Detection Principles based on GEMINI® Technology

Product Information

Nanotechnology has become a very active and highly charged discipline in science and technology, growing rapidly in industrial sectors and is part of almost every field of research and engineering. The intense interest in nanotechnology is being driven by visions of a stream of new nanotech commercial applications that will dominate future industrial appearance. Our latest FE-SEM technology enables, not only routine inspection and failure analysis, but also ultrahigh resolution imaging including the complete variety of state-of-the-art analytical features essential in nanotechnology research.

The Origin SFE

The GEMINI® column utilises the Schottky thermal field emission source (SFE) that has been developed to overcome the weaknesses of cold field emitters (CFE). The Schottky emitter combines high beam brightness and low energy spread of the cold field emitter together with long-term current stability and low beam noise. The required capability to deliver much higher probe currents is a consequence of a 100 times larger tip area than that of a CFE cathode. Tab.1 gives an overview of the operating parameters and performance of the two electron emitter types.

Fig. 1: The ULTRA PLUS FE-SEM.

Tab. 1: Comparison of FE sources.

Electron Source Performance Comparison

Emitter type	Schottky FE	Cold FE
Cathode material	ZrO/W (100)	W (310)
Operating temperature [K]	1,800	300
Cathode radius [nm]	-1,000	-100
Effective source radius [nm]	15 (a)	2.5 (a)
Emission current density [A/cm^2]	5,300	17,000
Total emission current [µA]	200	5
Normalised brightness [A/cm^2.sr.kV]	1 x 10^7	2 x 10^7
Maximum probe current [nA]	10	0.2
Energy spread at the cathode [eV]	0.31	0.26
Energy spread at the emitter exit [eV]	0.35 - 0.7	0.3 - 0.7
Beam noise [%]	1	5 - 10
Emission current drift [%/h]	<0.2	5
Operating vacuum [hPa]	-1.10^{-8}	-1.10^{-10}
Cathode life [h]	2,000	2,000
Cathode regeneration	not required	every 6 to 8 h
Sensitivity to external influence	low	high

(a) virtual source

The GEMINI® Column

The field emission scanning electron microscopes are all based on the GEMINI® principle, shown in Fig. 2. In order to reduce aberrations and sensitivity to interfering stray-fields the electron optical column possesses a positively biased booster that shifts the energy of the primary electrons. The incident beam is focussed by a combination of a magnetic lens with an axial gap that avoids field leak-age to the specimen and an electrostatic retarding lens formed by the beam booster, together with the grounded pole piece cap. Shortly before the electrons hit the specimen they are decelerated to the desired primary energy. A suitable explanation for the reduction of spherical and chromatic aberrations is that the electron beam is focussed by the objective lens at higher energies and smaller electron beam diameters.

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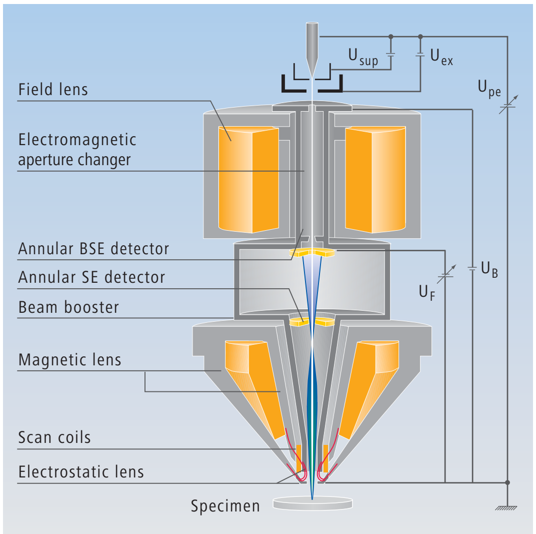


Fig. 2: GEMINI® bias concept.

Fig. 3 demonstrates the probe radius R50 % (resolution) over the whole energy range from 0.1 to 30 kV, where R50 % is defined as the radius that encircles 50 percent of the electron beam charge.

The advantage of the GEMINI® lens over the traditional single-pole lens is illustrated in Fig. 4 with regard to field leakage. The GEMINI® concept has overcome the problem with classical objective lens designs, which immerse the specimen in the magnetic field prohibiting imaging of magnetic samples.

