Seeing the Unseen: The Power of Electron Microscopy

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COVALENT
Material Insights

Contents

In this e-book, readers will learn:

Why electrons beat light for resolution – how wave–particle duality and tiny electron wavelengths let us "see" the nanoscale.

What limits resolution in practice – an intuitive look at the Rayleigh criterion and how it connects to real instruments.

The main electron signals – backscattered, secondary, and transmitted electrons, and what each tells you about a sample.

How different EM modes are used – SEM, TEM, and STEM for things like defects, grain structure, solder joints, and device features.

How TEM lamellae are made with FIB – from protective caps and trench milling to lift-out, mounting, and final thinning.

How imaging conditions shape your data – the roles of beam energy, probe size, sample thickness, dwell time, and charging in contrast and resolution.

Introduction

Many of us have seen images from electron microscopes and marveled at the incredible detail they reveal in everyday objects. A single strand of hair, the structure of a feather, the body of an insect—even the coronavirus—can all be viewed with astonishing clarity that is impossible to achieve with visible light microscopy.

Why is that? It comes down to something those of us familiar with quantum mechanics call wave-particle duality. You've probably heard of a photon—that's the particle associated with light. We also know that light behaves like a wave, which means it has a wavelength. The size of the features you can resolve with light (or any wave) depends on that wavelength.

Now, when electrons are accelerated to high energies, they too behave like waves. And here's the exciting part: the wavelength of an electron is much smaller than that of light. This means that by using beams of electrons instead of beams of light, we can resolve features that are much, much smaller.

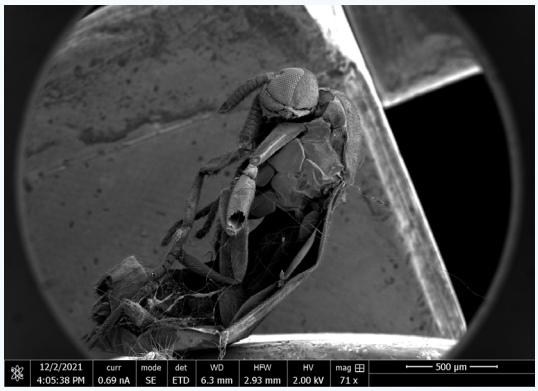

Figure 1: Image of a mite at a horizontal field width of 2.93mm.

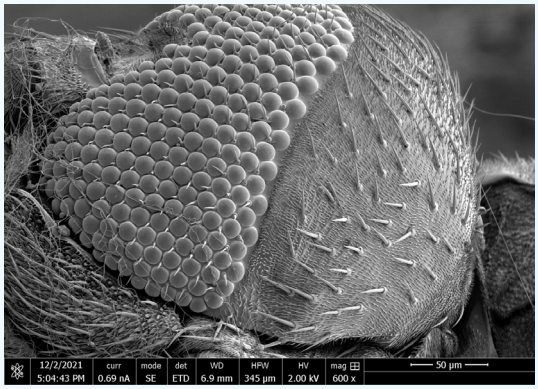

Figure 2: Image of a mite at a horizontal field width of 345um.

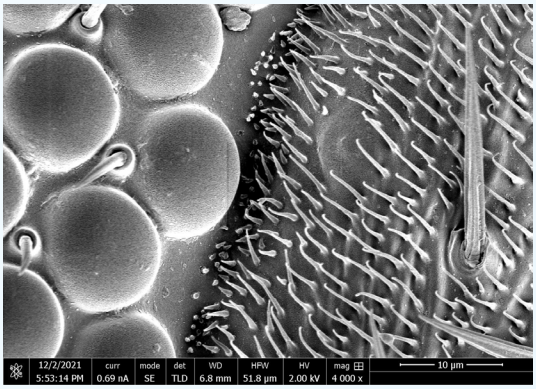

Figure 3: Image of a mite at a horizontal field width of 51.8 um.

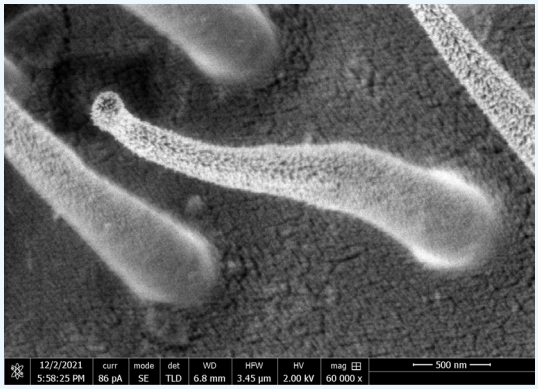

Figure 4: Image of a mite at a horizontal field width of 3.45um.

The **Rayleigh equation** describes the minimum resolvable distance between two points that can be distinguished as separate in an imaging system, such as a light or electron microscope.

Mathematically, it's expressed as:

$$d = 0.61 \frac{\lambda}{\mu \sin \alpha}$$

where:

- d = minimum resolvable distance (the resolution limit)
- λ = wavelength of the imaging beam (light or electrons)
- μ = refractive index of the medium between the lens and the sample (≈1 in vacuum)
- α = half-angle of the objective lens aperture (with = NA, the numerical aperture)

When high-speed electrons interact with a sample, different types of signals are produced. For the purposes of this E-book, we will focus on three interactions: **backscattered electrons**, **secondary electrons**, and **transmitted electrons**.

Backscattered Electrons (BSE)

Sometimes electrons from the primary beam collide with the nucleus of an atom and go straight back out. We call these electrons backscattered electrons.

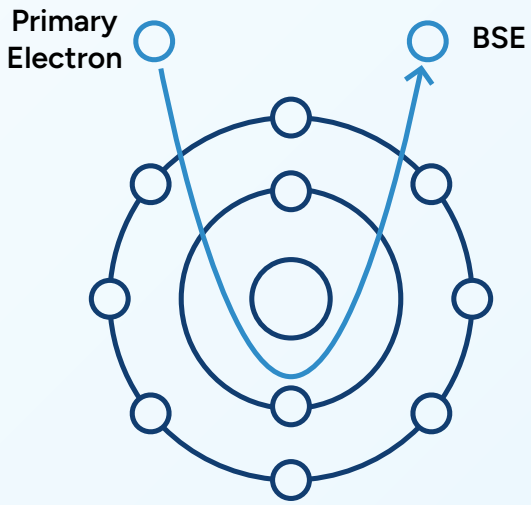

Figure 5: Illustrated depiction of backscattered electrons (BSE).

Backscattered electrons are much more likely to be generated when the electron beam is applied to samples that have a lot of big, heavy nuclei. For example, lead has 82 protons in its nucleus. Carbon, on the other hand, only has 6.

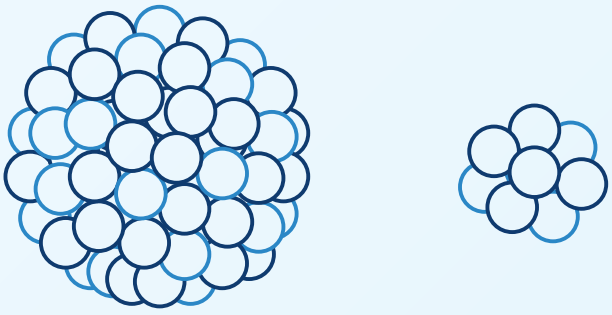

Figure 6: Illustration demonstrating the difference in size between lead and carbon atoms.

That means if you image lead and carbon next to each other, electrons are much more likely to collide with the lead nuclei and bounce straight back up to the detector, while sailing right past the carbon nuclei. As a result, BSE detectors receive much more signal from the lead, meaning it will appear bright in BSE mode while the carbon will be significantly darker.

