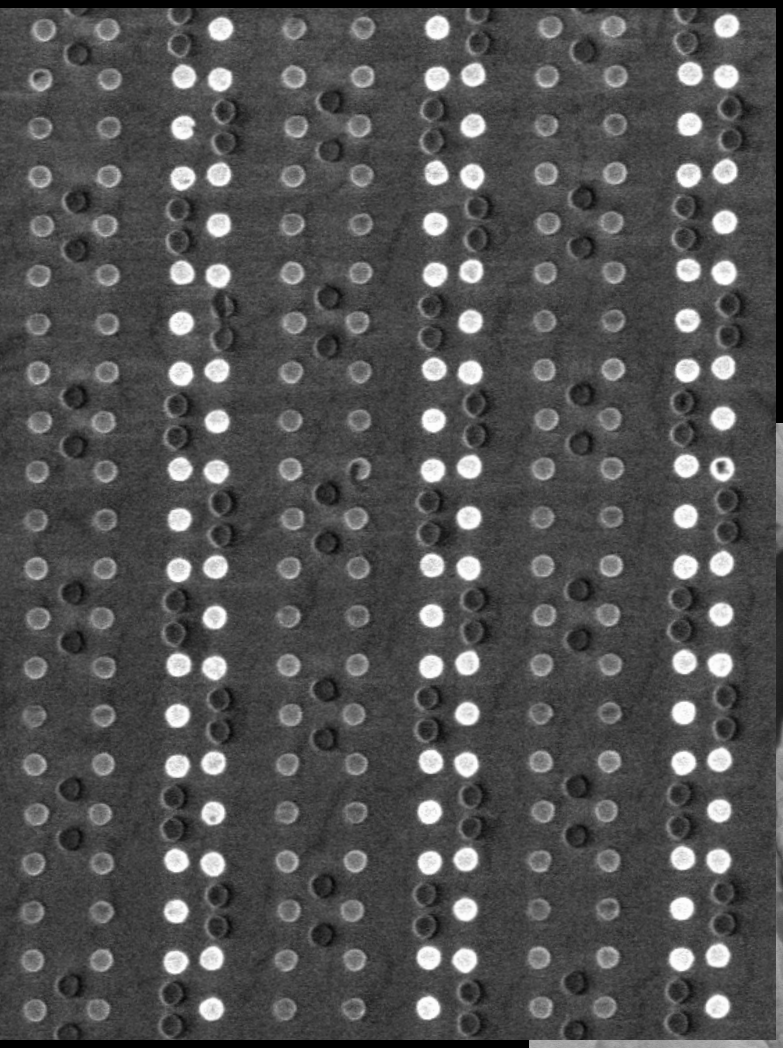
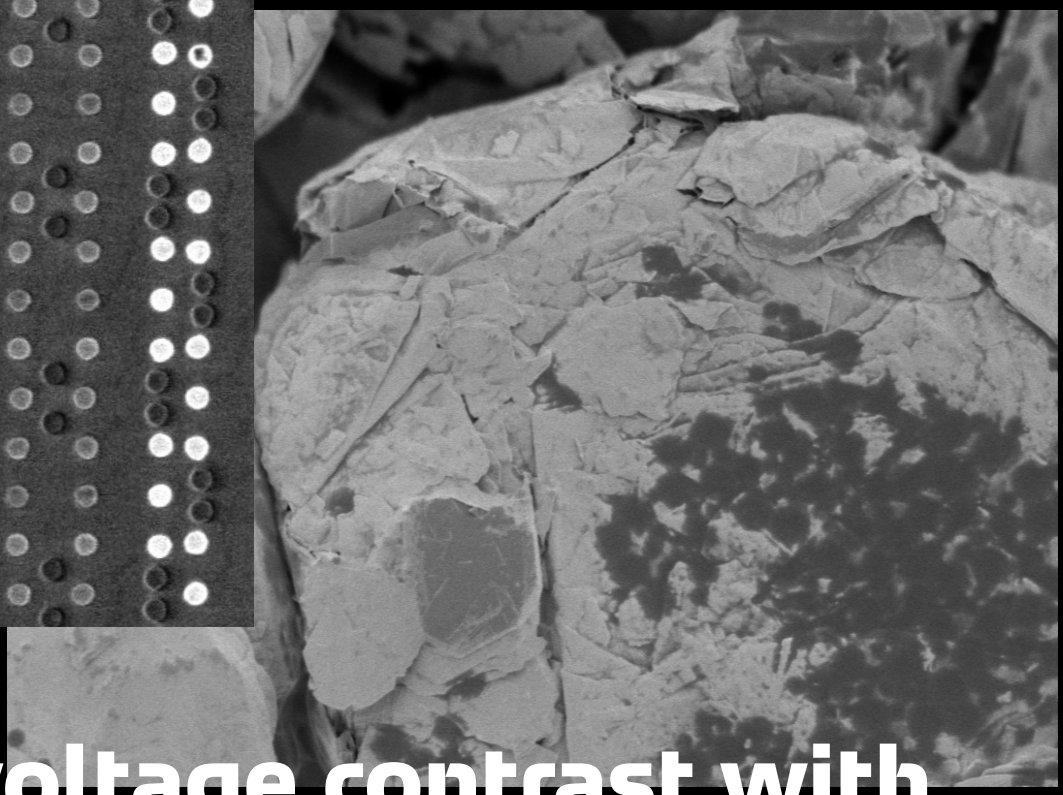
Technology note





