5

Electron Sources

CHAPTER PREVIEW

A reliable source of electrons to 'illuminate' the specimen is one of the most important parts of a TEM. Fortunately, electron sources are plentiful, but to get the best images and other signals out of our expensive microscope, we need to use the best available source. There are stringent requirements to produce the beam of electrons with the necessary properties and these are best met by only two types of source: thermionic and field-emission sources (or 'guns' as they are often called). Thermionic sources are (now rarely) tungsten filaments or (now commonly) lanthanum hexaboride (LaB_6) crystals, and field emitters are fine tungsten needles. In this chapter we'll first explain briefly the physics of the different electron-emission processes because then you'll understand why we operate the sources in certain ways. Next we'll tell you the characteristics we need from our electron beam. Then we'll compare the sources and show you that no one source is best for all aspects of TEM, but all have their roles. Finally, we'll explain ways to check that a particular source meets your needs.

Because the source is so critical to the performance of the microscope, the technology is advancing rapidly with the aim being to have complete computer control, which would leave you, the operator, with very little to do except push the 'on' button. This state of affairs is most advanced for the field-emission source, and since these are both delicate and expensive, it is just as well. But the majority of TEMs still use thermionic sources, and these may need a fair bit of operator control. In these circumstances, you should know how these sources work and why you do certain things to them. So we'll spend much of this chapter talking about thermionic sources, although field emission is essential for the best performing TEMs of any kind (imaging, analytical, etc.), so there's a good chance that field emission will expand to be the source of choice in the future.

5.1 THE PHYSICS OF DIFFERENT ELECTRON SOURCES

We use two kinds of electron sources in TEMs: the first kind is called a thermionic source, which, as the name suggests, produces electrons when heated, and the second type is a field-emission source, which produces electrons when a large electric potential is applied between it and an anode. Schottky sources combine both heat and field emissions. These sources are part of an assembly which we refer to as the electron 'gun.' Now, from a physics standpoint, it is really quite interesting to know the details of how electron sources work and there's a great deal of active research into new and improved sources, and carbon nanotubes show some real promise. (Like future TV screens but using higher voltages.)

From a practical standpoint, you don't have to know too much about the physics, and we can summarize the essential points very briefly, using two simple equations. Keep in mind two points as you read about sources

- Your TEM will use a thermionic source (W or LaB_6) or a field-emission (W) source and the two cannot be interchanged.
- Field-emission sources give more monochromatic electrons; thermionic sources are less monochromatic and give 'whiter' electrons.

The analogy here is to X-rays or visible light. The 'color' of electrons depends on their energy spread (which translates into a frequency or a wavelength range using equation 1.6); we'll discuss this in Section 5.2. You don't always need to use monochromatic electrons, even if your field-emission TEM did cost twice as much as a conventional microscope would with a thermionic source.

5.1.A Thermionic Emission

If we heat any material to a high-enough temperature, we can give the electrons sufficient energy to overcome the natural barrier that prevents them from *leaking out* from the surface. This barrier is termed the work function (Φ) and has a value of a few eV.

The physics of thermionic emission can be summarized in Richardson's law which relates the current density from the source, J, to the operating temperature, T in Kelvin

$$J = AT^2 e^{-\frac{\Phi}{kT}} \tag{5.1}$$

Here k is Boltzmann's constant (8.6×10^{-5} eV/K) and A is Richardson's constant ($A/m^2 K^2$), which is only constant for a given source material. From this equation you can see that we need to heat the source to a temperature T such that energy $> \Phi$ is given to the electrons; then they will escape from the source and be available to form an electron beam. Unfortunately, when we put a few eV of thermal energy into most materials they either melt or vaporize. So the only viable thermionic sources are either refractory (high melting point) materials or those with an exceptionally low Φ. The source used for the first several decades of TEMs (and still used in some SEMs) was tungsten which melts at 3660 K and the only thermionic source used by modern TEMs is lanthanum hexaboride (LaB_6) which has a low Φ. If you look at Table 5.1, you'll see the relative values of J_c, T, and Φ for tungsten and LaB_6.

We use several different words to describe the sources. We called tungsten sources *filaments*, because tungsten was drawn into fine wire similar to the filament used in an incandescent light bulb. LaB_6 crystals (which should not be called filaments) are usually grown with a <110> orientation to enhance emission. Sometimes we call both tungsten and LaB_6 sources *cathodes* because, as we'll see, the complete gun assembly acts as a triode system in which the source is the cathode.

So all you need to know from the physics is that heating up a thermionic source gives you a higher J. But there is a limit, because higher temperatures shorten the source life through evaporation and/or oxidation. So we seek a compromise operating temperature. We thus operate under a condition called 'saturation' which we'll discuss in 'Thermionic Guns.'

5.1.B Field Emission

Field-emission sources, usually called FEGs (for field-emission guns: pronounced either as 'F-E-Gs' or as 'fegs') operate in a fundamentally different way to thermionic sources. The principle behind FE is that the strength of an electric field E is considerably increased at sharp points because, if we have a voltage V applied to a (spherical) point of radius r, then

$$E = \frac{V}{r} \tag{5.2}$$

We call the fine needles 'tips.' The technique of atom-probe field-ion microscopy (APFIM) is another well-established experimental tool for materials characterization. APFIM uses *specimens* with a very fine needle shape, and so there's a lot of expertise available to help produce FE tips. One of the easiest materials to produce with a fine needle point is tungsten wire which can readily be given a tip radius of < 0.1 μm. If we apply a 1-kV potential to this tip then E is 10^{10} V/m and this lowers the work-function barrier sufficiently for electrons to tunnel out of the tungsten. The tunneling process is the same as you've met in semiconductor devices. Applying such high fields imposes a severe stress on the tip and the material must be mechanically strong to remain intact. FE, like thermionic emission from LaB_6, varies with the orientation of the tungsten crystalline tip; the <310> orientation is found to be best.

For FE to occur, the surface has to be pristine, i.e., it must be free of contaminants and oxide. We can achieve this by operating in ultra-high vacuum (UHV) conditions ($<10^{-9}$ Pa). In this case the tungsten is operated at ambient temperatures and the process is called 'cold' FE. Alternatively, we can keep the surface in a pristine condition at a poorer vacuum by heating the tip. The thermal energy assists in electron emission

TABLE 5.1 Characteristics of the Principal Electron Sources

	Units	Tungsten	LaB_6	Schottky FEG	Cold FEG
Work function, Φ	eV	4.5	2.4	3.0	4.5
Richardson's constant	A/m^2K^2	6×10^9	4×10^9		
Operating temperature	K	2700	1700	1700	300
Current density (at 100 kV)	A/m^2	5	10^2	10^5	10^6
Crossover size	nm	$> 10^5$	10^4	15	3
Brightness (at 100 kV)	A/m^2sr	10^{10}	5×10^{11}	5×10^{12}	10^{13}
Energy spread (at 100 kV)	eV	3	1.5	0.7	0.3
Emission current stability	%/hr	<1	<1	<1	5
Vacuum	Pa	10^{-2}	10^{-4}	10^{-6}	10^{-9}
Lifetime	hr	100	1000	>5000	>5000

so much that, in fact, the electrons don't tunnel through the barrier. For such 'thermal' FE, surface treatments with ZrO_2 improve the emission characteristics, particularly the stability of the source, and such Schottky emitters are the most popular. There are pros and cons for both CFE and TFE, which we'll talk about later in the chapter.

5.2 THE CHARACTERISTICS OF THE ELECTRON BEAM

The electron beam in a TEM requires certain characteristics which are controlled by the source itself and how we integrate the source into a gun assembly. We describe the performance of an electron source by such words as brightness, coherency, and stability. While these words mean something to you already, they have very precise meanings in TEM terminology, so we'll go through the various characteristics, tell you what they mean and why they are important in the TEM. We'll then compare the properties of the various sources that you may have in your microscopes. You'll see that there's no best source for all applications, but for specific applications one source or other is usually better.

Before we define the electron-beam characteristics needed in a TEM, it is worth summarizing a few of the properties of electron beams in general and how these vary with kV.

5.2.A Brightness

The word *brightness* is often confused with *intensity* and indeed the two terms are related. For instance, when we look at the viewing screen of a TEM, we may say how 'bright' it is, when we are really referring to the intensity of light coming from the screen. When we think of the intensity of any radiation source, it is in terms of the flux emanating from it. For a light bulb, it would be the number of photons per unit area per unit time. For electron sources we talk about the current density, which is the number of electrons (or charge) per unit area per unit time.

BRIGHTNESS
While current density can be a useful term, it is more important to define the brightness. Brightness is the current density per unit solid angle of the source.

Electron sources differ considerably in their size and, as a result, the electrons leave the source with a range of divergent angles, so we can't ignore the angular distribution of the electrons. Brightness is particularly important when we are using very small convergent probes, as we do in AEM and STEM. The concept of brightness is less important in conventional TEM where we use a relatively large, defocused beam, but it is still relevant to the intensity we see on the screen, and so it affects how easy it is to operate the microscope and see our images and DPs.

