

Observation of Void Formation Induced by Electromigration in Metallic Films *,**

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Observation has been made on void formation induced by electromigration in single crystal and bicrystal (100) Au films and polycrystalline Al films. In the Au film, voids were observed to be bound by crystal planes with low surface energies, and dislocations appeared to be the preferred sites for void formation. In the Al film, void formation was observed to begin at grain boundaries or grain boundary junctions. Under our experimental conditions, the formation of voids and hillocks is determined by the local concentration of defects at the grain boundary, but the overall effect is determined by the divergence of the diffusion flux under a temperature gradient.

Introduction

Recently, void formation in metallic films carrying high direct current densities has drawn considerable interest due to its technological importance in semiconductor devices¹. Such damage is generally known to be caused by electromigration². Metallic ions are driven by the conduction electrons and can precipitate at certain sites of lattice imperfections to form hillocks. Similarly, vacancies diffusing in a direction opposite to the ions can precipitate into voids at imperfection sites. The formation of hillocks (or voids) requires the net accumulation of the migrating ions (or vacancies) at the precipitation sites, i. e., the local divergence of the diffusion flux must be nonvanishing at the site. This condition is generally present in a metallic film due to either structural imperfections, e. g., grain boundary junctions, or a steep temperature gradient produced by the current. ATTARDO and ROSENBERG³ observed that structural defects are the primary sites for void formation in an aluminum film evaporated on a SiO₂ layer thermally grown on a Si wafer. Voids and hillocks were found to form randomly at grain boundaries and in the constant temperature portion of the film. On the other hand, BLECH and MEIER-

RAN⁴ observed electromigration damage in Al film supported on thin SiO₂ layer of about 1000 Å with the characteristics of the temperature gradient effects, i. e., void formation on the cathode side and hillock formation on the anode site. Both of these experiments showed that grain boundaries are the preferred sites for void formation and that the measured activation energy for void growth is 0.7 eV, consistent with that for grain boundary diffusion.

In this work, we planned to study mainly the grain boundary effects on void formation. We chose to study single-crystal and bicrystal Au films and polycrystalline Al films with highly oriented grain structures. The Au films were used to observe void formation in a film without any grain boundary or with a boundary of controlled orientation and dislocation structure. Al film can be evaporated under controlled conditions to yield relatively uniform grain boundary structure. Our aim was to study void formation in such film in order to reduce the number of parameters required for studying the effects of grain boundary structure. Here we report some of the preliminary results observed and we plan to have more detailed results reported in the near future.

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¹ I. A. BLECH, Report for Contract No. A.F. 30(602)-3776. Rome Air Development Center, December 1965; D. S. CHHABRA, N. G. AINSLIE, and D. JEPSON, Electrochem.

Soc. Meeting, Dallas, Tex., May 1967; P. B. GATE, Appl. Phys. Letters **11**, 14 [1967]; I. A. BLECH and E. S. MEIERAN, Appl. Phys. Letters **11**, 263 [1967]; R. ROSENBERG and L. BERENBAUM, Appl. Phys. Letters **12**, 201 [1968]; J. R. BLACK, IEEE Trans. Elect. Devices **16**, 338 [1969].

² See the review articles by H. B. HUNTINGTON and P. S. HO, J. Phys. Soc. Japan, Supplement II, **18**, 202 [1963] and H. B. HUNTINGTON, Trans. AIME **245**, 2571 [1969].

³ M. J. ATTARDO and R. ROSENBERG, J. Appl. Phys. **41**, 2386 [1970].

⁴ I. A. BLECH and E. S. MEIERAN, J. Appl. Phys. **40**, 485 [1969].



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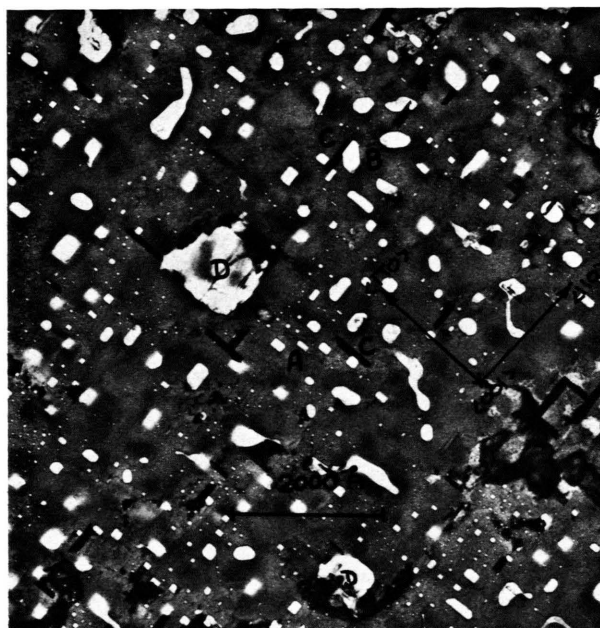


