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Enhancement of tunneling magnetoresistance by optimization of capping layer thicknesses in CoFeB/MgO/CoFeB magnetic tunnel junctions

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The main focus of improving the tunneling magnetoresistance (TMR) of magnetic tunnel junctions (MTJs) has been on optimizing the structure and thickness of the MgO barrier layer [Moriyama *et al.*, Appl. Phys. Lett. **88**, 222503 (2006); Yuasa *et al.*, Nat. Mater. **3**, 868 (2004)]. However, in this paper, we found that the thicknesses of the capping layers also play an important role in TMR. We studied the influence of the capping layers above the CoFeB/MgO/CoFeB. It was intuitively believed that these capping layers did not affect the TMR because they were deposited after the critical CoFeB/MgO/CoFeB structure. Surprisingly, we found that the thicknesses of the capping Ta and Ru layers have significant influence on the TMR. The stress or strain applied onto the MgO barrier by these capping layers appear to be responsible. The results in this paper shed light on optimizing TMR of MgO MTJs. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3063664]

I. INTRODUCTION

In order to enhance the tunneling magnetoresistance (TMR), various parameters of magnetic tunnel junction (MTJ) devices have to be optimized. Different magnetic materials such as NiFe, CoFe, and CoFeB, and insulating layers including MgO and Al_2O_3 have been used to obtain higher TMR.[1] Half metals are also incorporated into MTJs for their high spin polarization and thus theoretically larger TMR effect.[2] The focus of the optimization effort has been mostly on the choice of materials for magnetic layers and oxide barrier.[3,4] Oxide barrier materials (such as aluminum oxide,[5] magnesium oxide,[6] titanium oxide,[7] tantalum oxide,[8] and strontium titanium oxide[9]) and magnetic layer compositions[4,10,11] are the common considerations for optimizing the TMR. However, the structural geometry is also found to be influential to the performance of MTJ devices.[12] Moreover, different capping layer materials have significant effect on the magnitude of the TMR (see Fig. 26 in Ref. 3). In this paper, we further investigated the dependence of the TMR on the thicknesses of the capping layers of Ta and Ru.

II. EXPERIMENT

The MTJ thin films were deposited on thermally oxidized silicon wafers by dc magnetron sputtering in an ultrahigh vacuum chamber with a base pressure of 2×10^{-8} Pa. The oxide barrier layer was made by first depositing a thin Mg metal and then oxidizing it in oxygen plasma (0.4 Pa argon and 0.1 Pa oxygen). A magnetic field of 7 mT was applied during magnetic layer deposition to induce the easy axis and pinning direction. Wedge-shaped layer structures were fabricated for the capping layers by using a linear movable shutter during magnetron sputtering. The sample stage is rotatable and therefore double-wedge structure can be made by depositing one wedge after another with 90 degree rotation. The sample structure is substrate/1 Ta/2.5 Au/10 IrMn/4 CoFe/0.8 Ru/10 CoFeB/0.4Mg/2.5 MgO/1.5 CoFeB/(wedge) 0–10 Ta/(wedge) 3–10 Ru (all thicknesses in nm). Ta and Ru were chosen in this study because they are very commonly used as the capping layers in MTJ research. The samples were annealed in vacuum at 400 °C for 30 min with an applied magnetic field of 70 mT. Current-in-plane-tunneling technique (CIPT) was used to characterize the MTJ wafers. Figure 1 illustrates the CIPT measurement on the double-wedged MTJ sample. An array of 5×5 measurement points of TMR and *RA* were acquired to study the effect of the thicknesses of the capping layers on the MTJ performance.

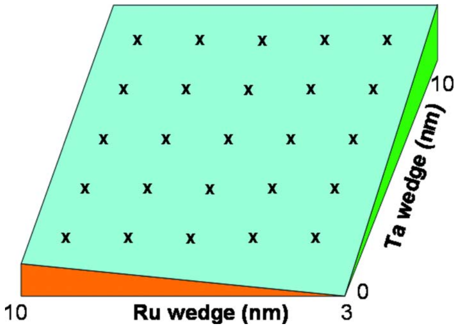

FIG. 1. (Color online) Schematic drawing illustrating the CIPT measurements on the double-wedged MTJ sample. An array of 5×5 data points were measured on the sample by CIPT. These data points are evenly distributed. The data points were measured at the thicknesses of 3.7, 5.1, 6.5, 7.9, and 9.3 of the Ru wedge and 1, 3, 5, 7, and 9 of the Ta wedge (all in nanometers).

