OBSERVATION AND MODELLING OF ELECTROMIGRATION-INDUCED VOID GROWTH IN Al-BASED INTERCONNECTS

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ABSTRACT

Accelerated electromigation tests on unpassivated, pure aluminum interconnects were performed. The failure mechanisms were observed by interrupting the tests and examining the conductor lines using an SEM. Because the metal thin film was subjected to a so-called laser reflow process before patterning, grain boundaries were visible in the SEM as thermal grooves. Voids were observed to move along the line and to grow in a transgranular manner, and a characteristic asymmetric void shape was identified which seems to be related to the failure mechanism. It is argued that substantial progress in modelling and understanding of electromigration failure can be made by consideration of such void shape effects.

INTRODUCTION

With further reduction of dimensions in VLSI (Very Large Scale Integration) technology, the role of electromigration (EM)-induced failure becomes increasingly more important. The reliability of aluminum alloy interconnects is limited by stress-induced open circuits [1] and by EM-induced open and short circuits. A linewidth of about 1 µm and grain size of typically more than 1 µm lead to a near-bamboo structure in the metal lines. Recent studies of mechanisms for EM-induced failures have shown that transgranular slit-like voiding seems to be characteristic for near-bamboo conductor lines [2,3]. This failure mechanism cannot be explained with earlier EM models, which generally require grain boundaries as diffusion paths. The morphology of the slit-like voids often resembles cracks rather than rounded pores. This observation suggests that mechanical stresses play an important role in this failure mechanism. We present SEM observations showing that stresses alone do not provide a satisfactory explanation for the void geometry, which appears to be the result of an interaction between electric current, diffusion and mechanical stress.

EXPERIMENTAL

Accelerated EM-tests were performed on unpassivated circuits consisting of 20 conductor parallel line arrays (PLAs). The metallization consisted of a 0.5 µm thick pure aluminum film, which was treated by a laser reflow process [4] after sputter deposition. This process affects the film microstructure in several ways. Grain growth during the laser heating yields large grains (here approximately 2.9 µm in diameter) and grain boundary grooves, which have the benefit that the microstructure of the film is visible in an SEM without any preparation. In addition, the typical (111) fiber texture of the as-deposited film is destroyed so that the film is composed of randomly oriented grains. Standard lithographic and etch techniques were used to pattern the samples. The tests were performed on lines with a width of 1.8 μm under constant voltage resulting in a current density of 2 MA/cm^2 at a temperature of 500 K. Constant voltage conditions prevent the destruction of the failure site when an open circuit occurrs in a line and therefore allow post-mortem microscopic examination. One test was interrupted several times for examination in order to investigate EM-induced void nucleation and to follow void motion and growth. The interruption did not significantly affect the failure mechanism as both void morphologies and sizes were comparable to those in the standard test [5].

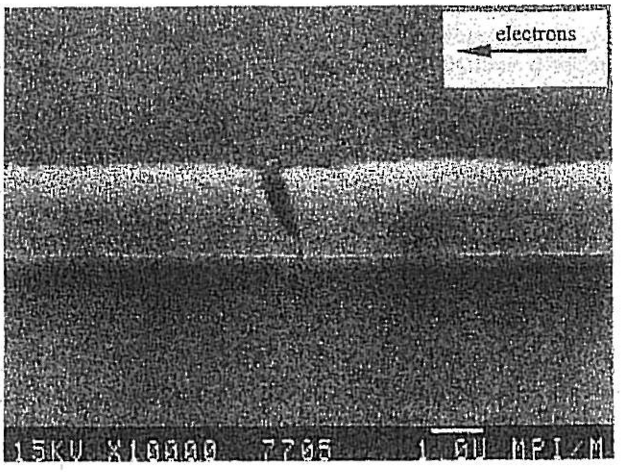
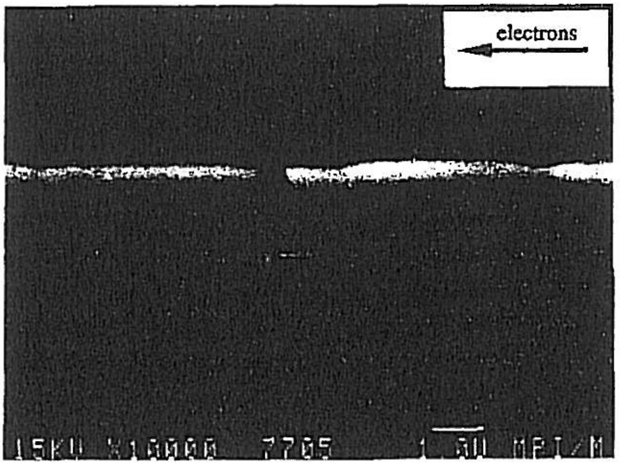


Fig. 1: SEM micrograph of a transgranular void producing an open circuit. The void shows the typical wedge shape, where the side turned against the direction of the electron flux (right side) is straight and almost perpendicular to the line. The angle between the other side and the line is smaller.

