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Journal of Magnetism and Magnetic Materials 247 (2002) 187–190

journal of magnetism and magnetic materials

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# Magnetic exchange bias enhancement through seed layer variation in FeMn/NiFe layered structures

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Received 30 November 2001

## Abstract

The exchange bias and crystalline texture of the multilayer structure (Ta/Al/seed/$Fe_{50}Mn_{50}$/$Ni_{81}Fe_{19}$/$Al_2O_3$/$Ni_{81}Fe_{19}$/Al/Ta with seed = $Ni_{81}Fe_{19}$ or $Ni_{81}Fe_{19}$/Cu) has been characterized. Measurements indicate an abrupt decrease in exchange bias of the $Ni_{81}Fe_{19}$ pinned layer for samples with very thin seed layers, and exchange bias as high as 325 Oe for thicker seed layers. Fluctuation of exchange bias with thickness was greatly reduced for the $Ni_{81}Fe_{19}$/Cu seed configuration. X-ray diffraction measurements demonstrate a correlation between exchange bias and strong (1 1 1) texture of FeMn. The results suggest a high sensitivity of $Ni_{81}Fe_{19}$ roughness and texture on deposition conditions, and corroborate previous observations of roughness in ultrathin NiFe films. © 2002 Elsevier Science B.V. All rights reserved.

*PACS:* 75.30.Gw; 75.70.Cn

*Keywords:* Exchange anisotropy; FeMn; NiFe

Magnetic tunnel junction (MTJ) based devices are emerging as the most promising candidates for the future development of magnetic random access memory (MRAM) [1,2] and magnetic sensor applications [2]. Thus, the high-yield fabrication of reliable MTJ structures is becoming an increasingly important technical concern. A large exchange biasing between the pinned ferromagnetic (FM) layer and the antiferromagnetic (AFM) pinning layer promotes magnetic stability of the pinned layer, which is key to the production of reliable, high-quality MTJ structures with decreased sensitivity to magnetic noise. The exchange biasing of NiFe/FeMn-based systems is known to be highly sensitive to the crystallographic texture [3–5] and interface roughness [6]. The purpose of the present study is to characterize the dependence of exchange bias on seed layer thickness and composition.

Two types of MTJ multilayer samples were prepared, both types having the overall structure (Ta 50 Å/Al 200 Å/seed/FeMn 120 Å/$Ni_{79}Fe_{21}$ 60 Å/$Al_2O_3$ 14 Å/$Ni_{79}Fe_{21}$ 120 Å/Al 200 Å/Ta 50 Å). In the present study, layers above the 60 Å NiFe pinned layer are inconsequential. The inclusion of these layers was intended only to allow for subsequent patterning of the multilayer samples

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PII: S0304-8853(02)00156-7

into working MTJ structures. For Type I samples, seed = ($Ni_{79}Fe_{21}$ $X$ Å) where $X$ is varied from 0 to 100 Å. For Type II samples, seed = ($Ni_{79}Fe_{21}$ $X$ Å/ Cu 15 Å) where $X$ is varied from 10 to 80 Å. The multilayers were deposited by DC magnetron sputtering in 5 mTorr of Ar on thermally oxidized Si substrates. To induce a uniaxial magnetic anisotropy in the NiFe layers, films were deposited at ambient temperature in a uniform magnetic field of ~150 Oe. Deposition rates of 2–4 Å/s were used, with rate calibration determined by low-angle X-ray diffraction measurement of single-layer films sputtered at working power. Typical base pressure of the vacuum chamber was $<4\times10^{-8}$ Torr.

After deposition, the samples were cut into $1\times1\,\text{in}^2$ quarter-wafers. To further enhance the magnetic properties of the samples, and especially the exchange biasing of the pinned layer, the quarters were annealed at 168°C for 5 min, and then allowed to cool in the presence of a strong (~480 Oe) unidirectional magnetic field. Hysteresis loops of the annealed quarters were measured at room temperature by vibrating sample magnetometry (VSM), while crystallographic texture of the samples was characterized by high-angle X-ray diffraction. To verify reliability of the magnetic measurements, reproducibility of the annealing process, and uniformity of the samples, the hysteresis loops of two independently annealed quarter-wafers were compared for each of the Type I samples. To allow for the comparison of X-ray peak intensities, all diffraction measurements were performed using identical X-ray system parameters.

Fig. 1 shows a representative series of hysteresis loops for Type I multilayers, labeled according to the NiFe seed layer thickness ($X$). The sub-loop near zero field is associated with the free NiFe layer, which serves as the top electrode in a MTJ. For $X=0$ and 10 Å, the exchange bias of the pinned layer is negligible and the switching of the free and pinned layers is indistinguishable. For $X=30$ Å, the offset sub-loop, corresponding to the pinned NiFe layer, exhibits a substantial exchange bias ($H_E \sim 250$ Oe). It is the exchange bias of the pinned layer, which serves as the bottom electrode in a MTJ, that is our main concern in this study. For $X$ larger than 10 Å, the seed layer will also contribute to the sample magnetization. For Type I samples, the seed layer will be exchange biased and appear as an offset sub-loop, sometimes nearly coincident with the pinned sub-loop.

