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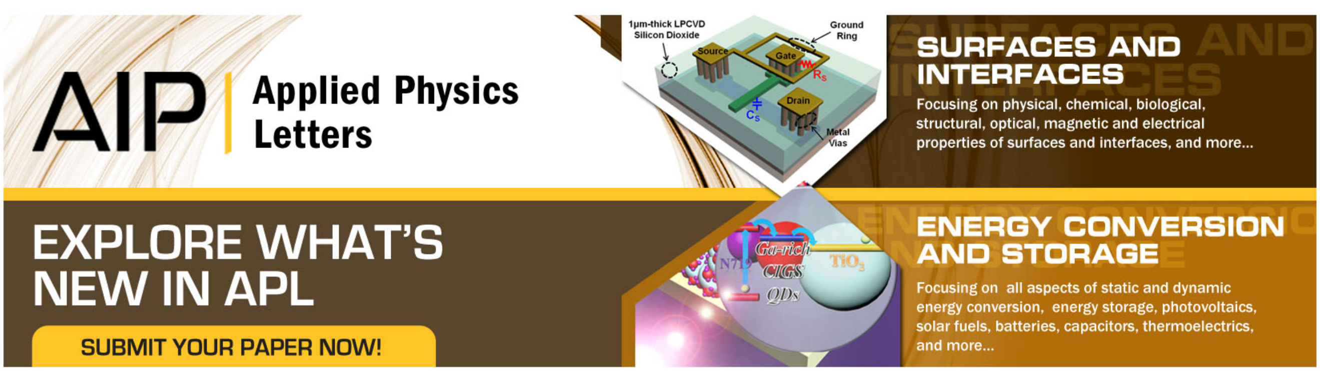

Switching current reduction using perpendicular anisotropy in CoFeB–MgO magnetic tunnel junctions

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We present in-plane CoFeB–MgO magnetic tunnel junctions with perpendicular magnetic anisotropy in the free layer to reduce the spin transfer induced switching current. The tunneling magnetoresistance ratio, resistance-area product, and switching current densities are compared in magnetic tunnel junctions with different CoFeB compositions. The effects of CoFeB free layer thickness on its magnetic anisotropy and current-induced switching characteristics are studied by vibrating sample magnetometry and electrical transport measurements on patterned elliptical nanopillar devices. Switching current densities $\sim 4\ \mathrm{MA/cm^2}$ are obtained at 10 ns write times. © *2011 American Institute of Physics*. [doi:10.1063/1.3567780]

Magnetoresistive random access memory (MRAM) utilizing the spin transfer torque (STT) effect[1–4] is of great interest as a nonvolatile memory candidate for both embedded and standalone applications.[5–11] It combines advantages such as high speed, nonvolatility, high density, and high endurance in a single scalable memory technology. MgO-based magnetic tunnel junctions (MTJs) have emerged as the predominant candidates for STT-MRAM bits, offering high tunneling magnetoresistance (TMR) and resistance-area (RA) products compatible with read and write in complementary metal-oxide-semiconductor (CMOS) technology. A major MTJ development challenge that needs to be overcome to ensure viability and scalability of this technology is to reduce the write currents required for current-induced switching. A large switching current increases the transistor size required for write operation (limiting the memory density), as well as increasing the write voltage, affecting energy dissipation and device endurance.

The switching current of an in-plane MTJ can be reduced by increasing the perpendicular anisotropy of the free layer, to counteract the effect of the large out-of-plane demagnetizing field which inhibits current-induced switching.[12–15] The switching current density J_c in an MTJ with in-plane and collinear free and fixed layers is given by $J_c \approx (2e\alpha M_s t/\hbar\eta)(H_k+(H_d-H_{k\perp})/2)$,[12] where α is the free layer damping factor, η is the spin-transfer efficiency, M_s and t are the free layer saturation magnetization and thickness, H_k is the in-plane shape-induced anisotropy field, $H_d \approx 4\pi M_s \gg H_k$ is the out-of-plane demagnetizing field, and $H_{k\perp}$ is the free layer perpendicular anisotropy. Increasing $H_{k\perp}$ can reduce J_c by partially cancelling the effect of the out-of-plane demagnetizing field H_d.