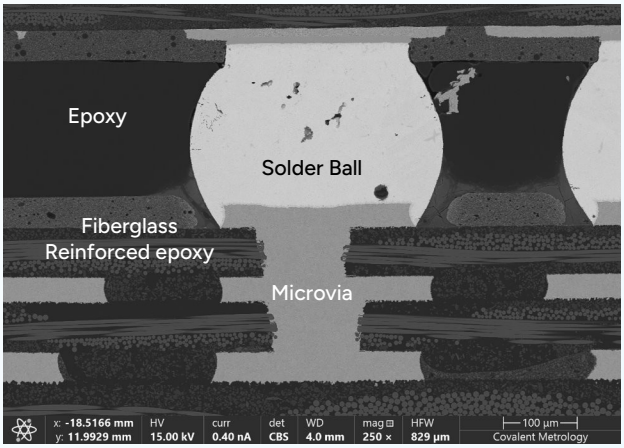

Figure 7: Cross section of a solder ball imaged with BSE.

The electron micrograph above is a cross section of a solder ball imaged with BSE. We can learn a lot from this image just by looking at the contrast! For example, the dark black material in the background must consist of a material with a light nucleus compared to the brighter solder ball in the center of the image. As it turns out, the solder ball is made of lead and tin while the background material is epoxy (mostly carbon). The microvia underneath the solder ball is copper, which is heavier than carbon but not as heavy as lead, this is why it's a shade of gray in between. The fiberglass reinforced epoxy to the left and right of the microvia is also interesting because it's similar to the epoxy, but it has woven glass fibers imbedded in the epoxy resin. Printed circuit board manufacturers add fiberglass because it offers an ideal combination of mechanical strength, electrical insulation, thermal stability, and manufacturability — all at relatively low cost. The lighter gray cross sections of fibers running parallel and perpendicular to the plane of our image represent silica filler inside of a carbon matrix.

Using BSE imaging on mechanical cross sections of printed circuit boards can provide valuable information about failure modes. For example, in the images below, cross-sectional SEM imaging with BSE revealed some delamination between the copper plating and the copper pad. Delamination like this can cause problems such as intermittent electrical connectivity, signal loss, or complete circuit failure. In high-reliability applications such as aerospace or automotive electronics, delamination can also lead to localized heating, corrosion, and eventual delamination of adjacent layers. Identifying such defects early through BSE imaging helps engineers pinpoint the root cause—whether it's due to poor adhesion, thermal cycling, or mechanical stress—and guide improvements in plating processes or material selection.

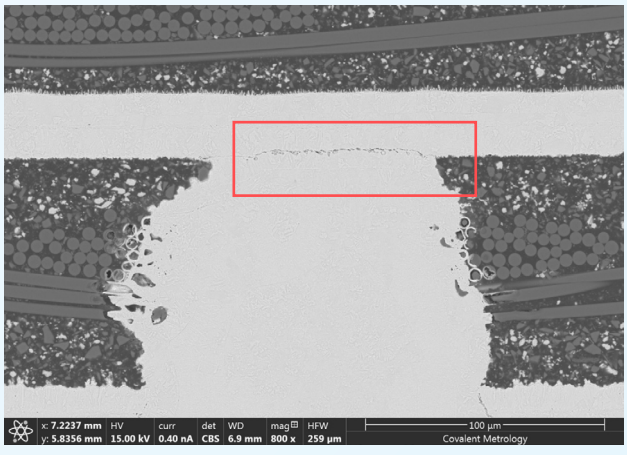

Figure 8: SEM image using BSE with delaminated region highlighted.

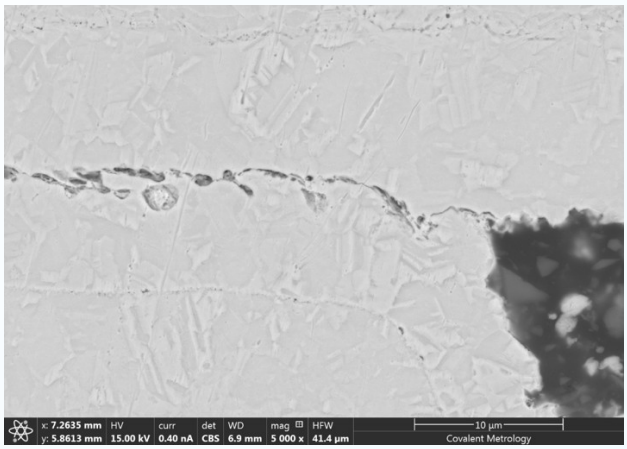

Figure 9: BSE image showing a close-up of the delaminated region.

BSE detectors are typically positioned directly above the sample. One common type, the Concentric Backscatter (CBS) detector, is made up of a series of annular rings. These rings collect electrons that have been scattered at different angles, providing distinct types of information about the materials in the sample.

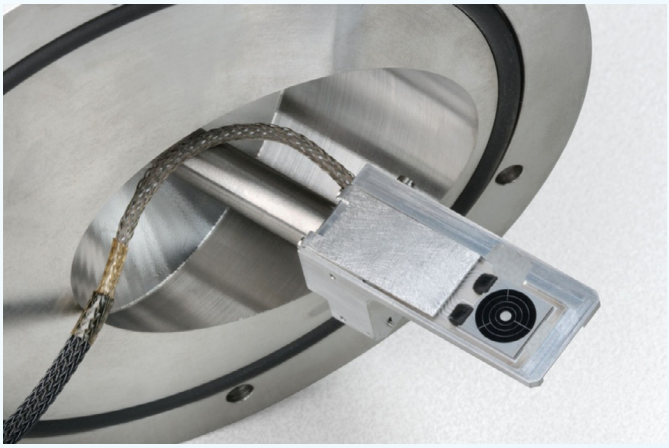

Figure 10: An insertable CBS detector.

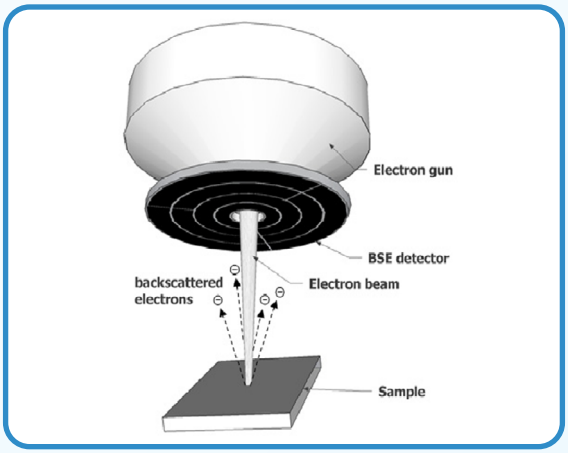

Figure 11: Illustration showing the insertable CBS detector, courtesy of Thermo Fisher.

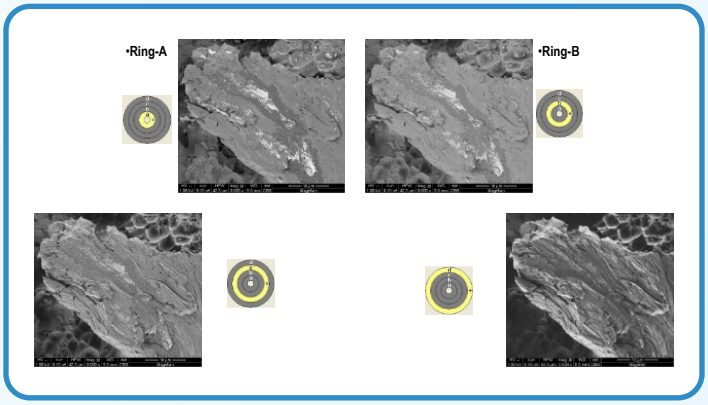

Figure 12: Demonstration of the different information that can be obtained for the different annular rings of the CBS detector, courtesy of Thermo Fisher.

