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Citation: Applied Physics Letters **82**, 3044 (2003); doi: 10.1063/1.1565711
View online: http://dx.doi.org/10.1063/1.1565711
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/82/18?ver=pdfcov
Published by the AIP Publishing

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(Received 19 November 2002; accepted 10 February 2003)

Exchange bias, H_E, and coercivity, H_C, of antiferromagnetic (AFM)/ferromagnetic bilayers can be adjusted, after deposition, at temperatures *below* the Néel temperature of the AFM by subjecting the samples to large pulsed fields (in excess of $H_{\text{Pulse}}=550$ kOe). The efficiency of the process depends on the AFM system and the direction of the applied field with respect of the unidirectional anisotropy direction. Textured (111) $Fe_{19}Ni_{81}/Fe_{50}Mn_{50}$ bilayers show an H_E reduction and a H_C increase when the pulse field is applied antiparallel to the unidirectional anisotropy, while they only exhibit a reduction in H_C when the pulse is applied parallel to their unidirectional anisotropy. On the other hand, textured (111) NiO/Co bilayers exhibit a change of the angular dependence of H_E when the pulse is applied away from the unidirectional anisotropy. The effects could be caused by field induced changes in the domain structure of the AFM or transitions in the AFM (spin–flop or AFM–paramagnetic). © *2003 American Institute of Physics.* [DOI: 10.1063/1.1565711]

Exchange bias, i.e., the shift of the hysteresis loop along the field axis,[1] resulting from the exchange coupling at the interface between ferromagnetic (FM) and antiferromagnetic (AFM) materials, plays a fundamental role in magnetoelectronic devices.[2] To induce exchange bias, AFM–FM systems are usually either (i) field cooled through the Néel temperature, T_N, of the AFM or (ii) deposited in the presence of a field.[1] At a fixed temperature, the loop shift, H_E, and the coercivity, H_C, of the system are controlled by intrinsic parameters such as AFM–FM coupling at the interface, FM and AFM thicknesses, interface roughness, or grain size.[1] Hence, H_E and H_C should remain fixed after deposition.

However, it has been shown that extrinsic parameters, such as annealing, different cooling procedures, or ion irradiation can tune the values of H_E and H_C after sample growth.[3–9] Irreversible approaches, such as high temperature annealing[3] or ion irradiation[4] induce structural changes in the bilayers. Hence, H_E and H_C can only be adjusted a limited number of times. Among the reversible techniques, cooling through T_N in large fields,[5–7] cooling in combinations of continuous and alternating fields,[8] or cooling in zero field from different magnetization states,[9] all require warming the bilayer above T_N. Another approach to tune H_E and H_C is to go to large negative fields to saturate the FM and to wait a certain time and subsequently carry out the remaining part of the loop.[10] H_E and H_C depend on the waiting time. This procedure can be slow, thus often to enhance its efficiency the samples are warmed close to T_N. Warming the bilayers with AFMs with $T_N \gg 300$ K could induce unwanted structural changes (e.g., interdiffusion) in the system, which could deteriorate the performance of the device.[3] Moreover, in other AFM materials, such as $LaFeO_3$ (Ref. 11) or α-Fe_2O_3,[12] the samples cannot be warmed close or above T_N, either because the AFM decomposes (e.g., $LaFeO_3$) or due to the exceedingly large T_N.

In this letter, we present a reversible process to tune H_E and H_C in exchange biased bilayers, with $T_N > 300$ K, without the need to warm the samples above T_N. The procedure involves applying large field pulses at room temperature (RT). The field induced changes depend on the direction of the applied pulse and the type of AFM material.

Textured (111) $Fe_{19}Ni_{81}/Fe_{50}Mn_{50}$ and textured (111) NiO/Co were studied. The $Fe_{19}Ni_{81}$(10 nm)/$Fe_{50}Mn_{50}$(15 nm) (FeNi/FeMn) bilayer was sputtered at RT onto Corning glass. Nonmagnetic $(Ni_{81}Fe_{19})_{50}Cr_{50}$ was used as buffer and capping layers. A field of $H=400$ Oe was applied during growth to induce a unidirectional anisotropy. The NiO (20 nm)/Co (15 nm) samples were evaporated onto oxidized Si(100) substrates. The NiO layer was *e*-beam evaporated from a Ni ingot in an O_2 atmosphere while the

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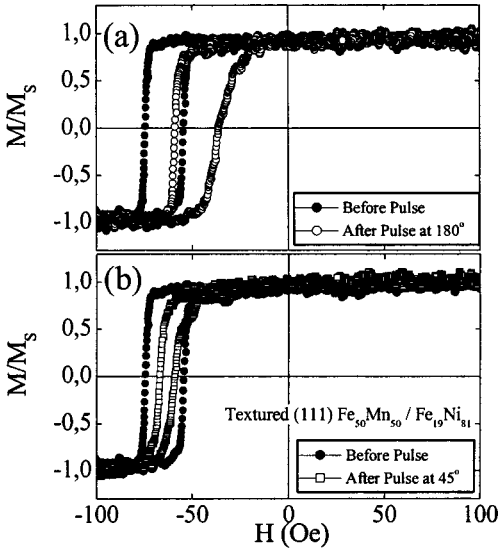

FIG. 1. Hysteresis loops measured along the unideirectional anisotropy direction for a $Fe_{19}Ni_{81}/Fe_{50}Mn_{50}$ bilayer (a) before (●) and after a field pulse at 180° away from the unidirectional anistropy (○) and (b) before (●) and after a field pulse at 45° away from the unidirectional anistropy (□).

