Effect of capping layer material on thermal tolerance of magnetic tunnel junctions with MgO/CoFeB-based free layer/MgO/capping layers

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Effect of capping layer material on thermal tolerance of magnetic tunnel junctions with MgO/CoFeB-based free layer/MgO/capping layers

ABSTRACT

We investigate the effect of the capping layer on the thermal tolerance of magnetic tunnel junctions (MTJs) with free layer of MgO/CoFeB/spacer layer/CoFeB/MgO/capping layers (CoFeB, Ru, or Ta). We observe the largest perpendicular magnetic anisotropy energy density for the free layer with CoFeB capping layer using Ta spacer after annealing at 400 °C for 1 h. Energy-dispersive X-ray (EDX) line analysis along film normal direction reveals the absorption of oxygen in MgO by Ta in the stack with Ta capping layer and Ru diffusion into CoFeB free layer in the stack with Ru capping layer, which could cause the reduction of perpendicular magnetic anisotropy. We also evaluate annealing temperature dependence of magnetic properties for the MTJ stacks with different spacer layer. We again observe the largest perpendicular magnetic anisotropy energy density for the MTJ stack using the CoFeB capping layer. The present study reveals that CoFeB capping layer is effective for achieving improved robustness against annealing.

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I. INTRODUCTION

Embedded nonvolatile memory is an essential constituent for future electronics as it can achieve significant reduction of standby power, which becomes a more serious issue for advancing technology nodes. Among proposed non-volatile memories, spintronics-based ones are most suitable for embedded memory applications owing to their low-voltage and high-speed operation capability.1–3 A high-performance CoFeB/MgO magnetic tunnel junction (MTJ) with perpendicular easy axis at junction diameter of ∼40 nm, where the perpendicular magnetic anisotropy (PMA) originates from interfacial anisotropy at the CoFeB/MgO interface, has triggered the intensive development on spin-transfer-torque magnetoresistive random access memories (STT-MRAM), from material, device, unit/integration processes to integrated circuits.4–21 To realize high-performance and high-capacity STT-MRAM, one needs to develop high PMA MTJ, while keeping robustness against annealing at 400 °C at least to maintain process compatibility with standard CMOS back-end-of-line process. For perpendicular anisotropy, one needs to enhance the interfacial anisotropy at the CoFeB/MgO interface, since this is the origin of PMA in CoFeB/MgO-based MTJs. To increase the interfacial anisotropy, capping layer material on the topmost MgO layer plays important role in determining the interfacial anisotropy for double and quad CoFeB/MgO interface MTJ.21 Much effort has been devoted to achieving the more robust MTJs against annealing; the CoFeB composition and materials adjacent to the CoFeB free layer are the
important factors.\textsuperscript{22–25} Although both high PMA and robust MTJ stack against annealing are critical for high-performance and high-capacity STT-MRAM, each study has been independently done. In this regard, the effect of the capping layer on the PMA should be studied annealing at 400 ℃.

In this study, we investigate the effect of the capping layer material on the magnetic properties of the free layer in MgO/CoFeB/spacer layer/CoFeB/MgO/capping layer structure as well as its underlying mechanism after annealing at 400 ℃.

II. EXPERIMENTAL PROCEDURE

All films are deposited onto a 300-mmϕ thermally oxidized Si substrate using DC and RF magnetron sputtering system at room temperature. We prepared three types of stacks (Stacks A–C). Stack A has a pseudo spin-valve structure; from the substrate side, Ta(5)/CoFeB(1)/MgO(1.2)/CoFeB(1.4)/Ta(0.5)/CoFeB(1, 1.2, 1.4, 1.6)/MgO(1.2)/capping layer where numbers in the parenthesis show the nominal thickness in nm. Stack B has the following structure, from substrate side, bottom electrode/Pt buffer layer/synthetic ferrimagnetic reference layer/MgO (1.2)/CoFeB(1.4)/Ta(0.5)/CoFeB(1)/MgO(1.2)/capping layer/Top electrode. Stack A, which corresponds to the free layer in Stack B, is prepared for evaluating the PMA. Note that bottom CoFeB (1) in Stack A is non-magnetic owing to dead-layer formation via annealing. For the free layer in the stack C, we use the different spacer layer in the CoFeB free layer from that for Stack A and B. In stack C, we adopt surface modification treatment\textsuperscript{26} and W bridge layer\textsuperscript{27} to improve upon the thermal tolerance of the reference layer. For all the stacks, Ta (2), Ru (5), or CoFeB (1) is employed as the capping layer. Note that 1 nm-thick CoFeB is non-magnetic owing to dead-layer formation due to the deposition of a top electrode, which is confirmed by magnetization measurement (not shown). After deposition, stacks A and B are annealed at 400 ℃ for 1 h, and Stack C is annealed at 300 ℃, 350 ℃, or 400 ℃ for 1 h in a vacuum. The magnetic moment per unit area versus the magnetic field ($m$–$H$) curves are measured using a vibrating sample magnetometer (VSM). $K_{eff}$ for Stack A was obtained from areal difference between the in-plane and out-of-plane $m$–$H$ curves.\textsuperscript{28} We employ vector-network-analyzer ferromagnetic resonance (VNA-FMR) under the out-of-plane applied magnetic field to determine the effective anisotropy field $H_{K_{eff}}$ for the stack C.\textsuperscript{29}

III. RESULTS AND DISCUSSION

Figure 1 shows areal perpendicular magnetic anisotropy energy density $K_{eff}$ with respect to CoFeB thickness for Stack A with different capping layer materials. All stacks show increasing $K_{eff}$ with decreasing $t$ due to the presence of the interfacial anisotropy at CoFeB/MgO interface. The largest $K_{eff}$ is observed in the stack using the CoFeB capping layer.

