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On the Relationship between Stress Induced Leakage Currents and Catastrophic Breakdown in Ultra-thin SiO_2 Based Dielectrics

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Stress induced leakage currents have been measured on capacitor structures with gate dielectrics approximately 19 Å thick, grown in N_2O. Both n^+/p and p^+/n (poly-silicon gate/ silicon substrate) structures were fabricated to allow electron injection using both positive and negative bias. We have measured the statistical distribution (64 devices for each condition) of the SILC as a function of the stress bias condition. Both charge to breakdown (Q_{DB}) and time to breakdown (T_{DB}) are found to be strong functions of the applied bias. The change in the stress induced leakage ($\Delta J/J_o$) at breakdown is found to be relatively independent of the magnitude and polarity of the bias during stress. We suggest that ($\Delta J/J_o$) at breakdown is a measure of a critical defect density required to cause catastrophic breakdown in ultra-thin dielectrics and this critical density is not dependent upon the electron energy during stress.

1. INTRODUCTION

As CMOS device dimensions are scaled, gate dielectrics are being reduced to not much more than a few monolayers. Dielectric thickness' as small as 1.5 nm have been used for sub 0.1 μm CMOS logic devices[1,2]. As the dielectric thickness has been reduced, so too has the applied bias. The electron transport has changed from Fowler-Nordheim tunneling, where the electrons tunnel through only a portion of the insulator, to direct tunneling where the electrons no longer appear in the conduction band of the dielectric. All of the above physical and technological details have led us to a precipice where our understanding of the mechanisms of breakdown are limited. Therefore we can no longer use the known physical concepts for defect generation to accurately predict the reliability of future MOS devices.

It has been shown[3] that stress-induced leakage currents (SILC) generated during high field stress and measured in the direct tunneling region are related to defects produced within SiO_2 films. The measured defects have been shown to be predominantly neutral electron traps and that the density of these defects (and therefore SILC) increase until a critical density is obtained and catastrophic breakdown occurs. Mathematical models of this phenomenon have been published[4,5] which suggest that when the critical density is obtained, breakdown occurs through the creation of a continuous defect link across the dielectric. The catastrophic breakdown, typically measured using charge to breakdown (Q_{DB}) or time to breakdown (T_{DB}) is related not only to the defect density but also to the rate at which such defects are produced[6]. This *"defect generation rate"* has been shown[6] to be inversely proportional Q_{DB}, and therefore dependent upon the electron energy and applied bias. On the other hand, the ***SILC at breakdown*** (as opposed to Q_{DB}) represents a measure of the defect density and therefore is not necessarily dependent upon the electron energy or applied bias, but rather, is a measure of a *critical defect density*.

2. DEVICES AND MEASUREMENTS

In the present work we measure the statistical distribution of the SILC as a function of the stress condition and relate this to the catastrophic breakdown in the insulating film. The stress induced leakage currents (SILC) in 1.9 nm N_2O grown oxide capacitors have been measured at 3.5, 3.75 and 4.0 V. The initial leakage currents are measured at 1.5, 2.0 and 2.5 V, prior to application of the stress bias. After a preset time interval, the stress bias is removed and the leakage currents are measured. This is repeated until catastrophic breakdown occurs as defined by an ***instantaneous*** doubling of the stress current. (The stress current is

monitored at a rate of approximately 5 data points/second).

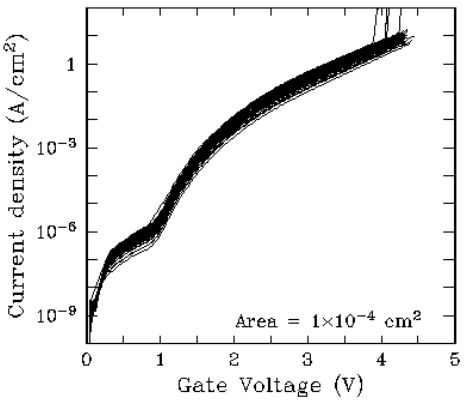

Figure 1 : A series of 64 1x10^{-4} cm^2 current density - voltage curves. These capacitors had a 1.8 nm N_2O grown gate dielectric with a p^+-poly-silicon gate and an n-type silicon substrate. The capacitors were measured from the same 200 mm wafer.

A series of capacitors (64 for each stress condition), each with an area of 1×10^{-4} cm^2, was measured to obtain statistical information regarding the distributions of the charge to breakdown (Q_{DB}), time to breakdown (T_{DB}) and the relative change in the stress induced leakage currents ($\Delta J/J_o$), where $\Delta J=J_t- J_o$ and J_t is the current density at some time t, and J_o in the initial leakage current at a given bias. The capacitors used were fabricated on a either 200 mm n-type substrates with boron doped poly-silicon gates or p-type substrates with phosphorus doped gates. Bias stress and leakage measurements were performed under positive and negative bias for samples with p^+ gates/n-type substrates and n^+ gates/ p-type substrates, respectively.

