Improving SEM Imaging Performance Using Beam Deceleration

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What is beam deceleration?

Beam Deceleration is a relatively simple method to reduce electron beam energy and improve imaging parameters such as resolution and contrast. The scanning electron microscope (SEM) uses a sharply focused electron beam to probe the specimen surface. The energy of the electrons forming such a probe is determined by the electrical potential of the electron source, referred to as accelerating voltage or high voltage (HV). No matter how many times the electrons are accelerated or decelerated inside the column, they leave the column with an energy corresponding to the high voltage. The high voltage is usually controllable within a range of 200 V to 30 kV for most commercially available SEMs, allowing the operator to select the electron beam energy suitable for the application. Imaging with very low electron beam energy has great importance, which is illustrated by SEM instrumentation development over the last few decades [1-2]. Low voltage microscopy is a topic discussed at most microscopy-related conferences these days, but generally, it is approached with an immersion lens and field emission gun (FEG) SEM system because of the better beam current densities. However, beam deceleration is also a means to bring low kV improvement to SEMs with thermionic electron sources.

Beam deceleration is a relatively simple method to reduce electron beam energy and improve imaging parameters, such as resolution and contrast, at the same time. The main characteristic of this method is that the specimen is held at a high negative bias voltage, so that the electrons leaving the column are decelerated before they reach the specimen. "Landing energy" is the term used to describe the energy of the decelerated electrons as they impact the sample. Landing energy can be calculated by means of a very simple formula:

$$LE = -e\,(HV - SB)$$

LE is landing energy of the probe electrons in electron volts (eV), e is the elementary charge, HV is high voltage (negative), and SB is specimen bias voltage (negative).

For example, if the high voltage is -5 kV and stage bias -4 kV, the electrons are first accelerated in the column to an energy of 5 keV then, after leaving the column, decelerated by 4 keV to give a landing energy of 1 keV. So primary electrons enter the specimen with exactly the same energy as if the high voltage were -1 kV without beam deceleration.

The original motivation for this work was to achieve reasonable imaging at very low landing energies, down to a few tens or hundreds of electron volts. Incidentally, beam deceleration and similar techniques are not new, and many scientific papers have been published on this topic. A good overview can be found in reference [3]. However, what is new is its use in commercial instruments for a wide range of applications, not just to achieve extreme imaging conditions, but also to improve performance for a range of operating conditions, as described below.

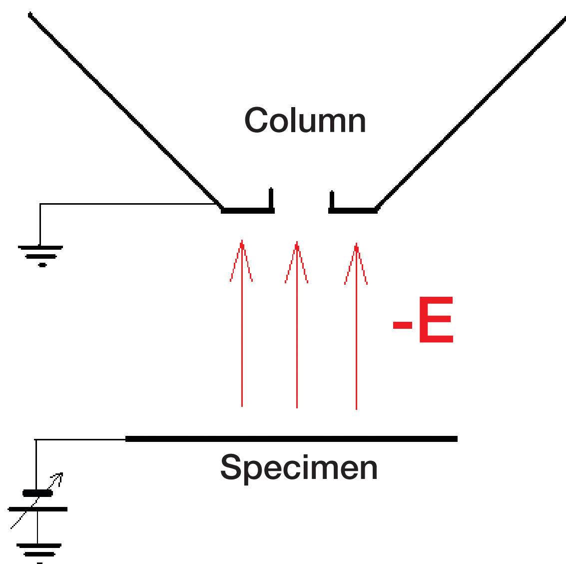

Figure 1: Beam deceleration principle: the specimen is held at a negative bias voltage, and the electrons leaving the column are decelerated before they reach the specimen.

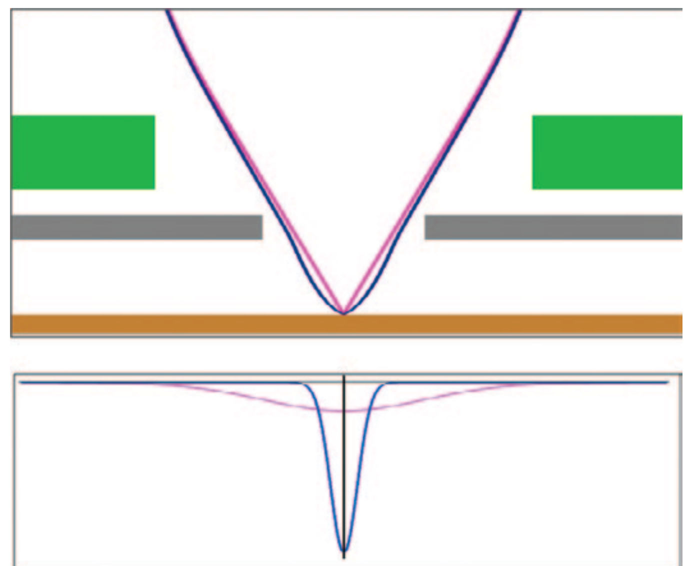

Figure 2: Schematic electron beam trajectories in a typical configuration with cathode lens off (magenta) and cathode lens on (blue) and corresponding beam profile (below). The green part is a lower polepiece of the magnetic lens. The beam is decelerated between the backscattered electron detector (gray) and the specimen (brown). Although the decelerated beam has a higher opening angle it creates a sharper spot.