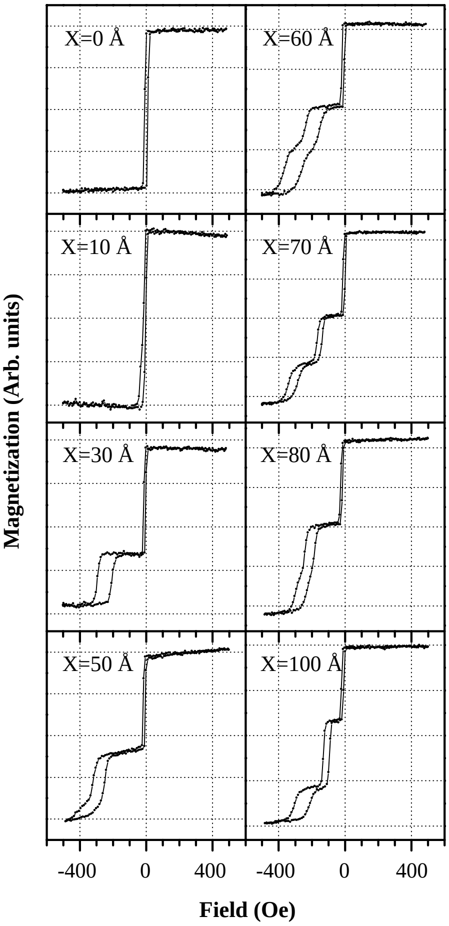

Fig. 1. Hysteresis loops after post-process annealing as a function of seed layer thickness ($X$) for samples without a Cu spacer layer.

The primary result of this study is given in Fig. 2, which shows the exchange bias of the pinned layer as a function of the seed layer thickness for both Type I (a) and Type II (b) structures. Several samples exhibit very large exchange biasing near 325 Oe. The two data points for each thickness in Fig. 2(a) correspond to magnetic measurements of two different quarter-wafers from a single sample. The close agreement

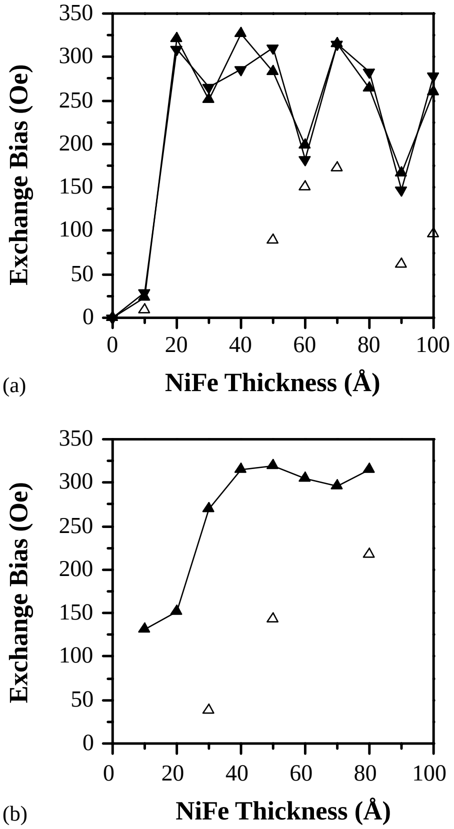

Fig. 2. Dependence of exchange bias ($H_E$) on seed layer thickness for samples before (open symbols) and after (closed symbols) post-process annealing: (a) no spacer layer; (b) 15 Å Cu spacer layer between seed and pinned layers.

of the two data series indicates a high level of sample uniformity.

Referring to Fig. 2(a), we see that the Type I structures exhibit a sharp decline in exchange bias for a 10 Å seed layer, while exchange bias disappears completely when the seed layer is eliminated. Clearly, there is some minimal seed layer thickness, >10 Å, which is necessary to achieve high exchange bias. The best seed layer, however, may not be a single NiFe layer. A 15 Å Cu spacer layer, inserted between the NiFe seed layer and the FeMn AFM layer, can also improve the exchange bias, as shown in Fig. 2(b). For a very thin NiFe seed layer, the insertion of a Cu spacer increases exchange bias by as much as 100 Oe. As the NiFe seed layer becomes thicker, this enhancement effect disappears.

The enhancement of exchange bias due to a given seed layer is a measure of the degree to which the seed layer promotes textured growth of the AFM layer. For the case of FeMn/NiFe, it is well known that the exchange bias is maximized for (1 1 1)-oriented layers [3]. Clearly, discontinuity or roughness of the seed layer will heavily impact the AFM growth. In a previous study of ultrathin NiFe films, a sharp increase in roughness-to-thickness ratio was observed for NiFe films below a 16 Å threshold thickness [7]. Our results suggest that the observed drop-off in exchange bias is a feature of the roughness of the ultrathin NiFe seed layer. The discontinuity and rough surface topography of a 10 Å NiFe seed layer impedes the growth of a well-textured FeMn layer, while a thicker NiFe layer, or the addition of a Cu spacer layer, reduces the roughness-to-thickness ratio and assists the growth of the FeMn layer.

