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Modelling interfacial coupling in thin film magnetic exchange springs at finite temperature

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We report a numerical study that demonstrates the interface layer between a soft and hard magnetic phase, the exchange transition layer, is the dominant factor that influences the magnetization reversal process at room temperature and long measurement times. It is found that the exchange transition layer thickness affects the magnetization reversal and the coupling of a bi-layer system by lowering the switching field and changing the angle dependent magnetization reversal. We show that the change in angle dependence of reversal is due to an increased incoherency in the lateral spin behavior. Changing the value of exchange coupling in the exchange transition layer affects only the angle dependent behavior and does not lower the switching field. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4826365]

INTRODUCTION

Multiple layer thin film structures are of interest in realizing advanced hybrid magnetic materials for technological applications (heat assisted magnetic recording, vortex core oscillators) as well as providing a platform to study theoretical aspects of granular magnetic composites. The combination of a ferromagnetic hard and soft phase has been proven to be advantageous for permanent magnets to achieve a high-energy product, high remanence, and high isotropic remanence ratio.[1] Chang[2] and Goto *et al*.[3] created multiple layer, exchange coupled thin films as magnetic exchange spring systems. More recently, improvements in thin film deposition processes where atomic level control of individual layers is now readily available have made it possible to fabricate materials with highly tailored magnetic properties. One key application of atomically engineered magnetic thin films is data storage, where companies have recently adopted bi/multi-layer ferromagnetic structures to create very high areal density magnetic recording media. In these structures, the thermal stability and switching field can be tailored such that the thin films have sufficient anisotropy to avoid thermally activated reversal, but can still be reversed by fields available from technologically realizable write heads.[4,5]

In order to take full advantage of these multilayer materials, there is a need to address fundamental questions arising from complex thin film ferromagnetic structures. Specifically, how do the magnetic properties of the different layers affect the magnetization reversal and what role does the interface between the layers play in terms of functionality and thermal stability? In general, it is difficult to explore experimentally the effect of varying individual parameters in isolation. For example, anisotropy can be varied by changing the crystal structure of a material or through diffusion effects. In both these cases, other parameters such as the exchange constant A and magnetic polarization $\boldsymbol{J}_s$ will also vary in a non-systematic manner. Also, the nature of the interfacial exchange coupling between the layers is highly dependent on interfacial quality and is difficult to control experimentally. In contrast, micromagnetic modeling does not suffer from these constraints and provides an ideal method to explore the effect of varying individual parameters.

Therefore, we conduct a numerical study, which develops a quantitative understanding of the role of the interface layer (the exchange transition layer) between the soft and hard ferromagnetic layers on the reversal of a bilayer ferromagnetic structure at finite temperature. Our current work goes beyond previous micromagnetic studies on multilayer structures where the magnetic layers are assumed to be continuous.[6–8] Here, we report an in depth study of the influence of material parameters on the magnetization behaviour and the switching fields in granular media systems based on our previous experimental work, Saharan *et al.*[9]

THEORY

To study the effect of an exchange transition layer in a ferromagnetic multilayer material, we model a cylindrical CoCrPt tri-layer system, which represents the hard/soft phase with an additional interface layer introduced between the two layers which we term the exchange transition layer. During the fabrication of the multiple layer system, there is the possibility of intermixing when the soft layer is sputtered onto the hard layer and the interfacial layer is included in the model to account for this intermixing. The ferromagnetic grain has a cylindrical geometry with an 8 nm diameter. The thickness of the hard and soft ferromagnet layers is kept constant at 11 nm and 6 nm, respectively. The thickness of the exchange transition layer is varied from 0.5 nm to 2 nm to represent the lattice distortions present between the soft and hard layers, Figure 1.