Passive voltage contrast with the ULV in-column detector

Advancing ultra-low-voltage imaging on ZEISS GeminiSEM

Seeing **beyond**

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Executive summary

Ultra-low-voltage (ULV) scanning electron microscopy (SEM) is becoming increasingly important for imaging thin layers, surface structures, soft materials, organic components, and electrically heterogeneous samples. Whereas 1 keV landing energy is considered as low voltage, landing energies around 500 eV and below are regarded as ultra-low voltage[1, 2]. With landing energies moving toward 1 keV and below, and in some cases toward 100 eV, conventional detector configurations can struggle to maintain high signal efficiency, material contrast, and resolution.

The in-column ultra-low-voltage detector on GeminiSEMs, a series of advanced field emission SEMs from ZEISS, addresses this challenge by improving the detection of low-energy secondary electrons. Because these electrons are highly sensitive to local surface potentials and near-surface material differences, the detector enables stronger passive voltage contrast, improved material discrimination, and clearer imaging at very low accelerating voltages. The approach is especially relevant for semiconductor devices, battery materials, polymer membranes, coatings, steel inclusions, and other samples where electrical, compositional, or surface-sensitive contrast is critical.

Introduction
Why ultra-low-voltage SEM matters

Low-voltage SEM has become an essential technique for materials and device characterization. Imaging at low landing energies reduces the interaction volume between the electron beam and the specimen, making the technique more surface-sensitive and better suited for thin films, nanometer-scaled structures, beam-sensitive materials, and samples containing soft or organic phases.

At landing energies of 1 keV and below, and particularly around 100 eV to 500 eV, a greater fraction of the electrons leaving the sample will carry highly localized information from the sample surface. This can reveal subtle differences in electrostatic potential, material composition, charging behavior, and near-surface structure. However, ultra-low-voltage operation also places demanding requirements on detector geometry and signal efficiency. If the detector does not efficiently collect the most relevant low-energy electrons, contrast may be weak, resolution may suffer, and important sample features may remain hidden.

The ULV detector concept is designed to overcome these limitations by collecting low-energy secondary electrons more effectively within the SEM column. This improves image quality and expands the practical usefulness of ultra-low-voltage SEM.

