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Mortality Dependence of Cu Dual Damascene Interconnects on Adjacent Segments

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***Abstract*— Electromigration experiments have been carried out on straight interconnects that have single vias at each end, and are divided into two segments by a via in the center ("dotted-I" structures). For dotted-i structures in the second metal layer (M2) and with 25µm-long segments length, failures occurred even when the product of the current density and segment length (*jL*) was as low as 1250A/cm, even though via terminated 25µm-long lines are "immortal" when $(jL)_{cr}$ < 1500 A/cm. Moreover, we found the mortalities of the dotted-I segments to be dependent on the current density and current direction in the adjacent segment. These result suggest that there is not a definite value of *jL* product that defines true immortality in individual segments that are part of an interconnect tree, and that the critical value of *jL* for Cu dual damascene segments is dependent on the magnitude and direction of current flow in adjacent segments. Therefore, $(jL)_{cr}$ values determined in two-terminal via-terminated lines cannot be directly applied to interconnects with branched segments, but rather the magnitude as well as the direction of the current flow in the adjoining segments must be taken into consideration in determining the immortality of interconnect segments.**

***Index Terms*—Electromigration, immortality, $(jL)_{cr}$.**

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I. INTRODUCTION

With increasing requirements for high clocking speeds and sophisticated functions for the integrated circuit (IC), more transistors and hence more metal layers and longer interconnects are incorporated into a single chip. In addition higher current densities in the interconnects is associated with the shrink of design rules due to changes of technology node. The 2002 International Technology Roadmap for Semiconductors [1] predicts that in the year 2005, a total length of 9 km of interconnects will be required in a 1 cm^2 chip with 10 metal layers. At the same time the tolerable interconnect failure rate would be reduced to 5 FITs (5 failures per 10^9 device-hours) to protect the overall functionality of the chip. This sets a great challenge to development of reliable interconnect technology, especially with respect to electromigration resistance.

Electromigration occurs through a net atomic flux as a result of the electron wind force that is countered by a force caused by the resulting stress gradient

$$J_a = -\frac{D_a C_a}{kT}\left(Z^* e\rho j - \Omega \frac{\partial \sigma}{\partial x}\right), \quad (1)$$

where D_a is the atomic diffusivity, C_a is the atomic concentration, kT is the thermal energy, Z^* is the effective charge number, e is the elementary charge, ρ is the resistivity, j is the current density, Ω is the atomic volume, σ is the hydrostatic stress as a function of position along the length of the interconnect σ. When the electron wind and stress gradient forces balance, so that J_a is zero and a steady state is attained, $\partial\sigma / \partial x = \Delta\sigma / \Delta L$, where $\Delta\sigma$ is the difference in the hydrostatic stress between the anode and cathode, and L is the length of the interconnect. The redistribution of metal atoms due to electromigration leads to build up of hydrostatic stresses at sites of atomic flux divergence, with compressive stress developing at the anode due to a net atomic accumulation and a tensile stress developing at the cathode due to a net atomic depletion. Tensile stress can eventually lead to voiding and an open circuit while compressive stress can lead to metal extrusion and a short circuit failure.

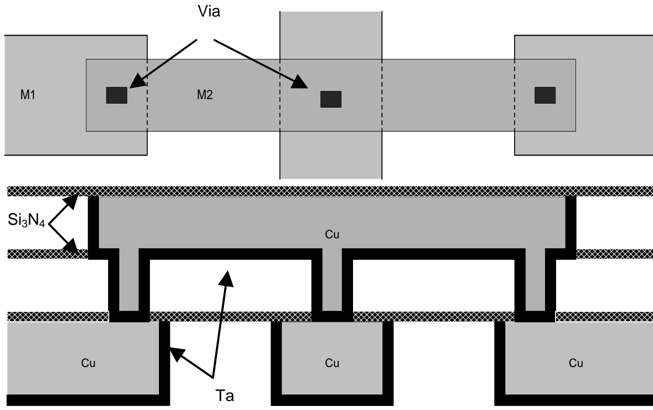

Figure 1: Top and cross-sectional view of the dotted-I test structure.

However, if the stresses stay low enough that void nucleation or metal extrusion does not occur, the line could be immortal. For short lines bound by zero-flux boundaries that are stressed at low current densities, the stress along the line will evolve to a uniform stress gradient, at which the back force due to the stress gradient balances the electron wind force [2]. For zero net atomic flux, equation 1 can be rearranged into the following form:

$$(jL)_{cr} = \frac{\Omega \Delta \sigma}{Z^{*} e \rho} \qquad (2)$$

Immortality has been demonstrated for Al-based metallization systems when the product of current density and line length stays below a critical value, $(jL)_{cr}$ [2-3]. This effect has also been recently reported for Cu interconnects [4-6], though with a wide range of values from 1500 A/cm to 3700 A/cm, depending on the structure of the interconnects. It has also been reported that Cu interconnects was reported that a small fraction of Cu-based interconnects may still be mortal at even lower *jL* products [7].

