Abstract—The effect of time-dependent stress voltage and temperature on the reliability of thin SiO₂ films is incorporated in a quantitative defect-induced breakdown model. Based on this model, design curves are presented which can be used along with a breakdown voltage distribution for an oxide technology to determine optimal burn-in conditions. The tradeoff between improved reliability and lower burn-in yield for different gate oxide technologies can also be examined quantitatively using the model presented here.

I. INTRODUCTION

TIME-DEPENDENT dielectric breakdown (TDBB) has received considerable attention as a principal failure mode in MOS circuits [1], [2]. In order to reduce the failure rate during operation, a burn-in is usually performed to screen out potentially defective samples. However, a quantitative model predicting the effects of burn-in time, voltage, and temperature on subsequent oxide lifetime has not been available. In this study, a general model is presented for determining the breakdown condition under time-dependent stress voltage and temperature. Based on this model, the effective thinning concept, and 1/Er dependence for SiO₂ breakdown, a general technique for projecting gate oxide reliability and optimizing screening conditions is presented. From the simple ramp voltage measurement, the cumulative defect distribution as a function of the severity of the defect (characterized by the effective oxide thickness) is determined. The reliability of oxides characterized by this defect distribution following a given burn-in condition can be projected for any oxide area, operating voltage, and temperature.

II. BREAKDOWN MODEL

A. Voltage and Temperature Acceleration

Based on constant voltage tests on small-area oxides (area < 400 μm²), the logarithm of the time-to-breakdown tBD has been shown to follow a reciprocal field dependence [3]

\[ t_{BD} = \tau_0 \exp \left[ \frac{G}{E_{ox}} \right] = \tau_0 \exp \left[ \frac{G X_{ox}}{V_{ox}} \right] \]  

where \( X_{ox} \) is the oxide thickness, \( V_{ox} \) is the voltage across the oxide, and \( G = (350 \text{ MV/cm}) \) and \( \tau_0 = (1 \times 10^{-11} \text{ s}) \) are the slope and intercept of the \( \ln(t_{BD}) \) versus \( 1/E_{ox} \) plot, respectively [4].

Early failure has been attributed to defects at or near the Si/SiO₂ interface: Recent studies by Lin [5] and Liehr [6] have demonstrated a correlation between low breakdown strength and the presence of decorated stacking faults. Honda [7], [8] and Wendt [9] attributed early failure to local thinning and discontinuities in the oxide caused by metallic precipitates. Lee [10] demonstrated that defect-induced breakdown can be modeled accurately by the effective thinning concept: defects are modeled as a localized oxide thinning such that

\[ t_{BD} = \tau_0 \exp \left[ \frac{G X_{eff}}{V_{ox}} \right] \]  

where \( X_{eff} \) is the effective oxide thickness at the weakest point in the oxide. This concept is used to model not only physical thin spots in the oxide film but also asperities at the interface (resulting in a higher field) and localized areas having a modified chemical composition which may increase the charge trapping rate or reduce the barrier height at the Si/SiO₂ interface (lower \( G \)). All of these possible sources of defects are mathematically equivalent to a localized oxide thinning in (2).

On the right hand side of (2), \( \tau_0 \) and \( G \) are the only temperature-dependent quantities. By expressing \( t_{BD} (T) \) in Arrhenius form with activation energy \( E_b \) and expanding \( G (T) \) in a Taylor series in \( 1/T \)

\[ t_{BD} = \tau_0 \exp \left( \frac{E}{k} \right) \left( \frac{1}{T} - \frac{1}{300} \right) \]  

the activation energy for \( t_{BD} \) in \( E_{bd} \) is obtained [11]

\[ E_{bd} = \left. \frac{\ln \left( \frac{t_{BD}(T)}{\tau_0} \right)}{k T \left( \frac{1}{T} - \frac{1}{300} \right)} \right|_{T=1} = E_b \]  

where

\[ \delta \approx \frac{k}{G} \frac{dG(T)}{d(1/T)} \]
III. TIME-DEPENDENT STRESS

A. Breakdown Condition

Conceptually, it is assumed that carrier flow causes oxide damage, which leads to an increase in electric field or carrier flow rate and, therefore, an increase in the rate of damage. This positive feedback eventually causes oxide breakdown. The physical mechanism(s) may involve positive charge buildup at the cathode [3], [15], electron trapping near the anode [16], resonant tunneling [17], etc. Considerable evidence exists suggesting that holes are involved in the damage generation although hole trapping may or may not be the ultimate damage responsible for breakdown [18]-[20].

