

Influence of Boron Diffusion on Transport and Magnetic Properties in CoFeB/MgO/CoFeB Magnetic Tunnel Junction

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Influence of boron concentration in CoFeB on the transport properties of CoFeB (B 20% and B 16%)/MgO/CoFeB magnetic tunnel junction (MTJ) was investigated. Boron distribution was studied by using X-ray photoelectron spectroscopy (XPS). High-resolution transmission electron microscope was utilized for analysis of the texture and interface quality. The MTJ with the boron diluted CoFeB (B 16%) pinned layer shows 10% higher MR than the CoFeB (B 20%). HRTEM shows that the MgO/CoFeB interface for the sample with diluted CoFeB layer has a better epitaxial MgO/CoFeB growth. Higher boron concentration in the as-deposited CoFeB stays high after annealing but boron content in the MgO increases as well. These results suggest that that MR improvement is directly related to the distribution of the boron in CoFeB/MgO/CoFeB MTJs after annealing.

Index Terms—Boron, crystallization, magnetic tunnel junction (MTJ), magnetoresistance, MgO barrier.

I. INTRODUCTION

MGO-based magnetic tunnel junctions (MTJs) show a high magnetoresistance (MR) effect and have become the most promising element for the application of magnetoresistive devices such as magnetic random access memory (MRAM), magnetic read heads, and magnetic sensors [1]. It has been reported that [100] orientation and a good epitaxial relation between MgO barrier and magnetic layers which are adjacent to the MgO barrier is required to produce high MR [2]. In order to obtain high MR ratio in amorphous CoFeB/crystalline MgO/amorphous CoFeB MTJs, an annealing step is necessary in order to produce crystallized bcc CoFeB (100)/MgO (100)/crystallized bcc CoFeB (100) [3]–[5]. Boron diffusion and its chemical state (B or BxOy) at the MgO interface were studied using X-ray photoelectron spectroscopy (XPS) by several research groups [6]–[8]. The formation of the boron oxide at the MgO/CoFeB interface after annealing has been revealed. Since crystallization of CoFeB is associated with the B [9], [10], boron distribution after annealing is the most important. It determines final microstructure and the performance of MgO based MTJ. In this paper, we investigated the effect of boron distribution and microstructure of film stack on the transport properties of patterned CoFeB/MgO/CoFeB magnetic tunnel junctions.

II. EXPERIMENTAL PROCEDURES

Layered stacks of SiO₂ (sub)/Ta 1.5 nm/Ru 1 nm/CoFeB (or diluted CoFeB) 2.5 nm/MgO 2 nm, SiO₂ (sub)/Ru 1 nm/MgO 1 nm/diluted CoFeB 2.5 nm/Ru 3 nm and MTJ structure (with Pinned layer: CoFeB or diluted CoFeB) were deposited. Boron content for undiluted CoFeB is 20%. For diluted CoFeB layer,

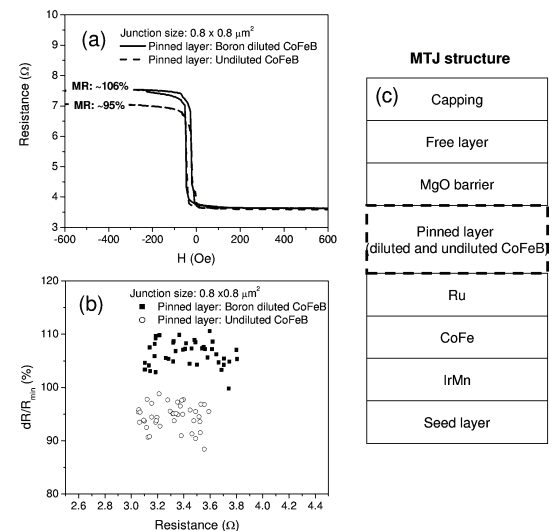


Fig. 1. (a) Magnetoresistance transfer curves of the patterned structures. (b) dR/R versus R_{min} of 100 patterned junctions with boron diluted CoFeB pinned layer and undiluted CoFeB pinned layer. (c) Schematic diagram for MTJ structure with boron diluted CoFeB pinned layer and undiluted CoFeB pinned layer.