II. EXPERIMENTS

Experiments were carried out on straight via-terminated lines with an additional via in the middle that creates two segments with 25 μm length ("dotted-I" structures). The test structures were in metal 2 (M2) and connected to metal 1 (M1) leads in "via-below" configurations, as shown in Figure 1. The test structures were fabricated using a dual damascene process with SiO_2 as the inter-level dielectric, Ta as the diffusion barrier and Si_3N_4 as the capping dielectric. The current density in the right segment was kept constant at 0.5 MA/cm^2 with the electrons flowing from the right via towards the middle via, while the current density in the left segment was varied from 0 to 2.5 MA/cm^2, with electrons flowing in both directions. All the samples were stressed for 780 hours and the failure criterion was set as a 30% resistance increase.

III. RESULTS AND DISCUSSION

Due to the low failure rate of the samples, comparison between the different test conditions was done by using the failure percentage instead of t_{50}. The failure percentages

Table 1: Failure percentages. The second column gives the current densities in the left segments.

+ j
0.5MA/cm^2
- j

Configuration (MA/cm^2)	Current Density (MA/cm^2)	Left segment (%)	Right segment (%)	Overall (%)
2.5 <-- <--0.5	2.5	68.75	68.75	81.25
1.5 <-- <--0.5	1.5	43.75	62.50	62.50
0.5 <-- <--0.5	0.5	12.50	37.50	37.50
0 <--0.5	0	0.00	18.52	18.52
0.5 --> <--0.5	-0.5	16.00	16.00	24.00
1.5 --> <--0.5	-1.5	50.00	50.00	57.14
2.5 --> <--0.5	-2.5	56.25	43.75	62.50

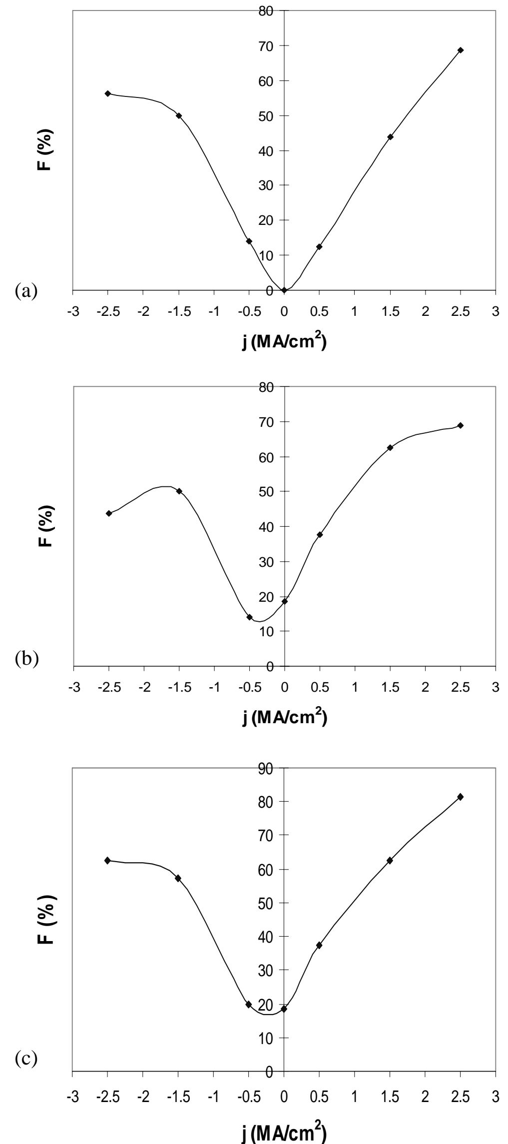

Figure 2: Plots of failure percentage versus current density in the left segment: for failure in the (a) left segment, (b) right segment or (c) either segment.

for the overall structure as well as for the respective segments are tabulated in Table 1, and plots of the failure percentages of respective segments as well as the overall failure percentage (failure of the dotted-I structure when either one of the segments failed) versus current density in the left segment are shown in Figure 2. The current density in the left segment was defined to be positive if the current direction was same as the right segment.

Failures were found in the dotted-I right segment even when jL was as low as 1250 A/cm, compared to the lowest reported $(jL)_{cr}$ value of 1500 A/cm. Moreover, we found that the mortality of a dotted-I segment was dependent on the direction and magnitude of the current in the adjacent segment. The failure percentage of the right segment reduces with reducing current density when the electron flow is in the same direction in the left segment. It increases with increasing current density when the electron flow is in the opposite direction, with the lowest failure percentage corresponding to about 0.35 MA/cm^2 in the opposite direction. For the cases in which the left segments have a current density of 1.5 MA/cm^2 or 2.5 MA/cm^2 flowing in the same direction as the right segment, over 40% of the samples' right segments failed earlier than the left segments, even though the current densities in the left segments were higher. Failure analysis using focused ion beam (FIB) showed that the right segments failed due to voiding near the cathodes, as shown in Figure 3. As the right segment acts as an active atomic source for the left segment in these cases, voids can form earlier in the right segment than the left segment either at area close to the middle via or near the terminal via of the right segment.

