Spin torque switching of perpendicular Ta|CoFeB|MgO-based magnetic tunnel junctions

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Spin torque switching is investigated in perpendicular magnetic tunnel junctions using Ta|CoFeB|MgO free layers and a synthetic antiferromagnet reference layer. We show that the Ta|CoFeB interface makes a key contribution to the perpendicular anisotropy. The quasistatic phase diagram for switching under applied field and voltage is reported. Low switching voltages, $V_{c\ 50\ ns}$=290 mV are obtained, in the range required for spin torque magnetic random access memory. Switching down to 1 ns is reported, with a rise in switching speed from increased overdrive that is eight times greater than for comparable in-plane devices, consistent with expectations from a single-domain model. © *2011 American Institute of Physics*. [doi:10.1063/1.3536482]

Driving a current through a magnetic tunnel junction (MTJ) can cause the free layer of the MTJ to switch due to spin transfer torque.[1–4] Application of this effect to magnetic random access memory (MRAM) requires lowering the switching voltage sufficiently to allow the distribution of MTJs to be switched reliably at a write voltage of around 400 mV. This write voltage is set by the requirement that the distribution of MTJs avoid breakdown during 10 yr of operation[5] (note that the single shot breakdown voltage of an average MTJ is around 1.5 V). It was recognized from the earliest work on spin transfer torque that using perpendicular magnetic anisotropy (PMA) would greatly reduce the required switching voltage[2,3] due to the absence of the easy-plane anisotropy term (caused by the demagnetization field) found for in-plane devices which increases the switching voltage without contributing to the activation energy.[3,6] However, demonstration of spin torque switching in PMA MTJs was hampered by the lack of magnetic material that simultaneously gave perpendicular magnetization and high magnetoresistance. Recent work on this topic includes single MTJ results using $L1_0$ alloys[7,8] and rare earth transition metal alloys,[9] and a technology demonstration showing tight switching distributions and high write reliability in 4 kbit arrays.[10]

PMA was recently reported in Ta|CoFeB|MgO|CoFeB|Ta tunnel junctions.[11] In that work, the PMA was attributed entirely to the CoFeB-MgO interfacial anisotropy, and quasistatic (down to 0.1 ms) spin torque switching was demonstrated, with an extrapolated switching voltage of $V_{c\ 50\ ns}$=1.0 V. Here, we follow up on this work by showing four key results on this PMA system: (1) the Ta|CoFeB interface has substantial PMA and the Ta seed is essential for obtaining perpendicular films. (2) The quasistatic magnetic switching phase diagram is measured, showing where the system switches under combined action of applied voltage and magnetic field. (3) Low switching voltage at 50 ns is achieved, $V_{c\ 50\ ns}$=290 mV, in the range required for spin torque MRAM. (4) Switching down to 1 ns is demonstrated, faster than for a comparable in-plane device due to the lower free layer magnetic moment, as predicted by the single domain model.

We have found that the Ta seed layer, and not just the MgO at the top interface, is critical to achieving perpendicular magnetic anisotropy. Two series of free-layer-only samples were grown, using either Ta or Ru seeds. The stack structure consisted of substrate |2 seed|t $Co_{60}Fe_{20}B_{20}$|0.9 MgO|0.3 Fe|5 TaN, with all thicknesses in nm, and t was varied from 0.3 to 1.6 nm. The 0.3 nm Fe cap was used to get the optimal oxidation state of the MgO and was thin enough to be nonmagnetic. The samples were annealed at 240 C for 1 h in an in-plane 1 T field. The effect of this in-plane field on the H_k of PMA samples was measured to be negligible. Next, the in-plane saturation field $+H_k$ (for perpendicular samples) was measured by vibrating sample magnetometry (VSM) and the perpendicular saturation field $-H_k$ (for in-plane samples) was measured using polar Kerr magnetometry. Magnetic moment was measured using VSM for all samples. Samples thinner than those plotted were nonmagnetic. Figure 1 shows that the Ru seed samples never go perpendicular, whereas the Ta seed samples have a substantial PMA and are perpendicular for thicknesses below 1.1 nm. Extrapolating[12] the measured anisotropy energy for the thicker Ta-seed samples to zero thickness of CoFeB gives a surface anisotropy (representing the contribution from both the Ta|CoFeB and CoFeB|MgO interfaces) of 1.8 erg/cm^2, compared to only 0.5 erg/cm^2 for the samples with Ru seed. The rounding of the curve for Ta seed samples with thinner CoFeB suggests intermixing of the

