Modified Weakest-Link Load-Sharing Model and Its Application to the Breakdown Process of High-κ Gate Dielectrics

David Han*

Abstract

In this work, a new probabilistic model is developed for the breakdown lifetime of high-κ gate dielectrics of a semiconductor under unipolar AC voltage stress. Assuming that the gate oxide layer is composed of a large number of potential breakdown cells, this model is derived based on the finite weakest-link model with a load sharing characteristic. Each potential breakdown cell is modeled as a series coupling of several sub-cells, which is analogous to the fiber bundle model for the strength statistics of material/structures. As in the previous engineering studies in this regard, the new model also shows that the dependence of the mean time to failure on the gate area deviates from the classical Weibull scaling law. Most importantly, it is demonstrated that the newly proposed model agrees better with the observed lifetimes of HfO_2-based gate dielectrics under unipolar AC voltage stress, providing a new insight into the failure process of a high-κ gate dielectrics in the risk management perspectives.

Key Words: dielectrics failure, finite weakest-link model, load-sharing model, step-stress ALT, Weibull scaling law

1. Introduction

The modern electronic age was born with Si-based CMOS FET. A transistor is a fundamental building block of semiconductor products such as the advanced microprocessors and memory. According to Moore's scaling law, performance of CMOS devices has continued to improve over half a century. The problem is that scaling of CMOSFET has resulted in an ultrathin layer ($t_{ox} < 2$ nm) of SiO_2 used as a gate dielectric. This makes the leakage current too high, which would increase its breakdown or failure rate. In order to reduce the leakage current and to increase the gate capacitance, a physically thicker oxide layer with higher relative permittivity, known as the dielectric constant κ has been investigated to replace the conventional SiO_2 native dielectrics. In this work, we aim to close the theoretical and practical gap of the current models for describing the breakdown distribution of a gate dielectric of specified dimensions under voltage stress. Through the convolution of pre/post-breakdown processes, this constructs a single, seamless probabilistic model of breakdown without any mathematical lapse, still obeying the power law at lower percentiles asymptotically. This new model is named as *the augmented finite weakest-link load-sharing model*. It provides consistent and cohesive explanation of the key features of the metal oxide breakdown of a semiconductor. The proposed model fits the dielectric breakdown data very well with or without presence of a suspected kink in Weibit plots.

2. Model Formulations

Here we construct the finite weakest-link model for SBD, using Weibull/exponential lifetimes for subcells under the equal load-sharing regime. This provides an explicit formulation for the lifetime of SBD. Then, the lifetime distribution for HBD is derived analytically via the convolution of the SBD lifetime and the residual time from I_g distribution. It potentially extends the overall lifetime of a semiconductor in a significant degree, resulting

---

[*] Department of Management Science and Statistics, University of Texas at San Antonio, TX 78249

in improved reliability as well as tremendous cost savings. Linder, et al. (2002) quantified the HBD evolution by the degradation rate (amperes/s) of the gate current I_g. It was found out that I_g increases at an exponential rate, independent of the device area and channel dopant type but highly dependent on the gate voltage V_g and the oxide thickness t_{ox}. That is, thinner oxides degrade more rapidly at the same voltage stress. As the current evolution is non-monotonic, Wiener process is found appropriate for describing the log-transformed I_g. Therefore, the residual time till HBD is modeled by an inverse Gaussian distribution. This indeed provides satisfactory explanation for the kinks observed on the Weibit plots.

Adopting the formulation of the lifetime distribution for a step-stress accelerated life test (ALT), the CDF and PDF of the lifetime under a step-stress ALT are given by

$$\begin{aligned} F(t) &= 1 - \exp\left(- \left(\frac{t-\tau_{i-1}}{\theta_i} + \sum_{l=1}^{i-1} \frac{\Delta_l}{\theta_l} \right)^{\alpha} \right), && \tau_{i-1} < t \leq \tau_i, \\ f(t) &= \frac{\alpha}{\theta_i} \left(\frac{t-\tau_{i-1}}{\theta_i} + \sum_{l=1}^{i-1} \frac{\Delta_l}{\theta_l} \right)^{\alpha-1} \exp\left(- \left(\frac{t-\tau_{i-1}}{\theta_i} + \sum_{l=1}^{i-1} \frac{\Delta_l}{\theta_l} \right)^{\alpha} \right), && \tau_{i-1} < t \leq \tau_i. \end{aligned}$$

