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The dipolar interaction in CoFeB/MgO/CoFeB perpendicular magnetic tunnel junction

C. C. Tsai,[1] Chih-Wei Cheng,[2] Yi-Chien Weng,[2] and G. Chern[2,a)]
[1]*Department of Engineering and Management of Advanced Technology, Chang Jung Christian University, Tainan 71101, Taiwan*
[2]*Department of Physics, National Chung Cheng University, Chia-Yi 62102, Taiwan*

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Ultrathin CoFeB/MgO/CoFeB system with perpendicular magnetic anisotropy is a promising candidate for the high density magnetic random access memory. However, a dipolar interaction between the CoFeB layers may introduce a minor loop shift (H_s) and causes uncertainty during the operation. In this report, we systematically studied the dipolar effect in these structures and found that the coupling may be either ferromagnetic or antiferromagnetic ($15\,Oe > H_s > -15\,Oe$) depending upon the CoFeB thickness (0.9–1.4 nm). A modified Fabry-Perot model, which accounts the Bloch wave interference, may explain the present observations of the dipolar effect in the perpendicular junctions of CoFeB/MgO/CoFeB.
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After the discovery of high perpendicular magnetic anisotropy (PMA) in CoFeB/MgO/CoFeB magnetic tunnel junctions (MTJs),[1] a considerable investigation has been drawn to this system due to its potential applications in the next-generation spintronic devices. However, an asymmetric switching field of the soft layer in a MTJ due to the interlayer coupling between the two magnetic electrodes may introduce a minor loop shift in the magnetic field (H_s) with respect to $H = 0$, which, in turn, may cause uncertainty during practical operations.

In our previous report,[2] we have studied both of the interlayer coupling and perpendicular magnetic anisotropy in a series of $Co_{40}Fe_{40}B_{20}$/MgO (t nm)/$Co_{20}Fe_{60}B_{20}$ tunnel junction structures with different thickness of MgO spacer and annealing temperature. Our results evidently showed an oscillatory behavior of the coupling strength as a function of MgO thickness. We have suggested that the Neel's orange-peel dipolar effect[3] accounts for the periodic varying in the interlayer coupling for the perpendicularly magnetized MTJ structures, where the ferromagnetic/antiferromagnetic coupling is determined by the contour of the interface boundary conditions, i.e., the interface roughness (amplitude and period) through the magnetostatically induced surface magnetic charges at the interface. More importantly, in our previous observations, a correlation between the interlayer coupling and perpendicular magnetic anisotropy was identified, where the perpendicular anisotropy increases with increasing annealing temperature while the interlayer coupling decreases from ferromagnetic to antiferromagnetic. This correlation between the coupling and perpendicular anisotropy in our experimental observations was attributed to the competition between the surface magnetic charge and volume charge. Furthermore, the dipolar interaction between CoFeB layers showed an oscillatory behavior as a function of the thickness of MgO layer and the coupling strength (H_s) oscillates between −25 Oe (anti-parallel coupling) and 15 Oe (parallel coupling) with a period ~0.15 nm.

In this report, instead of enquiring the interlayer coupling as a function of MgO thickness, we extend the study to the interlayer coupling in a series of CoFeB/MgO/CoFeB perpendicular MTJs (p-MTJs) by varying the thickness of the magnetic electrodes. Based on the Bruno's theory, an oscillatory coupling may also exist as a function of the thickness of the ferromagnetic layer and the oscillatory period is associated with the Fermi wave vector of the ferromagnetic electrodes.[4] The experimental observation of the oscillation, with period ~6 Å, has been shown in the (001) Co/Cu/Co structures as a function of Co thickness.[5] More recently, the interference of the electronic wave has been discussed in a [Co/Pt]/MgO/[Co/Pt] (Refs. 6 and 7) tunnel junction with a strong perpendicular magnetic anisotropy and this oscillation is modeled by a Fabry-Perot interference.[4]

Two series of pseudo spin valve magnetic tunnel junction samples are fabricated. Series A consists of sub/Ta(10)/$Co_{40}Fe_{40}B_{20}$(1.2)/MgO(1)/$Co_{20}Fe_{60}B_{20}$(x_t)/Ta(1) MTJ structures with the thickness of the top magnetic layer $x_t = 1.1$–1.5 (where the units in the parenthesis are in nm), and series B consists of sub/Ta(10)/$Co_{40}Fe_{40}B_{20}$(x_b)/ MgO(1)/$Co_{20}Fe_{60}B_{20}$(1.2)/Ta(1) with the thickness of the bottom magnetic layer $x_b = 0.9$–1.5 are fabricated by dc/rf magnetron sputtering.[2] In both series, the top ferromagnetic layer has higher coercivity and plays a roll as the reference layer while the bottom ferromagnetic layer has smaller coercivity and plays a role as the free layer. The samples were vacuum annealed at 225–255 °C after deposition for 1 h without further application of external magnetic fields. The magnetic properties were measured at room temperature using a vibrating sample magnetometer.

