TaN Resistor Reliability Studies

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Abstract

We present TaN thin-film resistor life test data for three different temperatures and three different current densities. A surprising decrease of resistance was observed over the course of the life tests. We show an exponential dependence of temperature for this degradation, with a more complicated current dependence. A relatively high activation energy of 2.3 eV was extracted from the life tests. Median time to failure predictions for the 10 μm wide, 100 μm long resistor investigated, are higher than 1×10^7 hours at 5.2×10^6 A/cm^2 current density and base plate temperatures up to 50 °C.

INTRODUCTION

The continuous effort throughout the electronic industry for decreasing die size has long ago posed the need for reliability assessment of current-carrying components. Electromigration (EM) has been, for many years, a hot topic in the silicon industry in relation to Al and Cu interconnects. Gold metallization has been also studied and its electromigration limits have been reflected in the design guides of GaAs manufacturers. Few studies exist, however, on the reliability of thin-film on-chip resistors used in compound semiconductor circuits. Design rules for such resistors are based on limited empirical data. The rules typically define a maximum allowed current density in a way similar to the rules for metal interconnect. Ramp-voltage burnout tests, however, have shown failures occur at different current densities for different resistor dimensions and aspect ratios. For instance, an order of magnitude difference in current density at failure during ramp-voltage test has been observed for the same nominal resistance TaN thin-film square structures with different physical dimensions. The significant amount of Joule heating in these resistor structures, makes the problem more difficult to solve compared to metal interconnects. In this paper, we present initial reliability test results and life-time predictions for TaN thin-film resistors. The purpose of our study is to investigate the failure mechanisms of these resistors and to assess the effects of resistor dimensions on current carrying capability with the ultimate goal of reflecting the findings into more comprehensive design rules.

LIFE TEST EXPERIMENTAL DETAILS

Tantalum nitride thin film with 50 Ω/sq nominal sheet resistance is used as the main building material for resistive components in TriQuint Texas' high density interconnect processes. The TaN film is sputtered over a thin layer of silicon nitride. The TaN film is then passivated with additional silicon nitride layers during several following processing steps.

A test mask containing several individual TaN resistors of different sizes and aspect ratios was selected for our study. The first structure tested, for which we report results in this paper, was a 10 μm wide, 100 μm long resistor (10x100) with 500 Ω nominal resistance. Additional resistor structures are planned for future testing.

Due to the relatively large resistivity of the TaN film, significant Joule heating was expected during the reliability tests. For this reason, thermal models for predicting peak temperature as a function of base plate temperature and power dissipation were generated for six different resistor structures using two different ANSYS software packages. The models were created taking into account all thermal interfaces present in the reliability test package. The resistors were represented by a surface heat source on the GaAs substrate. The existence of the thin SiN underneath the resistors was found not to have an appreciable effect on peak temperature results. A quarter model was created due to the symmetry of the structure. An example image of one of the thermal models is show in Figure 1. A large thermal gradient exists along the resistor length with the hottest point located, as expected, in the center and temperature dropping rapidly near the contacts.

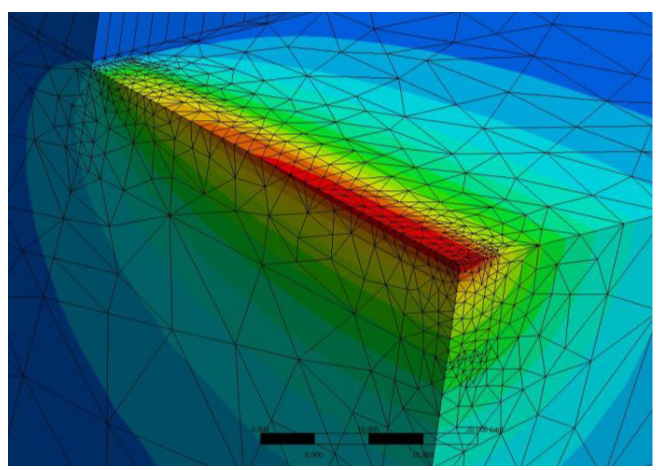

Fig. 1. Thermal model of quarter 10x100 TaN resistor. Peak temperature at corner of model coincides with center of resistor.

The thermal model was run for two different base plate temperatures and seven different power dissipation conditions. A two-variable non-linear fit of peak temperature was then created using the following approximation

$$T_{peak} = a_1 P + a_2 P^2 + (1 + b_1 P + b_2 P^2)\ T_{base} \qquad (1)$$

where T_{peak} is the peak temperature, T_{base} is the base temperature, P is the power dissipation and a_1, a_2, b_1, and b_2 are coefficients extracted from the fit.