So we can consider an electron source as having the following characteristics

- Diameter d_0
- Cathode emission current i_e
- Divergence angle α_0 (remember when we say angle we mean semi-angle)

We'll describe the actual way in which these characteristics are achieved in Section 5.3, where we discuss the complete gun assembly, but if you look at Figure 5.1 you'll see that i_e, d_0, and α_0 are actually defined at the gun crossover, that is, the point at which the electrons are focused *after* leaving the source. The current density

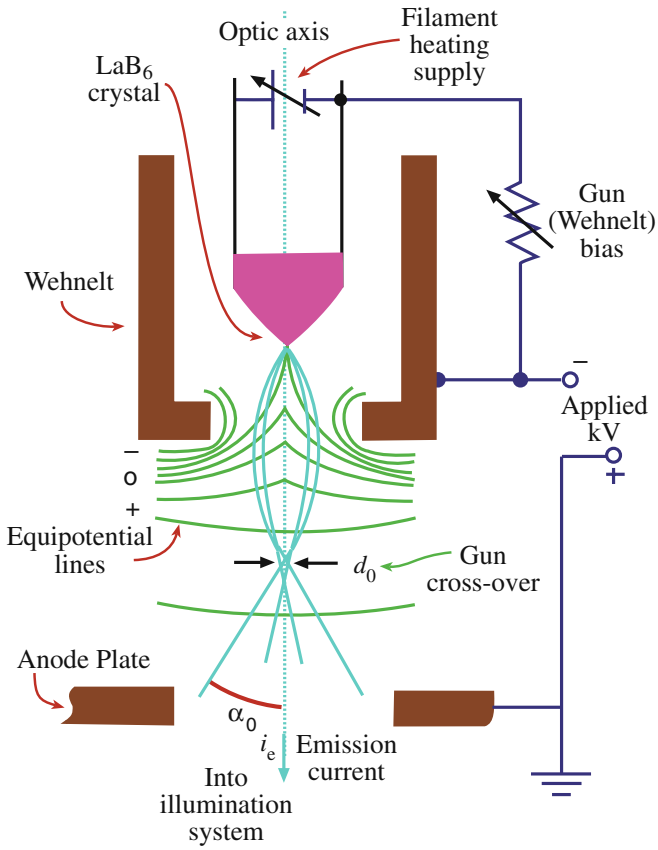


FIGURE 5.1. Schematic diagram of a thermionic electron gun. A high voltage is placed between the cathode and the anode, modified by a potential on the Wehnelt which acts as the grid in a triode system. The electric field from the Wehnelt focuses the electrons into a crossover, diameter d_0 and convergence/divergence angle α_0 which is the true source (object) for the lenses in the TEM illumination system.

(current per unit area) is $i_e/\pi(d_0/2)^2$ and the solid angle of the source is $\pi\alpha^2$, so we define the brightness β as

$$\beta = \frac{i_e}{\pi\left(\frac{d_0}{2}\right)^2 \pi(\alpha_0)^2} = \frac{4i_e}{(\pi d_0 \alpha_0)^2} \tag{5.3}$$

This brightness equation is an important one which you should remember. What is not shown in this equation is the important fact that β increases linearly with increasing accelerating voltage for thermionic sources. This was one reason for the development of intermediate-voltage (300–400 kV) instruments.

Obviously, the higher the value of β, the more electrons we can put into a beam of a given size, and so the more information we can generate from the specimen and also the more we can damage sensitive specimens. The beam current is an important part of the brightness equation. Measuring the beam current in situ can be a very good diagnostic tool. We'll talk about this later in the chapter when we discuss measuring β, but for the time being you can again look at Table 5.1 to see how the various sources compare in brightness.

UNITS FOR BRIGHTNESS

β is in units of $A/m^2\,sr$.

Now we can consider some real numbers. With a cold FEG at 100 keV, we can put 1 nA into an area of diameter 1 nm. If you convert this current density to units of power (1 watt = 1 J/s), you'll find that the energy the electron beam puts into this small area of the specimen is nearly $150\,MW/mm^2$. By comparison, the output of a typical electric power-generating turbine is anywhere from 350 to 1000 MW. If all this energy were in fact absorbed by the TEM specimen the technique would be useless since the specimen would vaporize. We'll find out later why this doesn't happen but clearly we can alter our specimen when we look at it in the TEM, as we discussed in relation to beam damage in the previous chapter. The energy density we just calculated is such that a TEM electron source is the brightest, continuously radiating source known; it is considerably brighter than a supernova.

The brightness is particularly important in AEM, which is the quantitative analysis of the many signals that come from a specimen irradiated by an electron beam, shown back in Figure 1.3. As you'll see in Part 4, we need to put the most beam current into the smallest probe to optimize both spatial resolution and analytical sensitivity. Similarly, as we go to higher magnifications in HRTEM, the intensity of light coming from the viewing screen (see Chapter 7) becomes less because we are viewing only a small fraction of the illuminated area of the specimen. The electron density can be increased by using the brightest source. Then images can be recorded with reasonably short exposure times minimizing image drift and other instabilities. So brighter is better for AEM and HREM.

5.2.B Temporal Coherency and Energy Spread

The coherency of a beam of electrons is a way of defining how well the electron waves are 'in step' with one another. You know that white light is incoherent, because it consists of photons with a range of frequencies (colors), and so to get a coherent beam of electrons we must create one in which all the electrons have the same frequency (i.e., wavelength) just like monochromatic light. We refer to this aspect of coherency as temporal coherency, which is a measure of how similar the wave packets are. If the packets are all identical they have the same coherence length. A definition of the coherence length λ_c is

$$\lambda_c = \frac{v\mathrm{h}}{\Delta E} \tag{5.4}$$

where v is the electron velocity, ΔE is the energy spread of the beam, and h is Planck's constant. This means we must have stable power supplies to the source and a stable high-voltage supply (or high tension, as it is sometimes called for historical reasons) so that all the electrons have a small ΔE, thus giving a well-defined wavelength. We'll show in detail in Section 37.7 how we can add an energy-selecting spectrometer to the gun to choose electrons with an energy-spread of as little as 10 meV. Such monochromators are expensive and cut down the total beam current tremendously but, for certain very specialized applications, they are invaluable. This loss of current can be offset somewhat by C_s correction (even more expense) and instruments with combinations of monochromators and C_s corrector are the most expensive (and rare) TEMs in the world. If you look at Table 5.1 you'll see that, without a monochromator, typical ΔE values for the three sources are in the range 0.3–3 eV (which is still remarkably small compared with a total energy of 100–400 keV). So it isn't really correct to imply as we did at the start of the chapter that thermionic sources give 'white' electrons since ΔE is so very small. From these values of ΔE, if you take care to get the units consistent, you can calculate typical coherence lengths, which turn out to be a few hundred nanometers.

Temporal coherency is important when the energy spread of the electrons that are *incident* on the specimen affects the microscopy. Because we can make such good high-voltage power supplies, the incident electron-energy spread rarely limits any aspect of TEM except the highest energy-resolution EELS (see Chapters 37–40). In other words, for most practical purposes our electron sources are stable enough. However, we'll see that it's a very different matter when we have to consider the electrons that have come *through* the specimen because they may have lost substantial amounts of

energy and that's where energy-filtered TEM technology really comes into its own (see Section 37.6).

5.2.C Spatial Coherency and Source Size

Spatial coherency is related to the size of the source. Perfect spatial coherence would imply that the electrons were all emanating from the same point at the source. So source size governs spatial coherence and smaller sources give better coherency (just as they give higher brightness). The spatial coherence is strictly defined by looking at electron-interference fringes in the equivalent of a Fresnel biprism experiment in light optics, with which you may be familiar. We can define the distance d_c, the effective source size for coherent illumination, to be

$$d_c = \frac{\lambda}{2\alpha} \tag{5.5}$$

where λ is the electron wavelength and α is the angle subtended by the source at the specimen. We can control α by inserting an aperture in the illumination system, as we'll see when we describe the construction of a TEM in Chapter 9. But if this aperture is not limiting then it is the smallest source which subtends the smallest angle, and thus has the highest spatial coherence. Putting reasonable values for 100-keV electrons into equation 5.5 we find that the spatial coherence is at best only about a nanometer. To maximize the coherency, you can choose several approaches

- Make the source size, d_c, smaller, e.g., by using a FE source. This explains why research into using nanotubes as electron sources is ongoing.
- Use a smaller illumination aperture, thus reducing α.
- If your source size is large (e.g., a W hairpin) decrease the accelerating voltage and thus increase λ.

A small electron source subtends a small angle at the specimen, and we can help by using small limiting apertures. Small beams are more spatially coherent than large beams and give better spatial resolution of analysis (see Part 4). The more coherent and parallel the beam, the better the quality of the phase-contrast images (Part 3), the sharper the DPs (Part 2), and the better the diffraction contrast in images of crystalline specimens (Part 3). So that's why spatial coherence is important. The whole concept of coherence is rather more complex than we have described here and an in-depth and rather mathematical description of electron coherency in the TEM is given in the review by Hawkes and in the companion text.

COHERENCY

Spatial coherency is more important practically than temporal coherency; smaller source –> higher β, better spatial coherency, but lower stability.

5.2.D Stability

In addition to the stability of the high-voltage supply to the source, it is also important that the electron current coming from the source is stable. Otherwise the screen intensity would vary, making it difficult for you to take correctly exposed images and also making quantitative analytical measurements impossible. Thermionic sources are generally very stable except when they are first installed or when they are about to fail. Typically, you can expect variations of $< \pm 1\%$/hr in the current and TFE sources are similarly stable. For CFE sources, however, the emission current is not very stable, and electrical feedback circuits are required to maintain stability to $<\pm 5\%$. Stability improves with better UHV conditions in the gun.

To summarize: the important properties of electron sources are their brightness, temporal coherency, energy spread, spatial coherency and stability. A smaller source size gives higher β and better spatial coherency, but less stability.

Now that we know the critical characteristics required of electron sources, let's examine those used in commercial TEMs.