In the model presented so far, the temperature and applied voltage are assumed to remain constant during the entire lifetime of the oxide. In order to apply this model to situations where the voltage and temperature are time-dependent (e.g., ramp voltage testing, burn-in and subsequent operation, etc.), the incremental damage dΔ incurred per unit time has to be determined. In general, the rate at which the oxide is damaged is a function of the stress voltage, temperature, and defect severity (Xeff).

One may also expect that the rate depends on the amount of damage already incurred from earlier stresses, i.e., the oxide may be more (or less) susceptible to further stress as the damage level increases. Assuming that the rate at which damage is incurred depends only on the instantaneous damage level but is independent of previous stress history, the damage rate can be expressed as

\[
\frac{d\Delta}{dt} = f(\Delta) g(V, T, X_{\text{eff}}) \tag{5}
\]

where the functional form of \( f \) and \( g \) are unknown for now and the voltage and temperature are time-dependent (\( V = V(t), T = T(t) \)). Equation (5) is integrated using separation of variables to obtain

\[
\int_0^{\Delta_D} \frac{d\Delta}{f(\Delta)} = \int_0^{\Delta_0} g(V, T, X_{\text{eff}}) \, dt = C \tag{6}
\]

where \( \Delta_D \) is the damage threshold level for destructive breakdown and both integrals are equal to a constant C. For a constant voltage and temperature stress, the second integral in (6) can be evaluated

\[
C = g(V_{\text{ox}}, T, X_{\text{eff}}) \tau_{BD} \tag{7}
\]

By comparing (7) and (2)

\[
\tau_{BD} = \tau_0(T) \exp \left( \frac{G(T)X_{\text{eff}}}{V_{\text{ox}}} \right) = \frac{C}{g(V_{\text{ox}}, T, X_{\text{eff}})} \tag{8}
\]

the functional form of \( g \) is obtained

\[
g(V_{\text{ox}}, T, X_{\text{eff}}) = \frac{C}{\tau_0(T)} \exp \left( \frac{-G(T)X_{\text{eff}}}{V_{\text{ox}}} \right). \tag{9}
\]

Substituting for \( g \) in (6), the breakdown condition for time-dependent voltage \( V = V(t) \) and temperature \( T = \ldots \)
\[ T(t) \text{ is determined} \]
\[ 1 = \int_{0}^{t_{BD}} \exp \left( \frac{-G(T) X_{\text{eff}}}{V} \right) \frac{dt}{\tau_{0}(T)}. \] (10)

B. Ramp Breakdown

Since the ramp voltage test is much shorter than the constant voltage test, it is very desirable to be able to characterize an oxide technology and project reliability from ramp breakdown data. Applying (10) in the case of the ramp voltage test where
\[ V(t) = R t \quad T(t) = T_{\text{BD}} \] (11)
and \( R \) is the ramp rate (in volts per second), the breakdown condition becomes
\[ 1 = \int_{0}^{t_{BD}} \exp \left( \frac{-G(T_{\text{BD}}) X_{\text{eff}}}{R t} \right) \frac{dt}{\tau_{0}(T_{\text{BD}})} \] (12)
which is evaluated to obtain
\[ 1 \cong \frac{V_{BD}}{R G(T_{\text{BD}}) \tau_{0}(T_{\text{BD}}) X_{\text{eff}}} \exp \left( \frac{-G(T_{\text{BD}}) X_{\text{eff}}}{V_{BD}} \right) \] (13)
where \( V_{BD} = R t_{BD} [21] \). In general, (13) has to be solved numerically to determine the \( X_{\text{eff}} \) corresponding to a measured \( V_{BD} \). However, since the \( X_{\text{eff}} \) dependence of the exponential term in (13) dominates over the \( X_{\text{eff}} \) dependence of the pre-exponential coefficient, it is possible to obtain an accurate closed-form solution for \( X_{\text{eff}} \) by setting \( X_{\text{eff}} \) in the pre-exponential term to 80 Å
\[ X_{\text{eff}} \cong \frac{V_{BD}}{G(T_{\text{BD}}) \ln \left( \frac{V_{BD}}{R G(T_{\text{BD}}) \tau_{0}(T_{\text{BD}}) 80 \, \text{Å}} \right)}. \] (14)
Substituting (14) into (2), an approximate relationship between \( V_{BD} \) of a ramp voltage test at temperature \( T_{\text{BD}} \) and \( t_{BD} \) of a constant voltage test at temperature \( T_{\text{BD}} \) is obtained
\[ t_{BD} \cong \tau_{0}(T_{\text{BD}}) \cdot \frac{V_{BD}^2}{R G(T_{\text{BD}}) \tau_{0}(T_{\text{BD}}) 80 \, \text{Å}} \] \( G(T_{\text{BD}})V_{BD}/G(T_{\text{BD}})V_{\text{BD}} \).
(15)