Detector concept
Complementary in-column signals

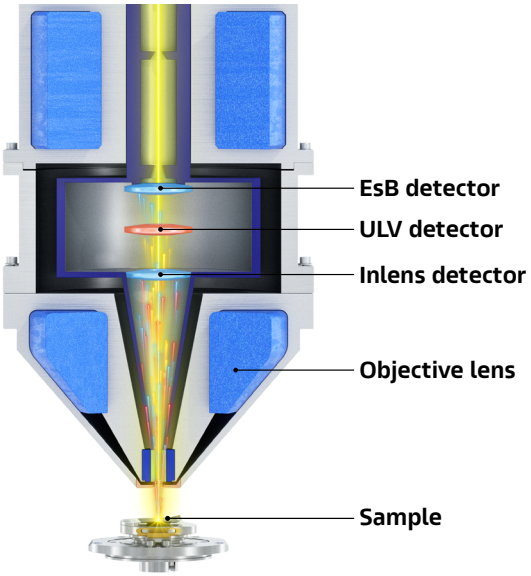


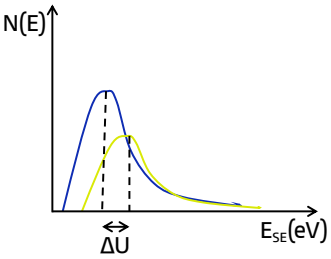
Figure 1: Schematic drawing of the GeminiSEM in-column detection system. SEs in yellow, low energy SEs in red, BSEs in blue.

The detector is integrated into the in-column detection system together with established detector channels such as the Inlens and EsB (energy selective backscatter electrons) detectors. Each detector channel emphasizes different signal contributions:

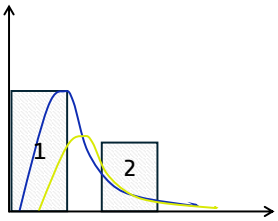
- **Inlens detector:** primarily provides topography and morphology information from medium-energy and angle-dependent secondary electrons (SE).
- **ULV detector:** efficiently detects low-energy secondary electrons, making it especially sensitive to voltage contrast, material contrast, and ultra-low-voltage surface information.
- **EsB detector:** provides energy-filtered backscattered electron information, supporting material and compositional contrast for low energy BSE signal applications.

Together, these channels provide complementary information rather than replacing one another. The ULV detector adds a new signal pathway for electrons that were previously less accessible, improving contrast generation at very low landing energies while preserving the value of conventional in-column detection.

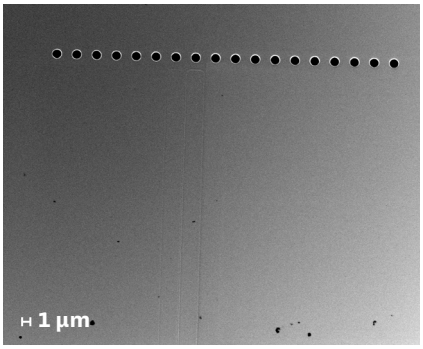
Passive voltage contrast mechanism

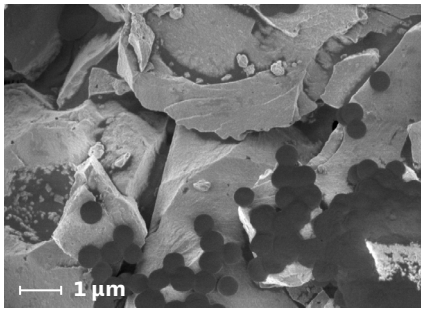


SE spectra conductive (indigo), non conductive (lime)



Imaging conditions:
1 low energy SE detection,
2 high energy SE detection





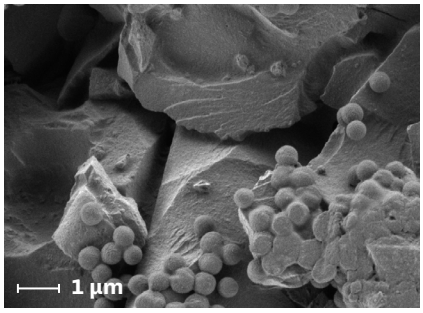


Figure 2: At the top SE spectra of conductive sites of a reference sample are shown in indigo blue, of non-conductive sites in lime green. The SEM image on the left displays the contrast enabled by the ULV detector using low energy electrons (left) and for the image on the right high energy SEs were detected using the Inlens detector (right).

