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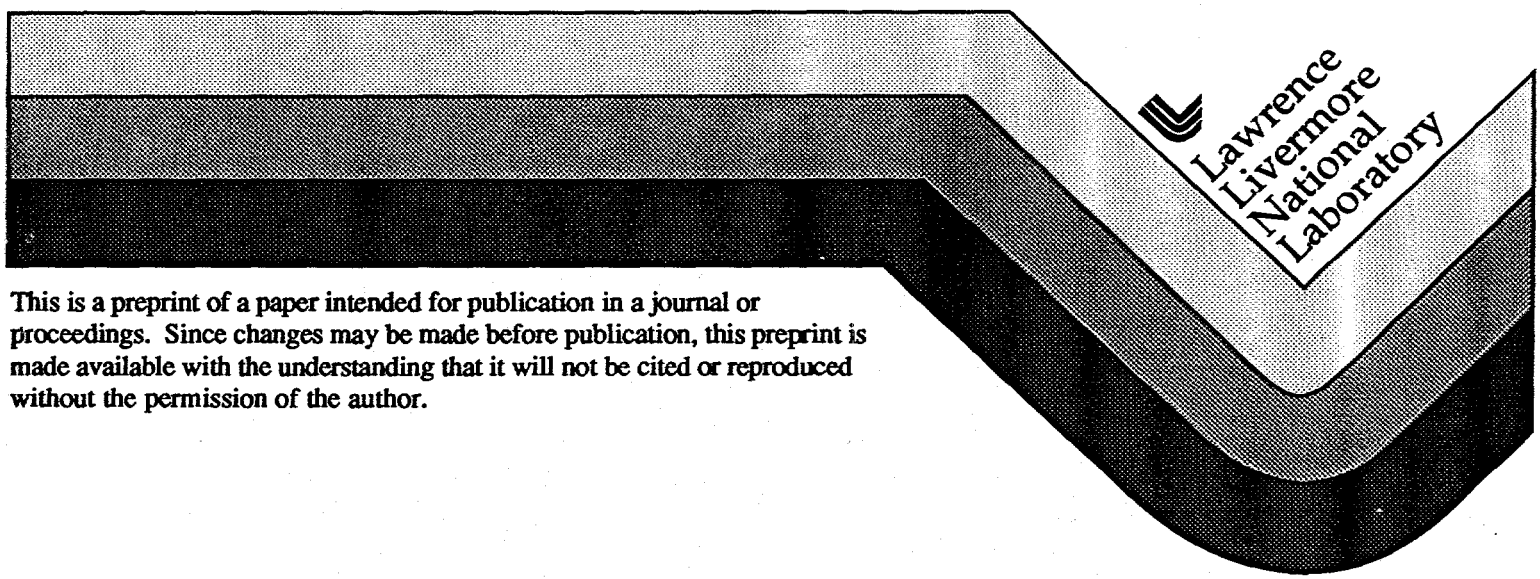

DISCLAIMER

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Abstract --**A new processes for fabricating NiO exchange bias layers has been developed. The process involves the direct ion beam sputtering (IBS) of a NiO target. The process is simpler than other deposition techniques for producing NiO buffer layers, and facilitates the deposition of an entire spin-valve layered structure using IBS without breaking vacuum. The layer thickness and temperature dependence of the exchange field for NiO/NiFe films produced using IBS are presented and are similar to those reported for similar films deposited using reactive magnetron sputtering. The magnetic properties of highly textured exchange couples deposited on single crystal substrates are compared to those of simultaneously deposited polycrystalline films, and both show comparable exchange fields. These results are compared to current theories describing the exchange coupling at the NiO/NiFe interface.**

INTRODUCTION

Antiferromagnetic (AF) NiO buffer layers used to exchange bias ferromagnetic layers and for domain stabilization in magnetoresistive sensors are primarily fabricated using a reactive sputtering technique developed by [1, 2]. Laser ablation[3] reactive MBE[4] and MOCVD[5] have also been employed for this purpose with some success. We have developed a new simpler process for depositing NiO films using ion beam sputtering. The technique involves the direct sputtering of a NiO target and so does not require an oxygen partial pressure.