The material properties for the CoCrPt hard ferromagnetic layer are taken from Morrison *et al.*:[10,11] magnetocrystalline anisotropy constant $K_h = 0.58\,\mathrm{MJ/m^3}$, magnetic

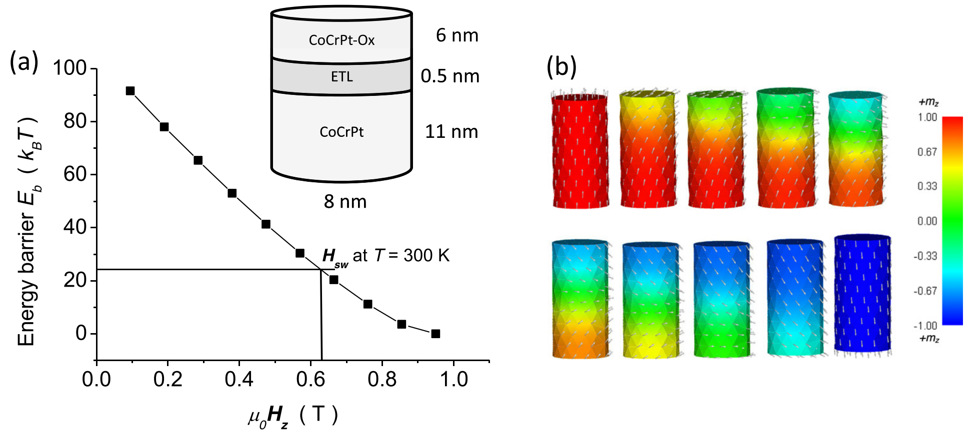

FIG. 1. (a) Energy barrier as a function of external applied field. H_{sw} in the graph describes the switching field for an energy barrier value of 25 k_BT with a measurement time of 1.39 s. (b) The non-uniform magnetization reversal of a grain with diameter 8 nm and thickness 16 nm, see inset, with $f_0 = 10^{10}$ Hz, $\tau = 10$ s, and $K_s = 20\%$ K_h. The different colours represent the different magnetization states of the grain at during the magnetization reversal of the grain. The colour scale gives the magnetization value of the grain. The red colour shows the initial state of the grain with its magnetization pointing upwards whereas the blue grains represent the final configuration of the grain with its magnetization pointing downwards.

polarization $\boldsymbol{J}_s = 0.90$ T, and exchange constant $A = 1 \times 10^{-11}$ J/m. The soft layer (CoCrPt-Ox) properties were reported by Thomson *et al.*[12] and are magnetic polarization $\boldsymbol{J}_s = 0.57$ T and exchange constant $A = 1 \times 10^{-11}$ J/m. The soft layer magneto-crystalline anisotropy constant K_s is varied between 20% and 60% of 0.58 MJ/m^3 (i.e., of K_h) as exact values are difficult to obtain experimentally.

Intermixing or surface modification at the soft/hard boundary leads to an interface layer, and therefore we model the exchange transition layer as having magnetic properties between those of the soft and hard layers. The values used in our model for the exchange transition layer are as follows: magnetic polarization $\boldsymbol{J}_s = 0.57$ T which is the same as the soft layer, magneto-crystalline anisotropy constant K_{ETL} is the same as the soft layer magneto-crystalline anisotropy and is varied between 20% and 60% of 0.58 MJ/m^3 (hard layer magneto-crystalline anisotropy) depending on the case studied, and the exchange constant A is varied in the range 0.2×10^{-11} J/m–1×10^{-11} J/m.

In order to understand the effect of the exchange transition layer and the soft layer on the tri-layer structure, we calculate the switching field of the magnetic structure for different angles of the applied field. The calculation of the switching field at finite temperatures is a three-step process. In the first step, the Landau-Lifshitz-Gilbert (LLG) micromagnetic model[13,14] is used to determine the two stable magnetic states in which the projection of the total magnetization onto the easy axis (z-direction) is either positive or negative. We use a finite element boundary element method for the micromagnetic model with tetrahedral elements with an edge length of 0.5 nm. This values is well below the minimum of the exchange length and the Bloch parameter, $\min((2\mu_0 A/J_s^2)^{1/2},(A/K)^{1/2})$ for all investigated materials, ranging from 1.8 nm to 9 nm.

In the second step, the Nudged Elastic Band (NEB) method[15,16] is used to calculate the energy barrier between the two pre-calculated stable magnetization configurations. The product of the anisotropy energy density and volume of the grain (KV) defines the energy barrier. To switch its magnetization direction, the magnetic grain needs to overcome the energy barrier between the two magnetization configurations.

The thermal stability calculation requires knowledge of the transition rates between the initial and final magnetization configuration of the magnetic grains. The NEB method initially guesses the minimum energy path (MEP) in the energy landscape between the two stable magnetization states. In order to obtain the MEP, the energy is minimized until the energy gradient of the path points along the current path and the energy is constant along the path for any degree of freedom perpendicular to it. The MEP calculation provides an energy barrier $E_b(\boldsymbol{H})$ of the transition in units of K_BT (K_B is the Boltzmann constant and T is the temperature) between the initial and final magnetic configurations of the grain at any given applied field and field angle. The energy barrier is directly associated with the thermal stability of the system.

