Electron Gun Using a Field Emission Source*

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A new electron gun has been built which features mechanical and optical simplicity. Theoretically, it can produce a focused spot having a radius smaller than 50 Å and provide 1000 times more intensity than a hot filament system having a similar final spot size. The increase in intensity is made possible by using a field emission electron source operating at a pressure of 10^{-9} Torr, which is provided (without baking) using commercially available pumps. The small spot is produced by using two properly shaped electrodes which accelerate and focus the electrons from the tip. It would take a hot filament gun and at least two additional lenses to replace this field emission gun when a spot radius less than 100 Å is required. Even then the brightness of the conventional source would be too low to make use of the small spot size obtained. The optical properties for the new gun were predicted on a computer and experimentally confirmed in a new scanning electron microscope. The aperture aberration coefficient was measured to be no more than a factor of two greater than the theoretical value of 1.5 cm. A spot radius of 250 Å has been measured, and this value is to be compared with the theoretical value of 150 Å. Although it was convenient to measure the spot directly only at a relatively large image distance (11.3 cm), calculations imply that the gun can provide a spot radius less than 25 Å when very small image distances are used. The gun can be used in pulsed operation because all optical properties are constant for a given voltage ratio so that application of the electrode voltages by means of a voltage divider provides automatic focusing for arbitrary changes in the applied voltage. The methods used to make and operate reliable high field emission tips are reviewed, and a technique is described for changing the required tip voltage to obtain a given emission current.

I. INTRODUCTION

A SIMPLE triode electron gun has been built in order to provide a beam for use in a scanning electron microscope. The properties of this gun are significantly different from those of a conventional gun so that a variety of different applications may exist. In particular, the available current density in small focused spots is considerably higher than can normally be achieved.

The aim of the program was to design a gun which would accelerate and focus electrons into a very small spot. When used in a scanning microscope, this spot is demagnified with an auxiliary lens[1,2] and focused on a specimen (see Fig. 1). In our particular instrument the final image is scanned across the specimen in a television-type raster, and the transmitted electron beam is used to modulate the intensity of a synchronously scanned display tube.[3] The ultimate resolving power of this type of instrument is determined by the spot size at the specimen, and the time required to form a recognizable picture is determined by statistical fluctuations in the intensity of the transmitted electron beam. If a conventional gun using a hot filament tip is used in the microscope arrangement shown in Fig. 1, the final spot size is limited to a range above 100 Å,[4] although in this case the necessary demagnification is obtained by using several auxiliary lenses in series. The brightness of a hot filament source is such that when a spot of less than 100 Å is produced by demagnification with conventional lenses there is insufficient intensity to produce a picture in a reasonable time. Any attempt to improve the resolution of the scanning electron microscope must therefore involve an increase in brightness (A/cm²/sr) of the source.

An electron source which is potentially very bright is a field emission source. A pointed whisker of tungsten will emit electrons when a negative potential is applied. Currents as high as 1 mA can be obtained from a piece of

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[1] A. V. Crewe, Science 154, 729 (1966).

[2] A. V. Crewe, D. N. Eggenberger, J. Wall, and L. M. Welter, J. Appl. Phys. 38, 4257 (1967).

[3] W. K. Brookshier and J. Gilroy, Trans. Nucl. Sci. IEEE NS-12 104 (1961).

[4] C. W. Oatley, W. C. Nixon, and R. F. W. Pease, Advan. Electron. Electron Phys. 21, 181 (1965).

tungsten only a few thousand angstroms in diameter. Such an electron source must be used in an electrode configuration which does not introduce excessive aberrations in the beam and which permits independent control of both emission current and electrode voltage.

II. THE FIELD EMISSION ELECTRON SOURCE

A. Characteristics of the Source

The current density of a high field emission tip is a complicated function of angle off the axis. Dyke and Trolan[5] have used an average technique to define the current density in terms of the emission current (I). Using this approach, they have measured continuous current densities up to 10^6 A/cm^2 compared to approximately 10 A/cm^2 for a hot filament tip.[6] This feature alone is interesting, but there is also the fact that the apparent source size is much smaller than the actual tip size. If we consider a tip with a hemispherical end and also assume that electrons will be emitted within a finite voltage range 0 to V_T, then one can show that the apparent source radius (r) is approximately[7]

$$r = R(V_T/V_1)^{1/2} \qquad (1)$$

where R is the radius of the tip and V_1 is the potential applied to the tip. This approximation is good for a spherical source only. The effect of the shank will be to change this value, but not by an order of magnitude. Reasonable values to insert in this equation are $R = 500$ Å, $V_T = 0.5$ V, and $V_1 = 1$ kV, which lead to $r = 11$ Å.