Detection System

GEMINI® FE-SEMs microscopes enable a large variety of detector types (Fig. 5) to analyse all scattering products emerging from the specimen: Secondary electrons (SEs) used mostly to resolve topographic and charging information, backscattered electrons (BSEs) to enhance compositional contrast and crystal orientation, as well as photons to visualise lattice structures or to show luminescence effects. Beside the already mentioned benefits of highest resolution and beam stability, the beam booster is also advantageous for secondary electron collection. SEs emer-ging from the sample surface are attracted and accelerated by the positively biased electrode of the beam booster and are collected with the SE in-lens detector.

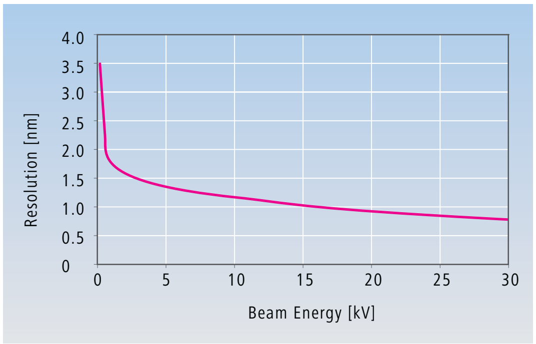


Fig. 3: Resolution of the GEMINI® column.

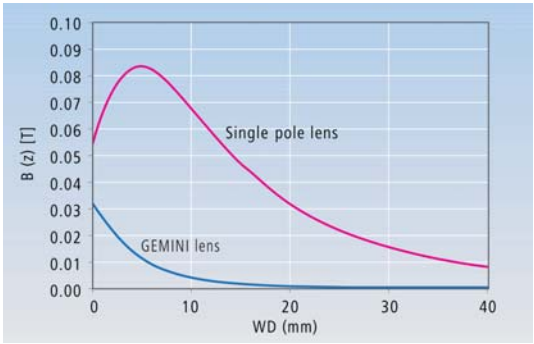


Fig. 4: Field leakage comparison of GEMINI® column against the classical single pole lens.

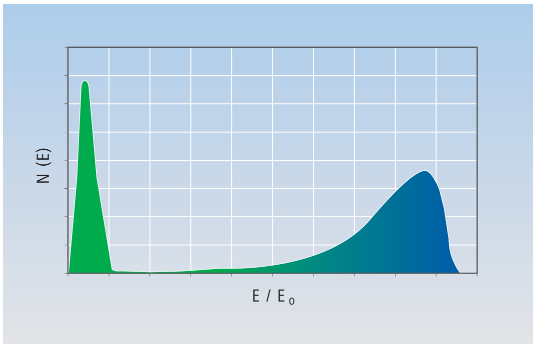


Fig. 5a: Electron energy spectrum.

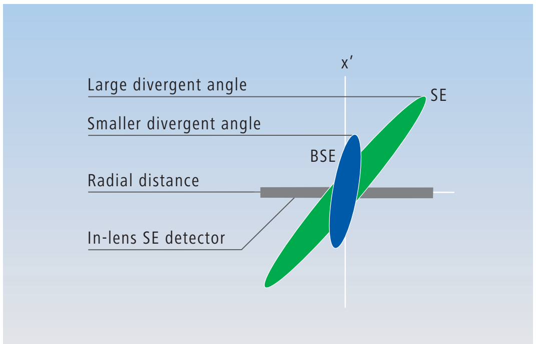


Fig. 5b: Phase space comparison.

An additional Everhart-Thornley chamber detector (ETD) collects remaining SEs that are not captured by the beam booster (especially at large working distances) or second generation secondary electrons, SE3 type, which are produced by BSE interaction with the objective lens. Hence, the ETD typically depicts compositionally enhanced con-trast combined with some surface information. Correct BSE detection is rather complicated and needs several detectors covering the whole solid angle depending on the primary energy of the initial electrons. A retractable quadrant diode detector installed beneath the objective lens collects BSE scattered under very low angle (almost parallel to the sample surface) and produces high quality material contrast images.

