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Citation: [Journal of Applied Physics](#) **95**, 7742 (2004); doi: 10.1063/1.1712019

View online: <http://dx.doi.org/10.1063/1.1712019>

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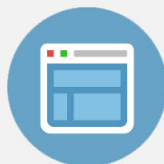
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Tin whisker growth driven by electrical currents

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(Received 4 August 2003; accepted 1 March 2004)

Tin whisker growth was investigated in pure Sn using Blech structure. Blech structure was used to investigate the electromigration behavior in pure tin, in which 5000 Å tin strips were on 700 Å titanium films. Tin whiskers grew on the anode side, and voids were observed on the cathode side after stressing at the current densities of 7.5×10^4 and 1.5×10^5 A/cm² at room temperature. To investigate temperature effect, samples are stressed at room temperature and 50 °C. The whisker growth rates were estimated to be 3 and 7.7 Å/s at room temperature and at 50 °C, respectively, in the current density of 1.5×10^5 A/cm². The whisker growth rate reduced to 0.4 Å/s at the current density of 7.5×10^4 A/cm², which is still faster than that driven by mechanical stress. Transmission electron microscopy results showed that the whiskers are single crystalline and a thin Sn oxide formed on their surfaces. The mechanism of tin whisker growth driven by electrical force is proposed in this article. © 2004 American Institute of Physics. [DOI: 10.1063/1.1712019]

I. INTRODUCTION

Tin whisker growth is an important reliability issue in lead-frame packaging.¹⁻³ The lead-free or lead-based solder finish on lead frames enhances wetting reaction during the mounting of the lead-frame legs to the print circuit board. Typically, the lead-free solder finish consists of eutectic SnCu or pure Sn. Nevertheless, Sn whiskers have been found in SnCu finish on the legs of lead frame, which may bridge the legs and cause electrical failure.³ Also, the Sn whisker has been a reliability problem in the aerospace applications. It was reported that control processors in commercial satellites fail due to tin whisker-induced short circuits where the whiskers grew on pure tin plated relays.⁴ It is commonly observed that the whiskers grew spontaneously during a storage at room temperature. The average growth rate of whiskers driven by mechanical stress is about 2 Å/s, and the typical length of a whisker is about a few tenths of a millimeter.⁵⁻⁷

With environmental concerns, the trend in the microelectronic package is forward to lead-free solution, instead of well-established SnPb platings. Tin is the richest element for most of the lead-free solders, and is a reactive species with Cu or Ni to form metallic bonding.^{8,9} Especially in the lead frame with the SnCu solder finish, tin whiskers grow rapidly.^{3,8} Such a high content of tin in lead-free solders is a concern under high current densities in microelectronic packaging. Liu, Chen, and Tu reported that Sn whiskers grew on pure tin films at the current density of 7.5×10^4 A/cm² at near ambient temperature.¹⁰ Therefore, tin whisker growth driven by electrical currents would be one of the most crucial reliability issues as the dimension of the microelectronic packages keep shrinking.

However, only few researches have been done on the Sn whisker growth driven by electrical currents.^{10,11} The electromigration behavior of pure Sn is unclear, and the growth rate of Sn whisker driven by electrical currents is still unknown. In this study, high current densities and elevated testing temperature are employed to perform an accelerated electromigration test on the tin whisker growth. Blech structure is adopted to investigate the electromigration behavior, in which a conductive film is deposited on a resistive film, as shown in Figs. 1(a) and 1(b). Current crowding occurs on both ends of the conductive film. Voids form on the cathode end, and hillocks accumulates on the anode end. Thus depletion volume caused by electromigration could be measured accurately in this specimen.¹²

II. EXPERIMENT

A. Fabrication of Blech structure

The substrate used in this experiment was a *n*-type four-inch (100) wafer. To fabricate the insulator SiO₂ on the silicon wafer, wafers were first cleaned, and then an oxide layer of 5000 Å was grown using wet oxidation method. *E*-beam evaporator was used to deposit a 700 Å titanium film on the substrate, and then a 5000-Å-thick tin film was deposited on the titanium film without breaking vacuum. The first-level mask and lithography process were applied to define Sn strips. The Sn film was selectively etched by the solution of FeCl₃ + H₂O at the ratio of 1:10. Afterward, the second-level mask was applied to define Ti pads, which served as electrical current probing pads. The titanium film residual was stripped away by the solution of NH₄OH + H₂O₂ at the ratio of 1:5. Figures 1(a) and 1(b) show the schematic drawing of the cross-section and plan-view of the test sample, respectively. Current was applied through the two probes. The cur-

