

Ferromagnetic Coupling Field Reduction in CoFeB Tunnel Junctions Deposited by Ion Beam

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Abstract—In this paper, junctions with reduced H_f coupling were fabricated by ion beam deposition and oxidation, using CoFeB electrodes. The CoFeB layer has a strong (111) texture that can be the origin of lower H_f and coercivity when compared with CoFe. Junctions processed down to $2 \times 4 \mu\text{m}^2$ with 40-Å-thick CoFeB bottom electrodes have 42% of tunneling magnetoresistance (TMR), ($R \times A \sim 400 \Omega \cdot \mu\text{m}^2$), H_c of ~ 10 Oe and H_f of ~ 2 Oe. CoFe-based junctions ($R \times A \sim 500 \Omega \cdot \mu\text{m}^2$) have lower TMR ($\sim 35\%$) and larger H_f (~ 5 – 6 Oe) and H_c (~ 12 – 14 Oe). Local chemical composition analysis of the cross section indicated Fe-O segregation with very little Co grown on top of the barrier for CoFe-based junctions and not for CoFeB ones.

Index Terms—CoFeB electrodes, ion beam deposition, low ferromagnetic coupling, tunnel junctions.

I. INTRODUCTION

THE USE OF magnetic tunnel junctions for MRAM or sensor applications requires precise control of the switching characteristics together with control of the ferromagnetic coupling between pinned and free layers [1].

The reduction of the ferromagnetic coupling in tunnel junctions has been addressed in various ways, e.g., by incorporating amorphous buffer layers reducing topology [2], or by using synthetic ferromagnetic structures reducing the effective moment [3]. Both cases contribute to a reduction of the ferromagnetic Néel's coupling. In this paper, the coupling field of magnetic tunnel junctions is reduced down to few oersted (or even zero in patterned structures) using ion beam deposited CoFeB electrodes. Amorphous or nanocrystalline CoFeB films have been previously used in spin valves and tunnel junctions for their soft properties.

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II. EXPERIMENTAL DETAILS

The tunnel junctions described in this paper were fabricated by ion beam deposition and oxidation using a Nordiko3000 tool [4] and have the structure (thickness in Å): Al 600/smooth/Ta 90/NiFe 50/ MnIr 90/X 40/Al 9+oxid/ Y 30/ NiFe 40/Ta 30/TiWN₂ 150 (X = CoFe or CoFeB, Y = CoFe, CoFeB or NiFe). The film composition is: Ni₈₀Fe₂₀ (NiFe), Co₈₂Fe₁₈ (CoFe) and Mn₇₄Ir₂₆ (MnIr). The CoFeB films were prepared from a bulk target with nominal composition Co_{73.8}Fe_{16.2}B₁₀ (Co:Fe ratio of 82:18). Heavy Ion ERDA measurements (35 MeV ³⁵Cl⁷⁺ beam) [5] indicated 9.9 ± 1 (at.%) of Boron incorporated in the films. CoFeB and CoFe films (500 Å) were measured with a DMS 880 Vibrating Sample Magnetometer (VSM). The magnetic moment of CoFeB films is 80% of the CoFe: $M_{\text{CoFeB}} = 1040 \text{ emu/c}^3$ ($H_{\text{c hard}} = 1.0$ Oe, $H_{\text{c easy}} = 2.1$ Oe), $M_{\text{CoFe}} = 1294 \text{ emu/c}^3$ ($H_{\text{c hard}} = 6.1$ Oe, $H_{\text{c easy}} = 13.6$ Oe). The crystalline structure of CoFe and CoFeB films (200 Å) was investigated by X-rays, in a Siemens D5000 tool. The 600-Å-thick Al electrode was heated at 450 °C and then smoothed by grazing ion milling [6] prior to the junction deposition. The barrier was formed by remote plasma oxidation of the 9-Å-thick Al films, where the oxidizing ions are not extracted ($V^+ = V^- = 0$ V) and reach the sample with an energy of ~ 20 eV. After deposition, the structures were annealed 10 min at 280 °C, in vacuum, under a magnetic field of 3 kOe during heating and cooling.