To generate high contrast BSE images, it's often necessary to accelerate the incoming electron beam to high energy.

Secondary Electrons

Another possible outcome when electrons interact with matter is that a primary electron from the beam undergoes an inelastic interaction, transferring some of its energy to an electron in the sample. This process can cause that electron within the sample to be ejected. These ejected electrons are called secondary electrons, and they typically have lower energy than backscattered electrons.

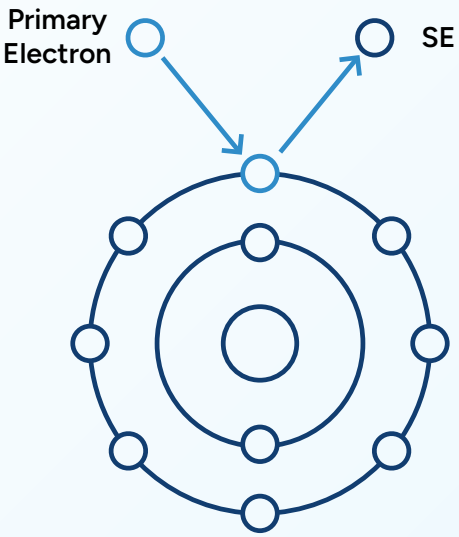

Figure 13: Illustration demonstrating how secondary electrons are generated.

Rather than showing materials contrast, signal received from secondary electrons will show surface topography.

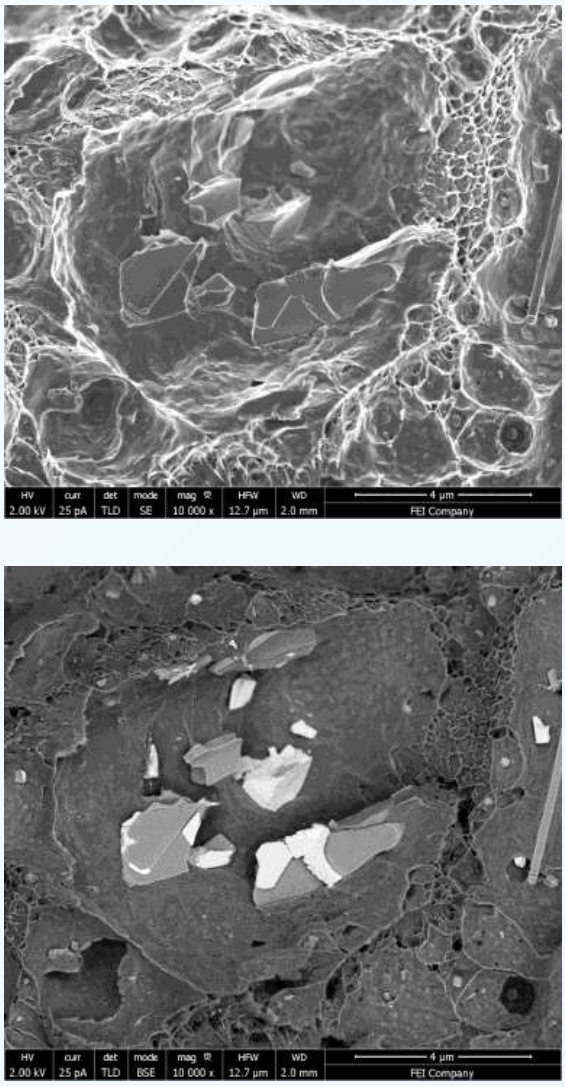

Figure 14: Two images of the same sample. The first image was taken with secondary electrons. The second was taken with back scattered electrons

If the goal is to study surface topography, it's best to use secondary electron (SE) detectors together with a low-energy electron beam, since low-energy electrons interact only with the top few nanometers of the sample. In modern SEMs, beam deceleration can be used to achieve this effect—reducing electron penetration depth while maintaining a high level of beam collimation. This amounts to applying a bias to the stage so that the beam travels to the sample with high energy and therefore remains tightly collimated but is slowed down just before interacting with the sample.

For example, in the images below, a semiconductor manufacturing company requested SEM imaging of unfilled vias to verify etch profile, dimensional uniformity, and surface cleanliness prior to metal fill and barrier deposition. This is an ideal application for SE imaging, which is great for visualizing surface features and topography that might be filtered out with BSE imaging.

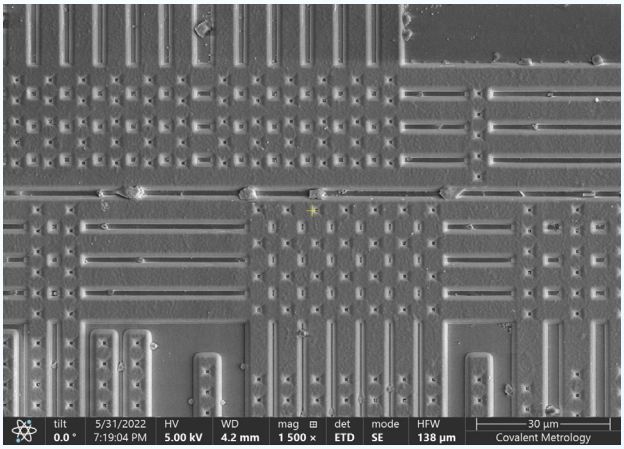

Figure 15: Semiconductor sample imaged using secondary electrons to show surface topography.

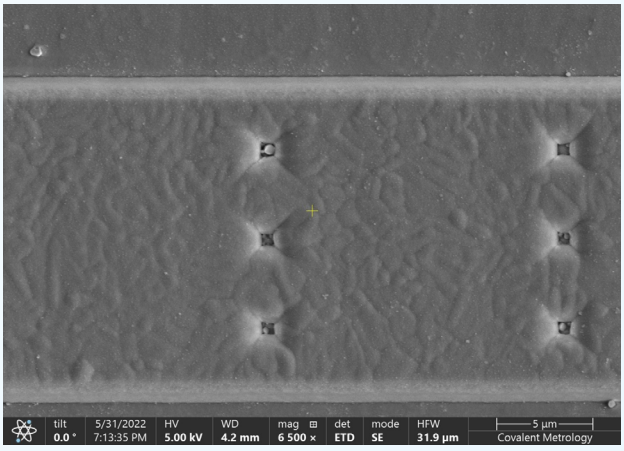

Figure 16: Semiconductor sample imaged using secondary electrons to show surface topography with higher magnification.

Transmitted Electrons

If a sample is thin enough—typically less than 100 nm—and the electron beam has sufficient energy (20–300 kV), the electrons can pass through the sample and reach a detector positioned below it. This technique, known as **Transmission Electron Microscopy (TEM)** or **Scanning Transmission Electron Microscopy (STEM)**, provides the highest resolution of all electron-based imaging methods, enabling researchers to resolve individual atoms. When comparing SEM to TEM, SEM can resolve features on the order of a few nanometers while TEM can resolve sub-angstrom features.