RESULTS

Fig. 1 shows an SEM micrograph of a typical open circuit produced by a transgranular void, which grew during an uninterrupted test. The direction of the electron flux in all figures is from right to left. About half of all opens were found to be transgranular under the test conditions used. Figs. 2a-c and Figs. 3a-c give two sequences of void motion, growth and ultimate failure obtained from an interrupted test. Fig. 2a shows, after a total testing time of 42.2 h, a small void which was not detected during a previous test interruption after 25.5 hours. The void was probably nucleated at the intersection of a grain boundary with the edge of the line. Then it moved along the edge through a small grain until it was pinned by a grain boundary (Fig. 2b). Note that for crystallographic reasons the void is facetted and these facets reorient as the void enters the adjacent bamboo grain, as suggested before [6]. The void does not move further into this grain, but now starts to grow in the transverse direction until it finally produces a transgranular open circuit (Fig. 2c). The sequence in Fig. 3 is similiar to the one in Fig. 2. Fig. 3a shows a void at the edge of the line in a bamboo grain; either the void was nucleated in pattern the samples. The tests were performed on lines with a width of 1.8 μm under constant voltage resulting in a current density of 2 MA/cm^2 at a temperature of 500 K. Constant voltage conditions prevent the destruction of the failure site when an open circuit occurrs in a line and therefore allow post-mortem microscopic examination. One test was interrupted several times for examination in order to investigate EM-induced void nucleation and to follow void motion and growth. The interruption did not significantly affect the failure mechanism as both void morphologies and sizes were comparable to those in the standard test [5].



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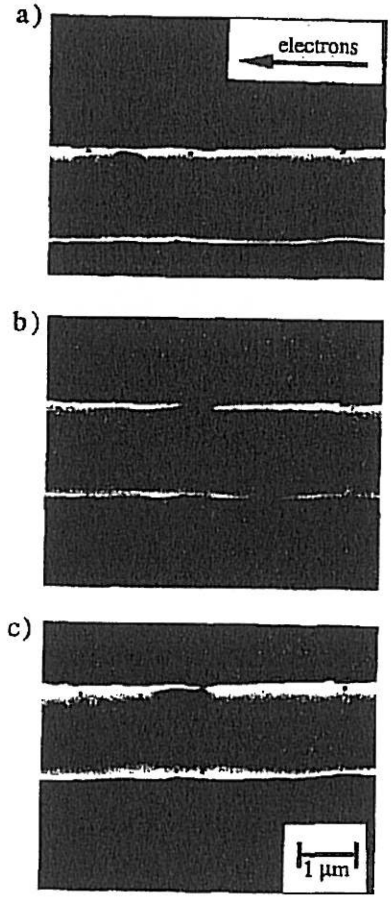

Fig. 2: SEM micrographs showing a time sequence of the same site on a conductor line after a) 42.2 h, b) 140.6 h, and c) 161.8 h total testing time. The void moved first along the edge of the line until it started to grow through a bamboo grain across the line. (Grain boundaries are artificially highlighted with dotted lines.)

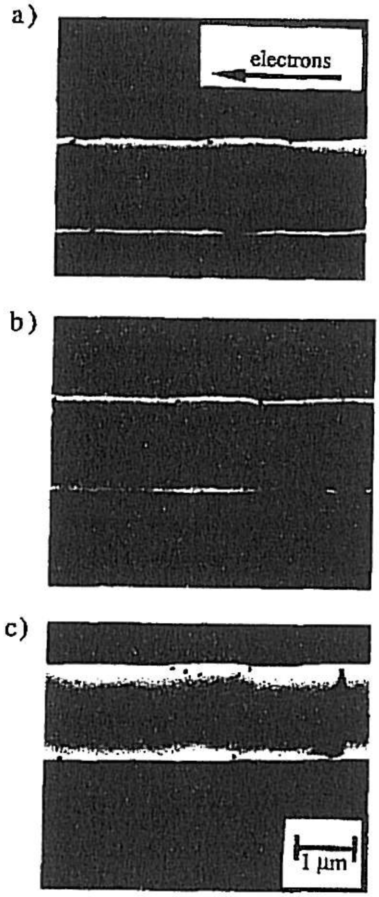

Fig. 3: Sequence of SEM micrographs similar to Fig. 2 (testing time: a) 42.2 h, b) 140.6 h, c) 144.9 h). The void moved along the edge of the line, crossed a grain boundary, and started to grow across the line in the "second" bamboo grain.

