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The perpendicular anisotropy of Co$_{40}$Fe$_{40}$B$_{20}$ sandwiched between Ta and MgO layers and its application in CoFeB/MgO/CoFeB tunnel junction

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Magnetic anisotropy of Co$_{40}$Fe$_{40}$B$_{20}$ thin films sandwiched between Ta and MgO layers was investigated. Magnetic properties of CoFeB layers deposited on top and bottom of MgO layer are different. The thickness of the CoFeB layer and annealing temperature are the critical parameters to achieve and keep the perpendicular magnetic anisotropy. The phase diagram of perpendicular anisotropy strength of CoFeB layers on annealing temperatures and thicknesses of CoFeB layers is observed. According to phase diagrams, perpendicular CoFeB/MgO/CoFeB tunnel junctions were fabricated, and tunneling magnetoresistance (TMR) ratio was higher than 30% at low temperatures.


Magnetic tunnel junctions (MTJs) with MgO as tunnel barrier show large magnetoresistance, owing to the prediction of almost perfect interfaces among crystalline MgO and Fe, Co, and their alloys as well as the perfect spin-filtering effect proved experimentally. In particular, perpendicular MTJs based on Ta/CoFeB/MgO/CoFeB/Ta structure (direction of magnetic easy axis of CoFeB thin film is out-of-plane) have promising features: relatively high perpendicular anisotropy of CoFeB layer and low coercive fields. However, a systematic study on perpendicular magnetic anisotropy (PMA) of CoFeB sandwiched by Ta and MgO is still lacking. In this letter, dependence of PMA of CoFeB layer on its thickness as well as on post-annealing temperature is explored. Our goal is to establish a phase diagram of PMA in CoFeB layers.

In previous reports, a magnetic dead layer at CoFeB/Ta interface (Ta layer is on top of CoFeB) was observed but no magnetic dead layer was reported at Ta/Co$_{20}$Fe$_{60}$B$_{20}$ interface (Ta layer is beneath CoFeB). In this letter, an alloy target with composition Co$_{20}$Fe$_{60}$B$_{20}$ (CoFeB), instead of Co$_{40}$Fe$_{40}$B$_{20}$, was used to deposit the magnetic layers. Therefore, two series of multilayers were fabricated. Series A with multilayer structure of sub/Ta(5)/Ru(10)/Ta(5)/CoFeB(t$_1$:0.6~1.8)/MgO(2.5) and series B with multilayer structure of sub/Ta(5)/MgO(2.5)/CoFeB(t$_2$:0.6~2.2)/Ta(5) (nominal thickness in nm) were deposited on thermal oxidized silicon by magnetron sputtering. The deposited CoFeB layer is rather smooth as evidenced from the high-resolution transmission electron microscopy (HRTEM) image (Fig. 1(a)). Samples were post-annealed in vacuum at different temperatures ($T_A$) for 1 hr. After annealing, MgO and CoFeB layers are crystallized and show better interface, as shown in Fig. 1(b).

