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Electromigration of Electroplated Gold Interconnects

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ABSTRACT

Electromigration tests were performed on passivated electroplated Au four terminal Kelvin line structures using the conventional *in situ* resistance monitoring technique. The stress conditions were a current density of 2.0 MA/cm^2 with ambient temperatures ranging from 325°C to 375°C. The temperature coefficients of resistance (TCR) values were measured prior to current stressing to calculate the Joule heated film temperatures. The times to failure (lifetimes) for the Au line structures were considered as a 50% $\Delta R/R_0$ change. The median time to failure ($t_{50\%}$) was plotted against the inverse film temperature to determine the activation energy value as 0.59 ± 0.09 eV. Failure analysis of void location and suggested diffusion mechanism will be discussed.

INTRODUCTION

Electromigration (EM) of metal interconnects has been well understood to cause semiconductor integrated circuit failures. Most of the earlier EM studies were focused mainly on aluminum interconnects in silicon based semiconductors [1-7]. Development of Radio Frequency (RF) high power devices on GaAs substrates having higher current density and junction (metal) temperatures requires improved reliability. Therefore, other metallizations were examined for uses as interconnects in order to find better comparability with GaAs (ohmic contacts) and to improve electromigration reliability. These GaAs devices converted to gold metallization in the early 1970's since it produces a better ohmic contact with better electrical and thermal conductivity properties and believed to have improved resistance to electromigration due to its higher melting point. Gold interconnects and bond pads also have a packaging advantage since the problems associated with $AuAl_2$ intermetallic formation that occurs when aluminum bond wires are connected to gold at elevated temperatures. Now gold-based metal systems are widely used for interconnects on GaAs based electronics such as metal semiconductor field effect transistors (MESFETs) and heterojunction bipolar transistors (HBTs) for high power applications. Thus, the understanding of the electromigration mechanisms of Au films is of significant importance to high power GaAs applications.

The study of electromigration has evolved from fundamental diffusion studies using visual techniques on limited samples [8] to statistically rigorous resistometric lifetime experiments involving evolution of void growth mechanisms [9]. The primary focus of EM experiments in industry today is predicting interconnect lifetimes under field operating conditions. The trend in the semiconductor industry has moved towards reduced dimensions on interconnects producing increased current densities and operating temperatures. Both of these conditions create a raised electromigration risk in integrated circuits. As has been extensively reported in literature [10-12], increased current density and temperature degrades the metal interconnect lifetimes. The median lifetime ($t_{50\%}$) as predicted by Black's equation [7] is given by:

$$t_{50\%} = \frac{A}{J^n} e^{\left(\frac{E_a}{kT}\right)} \tag{1}$$

where **A** is a material constant depending on the geometry and microstructure of the test sample, **E_a** is the activation energy of the diffusion process, **J** is current density, **n** is the current density exponent (typically between 1-2), **k** is Boltzmann's constant, and **T** is the metal conductor film temperature. Since the lifetime is dependent on the activation energy value exponentially it is extremely important to extract accurate values. Activation energies for Au electromigration have varied widely in literature [13-15]. Variation in E_a can be due to inaccuracy in the measurement methods, differences in the deposition process of the Au films, and varying diffusion mechanisms in these previous studies. Ultimately, the need to develop more reliable metal interconnects is of primary importance and is only limited by our understanding of the electromigration mechanisms. The purpose of this paper is to present some preliminary electromigration results of passivated electroplated Au interconnects.

EXPERIMENTAL DETAILS

Four terminal Kelvin test structures were designed to examine the electromigration behavior of passivated electroplated Au films. These straight line structures allow for laminar current flow and high-resolution *in situ* resistance measurements of the stress line. Structures were prepared on a GaAs substrate using a 300 Å thin Au seed sputtering deposition process on top of a 1000 Å TiW barrier layer to form the base for the electroplated Au layer. A polycrystalline 1.0 μm thick Au film was electroplated on the base and then passivated with a 0.8 μm nitride layer. The average grain size of the electroplated Au is 0.4 μm with a sheet resistance of 0.024 ohms / square. Dimensions of the Au line test structures are a line-width of 2 μm and length of 450 μm. Figure 1 shows the layout of the Au line test structure. All structures were in die form and were bonded inside a 20-pin ceramic Au lead package. One mil Au bond wires were used to electrically contact the four terminal Au structures to the corresponding package pins for testing.