Several works have reported perpendicular anisotropy in magnetic films aimed to reduce the switching current of in-plane spin-transfer devices, or realization of fully perpendicular MTJs. These reports have mostly focused on layered structures involving transition metals such as Co, Ni, and Fe along with nonmagnetic metals such as Pt or Pd to realize the perpendicular anisotropy.[14–18] The application of these materials is limited by increased damping, difficulties of integrating them into MTJs with high TMR, and the difficulty of realizing large perpendicular anisotropy in thin ($<\sim 2$ nm) films of these materials. The recent discovery of a significant perpendicular anisotropy in Fe-rich CoFeB films[19,20] allows for exploring switching current reduction by counteracting the out-of-plane demagnetizing field in CoFeB–MgO MTJs with high TMR. In this work, it is shown through both magnetic and electrical measurements that the switching current density and perpendicular anisotropy in Fe-rich CoFeB films are strongly dependent on the free layer thickness. Switching current densities $\sim 4\ \mathrm{MA/cm^2}$ for 10 ns pulse widths were obtained by optimizing the free layer thickness.

Material stacks were deposited in a Singulus TIMARIS physical vapor deposition (PVD) system. Test structures with a composition of Ta (5 nm)/MgO /$Co_{20}Fe_{60}B_{20}$/Ta (5 nm) were deposited and annealed at 300 °C for 2 h in an in-plane field of 1 T. The thickness of the $Co_{20}Fe_{60}B_{20}$ layer was varied to study the effect of film thickness on anisotropy. Results of vibrating sample magnetometry (VSM) measurements on these samples are shown in Fig. 1. A clear perpendicular anisotropy is evident, which increases with decreasing film thickness. The results indicate a transition thickness ~ 1.5 nm. This is consistent with electrical measurements on full MTJ stacks with thicker free layers showing in-plane anisotropy characteristics, as described below. The CoFeB thickness dependence of the saturation magnetization [inset in Fig. 1(a)] indicates a magnetically dead layer with a thick-

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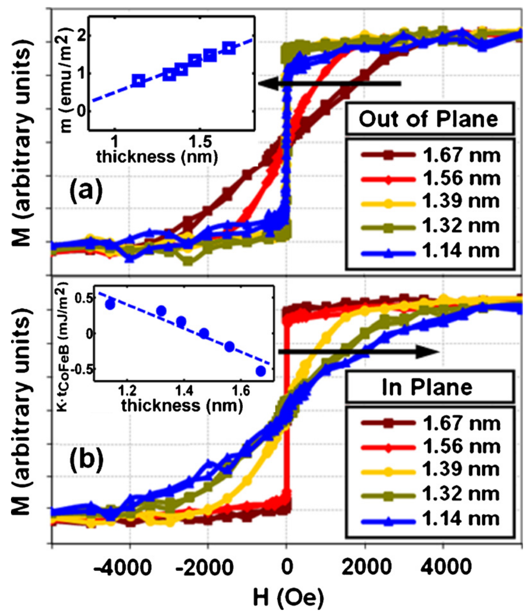

FIG. 1. (Color online) VSM measurements with (a) out-of-plane and (b) in-plane magnetic fields on test structures with varying $Co_{20}Fe_{60}B_{20}$ thickness, showing an increase in perpendicular anisotropy with decreasing film thickness (indicated by arrows). Inset in (a) shows the measured magnetic moment as a function of film thickness, indicating a magnetically dead layer with thickness of approximately 0.7 nm. The dashed line shows a linear fit to the data. Inset in (b) shows the dependence of total perpendicular anisotropy K on film thickness, obtained from VSM results, which is consistent with an interfacial origin of the perpendicular anisotropy described by $K = K_{\perp}/t_{\mathrm{CoFeB}} - 2\pi M_s^2$ (dashed line).