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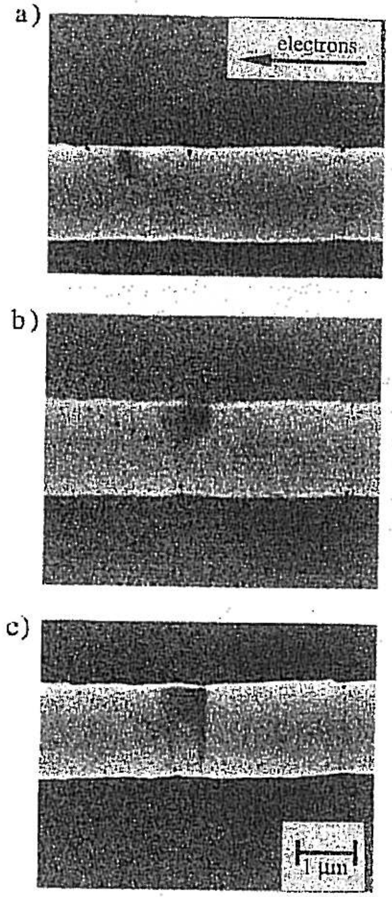

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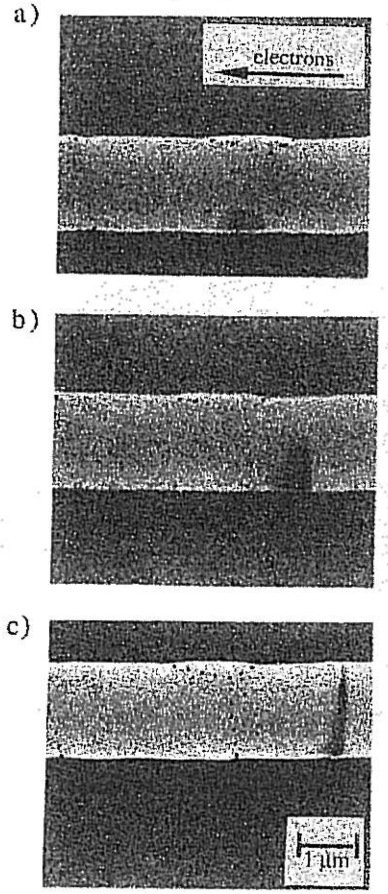

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DISCUSSION

In the course of our investigations a large number (ca. 500) of fatal voids have been studied and many of them are of the transgranular type, as found in earlier studies [2,3]. Such voids are similiar in morphology to voids produced by stress-induced processes or to voids which are nucleated by the hydrostatic stresses in passivated interconnects and grow under electromigration conditions [7]. Our observation, which we think is significant for the failure mechanism, pertains to the fact that all of these voids have a typical slit or wedge shape with a pronounced asymmetry: the cathode boundary of the wedge, which is turned against the direction of electrons, is straight and almost perpendicular to the line, while the angle between the more irregular anode boundary and the line is smaller. A void shape with an opposite boundary configuration was never observed.

Because of this systematic asymmetry, void growth in our experiments cannot be driven by stresses alone (which are by definition symmetric). Rather, the electron wind is expected to interact with mechanical stress in a way suggested qualitatively in Fig. 4: A driving force for electromigration does not appear on a void surface perpendicular to the direction of the electron flux. However, on the tilted void surface, a mass flux is set up which depends on the angle to the line. Following this reasoning a void with a shape as shown in Fig. 4a becomes critical, because EM-induced mass flux occurs from 2 to 1, but not from 3 to 2. Consequently mass is removed at 2 and the void grows across the line and tends to become fatal. Additionally the void tip sharpens and may act as a location of stress concentration, if the line is under mechanical tension. The mass flux on the void surface from 2 to 1 increases for larger voids, caused by the

