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THE USE OF LANTHANUM HEXABORIDE CATHODES IN ELECTRON BEAM LITHOGRAPHY

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Abstract

Lanthanum Hexaboride (LaB_6) is best known as a thermionic electron emitter with high brightness and long lifetime. It is used in a variety of electron optical instruments, including systems for electron beam lithography of integrated circuits.

The major limitation in present-day electron beam lithography systems is throughput, or the ability to process a wafer or mask in a reasonable time. The design of the electron optics is, therefore, governed by a desire to make the writing time as short as possible, together with the other system overhead times. This places inevitable constraints on the electron source.

The simplest systems employ a Gaussian round beam of minimal size, requiring maximum brightness. The fastest systems in use today employ the variable shaped beam concept. For these systems brightness is a minor consideration; however the illumination must be highly uniform. For all systems it is desirable to minimize the energy spread. This minimizes the chromatic aberration, which causes a deterioration of edge acuity of the focussed spot. For minimum energy spread one must use the largest possible fraction of the total emission current to form the writing probe.

Most shaped beam systems employ Koehler illumination, in which typically one percent of the total emission reaches the target. By using a flat, single crystal cathode with critical illumination it is possible to use nearly all of the emission current, thereby reducing the energy spread by roughly an order of magnitude.

KEY WORDS: Lanthanum Hexaboride, High Brightness Electron Sources, Electron Beam Lithography, Koehler Illumination, Critical Illumination, Minimal Energy Spread Systems, Single Crystal Cathodes, Cathode Facetting, High Throughput Lithography Systems.

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Introduction

Lanthanum hexaboride (LaB_6) is best known as a thermionic electron emitter with high brightness and long lifetime. Since its first description (Lafferty, 1951), its properties have been constantly studied and improved. It is now used in a variety of instruments, including scanning electron microscopes, electron microprobes, and more recently, systems for electron beam lithography of integrated circuits.

In electron beam lithography a focussed beam is used to expose an electron-sensitive resist. This is developed, leaving behind a patterned film, which then becomes a mask for further processing of the substrate. Lines as narrow as 175Å have been written in this way (Broers, 1980).

The main driving force behind the development of lithography systems is the manufacture of very large scale integrated circuits (VLSI). It has recently become practical to fabricate circuits with minimum dimensions less than 0.5 micron. A key prerequisite is the ability to position pattern features with an accuracy which is some small fraction of the minimum dimension. The reason for this is that a typical integrated circuit consists of 10 or more layers, all registered with respect to one another. A typical pattern contains 10^8 pixels. This is about a factor of 100 larger than the number of resolvable elements in a high quality electron micrograph.

The major limitation in present-day electron beam lithography systems is throughput, or the ability to process a wafer or mask in a reasonable time. The design of the electron optics is, therefore, governed by a desire to make the writing time as short as possible, together with the other system overhead times. These include moving the substrate into and out of the vacuum, registering the beam position relative to previously exposed layers, and waiting for the table and electronics to settle after moving to a fresh writing area. Minimization of the writing time places inevitable constraints on the electron gun. This is the subject of the next section.

Electron Optical Requirement for a LaB_6 Gun

An overriding requirement is stability of the current density at the writing surface to within about one percent. Early attempts with sintered LaB_6 cathodes failed to meet this criterion, due to large variations of the emission in space and time over the cathode surface. The more recent availability of single-crystal LaB_6 has eliminated this difficulty. These cathodes have run stably and routinely in our manufacturing systems for 2000 hours at 2×10^{-7} Torr. The reader is referred to Hohn et al. (1982) for a review of fabrication methods for single crystal LaB_6 and to Davis et al. (1986) for a discussion of life-limiting mechanisms.

Writing speed is determined by three factors: the sensitivity of the resist, the current density in the beam, and the degree of parallelism (number of pixels written simultaneously). With everything else equal, a tradeoff exists between the last two factors. The simplest electron optical columns expose one pixel at a time; i.e., are completely serial. They employ a round spot, equal in size to one pixel, with a Gaussian distribution of intensity. In order to obtain reasonable writing speed, it is necessary to maximize the current density. This translates to maximizing the brightness of the electron source. LaB_6 single crystal cathodes have been operated at a maximum brightness of 3×10^6 $A/(cm^2 sr)$ at 20 kV (Hohn et al., 1982). The equivalent brightness at other beam voltages can be calculated by remembering that brightness is proportional to voltage.

