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A COMPARISON OF LANTHANUM HEXABORIDE, COLD FIELD EMISSION AND THERMAL FIELD EMISSION ELECTRON GUNS FOR LOW VOLTAGE SCANNING ELECTRON MICROSCOPY

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Abstract

A comparison of lanthanum hexaboride, cold W(310) field emission and Zr/W thermal field emission cathodes was made by calculating the current-spot size relationship for each, using comparable lenses, to determine which would be suitable for high current operation at 1 keV beam energy, with a focused beam diameter $\lesssim$ 0.05 μm. On the criteria of highest current, reasonable operating conditions for the gun for low noise operation and long term cathode stability it was found that the lanthanum hexaboride and cold field emission cathodes are inadequate or marginal and that the best performance is obtainable from the thermal field emission cathode.

Key Words: Field Emission, Thermal Field Emission, Cold Field Emission, LaB_6, Electron Gun, Scanning Electron Microscopy, e-Beam Inspection

Introduction

Electron beam testing of semiconductor devices is a subject of rapidly increasing importance. In fact, e-beam testing may well be the most important use of low voltage scanning electron microscopy. It is of interest to make a comparison of the cathodes which can be used for low voltage SEM, because the performance of an electron gun is quite different at the ≈ 1 keV beam energy appropriate for e-beam testing than at the more usual energies for SEM, E ≈ 20 keV. High energy beams can only be used for testing robust devices which will not be damaged by the penetration of the beam through the passivation layer [59].

The problem of e-beam testing of semiconductor devices is a difficult one because, for a variety of reasons one would often like to work at high speed, which requires high beam current, yet a reasonably high resolution, 0.05 μm or better is usually necessary. The exception to this would be voltage contrast microscopy at a point, but for inspection or line width measurement--perhaps the most important applications in terms of the volume of work--high current and good resolution will both be necessary at low beam energy. This is a difficult requirement.

In this paper we compare three electron guns: lanthanum hexaboride (LaB_6); cold field emission (CFE); and thermal field emission (TFE), for low voltage, high current operation and to indicate which would be best suited for high current, moderately high resolution low voltage SEM. This is done by first comparing the current-spot size relations for the three guns using realistic optics in the voltage, current and spot size regime necessary for e-beam testing; such a comparison allows one to determine which cathode will give useful performance. Next, we consider the noise current, stability and lifetimes of the three kinds of cathodes, including design and vacuum constraints imposed by each.

The criteria for the best cathode are: (1) maximum current into a ≈ 0.05 μm beam spot at low (1 keV) energy; (2) sufficient long-term stability and reliability to be usable in a semiconductor fabrication line.

Symbols

Q	charge measured in coulombs
C_s	spherical aberration coefficient on lens object side (mm)
C_{si}	spherical aberration coefficient on lens image side (mm)
C_{co}	chromatic aberration coefficient on lens object side (mm)
C_{ci}	chromatic aberration coefficient on lens image side (mm)
δ	electron source optical size (μm)
M	linear magnification
m	angular magnification
α_o	divergence angle of beam entering optical system (mrad)
α_i	convergence angle of beam on target (mrad)
E	beam energy (eV)
ΔE	beam energy spread (eV)
V_o	voltage of beam on object side of lens (volts)
V_i	voltage of beam on image side of lens
V_B	beam voltage
h	Planck's constant
e	electronic charge
d	focused beam diameter (Å or μm)
I	electron current (A)
I_t	total cathode current (A)
I_b	focused beam current (A)
J_c	cathode current density (A/cm^2)
$\frac{dI}{d\Omega}$	angular intensity (A/sr)
β	source brightness (A/cm^2 sr)
F	electric field (volts cm^{-1})
ΔZ_i	shift of image position due to lens aberrations (μm)
f	frequency (Hz)
ΔI	noise current (A)
T	temperature (K)
θ	cone angle of field emitter
γ	surface tension (joule/m^2 or dyne/cm)
P	pressure (torr)

Properties of LaB_6, CFE and TFE Cathodes

LaB_6

The best thermionic cathode for SEM, in terms of brightness and lifetime, is LaB_6. Properties of this material and its applications as a cathode have been thoroughly treated in the literature [17,18,27,33,39,43,45,46,47,53,54,58,66,70]. The most commonly used thermionic cathode in electron microscopy is made from tungsten (W). While rugged, W cathodes are not able to provide high cathode current density (J_c) and long life simultaneously. The reason is that the work function of W is high--about 4.5 eV--so that it has to be operated at a very high temperature in order to achieve large values of J_c. For example, at a temperature of 2700 K J_c = 1.63 A cm^{-2} and the evaporation rate is 3.2×10^{-8} gm cm^{-2} sec^{-1}. At this rate the cathode life is only ~ 50 hours. Since the evaporation rate depends exponentially on the temperature, the lifetime is greatly shortened by further heating. Thus, while J_c is roughly doubled by raising the cathode temperature from 2700 K to 2800 K, the evaporation rate is increased by a factor of 3.5, from 3.2 to 11×10^{-8} gm cm^{-2} sec^{-1}, and the lifetime is reduced correspondingly.

LaB_6 is a rather unusual material in that its volatility is low when J_c is high by comparison with W, because it has a much lower work function. The work function of the (100) crystal plane of LaB_6 is approximately 2.5 eV [54], and J_c of 1.5 A cm^{-2} can be drawn from it at a temperature of ≈ 1500 K. At this temperature the evaporation rate is ≈ 10^{-13} gm cm^{-2} sec^{-1} [54]. If the temperature is raised to 1700 K, J_c = 13 A cm^{-2} and the evaporation rate is ≈ 10^{-10} gm cm^{-2} sec, implying a cathode life more than an order of magnitude greater than W. Clearly, LaB_6 can be a far superior cathode to W and, indeed, it is successfully used in many commercial SEMs and e-beam lithography systems. Because of the high J_c, LaB_6 cathodes can be made with a small emitting area and in single-crystal form, so that the emission is essentially drawn from only a few or even one crystal plane, and is uniform and stable [17,18,39,47,54,58].

About the only disadvantage of the LaB_6 cathode vis-a-vis the W cathode is the requirement for high vacuum. LaB_6 forms volatile oxides of La and B in the presence of water vapor or oxygen [47], consequently the vacuum must be better than that generally acceptable for W in order to achieve long life. Unfortunately, this means it is not simple to retrofit an SEM designed for a W cathode with a LaB_6 cathode. In our laboratory we have observed that different crystal planes oxidize at different rates, so that emission patterns from the cathode will change with time in poor vacuum ($P \gtrsim 10^{-7}$ torr) [46]. We have successfully operated cathodes for 3000 hours at 1×10^{-9} torr, while at 10^{-7} torr significant degradation of the cathode is seen in ~ 500 hours.