3. RESULTS

In Figure 1, the current density-voltage data is shown for a series of 64, capacitors. The spread in the J-V curves is typical of such thin oxides and represents a thickness variation of less than 0.1 nm across the 200 mm wafer. For these particular capacitors, the thickness was extracted

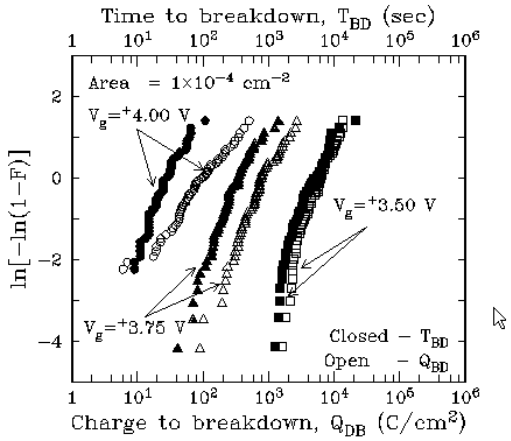

Figure 2(a) : The critical failure (Weibull) distributions of charge and time to breakdown for a series of 64 1x10^{-4} cm^2 capacitors as a function of the stress bias condition, (positive bias in this case). The closed and open symbols represent T_{DB} and Q_{DB}, respectively. Note the change in the Q_{DB} distribution as the stress bias is increased. Samples were p+ gates on an n-type substrate.

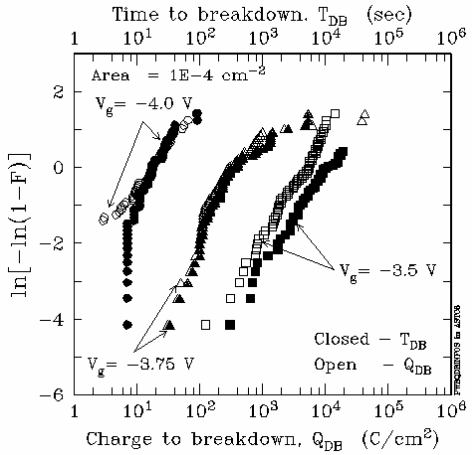

Figure 2(b) : The critical failure (Weibull) distributions of charge and time to breakdown as a function of the stress bias condition (negative bias in this case). Samples were n+ gates on p-type substrate The dielectric was grown at the same time as those shown in Figure 2(a).

using a self-consistent Schrödinger-Poisson solver, taking into account both quantum-mechanical, and poly-depletion effects. The thickness was determine to be 19.0 ± 0.4 Å.

The critical failure (Weibull) distributions for time to breakdown, $T_{DB,}$ and the charge to breakdown, Q_{DB} for stress voltages of ±3.5, ±3.75 and ±4.0 V in Figures 2(a) and (b) for V_g^+ and V_g^-, respectively. One should note the strong stress voltage dependence of these distributions. From highest to lowest stress bias the distributions shift by 3-4 orders of magnitude, proceeding, of course, to lower T_{DB} and Q_{DB} for higher bias conditions. The differences in these distributions between positive and negative bias (for the same absolute value) appear to be minimal.

In Figure 3, $\Delta J/J_o$ for all 64 capacitors is shown as a function of time for the stress current (at 3.5 V) and for the SILC measured at 2.0 V. The critical failure (Weibull) distributions for $\Delta J/J_o$, ***at breakdown,*** are shown in Figures 4(a) and 4(b), as a function of the stress bias. Two series of distributions are shown for SILC measured at ±1.5 and ±2.5 V.

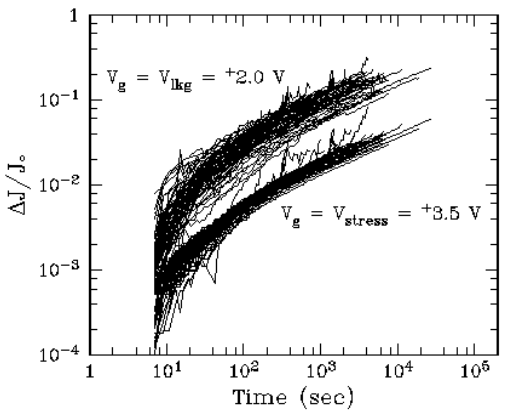

Figure 3 : A series of data from 64 capacitors showing $\Delta J/J_o$ as a function of time. For this set of data, the device was stressed at $^+3.5$ V and the stress-induced leakage current was monitored at $V_{sense}=^+2.0$ V is shown above.