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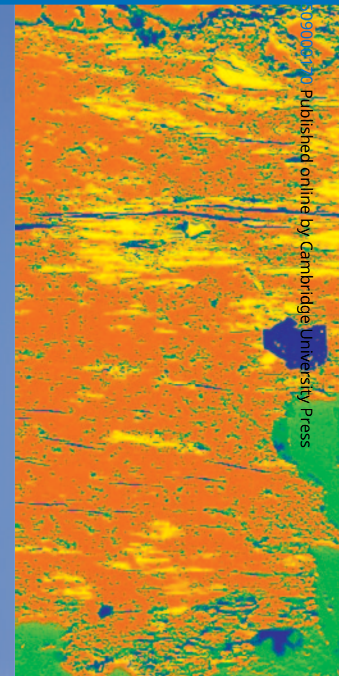

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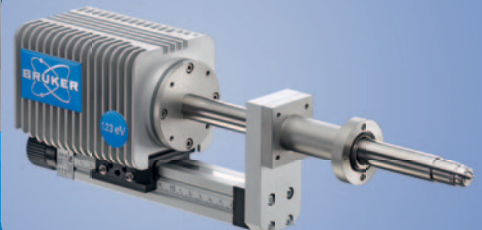

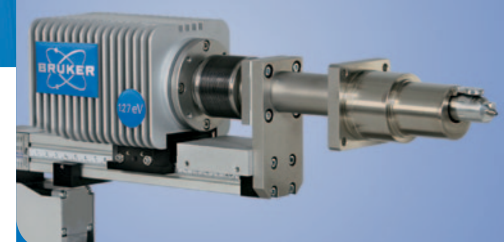

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What is beam deceleration good for?

The beam deceleration setup has several important benefits for imaging with the SEM:

1. The electrical field between the specimen and the column, or any detectors directly below the column, creates an electrostatic lens (cathode lens) that significantly affects the electron optical properties of the system. As it will be shown later, the cathode lens can improve image resolution at low landing energy.

2. All the signal electrons that escape from the negatively biased specimen are accelerated towards the grounded parts in the specimen chamber. The signal electrons have higher energy when reaching the detectors, and the signal electron trajectories are modified. This increases the efficiency of signal collection.

3. Imaging with very low landing energies can generally be accomplished with electron sources and columns designed for conventional higher voltage applications. Hence, it does not require a separate SEM system.

Cathode lens

As the electron beam leaves the electron optical column, it is already being focused by the objective lens. The decelerating electrical field acts as an extra immersion converging lens—a cathode lens. In this way, the primary electron beam becomes further focused during deceleration.

At a given geometrical configuration the cathode lens strength is described by just one parameter, the "immersion ratio." The immersion ratio (k) is the ratio between primary beam energy and landing energy and can be calculated as:

$$k = -e\ HV / LE = HV / (HV-SB)$$

The higher the immersion ratio, the stronger the cathode lens becomes.

The most interesting lens properties from the resolution point of view are axial aberrations, namely spherical and chromatic aberrations. Both of these axial aberration coefficients drop significantly with increasing immersion ratio k. For example, the coefficient of chromatic aberration C_c, which has a major impact on resolution at low landing energies, is almost inversely proportional to the immersion ratio k. This leads to partial compensation for the beam diameter deterioration at low beam energy seen in the cases where beam deceleration is not used. This situation is illustrated in Figure 2.

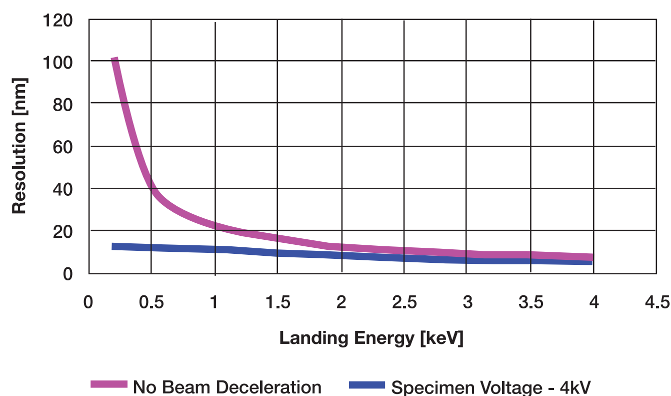

Figure 3: Calculated resolution of a typical beam deceleration setup on an SEM with a thermionic electron source and conventional magnetic lens, both with and without beam deceleration (specimen bias SB = – 4 kV).