The fastest systems in use today make use of the variable shaped beam concept (Fontijn, 1972; Pfeiffer, 1978). A composite image of two shaped apertures is formed on the writing surface. An image of the first aperture appears in the plane of the second aperture, and the image can be shifted laterally relative to the second aperture. A shaped spot of variable dimensions is thus formed. In this way a moderate degree of parallelism is achieved without sacrificing the ability to locally control and correct the position of the writing probe.

It is easy to see that, for the same writing speed, the required source brightness in the shaped beam case is reduced from the round beam case by a factor equal to the parallelism. The maximum beam current is now determined by factors other than the brightness of the source. This eliminates brightness as a major consideration. Another constraint arises in its place, however: the spot must be uniformly illuminated. In practice this requires that the source illuminate the first shaping aperture uniformly, as this aperture is imaged onto the writing surface.

Ideally one would like the intensity to fall off infinitely sharply at the edges of the shaped spot. In practice this is impossible, however. The spot is blurred by the aberrations of the optical system, and by the mutual Coulomb repulsion of the beam electrons.

The Coulomb interaction is manifest in two ways: the transverse component of the repulsive force gives rise to lateral spreading of the beam, while the longitudinal component gives rise to energy broadening. This latter, known as the Boersch effect, causes lateral broadening as well, due to the chromatic aberration of the lenses and deflectors. The theory of this process has been reviewed by Jansen and Stickel (1984), and Jansen et al. (1985).

In attempting to maximize the writing speed, one has no alternative but to increase the beam current until the edge acuity of the spot worsens to the point of being just acceptable. The Coulomb interaction, therefore, imposes a fundamental limit on the writing speed of any electron beam lithography system (Pfeiffer, 1971). While the interaction occurs along the entire length of the optical path, the energy broadening occurs primarily in the source region. Minimum energy spread is, then, a further requirement of the gun.

In summary, the requirements of a gun include stability and low energy spread. For Gaussian, round beam systems high brightness is needed. For shaped beam systems brightness is of minor importance, but uniformity of illumination is essential. Considerable attention has been devoted in the literature to LaB_6 guns for Gaussian probe forming systems. This subject has been reviewed by Hohn (1985). Relatively little has been written about LaB_6 guns for shaped beam systems. The following analysis will be devoted to this subject.

The Performance of a LaB_6 Gun for a Shaped Beam System

Most shaped beam systems in use today employ Koehler illumination. In this approach, which originated in classical light optics, the object is illuminated by a virtual source located a long distance away. The emission surface is thus greatly defocussed, and its structure does not appear in the final image.

The illumination of the first shaping aperture is shown schematically in Fig. 1(a) for typical operation. The aperture is flooded by a virtual crossover, represented by the "waist" or minimum of the solid rays in the figure. This crossover forms the exit pupil of the gun, and is imaged into the entrance pupil, or defining aperture, of the final lens (not shown). This insures that the maximum current is transmitted by this defining aperture, thus maximizing the intensity of the focussed spot.

The intensity distribution in the plane of the shaping aperture was measured for normal operation of a typical gun. The result is shown in Fig. 1(b). A single crystal LaB_6 cathode was used, with a flat emitting surface oriented perpendicular to the beam axis (Hohn, 1981). The gun was operated in the mode of space charge limited emission, in which the temperature is increased to the point where a space charge cloud exists around the cathode surface. In this mode the emission is insensitive to further small changes in temperature.

For measurement purposes only, the shaping aperture was replaced by a smaller pinhole aperture, and the beam swept across it. This allows observation of local variations in intensity. The pinhole aperture subtended a solid angle of 1.4×10^{-8} sr at the virtual crossover.

