ELECTROMIGRATION IN SINGLE-CRYSTAL ALUMINUM LINES PRE-DAMAGED BY NANOINDENTATION

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ABSTRACT

Electromigration tests have been performed on single-crystal Al lines which were pre-damaged by rows of submicrometer-depth indentations made using a nanoindentation device. Indentations were placed close to each other so that their plastic deformation zones overlapped. During subsequent electromigration testing at 280°C and 1 to 2 MA/cm^2, no damage was observed in non-indented single-crystal lines, while the indented lines showed electromigration-induced voids at the cathode-side ends of the indented areas, and hillocks at the anode-side ends. The voids grew and moved away from the indentations towards the cathode. The electromigration damage morphology of the indented lines indicates that the mechanical damage generates a local fast diffusion path in the single-crystal lines, which is believed to be due to dislocation core diffusion. A minimum indentation row length was observed, below which no void formed. This electromigration behavior is found to be phenomenologically similar to that of polygranular clusters in near-bamboo lines.

INTRODUCTION

The electromigration-induced failure of aluminum interconnects is a complicated process which involves flux divergence, vacancy and atom accumulation, void nucleation, void growth and shape changes. Furthermore, as the width of these interconnects is reduced to dimensions smaller than the average grain size, a "near-bamboo" grain structure is produced which contains both interconnected networks of grain boundaries as well as grains which span the width of the line. In this case electromigration-induced failure processes become more complicated due to the existence of at least two different diffusion mechanisms (*e.g.*, [1]). Therefore, it is desirable to study electromigration by performing idealized and simplified electromigration experiments in parallel with conventional electromigration lifetime measurements.

We have studied the electromigration behavior of Al conductor lines having pre-existing mechanical damage generated by nanoindentation. Due to the precise control of the depth and location of indentations which is possible with our machine, we can generate a row of indentations along a conductor line placed closely enough together so that their plastically deformed zones overlap. This row of indentations then forms a stripe of highly deformed material ranging from one to a few tens of micrometers in length. We subsequently studied the electromigration behavior of these lines by performing electromigration tests on them.

It has been suggested [2] that dislocations could act as an effective diffusion path under electromigration conditions. Thus, these damaged stripes might be expected to act as regions of rapid diffusion due to the high dislocation density there. In experiments conducted previously using *polycrystalline* Al and Al-2%Cu-1%Si lines [3], a series of indentations were made in the lines, and electromigration tests were then performed. In these experiments, electromigration-induced damage could not be correlated with the indentation-induced mechanical deformation. This was explained by the observation that these lines probably had a continuous network of grain boundaries. In this case, the diffusion flux would be dominated everywhere by the grain

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boundaries and mechanical deformation would have little or no effect. However, in lines having no continuous network of grain boundaries, diffusion along dislocations injected by mechanical deformation might be important for electromigration-induced damage.

Therefore, we have studied the effect of mechanical deformation on electromigration by using *single-crystal* Al lines. Since there are no grain boundaries in these lines, the effect of mechanical deformation on the electromigration behavior could be observed. In principle, perfect bamboo lines should exhibit similar behavior. However, the smaller line width of bamboo lines makes placing rows of indentations in them difficult.

EXPERIMENT

Single-crystal Al films were fabricated by epitaxial deposition of Al onto NaCl single-crystal substrates. The films were then transferred to oxidized silicon wafers, and conventional lithography techniques were used for patterning electromigration test structures consisting of arrays of parallel lines. The details of the fabrication procedures, along with a description of the electromigration behavior of these lines, can be found in reference [4]. The single-crystal Al lines used for this research had a (110) plane parallel to the substrate and the [001] in-plane direction oriented perpendicular to the lines. The lines were 1.9 μm wide, 0.4 μm thick, and 1 mm long, and were unpassivated.

Prior to electromigration testing, indentations were made using a depth-sensing submicrometer indenter (Nanoindenter II, Nano Instruments Inc.). Several different configurations of indentations were made in 11 of 16 parallel lines. Each indented line contained single indentations or rows of 3, 5, 7, or 9 indentations. The indentations in any one row were made to an indentation depth of either 350 or 150 nm using a Berkovich tip. The 350 nm deep indents were spaced 2.5 μm apart, so the length of the mechanically deformed stripe ranged from 3 to 24 μm. The 150 nm deep indentations were spaced 1 μm apart resulting in a deformed zone between 1 and 9 μm in length. Indentations were placed sufficiently close to each other to ensure that the plastic deformation zone is continuous along the line.

