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Statistical Modeling of Gate Oxide Breakdown under constant current stresses

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[ABSTRACT]

A breakdown model of gate oxides under constant current stresses is proposed, which directly relates the oxide lifetime to the stress current density, and includes statistical nature of oxide breakdown using the effective oxide thickness. It is shown that this model can reliably predict the TDDB characteristics for any current stress levels and oxide areas.

I. INTRODUCTION

The importance of gate oxide reliability cannot be overemphasized. As gate oxides get thinner and thinner, their breakdown becomes one of the dominant factors that determine yield and reliability of MOS circuits. A reliable oxide breakdown model is needed that can predict the oxide lifetime under the normal operating conditions. In addition, such a model should incorporate the statistical nature of oxide breakdown. A statistical model for oxide breakdown under the constant voltage stresses has been proposed[1], but a more useful model is one under the constant current stresses. This is because charge-to-breakdown can be more easily obtained from TDDB(time-dependent dielectric breakdown) data under the constant current stresses[2]. In addition, it has been shown experimentally that the TDDB distribution is sharper with constant currents thus allowing more precise evaluation of oxide breakdown characteristics[2]. Developing a reliable statistical model for oxide breakdown under the constant current stresses is the goal of this paper.

In this paper, an intrinsic breakdown model is derived first which can predict the intrinsic oxide lifetime at a given current density. Oxide breakdown, however, is usually governed by defect-related extrinsic effects. These effects are incorporated into the intrinsic model using the effective oxide thickness reduction(ΔT_{OX})[3], in which all the breakdown-causing defects are phenomenologically represented by the reduction in oxide thickness. From the experimentally determined ΔT_{OX}

distribution, it is shown that TDDB distributions for any current stresses and any oxide areas can be reliably predicted.

II. INTRINSIC BREAKDOWN MODEL

It has been shown that the oxide lifetime is determined by the time required for the hole inflow into oxide to reach a certain critical value[4]. The induced hole density, Q_P, is proportional to $J \cdot \alpha \cdot t$, where $J = AE^{2}_{ox}e^{-B/E_{ox}}$ is the Fowler-Nordheim(F-N) current density with constants A and B, and the electric field across the oxide, E_{OX}, and $\alpha \propto e^{-H/E_{ox}}$ is the hole-generation coefficient with a constant H. In the range of E_{OX} of interest, F-N current is dominated by the exponential term, and consequently, E^{2}_{OX} term can be ignored. Then,

$$Q_P \propto e^{-(B+H)/E_{ox}} \cdot t = \left(e^{-B/E_{ox}}\right)^{1+H/B} \; t \qquad (1)$$

From Eq. 1, time-to-breakdown(t_{BD}) has the following current density dependence:

$$t_{BD} \propto (1/J)^{1+H/B} \quad \text{or} \quad \ln(t_{BD}) = k_1 \ln(1/J) + k_2 \qquad (2)$$

where $k_1=1+(H/B)$ and k_2 is a constant. This explicitly shows the linear relationship between $\ln(t_{BD})$ and ln(1/J) that has been shown experimently[5],[6]. If t_{BD} at one current density and the numerical value of k_1 are known, the above model can predict the oxide lifetime at any other current densities. The value of k_1 was experimentally determined by measuring intrinsic t_{BD}'s of 110A thick, p-type MOS capacitors at five different current densities of 70, 100, 200, 500, and 1000 mA/cm^2.

