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Effects of Sn grain orientation on substrate dissolution and intermetallic precipitation in solder joints under electron current stressing

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Electron current stressing of Ni/Sn3Ag/Ni solder joints was conducted in a straight-line configuration to avoid the complication of current crowding. It was confirmed that Sn grain orientation dominated the dissolution of the Ni substrate and the precipitation of intermetallic inside Sn3Ag. Current crowding played no role here. Additionally, it was found that the direction of serrated cathode dissolution exhibited a strong correlation with Sn grain orientation. These effects were explained in terms of the extreme anisotropy of Ni diffusion in Sn.
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Certain transition metals, including Au, Ag, Cu and Ni, diffuse in white (body-centered tetragonal) Sn at rates orders of magnitude faster than the self-diffusion of Sn, and are known as "fast diffusers" [1–3]. These fast diffusers are believed to diffuse through Sn via an interstitial-type mechanism. Moreover, diffusion of these fast diffusers exhibits very pronounced anisotropy. These elements diffuse much faster along the more open c-axis of a Sn crystal [1–3]. This diffusion anisotropy raises the question of whether metal substrates made of these fast diffusers behave differently when exposed to Sn grains with different orientations. Indeed, multiple recent reports have shown that Sn grain orientation does dominate the principal failure mechanisms in electronic solder joints [4–6]. However, one difficulty of interpreting experimental observations in electronic solder joints is that in electronic solder joints, such as ball-grid array or flip-chip joints, high degrees of current crowding are always present. There is always doubt about whether a particular observation is caused by diffusion anisotropy or by current crowding. The objective of this study is to use samples with a straight-line configuration so that the complications from current crowding can be ruled out.

A line-type Ni/Sn3Ag/Ni structure, illustrated in Figure 1a, was used in this study for electromigration testing. This test structure ensured that there were no contributions from thermomigration or current crowding. The detailed procedure for the fabrication of the test structure has been described elsewhere [7], and is omitted here for brevity. Figure 1b is a top-view backscattered electron micrograph of an as-fabricated test structure, and Figure 1c is the corresponding electron backscattering diffraction (EBSD) inverse pole figure orientation image map (OIM) in the normal direction (ND). As shown in Figure 1b,c, the as-fabricated test structure had a planar interface with nearly no intermetallic compound at the interfaces, and the Sn3Ag solder was composed of numerous fine grains with random Sn grain orientations. After annealing at 150 °C for 48 h, a thin Ni_3Sn_4 layer formed at either of the Ni/solder interfaces, as shown in Figure 1d. Since 150 °C is a high homologous temperature for Sn3Ag, grain coarsening could easily occurred, as evident in the corresponding OIM shown in Figure 1e.

As one of the objectives of this study is to investigate the Sn orientation effect, it is more suitable to have samples with larger Sn grain sizes. Accordingly, in all

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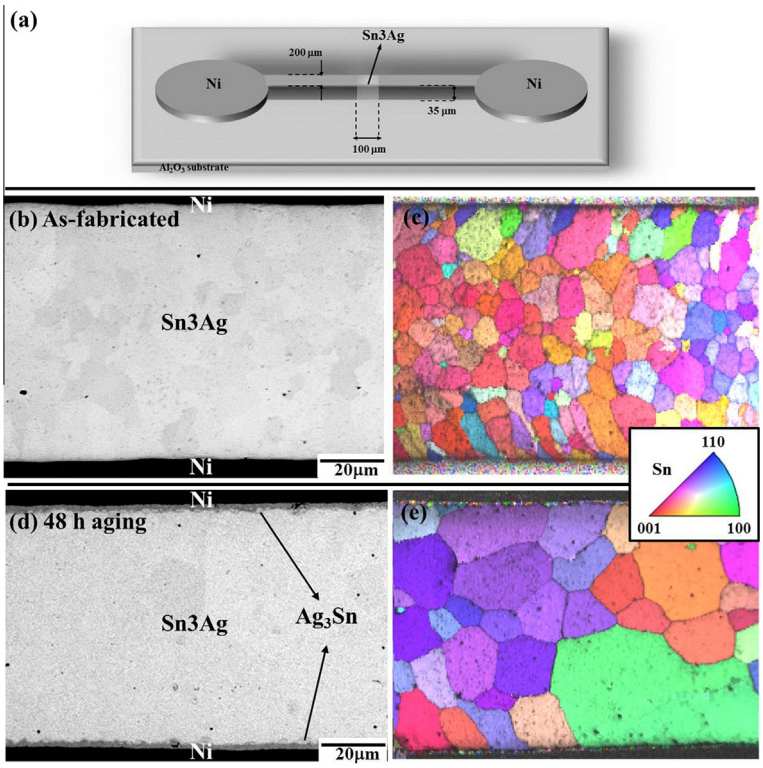

