From Transistors to Bumps: Preparing SEM Cross-Sections by Combining Site-specific Cleaving and Broad Ion Beam Milling

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Cross section sample preparation is demonstrated using a workflow that combines High Accuracy Cleaving (HAC) and Broad Ion Beam (BIB) milling.

In order to develop and manufacture new materials and processes, the cross section is essential (**FIGURE 1**). Cross sections allow one to visualize, measure, and characterize the chemistry of the film stack or device structures. This allows engineers to verify the integrity of devices and to make critical decisions about the process. To be able to provide this data, manufacturers and equipment suppliers invest close to a billion dollars annually [1] to purchase equipment for off-line use and out- of-fab support labs.

Because such labs are not considered a "make wafer" function, lab managers are under constant pressure to reduce costs, both per sample and for lab operations. This paper demonstrates cross section sample preparation using a workflow that combines High Accuracy Cleaving (HAC) and Broad Ion Beam (BIB) milling. Coupling these techniques, which are relatively low in cost when compared to Focused Ion Beam (FIB) or automated polishing or cleaving [2], reduces sample preparation time, complexity, and cost without sacrificing cross-section quality. The LatticeAxTM HAC and the Hitachi IM4000 BIB milling tools were used to demonstrate this process and are also described.

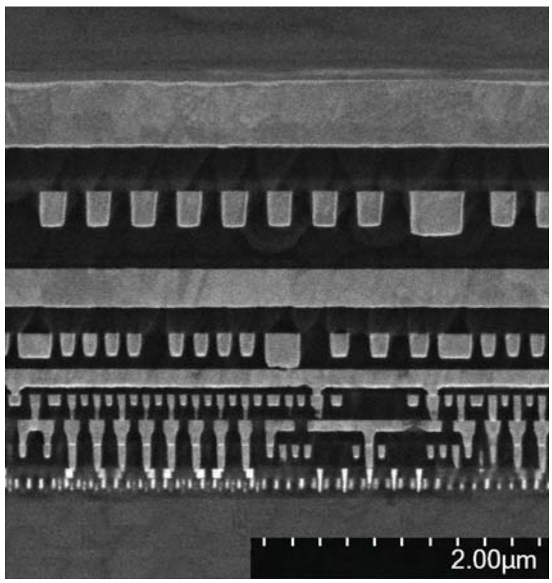

FIGURE 1. Cross section of a fully processed microprocessor prepared by high accuracy cleaving and flat milling

Preparing cross sections for SEM analysis

Characterization of semiconductor structures and material properties commonly begins with sample preparation. Semiconductor samples are inspected

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FIGURE 2. Wafers and wafer pieces enter a cross-section workflow that starts with cleaving and then follows a single- or multi-tool sample preparation process.

either as a cross section or "top down." Cross-section samples are needed to inspect layers of subsurface features. As shown in **FIGURE 2**, if a cross-section view is required and the original sample is a wafer or a die, cleaving is typically the first step in the sample preparation procedure.

In many cases, the sample can proceed directly to the Scanning Electron Microscope (SEM) as shown in the Single-Tool workflow. For fully processed devices and those with large metal structures, improving surface quality with another method enhances the results (see Multi-Tool workflow).

Advanced techniques used in the multi-tool workflow, such as FIB and automated polishing, have benefits in terms of submicron—or in the case of FIB, nanometer—targeting accuracy, but the tradeoff is high cost, long cycle time, and the need for skilled operators.

Methods

The following sections describe the techniques used to perform multi-tool, cross-section sample preparation workflow using HAC and BIB milling.

High Accuracy Cleaving An accurate and high quality cleave is critical to preparing a cross section for SEM imaging regardless of whether it follows the single- or multi-tool workflow. Manual cleaving, in which you scribe a line and then break the sample along the fracture over a raised edge or pin, has inherent problems with accuracy and repeatability. In addition, because the user handles the sample with

FIGURE 3a. Hand tools commonly used for cleaving semiconductor materials

fingers that are often gloved, great skill is required to achieve good results. **FIGURE 3a** shows traditional scribing hand tools used in manual cleaving. Cleaving results using these tools are obviously dependent on the hand-eye coordination of the operator.