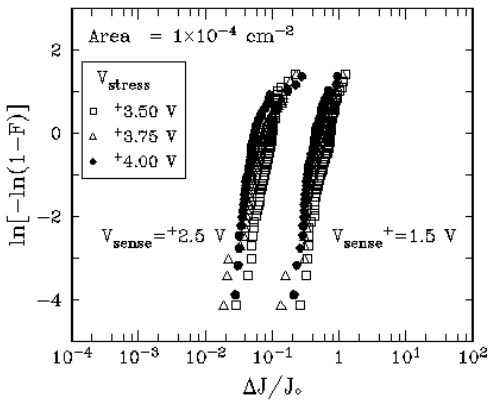

Figure 4(a) : Critical failure (Weibull) distributions of $\Delta J/J_o$(at breakdown) for different stress and sense conditions. Note the curves are relatively insensitive to V_{stress} (positive in this case). The distribution does, however shift to lower values with increasing V_{sense}.

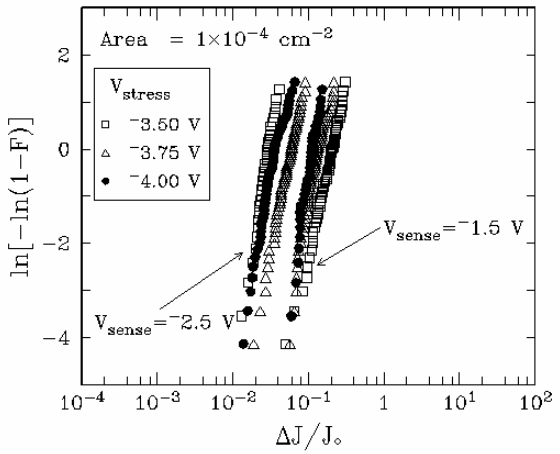

Figure 4(b) : Weibull distributions of $\Delta J/J_o$(at breakdown) similar stress and sense conditions as in Figure 4(a), but for negative stress bias. Note again the relative insensitivity to V_{stress}.

4. DISCUSSION

From the data shown in Figures 2(a) and 2(b), the both T_{DB} and Q_{DB} demonstrate a large voltage dependence shifting at least three orders of magnitude for bias changes from 3.5 to 4.0 V. Similar dependencies have been found for much

thicker dielectrics where Q_{DB} has been shown to be caused by hot electron induced "trap creation" and/or impact ionization[6]. In the present work, the dielectrics are substantially thinner and the electron energies during stress are below the "threshold" for trap creation. However, catastrophic breakdown and defect generation still occurs, suggesting that similar mechanisms of defect generation are occurring in these ultra-thin dielectrics even at the lower bias conditions. The measurement of $\Delta J/J_o$ at breakdown from Figures 4(a) and 4(b), show little stress voltage dependence. This implies that ***$\Delta J/J_o$ at breakdown*** may in fact be a measure of the ***critical defect density***; this being the precursor to catastrophic breakdown. Therefore, the measurement of T_{DB} (Q_{DB}) represents the time (charge) required to produce catastrophic breakdown and is ultimately dependent upon the rate at which the defects are created and the critical defect density. It is the defect generation rate, and not the critical defect density, that has a strong bias dependence. It is for this reason that this bias dependence is manifested in the T_{DB} (Q_{DB}) measurements.

Figures 4(a) and 4(b) show data for electron injection from the substrate and gate, respectively. Independent of the bias polarity, the measurement of $\Delta J/J_o$ (at breakdown) depends upon the sense voltage. Such a dependence has already been reported in 4.0-6.0 nm oxides, using sense voltages from 1.2-3.4 V. [3] This dependence may in part be caused by the specific shape of the current voltage characteristics. Alternately, it may represent the energy distribution of the generated defects within the gate dielectric. For different sense voltages, different portions of the defect distribution would be probed by trap-assisted tunneling. If this applies, one might conclude that the density of the generated defects increases sharply as the energy approaches the silicon conduction band edge.

5. CONCLUSIONS

Stress induced leakage currents have been measured on capacitor structures with gate dielectrics approximately 19 Å thick. Both charge to breakdown (Q_{DB}) and time to breakdown (T_{DB}) are found to be strong functions of the applied bias. The change in the statistical distribution of the stress induced leakage ($\Delta J/J_o$) at breakdown is found to be relatively independent of the magnitude and polarity of the bias during stress, implying that ($\Delta J/J_o$) at breakdown is a measure of a critical defect density required to cause catastrophic breakdown in ultra-thin dielectrics. This critical density (for a given sense bias) is not dependent upon the electron energy during stress. However, the dependence of ($\Delta J/J_o$) at breakdown on the sense bias suggests that the generated defect density, as measured by the SILC, is distributed in energy, if one assumes that the SILC increases as a result of an in increase trap-assisted tunneling

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