Hillock formation during electromigration in Cu and Al thin films: Three-dimensional grain growth

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The evolution of microstructure in Al and Cu thin film lines during electromigration has been studied using a transmission electron microscopy. Grain boundary migration was found to be critically involved in the electromigration induced hillock formation that can be described as a three-dimensional growth of a single grain. © *1995 American Institute of Physics.*

Electromigration (EM) damage in metal interconnection lines is a serious problem in the microelectronic industry. Al is the most commonly used as an interconnect material; and Cu is considered to be the most promising alternative for Al.[1–4] Recent observations show that the Cu lines may suffer from the same EM reliability problem as the Al ones.[5–8] The goal of our work was to reveal and compare microstructural changes in Al and Cu lines during EM.

An Al film of 160 nm thickness and a Cu film of 100 nm thickness were fabricated by e-beam evaporation onto an oxidized Si substrate at 200 °C in a vacuum of 5×10^{-7} Torr. The films were annealed at 400 °C during 0.5 h and patterned using a photolithography method to form four-probe geometry specimens with the linewidth of 10 μm and length of 100 μm. The direct electrical current with a density of 10^7 A/cm^2 was applied during 10 h, in vacuum at 200 and 350 °C for Al and Cu, respectively. The structure of the specimens was studied by using a transmission electron microscope Philips EM 300 at 100 kV.

Since the current distribution was not homogeneous near the contact pads, which could lead to a local heating we have chosen to investigate the structure of the damages only in the regions far from the pads. We compared the grain structure in the conductor lines stressed by the electrical current with that for the unstressed lines. Hillocks and voids were observed only in the stressed lines. We found significant grain growth in the areas of hillock formation, whereas far from hillock, the structure was similar for stressed and unstressed films. In the Cu film with the grain size of (0.03–0.2) μm we observed that the grain size increased up to 1 μm in the hillock area, Fig. 1(a). In the Al film, the grain size increased from (0.1–0.3) μm to 1 μm, Fig. 1(b). Such large grains were not observed in the unstressed lines.

The structural investigation described below in detail is focused on one region of the hillock creation in Al. However, it should be emphasized that the depicted area is a typical representation of the damaged areas. In Fig. 2(a) the region of increased film thickness (hillock) is clearly seen (the thicker region is darker due to the absorption contrast). The hillock covers a group of several adjacent grains (grains 1, 2, 3, and 4). We have analyzed the hillock structure using a goniometer stage which allowed to bring Bragg angle each grain from the group separately. Figures 2(b)–2(d) show the grains 1, 2 and 3, 4, respectively, at Bragg conditions. Fringes, so-called "thickness contours" (TCs),[9] in the grains indicate thickness variation, which can be estimated as $n\xi_g$, where n is the number of TCs and ξ_g is an extinction length. For our conditions $\xi_g=\xi_{111}\simeq55$ nm.

It is seen from comparison of the Figs. 2(b)–2(d) that the grain 1 overlaps the grains 2, 3, and 4. According to the observed TCs, all the grains have the variable thickness in the regions of overlapping. Therefore, the boundaries between grain 1 and grains 2, 3 and 4 are inclined. Up to three TCs in the areas of overlapping in the grains 2, 3, and 4 indicate the variation of their thickness to $\simeq3\xi_{111}$ that is about the film thickness. Up to seven TCs are observed on the image of the inclined boundaries ABD, BCD, and AFE of the grain 1, while not more than three TCs may appear for the film of 160 nm thick. It means that the grain 1, beside its thickness variation due to boundary inclination, has the thickness increase of about 220 nm ($4\xi_{111}$). Indeed, four TCs in the region BCHGE are related to the hillock whereas the other three TCs are hidden since the grain boundary (GB)

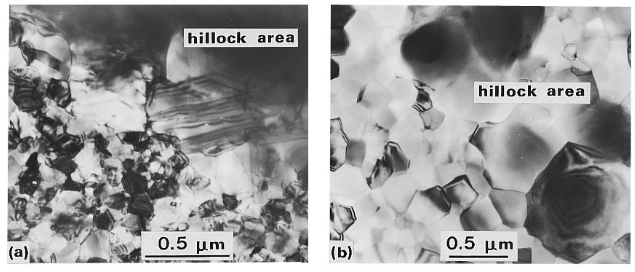

FIG. 1. Grain growth in lines of Cu (a) and Al (b) stressed by electrical current.

