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In Situ Study of Electromigration in Submicron-Wide Layered Al-0.5%Cu Lines by Side-View TEM Observation

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We made in situ transmission electron microscopy observation of electromigration in a submicron-wide Al-0.5%Cu-on-TiN line from the side of the line. Voiding at the cathode did not begin at the Al-TiN interface. Mass transport occurred even at ledges where essentially no current flow is expected. Voiding often accompanied vertical movement of faceted planes. The drift velocity at the cathode decreased after a certain current feeding time. The decrease was probably caused by separation of the Al.

1. INTRODUCTION

In situ observation of electromigration in Al lines for ICs by plan-view transmission electron microscopy (TEM)[1] has provided useful information, such as the effects of the microstructures of Al and precipitates on electromigration, and the dynamic behavior of voids. However, for analyzing electromigration in layered lines, which are commonly used in advanced devices, depth-resolved (side-view) observation is necessary. This is because voiding is influenced by the layer-interface properties in the layered lines. In addition, most of the reported plan-view observations have been for wide (>2 μm) lines. Therefore, these results cannot necessarily be applied to submicron-wide layered lines.

We have developed a side-view transmission electron microscopy (SVTEM) technique using an ultrahigh voltage electron microscope (UHVEM) and have used it for in situ study of electromigration in Al lines[2]. The significant advantage of SVTEM is that it provides depth-resolved information. In addition, since the substrates or lines do not need to be thinned, problems associated with use of thinned samples in the conventional technique are significantly reduced. We have made in situ SVTEM observation of submicron-wide layered Al-0.5%Cu lines. This paper presents the formation and evolution of voids at the cathode and between the cathode and the anode.

2. EXPERIMENTAL PROCEDURES

The lines used in this experiment had a drift-velocity-measurement structure (Fig. 1). The use of this structure provides the drift velocity and useful information for understanding electromigration in layered lines terminated by W plugs. The Ti and TiN were 2 μm wide and 0.2 μm thick. The Al-0.5%Cu line, which was 0.5 μm thick, 0.7 μm wide and 100 μm long, was overlaid on the central portion of the Ti/TiN conductor. All the conductor films were sputter-deposited in a vacuum. The lines were unpassivated, but a thin photoresist layer remained on the surface of the Al-Cu. The lines were annealed at 450 C for 30 minutes after fabrication. As-diced chips with a single line served as the SVTEM samples. The line, through which the current was fed, was observed intermittently from its side by TEM at a 2 MV acceleration voltage. The current was increased by stages up to $\sim$9 MA/cm^2. The SVTEM sample was heated, not intentionally but unintentionally, by joule-heating at the Ti/TiN portions. The temperature of the Al was not measured, but it may have been between 300-350℃ based on a comparison between the drift velocity obtained from in situ SVTEM measurements and those obtained from standard accelerated measurements.

3. RESULTS AND DISCUSSIONS

3.1. Voiding at the Cathode

The initial void at the cathode was created not at the Al/TiN interface but at a site 0.15 μm above the interface near the cathode edge (Fig. 2a). This suggests that voiding does not necessarily begin at either the highest current density site or the heterogeneous interfaces, and that the nucleation of voids rather than the generation of vacancies may have determined the voiding site in this case. The void grew first laterally and downward (Fig. 2b). After the void front reached the bottom surface, the void grew laterally and upward until the void front reached the grain boundary (Fig. 2c). This resulted in a ledge formation (Fig. 2c). Surprisingly the ledge shrank, although essentially no current flow was expected there. Part of the ledge shows a fairly sharp edge, suggesting formation of a faceted plane. When the first grain was almost depleted, the second grain began to deplete, probably from the Al/TiN interface at the anode-side of the grain boundary. The depletion proceeded mostly laterally (Fig. 2d) until the lateral front reached the second grain boundary. Then the void grew upward (Fig. 2e). Note that the edge of the ledge in the second grain is quite sharp, suggesting facetting of the bottom surface of the ledge. Analysis of the selected area diffraction pattern for the second grain shows that the ledge surface forms a {111} plane. Depletion in the third grain also started at the interface (Fig. 2f) and grew upward and laterally. A ledge with a {111} faceted plane also formed in the third grain.

