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# Reliability modeling of Magnetic Tunnel Junction using MgO barrier

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**Abstract**

**We investigation of reliability modeling of magnetic tunneling junctions (MTJs) using MgO barrier is presented. Existing literature indicates that there are two major mechanisms involved in the Time Dependents Dielectric Breakdown (TDDB) of silicon dioxide. We verify that the thermochemical (linear E) model and the anode hole injection (1/E) model can be used in MgO-based MTJs. Furthermore, MTJs for maintaining reliability over ten years against dielectric breakdown was discussed.**

## 1. Introduction

A Spin-transfer-torque magneto-resistive random access memory (STT-MRAM) is one of the promising next generation memories because of its non-volatility, high speed operation, large endurance, high density, low power, consumption, and compatibility with the standard complementary metal oxide semiconductor (CMOS) process. Much research has been performed STT-MRAM as a replacement for the dynamic random access memory (DRAM). Furthermore, crystalline MgO has been considered to be the best tunnel barrier for MTJ applications because a MgO barrier with (001) growth shows an enhancement of the tunnel magnetoresistance (TMR) effect compared to the values for amorphous alumina-based MTJs. However, because MgO has an extremely thin thickness of ~ 1 nm, a degradation of the barrier film by a voltage stress is predicted to be a severe problem for the reliability and an understanding of the degradation mechanism is very important for achieving reliable STT-MRAMs. Recently, much research has been performed to clarify the degradation mechanism in thin MgO-based MTJs, and many experimental results related to the MgO film's degradation have been reported. However, research on MTJ device TDDB model has been hardly proposed. In this paper, we investigated a reliability modeling of MgO-based MTJs using thermochemical (linear E) model and the anode hole injection (1/E) model and it was confirmed TDDB experiment data.

## 2. Reliability Modeling of MTJs

*Sample preparation*

In order to observe breakdown of MTJ, we fabricated a MTJ with CoFeB. The MgO barrier thickness and size of MTJ are 1nm and 0.2 x 0.1 μm$^2$. High-quality MgO film has been fabricated with 125% TMR at applied bias of 0.5V. Using this sample, during constant voltage stress (CVS), resistance of MTJ can be measured. Weibull distributions of TDDB lifetime on samples and their dependence on electric fields are shown in Fig. 1.

*Thermochemical (linear E) model*

The thermochemical model is based on the Eyring model, and has been applied to predict the oxide lifetime. McPherson and Baglee [1-2] proposed a quantitative thermodynamic free energy consideration. In the thermochemical model, the cause of low-field (< 10MV/cm) and high temperature TDDB is due to field-enhanced thermal bond-breakage. Time to failure occurs when broken bonds becomes sufficiently increase to cause a conductive path to form from anode to cathode. The time to breakdown equation as follow

$$T_{BD} = A_0 \exp\left(\frac{\Delta H_0}{K_B T} - \gamma E_{ox}\right) \quad (1)$$

where $\gamma$ and $E_{ox}$ is the field-acceleration parameter and the electric field in the oxide, and $\Delta H_0$ is enthalpy of activation energy, and $A_0$ is process/material dependent coefficient, $K_B$ is the Boltzmann's constant, $T$ is the absolute temperature. Many investigations have shown that $\gamma$ is temperature dependent and is given by

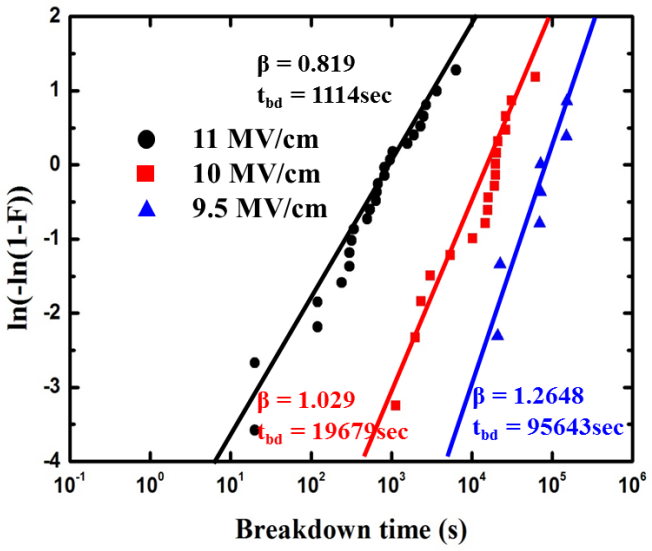


Fig. 1 Weibull distributions of TDDB lifetime on samples and their dependence on electric field.