Electromigration testing was performed inside a scanning electron microscope (SEM) which was equipped with a 4-point probe station in order to observe the evolution of electromigration damage *in-situ*. The testing temperature was 280°C, and the current density was 1.0×10^6 A/cm^2 for the first 68 hours and was then increased to 2.0×10^6 A/cm^2. The total testing time was 120 hours. The evolution of electromigration damage was recorded by taking SEM micrographs during the electromigration test.

RESULTS

Electromigration damage was 100% correlated with mechanical damage. Electromigration voids were generated in indented lines, and no voids were observed in the not-indented lines. Under these testing conditions, the predicted lifetime of non-indented lines is more than 2000 hours [4], so no electromigration damage was expected. However, in lines with rows of 3 to 9 indentations 350 nm deep, voids were observed after about 2 hours of electromigration testing and the lines failed between 9 and 12 hours. Figure 1 shows micrographs of a row of 3, 350 nm deep, indentations. Lines with 5, 7, and 9 indentation rows showed similar behavior. A small void formed at the cathode-side end of each indented area. This void grew and, at the same time, moved towards the cathode. The line failed when one such void grew to the width of the line. However, for the single 350 nm deep indentations, no void was observed during this

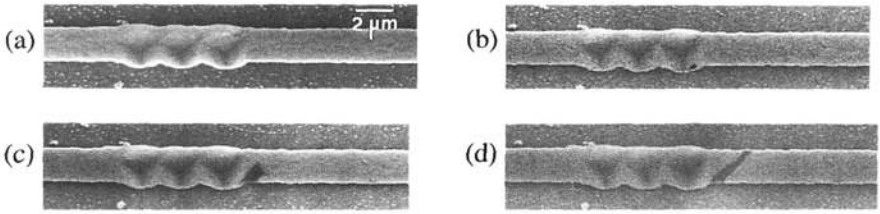

Figure 1. Evolution of electromigration damage associated with a row of 3, 350 nm deep, indentations (a) before electromigration testing, tested for (b) 2 hours, (c) 7 hours, and (d) after failure. Electron flow is from right to left.

time. Out of five different single 350 nm deep indentations, only 1 generated voids after 44 hours of testing.

For the 150 nm deep indentations, voids were nucleated only from rows of 9 indentations while the current density was 1×10^6 A/cm^2 (Figure 2). In lines with rows of 7 and 5, 150 nm deep, indentations, no voids were observed while the current density was 1×10^6 A/cm^2. But, after 68 hours the current density was increased to 2×10^6 A/cm^2, and voids were subsequently observed. Near rows of 3, and single, 150 nm deep, indentations, no voids were observed during the test.

The relationship of void nucleation and failure times versus the indentation zone length is summarized in Figure 3. In general, voids nucleated sooner and lines failed faster when the indentations were deep. However, the formation of a void was dependent on the total length of the mechanically deformed zone. There existed a minimum deformation zone length below which no void was observed at a given current density. For example, at 1×10^6 A/cm^2, voids were generated from the rows of indentations whose deformation zones were longer than about 8 μm, regardless of indentation depth. At 2×10^6 A/cm^2, the critical length was about 4 μm.

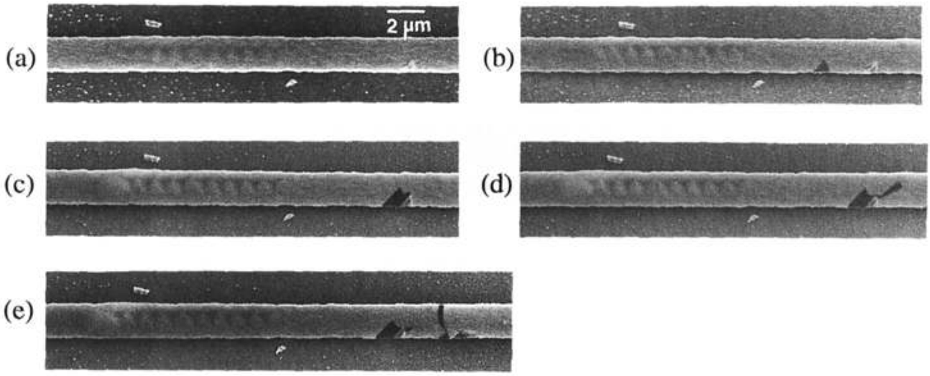

Figure 2. Evolution of electromigration damage associated with a row of 9, 150 nm deep, indentations (a) before electromigration testing, tested for (b) 20 hours, (c) 44 hours, (d) 67 hours, and (e) after failure (70 hours).

