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Effect of Sn Grain Orientation on Electromigration Degradation Mechanism in High Sn-Based Pb-free Solders

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Electromigration induced damage is strongly depend on Sn-grain orientation in Pb-free solders. Rapid depletion of intermetallic-compounds and Under-Bump-Metallurgy led to significant damages are caused by fast diffusion of Cu and Ni along the c-axis of Sn crystals. When c-axis of Sn-grain is not aligned with the current direction, electromigration damage is dominated by Sn self-diffusion, which takes longer to occur. This is a direct proof of the highly anisotropic diffusion behavior in Sn. Due to the presence of twin structures and stable Ag_3Sn network, SnAg(Cu) solders are less susceptible to grain orientation effects and showed better electromigration performance than SnCu solders.

Reliability issues resurfaces as flip chip packaging move from Pb-bearing to Pb-free solders[1,2]. Different from the f.c.c. structure of lead, tin (Sn) has a tetragonal crystal structure and tends to form large grains that exhibit highly anisotropic behaviors in mechanical, thermal, electrical, and diffusion properties[3-8]. With the lattice constant of a = b = 5.83Å much larger than that of the c-axis, c = 3.18 Å, the open structure along the c-axis facilitates faster interstitial diffusion of Ni and Cu than along the other two orthogonal directions[3,4]. Cu diffusivity was measured at about $2x10^{-6}$ cm^2/sec at 25°C along the c-axis, which is about 500 times faster than that along the a- or b-axis, and is ~10^{12} times the rate of Sn self diffusion[3]. For Ni, the anisotropy in diffusivity is even greater. The diffusivity of Ni along the tetragonal (c-) axis is ~$7x10^4$ times that at right angles (a- or b-axis) at 120°C[4]. Therefore, one could anticipate that Sn grain orientation plays an important role in Sn-based Pb-free solder reliability issues such as electromigration. In this study of the electromigration (EM) of Sn based Pb-free solders, we classify EM induced damage into two degradation mechanisms, both closely related to Sn-grain orientation[7]. Mode-I damage is dominated by Sn self-diffusion resulting in cavitations generated at the intermetallic-compounds (IMC)/solder interface. Mode-II damage is caused by fast interstitial diffusion of Cu and Ni through Sn, resulting in rapid dissolution of Under-Bump-Metallurgy (UBM) and IMC that lead to electrical failure at an early stage.

A Cu-solder-Cu wire test structure[9] is made by joining a 381 μm diameter solder ball to the polished ends of two Cu wires of 287 μm in diameter. Different types of UBM can be coated at the end of Cu wire to simulate the flip chip C4 structure, while eliminating the critical issues of current crowding and temperature non-uniformity that

often complicate the interpretation of EM data. The solders used are Sn0.7Cu and Sn1.8Ag. The Cu from the UBM will dissolve into the solder after reflow, making the final solder compositions SnCu and SnAgCu, respectively. The UBM deposited on the cathode side is 14 μm electroless plated Ni(P) and 400 Å sputtered Au (UBM-A) or 14 μm electroless plated Ni(P) and 500 Å sputtered Cu (UBM-B). The UBM on the anode side is a three-layer sequentially sputtered film of TiW (1650 Å)/ Ni (6 μm)/Cu (2 μm). The samples were stressed at 5 Ampere (7.7×10^3 A/cm^2) and 150°C. The cross-polarization image in Figure 1(a) is from a sample with SnCu solder and UBM-A after 555 hours EM stressing. It shows a bi-crystal structure that consists of two major grains with IMC accumulated at or near the grain boundary. Figure 1(c) is a SEM image on the cathode side of the boxed region in Figure 1(a). EDX (Energy Dispersive X-ray Spectroscopy), taken at the points indicated by arrows, shows the composition of the Ni barrier layer after EM testing. On the right side, the Ni barrier layer remains intact with approximately 14 μm of undamaged Ni. The intensities of the Ni and P signals indicate a typical electroless-plated Ni(P). The IMC formed on the Ni(P) is Ni_3Sn_4, which remains intact after EM testing. Voids are formed at the IMC/solder interface, which represents a typical Mode-I damage mainly caused by Sn self-diffusion. We believe the size of the voids are somewhat enlarged due to the mechanical damage during sample preparation. On the left side, however, the IMC layer which was originally formed at the UBM/solder interface after reflow was depleted and swept away. Sn was found not only in the Ni barrier layer but also, in some area, deep into the Cu wire as indicated by the yellow arrows. The remaining Ni barrier is rich in P and Sn, indicating Ni is degraded. Cu was found in the intermetallic compound that was swept to the grain boundary. This is

