Microstructural Analysis of Solar Cells

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Table of Contents

Introduction

The development and commercialization of photovoltaic (PV) cells is being carried out rapidly. Manufacturers of wafer cells and modules are expected to manufacture panels that are extremely reliable and durable. Although there is a huge demand for warranties of more than 25 years in the market, the quality of a product can deteriorate over time due to the persistent stress on the metallic interconnects. This issue can be overcome by performing cross-sectional microscopic analysis to enhance module/cell reliability from material inspection and interconnect verification of coating analysis. This article presents different techniques to prepare high-quality cross-section samples of crystalline silicon solar cells to

Common Anomalies

Exposure to thermal cycling is the main cause of failures in electronic assemblies. To resist repeated thermal stress, tab ribbon bonds should be durable and reliable. To assess thermo-mechanical stress during pre- and post-accelerated aging of cell interconnects, microstructural analysis is carried out. Aging of the solder interconnects causes constant expansion and contraction of the joint, which causes a solder to fatigue, become fragile, and break into larger grains, altering the mechanical properties of the solder interconnects. To evaluate the efficiency of old and new bonding materials, or when transitioning from leaded to lead-free solders, cell research is generally carried out. Cross sectional analysis of raw materials, microelectronic electric components, and wafers reveal the parameters mentioned below:

- Poor solder wetting
- Joint cracks
- Impurities
- Solder porosity and microvoids
- Solder thickness and delamination
- Solder meniscus
- Unacceptable solder, silicon, and copper microstructure
- Intermetallic phases, coarsening, etc.

Sampling Techniques

A solder joint, copper ribbon, and bus bar (metalized lines) can be extracted from a cell to prepare micro-sections. Solar cells are serially connected on back and front sides (Figure 1) with copper solder coated ribbons. These ribbons are soft soldered (lead based solder) to the paste-like bus bar material, which mainly consists of glass and silver particles. The latter enables solderability and electrical conductivity for the cells. To bond the bus bar material to the cell before the application of the solder-coated ribbons (Figure 2), it is hardened in an oven. To prolong the service life and enhance the electrical conductivity, the use of high-quality solder joints are essential.

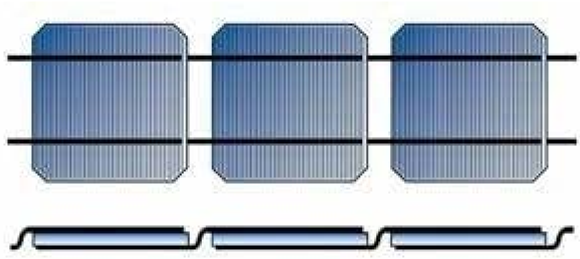

Figure 1. *Solar cells connected in series with tabbing ribbons*

Figure 2. *Interconnector on a soldered solar cell sample exhibiting a poor quality cut (top) and a good quality cut (bottom)*

Sectioning is carried out on monocrystalline (thick-films) or polycrystalline solar cells to downsize the sample, and bring it to a manageable size to mount, grind and polish. To carry out cross-sectional analysis of a PV cell interconnect, the wafer and the solder joint (Figure 3) have to be sectioned without causing any major damage to the cut surface. This preparation is tedious, as the materials are fragile and possess a wide variety of mechanical properties. It is recommended to perform encapsulation with a quick drying acrylic resin such as SamplKwick®, which cures in 15 to 25 minutes to inhibit chipping and cracking during sectioning. The resin is applied by painting the bus lines onto the sides of the cell with a brush (Figure 4). The resin may need to be removed after cutting and before potting to render a stronger bond of the sample while being mounted in epoxy.