5.3 ELECTRON GUNS

It's no good just having a source. We need to be able to control the electron beam and direct it into the illumination system of the TEM. We do this by incorporating the source into a gun assembly which, in effect, acts as a lens to focus the electrons coming from the source. The design of the gun is different for thermionic sources and FE sources.

5.3.A Thermionic Guns

LaB_6 is the only thermionic source used in modern TEMs so we'll just describe these. The LaB_6 crystal is used as the cathode in a triode gun shown in Figure 5.1. In addition to the cathode, there is a grid called a Wehnelt cylinder and an anode at earth potential with a hole in its center. What these three components look like in practice is shown in Figure 5.2, where they are all separated. The cathode is attached to the high-voltage cable that, in turn, connects to the high-voltage power supply. The LaB_6 crystal is bonded to a metal wire such as rhenium, which is resistively heated to cause thermionic emission.

When the electrons leave the cathode they have a negative potential of whatever accelerating voltage you have chosen (say 100 kV) with respect to the earthed anode. So they accelerate through this potential difference, acquiring an energy of 100 keV and a velocity greater than half the speed of light.

Now to get a controllable beam of electrons through the hole in the anode and into the microscope itself, we apply a small negative bias to the Wehnelt cylinder. The

FIGURE 5.2. The three major parts of a thermionic gun, from top to bottom: the cathode, the Wehnelt cylinder and the anode shown separated. The Wehnelt screws into the cathode support and both are attached to the high-voltage cable which also contains power supplies for heating the cathode and biasing the Wehnelt. The anode sits just below the Wehnelt and the whole assembly sits on the top of the column of lenses that make up the rest of the TEM.

BEAM CURRENT

As the cathode heating current (i_f) increases, T increases until thermionic emission occurs; then an emission current from the cathode i_e can be measured. Sometimes you'll find this current referred to as the beam current. This is misleading; the true beam current is that which enters the specimen after the electrons have left the gun and gone through the illumination system of the TEM.

electrons coming off the cathode see the negative field and are converged to a point called a crossover between the Wehnelt and the anode as shown in Figure 5.1. We could operate the controls for the cathode heating and the Wehnelt bias independently, but the electronic circuitry of the gun is designed so that as the emission current increases, the Wehnelt bias increases; this arrangement is called a self-biasing gun. The result is shown in Figure 5.3, which plots the emission current (i_e) against the current used to heat the cathode (i_f). As you can see, i_e reaches a maximum such that a further increase in i_f doesn't increase the current going into the TEM column. This is the *saturation condition* and all thermionic sources should be operated at or just below saturation. Operating above saturation reduces the source life without any compensating advantage; operating significantly below saturation reduces the current into your specimen, thus reducing the intensity of all the signals coming out of your specimen although on occasions, as we'll see later, undersaturation can be useful.

WEHNELT

The Wehnelt acts as a simple electrostatic lens: the first lens the electrons go through in the TEM.

In addition to optimizing the source life, operating at saturation also optimizes brightness. If you look at Figure 5.1, the crossover is the source size d_0 that we used back in the brightness equation (equation 5.3) and the divergence angle at the crossover is α_0 in that same equation. The current in the crossover is the emission current i_e. Now, as shown in Figure 5.4A, if the Wehnelt bias were too low (diagram i) d_0 would not be very small and if the bias were too high (diagram iii) the cathode-emission current would be suppressed. In either case β would be low. The optimum β is at an intermediate-bias setting (diagram ii), as summarized in Figure 5.4B. You would be right if you thought that the small bias on the

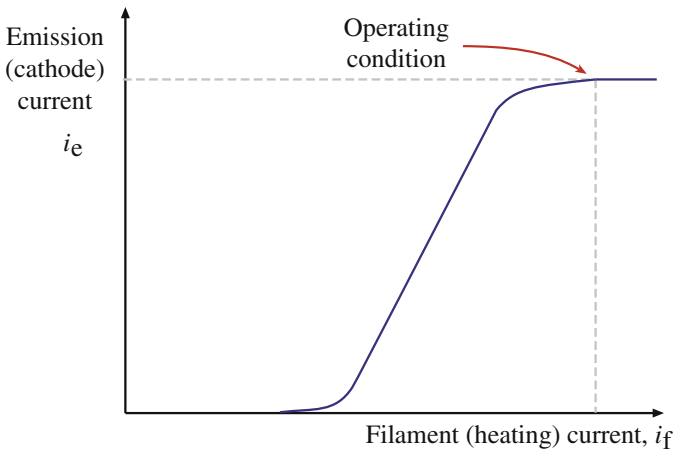


FIGURE 5.3. The relationship between the current emitted by the electron source and the source heating current for a self-biasing gun. Increasing the source current results in a maximum emission current termed saturation.

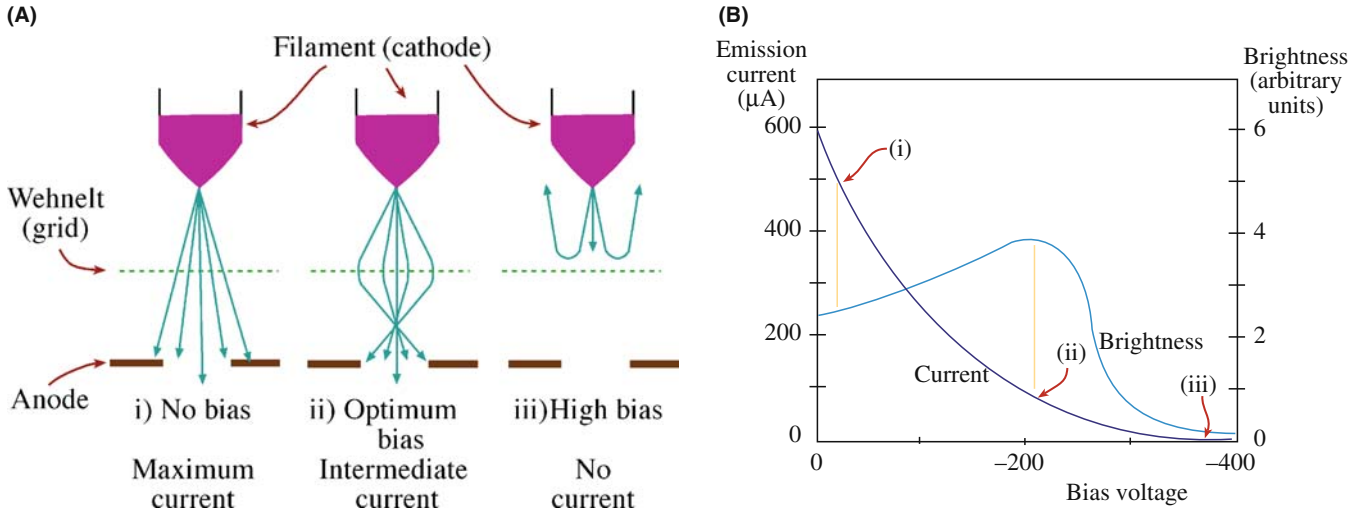


FIGURE 5.4. (A) The effect of increasing Wehnelt bias (i–iii) on the distribution of electrons coming through the anode. (B) The relationship between the bias and the emission current/gun brightness. Maximum brightness (ii) is achieved at an intermediate Wehnelt bias, and an intermediate emission current (ii).

Wehnelt acts against the accelerating voltage, so the true beam voltage should be the applied kV minus the Wehnelt bias (which may be up to 2 kV), but this is compensated for in the design of the gun, so don't worry.

So how do we achieve saturation? One way is to look at the meter which displays i_e and watch it rise to a maximum as i_f is continuously increased. This method may not be easy because the appropriate readouts may not be available or, if they are, they may not be very sensitive. So the standard way is to look at the image of the source crossover on the TEM screen. This image shows you the distribution of electrons coming off the source. As thermionic emission starts, the electrons may come from both the central tip and/or a region surrounding the tip of the crystal. Since LaB_6 sources have well-defined crystal facets (Figure 5.5A) the undersaturated image is as shown in Figure 5.5B. With increasing emission the halo collapses in on the central bright disk, although some structure may still be visible. The cathode is truly saturated when no structure is visible (Figure 5.5C).

It is best to operate an LaB_6 source just below saturation, since this will extend the source life without undue loss of signal. The electrons in the halo are more coherent than those in the central bright region and have reduced energy spread. LaB_6 crystals are susceptible to thermal shock which can cause them to break, and so you should take care when *heating* and *cooling* an LaB_6 source (often the TEM computer takes control of this). If you have to switch the source on and off manually then increase/decrease the heating current slowly, with 10–20 seconds pause between each setting. This is particularly critical after you've installed a new LaB_6 source.

The appearance of the image of the source, as in Figure 5.5, can also be used to align the gun assembly so that the beam is aligned along the optic axis of the TEM. This is the only other adjustment you have to do to the gun, apart from saturating it. The source is usually pre-aligned by the manufacturer, so alignment should be simple when it is put inside the Wehnelt. Typically, a misaligned, undersaturated source image is asymmetrical as in Figure 5.5B and, in those circumstances, all you have to do is adjust the gun to make it symmetrical prior to final saturation. Detailed instructions will be in the manufacturer's handbook. Most modern TEM guns are so well constructed that slight electronic corrections are all that you need to ensure alignment.

SMALL PROBES - FINE BEAMS

Achieving optimum β is critical in any operations that require a fine beam (<0.01 μm).

