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Spin-orbit torque efficiency enhancement to tungsten-based SOT-MTJs by interface modification with an ultrathin MgO

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Spin-orbital torque (SOT) based three-terminal magnetic tunnel junctions (MTJs) have attracted much interest as the next generation magnetic random-access memory (MRAM) key device both in the academy and the industry. This is because SOT-MTJs feature high endurance and fast switching speed, benefiting tremendously from the separation of read/write current paths and less incubation time during the write in contrast to the spin-transfer torque (STT) MTJs [1]. The pursuit of high density, ultrafast writing speed, and low power consumption of SOT-MRAM devices makes researchers work on higher charge-to-spin current conversion efficiency of the heavy metal (HM) layer. However, previous studies showed that the highest write efficiency was about -0.3 for β-W. This value is lower than the typical spin polarization $P \approx 0.6$ for widely used CoFeB materials in STT-MTJs [2]. So our purpose in the present study is to further improve the write efficiency. To reach this, we systematically investigated how an ultrathin MgO interlayer inserted in between the W and the CoFeB affects the write efficiency experimentally from the harmonic measurements as well as the switching behaviors of the fabricated SOT-MTJs. Moreover, we clarify the interfacial effects on the switching efficiency of the W/CoFeB-based MTJs from the first-principal calculations.

The film stacks are illustrated in Figure 1(a) and the interlayer is MgO with various thicknesses $t_{\rm MgO}$ ranging from 0.19 to 0.38 nm. In addition, the details of sample preparation are shown in Appendix A. The magnetization switching dynamics of samples were measured by the second harmonic, as shown in Appendix B. Then, we obtained the SOT induced the damping-like torque efficiency ($\xi_{\rm DL}$) and the field-like torque efficiency ($\xi_{\rm FL}$) of samples with various MgO thickness, as shown in Figure 1(b), in combination with the one without the MgO interlayer as a reference. It is found that the $|\xi_{\rm DL}|$ increases first with the increase of the $t_{\rm MgO}$. When the $t_{\rm MgO} = 0.22$ nm, $|\xi_{\rm DL}|$ reaches the maximum value of 0.58, suggesting 45% improvement as compared to the $|\xi_{\rm DL}|$ of the sample without the MgO interlayer. While for the sample with $t_{\rm MgO} > 0.22$ nm, $|\xi_{\rm DL}|$ tends to reduce with further increase the $t_{\rm MgO}$. $\xi_{\rm FL}$, contrary to $|\xi_{\rm DL}|$, is an order of magnitude smaller, and has almost no discernible dependence on the $t_{\rm MgO}$. So the contribution of $\xi_{\rm FL}$ can be negligible.

To properly understand the impact of the MgO interlayer thickness on $|\xi_{\rm DL}|$, we investigated the full MTJs with various MgO interlayer thicknesses as well. The film stacks and manufacturing process of MTJs can be found in our previous work [3]. We measured R-V loops of the MTJs with $t_{\rm MgO} =$ 0 and 0.22 nm at various RF pulse widths (from 1 to 100 ns) respectively. On top of that, we extracted the $J_{\rm SW}$ (the switching current density at the 50% switching probability) for P-to-AP and AP-to-P switching directions with different RF pulse widths shown in Figure 1(c). It can be clearly observed that the $J_{\rm SW}$ of the MTJs with 0.22-nm-thick MgO interlayer are considerably lower than those of the MTJs without the MgO interlayer under all RF pulse widths. In particular, the $J_{\rm SW}$ at 1-ns-width pulse is nearly 48% lower than those of the MTJs lacking the MgO interlayer. This is convincing evidence that the switching efficiency is improved remarkably when the interfaces are modified by the ultrathin MgO interlayer.

Besides the above-described results of $t_{\rm MgO} = 0$ and 0.22 nm, we also examined the $J_{\rm SW}$ for MTJs with other MgO interlayer thicknesses under both DC and 10-ns-width pulse test, as displayed in Figure 1(d). The $J_{\rm SW}$ decreases with increasing the MgO interlayer thickness till 0.22 nm in both cases, phenomenologically consistent with the behavior of the $|\xi_{\rm DL}|$ described before. This suggests that the $J_{\rm SW}$ reduction is probably caused by the enhanced $|\xi_{\rm DL}|$ due to the existence of the ultrathin MgO interlayer. After that, $J_{\rm SW}$ tends to slightly increase when the MgO interlayer is thicker than 0.22 nm at 10-ns-width pulse tests. This represents that the overall switching efficiency becomes small when further increasing the $t_{\rm MgO}$ beyond 0.22 nm.

Based on the above results, we will discuss the possible reasons for the switching efficiency enhancement with the ultrathin MgO interlayers inserted. As well known, the effective $\xi_{\rm DL}$ is proportional to the product of the $T_{\rm int}\theta_{\rm SH}$ [4].