The ion beam deposition chamber used to deposit the magnetic films has been described elsewhere[6]. A NiO target is sputtered by a neutralized Ar ion beam and the ejected material accumulates on substrates suspended 25 cm above the target. The deposition rate is 0.1 Å/sec. The substrate temperature is approximately 60°C during deposition unless otherwise noted. An uniaxial anisotropy is established in the NiFe layers with permanent magnets which produce a 300 Oe uniform bias field, H_b, at the substrates during deposition. We use high-angle x-ray diffraction (XRD) to study the morphology of the NiO layers and low angle XRD to calibrate the film thickness. A vibrating sample magnetometer equipped with a high temperature oven is used to determine the magnetic properties of the NiO/NiFe coupled films. Rutherford backscattering measurements show that the NiO is stoichiometric to within 1%.

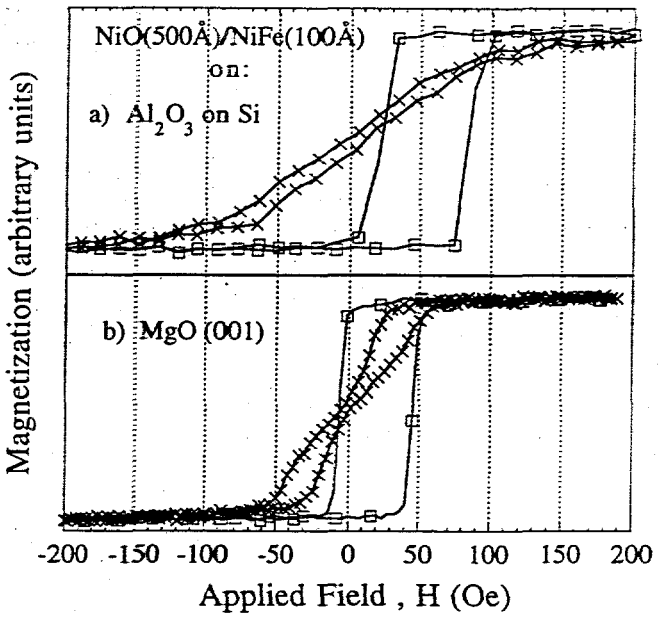

Fig. 1. Magnetization as a function of applied field for two NiO(500Å)/NiFe(100Å) films deposited simultaneously on different substrates are shown. a) shows the easy axis and hard axis response for the film deposited on an amorphous Al_2O_3 film. b) shows the response in the in-plane (100) directions on the (001) face of MgO, parallel and perpendicular to H_b.

EXPERIMENTAL RESULTS

Fig. 1a shows the easy and hard axis magnetization of a NiO(500Å)/NiFe(100Å) bilayer deposited on Si with an amorphous Al_2O_3 film. The NiO film is untextured with a grain size in the growth direction, derived from the FWHM of the NiO(200) Bragg peak, of 80Å. The easy axis loop is

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offset by H_E=56 Oe which corresponds to an interface exchange energy of J=0.04 erg/cm^2. The largest value we observed was J=0.06 erg/cm^2. The energies are in agreement with those observed by [1]. NiCoO/NiFe, and NiO/Co bilayers with promising exchange fields have also been fabricated using this new IBS sputtering technique. Fig. 1b shows the magnetization of a bilayer deposited simultaneously with the films shown in fig. 1a, but on a polished single crystal (001) oriented MgO substrate. XRD shows both the NiO and the NiFe are highly (001) textured. The magnetization of the NiFe shows evidence of both a induced uniaxial anisotropy along the H_b axis, and unidirectional anisotropy defined by the direction of H_b. Fig. 1b shows M(H) in the in-plane (100) directions, one parallel to H_b and one perpendicular to H_b. The exchange field H_E is 20 Oe (J=0.015 erg/cm^2).

The dependence of H_E on the thickness of the IBS grown NiO and NiFe layers was measured. Consistent with other studies[7], the exchange field agrees with $t_{(NiFe)}^{-1}$ behavior for 300Å>$t_{(NiFe)}$>50Å and $t_{(NiO)}$=500Å, as expected from the interfacial origin of the interaction. The H_E is approximately constant for $t_{(NiO)}$>400Å, and decreases to zero at a critical thickness of about 175Å. The easy axis coercivity peaks near the critical thickness. The optimum NiO thickness where the difference between H_E and H_c is maximum is between 400Å and 500Å. Finally we find the training effect, which is the reduction of H_E after multiple field cycles, is largest for NiO thicknesses near the critical thickness. No training effect was observed for NiO films greater than 400Å.