defined as a Mode-II type damage, which is dominated by the fast diffusion of Ni and Cu through the Sn grain along the c-axis, as shown in the Electron Backscattering Diffraction (EBSD) analysis in Figure 1(b). The legend of inverse pole figure color that is inserted in Figure 2 applies to all the EBSD maps in this paper. The grain orientation is indicated by the Sn unit cell insertion at the location of the grain in EBSD map. Figure 1(b) shows the grain on the left has c-axis almost parallel to the current direction; whereas the grain on the right has its c-axis roughly at right angle with respect to the current direction. As reported by Turnbull[3] and Huntington[4], the diffusivities of Cu and Ni along the c-axis of Sn are much faster than along the a- or b-axis. In Mode-I damage, the c-axis of the Sn grain is at a large angle to the current direction, where the rates of Cu and Ni diffusion in Sn is slow. Failure is characterized as mainly due to Sn self-diffusion or lattice diffusion resulting in void formation between the IMC and solder. In Mode-II damage, the c-axis is roughly aligned with the electrical current. Under high current, the rapid diffusion of Ni and Cu dissociates the IMC and sweep them to the grain boundary and through the grain to the other side of the solder joint. Once the IMC is depleted, the Ni is consumed rapidly by diffusion through the solder, along with Sn penetration into the Ni layer and further into the Cu wire under the degraded Ni layer. Voids are formed between the degraded Ni and solder due to the vacancy caused by depletion of IMC. Similar bi-modal failures have been found on C4 joints. Figure 2 is a SEM image of an EM stressed SnCu C4 bump and the insertion of the Sn unit cell indicating the grain orientation by EBSD analysis. Similar associations between degradation mode and grain orientation are observed.

Dominated by fast interstitial diffusion process, the Mode-II type mechanism is commonly found on samples failing early in EM test, and statistically more common in SnCu solder than in SnAg and SnAgCu solders. Figure 3 is a plot of the resistance change over time during EM stress. Curve A is from the sample with SnCu solder depicted in Figure 1, where about half of the solder joint has a mode–II failure resulting in an early electrical failure. Curve B is from a sample with Sn1.8Ag and UBM-B. The final composition of the solder is SnAgCu after reflow. This sample has very little change in resistance after 1342 hours of EM stressing. Failure analysis reveals that the solder has cyclic twinning and hardly any EM damage. Curves A and B are characteristic EM plots for SnCu and SnAgCu solders, respectively. Although Mode-I is common for SnAg(Cu) solder and mode-II is more frequent in SnCu solder, mix mode failures are observed in both solders. Curves C and D are from the samples shown in Figures 4(a) and 4(b). The EM damage has been mitigated by multiple grains (SnCu) and cyclic twinning (SnAg), resulting in longer lifetime than SnCu solders with Mode-II failure.

Figure 4(a) shows a Sn0.7Cu solder joint on UBM-B after 1342 hours of stressing, as shown in Curve C in Figure 3. The EBSD map showed multiple grains in the solder joint, where one smaller grain was oriented with its c-axis aligned with the current and the other larger grain was oriented with c-axis away from current direction. As expected, the area where the UBM is adjacent to the larger green grain showed Mode-I type damage and the portion of the UBM adjacent to the smaller red grain showed Mode-II type damage. Even with a small twinning, the yellow grain inside the red grain, the UBM consumption appears to be reduced. Figure 4(b) is an example of Mode-II damage in SnAg(Cu) solder on UBM-A after 1342 hours of stressing, as shown in Curve

D in Figure 3. The small red-colored grain has its c-axis aligned with the current direction. The two larger green-colored grains, where the c-axis is not aligned with current direction, are the cyclic twins of the red grain. As indicated by the arrows, the sample exhibits mixed modes of degradation depending on the grain orientation. The presence of multiple grains and twinning can mitigate EM damages caused by fast diffusion in Mode-II type failure in SnCu and SnAgCu solder.

