Letters

Field Dependence of Porous Low-k Dielectric Breakdown as Revealed by the Effects of Line Edge Roughness on Failure Distributions

S. C. Lee, A. S. Oates, and K. M. Chang

***Abstract*—We investigate the electric field (E) dependence of the breakdown of porous low-k dielectrics by measuring the changes in the failure time distribution resulting from the presence of line edge roughness. We show that the Weibull β increases with decreasing field, clearly demonstrating that dielectric breakdown does not exhibit $1/E$ or E^{-n} characteristics.**

***Index Terms*—Cu/low-k interconnect reliability, line edge roughness (LER), time-dependent dielectric breakdown (TDDB).**

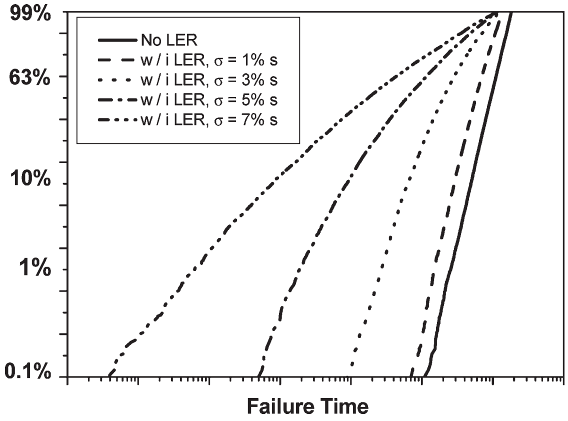

Fig. 1. Simulated failure time distribution of metal comb structures with different LER magnitudes ranging from $\sigma = 0\%$ s–7% s. Since all $f(E)$'s produce similar failure times at accelerated voltages, this choice is not critical to the estimation of the failure time distribution, and for convenience, we assume $f(E) = e^{-\gamma E}$, where $\gamma = 4$ (cm/MV). Details of the Monte Carlo simulation procedure are given in [15].

The reliability of Cu/low-k interconnects continues to be a concern due to the potential early breakdown of the dielectric as k is decreased because of its weaker intrinsic material breakdown strength [1]–[3]. With the continued scaling of interconnect dimensions, geometric variability due to line edge roughness (LER) complicates the reliability analysis and further reduces failure times [4]–[9]. One of the most important factors in determining the reliability of the dielectric is the field dependence of failure. Despite intense recent investigation, the field dependence has not been unambiguously determined, with E, $\sqrt{E}$, $1/E$, and E^{-n} (power law) models being proposed [1], [10]–[14].

The precise form of the E-field dependence has been proven difficult to quantify experimentally for two reasons. First and foremost, it is necessary to perform experiments at an extremely low field to distinguish unambiguously between the various models; such experiments take far too long to be practical. Second, we have recently shown that, for the most advanced process technologies, the LER impacts the apparent field dependence observed by experiment, leading to ambiguity in the interpretation of the experimental results [15]. However, the existence of LER offers a new avenue to determine the field dependence without the requirement of testing at an extremely low field. In this paper, we use the fact that LER gives rise to characteristic distortions of failure time distributions from the anticipated Weibull to investigate the field dependence of failure.

To understand the origin of the distortion in distribution shape resulting from LER, consider that, in its absence, the percolation theory indicates that failure times follow a Weibull distribution with the characteristic time given by [15]

$$t_{63} = t_0 (L/a_0)^{\frac{-1}{\beta_0}} f(E) \tag{1}$$

where t_0 and a_0 are the characteristic failure time and size of the unit cell, L is the length of the test structure, and $f(E)$ is the field dependence of failure time. Note that t_0 depends on the choice of $f(E)$. β_0 is the Weibull failure time dispersion