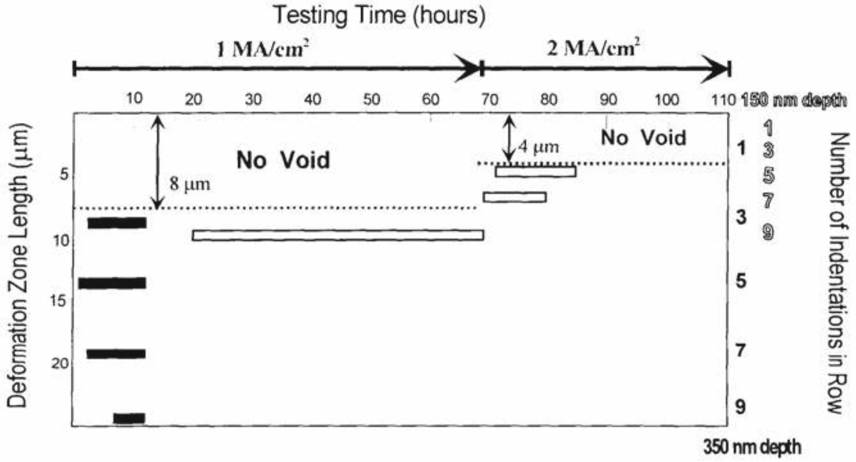

Figure 3. The nucleation and failure times of rows of indents having various deformation zone lengths. The bars indicate the times from void nucleation until failure. Solid bars correspondence to 350 nm and open bars to 150 nm deep indentations. At 1 MA/cm^2, no voids were observed from damage zones shorter than 8 μm, and at 2 MA/cm^2, voids were formed only from the rows of indentations longer than 4 μm.

Hillocks were observed at the anode-side ends of rows of 5, 7, and 9, 150 nm deep, indentations. They tended to first become noticeable only after voids were clearly observed. Hillocks also grew but did not move. No visible hillock was observed in the lines with 350 nm deep indentations.

DISCUSSION

The dramatically reduced electromigration lifetimes of indented single-crystal lines indicate that mechanical damage enhances electromigration damage processes in these lines. The fact that voids nucleate at the cathode end of the mechanical damage and that hillocks are formed at the anode end shows that flux divergences occur at these sites due to *faster diffusion along the indented region*. If electromigration-induced diffusion along the indented area were slower than in the rest of the single-crystal line, voids and hillocks would form at the opposite sides of the indented zone.

Indentation processes generate very high plastic strains and correspondingly high dislocation densities. The indentation depths in these experiments were 40 to 90% of the line thickness so that the plastically deformed zone extended through the line thickness for both types of indentation and across the line width as well for the 350 nm deep indentations. These stripes of mechanical damage must therefore contain a continuous region of high dislocation density. To the extent that dislocations can act as fast diffusion paths along this damaged zone (in comparison with diffusion through the single-crystal lattice or at Al/Al_2O_3 interfaces), the mechanically damaged stripe can act as a fast diffusion path for electromigration, similar to the grain boundary fast diffusion path in a polygranular segment in a near-bamboo line.