As discussed above, Mode-II failure is found more often in SnCu solder than in SnAgCu solder. We believe that it is related to the significant differences in the microstructures between SnCu and SnAgCu solders[7]. SnCu solders normally consist of multiple grains with few polysynthetic twins and rarely cyclic twins. Under high temperature and high current stress conditions, significant grain growth and re-orientation were observed, leading to Mode-II type failure where c-axis closely aligned to the current direction. For SnAg(Cu) solder, the solder joint begins with one or few large grains which are often associated with beach ball or interlaced cyclic twinning structures[7,8]. The grain structure is found to be more stable under EM stressing, due mainly to the stable Ag_3Sn IMC network. Cyclic twinning, both interlaced and beach ball twins commonly found in SnAg(Cu) solders, creates randomness in the grain orientation that reduces the propensity of Mode-II failure and thus extends EM lifetime[7]. In an study of the crystallography of 381μm diameter solder ball with different Ag concentration, it was found that a certain amount of Ag, about 1 wt.% or greater is needed to form more cyclic twins in solder. Figure 5 shows the typical EBSD maps of Sn0.7Cu, Sn0.5Ag, and Sn1.0Ag solders. All the solder balls have been thermally annealed at 150°C for 500 hours. The black lines mark the twinning boundary with 60±5° rotation about <100>

axis[10]. Figure 5(a) is a Sn0.7Cu solder ball, with multiple grains and two sets of laminar twins in orthogonal directions. Figure 5(b) is a Sn0.5Ag solder ball with multiple grains and laminar twins which is more close to SnCu than to Sn1.0Ag structure. Figure 5(c) is a Sn1.0Ag solder ball with beach ball twinning and Figure 5(d) is a Sn1.0Ag solder ball with two sets of interlaced twins. The interlaced twinning boundaries are decorated with Ag_3Sn IMC networks indicating the twinning is formed during the solidification process. The dense Ag_3Sn IMC network in high Ag content SnAg solders promote interlaced twinning structure, the lesser Ag_3Sn IMC network in lower Ag solders results in the SnCu–like multigrain structure. Therefore, high density Ag_3Sn network or a certain Ag level is needed to ensure cyclic twinning structure which benefits EM stability.

In summary, a strong correlation between EM degradation mechanisms and Sn grain orientations is established, which is consistent with the highly anisotropic diffusion behaviors of Cu and Ni in Sn. The presence of cyclic twinning and a stable IMC network are shown to effectively reduce EM damages by mitigating the grain orientation effect that causes the undesirable Mode-II type early failures.

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Figure 1(a) 1(b): A solder joint after 555 hour EM test, (a) cross polarized image, (b) EBSD map

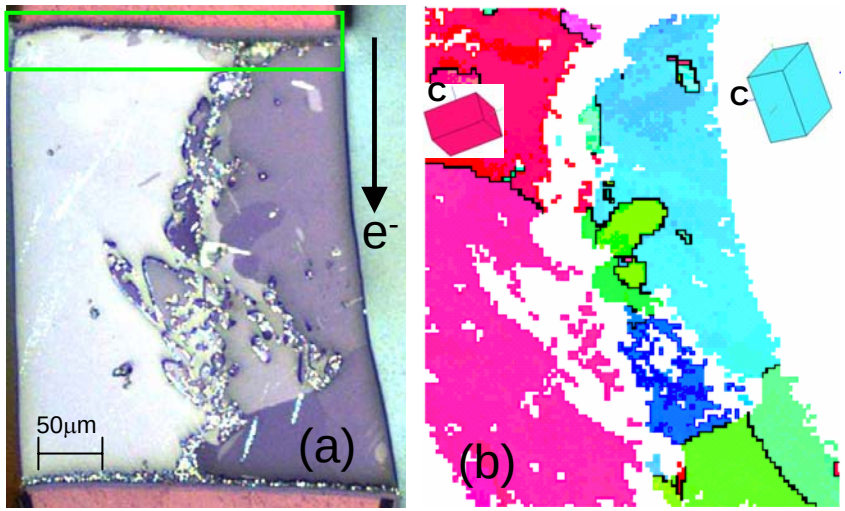


Figure 1(c): A solder joint after 555 hour EM test, (c) SEM image and EDX spectrums of the boxed region in (a).Figure 1(a) 1(b)

