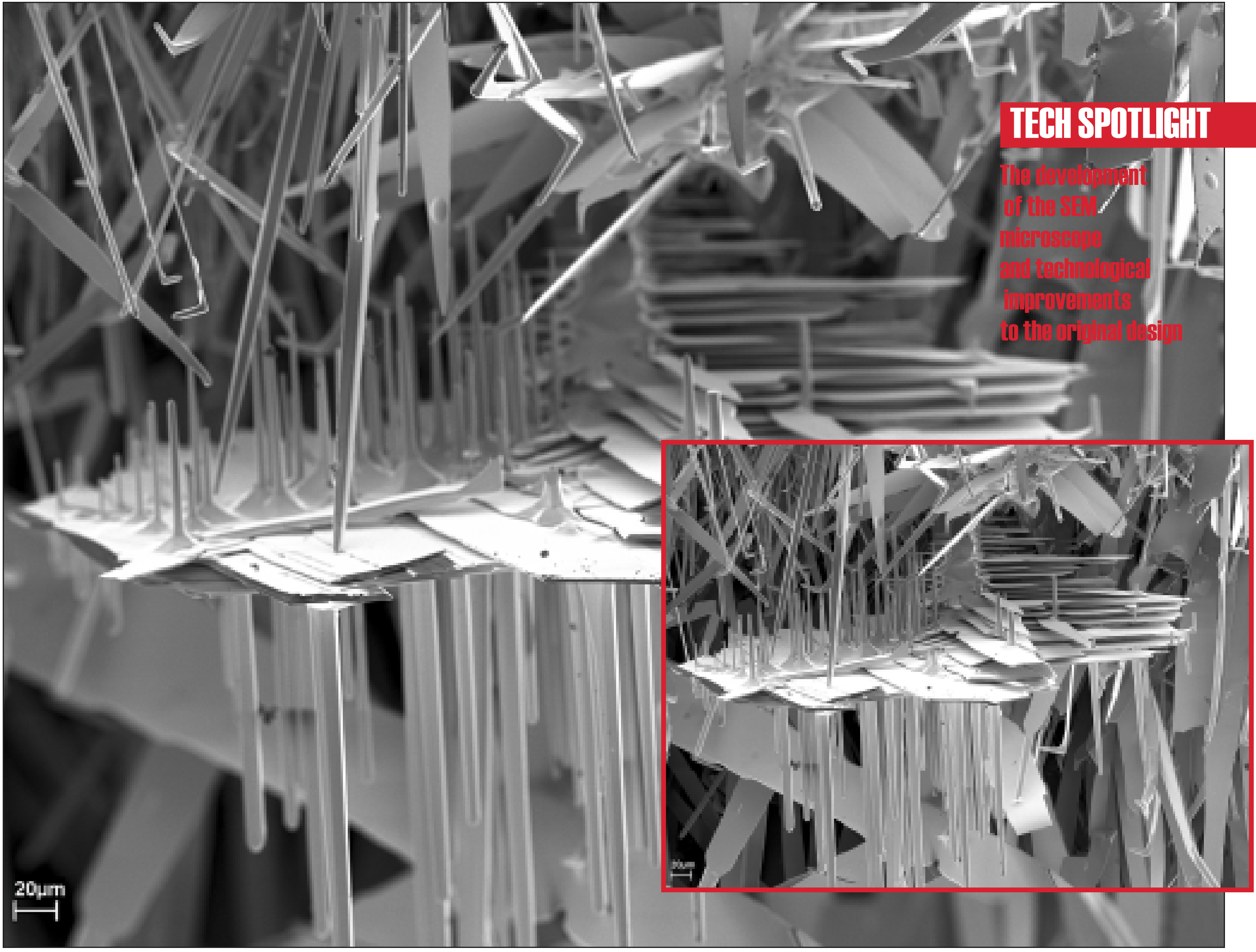

TECH SPOTLIGHT

The development of the SEM microscope and technological improvements to the original design

Normal imaging on high topography specimen in normal imaging mode. Specimen height is 4 mm, working distance is 4 mm, and voltage is 1.2 kV. The inset shows improved depth of field with the high current module on, under the same conditions. Note that even with a height of 4 mm, the complete specimen is in focus.

New developments in FESEM Technology

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Scanning electron microscopy is an analytical technique in which an image is formed on a cathode ray tube whose raster is synchronized with the raster of a point beam of electrons scanned over the surface of a specimen. The brightness of the image at any point is proportional to the scattering of the electrons from the beam at that point on the surface, or by secondary emissions of electrons from the point. The scanning electron microscope (SEM) provides two outstanding improvements over the optical microscope: it extends the resolution limits up to 30,000X or as high as 60,000X, and it improves depth of field by a factor of about 300.