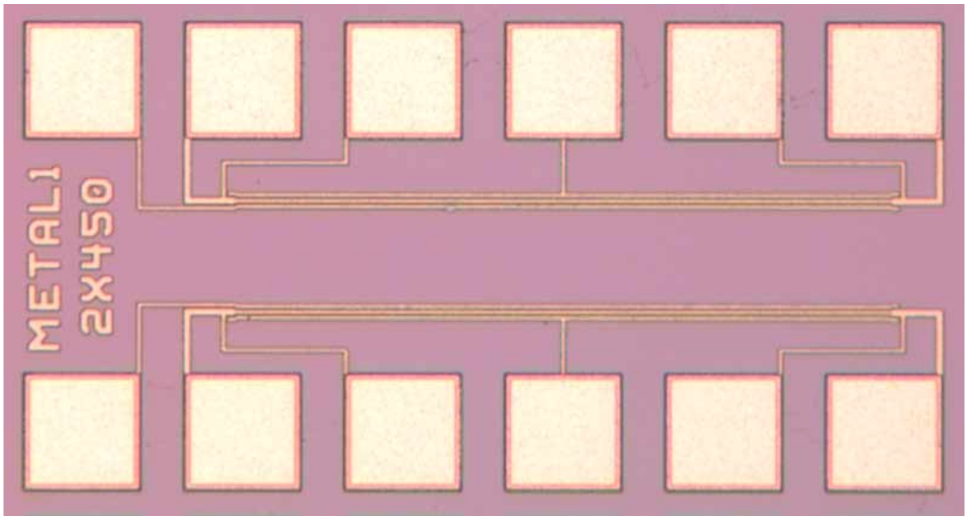

Figure 1. Au line test structure

For each EM test condition, the sample size of the Au line test structures was 60 devices under test (DUT). The temperature coefficients of resistance (TCR) values were measured on all Au line structures prior to applying the EM stress conditions. The EM test system automatically determines the Au film temperature by correcting for the Joule heating due to the high stress current. The reliability ovens are temperature calibrated to ±2°C. The EM stress conditions were a current density of 2.0 MA/cm^2 with three ambient oven temperatures of 325°C, 350°C and 375°C. The times to failure (TTF) for the Au line test structures were considered as a 50% $\Delta R/R_0$ change. Once the failure criterion was reached, the applied stress current was terminated. This increased criterion was selected to facilitate detection of the void locations. Failed Au structures were examined optically for voids and some were cross-sectioned using a focused ion beam (FIB).

RESULTS AND DISCUSSION

Temperature coefficient of resistance measured for the Au line structures was 0.00414/°C which is in close agreement with the reported value for pure gold films [16]. The average Joule heating temperature measured at 2.0 MA/cm^2 was 16°C. The resistance degradation versus time graph of a portion of the Au line structures stressed at 341°C (oven + joule heating) and 2.0 MA/cm^2 is shown in figure 2. The resistance degradation behavior of the stressed Au interconnects shows a slight increasing drift with a sharp spike in resistance leading to the failure criterion. The failure times (50% $\Delta R/R_0$) of the Au line structures are plotted on a lognormal cumulative probability graph shown in figure 3. The extracted estimates for the median failure time ($t_{50\%}$) and the standard deviation (σ) of the failure distribution were obtained from this graph. The sigma values ranged between 0.66 and 0.75. The activation energy for the diffusion process involved in electromigration is obtained using equation (1) by plotting the logarithm of the $t_{50\%}$ values against the inverse of film temperature.

