Comparison of E and 1/E TDDB Models for SiO_2 under long-term/low-field test conditions

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Abstract

A low-field three-year TDDB study was undertaken to clearly understand which TDDB model, E or 1/E, describes the observed time-to-failure data better. The results are unambiguous and strongly suggest that the physics of failure is described much better by the E-model. This has important design-limit implications for thin gate oxides relative to the maximum electric field which can be allowed for reliable operation.

Introduction

Time-dependent dielectric breakdown (TDDB) is an important failure mode in deep-submicron CMOS technology. While performance goals drive a reduction in gate oxide thickness, reliability considerations such as TDDB limit the minimum oxide thickness to a value normally determined by accelerated stress testing. Therefore, choosing the correct physical model for analyzing the TDDB data in thin SiO_2 dielectrics is very important for developing both a highly reliable and competitive technology. The choice of the proper TDDB model for SiO_2 has been the subject of much recent debate. Low-field time-to-failure has been successfully described by the relation,

$$\ln(TF) \propto \frac{\Delta H_o}{k_b T} - \gamma E_{ox} \qquad (1)$$

where ΔH_o is the enthalpy of activation for oxide breakdown (usually referred to as activation energy), E_{ox} is the electric field in the oxide, k_B is Boltzmann's constant, and γ is the field acceleration parameter. This equation was first introduced as an empirical relation [1-3] but was later given a thermochemical foundation [4,5,13-16] and is commonly referred to as the "E-model." Others [6,7] have suggested that the breakdown process is current driven and, as such, ln(TF) should show a 1/E dependence due to Fowler-Nordheim (F-N) current conduction. This model is commonly referred to as the "1/E model." The E versus 1/E controversy has continued for many years due to the fact that either model can fit TDDB data rather well over limited field ranges. In order to clearly differentiate between the two models, TDDB data must be collected over a wide range of fields and, hopefully, even extending testing fields close to normal VLSI operating fields of approximately 5 MV/cm.

In this three-year TDDB study, we have taken data from 10MV/cm to approximately 5MV/cm in an effort to clearly understand what is the proper TDDB model. The data presented here shows that the E-model gives a much better fit to the data, particularly at present-day design electric fields ≤ 5 MV/cm. Further, while previous works [8-12] have also shown that the E-model presents a better fit than the 1/E-model to low field TDDB data, we show that by analyzing the field acceleration parameter, γ, it can be clearly shown that the 1/E-model does not produce a good fit to the data and it significantly overestimates the observed time-to-failure.

Growth Conditions and Experimental Procedure

The 90Å SiO_2 films were grown on p-type substrates with (100) orientation using standard RCA-type cleaning technology and 1% HF dip prior to oxide growth. The oxides were grown in dry O_2 at 900°C and 4% HCl was used during the growth to minimize incorporation of any unwanted metal impurities. A standard Poly-n+ electrode layer was added and the MOS test capacitors were fabricated using standard photolithography and dry etching techniques.

TDDB data was collected over a period of three years on 90Å SiO_2 p-well block capacitors. The

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capacitors, biased in accumulation mode, were stressed at two temperatures (150°C and 175°C) and over an applied electric field, E_G, range of 7 MV/cm to 11 MV/cm. The actual oxide electric field, E_{ox}, was calculated with a Poisson solver by accounting for voltage drops in both the n+poly and p-well silicon. E_{ox} ranged from 5.3 MV/cm to 9.3 MV/cm. The devices were continuously polled during the TDDB testing and failure was defined as due to an abrupt change in measured current leading to a hard/irreversible short in the dielectric from anode to cathode. This could be verified for the failing devices by applying a low voltage during failure analysis and confirming the existence of short.

Results and Discussion

In Figs. 1 and 2 we show log-normal plots for the three-year TDDB data collected at 175°C and 150°C, respectively. The data is well described by a log-normal distribution and the acceleration with field appears to be very uniform (i.e., the slopes of the distributions, sigma, of the various data sets are nearly constant which is generally indicative of uniform acceleration). In Fig. 3, we have plotted the lnTF(50%) data versus the electric field. The linear fit to the data is excellent with a correlation coefficient of 0.999 for the 175°C data set. Note that we have plotted the data versus E_G ($=V_G/t_{ox}$) and also in terms of E_{ox} ($=V_{ox}/t_{ox}$) where E_{ox} reflects the true electric field in the oxide (i.e., corrected for band bending in the poly-silicon and p-substrate). A comparison of the E and 1/E model fits to the 175°C TDDB data is shown in Fig. 4. The 1/E model is observed to be overly optimistic at the lower fields regions (i.e., closer to normal use conditions).

