APPLICATION NOTE

Model 1061 SEM Mill

Solder bump joint sample preparation for failure analyses

Solder bump joint failure analyses of microelectronics devices are critical for ensuring device reliability. Argon broad ion beam milling is an ideal sample preparation technique because it does not introduce strain or structural changes to the sample and preserves the sample in its native state.

The packaging technologies of microelectronic devices include solder joints that connect both the chip to the package and the package to the circuit board (Figure 1). The reliability of these joints is critical to the reliability of the microelectronic device. Therefore, the ability to perform failure analyses on these joints is critical. One of the most common failures of this joint is the loss of connectivity between copper pads and solder bumps (Figure 1), which manifest in the form of cracks or delamination. These defects result from joint microstructural evolution induced by constant or cyclic loading conditions during device service.

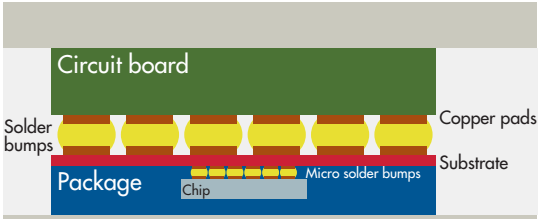

Figure 1. Schematic of a microelectronic device.

A solder joint typically comprises a Sn-based alloy (solder material), an intermetallic compound at the joint interface, and a copper pad. Knowledge of the nature of intermetallic phases that form during the joining process and the distribution of intermetallic phases over the solder joint are very important for understanding mechanical properties and behavior of the joint during the joining process and during device service.

Tin is a very soft and ductile material that is easily deformed; any exterior interference with the joint can lead to structural change. For that reason, preparation of solder bump samples is typically a delicate and potentially complex process. Any mechanical action, such as cutting, grinding, and polishing, can provoke structural changes and introduce strain at the joint interface that may lead to cracks and delamination.

A sample preparation technique that preserves the native state of the joint structure without introducing any artifacts is necessary to fully understand the failure mechanism. This application note describes a sample preparation technique that allows the preservation of the solder joint's native state. Mechanical polishing sample preparation is presented as a comparison. The solder bump samples used in this experiment were extracted from a commercially available smartphone.

Sample preparation

Mechanical polishing (MP) and argon broad ion beam milling (BIB) are two techniques that can be used to prepare a microelectronic device solder bump sample for failure analyses. The MP technique involves polishing the sample with abrasives of successively smaller grit sizes (Table 1). The total MP time, including post-polishing cleaning, can take up to 4 hours.

Table 1. Mechanical polishing procedure used to prepare a solder joint for failure analyses. Successively smaller grit sizes were employed to obtain a smooth sample surface.

Abrasive type	Time [min.]
#800 SiC paper	3
#1200 SiC paper	3
3 µm diamond paste	5
1 µm diamond paste	10
0.5 µm diamond paste	15
0.05 µm colloidal silica	120

The BIB milling technique was also used to prepare a solder bump sample. The BIB milling technique consists of material removal (polishing) by accelerated argon ions. We present here the capabilities of Fischione Instruments Model 1061 SEM Mill (Figure 2). The ion milling conditions described in Table 2 are the milling parameters used to prepare the solder bump sample. Because tin solder bumps are thermal sensitive, liquid nitrogen was used to cool the ion mill's sample stage to -150 °C during milling.

Table 2. Argon ion milling conditions used for preparing a solder joint for failure analyses. Two milling steps – the first at 6 keV, the second at 4 keV – were employed. The total milling time was 60 minutes.

Milling parameter	Step 1	Step 2
Number of ion sources	Two	Two
Milling mode	Planar	Planar
Beam angle	3°	3°
Voltage	6 keV	4 keV
Stage motion	Continuous rotation	Continuous rotation
Stage cooling	-150 °C	-150 °C
Milling time	20 min.	40 min.

