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Study on the breakdown characteristics of magnetic tunnel junctions and lifetime predictions for the high-density MRAM devices

Kwang-Seok Kim*, Chung-Hee Nam, Young-Man Jang, Ki-Su Lee, Hyung-Min Kim, and Beong-Ki Cho

Dept. of Materials Science and Engineering, Gwangju Institute of Science and Technology (GIST), 1 Oryong-dong Buk-gu, Gwangju, Korea

1. Introduction

To realize high-density MRAM devices, the successful application of new writing schemes such as thermal-assisted switching, spin-transfer torque switching, and local-field switching to MTJs seems to be essential. As the new writing schemes are requiring high current densities through tunnel barriers in MTJs, the development of low resistance MTJs with high tunnel barrier's reliability emerges as another important challenge. However, relatively little researches have so far carried out on the reliability issues of MTJs

In this study, we investigated the role of interface traps in the dielectric breakdown of MTJ system. In order to induce a variation in the trap density at the interface between a bottom electrode and an insulating layer, three different junctions were synthesized with different oxidation times, i.e. under-, optimally-, and over-oxidized ones. In addition, the reliability properties of an insulating barrier formed by nitrogen-mixed oxygen plasma were also compared with those formed by pure oxygen plasma. And, the lifetime of the two tunnel barriers with oxide and oxy-nitride was estimated for comparison.

2. Experimental Methods

MTJs are fabricated by an ultrahigh vacuum dc magnetron sputtering system under a base pressure of $\approx 2 \times 10^{-8}$ Torr. The junctions consist of layers in a sequence of Si/SiO_2(2000)/CoFeB(100)/Cu(250)/CoFe(50)/barrier ($\approx$20)/CoFe(25)/IrMn(200)/Cu(300), where the numbers in parenthesis represent the nominal thickness of each layer in Å. The tunnel barrier is formed by exposing a predeposited Al metal layer to oxygen plasma or nitrogen-mixed plasma.

For the reliability studies, time-dependent dielectric breakdown (TDDB) measurements were conducted for the junctions with different oxidation status and oxide or oxy-nitride tunnel barriers under different stress polarity directions.

3. Results and Discussion

3.1 Role of interface traps of magnetic tunnel junctions on the breakdown

Time dependent dielectric breakdown (TDDB) measurements were carried out for magnetic tunneling junctions (MTJs) with different electron trap densities at the interface between a bottom electrode and an insulating barrier. The TDDB shows a strong bias-polarity-dependence, which becomes bigger with increasing trap density. In addition, the current creep before total dielectric breakdown consistently shows bias-polarity dependence. The polarity dependence of the breakdown in MTJs with an ultrathin tunneling barrier (15-20 Å) is believed to be caused by precursor effect of the traps at the bottom interface, which enhances the trap generation rate in a tunneling barrier, resulting in acceleration of the breakdown process.

3.2 Effect of nitrogen incorporation to oxidation process on the reliability of MTJs

The reliability of MTJs with an oxy-nitride barrier is much improved with the incorporation of nitrogen to oxidation process. In addition, the reliability of the oxy-nitride barrier is gradually enhanced with increasing oxy-nitridation time even after the time exceeds the optimal value. The enhancement is believed due to the bonding of nitrogen to electron traps both in the oxide barriers and at the bottom interface.

3.3 Lifetime prediction

Under the specification of 1 MTJ (with the area of 200 μm^2) failure out of 10^{12} junctions within 10 years, maximum operating voltages of 0.1 V and 0.23 V are estimated for the tunneling barriers formed by pure oxygen plasma and nitrogen-mixed oxygen plasma, respectively. For the estimation of the lifetime for a realistic device, the t_{BD} values for the junctions with the area of 200 μm^2 are rescaled to 5.12 mm^2, which is the expected total junction area for a 256 Mbit device with a unit junction area of 0.2×0.1 μm^2 The annealed oxy-nitride barriers show a maximum operating voltage of 0.45 V within the specification of 1 device (with the integration density of 256 Mbit) failure out of 10^{12} devices in 10 years.