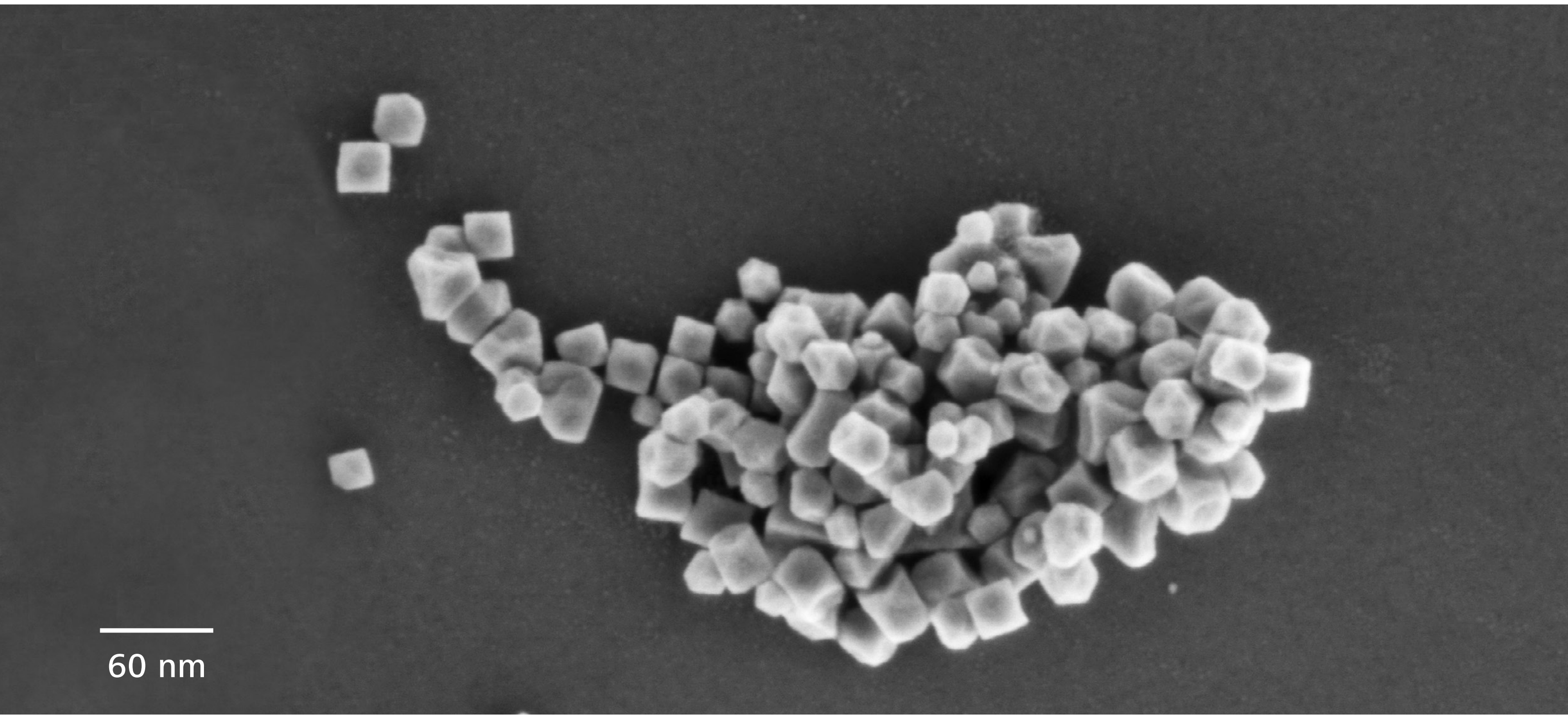
Technology Note

Evolution of Gemini Electron Optics: The Next Chapter in Sub-nanometer Imaging Below 1 kV



Seeing beyond

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Introduction

In the last 20 years, a major thrust of research in scanning electron microscopy (SEM) has been driving the performance of systems towards higher resolution at lower voltages. This is motivated by the requirement to further understand surface structures and their chemistry thanks to breakthroughs in such fields as 2D materials, metamaterials and semiconductor device manufacturing approaching the limit of Moore's law.

Key to the performance of any SEM, conventional or field emission SEM (FE-SEM), is its electron optical column. ZEISS FE-SEMs are based upon the Gemini column design which has seen a number of technological advancements since it was first launched in 1993. Low acceleration voltage imaging is attractive in that it reduces the interaction volume in the specimen, which allows surface sensitive information to be extracted. Additionally, the charging of insulating samples by SEM investigation can be avoided by reducing the electron energy used to probe the sample. The reduced radiation damage from low energy SEM imaging is also essential for imaging sensitive specimens such as biological samples and semiconductor devices [1].