Figure 3 shows an example of the calculated resolution of a typical beam deceleration setup on an SEM with a thermionic electron source (e.g. tungsten hairpin), conventional magnetic lens and specimen bias SB = – 4 kV, compared to an unbiased specimen. As can be seen, the resolution at low landing energies is dramatically improved for the beam deceleration case, particularly for energies below about 2 keV.

Even a modest value for the immersion ratio significantly improves the usable probe diameter. This is demonstrated by the images in Figure 4, obtained from a Quanta FEG (field emission source, with conventional, non-immersion, final lens). With and without beam deceleration, the resolution at landing energy 1 kV improves by a factor of 1.5.

Even higher resolution improvement (>50%) can be demonstrated at lower landing energies and higher immersion ratios, as shown in Figure 5.

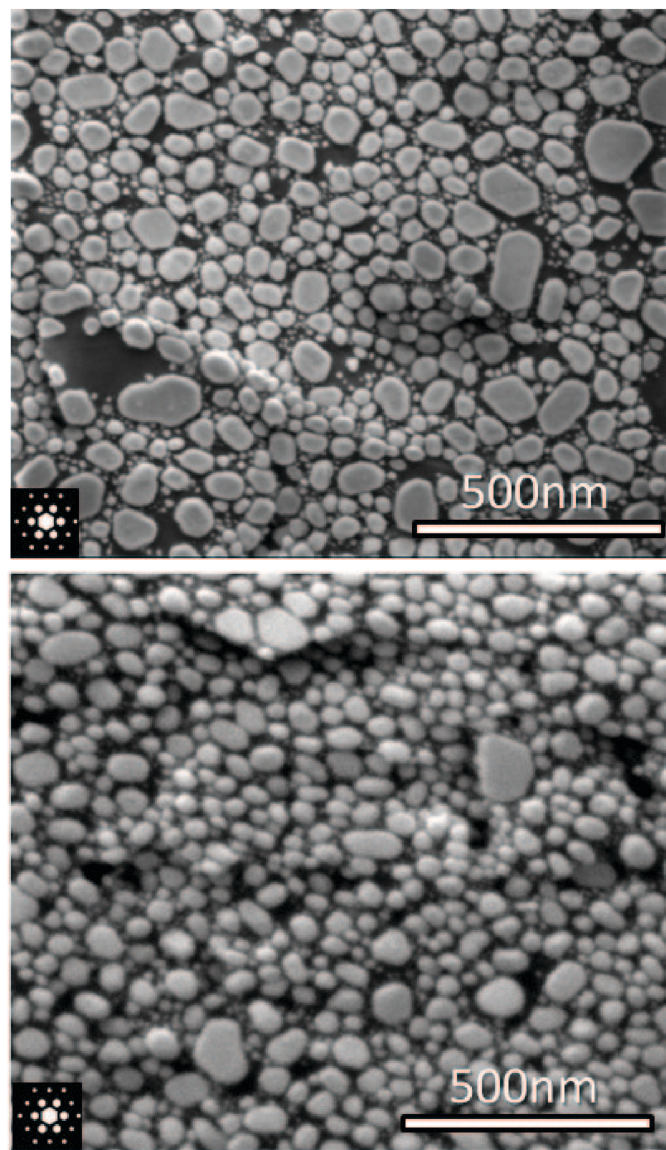

Figure 4: Image resolution improvement by using a cathode lens (beam deceleration). Landing energy LE = 1 keV without beam deceleration (k=1) on the bottom and stage bias SB = -3 kV (k=4) on the top. Horizontal field width of both images is 1300 nm.

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A similar trend in resolution improvement also exists when the cathode lens is combined with a magnetic immersion lens [2].

So far, it looks like the cathode lens has advantages only, but at least one potential drawback exists: the specimen surface becomes part of the electron optical system. The system works perfectly if the scanned surface is flat, smooth, large and perpendicular to the optical axis, so as not to disturb the electric field. If not, various problems such as image distortion or high astigmatism can occur (Figure 6). When the immersion ratio is higher and the cathode lens is stronger, the restrictions to the specimen become more significant. Fortunately, in many practical applications usability of the cathode lens is not limited. For example, with appropriate sample mounting even small specimens can be successfully imaged.