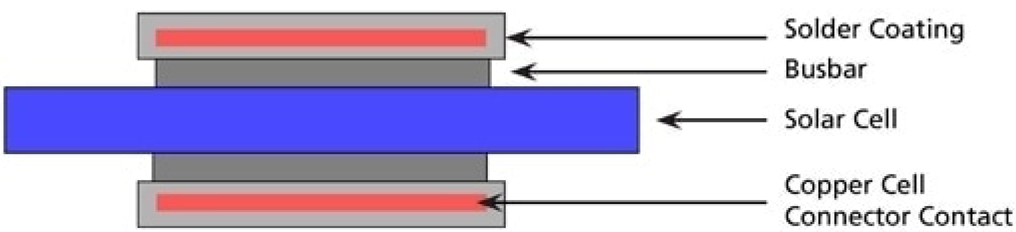

Figure 3. *Solder interconnect of a solar cell bus line*

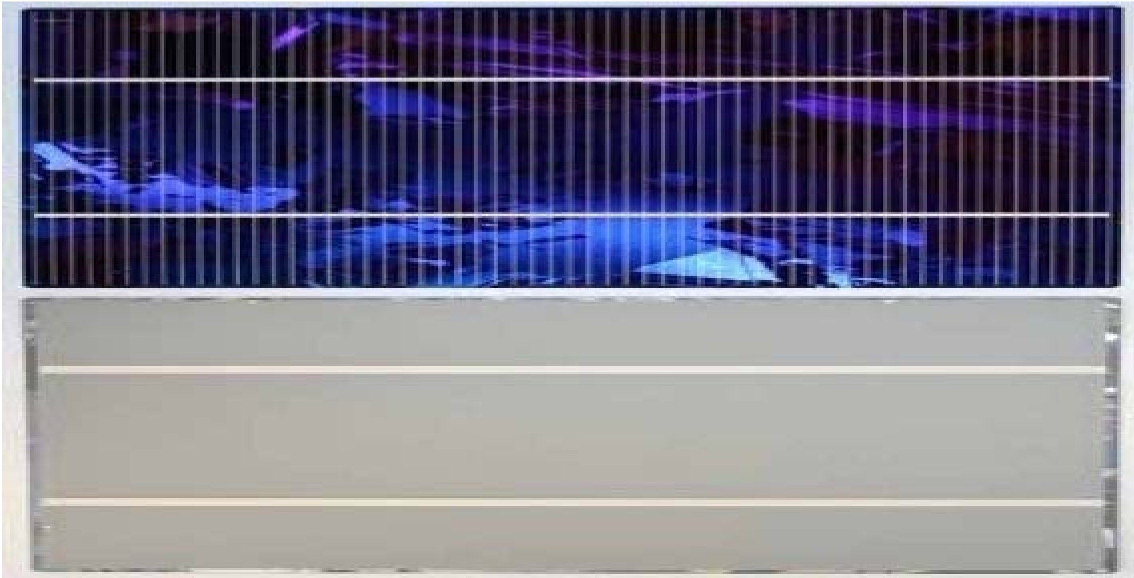

Figure 4. *Front side, top and back side of a polycrystalline Silicon solar cell*

After the acrylic resin covering the bus lines is completely cured, the whole cell, measuring 156 x 156 mm x roughly 0.2 mm in size, is positioned in a solar cell clamping device (Buehler #11-2706 holder) employed in the IsoMet® 4000 Linear Precision Saw (Figure 5). It should be noted that when utilizing a solar cell holder, an acrylic resin coating may no longer be needed.

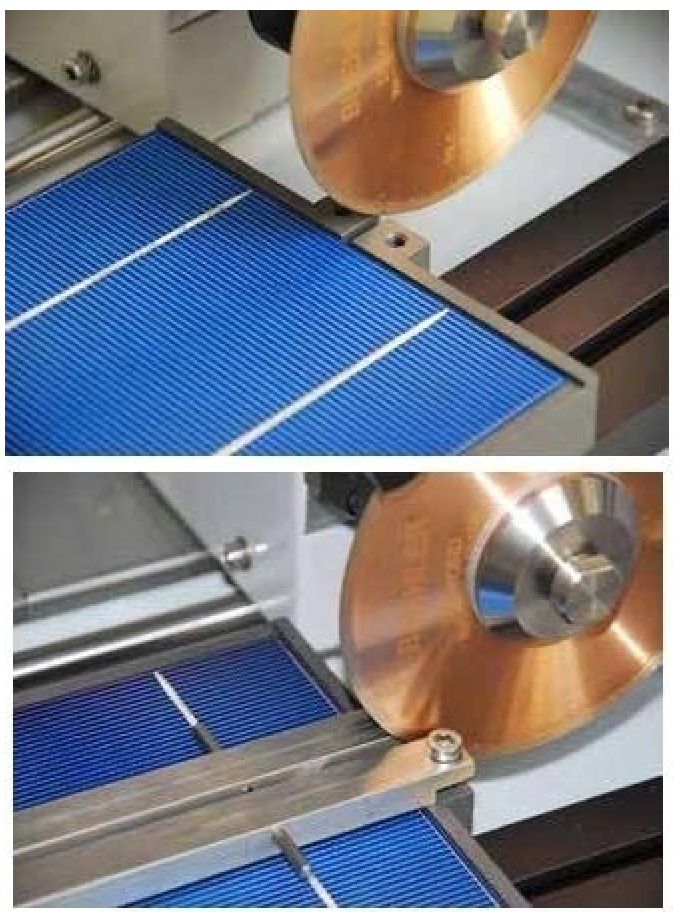

Figure 5. *Buehler solar cell holder for IsoMet® 4000 and 5000 Linear Precision Saws*