In an SEM, which always requires a small probe rather than a broad beam, the gun is carefully adjusted by the manufacturer to produce optimum β at saturation; you may not have any external control of the Wehnelt. In a TEM, particularly when you are operating in a broad-beam mode, there is no need to optimize β, but you may need to increase the current density and make the image appear brighter. You can do this by decreasing the Wehnelt bias, using the gun-emission control. When you decrease the bias, you should go back and adjust i_f to ensure you're at saturation, since the saturation condition will change with changing bias. So now you will have a greater current density falling on the screen, but the crossover size will have increased, thus decreasing β. This

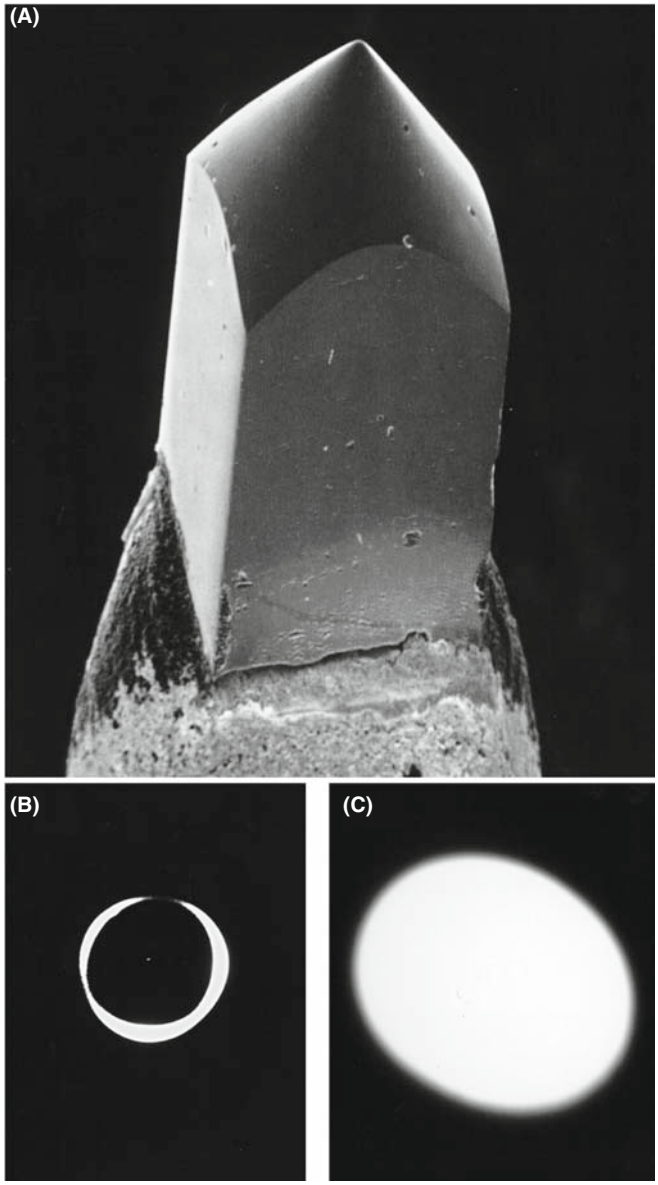


FIGURE 5.5. (A) An LaB_6 crystal and the electron distribution when the source is (B) undersaturated and (C) saturated.

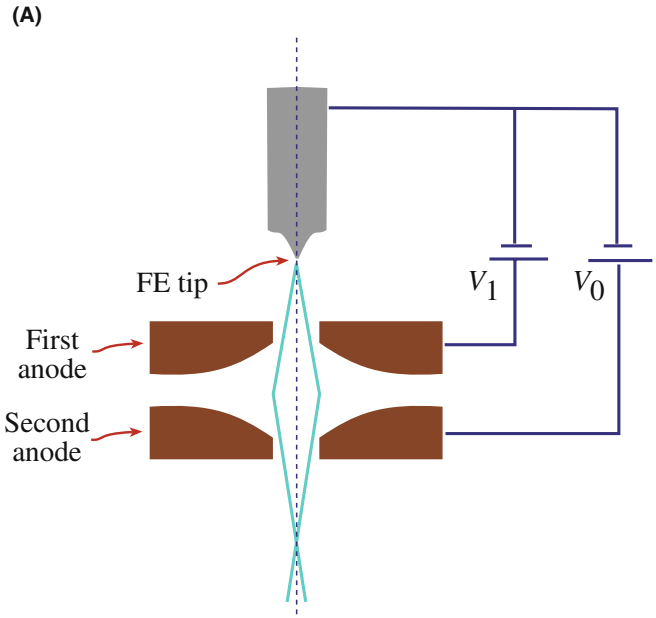
is not important when you're operating with a broad beam. However, if you want to operate at maximum β with a focused beam, as is the case for AEM, then you need to be able to measure β; we'll show you how to do this in Section 5.5.

5.3.B Field-Emission Guns (FEGs)

In many ways, FEGs are much simpler than thermionic guns. In order to get a FEG to work we make it the cathode with respect to *two* anodes. The first anode is positively charged by several kV with respect to the tip. This charge produces the extraction voltage since it generates the intense electric field which enables electrons to tunnel out of the tip. Increasing the extraction voltage when you first switch on the gun has to be done slowly, so the thermo-mechanical shock doesn't fracture the tip. This is the only practical step you have to carry out to run a FEG; it is invariably computer controlled.

- Anode 1 provides the extraction voltage to pull electrons out of the tip.
- Anode 2 accelerates the electrons to 100 kV or more.

The electrons are accelerated through the appropriate voltage by the second anode. The combined fields of the anodes act like a refined electrostatic lens to produce a crossover, as shown in Figure 5.6A. This



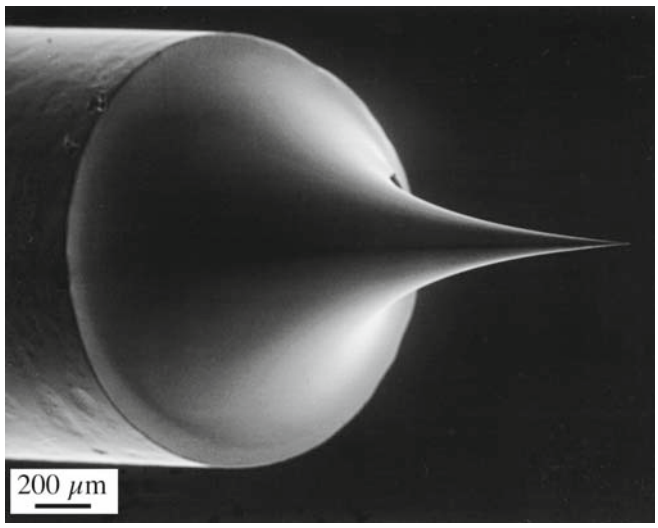


FIGURE 5.6. (A) Electron paths from a field-emission source showing how a fine crossover is formed by two anodes acting as an electrostatic lens. Sometimes an extra (gun) lens is added below the second anode. (B) A FEG tip, showing the extraordinarily fine W needle.

lens controls the effective source size and position, but it isn't very flexible. Incorporating a magnetic lens into the gun gives a more controllable beam and larger β. The faults (known as lens aberrations) in the gun lens are very important in determining the source size; we'll talk extensively about lens aberrations in Chapter 6.

VACUUM IS IMPORTANT

In a vacuum of 10^{-5} Pa, one monolayer of contaminants will form on a substrate in less than a minute. At 10^{-8} Pa, it will take 7 hours to form a monolayer.

We have already noted that CFE requires a pristine surface and, even in UHV conditions, surface contaminants build up on the tip. With time, the emission current falls and the extraction voltage must be increased to compensate. Eventually it becomes necessary to remove the contamination by 'flashing' the tip. This just means reversing the potential to the tip and 'blowing off' the surface layer of atoms, and/or heating the tip quickly to ~5000 K to evaporate the contaminants. In most CFE guns flashing occurs automatically, when the extraction voltage increases to a certain predetermined level. Because they are continuously heated, Schottky FEGs do not form the same surface contamination layer and so don't need flashing. A typical FEG tip is shown in Figure 5.6B.

A future generation of ultra-bright field-emission electron sources might well be based on carbon nanotubes which have already demonstrated a brightness in excess of 10^{14} A/m^2 sr although such a laboratory demonstration is a long way from reliable service in a commercial IVEM in a student-oriented lab. It is perhaps more likely that this technology will be developed for tips in scanning-probe microscopes or electron emitters for flat-panel display technology well before it becomes an electron source in a TEM.

5.4 COMPARISON OF GUNS

The important characteristics of the three guns we've talked about are summarized in Table 5.1. For historical reasons, we've included tungsten sources which are the worst in most respects (except price).

LaB_6 is a much more useful source for several reasons. While it is not as refractory as tungsten, LaB_6 has a much lower value of Φ and, since Φ appears in the exponential in the Richardson equation, its effect on the current density is dominant. LaB_6 crystals can be produced with a fine tip about 1 μm in radius, which accounts for the smaller crossover size. As a result, LaB_6 current densities are considerably higher than for tungsten and the brightness is typically 10 times greater, even though LaB_6 is usually operated at a much lower T to increase operating life. The decreased source size also results in improved coherency and the energy spread approaches 1 eV.

Because LaB_6 is highly reactive, the gun vacuum has to be good enough to minimize oxidation during operation, thus ensuring a reasonable life expectancy. Anything that requires improving the vacuum is good since better vacuums improve most aspects of TEM performance, but this improvement comes at a price.