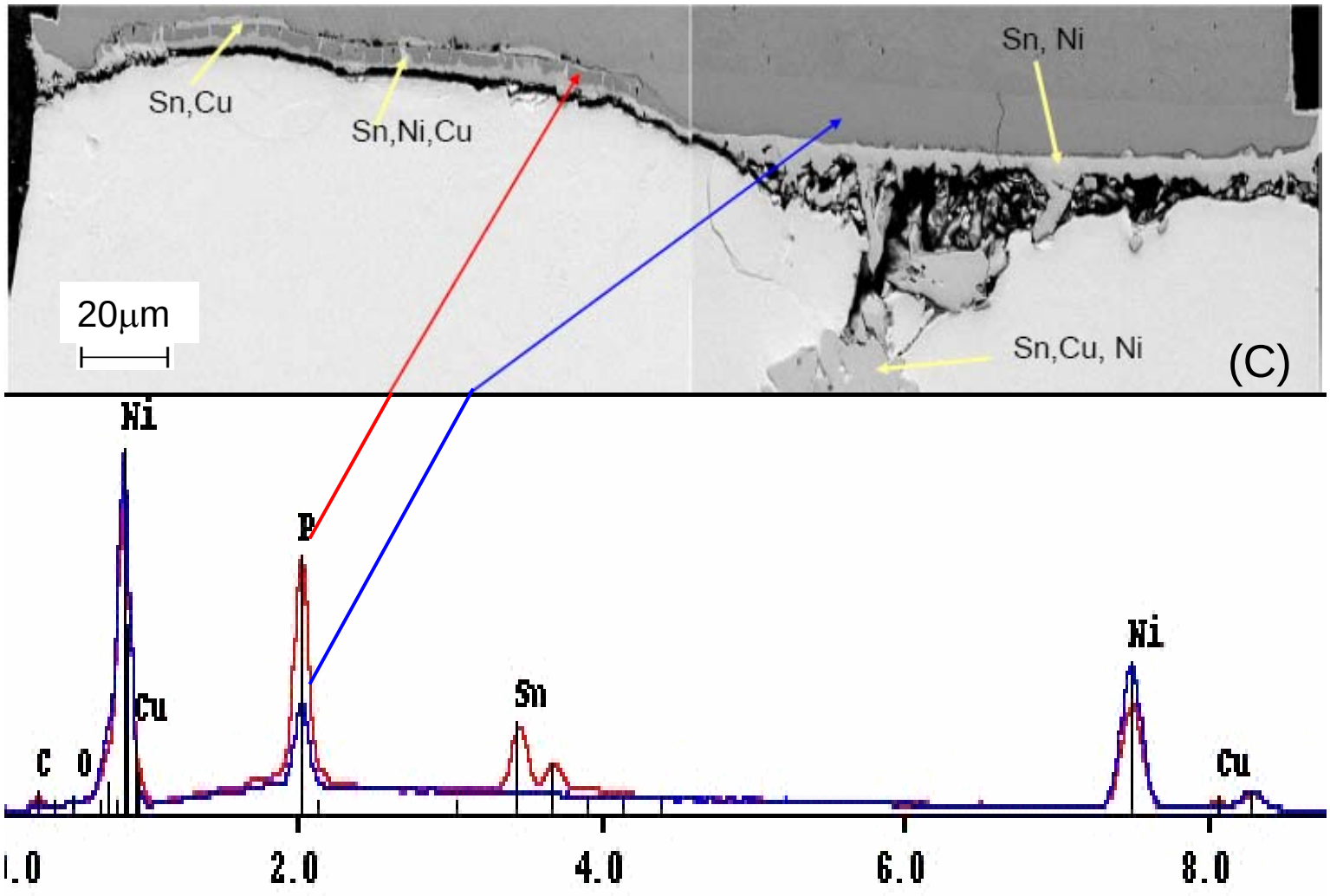


Figure 2. SEM image of a bi-crystal C4 bump with SnCu solder.