After sectioning the entire bus bar, it is cross cut to a manageable size for subsequent mounting (Figure 6). Samples measuring roughly 1 cm^2 are cut from the cell at a cutting speed of 3750 rpm and a feed rate of 5 mm/minute using an IsoMet® Diamond Wafering Blade LC-15 type. The suitable selection of blades reduces the damage that would have to be eliminated by further grinding and polishing. Typical issues experienced while carrying out sectioning are; silicon breakage, bus bar detachment, and edge cracking. Cracks or broken edges (Figure 2) occur due to an extremely high feed rate or a coarser blade.

Figure 6. *Sectioning of the bus bar into samples appropriate for mounting*

Sample Mounting

After the sample has been sectioned from the PV solar cell, it is mounted in epoxy by casting in an epoxy resin EpoxiCure® (Figure 7). EpoxiCure® ensures optimum sample edge retention and is cured within 6 hours, without any notable increase in the temperature in the mounting cup measuring 1.25" (32 mm). EpoxiCure® can be used in combination with a Conductive Filler to perform energy dispersive X-ray spectrometer (EDS) analysis, or scanning electron microscopy (SEM). For vertical positioning of the sample in the SamplKup® mounting cup, a UniClip Support Clip (Figure 8) is utilized. In case of additional edge support requirements, the epoxy is combined with a Flat Edge Filler (Figure 9). The Flat Edge Filler consists of globular ceramic oxide particles, which increase the mount hardness and minimize shrinkage. Sample edge retention is a key feature when observing features at the edge, or when measuring the coating thickness.

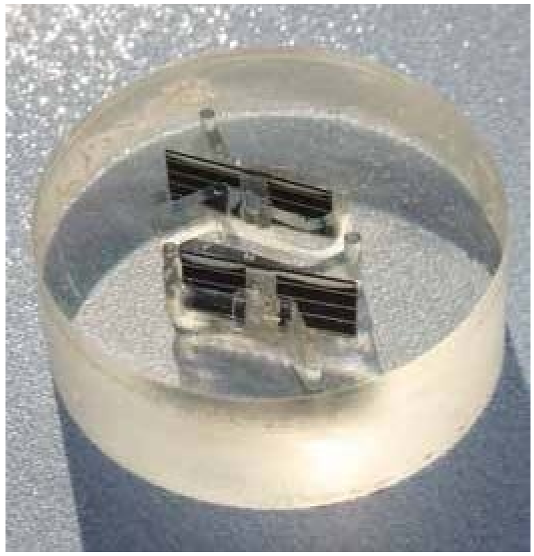

Figure 7. *Solar cell interconnects mounted in EpoxiCure® epoxy*

Figure 8. *Solar cell with interconnector held perpendicular to the cross section with a UniClip Support Clip before epoxy mounting.*

Figure 9. *EpoxiCure® mount solar cells interconnect with Flat Edge Filler (white layer) added to improve edge retention.*

Sample Grinding

After being mounted the samples are mechanically ground and polished. Initially, planar grinding of the samples is carried out using the CarbiMet® 2, 320 grit sized SiC grinding paper. Grinding eliminates any sectioning damage and ensures a flat surface. As induced artifacts can appear upon grinding, it is recommended to maintain a minimal grinding time. The ductile and soft metals (like solder and copper) that trap the abrasives break off upon grinding, and are usually removed at the time of polishing. With each preparation step after grinding care should be taken to thoroughly clean the sample holder that is utilized with semi-automated grinder polishers, and to clean machine components and samples with tap water. When using an UltraMet® Ultrasonic Cleaner, distilled water should be used to clean the samples, in order to prevent scratches in the sample when some of the abrasives are carried to the next step. Scratches can cause problems with electron backscatter diffraction (EBSD) microstructural analysis and fault analysis.

Sample Polishing

Following grinding, the samples are refined by multiple polishing steps. Polishing of Si cells involves four steps, including polishing with alumina and diamond abrasives charged on a polishing cloth. A finer abrasive, lubricated with MetaDi® Fluid, is utilized in each step. As a result of varied hardness of the cell material, hard polishing cloths are used to obtain excellent results. When compared with silicon which is hard, copper and solder are relatively soft and ductile. When the hard and soft materials are placed near each other in a solar cell the soft materials are removed at a greater pace, resulting in excessive relief. This makes sample analysis complicated, and reduces the depth of field because of greater differences in material heights.