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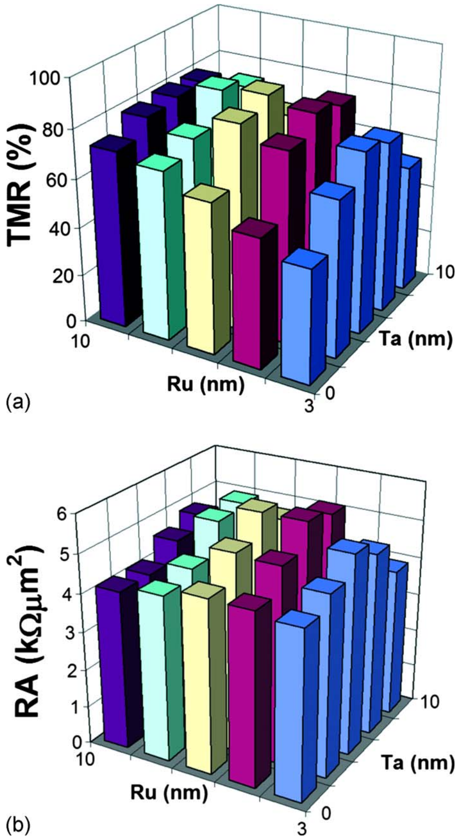

FIG. 2. (Color online) A plot of the (a) TMR and (b) *RA* of the 5 × 5 CIPT measurements on the double-wedged MTJ sample. In general, the central region of the sample shows higher TMR and *RA* than the areas toward the ends of the wedges. The capping layers with around 5 nm Ta and 6.5 nm Ru provide the highest TMR and *RA*.

III. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show the measurements of TMR and *RA* on the double-wedged MTJ sample. From Fig. 2(a), it can be observed that the region with higher TMR is in the central area of the sample. Similar phenomenon can also be seen in Fig. 2(b) where the region with higher *RA* is in the central sample area as well. Apparently the capping layers with around 5 nm Ta and 6.5 nm Ru provide higher TMR and *RA*. The general trends of the TMR dependence on the capping layer thicknesses at these two particular Ru and Ta thicknesses are shown in Figs. 3(a) and 3(b), respectively. In Fig. 3(a), the Ru thickness is fixed at 6.5 nm, the TMR increases from 62% at the thin side of the Ta wedge and reaches its peak of 89% at the thickness of 5 nm Ta, then decreases to 54% toward the thick side of the Ta wedge. In Fig. 3(b), the Ta thickness is fixed at 5 nm, the TMR increases from 75% at the thin side of the Ru wedge and reaches its peak of 89% at the thickness of 6.5 nm Ru, then decreases to 81% toward the thick side of the Ru wedge. Similar trends are also observed in *RA*. In Fig. 3(c), the Ru thickness is fixed at 6.5 nm, the *RA* increases from 4542 $\Omega\ \mu\text{m}^2$ at the thin side of the Ta wedge and reaches its peak of 5789 $\Omega\ \mu\text{m}^2$ at the thickness of 5 nm Ta, then decreases to 4207 $\Omega\ \mu\text{m}^2$ toward the thick side of the Ta wedge. In Fig. 3(d), the Ta thickness is fixed at 5 nm, the *RA* increases from 5240 $\Omega\ \mu\text{m}^2$ at the thin side of the Ru wedge and reaches its peak of 5789 $\Omega\ \mu\text{m}^2$ at the thickness of 6.5 nm Ru, then decreases to 4603 $\Omega\ \mu\text{m}^2$ toward the thick side of the Ru wedge.

The capping layers have the function of preventing the oxidation of magnetic layers and thus enhance the TMR. As the Ru and Ta capping layers increase in thickness from 3 and 0 nm, respectively, they start to protect the magnetic layers from oxidation and therefore we can see the increase in TMR with the Ru and Ta thicknesses from the thin sides of the wedges. It was previously studied that capping layer materials have significant influence on the crystallization of the top CoFeB layer which will greatly affect the MgO (100) crystallinity upon annealing and thus the TMR.[13] For example, a Permalloy cap layer grown on amorphous CoFeB has a textured fcc (111) structure and it will inhibit the crystallinity of the MgO layer and therefore coherent tunneling of Δ_1 electrons cannot occur,[14] leading to a great decrease in TMR. We believe that the detrimental effect on TMR by thicker Ta and Ru capping layers can also be explained similarly. The Ta and Ru capping layers induce stress strain onto the underlying MgO layer which damages the MgO crystallinity. As the capping layer thicknesses increase, the applied stress strain becomes stronger. Moreover, it was reported that a Ru capping layer will induce a CoFeB (110) structure upon annealing at 350 °C which is unfavorable to the formation of MgO (100).[15] As the Ta and Ru thicknesses increase beyond 5 and 6.5 nm, respectively, the TMR enhancement effect from the antioxidation protection is gradually overtaken by the detrimental effect of the stress strain. This explains why the TMR first increases with the thicknesses of the capping layers and then decreases. The trends of *RA* as shown in Figs. 3(c) and 3(d) are very similar to Figs. 3(a) and 3(b). These similarities suggest that the *RA* is also influenced, perhaps due to stress or strain, by the thicknesses of the Ru and Ta capping layers.