The morphology of the NiO deposited on an amorphous buffer layer is sensitive to the detailed deposition conditions. We have studied the effect of substrate deposition temperature, beam voltage, deposition rate and substrate voltage bias on the texture of 500Å thick NiO layers. We observe NiO(111), (200) and (220) Bragg reflections with various intensities (the positions indicate the NiO lattice is expanded relative to bulk by 1%). We find, however, that H_E is not sensitive to the changes in the bulk NiO morphology detected at this level. Though we find variations in the strength of H_E they are not correlated to variation on the NiO texture. This conclusion is illustrated in fig. 2 where the interface exchange energy, $J=H_EM_st_{(NiFe)}$, for a wide range of NiO(500Å)/NiFe(t_{NiFe}) films is plotted as a function of the ratio of the NiO(111) to the NiO(200) Bragg peak intensities. The data are space filling indicating that the bulk texture of the NiO layer is not a good predictor of the interface coupling strength.

The Neel transition temperature, T_N, for bulk NiO is 250°C. The H_E of NiO/NiFe bilayers typically drops to zero at a lower blocking temperature, T_b, which also varies with the interface and bulk morphological properties of the bilayer couple[7]. The temperature dependence of H_E and H_c of an IBS grown NiO(500Å)/NiFe(50Å) coupled film is shown in fig. 3. H_E drops approximately linearly with increasing temperature reaching a blocking temperature of T_b=200°C in this film. The slope of the decrease in H_E

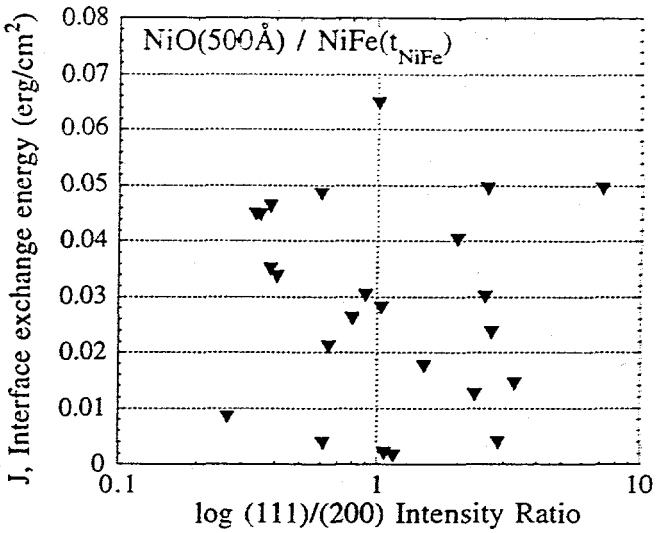

Fig. 2. Interface exchange energy, $J=H_EM_st_{(NiFe)}$, as a function of the x-ray intensity ratio of the NiO(111) to the NiO(200) reflections. The plot shows there is no correlation between the texture of the NiO buffer layer and the resulting exchange field.

with temperature is approximately the same for all of the films measured, indicating that the room temperature exchange field is a good predictor of T_b. H_c also decreases with increasing temperature but at a slower rate reaching the room temperature value of a free NiFe layer (1-2 Oe) at 230°C. Temperature cycles above T_N with subsequent cooling in modest fields reduced H_c of the NiFe from 84 Oe to 60 Oe, but did not change H_E significantly.

In some bilayer films no offset was produced in the NiFe magnetization loop by the NiO buffer, but a large room temperature coercivity as well as a clear uniaxial anisotropy was observed, (H_c=35 Oe H_s= 80 Oe as compared to H_c=1-2 Oe and H_s=5 Oe in a free NiFe layer). This enhanced H_c indicates that interface exchange coupling is present, but that it averages to zero[8],[9]. The temperature dependence of H_c in such a film composed of NiO(355Å)/NiFe(100Å) is also shown in fig. 3. The coercivity drops with increasing temperature similar to the behavior seen in films with H_E>0, reaching 1-2 Oe at 130°C. The hard axis saturation field has similar temperature dependence. The reduced temperature where H_c goes to zero may be a result of a reduced T_N for the thinner NiO layer, however it seems more likely that the reduction is linked in the same way as the lack of H_E to the interfacial properties.