For the larger seed layer thicknesses, exchange bias of the pinned layer fluctuates with no clear trend. Our observation of a relatively constant exchange bias for Type II multilayers (Fig. 2b) leads us to believe that this fluctuation of exchange bias is an indication of the sensitivity of NiFe texture and roughness on deposition conditions. Taking this view, the Cu spacer layer, possibly due to the superior lattice match between its (1 1 1) texture and the desired (1 1 1) texture of FeMn, serves to mitigate the bias fluctuation, allowing for more consistent fabrication of high-bias junctions. Although care was taken to ensure the uniformity of deposition conditions for each of the samples prepared in this study, our X-ray measurements, discussed below, reveal consistent shifts in sample characteristics from one fabrication run to the next.

To facilitate a comparison between exchange bias and FeMn texture, high-angle XRD measurements and an additional series of VSM measurements were performed on a subset of both Type I and II samples. For this part of the study, all measurements were performed on the samples as deposited, without benefit of post-process annealing. These pre-anneal magnetic measurements are included in Fig. 2. Our results show that annealing leads to a consistent and considerable increase in exchange bias. In most cases, we also observed a coincident decrease in pinned layer coercivity after annealing.

The significant results from our XRD measurements are shown in Fig. 3. The data for a series of representative X-ray diffraction peaks is displayed in Fig. 3(b). A plot of the (1 1 1) FeMn peak amplitudes in log scale versus measured exchange bias is given in Fig. 3(a), where different symbols correspond to distinct fabrication runs. Our data shows a roughly exponential relationship between exchange bias and the FeMn(1 1 1) peak intensity. The trend is clear; those samples with larger exchange bias exhibit larger and more well-defined X-ray diffraction peaks corresponding to FeMn(1 1 1) crystallographic texture. This relationship tells us that the enhancement of exchange bias through seed layer composition arises primarily from the promotion of a strong (1 1 1) texture of FeMn. Fig. 3 also shows a distinct shift of the exponential relationship for those samples grown during different fabrication runs. This observed shift is further evidence of the sensitivity of texture and interfacial characteristics on small and uncontrollable variations in growth conditions.

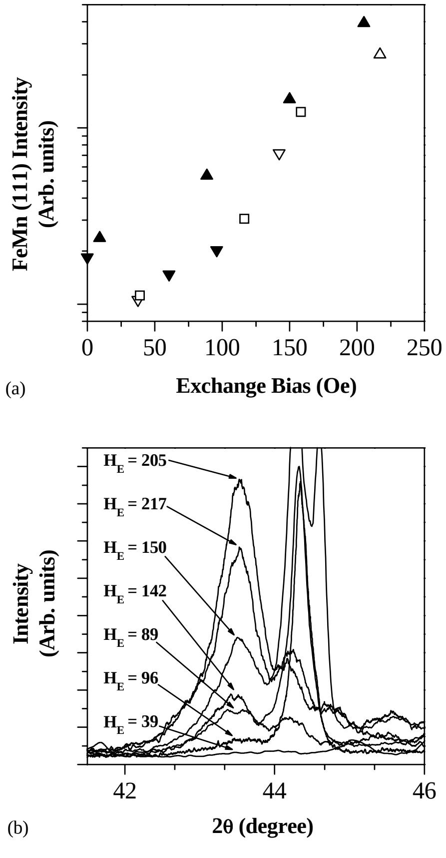

Fig. 3. High-angle XRD scans reveal relation between exchange bias and crystalline texture: (a) FeMn ⟨1 1 1⟩ XRD peak amplitude for samples with (open symbols) and without (closed symbols) Cu spacer layers; (b) Representative X-ray diffraction scans, with FeMn ⟨1 1 1⟩ peaks labeled by corresponding exchange bias.

In summary, the choice of a compatible seed layer of sufficient thickness is critical to the fabrication of reliable, strongly biased MTJ structures. A popular seed layer choice, NiFe, results in a highly degraded exchange bias for smaller thicknesses, and significant fluctuations in exchange bias for larger thicknesses. These features likely result from interface roughness and the sensitivity of NiFe growth on deposition conditions. Topping the NiFe seed layer with a thin Cu spacer layer can reduce this sensitivity, resulting in more reproducible junction fabrication. Finally, the relationship between exchange bias and FeMn texture demonstrates the importance of the textured growth of FeMn and suggests the use of XRD as a tool for the prediction of exchange bias when direct magnetic measurements are unfeasible or undesirable.

This work was supported by National Science Foundation Grant No. DMR-0071770.

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