Statistical Analysis of Lifetimes of MIM Capacitors with Monte Carlo Simulation

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Abstract

The accuracy of the lifetime of MIM capacitors measured by the ramp-voltage method has been analyzed by Monte Carlo simulation. The uncertainties associated with the sample size, variation of lifetime distribution, voltage step size, and voltage sourcing error, have been evaluated by simulation. The quantitative results presented in this work can provide a guideline for choosing appropriate measurement parameters for accurate and efficient lifetime evaluation using the ramp-voltage method.

INTRODUCTION

Determining the right sample size is critical in reliability testing in order to be cost-efficient without limiting the ability to draw meaningful conclusions. One needs to understand the sources of uncertainties in a reliability estimation approach when trying to minimize time consumption. Achieving such information by collecting sufficient empirical data is in many cases not practical. Simulation, on the other hand, is an efficient and effective approach to shed light on expected outcomes of experiments under certain preset conditions. This paper presents quantitative understanding of the potential uncertainties associated with the ramp-voltage method [1, 2], which is popularly utilized to assess the reliability of metal-insulator-metal (MIM) capacitors due to its testing speed, through Monte Carlo simulation.

The reliability of MIM capacitors, an indispensable element of monolithic microwave integrated circuits (MMIC), is as important as that of transistors. The intrinsic failure of MIM capacitors is characterized by time dependent dielectric breakdown (TDDB). The breakdown voltage of dielectrics depends on the prior history of bias conditions, i.e. the ramp rate in the ramp-voltage method [2]. There have been many literature reports [2-11] about experimental work using this method, but theoretical study of the associated uncertainties is limited. This work investigates the uncertainties induced by the sample size, uniformity of the capacitors, voltage step size and sourcing error, using Monte Carlo simulation. The results presented in this work can provide a guideline for choosing appropriate measurement parameters to improve the confidence of lifetime estimation.

SIMULATION METHODOLOGY

MIM capacitor lifetime (*t*) is dependent on the applied electric field (*E*). The field dependence is widely described by two major models: the linear field model where $t \propto \exp(-\gamma E)$ and the reciprocal field model where $t \propto \exp(G/E)$. In the lifetime expressions, γ and G are the field acceleration factors for the linear and reciprocal field model, respectively. The linear field model is often found to be more conservative and practical in evaluating MIM capacitors, while the predicted lifetime by the reciprocal field model can be too long to be physically reasonable [3, 4]. Therefore, the linear field model is widely adopted over reciprocal field model. Additionally, the ramp-voltage method relies on the application of the linear field model.

In a ramp-voltage test, a number of samples are tested with two ramp rates. Then, the field acceleration parameter and lifetime distribution at operating voltage are extracted. The obtained values are assumed to represent the whole population. The simulation procedure is designed to mimic the testing process. A population of MIM capacitors is assigned with a preset lognormal lifetime ($t_{V_{op}}$) distribution [3] at operating voltage (V_{op}). Default parameter values are the following unless otherwise noted: median time to failure MTTF = 10^{10} h at V_{op} = 50 V, lognormal standard deviation σ = 0.3, field acceleration parameter γ = 35 nm/V, dielectric film thickness h = 400 nm, voltage step ΔV = 0.25 V and ramp rate R = 1 and 0.1 V/s. These are typical values reported for SiN_x based MIM capacitors in literature [3, 4]. An operating voltage of 50 V is assumed considering high voltage GaN HEMT applications. A number of samples are randomly drawn from the population and the corresponding distributions of breakdown voltage (V_{br}) of the two ramp rates are calculated using the theory presented in ref. [1]:

$$t_{V_{op}} = hR/\gamma \cdot e^{-\gamma(V_{op}-V_{br})/h} \quad (1)$$

Then an average γ is extracted from the two V_{br} distributions following the method presented in ref. [2]:

$$\gamma = h\frac{\ln(R1/R2)}{V_{br1}-V_{br2}} \qquad (2)$$

A projected lifetime distribution (t_{Vop}) at V_{op} is subsequently back-calculated using equation (1). In the ideal case, the extracted γ and t_{Vop} should match the preset values. Deviations are expected depending on the sample size (n) drawn from the preset population, variation of lifetime distribution (σ), voltage step (ΔV), and voltage sourcing error (V_{Err}). All of these factors will be addressed in this work.