Fig. 3. Void formation observed in a single crystal Au film. Current passing time, 7 hrs. Current density 3×10^6 amp/cm². Maximum temperature about 450 °C. Film orientation [001], thickness 1000 Å.

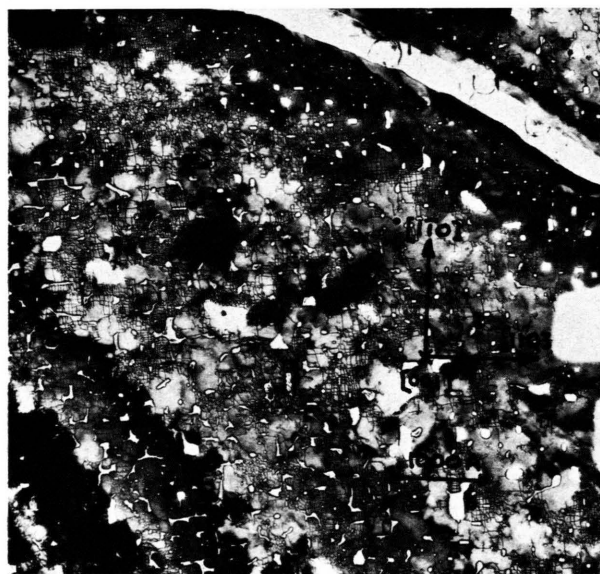
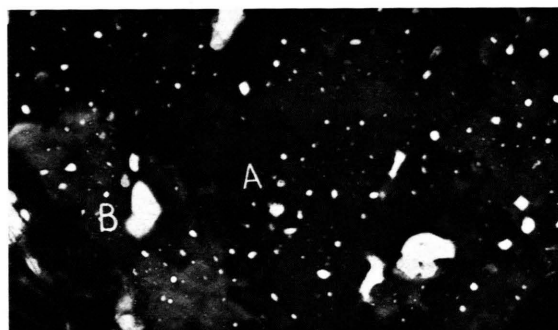
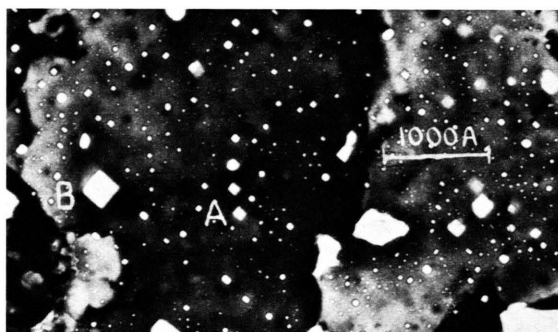


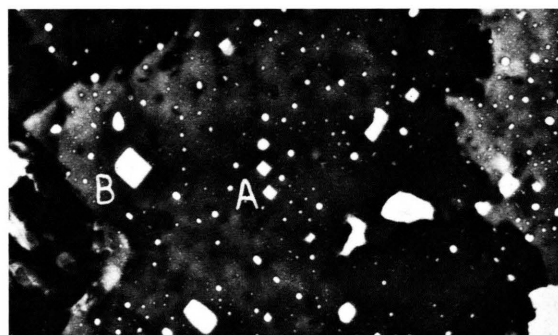
Fig. 4. Void formation observed in a [001] bicrystal Au film. The interface is a small angle pure twist boundary. Note the orthogonal network of dislocations along the $\langle 110 \rangle$ directions. Film thickness 1000 Å. Other experimental conditions are similar to the film shown in Fig. 3.



