Review of the Status of Cathodes for Electron Microscopy

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The subject of electron guns and cathodes is quite broad. In this abstract we briefly review the properties of thermionic, cold and thermal field emission cathodes for microscopy. The reader is referred to the literature mentioned here for extensive treatments of these subjects.

Although the superiority of field emission cathodes for electron microscopy was recognized at least as early as 1942 by Zworykin et al [1], thermionic cathodes were used almost exclusively until well into the 1980's. Thermionic W cathodes were to a considerable extent supplanted by LaB$_6$ cathodes beginning in the 1970's, but it was not until well into the 1980's that field emission cathodes began to become the norm for high resolution and for low voltage electron microscopy.

Electron guns for electron microscopes were originally made from a heated cathode consisting of a W filament and one or two electrodes to control the emission of electrons from the cathode. More recently LaB$_6$ has been used in place of W. The properties of such electron guns have been well studied [2-5] and we only briefly summarize them.

The advantages of the thermionic electron gun are: simplicity; the ability of a W cathode to operate in modest vacuum (~10$^{-5}$ torr); ruggedness; and relatively low cost. The disadvantages are: low brightness; and high current density near the cathode where the electrons have low energy, leading to a large energy spread due to the Boersch effect [6]. The unnormalized brightness of such guns is ~ 10$^5$ A cm$^{-2}$ sr$^{-1}$ for W and perhaps an order of magnitude higher for LaB$_6$[7,8].

Field emission electron guns utilize cold cathodes consisting of a single crystal W field emitter (CFE) oriented in the <310> or <111> direction, a heated (1800K) W <100> field emitter (TFE) for true thermionic field emission or a heated <100> W field emitter coated with ZrO. The last is not operated as a true field emitter but as a Schottky cathode. With the CFE cathode all electron emission is by true field emission - electrons tunnel from the Fermi level of the metal through a narrowed potential energy barrier created by the application of a very high (F ~ 10$^7$ V cm$^{-1}$) electric field [9,10]. The intrinsic energy spread of electrons so emitted is ~ 0.3 eV. In the case of thermal field emission many of the electrons are found in the conduction band above the Fermi level and so have a variable thickness barrier to penetrate. Consequently the TFE cathode has a larger energy spread (~ 1 eV) [10]. In a ZrO/W<100> (Schottky) cathode emission is from a limited area of the cathode where the field is high enough that the potential barrier is lowered, yet the emitted electrons cross over the barrier rather than tunneling through it.

The CFE electron gun usually consists of the field emitter and a nearby anode held at a potential of a few keV positive with respect to the cathode, followed by a final electrode placed at the desired beam final potential. Analysis of such a structure [11] and experiment [12] show that the unnormalized brightness of such a gun is ~ 10$^9$ A cm$^{-2}$ sr$^{-1}$. The TFE electron gun, which is rarely
employed, has a similar structure and comparable brightness. In the case of the CFE cathode, the end radius is \( \sim 100 \text{ nm} \). The end radius of the TFE cathode is \( \sim 10 \text{ nm} \).

The most widely used field emission cathode, though not a true field emitter, is the Schottky cathode [13]. An electron gun consists of the cathode, which is a blunt field emitter with an end radius of \( \approx 500 \text{ nm} \), and two or more electrodes. When covered with ZrO the work function of the (100) planes of W are lowered from 4.25 eV to 2.95 eV. Therefore the (100) planes emit far more electrons at a given operating temperature than do the other crystal planes. In particular, the (100) plane located at the emitter apex, which is in the highest electric field, emits very strongly according to the law

\[
I = A T^2 \exp\left(\frac{e^2}{2F} \frac{1}{T} \phi \right) / kT
\]

that governs Schottky emission [10], where \( e \) the electronic charge, \( \phi \) the work function, \( k \) is Boltzmann’s constant, \( T \) the temperature and \( A \) is a constant accounting for the arrival rate of electrons at the metal-vacuum interface (including reflections at the barrier). The other (100) planes oriented at 90° to the apex emit thermionic current abundantly as well. For this reason the gun structure requires that the cathode be surrounded by a control electrode usually called the suppressor, held at negative potential relative to the cathode, to prevent emission from the cathode shank. The apex of the emitter protrudes \( \approx 1 \text{ mm} \) through an aperture in the suppressor electrode and is exposed to the high voltage \( (\sim 3 - 5 \text{ kV}) \) on a nearby anode electrode. Final beam energy is often controlled with a second anode. The electric field at the apex of a Schottky cathode is about one order of magnitude less than in a true field emitter, \( F \approx 10^6 \text{ V cm}^{-1} \). The cathode produces an electron beam with an energy spread of \( 0.6 - 0.8 \text{ eV} \) in the normal emitting range. The actual end shape of the Schottky emitter is a flat surface with a diameter of \( \approx 500 \text{ nm} \).

The advantages of field emission cathodes are: very high brightness \( 10^8 - 10^9 \text{ A cm}^{-2} \text{ sr}^{-1} \); high angular intensity of \( 10^5 - 10^4 \text{ A sr}^{-1} \) for a CFE cathode and \( 10^4 - 10^5 \text{ A sr}^{-1} \) for TFE and Schottky cathodes; high degree of coherence of the electron beam [14]. Advantages of the TFE and Schottky cathodes vis a vis the CFE cathode are: relaxed vacuum requirement \( (10^9 \text{ torr vs. } 10^{10} - 10^{11} \text{ torr}) \); greater emission capability. The Schottky cathode has a lower noise than either the CFE or TFE cathodes. The disadvantage of the TFE cathode is the higher energy spread \( (\sim 1 \text{ eV}) \) due to the higher operating temperature \( (1800K) \) and the high current density at the cathode \( (\sim 10^7 \text{ A cm}^{-2}) \). The disadvantages of the Schottky cathode are: higher energy spread due to the high \( (1800K) \) operating temperature and higher current operation; larger virtual source size \( (\sim 15 \text{ nm vs. } 3-5 \text{ nm for the CFE and TFE cathodes}) \) due to the optics of the cathode - anode system (primarily the cathode shape).

References

1. V.K. Zworykin, J. Hillier and R.L. Snyder, *ASTM Bulletin* 117 (1942) 15