Final Polishing

Final polish is the last step of the standard technique, where extremely fine abrasive (0.02 µm) silica are used to eliminate fine scratches remaining from the prior step. Only a small amount of material is removed, so any damage that has been overlooked might not be rectified. Final polishing should be completed within 2 minutes if there has been proper preparation of the sample before this step. The sample can undergo a final preparation vibratory polishing at this point to eliminate any smearing effect, and to clearly define between materials and certain alloy phases. For copper and solder alloys, scratch removal may be extremely hard. To eliminate slight scratches and surplus surface damage, vibratory polishing is performed with a low nap polishing cloth and a colloidal silica suspension. Figures 10 and 11 illustrate the outcome of using a vibratory polisher on an SAC 305 solder alloy. The entire sample preparation method and related parameters are provided in Table 1.

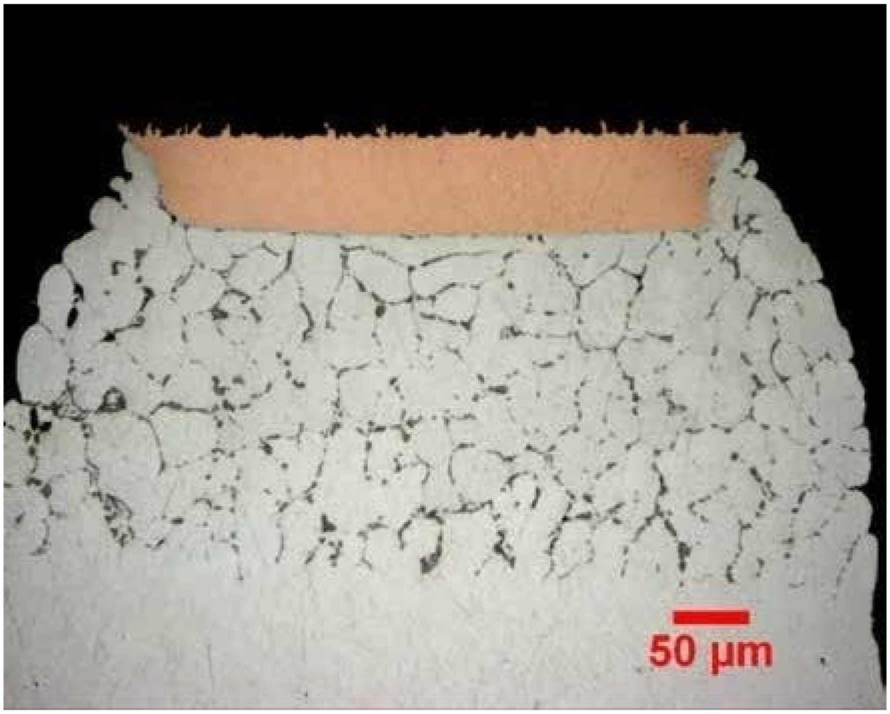

Figure 10. *Unetched SAC 305 solder alloy*

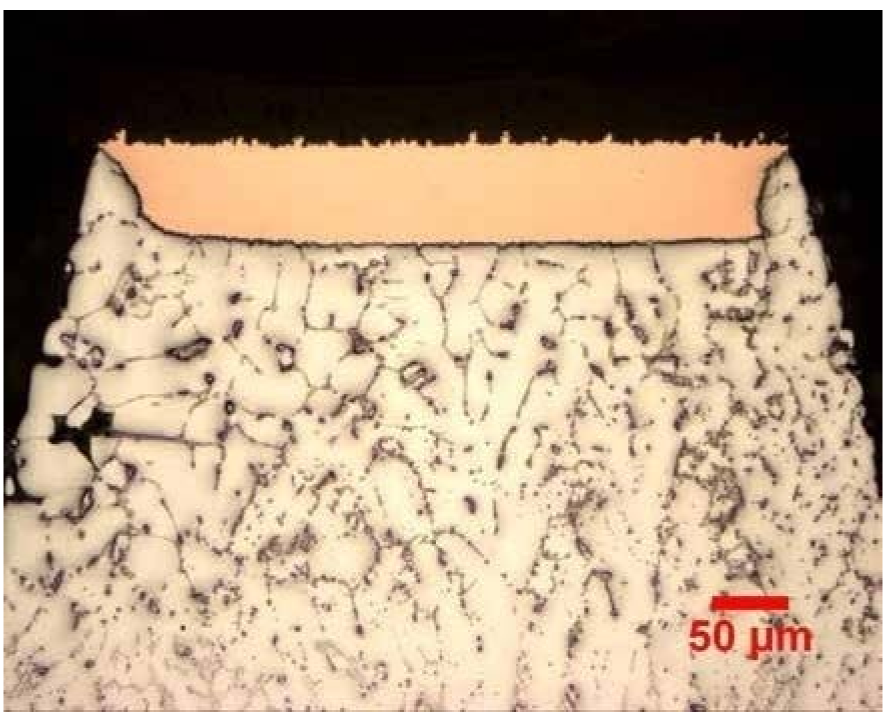

Figure 11. *Unetched SAC 305 Solder Photomicrograph after vibratory polishing*

Table 1. *Sample preparation of polycrystalline solar cell solder interconnect*