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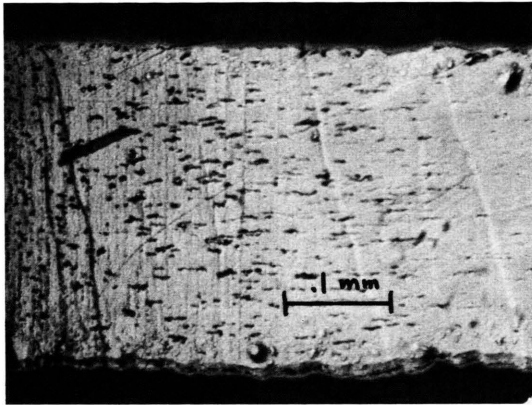


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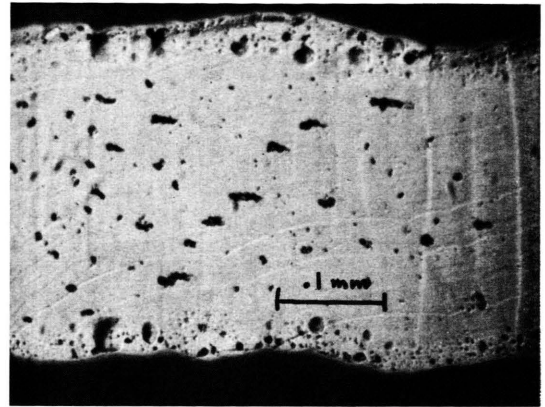


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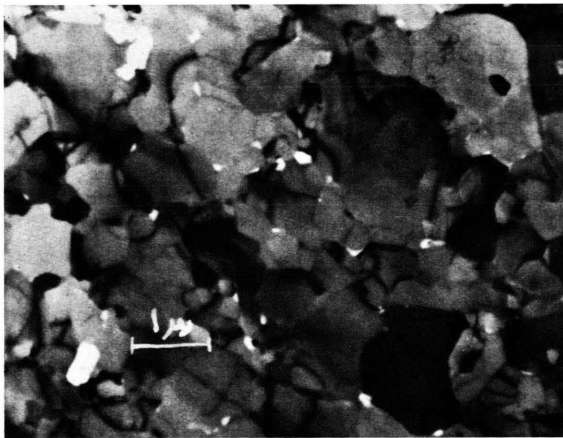
Fig. 5. a to c shows a sequence of in situ observation of void formation in a [001] single crystal Au film. Time between pictures is about 1 hour. Other experimental conditions are similar to the sample shown in Fig. 3. Note the void growth at A and B.



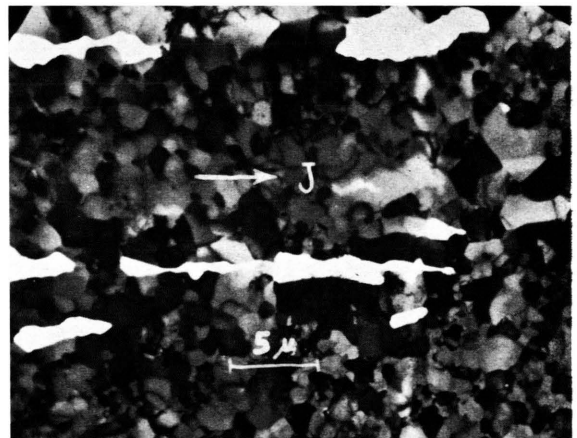
6 a



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7 a



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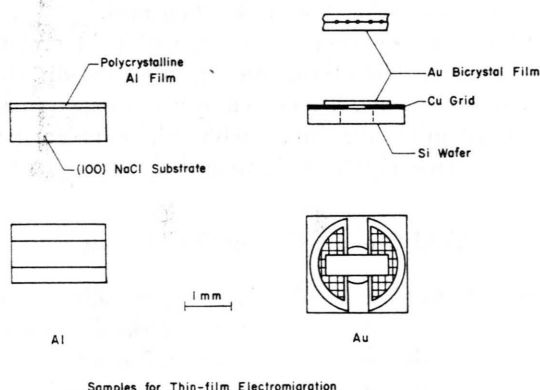
Fig. 6. Optical micrographs showing void formation on the cathode side of an Al film (a), and hillock formation on the anode side (b). Magnification, $200\times$. Substrate temperature 250°C , film thickness 3500 \AA , current density $6\times 10^5\text{ amp/cm}^2$, current passing time 12 hours.

Fig. 7. a) shows the early stage of void formation in Al film. Note that almost all the voids are formed at the grain boundaries or grain boundary junctions. b) shows a late stage of void formation; the current flow is parallel to the growth direction of the voids.