In the third step, the switching field at temperature T, for a particular applied field angle is calculated from the energy barrier.[17] The switching field value for the grains depends on the energy barrier, the attempt frequency, and the measurement time for which the field is applied in accordance with the Arrhenius–Neel law

$$\tau = \frac{1}{f_0} \exp^{-\frac{E_b}{k_BT}}, \tag{1}$$

where τ is the average time required for the grain to switch in the presence of the field in seconds and f_0 is the attempt frequency in Hz. The attempt frequency depends on the material parameters, damping constant, shape, and size of the grain, and is normally taken to be in the range of 10^9–10^{12} Hz.[18–21] In the model, we use an attempt frequency value of 10^{10} Hz, which has shown good agreement with experimental results.[11] Using the computed energy barriers at a range of $\boldsymbol{H}$ values, we fit a curve $E_b(\boldsymbol{H})$, Figure 1. The switching field at a given temperature T is the value of $\boldsymbol{H} = \boldsymbol{H}_{sw}$ ($\boldsymbol{H}_{sw}$ is the switching field) such that $E_b(\boldsymbol{H}_{sw}) = E^*$, with $E^* = k_BT\ln(\tau f_0)$, where τ is the time for which the field is applied.

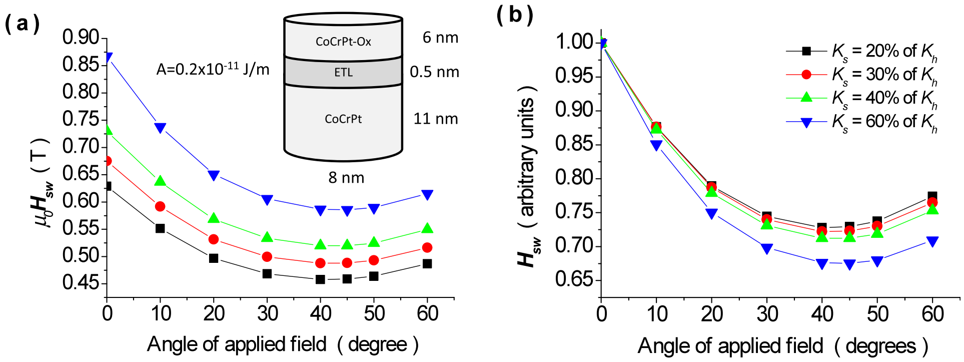

FIG. 2. (a) The switching field and (b) normalized switching field as a function of angle of applied field with an f_0 of 10^{10} Hz for the CoCrPt based multilayer structure with a diameter of 8 nm, a hard layer thickness of 11 nm, an exchange transition layer of 0.5 nm, and a soft phase of 6 nm at 292 K. The measurement time is 10 s and the exchange constant of the exchange transition layer is 0.2×10^{-11} J/m.

RESULTS AND DISCUSSION

Effect of soft phase anisotropy

The optimum value of the magneto-crystalline anisotropy for the different regions present in the multilayer system is crucial in determining the magnetization reversal mechanism of the grain. However, it is challenging to directly measure the anisotropy of individual layers in a multiple layer system. Therefore, we provide results from micromagnetic simulations, which will allow the anisotropy to be determined indirectly by comparing angle dependent reversal measurements with our model. Here, the magneto-crystalline anisotropy in the soft layer is varied between 20% and 60% of that of the hard layer for different values of exchange coupling in the exchange transition layer. Figures 2 and 3 show the switching field as a function of applied field angle in absolute values and normalized to the switching field at zero degrees for different values of magneto-crystalline anisotropy in the soft phase and for two different exchange constants 0.2×10^{-11} J/m and 0.8×10^{-11} J/m in the exchange transition layer, respectively. The value of the exchange constant in the exchange transition layer determines the coupling between the soft and hard magnetic layers, and therefore determines if the whole structure is weakly or strongly coupled.

