PROJECTING THE MINIMUM ACCEPTABLE OXIDE THICKNESS FOR TIME-DEPENDENT DIELECTRIC BREAKDOWN

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ABSTRACT

A technique is presented for determining the thinnest oxide which satisfies a given time-dependent dielectric breakdown reliability specification. The intrinsic limit for a 10-year lifetime at 125°C is estimated to be 80Å for 5.5V operation and 50Å for 3.6V operation. For the particular technology studied here, 150Å oxide meets typical reliability specifications for 5.5V operation and 80Å oxide is acceptable for 3.6V operation (both at 125°C).

INTRODUCTION

MOS device scaling and performance considerations require the thinnest allowable gate oxide. Time-dependent dielectric breakdown (TDDB) reliability sets one of the limits of the minimum acceptable thickness [1]. This paper presents a technique for projecting this minimum gate oxide thickness.

TDDB MODEL

Intrinsic time-to-breakdown (t_{BD}) data is plotted as a function of the oxide electric field for different oxide thicknesses in Figure 1. It can be seen that log t_{BD} should be extrapolated against $1/E_{ox}$ rather than E_{ox} as is commonly done. Therefore, t_{BD} can be expressed in the following form:

$$t_{BD} = \tau_o \, e^{\frac{G}{E_{ox}}} = \tau_o \, e^{\frac{GX_{ox}}{V_{ox}}} \quad (1)$$

where X_{ox} is the oxide thickness, V_{ox} is the voltage across the oxide, and G (350 MV/cm) and τ_o (1×10^{-11}sec) are the slope and intercept of the $\ln(t_{BD})$ versus $1/E_{ox}$ plot, respectively. According to a defect-density model [2], defects in the oxide can be modeled as an effective oxide thinning such that

$$t_{BD} = \tau_o \, e^{\frac{GX_{eff}}{V_{ox}}} \quad (2)$$

where X_{eff} is the effective oxide thickness at the defect site. This effective thinning model predicts the voltage and temperature dependence of cumulative failure versus time accurately down to 5V as shown in Figure 2 [3]-[5].

Scaling laws and performance requirements demand the thinnest allowable gate oxide or equivalently, the maximum allowable field. Using (2) and the temperature model for time-dependent dielectric breakdown proposed in [5], the maximum allowable field for an oxide with thickness X_{eff} subject to a 10-year lifetime at 125°C is determined to be approximately 7 MV/cm ($= V_{ox}/X_{eff}$). This field corresponds to a minimum X_{eff} of 80Å for V_{ox} = 5.5V and 50Å for V_{ox} = 3.6V (Figure 3). In other words, any oxide sample having a defect site characterized by X_{eff} < 80Å (for 5.5V operation) or X_{eff} < 50Å (for 3.6V operation) will fail before 10 years at 125°C.

Since the ramp breakdown voltage, V_{BD}, is related to X_{eff} according to

$$\frac{V_{BD}^2}{RGX_{eff}} \, e^{-\frac{GX_{eff}}{V_{BD}}} = \tau_o \quad (3)$$

(R is the ramp rate) measurements of V_{BD} can be projected to t_{BD} at a given voltage and temperature [2], [6]. As shown in Figure 4, there is good agreement between experimental results and the theoretical projection given in (3). An oxide sample that fails at any combination of testing times and voltages below the 80Å line in Figure 3 or the dotted line in Figure 4 will fail before 10 years at 5.5V.

In the above discussion, V_{ox} is the voltage across the oxide and is generally different from the applied voltage V_g because of band-bending and work function differences. The worst-case V_{ox} is approximately equal to V_g and occurs in an n-channel MOSFET in the on state (i.e., $+V_g$ with n$^+$ poly gate on p-type substrate). For $-V_g$, n$^+$ poly gate, and either p- or n-type substrates, $|V_{ox}|$ is approximately 1.2V less than $|V_g|$ [7]. This explains the observed higher oxide failure rate of n-channel devices over p-channel devices in CMOS ICs [8].

RELIABILITY PROJECTION

In order to project oxide reliability, the density and distribution of defects as a function of severity (character-

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CH2528-8/88/0000-0710 $1.00 © 1988 IEEE

ized by X_{eff}) must be known. Assuming defects are distributed randomly, the Poisson distribution can be used to determine the percent cumulative failure, P,

$$P = 1 - e^{-AD(X_{eff})} \tag{4}$$

where A is the oxide area and $D(X_{eff})$ is the defect distribution as a function of X_{eff}. Since the weakest spot (smallest X_{eff}) in an oxide sample sets the limit for reliability (see (2)), a sample can be characterized by the X_{eff} of its weakest spot. Therefore, from cumulative failure data versus t_{BD} or more conveniently V_{BD} (see Figure 5), the number of defect sites having an effective oxide thickness X_{eff} can be determined. Figure 6 is a plot of the defect density as a function of X_{eff} ($D(X_{eff})$) for several oxide thicknesses. Note that as the severity of the defect decreases (higher X_{eff}), the density increases.