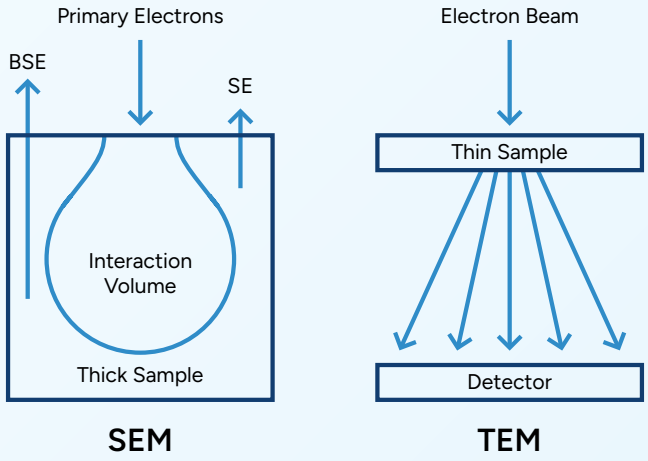

Figure 17: Illustration demonstrating the difference between SEM and TEM.

Why is Resolution Superior in TEM?

- **High energy:** As mentioned previously, the resolution of any imaging system is limited by the wavelength of the imaging beam. The wavelength of a particle depends on its energy. Therefore, when electrons are accelerated to high energies, as they are in TEM, features smaller on the order of atomic lattices can be resolved.
- **Low Interaction Volume:** In TEM, the electron beam passes through an ultra-thin sample, so the interaction volume is extremely small, essentially a two-dimensional plane with electrons interacting with only a few atoms. In SEM, on the other hand, the beam interacts with a much larger, three-dimensional volume within the sample, penetrating ten to hundreds of nanometers deep. This spreads out the signal and blurs fine details.

TEM can be used to resolve tiny defects that cause failures and performance issues in nanotechnology. In fact, failure analysis in integrated circuits is one of the largest applications for TEM.

TEM vs STEM: Two Ways to Use the Same Microscope

In transmission electron microscopy (TEM), the electron beam illuminates a broad area of the sample all at once, and the transmitted electrons are projected through a series of lenses to form an image directly on a camera or detector. This produces a true two-dimensional projection of the sample's internal structure, ideal for visualizing crystal defects, interfaces, and diffraction patterns. In scanning transmission electron microscopy (STEM), the same principle of transmission is used, but the approach is different: instead of a broad beam, a finely focused electron probe—often smaller than an atom—is scanned across the sample point by point. Detectors beneath the sample collect electrons scattered at different angles to generate images with atomic-scale resolution and chemical contrast. Because STEM is a mode within the TEM, the two terms are often used interchangeably, even though they refer to distinct imaging approaches. In simple terms, TEM shows the whole picture at once, while STEM builds the picture pixel by pixel, offering extraordinary control over how contrast and composition are revealed.

TEM for Process Characterization

The images below show a modern Complementary Metal-Oxide-Semiconductor (CMOS) chip cut such that we can see the gates and metal lines in the X-direction and Y-direction.

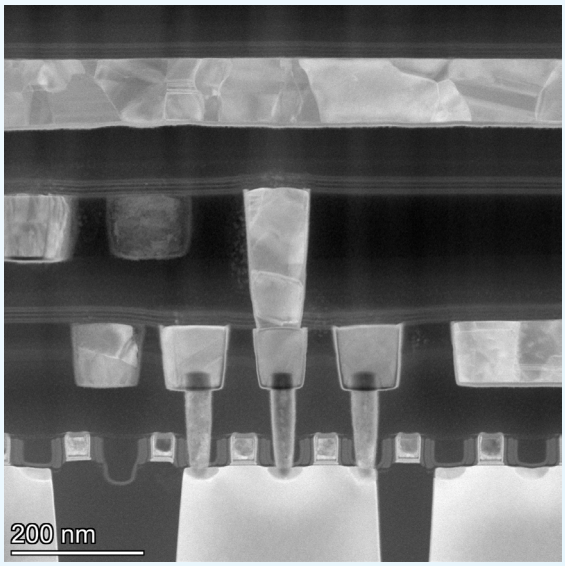

Figure 18: Y-cut STEM Image.

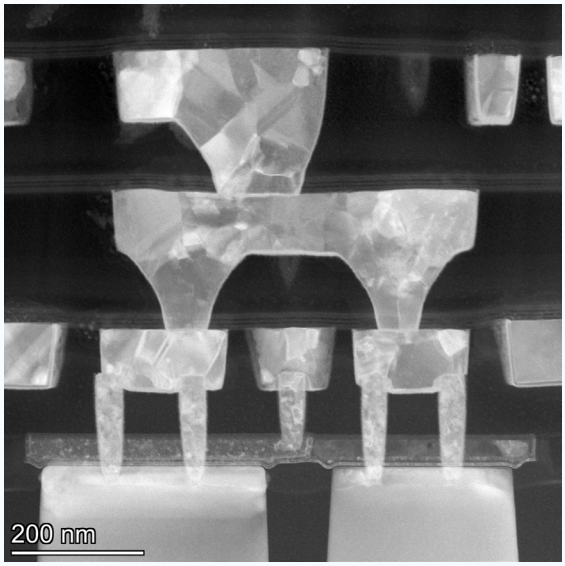

Figure 19: X-cut STEM Image.

These images reveal the grain structure of the metal lines with remarkable detail. In modern CMOS chips, the metal lines you see in a TEM image aren't just wiring — they're the nervous system of the device, carrying billions of electrical signals every second. But inside those lines, the metal isn't a perfect crystal. It's made up of countless microscopic grains, separated by grain boundaries — narrow zones where the crystal lattice is misaligned.

Those boundaries might look harmless, but at nanoscale dimensions they can make or break device performance by causing increased electrical resistance, creating diffusion pathways for migrating atoms which could lead to void formation, causing shorts or opens, and serve as channels for contaminants leading to barrier layer breakdown and other reliability failures.

TEM imaging allows engineers to visualize grain structure and correlate it with electrical reliability data. By revealing how metal grains evolve through processing, TEM helps semiconductor manufacturers optimize deposition and annealing conditions, keeping their interconnects fast, reliable, and future ready.

TEM for Defect Characterization

The images below reveal a crack in the gate region of a CMOS device.

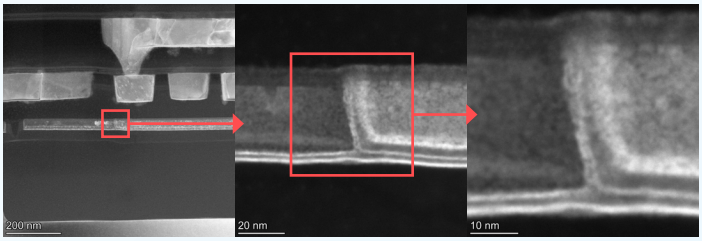

Figure 20: TEM images revealing a crack in the gate region of a CMOS device.

Such cracks can form due to thermal stress from post-deposition annealing, especially where neighboring materials expand at different rates, or from mechanical stress introduced during chemical-mechanical planarization (CMP) or later packaging steps. These fractures can disrupt gate continuity, leading to leakage, performance variation, or premature device failure.

High-resolution TEM imaging allows engineers to spot these defects early, often before electrical testing reveals a problem. By correlating crack formation with specific process steps, they can identify whether changes are needed in annealing temperature, film stress management, or CMP parameters, accelerating root-cause analysis and improving device reliability.

Bright Field vs Dark Field STEM Imaging

In electron microscopy, bright-field and dark-field imaging are two complementary ways of visualizing how electrons interact with a sample. In bright-field imaging, the microscope collects electrons that pass straight through the specimen or scatter only slightly, so thicker or denser regions—which scatter more strongly—appear darker in the image. In dark-field imaging, the opposite is true: the microscope blocks the unscattered beam and instead collects only electrons scattered to higher angles. As a result, regions that scatter strongly appear bright against a dark background. Bright-field imaging highlights overall structure and thickness variations, while dark-field emphasizes crystalline order, defects, and compositional contrast. Used together, they provide a richer, more complete picture of the material's internal structure.