The brightness β of LaB_6 cathodes has been measured by a number of workers [18,27,47,58] to lie in the range $5 \times 10^5 - 2 \times 10^6$ A cm^{-2} sr^{-1} at a cathode temperature of 1800 K and at 20 kV. Variations occur depending on the precise gun geometry and on the crystallographic orientation and shape of the cathode. Hohn et al [27] found the relative brightness of several orientations of conical cathodes having apex radii of 2 μm to be $\beta(100) = \beta(321) > \beta(210) > \beta(311)$. Takigawa et al [58] measured the brightness of <100>, <110> and <111> oriented LaB_6 cathodes with 15 μm radii and found $\beta(100) > \beta(110) > \beta(111)$. Of equal significance are the emission characteristics of cathodes with different end radii. If a conical shaped cathode has a small end radius, both the tip and part of the cone will contribute current to the crossover. If the end radius is large or the end of the cone has a flat ground on it, then it can be arranged that only the end or the flat will contribute significant current to the crossover. Furukawa et al [17] found that a cathode with a 100 µm end radius was capable of a uniform angular distribution at a total current I_t = 0.7 mA, whereas the angular distribution became nonuniform for smaller radii cathodes at lower currents, due to emission from the side of the cone. Although smaller crossover diameters could be achieved at high currents with large radii cathodes, the emittance, i.e. product of crossover size and angular spread of the beam, was also larger.

For use in SEM, the cathode radius seems not to be critical. The orientation is important, to maximize emission. The cone angle is also important, because of the anisotropy of volatilization rates for different crystal planes [46,54], unless the gun vacuum is very good ($\lesssim 10^{-7}$ torr).

At 1 kV, β will be reduced from its value at 20 kV by a factor of 20. This cannot be avoided, whether the electron gun is operated at 1 kV or at higher voltage with the beam decelerated by an electrostatic lens following the gun, however it may be useful to operate in the latter mode. It is well known that a high current electron beam can be spread spatially due to beam interaction effects, and this phenomenon is a function of beam energy [30]. If the beam were extracted from the gun at high voltage and decelerated after much of it had been removed by an aperture, beam interaction effects would be reduced.

The noise current ΔI associated with a beam current I_b will determine over what ranges of I_b and bandwidth an instrument can be employed. All cathodes will exhibit shot noise (statistical fluctuations proportional to $I_b^{1/2}$), and they may also suffer from additional (flicker) noise due to thermal motion of atoms, adsorption and desorption of gas molecules which affect the work function, current spikes from microgeometric changes due to ion bombardment etc. A discussion of the effect of noise as it relates to the above example of e-beam testing will be given below. In our laboratory we have measured the spectral density function and the fractional noise current $\frac{\Delta I}{I_b}$ for a LaB_6 cathode in a commercial SEM, and found that the flicker noise decreased as 1/f, as expected, where f is the frequency, with the spectral density function decreasing to the shot noise level at f ≈ 400 Hz. Shot noise current is given by

$$\Delta I_{shot} = \sqrt{2eI_b f} \qquad (1)$$

and for the LaB_6 cathode we found

$$\frac{\Delta I}{I_b} = \left[9.07 \times 10^{-9}\, \ell n\left(\frac{400}{0.1}\right) + \frac{2e(f-400)}{I_b}\right]^{1/2} \qquad (2)$$

For a bandwidth of f = 10^6 Hz, and I_b = 1 nA, ΔI is essentially all due to shot noise.

Measurements by Pfeiffer [40] indicate that the energy spread ΔE for an electron beam drawn from a pointed LaB_6 cathode is proportional to $\sqrt{\beta\delta}$, where δ is the optical source size, i.e., the crossover diameter. For $\beta = 1.5 \times 10^5$ A cm^{-2} sr^{-1}, Pfeiffer measured ΔE = 1 eV, when δ ≈ 10 µm.

CFE

CFE has been successfully exploited in commercial and laboratory SEMs, conventional transmission electron microscopes and scanning transmission electron microscopes and has been treated extensively in the literature [4,6-11,13,15,16,20,22,23,32,35,36,41,42, 49,52,60,61,63,64,69]. Field emission is a process whereby electrons are extracted from a conductor, usually a refractory metal, by deforming the potential barrier at the vacuum-metal interface to such an extent that electrons can tunnel through it [23]. This is in contrast with thermionic emission, where thermal energy has to be imparted to electrons to enable them to surmount the potential barrier. The barrier is deformed by applying an electric field F of the order of 10^7 V cm^{-1}. Such a high field can be produced with a reasonable voltage only if the field emitter has a very small radius of curvature, typically 0.01 to 0.3 µm; thus field emitters are made in the form of extremely sharp needles. For a field emitter, J_c is given by [23]

$$J_c = \frac{1.54 \times 10^{-6}\, F^2}{\phi\, t} \exp\left[-6.83 \times 10^7 \frac{\phi^{3/2}}{F} v\right] \text{ A cm}^{-2} \qquad (3)$$

where ϕ is the work function and t and v are slowly varying functions of F and ϕ and which are of the order of unity.

It is well known from classical electrodynamics that the stress due to an electric field is proportional to the square of the field. At the high fields necessary for a field emission cathode the emitter is highly stressed [15] and so the emitter must usually be fabricated from a refractory material. The most commonly used material for electron microscope cathodes is W, although there may be more suitable materials, as will be discussed below.

The current distribution from a CFE cathode is usually contained within a cone of half-angle ~ 20° [6]. If one assumes an approximately uniform distribution, then at 20 µA total current the angular intensity $\frac{dI}{d\Omega} \approx 5 \times 10^{-5}$ A sr^{-1} and the corresponding brightness, measured at the emitter is $\beta \approx 2 \times 10^8$ A sr^{-1} cm^{-2}, some 2-3 orders of magnitude greater than that of thermonic cathodes. In addition, the best thermionic cathodes achieve $\beta \sim 10^6$ at relatively high voltages, ≈ 20 kV, whereas the CFE cathode can achieve its high brightness at much lower voltages, with typical operating voltages lying in the range of 3-6 kV.

CFE requires very good vacuum for long-term, stable operation [10,11,35,36,42,60]. There are several reasons for this. Residual gas molecules which adsorb on the field emitter will cause a change in the work function with a consequent change in the field emission current. From Eq.(3), we see that $\frac{dI}{I} \sim 1.5 \frac{d\phi}{\phi}$. A 1% change in ϕ can cause a ≈ 15% change in I [35]. If the adsorbed molecule then diffuses about the emitter surface, the current will fluctuate; this is the source of flicker noise. Another source of noise is sputter induced damage to the emitter caused by ion bombardment of gas molecules ionized by the electron beam. Such damage results in a local change in the radius of curvature of the emitter and therefore of the electric field. The current change is $\frac{dI}{I} \sim \frac{dF}{F}$ and a 1% change in F can cause ≈ 10% change in I. This usually manifests itself in the form of random current spikes. Also, adsorbed gas molecules will be sputtered off the cathode surface, which will result in a random work function and current change. In addition to noise, ion bombardment which causes local changes in radius can lead to emitter failure by the initiation of a vacuum arc. The arc is caused by the increase of field emission current which heats the emitter near the sputtered asperity. The heated region deforms and becomes sharper under the stress of the field. Runaway emission follows, which destroys the emitter [4,6,35]. Since instabilities are seen even at $P \sim 10^{-9}$ torr, it has been found necessary to periodically "flash" the cathode to a high temperature, ≈ 2000 K, to both anneal the emitter and desorb gases [41,50]. The high voltage usually must be shut off during this procedure, necessitating shutting off the SEM. If in the electron gun $P < 10^{-9}$ torr, such tip conditioning is necessary on a time scale ~ 50 hours [10]. Long term operation without flashing requires $P \sim 10^{-12}$ torr [35,36].