Advancements in Objective Lens Designs

It is well known that in order to achieve a fine electron probe size at low energy, a special lens design with low spherical and chromatic aberration (Cs and Cc) is necessary. In basic implementations to overcome this problem, the specimen is immersed in either a strong magnetic field (magnetic single pole lens) or a strong electric field (sample bias), or even both. However, these methods put severe restrictions on the sample types that can be investigated in addition to their shape and the ability to tilt such samples. By combining an enclosed magnetic lens with in-column beam deceleration, the so called Gemini design, it is possible to achieve comparable if not better resolution than immersion-type lenses, while at the same time maintaining a high degree of sample flexibility [2] and avoiding immersing the sample in an electromagnetic field.

In 1993 ZEISS developed the first commercial FE-SEM, called the DSM-982 with Gemini electron optics based on such a principle. A distinct characteristic of this compound lens is that both chromatic and spherical aberrations (Cc and Cs) decrease with electron energy (Fig. 1), which is especially helpful to achieve good resolution at very low beam energies, such as those lower than 1 keV. The DSM-982 was the first commercial SEM to demonstrate resolution better than 10 nm with less than 1 keV electron energy [3]. Based on the same principle of a compound magnetic-electrostatic lens, the Gemini electron optics were constantly improved over the decades. In 2015, ZEISS GeminiSEM 500 was launched, equipped with the Nano-twin lens. Its Cs and Cc values were reduced to less than one third of the original Gemini lens design. This design also reduced the magnetic field strength on the sample, which was already a factor of 1000 less than the sample experiences with an immersion lens.

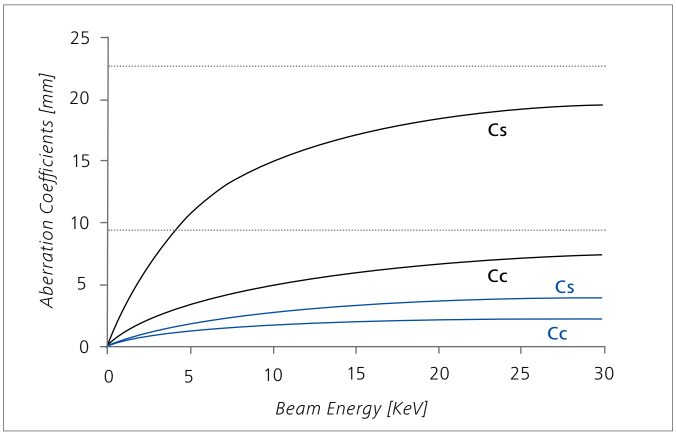

Figure 1 *Spherical and chromatic aberrations (Cs and Cs) of the original Gemini lens (black curve) and the Nano-twin lens (blue curve) with respect to different beam energies at 1 mm working distance.*

New Electron Optical Engine

ZEISS now introduces several technical achievements to further extend the usability and performance of the Gemini column design by an improved Nano-twin lens. Moreover, these developments achieve better than 1 nm resolution below 1 kV without immersing the specimen in an electric or magnetic field. Thanks to a new electron optical (EO) engine, the beam convergence angle is optimized on-the-fly for the current working condition to achieve the best possible resolution. The new engine enables a new scanning mode to achieve a very large field-of-view and provides a seamless transition between sample navigation over large distances and high-resolution imaging. Lastly, the engine delivers extremely rapid automated focus and beam alignment using a parallax method.

Examples of high-resolution images obtained at low beam energy are shown in the following figures. The montmorillonite particles shown in Fig. 2 are non-conducting. To avoid charging, this specimen is imaged at 800 V using 15 pA current by selecting a corresponding aperture size. The new engine automatically optimizes the condenser excitation to achieve the best resolution at this specific condition. Since such a sample is not conductive, it is not feasible to apply a potential on the specimen, as this would cause electrostatic charging effects which could damage the system. Thankfully such a potential is not required to achieve an image of exceptional resolution with the Gemini column design combined with Nano-twin lens and the new engine. Similarly, the FeMn magnetic nanoparticles shown in Fig. 3 cannot be immersed in a magnetic field for imaging as this would attract these nanoparticles towards the lens, possibly causing damage to the SEM system. Again, the Gemini column design with Nano-twin lens and new EO engine circumvent this problem through the well know Gemini optical design principle.

