

How to “See” Electrons

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CHAPTER PREVIEW

If we are studying the structure of a material, when all is said and done, all we have to show for our expensive electron microscope, hours of specimen preparation, and careful alignment, etc., is an image, a diffraction pattern, or a spectrum. These images and diffraction patterns, which are just different distributions of electron intensity, have first to be viewed in some manner. After viewing, we have to decide if we want to save the result for future reference, perhaps so we can print it for a technical report or scientific publication. Since, as we noted in the opening chapter, our eyes are not sensitive to electrons, we have to find ways to translate the electron intensity distributions into visible-light distributions. This chapter will explain how we “see” electrons.

We’ll break the process down into two parts: first, detection (and display) of the image, and second, recording of the image. Both these areas are undergoing rapid change because of advances in electronics, and so this chapter will undoubtedly contain anachronisms by the time you read it.

How to “See” Electrons

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7.1. ELECTRON DETECTION AND DISPLAY

Images and diffraction patterns are different two-dimensional electron-intensity distributions which can be produced by scattering by the same object. We detect and display them in different ways depending on whether we are using a TEM or STEM, as we’ll explain in Chapter 9. In a conventional TEM the images and diffraction patterns are static, because the incident beam is fixed, and so we can easily project them onto a viewing screen within the microscope column. TEM images, for example, are *analog* images of electron density variations in the image plane of the objective lens. We cannot manipulate the image or its contrast in any way between the electrons leaving the image plane and being projected onto the viewing screen. We will briefly discuss the properties of the viewing screen. The manufacturer controls the initial choice of screen materials so you might think there’s not much need to understand this aspect in any depth. You might be surprised by the limitations you don’t need to accept or the improvements which could be made.

When we operate our TEM as a STEM, or we use a dedicated STEM, the image is not static; it is built up over time as the small probe is scanned across the area of interest. Under these circumstances, we detect the electron signals by various types of electronic detection. If we are seeking secondary electron (SE) or backscattered electron (BSE) signals, then these detectors sit in the specimen stage area. If we are seeking to image the same forward-scattered electrons that we view on the TEM screen, the detectors are in the viewing chamber of the TEM. After we’ve detected any one of these signals, it is usually digitized and *digital* scanning images are presented on a fluorescent screen as an analog image. We often refer to this fluorescent screen as the CRT, which is the acronym for “cathode-ray tube” and a relic from the early days of electron physics.

We should point out that the sequential or serial nature of the scanning image makes it ideal for on-line image enhancement, image processing, and image analysis. The signal from any electronic detector can be digitized and electronically manipulated prior to display on the CRT, in a way that is impossible with analog images. We can adjust the digital signal to enhance the contrast or to reduce the noise. Alternatively, we can store the digital information and process it mathematically. The availability of cheap memory and fast computers permits on-line image processing and the rapid extraction of quantitative data from the scanning image; we discuss all this and more in Chapter 30. Because of developments in computer technology, there is great interest in recording analog TEM images via a TV camera in order to digitize them and charge-coupled device (CCD) cameras are already available for on-line viewing and processing, particularly of HRTEM images.

In attempting to compare the properties of detection and recording devices we often use the concept of the “detection quantum efficiency” or DQE. If the detector is linear in its response, then the DQE is defined simply as

$$\text{DQE} = \frac{\left(\frac{S_{\text{out}}}{N_{\text{out}}}\right)^2}{\left(\frac{S_{\text{in}}}{N_{\text{in}}}\right)^2} \quad [7.1]$$

where S/N is the signal-to-noise ratio of the output or input signal. So a perfect detector has a DQE of 1 and all practical detectors have a DQE < 1 .

Note on terminology: We use several different terms, often imprecisely, to describe how we “see” electrons. Since our eyes can’t in fact “see” electrons, we have to resort to the phenomenon of cathodoluminescence (CL) in order to provide an interface between electrons and our eyes. Any electron display system that we look at relies on CL. The CL process converts the energy of the electrons (cathode rays) to produce light (luminescence). As a result,

any electron display screen emits light in proportion to the intensity of electrons falling on it.

- *Light emission* caused by ionizing radiation is *scintillation*.
- The process of *fluorescence* implies *rapid emission*.
- *Phosphorescence* implies that the wavelength and the *delay time* are longer than for fluorescence.

All these terms are used in electron microscopy (interchangeably and often inaccurately) because the “fluorescent” screen is coated with a long-delay phosphor (see Chapter 9).