To evaluate the two sample preparation techniques, visual observation by backscatter electron contrast scanning electron microscopy (BSE SEM) was done, followed by electron backscatter diffraction (EBSD) analyses. MP (Figure 3a) and BIB milling (Figure 3b) BSE SEM observations show that the results of each technique are demonstrably different. The structural contrast of solder joint and copper pads is sharper in the BIB milling sample than is seen in the MP sample. The MP sample BSE SEM image also highlights that it can be difficult to clean colloidal silica suspension from the sample surface following MP. SiO_2 particles can adhere to the sample surface and be very difficult to remove. Attempts to remove the particles led to the introduction of scratches on the soft tin and copper, thus damaging the materials' structures.

Figure 2. Model 1061 SEM Mill.

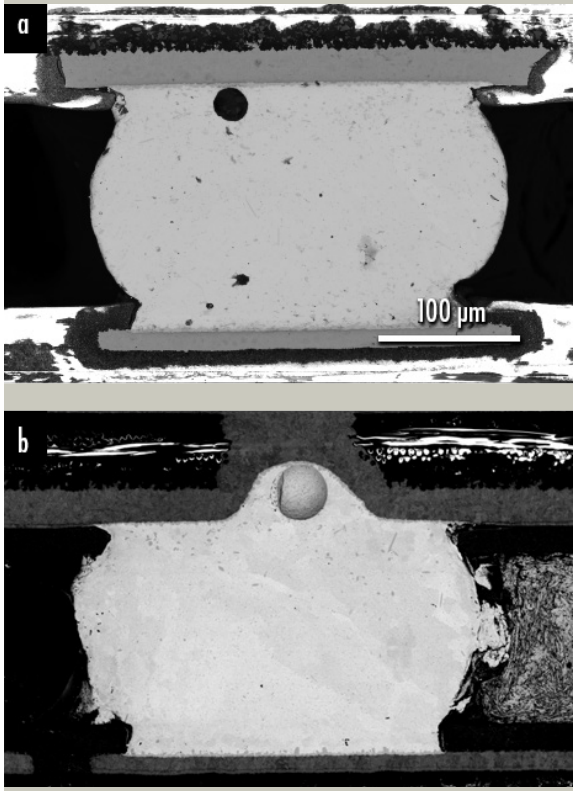

Figure 3. Backscatter electron contrast scanning electron microscopy images of solder joints after mechanical polishing (a) and after argon broad ion beam milling (b). Colloidal silica suspension residue is visible on the mechanically polished sample surface (a), which illustrates the difficulty in cleaning mechanically polished samples post sample preparation.

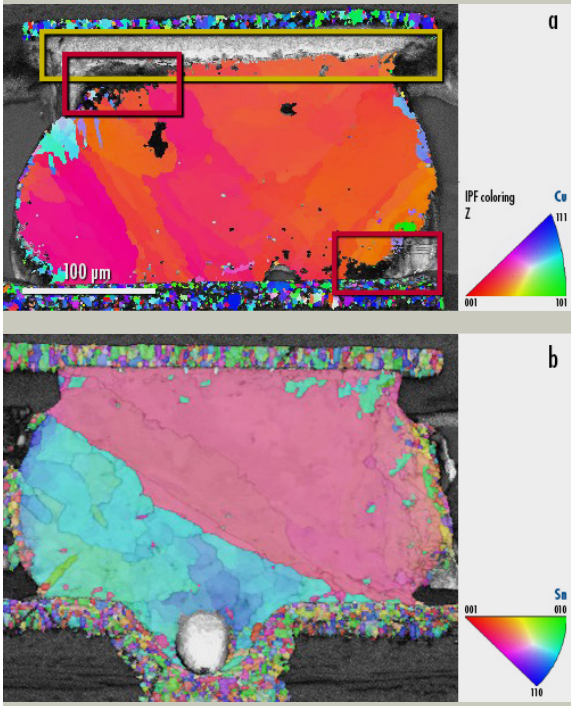

Figure 4. Electron backscatter diffraction inverse pole figure orientation maps overlaid on band contrast maps collected after mechanical polishing (a) and after broad ion beam milling (b). The yellow rectangle (a) indicates an area where the solder bump is shadowed by the copper pad. The red rectangles (a) indicate areas where corrosion product deposited onto the area of interest.