In the images below, we can compare a bright field vs dark field images of a plan-view CMOS device. This means the specimen was cut along the plane of the sample surface, so instead of looking at a cross section of the device as we were before, we are now looking top-down.

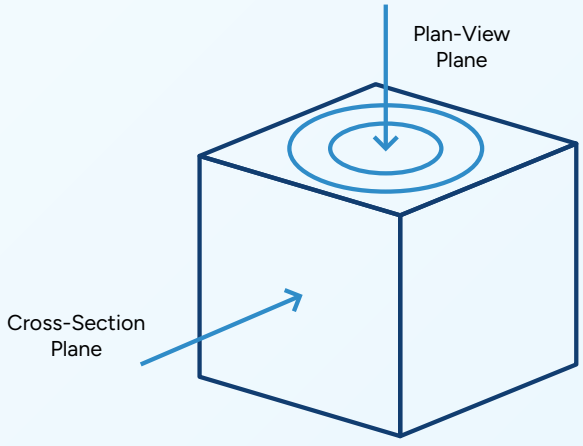

Figure 21: Illustration demonstrating the difference between cross-section and plan-view TEM samples.

The bright field images show areas with higher atomic mass, such as the vias and metal gate liners as appearing dark.

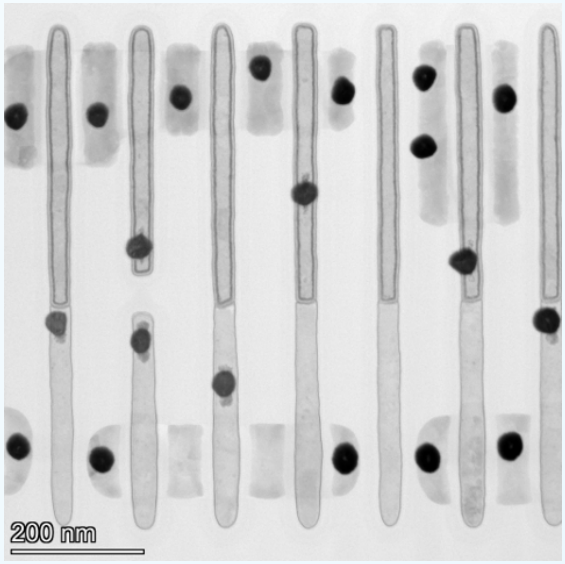

Figure 22: Bright Field STEM Image.

The dark field images, on the other hand, show the vias and metal gate liners as appearing bright. This mode also allows us to better visualize defects, stacking faults and dislocations. We can also use this mode to measure particles and grain size.

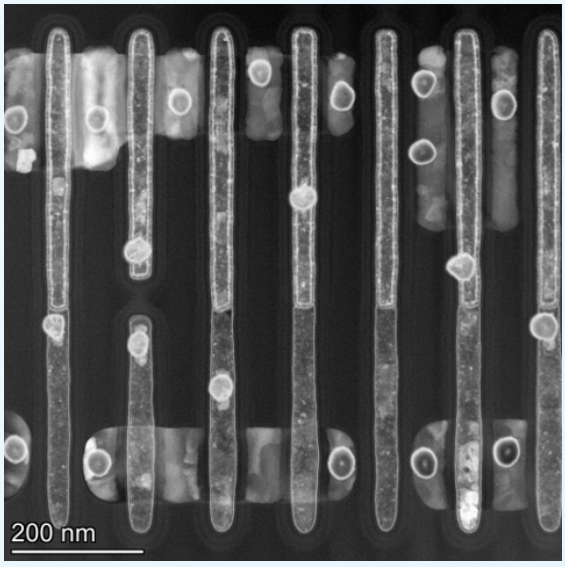

Figure 23: Dark Field STEM Image.

Preparing Samples for Transmission Electron Microscopy

So far, we've discussed that samples must be less than 100 nm thick to be suitable for TEM analysis. We've also shown several examples of TEM images taken from semiconductor chips. But how do we get from a bulk semiconductor device to a thin slice of material capable of transmitting electrons?

We'd love for TEM imaging to be as simple as aiming a camera and taking a picture. However, the truth is that each TEM micrograph represents hours of careful sample preparation.

Preparing these samples—called lamellae—is an entire field of science in itself. Given how subtly different materials respond to processing, it might be more accurate to describe it as an art. Creating a TEM-ready lamella from a bulk semiconductor chip has never been trivial, it's a process that engineers have been improving upon for decades. As device geometries continue to shrink, TEM lamellae must be thinner than ever. They must also be positioned with nanometer accuracy.

Today, the state of the art for TEM sample preparation relies on the **Focused Ion Beam (FIB)**—a tightly focused beam of energetic ions capable of precisely milling away material to expose regions of interest for analysis.

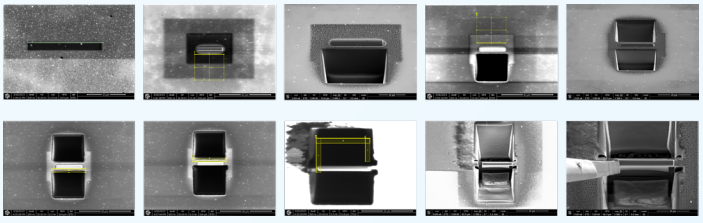

Figure 24: Workflow demonstrating the first few steps of TEM prep.

1. Protective Cap Deposition

A thin protective layer is applied over the region of interest by injecting an organometallic precursor gas into the vacuum chamber. The electron beam is first used to locally decompose the gas molecules, forming a gentle initial coating that minimizes ion damage. The ion beam is then rastered over the same area to thicken the deposit. This process leaves behind a metallic film—typically platinum, carbon, or tungsten—that protects the surface from sputtering and redeposition during subsequent milling. This prevents ion-beam damage and re-deposition artifacts during milling.

- The e-beam step lays down a clean initial layer, while the ion-beam step thickens it for durability.

2. Trench Milling

Using the high-current ion beam (often Ga^+ or Xe^+), deep trenches are milled on either side of the protected region, isolating a thin wall or membrane of material.

- This defines the future lamella — typically 10–20 µm wide and 1–2 µm thick at this stage.
- The trench geometry determines the final viewing orientation (X-cut or Y-cut, for example).

3. Undercutting and Final Isolation

Additional milling is performed underneath and behind the lamella to free three sides, leaving it attached to the rest of the bulk sample by a small "tab."

- This step reduces stress during lift-out and ensures the lamella can be safely extracted without bending or fracture.

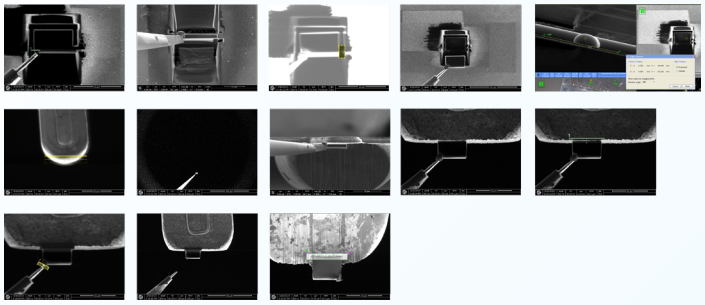

Figure 25: workflow demonstrating the lift-out steps in TEM prep.

4. Needle Attachment

A micromanipulator needle is precisely positioned and welded to the lamella using ion-beam-induced platinum deposition.

- The needle acts like a nanoscale crane arm, giving fine control during extraction.

5. Lift-Out and Mounting

The lamella is gently cut free from the bulk sample and transferred in situ to a TEM half-grid or Cu post.

- Once positioned, it is re-attached with Pt deposition at the mounting points for mechanical stability.
- The needle is then detached with a brief ion cut, leaving the lamella secured on the grid.