7.2. VIEWING SCREENS

The viewing screen in a TEM is coated with a material such as ZnS, which emits light with a wavelength of 450 nm. The ZnS is usually modified with impurities to give off green light at closer to 550 nm; hence you’ll see screens of different shades of green which, being in the middle of the visible spectrum, is most relaxing for the eyes. As long as sufficient light is emitted, the main requirement of the viewing screen is that the ZnS particle (grain) size be small enough so that the eye cannot resolve individual grains. This means that grain sizes <100 μm are acceptable (although you can see the grain size if you look at the screen through the auxiliary focusing binoculars). Typical screen coatings are made with a ZnS grain size of about 50 μm , although they may be as small as 10 μm for the highest-resolution screens.

As we’ve seen in Chapter 4, the emission intensity of most signals, including CL, decreases with increasing beam voltage. You would thus expect the light intensity to degrade at higher voltages, but this is offset by the increase in gun brightness. In some HVEMs the small focusing screen support is made of a heavy metal, such as Pt, to try and encourage backscatter and increase screen intensity. Of course, this backscattering will broaden the volume where light is generated and blur the image, so we don’t gain very much. In fact most TEMs have very similar screens. Other signals are also given off by the viewing screen, such as X-rays, and whenever you look at the screen you are protected from this lethal radiation flux by lead glass, carefully selected to absorb the radiation to levels at or below ambient background. In HVEMs this can amount to several centimeters of glass, and invariably the optical transmission capabilities are degraded as the glass

gets thicker, but obviously we have no alternative if we want to view the screen directly.

A few practical hints about your screen: There isn’t much you can do about choosing the best material for the viewing screen since the manufacturer selects it for you, but you can extend its life substantially by taking care to minimize overexposure. The greatest source of screen damage is the intense direct beam that comes through thin specimens and constitutes the central spot in diffraction patterns. You can minimize burning of the screen by (a) only going to diffraction mode with the selected area aperture inserted, (b) only going to diffraction mode with the C2 lens underfocused, and (c) if the spot appears exceptionally intense despite these precautions, then insert the beam stop while you’re observing the pattern on the screen.

7.3. ELECTRON DETECTORS

We have several alternatives to the fluorescent screen for detecting electrons. These other electron detectors play a major role in STEMs and AEMs (as well as in SEMs). They are actually essential to the STEM image-forming process that we’ll describe in Chapter 9. Such detectors are usually one of two kinds: semiconductor (silicon *p-n* junction) detectors or scintillator–photomultiplier systems. We’ll examine the pros and cons of each of these two types and end with a brief comment on CCDs.

7.3.A. Semiconductor Detectors

A full understanding of how semiconductor detectors work requires a fair knowledge of solid-state physics. We’ll just give a brief outline of the principles as they affect the use of the TEM.

The semiconductor detector, shown schematically in Figure 7.1, is a doped single-crystal sheet of Si (often inaccurately described as a solid-state detector). We make the Si into an electron-sensitive detector by creating a *p-n* junction beneath the Si surface in one of two ways. In one type of detector, we create the junction by doping the Si (e.g., by ion implantation of *n*-type impurity atoms into *p*-type Si or vice versa). This doping disturbs the equilibrium charge carrier concentration and creates a region across the *p-n* junction that is free of majority carriers. We call this region a “depletion region.” A conducting metal layer is evaporated onto both surfaces to provide ohmic contacts. The alternative type of detector is called a surface-barrier

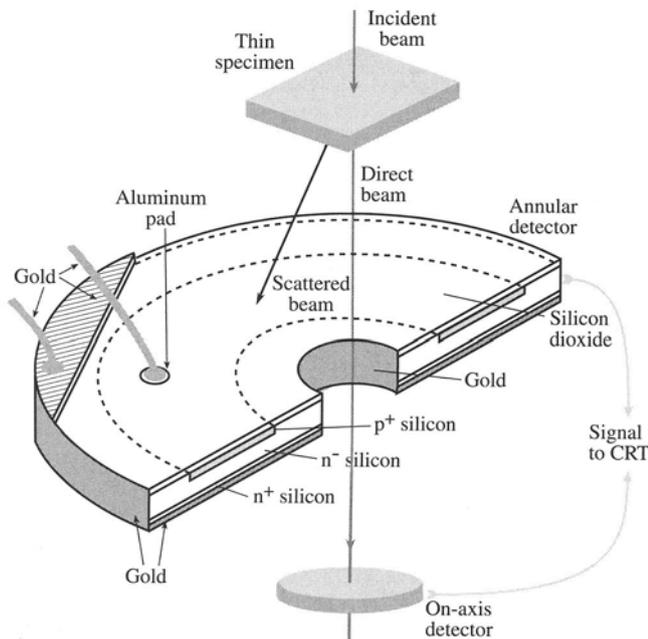


Figure 7.1. Semiconductor detector of the surface-barrier type, shown in a configuration where it would be used to detect high-energy forward-scattered electrons. The direct beam is detected by a small circular detector on the optic axis surrounded by a concentric wide-angle annular detector, which detects any scattered electrons.

detector (or sometimes a Schottky diode) and we fabricate this by evaporating a thin layer of Au on the surface of high-resistivity *n*-type Si, or evaporating Al onto *p*-type Si. This surface layer acts as an electrical contact and also creates a depletion layer and a *p-n* junction just inside the Si.