This article discusses the development of the SEM and the technological improvements that have been made to overcome the limitations of the original design.

Early developments

The SEM was developed by Charles Oatley and his talented team at Cambridge University in England. The SEM was commercially introduced 40 years ago by the Cambridge Instruments Corporation, also in England. Much effort has been focused on the development of detecting systems and suitable electron emitters.

The early SEMs were equipped with a tungsten hairpin-type electron emitter. In the early seventies, brighter lanthanum hexaboride (LaB_6) sources were introduced. Field emission (FE) was introduced to improve imaging resolution available with conventional SEMs with a tungsten or LaB_6 source.

Thermal-assisted or Schottky Field Emissions SEMs were introduced in the nineties to overcome the beam instability of the cold FESEMs introduced earlier.

Improving SEM technology

The drive to improve SEM technology was the need for a FESEM capable of ultrahigh resolution over the entire accelerating voltage range. It also required greater flexibility for a wider range of analytical applications. To achieve these goals, advances had to be made in the following areas:

- **Probe diameter** at the specimen surface should be reduced. The smaller the probe size, the better the resolution. However, this meant that a FESEM column was required.
- **The field emission** source should be thermal-assisted. This eliminates the need for flashing, and it gives stability for X-ray mapping and EBSD.
- **Depth of penetration** of the electron beam into the specimen surface must be reduced. Deeper penetration yields a larger interaction volume and

Electron source performance comparison

Emitter type	Thermionic	Thermionic	Cold FE	Schottky FE
Cathode material	W	LaB$_6$	W(310)	ZrO/W (100)
Operating temperature, K	2800	1900	300	1800
Cathode radius, nm	60,000	10,000	$\leq$100	$\leq$1000
Effective source radius, nm	15,000	5,000	2.5(a)	15 (a)
Emission current density, A/cm^2	3	30	17,000	5300
Total emission current, µA	200	80	5	200
Normalized brightness, A/cm^{2}sr.kV	1.10^4	1.10^5	2.10^7	1.10^7
Maximum probe current, nA	1000	1000	0.2	20
Energy spread at the cathode, eV	0.59	0.40	0.26	0.31
Energy spread at the gun exit, eV	1.5-2.5	1.3-2.5	0.3-0.7	0.35-0.71
Beam noise, %	1	1	5-10	1
Emission current drift, %/h	0.1	0.2	5	<0.5
Operating vacuum, kPa	$\leq 1.10^{-5}$	$\leq 1.10^{-6}$	$\leq 1.10^{-10}$	$\leq 1.10^{-8}$
Cathode life, hours	200	>500	>2000	>2000
Cathode regeneration	Not required	Not required	Every 6 to 8 h	Not required
Sensitivity to external influence	Minimal	Minimal	High	Low

(a) Virtual source

degrades resolution. Ultralow voltage capability is the solution.

- **Probe current** should be raised. Higher probe currents coupled to small probe diameter give higher signal to noise ratio. Therefore, a high-current module is needed.
- **Detector efficiency** should be improved. Higher efficiency gives better contrast and higher signal to noise ratio. However, in-column detectors are needed to improve resolution.

An advanced instrument would also integrate a number of other innovations, such as an integrated beam booster, magnetic/electrostatic objective, and annular in-column detectors. The result would be an instrument with imaging capabilities comparable those of in-lens FESEMs, but without specimen size limitations.