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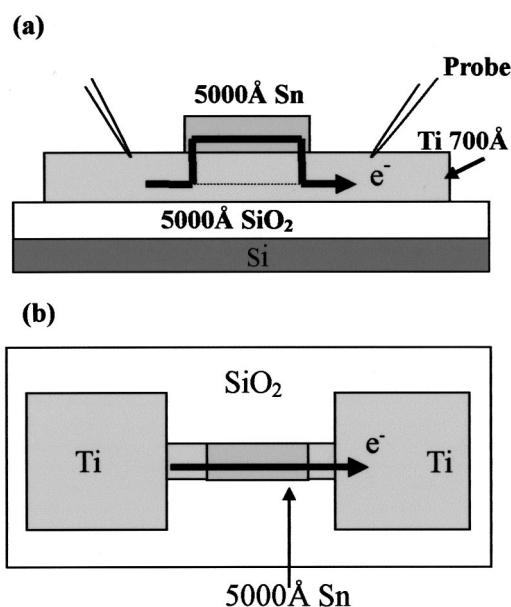


FIG. 1. Schematic drawing of a test sample and the direction of electron flow (a) cross sectional-view (b) plan-view.

rent source used in this study was Keithley 2400 $I-V$ source meter. The resolution of the current output was 500 nA.

B. Testing conditions

Three different stressing conditions were used in this study as shown in Table I. The current density estimated from the thickness and resistivities of Sn and Ti films. The Sn strip was 50 μm in width and 400 μm in length.

C. Cross-sectional TEM samples prepared by focused ion beam

Before the focused ion beam (FIB) etching, an epoxy coating of a thin stripe was deposited on the tin film to protect the whiskers from being etched away by focused ion beam. A thin slice was then cut along the direction of the whisker length. The dimension of this thin slice was about 15 $\mu\text{m} \times 10 \mu\text{m} \times 0.1 \mu\text{m}$. After the epoxy coating, FIB etching, and thin slice cutting were completed, the prepared samples were analyzed by transmission electron microscopy (TEM).

TABLE I. List of testing current, corresponding current density, and temperature for the investigation of Sn whisker growth.

	Sample 1	Sample 2	Sample 3
Testing current (mA)	40	20	40
Current density (A/cm^2)	1.5×10^5	7.5×10^4	1.5×10^5
Temperature ($^\circ\text{C}$)	Room temperature	Room temperature	50 $^\circ\text{C}$

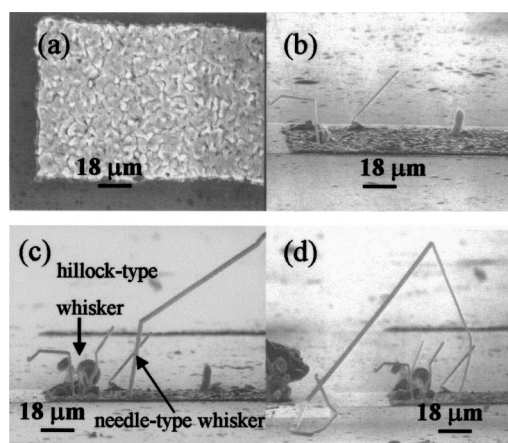


FIG. 2. SEM images of the anode end after the current stressing of $1.5 \times 10^5 \text{ A}/\text{cm}^2$ at room temperature for (a) 0 h, plan-view (b) 50 h, tilted-view (c) 160 h, tilted-view, and (d) 260 h, tilted-view.