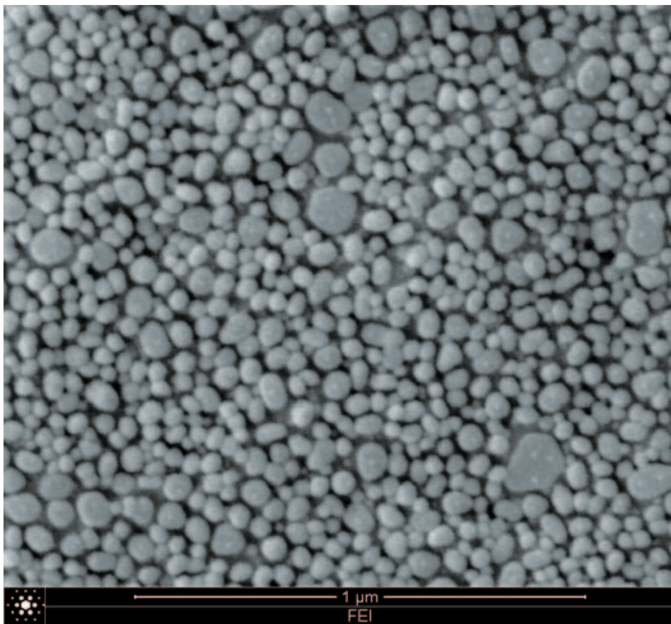

Figure 5: Image resolution with cathode lens and high immersion ratio. Landing energy LE = 100 eV and stage bias SB = -4 kV (k=41).

Detection of signal electrons

Backscattered electrons. In the absence of beam deceleration, backscattered electrons (BSE) reach the detector with the energy they have when they leave the specimen surface, close to the landing energy of primary electrons. The simplest and most used method of backscattered electron detection in most SEMs is their direct absorption in a semiconductor (solid state) or scintillator type detector held at ground potential. Solid state detectors lose their sensitivity as the incoming electron energy falls below a few keV, and although there are more sensitive detectors now available that have improved the lower limit, this is a fundamental limit in such detectors. In the beam deceleration mode, however, the backscattered electrons are accelerated toward the detector, which improves both the signal and the detection limit, enabling

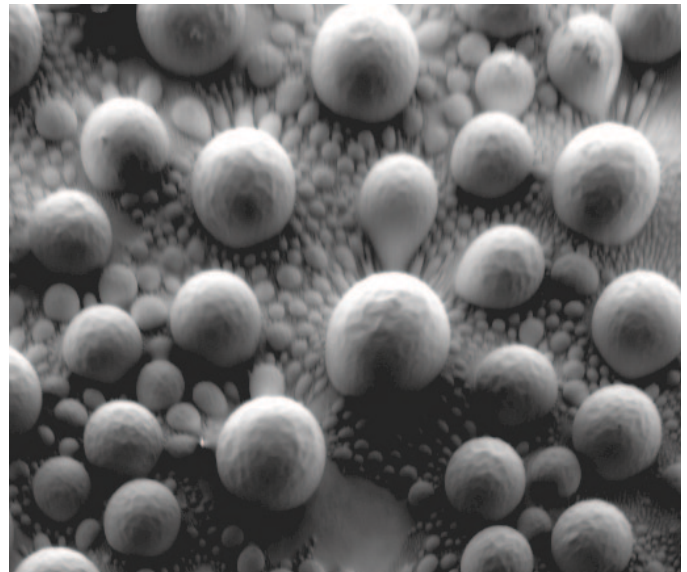

Figure 6: Example of extreme image artifacts (distortion) caused by a very strong cathode lens in combination with a tilted relief specimen (tin balls on carbon). Tin balls normally appear round and symmetrical but some distortion is present in this image due to the extreme non-optimal imaging setup.