Fig. 1 (a) shows simulated V_{br} distributions for two ramp rates with 1000 samples randomly drawn from the preset population. The extracted γ is 34.9 nm/V which is close to the preset value. A $t_{V\mathrm{op}}$ distribution is projected from each of the two V_{br} distributions and the two projected lifetime distributions converge into one single distribution, overlapping the preset distribution, as shown in Fig. 1 (b). The close match between the extracted lifetime and the preset lifetime distributions shows that the simulation methodology is self-consistent. To investigate the uncertainty induced by a factor (n, σ, ΔV, V_{Err}), the simulation procedure is repeated for 100 times to check the variations of the extracted parameters in comparison with the preset values.

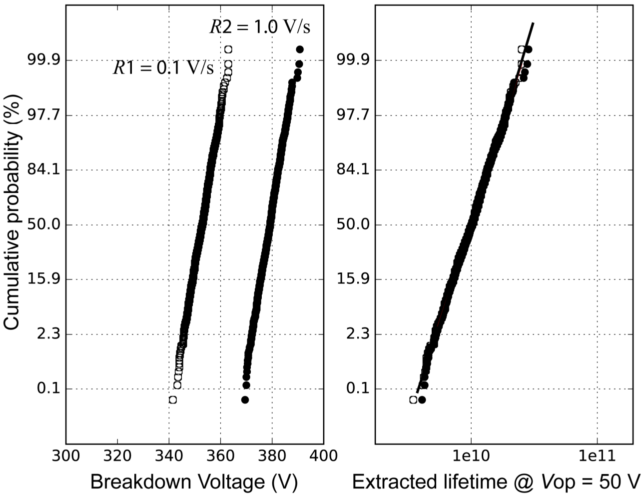

Fig. 1. Probability plots of: (a) the simulated breakdown voltage distributions for two ramp rates and (b) the projected lifetime distributions (symbols) with the preset distribution (solid line).

RESULTS AND DISCUSSION

A. Sample Size

It is expected that the larger the sample size, the lower the measurement uncertainty. In the literature reports, sample sizes range from 50 to 1000 [3, 4, 11], often being limited by practical testing time. Part of the uncertainty in the lifetime estimation comes from the limited sampling not fully representative of the entire population. Monte Carlo simulation was carried out for various sample sizes. For each sample size, the simulation was repeated for 100 times to study the distributions of the extracted MTTF and γ which are shown in box plots in Fig. 2. In all the box plots presented in this work, the bar within a box, the lower/upper edge of the box and the lower/upper whisker denote the median value, $1^{\mathrm{st}}/3^{\mathrm{rd}}$ quartile and the maximum/minimum value within 1.5 IQR (interquartile range) of the $1^{\mathrm{st}}/3^{\mathrm{rd}}$ quartile. The outliers are excluded in the plots due to their statistical insignificance. It is no surprise to see uncertainty reduction with increasing sample size as shown in Fig. 2, but the value of simulation is in its capability of providing *quantitative* information about the magnitude of the uncertainty. For instance, with a sample size of 100 and σ of 0.3, the real MTTF is very unlikely to be below 1E9 h if the extracted MTTF is 2E10 h. Figure 2 also shows that the spread of the extracted MTTF can be more than an order for n = 20 and reduces to a range of 5 times for n = 100 and 2 times for n = 500.

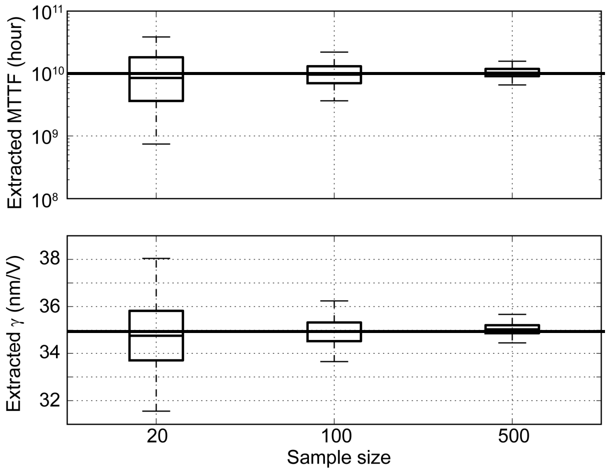

Fig. 2. Variations of extracted MTTF and γ for different sample sizes.

B. Variation of Lifetime Distribution

The intrinsic uniformity of the MIM capacitors under test is also a factor affecting the uncertainty of the extracted lifetime. Since MIM capacitor lifetime generally follows log-normal distribution, the standard deviation of its natural logarithm is chosen as the parameter to quantify the uniformity of the whole population. In order to investigate the influence of σ on the uncertainty of the extracted MTTF, the preset σ is varied from 0.1 to 1 in the Monte Carlo simulation. Given that σ is generally reported to be around 0.3 [3, 4], the variation range in the simulation should be sufficient to cover what could be encountered in practice.

