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Effect of interlayer exchange coupling parameter on switching time and critical current density in composite free layer

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We investigated the effect of interlayer exchange coupling parameter on switching current density and switching time in the [CoPt-ML]/Ta/CoFeB composite free layer. The fundamental parameters for the micromagnetic model were extracted from experimental results and *ab-initio* calculations of the Fe/MgO and Fe/Ta interfaces. We found that the critical current density and switching current decrease with decreasing interlayer exchange coupling. It was observed experimentally that perpendicular magnetic anisotropy (PMA) increases with increasing thickness of Ta insertion due to enhancement of CoFeB/MgO interfacial anisotropy, whereas the interlayer exchange coupling strength decreases. Therefore, our modeling and experimental results indicate that the optimized Ta insertion in the composite layer leads to improved thermal stability via combined interface and bulk anisotropies, lower critical current density, and reduced switching time as compared to the composite layer without Ta insertion. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4861215]

Switching current, switching time, and thermal stability are critical issues for applications of perpendicular magnetic tunnel junctions (p-MTJs) for spin-transfer-torque random access memory (STT RAM) and spin logic applications. It has been shown that in p-MTJs utilizing CoFeB/MgO interfacial anisotropy, the thermal stability ($\Delta = K_u V/k_B T$) factor reduces to around 30 for 20 nm diameter junctions.[1] There are reports of using composite electrodes, a hard/soft bi-layer free layer, to increase the thermal stability and maintain the fully spin polarized Δ_1 symmetry states.[2,3] In our previous work, we have fabricated a [Co/Pt-ML]/Ta/CoFeB composite free layer stack experimentally.[4] The Ta was used as the insertion element as it helps in crystallization of CoFeB by accumulating boron atoms upon annealing.[5,6] We observed that with increase in the Ta insertion thickness, the perpendicular magnetic anisotropy (PMA) of the composite layer increases due to increase in CoFeB/MgO interfacial anisotropy, but the interlayer exchange coupling parameter decreases. The exchange coupling parameter is a significant factor as it plays an important role in defining the switching field[7] and energy barrier for the composite free layer.[8] As the exchange constant decreases in magnitude, the energy barrier of the composite layer decreases, as only part of the hard layer's anisotropy contributes towards the anisotropy of the free layer. Therefore, we experimentally confirmed that increase in CoFeB/MgO interfacial anisotropy over-compensates for the loss due to the decrease in interlayer exchange coupling up to 0.5 nm thick Ta insertion, with overall increase of thermal stability due to combined interface and bulk type anisotropies in the composite free layer.[4] An important remaining question is whether the critical current and switching time remain favorable for applications using the aforementioned composite structures.

In this work, we study the effect of interlayer exchange coupling parameter on the switching time and switching current density in [Co/Pt multi-layer]/Ta/CoFeB composite free layer. The micromagnetic model to study the effect of interlayer coupling on the switching current density and switching time was set up on the basis of experimental results and *ab-initio* calculations of the Fe/MgO and Fe/Ta interfaces. The fundamental magnetic parameters for the micromagnetic model were extracted from the experimental results. The CoFeB/MgO interfacial anisotropy was found to be 0.9 erg/cm^2.[4] The material parameters extracted from magnetometry measurements for the Co/Pt-ML and CoFeB are shown in Table I.

The *ab-initio* calculations were performed for the Ta/Fe and Fe/MgO interfaces to parameterize the M_s parameter at the interfaces. We employed the projected augmented plane wave method (PAW),[9] implemented within the Vienna *ab-initio* simulation package (VASP).[10] The generalized gradient approximation[11] was used for the exchange-correlation energy. A monkhorst-pack $11 \times 11 \times 3$ k-point grid was applied to fully optimize the atomic configurations.

Fig. 1 shows the magnetic moment variation of Fe atoms near the MgO/Fe and Ta/Fe interfaces. The interfacial and bulk lattice parameters for Fe/MgO calculations were extracted from the experimental results.[12] We found that the magnetic moment of Fe atoms is enhanced at the interface with MgO, and for the next nearest Fe atom, there is a sharp

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TABLE I. Fundamental magnetic properties.

Layer type	(Exchange)$_\perp$ erg/cm	Anisotropy erg/cm^3	Magnetization emu/cm^3
CoFeB	1.6×10^{-6}	0	1060
CoPt	1.6×10^{-6}	8.5×10^6	1000

decrease in the magnetic moment. The magnetic moment converged to the bulk value of Fe with increasing distance between the Fe atoms and interface.