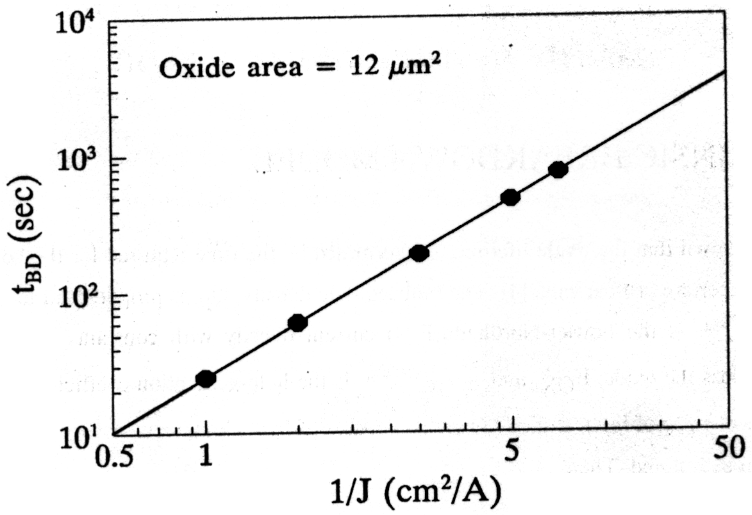

Fig. 1. Intrinsic oxide t_{BD}'s under constant current stresses.

In order to ensure intrinsic breakdown and not defect-related breakdown, capacitors with the small area(12μm^2) were used and the largest t_{BD} was selected from 10 to 20 samples. Fig. 1 shows the resulting t_{BD} dependence on (1/J). Clearly, ln(t_{BD}) and ln(1/J) have a linear relationship and from the slope of the line, k_1 is estimated to be 1.274. In order to confirm the accuracy of this k_1 estimation, F-N currents were measured for the same MOS capacitors and from this, 320.8 MV/cm was obtained for the value of B. This, along with the reported value of 82 MV/cm for H[7], gives k_1 of 1.256, confirming the accuracy of our k_1 estimation.

III. CURRENT-DENSITY DEPENDENCE

The model derived above is not sufficient for predicting the oxide lifetime in real cases as it does not include the influences of various oxide defects, which can substantially shorten the oxide lifetime. One simple solution is using the effective oxide thickness method, which regards the influence of any lifetime-shortening defects as the reduction of the oxide thickness that cause the same amount of lifetime reduction[3], and its schematic explanation is shown in Fig. 2.

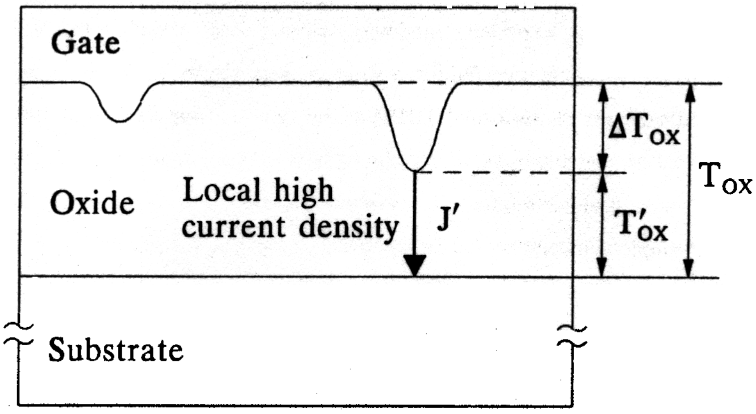

Fig. 2. Schematic explanation for effective oxide thinning.

If $t_{BD,I}$ is defined the intrinsic lifetime of oxide with thickness T_{OX} at a given current density J, and t'_{BD} the defect-related lifetime or the lifetime of gate oxide with a region whose thickness is $T'_{OX}=T_{OX}-\Delta T_{OX}$, then using Eq. 2,

$$\ln(t_{BD,I}) - \ln(t_{BD}) = k_1 \ln(J'/J) \qquad (3)$$

where J is the local current density in the region with T'_{OX}. In Eq. 3, J and J' are both F-N current densities and, again ignoring the E^2_{OX} dependence, proportional to $e^{-B/E_{ox}}$ and $e^{-B/E'_{ox}}$, respectively, where E'_{OX} is the local electric field corresponding to J'. As E_{OX} and E'_{OX} equal V_{OX}/T_{OX} and $V_{OX}/(T_{OX}-\Delta T_{OX})$, respectively, where V_{OX} is the initial voltage applied to oxides under the constant current stress, ΔT_{OX} can be expressed as

$$\Delta T_{OX} = \frac{[\ln(t_{BD,I}) - \ln(t_{BD})] \cdot E_{OX} \cdot T_{OX}}{k_1 B}. \qquad (4)$$

E_{OX} at any stress current density can be easily obtained from measured I-V characteristics of oxides and this along with $t_{BD,I}$ predicted using Eq. 3 allows the determination of ΔT_{OX} distribution from the TDDB data. Furthermore, once ΔT_{OX} distribution is known, the TDDB at any other stress current densities can be predicted using Eq. 4.