III. RESULTS

A. Electromigration at room temperature under current density of $1.5 \times 10^5 \text{ A}/\text{cm}^2$

Figures 2 show the morphology evolution of the Sn film as a function of time up to 260 h under current density of $1.5 \times 10^5 \text{ A}/\text{cm}^2$. As shown in Fig. 2(a), no whisker was observed on the test sample with Sn film deposit before current stressing. We found the formation of whiskers after current stressing on tin film at room temperature. The whiskers had the striation on their surface as reported in the literature.³⁻⁷ Two types of whiskers grew after the current stressing: needle-type and hillock-type whiskers, as indicated by arrows in Fig. 2(c). Since needle-type whiskers would be more critical to the reliability issues in the microelectronic packaging, we will investigate the growth of the needle-type whiskers. In the following text, needle-type whiskers will be referred as simply whiskers, and the hillock-type whiskers will be referred to as hillocks. The diameter of whiskers was measured to be 1 to 2 μm , and the length of the whiskers was up to 200 μm after 260-h current stressing. The theoretic resistivities of pure tin and titanium are 11 and 39 $\mu\Omega \text{ cm}$, respectively. Therefore, 95% of current drifted in the Sn film. Current crowding occurs at the two ends of the tin film as depicted in Fig. 1(a). Electromigration stress pushed tin atoms from the cathode to the anode and produced a compressive stress. This stress was released in the form of whisker growth and extrusion.¹⁰

Most whiskers continued to grow with increase in the stressing time as shown in Fig. 2, while some whiskers stopped growing after some period of time. The locations where hillocks or whiskers grow seemed irrelevant to surface morphology of the tin film and may be related to the stress relaxation in the weak spot of the tin film^{5,10} where the surface oxide has been broken on the tin surface.^{10,13} The total volume of whisker increases with an increase in the stressing time. The growth rate of whisker was measured to be 3 $\text{Å}/\text{s}$ at the current of $1.5 \times 10^5 \text{ A}/\text{cm}^2$ at room temperature. This growth rate was 15 times faster than that driven by mechanical stress.⁵

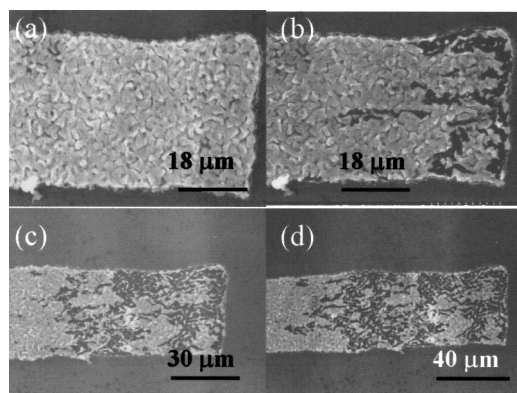


FIG. 3. Plan-view SEM images of the cathode end after the current stressing of 1.5×10^5 A/cm² at room temperature for (a) 0 h, (b) 50 h, (c) 160 h, and (d) 260 h.

As shown in Fig. 3, voids appeared on cathode side of the Sn strip after the current stressing. Voids formed near the cathode side and were found with less density toward the anode side. After stressing for 260 h at room temperature with a current density of 1.5×10^5 A/cm², the Sn film was depleted for approximately 20% out of total area.

B. Current density effect: Electromigration at room temperature under the current density of 7.5×10^4 A/cm²

There was only one whisker found under the current stressing of 7.5×10^4 A/cm² up to 280 h. The whisker grew near the middle of the strip, as indicated by the arrow in Fig. 4(a). The whisker started to grow around 20-h current stress-

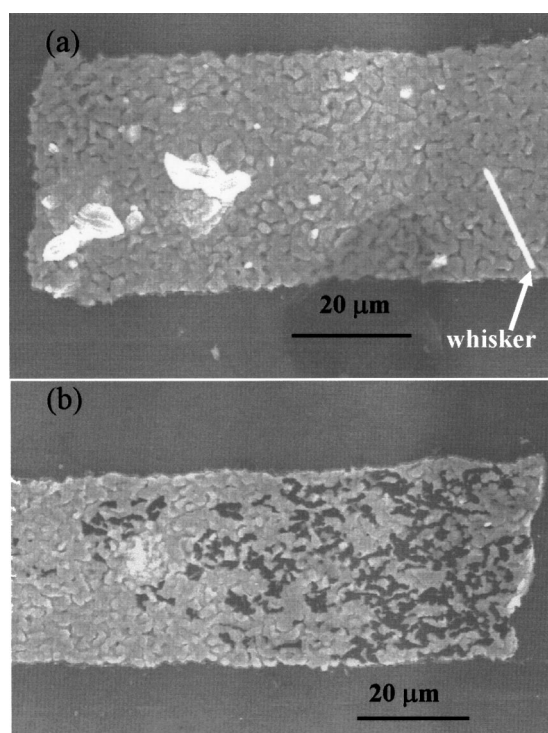


FIG. 4. Plan-view SEM images of the Sn strip after the current stressing of 7.5×10^4 A/cm² for 280 h. (a) Anode end and (b) cathode end.