The Fowler–Nordheim theory[8–10] for field emission gives the following equation for the current density:

$$J = aE^2 \exp[-B\Phi^{3/2}/E], \qquad (2)$$

where J is the current density in amperes per square centimeter, E is the electric field applied at the tip in volts per centimeter, Φ is the work function in electron volts, B is a constant equal to 6.12×10^8 in the above units, and a is a function of Φ ($a = 3.5\times10^{-6}$ A/V^2 for tungsten with $\Phi \approx 4.5$ eV).[11] Gomer[12] describes how the tip radius or the metal work function can be found experimentally using the slope

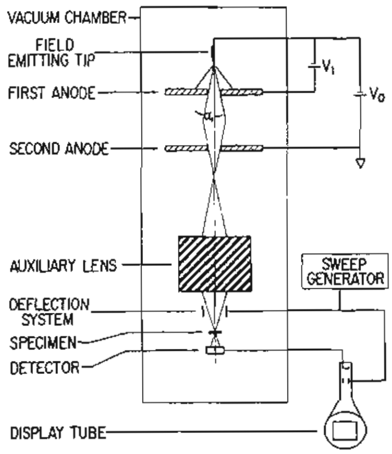

FIG. 1. Block diagram of the experimental scanning electron microscope.

of the Fowler–Nordheim equation. Charbonnier and Martin[13] present a unique method for obtaining information on tip geometry from the electrical data $I(V)$, the relationship between field emitted current and applied voltage.

A high field emission source has at least two advantages when it is considered for use in a scanning electron microscope, namely, increased current density and very small size. One disadvantage of this source is that it will only operate well when the pressure is below 10^{-9} Torr; however, this range is now readily available using modern pumps and vacuum techniques.

B. Making the Tip

Most high field emission work has been done using tungsten as the tip material. The reasons for this selection are its suitable properties, such as a high melting point, a low vapor pressure, relatively high electrical and thermal conductivity, and high mechanical strength.

We fabricated our tips using the techniques outlined by Dyke *et al.*[14] A piece of 0.125 mm diam tungsten wire 1–3 mm long is spot-welded onto a preformed 0.2 mm diam tungsten filament which is hairpin shaped. The

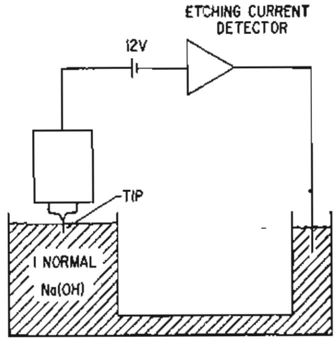

FIG. 2. Tip etching arrangement

[5] W. P. Dyke and J. K. Trolan, Phys. Rev. 89, 799 (1953).
[6] V. E. Cosslett and M. E. Haine, Intern. Conf. Electron Microscopy (London), p. 639 (July 1954).
[7] M. Drechsler, V. E. Cosslett, and W. C. Nixon, 4th Intern. Conf. Electron Microscopy (Berlin), p. 13 (Sept. 1958).
[8] R. H. Fowler and L. Nordheim, Proc. Roy. Soc. (London), **A119**, 173 (1928).
[9] L. W. Nordheim, Proc. Roy. Soc. (London) **A121**, 626 (1928).
[10] A. G. J. van Oostrom, Thesis, University of Amsterdam (June 1965).
[11] W. P. Dyke and F. M. Charbonnier, Advan. Electron Tube Tech. **2**, 199 (1962).
[12] Robert Gomer, *Field Emission and Field Ionization* (Harvard University Press, Cambridge, Massachusetts, 1961), Chap. 2, p. 47.
[13] F. M. Charbonnier and E. E. Martin, J. Appl. Phys. **33**, 1897 (1962).
[14] W. P. Dyke, J. K. Trolan, W. W. Dolan, and George Barnes, J. Appl. Phys. **24**, 570 (1953).

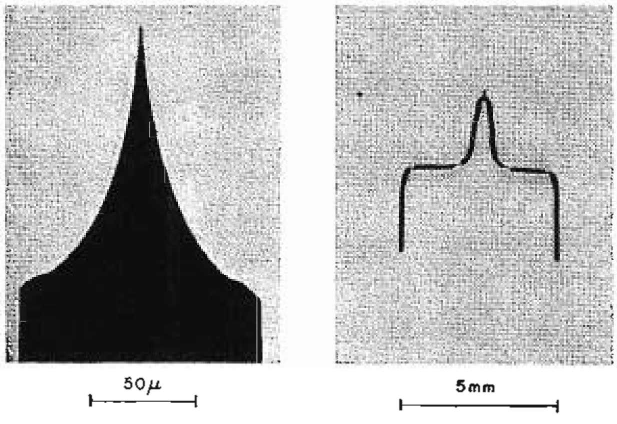

FIG. 3. (a) Typical shadowgraph of an etched tip. (b) Etched tip mounted on an electropolished hairpin filament.