The reliability of any of the oxides characterized by the defect density curves in Figure 6 for any given oxide area, operating voltage, and temperature can now be determined using (2) through (4). Since the maximum V_{ox}/X_{eff} for a 10-year lifetime at 125°C is 7 MV/cm (Figure 3), the actual oxide electric field is limited by $E_{max} = (7\text{MV/cm})(X_{eff}/X_{ox})$ and the oxide voltage is limited by $V_{max} = (7\text{MV/cm})\,X_{eff}$. The maximum allowable field and voltage for the oxides studied here are plotted in Figure 7. 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 from (4). For example, if 3% cumulative failure after 10 years at 5.5V and 125°C is acceptable for a $1mm^2$ oxide area (corresponding to approximately 3 defects per cm^2), the thinnest allowable oxide is approximately 150Å. The failure rate in the first year is over 1000 FIT. If a higher cumulative failure (corresponding to a higher defect density) can be tolerated, a higher operating voltage or equivalently, a thinner oxide, can be used.

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 Figure 8a, after 10 hours of burn-in at 7V and 150°C, about 10% of the 155Å samples will fail while approximately 1% of the remaining population will fail in the 10-year lifetime at 5.5V and 125°C. The failure rate is approximately 100 FIT.

The above discussion is summarized in Figure 9. Figure 9a shows that with a 10-hour burn-in (7V, 150°C), the 155Å oxide studied here has a projected cumulative failure of 1% in 10 years for $1mm^2$ samples. Similarly, Figure 9b shows that with a 1-hour burn-in (5V, 150°C), the 84Å oxide has approximately 0.1% failure (1% failure) in 10 years for $1mm^2$ ($10mm^2$) samples.

SUMMARY

The intrinsic limit for a 10-year lifetime at 125°C is estimated to be 80Å for 5.5V operation and 50Å for 3.6V operation. Based on the defect-density model, a technique is demonstrated for projecting the minimum acceptable oxide thickness which satisfies reliability specifications. From the simple ramp-breakdown measurement, the defect distribution as a function of the severity of the defect is determined. The reliability of the oxides characterized by this defect distribution can be projected for any oxide area, operating voltage, and temperature. Using this technique, 150Å and 80Å oxide are found to be acceptable for operation at 5.5V and 3.6V (both at 125°C), respectively, for the oxide technology studied here. Oxides grown at another laboratory may well have lower acceptable minimum thicknesses. Future improvements in processing technology and silicon substrate quality will further lower the limit.

ACKNOWLEDGEMENTS

This research was partially sponsored by Texas Instruments, Signetics (under the MICRO program), and the Innovative Science and Technology Office of SDIO administered through the Office of Naval Research under contract N00014-85-K-0603. Dr. D. A. Baglee and Dr. J. W. McPherson of Texas Instruments contributed the data in Figure 2 [3], [4].

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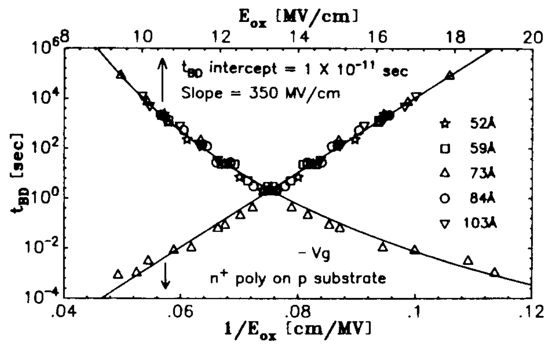


Figure 1. t_{BD} as a function of E_{ox} for different oxide thicknesses. According to this plot, lifetime should be extrapolated against $1/E_{ox}$ rather than E_{ox}. Oxides thicker than 100Å were not tested at these highly accelerated conditions due to deviation of the oxide current-voltage characteristics in the high-field regime from the Fowler-Nordheim theory [9].

