Lecture I. Field Emission and an Electron Gun

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MASTER

RECEIVED BY DTIC MAY 25 1970

Introduction

Field emission, as its name implies, is the process whereby electrons are emitted from a material by the influence of a large electric field. The process has been known for some time, and the basic equations were written down by Fowler and Nordheim in 1928.¹ The development of the technology and experimental understanding was begun by Müller in 1938² and he has been the most outstanding contributor in the field since that time.

This process has found its principal use in the elucidation of the properties of metal surfaces and their interaction with other materials such as gases. Very few devices have been developed which use this property. Apart from our own microscopes, the only other use appears to be as a source of high peak currents in pulsed electron beam generators.

For those not familiar with the field emission we will give a brief explanation. A much more complete discussion is given by Gomer.³

A much simplified picture of a metal is that of a large number of unbound electrons which are free to move among the relatively stationary positive charge centers. The number of these electrons is very large, there being perhaps one free electron for every positive charge center.

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Electrons are Fermions so that there can be only two electrons in each defined level. This means that all levels are filled successively and the highest level (the Fermi level) may be several volts above the lowest level. Such an energy corresponds to a temperature of 10^4 °K. This remains true almost independently of the actual temperature of the metal. A metal can be considered to be a material where the available band for electrons is only partially full.

Fig. 1(a) illustrates the various parameters that are used. The diagram is a representation of the electrical potentials which exist close to the surface of a metal. Inside the metal electrons fill the available bands up to a level μ . There remains a gap ϕ to reach the vacuum level. ϕ is the work function. That is, if we can give an energy $>\phi$ to an electron it can escape the metal (thermionic- or photo-emission, for example).

Now consider Fig. 1(b) which shows the same example except that an electric field E is applied to the metal. This causes the potential to fall linearly in the region outside the metal. Under these conditions it is possible for a completely new process to occur. It can be seen that an electron does not require any energy at all to escape from the metal because it can "tunnel" through the potential barrier along the line OP.

The phenomenon of tunneling was first described by Gamow⁴ who used it successfully to explain α -emission from radioactive nuclei. Briefly, the probability for tunneling to take place can be calculated using the Schrodinger equation and matching boundary conditions inside and outside the barrier. The probability depends strongly upon the height ϕ

of the barrier and upon the width $\frac{\phi}{E}$ (the distance OP in Fig. 1(b)).

The calculation was performed by Fowler and Nordheim who obtained a value for the emission current density i

$$i = 6.2 \times 10^6 \cdot \frac{(\mu/\phi)^{1/2}}{(\mu+\phi)} \cdot E^2 \exp \left[-6.8 \times 10^7 \frac{\phi^{3/2}}{E} \right]$$

We can consider the Fowler-Nordheim equation to be an accurate representation of an ideal condition, namely an atomically flat metal with no other materials (such as gas molecules) present.

The real world is considerably different from this, however, and we should now consider some perturbing effects.

Consider, for example, a monomolecular layer of gas molecules on the surface of the metal. Then these molecules will behave like a dielectric. Assuming the same potential on the metal as before and maintaining the same field E as before, we see that the field in the dielectric is reduced to E/k and so the point P moves to P' and the tunneling diagram is similar to the previous one except that the work function has apparently increased from ϕ to ϕ' . We can estimate this change because

$$\phi' - \phi \sim d \cdot E$$

where d is the thickness of the monolayer.

Assuming a rare-gas layer, $d \sim 2 \text{ \AA}$. Field emission usually occurs with values of E of about 0.5 volts/ $\text{\AA}$ and therefore

$$\phi' - \phi \sim 1 \text{ volt.} \sim \phi/4.$$

This is a small change, but it can cause a profound reduction of emission current in view of the exponential dependence of i on ϕ .

We can also see that the width of the barrier ϕ/E is of the order of a few Angstroms. ϕ is usually about 4 volts and E is about 0.5 volts/Å. Consequently the barrier width is only 8 Å.

In view of this, we can appreciate that the diagrams in Fig. 1 are very much idealized. The actual edge of the metal will be of the order of 1 Å thick and will vary considerably from point to point and should depend upon the crystal orientation of the surface atoms. We would therefore not be surprised if the current density I depends upon the crystal orientation.

Field Emission as an Electron Source.

One cannot conveniently achieve electric fields of the order of 1 v/Å using a flat surface. It is possible to do so, however, if the surface is small and hemispherical. Under these conditions

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

and if $V \sim 10^3$ v and $r \sim 10^3$ Å, one can achieve $E \sim 1$ v/Å.