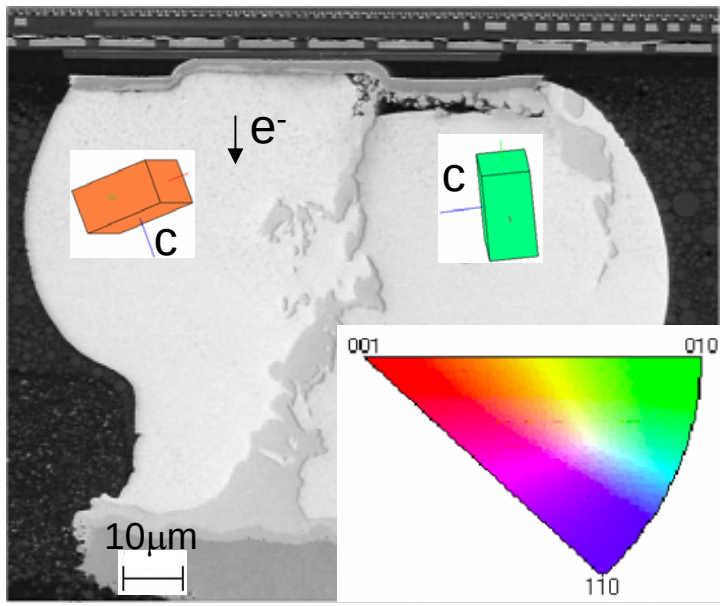


Figure 3. Plot of resistance change vs. stress time.