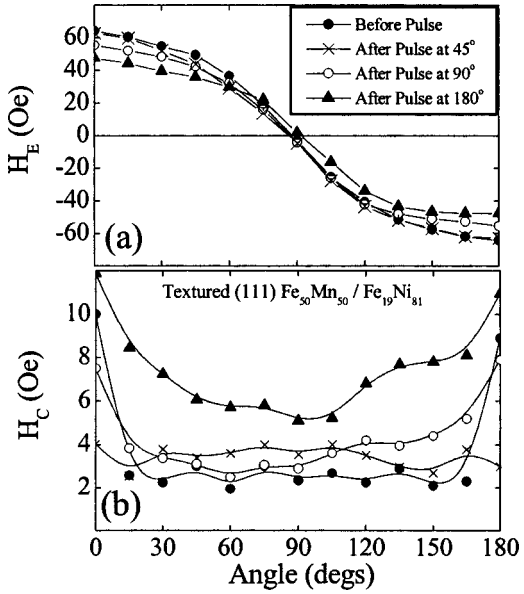

FIG. 2. Angular dependence of the exchange bias, H_E (a), and coercivity, H_C (b), for a $Fe_{19}Ni_{81}/Fe_{50}Mn_{50}$ bilayer before (●) and after the application of pulses along 45° (×), 90° (○), and 180° (▲) with respect to the unidirectional anisotropy. Lines are guides for the eye.

substrate was at $T_S = 200\,^{\circ}C$. Before the Co deposition the O_2 was evacuated to $<2\times10^{-7}$ Torr. The Co layer was *e*-beam evaporated at $T_S = 200\,^{\circ}C$. The samples were capped by an Al layer.

The in-plane dependence of the hysteresis loops was measured at RT using a magneto-optic Kerr effect apparatus, before and after the application of field pulses. The pulsed field was always applied in the sample plane and along different directions with respect to the unidirectional anisotropy direction (UAD). The FeNi/FeMn bilayer was cut in several pieces and pulses were applied at 0°, 45°, 90°, and 180° of the direction of the field applied during growth (i.e., the UAD). For the NiO/Co samples, the pulse was applied at 45° of the direction of maximum H_E. The rise and fall times of the pulse are about 22 and 150 ms, respectively, while the maximum achieved field is $H = 556$ kOe.

Shown in Fig. 1(a) are the hysteresis loops of the FeNi/FeMn bilayer before and after applying a field pulse antiparallel to the UAD. There is a clear reduction of H_E and an increase of H_C, after the 180° field pulse. However, applying a pulse along 45° [Fig. 1(b)] only results in the reduction of H_C. Moreover, the hysteresis loops become more asymmetric after the field pulses. When comparing the angular dependence of H_E and H_C for the FeNi/FeMn bilayer before and after field pulses applied along different directions (Fig. 2), one can observe that the shape of the angular dependence does not change significantly. However, H_E becomes smaller as the pulse direction moves away from the UAD. Remarkably, the coercivity decreases, along the unidirectional axis, for pulses applied at 0° (not shown), 45°, and 90°, while it increases considerably for pulses applied along 180°.

The NiO/Co bilayer exhibits a different behavior (Fig. 3). Although, H_E decreases and H_C increases after a 45° field pulse, the angular dependence of H_E changes considerably. Namely, a new UAD, i.e., the direction with maximum H_E, is created in a direction closer to the pulsed field.

From the results certain trends can be extracted: (i) the field induced changes appear to be maximum for pulses applied antiparallel to the UAD; (ii) the kind of tuning can be controlled by the pulse angle; and (iii) different AFMs with similar microstructure respond differently to the applied pulses.