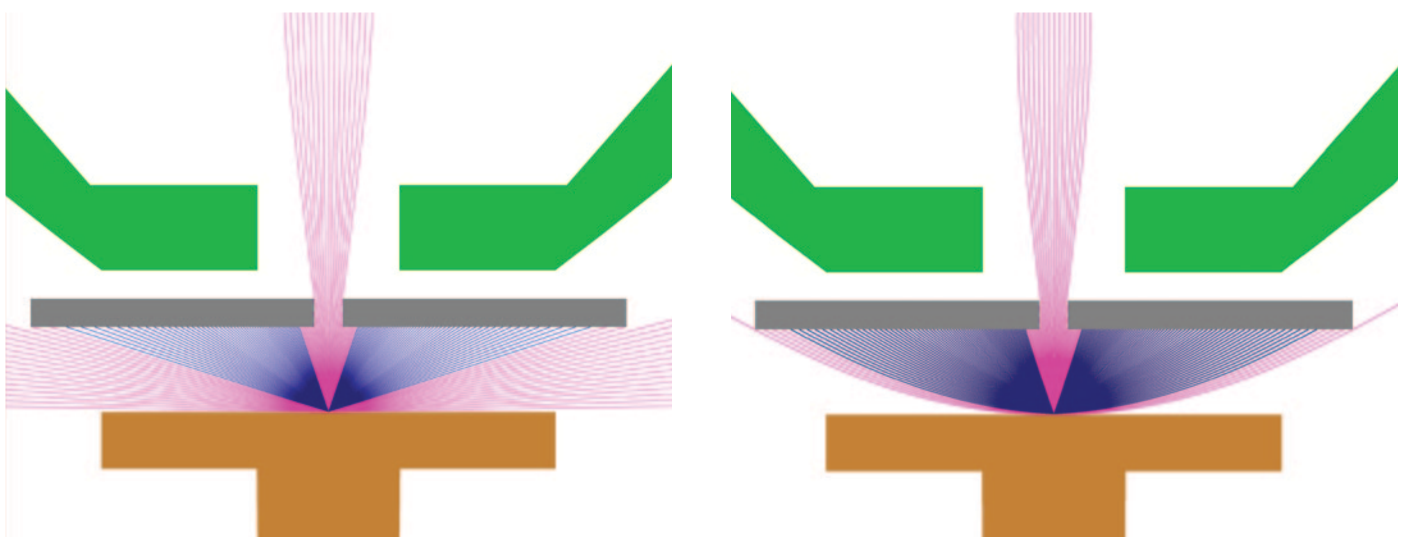

Figure 7: Trajectories of detected (blue) and undetected (magenta) BSEs without (left) and with (right) beam deceleration. Electron collection is improved at the BSE detector (gray) with beam deceleration.

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good signal detection even at very low landing energies.

Another consequence of using beam deceleration is that the trajectories of the backscattered electrons are bent by the additional electric field. Figure 7 shows an example of a typical configuration of BSE detection with a detector placed below the final lens.

In the first case, no specimen bias is applied, and the BSE trajectories are straight. The angular distribution of detected BSE is geometrically determined. In the second case, as the result of focusing in the cathode lens, more backscattered electrons with a wider angular distribution are collected. Moreover, by changing the immersion ratio (cathode lens strength), the user can continuously change the nature of the detected signal either toward topographical contrast with surface detail from low-angle BSEs (lower angles being more parallel to the sample surface) or to compositional contrast with high-angle BSEs.

Secondary electrons. Secondary electrons (SE) are emitted with much lower energy than BSE—less than 50 eV—and are usually collected by a scintillation detector in the specimen chamber (in non-immersion lens systems). Due to their low energy, they are strongly collimated to the optical axis when the beam deceleration mode is used. In this case they can be detected close to the optical axis near the final lens.

Imaging at very low landing energies. The usual range of high voltage starts at 200 V in common SEMs. To arrange imaging with lower accelerating voltages brings quite a few technical challenges: high voltage stability, magnetic material, vacuum and aperture quality, column calibration and alignment, coulomb interactions in the beam, etc, all of which act to increase the beam diameter and reduce resolution. Beam deceleration is a relatively simple method to push down the practically usable landing energy limits while maintaining beam integrity.

System Consequences

Implementation of beam deceleration mode has many consequences for the system design of an electron microscope.

The first requirement is safety of the users. In order to bring a few kilovolts to the specimen, the top part of the stage must be well isolated and connected to a high voltage supply. At the same time, the stage must not be charged whenever the operator is in contact with the specimen. This should be guaranteed by a system of safety interlocks independent of control software. It must also be guaranteed that if the biased specimen touches any part of the chamber, column or detector during operation, it cannot cause any risk for the operator or the system.

The specimen holder on top of the specimen manipulator must be well isolated to sustain a high voltage of a few kilovolts. This is not trivial because the applied voltage must be very stable. Any micro-discharges or leakage currents cause fluctuation of the specimen voltage and loss of image quality. This means that beam deceleration is absolutely not compatible with the low vacuum mode of operation. Stage isolation is also challenging for magnetic immersion lens columns where the strong crossed electrical and magnetic fields at short working distances create ideal conditions for discharge in residual gases even with high vacuum in the specimen chamber.

Another technical challenge is integration of the beam deceleration mode into the software controlling the optical elements of the electron column. The cathode lens is an extra, flexible lens. It works for any combination of high voltages, specimen bias voltages, and working distances. For all these combinations the accuracy of the optical model, namely working distance readout and magnification precision, should not be compromised. A system of calibration and alignment procedures must be developed as well.

On the other hand, beam deceleration improves system robustness. To achieve certain landing energy with beam deceleration, the column is operated with increased high voltage, which automatically means less sensitivity to the external magnetic field and higher tolerance to charging of the column parts and the aperture's quality.