Shown in Fig. 3 are box plots of the ratio of the extracted σ (σ_{e}) to the preset σ (σ_{p}). It is no surprise that the deviation of σ_{e} from σ_{p} reduces with smaller σ_{p} and larger sample size. For n = 500, the uncertainty of the extracted σ is within 10% of the preset σ regardless of the magnitude of the preset σ. Similarly, the accuracy of the extracted MTTF with a certain sample size depends on σ as well, as shown in Fig. 4. As expected, the uncertainty of the extracted MTTF decreases monotonically as σ decreases for all sample sizes. The variation can be significant especially when the sample size is small. For n = 20, the extracted MTTF can vary in almost 6 orders of magnitude when σ = 1.0, from 10^7 to above 10^{11} h. On the other hand, for σ = 0.1, even a small sample size of 20 can generate a pretty tight distribution of the extracted MTTF, while n has to be increased to 500 to achieve the same MTTF spread for σ = 0.3. For a quick estimate, one can start with n = 100 and get an estimate of σ. The final sample size can then be determined based on the extracted σ and the requirement of the expected MTTF accuracy. Figure 3 also shows that σ_e provides a rather accurate estimation of σ_p (< ±20% in error) when the sample size is as large as 100.

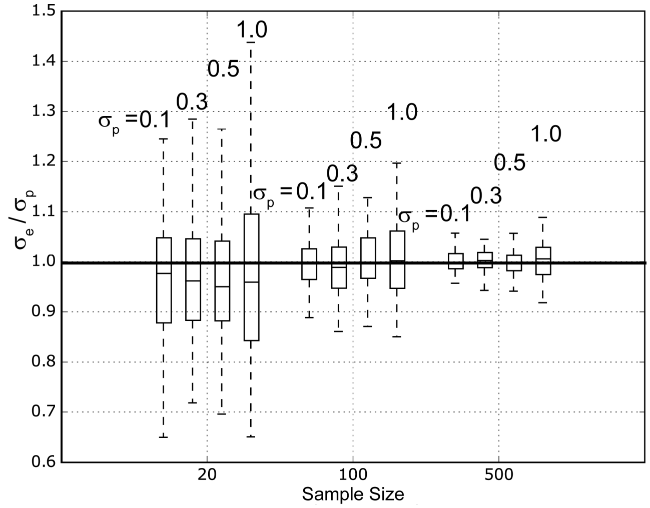

Fig. 3. The ratio of the extracted σ (σ_e) to the preset σ (σ_p) for different preset σ and sample sizes.

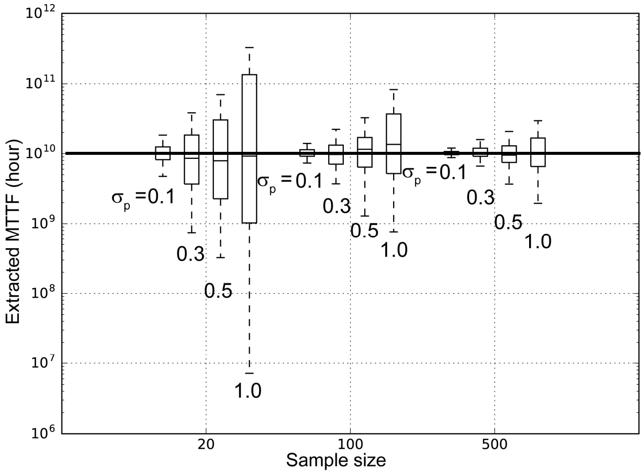

Fig. 4. Variations of extracted MTTF for different preset σ (σ_p) and sample sizes.

C. Voltage Step Size

The voltage step size is another source of inaccuracy. Larger ΔV is alluring in speeding up the test but a large ΔV may violate the assumption ($\gamma \bullet \Delta V/h \rightarrow 0$) made in deriving equation (1) and (2) used in the ramp-voltage method [1, 2]. The extracted MTTF and σ for different ΔV are shown in Fig. 5 for different ΔV. In the simulation, the voltage step is varied from 0.25 V to 5 V while the time intervals are 0.25 s and 2.5 s for each ΔV to get the two ramp rates needed in a ramp-voltage test. A sample size of 200 is used for simulations of all voltage steps. With increasing ΔV, the medians of extracted values deviate more and more from the preset values, but the variation range remains similar. Thicker dielectric films (400 nm in this work) have more tolerance of larger ΔV. It is worth noting that although the extracted MTTF spread does not degrade quickly with increasing the voltage step size, ΔV practically determines the resolution of measured V_{br} - large ΔV can distort the V_{br} distribution and thus lifetime distribution.