Post-annealing is a critical process in traditional MTJs fabrication in order to enhance quality of junctions and to obtain high tunneling magnetoresistance (TMR). Moreover, in CoFeB-based perpendicular MTJs, high temperature annealing is indispensable to obtain PMA in CoFeB layers. One sample in series A with $t_1$ = 1.0 nm was post-annealed at different temperatures. The magnetic hysteresis loops obtained after post-annealing at four typical temperatures are illustrated in Figs. 2(a)–2(d). For the as-deposited state and after post-annealing at temperatures lower than 150 °C, CoFeB layer does not show PMA [see Fig. 2(a)]. After post-annealing at intermediate temperatures (175 °C ≤ $T_A$ ≤ 250 °C), PMA emerges and in-plane remanence reaches to zero. At higher temperature ($T_A$ ≥ 275 °C), the in-plane remanence is higher than 10% of total saturation magnetization. However, saturation magnetic field increases. As seen from Fig. 2(f), the magnetic anisotropy energy density $K_u$ suggests that the magnitude of PMA increases as the post-annealing temperature is increased below 350 °C, i.e., $T_A < 350$ °C. $K_u$ does not depend monotonically on $T_A$, showing its maximum at around $T_A = 350$ °C. The coercivity ($H_C$) of the annealed CoFeB layer shows the same tendency as $K_u$, as shown in Fig. 2(e). $H_C$ and $K_u$ increase with $T_A$, indicating the crystallization of CoFeB layer. When annealing temperature is higher than 350 °C, both $H_C$ and $K_u$ decrease, which can be attributed to intermixing of CoFeB and Ta at their interface. The $T_A$ dependence of $H_C$ and $K_u$ for Co$_{40}$Fe$_{40}$B$_{20}$ is quite similar to those for Co$_{20}$Fe$_{60}$B$_{20}$. However, both $K_u$...
and $H_c$ show a little drop at $T_A = 275\,^\circ C$. Similar drop was also found in MgO/CoFeB/Pd trilayer. Moreover, at $T_A = 275\,^\circ C$, the in-plane remanence is not zero which suggests that in CoFeB layer magnetization rotation is not simultaneous and the magnetic easy axis is dispersed. The drops of $K_u$ and $H_c$ at $T_A = 275\,^\circ C$ can be attributed to the dispersion of easy axis.

The phase diagrams of perpendicular anisotropy in Ta/CoFeB/MgO (series A) and MgO/CoFeB/Ta (series B) are deduced from experimental data points, shown in Fig. 3. Out-of-plane remanence ($M_r/M_s$) is used as order parameter in plotting the phase diagram. Within the shadow area, CoFeB layer shows PMA and $M_r/M_s$ is larger than 0.9. Experimental data points are plotted as dots in Fig. 3. According to the phase diagram, both the series A and series B show strong PMA after post-annealing with proper thickness of CoFeB. However, after post-annealing at even higher temperatures, $M_r/M_s$ of these samples eventually decreases and PMA is destroyed. For different CoFeB thicknesses, annealing temperature toleration of PMA ($T_{\text{toler}}$) is different. For series A with $t_1 = 0.6\,\text{nm}$ (series A), $T_{\text{toler}}$ is 275 $\degree C$. For series A with $t_1 = 0.8\,\text{nm}$, $T_{\text{toler}}$ increases to 325 $\degree C$. $T_{\text{toler}}$ changes as a function of CoFeB thickness, shown as the top edges of the shadow areas in the phase diagrams. The phase diagrams give the parameters to obtain PMA in Ta/CoFeB/MgO (series A) and MgO/CoFeB/Ta (series B). The optimal thickness of CoFeB layer when located beneath MgO layer (series A) is between 0.8 and 1.2 $\text{nm}$, and the optimal post-annealing temperature is between 250 $\degree C$ and 325 $\degree C$. When CoFeB is deposited on top of MgO layer (series B), the optimal post-annealing temperature range is roughly the same as for Ta/CoFeB/MgO (series A). However, the optimal thickness of CoFeB layer is between 1.4 and 1.6 $\text{nm}$, which is roughly 0.4 $\text{nm}$ larger than that of Ta/CoFeB/MgO (series A). Ikeda et al. reported an approximately 0.5-nm-thick magnetic dead layer in MgO/CoFeB/Ta structure but no magnetic dead layer in Ta/CoFeB/MgO structure. Our diagram confirms this observation and is almost consistent with previous results.