When we put either of these detectors into a beam of high-energy electrons, most of the beam energy is transferred to valence-band electrons in the Si which are excited into the conduction band; we thus create electron-hole pairs. We can separate the electrons and holes most efficiently by applying an external reverse bias to the detector; that is, we put a negative bias on the *p* side of the junction and a positive bias on the *n* side. In practice, however, so many electron-hole pairs are created at TEM beam energies that an external bias is not usually necessary, and the internal bias of the *p-n* junction acts to separate the electrons and holes. Because the electrons and holes move quite quickly in Si, it takes only a few nanoseconds to gather most of the carriers over an area of about $1 \mu\text{m}^2$. So the semiconductor detector is remarkably responsive to the incoming electron signal. The net result of all this is that the incoming electron signal is converted to a current in the external circuit between the surface contacts, as shown in the surface-barrier detector in Figure 7.1.

Since it takes approximately 3.6 eV to produce an electron-hole pair in Si at room temperature, a 100-keV

electron can theoretically produce about 28,000 electrons. This represents a maximum detector gain of close to 3×10^4 but in practice there are losses due to electron absorption in the metal contact layer and recombination of the electrons and holes close to the Si surface (in a region called the dead layer), and we actually get a gain of closer to 2×10^4 .

These semiconductor detectors are very efficient at picking up and amplifying electron signals. Unfortunately, they have an inherently large capacitance, and so are not very responsive to rapid changes in signal intensity. Such changes are quite likely to occur during the rapid scanning process of STEM imaging. In other words, the detector has a narrow bandwidth (typically 100 kHz), and this is not a good property for a detector which is subject to widely varying signal intensities. We could lower the capacitance by decreasing the detector area, but if we do this, the signal-to-noise ratio will be lowered, and it is this latter factor which ultimately limits the quality of all scanning images.

Semiconductor detectors have several advantages:

- We can easily fabricate them.
- They are cheap to replace.
- They can be cut into any shape, as long as it is flat.

This latter advantage makes them ideal for squeezing into the confines of TEM stages and columns. For example, we can make the semiconductor detector in annular form so that the main electron beam goes through it, but the scattered electrons are very efficiently detected. We thus have a dark-field detector. We can also make detectors that are divided into halves or quadrants. These are very useful for discriminating directional signals such as those coming from magnetic specimens.

There are also some drawbacks to semiconductor detectors:

- They have a large dark current (the current registered when no signal is incident on the detector). This dark current arises from thermal activation of electron-hole pairs, or from light falling on an uncoated detector. Since the detectors in a TEM invariably have a metal ohmic contact, the light problem is minimal. Now we could minimize thermal activation by cooling the detector to liquid-nitrogen temperatures, but that step is impractical and introduces a cold surface into the vacuum which would simply collect contamination, so we live with noise due to the thermal activation.
- Because noise is inherent in the semiconductor detector, its DQE is poor for low-intensity sig-

nals, but rises almost to unity for high-intensity signals.

- The electron beam can damage the detector, particularly in intermediate voltage microscopes. In these circumstances a doped *p-n* detector is less sensitive than the surface-barrier detector, because the depletion region is deeper in the Si.
- They are insensitive to low-energy electrons such as secondary electrons.

Despite these drawbacks, both types of Si detector are far more robust than the alternative scintillator detector, which we will now describe.

7.3.B. Scintillator–Photomultiplier Detectors

A scintillator emits visible light when struck by electrons because of the same CL process that occurs in fluorescent screens. While we are viewing a static TEM image, we want the fluorescent screen to continue emitting light for some time after the electrons hit it, so we use a long-delay scintillator. Of course, when we are using a scintillator to detect rapid changes in signal as in scanning beam imaging, we want the light emission to decay rapidly. So we don't use ZnS in scintillator detectors but rather materials such as Ce-doped yttrium-aluminum garnet (YAG) and various doped plastics and glasses. These materials have decay times on the order of nanoseconds rather than microseconds for ZnS. Once we've converted the incoming electron signal to visible light, the light from the scintillator is amplified by a photomultiplier (PM) system, attached to the scintillator via a light pipe. Figure 7.2 shows a schematic diagram of a scintillator–PM detector set up to detect secondary electrons in a TEM, and the design used in the SEM is essentially identical.