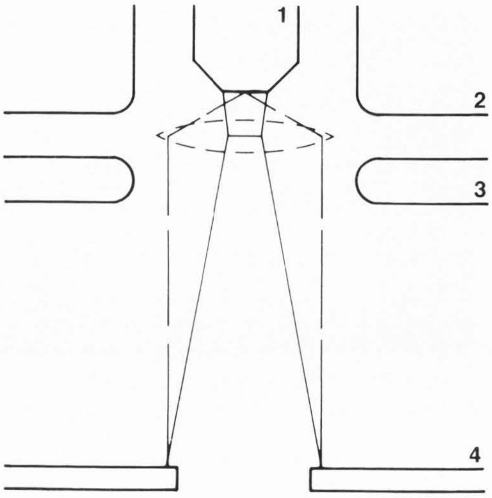

Fig. 1(a) Koehler illumination in a shaped beam system. A virtual image of the emitting surface is formed a long distance behind the cathode, resulting in parallel illumination of the first shaping aperture. This aperture represents the object, which is imaged onto the writing surface. A "waist" or crossover, represented by the solid rays, is formed in front of the emitting surface. This crossover is the exit pupil of the gun, and is imaged into the entrance pupil (defining aperture) of the optical system. This maximizes the intensity of the focussed spot. Elements of the gun are (1) LaB_6 cathode, (2) Control grid (Wehnelt), (3) Anode, (4) First shaping aperture (object plane).

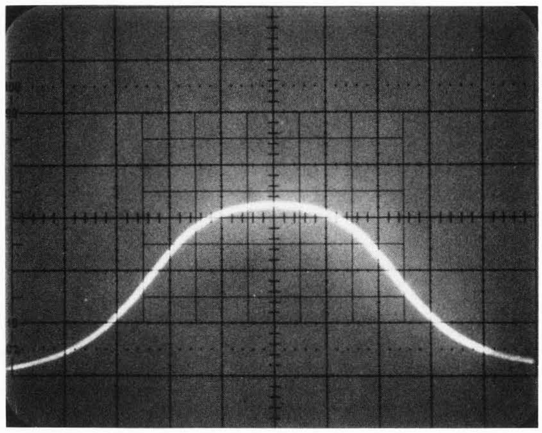

Fig. 1(b) Intensity distribution measured in the plane of the first shaping aperture with conventional illumination. Horizontal axis: emission angle from virtual crossover, 1 div = 5.9 mrad. Vertical axis: Current through pinhole aperture in plane of first shaping aperture, 1 div = 0.2 A/sr at virtual crossover.

The vertical axis in Fig. 1(b) shows the transmitted current, and the horizontal axis represents the emission angle, measured in the plane of the crossover.

We see that the intensity distribution is roughly Gaussian, reflecting the angular distribution of current from the crossover. This means that as the acceptance angle of the shaping aperture is increased, the intensity falls off at the edges, causing a loss of uniformity. In order to circumvent this, it is necessary to choose a geometry for which only a small central portion of the emission is used to form the writing probe. As a result most of the emission current is lost on the aperture. In typical operation only about one percent of the emission is used to form the writing probe.

Although it is possible to obtain acceptable uniformity with this approach, it is far from optimal from the point of view of low energy spread, as the following argument will show.

The energy spread of beam with crossover is given as follows, based on the theory of van Leeuwen and Jansen (1983):

$$\frac{\sigma V}{V} = \left(\frac{m}{8e\varepsilon_o^2}\right)^{1/4} (I/V^{3/2})^{1/2}\, F \qquad (1)$$

$$F^2 = \frac{8}{\pi \bar{r}_o}\int_o^1 dt\, \frac{\sqrt{1-t^2}}{t}\, \mathrm{arcsinh}(\bar{r}_o t/2) \qquad (2)$$

$$\bar{r}_o = \frac{8\pi\varepsilon_o}{e}\, \alpha_o^2 V r_c \qquad (3)$$

I is the total emission current, V is the beam voltage, α_o is the total emission semi-angle, and r_c is the crossover radius. The derivation assumes that a beam approaches the crossover from $-\infty$, and then recedes to $+\infty$. The path length is effectively half this for a gun, since the beam starts at a crossover. Consequently, we must divide the result in Eq. 1 by two. The theory also assumes a constant beam energy, which is not the case within the gun. Nevertheless, in an earlier paper (Jansen et al., 1985) the theory was shown to agree reasonably well with measured energy spreads over a wide range of operating conditions of a LaB_6 gun. We see that energy spread increases as the square root of the total emission current.

If the lowest possible energy spread is obtained by using the lowest total emission current, it follows that one would like to use the largest possible fraction of the emission current to form the writing probe. This is clearly at odds with the approach just described, where most of the emission is stopped on the first aperture.