The LatticeAx process overcomes these disadvantages by controlling the indent location and depth, as well as the cleaving operation, with fine-positioning knobs on the LatticeAx high magnification digital microscope. This new machine-assisted Indent and Cleave[3] approach bridges both manual scribing and fully automated cleaving or polishing, and increases success rates while keeping costs down.

The accurate, repeatable indent and slow, controlled cleaving that results from this hybrid tool (**FIGURE 3b**) speeds preparation time and produces high accuracy, quality results—regardless of user experience—and with greater flexibility of sample size and dimensions.

FIGURE 3b.

Broad Ion Beam Milling The BIB milling system is a specimen preparation device (**FIGURE 3c**) for SEM and surface analysis (EDX[4], EBSP[5], etc.). The device uses a defocused beam of argon ions that sputter material from the target specimen at a

FIGURE 3c. Hitachi IM4000Plus broad ion beam milling system

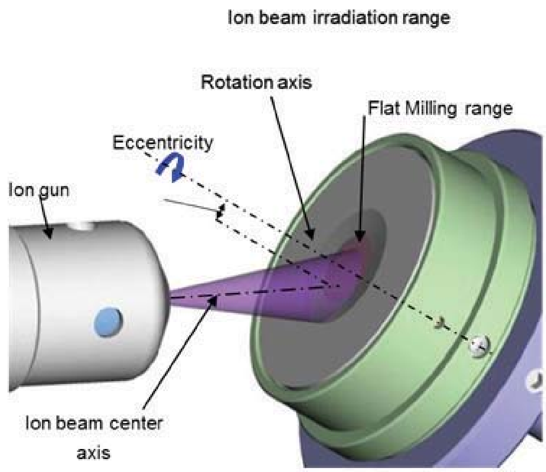

FIGURE 3d.

rate up to 2-500μm/hour, depending on the mode used. The BIB milling system uses a simple, repeatable process to remove surface layers of a specimen and for final finish of specimens in cross section. It is advantageous compared to mechanical polishing methods, which require well-trained operators to polish the specimen to a flat and mirror-like surface and hit a specific target. In addition, complex material composites that contain materials varying in hardness pose challenges when mechanically prepared using polishing wheels and compounds. This mechanical approach can lead to cracks, stress, relief (pull-out effects), and smearing. These adverse effects are minimized when using the low voltage (0-6kV) argon beam to remove material.

Flat Milling Mode Using the BIB's "Flat Milling" mode yields a high quality cross section in a short amount of time. It requires the initial high accuracy cleave to be through or within a few 100nms of the area of interest and the face of the cross section to be at 90 degrees to the sample surface. With a high quality cleave, the BIB's Flat Milling mode quickly polishes the cross-section face. Material is removed at a rate of 2μm/hr. Using the flat milling holder, the milling process can uniformly sputter an area approximately ~5mm across around the center of rotation of the specimen (**FIGURE 3d**). Typical operating parameters for the Hitachi IM4000Plus are 3kV accelerating voltage and a tilt of 70 degrees, with sample stage oscillation set to ±90 degrees and 10rpm. The best quality surface is achieved with a minimum mill time, thus the importance of cleaving through, or very close to, the region of interest. Otherwise, variations in the milling rates of different materials produce artifacts, often called "curtaining."

Cross-section Mode When more than a few microns of material need to be removed, the BIB system is operated in "Cross-section" mode. This is commonly used when exposing a sub-surface target structure. Mechanical grinding causes mechanical artifacts and deformation from stress, making it difficult to obtain a smooth surface for SEM analysis. When using the cross-section milling holder, the BIB IM4000Plus shields part of the argon ion beam with the mask arranged on the specimen, and produces a cross section along the trailing edge of the mask into the sample. For Cross-section mode, targeting accuracy is approximately +/- 15μm.