The scintillators that we use in STEMs or SEMs are often coated with a 100-nm-thick layer of Al to reflect any light generated in the microscope and stop it from entering the PM tube, where it would add noise to the signal. If the detector is in the stage of the microscope, this light could come from the specimen itself if it is cathodoluminescent, or it could be light coming down the column from a thermionic source and reflected from the polished surface of the specimen. If you have a scintillator detector in the viewing chamber, then room light may also hit the detector, so you should cover the windows of the viewing chamber.

The advantages of the scintillator–PM system are:

- The gain of the system is very high. The gain for the total detector system is of the order of 10^n , depending on the number (n) of dynodes in

the PM. A value of 10^8 is not unusual (compare with 10^4 for the semiconductor detector). This performance is reflected in a typical DQE of close to 0.9 for several commercial scintillators.

- The noise level in a scintillator is low compared with semiconductor detectors, and the bandwidth of the scintillator is in the MHz range. As a result, both low-intensity images and TV-rate images are easily displayed. There is a tremendous practical advantage to TV-rate imaging of digital signals, because such images, when suitably processed and displayed, can be viewed, stored, and recorded under normal room illumination conditions. So you don't have to work in the dark while operating your (S)TEM.

The disadvantages of the scintillator–PM system are:

- The scintillator is not as robust as the semiconductor detector, being more susceptible to radi-

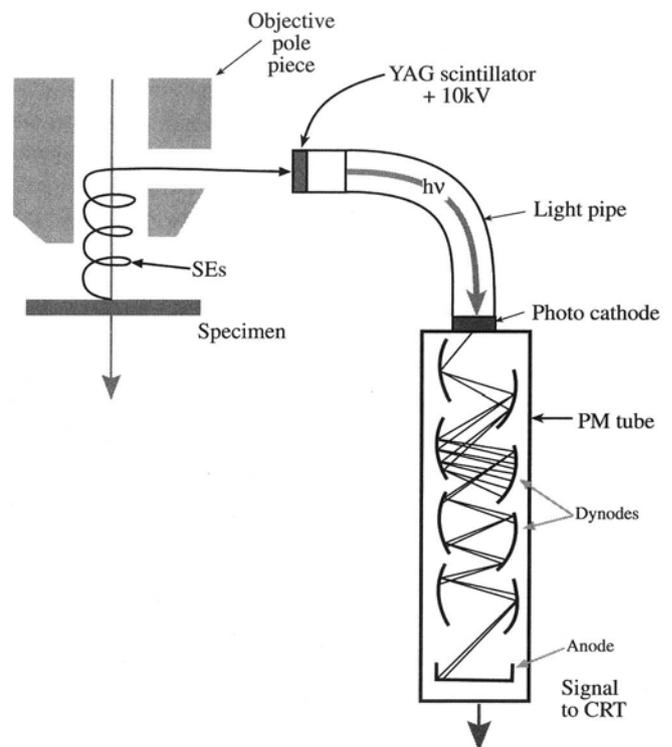


Figure 7.2. Scintillator–photomultiplier detector system in a TEM. SEs from the specimen spiral back up through the polepiece and are accelerated by the high voltage onto the scintillator, generating visible light which travels via fiber optics to a photocathode. There the light is reconverted to electrons. The electron signal is then multiplied by several electrodes in the PM tube.

ation damage, particularly after long-time exposure to the beam.

- The scintillator–PM combination is also substantially more expensive and bulky compared to semiconductor detectors and therefore it does not fit well within the TEM stage, nor is it easily manufactured into multidetector configurations. However, plastic scintillators can be shaped to give large-angle collection, such as in the Robinson BSE detector used in many SEMs.
- The energy conversion efficiency of a scintillator is also rather low (about 2%–20%) compared to a semiconductor detector and typically we only get about 4000 photons per incident 100-keV electron, about 7 times less than the semiconductor detector. This low efficiency is offset by the gain in the PM tube.

On balance, the scintillator–PM detector is preferred over the semiconductor detector for most general electron detection in TEM/STEM systems. However, you must take care to minimize any high-intensity beams that may damage the detector and lower its efficiency. Therefore, you need to take more care when operating scintillator detectors.

7.3.C. TV Cameras and Charge-Coupled Devices

We’ve already mentioned that you can view the TEM image directly through a TV camera, rather than looking at the fluorescent screen. There are real advantages to doing this for on-line viewing of faint HRTEM images (see Chapter 29), or for recording of dynamic *in situ* events. A standard TV camera is often quite sufficient for this job, although in the US, the TV-image resolution (500 lines/frame) is rather low and a high-resolution camera (1000 lines/frame) is preferred. Video storage and display again requires higher resolution than standard VHS video formats if you want to get the most out of your images. The best TV cameras are CCDs, which are replacing standard plumbicon tube TV cameras.