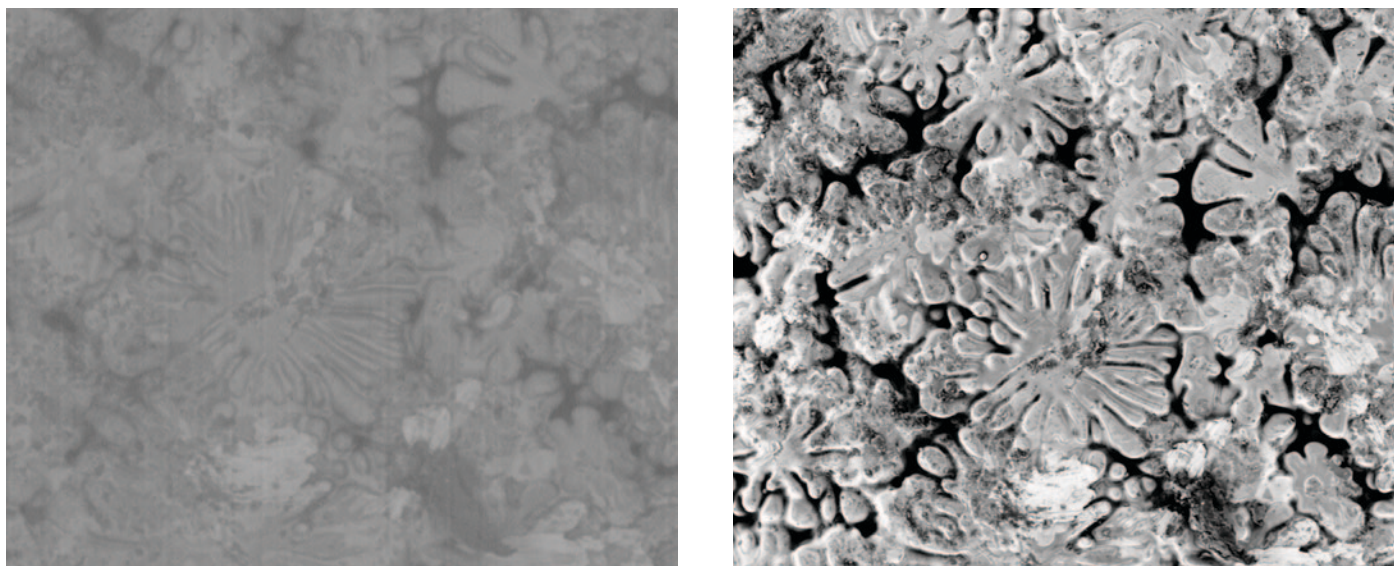

Figure 8: Image of copper/palladium solder alloy at the same landing energy of 1 keV without (left) and with beam deceleration (right)—immersion ratio k = 3.

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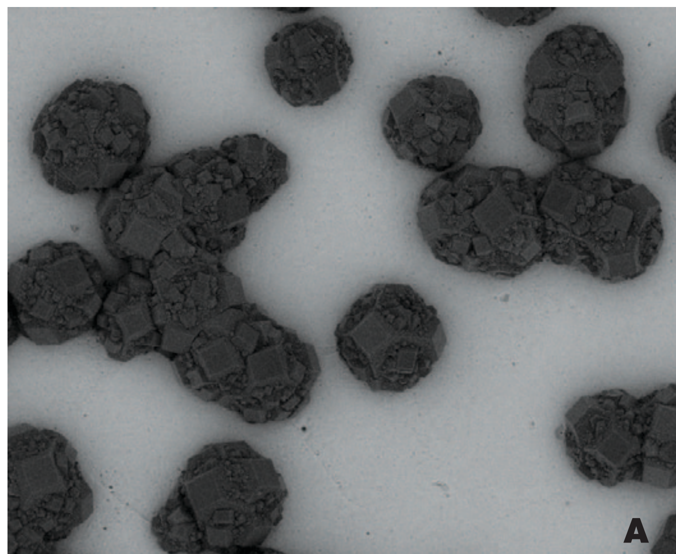
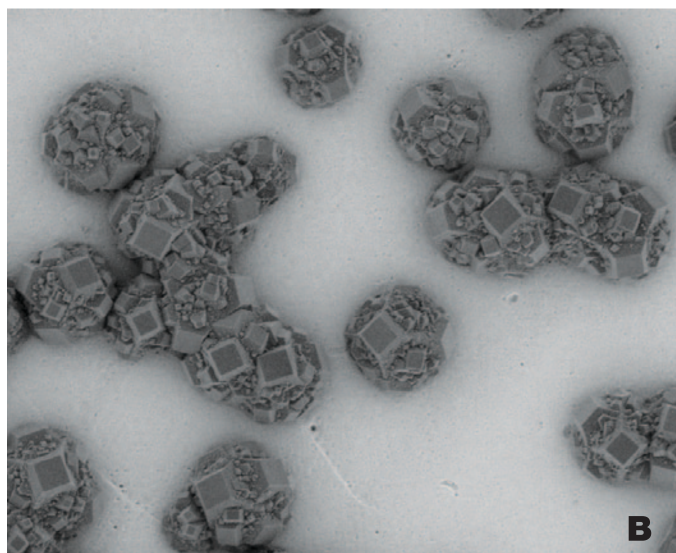




