What is the Dual-Detector FEG SEM, and Why Use It?

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The world of scanning electron microscopy seems to spin in such a way that every four years there is a dramatic step forward. Field emission sources (FEG), developed in the late 1960's, started life as a commercial disaster. In spite of the problems, certain manufacturers persisted with the first really user friendly FEG SEM reaching the market in the early 1980's. The FEG has been developed through the 1990's to be, without doubt, the source for SEM. But other advances in SEM performance have added to the instrument's performance, the most recent dramatic step being the introduction of semi-in-lens imaging, a technique based upon 1980's dual detector imaging systems.

We first must look at image formation and performance limiting factors before the real advantages of the new instrumentation may be understood.

The electron source sets the limits of the SEM system; once formed, everything that we do to improve the instrument's performance takes electrons away. Our condenser lenses reduce the size of the source by throwing electrons away, and the beam defining apertures also remove electrons. A crude rule of thumb is that the resolution attainable will be 10,000X smaller than the source size (50 µm source = 50 Å resolution). The answer to the FEG SEM success is its superb source: about 1000 times brighter than a tungsten hairpin – measured in nanometers rather than micrometers, and there are far more electrons available per unit area. This makes it possible to form smaller probes with sufficient current to generate a high level of signal. The FEG really comes into its own at low voltage for a couple of reasons.

First, the tungsten hairpin system loses efficiency as one moves away from the design kV. The gun has to be designed with a certain minimum anode to cathode distance (about 1 mm for every 2 kV) in order to prevent discharge at the highest kV. As soon as the accelerating voltage is changed from the highest kV, the system is no longer optimized and the gun becomes less efficient. Gun performance can be improved at low kV by raising the anode and moving the filament forward. Even with these modifications, the low kV performance still falls short because of the increased level of aberrations in the system. Lower operating lens currents and accelerating voltages mean that small instabilities have a greater effect. Add to these problems the increased beam spread when it strikes the specimen at lower voltages and it is easy to see why the resulting performance is pretty poor.

Secondly, using a FEG, we do not have the problems with gun design and the source is so much improved that even when using small spot sizes (compensating for beam spread in the specimen and that due to aberrations) there is more than enough current to generate a good signal.

So we can see the advances and advantages of the formation of a small intense source, but what about the advances in signal collection?

Most operators of scanning electron microscopes fall into the trap of believing that the image they see is formed solely by secondary electrons (SE). Sure, they are using a so-called secondary electron detector (Everhart-Thornley [E-T]), but there are a number of well known papers that would indicate that at less than 5,000X, a high degree of the imaging information is derived from backscattered electrons (BSE). Simple proof of this is the creation of shadows within the image. The E-T detector attracts secondary electrons into its scintillator, therefore in theory its image should not contain shadows. The shadows that we see in the image are the result of backscattered electrons with lines of sight to the E-T detector entering the detector and producing extra bright areas within the image.

The Everhart-Thornley detector has by convention been positioned within the specimen chamber, along with a specimen that is situated outside the final lens field. The specimen being outside the lens field only requires what is in effect a weak electron lens. The aberrations from such a weak lens are very high;

they are measured in mm and relate to spherical (Cs) and chromatic (Cc) aberration. Typical figures would be between 15 and 30 mm.

When scanning attachments on a transmission electron microscope were introduced, images were for the first time able to be restricted to secondary electrons only, due to the "filtering" effect of the lens. With no space for the Everhart-Thornley detector by the side of the specimen, it was placed above the "final lens" pole piece – the objective lens in the TEM. The very strong lens field focused the incident beam onto the specimen with both secondary and backscattered electrons being produced. The backscattered electrons tend to spray off the specimen over a wide angle, being prevented from having a line of sight to the detector by the very narrow upper bore of the lens. The secondary electrons are not able to move off axis because of the lens field, and hence spiral back up the beam path until they leave the lens field. These electrons are attracted into the Everhart-Thornley detector. Working in the very high field generated in a compact pole piece has a dramatic effect upon Cs and Cc, these figures falling to between 2.5 and 4.5 mm, with a corresponding improvement in performance.