Low Voltage BSE Imaging – EsB Detection

In order to detect high angle BSEs (almost perpendicular to the sample surface) backing up through the lens, a new detector has been developed and introduced in the new ULTRA FE-SEM. To understand the basic principle of this new detection system a closer examination of the energy spectra as well as the take-off angle distributions of the released electrons and their trajectories through the electron column is necessary. Fig. 5a illustrates a schematic energy spectrum of electrons escaping from the specimen. Secondary electrons (green), possessing very low energies by definition, are released near the surface and produce a signal rich in topographic information, where as backscattered electrons (blue), which have undergone at least one large angle scattering, originate from larger depths and possess compositional information.

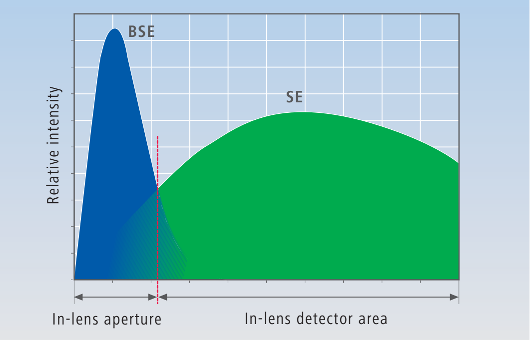


Fig. 5c: Radial electron distribution.

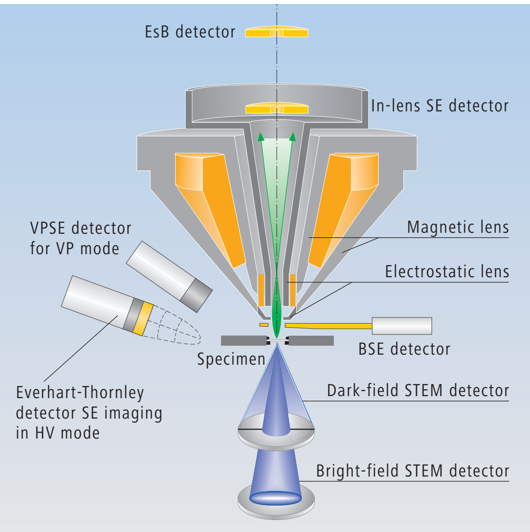
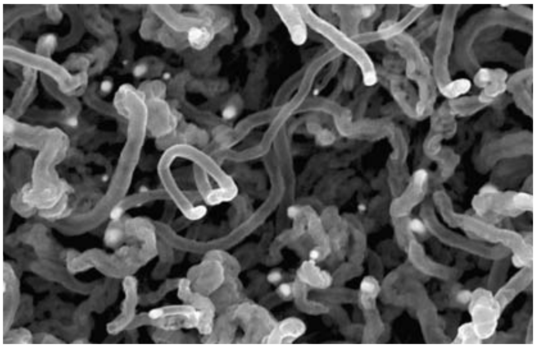
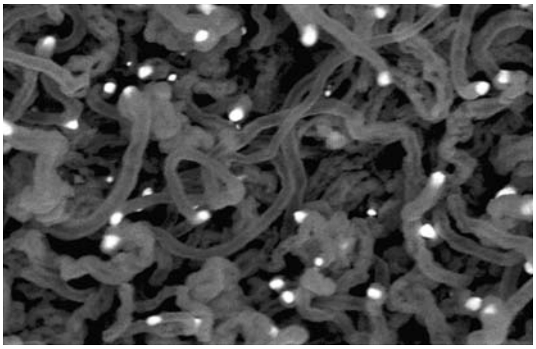


Fig. 6: GEMINI® detectors.

Fig. 7: Nanotube sample at 4kV.



Top: SE image.



Bottom: BSE image taken with EsB detector (filtering voltage 600 V).
Image courtesy of Dr. Heiner Jaksch, Carl Zeiss SMT.

Beside electron energy level, both electron types also differ in respect to their take-off angle distribution. While the distribution of secondary electrons orientates perpendicularly to topographic structures, backscattered electrons emerge from the bulk material and are therefore less sensitive to surface topography.

Emerging from the specimen surface most of the electrons are attracted by the beam booster and move upstream into the GEMINI® column. Because of the chromatic abe-ration of the magnetic lens the electrons are forced on different trajectories depending on their energy when traversing the focussing field. Both, the deflection of the lens and the different take-off angle distribution result in different phase spaces at the position of the lower annular in-lens detector (Fig. 5b). The green ellipse indicates secondary electrons possessing large divergence and a wide spatial spread, whereas the backscattered electron emittance is significantly smaller, resulting in an effective separation of secondary and backscattered electrons at the position of the lower in-lens detector.