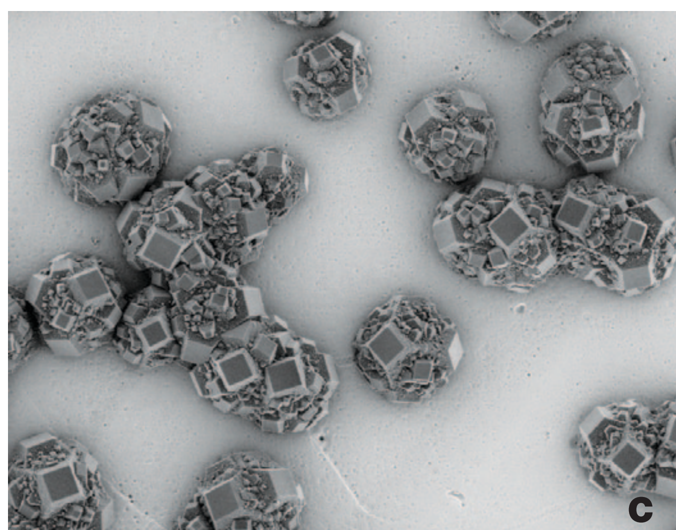


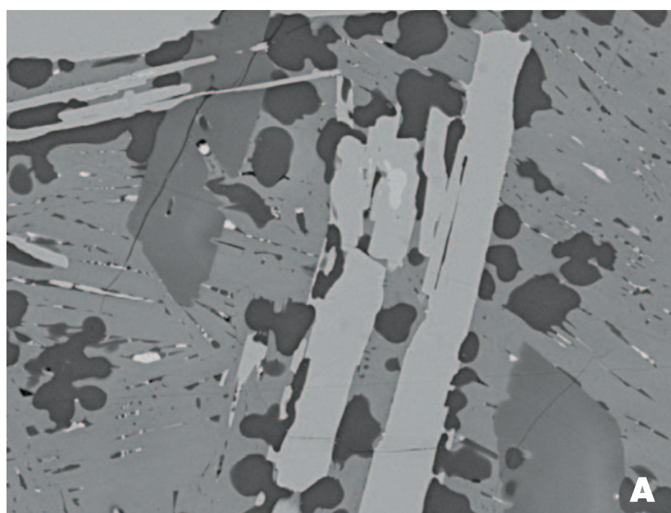
Figure 9: Images of microcrystalline diamond particles deposited on a silicon substrate, acquired with a backscattered electron detector placed below the pole piece. Landing energy LE = 3 keV with various immersion ratios: a) k=1, b) k= 1.33, c) and c) k=2.

Imaging that was previously impossible

Low energy imaging by means of backscattered electrons. The majority of commonly accessible BSE detectors provide good quality images only at electron beam energies above 2 keV. This limitation can be easily overcome by the acceleration of BSEs in beam deceleration mode (Figure 8). Naturally, a mix of high and low angle BSE is detected due to changes of BSE trajectories, as schematically shown in Figure 7.

Angularly selective detection of backscattered electrons. Detectors of backscattered electrons are primarily designed to provide images with compositional information by collecting high-angle backscattered electrons. Beam deceleration mode affects BSE trajectories such that the detection of low-angle BSEs is also easily achievable. Detection of high or low angle BSE depends mainly on the immersion ratio. Angularly selective BSE detection is illustrated in Figure 9 as a sequence of images with contrast varying from compositional (Figure 9a) to topographic (Figure 9c) with increasing immersion ratio.

Imaging of surface details. Low beam energy, and thus low penetration depth, is necessary to observe small surface



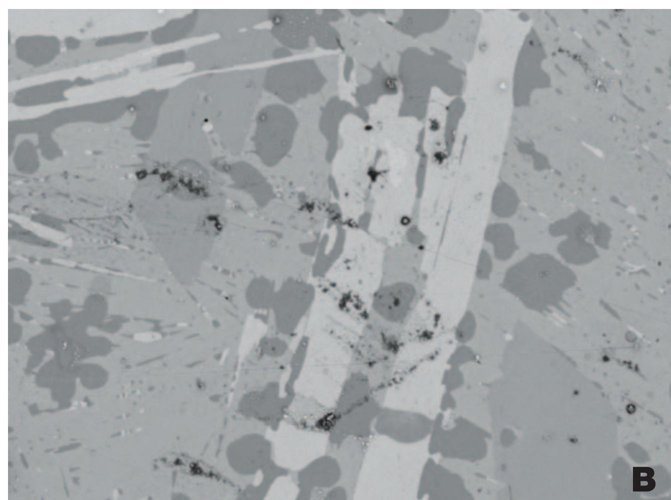


Figure 10: Blast furnace slag observed using a BSE detector at a) primary beam energy PE = 10 keV and b) with beam deceleration at landing energy LE = 1 keV.