$$\beta_0 = (ms/a_0)\left[1 - (1+\alpha)P\right] \tag{2}$$

where m is a constant, P is the dielectric porosity, s is the thickness of the dielectric, and α is the size of the field extension of the pores. When LER is significant (standard deviation of dielectric thickness $\sigma > 3\%$ s), s cannot be approximated as a constant, and its statistical distribution must be considered when determining the failure times. To a good approximation, at the voltages typical of accelerated testing, failure occurs at the minimum dielectric thickness, $s_{\min}$ and $f(E) \sim f(V/s_{\min})$, where V is the applied voltage. Therefore, each point in a failure distribution is characterized by a unique $s_{\min}$. The distribution of $s_{\min}$ follows extreme value statistics [15], and consequently, there is a distortion of the failure distribution at high percentiles to longer failure times than predicted by (1) for constant s. Examples of such distortions in simulated distributions are shown in Fig. 1. With the increase of LER magnitude, the failure time decreases since lower values of $s_{\min}$ occur, and the failure distribution also becomes broader. For a given magnitude of the LER, the deviation from the Weibull depends on $f(E)$, and in principle, it is possible to determine $f(E)$ from measurements of these deviations.

Practically, the distortion of experimental failure distributions from the Weibull may be quantified in two ways. The first method simply involves approximating the experimental failure distributions as Weibull and determining β. Fig. 2 shows the dependence of β as a function of the E extracted from Monte Carlo simulations of failure distributions that were approximated as Weibull. β shows an increase with decreasing field for both the E and $\sqrt{E}$ dependences, while

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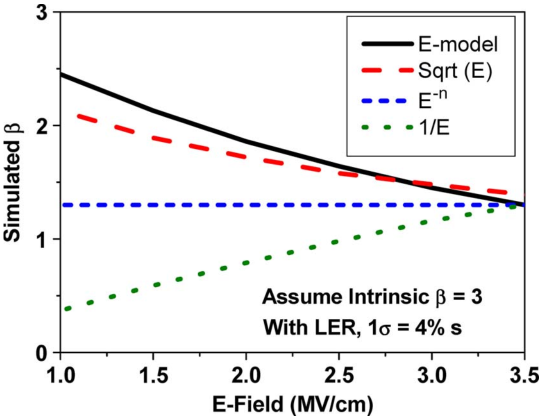

Fig. 2. Dependence of measured β on E for several $f(E)$'s. The field dependence arises because of the distortion of the failure distribution introduced by LER.

the $1/E$ field dependence leads to a decrease in β. A power law field dependence leaves β independent of E. The second method to characterize the distortions is more complex and requires knowledge of the $s_{\min}$ distribution to perform full statistical simulations of the failure distribution with a given $f(E)$. This presents no practical difficulty since $s_{\min}$ is given by the extreme value distribution of s, which itself is readily determined from electrical measurements routinely made in the manufacturing environment [15]. The simulated failure time distribution can then be directly compared with experimental data to determine $f(E)$. The simulation procedure, in principle, allows a more accurate estimate of $f(E)$ since all data in the failure distribution are used for evaluation compared to the measurements of β, which is defined using only two points on the failure distribution ($\beta \equiv (W_2 - W_1)/(\ln t_2 - \ln t_1)$ and $W \equiv \ln[-\ln(1-F)]$). In this paper, we shall use both methods to identify $f(E)$.

