Electric Current-Induced Liquation Features of Cast Pure Tin

Gong-An Lan, Tuan-Sheng Lui* and Li-Hui Chen

Department of Materials Science and Engineering, National Cheng Kung University,
No. 1 University Road, Tainan 701, Taiwan, R. O. China

Electric current-induced liquation feature of cast pure β-tin under alternating current (AC) was investigated in this study. According to the experimental results, the initial fusion emerges from grain interior. Since the fusion paths traverse the grain boundaries preferentially in a high-angle manner, their track inside a grain tends to be curved and thus longer than the grain size. Continued electro-migration leads fusion paths to form network-like interconnected fusion structure with most triple junctions residing within grain interior. Lateral thickening of the interconnected fusion paths leads to final failure. The result that the network-like fusion structure is rather equiaxed can eliminate the effect of crystal anisotropy on the fusion behavior if it exists. [doi:10.2320/matertrans.M2012162]

(Received May 7, 2012; Accepted August 22, 2012; Published October 25, 2012)

Keywords: lead-free solder, electro-migration-induced liquation phenomenon, critical fusion current density, fusion path, electronic properties

1. Introduction

With microminiaturization and rising operational efficiency, the tin-based solder joints of many electronic devices inevitably suffer higher current density.1) Since Joule heating effect is proportional to the square of current density,2) fusion failure of these solder joints is of great concern in reliability issue. Tin-based solder alloys are multiple in phase and non-uniform in microstructure, causing the fusion to start more likely from selective regions. Since little has been known regarding this subject, pure tin was chosen as the test material in this investigation to exclude the complexity arisen from the presence of second phase particles.

Like many bulk materials, the chosen pure tin was polycrystalline. In a two-dimensional simulation of silicon thin film taking grain boundaries as the trapping site of charge carriers, Kimura et al.3) have concluded that the current density is the highest in the center region of a grain. This phenomenon of non-uniform current distribution is more pronounced when the grain size is getting smaller (Fig. 1 cf. Fig. 2, Ref. 3). Trapping of charge carriers will effectively raise the electrical resistivity. For pure tin, impurity segregation should also cause the grain boundaries to have higher electrical resistivity although the segregation level is limited. An essence of the present study was therefore to explore whether the current-induced fusion of pure tin has a non-uniform characteristic caused by the presence of grain boundaries.

At temperatures above 13°C, pure tin, which is β-phase with body-centered tetragonal crystal structure, possesses anisotropic natures.4) Owing to the anisotropic behavior, Wu et al.5) have indicated decreasing electrical resistance of β-tin resulted from electro-migration-induced grain rotation. Since electro-migration can be generally ignored in the case of alternating current (AC),6) AC was applied in our experiment to reduce the influential factors of the fusion behavior. In this situation, to clarify whether the fusion is still anisotropic was another purpose of the study.

2. Experimental Procedures

A tin ingot of 99.9 mass% purity was melted to 100 K above the melting temperature, cast into a 473 K preheated graphite mold and solidified to room temperature at a cooling rate of 0.19 K·s⁻¹ to acquire the preliminary as-cast rectangular specimens. As shown in Fig. 1(a), the test specimens used for the electro-migration experiment are I-shaped with a gauge length of 20 mm (l) × 5 mm (w) × 0.8 mm (t). These specimens were cut from the preliminary rectangular specimens by electrical discharge machining, each with the thickness controlled by grinding carefully with a series of SiC papers and polishing with 0.3 μm Al₂O₃ suspension.

Figure 1(b) shows schematically the test rig to electrify a specimen. During this process, an AC power supply of 24 V capacity was connected to the two ends of the specimen by copper electrode, providing alternating current to the specimen with an increasing voltage rate of 0.1 V·s⁻¹.

The critical fusion current density (CFCD) to cause complete fusion failure was averaged from four test results as 1399 (× 10³) A·m⁻². Judging from our preliminary

*Corresponding author, E-mail: z7408020@email.ncku.edu.tw

Fig. 1 Schematic illustration for electro-migration-fusion test: (a) specimen dimension (unit: mm), and (b) the setting of AC power supply.
experiment, the three test conditions of 78, 95 and 98% CFCD were chosen to examine the emergence of initial fusion path, intermediate fusion and severe fusion, respectively. Since the joule heat generated from electricity is the largest in the middle of the I-shaped specimen, subsequent observation of the fusion phenomena was made at a region of about 7.5-mm width in the center portion of the gauge length section.

3. Results and Discussion

A typical panoramic view of the fusion features electrified to 98% CFCD is given in Fig. 2. The center region, which is designated as “severe fusion zone” in the figure, is close to the specimen’s middle that suffers the largest joule heat. Its dark blocky appearance is a consequence of severe fusion. Adjacent to this severe fusion zone are “network-like fusion zone” on both sides, where the network structure is a distinctive feature evolved from interconnection of the fusion paths. Similar network structure is also present in the severe fusion zone, but the interconnected fusion paths are wider in width. Apparently, complete fusion failure will take place upon further electrification when the specimen’s middle part is virtually covered continuously by fusion in blocky structure and network structure as well.

Figure 3(a) shows the as-cast microstructure of the test material, which is polycrystalline with an average grain size...
of 28.8 µm. After the same specimen of this micrograph was electrified to 78% of the critical fusion current density (78% CFCD), isolated initial fusion paths (as those encircled in Figs. 3(b) and 3(c)) can be found. Re-electrifying of the specimen to 95% CFCD gives rise to the network-like interconnected fusion paths depicted in Fig. 3(d). Subsequent re-electrification of the specimen to 98% CFCD results in sideward thickening of the network-like fusion paths as shown in Fig. 3(e). When sideward thickening continues to proceed, it is apparent that the network structure will change to blocky appearance as that in the severe fusion zone depicted in Fig. 2.