The accuracy of the above model was evaluated by comparing the results of prediction based on the model with those of actual measurements. Fig. 3 shows the measured TDDB from 110A thick, p-type MOS capacitors with the area of $42000\mu m^2$ as well as the results of prediction. For the measurement, 20 samples for each current stress level were randomly selected from a wafer, and their t'_{BD}'s were measured and the resulting cumulative failure percentage was obtained. For the prediction, ΔT_{OX} distribution was obtained from the measured TDDB at the stress current density of 100 mA/cm^2, and used to predict TDDB at 50 and 500 mA/cm^2. As can be seen from the figure, the prediction agrees well with the actual measurement indicating the validity of our approach. The slight disagreement is believed due to not sufficient sample numbers.

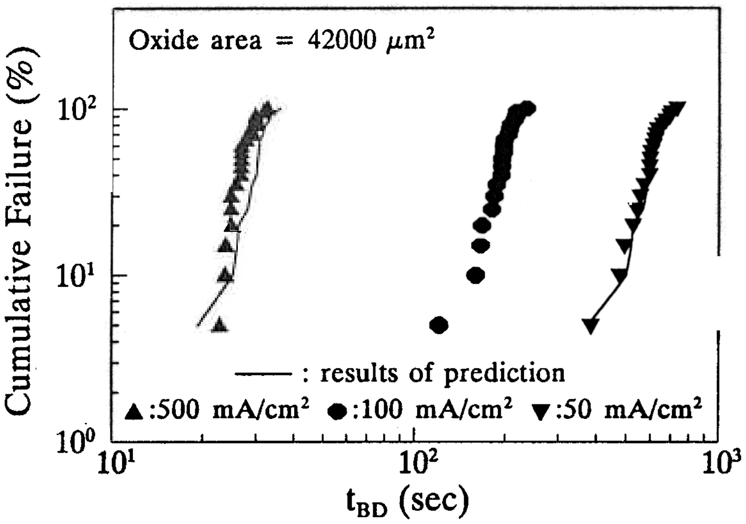

Fig. 3. Measured cumulative failure of oxides under different current stresses and the results of prediction.

IV. AREA DEPENDENCE

In order to evaluate dependence of the oxide lifetime on the oxide area, the defect density distribution should be known. The cumulative failure percentage, or the cumulative probability that oxide breakdown occurs before t'_{BD}, $P(t'_{BD})$, can be expressed as

$$P(t'_{BD}) = 1 - \frac{1}{[1 + A \cdot D(\Delta T_{OX}) \cdot S]^{1/S}} \qquad (5)$$

where A is the oxide area, $D(\Delta T_{OX})$, the cumulative area density of oxide defect corresponding to t'_{BD}, and S, the clustering factor[8]. t'_{BD} of an oxide with ΔT_{OX} can be determined from Eq. 4 and its cumulative failure percentage can be determined from Eq. 5 if $D(\Delta T_{OX})$ is known. In other words, from

Eq. 4 and Eq. 5, the TDDB for arbitrary oxide areas can be determined if $D(\Delta T_{OX})$ is known. In order to verify this under the constant current stresses, the TDDB for large oxides(1000 and 42000μm^2) were predicted using $D(\Delta T_{OX})$ estimated from the measured TDDB data of small oxides (12μm^2) and compared with the actual measurements. For this, the TDDB data were measured from 110A thick, p-type MOS capacitors with the area of 12μm^2 under the stress current densities of 70, 100, 200, 500, and 1000 mA/cm^2, and from the data them $D(\Delta T_{OX})$ was estimated using Eq. 5. The value of 0.65 for S was used for our estimation but the exact value of S was found not to greatly affect our final results.