Step	Surface	Lubricant	Abrasive/ Size	Time (mins.)	Force Lb (N)	Base/ Head rpm	Head Direction
1. Surface Grind	CarbiMet® 2 SiC Paper	Water	320 (P400) grit	Until Plane	5 lb (22)	300/60	Complementary
2.	UltraPad™	MetaDi®	9 µm MetaDi® Supreme Diamond	5:00	5 lb (22)	150/60	Contra
3.	TexMet™	MetaDi®	3 µm MetaDi® Supreme Diamond	4:00	5 lb (22)	150/60	Complementary
4.	MicroCloth®	MetaDi®	1 µm MetaDi® Supreme Diamond	2:00	5 lb (22)	150/60	Complementary
5.	ChemoMet®	MetaDi®	0.02 µm MasterMet® 2 Colloidal Silica Suspension	1:30	5 lb (22)	150/60	Contra
6. Optional	VibroMet® 2 Vibratory Polisher; MicroCloth®	N/A	0.02 µm MasterMet® 2 Colloidal Silica Suspension	≥ 60	N/A	N/A	N/A

Metallographic Examination

The quality of solar modular production is ensured by investigating the soft solder joints. Solder interconnect quality plays a vital role in increasing the lifetime of solar cells. Individual cells are serially connected by soldering flat copper solder coated ribbon to metalized bar traces. Figure 12 depicts a cross-sectional view of the ribbon interconnect. Figure 13 shows insufficient solder at each end of the solder encapsulated copper ribbon. Measurement can be made to ensure proper thickness of the other solder layers and bus bar.

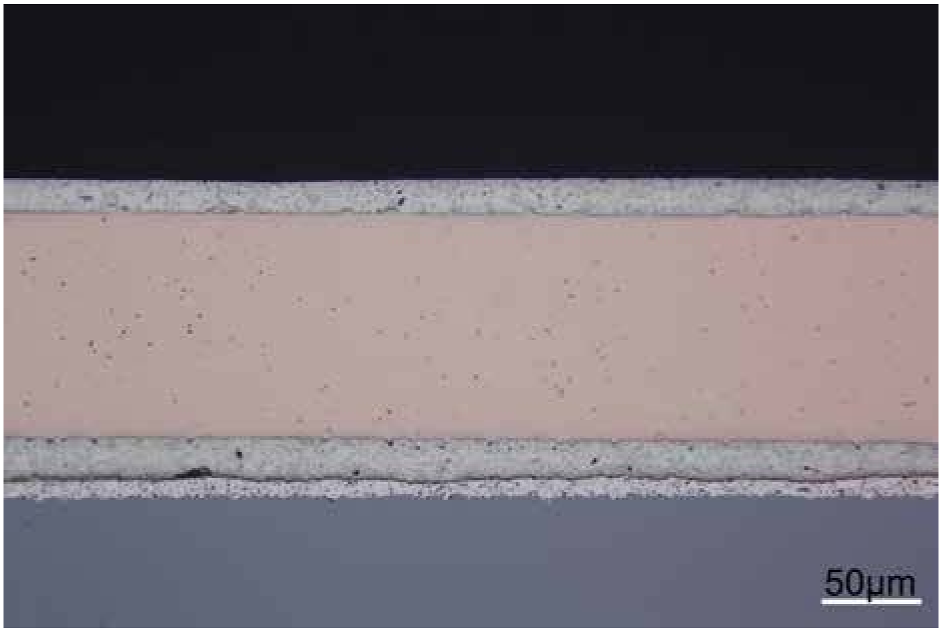

Figure 12. *Microstructure of Sn62-Pb36-Ag02 solder, unetched solar cell copper ribbon*