As a consequence of different phase spaces, backscattered electrons have a closer radial distance in comparison to SEs and transmit through the central aperture of the in-lens SE detector while secondary electrons land on the in-lens detector and are collected.

From Fig. 5c, depicting the radial distribution and the dimension of the detector aperture (red line), it is clear that for optimised conditions a filtering efficiency of 90 % may be achieved by applying the method of „**E**nergy and angle **s**elective **B**SE detection“. Electrons passing the lower in-lens detector may be collected at the upper EsB® detector. These are mainly the so-called „high angle“ backscattered electrons, including a small propotion of unwanted secondary electrons inside the phase space volume of the backscattered. The compositional information of the EsB® detector is superimposed by an undesirable surface signal.

To remove this contribution a negatively biased filtering grid is installed below the EsB detector to repel the se-condary electrons. Adjustment of the filtering grid in the range from 0 to minus 3000 volts enables real-time mixing and simultaneous observation of surface, voltage and material contrasts, without interfering with the primary electron beam. Fig. 8 clearly shows the beam shapes of both electron types and the general functioning of EsB® detection and filtering mechanism. Fig. 7 depicts the advantages of the new detector arrangement. While the upper image clearly shows topographical and voltage information, the lower micrograph pronounces compositional contrast and suppresses any charging or edge em-phasis effects allowing for accurate metrology to be performed.

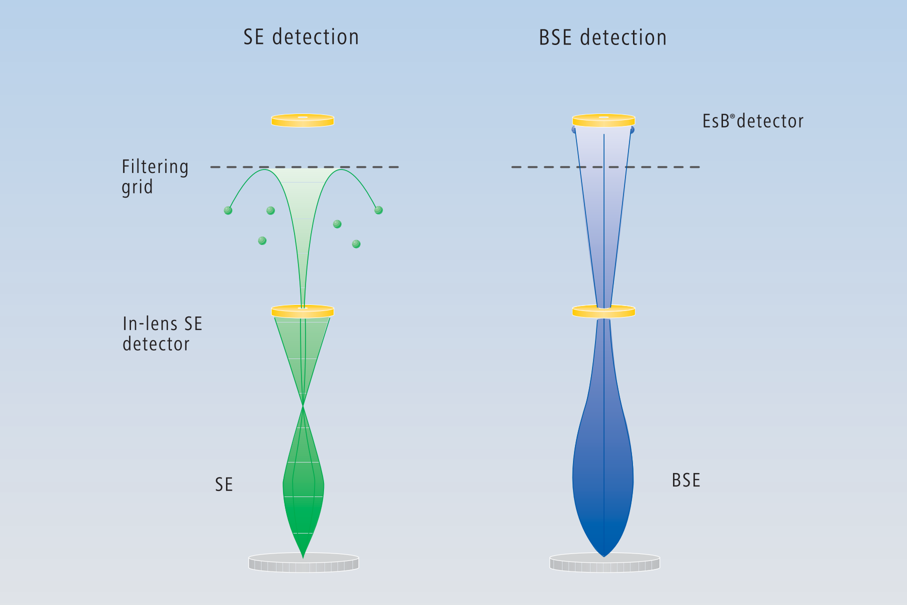


Fig. 8: The SEs (green) are projected onto the lower in-lens detector and the BSEs (blue) are guided onto the upper EsB® detector.

GEMINI® Multi-Mode STEM Detector

The GEMINI® Multi-Mode STEM detector, specially deve-loped for the SUPRA® and ULTRA series, consists of an electron detector underneath a thin specimen with the ability of simultaneous imaging and real-time mixing of bright-field and dark-field signals. The micrographs obtained with the STEM unit (see Fig. 10), usually taken with primary beam energies of around 30 kV to enable electron transmission, are similar to images obtained by a TEM with a scanning attachment. The most important benefit with employing the STEM method is the insensitivity to the interaction volume inside the specimen. Moreover, investigations at high primary energies cause low aberrations, resulting in highest resolution images.