assembly is electropolished, and the tip is etched by immersing it in a one normal sodium hydroxide (NaOH) solution and by applying 12 V dc between the tip and a remote electrode in the solution (see Fig. 2). The second electrode is removed some distance so that gas given off at this electrode will not disturb the liquid surrounding the tip. It is important that the NaOH solution be clean and that the etching assembly be mounted on a vibration free platform. A tip can be etched in about 3 min and a significant change in etching current occurs just as the unwanted part of the tip is etched off. An electronic sensing circuit is used to detect this change and to turn off the applied voltage within about 1 μsec. If the voltage is left on much longer than this, blunting of the tip will occur. Figure 3(a) shows the typical shape of an etched tip as viewed with our scanning microscope, and Fig. 3(b) shows an electropolished assembly of the tip and filament.

C. Tip Operation

The etched tip is mounted in an enclosure which is evacuated to about 10^{-9} Torr. The tip is "formed" (rounded off) by sending a brief pulse of current through the filament. As the magnitude of the current pulse is increased, the filament begins to glow red. By this time the heat has usually driven off the contaminants so that the pressure no longer rises during the flash. The tip is then tested to see whether cold field emission is occurring. After emission is detected, a check is made to determine if the tip is properly formed by comparing an experimental voltage–current curve with that predicted by the Fowler–Nordheim equation. A typical Fowler–Nordheim plot for a tungsten tip having the plane with Miller indices (310) perpendicular to the axis is shown in the next section. This crystal orientation was selected because it produces intense emission along the axis.[15]

[15] 310 oriented tungsten wire may be obtained from Field Emission Corp., McMinnville, Ore.

The subsequent performance of the tip appears to be more dependent on the local gas pressure than on any other parameter. In general, the emission current at constant voltage appears to be a curve similar to that of Fig. 4.[16] At first there is a small decline in emission current as the surface of the tip becomes coated with contaminants which increase the work function. Thereafter the current rises until it becomes erratic, and the tip eventually destroys itself by a vacuum arc.[17–19] The time scale for this process can vary from seconds to thousands of hours depending on the pressure.[16]

The stability of the emission current does not appear to have a severe dependence on the magnitude of this current. The principal effect is the rise in local pressure caused by the production of gas molecules as the electron beam strikes the surface of the first anode (see Fig. 1). This effect can be controlled by thoroughly preheating the anode. We have found that once the anode has been outgassed, cycling up to atmospheric pressure has almost no adverse effects as long as the system is not left at this pressure for many hours.

When the emission current becomes erratic, the performance of the tip can easily be restored to its original condition by providing a pulse of current through the filament to evaporate the contaminants. This "flashing" technique is used periodically and the frequency of flashing depends on the time scale in Fig. 4. We have operated a tip at a continuous emission current of 1 mA ±1.5% for over 70 h without flashing when the system was kept below a pressure of 10^{-9} Torr using a 400 liter/sec ion pump. This contamination problem is not severely limiting however because the tip can be flashed with operating voltages left on, and if the usable electron beam (beam contained within the limiting aperture) is confined to relatively small angles (less than a few degrees) about

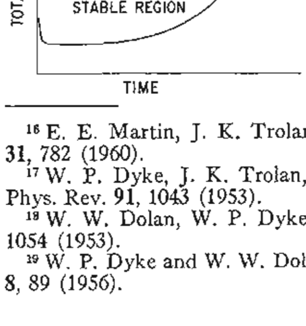

FIG. 4. Typical dependence of emission current with time. As the tip becomes coated with contaminates, the emission first of all drops, and then begins a steady rise until the emission becomes erratic and the tip will eventually destroy itself with a vacuum arc.

[16] E. E. Martin, J. K. Trolan, and W. P. Dyke, J. Appl. Phys. 31, 782 (1960).
[17] W. P. Dyke, J. K. Trolan, E. E. Martin, and J. P. Barbour, Phys. Rev. 91, 1043 (1953).
[18] W. W. Dolan, W. P. Dyke, and J. K. Trolan, Phys. Rev. 91, 1054 (1953).
[19] W. P. Dyke and W. W. Dolan, Advan. Electron Electron Phys. 8, 89 (1956).

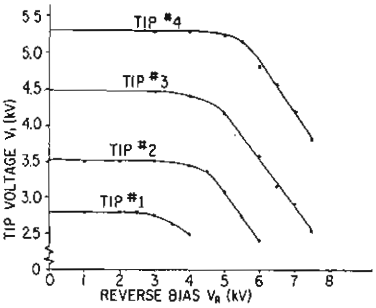

FIG. 5. Graphs illustrating the remolding process as a function of the applied reverse bias. The four curves are for different tungsten tips. The tip voltage shown in the ordinate is the voltage required to achieve emission of 1 μA after applying the indicated reverse bias.

the axis, the beam current within this solid angle is reasonably independent of the instability of the total emission current shown in Fig. 4.