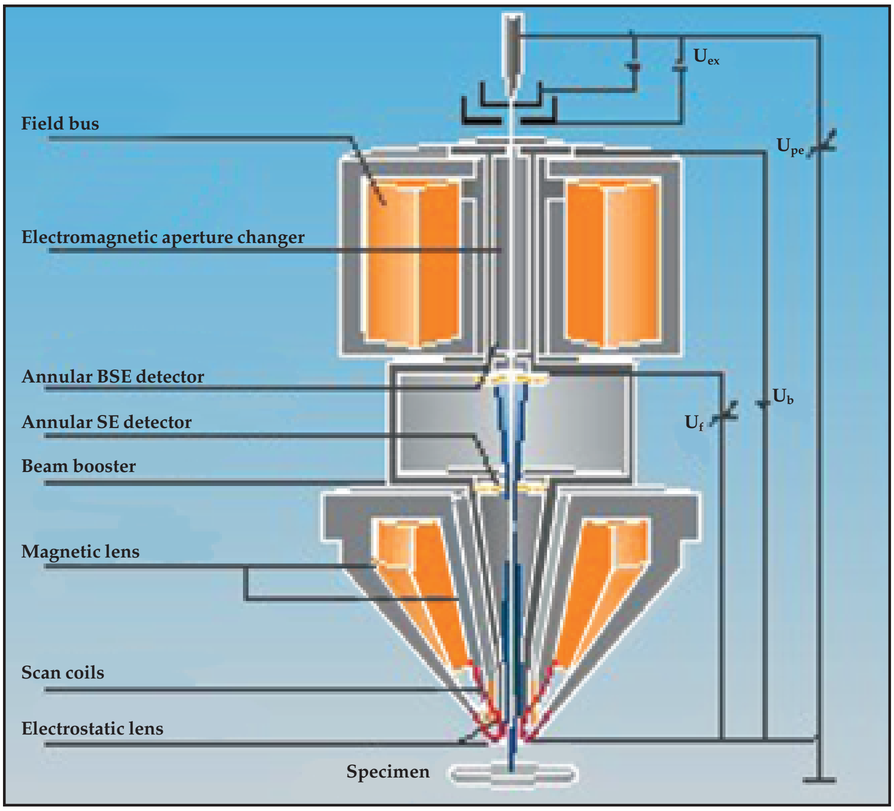

Fig.1 — Cross section of an FESEM column with integrated beam booster and annular in-column detectors: U$_{ex}$ — extractor voltage of first anode; U$_{pe}$ — primary beam voltage; U$_B$ — booster voltage; U$_F$ — EsB filtering grid voltage.

Probe size

The optics of the SEM actually focus a reduced source size on the specimen surface. The minimum diameter of the source determines the possible resolution. However, to achieve higher resolution, the size of the emitting source has to be reduced, and current density should increase to generate enough signal at the specimen surface.

The table shows the comparison of different electron sources and clearly shows that the Schottky field emitter source is much smaller than a tungsten or LaB$_6$ source coupled to much higher brightness.

Column design

The thermal-assisted or Schottky field emission source achieves a low energy spread similar to that of the cold field emission source, but with a much higher emission current coupled to much higher beam stability. Regeneration of the source tip (flashing) is not required.

Another improvement for the FE column is an integrated beam booster, which keeps a relatively high accelerating voltage in the column (Fig. 1). Furthermore, the design does not permit any cross over between source and specimen surface. The design with a Schottky type field emission source requires only one ion getter pump (IGP), against two for the cold field emission source.

Ultralow voltage capabilities

To improve resolution at low voltages (below 2 kV), the column design could be optimized for these conditions. However, this approach would degrade resolution at higher voltages. A preferable solution would be to keep the beam inside the column always at a higher voltage by means of a beam booster, and then decelerate the beam to the required landing energy.

The sophisticated design with the integrated beam booster (higher voltage inside the column) has the advantage of enabling reduced aberrations with lower beam energy. This ensures superb resolution over the entire voltage range, even at ultralow voltages.

Furthermore, the magnetic/electrostatic lens combination increases the incident beam aperture angle at the specimen, which improves both signal-to-noise ratio and resolution. The magnetic/electrostatic lens design, in contrast to magnetic immersion lenses, would also drastically minimize the magnetic field at the specimen surface. This in turn enables high resolution imaging of diamagnetic, paramagnetic, and ferromagnetic materials at very short working distances.

All of this is important, but in reality the design of a beam booster is a challenging exercise when detectors have to be integrated in the column at the higher potential of the booster voltage.

High-current module

One of the great challenges for FESEMs is to deliver a high current at the specimen surface without sacrificing resolution. This can be achieved in a number of ways. The more classical approach is to increase the strength of the condenser lens, but this method is limited by the current density and the crossovers in the beam: it generally improves beam current but deteriorates resolution.

Another approach is to redesign the Schottky source. This raises beam current, but unfortunately also increases the source size, which decreases resolution.

A better approach is to add the beam booster and magnetic/electromagnetic lenses to the FE column. With this method, the condenser control "moves" the virtual source much further away, thus creating a more parallel narrow beam that has the potential to double the beam current. Other advantages for parallel beam illumination are an increased depth of focus, as shown on the first page, and much less distortion for highly tilted specimens, in a manner similar to that of EBSD.