To further illustrate the poor correlation between the 1/E model and the long-term TDDB data, we have plotted in Fig. 5 the observed γ(T=175°C) as a function of field. According to the 1/E model, $TF = t_o(T) * \exp[G(T)/E_{ox}]$, gamma should exhibit a strong field dependence [6] given by:

$$\gamma \equiv -\left[\frac{\partial \ln(TF)}{\partial E_{ox}}\right]_T = \frac{G(T)}{E_{ox}^2} \qquad (2)$$

However, as shown in Fig. 5 we observe a field independent γ, as predicted by the E-model. This observation offers strong evidence that the 1/E model is not suitable for extrapolating TDDB data to low field (use) conditions.

In Fig. 6, the activation energy versus E_{ox} is plotted and no strong field dependence is observed and the average activation energy is approximately 0.85eV for fields between 6 MV/cm and 10 MV/cm. Such field-independent E_a behavior can be attributed to the mixing of multiple disturbed bonding states in these thin SiO_2 films [14] and is consistent with Suehle's work [8].

To further understand the reliability impact of proper TDDB lifetime model selection, the 175°C TDDB data has been extrapolated to a more realistic device temperature of 105°C (using the observed activation energy of 0.85eV) and a more realistic failure percentage of 0.1%. The extrapolated data was fitted to both the E and 1/E models in Fig. 7. Note that the maximum safe electric field prediction is quite different for the two models with more than three orders of magnitude difference in TDDB lifetime at typical operating electric fields.

Conclusion

In summary, we present a three-year TDDB study that shows that the E-model presents a much better fit to the data, particularly at design electric fields of ≤ 5 MV/cm. While previous investigations [8-12] have also indicated that the E-model gives a better fit to long-term/low-field TDDB data, this three-year TDDB study has shown that the electric-field dependence of γ is a much more useful parameter when comparing the two models and indicates clearly the poor fit of the 1/E model to the long-term/low-field TDDB data. The good fit of the E-Model to the low-field/long-term TDDB data suggests very strongly that it is field, not current, which causes the time-dependent degradation in the dielectric [16].