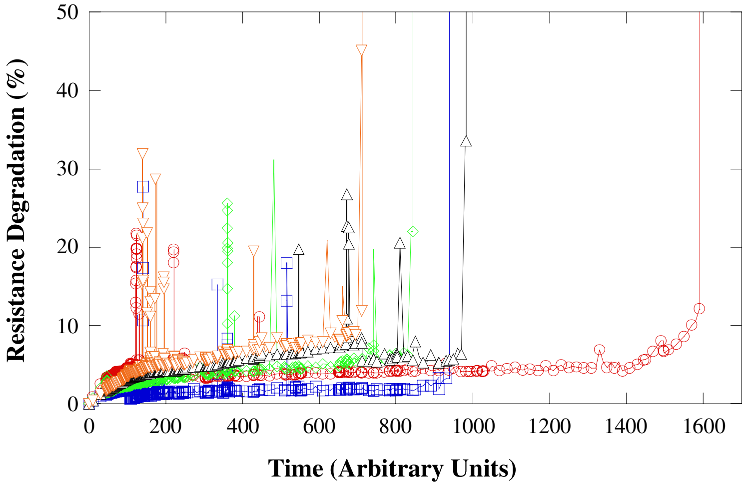

Figure 2. Resistance degradation for the Au line structures with 2.0 MA/cm^2 at 341°C

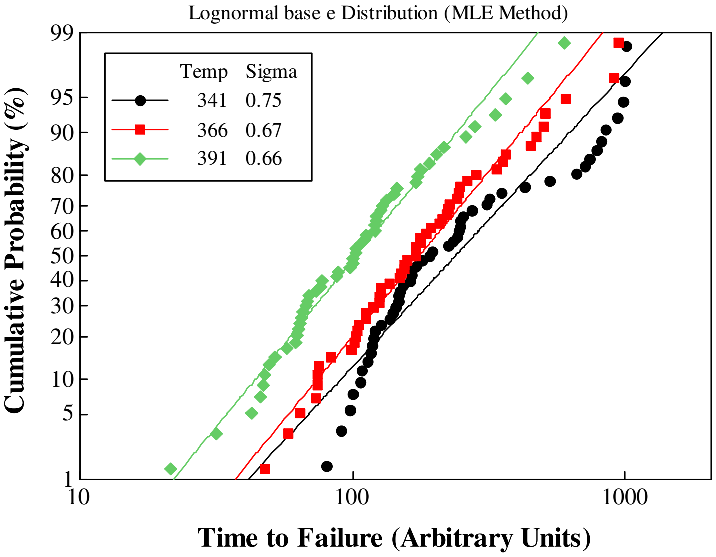

Figure 3. Lognormal cumulative probability for the Au line structures at 2.0 MA/cm^2

Figure 4 displays the Arrhenius plot from which the E_a value was determined to be 0.59 ± 0.09 eV. This E_a value is on the low end of the reported values (0.42 eV - 0.98 eV) in literature [13-15]. Notice in figure 3 that the early (75%) portion of the 341°C failure distribution is shifted from the last (25%) portion suggesting two different diffusion mechanisms are present at this temperature.

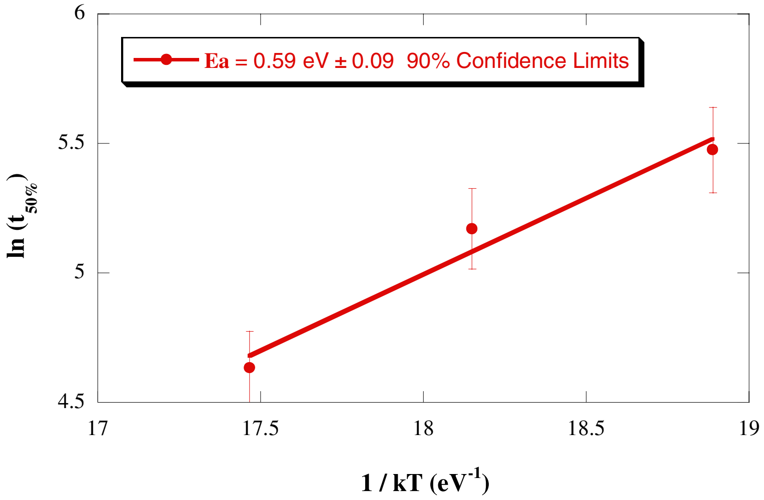

Figure 4. ln($t_{50\%}$) vs. 1 / kT (eV^{-1}) for the Au line structures at 2.0 MA/cm^2