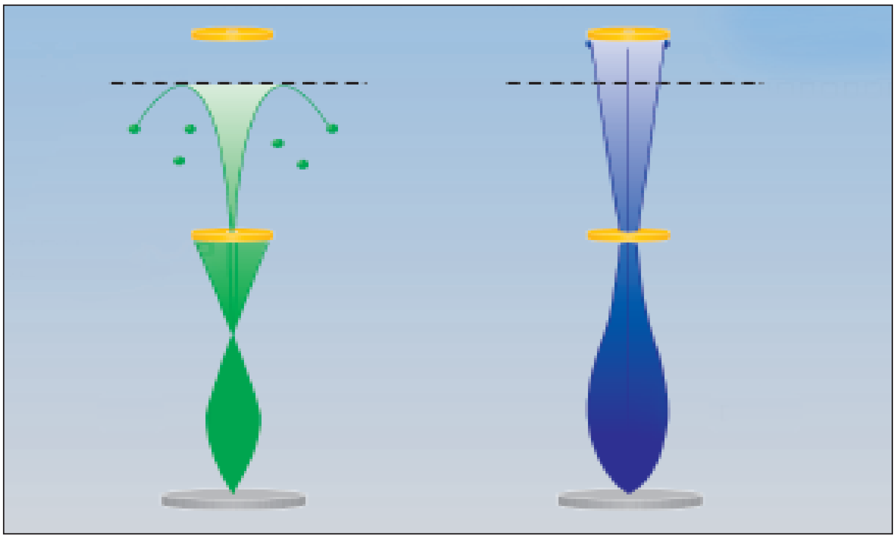

Fig.3 — The integrated beam booster projects the SE (green) electrons on the annular SE in-lens detector, and the BSE (blue) electrons are projected on the integrated EsB detector.

In-column detectors

Chamber type detectors, such as the Everhart-Thornley secondary electron (SE) detector or the backscattered electron (BSE) detector, have a number of intrinsic limitations. They are fine for conventional SEMs, but improved detectors are needed for FESEMs.

On-column, through-the-lens, or even better integrated in-lens detectors are capable of detecting the scattered electrons of the surface originating from the impact of the beam. The magnetic field at the specimen surface intercepts the secondary electrons at the point of impact, and they are then accelerated in the column. Standard columns need an extra field to accelerate the electrons on the detector surface or on a conversion plate.

However, the FESEM column with the integrated beam booster can accelerate the scattered electrons with sufficient energy to be directly detected by an annular in-lens detector. The beam booster also allows for a similar detection principle of backscattered electrons.

Although BSE electrons have energy close to that of the beam, they are also captured by the beam booster and projected through the annular scattered electrons detector onto a second annular detector above the SE detector (Fig. 3). Any unwanted scattered electrons (with a much lower energy) are repelled by a filtering grid installed in front of the annular BSE detector. The BSE detector is known as the energy selective backscattered electron (EsB) detector.

Complete detection system

A further improvement for full nanostructural analysis by the FESEM is expanding and completing the number of electron detection systems toward a so called Complete Detection System (CDS). STEM detectors are now widely used in FESEM to extend the resolution for thin specimens beyond the nanometer range. The resolution achievable with the FESEM is comparable with TEM for a range of standard applications.

Traditionally, BSE detectors are mounted on the chamber or the column, but these configurations limit resolution because of longer working distances and the introduction of astigmatism. A new approach for the integrated beam booster FESEM is to integrate one annular BSE in the column, and to integrate a second BSE detector in the objective lens.

This innovation enables BSE imaging at extremely short working distances of only one millimeter, and ultra low voltages. They can be down to 100 V, pushing the BSE resolution to the same level as SE (Fig 4). This is done with the in-column annular Energy-selective Backscatter electron (EsB) detector. The second BSE de-

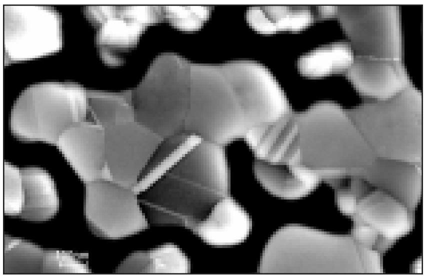

Fig.4 — Gold-particle (BSE), twin structure orientation is clearly visible.

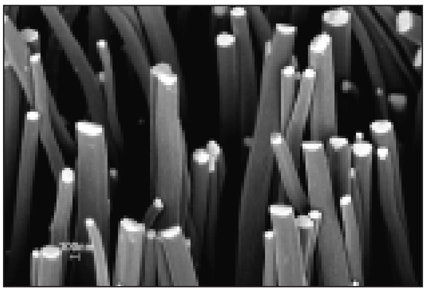

Fig. 5 — Carbon nanotubes with nickel particles (SE/BSE mix). Specimen courtesy Cornell University and Oak Ridge National Laboratory.

tector, the Angle-selective Backscattered electron (AsB) detector at the objective lens detects BSE with a larger angle, thereby giving extremely high resolution crystal orientation information. This new approach gives topography, compositional, and crystal orientation all down to the nanometer scale.

Real world instruments

All the above-described improvements and developments of the FESEM column, including technologies such as the integrated beam booster, the magnetic/electrostatic lens design, the high current module, annular direct detectors for scattered electrons and backscattered electrons, are incorporated in the Zeiss Supra and Ultra Gemini FESEMs. The result is a range of versatile FESEMs delivering ultrahigh resolution imaging at 30 kV down to 100 V, with full analytical capabilities (Fig. 5).

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