In addition, the use of water during attempts to clean silica colloidal solution from the MP sample provoked corrosion of different package components and made the polishing and cleaning process more complex. No sample cleaning is required after argon BIB milling.

EBSD analyses of the solder bumps prepared by MP and argon BIB milling are shown in Figure 4. In the MP sample, the area close to the joint interface (Figure 4a, yellow rectangle) cannot be analyzed by the EBSD technique. The copper pad caused a shadowing effect due to the difference in material removal during MP. In addition, corrosion product from package components contaminated the area of interest (Figure 4a, red rectangles); these areas also cannot be analyzed by EBSD technique.

In contrast, the sample prepared by BIB milling (Figure 4b) produced excellent quality EBSD patterns – the entire solder bump and the copper pad (including the joint interface) are easily visualized. Figure 4b shows the structure, size, and crystallographic orientation of the grains in the solder bump and the copper pads. From such high-quality sample preparation, accurate microstructural analyses and strain localization and measurements are possible. Figure 5 shows a row of solder bumps following BIB milling (with energy-dispersive X-ray spectroscopy [EDS] overlay maps of Si, O, Sn, and Cu) that is ready for investigation.

Structural characterization of solder joints

High-magnification observation of the copper pad/solder joint interface on the circuit board side and EDS mapping is shown in Figure 6.

At least four phases were distinguished by BSE SEM contrast imaging as seen in Figure 6a. This was confirmed by EDS analyses, which showed Cu, Sn, a Ag-rich phase, and a Cu/Sn-rich phase (Figure 6b).

EDS analyses, combined with EBSD technique, allowed identification of all of the phases shown in Figure 7. High-magnification observation of the copper/solder interface revealed a fifth phase, Cu_3Sn, as shown in Figure 8. The high quality EBSD patterns used for phase determination were possible because of the outstanding surface preparation after ion milling.

Strain analyses

Knowledge about strain presence and distribution in structures under thermo-mechanical loading is critical when attempting to determine the root cause of failure. Cracks and delamination result from the structural evolution and the strain accumulation induced by thermo-mechanical stress acting at the solder joint/copper pad during device lifetime.

Figure 9 shows EBSD investigation of the copper pad/solder joint interface. The EBSD data were collected at 20 kV using 60 nm step size. By using a misorientation calculation, one can

localize strain in the investigated structure. Strain accumulation in the upper right portion of copper pad was evident (Figure 9d). Detailed analyses of strain in the affected area (Figure 10) revealed that the grains with the greatest accumulated strain had an elongated shape with a preferred {110} crystallographic orientation (Figure 10b). The preferred orientation of the grains and elevated strain might indicate a structural evolution resulting from cyclic thermo-mechanical loading; this may eventually lead to delamination of the copper pad.

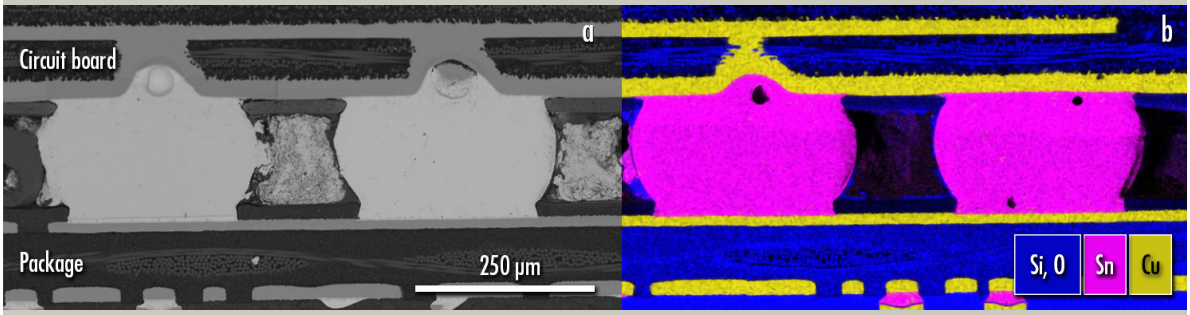

Figure 5. A cross-section sample from a chip package; the sample was created using argon broad ion beam milling. Backscatter electron contrast scanning electron microscopy image of four bumps located between the package (a) with energy-dispersive X-ray spectroscopy overlay maps of Si, O, Sn, and Cu (b).