Unpatterned junctions were characterized by VSM. Also, the junction cross section (for junctions deposited on Si/SiO₂ substrates) was analyzed by transmission electron microscopy (TEM) in an FEI Tecnai F20 transmission electron microscope operated at 200 keV and equipped with a field emission gun, an EDAX X-ray detector and a Gatan ENFINA electron spectrometer. Analysis of the chemical composition was performed locally by electron energy loss spectroscopy (EELS) using Gatan Digital Micrograph and Digiscan software. Transport measurements were done on junctions patterned by photolithography down to $2 \times 4 \mu\text{m}^2$, using a fully automated KLA1007E wafer prober (incorporating a small pancake coil to generate magnetic fields), in a 4-lead configuration.

III. RESULTS AND DISCUSSION

Fig. 1 shows the cross-sectional dark field STEM picture of junctions with X = Y = CoFe (CoFe-based) and X = Y = CoFeB (CoFeB based). In all samples analyzed, the continuous AlOx barrier is clearly seen as a narrow dark line. On the samples studied, the CoFe top electrode showed oxidized

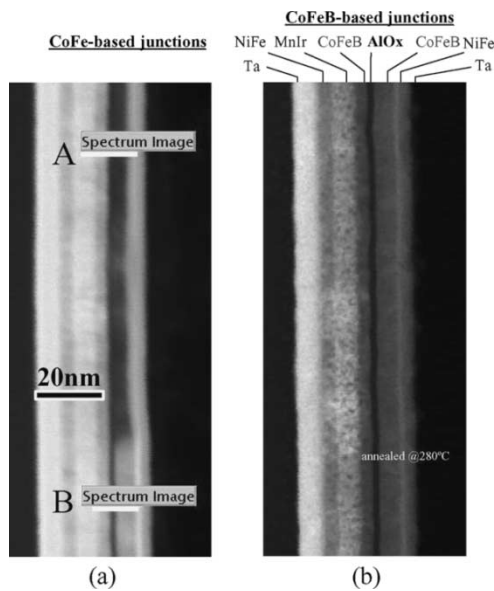


Fig. 1. Dark field STEM pictures of tunnel junction structures with (a) CoFe and (b) CoFeB electrodes. Both samples were annealed at 280 °C. The oxide layers are in black.

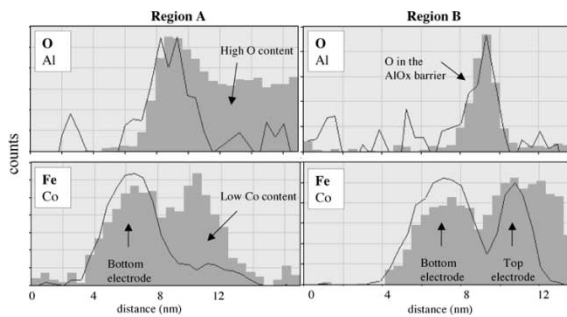


Fig. 2. Line profiles for O, Al, Fe, and Co extracted from a EELS spectrum image of CoFe-based junctions in regions A and B (see the lines marked in Fig. 1). Fe-O segregation on the top electrode was observed in CoFe-layers, not for NiFe or CoFeB.

regions extending over several micrometers [in Fig. 1(a), oxides appear dark and metals light; in region A, the top CoFe can barely be distinguished from the AlOx barrier, in region B clean CoFe/AlOx/CoFe interfaces are seen], while the CoFeB electrodes [Fig. 1(b)] were both nonoxidized. Fig. 2 shows the EELS elemental profiles in the two regions of the CoFe top electrode: segregation of Fe–O and very little Co presence is clearly seen in region A, while the expected elemental profiles were measured in region B. No evidence of these oxidized regions were observed in NiFe and CoFeB-based junctions.

High-resolution electron microscopy of the CoFe and CoFeB layers suggested crystals with similar grain sizes of ~ 10 nm and it appeared that there was some (111) texturing. This result was unexpected for the CoFeB films (40 Å thick), since other groups obtained amorphous films when $\sim 10\text{at\%}$ of Boron was incorporated [7].

X-ray measurements of bulk CoFe and CoFeB 200 Å thick films (Fig. 3) confirmed that the CoFeB films are not amorphous. In fact, the spectra show clearly the existence of a peak around 45.3° corresponding to a strong texture enhancement

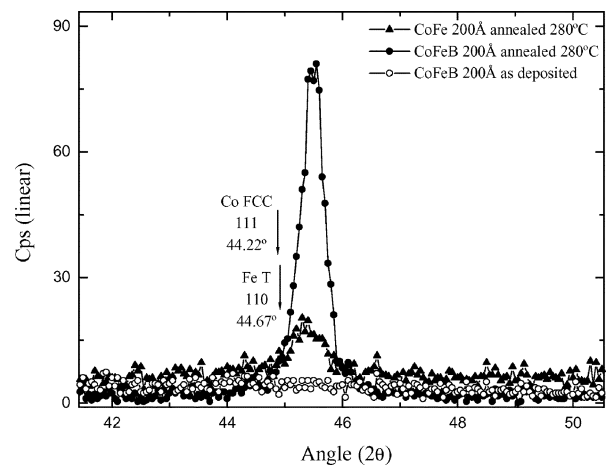


Fig. 3. X-rays measurements of Si/SiO₂/CoFe or CoFeB 200 Å thick films. The arrows show the position of Co (111), Fe (110) (tabled).

