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Alternate method of TDDB study for aluminum oxide using magneto-resistance

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Abstract- ***A sensitive and accurate method/ test to predict the lifetime of aluminum oxide used as a tunnel barrier in magnetic random access memory (MRAM) has been devised. The performance of magnetic tunnel junction is dependent upon the lifetime of aluminum oxide. Aluminum oxide has also been used in high dielectric constant gate dielectric MOS devices suitable for high speed applications.***

This method relies upon the measurement of anti parallel and parallel resistance of the magnetic stack in a tunnel magneto resistor using aluminum oxide as a tunnel barrier. This is a more sensitive method than the conventional methods.

Introduction

Aluminum oxide is the tunnel barrier in the Tunnel Magneto-resistor used in MRAM. In Magnetic Tunnel Junctions (MTJ), aluminum oxide separates the hard (pinned) magnetic layer and the soft or switching magnetic layer. Aluminum oxide is also considered for use as a high *K* (dielectric constant) gate oxide in high-speed CMOS application.[2] As device geometries continue to shrink, the gate oxide thickness is approaching 1 nm and leakage currents are significantly high. Since the dielectric constant of aluminum oxide is higher than that of silicon dioxide ($K_{Al2O3} \sim 9$ whereas $K_{SiO2} = 3.9$), the same capacitance can be attained with a thicker high *K* gate dielectric which reduces the leakage current. In both the applications, the quality and reliability of aluminum oxide determines the lifetime of the product. Therefore it is quite critical to reliably predict the lifetime of aluminum Oxide.

A Tunnel Magneto resistor consists of two ferromagnetic layers separated by an insulating barrier layer. The tunneling conductance of MTJs is determined by two contributions: those arising from the tunneling barrier and those related to the spin dependent density of states on the electrodes. The total magnetic moments on the electrodes determine the total flux of electrons available for conduction through the tunnel barrier by direct tunneling. The number of carriers available for tunneling is determined by spin polarization of the electronic density of states at the Fermi energy.[3] When the spin polarization is parallel in both the soft and hard magnetic layers, both layers have the same direction of magnetic polarization. When the spin polarization is antiparallel in either of the soft and hard magnetic layers, then the layers have the opposite direction of magnetic polarization. The tunneling resistance through the barrier is low for parallel spin polarization and high for antiparallel spin polarization. This effect provides the ability to detect small changes in the tunneling current. This paper describes the use of this effect as a potentially very sensitive technique to detect dielectric degradation and breakdown mechanisms.

Development of method

The topographic magnetostatic coupling energy, J_E,[3] between two ferromagnetic films of magnetization M and M', separated by a nonmagnetic spacer of thickness t with an interface waviness of wavelength λ amplitude h is given by:

$$J_E = \frac{\pi^2 h^2 \mu_o}{\sqrt{2}\lambda}\left(MM'\right) Exp\left[\frac{-2\sqrt{2}\pi}{\lambda}t\right] \qquad (1)$$

where μ_o is the permeability of free space. Equation 1 shows that the coupling energy between the two ferromagnetic layers decreases exponentially with increasing thickness of the spacer and vice-versa. Most importantly, because the magnetostatic coupling energy is inversely proportional to the measured parallel or anti parallel resistance of the Tunnel Magneto-resistor, then the magnetostatic coupling energy is proportional to current through the spacer.[4] Thus, as t increases, both the magnetostatic coupling energy and the current decreases.

The exponential dependence of t shown in equation 1 can also be observed in the current flux, J_F, of tunneling electrons through a barrier of thickness t. If n is the total number of electrons available to tunnel through the aluminum oxide barrier in the MTJ specification and T_{QM} is the potential barrier tunneling probability or quantum mechanical transmission coefficient, then the total number of carriers able to tunnel through the barrier is the product of n and T_{QM}:

$$J_F = n \cdot T_{QM} = n \cdot \frac{16E\left(V_0 - E\right)}{V_o^2} Exp\left[\frac{-2\sqrt{2m\left(V_0 - E\right)}}{\hbar}t\right] \qquad (2)$$

where V_o is the height of the quantum mechanical barrier of the aluminum oxide barrier layer, E ($E<V_o$) is the energy of electrons and t is the thickness of the barrier layer. As can be seen, the current flux is proportional to the exponential dependence on t. The resistance, as mentioned before, is inversely proportional to the current. Hence, it is expected that the ratio of measured resistivities (parallel, R_{P1}, or anti-parallel, R_{P2}) of the tunnel magneto-resistor is dependent on thickness. Thus, taking the ratio of either equation 1 or 2 gives:

$$\frac{R_{P_1}}{R_{P_2}} = Exp\left[C\left(\Delta t_{Al_2O_3}\right)\right] \qquad (3).$$

In equation 3, C is a constant and Δt_{Al2O3} is the effective change in thickness of the aluminum oxide layer. The focus of the method presented in this paper is on Δt_{Al2O3}.