The out-of-plane component of the magnetization can be probed by measurement of the M-H hysteresis loop with application of magnetic fields in the direction perpendicular to the junction. Figure 1 (left panel) shows both of the

a)Author to whom correspondence should be addressed. Electronic mail: gchern@ccu.edu.tw.

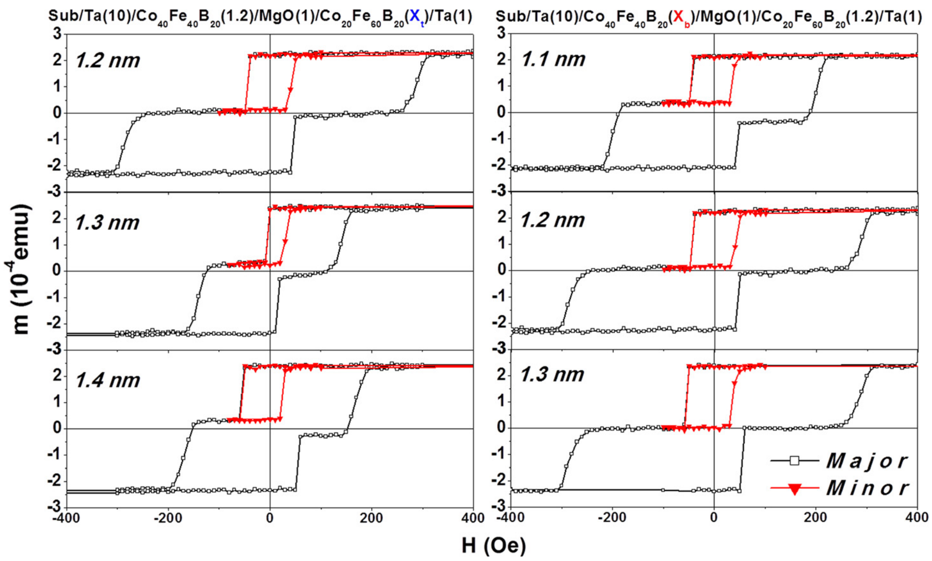

FIG. 1. M-H curves, including both the full loops and the minor loops, of CoFeB(x_b nm)/MgO(1 nm)/CoFeB(x_t nm) measured by the application of an external field along the perpendicular direction. The samples were annealed at temperature 225 °C after deposition.

representative full (major) and minor loop of M(H) curves of unpatterned CoFeB/MgO/CoFeB(x_t) films with the thickness of the top layer $x_t = 1.2$ to 1.4 nm. Perpendicular magnetic anisotropy is clearly observed in the figures with the M(H) curves showed hysteresis for all the samples. The magnetization reversal associated with the top and bottom layers can be easily identified from the switching fields correspondingly. As expected that the bottom layer, which is relatively softer than the top layer magnetically, is associated to the free layer, while the top layer is associated to the reference layer of an MTJ.[5]

We have also performed M(H) measurements in series B of CoFeB(x_b)/MgO/CoFeB tunneling structures with the thickness of the bottom layer x_b varies from 0.9–1.5 nm. Figure 1 (right panel) shows both of the full and minor hysteresis loop measurement of the samples. Perpendicular magnetic anisotropy is also clearly observed in the figures with the M(H) curves showed hysteresis.