Todokoro et al [60] and Saitou [42] have shown that virtually all of the ions which impinge on the emitting region of the cathode are formed very close to the cathode, generally within a few tip diameters, if the pressure is greater than about 2×10^{-11} torr. The percentage fluctuation $\frac{\Delta I}{I}$ due to residual gas pressure was found [42] to be proportional to log $(P \times I/9 \times 10^{-15})$, where P is in torr and I in amperes, with $\frac{\Delta I}{I} \approx 1\%$ at $P \times I = 9 \times 10^{-15}$ A torr. Thus at $P = 5 \times 10^{-9}$ torr and $I = 40\ \mu A$, $\frac{\Delta I}{I} \approx 3\%$ due to ion bombardment. At $I = 20\ \mu A$, $\frac{\Delta I}{I} \approx 2.5\%$. This underscores the need for high vacuum in the electron gun if high currents are to be produced. An additional source of noise in the CFE cathode is the migration of atoms across the crystal planes. It has been found [52] that for W emitters, this source of noise can be significant at room temperature on the (310) plane, which is commonly the plane oriented on the optical axis of a CFE cathode. The threshold for onset of noise on the (310) plane due to migration of W atoms, is 300 K, while the threshold temperatures on the (112) and (100) planes are 650 K and 1000 K respectively; unfortunately the work functions of the (112) and (100) planes are 4.65 eV and 4.52 eV, respectively, compared with ϕ = 4.35 eV for the (310) plane. Because of the exponential dependence on $\phi^{3/2}$, much higher electric fields would be required to obtain useful emission from the (110) or (100) planes than from the (310) plane, and it is not practical to orient CFE cathodes along those directons. Based on the results for the measurements of $\frac{\Delta I}{I_b}$ on the (310) plane of W at 900 K [34], it is estimated that at 300 K $\frac{\Delta I}{I_b}$ would be about 0.5%, over a bandwidth 50 Hz < f < 10^5 Hz [20].

In our laboratory we have modified a commercial CFE SEM (CWIKSCAN Model 100) for use with both CFE and TFE cathodes [56]. At $P \approx 7 \times 10^{-9}$ torr, measurements of the noise current of a CFE W(310) cathode, at room temperature, gave $\frac{\Delta I}{I_b} \approx 5\%$ at $I_b = 0.7$ nA and bandwidth 0.1 Hz < f < 25 kHz. The spectral density function fell to the shot noise level at f ≈ 20 kHz. The shot noise current in the bandwidth 0.1 Hz < f < 25 kHz at I = 0.78 nA is $\frac{\Delta I}{I_b} = 0.3\%$ [48], so the noise current is mainly due to flicker noise. Zaima et al [73] found similar results, although with a smaller bandwidth, at $P \approx 8 \times 10^{-10}$ torr.

From these results we see that shot noise and flicker noise due to the thermal motion of atoms on the emitter surface are negligible at room temperature but that there will be significant flicker noise and noise from sputter induced damage and desorption of adsorbed gas unless the pressure is very low. The magnitude of these effects is highly instrument dependent, and will be a strong function of the quality of the design of the electron gun and its vacuum system.

Energy spread measurements indicate that $\Delta E \approx 0.2$ eV at $\frac{dI}{d\Omega} = 1 \times 10^{4}$ A sr^{-1}, increasing to $\Delta E = 1 \pm 0.2$ eV at $\frac{dI}{d\Omega} = 5 \times 10^{-4}$ A sr^{-1} [3].

Because of the substantial noise current seen with W CFE cathodes, even when $P \approx 10^{-9}$ torr, interest has revived in development of cathodes which are less affected by residual gas, i.e., have a lower probability for adsorption. Martin and coworkers reported [36] field emission from ZrC, which is quite refractory but, perhaps because of the ease of fabrication of W cathodes in comparison with the carbides, it has been little used. Zaima et al [73] recently investigated emission from TaC and found that at $P \lesssim 3 \times 10^{-10}$ torr the flicker noise was absent, although there were still current spikes. These were attributed to sputtering events, as their number was proportional to P × I. The absence of flicker noise was believed to be due to a very low probability for O_2 and N_2 to adsorb on TaC, compared with W. When the pressure was increased to 2×10^{-9} torr, flicker noise was again seen. It could be made to disappear by flashing to 1500 K, when the pressure had been lowered to 3×10^{-10} torr again.

Similar results obtain with TiC emitters. This is a more difficult material to work with because it is hard to produce stoichiometric TiC:

HfC might be a better choice. However, Futamoto et al [19] found quite different results with TiC, noting little improvement over W(310). This was attributed to the reactivity of Ti with O_2 and N_2, when the concentration at the surface increased after heating. This seems to indicate the difficulty of producing, or maintaining the correct stoichiometry at the surface.

TFE

TFE developed out of attempts to overcome the stability problems of CFE by operating the field emitter at high temperature, $T \gtrsim 1500$ K, to anneal sputter-caused damage and to remove adsorbed gas molecules which would cause current fluctuations [14]. This was thought to be essential if field emission cathodes were to be employed on a practical basis, as it was clear that the level of vacuum required for long life without frequent flashing of the cathodes, $P \lesssim 10^{-12}$ torr, was impossible to achieve in any but the most highly specialized instrumentation. The TFE cathodes which have been developed have proven to be unique in their capabilities; they have been carefully studied [3,12,14,34,48,50,51,55,62] and a number of technologically important applications have been reported [28,29,31,56,52,65,67,71,72].

When a field emitter is heated in the absence of an electric field, the atoms migrate from the emitter apex towards the emitter shank [2,14], with the rate of increase of radius (or dulling) of the apex given for W, by

$$\frac{dr}{dt} = 2.6 \times 10^{-11}\ \theta\ \exp\left[\frac{-36300}{T}\right] (Tr^3)^{-1} \left(\frac{cm}{sec}\right), \quad (4)$$

where θ is the cone angle of the emitter, and T the temperature [41,42]. If an electric field is applied, the rate of dulling is modified by the factor $\left(1 - \frac{rF^2}{8\pi\gamma}\right)$, where γ is the surface tension [14,48]. If $F = F_c = \left(\frac{8\pi\gamma}{r}\right)^{1/2}$, the emitter should be stable; if F is less than or greater than F_c, the emitter will either become duller or sharper with time, respectively. Of course, the local radius is different at different locations near the apex of the emitter, so the value of F can vary and may exceed F_c at some points and equal F_c at others. If $F > F_c$, the emitter behavior is rather complex, because different crystal planes have different energies for the nucleation of new atomic layers and some will facet more quickly than others. The result is the emitter assumes a polyhedral shape ("build-up") [5]. Emission current can be very high at the intersections of the crystal planes, leading to further heating and eventual destruction of the emitter; consequently, there are few stable shapes.