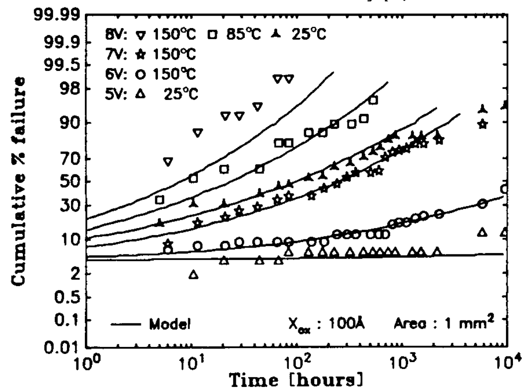


Figure 2. Time-dependent dielectric breakdown data for different temperatures and voltages down to 5V. The solid lines show the defect-density model prediction.

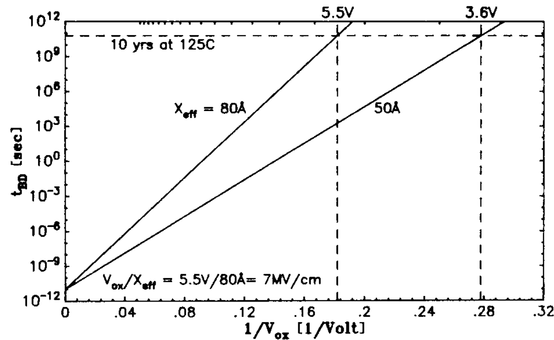


Figure 3. Theoretical curve for t_{BD} as a function of V_{ox}. Any combination of stress times (t_{BD}) and stress voltages above the X_{eff} = 80Å line (for 5.5V operation) and X_{eff} = 50Å line (for 3.6V operation) satisfies the 10-year lifetime requirement.

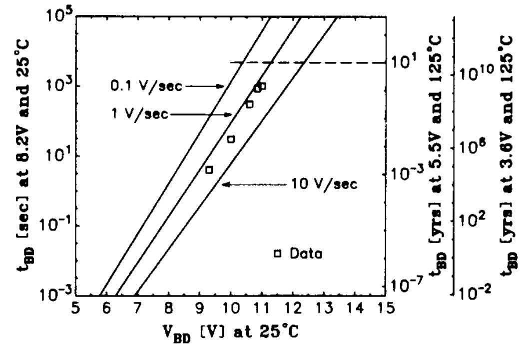


Figure 4. Correlation between t_{BD} and V_{BD}. The experimental data was taken at 8.2V (for constant voltage stress) and 1.0V/sec (for ramp voltage stress) for a 77Å oxide. Any combination of ramp-breakdown voltages and ramp rates above the dashed line satisfies the 10-year, 5.5V lifetime requirement.

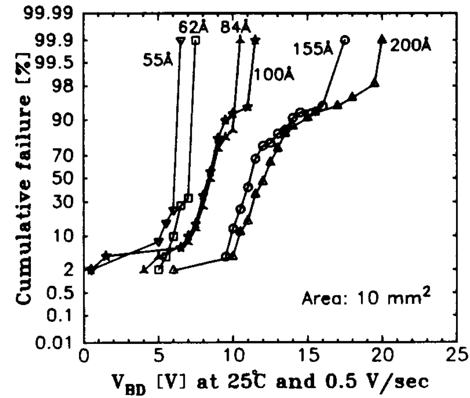


Figure 5. Cumulative failure ramp breakdown data for 10mm^2 oxide samples (n$^+$ polysilicon gate, p-type substrate, $-V_g$).

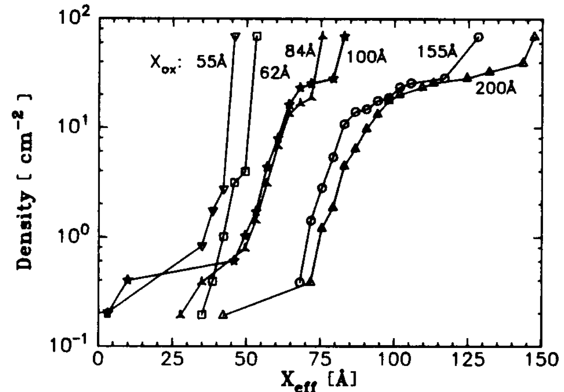
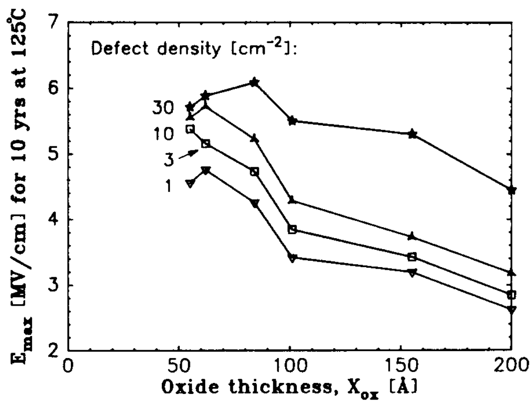


Figure 6. Distribution of defects as a function of X_{eff} for the oxide samples in Figure 5.