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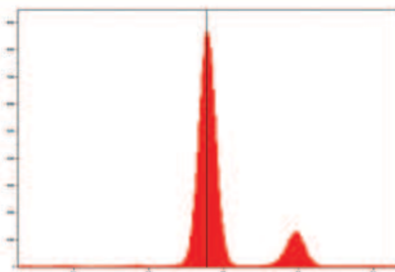
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features. As described above, beam deceleration can bring a high-resolution low-energy electron beam to the sample. Figure 10 shows a sample of blast furnace slag observed with a BSE detector at primary beam energy PE = 10 keV (no beam deceleration) and with beam deceleration at landing energy LE = 1 keV. New details that are not visible in 10 keV images appear when the landing energy decreases to 1 keV. Using beam deceleration, the compositional contrast of the sample remains, but additional surface details become visible (Figure 10b).

Conclusions

Beam deceleration is beneficial for many different types of SEM systems to improve imaging parameters, such as resolution and contrast. This technique can be used to improve the detection limit and to increase usability at low landing energy. For immersion lens systems, beam deceleration enables the ultimate in low-energy imaging capabilities. Moreover, for SEMs based on FEG and thermionic emitters with conventional lenses, the performance boost for low-energy imaging can be proportionately larger, greatly extending the imaging performance and flexibility of these systems. MT

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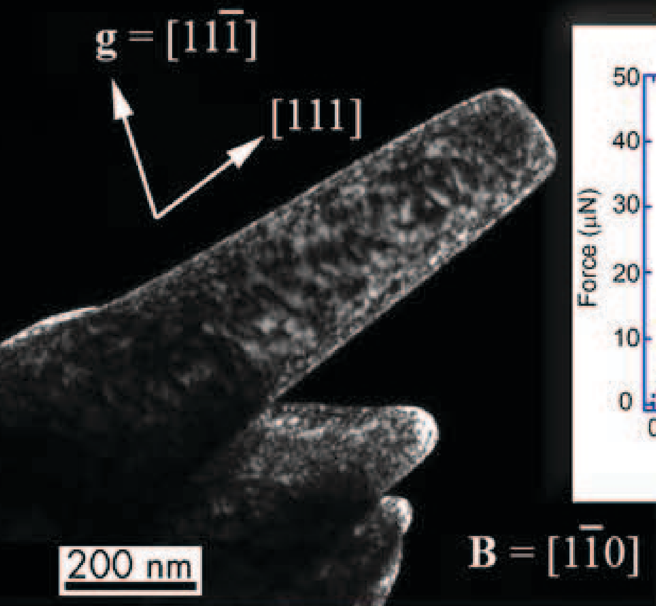

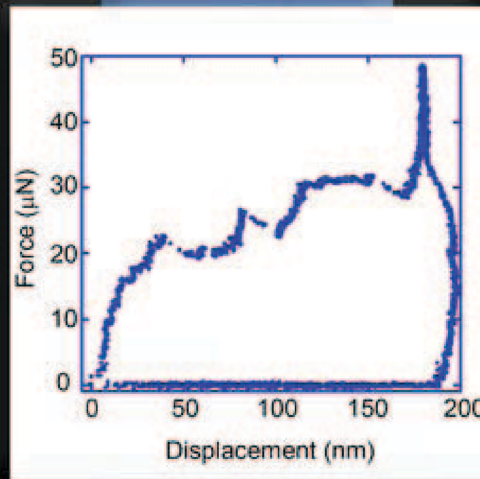

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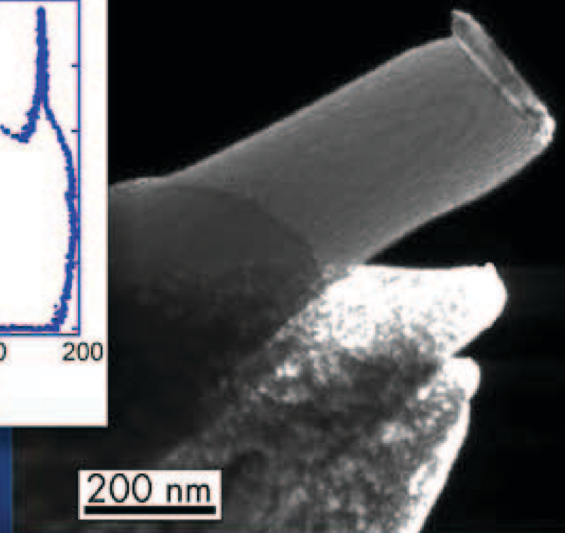

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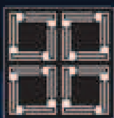

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