Our results show that the anisotropy of the soft layer is an important factor in defining the magnetization reversal and switching field and leads to an exchange spring effect in the multilayer structure. This exchange spring effect is revealed by a deviation from Stoner-Wohlfarth coherent reversal behaviour.[22] Figures 2 and 3 show that a reduction in the magneto-crystalline anisotropy (20% of K_h) leads to the shift in the minimum of switching field vs. applied field angle. In Figure 2, the minimum of switching field for the 60% of K_h case is 0.58 T at 45°, while for the 20% of K_h it is 0.46 T at 40°. In Figure 3, the minimum switching field changes from 0.59 T at 45° to 0.46 T at 40°. This indicates an increase in incoherency as the Stoner-Wohlfarth assumption of coherent reversal starts to break down. The magnetization reversal process of the $K_s = 20\%$ of K_h grain is shown in Figure 1(b) and reveals that at first the top soft layer starts to change its magnetization, canting it in plane, then being pinned at the interface layer before the magnetization reversal propagates and the grains magnetization reverses. This behaviour is in contrast to the Stoner-Wohlfarth reversal where the magnetization reverses coherently, meaning the spins reveres together throughout the grain. We also observe that the exchange interaction affects magnetization reversal more significantly at lower soft layer anisotropy values (20% of K_h), compared with higher anisotropy values (60% of K_h). This can be understood as follows: for lower anisotropy layers, the reversal is mainly driven by either shape anisotropy or exchange, while for high anisotropy materials we have a stabilizing energy provided by the magneto-crystalline anisotropy.

Effect of the exchange transition layer exchange constant

The strength of the exchange coupling in the exchange transition layer is expected to affect the coupling between the hard and soft ferromagnetic layers. In order to determine the effect of the exchange transition layer, its exchange constant is varied in the range 0.2×10^{-11} J/m to 1×10^{-11} J/m, in steps of 0.2×10^{-11} J/m. The study was performed for two magneto-crystalline anisotropy values of the soft layer, 20% and 60% of K_h. Figures 4 and 5 show the effect of varying this exchange constant for these two different anisotropies. When the magneto-crystalline anisotropy of the soft

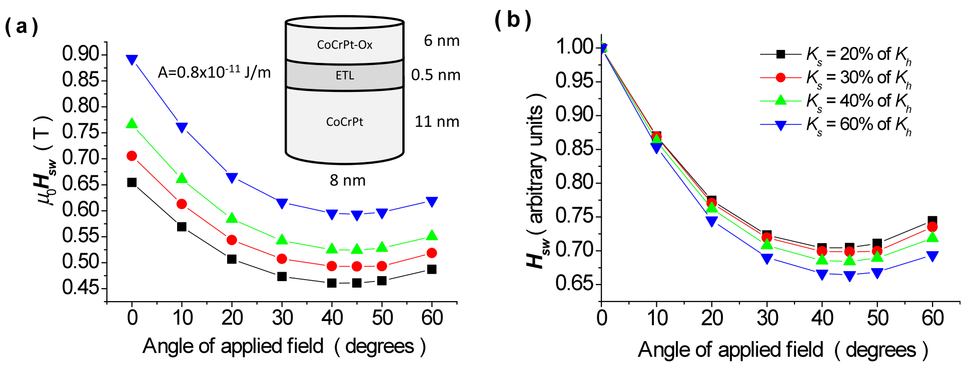

FIG. 3. (a) The switching field and (b) normalized switching field as a function of angle of applied field. Parameters as in Figure 2 except the exchange constant of the intergranular interface transition layer that was increased to 0.8×10^{-11} J/m.

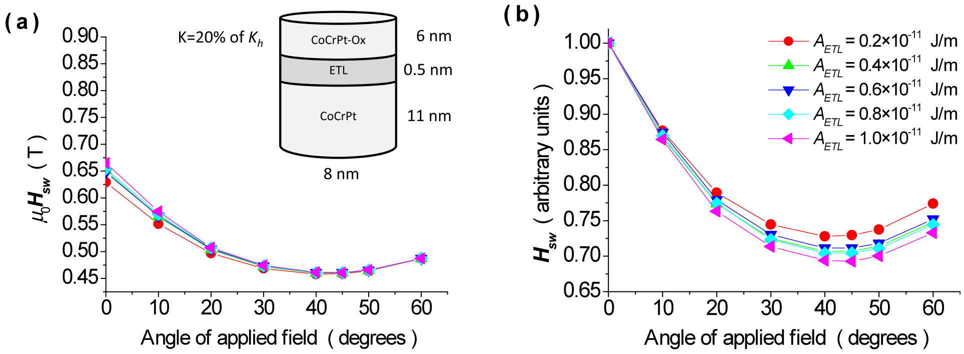

FIG. 4. (a) The switching field and (b) normalized switching field as a function of angle of applied field with attempt and frequency of 10^{10} Hz for the CoCrPt based multilayer structure with a diameter of 8 nm, a hard layer thickness of 11 nm, an exchange transition layer of 0.5 nm and a soft layer of 6 nm at 292 K. The measurement time is 10 s and the anisotropy of the soft phase is 20% of K_h.