Sample Preparation

To prepare the single crystal Au film, a single crystal silver film of about 300 Å was first deposited on the NaCl crystal substrate, then the Au film was epitaxially deposited on the silver layer at a substrate temperature of 200 °C⁵. The Au film produced was observed in the electron microscope and found to contain a very low planar defect density, about 10^3 to 10^6 cm⁻². A bicrystal Au film containing a grain boundary interface with known dislocation structure can be made by welding together two such single crystal films with proper orientations. For example, a pure twist (100) boundary can be formed by welding two (100) crystals with an angular misorientation about the [001] axis⁶.

After cutting the Au film to a size of 1/3 mm by 1.5 mm, it was stripped from the substrate by dissolving the silver layer and the NaCl substrate. Then it was carefully suspended between two halves of a Cu grid which were glued to a silicon wafer by silver paint. Figure 1 shows the details of the Au sample. The Si wafer was placed between the



Samples for Thin-film Electromigration

Fig. 1. Details of samples used for observing void formation in Al and Au films.

two electrodes in the grid heater stage of the AEI EM6 Electron Microscope. This arrangement allowed us to make in situ observations of void formation while a constant direct current passed through the sample.

The Al film was evaporated in a vacuum of 10^{-7} Torr on a {100} cleaved NaCl crystal surface.

The substrate temperature varied from 350 °C to 400 °C and the evaporation rate was about 45 Å/sec. The film thickness was usually of 3000 Å to 4000 Å. Under these conditions, we found that the grains have a preferred orientation along [111] axis and the grain size is about 1.2 microns and relatively uniform. The film strip of about 1/4 mm wide was made by covering the substrate during evaporation with a mask with the proper openings. After cutting the sample to about 2 mm long, it was placed between two electrodes on a small heater inside a vacuum chamber. We used the heater to control the substrate temperature to ± 1 °C, and passed a constant current through the film. Usually three films passing different current densities were placed on the same heater and tested together. An infrared pyrometer was used to measure the temperature distribution. We observed that the maximum temperature exceeded the substrate temperature by an amount which was generally quite small but a function of the current density. (See Fig. 2 for a typical temperature distribution.) By solving the heat flow equation for the film, we found that the above observation is not surprising since the heat generated by the current is almost completely conducted away due to substrate cooling⁷. Generally, we monitored the film temperature during the course of the run and found that the temperature distribution remained steady for most of the run except at the end when considerable amounts of void formation were present. At the completion of the experiment, the film was stripped from the substrate and observed in the electron microscope.

Void Observation on the Au Film

In the single crystal Au film, we observed formation of polyhedral voids which were evidently induced by electromigration since no voids were observed under alternating current. Most of the voids observed were bound originally by the low index planes {111} and {110}, the two crystal planes which have been measured to have the lowest surface energies⁸. In Fig. 3* we show a typical micrograph of voids observed in a (100) Au film. Most

⁵ For a detailed description of the process, see T. SCHÖBER, *J. Appl. Phys.* **40**, 4658 [1969].

⁶ For observation and analysis of the grain boundary structure, see T. SCHÖBER and R. W. BALLUFFI, *Phil. Mag.* **20**, 511 [1969].

⁷ P. S. Ho, to be published.

* Fig. 3—Fig. 7 on p. 32 a, b.

⁸ W. L. WINTERBOTTOM and N. A. GJORSTEIN, *Acta Met.* **14**, 1041 [1966].