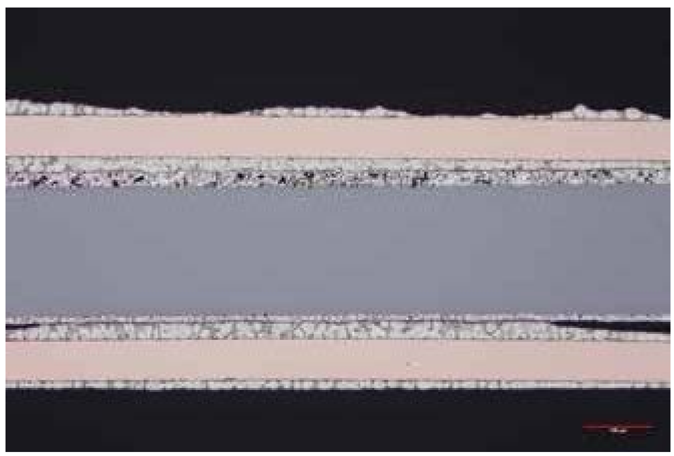

Figure 13. *The entire solar cell interconnect shows both top and bottom soldered seams.*

Wetting is an alloy process where the solder coated ribbon is soldered to the bus bar. To ensure strong stable connections it is crucial to perform proper wetting. In the field of electronics it is possible to determine a wetting angle, and a slightly concave wetting angle of less than 40° is sufficient. As screen-printed pastes are used for the bus lines in solar cells it is hard to attain this angle. A satisfactory solder wetting angle between the soldered coated copper ribbon and the bus bar is shown in Figure 14. Figure 15 displays an inappropriate wetting angle showing voids in the solder. Depending on their size and location, a specific percentage (area) of voids is allowed. Microvoiding (small voids along the interface), usually less than 1 mm in diameter, are often caused due to the surface finish or contamination.

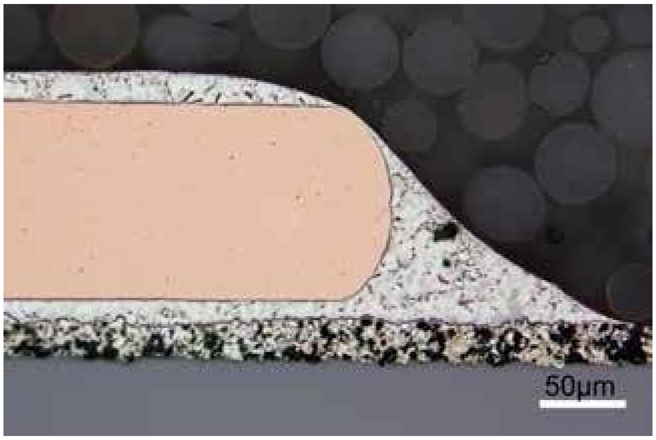

Figure 14. *Proper wetting angle of soldered copper*

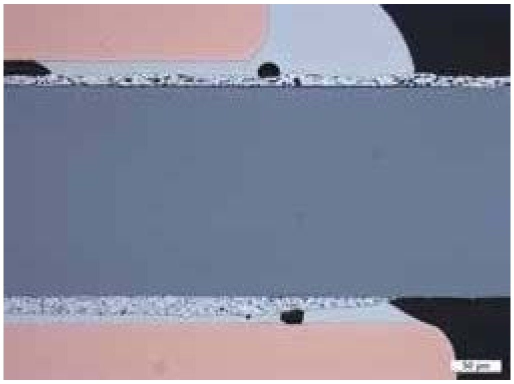

Figure 15. *Both solder interconnects show an insufficient wetting angle and several voids in the solder layer*

Thermal stresses can lead to delamination and the formation of cracks during wafer/cell manufacturing, or during soldering. So when preparing the sample, care must be taken to avoid smearing of soft metals that hide micro-cracks. Figure 16 displays a delamination of the bus bar and a crack in the silicon wafer.

Figure 16. *Light optical images showing delamination of a contacted bus bar at the cell interconnect and cracking seen across the wafer in dark gray at the bottom*

When two dissimilar metals diffuse into one another, intermetallic compounds can form. Numerous lead-free and leaded solders will develop over the lifetime of the cell. These compounds may become hard and brittle, and they can have greater electrical resistivity than the constituent metal. A bismuth with a lead-free solder interconnect is shown in Figure 17. Figure 18 shows Sn62-Pb36-Ag02, etched with Klemm II, Eutectic solder material, with Pb-rich solid solution and Sn-rich solid solution. Figure 19 displays SEM images of the intermetallic phase growth of the solder above the bus bar, both before and after the accelerated aging of a solder interconnect on a bismuth lead-free solder. The different compounds developed in this process are analyzed with EDX by labeling the materials and their elemental maps. Interpretation of the constantly evolving microstructure and its mechanical properties when subjected to accelerated aging, including the effects on the solder joint, would provide a better understanding about how to increase the lifetime of the interconnects.