For the Ta/Fe interface, the lattice parameter for Ta was relaxed in the z-direction. As the crystallization occurs from the CoFeB/MgO interface, the in-plane lattice parameters for Ta were constrained to the experimental value of the lattice parameter for the Fe atom. We observed that the Fe to Fe atoms spacing for the relaxed structure is large near the Fe/Ta interface compared to the bulk value. The magnetic moment of the Fe atoms next to Ta decreased, which has been experimentally observed in leading to a dead magnetic layer. From *ab-initio* calculations, it was noticed that only the Fe atoms which are nearest neighbors to the Ta atoms suffered loss in magnetic moment, whereas the next nearest neighbors remained unaffected. The comparatively large dead layer observed in experimental results can be due to surface roughness at the Ta/Fe interface, which significantly increases the surface area.

Based on these results of interface calculation, the micromagnetic model was set up as shown in Fig. 2. The CoFeB layer was divided into three sub-layers: (1) CoFeB-Ta, (2) bulk CoFeB, and (3) CoFeB-MgO. The magnetizations of three sub-layers were set up on the basis of *ab-initio* results. The CoFeB/MgO interfacial anisotropy was implemented as bulk anisotropy in the CoFeB-MgO layer. To study the effect of the interlayer exchange coupling on the switching current density and switching time, we used the STT extension module of the object oriented micromagnetic framework.[13] A spin polarization of 0.7 was used for the polarizer layer.

To investigate the switching current and switching time dependence, the interlayer exchange coupling (IEC) parameter was varied between 0.05 and 0.5 erg/cm^2. For

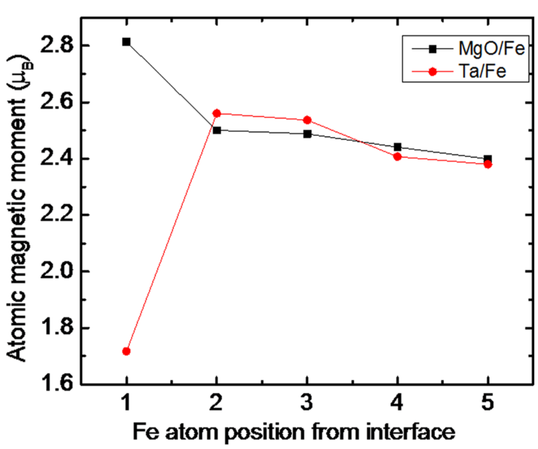

FIG. 1. Atomic magnetic moment behavior for the Fe atoms near the interfaces with MgO and Ta.

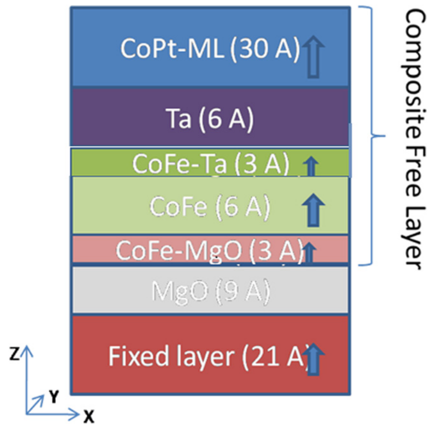

FIG. 2. The cartoon of the modeled stack.

IEC less than 0.05 erg/cm^2, the switching occurs only in the soft CoFeB layer. For values equal to and greater than 0.05 erg/cm^2, the coupling was strong enough to switch the two layers together. Figure 3(a) shows the magnetization switching as a function of simulation time for the range of the IEC parameter studied at a fixed current density of 7×10^6 A/cm^2. The switching time increased exponentially with increasing interlayer coupling parameter and had the highest value of about 9.8 ns for the 0.5 erg/cm^2 IEC, Fig. 3(b).

Figure 4 shows the critical current density as a function of interlayer coupling. The current density was increased in steps of 1×10^6 A/cm^2. The switching current density increased with increasing interlayer coupling and became constant for the IEC parameter greater than 0.3 erg/cm^2.

Next, we compare the switching diagram for the IEC parameters 0.5 erg/cm^2 and 0.05 erg/cm^2 at constant current density 7×10^6 A/cm^2, as shown in Fig. 5. For the IEC parameter 0.5 erg/cm^2, the coupling was strong enough to switch the soft and hard layer together coherently. In the case of IEC parameter 0.05 erg/cm^2, the switching was still strong enough to switch the two layers together, but the switching was incoherent. For the coherent switching of the CoFeB and Co/Pt ML, the effective anisotropy of the composite layer can be written as the volume average of the anisotropies of individual CoPt-ML and CoFeB sub-layers: $K_{CL} = \frac{t_{CoPt}}{t_{CL}} K_{CoPt} + \frac{t_{CoFeB}}{t_{CL}} K_{CoFeB}$ where t_{CL}, t_{CoPt}, and t_{CoFeB} are the thicknesses, and K_{CL}, K_{CoPt}, and K_{CoFeB} are the corresponding magnetic anisotropies of the composite layer, Co/Pt ML and CoFeB sub-layers. As the insertion thickness increased, the interlayer exchange coupling decreased.[4] For the weaker exchange two layers behaved incoherently and only a fraction of the hard layer's anisotropy contributed towards the anisotropy of the composite layer.