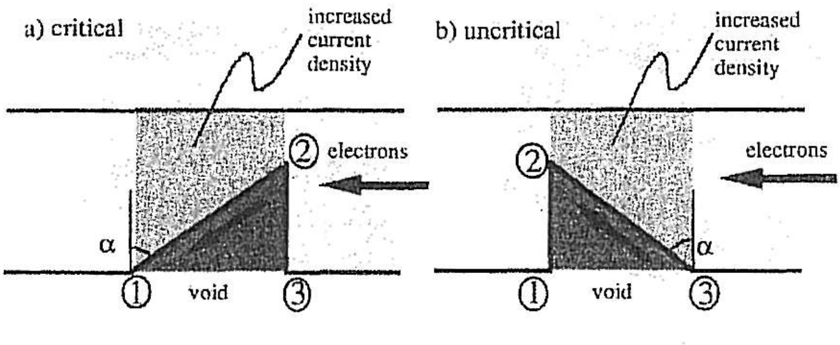

Fig. 4: Schematic illustration of the interconnection between void shape and electron wind:
a) no EM-induced mass flux on the void surface from 3 to 2, but from 2 to 1 (as a function of α). As a result mass is removed at 2 and the void tends to become fatal ("critical" configuration).
b) no EM-induced mass flux from 2 to 1 but from 3 to 2, consequently the void grows along the line ("uncritical" configuration).

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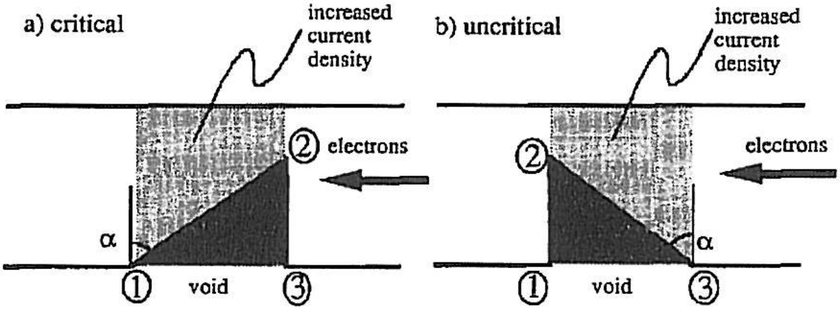

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locally increased current density. Therefore the void growth accelerates with increasing void size. Contrary to this, a void with a shape as shown in Fig. 4b should be uncritical because EM-induced mass flux occurs only from 3 to 2, but not from 2 to 1. Hence mass is removed at 3 and added at 2: the void grows along the line and the void tip rounds off. Even a large void with this shape does not become critical because of the "self-healing" tendency which is further enhanced by the locally increased current density.

The time sequence of a growing void in Fig. 5a-c illustrates this simple model for microstructural failure. Fig. 5a shows a void whith an "uncritical" shape and as expected the void grows mainly along the line and less across the line (in b). Nevertheless after 172.2 h it seems that the void is almost fatal (in c), but even 50 h later the uncritical part of the void (on the left) has not grown further across the line, and the void tip has been rounded off. In the

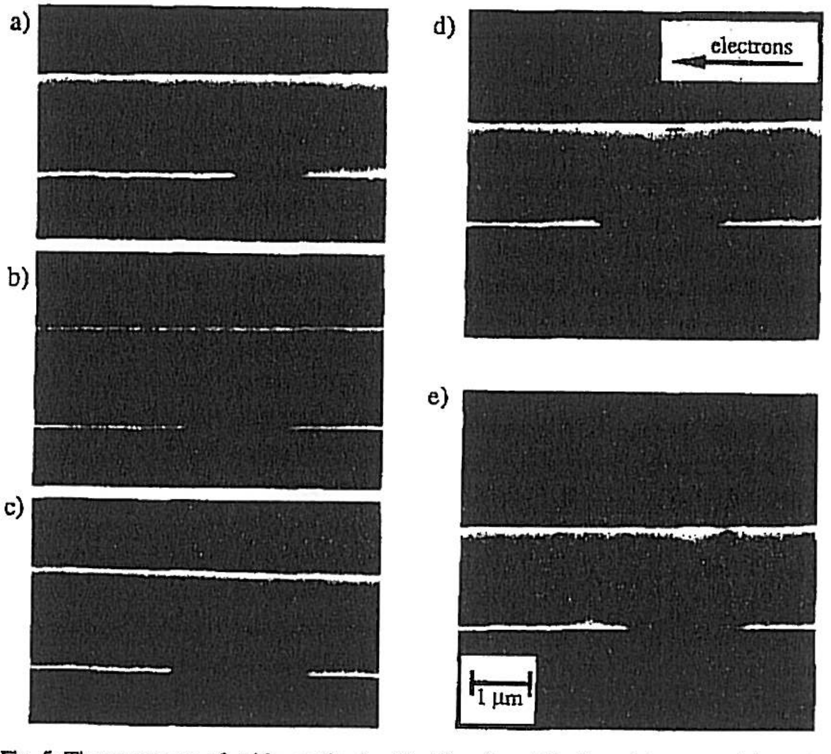

Fig. 5: Time sequence of void growth: a) void at the edge of the line with an „uncritical" shape (65.8 h); b) void grows mainly along the line (131.8 h); c) void seems to be almost fatal (172.2 h); d) uncritical site: void growth stopped, critical site: void started to grow (224.3 h); e) fatal void where the cathode end of the void is perpendicular to the line (227.2 h). This Al film was not laser reflowed and therefore grain boundaries are not visible.

