A model for nucleation of tin whisker through dislocation behavior

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Abstract. A model for the nucleation and growth processes of Sn whisker is offered. High density of localized screw dislocations by deformation form the dense spiral steps of atomic scale on Sn surface. The spiral steps would induce the nucleation of Sn whisker. Edge dislocations localized at the same region where dense screw dislocations exist supply Sn atoms to the Sn whisker through pipe diffusion. Both screw and edge dislocations would bend along almost one direction, namely, to relax the external shear stress. The image force also helps to bend the dislocations perpendicular to the whisker side-surface. The bending of dislocations at root of whisker leads the bend of whisker. The pipe diffusion of Sn atoms through edge dislocations from bulk Sn toward whisker is suppressed at the bent part of edge dislocation, resulting in release of Sn atoms inside whisker and leading to the growth of whisker near its root.

1. Introduction
Whisker formation on an electroplate of Sn is an important problem in electronic packages because a whisker induces electric short-circuit in electronic devices. In order to prevent whisker formation, fundamental researches for mechanism of the whisker formation have been carried out until now [1]. Addition of Pb to Sn is effective to reduce whisker formation [2]. However, the use of Pb is strictly prohibited according to RoHS. An alternative Pb-free Sn electroplate is required.

Sn whisker formation is promoted in the region where stress is applied, such as electronic joint parts [3]. This fact suggests that whisker formation is in association with dislocation behavior.

In this study, the formation of Sn whisker in bulk Sn under tensile stress has been investigated.

2. Experimental procedures
Two specimens of pure bulk Sn were cut into the parallelepiped shape of about 15mm×50mm×3mm, and they were kept with and without tensile stress for 7 to 20 days, respectively. The tensile stress was applied as shown in figure 1. The specimen was deformed around 10%, and the cross-head of tensile...
test equipment (Shimadzu Autograph AG-10kNIS) was stopped. Stress relaxation then started. After about two thirds of yield stress is relaxed, the tensile stress was applied again. Such operation was repeated for 7 to 20 days. The microstructures of specimens were observed by a scanning electron microscope (SEM).

3. Results and discussion

Figure 2 shows that nodular whiskers are observed on the specimen with tensile stress while few whiskers are observed in the specimen without tensile stress. The diameter of whisker is much smaller than grain size (average grain size is 35μm) unlike whiskers on a tin electroplate has nearly the same diameter with the grain size [1]. Another feature of whiskers on bulk Sn is that the whiskers are mainly formed at and/or near grain boundary.

Figure 3 shows a SEM micrograph of a whisker near grain boundary. A lot of slip bands are observed as indicated by arrows in the figure. The whisker is formed at the area where slip bands intersect.

The whisker formation at the area where the intersection of slip bands occurs suggests that the whisker formation is caused by the accumulation of dislocations. According to the results of figures 2 and 3, nucleation of whiskers would be affected by the inhomogeneity of the deformation.

![Figure 1. Stress-strain curve during tensile test for whisker formation.](image1)

![Figure 2. SEM micrograph taken from the bulk Sn kept under tensile stress for 20 days at ambient temperature. Whiskers (encircled) are formed at and/or near grain boundary.](image2)

![Figure 3. SEM micrograph taken from the bulk Sn under tensile stress for 7.5 days. A whisker was formed at the intersection of slip bands indicated by arrows.](image3)
deformation induces multiplication of dislocations and their conservative motions, resulting in their local accumulation around grain boundary. High density of dislocations are localized around the ends of slip bands at grain boundary. It could be suggested that the dislocations consist of both screw and edge dislocations, because various directions of slip bands due to the operations of various slip systems accumulate around grain boundary as shown in figure 3.

Based on above results, a model of whisker formation is considered as follows. The motion of screw dislocation causes a step on Sn surface in atomic scale. The step tends to trap Sn atoms and/or their aggregates migrating on Sn surface because the step has combination sites with Sn atoms. Such a process would form a spiral step around a screw dislocation. The height of a step is one atomic distance, and the spiral step continues to increase with increasing trapped Sn atoms [4]. However, the spiral steps combine with each other when screw dislocations are densely localized by deformation [4]. When Sn atom migrates into the valley between spiral steps (designated as “V” in figure 4), the Sn atom is easily combined with spiral steps, resulting in reduction of surface energy of spiral steps. The regions where screw dislocations are densely localized act as nucleation sites for whiskers because diffusing Sn atoms on crystal surface are preferably captured in the region.

For the growth of whisker, it is indispensable that Sn atoms are supplied from the bulk Sn into whisker. The dense localization of edge dislocations at the same place where screw dislocations exist is also indispensable because pipe diffusion of Sn atoms should occur along edge dislocations. The pipe diffusion of Sn atoms along edge dislocations facilitates the supply of Sn atoms from bulk Sn into whisker.

Figure 4. Growth of whisker in association with screw and edge dislocations.

Figure 5. Dislocations inside whisker during growth process of whisker. \( b \) is the Burgers vector.
Figure 5(a) shows a whisker just after its nucleation. An edge dislocation and a screw dislocation are shown for simplicity. In the course of growth of whisker, both dislocations would bend towards side-surface of whisker in almost the same direction because external stress and image force are applied to the dislocations.

The bending of dislocations changes their natures, namely, screw and edge dislocations bent near the whisker side-surface change into edge and screw dislocations, respectively (see figure 5(b)). This phenomenon could induce the whisker growth from its root [1]. Migrating Sn atoms in bulk Sn are supplied into whisker through the pipe diffusion only along edge dislocation, but Sn atoms scarcely migrate along screw dislocation which is formed by the bending of edge dislocation. Sn atoms are accumulated around the area where edge dislocation changes to screw one. Jogs are formed here. In order to lower the edge dislocation energy which increases by the jogs of Sn atoms, namely, the increase in dislocation length, the jogs of Sn atoms would easily dissociate from the edge dislocation, resulting in diffusion of Sn atoms into the root of whisker.

Concentration of vacancies in whisker would be lower than that in bulk Sn, because a unit volume of whisker has more amount of surface where vacancies disappear than a unit volume of bulk Sn has. Then, vacancy migrates into whisker along the concentration gradient of vacancies. Sn atoms dissociated from edge dislocation easily diffuse into whisker, and the growth of whisker occurs remarkably at its root.

Trace analysis of a slip band near a whisker shows that the slip plane is \{101\}. It is suggested that the slip system is \{101\}<10\overline{1}> according to the literature [5]. The magnitude of the Burgers vector of <10\overline{1}> is larger than that of <001>, along which the atomic spacing between Sn atoms is the smallest in \beta-Sn. Edge dislocation with the Burgers vector of <10\overline{1}> has sufficiently broad space under the extra half plane so that Sn atoms should move easily through pipe diffusion, while other metals usually has the Burgers vectors with the smallest atomic spacing. This fact enables whisker to be formed on Sn unlike on other metals.

4. Conclusions
A model of whisker formation on bulk Sn under tensile stress has been offered. Whiskers, whose diameters are much smaller than that of grain in matrix, are nucleated at the area where intersection of slip bands occurs near grain boundary of the matrix, because high density of screw dislocations accumulated by deformation make atomic steps and valleys on the surface of bulk Sn. Edge dislocations accumulated in the same region supply Sn atoms for growth of whisker through pipe diffusion. The diffusion of Sn atom along the edge dislocation is retarded at the point where the edge dislocation changes into screw one because the edge dislocation bends towards the side-surface of whisker by external stress and image force. The accumulated Sn atoms are dissociated from the edge dislocation in order to lower the dislocation energy, resulting in the growth of whisker near its root.

5. References
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