Life Tests and TDDB Life Prediction Modeling of 50 nm Silicon Nitride Capacitors

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Abstract

In this paper we report room temperature constant voltage life-time measurements of silicon nitride capacitors with 50 nm dielectric thickness for both voltage polarities. We show that the measured life times are longer than predicted by both the linear field model and a model based on dielectric conduction due to Frenkel-Poole emission from traps. Of the two models, the latter fits better the collected data. We point out areas for its improvement and provide additional measurements of leakage as a function of time and a calculation of total charge to failure. Life-time measurements at elevated temperatures were performed and showed an expected exponential behavior.

INTRODUCTION

A typical modern gallium arsenide process uses multi-layer metal interconnect, separated by layers of silicon nitride, thus, providing a possibility for the formation of various capacitor structures. In particular, the process flow used for the fabrication of the capacitors in this study allows for the following dielectric thicknesses: 50 nm, 200 nm, and 250 nm. This process flow is similar to the one described in [1].

In the past, we have reported ramped voltage test results [2] on capacitors of the above three dielectric thicknesses. The ramped voltage tests are widely used because they are suitable for in-process automated testing and because they provide fast results. However, in most real applications the capacitors would be under a fixed bias. In order to investigate the capacitor behavior under actual operating conditions, we conducted constant voltage (both polarities) life tests, the results of which we present in this work.

We regularly fabricate test patterns for monitoring the quality of our product. The results reported in this paper are from measurements performed on a single wafer from such a test structure, consisting of capacitors with various plate areas and dielectric thicknesses. Since the constant voltage life tests are time consuming, they were performed on the 50 nm thick (100 μm x 100 μm square plates) capacitors only, as they are the most critical structures with the lowest breakdown voltage and potentially the shortest life time. Measurements at voltages ≥ 27 V were performed using a probe station and a Keithley test system which monitored the time to failure and recorded the leakage current. A custom-made test setup was utilized for the lower voltage long-term life tests, where parts were bonded, packaged, and assembled into test boards.

LIFE TEST RESULTS AND MODELS FOR PREDICTING LIFETIMES

The life tests cover voltages in a range starting just below the instantaneous breakdown and extending to mean life times of near 700 h at –23 V. Currently, additional life tests at even lower magnitude voltages are in progress. Figure 1 presents the life-test data collected at room temperature and both positive and negative fixed bias, as well as two different fits to the observed at high voltages mean life times.

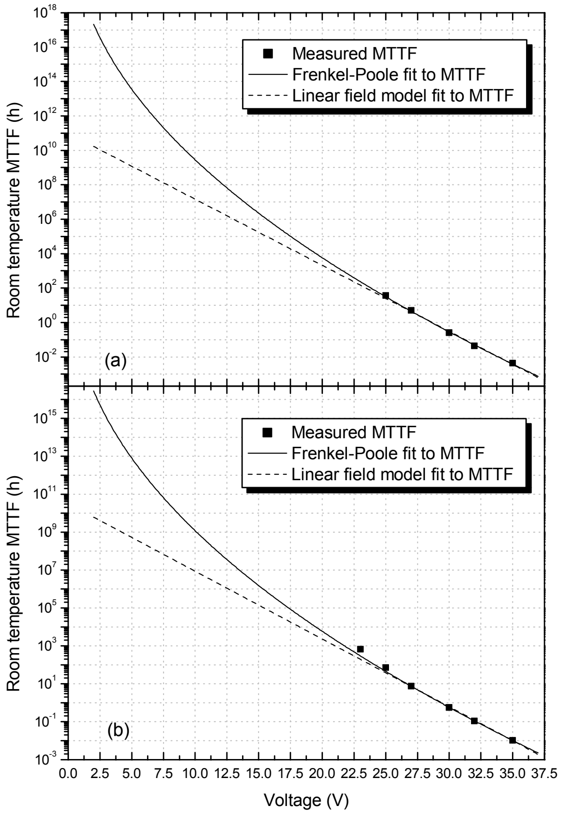

Fig. 1. Measured mean time to failure as a function of applied voltage: (a) positive; (b) negative. Lines represent fits to data at ≥ 27 V using linear field model and a model based on a conduction due to Frenkel-Poole emission from traps.