Due to the high dislocation density along the indented areas and the relatively high temperature of the electromigration tests (280°C is nearly 60% of the melting temperature of aluminum), some of the dislocations might be expected to anneal out or be eliminated through recrystallization. However, we believe that the material in the mechanically damaged region did not form random high angle grain boundaries for the following reasons. First, although the failure times of indented lines are much shorter than those of single crystal lines, they are still longer than those of polycrystalline lines. This indicates that diffusion along the indented area is less effective than diffusion along randomly oriented grain boundaries. Second, we have examined the grain orientations of the indented regions using both focused ion beam (FIB) and SEM back-scattered Kikuchi pattern analyses following electromigration testing. In the FIB examination, the indented area was first covered with Pt and a narrow vertical trench was milled through the Pt and Al layers and into the substrate using the FIB. The resulting cross-sectional view of the indented area could then be examined. Differences in orientation of 4 degrees or more can be identified by contrast differences in FIB images, but no contrast difference was observed. The backscattered Kikuchi patterns also confirmed that the grain orientations in the indented area did not differ from that of the single crystal region by more than 4 degrees. Thus the primary mass transport mechanism in the mechanically damaged regions is expected to be diffusion along the cores of dislocations (pipe diffusion), which might well have rearranged to form low angle grain boundaries.

The dislocation densities in the indented region can be estimated roughly from the failure times. The electromigration-induced flux along one dislocation core parallel to the line is

$$J = \frac{D_c A_c}{\Omega k T} Z^* e \rho j, \tag{1}$$

where Ω is the atomic volume, k Boltzmann's constant, T the absolute temperature, Z^* the effective charge, ρ the resistivity, j the current density, and $D_c A_c$ the effective dislocation core diffusivity. Using typical values for aluminum with a Z^* value of 20 and a value of $7.0 \times 10^{-17} \exp(-0.85 eV/kT)$ cm^4/s [5] for $D_c A_c$, the dislocation density can be calculated from the void volume and failure times. The resulting value of dislocation spacing is 8.5 nm for the deep indentations, and 22 nm for the shallow indentations.

A possible additional effect of indentations on electromigration is flux divergences induced by shape changes in the indented regions. Current crowding can occur at the sharp corners of the indentations or in regions where the line cross section is reduced. However, changes in cross-sectional area are expected to be negligible since the line can bulge out to the sides. The flux divergences arising due to indentation shape would occur on very short length scales *within* the indented region. However, voids and damage were only observed *outside* the indented region.

The electromigration behavior in a mechanically damaged stripe in a single-crystal line is phenomenologically similar to that of a polygranular segment in a near-bamboo line. There, flux divergences occur, and voids and hillocks are generated, at the ends of the polygranular segments. *In-situ* observations of near-bamboo lines have shown that voids are nucleated at the cathode-side of the polygranular segment and move towards the cathode [6].

The critical length of the mechanical deformation zone for void nucleation is similar to the critical length of polygranular segments below which no failure occurs [7]. In polygranular segments, the critical length effect has been explained as arising because electromigration generates local tensile and compressive stresses at the cathode and anode sides, respectively [8]. This stress gradient can prevent further electromigration for short segments. If a similar stress gradient also exists along the indented regions, voids or hillocks can form when the stress at the edge of the indented area is larger than the critical stress for nucleation. It is interesting that the value determined for the critical-current-density-length product $(jL)_{cr}$ is 800 A/cm, independent of indentation depth. This value is close to the values for unpassivated polycrystalline Al, 500 to 1200 A/cm, reported by other researchers [8, 9].

In lines containing a network of grain boundaries, local mechanical damage is not important for electromigration-limited reliability. However, in bamboo lines, it may significantly reduce the electromigration lifetimes of the interconnects. Therefore, special care should be taken to prevent local mechanical damage during the processing or handling of integrated circuits having bamboo-structured interconnects. From the experimental point of view, indented bamboo or single crystal lines are very convenient for electromigration study, because one can make and test a line which has a fast diffusion path in whatever length and location is desired, and one knows the void or hillock formation sites in advance.

CONCLUSIONS

We have generated local fast diffusion paths in single-crystal Al lines by making rows of nanoindentations placed close to each other. These fast diffusion paths are thought to be dislocation cores (which may be organized into sub-grain boundaries) rather than high-angle random grain boundaries. The electromigration behavior of mechanically damaged stripes in single-crystal lines is phenomenologically similar to that of the polygranular segments in near-bamboo lines. There exists a minimum deformation zone length for void nucleation, similar to the critical length of polygranular clusters in near-bamboo lines. Investigations of single-crystal lines with differing lengths of indented area, indentation depths, and heat treatments can provide insights into electromigration behavior as well as the interaction between electromigration and pre-existing mechanical damage.

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