The ideal intensity distribution utilizes all of the emission without sacrificing uniformity of illumination. This requires uniform intensity within the shaping aperture, and zero intensity outside. A method has been proposed

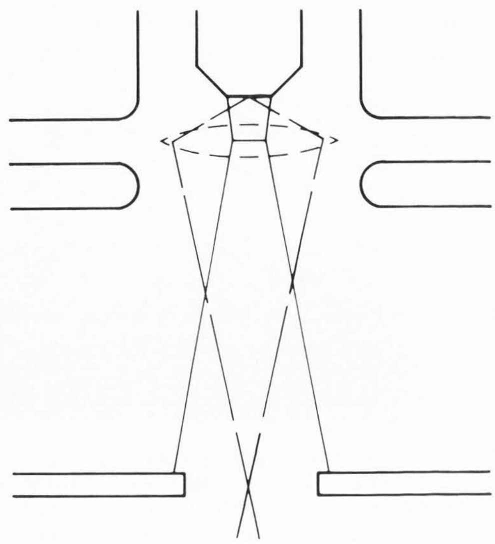

Fig. 2(a) Critical illumination for a shaped beam system. The emission surface is imaged into the first shaping aperture. As in the previous case, the crossover is imaged into the entrance pupil of the final lens.

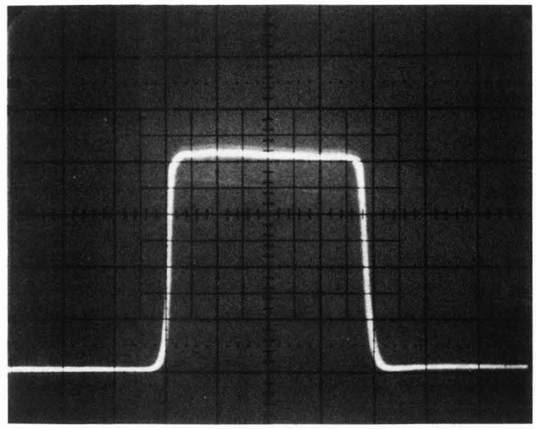

Fig. 2(b) Intensity distribution measured in the plane of the first shaping aperture with critical illumination. Horizontal axis: emission angle from virtual crossover, 1 div = 3.0 mrad. Vertical axis: Current transmitted by pinhole aperture, 1 div = 0.2 A/sr at virtual crossover.

to obtain such a distribution, for the purpose of minimizing the energy spread (Essig, 1984; Essig and Pfeiffer, 1986). They employ a single crystal LaB_6 cathode with a flat emitting surface oriented perpendicular to the beam axis. The emitting surface is imaged onto the plane of the first shaping aperture, and hence, onto the writing surface.

The electron optics is shown schematically in Fig. 2(a). The broken rays show that a point on the emission surface is imaged to a point in the shaping aperture. The resulting intensity distribution was measured, and is shown in Fig. 2(b). The gun is identical with the previous case. Only the temperature and grid potential were changed. We see that excellent uniformity is achieved using most, if not all, of the emitted current.

It is perhaps surprising at first that no additional lens is required to produce the image. In fact the lens is provided by the field in the gun itself. That these fields can be adjusted to form a cathode image has been known for many years, but was never before used in the context. For a given accelerating voltage, the grid voltage determines the focal length of the cathode lens. A unique grid voltage exists which produces an image of the emission surface in the first shaping aperture.

The structure of the emitting surface is reproduced in the object plane, and again in the final image. It is, therefore, important that the cathode surface be kept free of imperfections. A crossover exists, and is displaced from the cathode surface, as shown in Fig. 2(a). As in the previous case, this crossover defines the exit pupil of the gun. It can be independently imaged into the entrance pupil (defining aperture) of the final lens, thus maximizing the intensity in the final image.

This approach, in which the source is optically conjugate with the object and final image, is known from light optics as critical illumination. A potential source of confusion exists here. Some of the electron optics literature treats the crossover, rather than the cathode surface, as the source. In this paper we will adhere to the convention that the cathode surface represents the electron source. The illumination scheme depicted in Fig. 2(a) should then properly be called critical illumination.

The cathode temperature provides a degree of freedom by which the emission current is controlled. The intensity distribution measured for a number of temperatures is shown in Fig. 3. The grid potential was held constant, while the temperature was varied by changing the filament current. It is significant that little change in the illumination uniformity occurs.