D. Remodeling the Tip

Field emission can be obtained by applying potentials of 2–5 kV to a tip with a radius of 1000 Å. In our application it was desirable to obtain an emission current of approximately 0.1 μA at a potential of 1–2 kV. If the tips are formed in the normal manner, the necessary potential for the required emission current frequently reaches 3–5 kV after they have been formed by heating. In order to obtain the same emission current but at a lower applied voltage (V_1), we flash the tip with a pulse of filament current equal in magnitude to that used to form it and at the same time apply a positive dc voltage (V_R) to the tip with respect to the anode.[20] Using this reverse bias technique we have consistently reduced the necessary potential to achieve a given emission current. Figure 5 illustrates this phenomenon as a function of the reverse voltage (V_R) for several different tips. The curves are reproducible to within 5%. We have also observed a threshold temperature (flashing current) below which the remolding process does not occur even though the reverse voltage is applied. If the remolded tip is flashed at the forming current with no reverse bias, the operating conditions immediately return to those at the starting point ($V_R=0$ for any given tip in Fig. 5).

Typical Fowler–Nordheim plots for the normal and remolded tips are shown in Fig. 6 with the tip radii found using the slope method.[12] The emission pattern for a normal tip is shown in Fig. 7(a) where the relatively intense spot on the axis corresponds to emission from the 310 plane. After remolding the tip, emission from this plane becomes dominant and the solid angle subtended by the more intense emitting area is almost unchanged [see Fig. 7(b)]. We have also examined the physical shape of these tips with our scanning microscope. The normally formed tip is shown in Figs. 7(c) and 7(d), and this tip has the typical hemispherical end. The tip radius is in good agreement with the value found from the Fowler–Nordheim plot in Fig. 6.

A typical shadowgraph of a remolded tip is shown in Figs. 7(e) and 7(f); however this tip is not the one used to obtain the Fowler–Nordheim plot (Fig. 6) so the tip "radii" cannot be directly compared. The exact meaning of the radius of a remolded tip is not clearly defined, and the term is only used to serve as a comparison with a normal tip. The effect of "buildup" (enlargement of certain crystal planes caused by the application of the reverse voltage during the remolding process)[21] is shown in these shadowgraphs. Although our typical emission current is only 0.1 μA, we have operated a remolded tip continuously at 500 μA $\pm4\%$ for over 90 min without flashing. During this test a 400 liter/sec ion pump kept the pressure below 10^{-9} Torr and no signs of catastrophic failure were observed. A Fowler–Nordheim plot was taken and space charge effects[5] were observed. The remolded tip may be cleaned using the flashing technique as previously mentioned (without reverse bias), but because the shape of a remolded tip has a severe dependence upon flashing temperature, we usually reapply the reverse bias during the flashing process.

The remolding process, then, is a method of adjusting the required voltage (V_1) to achieve a given emission current (I). This variability of tip potential is important since V_1 also affects the optical parameters of the electron gun as will be discussed in the next section. We have not yet examined the effect of tip remolding on the apparent source size for this electron gun, but no change in microscope resolution is observed when the tip is remolded.

III. ELECTRON GUN

A. Gun Design I

The electron gun must have a minimum of three electrodes when using a field emission source in an electron

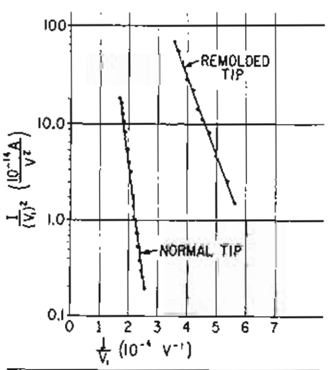

FIG. 6. Typical Fowler–Nordheim plots for a normal tip and a remolded tip. The tip radii are calculated from the slopes of the curves.

	NORMAL TIP	REMOLDED TIP
TIP RADIUS	1900±400 Å	600±120 Å
VOLTAGE FOR $I=0.1$ μA	4300 V	1880 V

[20] I. L. Sokolovskaia, Soviet Phys.-Tech. Phys. (English Transl.) **26**, 1147 (1956).

[21] P. C. Bettler and F. M. Charbonnier, Phys. Rev. **119**, 85 (1960).