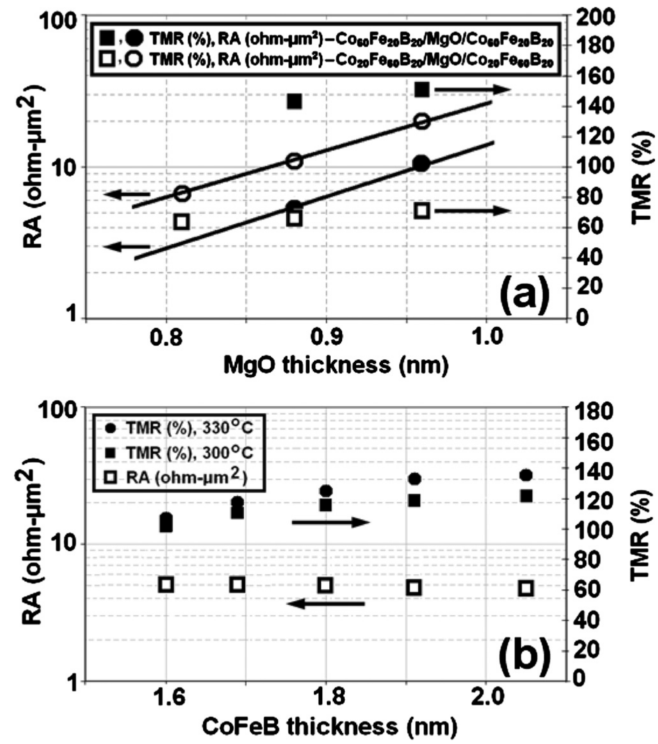

FIG. 2. CIPT results showing (a) comparison of RA product and TMR ratio in two generic MTJ structures with $Co_{20}Fe_{60}B_{20}$ and $Co_{60}Fe_{20}B_{20}$ compositions in both free and fixed layers, indicating a decrease in TMR in MTJ structures that use $Co_{20}Fe_{60}B_{20}$. (b) TMR ratio is significantly improved in $Co_{40}Fe_{40}B_{20}$/MgO/$Co_{20}Fe_{60}B_{20}$ structures, and shows a slight increase with $Co_{20}Fe_{60}B_{20}$ thickness, as well as an increase with annealing temperature. This MTJ structure was used for electrical measurements on patterned devices.

ness of approximately 0.7 nm. The overall perpendicular anisotropy K obtained from VSM measurements was well described by $K = K_{\perp}/t_{\mathrm{CoFeB}} - 2\pi M_s^2$ [see dashed line in inset, Fig. 1(b)], indicating an interfacial origin of the anisotropy with $K_{\perp} \approx 2.4$ mJ/m^2.

To investigate the effect of CoFeB composition on device characteristics, full MTJ stacks with composition of [bottom electrode]/PtMn (15 nm)/CoFe (2.3 nm)/Ru (0.85 nm)/$Co_{80-x1}Fe_{x1}B_{20}$ (2.4 nm)/MgO/$Co_{80-x2}Fe_{x2}B_{20}$/[top electrode] were deposited and annealed at 300 °C for 2 h in an in-plane field of 1 T, where x1=20, 40, 60 and x2=20,60. Both free layer and MgO thickness were varied in the depositions to study their effects on MTJ characteristics. Figure 2 shows current-in-plane tunneling (CIPT) measurements on these structures. It is seen that moving from a Co-rich composition (x1=x2=20) to a Fe-rich composition (x1=x2=60) reduces the TMR while increasing RA, both by a factor of ~2 [Fig. 2(a)]. Note that the increase in RA, however, can be accompanied by a net reduction in the write voltage since the switching current can be reduced by an even larger factor. The TMR can be increased by using a different composition in the pinned layer (x1=40) along with the Fe-rich (x2=60) free layer. CIPT results for this case are shown in Fig. 2(b). While a slight increase in TMR is observed with increasing free layer thickness, the TMR is >100% for all measured thickness values. An increase in TMR with annealing temperature is also observed, reaching values close to the Co-rich MTJs after annealing at 330 °C.

Samples annealed at 300 °C with Fe-rich free layers (x1=40 and x2=60) were patterned into elliptical nanopillars using electron beam lithography and ion milling. Figure 3 shows magnetoresistance measurements with in-plane and out-of plane fields for 60 nm × 170 nm samples with different free layer thickness. TMR values were consistent with the film-level CIPT measurement results. It is worth noting that while an easy axis behavior is clearly seen in the in-plane measurements for all values of free layer thickness (>1.6 nm), a tilt becomes visible in the in-plane loops with the reduction in film thickness. This is accompanied by perpendicular saturation fields much smaller than the saturation magnetization, consistent with results reported in Ref. 20 and VSM measurements on thinner $Co_{20}Fe_{60}B_{20}$ films (Fig. 1). Comparing MTJs with a free layer thickness of 1.80 nm with