Previous research has reported that Al depletion started from the edge of the Al line in tungsten plug contact structures with two and four contacts, although little current flow is expected there. Al was completely swept away from the contact area[3]. This fact may be accounted for by mass transport from the region without current flow, as observed in this experiment. Thinning of the ledge may be caused by surface diffusion of atoms on the ledge. Electromigration in the top region of the TiN/Al contact may act as a good sink for the surface-diffused atoms.

3.2. Voiding between the Cathode and the Anode

Most voids between the cathode and anode formed at the intersections between grain-boundaries and the Al surface. These voids grew predominantly downward toward the TiN surface (Figs. 3a-3b). After the Al separated, they grew laterally toward the anode (Figs. 3b-3c). Note that the cathode-side surface of the void did not move, while the anode-side surface moved toward the anode during growth. This fact contrasts with the reported void growth toward the cathode[4]. The difference in growth direction may have resulted from the difference in the line structure in these cases. The Al line used in this experiment is nearly bamboo-grained and is layered on a TiN conductor. When the Al separated, the anode-side void-front acted as a new cathode. Thus the edge was displaced toward the anode by electromigration due to electrons flowing from the TiN into the new cathode. In the reported single-layered wide lines with a normal grain structure, voids tended to form at the grain boundary triple junctions. The mass transported from the void into the grain boundaries connected to the void supplied from the void surface, particularly that at the intersection of the void trailing edge and the grain boundary connected to the void. This may be because the migration of atoms through the void surface (clean surface) is expected to be much faster than that in the grain boundary connected to the void trailing edge. Thus the atoms are removed and migrate from the intersection between the void trailing edge and the grain boundary, resulting in void growth toward the cathode.

Some voids shrank and disappeared (Figs. 3d-3e). Note that the anode-side edge of the void moved backward during shrinkage, but the cathode-side edge remained stationary.

3.3. Mass Transport

Figure 4 shows the average depletion length versus current feeding time. The average depletion length, which was defined as the side-view depletion area divided by the Al thickness, increases linearly with time. The drift velocity at the cathode, which is given by the increase rate of the average cathode depletion length, decreased to ~half the initial value at ~100 min. A similar decrease was also observed in the pure Al-on-TiN case, where the decrease was attributed to separation of the Al[2]. The decrease in the present case may be also caused by separation of the Al.

4. CONCLUSION

The following results have been obtained from in situ side-view transmission electron microscopy (SVTEM) observation of electromigration in a submicron-wide Al-0.5%Cu-on-TiN line. 1) Voiding at the cathode began not at the Al-TiN interface but ~0.15 μm above it. 2) Mass was transported even from ledges where essentially no current flow is expected. 3) Voiding often accompanied vertical movements of faceted planes. 4) Voiding between the cathode and the anode began at the intersection between the grain boundaries and the Al top surface, and proceeded predominantly downward till the Al separated and then laterally toward the anode. 5) Separation of the Al, which was caused by extensive growth of voids, probably decreased the drift velocity at the cathode.

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2) H. Okabayashi, H. Kitamura, M. Komatsu and H. Mori, presented at the Third Int. Workshop on Stress-Induced Phenomena in Metallization, Stanford Univ., June 21-23, 1995.
3) H. Kawasaki, C. Lee and T-K. Yu, Thin Solid Films, 253(1994)508.
4) C.Y. Chang and R.W. Vook, Mat. Res. Symp. Proc. Vol. 225, p. 125.

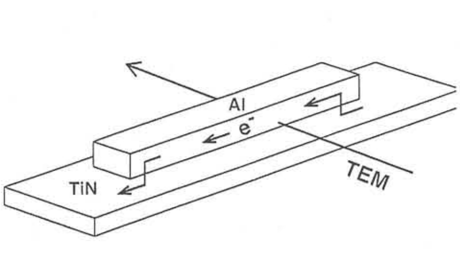
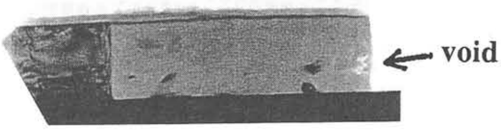
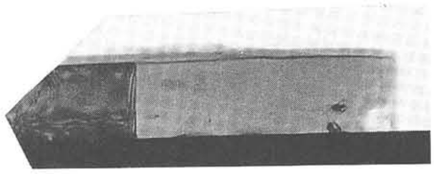


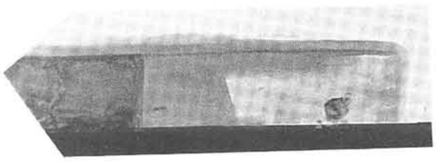
Fig. 1. Line structure and direction of TEM observation.