CCDs are MOS devices that store charge generated by light or electron beams. CCD arrays consist of thousands or millions of pixels which are electrically isolated from each other by creating potential wells under each CCD cell so they can accumulate charge in proportion to the incident beam intensity, as shown in Figure 7.3A. The cells currently can be as small as 6 μm . To create a picture we have to read out the array, which can be done by changing the applied potentials to transfer the charge serially

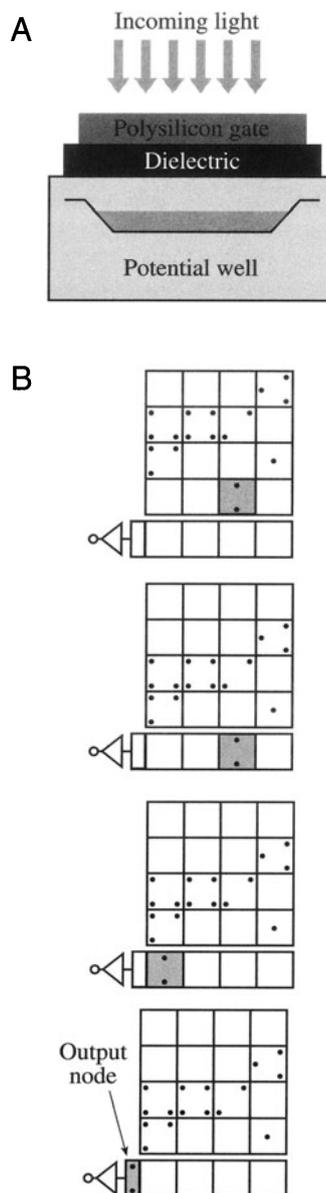


Figure 7.3. (A) A single cell in a CCD array showing the storage of charge in the potential well under one pixel. If we vary the applied potential to rows of pixels in sequence, as in (B), one pixel row is shifted to the parallel register, and is read out pixel by pixel, after which the next row is moved to the parallel register, and so on. The stored charge in each pixel is thus fed into an amplifier and digitized.

from each potential well along a line into an output amplifier as shown in Figure 7.3B. Once all the cells are empty the array can be re-exposed. We thus have a frame time for reading the display which can be as short as 0.01 s, well below standard TV rates (0.033 s). Rather than serial readout, it is also possible to have full frame CCDs in which the whole frame is transferred to an adjacent storage array leaving the main array free to collect a new signal flux. We get an analog output, i.e., a charge current, which we then

digitize, usually through an 8-bit A to D converter to give 256 gray levels.

CCD arrays have several advantages:

- When cooled, they have a very low noise and a good DQE (>0.5) even at low input signal levels.
- The dynamic range of a CCD is high, making it ideal for recording diffraction patterns which can span an enormous intensity range.

The major disadvantages are the speed and the expense. These devices can also be used as two-dimensional arrays for parallel-collection electron energy-loss spectrometers rather than the more conventional one-dimensional silicon diode arrays described in Chapter 37.

7.3.D. Faraday Cup

In conventional TEM there isn't much need to know the beam current, but in the AEM it is essential since there is often a need to compare analytical results obtained under identical beam current conditions. A Faraday cup is a detector that simply measures the total electron current in the beam. We don't use it for any imaging process, but rather as a way of characterizing the performance of the electron source, as we saw in Chapter 5. Once the electrons enter the Faraday cup, they cannot leave except by flowing to ground through an attached picoammeter that measures the electron current.

A Faraday cup is a black hole for electrons.

You can easily construct a Faraday cup to go in an SEM, but it is more difficult to design one that fits in the stage of a TEM. Fortunately, some manufacturers now incorporate a Faraday cup in the specimen holder. You can measure the current by deflecting the beam into the cup or partially extracting the holder (Figure 7.4B). These cups are not ideal because they don't trap all the electrons. A dedicated Faraday-cup holder is shown in Figure 7.4A. The entrance aperture is small and the chamber is relatively deep and lined with a low-Z material to minimize backscatter. If you tilt it slightly, the electrons have little chance of being scattered directly back. With such a holder you can only find the hole if you can image the upper surface with SE or BSE detectors, and if these are not available then you must have a cup with a hole in the lower surface too. When the cup is not tilted, the electrons go straight through; if you tilt the cup, then all the electrons are trapped as shown in Figure 7.4A. The way to ensure that you are measuring the maximum current is to look at the picoammeter reading as you tilt the cup.