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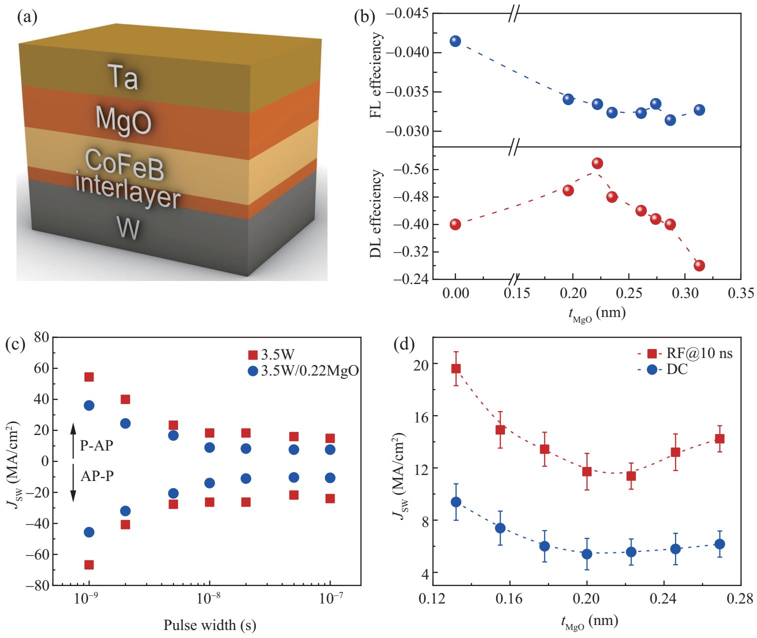

Figure 1 (Color online) (a) Schematic diagram of the film stacks. (b) The subtracted damping-like torque and field-like torque efficiencies obtained from samples with various MgO thicknesses. (c) The extracted J_{SW} as a function of the pulse widths for both P-to-AP and AP-to-P switching directions. The red squares (blue circles) are the data for the MTJs without (with) the MgO interlayer. (d) The MgO interlayer thickness dependence of the extracted J_{SW} under the DC and 10-ns width pulse testes, respectively. The error bars are the standard deviations of the J_{SW} measured for 10 devices.

The $T_{\rm int}$ reflects the spin transparency at the W/CoFeB interface and $\theta_{\rm SH}$ means spin Hall angle. Both parameters $T_{\rm int}$ and/or $\theta_{\rm SH}$ here would contribute to the increase of the $\xi_{\rm DL}$ in our study. To begin with, we calculated and analyzed the $T_{\rm int}$ of samples, shown in Appendix C. The $T_{\rm int}$ is 0.45 for the sample with the $t_{\rm MgO} = 0.22$ nm, which is slightly smaller than that of 0.49 for the $t_{\rm MgO} = 0$. This means that the 0.22-nm-thick MgO interlayer plays a negative role in the interfacial spin transparency $T_{\rm int}$ relative to the $t_{\rm MgO} = 0$. Therefore, we can conclude that the $T_{\rm int}$ is not the factor that contributed to the enhancement of the $\xi_{\rm DL}$. Furthermore, we will examine the contribution of $\theta_{\rm SH}$ to the effective $\xi_{\rm DL}$. As already known, the $\theta_{\rm SH}$ has two major sources: one comes from the spin Hall effect in the bulk HM intrinsically and/or due to defects extrinsically; another comes from the Rashba effect due to the HM/FM interfacial symmetry broken. In our study, we used the same HM of the 3.5-nm-thick W prepared by the same condition. Thus, we believe that the term of $\theta_{\rm SH}$ coming from the bulk W HM should be the same. There would be another possibility that the MgO interlayer at the W/CoFeB interface resulted in the strength change of the Rashba effect, leading to an enlarged $\xi_{\rm DL}$. We conducted first-principal calculations to further verify our hypothesis, as shown in Appendix D. We proposed a slab model containing two A-15 β-W lattices, on top of which one monolayer MgO was placed. By comparing the electron band structures at the Fermi level, it is evident that the existence of MgO induces a typical Rashba-type band splitting around Γ-point. Therefore, the model we proposed indicates that the $\theta_{\rm SH}$ can be enlarged due to the Rashba effect originating from the MgO interlayer, which supports our hypothesis to explain the above-mentioned MgO thickness dependence of the $\xi_{\rm DL}$ and/or the $J_{\rm SW}$.

Conclusion. The effect of the MgO interlayer in the W/CoFeB interface on the charge-to-spin current conversion efficiency was experimentally investigated by changing the MgO interlayer thicknesses. Experimental results show high $|\xi_{\rm DL}|$ up to 0.58 by introducing a 0.22-nm-thick MgO interlayer, which is 45% enhanced as compared to the one without the MgO interlayer. The switching current density in the corresponding MTJs was also reduced by nearly 48% under 1-ns-width pulse tests. The improved switching efficiency can be explained by the enhanced Rashba effect at the W/MgO interface theoretically. In summary, these findings give potential solutions to the high-power dissipation issue for the tungsten-based SOT-MTJs.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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