The illumination is, of course, only a part of the optical column. Next we must determine what constraints, if any, are imposed by considering the optical system as a whole. This is the subject of the next section.

Impact of Critical Illumination on the Overall Optical Design

In order to utilize all of the emission current, and thereby minimize the energy spread, two conditions must be met: (1) The cathode image just fills the first shaping aperture; (2) The beam convergence semi-angle α measured at the writing surface coincides with the optimum value determined by the Coulomb interaction, and by the aberrations of the optical system.

In the normal operation of the shaped beam system, the gun crossover is imaged into the plane of the final lens. The radius of the magnified crossover divided by the image distance of the final lens thus determines the

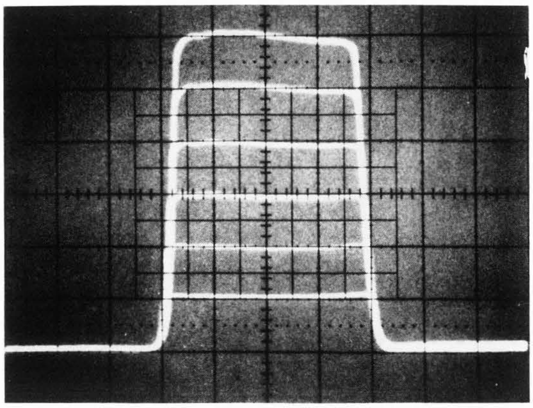

Fig. 3 Intensity distribution measured in the plane of the first shaping aperture for various temperatures. Good control of the emission current is obtained with little variation in illumination uniformity. The horizontal and vertical scales are the same as Fig. 2(b). The temperatures for the six traces range between 1380°K and 1620°K.

beam semi-angle α. Although α can be reduced by the presence of an aperture, our scheme of optimization requires that no aperture be used.

According to the law of Helmholtz-Lagrange, the quantity $r\alpha\sqrt{V}$ is conserved in the limit of paraxial optics, where r=radius of the ray bundle, α=slope, and V=beam voltage. Using this, we can write:

$$r_E\alpha_E\sqrt{V}_E = r_A\alpha_A\sqrt{V}_A = r\alpha\sqrt{V} \quad (4)$$

where the subscripts E and A refer to the emitting surface and the first shaping aperture, respectively, and variables without subscript refer to the final target. To first approximation $\alpha_E \simeq 1$ and $V_E \simeq kT/e$. Furthermore, $\alpha_A = r_c/L$, where r_c=radius of the virtual crossover and L=distance from the crossover to the first shaping aperture. It is easily shown that these relationships yield the following two equations:

$$L = r_c/(M\alpha) \quad (5)$$

$$r_E = r\alpha[eV/(kT)]^{1/2} \quad (6)$$

where $M=r/r_A$= magnification from the first aperture to the target, and r_E= radius of the flat emitting surface. These equations govern the optics of a minimum energy spread system.

It is possible to make the emitting surface square to match an optically conjugate square spot, in which case r_E and r refer to the semi-diagonal dimensions. For the EL3 system (Pfeiffer, 1978) we substitute α=0.007, M=1/70, V=25kV, and r=2.8µm (corresponding to the semi-diagonal dimension of a 4µm spot). We also substitute the measured values r_c=4.3µm and

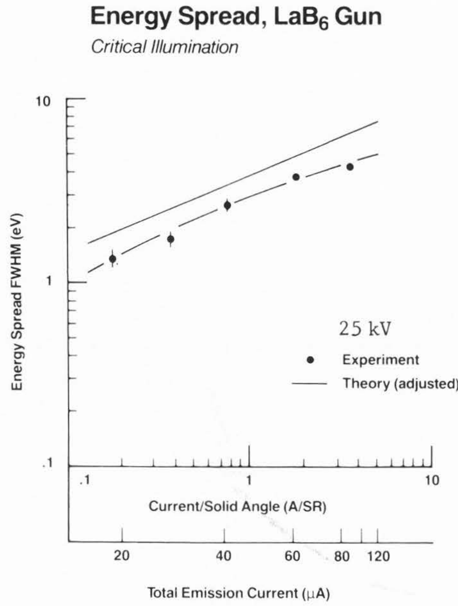

Fig. 4 Energy spread as a function of total emission current and current per unit solid angle, measured at the virtual crossover. Critical illumination was used. The theory of van Leeuwen and Jansen is used to calculate the solid curve. The theoretical values are reduced by a factor of two to derive the curve, in order to account for the semi-infinite approximation to a gun. The energy spread increases roughly as the square root of the total emission current.

