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Research paper

Asymmetric dielectric breakdown behavior in MgO based magnetic tunnel junctions

J.H. Lim [a,b,*], N. Raghavan [a], S. Mei [a], K.H. Lee [b], S.M. Noh [b], J.H. Kwon [b], E. Quek [b], K.L. Pey [a]

[a] Engineering Product Development Pillar, Singapore University of Technology and Design (SUTD), 487372, Singapore
[b] GLOBALFOUNDRIES Singapore Pte. Ltd., 738406, Singapore

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ABSTRACT

The time-dependent dielectric breakdown phenomenon (TDDB) has been investigated in a series of nominally identical MgO based magnetic tunnel junctions (MTJs) by pulsed voltage endurance test. Results from the pulsed endurance test reveal that the breakdown voltage is dependent on the polarity of the applied voltage. MTJs with "UP" current stress (I_{up}) (flowing from reference layer (RL) to free layer (FL)) show higher endurance than that of MTJs with "DOWN" current stress (I_{down}). We also found that bipolar stressing could result in reduced cumulative stress time before failure as compared to unipolar stressing. This could be explained by increased charge trapping/detrapping effects during bipolar stressing. The asymmetric breakdown behavior for different polarity was further supported by the different field acceleration slopes observed in the mean time to failure (MTTF) – voltage bias trend line. Symmetric pulse scheme breakdown measurements were also carried out at different temperatures ranging from 25–85 °C. The time-dependent clustering model is applied here to best describe the breakdown statistics in view of the non-uniformity in percolation breakdown due to thickness variations (interface roughness) and other process-induced damages to the ultra-thin MgO barrier layer.

1. Introduction

Spin Transfer Torque MRAM (STT-MRAM) is a promising device for future universal memory due to spin non-volatility, high density, low power consumption and high endurance. The typical stack of STT-MRAM is based on a magnetic tunnel junction (MTJ) which consists of MgO sandwiched between two layers of ferromagnetic CoFeB (reference and free layers). The dielectric breakdown of MTJ is a severe reliability issue in spintronic devices as technology continues to scale down towards smaller devices with thinner oxide layers. In particular, as the MgO barrier layer for perpendicular MTJ (p-MTJ) devices is very thin (≤1 nm) and designed to transmit a high density spin-polarized current (>1 MA/cm^2), the time-dependent dielectric breakdown (TDDB) lifetime is expected to be a serious concern.

The outline of the study is as follows. We first describe the test characterization setup in Section II and then move on to discuss the degradation trends prior to MgO breakdown in Section III. Our results supporting the asymmetric dielectric breakdown behavior are presented in Section IV and the role of temperature on the reliability of MTJs is discussed in Section V. Finally, Section VI reports the non-Weibullian behavior at the higher percentile region, wherein we propose to use the time-dependent clustering model to best fit the failure data due to the non-uniform defect generation trends resulting in MgO breakdown.

2. Test structure and electrical characterization

The entire multi-layer STT-MRAM stacks was deposited by magnetron sputtering on 300 mm Si wafers. The stack is based on a magnetic tunnel junction (MTJ) [Fig. 1(a)], consisting of approximately 1 nm MgO tunnel barrier sandwiched between a free layer (FL) and reference layer (RL) of ferromagnetic CoFeB. The FL is able to switch its magnetic state, whereas the magnetic orientation of the RL remains fixed. The RL is usually pinned to a Co/Pt or Co/Ni based synthetic antiferromagnet (SAF layer). The MRAM pillars tested are cylindrical with nominal diameters of 85 nm. Devices were subjected to pulsed voltage endurance measurements under constant voltage stress (CVS) with a fixed pulse period of 200 ns to characterize the MgO barrier endurance. As shown in Fig. 1(b), in all stress tests, I_{up} refers to the current flowing from RL to FL for a positive polarity applied to the bottom electrode. Stress induced breakdown for I_{up} occurs after transition from the parallel configuration low resistance state (denoted as R_{min} or R_P) to the anti-parallel configuration high resistance state (denoted as R_{max} or R_{AP}). On the other hand, for stresses involving downwards current, I_{down}, defect generation and breakdown occurs after transition from R_{AP} to R_P (high to low resistance).

* Corresponding author at: Engineering Product Development Pillar, Singapore University of Technology and Design (SUTD), 487372, Singapore.
E-mail address: jiahao_lim@mymail.sutd.edu.sg (J.H. Lim).

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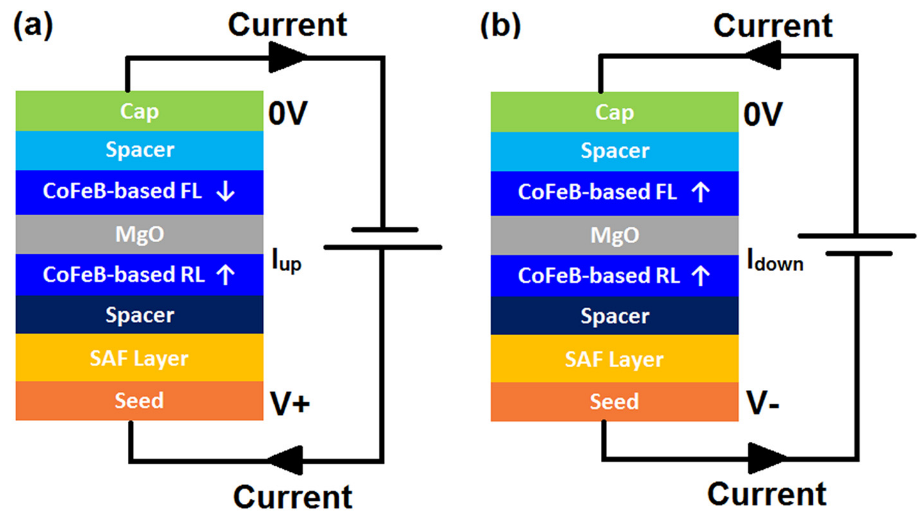

Fig. 1. Vertical layout of the material stack of MgO based p-MTJ structure used in this study and definition of (a) I_{up} and (b) I_{down} current stress resulting in the anti-parallel (AP) and parallel (P) states. Arrows indicate direction of current. RL, FL and SAF refer to the reference, free and synthetic anti-ferromagnetic layer respectively.