Under normal circumstances one does not have an isolated sphere but rather a hemispherical boss on the end of a cylindrical shank. Under these conditions one has

$$E = \frac{V}{kr}$$

where k is a constant and $k \sim 5$. Higher voltages are therefore required.

The current density of a high field emission tip is a complicated function of angle off the axis. Dyke and Trolan⁵ 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/cm² compared to approximately 10 A/cm² 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 approximately⁷

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

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 $R = 500 \text{ \AA}$, $V_T = 0.5 \text{ V}$, and $V_1 = 1 \text{ kV}$, which lead to $r = 11 \text{ \AA}$.

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.⁸ 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 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. (Fig. 2)

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.⁹

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. 3.¹⁰ 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.¹¹⁻¹³ The time scale for this process can vary from seconds to thousands of hours depending on the pressure.¹⁰

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.

The Electron Gun

The type of electron gun used in conventional microscopes has been developed to satisfy the needs of that instrument. Rather than attempting to modify such a gun for use with a field emission source, we decided to design a gun for this application alone.

We require a potential of a few kilovolts to provide the emission current from the tip and we would like to operate the microscope using an electron beam of a few tens of kilovolts. We must therefore use a system with at least three electrodes.

The electrons from the field emission source will be attracted towards a first anode which is held at a few kilovolts. Some of these electrons must be allowed to pass through an aperture in this anode so that they can be accelerated towards a second anode which is held at a potential of a few tens of kilovolts. A fraction of these electrons must be allowed to pass through a second aperture to form the usable electron beam.

We therefore have a requirement for two anodes, each with an aperture. It is well known that apertures in anodes such as this can act as lenses. Such lenses have large aberrations which can easily degrade the quality of the electron beam. This lens effect is produced whenever the electric field strength on the two sides of the aperture is different.

We decided that it would be better to design an electron gun in such a way that these aperture lenses were as weak as possible. In this way, any lens effect would be produced by the accelerating field itself and this field can be shaped to reduce aberrations.

The way in which this was accomplished is shown in Fig. 4. The electric potential rises sharply in the neighborhood of the tip and levels off at a distance of several tip radii. Thereafter the electric field is almost zero. Assuming that an anode must be placed at position A, we now insist that the field remains zero through the aperture in this anode. The potential must then be allowed to rise towards the second anode (at position B), but immediately before the aperture in this anode we must reduce the slope to zero so that the electric field on this side of the aperture will be zero. On the other side of the aperture in the second anode the electric field is automatically zero because this anode is kept at ground potential.

It can be seen that we need some kind of S-shaped curve for the variation of potential between the two anodes. The particular shape of curve can be selected to reduce aberrations as much as possible and the required field shape can be produced by a suitable shaping of the electrodes.

The shape of the potential curve is such that there are two zeros in the slope. We therefore require at least a cubic term, and the simplest possible expression for the variation of potential with axial distance would be

$$V = az^2 + bz^3$$

We will take $z = 0$ at the first anode, $z = 1$ at the second anode, $V_{z=0} = 0$ and $V_{z=1} = 1$. We can therefore rewrite the expression as

$$V = az^2 + (1-a)z^3.$$

Differentiating, we obtain

$$\frac{\partial V}{\partial z} = 2az + 3(1-a)z^2.$$

$\frac{\partial V}{\partial z}$ is zero when $z = 0$, and if we put $a = 3$, then $\frac{\partial V}{\partial z} = 0$ when $z = 1$, which is the required condition. We now have

$$V = 3z^2 - 2z^3.$$

V must also be a function of r , the radial distance from the beam axis. This dependence can be determined by inserting the above expression for V into Laplace's equation. We then obtain the complete expression for V .

$$V = 3[z^2(1 - \frac{2}{3}z) - \frac{r^2}{2}(1 - 2z)].$$

The shape of the electrodes can now be obtained by putting $V = 0$ or 1 . For $V = 0$, we have

$$r^2 = \frac{2}{3}z^2 \cdot \left[\frac{3 - 2z}{1 - 2z} \right].$$

The electrode shape for $V = 1$ is a mirror image of that for $V = 0$ about the $z = \frac{1}{2}$ plane. Fig. 5 shows the shape of the electrodes calculated from this expression.