The left segment can be treated as an active sink for the right segment if the current flow in the same direction as the right segment, and as active source for current flow in opposite direction. The left segment is a passive sink for zero current flow. The mortality of the right segment reduces with the current density in the left segment when the electrons flow in the same direction, because the left segment is draining less material from the middle via. This helps to develop the compressive stress build up at the middle via area and reduces the failure of the right segment. The near-immortality of the right segment does not correspond to zero current flow in the left segment, but around 0.35 MA/cm^2 in the opposite direction. This is because the compressive stress build up in the middle via by the electron flow in the right segment is assisted by the electron flow in opposite direction in the left segment, and reducing the probability of failure of the right segment. However when the current density in the left segment exceeds 0.5 MA/cm^2 in the opposite direction, the failure probability of the right segment increases again. This because more left segments failed earlier than the right segments. Void that form in the left segment can act as effective sinks for the right segment and causes the failure percentage to increase.

It is observed that the failure percentage of the right segment drops when the current density in the left segment increases beyond 1.5 MA/cm^2 in the opposite direction. This is due to the build up of a high compressive stress at the middle via area, due to the high current density in the left segment that reduces the failure in the right segment.

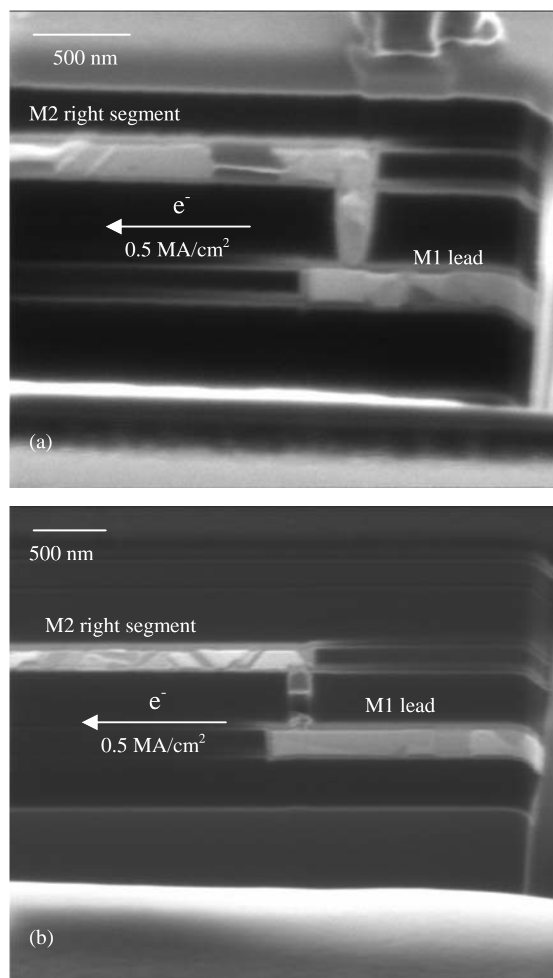

Figure 3: FIB cross-sectional views of void locations in the M2 right segments at the terminal via for different current densities in the left segments: (a) 1.5 MA/cm^2 and (b) 2.5 MA/cm^2.

The lowest reported $(jL)_{cr}$ value for M1 ("via-above") structures and M2 ("via-below") structures is different. The $(jL)_{cr}$ for M1 is reported to be 1500 A/cm [6], while M2 is 3700 A/cm [5]. M2 test structures were used in our experiments. If comparison of the jL values is made among similar structures, the jL value of 1250 A/cm in the dotted-I segment is 33% of the lowest reported $(jL)_{cr}$ for M2.

IV. CONCLUSIONS

The dependence of the immortality criterion in a Cu dual damascene interconnect segment on the stress conditions in adjacent segments has been demonstrated. The failure percentage of an interconnect segment was found to reduce with reducing current density in the adjacent segment when the current flow was in the same direction, and increases with increasing current density in the adjacent segment when the current flow was in the opposite direction. A near-immortality condition can be achieved with a finite current flow in the adjacent segment in the opposite direction. Theses results demonstrate that an immortality criterion can not be defined

for an individual segment within an interconnect tree, since the critical *jL* value for a single segment of Cu interconnect may be reduced or increased due to the presence and stress conditions in an adjoining segment. Therefore, independently determined $(jL)_{cr}$ values in two-terminal via-terminated lines cannot be directly applied to interconnects with branched segments, but rather the magnitude as well as the direction of the current flow in the adjoining segments must be taken into consideration in evaluating the immortality of interconnect segments [8].

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