the boron content was estimated around 16%. After film deposition samples were vacuum-annealed in a field of 1 Tesla along the direction of deposition field at 285 °C for 5 h. The junctions were patterned by photolithography and ion beam etching. The junction sizes varied from $0.2 \times 0.2 \mu\text{m}^2$ to $0.8 \times 0.8 \mu\text{m}^2$. The tunnel barrier layer was formed by sputtering from MgO target. The boron distribution and interface of the films was investigated by XPS and high resolution transmission electron microscopy (HRTEM). For XPS analysis, oxygen is the first element evaluated after etching, to minimize effect of surface reoxidation. The magnetic properties were measured at room temperature using a vibrating sample magnetometer (VSM) and Magnetic-Optic Kerr Effect (MOKE) spectroscopy. The magnetoresistance (MR) transfer curve was measured using a four-point probe measurement system with fields up to 600 Oe.

Manuscript received March 06, 2009. Current version published September 18, 2009. Corresponding author: C. Park (e-mail: chando.park@wdc.com).
Digital Object Identifier 10.1109/TMAG.2009.2022495

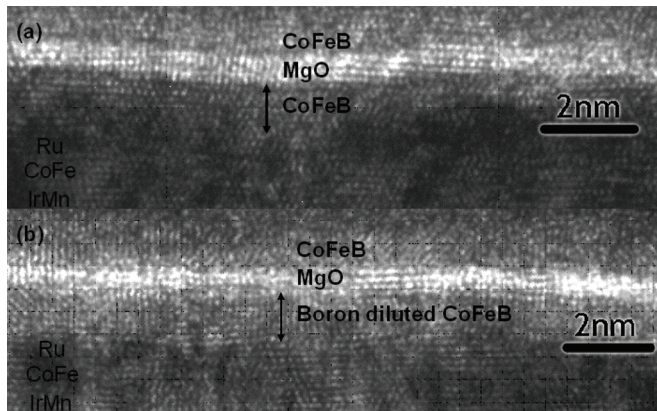


Fig. 2. HRTEM images of the annealed structures. (a) Bottom electrode/IrMn/CoFe/Ru/undiluted CoFeB/MgO/CoFeB. (b) bottom electrode/IrMn/CoFe/Ru/diluted CoFeB/MgO/CoFeB.

III. RESULTS AND DISCUSSION

Fig. 1(a) shows minor MR transfer curves of the MTJs with boron diluted CoFeB pinned layer and undiluted CoFeB pinned layers. MR ratio here is defined as dR/R_{min} , where R_{min} is the resistance in parallel states and dR is the resistance difference between the antiparallel and the parallel states. As seen in Fig. 1(a), MTJ with boron diluted CoFeB pinned layer shows significantly better MR than undiluted CoFeB pinned layer. Fig. 1(b) shows dR/R versus R_{min} for ~ 100 patterned MTJs with diluted CoFeB pinned and undiluted CoFeB pinned layers. Based on this statistical data we conclude that there is a clear gap in dR/R_{min} between two different CoFeB pinned layers. These findings indicate that the boron concentration in the CoFeB pinned layer has critical effect on the transport properties of MTJs: less boron concentration in the CoFeB pinned layer leads to higher MR. Since the degree of crystallization of CoFeB layer and the MgO/CoFeB interfaces can influence the MR, HRTEM analysis was performed to see the interfaces and the degree of the crystallization in the CoFeB layer. As seen in Fig. 2, HRTEMs of the annealed samples show no discernible difference in MgO crystalline structure. However, we observed significant difference in epitaxial growth between MgO and CoFeB layer. The MgO/CoFeB interface in film with diluted CoFeB has better epitaxial relationship between MgO and CoFeB layers, indicating that CoFeB layers crystallized from the interface with MgO barrier. HRTEM analysis on at least four different samples shows similar images, confirming that the diluted CoFeB layer produces better interface after annealing. The undiluted CoFeB pinned layer adjacent to the MgO barrier seems to be crystallized completely. It is important to note that the moments of the diluted CoFeB and undiluted CoFeB layers are almost same based on the VSM measurement. Longer annealing time, which is more than 20 hrs was performed on these MTJs to ensure the complete crystallization. We did not observe significant difference in MR between 5 and 20 h annealing; hence 5 h annealing at 285 °C is sufficient for the complete CoFeB crystallization. It is reported that crystallization of amorphous CoFeB layer causes the diffusion of boron atoms into other layers because crystalline CoFeB can incorporate less than 10% [9], [10].