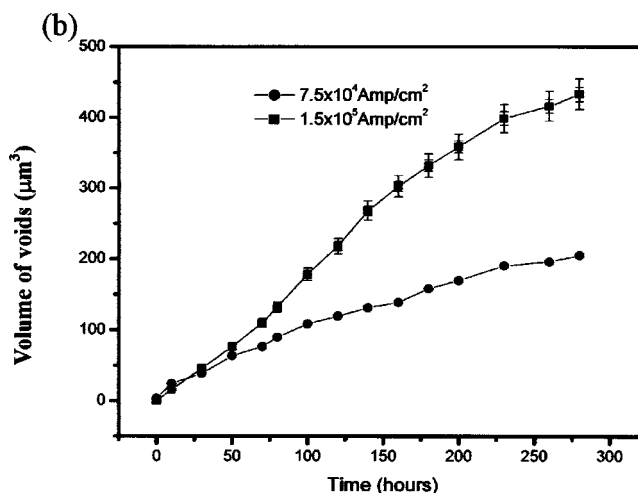
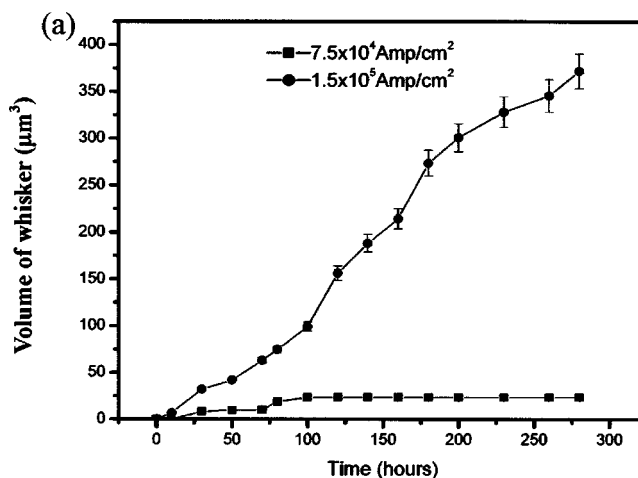


FIG. 5. (a) Measured whisker volume as a function of stressing time and (b) depletion volume of the Sn strip as a function of stressing time at the current densities of 1.5×10^5 and 7.5×10^4 A/cm².

ing, and stopped growing after 120-h current stressing. Hillocks were also found near anode side after current stressing, and the volume of hillocks continued to increase up to 280 h. Figure 4(b) shows the cathode side of the Sn film after the current stressing of 7.5×10^4 A/cm² for 280 h. Tin grains near the cathode end were also depleted by electron flow.

Figure 5(a) shows the measured whisker volume as a function of stressing time for the two stressing conditions listed above. The average growth rate is about 0.4 and 3 Å/s at the current density of 7.5×10^4 and 1.5×10^5 A/cm², respectively. Accordingly, the depletion rate is expected to be lower in current density of 7.5×10^4 A/cm², than in current density of 1.5×10^5 A/cm² shown in Fig. 5(b). The volume of voids grown at current stressing 7.5×10^4 A/cm² is estimated to be one-third of that at 1.5×10^5 A/cm² at room temperature.

C. Temperature effect: Electromigration at 50 °C under the current density of 1.5×10^5 A/cm²

Figure 6 shows the whisker growth at as a function of current stressing time up to 280 h at 50 °C. Both whiskers and hillocks were observed near anode. The increase in the

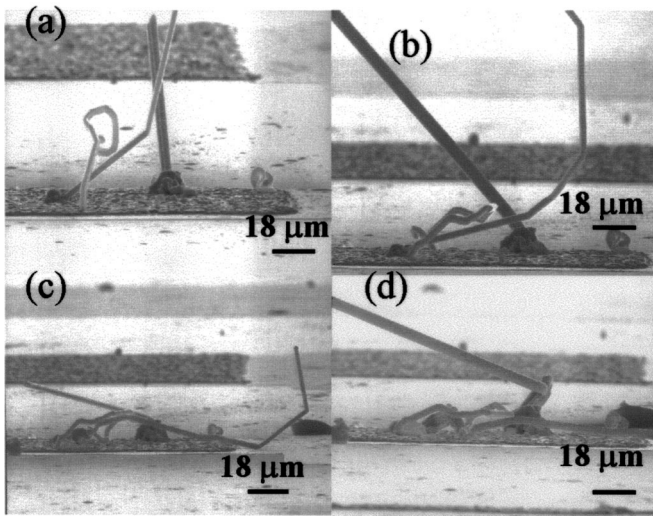


FIG. 6. Tilted-view SEM images of the anode end after the current stressing of 1.5×10^5 A/cm² at 50 °C for (a) 90 h, (b) 150 h, (c) 210 h, and (d) 280 h.