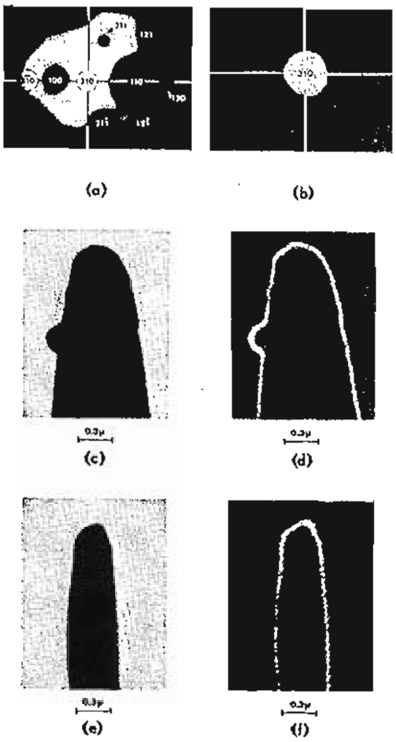

FIG. 7. Field emission patterns for (a) a normal (310) tip, and (b) a remolded (310) tip. Shadowgraphs of a normal tip (c,d). Shadowgraphs showing "build up" for a remolded tip (e,f). (c) and (e) were produced by collecting electrons having primary energy (V_0 eV), and the "halo" of these tips shown in (d) and (f), respectively, is obtained by collecting electrons which have lost less than 1 eV of energy. This technique involves the use[1] of an energy analyzer in conjunction with the scanning microscope.

microscope. Two voltages can then be applied in order to allow independent control of the emission current and the final electron energy (see Fig. 1). The voltage (V_1) applied between the tip and the first anode defines the total emission current and the voltage (V_0) defines the electron energy. Apertures in the first and second anode allow electrons to pass through to form the beam.

This simple design has many defects which could contribute to third order aberrations in the beam and cause some of the beam quality to be lost. The design can be improved by reducing these aberrations. For example, the region between the tip and the first anode can be improved by retaining the spherical symmetry of the emitting surface. This means that the first anode should consist of a spherical shell with the apparent source at the center of the sphere. The position of the apparent source does not occur at the center of the hemispherical tip because the effect of the shank is to distort the field near the tip; however, we have found this effect to be small.

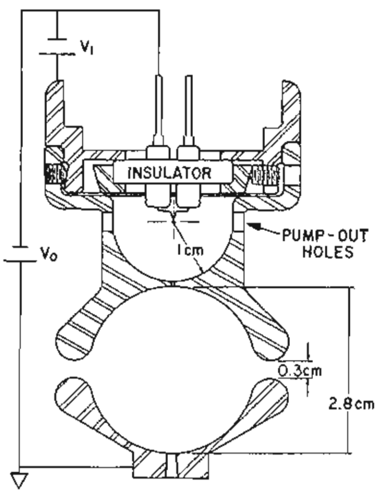

FIG. 8. Scale diagram for Gun I.

Another problem is caused by the necessity of having holes in the two anodes. The aperture in each electrode acts as an electron lens with a strength determined by the difference of the electric fields on either side of the aperture. This arrangement has aperture aberrations which degrade the beam quality. Our attempt to improve this situation consists of reducing the electric field in the region around the holes to very low values so that the lens effect is small.

Figure 8 shows our first electron gun based on the above principles. The tip emits to a hemispherical anode of 1 cm radius. The two accelerating anodes were made in the shape of a split sphere in an attempt to reduce the field at the two apertures. The second anode was connected to ground, and the tip and first anode were raised to a high negative voltage. The entire first anode assembly was then made a few kilovolts positive (V_1) with respect to the filament to control the emission. The tip was optically prealigned with the first anode before installation into the microscope, and this entire assembly could be moved with respect to the second anode while the microscope was at high vacuum and the gun was in operation. A bellows was used to provide a movable high vacuum feedthrough.

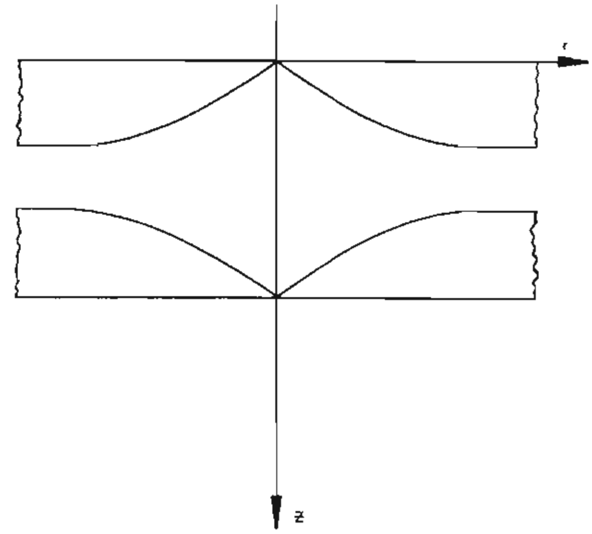

FIG. 9. Optimum shape of gun electrodes as calculated by J. W. Butler.