The characterization of magnetization of the $Co_{40}Fe_{40}B_{20}(1.2)/MgO(1)/Co_{20}Fe_{60}B_{20}(x_t)$ films is shown in Fig. 2(a). The relation between the areal magnetization vs. $Co_{20}Fe_{60}B_{20}$ thickness is well fitted with a straight line. The intercept at x-axis is identified as the thickness of the magnetic dead layer (MDL) and the slope gives an average of M_s and these numbers are 0.17 nm and 1195 emu/cm^3, respectively. The magnetic moment of the $Co_{40}Fe_{40}B_{20}(1.2)$ in the films is also shown for comparison. Since the thickness is fixed, the moment exhibits a nearly constant value of 1150 emu/cm^3. The small difference between the top and bottom is due to the formation of MDL (see below). Similar magnetization analysis of $Co_{40}Fe_{40}B_{20}(x_b)/MgO(1)/Co_{20}Fe_{60}B_{20}(1.2)$ films is shown in Fig. 2(b). Again, a linear relation between the areal magnetization vs. the thickness of ferromagnetic layer is obtained. The MDL and the M_s are 0.245 nm and 1214 emu/cm^3, respectively. Notice that the M_s of all the top and bottom CoFeB layers is ~1200 emu/cm^3 while the MDL of the bottom layer is ~0.1 nm thicker than the MDL of the top layer.

Since the nature of magnetic coupling between the two ferromagnetic electrodes of an MTJ is revealed by the asymmetrical shift of a minor hysteresis loop with respect to $H = 0$, we now focus on the minor hysteresis loops with the magnetization reversal of the soft layer. The shift of the magnetic field H_s in a minor loop with respect to zero external fields is associated with the interlayer coupling. The areal density of coupling strength J can be quantitatively estimated by the characteristic fields H_s with $J = H_s M_s t$, where M_s is the magnetization and t is the thickness of the magnetic layer.[2] A negative value favors antiparallel alignment of the magnetization directions between the two layers, whereas a positive value favors parallel alignment. The results are illustrated in Fig. 3(a). Most strikingly, an oscillation in the coupling is revealed and variation period of ~0.25 nm with

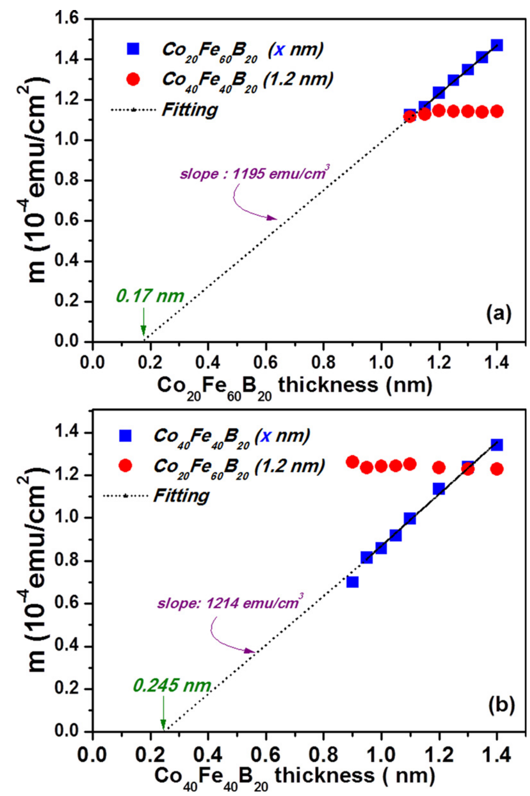

FIG. 2. Curves of areal saturation magnetization vs. CoFeB thickness for the (a) $Co_{20}Fe_{60}B_{20}$ and (b) $Co_{40}Fe_{40}B_{20}$ structures after the annealing temperature 225 °C. The lines are the results of the best fits. The thicknesses of magnetically dead layer are determined by the intercept and saturation magnetizations are determined by the slops, as shown in the figures.

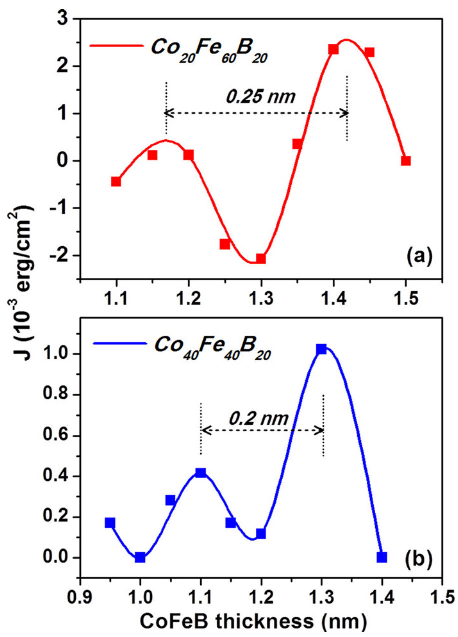

FIG. 3. The areal density of coupling strength J as a function of the thickness of the bottom layer $Co_{40}Fe_{40}B_{20}$ and top layer $Co_{20}Fe_{60}B_{20}$ in $Co_{40}Fe_{40}B_{20}$/MgO(1 nm)/ $Co_{20}Fe_{60}B_{20}$ MTJ structures.