According to our examination, the initial fusion paths at 78% CFCD either have already crossed over a few grains (see Fig. 3(b)) or still reside inside a grain (see Fig. 3(c)). Since none of them were found intergranularly, it can be concluded that grain interior rather than grain boundary is the preferred emergence site of initial fusion. Presuming that fusion starts at locations of high current density, the conclusion suggests a non-uniform current distribution similar to that proposed by Kimura et al.\textsuperscript{3} in their modeling of silicon thin film, i.e., the center region of a grain has larger current density than its surrounding grain boundaries. As supporting evidence, most triple junctions of the fusion network in Fig. 3(d) are encircled and mapped by the encircled dots in the as-cast microstructure shown in Fig. 3(a) to reveal that the triple junctions locate preferentially at grain interior. In fact, Fig. 3(d) shows that the network-like fusion structure evolves transgranularly but seldom intergranularly. The transgranular fusion paths reveal no apparent inflection when they cross over the grain boundaries (see Figs. 3(b) and 3(d)). Meanwhile, the polygons which form network-like fusion structure are more or less equiaxed (see Figs. 2, 3(d) and 3(e)). Therefore, the fusion behavior reveals virtually no anisotropic effect.

To have a more precise picture of the fusion structure, statistical data of how a fusion path meets a grain boundary are listed in Table 1, where the sample size is 1035 (collected from the specimen electrified to 95% CFCD). As indicated, 77.9% of the observed fusion paths traverse grain boundary directly, a large proportion relative to the remaining 7.8% which pass over grain boundary triple junction and 14.3% of intergranular manner. For the majority which traverse grain boundary directly, the histogram of their intersecting angles given in Fig. 4 reveals a tendency of normal intersection. The results of Table 1 and Fig. 4 are reasonable since the grain boundaries and their triple junctions are higher in electrical resistivity. In other words, an electric current tends to pass through the path (grain interior) with lower electrical resistivity. On the one hand, there may be a higher current density at grain interior than grain boundary. Thus, fusion paths can mostly be observed at grain interior compared with grain boundary. On the other hand, an electric current may traverse grain boundary in a less-cross-section-area, more perpendicular-path manner to ensure that an electric current passes through the lower electrical-resistivity paths as possible as it can. These results are also consistent with the analysis by Kimura et al.\textsuperscript{3} which concluded that the current tends to flow over grain boundary perpendicularly and avoid passing through grain boundary triple junction.

Since the two grain boundaries through which a fusion path crosses to adjacent grains are usually nonparallel, geometrical constraint of normal intersection requires the fusion path to be curved inside the grain. Therefore, the tendency of normal intersection shown in Fig. 4 implies that the average travelling distance of a fusion path through each grain is larger than the average grain size. Taking the same specimen as that used to evaluate the intersecting angles in Fig. 4, this average travelling distance was measured as 34.3 µm, which is substantially larger than the average grain size of 28.8 µm mentioned previously. This measurement counted 495 grains, where 207 grains (less than half of the total) have their size exceeding the average grain size. Since less than half of the total measured grains are larger than the average grain size, the above result of long average travelling distance of a fusion path inside a grain does support the statement of curved fusion paths.

Moreover, the result of the larger travelling distance of a fusion path inside a grain than the average grain size can provide additional information as follows: (1) The result reinforces the viewpoint that an electric current is apt to pass through grain interior with a longer distance as possible as it can because of the lower electrical resistivity in grain interior. (2) Since the property of a material generally depends on the microstructural features such as grain size and precipitation distributions etc., the microstructural difference between pure metals and alloys may possess different fusion behaviors. Thus, the result might also provide a referential data for the electric current-induced liquation phenomena of binary or ternary tin-based alloys.

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traversing grain boundary</td>
<td>77.9%</td>
</tr>
<tr>
<td>Through grain boundary triple junction</td>
<td>7.8%</td>
</tr>
<tr>
<td>Along grain boundary</td>
<td>14.3%</td>
</tr>
</tbody>
</table>

Fig. 4 Histogram of intersecting angle between fusion path and grain boundary (1035 data measured from the specimen electrified to 95% CFCD).
4. Conclusions

According to the above results and discussion, the current induced fusion development can be summarized as follows:

1. The fusion paths start to form preferentially in grain interior. Most of them develop transgranularly and tend to intersect the grain boundaries perpendicularly. Owing to this constraint of perpendicularity, the intergranular fusion paths tend to be curved, and the average travelling distance of a fusion path inside a grain is longer than the average grain size. The above results are probably due to the fact that the grain boundaries and their triple junctions have higher electrical resistivity than the grain interior.

2. Upon increasing current, the fusion paths are interconnected to form network-like structure. Since most fusion paths evolve transgranularly rather than intergranularly, the triple junctions of the interconnected fusion paths locate preferentially in grain interior. Further electrification will eventually result in fusion failure by sideward spreading of the interconnected fusion paths.

3. The transgranular fusion paths traverse the grain boundaries with no apparent inflection. The network-like fusion structure is rather equiaxed. Therefore effect of crystal anisotropy on the fusion behavior can be neglected if it exists.

Acknowledgement

This study was financially supported by the National Science Council of Taiwan for which we are grateful (Contract No. NSC 101-2221-E-006-115).

REFERENCES