In order to extract the activation energy and current dependence of the 10x100 TaN resistors, a comprehensive set of accelerated life tests were performed at three different peak temperatures and three different current levels. All tests were performed on resistors from a single wafer. The peak temperatures used in our tests were 383 °C, 400 °C, and 420 °C. Base temperature was adjusted actively during life test to account for the changes in power dissipation resulting from resistance change. The currents used were 26 mA (5.2×10^6 A/cm^2), 32 mA (6.4×10^6 A/cm^2), and 36 mA (7.2×10^6 A/cm^2). These current levels were kept constant throughout the life tests. Resistor degradation was gauged by the shift in voltages observed.

LIFE TEST RESULTS

It was surprisingly found that resistance decreased over the course of life test. This finding is counterintuitive as it was expected that resistance would increase as a result of void formation due to electromigration. The decrease in resistance was followed by a catastrophic failure, presenting itself as a sudden jump in resistance.

1. Gradual resistance decrease

Over the main portion of the gradual degradation range, the resistance drop appears exponential with time. The degradation is slower at the very beginning of the test and at resistance drops $|\Delta R/R| > 9$ % (Figures 2, 3). The exponential slope of the resistance change over time does not appear to be dependent on temperature but it is current dependent. The initial delay prior to the beginning of the resistance degradation is both temperature and current dependent. The observed behavior can be approximated as

$$\left|\frac{\Delta R}{R}\right| = B(I) \ln\left(\frac{t_m}{t_0}\right) \quad for \quad t_m > t_0,$$

$$\left|\frac{\Delta R}{R}\right| = 0 \quad for \quad t_m \le t_0,$$

$$t_0 = A(I) e^{C(T)} \qquad (2)$$

where I is current, T is temperature, t_m is median life, t_0 is the time at which degradation begins, A and B are both decreasing functions of current and C is a decreasing function of temperature.

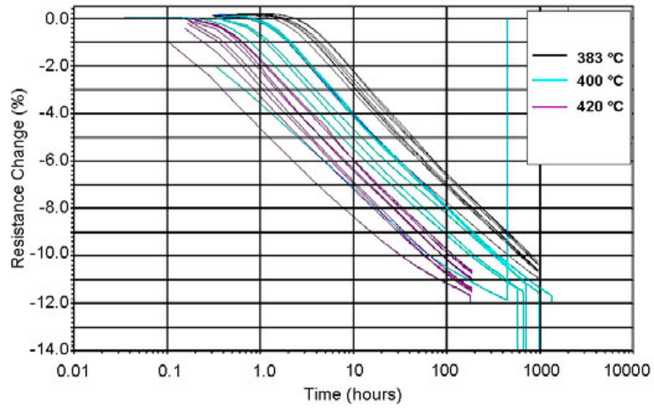

Fig. 2. Resistance drop as a function of time during three-temperature life test conducted at 32 mA of current.

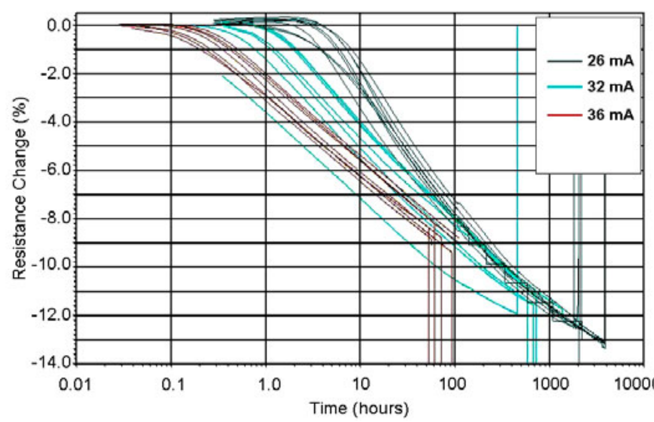

Fig. 3. Resistance drop as a function of time during three-current life test conducted at 400 °C peak temperature.

Further investigation of the temperature dependence (Figure 4) reveals that

$$C(T) = \frac{E_a}{kT} \qquad (3)$$

where E_a is the degradation mechanism activation energy and k is Boltzmann's constant.