Table I. Thermochemical model parameters of the $SiO_2$ and MgO

| Parameters | $SiO_2$ | MgO |
|---|---|---|
| $Z^*$ | 2.4 | 3.6 |
| $r_0$ | 1.7 Å | 2.4 Å |
| $\eta(m,n)$ | 0.6 | 0.6 |
| $K$ | 3.9 | 9.8 |
| $\Delta H_0$ | 1.5 eV | 6.23 eV |
| $A_0$ | $10^2$ sec | $10^4$ sec |

$$\gamma(T) = \left[\frac{\partial \ln(T_{BD})}{\partial E}\right]_T = \frac{P_{eff}}{K_B T} \quad (2)$$

where $P_{eff}$ is related to the amount of polar bonding in the molecule and is given by

$$P_{eff}(m,n) = (z^* e) r_o \eta(m,n)^{-1}\left(\frac{2+K}{3}\right) \quad (3)$$

Where $Z^*$ is the effective charge transferred between neighbor ions, $r_o$ is the equilibrium bonding distance, η is related purely to the bonding parameters in the Mie-Gruneisen bonding parameter, and $K$ is dielectric constant. Table I presents thermochemical model parameters of the $SiO_2$ and MgO.

*Anode hole injection (1/E) model*

In contrast to the thermochemical model, Chen et al. [3-4] proposed a anode hole injection model in which the injected electrons exiting from the oxide lose their energy at the interface through impact ionization in the anode to create electron-hole pairs. A fraction of the tunneling electrons reaching the anode are able to elastically transfer their energy to a deep valence-band electron. The valence-band electron is promoted to the lowest available electron energy state, thereby creating a hot hole which tunnels back into the oxide. These injected holes act to increase the localized traps. These processes eventually cause dielectric breakdown. The time to breakdown equation as follow

$$T_{BD} \propto Q_h / J\alpha \propto e^{G/E_{ox}} \quad (4)$$

where J, α, and G are the Fowler-Nordheim (F-N) current, the hole generation coefficient, and the field acceleration factor, respectively, which are given by

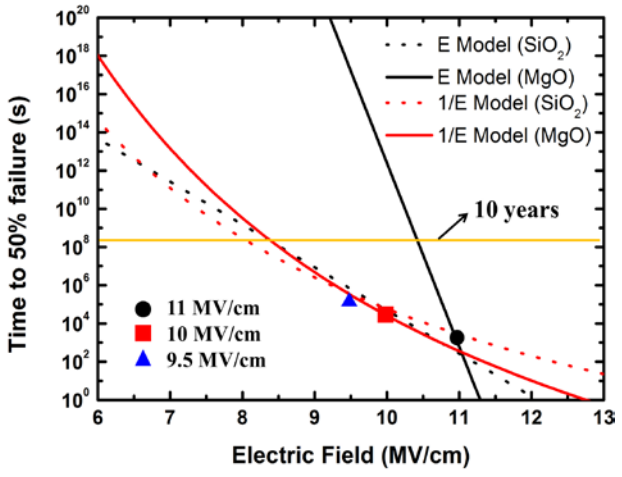


Fig. 2 Lifetime prediction based on linear E model and 1/E model for $SiO_2$ and MgO.

Table II. AHI model parameters of the $SiO_2$ and MgO

| Parameters | $SiO_2$ | MgO |
|---|---|---|
| $m_n$ | $0.33m_e$ | $0.35m_e$ |
| $m_P$ | $0.81m_e$ | $0.33m_e$ |
| $q\Phi_B$ | 3.1 eV | 3.3 eV |
| $q\Phi_P$ | 1.8 eV | 3.25 eV |
| $B$ | 240 MV/cm | 242 MV/cm |
| $H$ | 100MV/cm | 230 MV/cm |
| $G$ | 340 MV/cm | 470 MV/cm |
| $\tau_0$ | $10^{-10}$ sec | $10^{-16}$ sec |

$$J \propto e^{-B/E_{ox}}, \quad (5)$$

$$B = 8\pi(2m_n^*)^{1/2}(q\phi_B)^{3/2}/3hq \quad (6)$$

and

$$\alpha \propto e^{-H/E_{ox}}, \quad (7)$$

$$H = 8\pi(2m_p^*)^{1/2}(q\phi_P)^{3/2}/3hq \quad (8)$$

$$G = B + H \quad (9)$$

where $m_n^*$, $m_P^*$ is electron and hole effective mass, $\Phi_B$, $\Phi_P$ is barrier height, h is planck's constant. Eq. (4) is represented by

$$T_{BD} = \tau_0(T) Exp\left[\frac{G(T)}{E_{ox}}\right] \quad (10)$$

where $\tau_0(T)$ is a temperature dependent prefactor, and $G(T)$ is a temperature dependent field acceleration parameter. Table II presents anode hole injection (AHI) model parameters of the $SiO_2$ and MgO.

*Results and discussion*

The 50% value of the TBD distribution in Fig. 1 versus electric field was plotted in Fig. 2, simultaneously. The figure reveals that the 1/E model matches with the TDDB measurement data. Assuming based on this results, breakdown occurs due to localized trap rather than bond breakage since MgO barrier is crystalline.

## 3. Conclusions

We investigated the reliability modeling of MTJ using MgO barrier. The linear E and 1/E model has been sucessfully developed and 1/E model matches with the measurement data. From these results, main breakdown mechanism of crystalline MgO barrier is assumed to be the effect of localized traps. Furthermore, we predict that MgO-based MTJs satisfies 50% failure in 10 years with an operating voltage of less than 0.83 V.


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