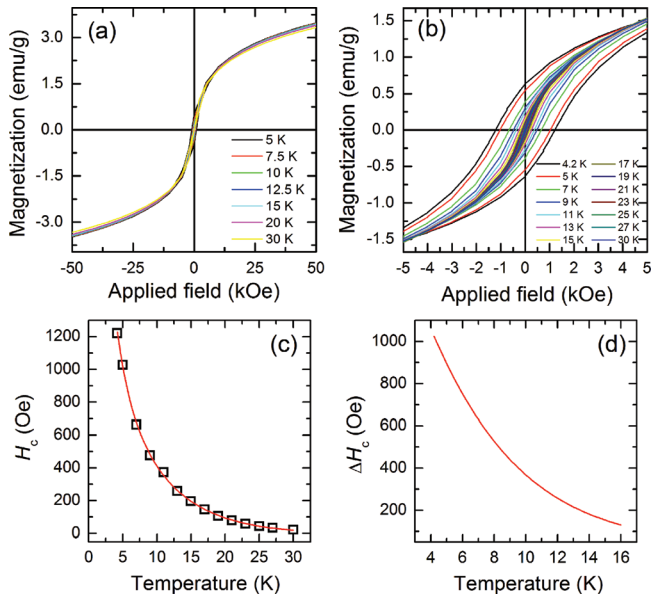

FIG. 2. (Color online) Hysteresis loops for Fe-Au powder sample measured at temperatures from (a) 5 to 30 K with maximum applied field of 5 T, (b) 4.2 to 30 K with maximum applied field of 5 kOe. Dependence on temperature of (c) coercivity H_c and (d) difference in H_c between Fe-Au powder and Fe-Au/Ni-Fe thin films ΔH_c with $t_{sg} = 100$ nm. The experimental data in (d) was fitted to second-order exponential decay function as shown by the solid line.

Training effect for the Fe-Au/Ni-Fe samples with $t_{sg} = 30$ nm was studied. The sample was field cooled to 4.2 K and then raised to the target temperatures of 6, 8, and 13 K to perform the hysteresis measurements. The corresponding results are shown in Figs. 3(a), 3(b), and 3(d), respectively. Figure 3(c) shows the hysteresis loops obtained immediately after the training measurement at 6 K without

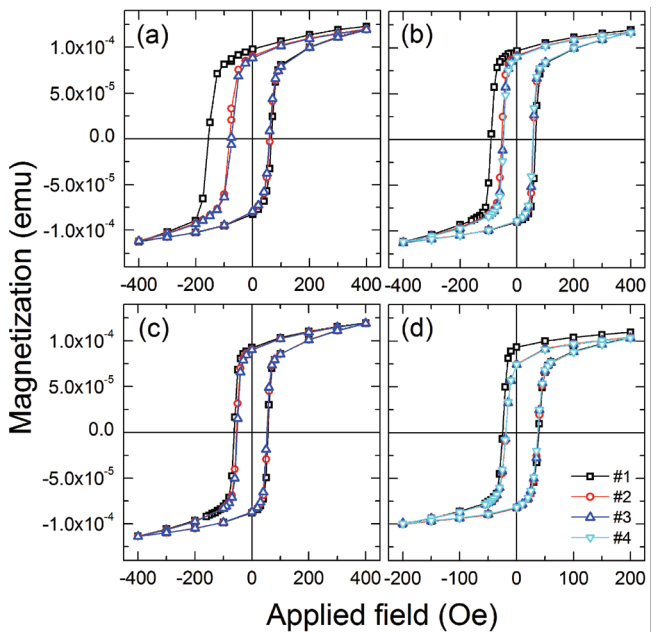

FIG. 3. (Color online) Training effect for the Fe-Au/Ni-Fe samples with $t_{sg} = 30$ nm field cooled at 5 kOe from RT to 4.2 K measured at temperatures of (a) 6 K, (b) 8 K, and (d) 13 K. (c) Training effect at 8 K obtained immediately after the measurement at 6 K without redoing field cooling. Measurements of different cycles are denoted by different symbols.

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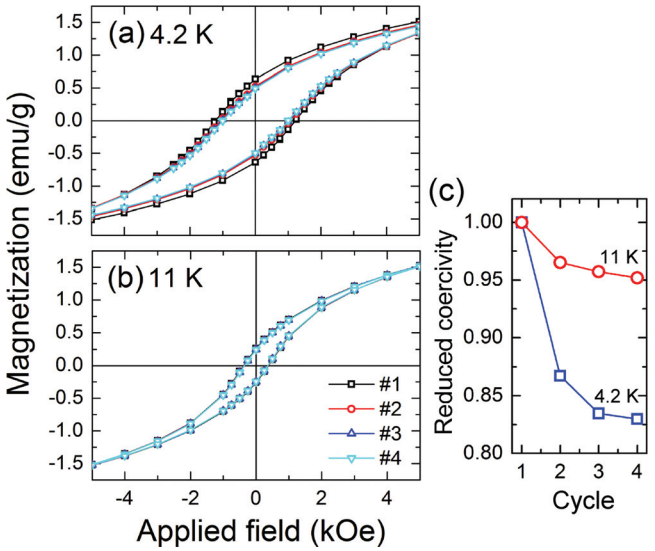

FIG. 4. (Color online) Training effect for Fe-Au powder at (a) 4 K and (b) 11 K. (c) Reduced H_c as a function of hysteresis cycle.

redoing field cooling. The difference in H_c, representing the magnitude of the training effect, was observed only in the descending part of the loop; similar results were found in the AFM/FM systems.[9,10] Training was found only in the first and second loop, consistent with the case of CuMn/Co.[6] In AFM/FM, the training effect is explained as a result of irreversible movement of the domain wall in AFM layer.[11,12] For spin glass, a system without clearly defined magnetic regions, training behavior could be understood as the irreversible rearrangement of spin structure triggered by the magnetic reversal of the Ni-Fe layer and external field. The size of training decreased markedly from 78 to 5 Oe with increasing T, indicating that thermal activation allows the rearrangement of interfacial spins of Fe-Au to be driven at small additional magnetic fields. For the measurement without redoing field cooling, the largely reduced training effect [Fig. 3(c)] indicates that the rearranging of spins nearly completes magnetic reversal of the Ni-Fe layer by the first cycle.

Figures 4(a) and 4(b) show the training effect measured at 4.2 and 11 K, respectively, for the Fe-Au powder sample field cooled from RT to 4.2 K. Dependence of reduced H_c on hysteresis cycle is plotted in Fig. 4(c). The observation of training behavior in Fe-Au confirms the nature of irreversible spin rearrangement induced by a magnetic field; and the temperature dependence evidences the activation of the spins by thermal energy. The training effect in Fe-Au exists even in the fourth cycle, differing from the Fe-Au/Ni-Fe films. This result reveals that interfacial coupling of the magnetic moment of Ni-Fe effectively facilitates the rotation/rearrangement of Fe-Au spins.

In summary, we have reported the coercive mechanism and training effect in Fe-Au/Ni-Fe thin films. Experimental results confirm that direct coupling of interfacial spins to the Ni-Fe layer dominates the H_c of the bilayer at T well below T_b. When T increases, thermal fluctuation activates the spin on Fe-Au, resulting in extensive reversible rotation induced by the magnetic reversal of Ni-Fe. H_c is determined by spin-flop coupling and the defects in Ni-Fe layer. The results confirm the validity of the spin structure model that we have proposed. The study of the training effect indicates the irreversible rearrangement of Fe-Au spins from the field cooling state and reveals the significant role that Ni-Fe plays during the process.

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