The linear field model, widely used in industry [3-4], relies on an empirical exponential voltage dependence of the leakage current and has no direct physical meaning. It appears to fit well the data in a narrow high-voltage range but deviates significantly from the measured life times at lower voltages and predicts finite life times at zero bias. The linear field model is clearly not suitable for life-time predictions at operating voltages (3-15 V) since it severely underestimates the actual results.

Another model for predicting capacitor life times [5] is based on a leakage current due to Frenkel-Poole emission from traps. The current density due to such a conduction mechanism has the following form [6]

$$J = C_1 E e^{-q(\phi_B - \sqrt{qE/\pi\varepsilon_i})/kT} = \frac{C_1 V}{d} e^{-q(\phi_B - \sqrt{qV/\pi\varepsilon_i d})/kT} \qquad (1)$$

where C_1 is a constant, E is the electric field, V is the applied voltage, T is the temperature, ϕ_B is the barrier height of the traps, d is the capacitor dielectric thickness, $\varepsilon_i = \varepsilon_0\, \varepsilon_r$ is the dielectric constant, q is the charge of the electron, and k is Boltzmann's constant. If we assume [5] that the leakage current through the capacitor is constant with time, charge is being trapped at a constant fraction η, and breakdown occurs when a certain fixed amount of trapped charge per unit area $Q_{BD} = \eta\, Q_{tot}$ is accumulated, we arrive at the following expression for the capacitor life time

$$t_{BD} = \frac{\eta Q_{tot}\, d}{C_1 V}\; e^{q(\phi_B - \sqrt{qV/\pi\varepsilon_i d})/kT}. \qquad (2)$$

Like the linear field model, this model appears to fit well the measured life times at high voltages (Figure 1) but underestimates the life times observed at lower voltages. This tendency can be better seen in Figure 2, where the data is displayed on a scale for which Eq. 2 results in a straight line. Still, compared to the linear field model, the model based on conduction due to Frenkel-Poole emission provides a better fit to the collected data. It also correctly predicts an infinite capacitor life time when no bias is applied. It is worth noting that it predicts capacitor life times higher than 10^9 h for a ± 10 V bias and 10^6 h for a ± 15 V bias.

We observed a slight difference in capacitor life times for the two voltage polarities. At higher voltage magnitudes the negative bias provides longer capacitor life times. However, the fits utilizing Eq. 2 intersect near 20 V suggesting longer life times at positive bias in the operating voltage range. The ongoing low-voltage life tests will shed more light on this subject, although present data indicates that either polarity can be used at voltage magnitudes ≤ 15 V.

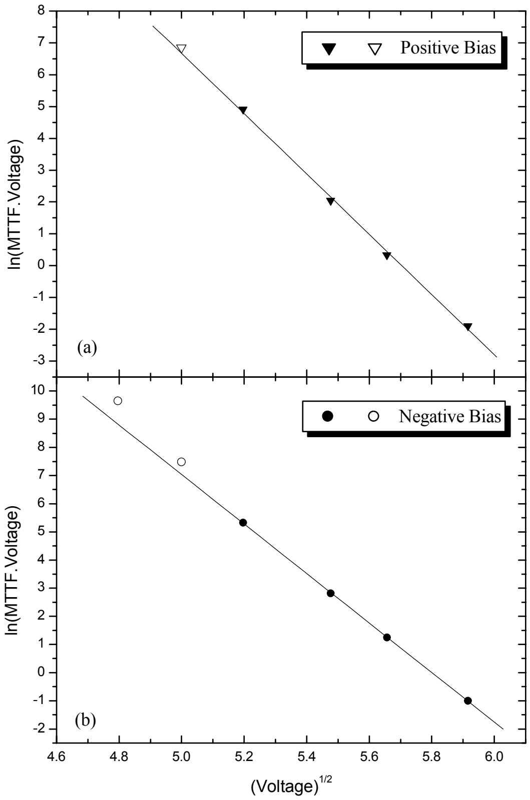

Fig. 2. Life-time data presented in a different format: (a) positive voltage; (b) negative voltage. Straight-line fits are made using data shown with solid markers.