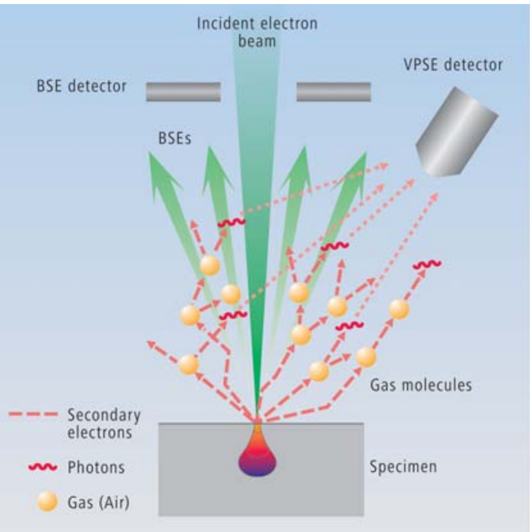


Fig. 9: Principle of VPSE detection

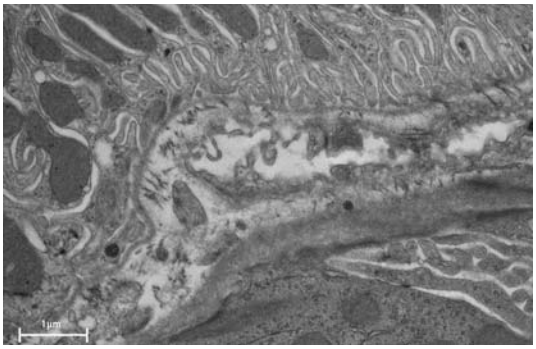


Fig. 10: STEM image of a kidney cross section, bright-field mode.

Charge Compensation – VP Operation

The variable pressure (VP) mode enables imaging of dielectric specimens, without charging artefacts. This is possible because positively ionised gas molecules stabilise local charging that is not able to flow of. For operating the VP mode it is essential to separate the ultra high vacuum needed for the cathode from the specimen chamber by differ-ential pumping stages.

The detection principle works as follows (Fig. 9): Electrons leaving the specimen are accelerated by an attractive po-tential biased to the VPSE detector and excite gas mo-lecules which emit a photon when they de-excite to the ground state. These photons are detected by a glass rod pointing into the direction of the specimen. Although BSEs also cause collisions their contribution is less than 1% because of the lower ionising cross section. Hence, the VPSE is a genuine secondary electron detector (Fig. 11). Nevertheless, BSE imaging is of course a suitable method to achieve material contrast in VP mode (Fig. 12).

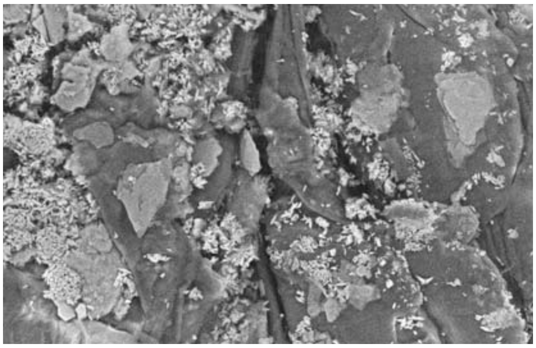


Fig. 11: SE image with the VPSE detector of uncoated paper with 7 kV and a chamber pressure of 38 Pa. The image shows the paper fibres with the filler material without any charging.

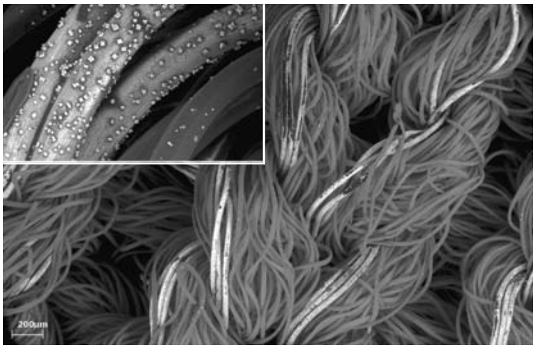


Fig. 12: BSE imaging of corroded polymer fibres in VP mode (12 kV/43 Pa chamber pressure). Inset image showing 15x higher magnification.

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