DISCUSSION

The simplest model describing NiO/NiFe exchange coupling indicates the highest H_E should be observed when the NiO surface is oriented to maximize the number of uncompensated spins. i. e. the (111) planes[10]. We have shown that this model clearly does not describe NiO/NiFe exchange couples. The data represented in fig. 2 indicate the bulk texture of the NiO layer has very little influence on

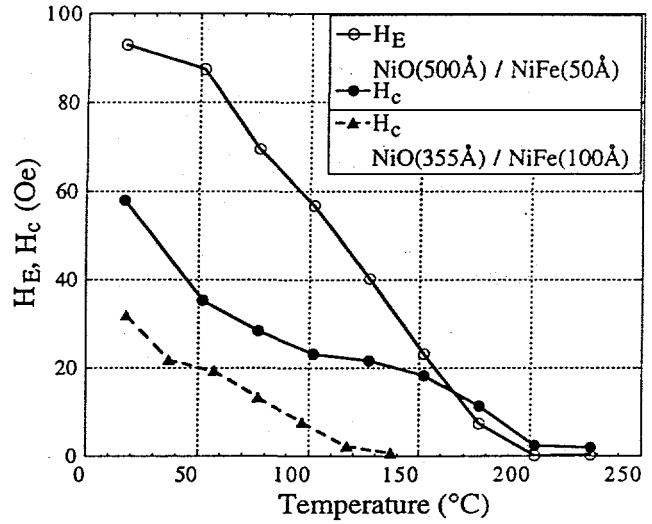

Fig. 3. Exchange field and coercive field for two NiO/NiFe coupled bilayer films as a function of temperature. The circles show H_E and H_c for a strongly exchange biased bilayer. The triangles show H_c for a bilayer with zero exchange field but elevated coercivity due to the interface coupling. H_E goes to zero at the blocking temperature, T_b, which is lower than the bulk Neel phase transition temperature, T_N (T_N=250°C for NiO).

the interface exchange coupling energy since the exchange field does not correlate with the texture of the NiO films. Further, fig. 1b shows a strong H_E for NiFe films grown on the compensated (001) surface which should produce zero exchange field. The substrate properties clearly affect H_E, however, since H_E for the bilayer on MgO is roughly one third that of the polycrystalline film deposited simultaneously on an amorphous buffer layer. This decrease may be the result of the larger grain size or higher interface roughness observed in the bilayer deposited on MgO.

Our results agree with [5] who use an MOCVD technique to grow epitaxial (001) oriented NiO buffer layers. They also find non-zero H_E values for NiFe grown on (001) oriented NiO, which are roughly half what they measure for NiFe grown on polycrystalline NiO buffers. However, they measure isotropic coercivities which are nearly an order of magnitude larger than those of reactively sputtered or IBS NiO films. This difference in coercivity may be due to the elevated surface roughness of the epitaxial MOCVD NiO layers relative to those deposited using the other techniques. [11] describes NiFe layers deposited on single crystal CoO substrates and shows that rougher interfaces or interfaces with more crystalline disorder produce higher exchange fields (CoO has structural and magnetic properties similar to NiO). Growth studies of IBS films indicate the broad distribution of adatom energies present in IBS deposition can produce very smooth surfaces and interfaces[12]. Low angle XRD data on the IBS grown NiO/NiFe bilayers show the surface has approximately 3Å of surface roughness. The IBS NiO grown on MgO(001) is about twice as rough.

In summary, models for the bilayer magnetic response should divide the NiO into two layers. We can estimate the thickness of a surface layer in the NiO, whose spins are dynamic during the NiFe reversal and so are responsible for the large NiFe coercivity, is equal to the critical NiO thickness needed to produce the unidirectional exchange anisotropy. A static NiO layer below the dynamic layer establishes the direction of H_E. Large H_E are observed independent of the average texture of the NiO layer. Thus the interfacial interaction of the NiFe and the NiO is not influenced by the average NiO morphology. Unfortunately it is difficult to probe the properties of the interface independently of the rest of the NiO film and observe the magnetic structures that form. Variations in H_c and H_E in coupled bilayers as well as the presence of a critical thickness, and the training effect, indicate that the dynamics of the interfacial antiferromagnetic domain structure of the NiO during the NiFe magnetization reversal is the key to understanding the magnetic response of oxide based exchange couples[8].

The antiferromagnetic order of the NiO and the presence of non-zero H_E is unaffected by bulk morphological variations. In this sense, the NiO is a more forgiving exchange bias layer than FeMn/NiFe or NiMn/NiFe exchange couples, since these compounds require the specific FCC structure throughout the buffer layer to produce the antiferromagnetic phase and achieve a non-zero H_E[13]. This difference may be due to the more robust antiferromagnetism associated with the super-exchange interaction and ionic bonding in the oxide materials.

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