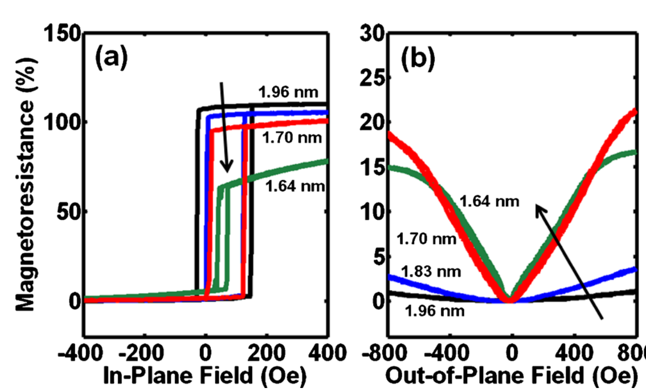

FIG. 3. (Color online) Magnetoresistance curves obtained from R-H measurements on patterned $Co_{40}Fe_{40}B_{20}$/MgO/$Co_{20}Fe_{60}B_{20}$ devices for different $Co_{20}Fe_{60}B_{20}$ free layer thickness values (indicated on the graphs). An increasing perpendicular anisotropy can be seen with reducing film thickness (indicated by arrows), consistent with the results of Fig. 1.

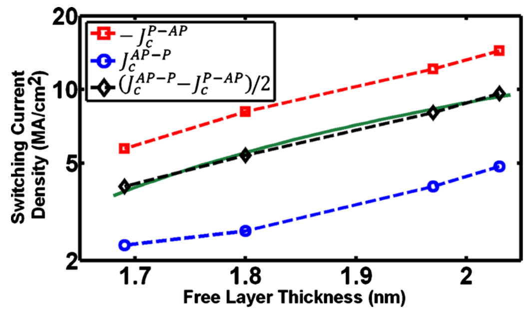

FIG. 4. (Color online) Reduction in the switching current density (at 10 ns write pulse width) for both switching directions due to increased perpendicular anisotropy when free layer thickness is reduced. The average switching current density drops by a factor of 2.4 when free layer thickness is reduced from 2.03 to 1.69 nm, reaching ~4 MA/cm^2 for a free layer thickness of 1.69 nm. The energy barrier for thermally activated switching was estimated using field-induced switching measurements to be $42k_BT$ for this free layer thickness, where k_B and T denote the Boltzmann constant and temperature, respectively. The solid line represents a fit to the expression for switching current density J_c, taking into account the thickness dependence of perpendicular anisotropy shown in Fig. 1(b) (inset).

control devices, a reduction in the average quasistatic switching current density by >40% (from ~2.8 to 1.6 MA/cm^2) was seen when the free layer was changed from a Co-rich (x1=40 and x2=20) to a Fe-rich (x1=40 and x2=60) composition. The switching current reduction is expected to be stronger for thinner free layers with a larger perpendicular anisotropy. Switching current densities obtained from 10 ns pulsed switching measurements for Fe-rich (x1=40 and x2=60) free layers are given in Fig. 4, where positive currents correspond to electrons flowing from the pinned to the free layer, favoring the parallel state. Measurements were taken at applied easy axis magnetic fields canceling the free layer offset fields, i.e., at the center of the measured easy axis R-H loop for all devices. A strong reduction in the current density for both switching directions (J_c^{AP-P} and J_c^{P-AP}) can be observed when the free layer thickness is reduced. The average switching current density $J_c=(J_c^{AP-P}-J_c^{P-AP})/2$ reduces by a factor of ~2.4 with moderate reduction in the free layer thickness from 2.03 to 1.69 nm, as expected from the increase in free layer perpendicular anisotropy, reaching ~4 MA/cm^2 for a free layer thickness of 1.69 nm. Note that this reduction is much larger than would be expected from the corresponding reduction in free layer volume alone, and can be attributed to the increased perpendicular anisotropy for thinner free layers (see solid line in Fig. 4). Similar results were observed in quasistatic measurements, with the average switching current density reaching ~1 MA/cm^2 for 1.69 nm free layers.

In summary, we have demonstrated the reduction in spin-transfer-induced switching current in CoFeB–MgO MTJ structures, using the interfacial perpendicular anisotropy of the Fe-rich CoFeB free layer to overcome the out-of-plane demagnetizing field. The effects of CoFeB thickness on TMR, RA, perpendicular anisotropy, and switching current density were investigated. Switching currents as low as ~4 MA/cm^2 were demonstrated at write times of 10 ns.

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