For the typical case where the ramp voltage test is performed at room temperature (\( T_{\text{BD}} = 25^\circ \text{C} \) and \( T_{\text{BD}} = T \)), (15) reduces to
\[ t_{BD} \cong \tau_{0}(T) \left[ 3.6 \times 10^{8} \frac{1}{V \cdot \text{s} R} \right] \left( G(T)/350 \right) \frac{V_{BD}}{V_{BD}/V_{\text{BD}}} \] \( G(T)/350 \).
(16)

where \( G(T) \) (expressed in megavolts per centimeter) and \( \tau_{0}(T) \) are given in (3). Therefore, a lifetime of 10 years at 5.5 V and 125°C corresponds to \( V_{BD} \cong 11.5 \) V at 1 V/s and a lifetime of 100 years corresponds to \( V_{BD} \cong 12 \) V at 1 V/s (see Fig. 2). In order to verify the correlation between ramp breakdown and TDDB (16), both ramp and constant voltage tests were performed on 125 Å oxides. As shown in Fig. 2, there is very good agreement between the experimental data and the theoretical prediction. The raw data used in this comparison will be presented in Section IV.

C. Burn-In

Another application of (10) of practical importance is to model the effect of burn-in on the subsequent lifetime of an oxide [22]. With the addition of a burn-in step, the breakdown condition (10) is simply a summation of the damage incurred during burn-in \( \Delta_{\text{Bi}} \) and that incurred during operation of the device \( \Delta_{\text{op}} \)
\[ 1 = 1 = \Delta_{\text{Bi}} + \Delta_{\text{op}}. \] (17a)
\[ 1 = \frac{t_{\text{Bi}}}{\tau_{0}(T_{\text{Bi}})} \exp \left( \frac{-G(T_{\text{Bi}}) X_{\text{eff}}}{V_{\text{Bi}}} \right) \]
\[ + \frac{t_{\text{op}}}{\tau_{0}(T_{\text{op}})} \exp \left( \frac{-G(T_{\text{op}}) X_{\text{eff}}}{V_{\text{op}}} \right) \] (17b)
where the oxide is subjected to a burn-in at \( V_{\text{Bi}} \) volts and \( T_{\text{Bi}} \) kelvin for \( t_{\text{Bi}} \) seconds and has a subsequent lifetime \( t_{\text{op}} \) at \( V_{\text{op}} \) volts and \( T_{\text{op}} \) kelvin. By solving (17b) for the lifetime \( t_{\text{op}} \), one can assess the effect of a given burn-in condition on the subsequent lifetime of a device
\[ t_{\text{op}} = \tau_{0}(T_{\text{op}}) \exp \left( \frac{G(T_{\text{op}}) X_{\text{eff}}}{V_{\text{op}}} \right) \left[ 1 - \frac{\Delta_{\text{Bi}}}{\tau_{0}(T_{\text{Bi}})} \right] \] (18a)
\[ t_{\text{op}} = \tau_{0}(T_{\text{op}}) \exp \left( \frac{G(T_{\text{op}}) X_{\text{eff}}}{V_{\text{op}}} \right) \left[ 1 - \frac{t_{\text{Bi}}}{\tau_{0}(T_{\text{Bi}})} \right] \] (18b)
Comparing (18b) with (2), it is clear that the first two product terms give the original oxide lifetime, i.e., the lifetime without burn-in. Therefore, the quantity enclosed in square brackets in (18b) represents the fraction of the original oxide lifetime remaining after burn-in. This quantity is plotted in Fig. 3 as a function of \( X_{\text{eff}} \) as well
as the corresponding ramp breakdown voltage (using (13)) and the expected lifetime at 5.5 V and 150°C before burn-in (using (2)). As shown in Fig. 3, only a small fraction of the samples surviving burn-in, e.g., for the 7 V burn-in, those oxides having breakdown voltages between 11.5 and 12 V, are predicted to be significantly damaged during burn-in. The same conclusion is reached when comparing the expected lifetime after burn-in versus the original oxide lifetime before burn-in as shown in Fig. 4: Of the oxides remaining after burn-in, only those having lifetimes within one half of one decade have significantly reduced lifetimes (i.e., a reduction of more than 10% from the original lifetime) after burn-in.