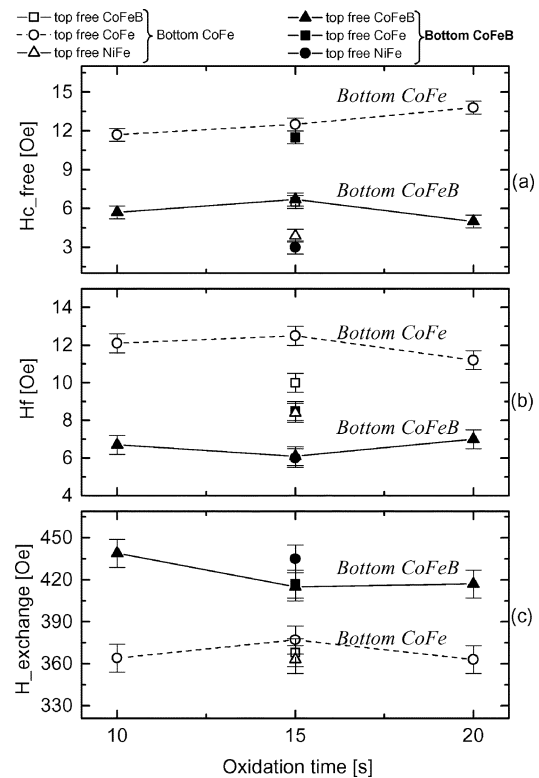


Fig. 4. VSM measurements of unpatterned tunnel junctions with different electrodes, as a function of the barrier oxidation time. Samples were annealed at 280°C.

upon annealing. The intensity of the peak is much larger for CoFeB films than for the CoFe.

The junctions were also characterized by vibrating sample magnetometry (VSM). In Fig. 4 the free layer coercivity ($H_{c\text{ free}}$), the ferromagnetic coupling between both electrodes (H_f), and the exchange coupling field of the pinned layer (H_{exch}) are plotted for several top-bottom electrode material combinations and barrier oxidation times. For these bottom-pinned structures, the H_f [Fig. 4(b)] is significantly reduced from ~ 12 Oe (with bottom CoFe) to ~ 6 Oe (with bottom CoFeB). The coercivity of the top-free electrodes (either CoFe or CoFeB) is also decreased from ~ 13 Oe to 6

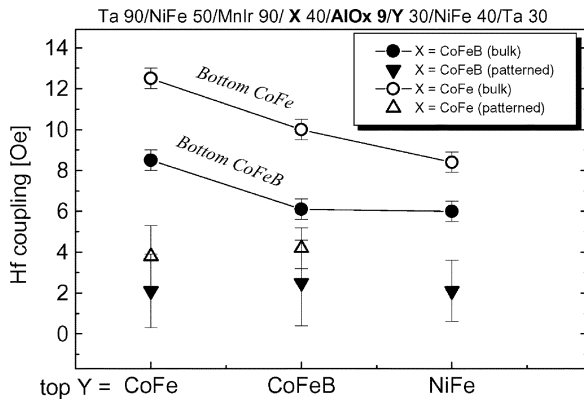


Fig. 5. H_f coupling dependence on the materials (X, Y) used for the electrodes. Data is shown for unpatterned samples and for processed junctions (error bars include dispersion within a sample).

Oe if bottom CoFeB electrodes are used [Fig. 4(a)]. Notice that the CoFeB free-layer coercivity values are closer to those obtained with NiFe rather than with CoFe. This is probably a consequence of the strong (111) texture of the CoFeB films, as described previously in Fig. 3. The improved crystalline texture can also be the reason for the higher exchange coupling [Fig. 4(c)] measured for the CoFeB-based junctions (~ 420 Oe), when compared with CoFe-based ones (360 Oe).