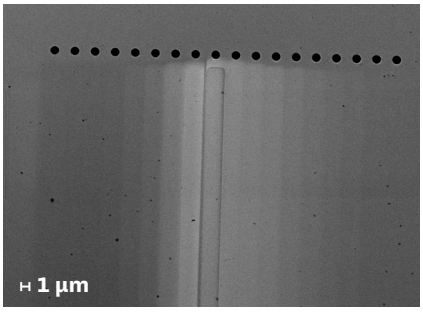


Figure 3: Silicon doping calibration standard, with both N- and P-doped regions. Inlens detector at 250 eV, 2.0 mm WD (top). ULV detector with same conditions (bottom). The ULV detector enables differentiation of doping levels which the Inlens could only achieve at much higher landing energy and working distances.

Passive voltage contrast (PVC) occurs when local electrostatic potentials at or near the sample surface influence the secondary-electron emission process. One of the most important capabilities of the ULV detector is enhancing the detection of PVC.

In simplified terms, different conductive and non-conductive regions can develop different local surface potentials. These potentials shift the energy distribution of emitted secondary electrons[3]. Low-energy secondary electrons are especially sensitive to this shift. As a result, a detector optimized for these electrons can reveal contrast that is much weaker or less visible in conventional detector signal.

This mechanism is particularly useful for samples such as semiconductor devices. It is also observed in battery electrodes, examples for composites containing conductive and non-conductive materials. A third group of materials shows doping contrast. Here, the approach enables the identification of differently doped materials. Different doping levels can be observed and contrast on the known doping profile can be measured in a quantitative manner[4] (Fig 3.).

In all these cases, contrast is not a result of surface shape; it reflects local electrical behavior, charging, or material-dependent emission properties.

Application examples
Semiconductor structures

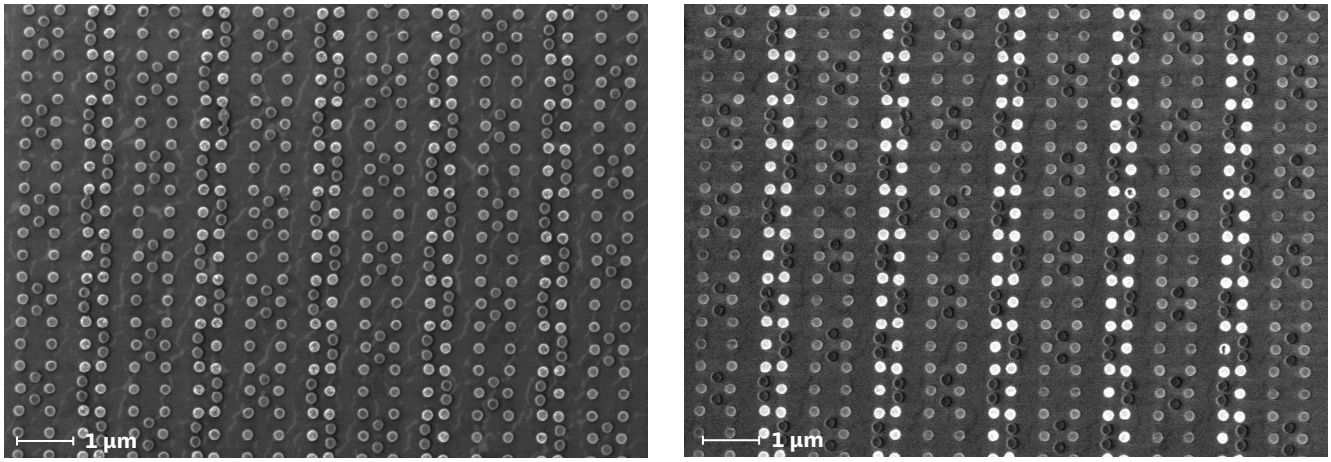


Figure 4: PVC in a vias of an SRAM device, 300 eV, WD 2.5 mm, Inlens (left), ULV (right).