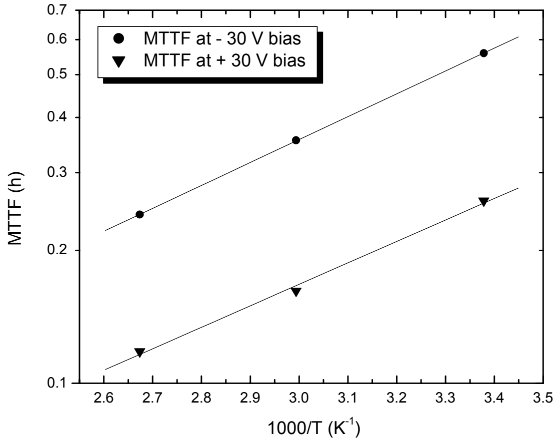

Fig. 3. Mean time to failure as a function of temperature for a ± 30 V bias.

We also studied the capacitor life-time dependence of temperature. Tests were conducted at 23 °C, 61 °C, and 101 °C for ± 30 V bias. The results presented in Figure 3 show an exponential behavior as a funcition of inverse temperature. We extracted from Figure 3 the following slopes: 1194 K (corresponding to 0.102 eV) for the negative bias and 1119 K (corresponding to 0.096 eV) for the positive bias. As it can be seen from Eq. 2, the slopes depende on the voltage magnitude and the quoted values are valid for the ± 30 V biases only. We do not further calculate the barrier height ϕ_B since, as discussed in the next section, the actual capacitor life time dependence of voltage is more complicated than the one shown in Eq. 2. This dependence needs to be further examined before we can accurately determine ϕ_B.

DISCUSSION OF RESULTS

In this section we point out some of the weaknesses of the model leading to Eq. 2 and discuss qualitatively how they affect the life-time estimations.

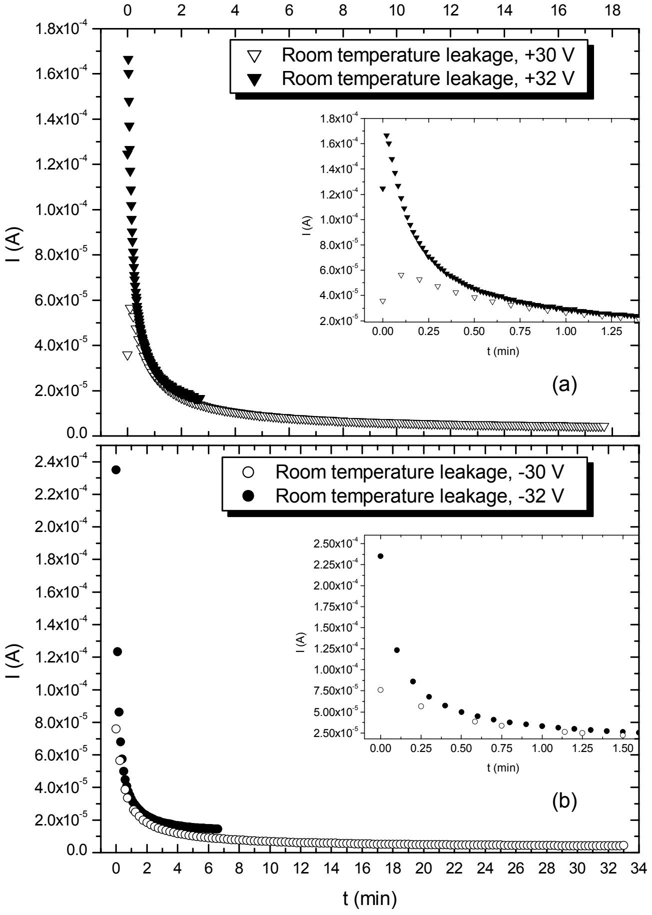

Fig. 4. Leakage current through individual capacitors at room temperature for two different voltage levels at both positive (a) and negative (b) bias. Traces extend in time until failure. The insets show the leakage soon after turn-on, where the strongest dependence of applied voltage is observed.