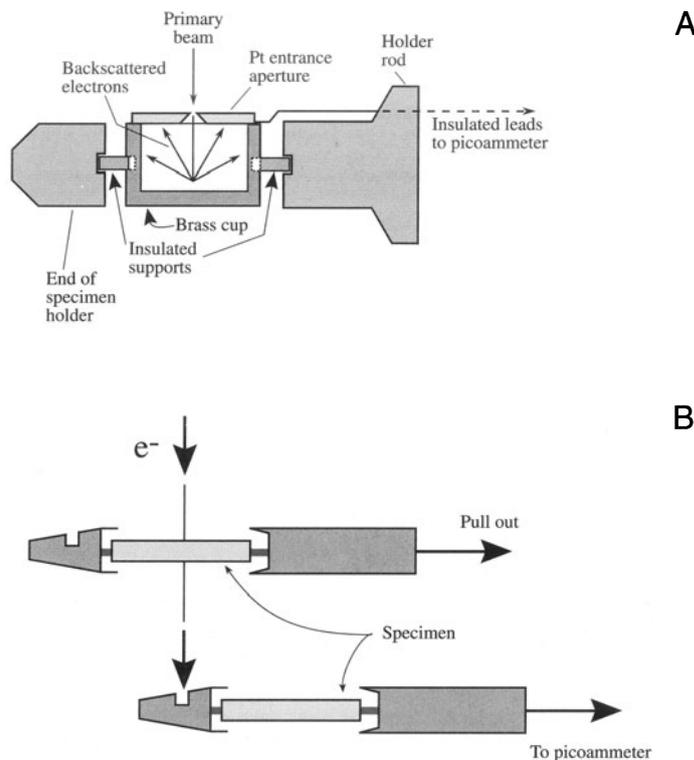


Figure 7.4. (A) Schematic diagram of a Faraday cup in the end of a side-entry specimen holder. The entrance aperture has to be found using SEs or BSEs. In (B) the holder is retracted slightly so the electrons fall into a cup on the tip of the holder. The electron current is measured as it goes to ground through a picoammeter attached to the outside of the holder.

If you don't have a Faraday cup, it is possible to get an approximate reading of the current by just measuring the current through an insulated line from a bulk region of the specimen and correcting for electron backscatter. Backscattering is independent of the accelerating voltage and approximately linear with atomic number up to about $Z = 30$. For example, the backscatter coefficient for Cu is about 0.3 and for Al it is about 0.15. It is also possible to deflect the beam onto the last beam-defining diaphragm and measure the current via an insulated feed-through (also correcting for backscatter).

7.4. WHICH DETECTOR DO WE USE FOR WHICH SIGNAL?

As we mentioned at the start of the chapter, the principal electron signals that we can detect are the forward-scattered electrons, which as we'll see in Chapter 9 are the most common TEM images, and the BSE and SE signals from the beam-entry surface of the specimen.

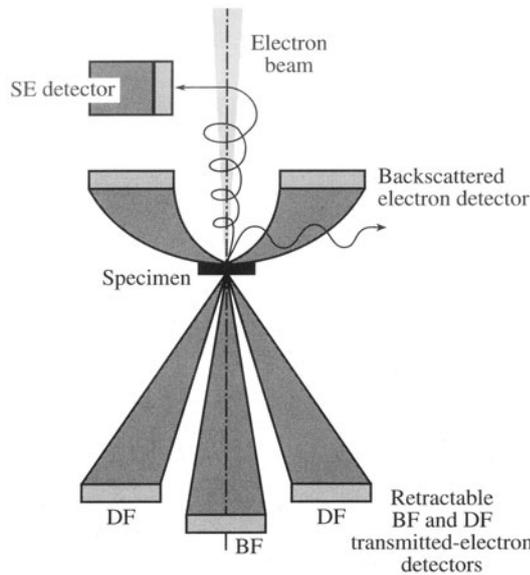


Figure 7.5. The various electron detectors in a STEM. Scintillator-PM detectors are invariably used for SE detection and semiconductor detectors for the BSE. The on-axis and annular forward-scattered detectors may be either type, depending on the microscope.

Semiconductor detectors are only sensitive to electrons with sufficient energy (>5 keV) to penetrate the metal contact layer. So we use these detectors mainly for *high-energy* forward-scattered imaging and *high-energy* BSE imaging. Because of the surface contact layer we don't use semi-

conductor detectors for *low-energy* SEs and a scintillator-PM system is required. Remember that the scintillator may also be coated with Al to prevent visible light from generating noise. This coating would also prevent low-energy SEs from being detected. So for SE detection, either there must be no coating, or the electrons must be accelerated to an energy high enough to penetrate the coating; we achieve the latter by applying a high kV (>10 kV) positive bias to the scintillator.

The capacitance is relatively high for semiconductor detectors, so they are not the detector of choice in dedicated STEMs where high scan-rate TV images are the normal viewing mode, i.e., where you need a quick response. The scintillator-PM system is again preferred under these circumstances. As most microscopes move toward TV-rate display of scanning images it is likely that the scintillator-PM will be used increasingly for forward-scattered TEM imaging. Semiconductor detectors may only be used for BSEs, which is not a major imaging mode in TEMs. A summary of all the various electron detectors in a TEM/STEM is given in Figure 7.5.