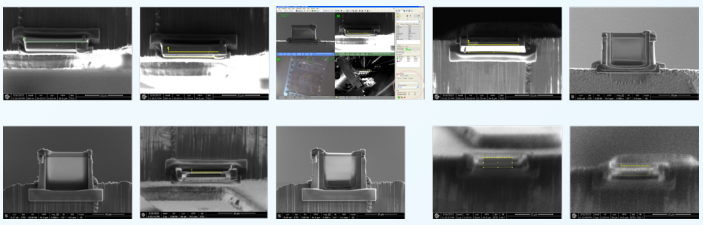

Figure 26: Workflow demonstrating the thinning process.

6. Final Thinning and Polishing

With the lamella now isolated and supported, the ion beam is operated at progressively lower beam energies to thin the sample to electron transparency (<100 nm).

- Low-kV polishing (2–5 kV) removes amorphous damage layers that were created from the larger beam energies.

7. TEM Ready

The finished lamella, now a tens-of-nanometers-thick window through the sample, is ready for analysis by TEM. The image below shows a lamella made from blank silicon that has been thinned down to electron transparency.

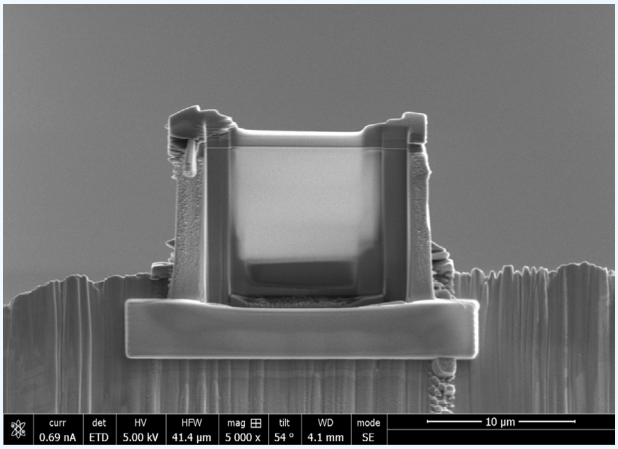

Figure 27: The final, thinned lamella. Ready for TEM imaging!

The bright region in the center of the lamella is the thinnest part of the lamella. It's bright because the detector can collect electrons that are bouncing off the surface of the sample as well as electrons that transmit through the thin region.

Factors Influencing Image Quality

We've talked about how choosing between the types of electrons we collect from a sample (back-scatter, secondary or transmitted) will greatly influence the kind of information that shows up in EM images. We've also talked about what it takes to prepare a thin sample for TEM. Now let's discuss the many factors that play into getting the most desirable electron micrograph!

Achieving the desired resolution and contrast in electron microscopy requires a delicate balance between many variables. Often, turning knobs that increase contrast will decrease resolution and vice versa. A skilled microscopist must understand the resulting impact of each variable and make appropriate choices to obtain the desired information.

Beam Energy

In SEM, increasing the beam energy expands the interaction volume within a bulk sample, which can reduce spatial resolution because electrons scatter over a larger region. However, higher beam energy also produces a shorter electron wavelength, which can improve resolution—a factor especially important in TEM imaging.

At the same time, higher beam energy increases the number of electrons reaching the detectors. The faster the electrons strike the sample, the more likely they are to bounce back, resulting in greater image contrast. Thus, while higher beam energy can enhance contrast in SEM images, it often does so at the expense of resolution.

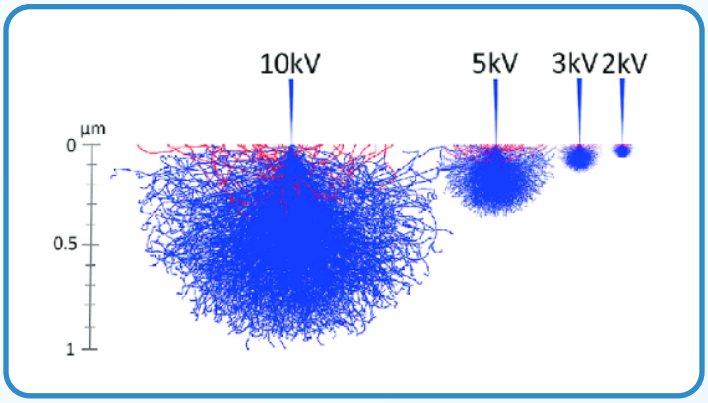

Figure 28: Diagram demonstrating the difference in interaction volumes between different beam energies.

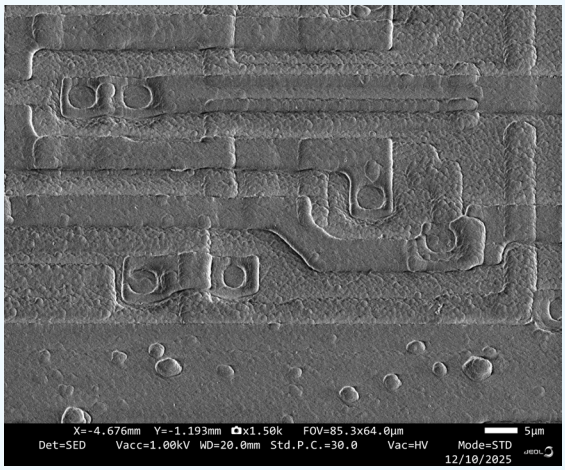

Figure 29: Imaging on an electronics sample at 1kV. In this low energy image, surface topography is apparent and sharp

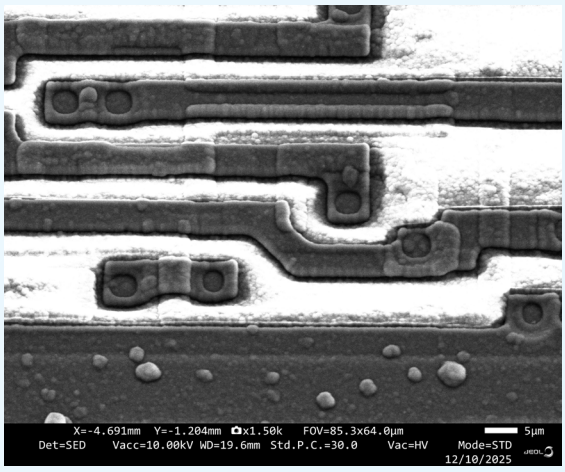

Figure 30: Sample at 10 kV. In this higher energy image, the beam penetrates into a deeper layer, revealing voltage contrast unseen at lower energy

Probe Size (Beam Current)

The beam current determines the diameter of the electron beam—a higher current produces a larger beam. Because we can only resolve features that are as small as the probe itself, a larger beam current results in lower spatial resolution. However, increasing the beam current also raises the number of electrons reaching the detectors, which in turn improves image contrast.

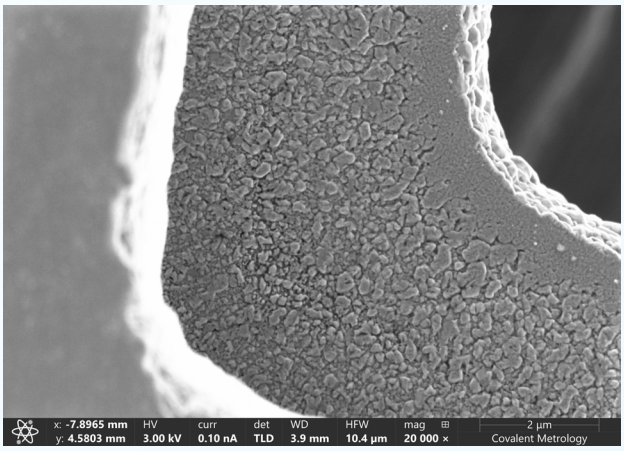

Figure 31: Imaging at 0.1nA. Note the sharpness of the small surface particles.