In the measurements performed using the Keithley test system, it was observed that the leakage current through the capacitors was not constant with time. It decreased monotonically with time at negative biases, while at positive biases, in most cases it initially increased for a short time, reached a peak, and then decreased until failure occurred. We found that larger magnitude voltages result in a larger initial current, which then rapidly decreases. At lower magnitude voltages we observed a smaller current variation with a smaller initial peak. Examples of the time dependence of current for both voltage polarities are shown in Figure 4.

As charge is trapped inside the capacitor dielectric, it creates an additional electric field which opposes more charge to enter the insulator and, thus, the current will decrease. We also found that the current in a capacitor taken off the bias at time t before failure and biased back again does not begin from the original value $I(0)$; instead, it continues from the value just before the bias was removed $I(t)$.

The difference in the leakage currents at positive and negative biases accounts for the difference in the observed corresponding life times. As described in [2], a possible reason for the bias polarity asymmetry is the geometrical asymmetry in the capacitor plates. Typically, the bottom plate extends outside the top plate by many multiples of the dielectric thickness. Thus, the edge of the top plate experiences a higher electric field.

Another weakness of Eq. 2 is that it assumes a constant charge to failure. Instead, breakdown occurs when the electric field at certain point in the capacitor and not the built-in charge reaches a critical level. The internal field is a combination of the field due to the applied voltage and the field due to the built-in charge. Therefore, at higher voltages less charge will be required to reach the critical breakdown field. This tendency is shown in Figure 5, where we plot the total charge to failure per unit area Q_{tot}. The data was obtained by integrating the leakage current through the capacitor from turn-on to failure. Taking into account the observed charge-to-failure voltage dependence would result in correctly obtaining longer life times than predicted by Eq. 2.

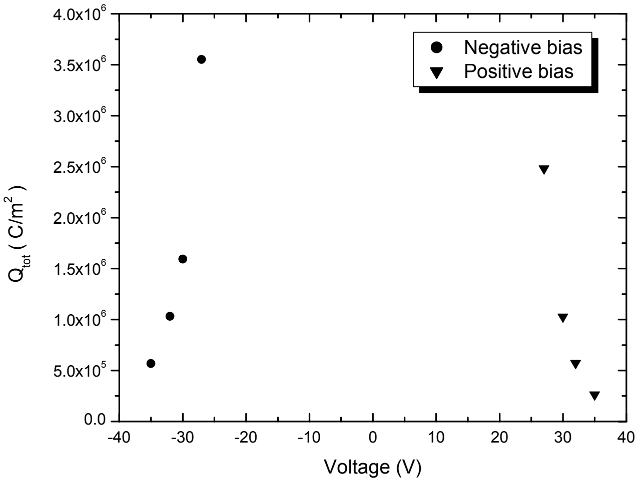

Fig. 5. Total charge to failure per unit area Q_{tot} for both voltage polarities.

Finally, the assumption of a constant trapping fraction η, used widely in capacitor life-time modeling, may also be an oversimplification of the actual charge trapping process.

CONCLUSIONS

We presented room temperature life-test measurements which show that we can expect 50 nm thick defect-free capacitors to have life times longer than 10^9 h for a ± 10 V bias and 10^6 h for a ± 15 V bias.

A model based on a Frenkel-Poole emission conduction mechanism in dielectrics can be used for providing a lower bound on estimates of capacitor life times. In this model, the lifetime depends exponentially on inverse temperature and has a more complicated voltage dependence. The adopted model however, assumes several conditions which we have shown are not accurate: namely, (a) a constant current with time and (b) a constant charge-to-failure per unit area, independent of applied voltage. Further improvements in life-time predictions will require a more elaborate model, probably involving the use of numerical methods.

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ACRONYMS

TDDB: Time Dependent Dielectric Breakdown
MTTF: Mean Time To Failure