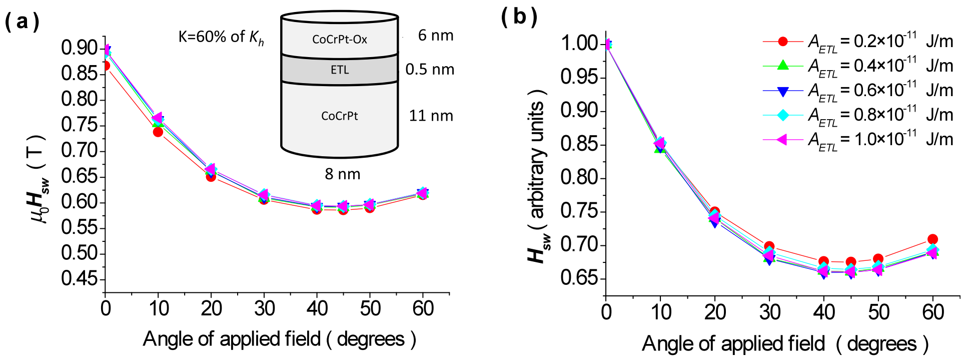

FIG. 5. (a) The switching field and (b) normalized switching field as a function of angle of applied field. Parameters as in Figure 4 except the anisotropy of the soft phase that was increased to 60% of K_h.

layer is 20% of K_h, a clear shift in the minimum switching field angle is observed, see Figure 4(b) (the minimum angle for A = 0.2×10^{-11} J/m is at 40° while for A = 01.0×10^{-11} J/m it is at 45°), indicative of greater incoherency during switching of the magnetization, but shows no effect on the absolute switching field values, which is different to previous reported Work done on exchange spring media.[4,5] The normalized curves for the soft layer with 60% of K_h are similar for all values of exchange constant, which is different compared to simulations with lower magnetocrystalline anisotropy in the soft layer. The greater minimum angle change for the 20% K_h layer can be explained by the reduced anisotropy energy allowing the exchange interaction to be the dominant factor, resulting in an increased incoherency of the system. In terms of the absolute switching field values, the structure with a lower magneto-crystalline anisotropy has a switching field 0.25 T lower than the grain with a higher soft layer anisotropy when measured along the easy axis.

Effect of the intergranular interface layer thickness

The thickness of the exchange transition layer can affect the magnetization reversal of the multiple layer system. To study the effect of intergranular interface layer thickness, we vary its value in the range 0.5 nm to 2 nm. Figures 6 and 7 show the effect of varying the exchange coupling layer thickness with an exchange constant of 0.2×10^{-11} J/m and 0.8×10^{-11} J/m, respectively. Again, these two values were chosen to explore the magnitude of the effect in weak and strong coupled systems. As expected, the results show that the multilayer system is more strongly coupled with an exchange of 0.8×10^{-11} J/m compared to 0.2×10^{-11} J/m.

Increasing the exchange transition layer thickness leads to weaker coupling between the hard and soft layers as expected, resulting in greater incoherency during the magnetization reversal. The minimum angle of the normalized switching field vs applied field curve shifts towards 30° as thickness is increased from 0.5 nm to 2 nm.