This gun was operated successfully for several months in a series of experiments with the scanning electron microscope. Although the gun showed some merit, it was never completely evaluated because a second model with significant improvements had been built.

B. Gun Design II

An essential characteristic of the gun shown in Fig. 8 is that the optical properties of the system are determined by the shape of the field between the two anodes. We can assume that the holes in the anodes do not contribute to first or third order optical properties because the electric field is specified to be zero on either side of the aperture in the neighborhood of the hole. The field shape between the two anodes is now a free parameter which may be adjusted to minimize aperture aberrations. This problem has been solved (neglecting relativistic effects) by Butler[22] with the boundary condition that the field in the neighborhood of the anode apertures is zero. The results of his calculations are shown in Figs. 9 and 10.

Figure 9 shows a universal curve for the cross section of the electrodes where the two anodes meet at an infinite radius. A universal set of theoretical gun parameters is given in Fig. 10 for the geometry shown in the upper part of the diagram, namely, a 1 cm distance from tip to first anode and a 2 cm distance between the apertures. The image distance (S) is defined as the position of the image of the tip measured from the exit plane of the second anode. The conventional geometrical optics definition for magnification is used $[m=\alpha_1(V_1/V_0)^{1/2}/\alpha_0]$. The aperture aberration coefficient (C_s) is defined in the usual manner except that it is referred to the source. That is, the effect of this aberration is to convert an ideal point source into one with an apparent radius of

$$r_1=C_s\alpha_1^3=C_s m^3(V_0/V_1)^{3/2}\alpha_0^3, \tag{3}$$

where α_1 and α_0 are the electron beam half-angles at the source and image plane, respectively (see Fig. 10).[23] The theoretical radius at the Gaussian image plane due only to aperture aberration is then

$$r_a=mr_1=C_s m^4(V_0/V_1)^{3/2}\alpha_0^3. \tag{4}$$

To obtain the actual image size, we must include the effect of source size [Eq. (1)],

$$r_s=mr=mR(V_T/V_1)^{1/2}, \tag{5}$$

and the effect of diffraction,

$$r_d=0.3\lambda_0/\alpha_0, \tag{6}$$

where λ_0 is the wavelength of the particle and r_d is the half width at half maximum of the first diffraction zone.[24]

The gun parameters are predicted for voltage ratios (V_0/V_1) well above 29 even though they are not included in Fig. 10. The curves are smooth functions and for a voltage ratio of 60 (for example, $V_0=60$ kV and $V_1=1$ kV) the image distance is -0.9 cm, the magnification is 0.23, and the aperture aberration coefficient is 11 cm.

[22] J. W. Butler, 6th Intern. Congr. Electron Microscopy (Kyoto), p. 191 (1966).

[23] The approximate formulas given here are for the Gaussian image plane. It should also be noted that the chromatic aberration effect has been neglected.

[24] M. E. Haine, *The Electron Microscope* (E. and F. N. Spon Ltd., London, 1961), Chap. 3, p. 52.

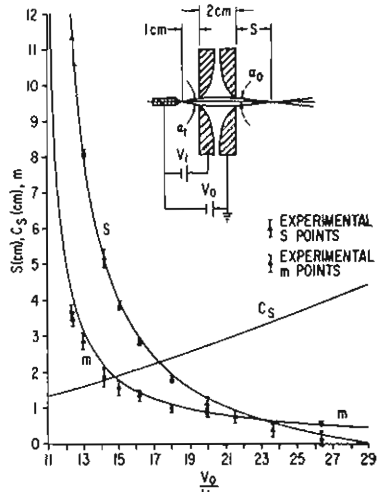

FIG. 10. Theoretical and experimental optical properties for Gun II. The three curves shown are for geometrical magnification (m), the image distance (S), and the spherical aberration (C_s). The experimental measurements confirm the calculations for m and S, but only limited information is available so far on C_s.

C. Experimental Application

A practical design based on the electrode shape of Fig. 9 is shown in Fig. 11. In this design we attempted to take advantage of the knowledge gained from using Gun I. We rigidly connected the two anodes together by cementing them to an alumina insulator. In this way a compact "sandwich" is formed which can be carefully aligned at assembly rather than repeating the alignment procedure many times throughout the life of the gun. The anodes are separate inserts so that they can easily be removed for cleaning. The emitting tip is suspended above the first anode and can be moved in a plane perpendicular to the axis of the gun without breaking the vacuum. Magnetic shielding is provided by surrounding the entire assembly with a mumetal shield.