Fig. 5 shows the effect of different CoFe/CoFeB electrode combinations on the coupling field. Again, it is clear that using CoFeB in the bottom electrode reduces the H_f coupling significantly, independently of the top electrode material. The demagnetizing field further compensates H_f in patterned junctions, leading to an effective coupling field than can be even negative.

Junctions were processed and measured automatically, and the results were mapped over the sample area (not shown in this paper). Typical junctions with 40-Å-thick CoFeB bottom electrodes show 42% TMR ($R \times A \sim 400 \Omega \cdot \mu\text{m}^2$), H_c ranging from 6 to 12 Oe and H_f of 2–3 Oe. The AlOx barrier growth is in a first approximation independent of the electrode used, since breakdown voltages of ~ 1 V were measured using either CoFe or CoFeB. However, CoFe-based junctions ($R \times A \sim 500 \Omega \cdot \mu\text{m}^2$) have lower TMR ($\sim 35\%$) and larger H_f (~ 5 –6 Oe) and H_c (~ 12 –14 Oe), which can be related to the partially oxidized CoFe electrode as found by TEM (Fig. 1).

Higher TMR values were obtained using thicker CoFeB bottom electrodes (50 or 60 Å, instead of the standard 40 Å). Fig. 6(a) shows the transfer curve of a junction ($2 \times 4 \mu\text{m}^2$) with $X = \text{CoFeB}$ (50 Å) and $Y = \text{CoFe}$. Most of the 540 junctions processed with this structure showed TMR $> 44\%$, with the maximum of 47.6%. The histogram plot H_f coupling measured for one sample is shown in Fig. 6(b), where values ranging from ~ 0 to 12 Oe are obtained. The spread in values is related to the different junction areas used in the mask layout (from 50 to $8 \mu\text{m}^2$), so that the lower H_f values correspond to junctions with the lower areas, thus with the higher magnetostatic coupling field. The H_f measured for the unpatterned samples is ~ 8 Oe. Notice the large coercivity (22 Oe) of the CoFe free layer, in the transfer curve. In fact, Fig. 7 shows that the use of CoFeB bottom electrodes thicker than 40 Å increases the free layer

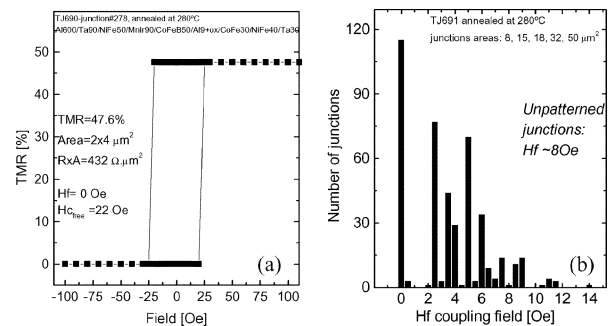


Fig. 6. (a) Transfer curve for a $2 \times 4 \mu\text{m}^2$ junction with increased bottom electrode thickness ($X = \text{CoFeB}$, 50 Å) and (b) statistics on the H_f coupling fields over 540 junctions measured on a sample.

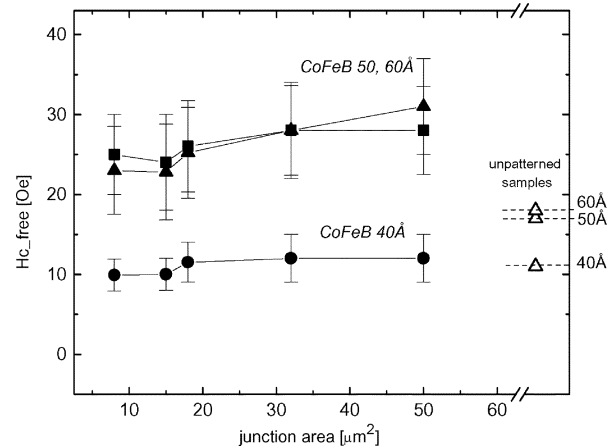


Fig. 7. Dependence of the CoFe free layer coercivity on the junction area, for 40, 50, and 60 Å thick bottom CoFeB electrodes. The error bars show the dispersion on the measurements for different junctions in each sample.

coercivity from ~ 10 Oe (similar to that obtained in Fig. 4(a) for unpatterned CoFeB 40 Å/AlOx/CoFe junctions) up to ~ 30 Oe (60 Å of CoFeB).

These results show that either the H_f and TMR can be further improved by controlling the microstructure and the oxidation conditions.

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