We observed experimentally that with increasing Ta insertion thickness, the PMA increased because of enhancement of the CoFeB interfacial anisotropy. This means that increase in PMA due to enhancement in the interfacial anisotropy has a larger benefit than the loss due to weakening of the coupling parameter. Now from the STT simulations we observed that the critical current density and switching time decreased with increasing Ta insertion thickness. Therefore

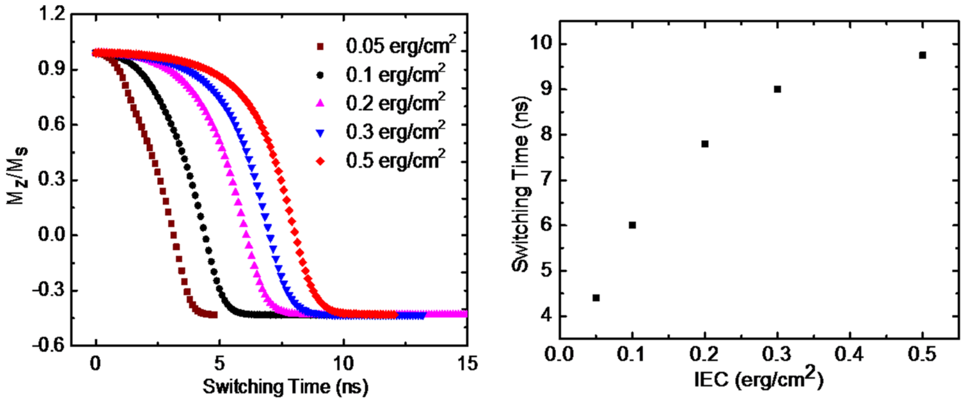

FIG. 3. (a) Magnetization switching for different exchange parameters at the constant current density 7×10^6 A/cm^2. (b) Switching time as a function of exchange parameter.

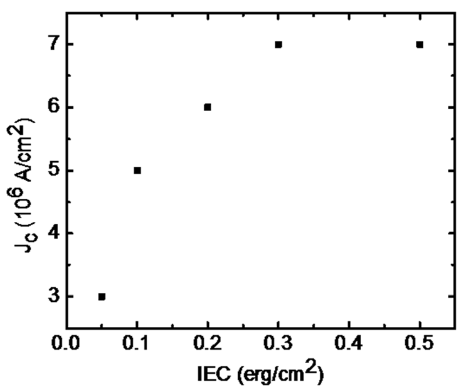

FIG. 4. Critical current density as a function of interlayer exchange parameter.

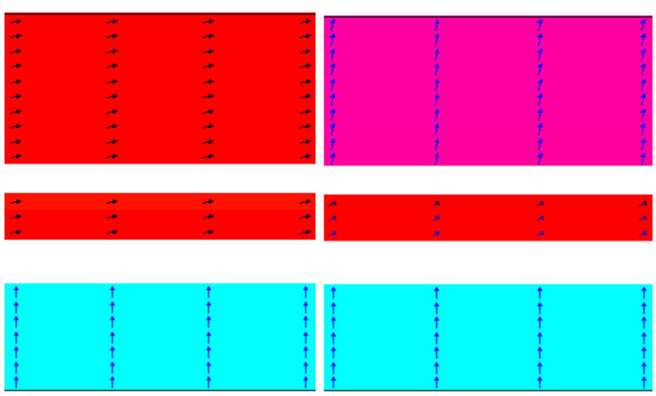

FIG. 5. Switching diagram for the IEC parameters 0.5 erg/cm^2 (left) and 0.05 erg/cm^2 (right) at the current density 7×10^6 A/cm^2. Bottom layer is the polarizer layer, middle layer is the CoFeB layer with interfacial anisotropy and top layer is the Co/Pt-ML with bulk anisotropy.

increase in Ta thickness helps in increasing the energy barrier and decreasing the switching current density and simulation time. Hence, the composite layer with non-magnetic insertion (Ta) may have high PMA, low switching current density and switching time as compared to the conventional single material free layer.

In summary, we have studied the effect of Ta insertion thickness on switching current density and switching time. The critical current density and switching time decreased with decrease in interlayer coupling parameter. Therefore, based on our prior result,[4] Ta insertion thickness in the composite layer can be chosen in the range where it is accompanied by the increase of the PMA[4] and decrease of the switching current and switching time.

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