Figure 17. *Microstructure of Bismuth containing lead-free solder Sn60-Bi38-Ag02 (unetched) interconnect*

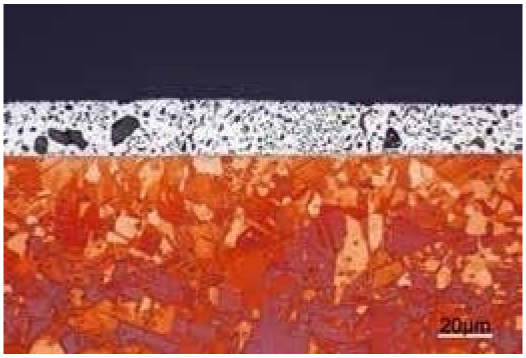

Figure 18. *Sn62-Pb36-Ag02, etched with Klemm II, Eutectic solder material with Pb-rich solid solution (dark) and Sn-rich solid solution (light-colored)*

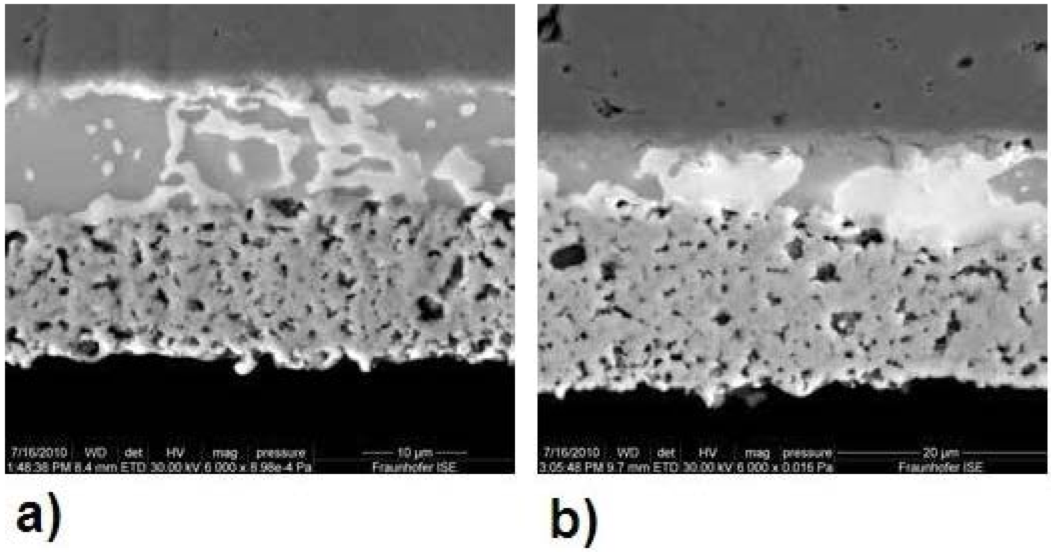

Figure 19. *SEM image showing the intermetallic phase growth after accelerated aging: (a) Bismuth containing solder on (b) bus bar*

Silicon Ingot Sample Preparation

Performing microstructural analysis of amorphous silicon ingots, utilized in wafer cell production, is crucial to enhance product performance. The characterization of the material for quality purposes can expose grain size, structure, impurities, annealing twins, and give a record of its process for future purposes. Preparation of pure silicon or pure metals is a complicated and time-consuming process compared to alloys.

This process starts with removal of the material from the ingot, but most of the damage occurs during sectioning, so care must be taken to ensure that the right sectioning blade is used to reduce thermal and mechanical damage. It is advisable to perform compression mounting using a SimpliMet®automated Mounting Press when the sample is ready to be mounted, as it is not as delicate as the solar cell interconnects. To ensure better hardness and edge support, EpoMet® F Molding Compound is utilized for the mount media. After mounting the sample, the sample preparation can be performed with a seven-step preparation method (Table 2).