The described field induced changes could have different origins, such as changes in the AFM domain structure or field induced transitions in the AFM. Several theories outline the importance AFM domains may have in exchange bias.[13] Such AFM domains could be in metastable states. For example, changes in the AFM domain configuration have been claimed to be responsible for time dependence effects[10] or training effects.[14] Thus, such domains could probably be altered by the large pulsed fields. Certainly, in NiO single crys-

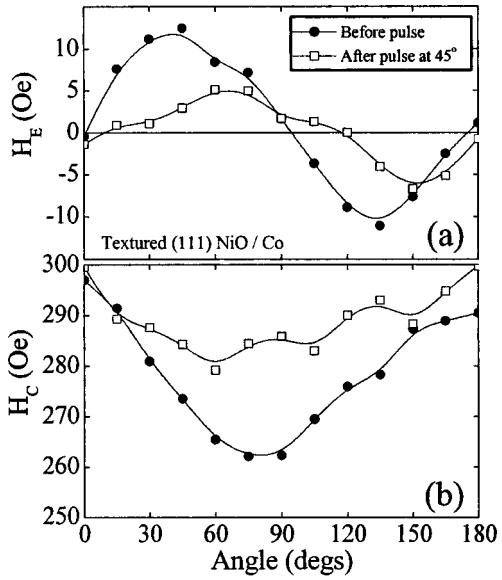

FIG. 3. Angular dependence of the exchange bias, H_E (a), and coercivity, H_C (b), for a NiO/Co bilayer before (●) and after the application of a pulse along 45° (□) away from the unidirectional anisotropy. Lines are guides for the eye.

tals AFM domains have been found to reorient after being subjected to large fields,[15] when in contact with a FM (Ref. 16) or when subjected to strains.[17] Thus, if the AFM domains are modified by the pulse field, this effect should, in turn, influence H_E and H_C or even their angular dependence. Moreover, due to magnetostriction the pulsed fields could generate large strains at the interface, which could affect the AFM domain configuration. Note that since the AFM anisotropy for NiO is much smaller than for FeMn, and in the latter case the unidirectional anisotropy is better established, one would expect larger domain based effects in the NiO case. Although the absolute change in H_E is larger in FeMn, the fact that the angular dependence in textured NiO actually changes after the field pulse could be regarded as an indication of stronger reaction to the field pulse.

AFM materials have, below T_N, a transition from AFM to paramagnetic (PM) at high enough applied fields.[18] Thus, in principle, in order to induce exchange bias it should be analogous to field cooling through T_N or to apply large enough fields (larger than the AFM–PM phase transition) at a given temperature below T_N. In both cases, the AFM reaches a PM state and returns to the AFM state in the presence of a field. Since the samples are textured, i.e., without a clear AFM anisotropy axis in plane, pulses applied away from the original UAD should reset it to the pulse direction. However, the critical field for the AFM–PM transition, $H_{\mathrm{AFM-PM}}$, is proportional to the exchange field of the AFM, which can be rather large in FeMn and NiO due to their large T_N.[18] For example, in bulk NiO, $H_{\mathrm{AFM-PM}} > 4000$ kOe at RT.[19] Therefore, due to the limited strength of the field pulse, AFM–PM transitions would appear as an unlikely cause for the observed effects. However, AFM/FM bilayers typically exhibit rather large distributions of blocking temperatures, ΔT_B,[20–22] with a sizable percentage of the AFM particles having T_B close to RT. Moreover, considering that $H_{\mathrm{AFM-PM}}$ is drastically reduced close to T_N (or T_B) (Ref. 18) this would lead to *some* of the AFM particles to actually being sensitive to the field pulse. Consequently, H_E and H_C could be in practice partially reset. Due to the larger ΔT_B usually observed for NiO,[20,21] this AFM would be expected to be more sensitive to the field pulses. Moreover, ΔT_B will lead to a ''distribution of responses,'' which should result in an asymmetry of the hysteresis loop.[23]

Finally, it is well known that moderate fields applied along the easy axis of the AFM material induce a spin–flop transition[18] (e.g., for the NiO the spin–flop field can be estimated to be ~90 kOe at RT).[19] This transition is known to affect exchange bias for highly crystalline AFM materials.[6] Since the spin–flop transition is rather sensitive to the angle between the AFM easy axis and the applied field,[24] this effect should be expected to be small on textured AFMs (i.e., with a random orientation of AFM easy axes). However, due to random in-plane distribution of crystallites *some* of them would actually have their easy axes aligned within a few degrees of the pulse direction. Hence, a percentage of particles could contribute to the changes observed in the exchange bias properties and the loop asymmeties.

In conclusion, we have demonstrated that H_E and H_C can be controlled at room temperature (i.e., below T_N), after sample growth, by applying pulsed fields. The effects observed in textured $Fe_{50}Mn_{50}$ based bilayers are a decrease in H_E, while H_C can either increase or decrease depending on the direction of the pulsed field. Similar effects are observed in textured NiO based bilayers, although in this case there is a reconfiguration of the unidirectional anisotropy axis towards the pulse direction. Hence, NiO appears to be more sensitive to the pulse, probably due to its smaller anisotropy or its larger T_B distribution. These effects are probably due to field induced transitions in the AFM (AFM–PM or spin–flop) or changes in the AFM domain structure.

This work was supported by CICYT (MAT2001-2555), DGR (2001SGR00189), the Generalitat de Catalunya (ITT2000-14), and Midi Pyrénées Council (CTP Grant). Two of the authors (J.S. and U.L.) thank the DGU and the Marie Curie Fellowship of the European Community program Human Potential (HPMT-CT-2000-00106), respectively.

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