The surface tension of W is 2.9 joule m^{-2} = 2900 dyne cm^{-1}, so $\frac{dr}{dt}$ nominally vanishes when $F_c = 8.1 \times 10^4\ r^{-1/2}$ V cm^{-1}. For clean W, the work function of 4.5 eV requires $F \sim 4$ to 8×10^7 V cm^{-1} in order to obtain useful currents, that is $I_t \sim 1$ to 1000 μA, according to Eq.(3). If $F = 6 \times 10^7$ V cm^{-1}, corresponding to $I \sim 10$ to 100 μA, $r < 0.02$ μm in order to avoid buildup. This is an extremely small value for the radius.

There are two practical, tungsten TFE cathodes. One is clean W, oriented in the <100> crystalline direction (W(100)), the other is zirconiated, <100> oriented W (ZrO/W(100)) [51]. No other practical TFE cathodes have been reported, although it is possible to fabricate TFE cathodes from other refractory materials. We limit our discussion to these two.

The W(100) TFE cathode is formed by operating a slightly oxidized emitter at ≈ 1800 K and allowing build-up to occur. The apex of the emitter changes shape as the (110), (112) and (310) planes facet at the expense of the (100) plane [48]. After a fairly short time, the (100) plane is reduced to a very small area at the end of a pyramidal shape. This area is $\lesssim 100$ Å in diameter and consequently the local radius of the emitter is quite small, so electron emission is very intense and localized to within ≈ 6° of the axis of the emitter [65] and $\frac{dI}{d\Omega} = 1$ mA sr^{-1} is easily attained. Long lifetimes have been measured for this cathode, and it can be operated reliably at pressures up to 1×10^{-8} torr [51].

There are two difficulties with the W(100) cathode. Because the area of emission is extremely small J_c is extremely high, $\sim 10^7$-10^8 A cm^{-2} at $\frac{dI}{d\Omega} = 10^{-3}$ A sr^{-1}. Consequently, the energy spread in the beam is quite large [3,51], $\Delta E \approx 2$-3 eV. This severely tests the electron optics of any system. A second problem stems from the very small area of emission; since only a rather small number of atoms are included in this area, any change in the number or position of these atoms will cause a significant fluctuation in the beam current [22]. Noise studies on W(100) typically show $\frac{\Delta I}{I} \approx 3$-10% in the frequency interval 1 Hz < f < 10^4 Hz at currents ranging from 30 nA to 220 nA. These two characteristics make it difficult to apply the cathode for electron beam testing.

The ZrO/W(100) TFE cathode takes advantage of the fact that ZrO selectively lowers the work function of the (100) plane of W to ≈ 2.6 eV [23]. From Eq.(3) we see that a reduction of ϕ from 4.5 eV to 2.6 eV would permit a reduction of F by a factor of ~ 2 while maintaining J constant. Consequently, it is possible to operate the ZrO/W cathode with a radius ~ 0.1 μm at high angular intensities while remaining below the field strengths that would cause build up [48,50,51]. It is actually possible to use cathodes with even a larger emitting area, ~ 1 μm in diameter, because the low work function (100) plane forms a relatively stable facet after which the emission current is unchanged.

Many more emitting sites are included than in the case of W(100), and noise studies confirm this, with $\frac{\Delta I}{I_b}$ typically < 1% in the interval 1 Hz < f < 10 kHz and I_b ranging from 25 nA to 250 nA [51,62]. At frequencies up to ~ 25 kHz the main component of noise in the current is flicker noise due to thermal motion of the atoms in the emitting area. The spectral density function falls off slowly in

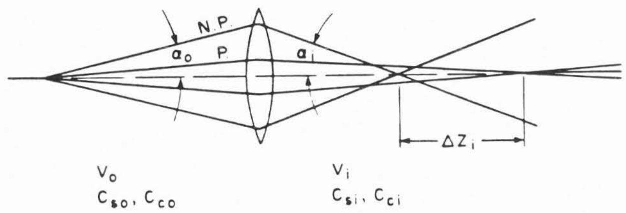

Figure 1. A schematic representation of a lens with spherical and chromatic aberration coefficients C_{so} and C_{co} referred to object space, C_{si} and C_{ci} referred to image space. The spherical aberration causes a shift Δz_i in the image position for non-paraxial (N.P.) rays subtending angle α_o, compared with paraxial (P.) rays. V_o and V_i are the potentials of object and image space, respectively, and $\alpha_i = m\alpha_o$.

the range 1 Hz-10 kHz and then decreases as ~ $\frac{1}{f}$ [62], reaching the shot noise level at roughly 25 kHz [48]. Empirically, it has been found [34] that

$$\frac{\Delta I}{I_b} = \left[\frac{2.53 \times 10^{-9}}{\alpha_o} + \frac{2e\,(f - 25{,}000)}{I_b}\right]^{1/2} \qquad (5)$$

At a temperature $T \approx 1800$ K and $P < 1 \times 10^{-8}$ torr, current spikes are not seen in either the W(100) or the ZrO/W cathode.

Method of Calculation

We now make a comparison of the current-spot size relations for the three electron guns. This is done by calculating the contribution to the final beam spot size of: (1) the optical size of the electron source; (2) the spherical and chromatic aberrations of the optical system; and (3) the effect of diffraction at the beam limiting aperture. For the relatively small viewing areas involved, the off-axis aberrations such as coma are not important and are ignored. This topic has been thoroughly developed and notation standardized in numerous articles on electron optics; the reader is referred to the standard textbooks for complete treatments, e.g., Klemperer and Barnett [30], Grivet [24], Septier [44], Hawkes [26], Glaser [21], and Zworykin et al. [74]. We briefly review the concept.

Spherical aberration is the result of a lens focusing rays which are farther from the axis more strongly than those which are close to the axis, as shown in Figure 1. The resultant minimum beam diameter for a point object is

$$d_s = \frac{1}{2} C_{si}\, \alpha_i^3 \qquad (6)$$

where C_{si} is the spherical aberration coefficient (units-length) referred to the image side of the lens. The aberration coefficient when referred to the object side of the lens is

$C_{so} = \left(\frac{V_o}{V_i}\right)^{3/2} M^{-4}\, C_{si}$, in which case $d_s = \frac{1}{2} M\, C_{so}\, \alpha_o^3$. α_i and α_o, the angles of the trajectories with respect to the lens axis are defined in Figure 1. The linear magnification of the lens is M and the corresponding angular magnification is $m = M^{-1} \left(\frac{V_o}{V_i}\right)^{1/2}$. Here, V_o and V_i refer to the energy, or voltage of the electron beam on the object and image sides of the lens, respectively. For a magnetic lens $V_o = V_i$; V_o is often different from V_i for an electrostatic lens.