The new method utilizes the above equation to measure Δt_{Al2O3} due to degradation caused by stress. Breakdown of the oxide occurs when a critical level of thinning of the oxide occurs due to defects created by voltage stress. This is in line with the most widely accepted model of oxide breakdown, the effective oxide thinning model.[5,6] The creation of defects is assumed to be equivalent to thinning of the oxide by an amount equal to the width of the defect. Once the total thinning (or the sum of widths of all defects) reaches a critical thickness, an electrical breakdown of the oxide occurs. There is a statistical distribution of defects through the area. The essence of the statistics is based on the percolation model.[7-10] Typically, Weibull statistics are used to predict the time to breakdown, t_{bd}, at use conditions and its area dependence.[12]

The method to determine the time dependent dielectric breakdown (TDDB) distribution of aluminum oxide proposed in this paper is based on the reduction in effective thickness of aluminum oxide with the application of stress. As can be seen from equation 1, a reduction in the thickness of aluminum oxide by 1/15 (this number is used because in the MRAM used, the thickness of the aluminum oxide is close to 15 Å) changes the exchange coupling energy by 3 orders of magnitude which proportionately affects the current and the resistance. On the other hand, the increase in leakage current due to a 1/15 reduction in thickness for a MOS capacitor is less than an order of magnitude.[14]

The time to breakdown, may be calculated using a model that considers oxide thinning[15] and is given by:

$$t_{bd} = \tau_o Exp\left[\Psi(T,V)\left(t_{Al_2O_3} - \Delta t_{Al_2O_3}\right)\right] \qquad (4)$$

where τ_o and Ψ are constants and T and V represent temperature and voltage dependence, respectively. The aluminum oxide thickness is t_{Al2O3} and Δt_{Al2O3} is the reduction in the thickness of aluminum oxide due to stress. The use of $\Psi(T,V)$ allows the freedom to use the 1/E-model[16-17], E-model[18], or voltage-driven model[19].

Method, Data and Calculations

The method requires formation of MTJ across the aluminum oxide in a test structure as shown in figure 1. Voltage should be applied across the aluminum oxide by using the ferromagnetic layers as capacitor plates. The parallel and anti-parallel resistance should be measured after each voltage stress. Care should be taken not to exceed the absolute breakdown field of aluminum oxide which is 4 to 5 MV/cm.[13]

Following are the steps involved in determining the breakdown:

1. Build a tunnel magneto-resistor with aluminum oxide as the tunnel barrier as shown in figure 2.
2. Apply 0.2, 0.4, 0.6 V at 5 minutes, 10 minutes, 20 minutes and 30 minutes intervals.
3. Measure the parallel and antiparallel resistances.
4. Determine Δt_{Al2O3} by fitting the data to equation 3.
5. Calculate t_{bd} using equation 4.

Results and Discussion

The sensitivity of the MTJ measurement to detect oxide degradation and the traditional leakage current measurement (TDDB type stress) are compared in figure 3. The sensitivity of the magnetoresistance (MR) is at least five times greater than the resistance of a MOS device with equivalent oxide thickness. Studies have shown that for thin oxides [14] that monitoring the leakage current is not a sensitive predictor of oxide breakdown. For large area MOS devices, soft breakdown (SBD) is difficult to detect by monitoring the leakage current. The MJT method presented in this paper may be a superior technique to identify SBD when using the correct limits for change in magneto-resistance.

This method may be invalid if MR as a function of voltage data are unstable or time-zero dielectric breakdown (TZDB) data are multimodal. Both issues were examined. Figure 4 shows that the magnetoresistance of an aluminum oxide tunnel barrier decreases rapidly with increasing stress voltage. Dielectric breakdown eventually occurs. The absence of noise or spikes in the magnetoresistance data suggests that there is one type of breakdown mechanism. A typical distribution of breakdown voltages of 1.5 nm aluminum oxide is shown in figure 5. It can be seen that the peak of the distribution is around 1.7 V and the distribution is unimodal (it has only one peak and distribution). This again illustrates the well-behaved breakdown of aluminum oxide and indicates the presence of a single mechanism.

Magtoto *et al.* have observed void formation in Al_2O_3 induced by high electric fields using STM (see figure 6). We have observed void formation in both SiO_2 and Al_2O_3 following breakdown. This suggests that the defect mediated dielectric breakdown mechanism in SiO_2 is similar to Al_2O_3. One direct advantage of this inference is that the percolation (and effective thickness reduction) theory can be applied to predict the breakdown of Al_2O_3.