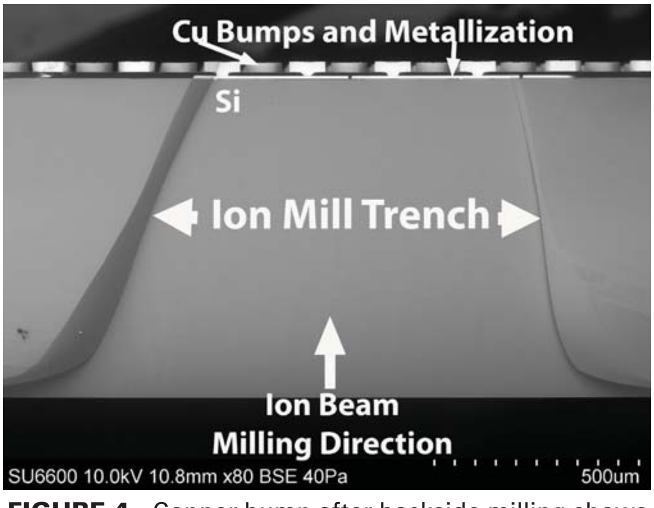

FIGURE 4. Copper bump after backside milling shows both the milling direction and the trench created by the ion beam

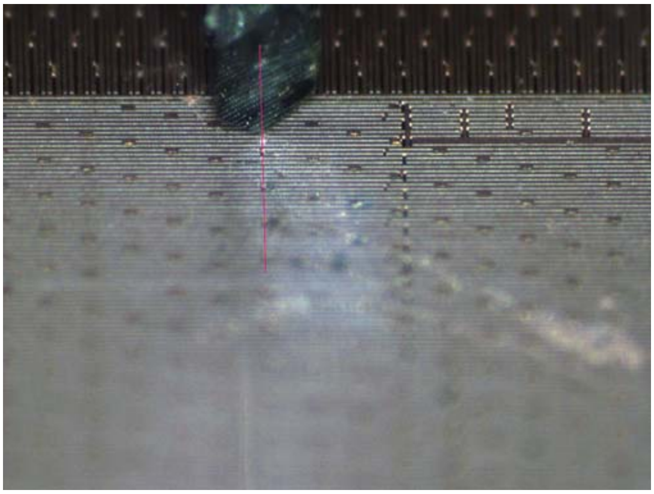

FIGURE 5a. Case Study 1 –HAC and flat milling processes for cross section final polish

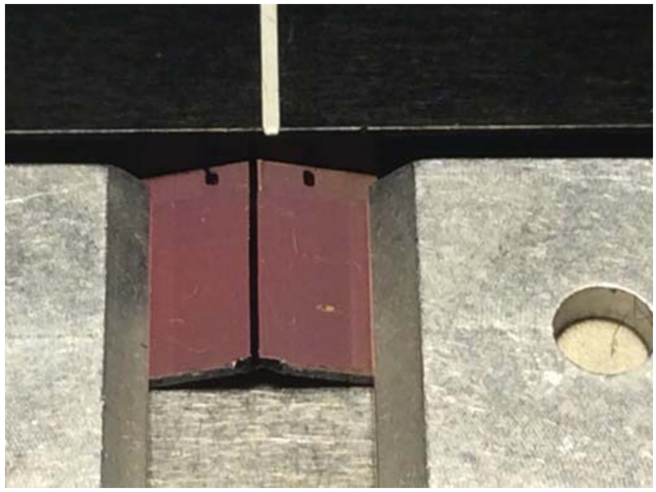

FIGURE 5b. View of sample after cleaving with the small sample cleaver

Backside Milling Backside (as opposed to topside) milling mode can be used in both flat milling and cross-section modes. Backside milling is effective and necessary to alleviate curtaining effects[6] that can occur when traditional top-down ion milling induces striations. These striations are caused by the milling differential from neighboring materials that are atomically denser than the surrounding area. **FIGURE 4** shows the direction of the ion beam during backside milling and the trench milled by the ion beam.

Case Study 1. Quick 5-minute HAC and Flat Milling for Cross Section Final Polish

In this example, a cross section was prepared of an Intel microprocessor removed from its package. The size of the sample available after deprocessing was 8 x 8mm. To prepare the cross section, the sample was cleaved parallel to 15µm contacts visible on the sample surface. The Hitachi IM4000 was then used to prepare the final surface using flat milling mode. Approximately 100nm of material was removed in 10 minutes to achieve the polished surface of the final cross section.