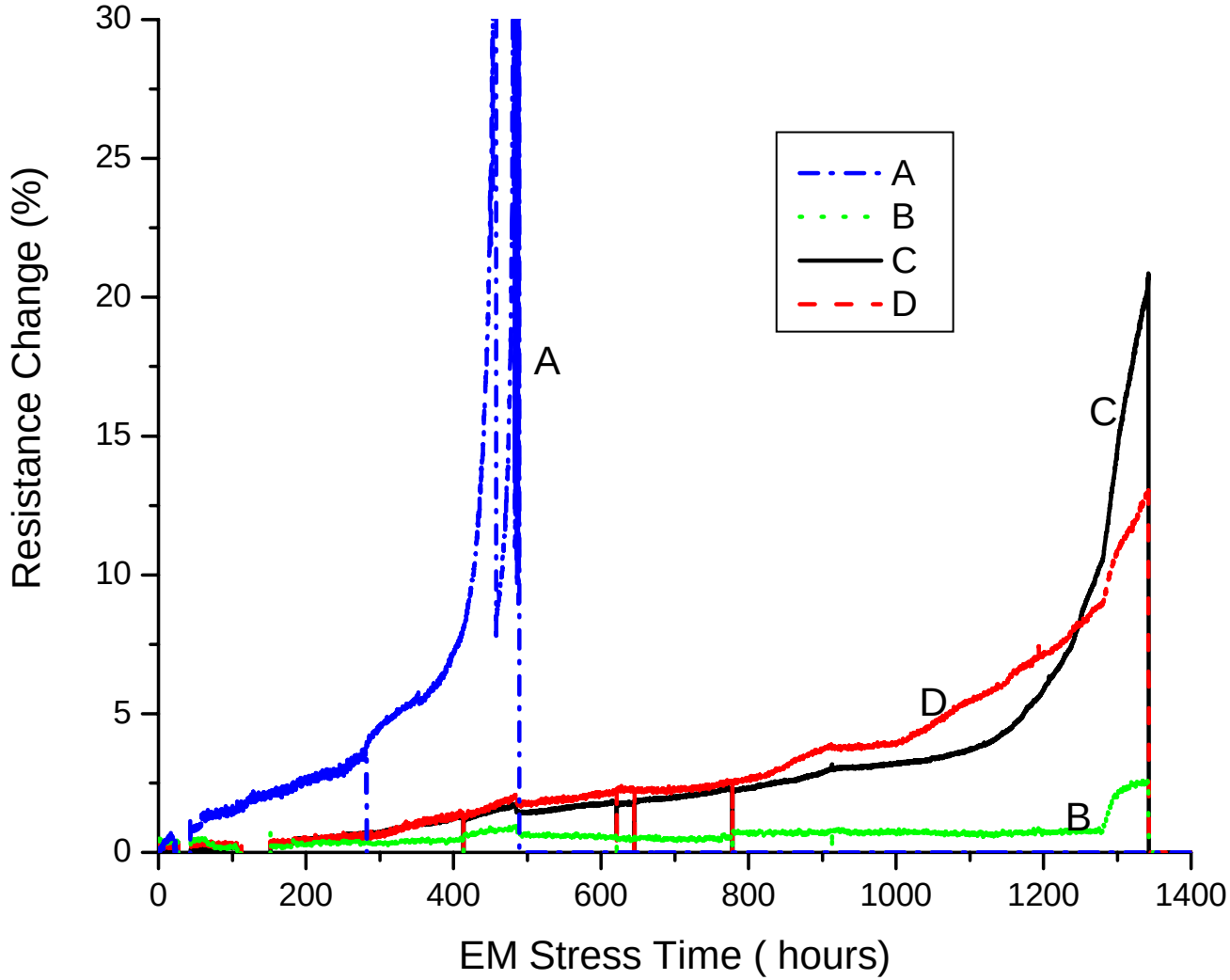
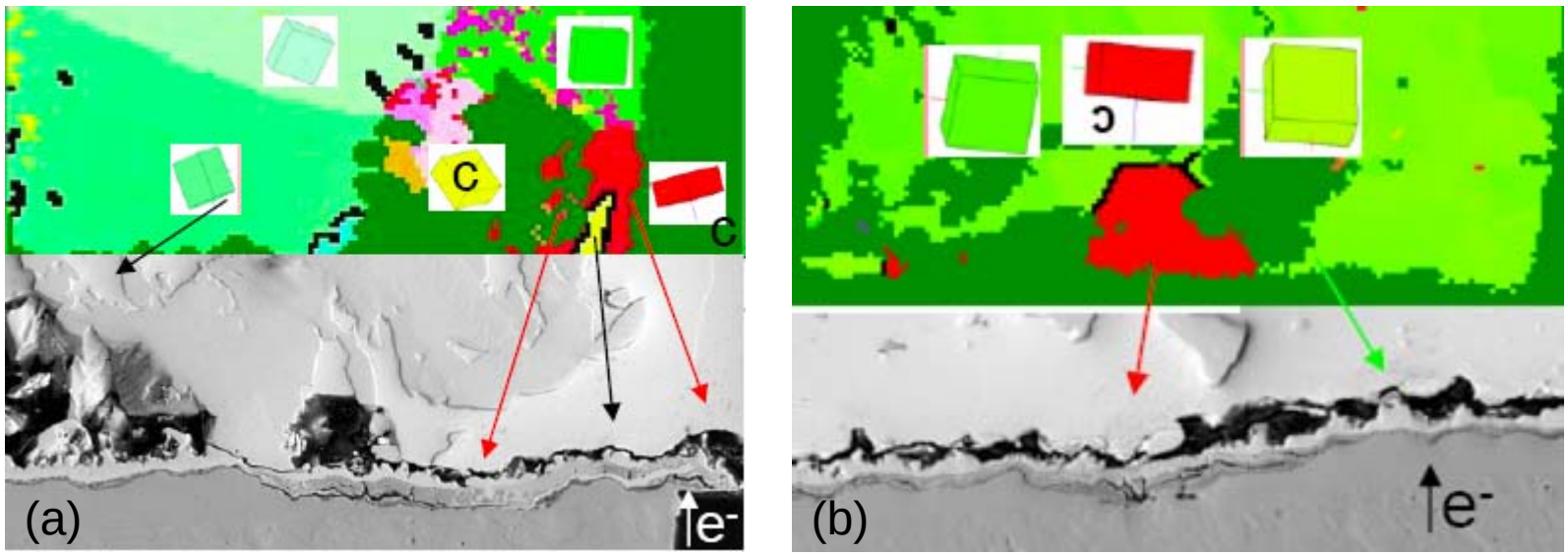


Figure 4. The SEM image and corresponding
EBSD map of a Sn0.7Cu (a) and Sn1.8Ag (b) solder joint after 1342 hour EM stress.