Conclusion

A novel method to study and predict aluminum oxide breakdown mechanisms using magnetoresistance was presented. Preliminary data suggests that this method is more sensitive than the traditional leakage current measurement method to determine the breakdown of a dielectric. Initial studies indicate that the breakdown of aluminum oxide is not bimodal or multimodal and is well behaved. Further work is required to acquire data examining the thickness (1 – 1.5 nm) dependence on both leakage current and MR of Al_2O_3.

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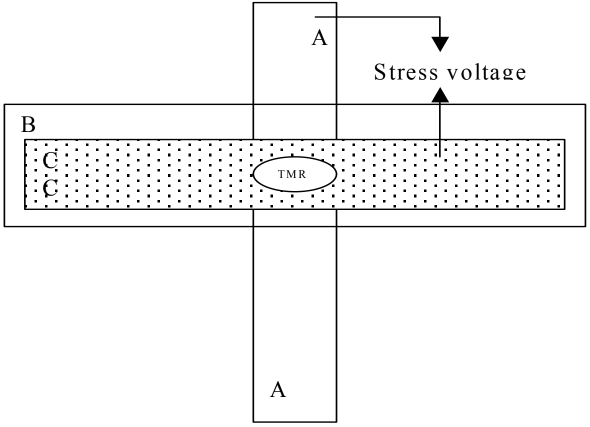

Figure 1: Test structure used for the Al_2O_3 breakdown study.

Figure 2: Magnetic Tunnel Junction stack.

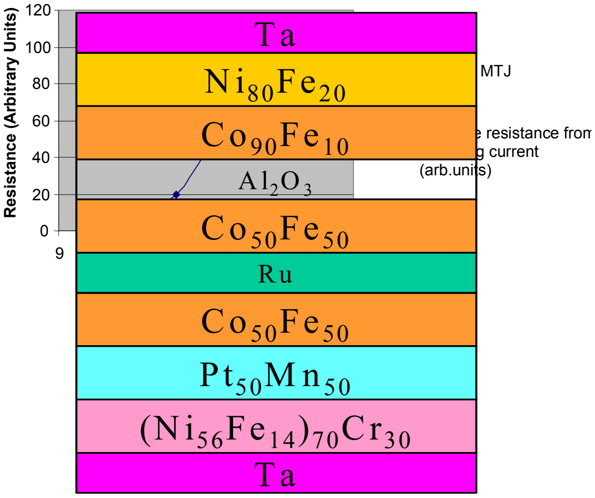

Figure 3: Comparison of MR sensitivity with leakage current sensitivity[14] as a function of dielectric thickness (Å).

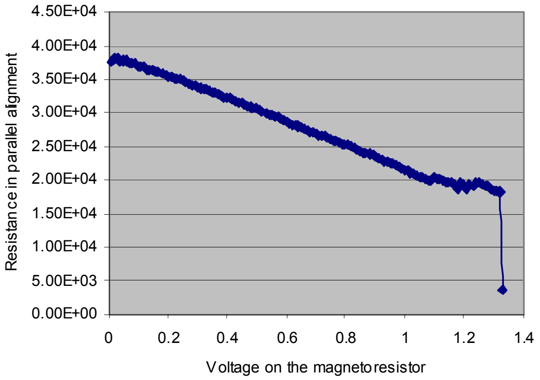

Figure 4: Measurement of magnetoresistance (Ω) as a function of applied voltage on the magnetic tunnel junction.

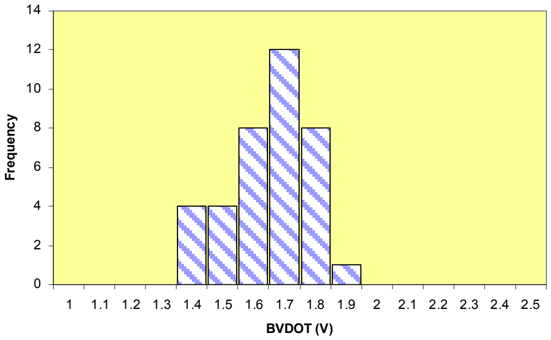

Figure 5: Typical distribution of breakdown voltages of 1.5 nm Al_2O_3.

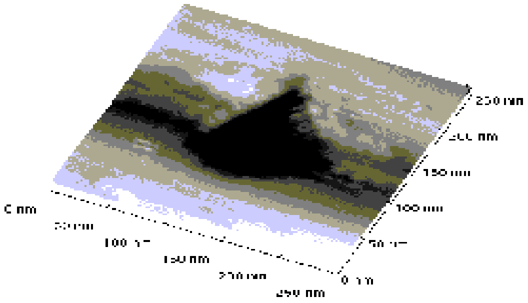

Figure 6: STM-induced void formation in Al_2O_3 due to dielectric breakdown.[20]