The cross-section process included:

1. Indenting the 15µm area of interest (AOI) with the LatticeAx (**FIGURE 5a**) (3 min)
2. Cleaving through the AOI using the small sample cleaving accessory[7] (2 min) (**FIG 5b-c**)
3. Mounting the sample for the IM4000Plus and backside milling using flat milling mode (15 min)

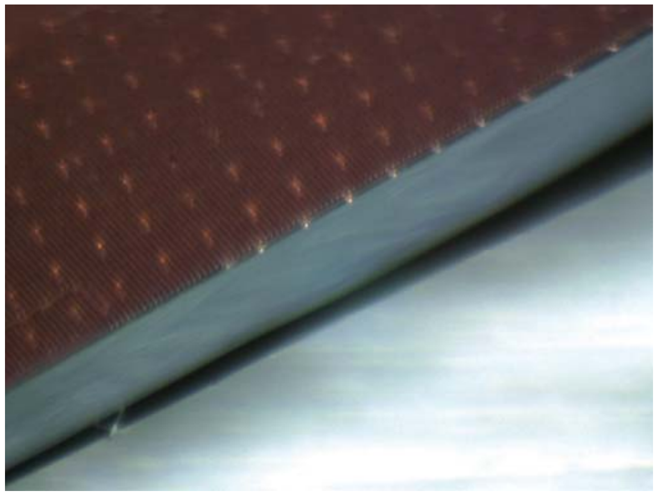

FIGURE 5c. Optical view of the cross section after cleaving

Results

This demonstrates a rapid (15-minute) method to obtain a damage-free cross section from a fully processed microprocessor over a very large area (5mm in diameter). A comparison of the results before and after milling shows the clear improvement in surface quality and SEM imaging results (**FIGURE 5d and e**). Using other methods such as mechanical polishing or FIB can take several hours to achieve a comparable size produced by the large flat-milled region. The best results were obtained when removing a minimum of material (nms), demonstrating the importance of an accurate, high quality cleave prior to BIB milling. **FIGURE 5f** shows a high-magnification view of the resulting cross section after flat milling that is high quality and without curtaining.

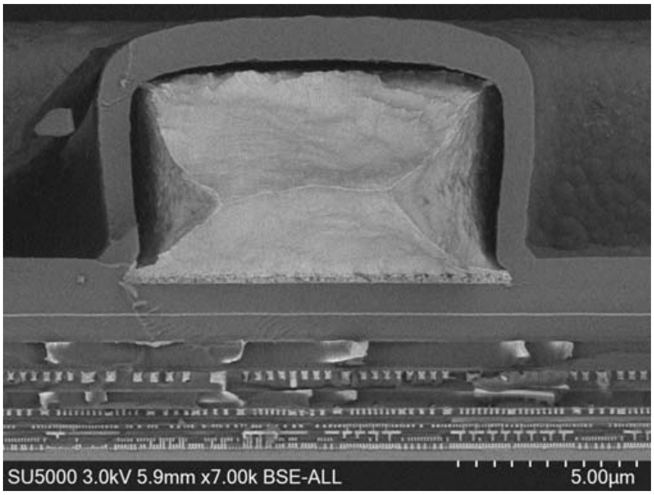

FIGURE 5d. SEM image of the microprocessor after cleaving

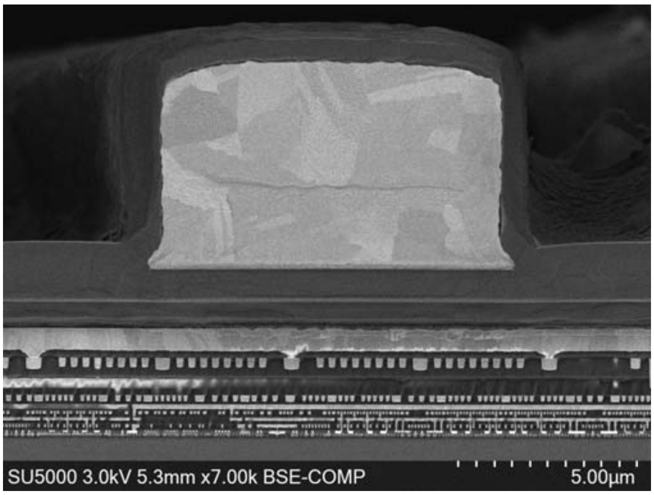

FIGURE 5e. SEM image of the microprocessor after 10 minutes of BIB milling using flat milling mode