The increased brightness, higher coherency, and longer life are tremendous advantages and explain why the only thermionic sources we should now use in TEM are LaB_6. You, as the operator, may have considerable control over its performance and unless the computer control overrides you, careless heating, cooling, and oversaturation can easily destroy a LaB_6 crystal. So treat LaB_6 sources gently and you will be well rewarded. If users are not careful, your TEM supervisor may extend the life of the LaB_6 to the point where it behaves no better than a W filament. LaB_6 sources don't die, they fade away.

In FEGs, the current density is enormous and β is correspondingly high. The values in Table 5.1 are all for 100 kV-accelerating voltage and you should remember that for thermionic sources, β increases linearly with kV, so there are advantages to using 300- and 400-kV instruments. However, the LaB_6 source brightness at 400 kV still does not approach β of a FEG at 100 kV. So for all applications that require a bright, coherent source, the FEG is best. This is the case for AEM, HRTEM, and such special applications as electron holography and Lorentz microscopy (for looking at magnetic domains). However, as we'll see later, the coherence of the source may produce a new complication: we must interpret the image!

There are significant differences between a CFE and a Schottky (TFE) sources and, depending on what you need from your TEM, one or the other may be significantly better. First of all, the extremely small source size of a cold FEG means that the beam is highly spatially coherent and the resulting energy spread is the smallest available without monochromation. Thermally assisted Schottky FEGs have a somewhat larger source size and larger energy spread but they provide greater stability of beam current and lower noise. A CFE requires UHV; such technology is expensive and generally requires a higher level of operator competence. However, a UHV brings other advantages such as a cleaner specimen stage and reduced contamination from the microscope system. Cleaning the tip by heating as we do for a Schottky rather than flashing as in a CFE lowers the stress on the tip, ensuring a longer life. But the cleaner UHV system for a CFE gun also

ensures a long life and so both FE sources offer similar lifetimes measured in the thousands of hours (if you're careful!). In summary, if you are doing EELS and need the lowest possible energy spread or you are doing the highest resolution STEM imaging and X-ray analysis in which the highest brightness and smallest probe size are required, then a cold FEG has advantages. For routine FEG work a Schottky gun is better, more reliable, and easier to operate.

Lastly, we should note that for routine, relatively low magnification (<50–100,000×) TEM imaging, a FEG is far from ideal because the source size is too small. It is thus not possible to illuminate large areas of your specimen at low image magnifications without losing current density, and therefore intensity, on the screen. So you can't see your image clearly at low magnifications. Under these circumstances, a LaB_6 source is better. However, increased computer control and the need for optimal performance means that FEG TEMs are increasingly popular and for the best high-resolution imaging and analytical performance, as we've made clear, there is no alternative. If you still don't get it, there's a good interactive summary of both thermionic and FE electron guns and how they work on URL #1.

5.5 MEASURING YOUR GUN CHARACTERISTICS

This section requires that you know how to operate a TEM. If you're a novice, you should skip this part of the chapter for now because we are going to refer ahead in the book for much of what you need to know.

For conventional TEM imaging and diffraction and many other routine uses, all you need to do is saturate and align the (thermionic) gun or just switch on the FEG and then ignore it. In many instruments the computer takes care of this. There are, however, times when we need to be able to measure the brightness and coherency. The source brightness is a most important parameter to measure in an AEM since, if the gun is not operating at its maximum β, then the quality of the analytical information that is generated will be poorer. Similarly, knowing the energy spread of your source is important for EELS and having a measure of the beam coherency can be important for some more advanced techniques that we've just mentioned. So let's see how we can measure the various parameters that we've just discussed. We'll start with β, then ΔE, and finally the coherency.

By measuring the three variables in equation 5.3, i.e., the beam current, the beam diameter, and the angle of convergence, we can determine β. However, while we can easily get a measure of the emission current at the gun, it is impossible to measure d_0 and α_0 there (think about why this is so). So we make the approximation that, if we neglect lens aberrations, β is constant throughout the electron-optical system so it doesn't matter where it is measured. It is easiest, practically, to determine β at the plane of the specimen and we'll now show you how to do this. (Neglecting lens aberrations is reasonable but you should be aware that C_s correction in TEMs can effectively increase the brightness of the electron beam *at the specimen* since we can use larger apertures to permit higher currents in the probe without broadening the probe dimensions.)

5.5.A Beam Current

You can measure the beam current at the specimen i_b directly using a Faraday cup in a specimen holder. A Faraday cup consists of a small aperture above a relatively deep hole in an earthed metal block. If the aperture is small enough (e.g., ~50 μm) and the metal block deep enough (~2 mm), and made of something light like Al to minimize backscatter, then it is a reasonable assumption that no electrons escape back out of the entrance aperture. All the electrons going into the aperture therefore go to earth, and you can measure the electron current using a picoammeter in the earth line. (Ideally a Faraday cup would be available permanently in the column of a TEM, and this would permit constant monitoring of the beam current but no TEM manufacturer offers such.) You should calibrate your Faraday-cup measurement against the TEM screen exposure meter or the electron energy-loss spectrometer shield current. Carrying out this procedure allows you to make a rapid estimate of i_b at any time you need it.

In modern TEMs equipped with a Schottky FEG, the beam-current fluctuation should be less than a few percent over many hours of operation. The stable beam current in Schottky-FEG TEMs does not need to be monitored frequently and can be calibrated easily through the readout from the viewing screen. Conversely, the beam current decreases with time in cold-FEG TEMs. Figure 5.7 shows the time dependence of the emission and the beam current measured after tip-flashing in the cold-FEG STEM. While the emission current decreases almost linearly, the beam current drops parabolically up to 3 hours after flashing. In thermionic-source TEMs, the beam current also decreases after stabilization. This variation would not be nearly so large for a Schottky FEG which, of course, never needs flashing.

MEASURING THE BEAM

A Faraday cup is a black hole for electrons and a very useful diagnostic tool for your TEM performance.

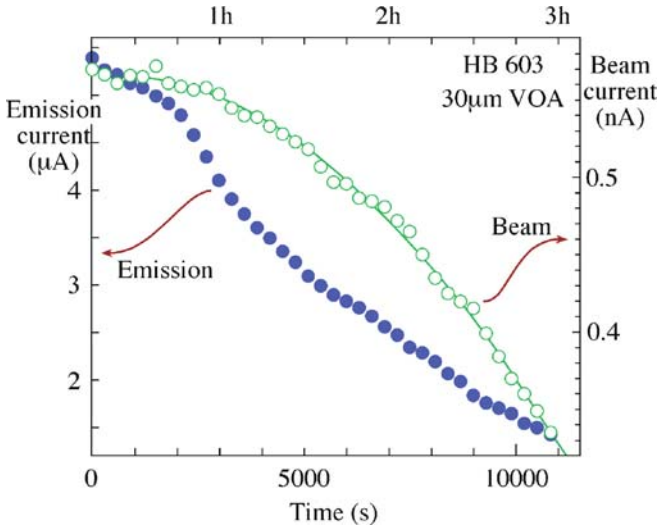


FIGURE 5.7. Time dependence of the emission and the beam currents of a cold FEG in a 300-keV VG HB603 STEM. Both the currents were measured after flashing the tip.

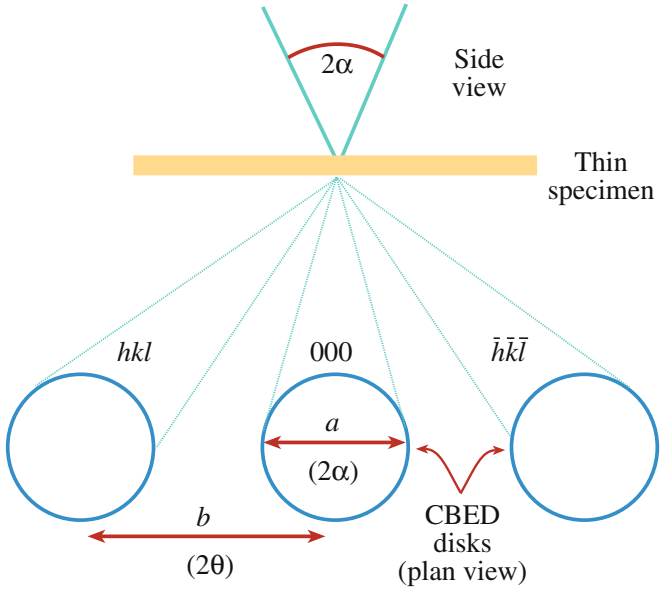


FIGURE 5.8. The distances on a convergent beam DP from which you can measure the beam convergence angle, α, which is proportional to the width of each diffraction disk.

As we'll show in Chapter 6, i_b is a strong function of the beam size. Therefore, the current is controlled by the first condenser (C1) lens strength and the size of the final beam-limiting aperture in the second condenser (C2) lens. If you look ahead to Figures 9.10 and 9.11 you will see the variation of i_b as a function of C1 lens strength and the effect of C2 aperture size on α_0.

- The beam current is usually in the range from nanoamps to picoamps.
- The emission current is typically several microamps.

So the current decreases by three to six orders of magnitude between the gun and the specimen: most is lost in the illumination system, as we'll see in Chapter 9.

5.5.B Convergence Angle

You can easily measure the convergence angle α from the convergent-beam electron diffraction (CBED) pattern, which you can see directly on the TEM screen. (You will need to read Chapter 21 in order to find out how to generate CBED patterns.) In the schematic diagram in Figure 5.8, the total convergence angle 2α is proportional to the width of the diffraction discs, *a*. This width can easily be calibrated if the specimen has a known Bragg angle $2\theta_B$ (see Chapter 11), since $2\theta_B$ is proportional to the distance, *b*, from the 000 disc to the *hkl* disc. Thus

$$2\alpha = 2\theta_B \frac{a}{b} \tag{5.6}$$

The convergence angle, α, at the specimen is not only important in the brightness equation, but we'll see that it also plays a major role in CBED, STEM imaging, XEDS, and EELS. So you must know how to measure and control α because it is essential in many aspects of TEM. The value of α is controlled by the size of the final limiting aperture in the illumination system and we'll see how this works in Chapter 6.