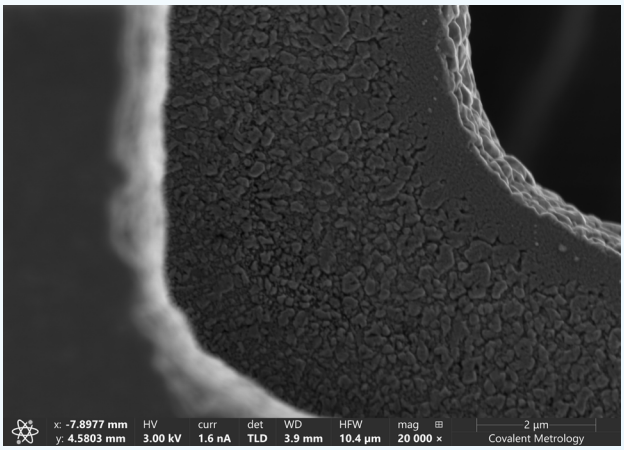

Figure 32: Imaging at 1.6nA. Note the reduced sharpness of the small surface particles but higher contrast between gray levels.

Sample Thickness

In TEM, sample thickness has a major impact on resolution. A thicker sample increases the interaction volume, causing more electron scattering, which blurs features and reduces resolution. In contrast, a thin sample allows the high-energy electron beam to pass directly through, ideally interacting with only a few atoms along its path. When this happens, each bright spot on the detector can correspond to a single atomic column or even an individual atom.

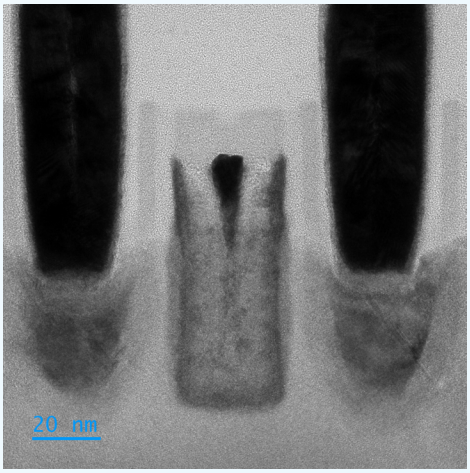

Figure 33: TEM imaging on a sample that is slightly thick.

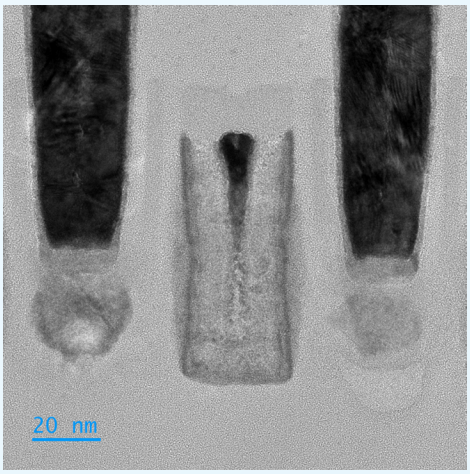

Figure 34: TEM imaging on the same sample after further thinning. Notice how the grain structure and atomic lattices are now more apparent.

Dwell Time

In both SEM and STEM, the electron beam scans (rasters) across the sample surface, pausing on each pixel for a defined period—this is known as the dwell time. A longer dwell time increases the signal-to-noise ratio, producing a clearer image. However, it also slows down image acquisition and can increase sample damage or beam-induced contamination.

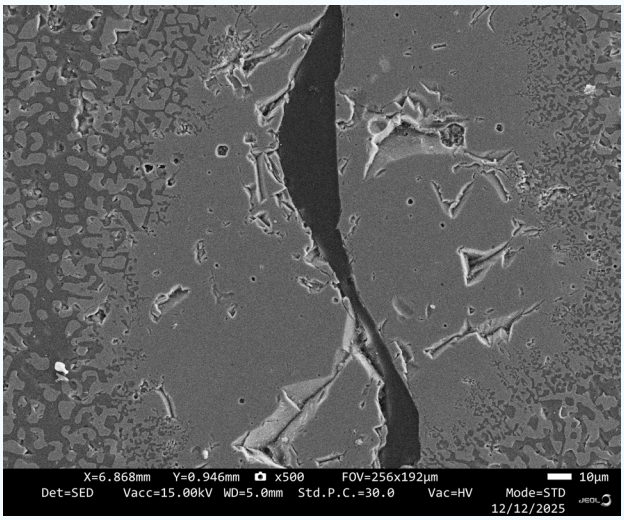

Figure 35: Short dwell time, notice how this image is grainy.

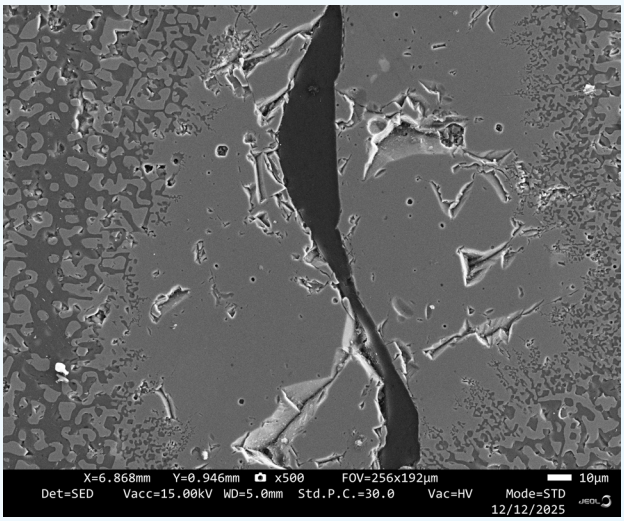

Figure 36: Long dwell time, notice how this image is clearer.

Sample Charging

Nonconductive samples are the bane of electron microscopists. Because imaging relies on a beam of charged particles, excess electrons accumulate on nonconductive surfaces instead of dissipating, deflecting the beam and distorting the image. Charging can appear as glowing or shifting bright and dark spots, apparent sample drift, or overall image noise and low contrast. To mitigate charging, microscopists can ground the sample with a conductive coating (e.g., gold or carbon), touch a manipulator probe to the surface, or connect the sample to the holder with conductive tape. If these methods fail, reducing beam energy and current or using advanced scan modes—such as drift-corrected frame integration, which aligns multiple fast scans using pattern recognition—can help stabilize the image. These techniques don't directly reduce charging, rather they compensate for it with sophisticated scanning strategies.

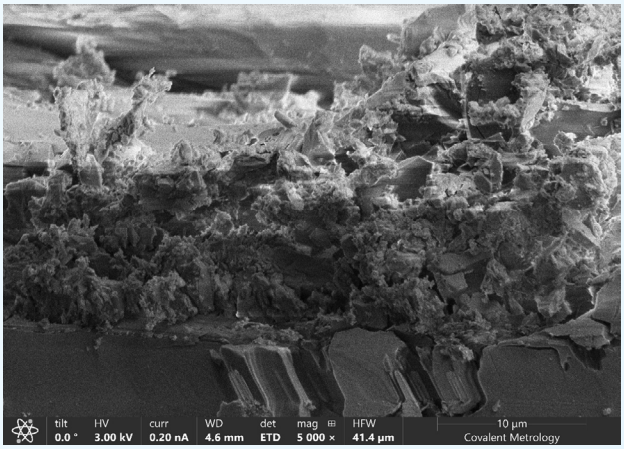

Figure 37: Image of cracked glass with no charge mitigation, notice the drift artifacts at the bottom of the image.