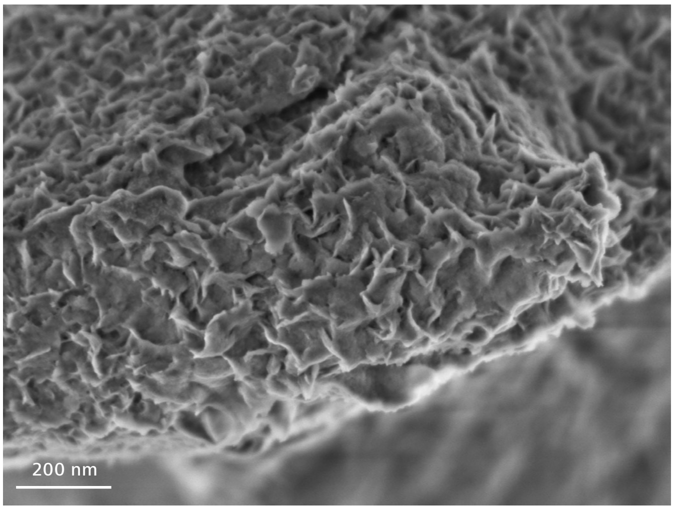

Figure 2 *High resolution image of montmorillonite particles obtained at 800 V beam energy. Even though the sample is non-conductive, fine flakes on the fractured surface can be well resolved.*

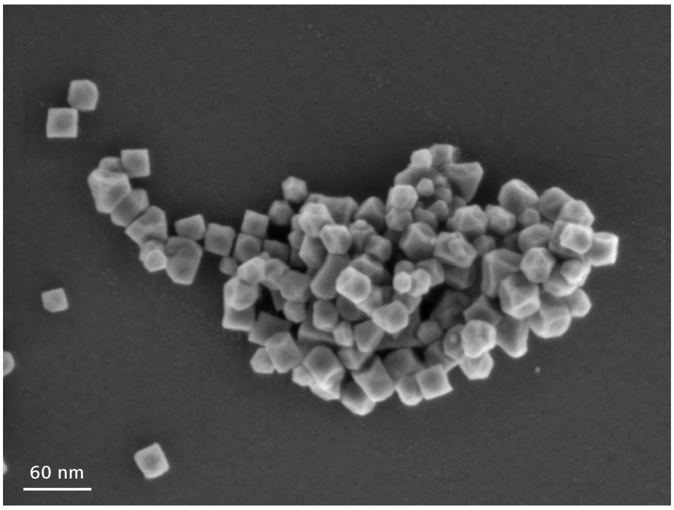

Figure 3 *High resolution image of FeMn magnetic nanoparticles obtained at 1 kV beam energy. Even though the sample is magnetic, the highest resolution can still be achieved.*

While resolution is usually treated as the benchmark of any SEM, the importance of lower magnification performance is usually underappreciated. The new EO engine from ZEISS provides a novel scanning mode to achieve a large field of view (FoV) to help navigate across the specimen. This is achieved by a different arrangement of the scanning system, while maintaining the beam energy and lens configuration unchanged.

This assures fast transition between the normal imaging mode and large field of view mode without changing the voltage of any electron-optic components, and all detectors in the FE-SEM system maintain a consistent contrast and performance. In the example shown in Fig. 4, three Euro coins are imaged at 5 kV beam energy. In normal imaging mode the maximum FoV is about 4 mm, only enough to cover a small portion of a single coin. The new EO engine drives the system to allow all three coins to be imaged in the same frame.