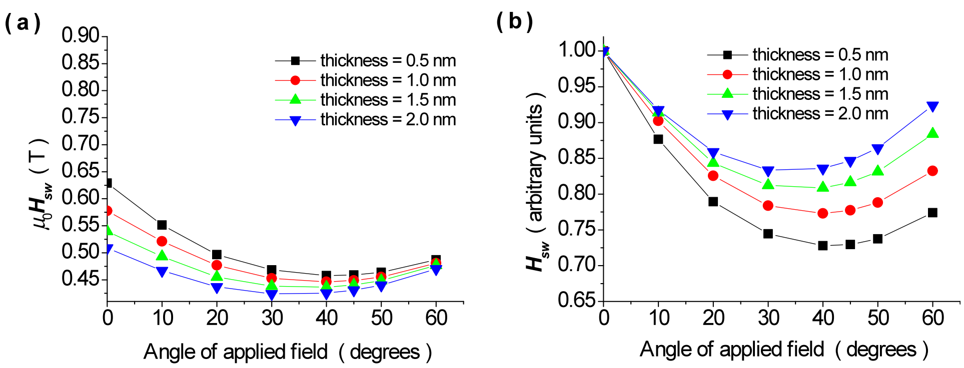

FIG. 6. (a) The switching field and (b) normalized switching field as a function of angle of applied with an attempt frequency of 10^{10} Hz for the CoCrPt based multilayer structure with a diameter of 8 nm, a hard layer thickness of 11 nm, an exchange transition layer of 0.5 nm, and a soft layer of 6 nm at 292 K. The measurement time is 10 s. The soft phase anisotropy is 20% of K_h and the exchange constant of the exchange transition layer is 0.2×10^{-11} J/m.

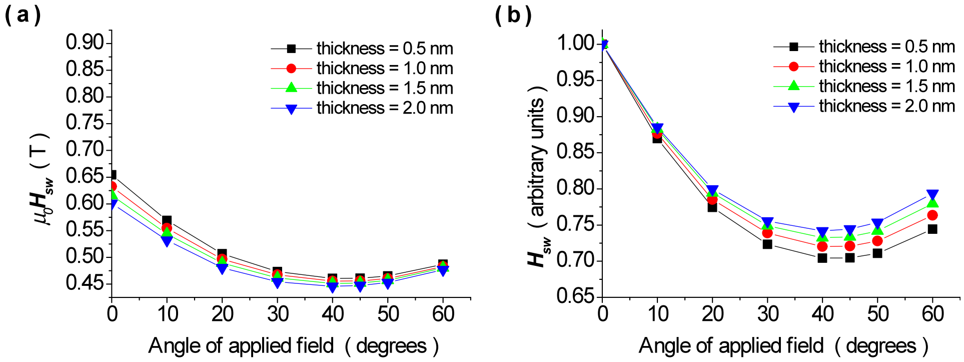

FIG. 7. (a) The switching field and (b) normalized switching field as function of angle of applied field. Parameters as in Figure 6 except the exchange constant of the exchange transition layer that was increased to 0.8×10^{-11} J/m.

CONCLUSIONS

We have performed a finite temperature micromagnetic study using parameters appropriate for a segregated CoCrPt ferromagnetic multiple layer system used as magnetic recording media. This allows us to understand the effect of the various layers of the magnetic structure on the switching characteristics of the system at finite temperatures of 292 K and long measurement times of 10 s to be comparable to vibrating sample magnetometer (VSM) measurements. The effect of the exchange constant, thickness of the exchange transition layer, and anisotropy of the soft phase on the switching field at 292 K was determined. It is shown that the magnetization reversal mechanism depends on the material properties of the exchange transition layer as well as the thickness of the layer. For high magnetic anisotropy and low exchange transition layer thickness, the coupling between the soft/hard layers is stronger compared to a low magnetic anisotropy and high exchange transition thickness. This has the consequence that for a strongly coupled system, we do not observe a shift in the angle at which the minimum switching field occurs. In the case of weaker coupled systems, we observe a clear shift in the minimum angle, which changes from 45° to 40°. Reducing the exchange constant of the exchange transition layer from 0.8×10^{-11} J/m to 0.2×10^{-11} J/m also leads to a shift in the minimum angle from 45° towards 40° but contrary to previous published work does not show an effect on the absolute switching field. In addition, we show that increasing the intergranular layer thickness from 0.5 to 2 nm also leads to a clear shift in the minimum angle, from 45° to 40°. In all the simulations, we see that the shift of the minimum angle can be attributed to increased incoherency of the magnetization reversal as the Stoner-Wohlfarth assumption of coherent reversal becomes less valid, and that material parameters like exchange constant have different effects on the switching field at elevated temperatures. The largest change in switching field value can be attributed first to the ETL thickness followed by the magneto-crystalline anisotropy of the soft layer and the change in the minimum angle is governed by the ETL thickness and the exchange coupling strength between the layers.

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