Dual detector imaging, often known as semi-in-lens imaging, relies upon the SE being attracted to a detector which is situated above the final lens pole piece. Initially, dedicated commercial scanning electron microscopes with two Everhart-Thornley detectors used the field from the final lens to "pull" SE into the upper detector. ISI was first with their SS Series, then Hitachi with the S570 took this route. In these instruments, they allowed the specimen to be anywhere between 100% out of lens, through to what we would consider to be a working distance (WD) of -5 mm. That is 5 mm up inside the pole piece! Problems arose if magnetic materials were being used, hence the development of a twin detector system by Hitachi that used a field coil to drag electrons up to the detector, and a pole piece design that retained the lens field within the pole piece.

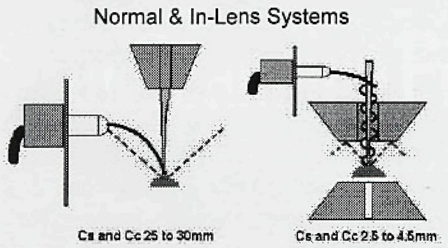

Figure 1. Left: Signal detector geometry of a convential SEM. Both SE (solid lines) and BSE (dashed lines) may enter the SE detector. Right: The geometry for an in-lens or TEM-style detection system. Here, the BSE are prevented from reaching the detector. Cs is spherical aberration and Cc is chromatic aberration.

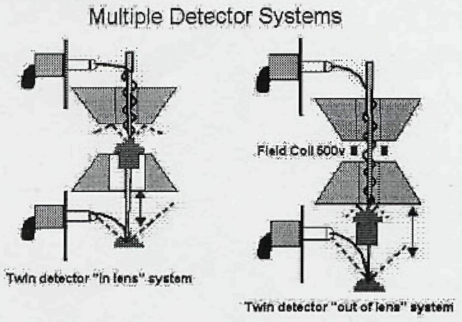

Figure 2. Left: The ISI/Hitachi double detecting system with totally variable in and out of lens specimen geometry. Right: The latest detecting system that is used with the specimen out of the lens, but with the assistance of a field coil to attract SE to the upper detector when working at short focal lengths. Double-headed arrow is working distance. SE are solid lines, BSE are dashed lines.

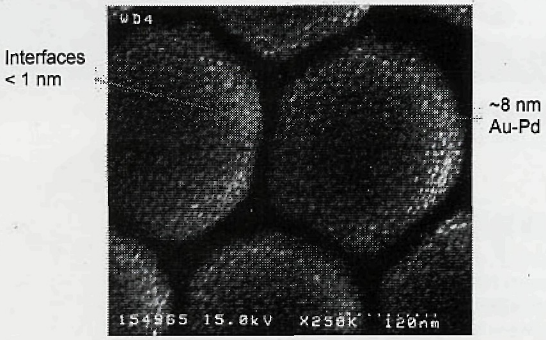

Figure 3. SEM taken at Intel using a Hitachi semi-in-lens FEG SEM, with emphasis on the upper detector. 15 kV at 10 μA emission and spot size 8.

The twin detector system gives the microscopist the best of all worlds:

1. The upper detector provides an opportunity to sift out the BSE and obtain a pretty pure SE image. The high lens strength at very short WD (~3 mm) enables the instruments to reach very high resolution levels. The down side of this is, as SE are effected by charge, this mode is more prone to charge problems. However, at <5 kV in my experience we have very few problems, provided the operator knows about low charge, low damage, techniques.

2. The lower detector offers the type of contrast that we all see in our conventional single detector SEM, SE+BSE. The up side is that the BSE contribution to this image results in far fewer charging problems, and may be a good compromise for the biologist.

3. Add a BSE detector to such a system, and more options become available: "pure" SE or SE + BSE or pure BSE. Drop the kV and the BSE becomes even more interesting as the volumes of material involved almost mimic SE volumes. This is not to be discounted for biological applications.

With a tungsten hairpin system at 20,000x and 2 kV, it is difficult to obtain good quality. However, with a good FEG SEM at 90,000X and 2 kV, there is not quite that problem. The best FEG systems, from my experience, use a double detecting system – as the choice of signals makes the operation of the instrument an operator's dream.

I hope that these comments may help those who have little experience with the new, dual detector FEG SEM. ■