Experiments were performed using test structures consisting of either vias with adjacent upper level metal lines or simple metal combs. Test samples were fabricated using three different process technologies to avoid any systematic process issues that might skew the experimental data. Test structures exhibited nominal metal space in the combs of $s = 60$, 40, and 30 nm, corresponding to process technologies at the 45-, 28-, and 20-nm technology nodes, respectively. In all cases, an interlevel dielectric was used with $k = 2.5$. Damascene trenches were photolithographically defined in the dielectric followed by the deposition of a Ta-based liner, a Cu seed layer, and ECP Cu, CMP planarization, and passivation with a SiN-based dielectric. Wafers were processed with at least three layers of interconnect, and test samples were obtained from the second lowest metal level. The dielectric breakdown tests were performed at the wafer level to avoid any possibility of latent damage being introduced by packaging processes. Our experience has been that, for dielectric structures without protection circuitry, latent damage can occur that is sometimes impossible to observe from the initial characteristics of the devices before reliability testing. Avoiding latent damage in these experiments is particularly important since the effects of damage on dielectric breakdown are not known (e.g., acceleration factors, characteristic β, etc.). Testing was carried out at 125 °C using either constant voltage [time-dependent dielectric breakdown (TDDB)] or ramped voltage [voltage ramp dielectric breakdown (VRDB)] techniques. Data from either techniques are readily transformed into the other with knowledge of the field acceleration factors of breakdown [16], [17]. Failure was defined as an increase of a factor of ten in the leakage current for the TDDB and an increase of a factor of ten in the leakage current for the VRDB.

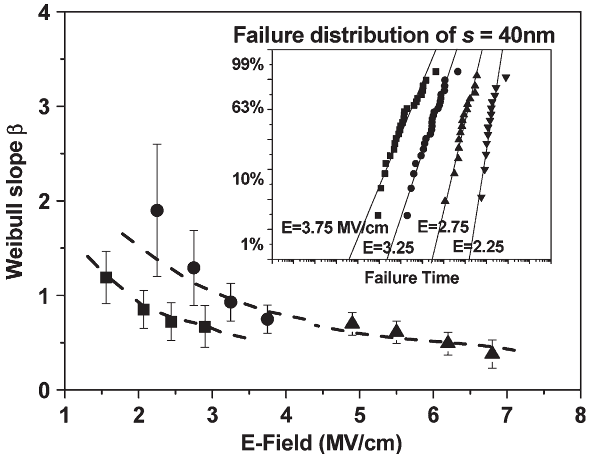

Fig. 3. Field dependence of the measured β (symbols) of metal comb structures for the $k = 2.5$ dielectric with nominal dielectric thickness $s = 60$, 40, and 30 nm. (square: $s = 60$ nm; circle: $s = 40$ nm; triangle: $s = 30$ nm). The dotted lines are β values calculated from simulated failure distributions, including LER effects, and assuming a $\sqrt{E}$ or E dependence of failure: Both field models produce β values that are indistinguishable in the range of these measurements. The inset is an example of experimental failure distributions for $s = 40$ nm.

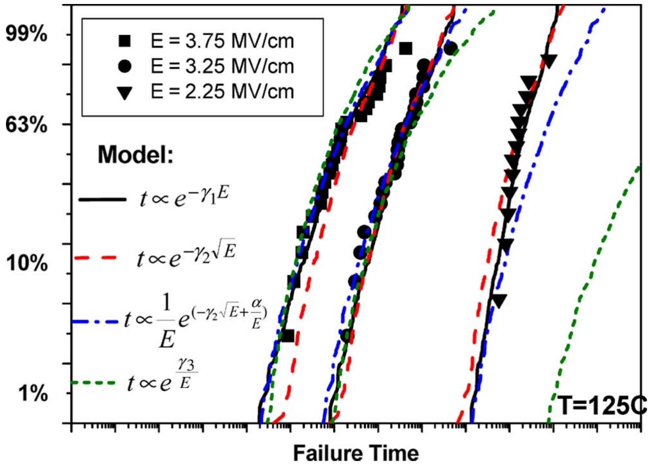

Fig. 4. Comparison of measured failure distributions with several $f(E)$'s. The E and $\sqrt{E}$ models provide best fits to the experimental data while the $1/E$ and impact damage models show significant deviations from the experimental data. The parameters used in each field model are $\gamma_1 = 3.7$ cm/MV (E model), $\gamma_2 = 15$ (cm/MV)$^{0.5}$ and $\alpha = 10$ MV/cm ($\sqrt{E}$ and impact damage models), and $\gamma_3 = 140$ cm/MV ($1/E$ model).