Semiconductor devices are a well-known application area for passive voltage contrast. In the following example, the ULV detector reveals electrical contacts and transistor-related structures more clearly than conventional Inlens imaging, which primarily emphasizes topography. This makes the ULV detector especially relevant for semiconductor inspection, failure analysis, and research applications where electrical connectivity or local potential differences need to be visualized.

Boron oxide on steel

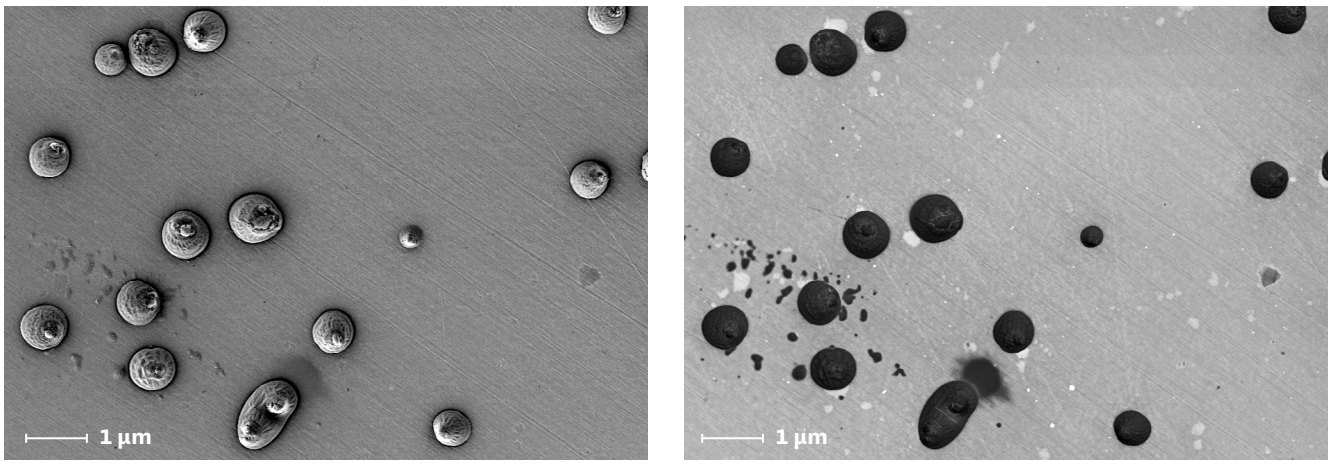


Figure 5: Steel with boron oxide deposits on the surface and bright precipitates (250 eV), Inlens (left), ULV (right).

In samples containing boron oxide deposits on steel, the ULV detector provides enhanced material contrast. Boron oxide precipitates appear dark, while precipitates at grain boundaries become visible as bright features. By comparison, the Inlens detector emphasizes surface morphology more strongly. This illustrates the value of the ULV channel for distinguishing material phases that may be difficult to separate using topographic contrast alone.