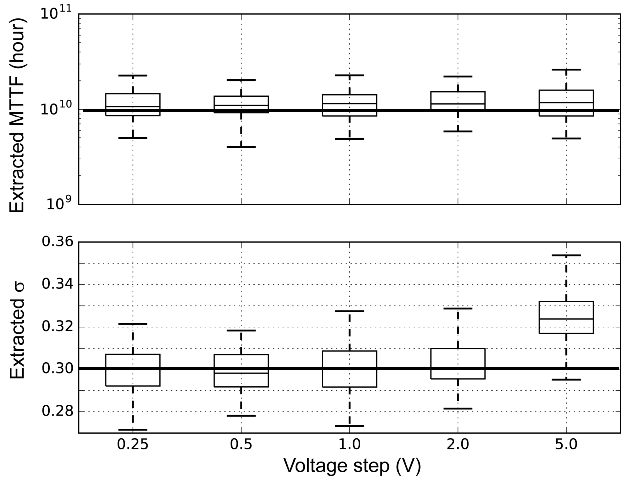

Fig. 5. Variations of extracted MTTF and σ for different voltage step sizes.

D. Voltage Sourcing Error

MIM capacitors designed for operating at 50 V or above usually contain dielectric films thicker than 300 nm with V_{br} > 300 V, requiring high voltage source meters. The sourcing resolution in the high voltage mode can be nontrivial compared with ΔV. The effect of random voltage error is simulated and shown in Fig. 6. The lateral spread in Fig. 6 is randomly added to improve the readability of the plot. In the simulation, the voltage sourcing error is assumed to have a uniform distribution within [-0.2, 0.2] V and a voltage error randomly picked from the range is assigned to each voltage step. It can be seen from Fig. 6 that the observed influence is minimal. The reasons are two folds. First, errors of opposite signs tend to cancel the effect of each other. Second, the weight of the time interval (Δt) at a certain voltage V in the total lifetime at V_{br} is determined by $\exp[\gamma\bullet(V-V_{br})/h]$ according to ref. [1]. Therefore, the error due to V_{Err} is determined by a factor of $\exp(\gamma\bullet V_{Err}/h)$. For $V_{Err} = 0.2$ V, the error induced in the extracted lifetime is less than 2% for $\gamma = 35$ nm/V and $h = 400$ nm assumed in this work. The reported values of γ and h range from 30 to 45 nm/V and 50 to 400 nm respectively [2-11] for SiNx based MIM capacitors, leading to a high end value of ~ 0.9 V^{-1} for the ratio of γ/h. Even for this high end number of γ/h, the uncertainty induced in the lifetime by V_{Err} is only 20%, far below the variation caused by other factors such as sample size and standard deviation.

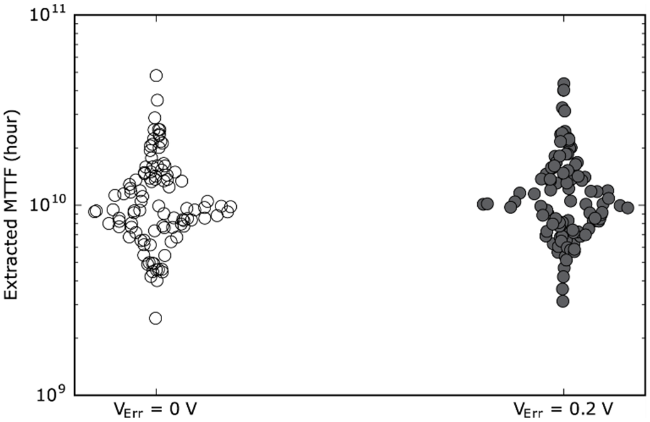

Fig. 6. Comparison of extracted MTTF with and without random voltage sourcing errors.

CONCLUSIONS

Monte Carlo simulation has been carried out to quantitatively understand the uncertainty in the lifetime of MIM capacitors evaluated by the ramp-voltage method. The uncertainties associated with the sample size, variation of lifetime distribution, voltage step size, and voltage sourcing error, have been evaluated. The uncertainty of the extracted lifetime is shown to be dependent mainly on the sample size and the intrinsic uniformity of the fabricated MIM capacitors, while the voltage step size and sourcing error exhibit insignificant impact. The quantitative information shown in this work can provide a guideline for choosing appropriate parameters for accurate and efficient lifetime evaluation using the ramp-voltage method.

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ACRONYMS

MIM: Metal-Insulator-Metal
TDDB: Time Dependent Dielectric Breakdown
MTTF: Median Time to Failure