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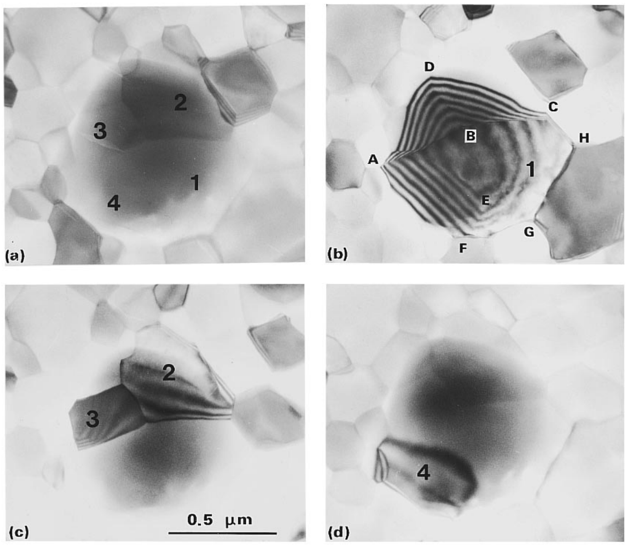

FIG. 2. The hillocked region in Al line. All four TEM micrographs show the same place, but were obtained at different specimens' tilt angles.

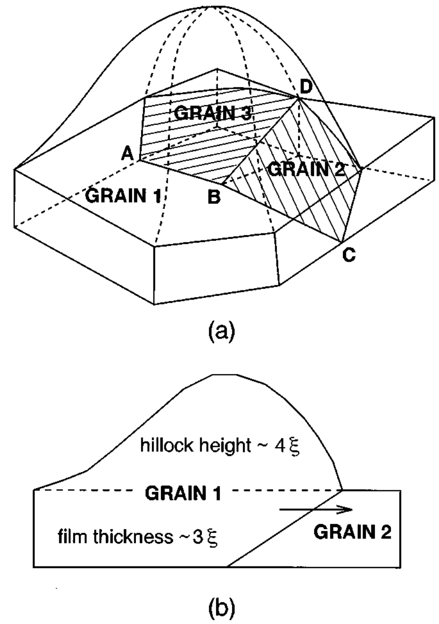

FIG. 3. The scheme of the hillock: spatial geometry (a) and cross section of the hillock through the grains 1 and 2 (b). Arrow shows the direction of the GB migration that yields the lateral growth of hillocked grain 1.

from this side is nearly vertical (they can be resolved at facet CH).

The above analysis results in the spatial geometry of the hillock, depicted in Fig. 3. The thickness increase belongs only to the grain 1 with boundaries strongly inclined from the normal position roughly perpendicular to the film plane. Such large inclinations (more than 50°) were never observed in the unstressed film and, hence, are a result of GB movement. The peak of hillock is formed near the triple junction with the boundaries which experienced migration.

Related observations on Cu lines have revealed the same characteristic features of hillocks regions although small grain size and numerous twins make their observation more difficult.

To summarize, the important results are as follows: (i) only the grains which experienced lateral growth are the hillocked ones and the majority of them overlay triple junctions; (ii) the higher the hillock above the film surface, the larger the area hillock occupies; (iii) each grain-hillock has at least part of its boundaries tilted considerably to the film surface. Therefore, it can be concluded that two tightly connected processes are involved in the hillock formation: first is the increase of the grain thickness, second is GB migration and, so, hillock formation can be described as three-dimensional grain growth.

Now, a few comments can be made on the possible relationship between the GB migration and the hillock growth. Positive mass flux divergence at the triple junction causes the climb of GB dislocations that results in both GB migration and sliding. Compressive stress due to the climb of GB dislocations can be relieved by lattice dislocations, which are emitted from the GB steps and glide to the free top surface. Emitting of the lattice dislocations is accompanied by a change of the GB step height that should lead to reorientation of the whole GB profile and can be seen as the GB tilt. The GB sliding and exit of the lattice dislocations on the surface result in increase of the grain thickness, hillock growth.

It would be interesting to study the orientation relationship between the grains at the hillock area. The small size of the grains made it extremely difficult to address this issue in this work. This, however is planned to be investigated in the future.

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