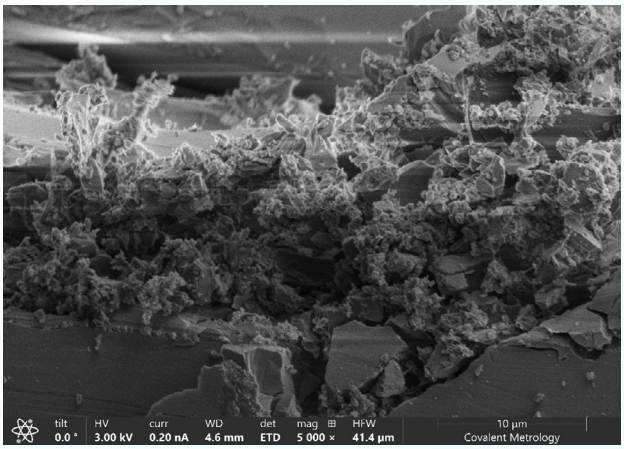

Figure 38: This image was taken with DCFI and shows significantly less drift artifacts in the bottom of the image.

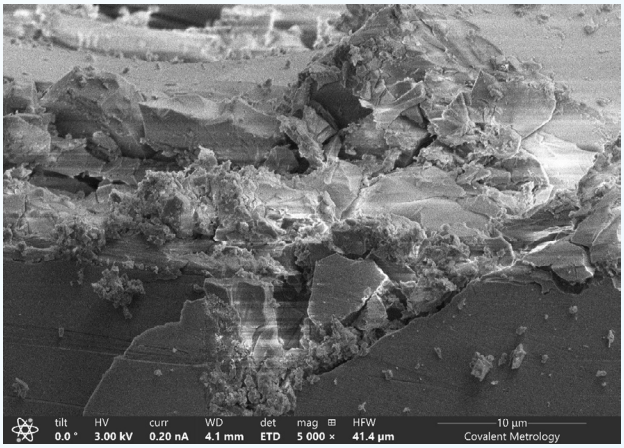

Figure 39: This image was taken after the sample was locally grounded with the manipulator needle.

Lens Optics

Just like in optical microscopy, electron microscopy depends on lenses to focus the beam into a small spot. However, unlike in optical microscopy, instead of solid lenses made of glass, electron microscope lenses are created with magnetic or electrostatic fields that bend the beam to focus it. In an electron microscope, a coil of wire (the lens) carries current, creating a magnetic field shaped by an iron pole piece with a small circular opening.

As electrons pass through this field, they experience a Lorentz force that causes their paths to curve — much like light refracts in glass. By adjusting the current through the coil, the strength of the magnetic field (and therefore the focal length) can be precisely controlled.

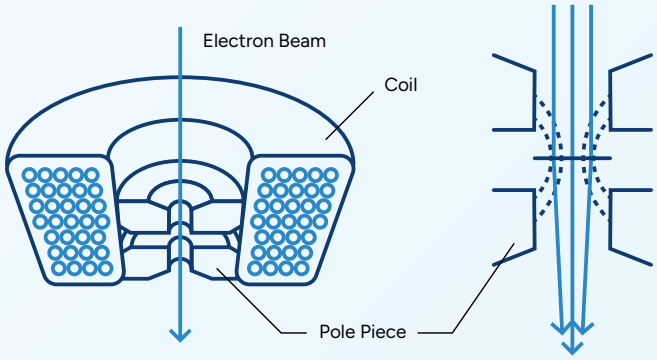

Figure40: Illustration demonstrating electron lens optics.

Changing the shape of the magnetic field that electrons pass through on their way to the sample has a major impact on image resolution. For example, many SEMs use immersion lenses, which extend the lens's magnetic field down into the sample region. In this configuration, the specimen sits within the focusing field, effectively placing the lens much closer to the surface. The result is a more tightly focused electron probe, producing higher-resolution images. This setup also improves signal collection—especially for secondary electrons—because the magnetic field helps guide emitted electrons toward the detector.

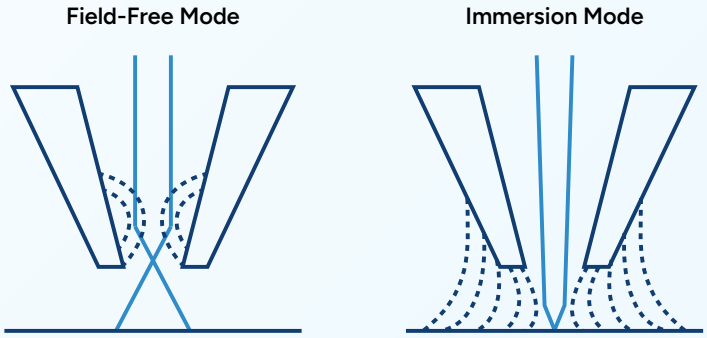

Figure 41: Illustration demonstrating the difference between field-free mode and immersion mode.

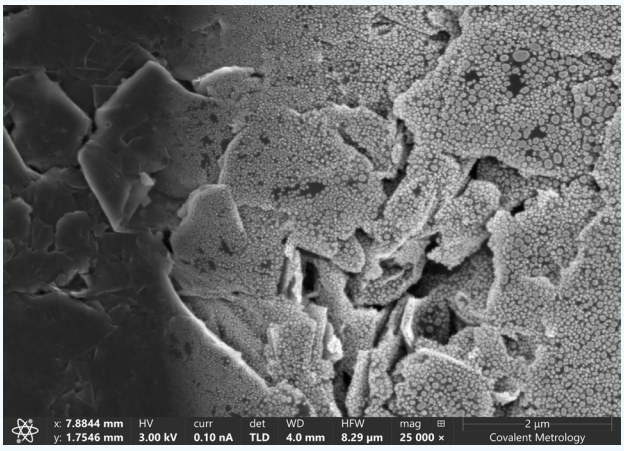

Figure 42: SEM image with immersion mode off.

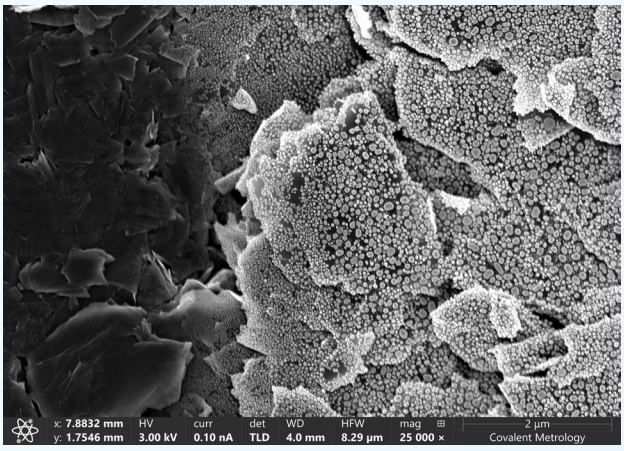

Figure 43: SEM image with immersion mode on

A Dance Between Energy and Matter: The Art of Seeing with Electrons

From the scattering of electrons off heavy atoms to the transmission of high-energy beams through ultrathin films, each imaging mode in electron microscopy reveals a different layer of truth about the material world. Understanding these interactions—whether they produce compositional contrast in backscattered images, surface detail in secondary electron maps, or atomic-scale structure in TEM—empowers researchers to choose the right technique for the question at hand. Together, these approaches transform invisible nanoscale structures into tangible insights, enabling breakthroughs in everything from semiconductor reliability to biological discovery. The next time you see an electron micrograph, remember: behind every image lies a carefully tuned dance between energy, matter, and the wave-particle nature of the electron itself.

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