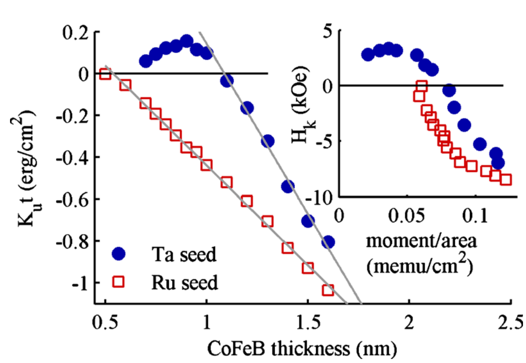

FIG. 1. (Color online) Perpendicular magnetic anisotropy energy of blanket Ta|CoFeB|MgO and Ru|CoFeB|MgO layers. The Ta seed is required for obtaining perpendicular magnetization ($K_u t > 0$). Inset shows the same data plotted as anisotropy field versus moment/area.

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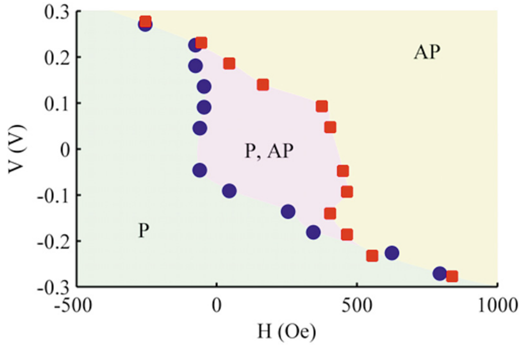

FIG. 2. (Color online) Phase diagram of quasistatic magnetic switching under applied voltage and field for one 80 nm circular junction with R_{low} $=2036\ \Omega$ and MR=41%. Red squares mark the coercivity for increasing H, and blue circles for decreasing H, at fixed V. Colored regions are guides to the eye, with yellow showing the stability region for the AP state, green for the P state, and pink for the region where both AP and P states are stable.

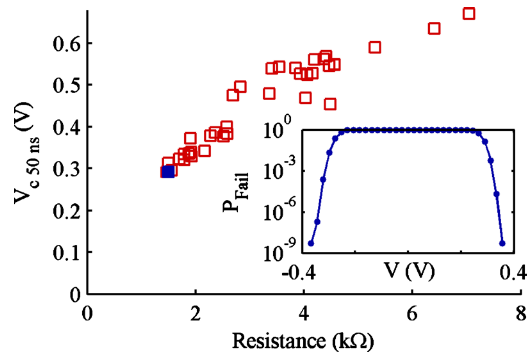

FIG. 3. (Color online) Dependence of switching voltage on resistance for devices with different junction areas. The switching voltage for each junction was measured using single 50 ns pulses at each voltage to switch from the P to the AP state. Each data point is the average result from about 100 junctions. The single domain model predicts no dependence of $V_{c\ 50\ ns}$ on junction area, whereas we observe a significant change. The solid blue data point, for junctions with 110 nm diameter, has array average $V_{c\ 50\ ns}$ $=290$ mV, $R_{low}=1.5$ kΩ, and $E_a=45\ k_BT$. Write reliability data for a single junction from this array are shown in the inset, down to a failure probability of 5×10^{-9} for 50 ns pulses.

Ta and CoFeB.[12] The inset shows the same data plotted as H_k versus moment/area. These data show that the Ta|CoFeB interface plays a key role in making the CoFeB perpendicular.