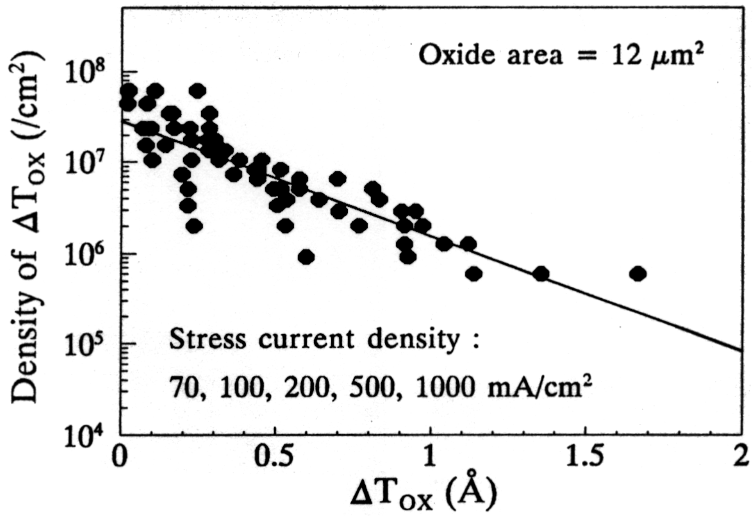

Fig. 4. Measured cumulative area density of defects(ΔT_{OX}) for 12μm^2 oxides as a function of ΔT_{OX} and the best exponential fit.

Fig. 4 shows the experimentally obtained $D(\Delta T_{OX})$ as a function of ΔT_{OX} and the best exponential fit. TDDB under the stress current density of 100 mA/cm^2 for larger oxides predicted from Eq. 5 using the exponential fit for $D(\Delta T_{OX})$ is shown in Fig. 5 as well as the results of actual measurements. For 12 μm^2 oxides, the agreement between prediction and measurement is, as expected, very good since $D(\Delta T_{OX})$ used for prediction is obtained from the same data. The agreement gets worse for larger oxides, but considering the difference in sizes between 12 and 42000μm^2 such disagreement may not be severe at all. Clearly, this shows that with our approach TDDB under the constant current stresses for gate oxides having arbitrary areas can be reliably predicted.

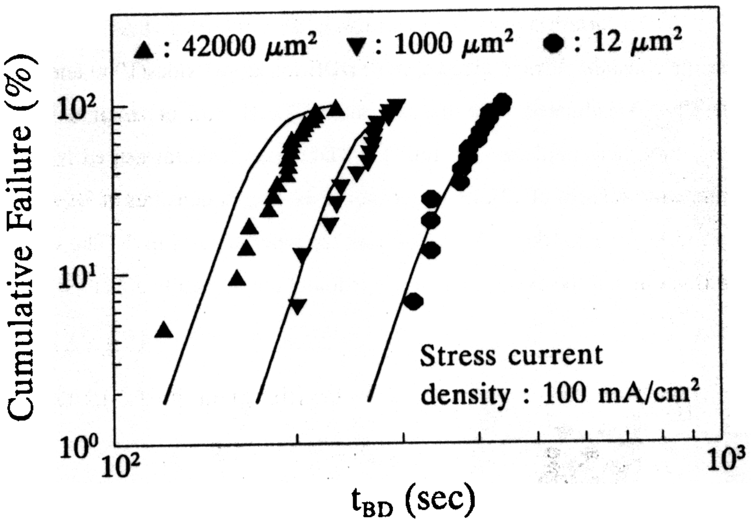

Fig. 5. Measured cumulative failure of oxides with different areas and the results of prediction.

V. CONCLUSION

It has been shown that a simple statistical model for gate oxide breakdown under the constant current stresses along with the effective oxide thickness can reliably predicted the TDDB characteristics for any arbitrary current stress levels and oxide areas.

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