T=1530°K. These values yield L=4.3 cm and r_E=8.7µm for a minimum energy spread system.

Finally, it is interesting to look quantitatively at the energy spread with critical illumination. This is shown in Fig. 4. Using a lens below the shaping aperture, the gun crossover was imaged into the entrance of a retarding field analyzer. Again, a pinhole aperture was used in place of the shaping aperture. This limited the current, and insured that the only significant energy broadening due to Boersch effect took place above the aperture. The figure shows 4.5 eV energy spread (FWHM) measured at 25kV and 100µA total emission. This corresponds to a brightness of 8.2×10^5 A/(cm^{2}sr).

Values derived from the theory of van Leeuwen and Jansen (see Eqs. 1-3) are shown for comparison in Fig. 4. They are reduced by a factor of two to account for the semi-infinite approximation of the geometry. The angular distribution of current from the virtual crossover was observed to have a Gaussian distribution. The value of α_o in Eq. 3 is, therefore, calculated as follows:

$$dI/d\Omega = I_E/(\pi\alpha_o^2)\cdot\exp(-\alpha^2/\alpha_o^2) \quad (7)$$

$$\alpha_o = [I_E/(\pi dI_E/d\Omega)_o]^{1/2} \quad (8)$$

where $(dI_E/d\Omega)_o$=peak current per unit solid angle, and I_E=total emission current. These two quantities were measured separately, and are shown on the horizontal axis of Fig. 4. The virtual crossover radius r_c was found to depend only weakly on the emission current, and its value was assumed to be constant with r_c=12.5μm. The energy spread departs slightly from a $\sqrt{I_E}$ dependence, due to a variation of α_o with current. The agreement between experiment and theory only approximately accounts for the geometry and beam energy.

We can define a quantity called the gun efficiency, equal to the target current divided by the total emission current. For a given target current the above arguments show that the energy spread is proportional to the square root of the efficiency. As mentioned, the efficiency is typically 0.01 for conventional Koehler illumination, and close to unity for critical illumination. Critical illumination, therefore, is expected to yield an order of magnitude improvement to energy spread for the range in which Boersch effect is prevalent. For current below this range, the energy spread is thermal, and about equal to kT.

Conclusions

The requirements of the source for electron beam lithography depend on the writing strategy. For Gaussian round beam systems, which expose a pattern serially, high brightness is needed to obtain reasonable writing rates. In shaped beam systems, uniformity of illumination replaces brightness as a key consideration. Stability of the emission in space and time is essential to all modes of operation. Finally, low energy spread is needed in order to obtain optimum edge acuity of the focussed spot.

The fastest systems in use today employ the shaped beam concept. Since the energy spread of emitted electrons depends on the total emission current, it is advantageous to use the maximum possible fraction of the emission to form the writing probe. With conventional Koehler illumination a tradeoff exists between the fraction of the emission used and the uniformity of illumination.

This trade-off is circumvented by employing critical illumination with a flat, single crystal cathode. Using this approach, nearly all of the emission current can be used to form the writing probe. In an optimum column, the size of the emitting surface and the distance from the gun to the first shaping aperture are constrained to specific values.

For constant target current, the energy spread is proportional to the square root of the gun efficiency, defined as the target current divided by the total emission current. Relative to Koehler illumination, in which the gun efficiency is about 0.01, critical illumination results in about an order of magnitude decrease in energy spread for the same target current. This assumes that the current is in the range where Boersch effect determines the energy spread. For emission current below this range, the energy spread is about kT.

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Discussion with Reviewers

G. Owen: In Figs. 1(a) and 2(a) the virtual crossover appears to coincide with the center of a thin lens representing the gun. Is this the case in practice?
Authors: The figures are a schematic representation only. In practice the cathode lens is a thick immersion lens, and the crossover is located within the lens field. The virtual crossover size depends only weakly on the strength of this lens, however. This is the reason for showing the crossover in the plane of the effective lens.