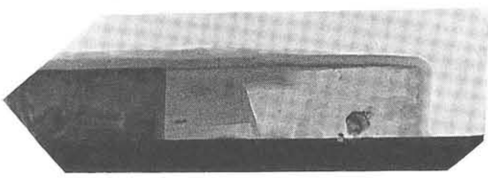
(a) t_1=10M



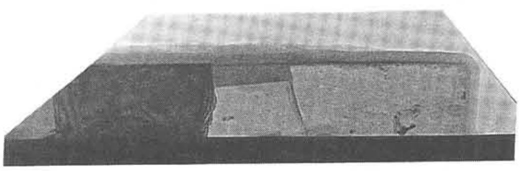
(b) t_1=36M



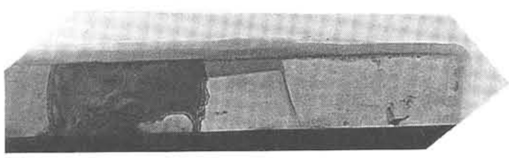
(c) t=111M



(d) t=143M

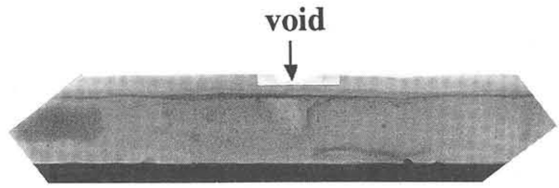


(e) t=250M

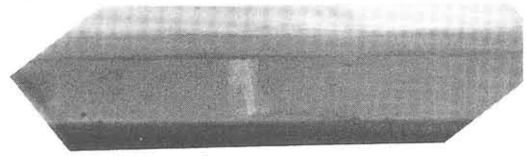


(f) t=281M

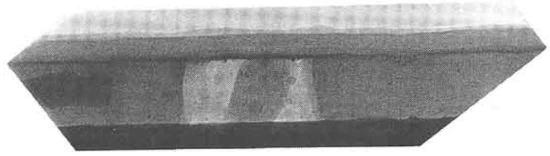
Fig. 2. SVTEM images showing growth of a void at the cathode. t_1 and t are the current feeding time at j=~8 MA/cm^2 and at j=~9 MA/cm^2, respectively.



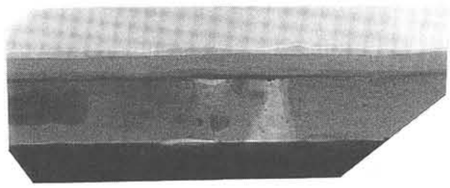
(a) t=20M



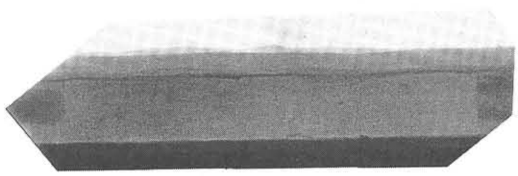
(b) t=57M



(c) t=103M



(d) t=140M



(e) t=175M

Fig. 3. SVTEM images showing the growth of a void formed between the cathode and the anode. t is the current feeding time at j=~9 MA/cm^2.

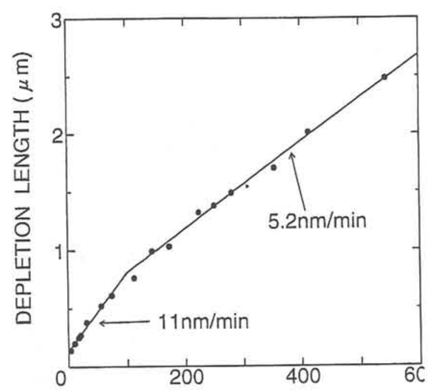


Fig. 4. Average cathode-depletion length as a function of time.