Chromatic aberration is a lens defect caused by the inability of a lens to focus particles of different energies initially following identical trajectories, to the same point. This effect is proportional to the spread of energy in the beam, thus if $E = E_o \pm \Delta E$,

$$d_c = C_{ci} \frac{\Delta E}{E_i} \alpha_i = M\, C_{co} \frac{\Delta E}{E_o} \alpha_o \qquad (7)$$

where C_{ci} and C_{co} are the image and object side aberration coefficients, respectively, $E_o = eV_o$ and $E_i = eV_i$ are the nominal beam energies on the object and image sides of the lens, respectively and ΔE the spread in the energy of the beam, usually taken to be the full width at half maximum of the current vs energy distribution. The units of C_c are length and $C_{co} = (V_o/V_i)^{3/2} M^{-2} C_{ci}$.

The wave nature of matter is expressed by the deBroglie relation $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$. For an electron, $\lambda \approx \frac{12}{\sqrt{V}}$ Å, where V is the voltage through which the electron has been accelerated from rest. This manifests itself in the diffraction of a beam of electrons when it passes through a small aperture. If the aperture is on the image side of the lens, the effect of diffraction is to contribute to the final beam size an amount

$$d_d \approx \frac{15}{\sqrt{V_i}\, \alpha_i} \text{ Å} \qquad (8)$$

If the aperture is on the object side of the lens, $d_d \approx \frac{M\, 15}{\sqrt{V_o}\, \alpha_o}$ Å.

Finally, there is the contribution of the optical size of the source. This is $d_g = M\delta$, where δ is the optical diameter of the crossover and M is the total linear magnification of the optical system: if the system consists of several lenses with magnification $M_1, M_2 \ldots M_k$, then $M = M_1 \times M_2 \ldots \times M_k$. In a field emission gun there is no actual, physical crossover; δ is the "virtual" crossover diameter, determined by tracing the tangents to the trajectories far from the field emitter, back inside the emitter [16,69]. The waist of these tangents gives δ (see Fig. 2). The crossover in a gun with a thermionic

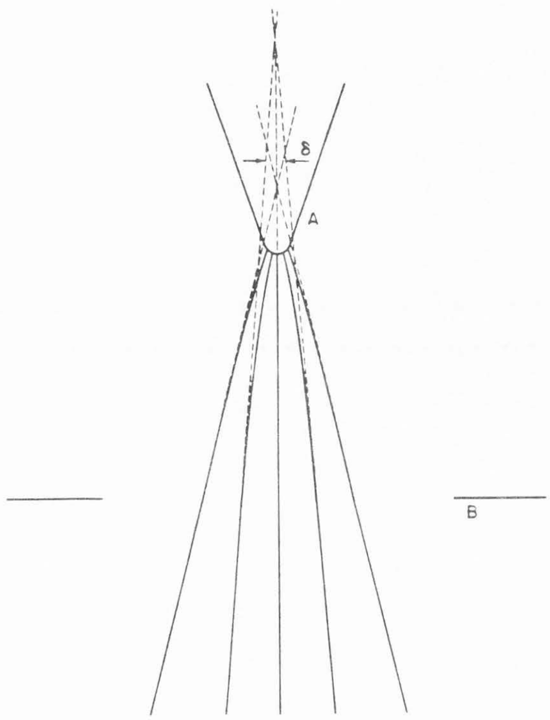

Figure 2. Schematic diagram indicating the origin of the virtual source size δ for a field emitter A. δ represents the minimum diameter subtended by the tangents to the trajectories when extended back from the aperture B to their intersection inside the emitter. Drawing is not to scale.

cathode is the waist of the current distribution produced by an optical system consisting of the cathode, an anode and a control electrode (wehnelt), as shown in Figure 3. By proper location of the physical elements with respect to one another and by application of appropriate voltages, the crossover can be made small and uniform in cross section [1,25,57]. The final beam spot size is estimated by [68]

$$d^2 = d_s^{\,2} + d_c^{\,2} + d_d^{\,2} + M^2\,\delta^2 \qquad (9)$$

A useful measure of the current, crossover size and angular confinement of the electron beam from a gun is the brightness, β, which has units of amperes per square centimeter per steradian:

$$\beta = \frac{I}{\frac{\pi}{4}\,\delta^2 2\pi[1 - \cos\alpha_0]}.$$ For small angles,

$\alpha_0 << 1$,

$$\beta = \frac{I}{\frac{\pi}{4}\,\delta^2\,\pi\,\alpha_0^{\,2}} \quad . \qquad (10)$$

The solid angle containing the beam current I is determined by the angle α_0. In the limit $\delta \to 0$,

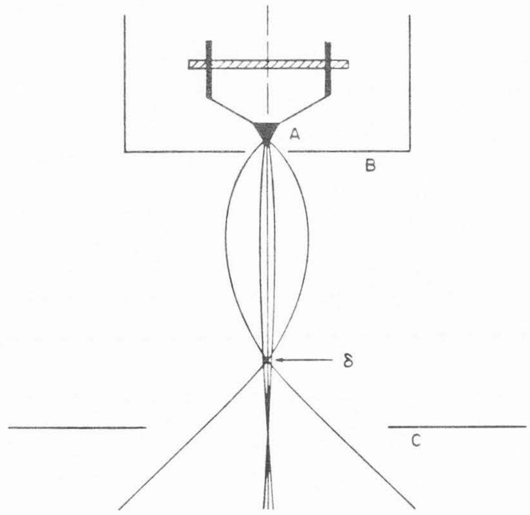

Figure 3. Schematic diagram of the crossover with diameter δ in a thermionic gun. Cathode is A, Wehnelt is B, anode is C. Trajectories are greatly exaggerated. In actuality, the angles would be very small and an image of the cathode would be formed below the anode.

$\alpha_0 \to 0$, $I \to 0$, $\frac{\beta}{V}$ is a conserved quantity for the optical system, where V is the beam voltage. For a finite α_0 and δ, $\frac{\beta}{V}$ is degraded by the lens aberrations. It can be shown [37] that $\beta \approx \frac{J_c}{\pi}\frac{eV}{kT}$ for a thermionic cathode, where J_c is the current density at the cathode surface. The larger β, the more current can be delivered to a given spot size within a given solid angle on the target. Typically, at V = 20 kV, $\beta \approx 10^4$-10^5 for W and $\beta \approx 10^6$ for LaB_6.

It is sometimes convenient to characterize an electron gun in terms of the angular intensity, $dI/d\Omega$. This is true if the source dimensions are small compared with the desired focused beam size, as in a field emission gun; in that case the beam diameter will generally be determined by the aberrations of the optical system.

β is then given by $\frac{4dI/d\Omega}{\pi\delta^2}$ and, for $\alpha_0 < 10^{-1}$ rad

$$I_b = \pi\alpha_0^{\,2}\,\frac{dI}{d\Omega} \qquad (11)$$

Since J_c depends exponentially on F for a field emitter the brightness is exponentially dependent on the applied voltage, which determines the field. Because of the strong dependence of the current on the voltage, one usually chooses a fixed operating or extraction voltage, V_E and varies the beam energy by means of an electrostatic lens.