3. Stress-induced degradation trends of MgO MTJ

The intrinsic failure due to voltage stress induced degradation of the MgO barrier layer is characterized by an abrupt decrease in the resistance after a critical amount of cumulative stress time as evident from the bit failures shown in Fig. 2. During the stressing phase, inelastic electron trap-assisted tunneling will result in distortion and breakage of the Mg—O bond and an increase of vacancies (trap sites). The resistance gradually decreases as the number of trap sites increases with stress time until a highly conductive percolation path is irreversibly formed which shunts the current [1]. Interestingly, the MR value of the devices increases by an average of 4% prior to breakdown as seen in Fig. 2(c). This could possibly suggest that the vacancies formed during the breakdown process of the devices are neutral and/or singly charged Mg vacancy which can introduce magnetic moments in MgO and reduce scattering of electrons during tunneling, resulting in a slight increase of MR [2].

4. Breakdown trends for unipolar and bipolar stressing

Fig. 3 shows the Weibull plot of the cumulative time to breakdown for the endurance cycling done with unipolar (I_{up} or I_{down}) and bipolar (I_{up} and I_{down}) sequences of current stressing. From the experimental results, the I_{down} stress scheme was found to yield shorter time-to-breakdown than I_{up} stress. This could be attributed to the smaller current that flows through the MTJ during I_{up} stress (after the $R_P \rightarrow R_{AP}$ transition), when compared to the larger current for I_{down} stress (after the $R_{AP} \rightarrow R_P$ transition) [3]. For I_{up} stress, the device transits from parallel state to anti-parallel state as soon as the stress is applied and the device degrades predominantly in the anti-parallel state (with high resistance), implying lower current density. On the contrary, for I_{down} stress, the device transits from anti-parallel state to parallel state as soon as the stress is applied and the device degrades predominantly in the parallel state (with low resistance), implying higher current density. Since higher current densities imply larger electron fluence, the anode terminal (high electron energy regions where traps could more likely nucleate first) for I_{down} stress (top electrode - free layer) may have higher defect generation rate than the anode terminal for I_{up} stress (bottom electrode – reference layer). The current density for I_{down} stress is 1.8 times larger than I_{up} stress, resulting in a 3× shift in the mean time to MgO breakdown. This implies that defect generation in MgO is not purely driven by thermochemical field-driven processes (for purely field-driven breakdown, we should have observed closely overlapping lifetime distributions for I_{up} and I_{down} stress, i.e. for stress voltages, V_+ and V_-, where $|V_+| = |V_-|$). Rather, it involves the role of charge carriers and their assistance in additional trap generation through mechanisms such as anode hole injection, for example.

Considering Figs. 3(c) and 4(a), it is clear that bipolar stressing shows lower cumulative stress time to breakdown and higher field acceleration factor (steeper slope) than for unipolar stressing. This could be due to the effects of charge trapping/detrapping in the MgO. When a pulse is applied across the oxide, some of the

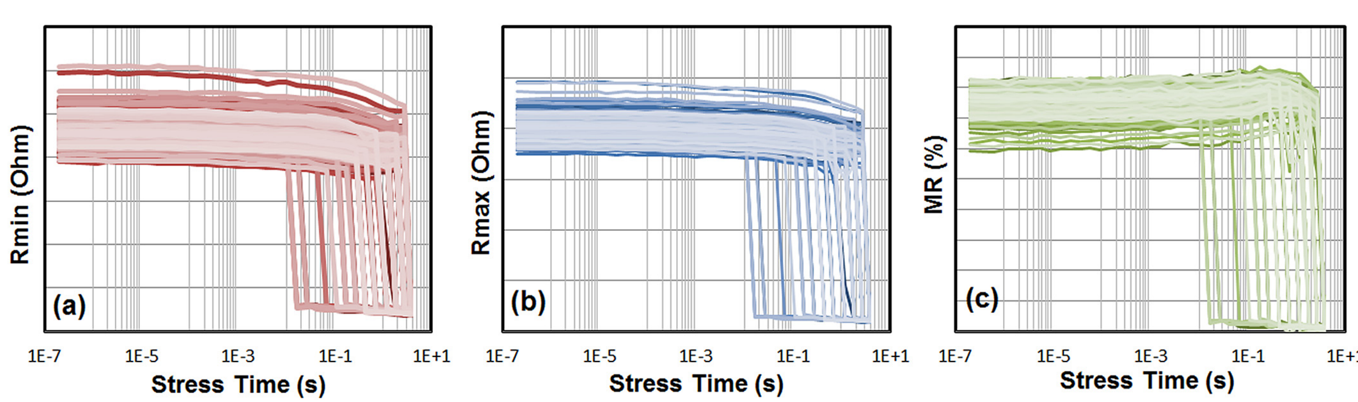

Fig. 2. (a) R_{min-t}, (b) R_{max-t} and (c) *MR-t* traces obtained during endurance pulse stressing. Gradual resistance decay with stress time is indicative of generation of defects in the barrier layer before abrupt breakdown (step drop in resistance corresponding to percolation path formation). MR gradually increases with stress time prior to abrupt failure.