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Impacts of Boron Concentration and Annealing Temperature on Electrical Characteristics of CoFeB/MgO/CoFeB Magnetic Tunnel Junction

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Abstract

In this study, we investigated electrical characteristics of CoFeB/MgO/CoFeB magnetic tunneling junction (MTJ) formed with different boron concentrations in CoFeB and different annealing temperatures. For boron concentration of 20 at.%, early failure probability increased at annealing temperature of 400 ºC. For boron concentration of 30 at.%, higher breakdown voltage with lower early failure probability were obtained at annealing temperature at 400 ºC.

1. Introduction

Spin-transfer Torque Magnetoresistive Random Access Memory (STT-MRAM) has been actively researched by various groups for its high speed and non-volatility [1-3]. The stack of CoFeB/MgO/CoFeB is one of the most effective structures for obtaining a superior magnetoresistance (MR) ratio and high temperature stability [4-5]. The result that the composition of boron in CoFeB electrode highly impacts on the MR ratio has been reported in previous research [6]. However, the impacts of boron concentration and annealing temperature on the electrical characteristics has not been clarified in detail. In this study, we investigated the electrical characteristics and the reliability of CoFeB/MgO/CoFeB structures with different boron concentrations in CoFeB from 0 to 30 at.% with annealing temperature up to 400 ºC.

2. Experimental Setup

Figures 1 (a) and (b) show a schematic cross-sectional view of the MTJ structure and its fabrication process flow, respectively. The fabricated MTJ is CoFeB/MgO/CoFeB formed on 200 mm diameter Si wafer. Table 1 shows the details of the sample fabrications and the measurement condition. 14 types of samples have been used for this investigation. One of the major parameters was MgO fabrication methods; Radio Frequency sputtering (RF-MgO) and Mg Oxidation after sputtering (Mg Oxidation). Another was the boron concentration in CoFeB (0, 20, and 30 at.%). In addition, these samples were annealed at various temperature after the fabrication (w/o annealing, 300ºC – 1hr. and 400ºC – 1hr.). Figure 2(a-d) shows typical transmission electron microscope (TEM) images of fabricated samples. I-V measurements were conducted for 57 devices across the whole wafer position for each sample type. The MTJ area was 1×1 μm^2, and the MgO thickness was 2.0 nm. The measurement condition was increasing voltage from 0 to 4 V with the voltage steps of 0.01 V. This measurement was conducted at room temperature. Current at 1V, breakdown voltage and early failure probability were extracted and compared for discussion.

3. Results and Discussions

Figure 3(a-b) shows I-V characteristics of the fabricated samples having median characteristics for each fabrication condition for (a) Mg Oxidation and (b) RF-MgO, respectively.

Figure 4 shows wafer map of breakdown voltage for RF-MgO samples with 20 at.% and 30 at % after 300 or 400 ºC annealing.

Figure 5 shows the current at 1V as a function of annealing temperature for (a) Mg Oxidation and (b) RF-MgO, respectively. Median, top 10%, and bottom 10% values from the 57 samples are shown in each plot. It should be noted that early failures were excluded from these figures. The samples without annealing process were plotted at the annealing temperature of 180 ºC, which is the highest temperature during the fabrication process. In Fig. 5(a) for Mg Oxidation samples, as annealing temperature increases, the current value increased for boron concentration of 20 at.%. This result is consistent with the previous research [7]. However, the current decreased for 30 at.%. The current values are smaller for 20 at.% than 30 at.%. In Fig.5(b) for RF-MgO samples, annealing temperature dependences are small for both boron concentrations of 20 and 30 at.%.

Figure 6 shows the median breakdown voltage as a function of annealing temperatures with different boron concentrations. Breakdown voltage tends to increase as an increase of annealing temperature for boron concentrations of 20 and 30 at.%, while it slightly decreases without boron content. For RF-MgO samples, breakdown voltages are higher than Mg Oxidation samples, and almost the same characteristics were obtained for boron concentration of 20 and 30 at.%.

