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Prediction of TDDB characteristics under constant current stresses

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Indexing terms: Semiconductor technology, Integrated circuit technology

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

Introduction: The importance of gate oxide reliability cannot be overemphasised. 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 normal operating conditions. In addition, such a model should incorporate the statistical nature of oxide breakdown. A statistical model for oxide breakdown under constant voltage stresses has been proposed [1], but a more useful model is one under constant current stresses. This is because charge-to-breakdown can be more easily obtained from TDDB (time-dependent dielectric breakdown) data under 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].

In this Letter, a reliable statistical model for oxide breakdown is developed and experimentally confirmed. First an intrinsic breakdown model which can predict the intrinsic oxide lifetime at a given current density is derived. 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 the TDDB of oxides for any current stress levels and any oxide areas can be reliably predicted.

Intrinsic breakdown model: It has been shown that the oxide lifetime is determined by the time required for the hole inflow into the 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 $a \propto e^{-H/E_{ox}}$ 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 the influence of the E^2_{ox} term can be ignored. Then

$$Q_P \propto e^{-(B+H)/Eox} \cdot t = (e^{-B/Eox})^{1+H/B} \cdot t \quad (1)$$

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

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

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 experimentally [5, 6] but not analytically. 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 110Å thick, *p*-type MOS capacitors at five different current densities of 70, 100, 200, 500, and 1000mA/cm². 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. To confirm the accuracy of this k_1 estimation, *F-N* currents were measured for the same MOS capacitors, and from this 320.8MV/cm was obtained for the value of *B*. This, along with the reported value of 82MV/cm for *H* [7], gives k_1 of 1.256, confirming the accuracy of our k_1 estimation.

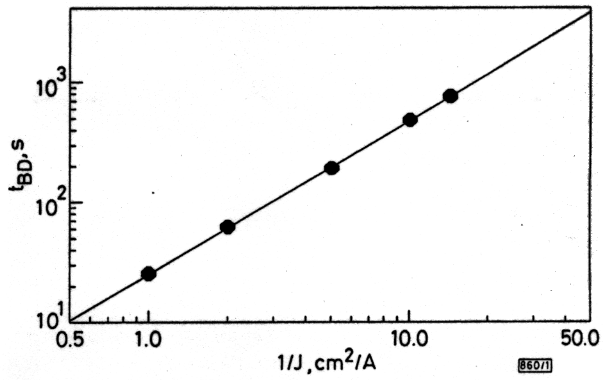

Fig. 1 *Intrinsic oxide t_{BD}s under constant current stresses*

Defect-related breakdown model: The model derived above is not sufficient for predicting the oxide lifetime in real cases, as it does not include 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 causes the same amount of lifetime reduction [3].

If $t_{BD,I}$ is defined the intrinsic lifetime of oxide with tickness T_{ox} at a given current density J, and t'_{BD} as 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 eqn. 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 eqn. 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} are equal to V_{ox}/T_{ox} and $V_{ox}/(T_{ox}-\Delta T_{ox})$, respectively, where V_{ox} is the initial voltage applied to oxides during the constant current stress, ΔT_{ox} can be expressed as

$$\Delta T_{OX} \simeq \frac{[\ln(t_{BD,I}) - \ln(t'_{BD})] \cdot E_{OX} \cdot T_{OX}}{k_1 B} \qquad (4)$$

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

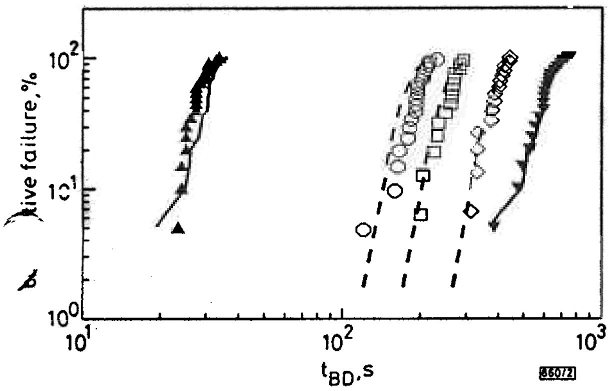

Fig. 2 *Measured TDDB and results of prediction*

▼, ▲, solid lines: for different current densities of 50, 100 and 100mA/cm² for 42000µm² oxides
◇, □, ○, dotted lines: for different oxide areas of 12, 1000 and 42000 µm² at 100mA/cm²
Shapes: measured, lines: predicted

Fig. 2 shows measured TDDB of 110Å thick, p-type MOS capacitors with an area of 42000µm² under the three different current densities, and the results of prediction. For the prediction, ΔT_{ox} distribution was obtained from the measured TDDB at 100mA/cm², and used to predict TDDB at 50 and 500mA/cm². As can be seen from the figure, the prediction agrees well with the actual measurement, indicating the validity of our approach.

The TDDB for arbitrary oxide areas can also be predicted if the cumulative area density of defects is known [1]. The cumulative failure percentage, or the cumulative probability that oxide breakdown occurs before t'_{BD}, $P(t'_{BD})$, is expressed as

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

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]. Using eqns. 4 and 5 $D(\Delta T_{ox})$ can be deduced from the measured TDDB for a certain oxide area, and once $D(\Delta T_{ox})$ is known, TDDB for arbitrary oxide areas can be predicted.

Fig. 3 shows the $D(\Delta T_{ox})$ deduced from the TDDB of 110Å thick, p-type MOS capacitors with an area of 12µm² under the stress current densities of 70, 100, 200, 500 and 1000mA/cm² using eqns. 4 and 5, and the best exponential fit. The value of 0.65 for S was used for our estimation. The measured TDDB for oxides with areas of 12, 1000 and 42000µm² under the stress current density of 100mA/cm², and the results of prediction from eqns. 4 and 5 using the exponential fit for $D(\Delta T_{ox})$ are shown in Fig. 2. The agreement decreases for larger oxides, but considering the difference in sises between 12 and 42000µm² such disagreement may not be severe at all. Clearly, this shows that with our approach, TDDB under constant current stresses for oxides with arbitrary areas can be reliably predicted.

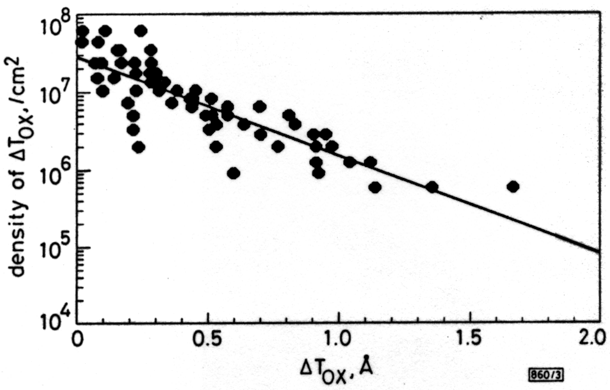

Fig. 3 *Measured cumulative area density of defects* (ΔT_{ox}) *for 12 µm² oxides against* ΔT_{ox} *and best exponential fit*

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

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