J. Cowley: What are the desirable shapes for a shaped spot? Are the shapes and dimensions arbitrarily variable? How is the shaping done by use of two apertures?
Authors: The most useful shapes include all rectangles with the narrow dimension greater than or equal to the minimum linewidth to be written. The largest useful rectangle is a square of several microns on a side. For most integrated circuit patterns it is sufficient to have all rectangles oriented along a single set of Cartesian axes, without rotation. The shapes and dimensions should be arbitrarily variable, in order to correct for small linewidth variations arising from the process. This can all be accomplished using a square aperture, imaged via a lens onto a second square aperture, with an intermediate deflector to move the image of the first aperture in the plane of the second aperture.

T. Mulvey: There appears to be a discrepancy between what you mean by Koehler illumination and what Koehler himself meant. His idea was to control, independently, the size of the illuminating beam reaching the specimen and the angular aperture of the ray pencils forming the beam. This was done by the judicious placing of two apertures and two lenses. Could you please comment?
Authors: This was not all that Koehler had in mind. His idea also included placing an image of the source at the back focal plane of a condenser lens (in our case the cathode lens). A virtual image of the emitting surface is thus formed at infinity, with the advantage that the structure of the emitter does not appear in the object plane (our first shaping aperture).

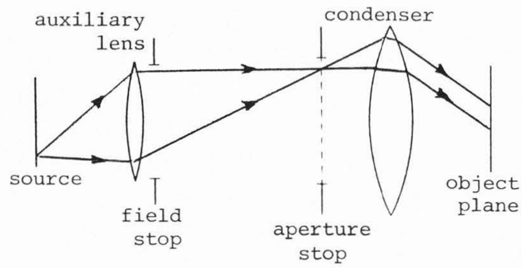

Fig. 5 Koehler's Illumination Scheme

Koehler's illumination scheme is shown above in figure 5, after Born and Wolf (text ref. 1). An intermediate image of the source is formed in the plane of the aperture stop. In our case this image is replaced by the emitting surface itself. His aperture stop limits the aperture angle at the object plane. In our case this function is provided by the finite extent of the emitter, which is fully equivalent to an aperture in this regard.

Koehler's field stop limits the illumination area. It does this by limiting the cone angle of rays emanating from any given point in the plane of the aperture stop. In our case this cone angle is limited by the maximum emission angle of electrons from the cathode surface. Herein lies the essential difference between what is generally called Koehler illumination in electron optics, and what Koehler himself meant: in electron guns one has little or no control over the emission angle, whereas Koehler could effectively control this parameter by altering the size of the field stop. There is nothing to prevent the use of Koehler's lenses and apertures in electron optical instruments. Why, then, is this not typically done? The reason is that it is not necessary to go to such lengths to obtain the illumination one desires.

A strict adherence to Koehler's original illumination scheme would not lead to a higher gun efficiency either, since it would still be necessary to stop most of the emission current on the field stop in order to obtain adequate uniformity of illumination. Here, too, we are limited by the non-uniform angular distribution of the emission at the cathode surface. You are correct in pointing out that our use of the term Koehler illumination does not correspond precisely with Koehler's. The end result is the same in most respects, however. It should be added that, for better or worse, this usage has been widely adopted by the engineering community.

G. Owen: In the section of text between Eq. (4) and (5), you state that "$\alpha_A=r_c/L$, where r_c=radius of the virtual crossover and L=distance from the crossover to the first shaping aperture." This is not clear. Could you please elaborate?
Authors: The virtual crossover is represented by the waist in the solid rays in Fig. 2(a). A ray from the edge of this disk to the midpoint of the first shaping aperture makes an angle α_A with the optic axis. This defines the beam cone at the object plane.

J. Cowley: Could the same advantages be achieved by use of critical illumination when a tungsten hairpin filament is used?
Authors: The illumination from a typical tungsten hairpin filament is not sufficiently uniform to be of use. It is conceivable that a flat, single crystal tungsten cathode could be used. Due to its higher operating temperature tungsten evaporates at a faster rate than LaB_6, however. The dimensional stability and lifetime of a tungsten cathode would, therefore, be limited.

G. Owen: Would I be correct in thinking that if critical-Koehler illumination is used, the emitting surface of the source must be physically perfect if uniform illumination is to be obtained? Does this pose a problem in practice?
Authors: The easiest way to implement this scheme is to start with a physically perfect emitting surface. In our experience a surface of adequate quality can be obtained from a polished, oriented LaB_6 crystal made by conventional zone refining techniques.