Sometimes we examine specimens which themselves exhibit cathodoluminescence under electron bombardment. We'll discuss why this is done in Chapter 31. A mirror is used to focus the light into a scintillator-PM system, and one such design is shown in Figure 7.6. This setup effectively prevents detection of all other signals, including X-rays, because the mirror occupies all the free space in the TEM stage. So you have to dedicate the TEM to CL detection alone and ignore other signals.

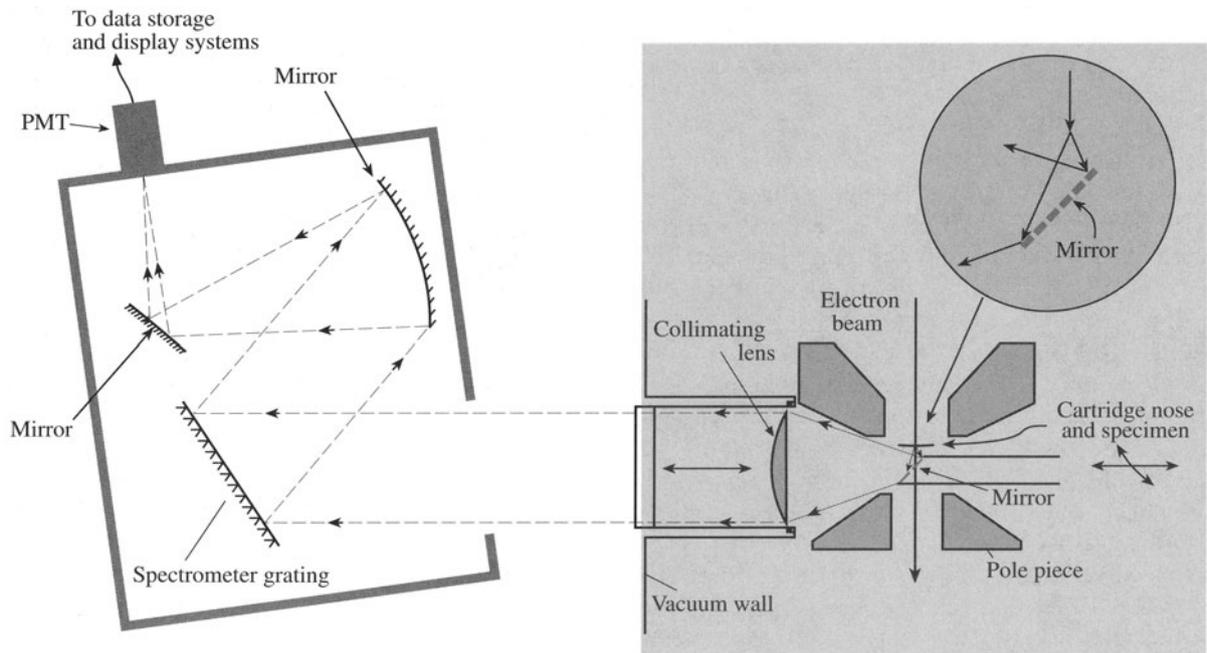


Figure 7.6. Cross section of a mirror detector below a thin cathodoluminescent specimen that collects light and focuses it into a spectrometer-PM system. The CL signal is usually very weak and so the detector has to be as large as possible, and it takes up much of the free volume in the TEM stage.

7.5. IMAGE RECORDING

7.5.A. Photographic Emulsions

Although film is the oldest recording medium, it still retains sufficient advantages that we continue to use it in virtually all TEMs. Photographic emulsions are suspensions of silver halide grains in a gel. Electrons strike the halide, ionize it, and transform it to silver. The emulsions are usually supported on a polymer film or (very rarely) glass plates. Unlike polymer film, glass plates do not outgas and do not shrink during prepumping or processing. However, glass plates are heavy and occupy an enormous volume compared to polymer film, so you can't load as many into the microscope at once and you need more storage space in general. Also, Murphy's law means that your best plates will invariably break because you spend more time looking at those than the others. Most microscopists use film rather than plate, but we still sometimes call them "plates."

You do have a choice of photographic emulsion, just as you do for your own camera. Different speed emulsions are available, with the usual compromise that faster film means a larger grain size and therefore less resolution.

- In principle, for the highest-resolution images, the slowest (finest grain) film is best.
- In practice, we usually minimize the exposure time and go for the fastest film.