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Figures

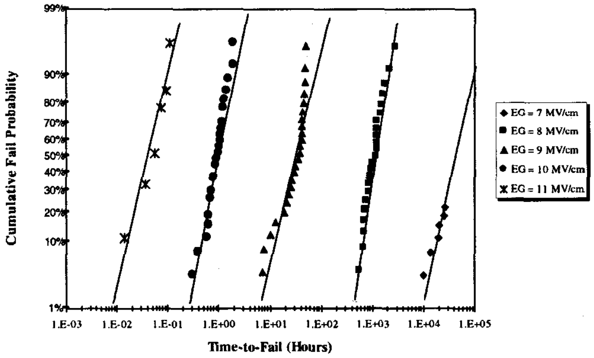

Fig. 1 TDDB Data at T=175°C

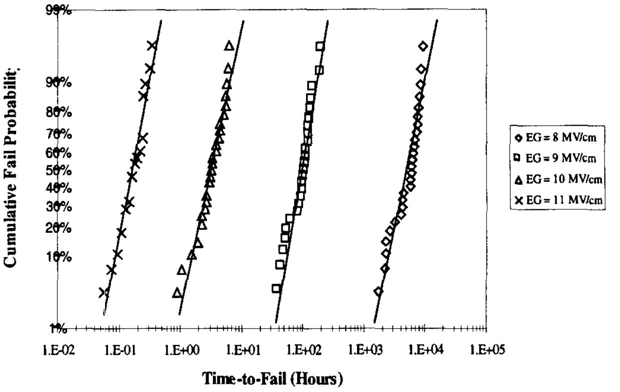

Fig. 2 TDDB Data at T=150°C

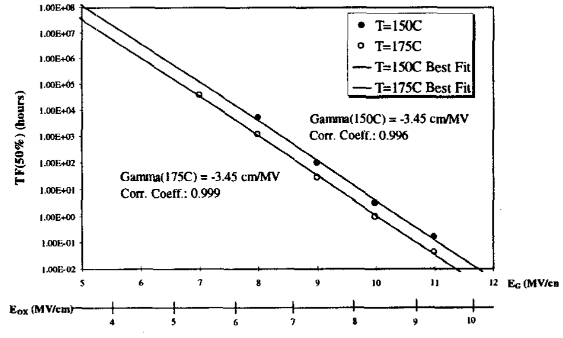

Fig. 3 TF(50%) vs Electric field at T=150°C and T=175°C.

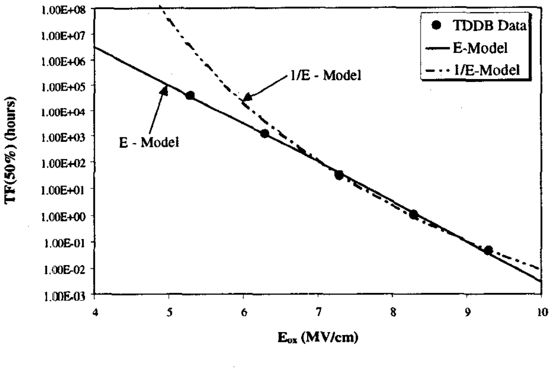

Fig. 4 Comparison of E-model and 1/E-model fit to T=175°C TDDB data.

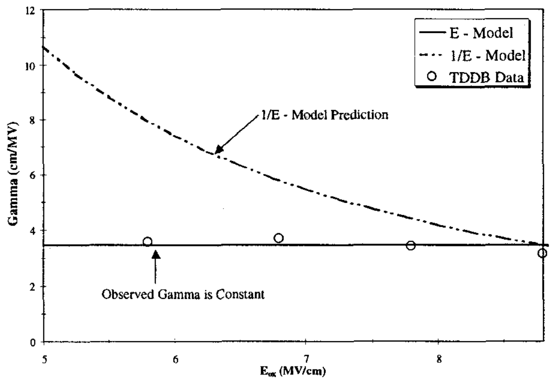

Fig.5 Comparison of Electric Field Acceleration Parameter, Gamma, dependence of E-Model and 1/E-Model.

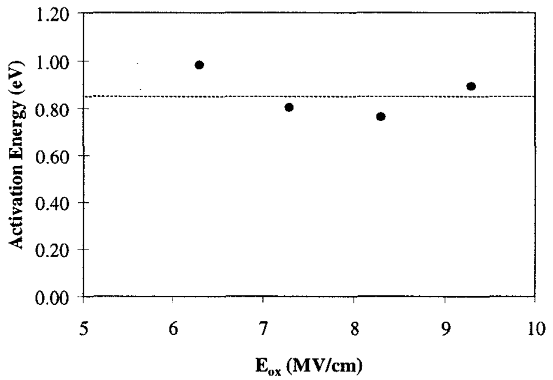

Fig. 6 Activation Energy versus E_{ox}

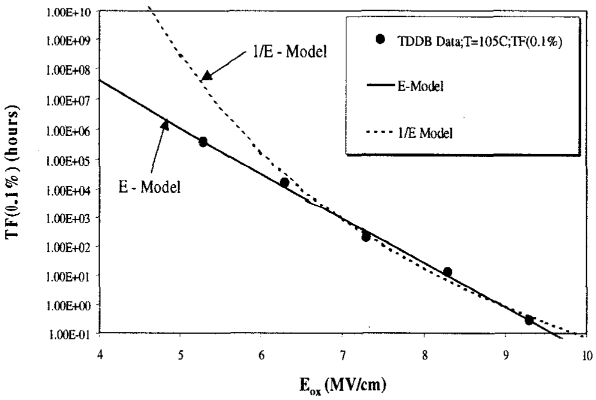

Fig. 7 Impact of TDDB lifetime model selection where the T=175°C data has been extrapolated to realistic conditions of T=105°C and TF(0.1%).