Table 2. *Pure silicon preparation method*

Step	Surface	Lubricant	Abrasive/ Size	Time (mins.)	Force lb [N]	Base/ Head rpm	Head Direction
1. Surface Grind	CarbiMet® 2 SiC Paper	Water Cooled	240 grit [P280] SiC	Until Plane	5lb [22]	300	Complementary
2.	CarbiMet® 2	Water	320 grit [P400] SiC	1	5lb [22]	300	Complementary

	SiC Paper	Cooled					
3.	UltraPad™ Silk	MetaDi® Fluid	9 µm MetaDi®	5	5lb [22]	150	Contra
4.	TriDent®	MetaDi® Fluid	3 µm MetaDi®	5	5lb [22]	150	Complementary
5.	TriDent®	MetaDi® Fluid	1 µm MetaDi®	2	5lb [22]	150	Complementary
6.	MicroCloth®		0.02 µm MasterMet® 2 Colloidal Silica	3	5lb [22]	150	Contra
7.	MicroCloth®		0.02 µm MasterMet® 2 Colloidal Silica	≥ 60	VibroMet® 2 Vibratory Polisher		

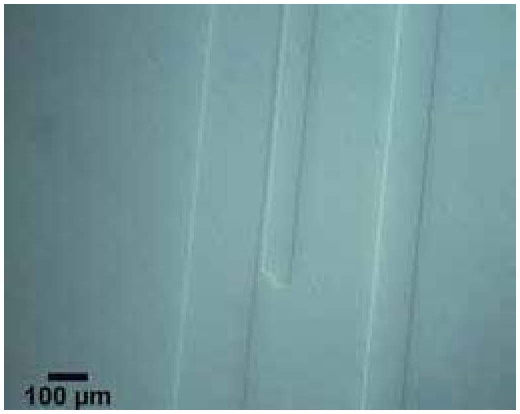

Figure 20. *High purity, defect-free, polycrystalline silicon viewed with Nomarski DIC (etched with 100mL water, 75g NaOH)*

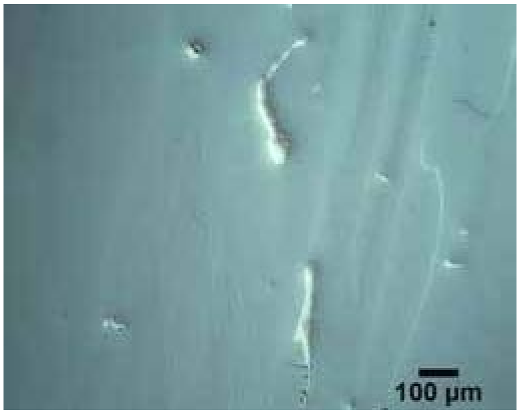

Figure 21. *Polycrystalline silicon viewed with Nomarski DIC (etched with 100mL water, 75g NaOH)*

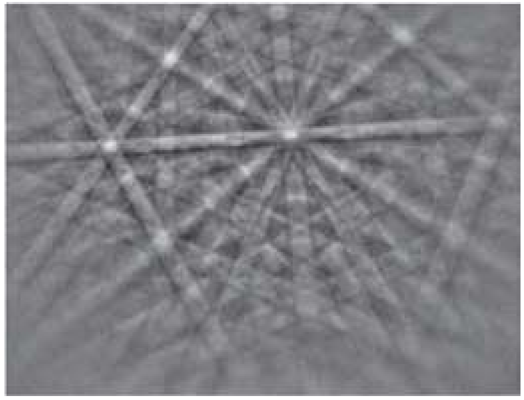

Figure 22. *Standard sample preparation of pure single-crystal, band contrast 205.8*

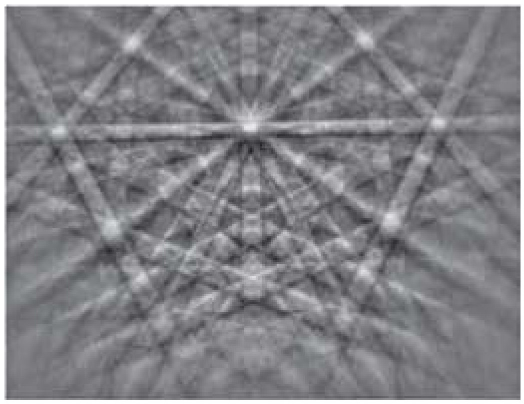

Figure 23. *Standard sample preparation plus vibratory polishing of pure single- crystal, band contrast 233*

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ASTM B795-13: Standard Test Method for Determining the Percentage of Alloyed or Unalloyed Iron Contamination Present in Powder Forged (PF) Steel Materials

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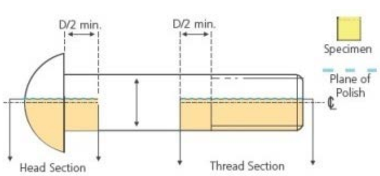

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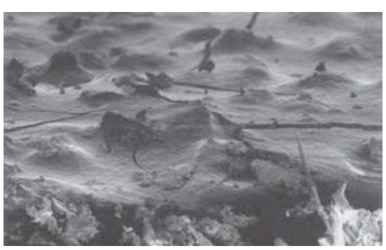

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