Battery materials

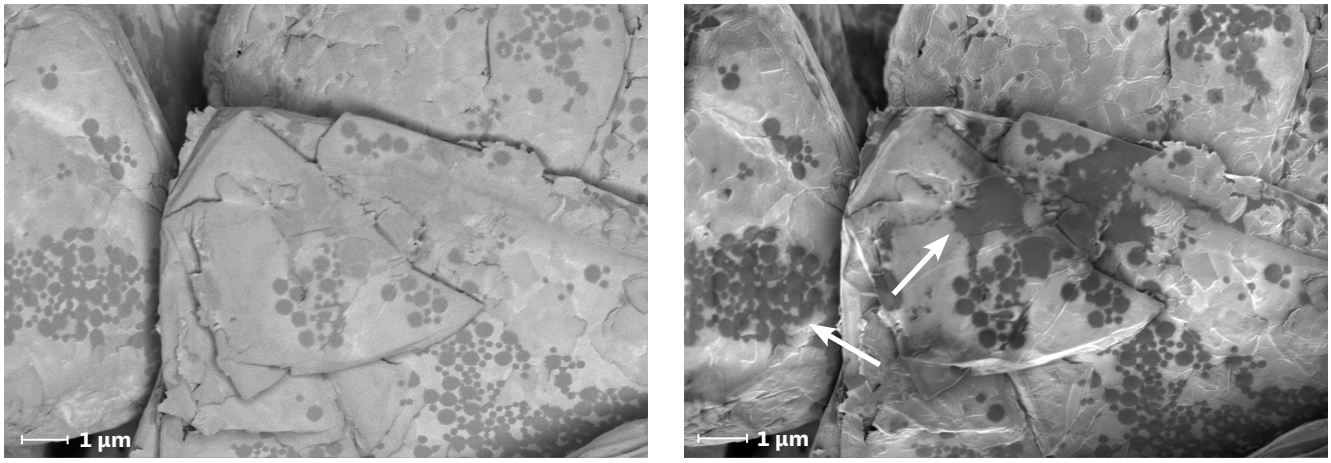


Figure 6: Battery sample with two different binder compounds, barely visible in the backscattered electron image (left) but clearly visible in the image taken with the ULV detector (right, arrows), 500 eV, WD 3 mm, EsB BSE image (left), ULV (right).

Battery electrodes often contain complex mixtures of conductive particles, binders, coatings, and other functional materials. In graphite battery anode examples, different binder compounds can be distinguished more clearly with the ULV detector due to their voltage-contrast signature. Graphite particles appear dark, while binder-related phases look bright (Fig. 6). This improved contrast can support segmentation and quantitative phase analysis in battery research and quality control.

Polymer membranes and fuel-cell materials

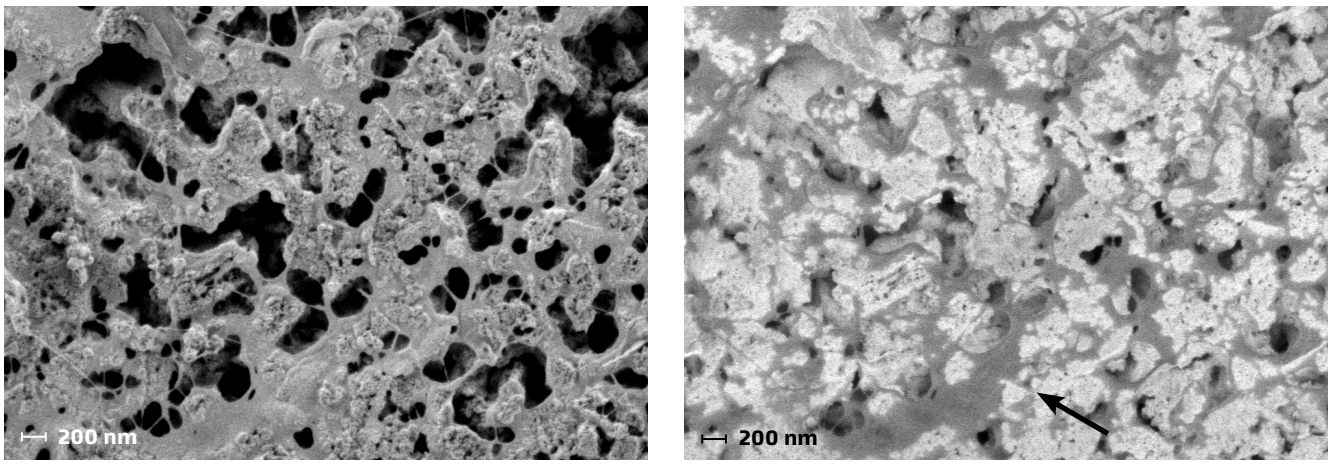


Figure 7: MEA ionomer (right, arrow) is nicely visible next to bright metal particles. Note how the ULV signal is coming from deeper membrane areas inside the holes. 200 eV, WD 2.0 mm, Inlens (left), ULV (right).