5.5.C Calculating the Beam Diameter

While it is a relatively simple matter to measure i_b and determine α, the measurement of *d*, the beam diameter, is not so straightforward. However, *d* is a major factor in all aspects of TEM such as AEM and STEM imaging where we use a fine focused beam. We can either calculate *d* or measure it experimentally. The former is easy but imprecise, the latter is difficult and can be equally imprecise. The first problem with determining *d* is that there is no universally accepted definition of the beam diameter. The manufacturer will give you a list of nominal beam sizes for each setting of the C1 lens. These values are *calculated* and may differ from the actual beam size by large amounts. The calculation assumes that the electron-intensity distribution in the beam is Gaussian, and the beam diameter is defined as the full-width at half-maximum (FWHM) of the Gaussian distribution, defined in Figure 5.9. To approach a Gaussian intensity distribution, the beam must be well aligned, any astigmatism in the condenser lenses corrected (see Chapter 9), and all apertures in the illumination system accurately centered. Even under these conditions you cannot obtain Gaussian conditions for

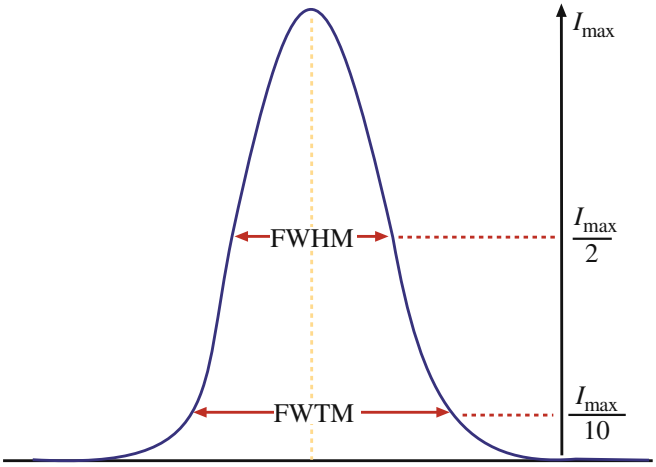


FIGURE 5.9. The definition of the full width at half maximum (FWHM) and the full width at tenth maximum (FWTM) of a Gaussian intensity distribution which is typical of a well-aligned electron beam. Ideally the beam hitting your specimen should always approximate to this kind of intensity distribution.

every possible beam size. For example, there may be six different C1 lens excitations, each of which gives a different calculated beam size, but there are invariably fewer than six C2 apertures available, so each beam size cannot be correctly apertured; spherical-aberration (C_s) effects will broaden the beam size beyond a true Gaussian (see Chapter 6). If you select too small an aperture, then the intensity distribution will be truncated at a fraction of the full Gaussian curve. If you use too large an aperture, the actual beam will extend out well beyond the calculated size and this has very important implications for XEDS in the TEM as we describe in Section 33.3.A.

To make a complete calculation of the beam size, we assume that it is determined by an initial Gaussian diameter at the gun (d_g). This diameter is broadened by the effects of spherical aberration in the beam-forming lens (d_s) and diffraction at the final aperture (d_d). All these terms can be added in quadrature (although for no better reason than that it seems reasonable) to give a total, calculated beam size, d_t

$$d_t = (d_g^2 + d_s^2 + d_d^2)^{1/2} \tag{5.7}$$

This equation gives us only a first-order estimate, since the contributions are not all Gaussian. We'll now briefly discuss the origin of each of these terms.

The value of d_g is a function of β, and a value of β has to be assumed for the purposes of calculation. The expression for d_g is

$$d_g = \frac{2}{\pi}\left(\frac{i}{\beta}\right)^2 \frac{1}{\alpha} \tag{5.8}$$

We have already defined i, β, and α.

The disc of minimum confusion caused by spherical aberration has a diameter given by

$$d_s = 0.5 C_s \alpha^3 \tag{5.9}$$

where C_s is the spherical-aberration coefficient, which we discuss in detail in Chapter 6. This is the full diameter containing 100% of the beam current. Clearly, this term is not Gaussian unless the beam is correctly apertured, which, as we just discussed, is not always possible. However, C_s correction is now available in probe-forming TEMs and then, of course, this contribution to the beam broadening goes away. The calculated diameter due to diffraction is

$$d_d = 1.22 \frac{\lambda}{\alpha} \tag{5.10}$$

which is the Rayleigh criterion that we discussed in Section 1.2.B and refers to a spacing between two overlapping images of the probe. Although all these definitions clearly do not define the same diameter of the electron distribution, the summation in quadrature is still assumed to give a first approximation of the FWHM of the beam. Figure 5.10 shows the result of calculations of the three contributions to the beam diameter in a VG HB501 STEM and the comparison with two experimental measurements carried out, as we'll now describe.

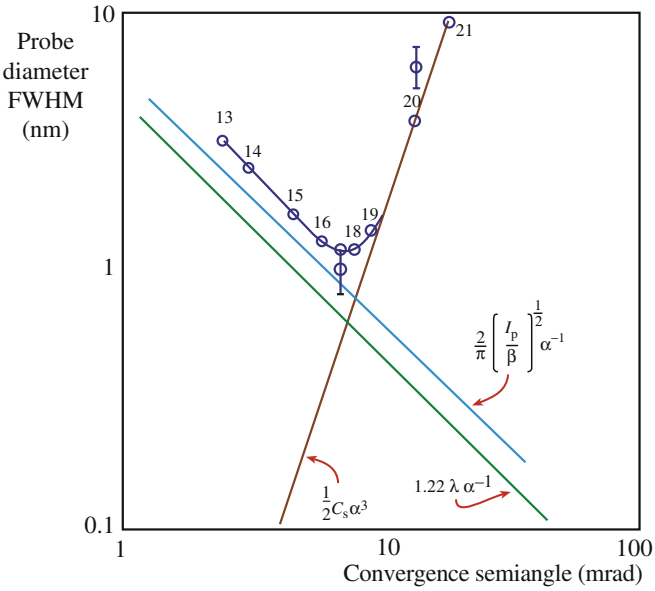


FIGURE 5.10. Calculations of the various contributions to the beam size as a function of the convergence angle α, in a FEG STEM with a probe current I_p of 0.85×10^{-8} A. Two experimental points are shown (with error bars) at first-condenser lens settings 17 and 20 (corresponding close to the minimum and the maximum probe sizes, respectively). The minimum diameter is ~ 1 nm with $\alpha < 10$ mrads.

Given all the (somewhat inaccurate) assumptions we made, the agreement with experiment is quite reasonable.

5.5.D Measuring the Beam Diameter

Given the uncertainties in the calculation of the probe size which we just described, it would seem much more reliable to measure d experimentally. To measure the beam size in a TEM you must form an image of the beam on the viewing screen or computer display under conditions where you know, or can calibrate the magnification. This is a non-trivial exercise and you may need to consult the manufacturer's handbook to be sure that you are doing it correctly. You can then *photograph* the beam and determine the intensity distribution from a microdensitometer trace across the film, or an electronic scan across the readout from the CCD detector (see Chapter 7) as shown in Figure 5.11. What you'll learn later on in Chapter 9 is that the first-condenser lens (C1) is responsible for controlling the beam size (and hence the current) and that is why different settings of C1 are mentioned in Figures 5.10–5.12. From Figure 5.11 a couple of important points can be drawn

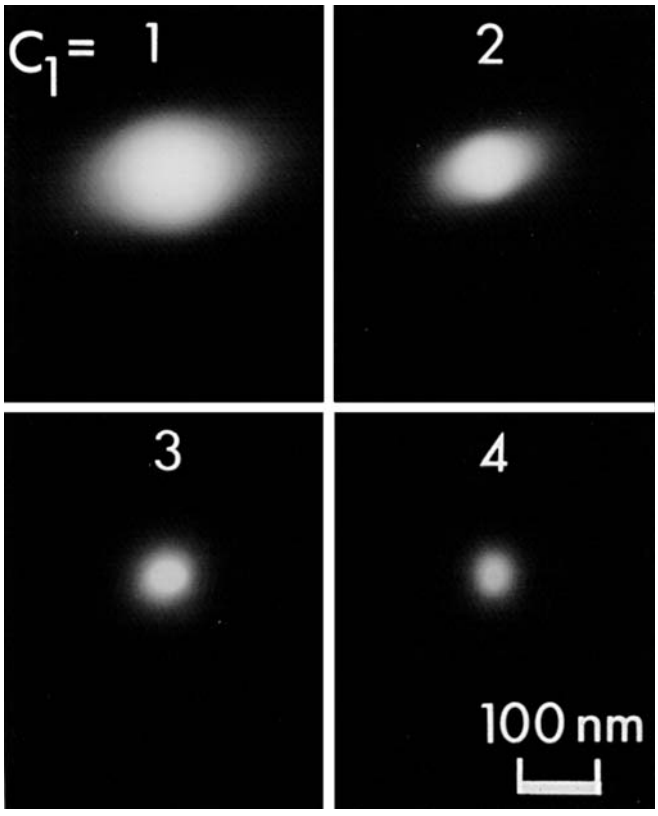


FIGURE 5.11. Four images of the beam formed on the TEM screen at different C1 lens settings. Spot #3 most closely corresponds to the Gaussian intensity distribution shown in Figure 5.9.