Naturally, the maximum order statistic $T_{(n)}$ denotes a cell lifetime. When $\alpha = 1$, its CDF is derived as

$$F_{cell}(t) = \sum_{i=1}^{n} C_{i:n} F_i\big((n-i+1)t\big), \tag{1}$$

where

$$C_{n-i+1:n} = \prod_{\substack{l=1 \\ l \neq i}}^{n} \left[1 - (l/i)^{\rho-1} \right]^{-1},$$

adopting the results from Balakrishnan and Han (2007) along with the equal load sharing applied to the inverse power law $\log \theta_i = \log \theta_0 - \rho \log \left(\frac{V_g}{n-i+1} \right)$. Since $\sum_{i=1}^{n} C_{i:n} = \sum_{i=1}^{n} C_{n-i+1:n} = 1$, it follows that the CDF in (1) simplifies to

$$F_{cell}(t) = \sum_{i=1}^{n} C_{i:n} \left(1 - e^{-(n-i+1)t/\theta_i} \right) = 1 - \sum_{i=1}^{n} C_{i:n} e^{-(n-i+1)t/\theta_i}$$

and the cell reliability at t is defined as $S_{cell}(t) = 1 - F_{cell}(t)$. Subsequently, using the weakest-link mode, the CDF of SBD is obtained to be

$$F_{SBD}(t) = 1 - \left[S_{cell}(t) \right]^N = 1 - \left[\sum_{i=1}^{n} C_{i:n} e^{-(n-i+1)t/\theta_i} \right]^N .$$

Now, let T_{SBD} be the time till SBD as all SBD eventually leads to the catastrophic physical failure HBD. Also, let T_{inter} be the time till HBD. Then, $T_{HBD} = T_{SBD} + T_{inter}$ for any given cell, and acknowledging the temporal and spatial independence of T_{inter} from T_{SBD}, the CDF of T_{HBD} can be expressed as

$$F_{HBD}(t) = \int_0^t f_{SBD}(u)\, F_{inter}(t-u)\, du$$

and

$$S_{HBD}(t) = S_{SBD}(t) + \int_0^t f_{SBD}(u)\, S_{inter}(t-u)\, du = S_{SBD}(t) + \xi(t),$$

where $S_{SBD}(t) = 1 - F_{SBD}(t)$ and $S_{inter}(t) = 1 - F_{inter}(t)$. Note that $\xi(t)$ is a non-negative function with $\lim_{t \to 0} \xi(t) = \lim_{t \to \infty} \xi(t) = 0$. Based on the previous formulation, we have

$$f_{cell}(t) = \frac{d}{dt} F_{cell}(t) = \int_0^t \cdots \int_0^{t_{(3)}} \int_0^{t_{(2)}} f(\boldsymbol{t})\, dt_{(1)} dt_{(2)} \cdots dt_{(n-1)} \bigg|_{t_{(n)}=t}.$$

It can be seen that $\xi(t)$ is essentially the simplex integration with the same $(n+1)$ vertices and the integrand changed to $f(\boldsymbol{t})\, S_{inter}(t-u)\Big|_{t_{(n)}=u}$. Based on the weakest-link model, the distribution of the overall failure time of a dielectric T is

$$F(t) = 1 - S(t) = 1 - \left[S_{HBD}(t)\right]^N = 1 - \left[S_{SBD}(t) + \xi(t)\right]^N,$$

indicating that no cells should experience a catastrophic failure if the dielectric is still operational at time t. With the property of $\xi(t)$, we can see that as $t \to \infty$, $F(t) \approx 1 - \left[1 - F_{cell}(t)\right]^N$, and thus, $F(t)$ converges to the conventional weakest-link model considered by Le (2012) at the extreme right tail of the distribution.

3. Model Interpretation & Application

Under this framework, the Weibit of the model is obtained to be

$$W(t) = \log\left(-\log\left(1 - F(t)\right)\right) = W_{WL}(t) + D(t),$$

where

$$W_{WL}(t) = \log\left(-N \log\left(1 - F_{cell}(t)\right)\right)$$

is the Weibit of the conventional weakest-link model, linear in $\log t$ (especially at the left tail). The deviation term is

$$D(t) = \log\left(\frac{\log\left(S_{cell}(t) + \xi(t)\right)}{\log\left(S_{cell}(t)\right)}\right) \leq 0$$

since $0 < S_{cell}(t) \leq S_{cell}(t) + \xi(t) < 1$. It is noted that $\lim_{t \to \infty} D(t) = 0$.