highest oscillatory amplitude $\sim$2.5 merg/cm^2 (corresponded $H_s > 15$ Oe) are obtained. In addition, the amplitude of the coupling tends to increase with increasing thickness of the ferromagnetic layer. Notice that the J in the present structure also depends upon the thickness of MgO insulating layer.[2] The oscillatory period associated with MgO thickness is 0.15 nm and the amplitude of the exchange coupling is $\sim$25 Oe. In the present case, the MgO thickness of 1.0 nm corresponds to a weak exchange coupling strength of $\sim$a few Oe as both reference and free layer thicknesses are 1.2 nm.

Similar phenomenon of oscillatory variation in the interlayer exchange coupling have been observed in Pt/Co/MgO/Co(x)/Pt perpendicular MTJ structures as a function of Co thickness[6] The oscillatory variation in coupling as a function of magnetic layer thickness has been theoretically predicted by Bruno.[4] According to the theory, the oscillatory behavior originates from a Fabry-Perot-like interference by multi-reflections of the electron Block waves in the magnetic layers. The interlayer exchange coupling J within the model can be expressed as[4]

$$J = \frac{A}{C^2} \sin\left(\frac{2\pi t}{\lambda} + \phi\right), \quad (1)$$

where t is the thickness of the magnetic layer, λ and ϕ indicates the period and phase of the oscillation, respectively. A is a constant, while $C = 1 + \frac{k_F t}{k_F^{\downarrow} D}$ with k_F the imaginary part of the Fermi wave vector in the insulating spacer, $k_F^{\downarrow}$ the Fermi wave vector of spin down electrons, and D the thickness of insulating layer. We have tried fitting of experimental results of J with respect to Eq. (1) and obtained values of $\lambda = 0.25$ nm, $\phi = 1.1\pi$, $k_F = 5\,\text{nm}^{-1}$, and $A = 0.003$. Despite the deviation for the amplitude of the coupling strength in the fitting, the variation of J values with the period of oscillation $\lambda = 0.25$ nm obtained from Eq. (1) gives a good agreement with our experimental data.

The interlayer coupling field H_s acquired from the minor loop shift and therefore the coupling strength J deduced from the bottom CoFeB layer from 0.9 to 1.5 nm are shown in Fig. 3(b). Here, an oscillatory behavior in the coupling strength as a function of the bottom layer thickness can be identified as well. However, the amplitude of the oscillatory variation in the coupling strength for the bottom layer case is comparatively smaller than those of the top layer. The oscillatory phenomenon in the coupling strength indicates that Fabry-Perot-like interference by multi-reflections of the electron Block waves also occurs in the bottom magnetic layers. We apply this model and find the corresponded J of Eq. (1). The results give a reasonable agreement with experiment for period with $\lambda = 0.2$ nm, $\phi = 1.1\pi$, $k_F = 5\,\text{nm}^{-1}$, and $A = 0.001$.

Finally, the anneal effect on the interlayer coupling is briefly discussed. The results presented above are taken from the samples annealed at 225 °C. While increases the annealing temperature to 255 °C, the coupling strength tends to change to more negative (from -2×10^{-3} erg/cm^2 to -8×10^{-3} erg/cm^2) and the oscillation period also becomes larger ($\sim$0.4 nm). This strong annealing effect results probably from the interface of CoFeB/MgO, which is sensitive to the perpendicular magnetic anisotropic systems, and more study will be needed to explore the basic mechanism.

In conclusion, we have provided a systematic study of the coupling between the magnetic layers in CoFeB/MgO /CoFeB pseudo-spin valve structures by changing the thickness of top and bottom layers, respectively. Our observations evidently show that the coupling may be either ferromagnetic or antiferromagnetic depending upon either the top or the bottom CoFeB layer thickness. The oscillatory behavior in the coupling strength between the two layers can be explained fitted with a Fabry-Perot-like interference model. Combining our previous results on the MgO thickness dependence on the perpendicular magnetic anisotropic CoFeB/MgO/CoFeB MTJ, we conclude that the dipolar interaction is important in these MTJ structures. A positive or negative dipolar field in the range of positive and negative 20 Oe may exist depending on the thickness of either ferromagnetic or MgO spacer layer. A mechanism on the reduction of the dipolar interaction needs to be considered for the future application.

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