In order to verify the effect of burn-in on subsequent oxide integrity, intrinsic 125 Å oxides (100 μm²) were subjected to different burn-in conditions and the subsequent ramp breakdown voltage $V_{BD}$ was measured. According to (10) and (13), the breakdown condition for this experiment is

$$1 = \frac{I_{BD}}{I_{0}(T_B)} \exp\left(\frac{-G(T_B) X_{ON}}{V_{BI}}\right) + 3.6 \times 10^8 \frac{1}{V \cdot s} \frac{V_{BD}^2}{R} \exp\left(\frac{-G X_{ON}}{V_{BD}}\right).$$

Four different samples were tested for each burn-in condition. The average breakdown voltage for the four samples for each test is plotted in Fig. 5(a) as a function of the burn-in voltage. Also shown are the model predictions. Close inspection of the transition from unaffected oxides (normal $V_{BD}$) to severely damaged oxides (very low $V_{BD}$) shows that only a few oxides are significantly damaged by burn-in as predicted by (19) and plotted in Fig. 5(b).

**IV. RELIABILITY PROJECTION**

**A. Experiment**

In order to project oxide reliability, the density and distribution of defects as a function of severity (characterized by $X_{eff}$) must be known. If defects are distributed randomly across a wafer, the Poisson distribution relates the defect density to the cumulative failure probability $P$

$$P = 1 - \exp\left(-AD(X_{eff})\right)$$

where $A$ is the oxide area and $D(X_{eff})$ is the cumulative defect density as a function of $X_{eff}$. $D(X_{eff})$ can be determined from cumulative failure versus $t_{BD}$ data (Fig. 6(a)) or more conveniently, from cumulative failure data versus the breakdown voltage in a ramp voltage test (Fig. 6(b)). The same defect distribution is deduced from either test as shown in Fig. 7. Based on this defect distribution and (18b), the burn-in yield and lifetime distribution after any burn-in condition can be estimated. The projected and measured burn-in yield are plotted in Fig. 8. Fig. 9 shows cumulative failure data at 6.5 V and 25°C following two
different oxide technologies or thicknesses [4]. In order to demonstrate this technique, the thinnest oxide which satisfies a given reliability specification will be determined for the oxide technology characterized by the ramp voltage test results shown in Fig. 10. No screening was performed before the ramp voltage test. Since 10-year lifetime at 5.5 V and 125°C corresponds to $V_{BD} \approx 11.5$ V at 1 V/s (Fig. 2), one can immediately estimate that 10% of the 10 mm$^2$ 200 Å oxides will fail before 10 years. From (20) and (13) the cumulative defect density as a function of $X_{ox}$, $D(X_{ox})$, is obtained for each of the oxide thicknesses as shown in Fig. 11. The reliability of any of the oxides characterized by the defect density curves in Fig. 11 for any given oxide area, operating voltage, and temperature can be determined now using (2) and (20). For example, Fig. 12 is a plot of the projected reliability for 5.5 V operation at 125°C for 1 mm$^2$ oxides. Note that the cumulative failure for the 155 Å oxide after 10 years is projected to be approximately 5%.