In an SEM with a thermionic cathode there are usually two or three lenses and the beam is demagnified at each lens. δ is typically 10-50 μm, depending on the geometry of the gun and the type of cathode employed. If the final beam spot

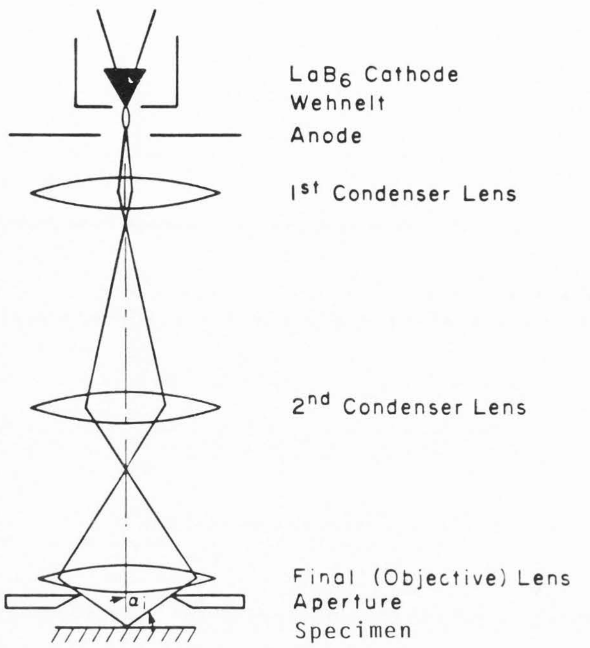

Figure 4. Schematic diagram of the optical system for an SEM employing a LaB_6 thermionic cathode. Scan coils, astigmatism correction coils and spray apertures are not shown, for simplicity.

is to be, say 100 Å in diameter, then if $\delta = 25$ µm, $M \leq 4 \times 10^{-4}$, with the equality holding only if the aberrations are negligible compared to 100 Å. The situation is very different for field emission. Here, $\delta \approx 50$ Å for a CFE source and $\approx$ 150 Å for a TFE source [16,69], hence $M \approx 1$, and fewer lenses may be needed; the very different system magnifications result in very different designs for thermionic and field emission optical systems.

Parameters for Calculations

For the purpose of comparing the current-spot size relations of these three cathodes, we assume that only the final, objective lens is important for the LaB_6 system, and for the calculations, employ a magnetic lens with good aberration coefficients. We may do this because, the contributions to the final spot size of the lens aberrations are important only for reasonably large values of the angle α. Since the magnification of the final lens will be $\lesssim 0.1$, the angular magnification will be $\gtrsim 10$ and so the angle subtended in lenses preceding the final lens will be negligible. For the field emission cathodes, we assume a two-lens system consisting of an electrostatic gun lens and a magnetic final lens, with overall magnification $\approx$ 1. We assume the same final lens as for the LaB_6 system, although operated with different magnification. Consequently, the aberration coefficients of the final lens are different in the field emission cases than in the LaB_6 case.

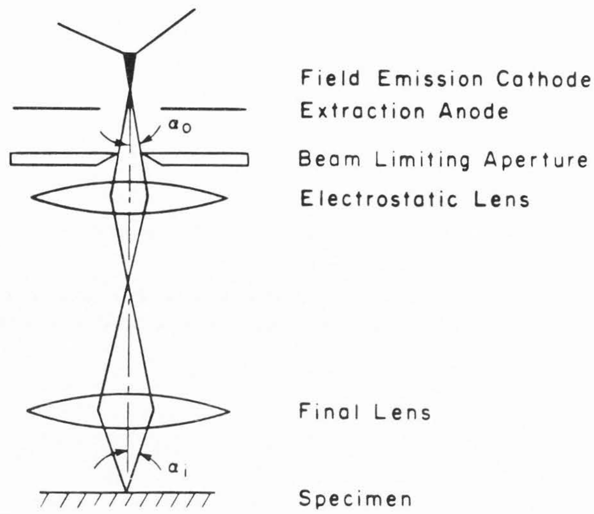

Figure 5. Schematic diagram of the optical system for an SEM with a field emission cathode. Scan and astigmatism correction coils are not shown. The beam limiting aperture is placed above the electrostatic lens so that I_b remains constant as the beam energy is changed, since α_i is a function of e_{beam}.

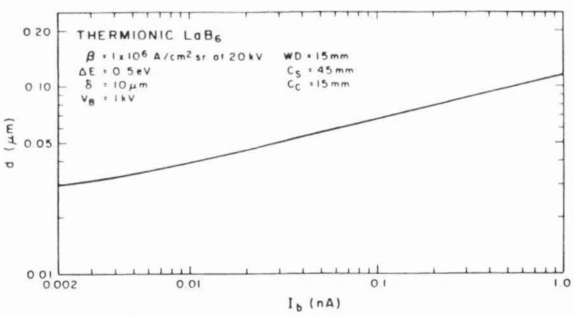

Figure 6. Focused spot size d vs beam current I_b for a thermionic LaB_6 electron gun, with optical parameters and objective lens parameters as shown.

In all cases we assume a working distance of 15 mm from the polepiece of the final lens. For the gun lens we chose a particular design of a three-element, asymmetrical electrostatic lens with good chromatic aberration properties [38], which is used to decelerate the beam. The optical systems used for the calculations are shown schematically in Figures 4 and 5, while the details of the system parameters are shown in Tables 1 and 2.

From the brightness relation we find $\frac{dI}{d\Omega}$ for the LaB_6 cathode to be $\frac{dI}{d\Omega} = \beta \frac{\pi\delta^2}{4}$. With $\delta = 10$ µm, $\frac{dI}{d\Omega} = 3.9 \times 10^{-2}$ A sr^{-1} at 1 kV. If we now replace α_0 by $\left(I_b/\pi \frac{dI}{d\Omega}\right)^{1/2}$ in equation (9), we find the optimum value for M, M_{opt} as a function of I_b by differentiation. M_{opt} was calculated for each value of I_b, and then used to find d. The values ranged from $M_{opt} = 1.53 \times 10^{-3}$ at $I_b = 10^{-12}$ A, to $M_{opt} = 1.35 \times 10^{-2}$ at $I_b = 10^{-9}$ A. A β of 1×10^6 A cm^{-2} sr^{-1} at 20 kV was chosen, which is reduced to 0.5×10^5 A cm^{-2} sr^{-1} at 1 kV, and with δ = 10 μm, Pfeiffer's results [40] were used to assign a value of ΔE = 0.5 eV.

For the field emission guns, d and I_b were calculated using Eqs.(9) and (10), with α_0 the variable and the other parameters taken from Table 2.

Table 1

Parameters for the LaB_6 Gun

β	1×10^6 A cm^{-2} sr^{-1} at 20 kV
ΔE	0.5 eV
δ	10 μm
V_B	1 kV
C_{si}	45 mm
C_{ci}	15 mm

Results of Calculations and Discussion

The results of calculations of d vs I_b are shown in Figures 6 and 7. In addition, the convergence half-angles of the beam on the target, α_i, are shown in Figure 8.

For the case of LaB_6, I_b = 1 nA at d ≈ 0.1 μm and I_b ≈ 0.03 nA at d = 0.05 μm. In addition, at I_b = 1 nA, $\alpha_i \approx 10^{-2}$ rad, implying a depth of field of approximately 10 μm.