To understand physical mechanisms for this result, we perform energy dispersive X-ray (EDX) line analysis along the film normal direction for Stack B. Figures 2(a)–(c) show EDX line analysis results for stack B with Ta, Ru, and CoFeB capping layers, respectively. In Stack B with Ta capping layer, the presence of oxygen atoms is observed in the capping layer, whereas it is not reflected in the other two capping layers. The results indicate that the oxygen atoms in the top MgO layer diffuse into Ta capping layer, which could be due to high reduction ability of Ta. In addition, we do not see any notable structural change around at the bottom CoFeB/MgO interface, which supports that the small $K_{eff}$ in the sample with Ta capping layer is attributed to the oxygen diffusion in MgO layer at top CoFeB/MgO interface. In contrast, in the stack with Ru capping layer, another feature is observed. Figure 2(d) and (e) show magnified images of the free layer region in the EDX results about the stack with Ru and CoFeB capping layers, respectively. As it can be seen, much larger amount of Ru atoms is observed in the stack with Ru capping layer compared with that with CoFeB capping layer. The results reveal that Ru atoms in the capping layer diffuse into the free layer region through top MgO layer in the case of Ru capping layer, which could degrade the PMA of the free layer. As a result, the stack with CoFeB capping layer shows the largest $K_{eff}$ among the three stacks with different capping layers.

To obtain more solid experimental evidence for oxide diffusion into the Ta capping layer, structural analysis is performed using a cross-sectional transmission electron microscopy (TEM). The cross-sectional TEM images for Stack B with a Ta capping layer (2 nm) and with a thicker Ta capping layer (5 nm) are shown in Fig. 3(a) and (b), respectively. Although nominal thickness of top MgO and

![FIG. 1. Areal perpendicular magnetic anisotropy energy density $K_{eff}$ of the free layer as a function of the total free layer thickness $t$ for Stack A with different capping layer materials.](image-url)
bottom MgO are the same, the top MgO layer becomes unclear compared with the bottom MgO layer as shown in Fig. 3(a) and 3(b). With increasing Ta capping layer thickness from 2 to 5 nm, the topmost MgO layer becomes more unclear and its thickness is clearly reduced. These results support the oxygen diffusion into the Ta capping layer mentioned in Fig. 2. As the interfacial anisotropy of the CoFeB/MgO system originates from hybridization of Fe 3d and O 2p orbitals, the diffusion of oxygen atoms in the MgO layer could deteriorate the perpendicular anisotropy, which is consistent with the results of previous report.  

Finally, we evaluate the effect of the capping layer material on magnetic properties as a function of annealing temperature to understand the robustness of each capping layer material against annealing. Figures 4(a) and (b) show annealing temperature $T_a$ dependence of spontaneous magnetic moment per unit area $m_s$ and $K_{eff}$ for stack C with Ta, Ru, or CoFeB capping layer. In stack C, $K_{eff}$ was calculated from the $H_{k\text{eff}}$ and $m_s$ values obtained from the FMR and VSM measurements using following equation: $K_{eff} = (H_{k\text{eff}} \times m_s)/2$. The $m_s$ of the free layer with the Ta and CoFeB capping layer increases with increasing $T_a$, which can be ascribed to boron....
diffusion from CoFeB layers into the spacer layer. On the other hand, $m_s$ of the free layer with Ru capping layer reduces via annealing at $T_a = 400^\circ$C, which is consistent with Ru diffusion into the CoFeB layer through the topmost MgO layer, as shown in Fig. 2. Similar behavior is also observed for the $T_a$ dependence of $K_{eff}$. The free layer with Ta and CoFeB capping layers shows a monotonic increasing $K_{eff}$ with increasing $T_a$; however, we cannot evaluate the $K_{eff}$ of the free layer with the Ru capping layer because the FMR spectrum linewidth is too broad. Such a large FMR spectra probably correlates with increasing inhomogeneity owing to Ru diffusion. As a result, via annealing at 400°C, the free layer with CoFeB capping layer shows the largest $K_{eff}$, which is consistent with the result using Ta spacer layer, as shown in Fig. 1.

IV. CONCLUSIONS

In this study, we investigate the effect of capping layer material on thermal tolerance of a free layer with a structure of MgO/CoFeB/spacer layer/CoFeB/MgO/capping layers (CoFeB, Ru, or Ta). The free layer with Ta spacer layer shows the largest PMA when the CoFeB capping layer is employed. EDX line analysis reveals the diffusion of oxygen from MgO into the Ta capping layer and Ru into CoFeB layers, which could degrade the PMA for free layers with the Ta and Ru capping layers. A cross-sectional transmission microscope image with the Ta capping layer indicates an unclear interface at the MgO/Ta capping layer, which supports the oxygen diffusion indicated by the EDX line analysis. To understand the effect of the capping layer on the robustness of the free layer against annealing, we evaluate annealing temperature dependence of magnetic properties for the free layer with the three different capping layer materials where we adopt a spacer layer material different from Ta. The spontaneous magnetic moment per unit area of the free layer with a Ta capping layer and CoFeB capping layer increases as $T_a$ increases, whereas it reduces in the free layer with a Ru capping layer at annealing temperature of 400°C. This result is consistent with the EDX line analysis results. The perpendicular magnetic anisotropy of the free layer with the Ta capping layer and with the CoFeB capping layer increases with increasing $T_a$; however, we cannot evaluate it for the free layer with the Ru capping layer at an annealing temperature of 400°C due to too broad FMR spectra linewidth. As a result, the largest perpendicular magnetic anisotropy can be obtained in the free layer with the CoFeB capping layer after annealing at 400°C. These experimental results allow us to conclude that CoFeB is the most suitable capping layer material for high-performance and high-density STT-MRAM.

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