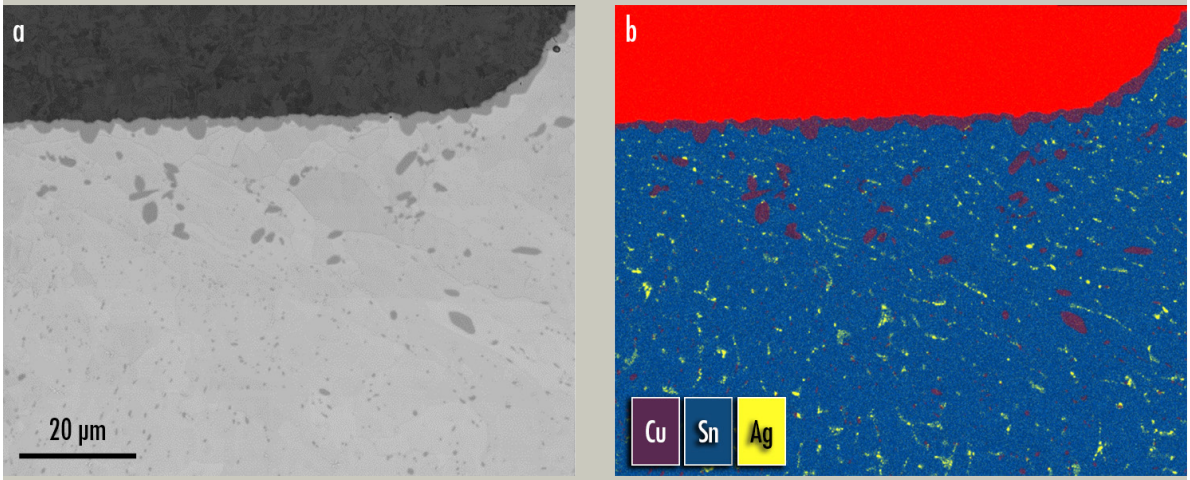

Figure 6. Backscatter electron contrast image of copper pad/solder joint interface on circuit board side of the chip package (a). Energy-dispersive X-ray spectroscopy overlay maps of Cu, Sn, and Ag (b).