The particular potential distribution given above is not, of course, the only S-shaped curve which can be drawn to satisfy the prescribed condition. It is, however, the one with the greatest mathematical simplicity.

Butler investigated many such curves in an attempt to find the one which gives the smallest spherical aberrations when used as an accelerating system.¹⁴ He computed the first and third order optical properties of families of such curves, but concluded that the simplest solution given above was among the best. This is the basis of all the electron guns which we have used.^{15, 16, 17}

In spite of the simplicity of the electric field distribution, it is easier to compute the optical properties of the gun rather than attempt an analytical solution. In particular, both Butler and Thomson¹⁹ have written programs which can compute all the essential optical properties.

Optical properties of the electron gun

In order to use this electron gun in an electron microscope we need to know a few of the more important characteristics of the gun. In particular, we need

- (a) the position and magnification of the image of an electron source
- (b) the chromatic aberration coefficient
- (c) the spherical aberration coefficient.

Each of these quantities is a function of the position of the electron source and the voltages on the two electrodes.

This information is given in Figs. 6(a), 6(b) and 6(c) for a 2 cm. gun. That is, for a gun where the distance between the two

anode apertures is 2 cm. Together with the characteristics of the field emission sources, such as effective source size and the energy spread of the electrons, these figures give the information necessary to calculate all the relevant properties of the gun.

As an example of the characteristics of this gun, we can calculate the properties of the real image of the tip which can be produced at various distances from the second anode. In order to produce a good image we must include a small defining aperture. Experimentally we have concluded that the best location for this defining aperture is at the second anode. The reason for this choice is that small amounts of contamination on such an aperture tend to become electrically charged and introduce astigmatism into the beam. This effect is most pronounced when this charging process occurs in a region where the electron beam energy is the lowest and least pronounced when the beam energy is high and the electron beam current available to charge the contamination is low.

We therefore include an aperture at the second anode and can now calculate the following properties of a real image of the tip.

- (a) The beam current in the focused spot
- (b) The gaussian image size
- (c) The contribution to image size from spherical aberration
- (d) The contribution to image size from chromatic aberration
- (e) The effects of diffraction at the aperture.

The various terms (b)-(e) can be combined quadratically to give an estimate of the final image size.

All these factors can be readily calculated from the information we have given previously and in Figs. 7 and 8 we present the results for image distances of 1, 4 and 8 cm.

It can be seen from these figures that a very small image of the tip can be produced and furthermore, the beam current available in this image is more than adequate for scanning microscopy. It is interesting to note that the spherical aberration of the gun is not a significant contributing factor to the spot size when the aperture is optimised for the smallest spot size. Chromatic aberration effects are much larger and probably cannot be reduced because such effects are inherent in any electrostatic focusing system.

Acknowledgements

Figures 2 and 3 have appeared previously in Rev. Sci. Inst. 39, No. 4, 1968.

Figures 4 through 8 will, by the time these lectures are published, have appeared in Quarterly Reviews of Biophysics.

Work reported here was supported by the U. S. Atomic Energy Commission.

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Figure Captions

- Fig. 1 Illustration of the variation of the potential as a function of distance from the surface of a metal.
- (a) with no applied field.
 - (b) with an applied field E .
 - (c) the metal is covered with a layer of gas and the field E is applied.

- Fig. 2 Tip etching arrangement.

- Fig. 3 Typical dependence of emission current with time.
- As the tip becomes coated with contaminants, 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.

- Fig. 4 Schematic drawing of the required axial potential distribution for an electron gun. The principal requirement is that the slope of the curve be zero when passing through the anode aperture.

Fig. 5 Scale drawing of the anode slopes which produce the required accelerating field.

Fig. 6 Calculated gun characteristics for three different positions of the image distance

(a) Image of the tip at 1 cm from the gun.

(b) Image of the tip at 4 cm from the gun.

(c) Image of the tip at 8 cm from the gun.

Fig. 7 Graph of the dependence of the optimum probe diameter (d_{rms}) upon the ratio V_0/V_1 for various fixed image distances.

Fig. 8 Beam intensity in the focused spot for the conditions given in Fig. 7.

Fig. 1

ETCHING CURRENT DETECTOR

TOTAL EMISSION CURRENT I

VACUUM ARC REGION

UNSTABLE REGION

STABLE REGION

TIME

Fig. 4

Fig. 5

Fig.6(a)

Fig.6(b)

Fig.6(c)

Fig. 7

Fig. 8