Since the maximum $V_{ox}/X_{ox}$ for a 10-year lifetime at 125°C is 7 MV/cm (see Section II), the actual oxide electric field is limited by $E_{max} = (7 \text{ MV/cm}) (X_{ox}/X_{dr})$, and the oxide voltage is limited by $V_{max} = (7 \text{ MV/cm}) X_{dr}$. The maximum allowable field and voltage for the oxides studied here are plotted in Fig. 13. In order to determine $E_{max}$ or $V_{max}$, the maximum acceptable defect density for a desired failure specification and a given oxide area must be obtained using (20). For example, if 3% cumulative failure after 10 years at 5.5 V and 125°C is acceptable for a 1 mm$^2$ oxide area (corresponding to approximately 3 defects per square centimeter), the thinnest allowable oxide for this technology is approximately 150 Å (see Fig. 13(b)). The failure rate in the first year is expected to be over 1000 FIT. If a higher cumulative failure (corresponding to a higher defect density) were tolerable, a higher operating voltage or equivalently, a thinner oxide, could be used. Since the inversion layer charge density and the maximum MOSFET current are roughly proportional to the maximum oxide field, Fig. 13(a) shows that thinner oxides for this technology provide larger current drive for the same reliability specification than thicker oxides even though thin oxides cannot tolerate high voltages (Fig. 13(b)) [23].

Screening (burn-in) can reduce the projected failure rate. Furthermore, since a longer burn-in time lowers the
failure rate but increases the yield loss, it is possible to obtain an optimum burn-in time. For example, as shown in Fig. 14, after 10 h of burn-in at 7 V and 150°C, less than 10% of 1 mm² 155 Å samples is projected to fail while approximately 1% (reduced from the 5% failure without burn-in) of the remaining population is projected to fail in the 10-year lifetime at 5.5 V and 125°C. The failure rate is approximately 100 FIT. Identical burn-in yield and subsequent failure rate are achieved for any burn-in voltage and time combination that falls on the 90% yield/100 FIT curve in Fig. 15. This curve gives the burn-in time and voltage combinations that cause the same damage $\Delta_{\text{eq}}$ according to (17).

Even though the example given here compares oxides with different thicknesses for the same technology, the same analysis can be performed when comparing different oxide technologies. For example, the horizontal axis in Fig. 13 can alternatively represent different oxidation ambients or temperatures in order to determine the maximum allowable power supply voltage for each technology and Figs. 14 and 15 can be used to study the tradeoffs between
burn-in yield and subsequent failure rate for various technologies.

C. Optimization of Burn-In Conditions

In order to choose burn-in conditions which maximize the burn-in yield while improving the projected failure rate, both the defect distribution for a particular technology and the model predictions need to be examined. The defect distribution is determined by performing a constant voltage test, or more conveniently, a ramp voltage test, as demonstrated in Figs. 6 and 7. The model predictions are summarized here. For example, as shown in Fig. 16(a), (16) predicts that a burn-in at 7 V and 150°C for 10 h screens out oxides with $V_{BD}$ below 11.5 V (at a ramp rate of 1 V/s). This burn-in condition is believed to be nearly optimal for typical oxide technologies since it screens out only those samples which are expected to fail during the first 10 years at 5.5 V and 125°C. The yield loss from burn-in is determined by the fraction of the total oxide population with a breakdown voltage below 11.5 V. Following this burn-in, oxides with 11.5 V < $V_{BD}$ < 11.6 V are projected to fail during a 10-year lifetime at 5.5 V and 125°C (see (17) and Fig. 16(a)). The corresponding average failure rate is determined by the fraction of the population with 11.5 V < $V_{BD}$ < 11.6 V. Therefore, it is clear that the burn-in condition has to be chosen such that the fraction of the population which fails during the operating lifetime (i.e., in this case, the fraction with 11.5 V < $V_{BD}$ < 11.6 V) is minimized while also keeping the yield loss from burn-in as low as possible. If, for a given technology, a large fraction of oxides have 11.5 V < $V_{BD}$ < 11.6 V (80.5 Å < $X_{eff}$ < 81.5 Å), further screening is necessary to reduce the failure rate. Conversely, an oxide technology may have such a low fraction of oxides with $V_{BD}$ ≤ 11.5 V (i.e., the defect density may be very low) that no screening is necessary.