Current shunting effect does not artificially affect the TMR measurement in this case because of the nature of CIPT technique. In a CIPT measurement,[16] *RA* is measured by making a series of four probe resistance measurements on the surface of a MTJ thin film wafer at various probe spacings. The probes are placed at the appropriate spacings typically on the order of microns. The TMR is acquired by repeating the measurement at different magnetic fields. Current shunting is a giant magnetoresistance (GMR) effect in which in-plane current can dilute the GMR effect. In the TMR effect, the current must tunnel perpendicular to the insulating barrier to give TMR, and lowering the in-plane resistance of the top electrode does not impair the tunneling process.

IV. CONCLUSION

The influence of the Ta and Ru capping layer thicknesses on the TMR of CoFeB/MgO/CoFeB MTJs was studied. The capping layers have an enhancement effect on the TMR because they can prevent the oxidation of magnetic layers. However, as the capping layer thicknesses further increase, the stress or strain applied onto the MgO layer becomes stronger which may distort the MgO (100) crystallinity and thus have a detrimental effect on the TMR. As such, the

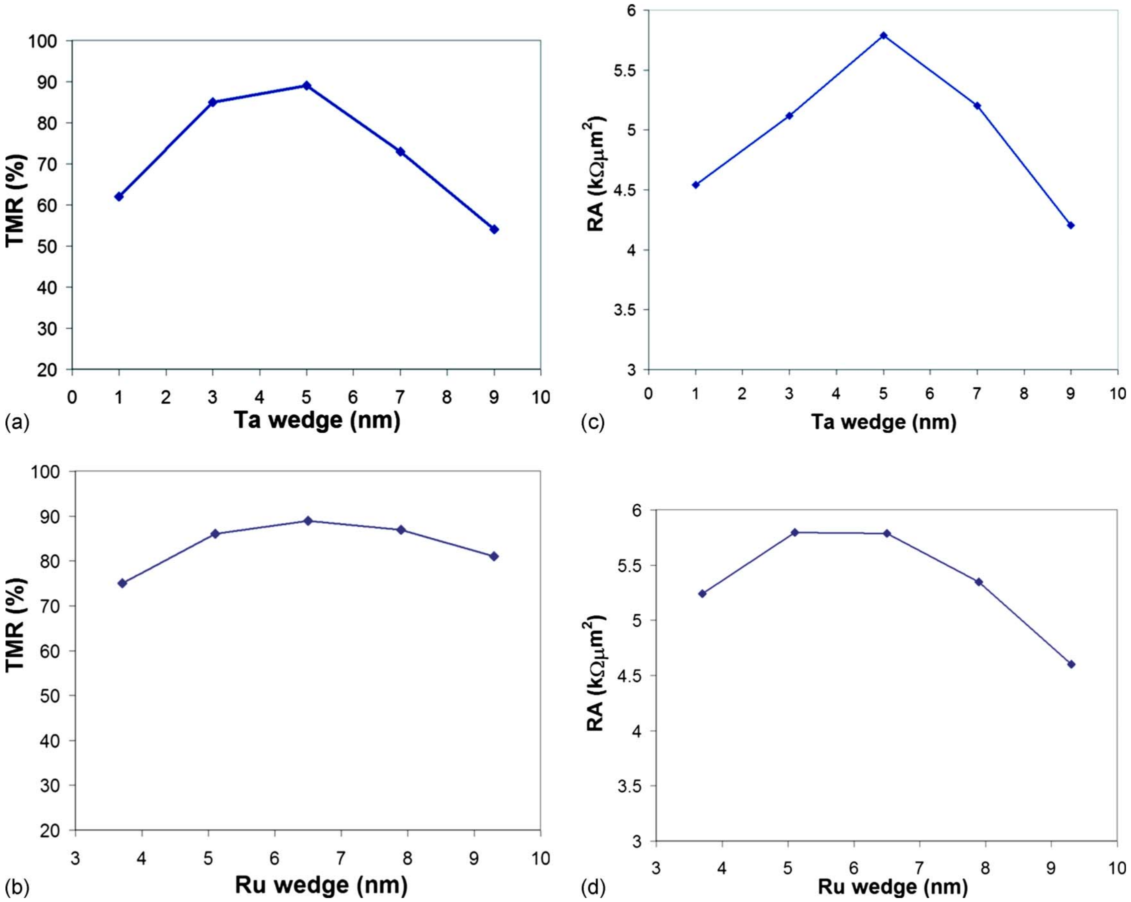

FIG. 3. (Color online) (a) The TMR variation with the thickness of Ta capping layer. The thickness of the Ru capping layer is fixed at 6.5 nm. (b) The TMR variation with the thickness of Ru capping layer. The thickness of the Ta capping layer is fixed at 5 nm. (c) The *RA* variation with the thickness of Ta capping layer. The thickness of the Ru capping layer is fixed at 6.5 nm. (d) The *RA* variation with the thickness of Ru capping layer. The thickness of the Ta capping layer is fixed at 5 nm.

thicknesses of the capping layers have to be optimized in order to obtain higher TMR on CoFeB/MgO/CoFeB MTJs.

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