The ULV detector also improves visualization of porous polymer membranes and multi-material structures such as fuel-cell membrane electrode assemblies (MEA). In these examples, polymers and metal particles can be distinguished more independently (Fig. 7). Metallic particles appear bright, while the polymer matrix is displayed in gray tones. Compared with Inlens imaging, which mainly highlights pore topography, the ULV detector can make internal pore structures and material differences easier to interpret.

High-resolution ultra-low-voltage imaging

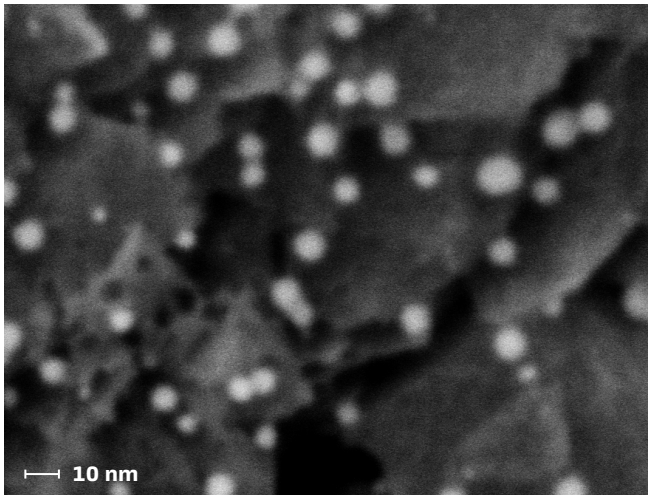


Figure 8: ULV detector image of a gold-on-carbon resolution measurement sample showing sub-nanometer resolution at 200 eV at WD 1.2 mm.

The ULV detector delivers optimal signal-to-noise ratios even at ultra-low voltages at values as low as 200 eV and at small working distances of only about 1 mm (Fig. 8). Using a low working distance at low and ultra-low voltages is especially important because here the electron optical conditions are optimal for the ULV detector. Other detectors are suffering from efficiency issues under these conditions. But the enhanced efficiency at low working distance of the ULV enables the detection of low-energy secondary electrons even at ultra-low accelerating voltages.

Key findings

- **Improved sensitivity to low-energy secondary electrons:** the ULV detector captures signal components that are highly responsive to surface potential and near-surface material differences.
- **Stronger contrast for segmentation and quantitative analysis:** enhanced material and voltage contrast can improve the separation of phases in complex samples such as battery electrodes, steel inclusions, and polymer membranes.
- **Better ultra-low-voltage image quality:** at very low accelerating voltages, improved detection efficiency at low working distance supports clearer imaging and better apparent resolution.

Practical implications

The ULV detector expands the range of practical SEM investigations at ultra-low voltage. Its value is greatest where conventional imaging is limited by weak contrast, excessive topographic influence, or insufficient sensitivity to local electrical potential. Relevant application areas include:

- Semiconductor passive voltage contrast and device analysis
- Battery binder and electrode characterization
- Conductive and non-conductive composite materials
- Thin films and coatings
- Steel inclusions and precipitates
- Polymer and membrane porosity studies
- Beam-sensitive or surface-sensitive materials

Because the ULV detector provides complementary information alongside Inlens and EsB signals, users can compare topographic, material, and voltage-sensitive contrast channels within a single imaging workflow.

Conclusion

Ultra-low-voltage SEM is increasingly important for advanced materials and device characterization, but its full potential depends on efficient detection of the most informative low-energy secondary electrons. The in-column ULV detector strengthens this capability by improving voltage contrast, material contrast, detection efficiency, and low-voltage image quality.

Across semiconductor, battery, steel, polymer membrane, and nanoparticle examples, the detector reveals features that are less visible or more difficult to interpret using conventional in-column detection alone. By reducing the dominance of purely topographic contrast and increasing sensitivity to local surface-potential effects, the ULV detector provides a powerful tool for surface-sensitive imaging, segmentation, and quantitative materials analysis.

References

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