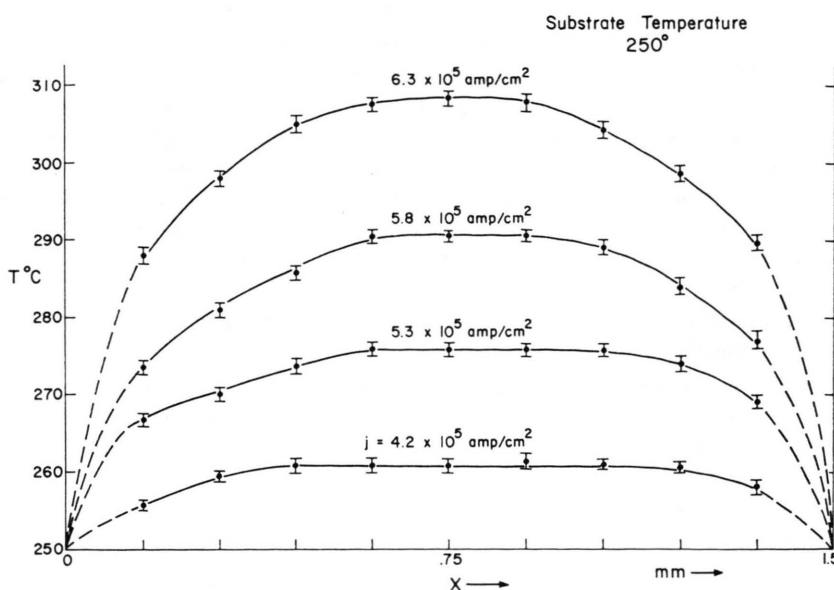


Fig. 2. Temperature distribution measured on the Al sample.

of the void boundaries are parallel to the $\langle 110 \rangle$ directions (see A in Fig. 3); the geometry is consistent with a (100) cut of an octahedron formed by the $\{111\}$ planes (surfaces with the lowest surface energy). A smaller number of boundaries are parallel to the $\langle 100 \rangle$ directions, which is consistent with the intersection of a (100) plane with the $\{110\}$ type planes (see B in Fig. 3). To minimize the void surface energy also appeared to be a reason why some voids were anchored at the stacking faults (see C in Fig. 3). When a void touched the stacking fault, further growth tended to be along the fault in order to reduce surface energy. The equilibrium void shape with minimum surface energy has also been observed for void formation in other metals when subjected to neutron irradiation⁹.

Crystallites of 1000 Å to 2000 Å size are seen to form in the proximity of some voids (see D in Fig. 3). This indicates that precipitation of excessive atoms or vacancies depends primarily on the local concentration of the defects, an observation which was emphasized by ATTARDO and ROSENBERG³ for void formation in Al film. A large number of small voids were observed along dislocations; it appears that dislocations, acting as high diffusivity paths, can facilitate void growth. This is further supported by the observation of the early stage of void formation in the bicrystal sample (see

Fig. 4). However, it is not clear whether dislocations are the preferred sites for nucleation or whether voids, after being nucleated, are driven by the current to the dislocations and then grown.

In Fig. 5, we show a sequence of void growth in a (100) single crystal Au film observed directly in the microscope. There, one can see many small voids attaining the shape with minimum surface energy at an early stage of formation.

Void Observation on the Al Film

We observed that voids formed generally on the cathode side of the sample and hillocks formed on the anode side (see Fig. 6). In Fig. 7a, we showed the initial stage of void formation. The voids are seen to form initially at the grain boundaries or grain boundary junctions. This observation agrees with the previous experiments^{3,4} that grain boundaries are the preferred sites for void formation. At a later stage, the voids tended to grow along current flow direction (see Fig. 7b). These observations indicate that under our experimental conditions, even though void formation is caused by the local supersaturation of defects at the grain boundaries, the overall characteristics of electromigration damage is primarily determined by defect precipitation under a thermal gradient, an observation similar to that of BLECH and MEIERAN⁴. However, our film was evaporated on NaCl substrate, so we ex-

⁹ See for example, C. L. KULCINSKI, B. MASTEL, and J. L. BRINHALL, *Radiation Effects* **2**, 57 [1969].

pected that because of more effective substrate cooling, the temperature gradient in our film should be significantly less than the value obtained by Blech and Meieran, and was probably close to that in the experiment of ATTARDO and ROSENBERG³. In our film, there is a highly preferred grain orientation and the grain size is quite uniform; these may be important factors in determining the overall characteristics of the void formation that we observed. Further investigation on the characteristics of the void formation as a function of the grain structure, substrate condition and film temperature distribution appears to be worthwhile. We are continuing our efforts in this direction and hope to report some results shortly.

Under proper diffraction conditions, we were able to determine that all voids started from the

upper film surface and not from the interface between the film and the substrate. This observation may have some practical importance in reducing electromigration damage by surface treatment. From the void shape, it appeared that grain boundary grooving caused by surface electromigration may be the important mechanism for void growth in polycrystalline films. Such a mechanism has been proposed by OHRING and ROSENBERG¹⁰.

Acknowledgement

The authors wish to thank Dr. T. SCHÖBER for supplying the Au film in this work and also for valuable discussions, also Mr. H. C. SHIH for preparing the Al samples.

¹⁰ M. OHRING and R. ROSENBERG, AIME Fall Meeting, Philadelphia, October 1969.