According to the phase diagrams, MTJ with core structure of Ta(5)/Ru(10)/Ta(5)/CoFeB(1.2)/MgO(1.9)/CoFeB(1.4)/Ta(5) (nominal thickness in nm) was fabricated. The free and reference layers were chosen with different $H_c$. The multilayers were annealed at 250 $\degree C$ for 1 h. The out-of-plane $M-H$ loop of multilayers shows steps at about $M/M_s = 0.1$, half of which is shown in Fig. 4(a). The $H_c$ of Ta/MgO/CoFeB(1.4 nm)/Ta is larger than that of Ta/Ru/Ta/CoFeB(1.2 nm)/MgO, so the magnetization of bottom CoFeB layer switches first during the magnetic field changes from positive to negative. In the half
M-H loop, the magnetization switching at low magnetic field [shown in Fig. 4(a): from point A to point B] corresponds to the magnetization switching of bottom CoFeB, while the magnetization switching of top CoFeB corresponds to the magnetization switching at relative high magnetic field [shown in Fig. 4(a): from point C to point D]. Therefore, the saturation magnetization of top CoFeB electrode is 45% of the total saturation magnetization, and the other 55% is contributed by the bottom CoFeB electrode. We assume that no magnetic dead layer is present in 1.2-nm-thick bottom CoFeB.\(^8,9\) In the top 1.4-nm-thick CoFeB electrode, the magnetic effective layer is 1.0 nm and the magnetic dead layer is 0.4 nm. This is consistent with the phase diagrams. The multilayers were patterned into junctions with area of 50 \(\mu\text{m}^2\). For the MTJ, the perpendicular magnetic field dependence of resistance is shown in Fig. 4(c). As temperature decreases, the two resistance switching magnetic fields and the difference between them increase monotonically. The sharp switching of resistance with magnetic field confirms the good PMA in top and bottom CoFeB electrodes. Temperature dependence of TMR ratio and resistance in parallel and anti-parallel configurations \((R_{AP} \text{ and } R_P)\) down to 50 K are shown in Fig. 4(d). \(R_{AP}\) and \(R_P\) increase monotonically when measuring temperature decreases from 300 K to 50 K. Meanwhile, the MR ratio increases monotonically from 16.2% (300 K) to 31.3% (50 K). The relatively low TMR ratio\(^1\) is attributed to the weak crystallization of MgO barrier due to the low annealing temperature of 250 °C, as shown in Fig. 4(b).

In summary, we investigated the post-annealing temperature dependence of PMA in Ta/Co\(_{40}\)Fe\(_{40}\)B\(_{20}\)/MgO (series A) and MgO/Co\(_{40}\)Fe\(_{40}\)B\(_{20}\)/Ta (series B). Similar to Co\(_{20}\)Fe\(_{60}\)B\(_{20}\), in Co\(_{40}\)Fe\(_{40}\)B\(_{20}\) layers, PMA increase significantly by annealing. The thickness of CoFeB layer and post-annealing temperature are critical parameters to achieve PMA. Experimental data points with different CoFeB thicknesses and different post-annealing temperatures are used to deduce phase diagrams of PMA in Ta/CoFeB/MgO and MgO/CoFeB/Ta. The optimal thicknesses of CoFeB layers are different in Ta/CoFeB/MgO and MgO/CoFeB/Ta. In MgO/CoFeB/Ta, there is a roughly 0.4-nm-thick magnetic dead layer, so optimal thickness of CoFeB is 0.4 nm larger than that in Ta/CoFeB/MgO. However, the optimal post-annealing temperature for both structures is roughly at the same interval and is between 250 and 325 °C. Too high annealing temperatures destroy perpendicular anisotropy. The annealing temperature tolerance of PMA is sensitive to the thickness of CoFeB. According to the phase diagram, perpendicular Co\(_{40}\)Fe\(_{40}\)B\(_{20}\)/MgO/Co\(_{40}\)Fe\(_{40}\)B\(_{20}\) MTJs were fabricated. A 16.2%, TMR ratio was observed at room temperature. The TMR ratio increases to two times (31.3%) when measured at 50 K.

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\(^{10}\)F. D. Wan, and X. L. Ma, Magnetic Physics, (Publishing House of Electronics Industry, China, 1998). Uniaxial magnetic anisotropy density \(K_a\) is calculated from M-H loop

\[ K_a = \int_{H_{in}}^{H_{out}} \mu_0 H_d dM - \int_{H_{in}}^{H_{out}} \mu_0 H_{sat} dM \]

where \(H_{in}\) and \(H_{sat}\) are in-plane and out-of-plane magnetic fields and \(M_s\) is the saturation magnetization, respectively.