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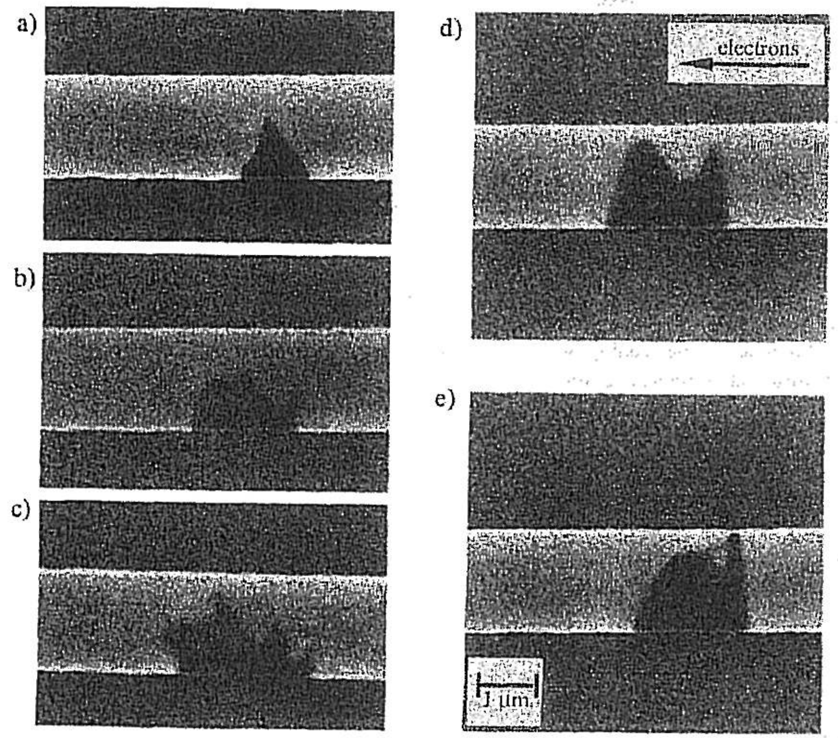
The time sequence of a growing void in Fig. 5a-e illustrates this simple model for microstructural failure. Fig. 5a shows a void whith an "uncritical" shape and as expected the void grows mainly <u>along</u> the line and less <u>across</u> the line (in b). Nevertheless after 172.2 h it seems that the void is almost fatal (in c), but even 50 h later the uncritical part of the void (on the left) has not grown further across the line, and the void tip has been rounded off. In the



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meantime the void has developed, on its cathode end, a facet perpendicular to the line ("critical" shape), which starts to grow (in d). Finally this facet produces the opening of the line, showing the typical wedge shape (in e). Note that the void became critical only after a facet perpendicular to the line was established. From this moment the total void volume remained about constant, only the shape of the void was changed by surface diffusion in a manner as described above. A similiar shape change mechanism is visible in Figs. 3b-c.

CONCLUSIONS

Based on these findings we suggest the following sequence for the formation of transgranular voids in unpassivated near-bamboo conductor lines:

i) Voids are nucleated at the edge of the line, probably where it is intersected by a grain boundary; for crystallographic reasons, these voids tend to be facetted.

ii) Under the action of the electron wind, the voids grow in size and move opposite to the direction of the electron flux. During this motion they may penetrate one or several grain boundaries without becoming fatal.

iii) A critical situation arises after a void has entered a grain which, because of its particular orientation, favors the development of a void facet perpendicular to the line. If this facet lies on the cathode end, a geometry develops which enhances the removal of atoms from the void tip by electromigration-assisted surface diffusion. A transgranular void is formed which results in an open circuit.

Because of the transgranular nature of these voids, grain boundary diffusion is ineffective and our argument considers only surface diffusion. Surface diffusion has been shown to account for void motion [8]. For void growth it will be necessary to also consider the effects of volume diffusion and of mechanical stresses. A microscopic failure model based on these elements and on further observations is currently being developed.

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