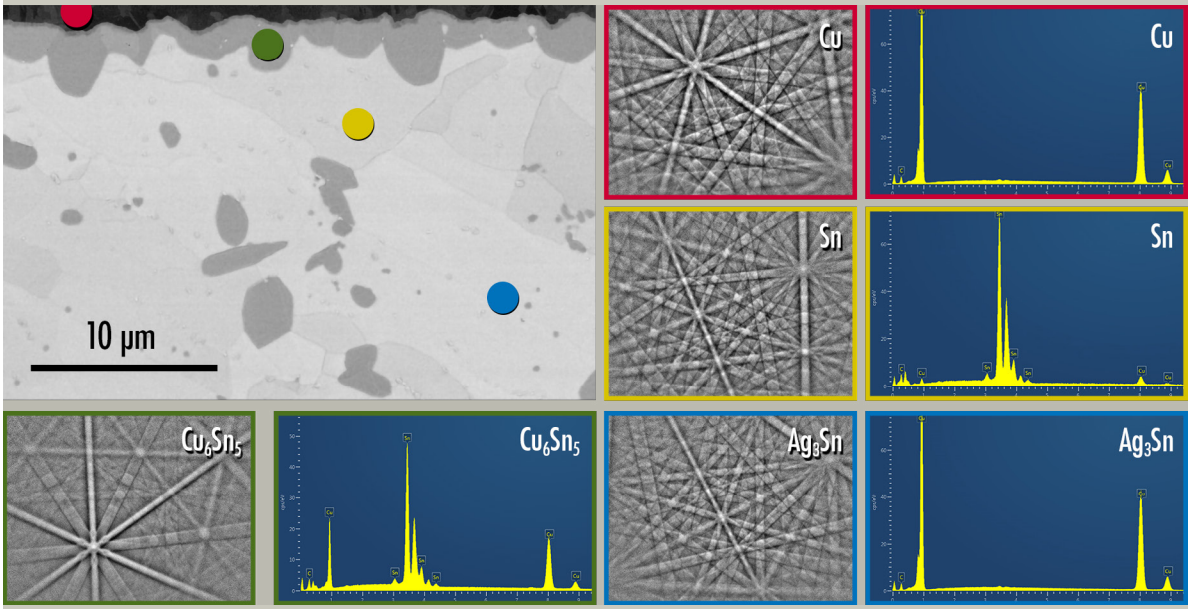

Figure 7. Copper pad/solder joint interface showing different intermetallic phases identified using electron backscatter diffraction and energy-dispersive X-ray spectroscopy analyses.

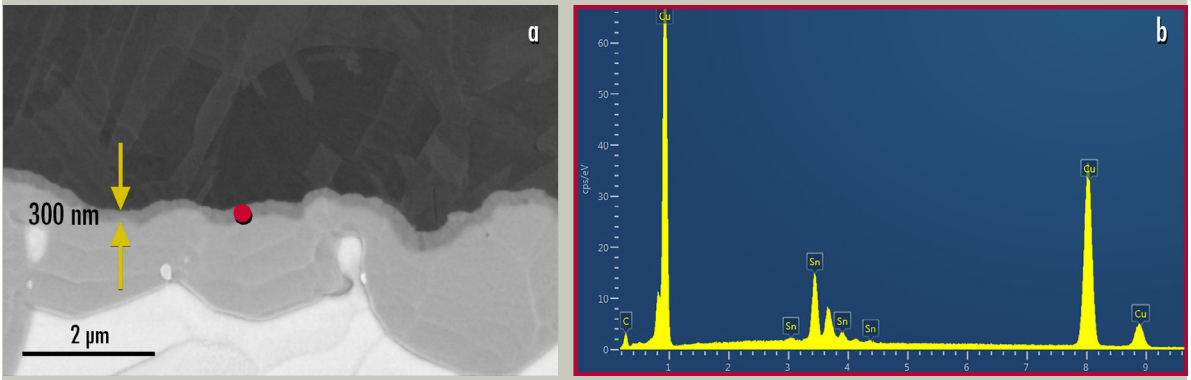

Figure 8. High-magnification scanning electron microscopy image of a copper pad/solder joint interface (a); energy-dispersive X-ray spectroscopy analysis identified a nanostructural intermetallic phase identified as Cu_3Sn (b).