whiskers volume on the strip is mainly from the three whiskers as seen in Figs. 6(a)–6(d). Figure 7(a) depicts the measured whisker volume as a function of stressing time at current density of 1.5×10^5 A/cm² at 50 °C. The average growth

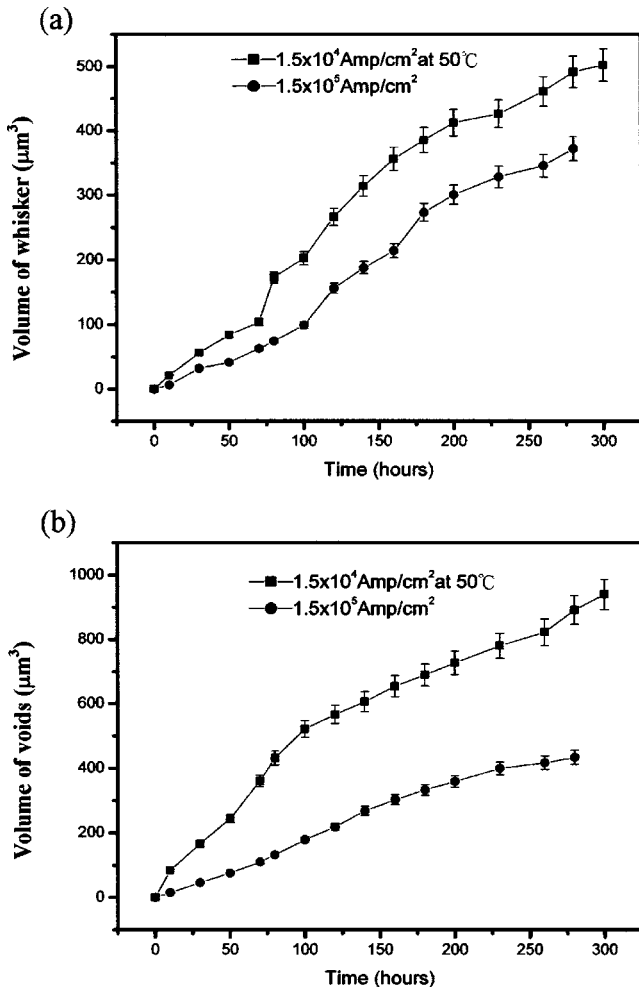


FIG. 7. (a) Measured whisker volume as a function of stressing time and (b) depletion volume of the Sn strip as a function of stressing time at the current density of 1.5×10^5 A/cm² at room temperature and 50 °C.

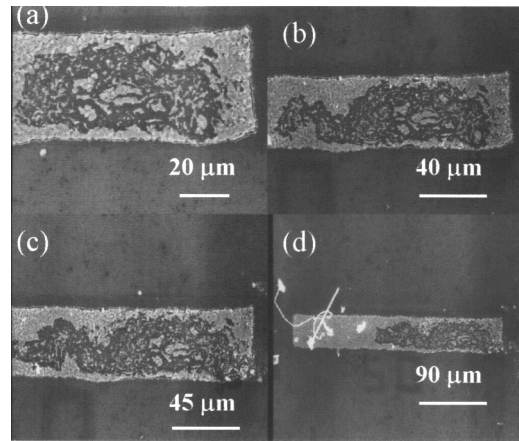


FIG. 8. Plan-view SEM images of the cathode end after under current stressing of 1.5×10^5 A/cm² at 50 °C for (a) 90 h, (b) 150 h, (c) 210 h, and (d) 280 h.

rate was measured to be 3 Å/s at 1.5×10^5 A/cm² at room temperature; while 7.7 Å/s at 1.5×10^5 A/cm² at 50 °C.

The area of voids in the cathode end expanded at 50 °C in comparison with room temperature. Figures 8(a) through 8(d) demonstrate the evolution of Sn film depletion near the cathode end. As shown in Fig. 8(d), the depletion region progressed over the middle of the strip. It appears that the effect of temperature on creation of Sn depletion region is much greater than that of stressing time.