Thus, we arrive at the following dependence of median time to failure as a function of resistance degradation, current, and temperature.

$$t_m = A(I)\ e^{\left(\frac{1}{B(I)}\left|\frac{\Delta R}{R}\right| + \frac{Ea}{kT}\right)} \qquad (3)$$

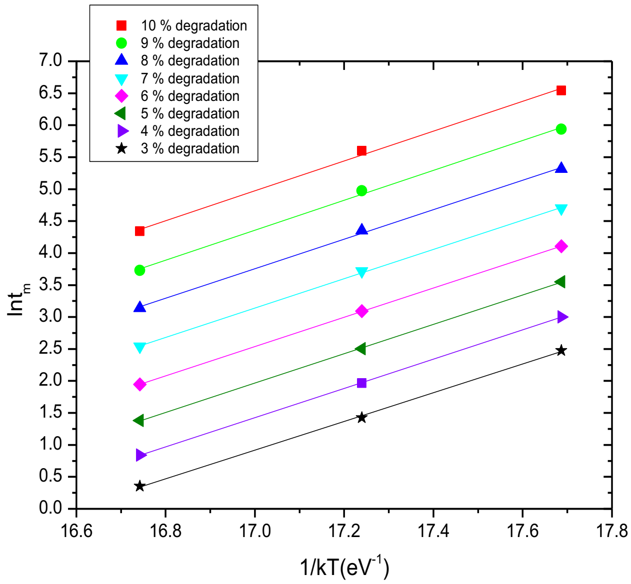

Fig. 4. Median time to failure as a function of temperature plotted at different degradation levels $|\Delta R/R|$. Measurements performed at 32 mA of current.

Values of the functions t_0, A, and B for the five different life-test conditions we explored are presented in Table 1. As expected, A and B have the same values for the life tests run at the same current. Additional work is needed to extract a more explicit dependence on current.

TABLE 1
EQN. 3 COEFFICIENTS EXTRACTED FROM LIFE TEST DATA

Current (mA)	Temperature (°C)	t0 (h)	A (h)	B
26	400	3.1	2.E-17	2.2
32	383	1.9	4.E-18	1.7
32	400	0.6	4.E-18	1.7
32	420	0.2	4.E-18	1.7
36	400	0.2	9.E-19	1.4

The activation energy E_a, associated with the resistance decrease phenomenon, was calculated to be 2.3 eV. A similar activation energy was obtained in a previous set of life tests run on a different TaN resistor (30x30 µm, 50 Ω nominal resistance) from a different processing lot than the 10x100 resistors. The 30x30 resistor life tests were performed at constant voltage rather than at constant current. The starting current density for these tests was 5.5 x 10^6 A/cm^2. Obtaining the same activation energy from different test structures and different processing lots increases the confidence of our results.

The extracted activation energy is relatively large and provides for long resistor life at lower temperatures in the absence of other failure mechanisms with lower activation energy. For instance, we predict over 1 x 10^7 hours of life before 10 % resistance change for 10x100 TaN resistors used in 4-mil thick GaAs die soldered onto 25-mil thick Cu/Mo carriers, when the resistors are operated at 5.2 x 10^6 A/cm^2 current density and 50 °C base plate temperature. This result speaks for the durability of the TaN thin film, which can be safely operated at current densities comparable or higher than the maximum current density for gold. Completing life tests on other resistors should allow us to expand our reliability predictions to any TaN resistor, regardless of its shape or size.

2. <u>Catastrophic failure</u>

The resistors were taken to catastrophic failure in several of the legs of the experiment. In most cases, catastrophic failure occurred abruptly with the exception of two catastrophic failures observed at the lowest current (26 mA) which showed an increase in resistance in a short period of time prior to burnout. The catastrophically failed resistors showed signs of voiding, delamination, and melting in the SiN/TaN/SiN sandwich and the GaAs substrate. The catastrophic failures occur off center, closer to the cathode. Reversing the direction of the current results in creating 'mirror-image' failures. All of these observations are consistent with electromigration [1-3].

Additional life tests are underway to investigate the current and temperature acceleration of the electromigration process. It was noted that catastrophic failures occurred at larger resistance drops for lower current densities. Depending on the tolerance of a design to resistance variation, circuit functionality could be lost prior to catastrophic burnout due to the preceding gradual resistance decrease. Thus, understanding the current and temperature acceleration of this decrease must remain a primary concern.

CONCLUSIONS

Life test studies were conducted in order to assess the robustness of TaN thin-film resistors, one of the main building blocks in TriQuint Texas' circuitry. We found resistance decreased over time as a function of both current density and temperature. The high activation energy for this process suggests very high resistor reliability at base-plate temperatures close to room temperature and at current densities in excess of 1 x 10^6 A/cm^2. Further studies are planned in order to assess the effects of resistor size and shape. As a result of these studies, design rules could be relaxed at least for some resistor structures, which would be very beneficial as it would allow for further reduction in die size.

ACKNOWLEDGEMENTS

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ACRONYMS

EM: Electromigration

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