Figures 7 shows the early failure probability as a function of annealing temperature with different boron concentrations. Without boron content, early failure probability increases after annealing process. For the samples with boron concentration of 20 at.%, early failure probability was very low without and with 300ºC annealing, and it increased after 400ºC annealing. On the contrary for the samples with boron concentration of 30 at.%, early failure probability is high without annealing, and it decreased after 400ºC significantly.

These results indicate that a relatively higher annealing temperature is effective for higher boron concentration case, and the highest breakdown voltage with low early failure probability was obtained after 400ºC for RF-MgO samples in this experiment.

4. Conclusions

The electrical characteristics of CoFeB/MgO/CoFeB MTJ with different boron concentrations in CoFeB and annealing temperature have been measured and analyzed. For boron concentration of 20 at.%, annealing temperature up to 300ºC was found to be effective improve electrical characteristics but early failure characteristics degraded after 400ºC. For boron concentration of 30 at.%, annealing temperature at 400ºC was found to be effective to improve breakdown voltage and suppression of early failure. These findings are to be important for the development of high quality MTJ with different boron concentration in CoFeB.

Acknowledgment

The MTJ-fabrication steps except for the lithography processes were performed at the CANON ANELVA CORPORATION. The lithography processes and electrical evaluations were performed at Fluctuation Free Facility of Tohoku University.

Reference

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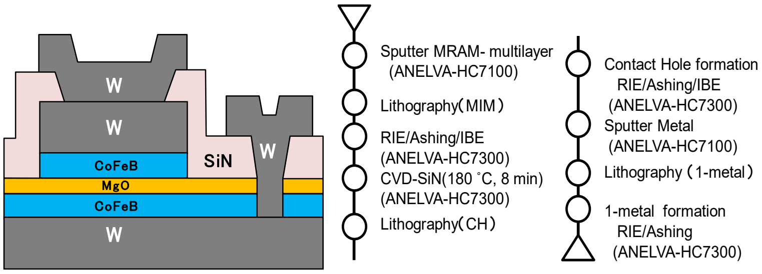
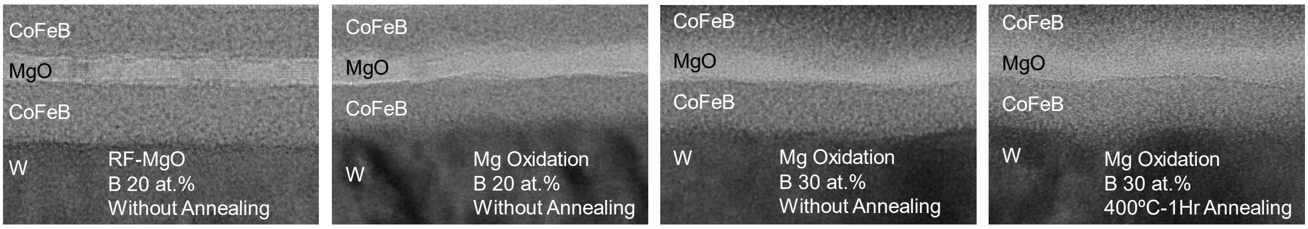


(a) (b)

Fig. 1 (a) Cross sectional view of CoFeB/MgO/CoFeB sample and (b) its process flow.

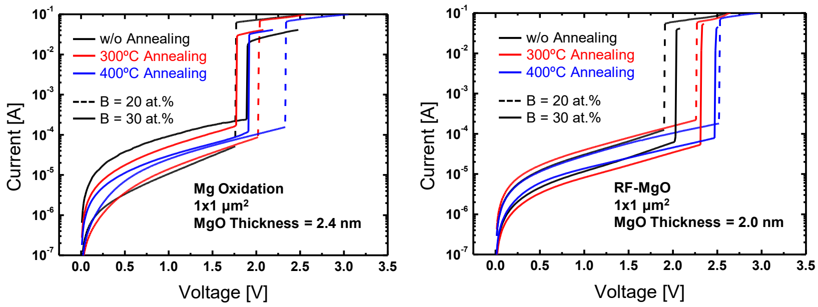
Table 1 Sample characteristics and measurement condition.