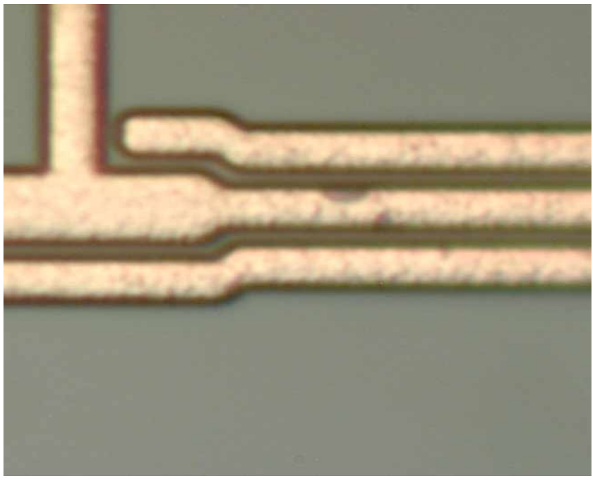

Figure 5. An optical micrograph of an EM void on the Au line structure

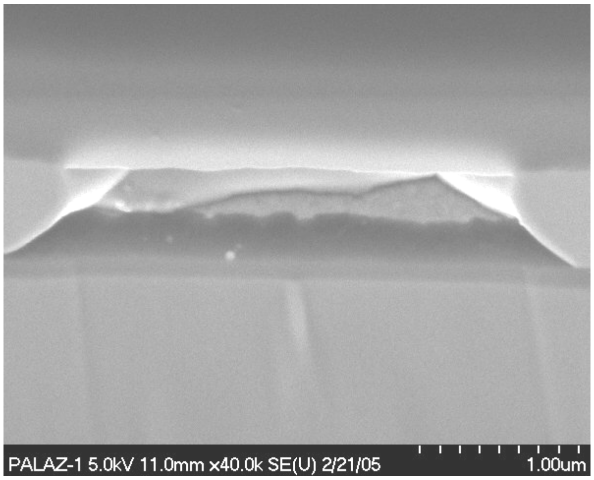

Figure 6. A SEM micrograph of a FIB cross section of the void shown in figure 6

The bi-modality (high sigma value) of the 341°C Au line failure distribution is the cause of this low E_a value and is under investigation. Determining E_a based on only the two highest temperature distributions increases it to a value of 0.92 eV. A top-down optical micrograph of the Au line structure is shown in figure 5. An EM void is visible through the passivation layer in this micrograph. Subsequently, a FIB cross section was performed adjacent to the void region. Figure 6 shows the high resolution SEM micrograph (side view) of the EM void in the Au line. It is observed that the bottom of the Au line has been completely migrated leaving only some electroplated Au remaining on the top back portion of the void. Based on the EM void shape it is suggested that its growth initiated at the TiW / Au seed layer interface and migrated upward. This proposed EM mechanism is considered surface / interface diffusion. Activation energies for this type of EM mechanism are typically around 0.6 eV [15] which is consistent with the value reported in this study.

CONCLUSIONS

(i) Passivated electroplated Au interconnects stressed with high current at the elevated temperature (340°C – 391°C) range fail due to electromigration voids.

(ii) The resistance degradation behavior of the stressed Au interconnects showed a slight increasing drift with a sharp spike in resistance leading to the 50% $\Delta R/R_0$ failure criterion.

(iii) The effective activation energy of electromigration in these Au interconnects was measured from three different temperature lifetime experiments and was found to be 0.59 ± 0.09 eV.

(iv) It is suggested that the growth of the EM void initiated at the TiW / Au seed layer interface. Therefore, the proposed EM mechanism is considered surface / interface diffusion with activation energy values typically around 0.6 eV. The value reported in this study is consistent with the interface diffusion mechanism.

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