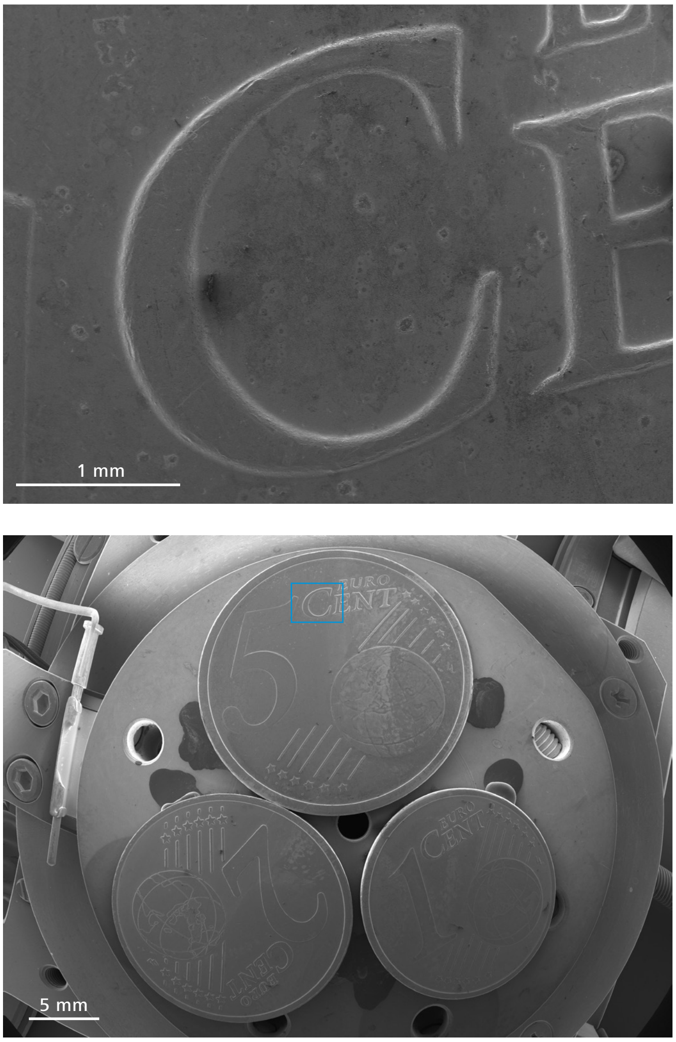

Figure 4 *Euro coins imaged at maximum FoV in normal imaging mode (upper) and in high FoV mode (lower) using the new EO engine. The blue square shows the position and size of maximum FoV in normal imaging mode.*

Another advantage of the new EO engine can be seen in the resulting auto functions for fine focusing and beam alignment. Here EO calculations are used to adjust focus and align the microscope. The time to result is shown in Table 1 showing a particularly fast autofocusing time. As an example, in Fig. 5 the precision of the fine autofocus is shown in an image pair, before and after autofocusing. This new capability compliments the coarse-autofocus, auto-stigmation and auto-contrast brightness functions available today. With the design of various degrees of automation, the improved speed and ease of use will be available to all users independent of their skills.

	Duration
Auto focus	<1s
Auto align	<4s

Table 1 *Performance of EO engine based auto functions.*

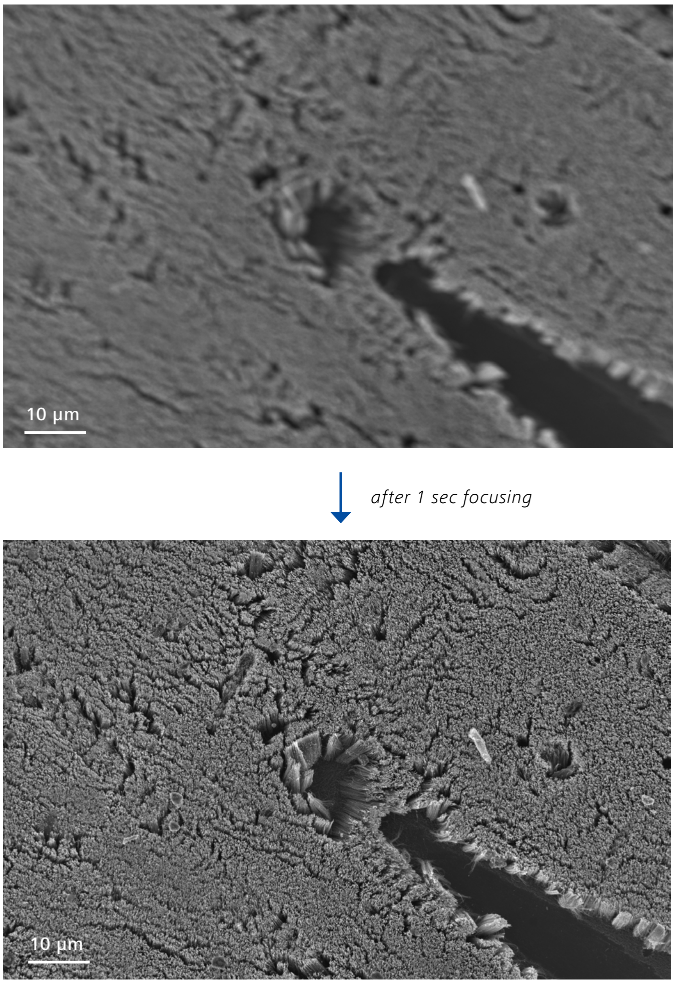

Figure 5 *Example of ultra-fast fine focus.*

Conclusion

After pioneering the development of low kV imaging without using immersion lenses, ZEISS has continued to innovate in this field with the introduction of the Nano-twin lens in 2015. The latest development in this field is the new EO optical engine. This EO engine provides further increases in resolution at low kV by optimizing the convergence angle of electrons travelling through the column at given conditions. The engine also substantially increases the available field of view using the high-performance Nano-twin lens. System ease of use is further enhanced through the engine's new autofocus and auto beam alignment functions. Notably, the new autofocus capability of the system brings the operation into the millisecond domain for the first time.

Reference:

[1] Imaging formation in Low-voltage scanning electron microcopy, L. Reimer, SPIE optical engineering press, 1993

[2] Handbook of Charged Particle Optics (2nd edition), J. Orloff, CRC Press, 2009

[3] H. Jaksch, J. P. Martin, Fresenius, Journal of Analytical Chemistry October 1995, Volume 353, Issue 3-4, pp 378-382
High-resolution, low-voltage SEM for true surface imaging and analysis

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