- The FWHM contains 50% of the integrated intensity. It is the value used by the manufacturers when they calculate beam sizes. It is also the important dimension when considering the effect of d on the (S)TEM image resolution.
- The full width at tenth maximum (FWTM) contains 90% of the integrated intensity. It is a more relevant dimension generally because the Faraday cup (or any probe-current measuring method) measures the current in the total beam, which is much closer in size to the FWTM. This dimension is also more relevant to measurement of the XEDS spatial resolution. (Think about it and see Chapter 36 later.)

When you insert the beam diameter in the brightness equation, either the FWHM or the FWTM can be used. The FWTM is equal to 1.82 × FWHM and this is also shown in Figure 5.9. You should note, therefore, that you overestimate β if you use the smaller FWHM.

In a dedicated STEM you can't image the beam directly, since there are no post-specimen lenses to magnify its image, no screen on which to project it, and no photographic film to record it. The value of d must be determined indirectly, as in other scanning instruments. The worst method (apart from all the rest) involves scanning the beam across a knife-edge specimen and monitoring the intensity change that occurs, for example, by recording the output from the annular dark-field detector (see Chapter 9). The specimen should be atomically sharp and not transparent to electrons until right at the edge. Such specimens don't exist. This approach yields an integrated intensity profile, as shown in Figure 5.12. In order to extract a value of the FWHM or FWTM from the profile, you must make measurements between various points determined by integrating the intensity from one side of a two-dimensional Gaussian to the other. Nevertheless, the two experimental beam-size measurements in Figure 5.10 show reasonable agreement with the values calculated from the brightness equation. The measurement of d is clearly not a simple procedure.

5.5.E Energy Spread

Remember that the energy spread (ΔE) of the electron beam is a measure of the temporal coherency. This spread is important in EELS and, in fact, the only way to measure the energy spread is to use an electron spectrometer. Under conditions where the spectrometer itself is not limiting the resolution of the spectrum, the value of ΔE can be simply measured by collecting a spectrum of electrons without a specimen in the way of the beam as we describe in Section 37.3.C. The spectrum then consists of a single Gaussian peak and the resolution of the spectrum is defined as the FWHM of this peak. Typical values of ΔE for the various electron

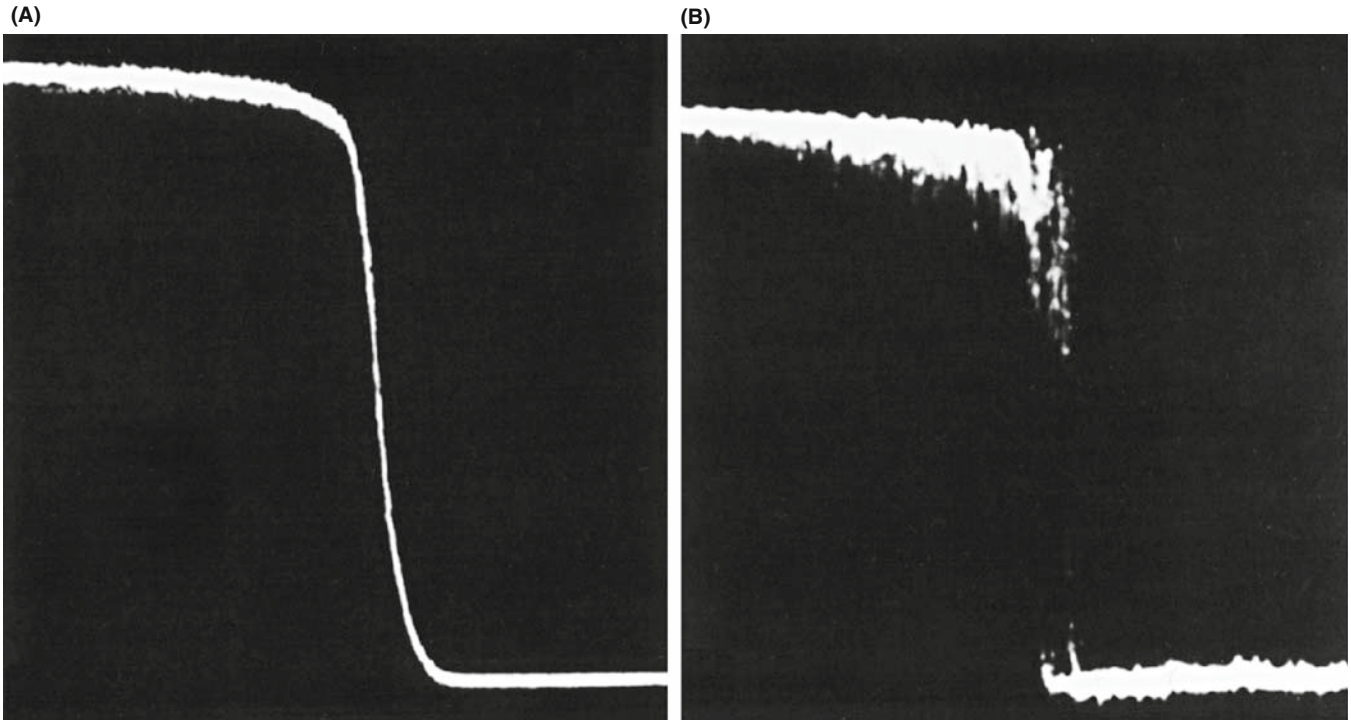


FIGURE 5.12. Intensity profiles obtained by scanning a fine beam across a sharp edge of a cube of MgO. The measured probe size (FWTM) in (A) is 7.4 nm (magnification 1×10^6) and in (B) 1.8 nm (magnification 11×10^6). The smaller probe contains a much smaller current and is thus a much noisier trace.

sources are given in Table 5.1; with a monochromator (see Section 37.7) ΔE for any source can be reduced to $<\sim$100 meV.

5.5.F Spatial Coherency

It's difficult to measure the coherency of the beam experimentally although, as we've discussed, small sources ensure spatial coherency. One practical way of measuring the coherency is to form an image of the edge of a hole in a specimen such as a thin holey carbon film. When you operate slightly out of focus you see alternating dark and bright fringes called Fresnel fringes as shown in Figure 5.13A. Typically, for a thermionic source, only one or two fringes are visible. These fringes are a phase-contrast effect (which we cover in great detail in Part 3). We can also use the fringes to correct astigmatism in the objective lens, as we'll see in Chapter 6. The number of visible fringes is a measure of the beam coherency and Figure 5.13B shows the enormous number that can be generated by a FEG.

5.6 WHAT kV SHOULD YOU USE?

For the materials scientist and nanotechnologist, this is usually an easy question to answer: we'll call it the kV axiom.

THE kV AXIOM

You should always operate at the maximum available kV (unless you shouldn't).

However, there are exceptions to this axiom and the most obvious is avoiding knock-on beam damage, but we'll see others later in the book. So don't forget that you can always operate a modern 300-kV TEM at 100 kV. It's like being able to change the wavelength of a monochromatic light source in a visible-light microscope. As we saw in Chapter 4, the threshold for displacement damage for most metals is less than 400 kV, which is the highest available voltage on 'off-the-shelf' TEMs. For lighter and more beam-sensitive materials such as some ceramics and polymers, lower kV may be better. For most materials specimens, there is not much use going below 100 kV since the images will be rather dim and you'll have to make *very* thin specimens to see anything useful. However, when studying a crystalline specimen by diffraction contrast, 100 kV is better than 200 kV is better than 300 kV, providing you can still see through the specimen! For biological specimens, there is significant advantage to the increased contrast available in lower-kV images and STEM in (30-kV) SEMs is an increasingly useful imaging tool.