The case of CFE is quite different. We have plotted d vs I_b for four cases: $\frac{dI}{d\Omega} = 1 \times 10^{-4}$ and 5×10^{-4} A sr^{-1} with V_E = 3 kV and 6 kV. The two extraction voltages were chosen to show the effects of chromatic aberration, which are also evident from the difference in spot size for the two values of $\frac{dI}{d\Omega}$ for a given value of I_b. There could be an uncertainty of ± 0.2 eV in ΔE and so curves C and D could be lower or higher by 20%, since the minimum in the d vs I_b curve is determined by the value of d_c. Higher values of angular intensity were not used because of the rapid increase of ΔE.

The highest resolution, d = 0.03 μm, was achieved with the CFE cathode at $\frac{dI}{d\Omega} = 1 \times 10^{-4}$ A sr^{-1} and I_b = 0.3 nA. This is a factor of 2.5 better than LaB_6 at the same I_b. However, CFE operation at the higher angular intensity results in much larger values of d.

The TFE cathode, Zr/W(100), provides good resolution, with d having a minimum of ≈ 0.057 μm and I_b = 2.5 nA: five times as much current as

Table 2

Parameters for the Field Emission Guns

	CFE				TFE	
	A	B	C	D	E	
$\frac{dI}{d\Omega}$	1×10^{-4}	1×10^{-4}	5×10^{-4}	5×10^{-4}	7.5×10^{-4}	A sr^{-1}
ΔE	0.2	0.2	1.0	1.0	1.0	eV
δ	50	50	50	50	150	Å
I_{tot}	40	40	200	200	300	μA
J_c	4×10^5	4×10^5	2×10^6	2×10^6	4.5×10^4	A cm^{-2}
V_E	6.0	3.0	6.0	3.0	6.0	kV
V_B	1.0	1.0	1.0	1.0	1.0	kV

C_{so} (electrostatic lens)	1.49×10^4	mm
C_{co} (electrostatic lens)	265	mm
C_{si} (magnetic lens)	10	mm
C_{ci} (magnetic lens)	5	mm
M	1.28	

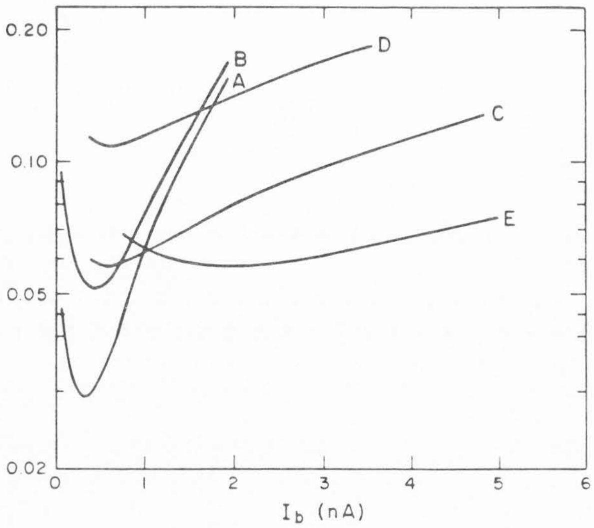

Figure 7. Focused spot size d vs beam current I_b for field emission electron guns. Curves A and B are CFE at 6 kV and 3 kV, respectively and $\frac{dI}{d\Omega} = 10^{-4}$ A sr^{-1}. Curves C and D are for CFE with V_E = 6 kV and 3 kV, respectively and $\frac{dI}{d\Omega} = 5 \times 10^{-4}$ A sr^{-1}. Curve E is for TFE with V_E = 6 kV and $\frac{dI}{d\Omega} = 7.5 \times 10^{-4}$ A sr^{-1}. See Table 1 for other parameters.

the CFE cathode operated at either $\frac{dI}{d\Omega} = 1 \times 10^{-4}$ or 5×10^{-4} A sr^{-1}, and 25 times as much current as the LaB_6 cathode, at the same spot size. This is because at ΔE = 1 eV, $\frac{dI}{d\Omega} = 7.5 \times 10^{-4}$ A sr^{-1} [65] and at M = 1.28, the effect of δ is unimportant. An additional benefit of the field emission optical columns is that at I_b = 1 nA, $\alpha_i \approx 10^{-3}$, rad, implying a depth of field of ≈ 50 μm.

Based upon the d vs I_b calculations, LaB_6 is quite inadequate for high throughput applications where low beam voltage (1 kV) and moderately high resolution (≈ 0.05 μm) are required. CFE is best suited for high resolution, d ≈ 0.03 μm, with fairly high current, I_b ≈ 0.3 nA. TFE provides lower resolution, d ≈ 0.05-0.06 μm, but also an order of magnitude higher current, ≈ 4 nA at d = 0.06 μm, and shows much better performance than CFE over most of the current range.

These statements must be carefully qualified by noting that we have chosen optical systems with a working distance of 15 mm. A shorter working distance would result in improved values of d for a given I_b or improved values of I_b for a given d, as shown in Figure 9. However it seems highly unlikely that sufficient improvement could be made for LaB_6 to be useful for high throughput applications, and LaB_6 certainly would not be competitive with field emission. We add a parenthetical comment that workers in our

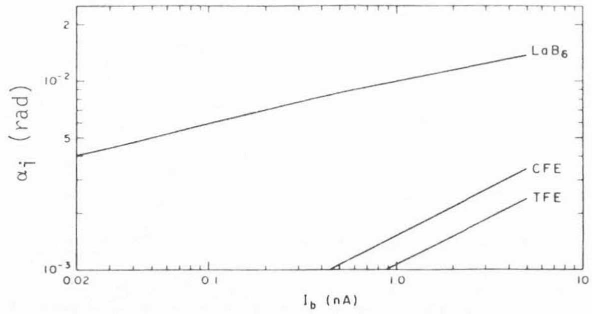

Figure 8. The convergence angle α_i of the focused beam on the target for LaB_6, CFE and TFE electron guns, as a function of beam current I_b. The depth of focus is inversely proportional to α_i.

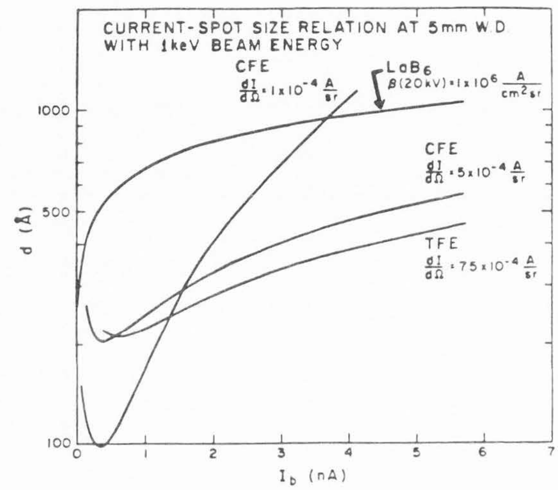

Figure 9. Focused beam spot size vs. beam current at 5 mm working distance for LaB_6, CFE and TFE guns, with the same optical systems as were used for 15 mm working distance. The gun voltage was 6 kV for the field emission cases and ΔE was the same as for the 15 mm working distance case.

laboratory have measured d vs I_b at low voltages with commercial SEMs employing LaB_6 cathodes, and have found that at E = 1 keV, when d ≈ 0.03-0.06 μm I_b ~ 0.001-0.01 nA, at working distances in the range 15-30 mm.