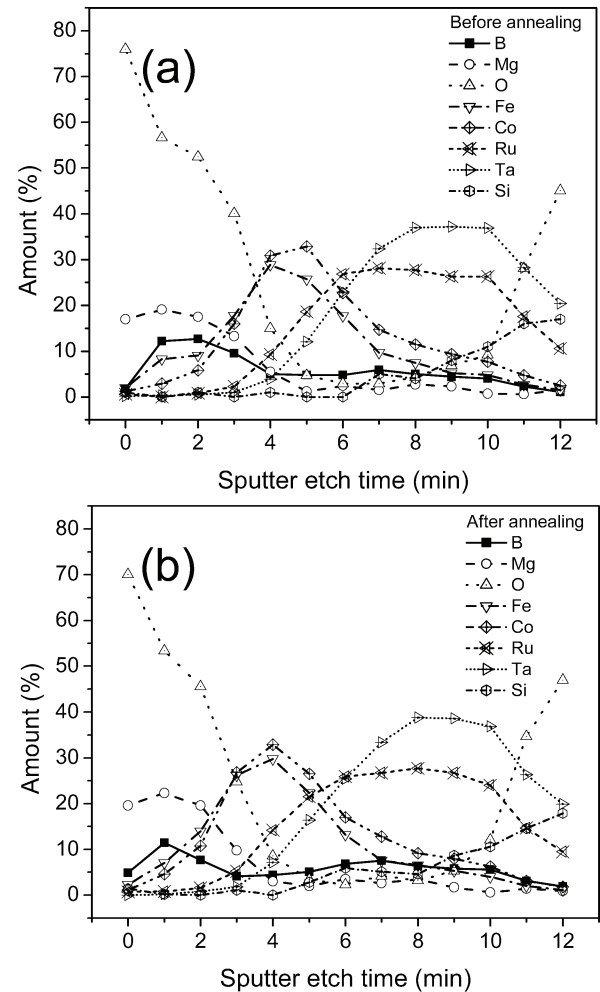


Fig. 3. XPS depth profiles of: (a) as deposited and (b) annealed substrate/Ru 1.5 nm/undiluted CoFeB 2.5 nm/MgO 2 nm.

This indicates that the boron diffusion during annealing is a possible reason for the difference in the annealed CoFeB structure and the MgO/CoFeB interface, which is strongly related to the transport properties of MTJs. XPS analysis was conducted to investigate the boron diffusion on the following structures: SiO₂ (sub) Ta 1.5 nm/Ru 1 nm/CoFeB (or diluted CoFeB) 2.5 nm/MgO 2 nm. These structures mimic the real MTJ structure. Comparison of XPS results for as-deposited and annealed (see Fig. 3) shows that there is no significant difference in XPS depth profiles for all but boron elements. The layer position was estimated from the elements peak in XPS depth profiles shown in Fig. 3. Fig. 4 reveals that boron atoms from the CoFeB layer diffuse out not only toward the MgO barrier, but also toward the underneath Ru layer during deposition. It is important to note that significant amount of boron diffuse into Ru layer during deposition, which was also observed by another group [8]. This could lead to a reduction in the exchange constant in the antiferromagnetic layer and the synthetic antiferromagnetic layer coupling strength. In the case of the diluted CoFeB layer, less boron exists in the MgO barrier, which, we believe, is a part of the reason for higher MR because boron in the MgO barrier forms boron oxide (B₂O₃, BO_x), which act as defects [6]–[8]. The plateau region (see Fig. 4) in

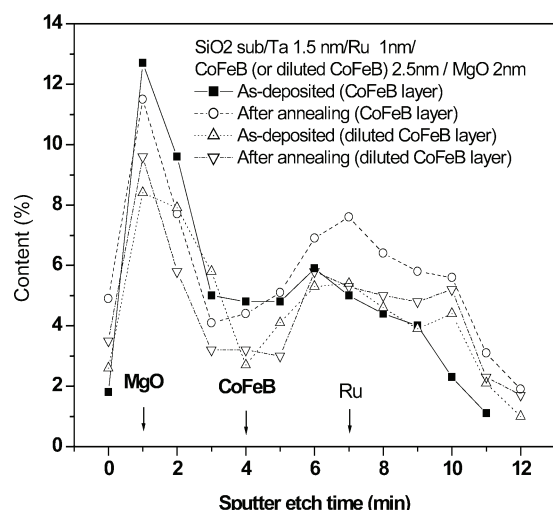


Fig. 4. XPS boron content depth profiles of as deposited and annealed SiO₂ (sub)/Ta 1.5 nm/Ru 1 nm/CoFeB (or diluted) 2.5 nm/MgO 2 nm.