We usually want to minimize beam damage and blurring due to movement (drift) of the specimen/stage, so we keep the exposure short. In fact the faster film grain sizes are about 5 μm compared to about 4 μm for the slowest film, so we don't lose much resolution. The loss of resolution is more than offset by the shorter exposure times, which mean that the overall dose to the specimen is minimized. The only time you may need to use the slower film is if you have a problem with poor image contrast. This problem is more common when imaging amorphous, biological, or polymer specimens.

Although the grain size of the emulsion may be as small as a few micrometers, the actual resolution of the recorded image is worse than this because of electron spreading in the emulsion. The practical resolution may only be about 20–50 μm . Despite this degradation we still have more than 10^7 picture elements or pixels available to store information in a 10 cm \times 10 cm image (Kodachrome film has the silver halide equivalent of 1.8×10^7 pixels). Film has a high DQE, although its dynamic range is rather limited. What this means is that you can easily saturate the film (change all the halide to silver). CCDs will eventually replace the photographic plate because the device size is

already comparable with silver halide grains. As we've already noted, CCDs have high dynamic range. In fact, the latest CCDs boast $> 2.5 \times 10^7$ pixels, and while the cost is currently prohibitive, it is falling as is the cost of storing the data.

We use instant film for recording CRT images in STEM mode. Different film speeds are available. For example, Polaroid instant film comes in positive-negative form (Type 55) or just a positive print (Type 52), which is also slightly faster. Instant color is also available for recording false-color images from a digital CRT display (such as X-ray maps, as we discuss in Chapter 36). The main drawback to instant film is its expense. Although you can see the image "instantly," you still need to coat the print chemically to prevent degradation of the image with time.

7.5.B. Other Image Recording Methods

Digital images can be stored and retrieved magnetically, for example on floppy disks and hard disks or optically on compact disks. These devices are cheaper and easier to use than photographic recording and images on an optical disk will not degrade with time even after years of storage. To present a stored image for publication you still have to print it in some way and photographic methods still dominate. However, alternative devices such as thermal printers, laser printers, and image plates are approaching the quality required for published images.

So currently the photographic method still dominates both in TEM analog recording and hard copy output from STEM or any digital imaging system. If we can remove photographic film from the TEM it will be a major improvement, because the absorbed water degrades the vacuum.

A photographic emulsion on a polymer support is one of the worst things you can put into a high vacuum instrument.

Both the emulsion and the support outgas, which is a major contribution to the residual pressure of hydrocarbons and water vapor in the instrument, and in turn causes contamination of the specimen. We are often caught in a compromise between drying the film before putting it in the TEM (prepumping) and avoiding the static electricity discharge which can cause white lines on your film if it is too dry. Anything that gives you a high-quality print from digital storage and doesn't require instant film recording from a CRT display will also make the microscopist's life considerably easier and microscopy cheaper.

7.6. COMPARISON OF SCANNING IMAGES AND STATIC TEM IMAGES

We have a choice of creating analog static images in conventional TEM mode or digital scanning images via electronic detection and display. Which is best? While we can only form BSE and SE images in a scanning mode, the answer is not clear for the conventional BF and DF images, and the answer depends somewhat on the contrast mechanism that is operating in the specimen, as we'll see in Chapter 22. Regardless of which detector you use, scanning images are always displayed on a CRT, and this limits the amount of information in the image. Typically, the viewing CRT will have up to 10^3 lines with a maximum of 10^3 pixels per line, giving a total of 10^6 pixels in each frame. The

recording CRT may have up to 2×10^3 lines, giving a total of 2×10^6 pixels in the $10 \text{ cm} \times 10 \text{ cm}$ final image. In contrast, as we just noted, a TEM image recorded directly onto photographic emulsion will have a higher information density, with more than 10^7 pixels of information available in the same $10 \text{ cm} \times 10 \text{ cm}$ image. Furthermore, if a scanning image is to be recorded in a reasonable time, the electron beam can only stay on each point in the image (i.e., each pixel on the CRT) for a very short time. Typical dwell times per pixel are $\ll 1$ ms and this means that the signal-to-noise ratio in a scanning image is liable to be quite low. The combination of the lower pixel density compared to a photographic emulsion and the short dwell time means that, almost invariably, STEM images are poorer in quality than static TEM images. Only in FEG STEMs does the picture quality compare with analog TEM images.

CHAPTER SUMMARY

The TEM is still in the age of analog images. We look at fluorescent screens and CRTs and we record our pictures on photographic film. However, the whole area of electron detection is in a state of rapid flux as electronic systems develop. Semiconductor detectors, scintillators, and CCDs all bring with them the advantage of digital signal collection and therefore the images can be processed and subsequently stored either magnetically or optically. Anything we say about this technology will probably be obsolete before it is published. It is probably safe to speculate that most analog detection, recording, and storage of images and diffraction patterns will eventually be replaced by digital methods.

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