The inset of Fig. 3 shows a typical example of experimental failure distributions as a function of the stress voltage for a metal comb with a 40-nm nominal space. With the relatively small sample sizes of these experiments, the distortion of the distribution from the Weibull is not obvious, and linear fits are good approximations. It is clear that β exhibits an increase as E is decreased. Similar results were obtained from all three process technologies, and Fig. 3 summarizes the field dependence of the measured β. Comparing Figs. 2 and 3, it is clear that the breakdown of the porous low-k dielectric is consistent with either E or $\sqrt{E}$ as the dominant field functionality, $1/E$, and power law behavior can be excluded.

To attempt to further differentiate between the E and $\sqrt{E}$ models, we compared the simulations with the experimental failure distributions. Fig. 4 shows that the simulation fits to the experimental data are excellent for both E and $\sqrt{E}$ for all bias conditions used in this paper for a dielectric thickness of $s = 40$ nm. We also calculated the

β values of the simulated distributions for all dielectric thicknesses, and these are also plotted in Fig. 3. The simulations accurately reproduce the increase of β with decreasing field, but unfortunately, identical β results are obtained for both models in the range of our measurements. Additional simulations (not shown here) suggest that fields below 1.5 MV/cm or VRDB ramp rates $< 10^{-6}$ V/s are required to unambiguously resolve differences between the E and $\sqrt{E}$ models.

Also included in Fig. 4 are the simulations performed assuming that $f(E) = e^{(-\gamma\sqrt{E}+\alpha/E)}$. This functionality arises when breakdown occurs by the formation of defects that are created by the impact of energetic electrons with the constituent atoms of the dielectric [12], [13]. The parameters γ and α are not arbitrarily determined from the fitting of experimental data but are material constants. γ is determined by the current conduction mechanism (Frenkel–Poole or Schottky) of the dielectric and is identical to the field acceleration parameter of the $\sqrt{E}$ model, while $\alpha = E_{\mathrm{th}}/e\lambda$, where E_{th} is the threshold energy required to create damage, e is the electronic charge, and λ is the electron mean free path. The nature of the defect involved in the breakdown process is unknown, but assuming E_{th} is equivalent to the bonding energy, then α can be estimated to be in the range of 10–15 (MV/cm) for the Si–H, Si–C, and Si–O bonds (bonding energy ranges from 3.2 to 4.7 eV) with $\lambda \sim 3$ nm for fused silica [18], [19]. In Fig. 4, it can be seen that, with $\alpha = 10$ MV/cm, the model fit to the data is poor, and the fit becomes much worse as α is increased (not shown here). A value of $\alpha = 5$ MV/cm is required to obtain reasonable agreement with our experimental data, but it is unclear how such a low value could arise on the basis of bonding energies in the dielectric. Without additional support for such low values of α, the validity of this model of failure is questionable.

Our results for the field dependence of β are at variance with those of Croes and Tokei [20], who observed a decrease of β with decreasing field and a field functionality of failure close to $1/E$. The cause of the discrepancy between studies is not known at the present time but could be related to the use of packaged devices for testing. Moreover, the presence of LER was not explicitly considered in the latter study, which introduces ambiguity in the interpretation of the measured field dependence of the failure time [15].

In summary, we have used measurements of changes in the shape of the failure time distribution resulting from LER to investigate the field dependence of the breakdown of porous low-k dielectrics. We find a systematic increase of the Weibull β with decreasing field, independent of process technology. Our results clearly show that a dominant $1/E$ or E^{-n} component to the field dependence of failure is not consistent with observations, indicating that the breakdown must be determined by an E or $\sqrt{E}$ field functionality. We are unable to unambiguously distinguish between the E and $\sqrt{E}$ models because of the relatively high fields used in our experiments. However, our work suggests that, for dielectric thicknesses associated with the most advanced process technologies, it may be feasible to use this technique to clearly determine the field dependence of dielectric breakdown.

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