Film Fabrication	MgO Sputtering	Mg Oxidation after sputtering
Film Thickness	2.0 nm	
B concentration In CoFeB Layer	20, 30 at% (for all annealing conditions)	
	0 at% (for only RF-MgO w/o annealing and with 300°C – 1Hr. annealing)	
Annealing condition	w/o annealing, 300°C-1Hr, 400°C-1Hr	
Film area	1x1 μm²	
No. of chips/wafer	57	
Measurement condition	I-V Measurement (From 0 to 4 V, 0.01V Steps)	
Temperature	25 °C	



(a) (b) (c) (d)

Fig. 2 TEM images of CoFeB/MgO/CoFeB structures on the respective conditions.



(a) (b)

Fig. 3 I-V characteristics of the (a) Mg Oxidation and (b) RF-MgO samples.

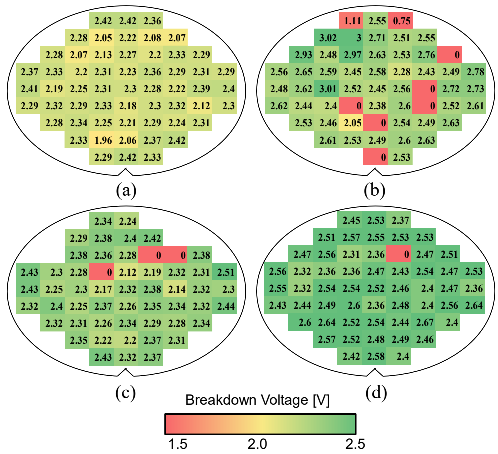
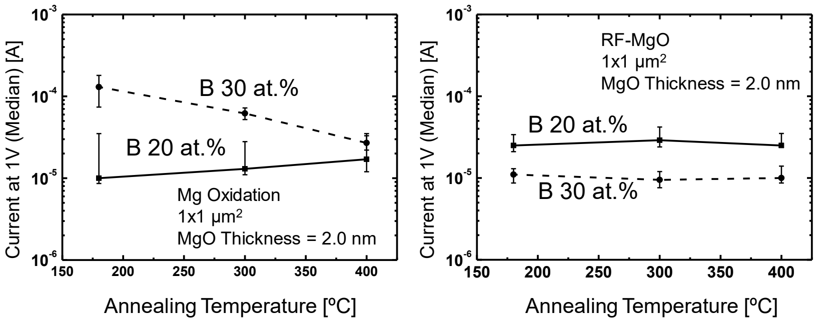


Fig. 4 Breakdown voltage distributions on each wafer of RF-MgO samples. In details, (a) B=20 at.%, 300 °C Annealing, (b) B=20 at.%, 400 °C Annealing, (c) B=30 at.%, 300 °C Annealing, and (d) B=30 at.%, 400 °C Annealing.



(a) (b)

Fig. 5 Current at 1V as a function of the annealing temperature; (a) Mg Oxidation, (b) RF-MgO samples.

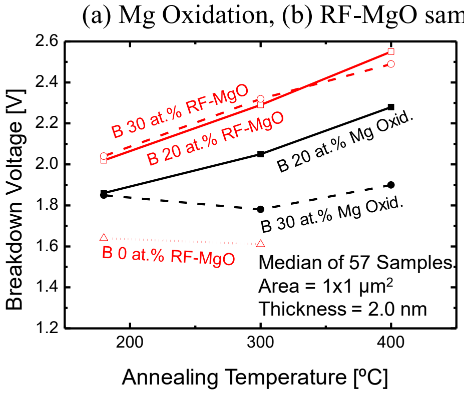


Fig. 6 Breakdown voltage as a function of annealing temperature.

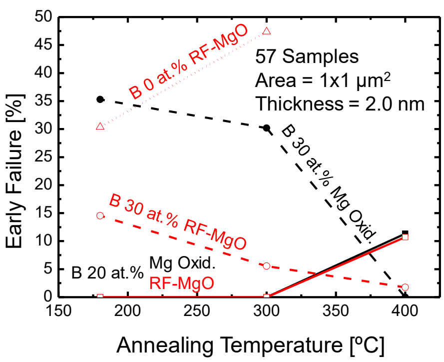


Fig. 7 Early failure rate as a function of annealing temperature.