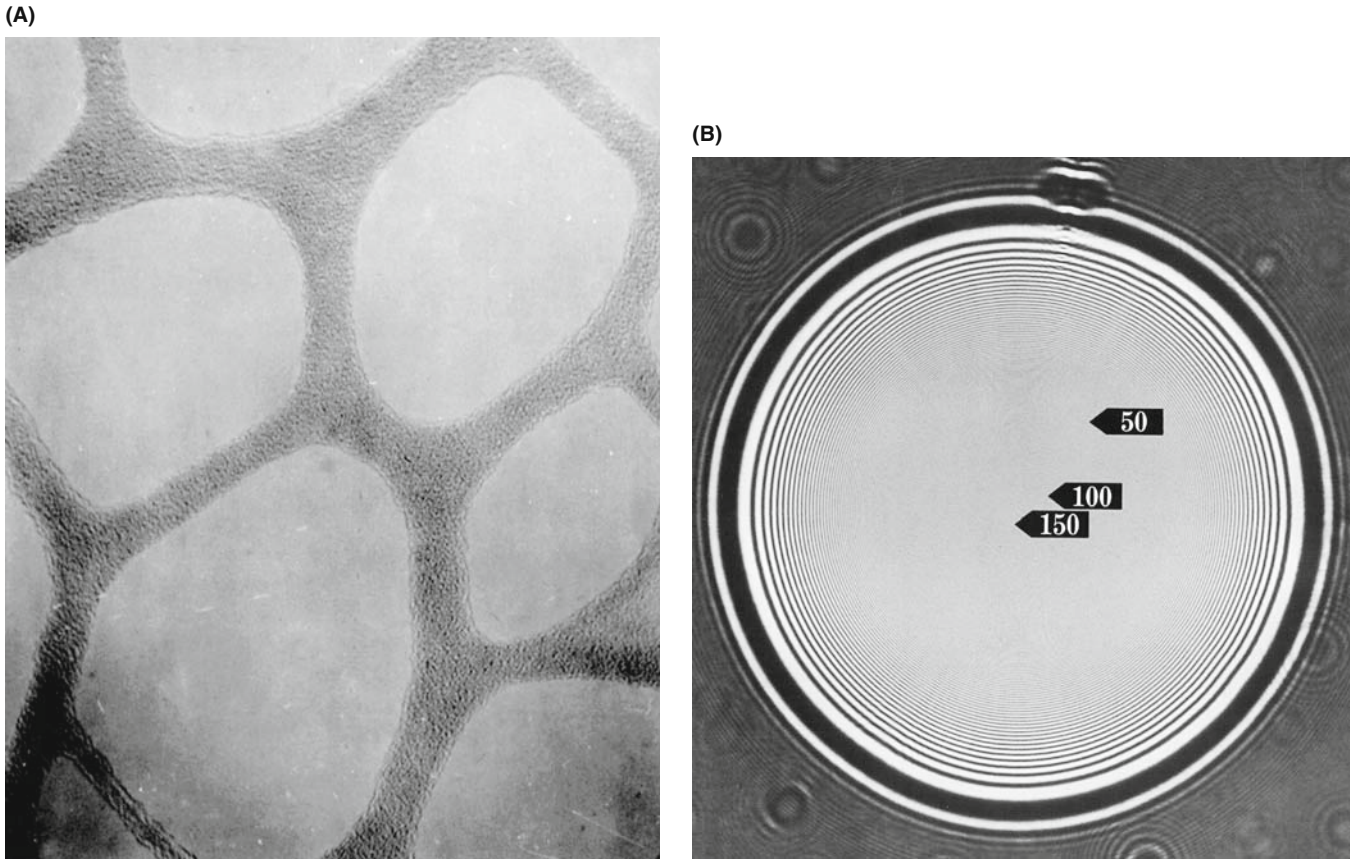


FIGURE 5.13. Fresnel fringes from (A) a thermionic source with poor coherency and (B) a FEG with high coherency.

Apart from these exceptions, the reasons for choosing the highest kV are

- The gun is brightest so you get the most signal to put into your specimen.
- The wavelength is shortest; the image resolution is potentially better.
- The cross section for elastic scatter is also reduced so beam broadening is reduced and analytical spatial resolution is enhanced.
- The cross section for inelastic scatter is smaller, so heating effects may be smaller.
- You can 'see' through thicker specimens.
- The peak to background ratio in X-ray spectra is improved (see Chapter 36).

When you've learned about EFTEM later on, return to this chapter and ask: why not 80 kV?

CHAPTER SUMMARY

Most TEMs use LaB_6 thermionic sources. Take care when heating and cooling your LaB_6 crystal; always operate just below saturation to maximize the lifetime of the source and (almost) always operate at the highest kV. If you're doing high-resolution work of any kind, find a FEG TEM and for high-resolution imaging, then the degree of coherency is important too. If you're doing XEDS, get some idea of the beam current that you can get from your FEG under typical operating conditions. Also measure the beam size and convergence angle to give a measure of β. If you're doing EELS then the energy spread is essential information and you may need to find one of the rare, monochromated TEMs. Treat your source particularly carefully if your TEM is of such a vintage that you have to change it, align it, saturate it, or switch it off. There's nothing more annoying than losing your source since it usually happens at some critical point during your work. Fortunately, computer control is making such events much rarer.

SOME HISTORY

Why include a note on history? Because you should/will study old papers. The sources used in the 1950s and 1960s were so-called W hairpins. The simple hairpins were replaced by pointed W filaments (hairpins with an atom-probe-like tip attached). In the 1970s, LaB_6 filaments replaced W as more efficient emitters. Other materials might be more efficient, but... In the late 1980s, FEGs began to be used in several labs. By the 2000s, these are the sources of choice, especially for those who can afford them. So, we are back to the pointed filament. Now, consider how the TEM techniques had to be different in those old papers.

SOURCES

Broers, AN 1974 in *Recent Advances in Scanning Electron Microscopy with Lanthanum Hexaboride Cathodes* SEM 1974 9–18, Ed. O Johari IITRI Chicago IL.

de Jonge, N and van Druten, NJ 2003 *Field Emission from Individual Multiwalled Carbon Nanotubes Prepared in an Electron Microscope* Ultramicroscopy **95** 85–91. Demonstrated a brightness in excess of $10^{14}A/m^2sr$.

Hawkes, PW 1978 *Coherence in Electron Optics* Adv. Opt. Electr. Microsc. **7** 101–184.

Orloff, J 1989 *Survey of Electron Sources for High-Resolution Microscopy* Ultramicroscopy **58** 88–97.

Veneklasen, LH 1972 *Some General Considerations Concerning the Optics of the Field Emission Illumination System* Optik **36** 410–433.

THE PROBE

Michael, JR and Williams, DB 1987 *A Consistent Definition of Probe Size and Spatial Resolution in the Analytical Electron Microscope* J. Microsc. **147** 289–303. Details on how to measure the diameter of the probe.

Mook, HW and Kruit, P 1999 *On the Monochromatisation of High Brightness Electron Sources for Electron Microscopy* Ultramicroscopy **78** 43–51. Application to EFTEM.

THE COMPANION TEXT

There is much more in-depth treatment of electron guns in the companion text. Electron coherence is a very tricky topic that the most experienced of us can still confuse. It is examined in the discussion of lenses and of holography in the companion text.

URLs

1) http://www.matter.org.uk/tem/electron_gun/electron_sources.htm

SELF-ASSESSMENT QUESTIONS

Q5.1 State the two types of electron sources currently used in TEMs and explain how they work.
Q5.2 Name two thermionic sources and the properties that make them useful.
Q5.3 What is the difference between a field-emission and thermionic source TEMs?
Q5.4 What is brightness and how does it change with kV?
Q5.5 When is high brightness most useful? When is low brightness useful?
Q5.6 Name the five most important properties or characteristics of an electron beam?
Q5.7 What are some reasons to choosing the highest kV when operating a TEM?
Q5.8 What is the purpose of the Wehnelt in a thermionic source? Why don't we need one in a FEG?
Q5.9 Describe the purpose of the two anodes in a FEG.
Q5.10 Why is a FEG operated under high-vacuum conditions?
Q5.11 If faced with the urge to 'crank up the temperature' on the LaB_6, how long between each heat setting should a wise microscopist wait?
Q5.12 What are the limitations of a field-emission TEM?
Q5.13 How would you maximize the coherency of the source?
Q5.14 What is the 'saturation condition' for a thermionic source?
Q5.15 Why would you operate your thermionic filament just under the saturation condition?
Q5.16 How do you know you have achieved gun saturation while using the TEM?
Q5.17 What is spatial coherency and why is it important?
Q5.17 What is temporal coherency and how is it measured?
Q5.19 Name three ways to increase the coherency of the beam.

TEXT-SPECIFIC QUESTIONS

T5.1 Carefully redraw Figure 5.1 to scale.
T5.2 Sketch Figures 5.5A and 5.5C with scale bars.
T5.3 By considering equation 5.3 explain
A. Why a LaB_6 source brightness varies as a function of the orientation of the LaB_6 crystal?

B. Why adjusting the voltage on the Wehnelt can change the apparent brightness of a thermionic source? (Hint: look at Figure 5.4.)
C. Why the brightness of a cold FEG is generally higher than that of a (thermally assisted) Schottky FEG?
D. Why a tungsten source gets brighter if you sharpen the tip of the hairpin?

T5.4 Why is the concept of gun brightness generally not relevant when observing a specimen in TEM mode? Under what operating conditions does the brightness become crucial and why?

T5.5 Estimate the approximate power density in the probe when a FEG puts 1nm of current into a spot of diameter 1nm and a LaB_6 gun puts 10 pA into 1nm. Show all steps and justify any approximations.

T5.6 If the emission current from a thermionic source is several hundred μA (see Figure 5.4B), why does the beam at the specimen contain only a few hundreds or thousands of picoamps?

T5.7 Calculate the beam size for a 100-keV FEG source from the data in Chapter 1, Table 5.1, and equations 5.7, 5.8, 5.9, and 5.10. State any assumptions. Compare your data with Figure 5.10.

T5.8 From Figure 5.10, explain why it would be useful to be able to use larger apertures in the probe-forming system and what prevents us from doing so in most TEMs until recently? (Hint: go back to the questions for Chapter 1.)

T5.9 From the data in Figure 5.10 calculate the beam brightness.

T5.10 Why do you need a different C2 aperture for each possible C1 lens setting? Do you have such a range of apertures on your microscope? (Hint: look at Figure 5.11.)

T5.11 Why is the probe size measured in different ways in a TEM and a dedicated STEM (compare Figures 5.11 and 5.12).

T5.12 Can you think of any use for the much larger number of Fresnel fringes in FEG-TEM images compared with thermionic-source TEM images, such as in Figure 5.13?

T5.13 How would the data in Figure 5.7 change if you had not flashed the tip?

T5.14 Can you think of any other suitable specimens for measuring the experimental probe size by the method shown in Figure 5.12?

T5.15 Can you think of what effect a non-Gaussian probe shape might have on (A) your STEM images and (B) your analyses in AEM?

T5.16 Which line in Figure 5.10 would change for a TEM with a spherical-aberration corrector? Which way would it move and what would be the consequence for the minimum probe dimension?

T5.17 Why is a Schottky field emitter so called?