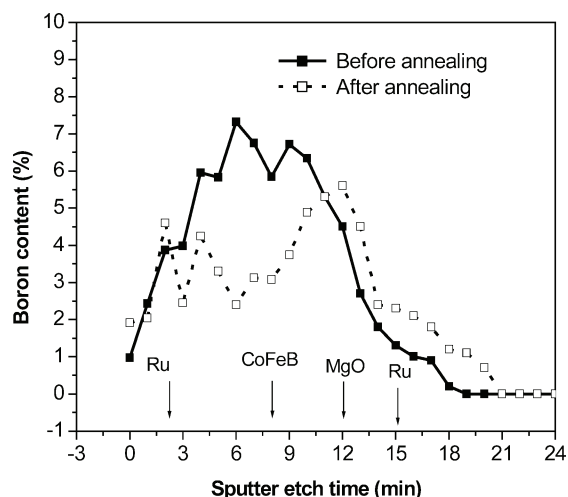


Fig. 5. XPS boron content depth profiles of as deposited and annealed SiO₂ (sub)/Ru 1 nm/MgO 1 nm/diluted CoFeB 2.5 nm/Ru 3 nm.

boron concentration after annealing corresponds to the CoFeB layer. HRTEM analysis in Fig. 2 revealed structural differences consistent with observed difference in B distribution for the diluted and undiluted CoFeB. Fig. 5 shows XPS depth profiles of the stacks of SiO₂ (sub)/Ru 1 nm/MgO 1 nm/diluted CoFeB 2.5 nm/Ru 3 nm. This is the case when a CoFeB free layer is deposited on top of the MgO barrier. In this case, boron atoms do not diffuse significantly into the MgO and Ru layer during deposition. Boron diffusion toward the both MgO and Ru layers occurs only after annealing, indicating that boron diffusion is driven by O and Ru. We observed that boron distribution can be changed significantly depending on whether the CoFeB layer is deposited before or after MgO deposition. It seems that MgO deposition increases the temperature in the CoFeB pinned layer high enough for boron to diffuse into other layers such as MgO and Ru. Therefore boron diffusion is more pronounced in CoFeB free layer rather than CoFeB pinned layer during annealing. Based on our results of Figs. 4 and 5, as-deposited boron concentration in CoFeB layers affects the boron dis-

tribution in the stack after annealing, resulting in a different CoFeB structure and consequently the MgO/CoFeB interface. Higher boron concentration in the as-deposited CoFeB layer stays higher after annealing however boron concentration in the MgO increases as well. Read *et al.* indicate that the incorporation of boron into the MgO barrier is desirable for high MR if it fills the defect sites in the barrier [6]. In our experiment based on the current in plane tunneling (CIPT) measurement, the boron concentration in the CoFeB layer which is less than 14% reduces MR compared to 16% boron concentration. It means that there is an optimum boron concentration in the barrier for the better performance. These results suggest that the MR improvement seen in the Fig. 1 is related to the boron distribution in CoFeB/MgO/CoFeB after annealing.

IV. CONCLUSION

We report herein on the influence of boron concentration in the CoFeB layer on the transport properties of the CoFeB/MgO/CoFeB MTJs. The boron diluted CoFeB layer shows much higher MR (10%) than the undiluted CoFeB layer. XPS and HRTEM results suggest that the boron concentration in the as-deposited CoFeB layer determines the final boron concentration in the CoFeB and MgO barrier layers as well as the CoFeB/MgO interface. Higher boron concentration in the as-deposited CoFeB layer leads to higher boron concentration in the CoFeB and MgO barrier MgO layers after annealing. These results suggest that the MR improvement is related to the distribution of the boron CoFeB/MgO/CoFeB. In other words, less boron concentration in MgO shows higher MR.

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