It is worthy noting that the above whisker growth was mainly attributed to the current stressing, since when the Sn strips were kept at same conditions without current, no obvious whisker growth was observed on the strips.

D. Microstructure investigation by TEM

Figure 9 shows the cross-sectional TEM images of a whisker grown with a current stressing of 1.5×10^5 A/cm² for 280 h at 50 °C. The whisker grew from a parent Sn grain, as seen in Fig. 9(a). The root of the whisker is indicated by the arrow. Besides, the Ti layer under the tin film is clearly seen in this figure, which shows that the Ti film stayed intact after the stressing condition. There was residual titanium film under the whisker, presumably due to the over etching of the tin film during sample preparation. The whisker was found to be a single grain, as shown by the diffraction pattern of the whisker in Fig. 9(b). Its crystallographic orientation in the length direction was determined to be [100], as shown in Fig. 9(a). Figure 9(c) is the enlarged image of Fig. 9(a), showing the junction of the whisker and the parent Sn grain from which the whisker grew. It is intriguing that a continuous amorphous layer was observed on the surface of the whisker and the parent grain. The thickness of the amorphous layer was about 100 Å. It was speculated that this layer may be Sn oxide, since it is well known that Sn forms native oxide on surface spontaneously.^{8,13}

IV. DISCUSSION

As a driving force for whisker growth, electrical currents differ from mechanical stress. The whisker growth by elec-

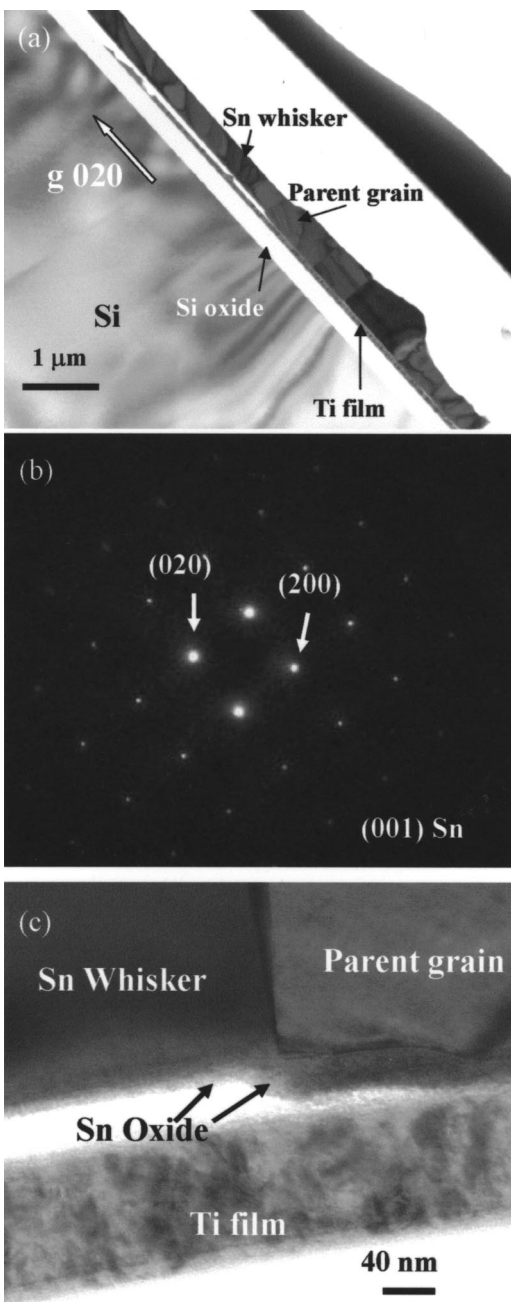


FIG. 9. (a) The cross-sectional TEM image of a whisker grown from a Sn grain. (b) The diffraction pattern of the Sn whisker in (a). (c) The enlarged image the Sn whisker in (a), showing the junction of the whisker and the Sn parent grain.

trical currents is mainly originated from the bombardment of electron moving in the electric field. Tu reported that Sn whiskers grow spontaneously due to interfacial reaction at room temperature in bimetallic copper-tin thin films.¹³ This reaction forms an intermetallic compound of Cu_6Sn_5 , which produces a compressive stress in the neighboring grains. Under this mechanical stress, the thin films undergo a relaxation process by whisker growth. In spite of intrinsic stress in the as-deposited Sn film, the stress does not seem to be great enough to induce the whisker growth in this study. On the other hand, current stressing caused the whisker formation.