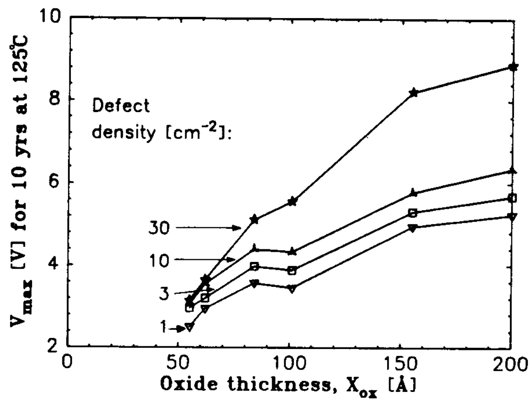


Figure 7. Maximum allowable a) oxide field and b) voltage versus X_{ox} for various defect densities.

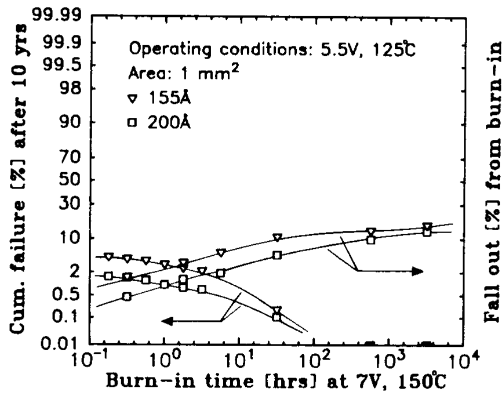


Figure 8a. The effects of burn-in time on projected reliability for 5.5V operation at 125°C. By selecting an optimum burn-in condition, the burn-in fallout can be minimized while improving the reliability.

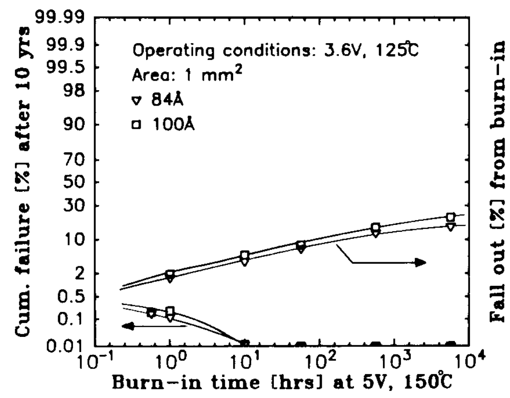
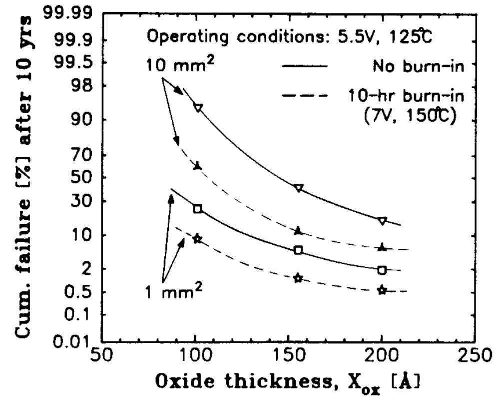


Figure 8b. The effects of burn-in time on projected reliability for 3.6V operation at 125°C.



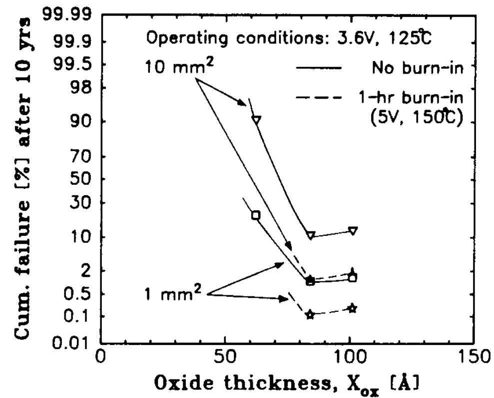


Figure 9. Oxide reliability comparison for a) 5.5V and b) 3.6V operation at 125°C. Note that, in 9b), all of the 62Å samples are projected to fail after 1 hour of burn-in.