In order to better center the free layer hysteresis loop, a synthetic antiferromagnetic reference layer was developed. The full stack structure consisted of substrate |5 RuCoFe|2 Ta|0.8 CoFeB|0.9 MgO|0.5 Fe| 0.8 CoFeB | 0.3 Ta | 0.25 Co | 0.8 Pt| [0.25 Co| 0.8 Pd] $\times$4|0.3 Co|0.9 Ru|[0.25 Co|0.8 Pd]$\times$14|20 Ru. The samples were annealed at 240 C for 1 h in an in-plane 1 T field and then patterned into circles with diameters varying from 70 to 110 nm. Figure 2 shows the phase diagram of quasistatic switching as a function of field and voltage for one 80 nm device. At each applied voltage a hysteresis loop was measured by stepping the field in 30 Oe steps, dwelling at each field for about 1 s, and then applying the voltage for 1 ms to measure the resistance. The device switched with sharp square hysteresis loops at small voltage and with some telegraph switching at larger voltage. The symbols plotted in Fig. 2 represent the switching field (or average switching field when telegraph switching was present), using squares for increasing field and circles for decreasing field. The three colored regions are guides to the eye showing where the junction was stable, with yellow indicating the antiparallel (AP) state, green indicating the parallel (P) state, and pink indicating both AP and P states. Note that in this phase diagram the voltage across the device was held constant, whereas in previous work on PMA spin valves the current through the device was held constant, which gives rise to an additional precessional region.[13]

The dependence of the switching voltage on the device area was measured. Each point in Fig. 3 represents the average results from over 100 nominally identical junctions in a given array, using the same wafer as in Fig. 2. Each array used a different junction diameter, varying from 70 to 110 nm. We observed a variation in junction resistance by a factor of 5, which is significantly more than the ratio of maximum to minimum device area, equal to $(110/70)^2=2.5$. This indicates the presence of an electrically dead layer around the periphery of the junctions. The switching voltage to write from the P to the AP state, using a single 50 ns pulse per junction, is shown (the switching voltage for AP to P was similar, but about 6% smaller). A field was applied in order to center the loops during each test, with magnitude typically around 250 Oe and dependent on the size of the junctions. The data show that as the junctions were made smaller the switching voltage increased, instead of staying constant as the single domain model would predict.[3] For the array with the largest junctions (diameter of 110 nm) the average switching voltage was 290 mV at 1.5 kΩ. This suggests that it may be possible to achieve low enough switching voltage while still maintaining sufficiently high resistance to meet a basic requirement of spin torque MRAM: write voltage less than about 400 mV (required to avoid breakdown in a distribution of MTJs during 10 yr of operation[5]) at a resistance larger than 1 kΩ (required for sufficient read margin). Activation energy, E_a, measured by the sweep rate dependence of hysteresis loops measured at slow speeds (0.02–20 Hz) was $E_a=45\ k_BT$ for this array. The write probability as a function of voltage of one junction in this array was measured carefully, as shown in the inset to Fig. 3. Here each point represents the average of many trials at each voltage. For a probability of failing to write of $P_{Fail}\sim0.5$ we regain the single shot result of about 270 mV, whereas to write with only a probability of failure $P_{Fail}\sim5\times10^{-9}$, a voltage of 360 mV was required. This junction had R=1407 Ω, MR=46.5%, and $H_c=312$ Oe.

In addition to lower switching currents, another benefit of using perpendicularly magnetized bits for spin torque MRAM is that larger anisotropy fields are accessible, allowing the use of smaller magnetic moments and hence faster switching speeds[3,14] compared to in-plane devices, for the same activation energy. In-plane devices typically have H_k in the range 100–300 Oe, determined by the in-plane shape anisotropy of the elliptical device. In contrast, as shown in Fig. 1, the anisotropy of these perpendicular devices can be as large as 3300 Oe, allowing the use of very thin layers of CoFeB (here 0.8 nm). Figure 4 shows the switching speed for a perpendicular junction compared to an in-plane junction for a range of switching times from 10 ns down to 1 ns. The stack for the in-plane junction consisted of substrate |1 Ru|0.5 MgO|1 Ru|17.5 PtMn|0.5 $Co_{60}Fe_{20}B_{20}$| 1.4 $Co_{70}Fe_{30}$ | 0.85 Ru | 1.5 CoFeB | 0.5 $Co_{70}Fe_{30}$ | 0.95 MgO|1.9 $Co_{60}Fe_{20}B_{20}$|2 V and the perpendicular