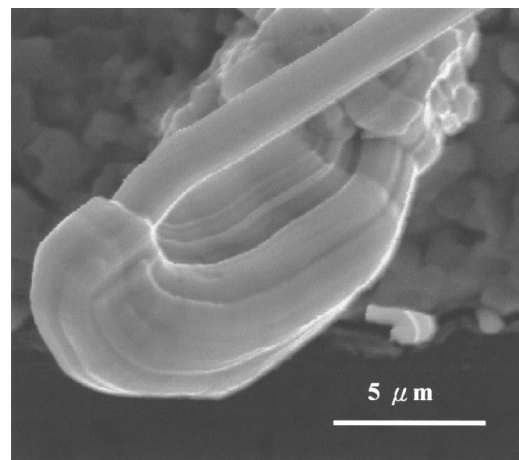


FIG. 10. SEM image of a Sn whisker grown from a hillock after stressing at $1.5 \times 10^5 \text{ A/cm}^2$ at $50 \text{ }^\circ\text{C}$ for 280 h.

Based on the above results, the growth mechanism for Sn whiskers driven by electrical currents could be proposed as follows: moving electrons bombard Sn atoms and drift them to the anode end *via* vacancy-mediated process.^{14,15} This process builds up compressive stress field on the anode end. When the compressive stress is large enough to break the surface oxide of Sn, whiskers grow in order to release the stress. The Sn oxide is not a good vacancy source since it is known to be very protective.¹⁰ As soon as the oxide is broken, it becomes a free surface and supplies the vacancies. On the other hand, the vacancies move to the cathode end, accumulate there to form voids. The diameter of the whisker might depend on the size of the broken surface oxide.

If the broken area is too large, it forms a hillock on the anode end instead of a whisker to release the stress. For both whiskers and hillocks growth, they create fresh surface, where surface oxide forms immediately as soon as the new surface emerges. However, if the newly formed Sn oxide on the hillock surface is broken, another whisker may grow from the hillock as shown in Fig. 10. If the local stress field varies, stress concentration may occur at another place, breaking another spot of surface oxide. As a result, another whisker appears, and stress relaxes through the newly grown whisker. Hence, the previous whisker may stop growing.

Regarding the kinking of whisker, it is postulated that kinking of tin whisker may be due to the unsteady atomic flux under the current stressing. In the initial stage of whisker growth, the atoms will be supplied to the bottom of a whisker, and enhance the whisker growth. However, if the local distribution of Sn flux changes, the direction of incoming Sn flux also changes. This might result as kinking.

As seen in Fig. 9(c), Sn oxide formed on the surface of the whisker and on the parent grain. Although, the oxide layer at the junction of the whisker and the parent grain is continuous, the oxide layer on the whisker is thinner than that on the parent grain. It is speculated that the oxide on the Sn parent might need to be broken in order to grow the whisker. In addition, as soon as the whisker starts to grow, oxide forms on its surface.

Compared with eutectic SnPb films, whisker growth in pure Sn films appears to be much more serious.¹⁶ It is known that the addition of Pb in Sn would mitigate the formation of Sn whiskers.¹⁷ Therefore, the stress in the SnPb films was released by short hillock formation rather than long whisker formation during current stressing; while whisker may grow as long as hundreds of micrometers on pure Sn film, as seen in Fig. 2(d).

V. CONCLUSIONS

Tin whisker formation of pure tin film has been examined. Voids formed at the cathode end and whiskers grew at the anode end after the current stressing. Average growth rate of tin whiskers at 1.5×10^5 A/cm² was measured to be 3 Å/s at room temperature, and it increased to 7.7 Å/s at 50 °C. The growth rate reduced to 0.4 Å/s at lower current density of 7.5×10^4 A/cm² at room temperature. Transmission electron microscopy revealed the Sn whisker orientation successfully with showing a continuous Sn oxide layer on the surface. The mechanism of the whisker growth driven by electrical currents has been proposed in comparison with eutectic SnPb alloy. When the compressive stress by electron flow is large enough to break the localized weak spots on Sn oxide on the anode side, Sn whiskers may grow from the locations where the Sn oxide cracks.

ACKNOWLEDGMENTS

The authors would like to thank Professor K. N. Tu at UCLA for his helpful comments and for the financial support by NSC 89-2218-E-009-109.

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