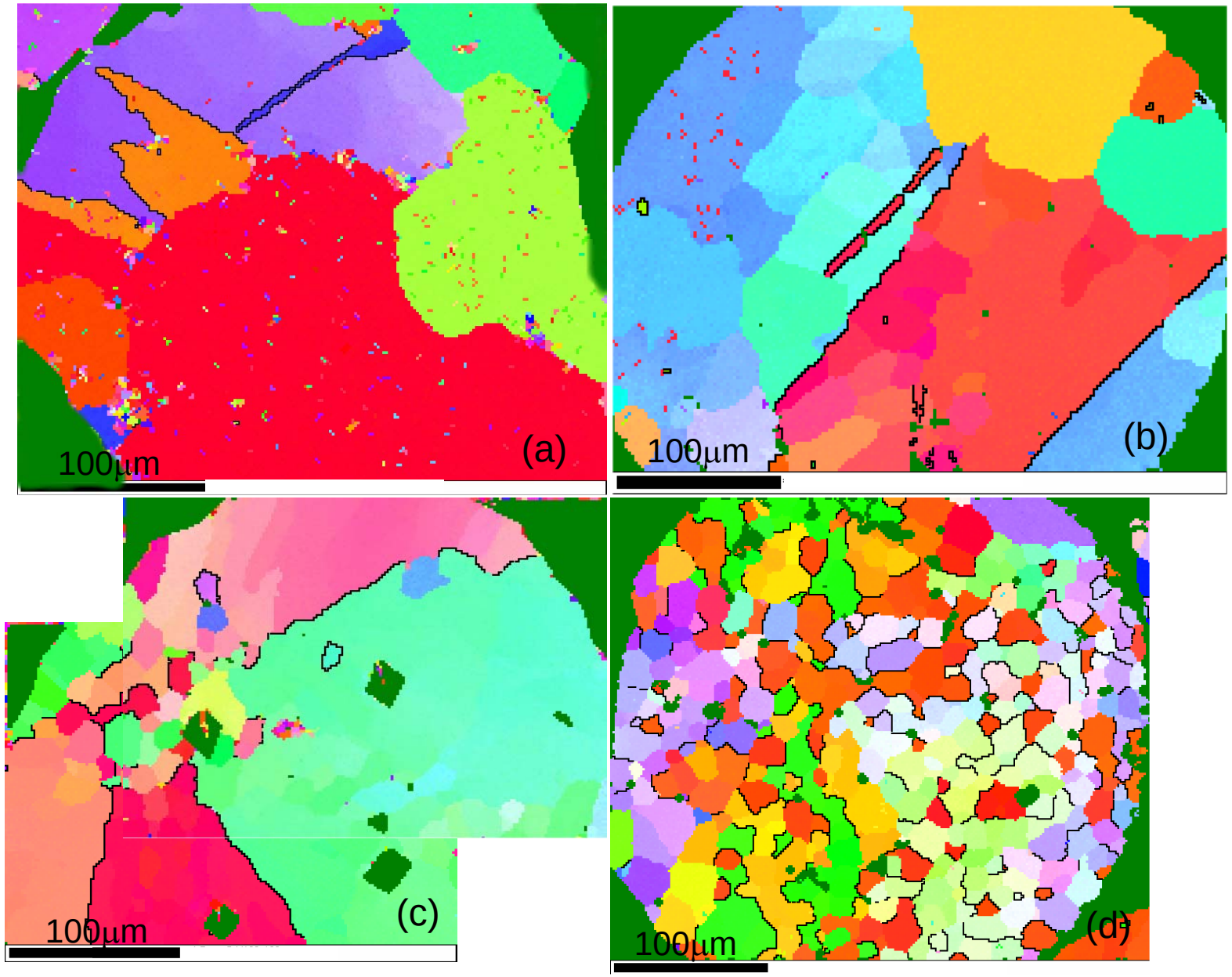


Figure 5. EBSD map of 381mm solder ball after 150° C 1000 hours thermal aging. (a) Sn0.7Cu, (b) Sn0.5Ag, (c) Sn1.0Ag, (d) Sn1.0Ag.