This gun has been operated in a scanning electron microscope for several years and many measurements of its properties have been made. The gun has been used in conjunction with an electron lens which demagnifies the image of the tip produced by the gun and results in a very small probe size at the specimen (see Fig. 1). The optical

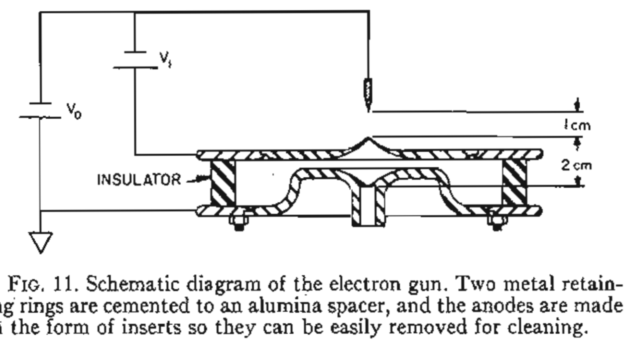

FIG. 11. Schematic diagram of the electron gun. Two metal retaining rings are cemented to an alumina spacer, and the anodes are made in the form of inserts so they can be easily removed for cleaning.

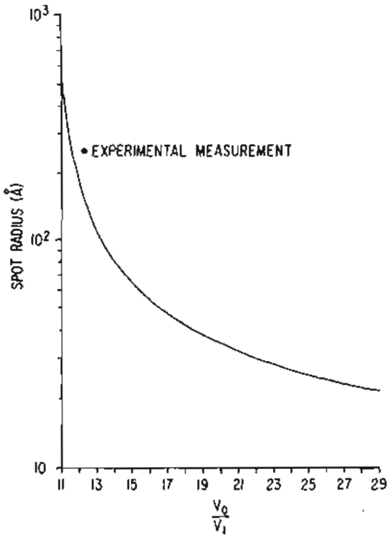

FIG. 12. Spot size produced by the electron gun. The curve is calculated using the first and third order theoretical optical properties. Included in this calculation are source size, aperture aberration and diffraction. Owing to the geometry of our particular arrangement, only one point could be measured so far.

properties of the gun have been measured in this scanning microscope and the experimental values are included in Fig. 10. The coefficient of aperture aberration has not been measured as a function of the voltage ratio; however, we have made many direct measurements of gun properties by removing the auxiliary lens excitation and focusing on the specimen which is approximately 11.3 cm from the exit of the gun. This focusing procedure is accomplished by varying either V_1 or V_0 to obtain a ratio of 12.34 (see Fig. 10). Typically a spot radius of 250 Å can be achieved for this ratio with an aperture of 100 μ diam at the first anode ($\alpha_1 = 5$ mrad). Since this is only about twice the theoretical spot radius found by taking the rms value for Eqs. (4) through (6) (see Fig. 12) and since the first order properties have been confirmed within the accuracy of our measurements, we conclude that the theoretical curves in Fig. 10 are essentially correct. Even if the total experimental error in spot size is due to aperture aberration, the value of C_s would only be a factor of two higher than the theoretical value given. We already have indirect experimental confirmation for spot radii at higher voltage ratios (see Fig. 12), but a system is presently being designed to directly measure these values more accurately.

IV. COMPARISON WITH A CONVENTIONAL ELECTRON GUN

A convenient way of comparing this electron gun to a conventional hot filament type is to calculate the current in a focused spot as a function of the spot size. We make this calculation for our gun (using no auxiliary lens) assuming that: (a) a maximum current of 1 mA is uniformly emitted into a cone with the experimentally observed half angle of 300 mrad, (b) the theoretical curves in Fig. 10 are correct, (c) Eqs. (4) through (6) can be combined by taking their rms value to obtain the spot size using an apparent source radius (r) of 4 Å [this source radius is obtained from Eq. (1) using $V_T = 0.5$ V and the experimental values of $V_1 = 5$ kV and $R = 400$ Å],[25] and (d) the V_0/V_1 ratio is chosen as 15 or 29 corresponding to an image distance (S) of 4 or 0 cm, respectively. Then by selecting arbitrary values for the half angle (α_1 or α_0), we find the beam current (I_B) contained in the spot from

$$I_B = 10^{-3}\alpha_1^2/(300\text{ mrad})^2 = 0.0111m^2\alpha_0^2V_0/V_1 \qquad (7)$$

where I_B is in microamperes when the half angles are in milliradians. The corresponding rms value for spot radius is found using Eqs. (4) through (6).