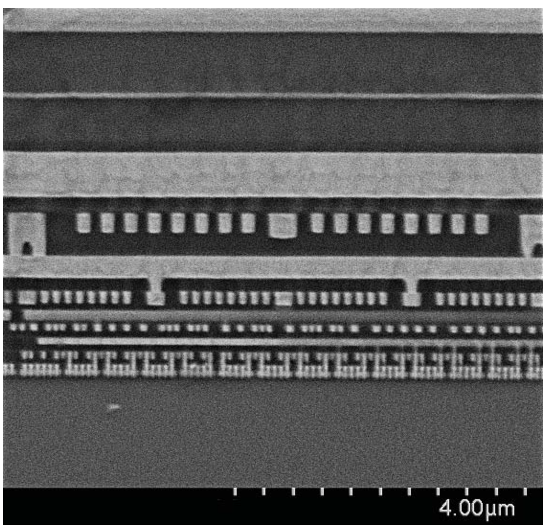

FIGURE 5f. SEM image showing planar cross section after flat milling

Case Study 2. Using HAC and BIB Milling in Cross-section Mode to Prepare Cross Sections of Solder Bumps

Cross sections are required to inspect solder bump reliability for interconnect problems during development and production, or for electromigration failure after aging. Creating these cross sections in a targeted location is critical for effective fault isolation and SEM analysis. With the advent of large Through-Silicon-Via (TSV) and solder bump structures—often 100μm in depth or width—high throughput methods are necessary to make cross sections efficiently and effectively.[8]

In this case study, the solder bumps were prepared for SEM in a two-step process. In step 1, the LatticeAx cleaver was used to cleanly cross-section close to, and parallel to, a specific row of copper bumps. The copper bumps had a diameter of 85μm and were cleaved 30 μm from the center of a bump. Time to cleave was 5 minutes and yielded the results shown in **FIGURE 6a and FIGURE 6b.**

In step 2, a broad argon ion beam instrument, the Hitachi IM4000, was used to prepare the final imaging surface within the copper bump. The backside milling method was used; no further preparation was performed.

Results

FIGURES 6c and 6d, taken after ion milling, plainly show the improved surface quality and copper grain structures, as well as fine details at the interface between the bump and adjacent structures. By cleaving close to the center of the copper bumps, the milling time on the BIB was reduced to less than 2 hours versus tens of hours for large cross-section areas (multiple bumps).

This two-step sample preparation process described has been implemented in production by a large semiconductor manufacturer. The technique described reduces turn-around time and repeatedly results in artifact-free cross sections of copper solder bumps.

Conclusion

For "off-line" laboratories, using HAC and BIB together for creating high quality cross sections is a compelling, low-cost alternative to investments in