Extensive efforts have been devoted to modeling the lifetime of high-κ dielectrics under both constant and unipolar AC voltage stresses. Kim and Lee (2004) presents the comprehensive breakdown data of HfO_2-based high-κ gate dielectrics with the area $A = 4 \times 10^{-4}$ mm^2 and the oxide thickness of $t_{ox} = 4.8$ to 5 nm (or $EOT = 1.4$ nm) at $V_g = 2.9V$. Their experimental results inferred that based on the minimum spacing, the effective size of these defects is about 1.5 nm, implying that the lower tail of the Weibit has a shape parameter of 5, which is the number of subcells. For TBD under the cyclic loading, the curvature in the Weibit plots indicates that the asymptotics of the conventional chain-of-bundles does not hold even though there are $N = 4,000,000$ bundles in the chain; see Figure 1. It was demonstrated that the proposed model provides superior fits to the observed lifetimes under any voltage loading.

4. Concluding Remark

Here we developed a new probabilistic model for the breakdown lifetime of high-κ gate dielectrics of a semiconductor under voltage stress based on the finite weakest-link model with a load sharing characteristic. It is achieved via the convolution of pre/post-breakdown

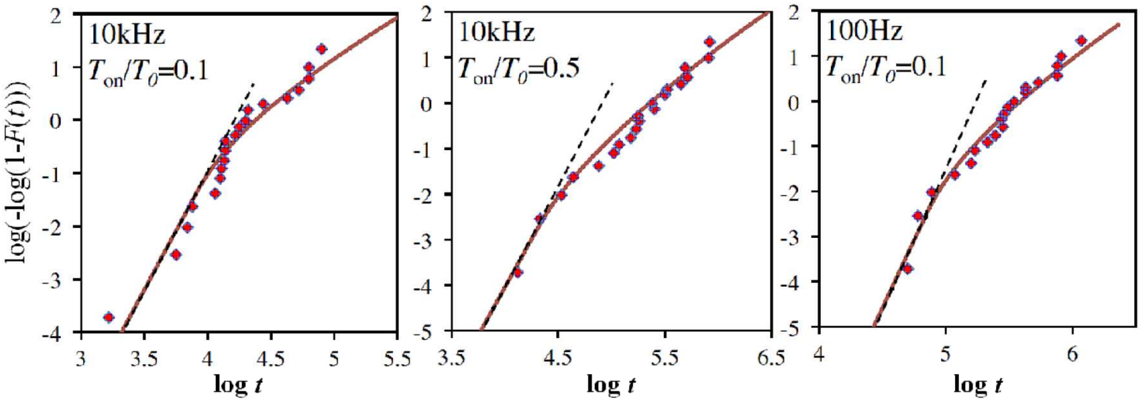

Figure 1: Weibit plots with the optimal fits at $V_g = 2.9V$

processes, explaining the dependence of the mean time to failure on the gate area, deviating from the classical Weibull scaling law. It provides better fits to the observed lifetimes of HfO_2-based gate dielectrics under voltage stress. It provides a new insight into the failure process of a high-κ gate dielectrics in the risk management perspectives. It also provides the extra reliability margin associated with the tolerance (or delayed failure) of MOS devices and circuits to the gate oxide breakdown. Since the chip reliability is governed by total leakage current or power dissipation, the work is directly applicable for the assessment of chip reliability.

REFERENCES

Balakrishnan, N. and Han, D. (2007). Optimal progressive Type-II censoring schemes for nonparametric confidence intervals of quantiles. *Communications in Statistics – Simulation and Computation*, **36:** 1247–1262.

Bazant, Z.P. and Le, J.L. (2017). *Probabilistic Mechanics of Quasi-brittle Structures: Strength, Lifetime, and Size Effect.* Cambridge, UK: Cambridge University Press.

Kim, Y.H. and Lee, J.C. (2004). Reliability characteristics of high-κ dielectrics. *Microelectronics Reliability*, **44:** 183–193.

Le, J.L. (2012). A finite weakest-link model of lifetime distribution of high-κ gate dielectrics under unipolar AC voltage stress. *Microelectronics Reliability*, **52:** 100–106.

Linder, B.P., Lombardo, S., Stathis, J.H., Vayshenker, A., and Frank, D.J. (2002). Voltage dependence of hard breakdown growth and the reliability implication in thin dielectrics. *IEEE Electron Device Letters*, **23:** 661–663.