With the considerations discussed above in mind, optimal burn-in conditions for a given technology can be determined using Figs. 16(b) and 17 and a breakdown distribution for that technology. Since there are three variables to be chosen (burn-in time, temperature, and voltage), it is possible to obtain the same burn-in yield and projected failure rate for many different combinations of burn-in times, temperatures, and voltages. For example, if the optimal burn-in condition is determined to be 7 V, 150°C, and $3 \times 10^5$ s from Fig. 16(b) (corresponding to a breakdown voltage of 11.4 V), all equivalent burn-in conditions are given by the 11.4 V/80 Å line in Fig. 17(a) or the 10-year/11.3 V line in Fig. 17(b). In other words, any burn-in voltage and time combination on the 11.4 V/80 Å line in Fig. 17(a) or the 11.3 V/10-year line in Fig. 17(b) can be used to screen out oxides characterized by $V_{BD}$ ≤ 11.4 V or $X_{eff}$ < 80 Å (i.e., to screen out those oxides that are projected to fail within 10 years at 5.5 V and 125°C). It is desirable to choose burn-in conditions which minimize burn-in cost. Typically, this implies choosing the shortest burn-in time at the highest acceptable burn-in voltage. The maximum allowable burn-in voltage is usually set by circuit or technology constraints such as junction breakdown voltage.

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Fig. 16. Burn-in conditions can be optimized using the design curves shown here. Samples with breakdown voltages below the dashed line in (a) are screened out after burn-in, samples with breakdown voltages between the dashed line and the solid line are projected to fail during operation at 5.5 V and 125°C and those with breakdown voltages above the solid line are projected to satisfy a 10-year lifetime specification. The optimal burn-in condition can be chosen using (b) and a breakdown voltage distribution characterizing the oxide technology.

Fig. 17. Once an optimal burn-in condition is chosen using Fig. 16, equivalent burn-in conditions can be determined using the curves shown here. For example, burn-in conditions which screen out all oxides with breakdown voltages below 10 V, i.e., $X_{eff}$ < 70 Å (see the 10 V/70 Å curve for 150°C burn-in in (a) or the 0.1-year lifetime/10.1 V curve in (b)) will have the same burn-in yield and projected reliability.
V. SUMMARY AND CONCLUSIONS

A general model is developed to determine the oxide breakdown condition for time-dependent stress voltage and temperature. Based on this model, the effective trapping concept, and $1/E_{ox}$ field dependence for SiO₂ breakdown, a general technique for projecting gate oxide reliability and optimizing screening conditions is presented. From the simple ramp breakdown measurement, the cumulative defect distribution as a function of the severity of the defect (characterized by the effective oxide thickness) is determined. The reliability of oxides characterized by this defect distribution is projected for any oxide area, operating voltage, and temperature. For 5.5 V operation, all oxides with an effective thickness less than 80.5 Å or equivalently with a ramp breakdown voltage $V_{BD}$ less than 11.5 V (at a ramp rate of 1 V/s) are projected to fail before 10 years at 125°C. These oxides must generally be screened out in order to reduce the failure rate. This is accomplished using a 10-h burn-in at 7 V and 150°C. It is also possible to obtain the same burn-in yield and operational reliability using many different combinations of burn-in voltage, time, and temperature. After burn-in, only oxides with effective thickness between 80.5 and 81.5 Å or equivalently $11.5 \text{ V} < V_{BD} < 11.6 \text{ V}$ are projected to fail in 10 years; this provides an estimate for the failure rate. If the failure rate is expected to be too high, i.e., a significant portion of the ramp breakdown distribution lies below $11.5 \text{ V} < V_{BD} < 11.6 \text{ V}$, more stringent screening may be needed to meet a desired failure rate specification.

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REFERENCES


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