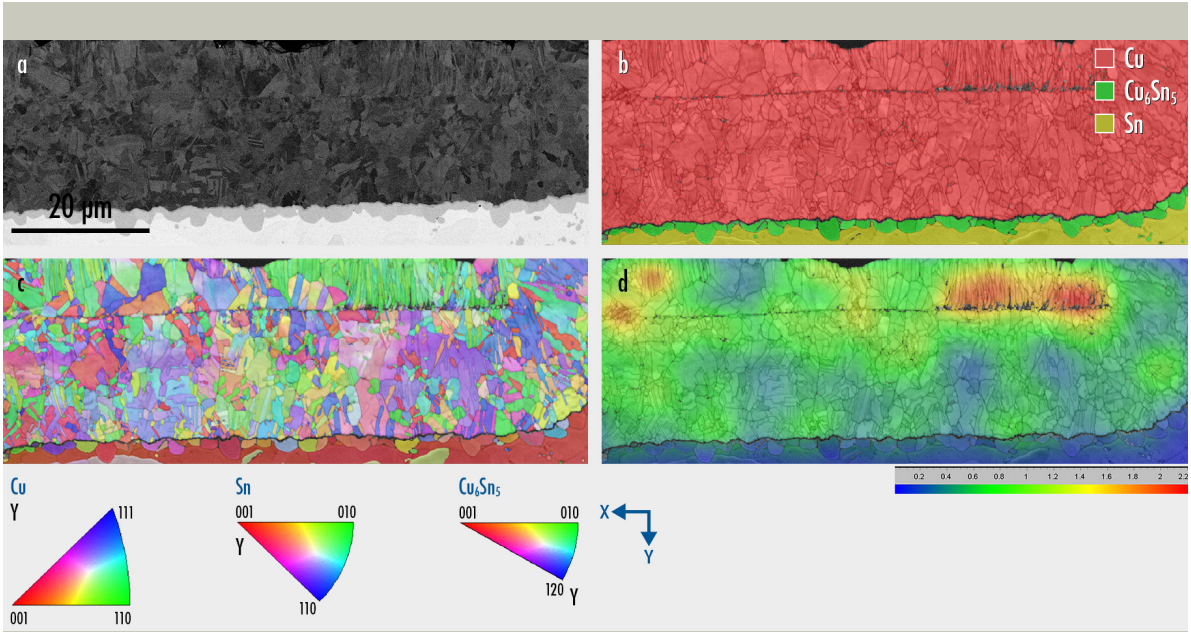

Figure 9. Structural observation of copper pad/joint interface: backscatter electron contrast image (a), electron backscatter diffraction phases distribution map (b), inverse pole figure color code electron backscatter diffraction map (c), and strain contouring electron backscatter diffraction map (d).

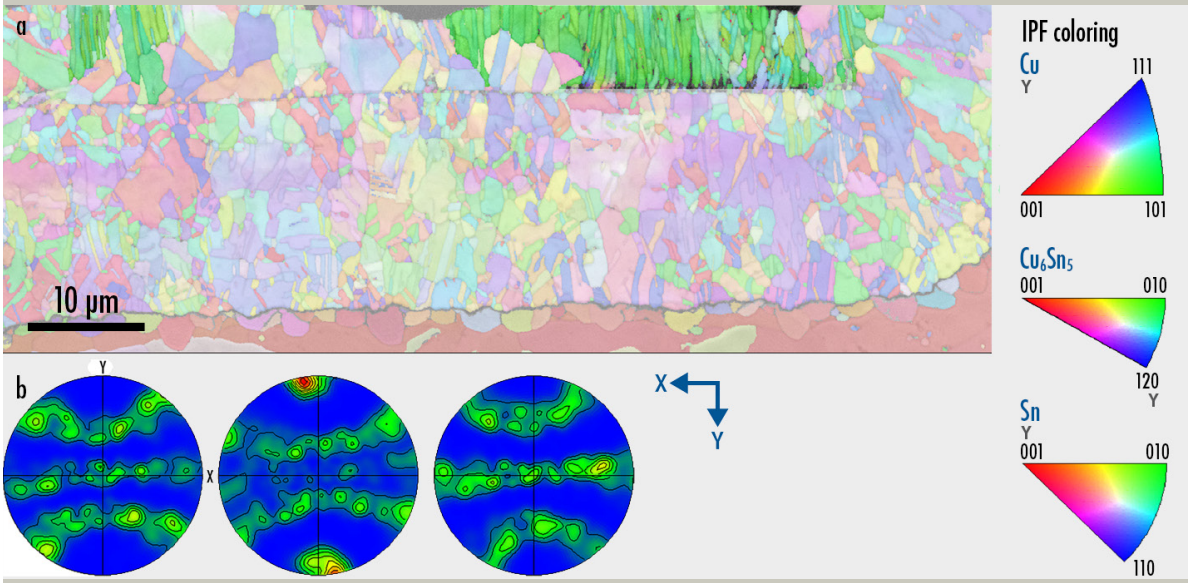

Figure 10. Inverse pole figure color code map in Y-direction (a), set of pole figures showing strong {110} grain texture from highlighted area (b). Strain has accumulated in the same areas (compare to Figure 9).

Conclusion

Argon BIB milling was found superior to MP because it did not introduce additional mechanical stress or defects to the sample. In addition, argon BIB milling allowed accurate structure and microstructure investigation of the solder junction, which includes accurate phase identification and strain analyses. The presence of strain is associated with the development of delamination and cracks. Understanding strain characteristics is the first step toward understanding the failure mechanism and, ultimately, how to prevent future failures of this type.

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