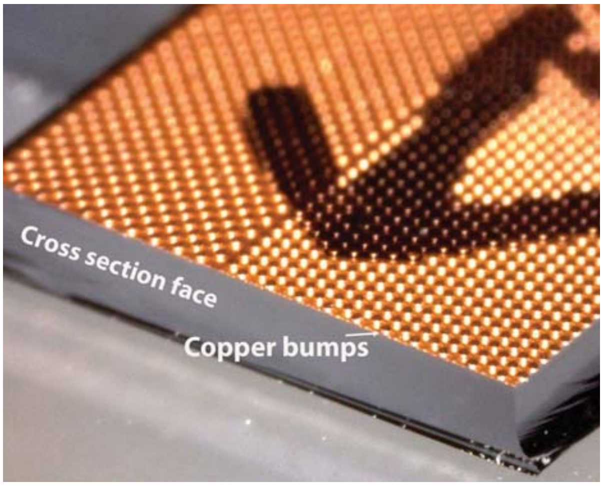

FIGURE 6a. SEM image of the microprocessor after cleaving

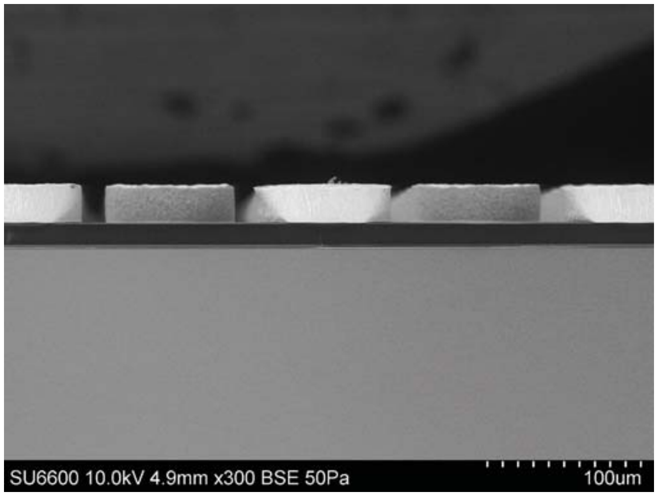

FIGURE 6b. SEM image of the microprocessor after cleaving

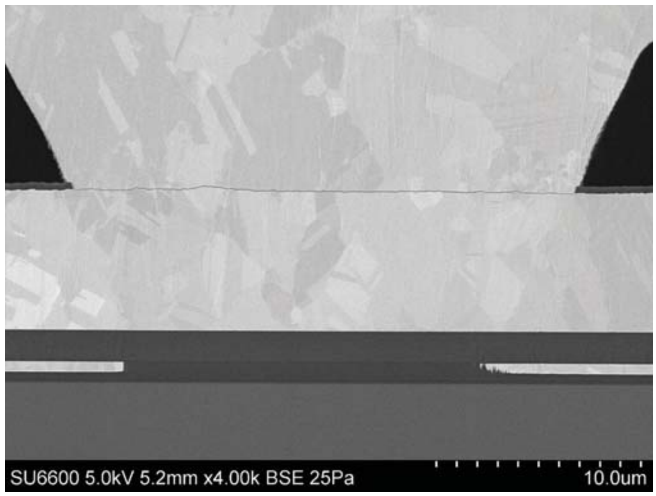

FIGURE 6c. SEM image of the microprocessor after cleaving

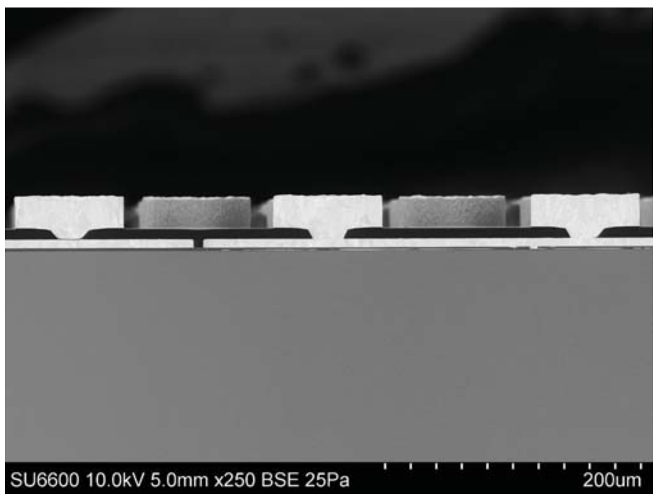

FIGURE 6d. SEM image of the microprocessor after cleaving

FIBs or automated polishing or cleaving equipment. High accuracy cleaving reduces sample preparation time, complexity, and cost without sacrificing cross-section quality. Combining this with a broad argon ion beam instrument for quick removal of minimal amounts of material or for milling of large flat areas, HAC presents effective, accurate results critical to product or failure analysis, while keeping both equipment and per- sample costs low.

Whether for final polish or in sample preparation of solder bumps, the results from the machine-assisted high accuracy Indent and Cleave approach combined with broad ion beam milling rival those of fully automated cleaving or polishing systems.

References

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