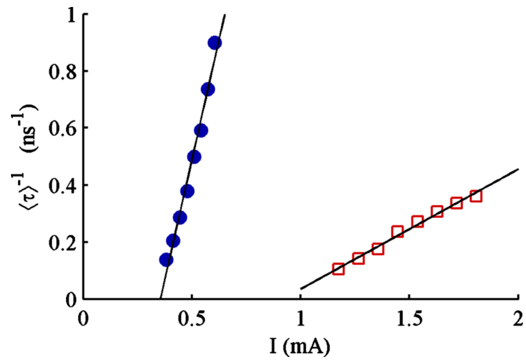

FIG. 4. (Color online) Switching speed as a function of overdrive current for a PMA junction (blue circles) and an in-plane junction (red squares), showing that PMA junctions switch faster than in-plane junctions. The linear dependence is a reflection of conservation of angular momentum, and so the slope depends principally on the magnetic moment of the free layer. The lower moment PMA junction has a slope 8.0 times steeper than the higher moment in-plane junction, as expected by the single domain model which predicts a ratio of 9.1. Furthermore, due to its higher H_k, the PMA junction has $E_a=66\ k_BT$, compared to $E_a=48\ k_BT$ for the in-plane junction.

junction used a free layer of 0.8 CoFeB and a pinned layer similar to that described earlier. An easy axis field was applied during the measurement to center the hysteresis loop. A fixed voltage was applied to the junction and the resistance was monitored in real time to record when the junction switched from the AP to the P state. The experiment was repeated 300 times and the results averaged in order to obtain sufficient signal above the noise. The figure shows that the switching current for the perpendicular sample was lower than for the in-plane sample and that furthermore the slope was steeper, corresponding to a faster rise in switching-speed with increased overdrive.

In the single domain model in the high bias regime, the switching speed is linearly related to the switching current, due to conservation of angular momentum.[3] Taking into account thermal fluctuations and following the calculation given in Ref. 14 we obtain, for uniaxial anisotropy only,

$$\frac{1}{\langle\tau\rangle} = \left[\frac{2}{C+\ln(\pi^2\xi/4)}\right]\frac{\mu_B P_{ref}}{em(1+P_{ref}P_{free})}(I-I_c). \quad (1)$$

Here $\langle\tau\rangle$ is the average switching time, $C\approx 0.577$ is Euler's constant, $\xi = E_a/k_BT$ is the activation energy in units of k_BT, μ_B is the Bohr magneton, P_{ref} and P_{free} are the tunneling spin polarizations of the reference and free layers, e is the magnitude of the electron charge, m is the free layer magnetic moment, and I_c is the zero temperature threshold current. A similar equation holds for the case of easy-plane plus uniaxial anisotropy, but with C replaced by $C+1.34-f(h_p)$, where $h_p=(4\pi M_s - H_{k\perp})/H_k$ is the effective easy-plane anisotropy, in reduced units. There is no analytic expression for $f(h_p)$, however $f(h_p)=3\ln(h_p)/h_p$ is a good approximation (giving $\langle\tau\rangle^{-1}$ correct to within 7% if $h_p\geq 2$ and $\xi\geq 20$). In both cases, smaller free layer magnetic moment, m, leads to a faster switching speed.

The perpendicular data in Fig. 4 were fit using Eq. (1) with the measured values $\xi=66$ and $P=0.56$ (inferred from MR=46%, using the Julliere formula[15] and the assumption that $P_{ref}=P_{free}\equiv P$), while varying m and I_c. Fits to the in-plane data used the measured values $\xi=48$, $P=0.63$ (inferred from MR=65%), $4\pi M_s - H_{k\perp}=6750$ Oe (from a VSM measurement of the saturation field of an un-patterned companion wafer), and $H_k=150$ Oe. Using the nominal sample dimensions of 105 nm×105 nm×0.8 nm and 66 nm ×239 nm×1.9 nm and the known magnetizations of 456 emu/cm^3 and 842 emu/cm^3 (the difference is due to the different thickness of CoFeB and interfacial intermixing) for the perpendicular and in-plane samples, respectively, we expect from the single domain model a ratio of slopes of 9.1. The fitted values give 8.0, showing the importance of having a low moment free layer for high speed switching.

In summary, we have shown that a key contribution to the perpendicular anisotropy is from the Ta|CoFeB interface. The quasistatic V-H switching phase diagram for perpendicular magnetic tunnel junctions was measured. High speed, low voltage switching was demonstrated, $V_{c\ 50\ ns}=290$ mV at 1.5 kΩ, in the range required for spin torque MRAM. $V_{c\ 50\ ns}$ was shown to increase with decreasing area, in disagreement with the single domain model. Due to the lower moment, the switching speed response of perpendicular junctions was measured to be eight times greater than for in-plane devices, in agreement with the single domain model.

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