Figure 1. (a) Schematic diagram of the line-type Ni/Sn3Ag/Ni test structure. (b) Top-view micrograph showing the as-fabricated test structure (c) EBSD inverse pole figure OIM in ND of sample shown in (b). (d) Top-view micrograph showing the test structure after aging at150 °C for 48 h. (e) EBSD inverse pole figure OIM in ND of the sample shown in (d).

of the following electromigration tests, the samples were pre-aged at 150 °C for 48 h to increase the Sn grain size. Figure 2a–f shows the microstructure evolution after current stressing at 150 °C and 10^4 A cm^{-2} current density for 0–500 h. As can be seen in Figure 2, rapid dissolution of Ni occurred at the cathode interfaces and accumulation of Ni_3Sn_4 occurred at the anode interfaces. The Ni dissolution in Figure 2d,e exhibited a serrated morphology at the cathode interface similar to those observed in previous studies [8–10]. As current crowding was not important in the present study, it can be concluded that the serrated cathode dissolution observed here was not induced by current crowding.

The most striking feature in Figure 2 is the inconsistent dissolution at the cathode and the preferential Ni_3Sn_4 accumulation at certain locations of the anode across the width of the interface. For example, in Figure 2e, Ni dissolution was more pronounced on the right side of the micrograph, but the large-scale precipitation of Ni_3Sn_4 was more prominent on the left side of the micrograph. Another example is shown in Figure 2f, where Ni dissolution and Ni_3Sn_4 precipitation were both more pronounced on the left side of the micrograph. In order to understand this preferential metal consumption and intermetallic compound accumulation, EBSD was utilized to analyze the Ni/Sn3Ag/Ni solder joints. Shown in Figure 3a,b are an SEM micrograph and its corresponding EBSD inverse pole figure OIM for the solder joint after 200 h of current stressing. It is highly significant that the Ni cathode region bordering the Sn grain A in Figure 3b experienced evident Ni consumption, whereas hardly any Ni was consumed from those Ni cathode regions bordering Sn grains B, C, D and F. The c-axis of the A grain had a crystallographic orientation relatively parallel to the direction of the applied electron flux. Because Ni atoms have a higher diffusivity along the c-axis of Sn, a larger Ni diffusion flux was consequently induced by electromigration along the Ni cathode neighboring the A grain. However, the c-axes of grains B, C, D or F are almost perpendicular to the direction of the applied electron flux, and as a result the Ni electromigration flux was not as significant and a stable Ni_3Sn_4 layer formed under these Sn grains.

The same phenomenon also occurred when the current stressing time was 500 h. As shown in Figure 3c,d, the grain A′ had its c-axis nearly parallel to the direction of electron flow and the Ni cathode experienced severe dissolution. Grains B′, C′, D′, E′ or F′ had their c-axes almost perpendicular to the direction of electron flow, and experienced relatively little Ni dissolution. The two examples shown in Figure 3 conclusively proved that inconsistent Ni dissolution at the cathode was dominated by Sn grain orientation. The results reported here confirmed the earlier observations of Lu et al. [4], who also used samples with a straight-line configuration with proper heat dissipation so that current crowding and thermomigration were not important. However, there is one new observation from this study. We found that the orientation of Sn grain controlled not only the locations of excess cathode dissolution but also the locations where Ni_3Sn_4 precipitated. As shown in Figure 3c,d, the accumulation of Ni_3Sn_4 near the anode was much more pronounced

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