As reported by Swanson et al [56], a CWIKSCAN Model 100 SEM, modified to operate with a Zr/W TFE cathode has achieved I_b = 9 nA at E = 1.33 keV and d = 0.22 μm, at 30 mm working distance. The optical system employs a two-element immersion lens, and hence has little flexibility in the beam voltage. Nonetheless, the performance was noteworthy for the high current.

Besides the d vs I_b relations, it is important to consider the noise in the beam, since a cathode may not be usable if $\frac{\Delta I}{I_b}$ is too large. If we use the criteria of Wells [68], the signal to noise $\frac{I_b}{\Delta I} \geq 20$, for a system with 8 gray levels. For example, if we require a bandwidth $f = 10^6$ Hz, a reasonable figure for high speed inspection, we note that $\frac{I_b}{\Delta I_{shot}} = 20$ at $I_b = 0.13$ nA. From Figure 6, the LaB_6 results give $I_b = 0.05$ nA at $d = 0.055$ μm, and from Eq.(3) $\frac{I_b}{\Delta I} = 13$. Therefore, from the point of view of signal to noise, LaB_6 is quite marginal. From Figure 7, the TFE results give $I_b = 2.3$ nA when $d = 0.057$ μm, and from Eq.(5), with $\alpha_o = 10^{-4}$ rad $\frac{I_b}{\Delta I} = 79$. The main component of the noise current is ΔI_{shot}, because of the bandwidth of 10^6 Hz. The flicker noise component of ΔI equals the shot noise component only when f is reduced to 43 kHz.

The situation for CFE is more complicated. If the vacuum were extremely high the noise would be entirely shot noise. At $P = 7 \times 10^{-9}$ torr, $\frac{I}{\Delta I}$ for a W(310) cathode was measured [48] to be ≈ 5% for f = 25 kHz and I = 0.7 nA. Above this frequency the noise is dominated by shot noise, which is negligible. In this case $\frac{I_b}{\Delta I} \approx 20$ and the cathode would be usable in terms of its signal to noise ratio. Based on results of Zaima et al [73], the signal to noise ratio of a TaC CFE cathode is at least an order of magnitude superior to that of the W(310) CFE cathode, at $P = 3 \times 10^{-10}$ torr. Therefore, from the point of view of noise current, such a cathode would be an improvement over W. Results for TiC are uncertain and seem to be sensitive to surface stoichiometry. However, a vacuum in the electron gun of $P < 10^{-9}$ torr is still necessary.

It is clear from the discussion so far that the TFE cathode is best suited for high throughput e-beam testing, taking into consideration current and beam spot size at E = 1 kV, noise and vacuum requirements of the electron gun necessary for reliable, long term cathode life. CFE is marginal in terms of noise if the W(310) cathode is used; carbide cathodes may offer an improvement in this regard. CFE is substantially better than LaB_6 in terms of current and beam spot size at E = 1 kV, but is inferior to TFE. Its vacuum requirements are an order of magnitude higher.

The issue of stability is usually brought up when field emission cathodes are considered, and this is an important issue from the point of view of practical applications. By stability is meant random current spikes or increasing current fluctuations with time, which lead to cathode failure. In the case of TFE, current spikes are not seen; in the case of CFE, even at $P < 10^{-9}$ torr and with carbide cathodes they are present.

The increases in current fluctuations with time seen in CFE, which are totally absent in the case of TFE, are due to increasing surface roughness due to ion bombardment. The rate at which this happens is proportional to $P \times I$ and occurs with all CFE cathodes. The problem cannot be made to go away at any practically attainable vacuum, but it can be controlled by periodic flashing of the cathode to high temperature. The frequency of flashing is determined by P, but it is impractical to operate an electron gun at $P \sim 10^{-10}$ torr in conjunction with frequent specimen changes. For this reason, CFE is not suitable for long term work requiring minimal operator attendance.

Taking all of the issues into account, it appears that the TFE cathode is best suited in terms of beam current with acceptable noise at E = 1 kV, or below.

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Additional Discussion

P. B. Sewell: The superior performance characteristics of the TFE source have been well established by many excellent publications such as the above. However, the general acceptance of a 'new' source seems to be influenced by many practical operating factors. For example, the slow turnaround time for the vacuum processing of LaB_6 cathodes as compared with tungsten, is considered by some to be a disadvantage in routine SEM applications. Could the author comment on the cycle time from loading of a TFE source to its stable operation in the electron optical column?

Author: To assure reliable operation of the ZrO/W cathode a vacuum level $< 1 \times 10^{-8}$ torr is necessary. To achieve such a vacuum in an electron gun connected to a specimen chamber which operates at the usual SEM vacuum level ~ 10^{-6} torr, it will be necessary to differentially pump the gun through a small (~ 0.5 mm) aperture which should be located some distance from the cathode. This means the gun chamber will have its own independent vacuum pumps and should be capable of sustaining a mild bake to speed pumping of water vapor. For example, in the rebuilt CWIKSCAN 100 SEM at the Oregon Graduate Center, the gun chamber is pumped by two 20 l/s ion pumps connected by high conductance lines. The turnaround time for a cathode change is typically 12 hours, including the bake cycle. This is probably a typical number for a system which will operate at 5×10^{-9} torr and, while it may seem long compared with the 1/4 hour cycle time typical for a thermionic W cathode, it should be kept in mind that the cathode life will be 1000 - 2000 hours, barring accident. This is 15 - 30 times the life of a thermionic W cathode (assuming a 60 hour life) and when the cycle is amortized over the life, it is only 1 - 2%. The cycle time for the thermionic W cathode is 0.5%, which is not much different.

P. B. Sewell: As the TFE emitter and single crystal LaB_6 emitters have been under development for about the same time, could the author comment on possible reasons for the slow acceptance of this type of source in electron optical instruments. Does any currently manufactured commercial instrument employ the TFE type source?

Author: Undoubtedly the main reason that LaB_6 cathodes caught on quickly was that they are a greatly improved version of the type of cathode that was in wide use already. This means that only minor, if any changes in the electron optics were required in the instrumentation. The main change required was in the gun vacuum system, which has not been difficult for the manufacturers to put into place. Use of the TFE cathode requires a completely new electron optical design, which is a much more serious proposition.

The commercial applications of the TFE cathode have been primarily in e-beam lithography machines. To date A.T.& T. Bell Labs, E-Beam Corporation, Hewlett-Packard Corporation have built such instruments. The latter two efforts have not been commercially successful, but the reasons for this are not clear. A number of CWIKSCAN 100 SEM's have been converted to use the ZrO/W cathode and electron guns with this cathode are being sold by FEI Co. At this time there are no complete systems employing the TFE cathode which are commercially available.