A similar calculation can be made for a hot filament source. Here we assume the electrons are accelerated by the potential V_0 from a cathode which has a maximum current density (ρ_0) of 5 A/cm².[7] This system is followed by an electromagnetic lens which has an aperture aberration coefficient (C_s) of 1 mm. For direct comparison with our gun we will also assume that V_T is 0.5 V and V_0 is 75 kV or 145 kV. The equations for the hot filament source [6] are then

$$I_B = \pi\rho_0 r_s^2\alpha_0^2V_0/V_T \qquad (8)$$

and

$$r_a = C_s\alpha_0^3, \qquad (9)$$

where it is understood that all quantities in Eqs. (8) and (9) refer to the conventional source. The diffraction term is negligible because its effect is confined to a vanishingly small value of beam current. We now make the general assumption that

$$\text{SPOT RADIUS} = r_a = r_s, \qquad (10)$$

and calculate I_B as a function of the spot radius. Note that Eq. (10) puts a constraint on the necessary lens demagnification since the source size effect (r_s) in image space is related to the apparent source size in object space by the magnification of the lens [see Eq. (5)], and the size of a hot filament source is at the very best greater than 10 μ. We assume that this necessary demagnification can always be obtained.

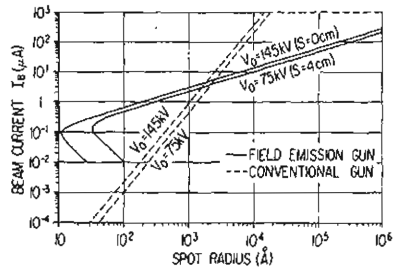

FIG. 13. Comparison of the performance expected from this electron gun with the performance which can be achieved using a conventional electron gun together with auxiliary electron lenses. The details of the comparison are explained in the text.

[25] The experimental values of V_1 and R given here were obtained in the space charge limited region for field emission and thus result in fictitiously high values for the applied field when this field is calculated using the conventional approximation[5] for the geometric factor β.

The results of these calculations are shown in Fig. 13 for two values of energy (V_0). The minimum spot size for the field emission gun is determined by selecting the optimum half angle (α_0) as determined by the conventional compromise between diffraction and aperture aberration [set Eq. (4) equal to Eq. (6) to find α_0]. A similar minimum occurs for the hot filament gun, but only at a beam current value of 5×10^{-14} A. The critical spot size given here is in good agreement with that already predicted by Cosslett and Haine.[6] It is interesting to calculate the brightness (β_1) [not to be confused with brightness at the cathode (β_0)][7] for the field emission source after the electrons have gained energy (eV_1) assuming that 1 mA of current is emitted into the observed solid angle ($\alpha=300$ mrad) and that the apparent radius for the remolded tip is actually $r=4$ Å. The brightness is then

$$\beta_1=(I/\pi^2r^2\alpha^2)=7\times10^{11}\ \text{A/cm}^2/\text{sr}. \qquad (11)$$

This corresponds to a current density at the cathode (ρ_0) of[7]

$$\rho_0=(I/\pi R^2)=\pi\alpha^2\beta_1V_1/V_T=2\times10^7\ \text{A/cm}^2. \qquad (12)$$

In practice we operate our microscope with a total emission current ranging from 0.1 to 50 μA rather than the value of 1 mA assumed above. However, we have obtained good stability operating a tip at 1 mA in an auxiliary system, as already mentioned.

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Method for Measuring Small Optical Losses Using a He–Ne Laser

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The output power or threshold for oscillation, respectively, of a He–Ne gas laser are severely influenced by the presence of small losses in the resonator. Small losses between about 0.01 and 1% may be measured by substituting the unknown loss of a sample for linearly polarized light by the known and adjustable reflection losses due to a plane parallel glass plate near the Brewster angle. A measurement apparatus based on this principle was built and the influence of various sources of error was evaluated. One source of error is the deviation from ideal linear polarization found in the output of gas lasers with Brewster angle windows. Measurements are given of the residual single pass transmission loss of doubly antireflection coated glass plates.

INTRODUCTION

THE output power and the excitation needed for threshold of a He–Ne laser depend rather strongly on the losses inside the optical resonator. For example, with a single pass gain of 0.6%, a change in single pass loss of only 0.01% may change the output power by 5% (see Fig. 1). This strong dependence may be used to advantage for the measurement of small optical losses. Two variations for a measurement procedure suggest themselves.[1,2] Both make use of the substitution of the unknown loss by a known and adjustable one. In one variation the laser output power is made to assume the same value after the substitution. In the other, threshold is made to occur at the same excitation after the substitution. During either procedure all other laser parameters such as gas discharge excitation and cavity Q must be kept constant. The reflection losses of glass plates oriented near the Brewster angle are utilized as adjustable and known loss mechanism. Numerical values of the reflection losses are computed through Fresnel's formula as a function of the angle of incidence.

The comparatively high reflection loss of typically 4% per interface for glass plates at perpendicular incidence usually prevents an accurate determination of the small intrinsic transmission loss. In our method, however, the plane parallel plate is located inside an optical resonator and exposed to a field of coherent radiation. It is then possible to determine such small intrinsic transmission losses directly by utilizing resonant effects, despite the presence of the numerically much greater reflection. In this way it is possible to determine single pass losses in

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