Tunnel Magnetoresistance and Spin Torque Switching in MgO-Based Magnetic Tunnel Junctions with a Co/Ni Multilayer Electrode

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Abstract:
We have fabricated MgO-barrier magnetic tunnel junctions with a Co/Ni free layer designed to reduce the demagnetizing field via interface perpendicular anisotropy. With an fcc-(111) oriented Co/Ni multilayer combined with a thin FeCoB insertion layer, the demagnetizing field is 0.2 T and the tunnel magnetoresistance can be as high as 106%. Measurements of spin-torque switching are in good agreement with predictions for a reduced critical current associated with the small demagnetization field for antiparallel-to-parallel switching. For parallel-to-antiparallel switching the small demagnetization field leads to a spatially-nonuniform reversal mode having a low energy barrier and a higher switching current [1].

Summary of Research:
MgO-based magnetic tunnel junctions (MTJs) with a large tunneling magnetoresistance (TMR) whose magnetic orientations can be controlled by spin-torque switching [2] are promising candidates for magnetic random access memories [3]. However, for widespread application it will be necessary to reduce the switching current density while maintaining thermal stability for the magnetic states. One strategy is to tune the perpendicular anisotropy of the switching layer to reduce the demagnetization field, but to keep the equilibrium orientation of the switching layer in the sample plane.

For an in-plane magnetized switching layer within a macrospin approximation for the magnetization dynamics, the critical current for spin-torque switching for an MTJ in the absence of thermal fluctuations has the approximate form [4],

\[ I_{c0} = \frac{2e}{\hbar} \frac{\alpha M_s V}{\eta(\theta)} \left( H_{c0} + \frac{H_{eff}}{2} \right) \]

where \( \alpha \) is the damping constant, \( M_s \) is the saturation magnetization of the switching layer, \( V \) is the volume of the layer, \( \eta(\theta) = p/(1 + p^2) \) for parallel-to-antiparallel (P-to-AP) switching, and \( \eta(\theta) = p/(1 - p^2) \) for AP-to-P switching, where the spin polarization,

\[ p = \sqrt{\text{TMR}/(\text{TMR} + 2)} \]

\( H_{c0} \) is the coercive field in the absence of thermal fluctuations, and \( H_{c0}^{\text{eff}} \) is the effective demagnetization field. For a uniform transition-metal magnetic film, \( H_{c0}^{\text{eff}} \) is generally determined by the saturation magnetization, \( H_{eff} \approx 4\pi M_s \approx 10,000 \text{ Oe} \), while \( H_{c0} \) is much smaller, usually \( \approx 100 \text{ Oe} \), as determined by lateral shape anisotropy. However, the thermal stability of the magnetic bit is governed by \( H_{c0} \), and does not depend on \( H_{c0}^{\text{eff}} \) as long as \( H_{c0} < H_{c0}^{\text{eff}} \). This suggests that \( I_{c0} \) may be reduced by using the interface anisotropy of multilayers like Co/Ni to decrease \( H_{c0}^{\text{eff}} \), while leaving \( H_{c0} \) unchanged so as to maintain thermal stability. We report the successful fabrication of high-TMR MTJs with reduced-demagnetization switching layers consisting of a Co/Ni multilayer together with a thin FeCoB insertion layer contacting the MgO.

Our MTJ layer stack was prepared on SiO2/Si(001) wafers by a magnetron sputtering with a base pressure of \( 10^{-9} \text{ Torr} \). The layer structure is Ta(3)/[CuN(20)/Ta(3)]2/Cu(2)/[Co(0.4)/Ni(0.8)]2/Fe60Co20B20(1.1)/MgO(t)/Fe60Co20B20(20)/Pt(30). The numbers in the parentheses are the layer thicknesses in nm. The MgO thickness, \( t \), was varied from 0.7 to 1.5 nm across the wafer.

After the deposition of all layers, the wafers were annealed in an \( \text{N}_2 \) atmosphere at 375\degree C for up to 10 minutes on a sample stage, allowing for a fast cooling rate of 43\degree C/min. Individual tunnel junctions were then patterned using e-beam lithography and ion-beam etching. Magnetization measurements show that the equilibrium moment of the \([\text{Co}(0.4)/\text{Ni}(0.8)]/\text{FeCoB}(1.1)\) film lies in plane with a perpendicular saturation field of 2 kOe, which indicates that interface anisotropy reduces the demagnetizing field by about 1 T relative to the averaged saturation magnetization of 1.2 T. From ferromagnetic resonance measurements, the Gilbert damping parameter of the \([\text{Co}(0.4)/\text{Ni}(0.8)]/\text{FeCoB}(1.1)\) film.
FeCoB(1.1) film is \( \alpha = 0.015 \pm 0.005 \).

Figure 1 shows STEM images of the MTJ layer stack after a three minute anneal, for which we achieved room-temperature TMR ratios as large as 106% (see Figure 2). We observe a high degree of crystal coherence extending from the Co/Ni multilayer up through the FeCoB insertion layer to the MgO [Figure 1(b)].

To estimate the effective activation energy \( E_a \) and the zero-thermal-fluctuation critical current \( I_{c0} \), we performed current-pulse measurements of a 70 \times 220 nm\(^2\) device with \( RA = 4.3 \, \Omega \mu m^2 \) and TMR = 38%, as shown in Fig. 3. Assuming that current-induced heating effects are negligible, for thermally activated switching the average switching current \( \langle I_c \rangle \) should take the form [5],

\[
\langle I_c \rangle = I_{c0} \left[ 1 - \frac{k_B T}{E_a} \ln \left( \frac{t_p}{\tau_0} \right) \right] \tag{2}
\]

where \( k_B \) is Boltzmann’s constant, \( t_p \) is the pulse duration, and \( \tau_0 \) is the inverse of the attempt frequency, which we assume to be \( 10^{-9} \) sec.

From the fits to the current-pulse data in Figure 2, we obtain for P-to-AP switching; \( E_a^- = 1.12 \pm 0.07 \) eV and \( I_{c0}^- = 0.60 \pm 0.02 \) mA. For P-to-AP switching, we obtain; \( E_a^+ = 0.68 \pm 0.02 \) eV and \( I_{c0}^+ = 1.60 \pm 0.06 \) mA.

We can compare the results for the zero temperature switching currents to the values expected from Equation (1). Using \( \alpha = 0.015, 4\pi M_s = 12,000 \) Oe, \( H_c^0 = 130 \) Oe, \( H_{eff} = 2 \) kOe, and \( p = 0.4 \), based on the TMR = 38%, Equation (1) predicts \( I_{c0}^- \approx 0.44 \) mA and \( I_{c0}^+ \approx 0.61 \) mA.

Our measured critical current for AP-to-P switching is in reasonable agreement with the predicted value, confirming that the reduction of the demagnetization field from 12,000 to 2000 Oe has the desired effect of reducing \( I_{c0} \).

Our micromagnetic simulations suggest that the P-to-AP switching is more spatially non-uniform than AP-to-P switching and that this non-uniformity gives higher \( I_{c0} \) for P-to-AP switching.

References: