1986

The Effect of Temperature and Humidity Stress on Plasma Progesterone, Luteinizing Hormone and Cortisol Profiles Following Cloprostenol Injection in Cycling Holstein Cows in a Controlled Environment (Environmental Physiology, Reproduction, Prostaglandins).

Anandarajah Sri kanda kumar
Louisiana State University and Agricultural & Mechanical College

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CURRENT LIMITING OF FIELD EMITTER ARRAY CATHODES

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A THESIS
Presented to
The Faculty of the Division of Graduate Studies
by
Kon Jiun Lee

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
in the School of Materials Engineering

Georgia Institute of Technology
August, 1986
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CURRENT LIMITING OF FIELD EMITTER ARRAY CATHODES

Approved:

David N. Hill, Chairman

Joel K. Cochran

A. T. Chapman

Date Approved by Chairman 8/21/86

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Finally, to my parents, the rest of the family and dear Sara, I dedicate this achievement with great pleasure.
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SUMMARY

The Field Emitter Array (FEA) cathode possesses high emission potential (~30 A/cm²) at low applied voltages (100-200 volts) but performance has been hampered by non-uniform emission across the array. Poor emission uniformity is mainly related to small variations in emitter tip geometry (of the order of 10-100Å), which can not be rectified by present fabrication techniques. For increasing emission uniformity from the arrays, this dissertation investigated the use of current-limiting resistors, individually dedicated to and in series with each emitter, to compensate for the differences in emission. A thin film of silicon was deposited on the back side of a ZrO₂-W composite chip (the substrate on which emitter structure was based) to form series resistors. Characterization of the silicon film was carried out in a SEM with a micromanipulator capable of making contact with a single tungsten pin so that direct I-V measurement of individual series resistors was possible. The measurements indicated a series resistance ranging from 10⁸ to 10⁹ ohms per emitter, with a negative field dependence of -2% per volt. To supplement the experimental effort, a mathematical model of the Current-Limited Field Emitter Array (CLFEA) cathode was devised. A study of the model indicated the Fowler-Nordheim (F-N) plot of resistor current-limited emission from an array would have an upturning curvature, accompanied by a reduction of emission of up to two orders of magnitude. Such deviation from linearity probably results from a transition of the major
emission contributors from emitters of preferred geometry to emitters of less favorable geometry but more populous in number. The characteristic upturning curvature was displayed by most experimental F-N plots. An event involving massive breakdown of the resistors offered an opportunity to compare current-limited emission characteristics to those of the same cathode after current limitation was removed. In this case, current limitation accounted for a two-fold reduction in emission, and at the same time produced the curvature of the F-N plots predicted by the model. Due to the series resistance, or residual resistance after breakdown, there was only limited energy dissipation at each failure site, so that failures occurred almost exclusively in an isolated fashion. Current-limiting also caused a time-dependent decline in emission, which signified emission-induced rounding of the sharp emitter tips. This occurred at a rate slow enough so that the process was observable. The variability of emission from emitter to emitter proved to be too great to be normalized by current limitation.
CHAPTER I

INTRODUCTION

The Field Emitter Array (FEA) cathode is a field-effect electron device capable of delivering current densities of up to 30 A/cm$^2$ at low applied voltages (100-200 volts) with no output of thermal energy. The device consists of arrays of micron-sized field emitters (Fig. 1-1) made of pointed tungsten fibers embedded in a semi-insulating matrix of UO$_2$ or an insulating matrix of stabilized ZrO$_2$. Each emitter is positioned at the center of a 2 $\mu$m diameter aperture in a metallic thin film electrode that is supported on a dielectric thin film. The close spacing between the emitter and aperture electrode converts low applied voltages to high fields, which are further enhanced by the small radius tip to fields $> 10^7$/cm. This is sufficient for field emission of electrons.

The potential for both high emission current and current density of a field emitter array (FEA) is attributed to its having a large number of emitters operating simultaneously. Due to the exceptionally high packing density ($5 \times 10^6$ to $2 \times 10^7$ emitters per cm$^2$), a typical FEA cathode often contains arrays of several hundred emitters in an active area approximately 100 $\mu$m in diameter. Since each emitter is surrounded by a concentric extractor aperture, the possibility of field reduction at the emitting tip due to mutual shielding is eliminated. Hence each and every emitter in the array should be
Figure 1-1. Single Element of Field Emitter Array Cathode.
capable of operating free from electrostatic interference of neighboring emitters, despite their close proximity. Should all emitters operate simultaneously and independently, and each contributes a modest emission current of 1 μA, one could expect to obtain a total current equal to the sum of the individual pin currents, producing current densities as high as 5-20 A/cm². Assuming a more generous, but not unrealistic, estimate of 10μA of emission per pin, a current density of 50 to 200 A/cm² should be achievable. Indeed, a FEA cathode has been operated at 22 mA (31 A/cm²) of total emission current. Such performance, however, is not consistently attainable. One explanation, supported in part by experimental evidence¹, is that there is often only a fraction of the emitters contributing emission up to expectation, while others emit significantly less current or none at all. Such a lack of emission uniformity has been a major drawback in realizing the full potential of FEA cathodes.

It has been suggested that the non-uniform emission may result from variations in the emitter tip geometry. Such variations could occur on a very small scale, on the order of 10-100Å, (easily overlooked during a normal screening examination), yet still have a major effect on field enhancement at the surface of the tips. With present emitter processing techniques, it is very difficult, if not impossible, to control the geometric variation of the emitter tips to meet the requirements of uniform emission. The fact that there is a non-rectifiable variation in tip geometry must be accepted and its consequence investigated.
The problem caused by the variations in emitter tip geometry is that emitters with favorable geometry provide most of the emission and subsequently melt when higher fields are applied in an attempt to activate emission from the rest of the array. If melting failures involve only individual emitters which do not short-circuit the cathode, such failures may be tolerated, since the cathode itself could still be operated with the remaining emitters. The performance of a "partially-failed" cathode, would of course suffer from the attendant reduction in emission current. The current reduction could be significant with the failure of only a small number of the sharpest emitters.

The large number of available emitters offers a considerable degree of redundancy, provided one can prevent the failure of individual emitters from shorting the entire active area. For example, a shorting path with a remanent impedance greater than $10^6$ ohm would qualify as an open-circuit failure and have little or no effect on the ability of the cathode to operate.

Unfortunately, short-circuit failures that resulted primarily from melted emitters have been a common occurrence throughout the development of the FEA cathode. The concept of current-limiting the FEA cathode with series resistors evolved in the course of finding a viable solution to the parallel difficulties of premature short-circuit failure and non-uniform emission. By adding an adequate resistance to each emitter, emission current could be limited to a safe level, making a short less likely, and thereby increasing the reliability of the device. Presumably, emission uniformity could also
be improved by the addition of series resistors. Since emission current must flow through a resistor in series with the emitter, a voltage drop, proportional to the magnitude of the current, will be developed across the resistor. As a result, the more emission current a particular pin produces, the higher will be the voltage drop across the series resistor. This voltage drop reduces the net applied voltage at the emitting tip, and hence the electric field, and thus reduces the emission current accordingly. Such a closed-circuit feedback process should continue until an equilibrium state is achieved. The decrease in emission current will be proportional to the emission level; thus the result of current-limiting should be a reduction in emission variation from pin-to-pin, and improved emission uniformity.

The goal of this investigation was to study the applicability of current-limiting the FEA cathode in order to improve the reliability of the device. A monolithic thin semiconductor film was developed and vapor deposited on the backside of the cathode to form an array of individual resistors in series with each emitter. The electrical properties of the resistor film and the well-documented emission characteristics of FEA cathodes were used to construct a mathematical model. With this model the theoretically-derived current-limiting effects were analyzed and compared to actual emission results of experimental cathodes.
CHAPTER II

LITERATURE SURVEY

Field Emission

Field emission is best defined as the tunneling of electrons from cold metals through a surface potential barrier into a high electric field. Using wave mechanics, Fowler and Nordheim developed a theory to explain the phenomenon sixty years ago. The usefulness of the Fowler-Nordheim (F-N) theory has been verified by numerous researchers.

Electrons (or, more appropriately, the conduction electrons) inside a metal behave like a free gas in a box, i.e., the free electron model proposed by Sommerfeld. They are confined by a potential barrier at the surface (Fig. 2-1a). The height of the barrier, denoted by $\phi$, is known as the work function. In the case of thermionic emission, electrons have to surmount the potential barrier to escape from the solid. High operating temperatures, e.g., $> 2500^\circ K$ for tungsten, are required to thermally activate the electrons for thermionic emission to be operative. Field emission, on the other hand, does not require thermal activation and is thus virtually temperature insensitive.

The Fowler-Nordheim Equation

The quantum mechanical solution of field emission involves the use of $\psi^2$, i.e., the probability of an electron being at any
Figure 2-1. Diagrams of Potential Barrier at Metal-Vacuum Interface, (a) Classical Potential Well Model, (b) Potential Barrier Modified by Image Potential and Lowered by an External Field.
particular position, where $\psi$ is the wave function of an electron obeying the Schrodinger equation. Considering the time-independent, one-dimensional case (in the $x$ direction, normal to the surface), which is sufficient for description of the field emission process, the Schrodinger equation is

$$\frac{d^2 \psi}{dx^2} + \frac{2m}{\hbar^2} W \psi = 0 \quad [2-1a]$$

inside the solid ($x<0$), and

$$\frac{d^2 \psi}{dx^2} + \frac{2m}{\hbar^2} [W - V(x)] \psi = 0 \quad [2-1b]$$

outside the solid and within the potential barrier ($x>0$). The terms $V(x)$ and $W$ are, respectively, the potential function (determined by the host lattice atomic structure) and energy of the electron in the $x$ direction. Equation 2-1b can be solved using appropriate boundary conditions, i.e., $\psi$ and $\frac{d\psi}{dx}$ must be continuous at the interface ($x=0$). The solution inside the potential barrier is found to be an attenuating wave.

Under a positive external field $E$, the surface potential barrier assumes a triangular shape. The Schottky effect (i.e., the image potential) further modifies the shape of the potential barrier by rounding its top (Fig. 2-1b). The image potential $U_i(x)$ is produced by the electrostatic attraction between an escaping electron and the induced charge inside the metal, as its name implies. The magnitude of the potential is given by
$$U_1(x) = \frac{-e^2}{16 \pi \varepsilon_0 x} \tag{2-2}$$

for $x$ greater than a critical distance $x_0$, where $\varepsilon_0$ is the permittivity of vacuum. For $x$ less than $x_0$, Schottky assumed a constant image force, i.e., $U_1(x)$ as a linear function of $x$, to match the potential with the bottom of the conduction band at $x = 0$.

Under the influence of an external field and the attendant Schottky effect, the composite potential barrier $\phi(x)$ is expressed as

$$\phi(x) = \phi + U_1(x) - eE \tag{2-3}$$

with respect to the Fermi level. The effective reduction of barrier height $\Delta\phi$, i.e., the difference between $\phi$ and $\phi(x)$ at the point where $\phi(x)$ has a maximum value, is given by

$$\Delta\phi = \left(\frac{e^2 E}{\pi \varepsilon_0}\right)^{1/2} \tag{2-4}$$

With a large enough $E$, the height as well as the thickness of the potential barrier is reduced to the point that $\psi$ may not be attenuated completely. A non-zero value of $\psi$ penetrating into the vacuum region beyond the metal-vacuum interface represents a finite probability of the existence of an escaping electron. Emerging from the barrier into vacuum, a free electron will be swept away by the high $E$ field; hence the tunneling process cannot be reversed. Taking the image potential into account, equation 2-1b is modified by substituting $\phi(x)$ for $\phi$. 

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The probability of barrier penetration, which can be obtained by solving the modified equation 2-1b with the WKB approximation\(^9\), is often represented by a transmission function \(D(W)\):

\[
D(W) = \exp \left[ \frac{-4(2m^3)\phi^{1/2}f(y)}{3\hbar E} + \frac{W-\phi}{\hbar E} \right]. \tag{2-5}
\]

In equation 2-5, \(t(y)\) and \(f(y)\) are slowly varying elliptical functions of \(y\), which has the value of \((e^3E)^{1/2}/\phi\), i.e., a ratio of \(\Delta \phi\) to \(\phi\). Both \(f(y)\) and \(t(y)\) represent the correction of \(D(W)\) for the image potential. Tabulated numerical values of \(t(y)\) and \(f(y)\) can be found in the literature.\(^9,10\)

Since conduction electrons inside the metal approximate a free gas, they obey Fermi-Dirac statistics in terms of their energy distribution. The number of electrons arriving at the barrier per unit area and time in the interval \(dW\), the so-called supply function \(N(W)dW\), is given as follows

\[
N(W)dW = \frac{4\pi m KT}{\hbar^3} \ln[1 + \exp(-\frac{W-\phi}{kT})], \tag{2-6a}
\]

where \(K\) is the Boltzmann's constant. At ordinary temperatures, where \(W - \phi >> KT\) and \(\phi >> W\), equation 2-6a reduces to

\[
N(W)dW = \frac{4\pi m (\phi - W)}{\hbar^3}, \tag{2-6b}
\]

The transmission function \(D(W)\) (equation 2-5) is then multiplied by the supply function \(N(W)dW\) (equation 2-6b) to obtain the normal energy...
distribution of emitted electrons, i.e., \( D(W) N(W) dW \). The total number of electrons \( N_T \) tunneling through the barrier per unit area and time can thus be obtained by integrating \( D(W) N(W) dW \) over the entire spectrum,

\[
N_T = \int D(W) N(W) dW
\]  

An actual integration of equation 2-7 results in the Fowler-Nordheim relationship

\[
J = \frac{e^3 E^2}{8 m^3 \phi^2(y)} \exp \left[ -\frac{4(2m \phi)^{1/2}}{3\hbar E} f(y) \right]. \tag{2-8}
\]

Finally, expressing current density \( J \) in \( \text{amp/cm}^2 \), \( E \) in \( \text{volt/cm} \), and \( \phi \) in \( \text{eV} \), and inserting appropriate numerical values of all constants, yields the F-N equation in the more familiar form:

\[
J = 1.54 \times 10^{-6} \frac{E^2}{\phi^2(y)} \exp[-6.83 \times 10^7 \frac{\phi^{3/2} f(y)}{E}] \tag{2-9}
\]

The theoretical derivation and more detailed discussions of the F-N equation have been summarized by van Oostrom.  

**Experimental Tests of the Field Emission Theory**

Ever since Wood observed the "fire works" in his discharge tube, today known as field electron emission, the phenomenon has been studied by numerous experimenters and theoreticians. Some significant experimental works on field emission, which contributed to the preception of field emission theory, its refinement, and verification, are briefly reviewed.
Because the intense electric field necessary for field emission will cause severe mechanical stresses on the cathode, the choice of suitable cathode materials is limited. In addition to having a low surface potential barrier (work function, $\phi$), a capable cathode should have reasonably good refractoriness, high tensile strength, and good electrical and thermal conductivity in order to withstand the field stress. Possessing all of these attributes, tungsten is by far the most suitable metal for field emission experiments.

Based on the Fowler-Nordheim (F-N) equation, an electric field in excess of $10^7$ V/cm is required to draw measurable emission current from a clean surface of tungsten, assuming an average $\phi$ of 4.5 eV. It is a formidable task to create such high field by sheer application of potential difference. Fortunately, the potential gradient at a surface of large curvature (sharp protuberances) is enhanced in proportion to the arc of the curvature, which is known as field enhancement. This phenomenon is essential to the practicality of field emission. That is why most, if not all, field emission experiments have been performed with pointed cathodes, whose diameter is often less than one $\mu$m.

The field enhancement factor at the apex of a pointed pin of radius $r$ is proportional to $1/r$. The exact proportionality is determined by the actual shape of the tip and the cathode-anode geometries. The enhancement factor $\beta$ as a function of emitter geometry is given by

$$\beta = \frac{2}{r \ln \left( \frac{2a}{r} \right)}$$

[2-10a]
for a tip shape approximated by a paraboloid of revolution\textsuperscript{13}, and

\[ \beta = \frac{2}{r \ln \left( \frac{4x}{r} \right)} \quad [2-10b] \]

using an approximation of the hyperboloid of revolution\textsuperscript{14,15}, where \( x \) is the interelectrode spacing and \( \beta \) is usually expressed in cm\textsuperscript{-1}.

The electric field \( E \) at the apex with an interelectrode potential \( V \) can be calculated as

\[ E = V \cdot \beta \quad [2-11] \]

Direct measurement of the cathode electric field is difficult because of its high value, large spatial rate of change, and the small size of the cathode. Normally, the emission current \( I \) is measured instead of the current density \( J \). By definition, \( I \) is related to \( J \) by

\[ I = J \cdot \alpha \quad [2-12] \]

To convert \( I \) to \( J \) requires the knowledge of \( \alpha \), the microscopic emitting area. In terms of tip radius \( r \) and emission half cone angle \( \theta \), a theoretical emitting area is given by

\[ \alpha = 2\pi r^2 (1 - \cos \theta) \quad [2-13] \]

according to Dyke and Dolan\textsuperscript{16}.
Substituting in measurable quantities of $I$ and $V$ for $J$ and $E$, an experimental form of the F-N equation is obtained

$$I = 1.54 \times 10^{-6} \frac{2V^2\alpha}{\phi^2(y)} \exp \left[ -6.83 \times 10^7 \frac{\phi^{3/2}f(y)}{\beta V} \right] \quad [2-14]$$

A typical F-N plot, i.e., a plot of $\log I/V^2$ vs. $1/V$, is shown in Fig. 2-2. If $\phi$, $\alpha$, and $\beta$ are independent of $V$, then the plot will be nearly a straight line. Due to a weak field-dependence of the functions $t(y)$ and $f(y)$, the correction terms for image potential, the F-N plot departs slightly from linearity towards high current density at higher fields. The slope $m_{FN}$ of the curve is obtained by differentiating $\log I/V^2$ with respect to $1/V$

$$m_{FN} = \frac{d \log \frac{I}{V^2}}{d \frac{1}{V}} = -2.97 \times 10^7 \frac{\phi^{3/2}s(y)}{\beta} \quad [2-15]$$

The function $s(y)$ is close to unity for the range of field strength and work function generally encountered in practice. The numerical values of $s(y)$ tabulated by Burgess$^9$ et al. have been approximated as an exponential expression of $y$ by Ohlinger$^{17}$, for the convenience of numerical computation.

The fundamental hypothesis of the F-N theory (i.e., the electrons that escape by tunneling come from the top of the Fermi energy distribution in the metal and well below the top of the surface potential barrier) was confirmed by Müller$^5,6$ in 1936. It was reasoned that if the escaping electron had appreciable thermal energy, cooling of the
Figure 2-2. Example of a Typical Fowler–Nordheim Plot.
emitting tip could be expected due to energy loss. This is similar to the effect observed when a high thermionic current is drawn from a hot cathode. A calculation showed that for field electrons having only 0.1 eV of thermal energy, there would be a 10° drop in temperature at the tip with an emission current of 5 mA. His experiment measured no temperature change at all under the prescribed conditions, confirming that the field electrons indeed carry little thermal energy. Fleming and Henderson made a similar measurement using a tungsten-tantalum thermocouple as a part of the cathode and arrived at the same conclusion.

Later, a reverse effect, i.e., heating of a field emission tip at high currents, was suggested by Nottingham. Referred to as the Nottingham effect, since the energy of emitted electrons is less than that of their replacements from the conduction level, the energy difference could possibly heat the emitting tip. However, no published experimental verification of emission heating has been found, suggesting a negligible magnitude of heating even if the hypothesis is true.

Another critical test of field emission theory is the energy distribution of the electrons. A retarding potential tube with spherical symmetry developed by Müller also demonstrated that the electrons essentially come from below the Fermi level. The distribution width of less than 0.5 eV seemed to fulfill the expectation.

Even before the development of the Fowler-Nordheim theory, field currents were observed to be indifferent to temperature over the temperature range from 300 to 1000°K. The temperature-independence of field current was used as strong evidence for the tunneling process.
and against the potential trough model proposed Schottky\(^2\), since emitting "over" the classical potential barrier is strongly dependent on temperature. Fowler and Nordheim\(^2\) developed the tunneling theory assuming the temperature of the metal is 0°K, for which a supply function of electrons was derived. Since this assumption cannot be tested under practical experimental conditions, the influence of temperature on field emission must be examined.

For temperature \(T\) greater than 0°K, a small number of electrons will have energies greater than the Fermi level, adding a thermal tail to the supply function. These electrons will have a higher probability of tunneling through the barrier, at a point where the barrier itself is more transparent. Hence, an increase in emission would be expected. Murphy and Good\(^2\) showed the relative increase in emission current can be written as

\[
\Delta I = 1.279 \times 10^8 \frac{T^2 \phi^2(y)}{E^2},
\]

where the variables are in the same units defined earlier. At room temperature (273°K), the relative increase is only 2% of the uncompensated emission current at an electric field of 5 \(\times\) 10\(^7\) V/cm and a work function of 4.5 eV. They concluded that the temperature effect is rather small at temperatures < 1000°K, and is generally not of concern in most field emission work.

Although the emission current does not exhibit a large temperature effect, observations by van Ooström\(^1\) indicated a marked change in the total energy distribution of field electrons. The influence of
temperature on the energy distribution adds a thermal tail to its higher energy side, causing the relative peak height to decrease and the half width to increase. He suggested that the temperature tail could be used to calculate the tip temperature, if the work function and field strength were known.

The high electric field precludes the existence of a significant space charge in the neighborhood of the emitter surface until the current density exceeds a certain level. One of the effects of space charge is to reduce the local electric field strength, causing measured emission current to fall below the value predicted by the F-N equation.

Stern, et al., by solving Poisson's equation for a plane parallel geometry with boundary conditions appropriate to field emission, predicted negligible space charge below a current density of $6 \times 10^6$ A/cm$^2$. The space-charge-free condition was extended to current densities below $4 \times 10^7$ A/cm$^2$ by Barbour et al. in a more refined study of space charge effects. In their studies, they also noted the current-limiting effect of space charge. Using a Müller type projection tube (i.e., a field emission projection microscope), one of the principal features they observed was an increase in uniformity of emission with increasing current density. The improved uniformity was characterized by the disappearance of dark patches, corresponding to crystallographic directions of high work function, in emission patterns under the influence of space charge. This was interpreted as evidence that space charge retards further increase of emission from low work function planes, thus allowing high work function planes to
"catch up" in emission with increasing voltage. The experimental data indicated that the level of current density for different crystallographic planes would become indistinguishable at current densities greater than $10^3$ A/cm$^2$.

The work function of the metal is the most important material constant affecting emission, since, from equation 2-14, the emission current density should be expected to increase exponentially with $\phi^{3/2}$. The $\phi^{3/2}$ dependence of the F-N equation was verified by Wilkinson using several crystal faces of a tungsten monocrystal, the work functions of which had been measured by other methods.

A very useful application of the field emission microscope (FEM) is to measure the work function in different crystallographic directions at the same time. Müller used such a device with a small aperture in the anode, to make quantitative measurements of the emission current from each single faces of a tungsten monocrystal. A system for tilting and rotating the crystal permitted measurement of the work function of several faces.

Adsorption of various elements on the emitting surface affects the work function $\phi$ and the emitting surface area $a$, thus altering both the exponential and pre-exponential terms in the F-N equation. Ehrlich and Hudda showed that large variations occur in the pre-exponential term when they measured the total emission from a tungsten tip during nitrogen adsorption. Gomer offered an explanation based on the polarizability of the absorbed atom or molecule. The adsorbed atom or molecule is polarized by the high electric field, and the induced dipole increases the work function by $4\pi N_\alpha$, where $n$ is the
number of absorbed species per cm$^2$ and $\alpha_p$ is the polarizability in cm$^3$. Van Oostrom\textsuperscript{11} observed the changes in both the preexponential term and the slope of the F-N plot, as a function of the dosage of $N_2$, on various tungsten faces. For most crystal planes, the adsorption of nitrogen causes a reduction in $\alpha$ and an increase in $\phi$. However, certain crystal planes, e.g., (160) and (411), were found to experience a decrease in $\phi$. He also noted that no changes in either $\phi$ or $\alpha$ could be detected for the most densely packed plane (110) even at high values of $N_2$ dosage. It was concluded that the effect of nitrogen adsorption on emission is complex and dependent on crystal orientation.

**Conventional Field Emitters**

Field emitters made of electrolytically sharpened tungsten tips have been extensively investigated, leading to interpretations in terms of the emission phenomenon itself and of the atomic and electronic structure of the surface. The tungsten tips are usually mounted on a hairpin filament to permit flash-cleaning the tips by passing a current through the assembly.

Dyke and Dolan\textsuperscript{29} reported obtaining 6.5 amperes of emission current from a single tungsten needle, reaching an estimated current density of the order of $10^8$ amp/cm$^2$ at 100 KV. However, such emission level could only be maintained for a time period of microseconds. For 100% duty cycle operation (i.e., continuous wave, CW), the maximum current densities achieved were of the order of $10^6$ amp/cm$^2$, a reduction by a factor of 100\textsuperscript{30}. Dolan and colleagues\textsuperscript{31} found that
emission became unstable when current densities reached these maxima and was generally disrupted with a vacuum arc. Many theories have been proposed to account for the field emission-initiated arc in high vacuum. The diversity of theory reflects the complexity of the various physical processes involved.

Two interpretations of the cause of vacuum arcs have received particular emphasis. First, cathode resistive heating at large current densities is regarded as the most likely arc-initiating factor. In this case, the current density that may be safely drawn from a given cathode can be estimated. Secondly, anode-formed ions enhance the cathode emission, leading to similar breakdown. The latter case limits the power loading at the anode. Boyle et al. showed that field emission currents evaporate metal from the anode and breakdown occurs in the resulting vapor. The possibility also exists that an arc could be initiated by the resistive heating that results from highly localized emission when the cathode surface is roughened by the impact of ions from the anode.

Inevitably, high electric field needed for emission would also tend to ionize any ambient residual gas. Directed by the field lines, positive ions are accelerated toward the emitter tip. Bombardment by these energetic ions causes emitter material to be sputtered from the surface, leading to a shortened useful lifetime for these field emitters. Muller has proposed such a mechanism, whereby incident particles can cause localized increases in current density which may lead to an arc.
Brodie\textsuperscript{37} points out that the sputtering effect could be reduced by operating the cathode at low voltages (<150 volts). However, conventional emitters can barely produce any measurable emission if the voltage is limited to this level.

At a given value of emission current density, there are several methods for achieving high current in practice:

1) using emitters with a larger tip radius, i.e.,
   greater microscopic emitting area;
2) using several cathodes operated in parallel;
3) using emitters of other geometries, such as a razor edge.

The latter possibility has had little study until recently. A development program of a wedge-shaped thin film field emission cathode is under investigation by Spindt\textsuperscript{38,39}, and will be described later. The first method can be self-defeating, since it is done at the expense of field enhancement, which requires higher working voltages. The second possibility was investigated by Dyke and Dolan\textsuperscript{29} and Shirokov\textsuperscript{40}, and others\textsuperscript{41,42}, long before eutectic composites were adopted as the substrate for multi-pin cathodes in the early seventies. These investigators used the comb-type cathode, i.e., a linear array of needle-shaped emitters mounted on a common support. Theoretically, a multiplicity of identical emitters should produce equal emission currents under the same conditions, hence increase the total emission current. However, this advantage remains a theoretical one because of two factors: 1) it is extremely difficult to mechanically fabricate two identical tips; and 2) the electric field as seen by a single tip
is reduced by the mutual shielding effect of its neighbor in close proximity. For example, for a current density variation of less than 10%, the value of $\beta$ can differ no more than 1% for a tungsten tip of about 1 $\mu$m tip radius. With smaller tip radii, the tip uniformity must be even better than 1% to achieve the same level of emission uniformity. Although simultaneous electrolytical etching (to create the same length and cone angle) and heat treatment (to have equal tip radius by controlled dulling) seem to be viable methods, fabrication of large arrays of identical single-pin emitters have never been realized in practice. In addition to non-uniform emission, higher voltages are needed to establish the required field strength at the tips in a close packing arrangement than would be necessary for the same field strength at a single tip of comparable size. This results from packing the pins into an array which induces a mutual shielding effect among pins. Independent theoretical treatments of the packing effect were made by Levine$^{43,44}$ and Garber$^{45}$.

With packing densities of up to $10^7$/cm$^2$, eutectic composites featuring a micron-sized second phase (usually in rod shape) of material suitable for field emission have been successfully fabricated into multi-pin array cathodes. Cline$^{46}$ experimented with Ni-W in a planar diode configuration. A maximum emission current of two mA was reported. Using the same approach, Pfleiderer and Rehme$^{47}$ studied the emission characteristics of InSb-NiSb and InSb-CrSb derived cathodes. They also attempted to calculate the threshold field for emission in terms of macroscopic field between the electrodes. Experimentally, a cathode with CrSb pins produced an array current density of 2 mA/cm$^2$.
at a macroscopic field of $14 \times 10^5$ volt/cm.

Feeney\textsuperscript{48,49}, Chapman\textsuperscript{50} and a group of researchers at Georgia Tech made a thorough investigation in the area of dense-array field emitters. They not only experimented with several unidirectionally solidified electric composites, e.g., \ce{ZrO2-W}, \ce{Gd2O3-Mo} and \ce{UO2-W}, but also made theoretical studies of the effects of pin tip radius, pin separation, and interelectrode spacing on emission. They were able to control the growth of the composites to vary its packing density (2-20 x $10^6$/cm$^2$). The effects of various shape and length of the exposed fibers on emission were also investigated in experiments. These emitter samples were tested in diode configurations in either pulse or CW mode. One sample operated with 21 mA of emission, corresponding to an array current density of 1.2 A/cm$^2$. An emission lifetime of over 100 hours at the maximum array current density was reported.

A model developed in their study predicted macroscopic current densities, at practical electric fields, of over 10 A/cm$^2$. Inability to achieve current densities of this level experimentally was concluded to be a combined result of non-uniform emission and field reduction due to mutual shielding. They speculated that only one percent of the total pins contributed to the overall emission current due to non-uniform emission.

\textbf{Thin Film Field Emitter Arrays}

The advantages of field effect cathodes over thermionic cathodes are numerous, including ambient temperature operation, insensitivity
to large temperature variations (up to 1000 °K), instant turn-on, and high current-density capability (safely up to 10^6 A/cm^2). However, the inherent sputtering damage to cathodes operating under high field conditions often leads to unstable emission and shortened useful lifetimes. Although high-packing-density multi-pin cathodes are technically feasible, there are difficulties in achieving the potential high emission currents available from simultaneous operation of many emitters in parallel. The major problem is the field reduction resulting from pin-to-pin interaction. Through the application of thin film micro fabrication, however, field emitter arrays consisting of a large number of electrostatically isolated emitting elements with an integral close-spaced anode have been developed. These cathodes are practically immune to sputtering effects and mutual shielding because of low working voltages and because of the field isolation offered by the integrated anode. The construction, emission characteristics, stability and failure mechanisms of these thin film FEA's are described below.

**Construction of Thin Film FEA**

The Thin Film Field Emission Cathode (TFFEC), which was the first operational device of such construction, was developed by Spindt, et al. It is a sandwich structure of conductor (Si)-insulator (SiO_2)-conductor (Mo) fabricated using conventional silicon technology coupled with electron-beam lithography (Fig. 2-3).

Referring to Fig. 2-3a, a silicon substrate is first oxidized to a depth of 1 - 1.5 μm and a Mo film is deposited over the oxidized layer. Electron beam lithography is employed to generate a hole-
Figure 2-3. Thin Film Field Emission Cathode Developed by SRI, after Spindt[51], (a) Schematic Diagram Depicting Emitter Tip Fabrication Sequence, (b) TFFEC Array with a Packing Density of $6.4 \times 10^7$/cm$^2$, (c) Single Element of TFFEC, Showing Sharp Emitter Cone Surrounded by a Metal Gate.
pattern on an electron-sensitive resist applied to the Mo surface, after which holes are etched down to the Si base. Emitter cones are formed by depositing Mo into the holes at normal incidence while the substrate is rotating. A parting material is deposited simultaneously at an oblique angle, which closes the holes. The Mo emitter cone is formed into a sharp tip (~500 Å) as the hole closes. The parting layer is removed to give the final structure. A typical TFFEC consisted of a 5000-tip array with the tips on 12.5 μm centers (i.e., a packing density of 6.4 x 10⁵/cm²). The primary factor limiting packing density was the undercutting of the Mo gate film while etching the holes in the SiO₂ layer. In a recent report, the array packing density was increased to 5 x 10⁶ tips/cm² by incorporating an anisotropic dry etching process (reactive ion beam etching, RIBE) into the fabrication scheme. Small arrays of emitter tips having about 10 tips were fabricated for high current density experiments.

In a calculation of microscopic emitting area, Spindt showed, in principle, that an emitter with razor-blade geometry would have orders of magnitude more emitting area than a cone-shaped emitter. For example, a wedge 1 mm long with a 500Å radius of curvature (r) would have an emitting area equivalent to that of a 20,000-tip array of cones with a tip radius equal to r. Wedge-shaped emitters were fabricated by translating the substrate during e-beam lithographing so that slots were generated instead of holes, followed by Mo deposition to form the wedges.

Cochran, et al. developed the Low Voltage Field Emitter (LVFE) using a combined technology of high temperature composite and
thin film microfabrication (Fig. 1-1). LVFE's were fabricated based on UO₂-W unidirectionally solidified eutectic composites featuring continuous and parallel metal fibers (W) embedded in an oxide (UO₂) matrix. Typically the tungsten fibers are ~0.5 μm in diameter having a packing density of 10⁷/cm².

After the composite had been selectively etched to expose and point the fibers 2-3 μm above the matrix, an oxide layer (SiO₂ or Al₂O₃) was deposited over the insulating layer. The process produced micron-sized apertures in the counter electrode, called the extractor, which are concentric with the fiber tips.

The emitter structure was made possible by the discovery⁵⁴ that vapor-deposited immobile materials grow laterally on a step, such as the tip of a fiber, during a line-of-sight deposition. This produces an inverse cone-shaped deposit on the fiber tip, shadowing the area surrounding a fiber and leaving a conical cavity in the insulator and extractor. The cones grow at a characteristic angle of 30° for Al₂O₃ and 20° for Mo. Consequently, the final diameter of the hole in the extractor was determined primarily by the total thickness of the deposited films. The cones were removed by hot acid etching and mechanical forces of ultrasonic vibration, providing the final structure.

The packing density of emitters was determined by the density of fibers in the composite, which ranged from 2-20 x 10⁶/cm². Various shapes and lengths of fibers could be obtained by varying the etching parameters. Tip radii of pointed tungsten fibers were made as sharp as 50 Å. Perfect hemispherical tips be achieved by thermal annealing. The thickness of the insulating oxide, which supported the
extractor and determined the diameter of the aperture, was chosen to match the fiber height.

In the early stages of LVFE development, the composite and insulator film used were UO₂-W and SiO₂. To reduce the leakage current, SiO₂ was replaced by Al₂O₃, which is several orders of magnitude better in terms of electrical resistivity. Another effort for leakage reduction was to replace UO₂-W composite by ZrO₂-W. In the UO₂-W composite, the UO₂ matrix is a semiconductor with a resistivity of 10³ Ω-cm. Considering the close spacing of the fibers, UO₂ acts practically as a conductor. In the ZrO₂-W composite, ZrO₂ is an excellent insulator having a resistivity as high as 10¹⁴ Ω-cm. The insulating matrix greatly reduces leakage current by having a longer leakage path along the side wall in the emitter cavity. Emission testing of ZrO₂-W based LVFE's resulted in leakage currents that were substantially less than that of UO₂-W based LVFE's.

Use of an insulating matrix composite for the LVFE offered advantages in addition to leakage reduction. The capacitance of the device was greatly reduced, allowing rapid voltage response. Also, field enhancement at the tips of the fibers was probably increased, because the field would not be affected as much by the insulating substrate as by a conducting one. Finally, since the fibers are electrically isolated, there exists a possibility of current limiting the individual emitters. By depositing a thin film of resistor material on the back side of the LVFE substrate, each fiber would have a current limiting series resistor. Thus preferentially emitting fibers, which might melt and cause premature failure, could be
restricted to safe current levels.

Emission Characteristics

The unique geometry and small dimension of the thin film FEA enables significant emission to be produced at low voltages (100-200 volts). This was due to the integration of the anode (extactor or gate) in close proximity (~1 μm) to the emitter tips. Small applied voltages resulted in large field gradients (which were further enhanced by the sharp tips), because of the close spacing between the anode and cathode. The large number of emitters gave these devices a potential for high gross currents. Simultaneous operation of the emitters was assured because each emitter was completely surrounded by the anode aperture and was electrostatically isolated from its neighbors. Shielding of the tips by the integral anode aperture also reduced the possibility of ion sputtering of the sharp emitting tips. Furthermore, due to low-voltage operation, any ions formed in anode-cathode gap would not have sufficient energy to cause significant sputtering damage if they did strike the tips.

Both TFFEC's and LVFE's were usually tested by driving the emitters at a negative potential with respect to the grounded extractor (or gate electrode). The driving voltage was applied in a variety of waveforms, i.e., CW, pulsed square-wave, and rectified AC. Emission tests were usually performed in high vacuum (10^{-9} torr) to minimize emission induced arcs. However, the capability of operating in elevated pressure environments (> 10^{-5} torr) has been demonstrated.

One TFFEC was reported to have produced 6 mA of emission from a total of 12 tips, equivalent to 330 A/cm^2, for three days. There were
two other small-array samples that ran with current densities over 300 A/cm$^2$. A total of nine TFFEC's tested in rectified AC mode (1% duty cycle) with peak voltage up to 245 volts, exceeded 100 A/cm$^2$. The highest overall emission achieved was 160 mA, obtained from a 5000-tip cathode. One sample, containing an array of 16 wedge-shaped emitters, produced emission with a current density of 50 A/cm$^2$. This device, however, required relatively high voltages (~ 440 volts) to sustain emission at such level.

All of the LVFE devices were driven with pulsed square-wave voltages at duty cycles from 0.1 to 1.0 percent. The maximum overall current produced by one UO$_2$-W composite based cathode was 100 mA (20 A/cm$^2$). Another cathode operated for 700 hours at a current density of 31 A/cm$^2$ before being terminated for examination.

The effect of space charge has been noted at array current densities below 5 A/cm$^2$, indicating the existence of highly localized emission, for both TFFEC's and LVFE's$^{38,39}$. The cause of highly localized emission was believed to be non-uniformity of the emitters in the array.

Feeney$^{53}$ made a parametric study of the LVFE with computer simulations of the effect of cathode geometry on electron emission and trajectories. The results of his study showed that the single, most important variable controlling emission was the emitter tip radius. It was suggested that any reduction in the emitter tip radius could be accompanied by a large increase in electric field enhancement, and hence emission current. A second conclusion regarding the emitter tip radius was that its size distribution must be carefully controlled if
spatially uniform emission is to be achieved. The study also indicated a weaker dependence of emission on the emitter cone angle and extractor hole diameter. An important conclusion of Feeney's study was that the peak electric field in insensitive to the position of the tip, provided the tip is positioned at least midway in the extractor. These results are in good agreement with those observed experimentally by Hill.

**Emission Stability and Failure Mechanisms**

The failure to make a commercially viable field emission cathode is primarily due to limitations in lifetime and stability of the present devices. The instability of emission current and emission-related failure of the device are often ascribed to its operation at high fields, which causes the shape of the emitting tip to change. High field leads to sputtering of the tip by energetic ions and desorption/adsorption of surface contaminants, which alter the field enhancement and work function appreciably. The strong dependence of emission current on the work function and tip radius (or field enhancement) of a field emitter can be easily perceived from the Fowler-Nordheim equation.

Ion-sputtering removes the emitter material from the tip and creates microscopic protuberances, leading to highly localized emission and perhaps a sudden vacuum arc. Desorption of contaminants may increase or decrease the effective work function depending on the interaction between the surface and the contaminants. In any event, changes in the emitter, gradual or sudden, lead to an undesirable, time-varying current-voltage response of the emitter. The lifetime of
an emitter of course depends of the amount of change one considers as admissible.

Thin film FEA's are relatively immune to sputtering due to their unique geometry, as described earlier. However, compared to conventional field emitters, thin film emitters are more prone to adsorption/desorption phenomena because they cannot be flashcleaned. Usually, the emitting surface needs to be cleaned frequently by heating to incandescence in order to be free of any contamination. This is quite impossible for a thin film device which usually has a limited temperature capability and thermal expansion tolerance due to its delicate and complex sandwich structure.

Spindt^38,39 and Hill^1 observed similar "seasoning" effects upon activation of thin film FEA's, during which the emission current obtained at a given voltage increased by several orders of magnitude. Changes in emission caused by seasoning effects were exemplified by shifting of the intercept of the F-N plots, indicating a varying value of the work function and emitting area. The effect was concluded to be attributed to desorption-adsorption processes because it was also reversible. The results of a study of work function as a function of adsorption (N\textsubscript{2} on tungsten) by van Oostrom^11 seems to support this conclusion.

The emission initiated vacuum arc, common to all field emitters, is one of the major failures that thin films FEA's have experienced. The leading causes and possible mechanisms of arcs in high vacuum were described in a previous sections. It is believed^38 that the risk of vacuum arc can be reduced by proper baking and outgassing of the
emitter and testing facility, by proper design of the collector so that power loading can be handled safely, and by controlling the cathode loading at safe levels, etc.

Placing the anode of the thin film devices in close proximity to the emitters permits field emission to be drawn at relatively low operating voltages. However, leakage current between the electrodes can be appreciable, because there is a finite conductivity associated with even the best insulating materials in thin film form. Dielectric breakdown or resistive heating and subsequent failure of the thin film insulator may result in a complete short circuit of the cathode, a mode of failure unique to the thin film FEA.

Failure of FEA due to excessive leakage has impaired the advancement of such devices. The leakage current in a FEA is defined as the transport of charge carriers of any kind between the emitter (K) and the extractor (E) (gate electrode). All possible sources of leakage are depicted in Fig. 2-4. A very important leakage source is described by process 1, which is bulk conduction through the dielectric film sandwich between K and E. It depends primarily on the high field conductivity of the dielectric supporting film. This, in turn, is controlled by the dielectric constant and the number of defects and impurities in the film. In process 2, primary emission electrons from either short tips or surface irregularities on a tip may have sufficiently low-angle trajectories that they are intercepted by the extractor, contributing to a significant quantity of the leakage current. Process 3, similar to process 2, represents collection of diverted primary electrons by the extractor in the presence of space

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Figure 2-4. Schematic Diagram Illustrating Charge Transport Processes as Sources of Leakage Current in a Field Emitter.
change. This process occurs only when emission current density is high, creating a significant space charge region above the emitter. Depending on the magnitude and location of space charge, higher collector voltages will sometimes reduce space charge build-up, permitting the collection of low-angle emission more effectively.

Surface conduction certainly cannot be overlooked either. There are two possible leakage paths: one on the surface inside the emitter cavity (process 4) and the other on the external surface (process 5). Conduction in both processes (4 and 5) is affected by the state of surface cleanliness. High leakage via surface conduction may be due to the presence of mobile sodium ions and carbon films deposited from cracked organic solvents. If the surface conduction resulted from contamination problems, a logical remedy would simply be carefully processing, e.g., thorough rinsing, use of certified chemicals, and avoiding the use of sodium-bearing processing materials. For the LVFE, undercutting of the Mo extractor resulted in a recessed insulator wall and a reduction of leakage, most possibly due to increased leakage pathlength.

Interception of energetic primary electrons will result in the emission of secondary electrons (process 6). Referring to the emitter geometry, most intercepted primary electrons, with an energy of 100-200 eV, may impinge on the extractor at grazing angles. Under such conditions, the coefficient of secondary emission ($\delta$) from the extractor, which is made of Mo, is close to or greater than unity$^{55}$. Therefore not only secondary emission is possible, it may even surpass the primary emission. When $\delta$ is greater than unity, the impinging
primaries will be outnumbered by the secondaries, resulting in a net flow of current into the extractor. Should this incoming current become larger than that of all other processes combined, there will be a reversal of the observed polarity of the leakage current. Polarity reversal is also indicative of a highly active process \(2\), which has been commonly observed\(^1\).

Process 7 accounts for a possible charge transport by ions or reflected primary electrons (Bragg diffraction) from the collector. There is a finite capacitance associated with the supporting dielectric film. Operating in AC or pulse mode, the capacitive current becomes an additional component of extractor current (process \(8\)). The time involved with a charging-discharging cycle will delay the voltage response of the device.

**High Field Conduction in Solids**

In terms of the ability to conduct electricity, solids can be divided into three classes: metals, semiconductors, and insulators. Energy band theory is used to explain the difference in the electrical properties of these solids. When atoms are placed together to form a solid, the discrete energy levels of electrons in the atoms broaden into bands. A band which is completely full or empty carries no electric current even in the presence of an electric field. In metals, the valence band overlaps the conduction band, allowing free movement of electrons; therefore, metals are good electrical conductors. Semiconductors and insulators have a full valence band and an empty conduction band, separated by a forbidden energy gap at \(0^\circ\)K.
Semiconductors usually have energy gaps of less than 2 eV, while solids with energy gaps greater than 2 eV are regarded as insulators. If the gap is small enough, the valence electrons can be readily excited into the conduction band by thermal activation, giving rise to a limited conductivity. For insulators, the thermal energy needed for excitation of valence electrons may require very high temperatures in order to have any significant conductivity. Impurities or defects in semiconductors and insulators can introduce trapped energy states inside the forbidden gap, which may modify the band structure and facilitate the thermal activation processes.

Because of a great similarity in electrical behavior of semiconductors and insulators, except for the difference in width of the energy gap, the word "semiconductor" is used to represent both in the following discussion.

The electrical conduction through, rather than along the plane of a thin film several microns thick may inevitably fall in the high field region ($> 10^5$ volts/cm), even with a bias of only a few volts. Usually high field electrical properties cannot be adequately described by a single conduction process, since various field-strength ranges manifest different electrical phenomena. Furthermore, thin films have a large surface to-volume ratio, which often introduces additional factors, (such as the nature of the electrode contacts), that will interact with the actual conduction mechanisms. In other words, thin films may behave quite differently from that expected of the same material in bulk form.

To measure the electrical properties of semiconductors, elec-
trodes are connected to the sample to collect the charge carriers at one end and to replenish the same at the other end. Good electrodes are made of metals, which have a different band structure than the sample being measured. At the interface, re-alignment of the band structure of the materials brought into intimate contact must take place, since the vacuum and Fermi levels must be continuous in a thermally equilibrated system. Work function, the difference between the vacuum level and Fermi levels, is an important parameter determining the way the band structures match up. Depending on the work function of the materials involved, three types of contact are possible, namely ohmic contact \( \phi_e < \phi_s \), neutral contact \( \phi_e = \phi_s \), and blocking contact \( \phi_e > \phi_s \), where \( \phi_e \) and \( \phi_s \) are work functions of electrode and sample. Ohmic and neutral contacts are capable of supplying electrons to the sample as needed. With these kinds of contacts, the condition is mainly controlled by the bulk of the sample, given a name of bulk-limited conduction process. For an electrode having a larger work function (blocking contact), a certain number of electrons will flow from the low work function side of the sample into the electrode to establish thermal equilibrium, creating a "blocking" space charge region at the interface. Under certain test conditions and electric field strengths at the contact, the charges that the electrode is capable of injecting into the sample may be less than the bulk of the sample can conduct. In this case, the conduction becomes characteristic of the contact instead of the bulk, a phenomenon referred to as an electrode-limited conduction process.
The conductivity of semiconductors is usually expressed as

\[ \sigma = n q u \]  \hspace{1cm} [2-17]

where \( \sigma \) is the conductivity (1/ohm-cm)
n is the charge carrier concentration
q is the charge of carrier
u is the carrier mobility (cm²/volt-sec)

The charge carriers referred to can be either electrons or electron holes. The electron hole represents a mobile, vacant site of an electron in an otherwise filled band; it behaves exactly like a particle with the same mass as an electron but of opposite charge. Since the charge carriers in intrinsic semiconductors are generated by thermal excitation, their concentration is temperature dependent. The charge carrier concentration can be readily calculated using the Maxwell-Boltzmann statistics, because charge carriers in semiconductors are sufficiently sparsely distributed (Note the distribution of charge carriers in metals, i.e., electrons, obeys the Fermi-Dirac statistics.) The carrier mobility also depends on temperature, although its dependence is weak compared to the temperature dependence of concentration, varying with the reciprocal square root of the absolute temperature. The nature of the declining mobility with rising temperature is due to the increased interaction with phonons (lattice vibrations), and with impurities and defects.

Semiconductors exhibit ohmic behavior, i.e., current density proportional to the applied field, only at low electric fields (\(< 10^3\)
volts/cm). Significant deviation from ohmic behavior can be observed above a certain electric field, in which case the measured current becomes less than the expected value. This is caused by a slow-down in the rate of increase of the carrier drift velocity with the applied field. The drift velocity eventually saturates at a constant value, characteristic to that material. The physical basis for this phenomenon is the achievement of a dynamic balance between the energy gained by the charge carriers through the accelerating field and the energy lost to the lattice upon collision. The energy loss to the lattice manifests itself as Joule heat. Besides energy dissipation to the lattice, a self-heating process of electrons is possible, causing electrons to become hotter by, possibly, several hundred degrees than the lattice temperature. These hot electrons may be one of the breakdown mechanisms of semiconductors in high fields.

**Conduction by Means of Conduction Band**

Various conduction mechanisms have been proposed to explain the electrical behavior of solids at high fields using the band structure theory. Strictly speaking, the band structure of thin film, cannot be easily defined, because of its less-ordered structure. However, in most cases, the band theory is adequate enough to analyze the experimental results of thin films. The electronic processes that can contribute to conduction are presented in Fig. 2-5. They are best classified into four categories depending on the nature of their activation.

Electrons can be excited from the valence band into the conduction band, provided their thermal energy is comparable to the band gap
Figure 2-5. Schematic Diagram of Various Conduction Processes in Thin Film Dielectric at High Fields.
Process 1). Process 2 describes the injection of conduction electrons from an electrode directly into the conduction band by Schottky emission, a process of electron emission aided by the image force and an applied field. From trapping levels in the forbidden band, ionization of electrons into the conduction band can be assisted by a sufficiently high applied field (Process 3). This is called Poole-Frenkel conduction, which is the bulk analogy of Schottky emission.

**Tunneling of Electrons through the Potential Barrier**

Electrons can quantum-mechanically tunnel through the potential barrier if the latter is reduced in its effective thickness in the presence of a high field. The tunneling can of charge carriers be from the metal into the conduction band, similar to field emission into vacuum (Process 4); from the shallow traps (Process 5); from the valence band into the condition (Process 6) band; or directly from cathode to anode if the physical separation is very thin (< 30Å, angstroms, Process 8).

**Impurity Conduction**

If the impurity concentration is high, thus presenting numerous trapping centers in the forbidden energy band, significant conduction is possible, with the electrons hopping from one center to another without being raised into the conduction band (Process 9). Although similar to Processes 3 and 5, which are also originated from trapped impurities, impurity conducting differs from them because it does not involve the conduction band. Therefore, Process 9 can take place at lower fields than required for Process 3 or 5. Impurity conduction is
ohmic.

**Space Charge Effects**

Space-charge-limited conduction is a phenomenon rather than a mechanism by itself. Trapped electrons or electrons in transition in the conduction band can build up regions of significant space charge. In the presence of space charge, conduction may be limited by it instead of by the underlying mechanisms, which can be any of the processes just described.

**Electrical Breakdown**

Electrical breakdown is a destructive high field effect that is frequently associated with thin film devices. Flaws and defects, by introducing regions of enhanced electrical stress or high-leakage paths, will reduce the breakdown field strength. In a carefully prepared film, breakdown can be expected to approach its intrinsic dielectric strength. Breakdown mechanisms can be ascribed to these interactions:

1. Avalanche Breakdown. An itinerant conduction electron, acquiring sufficient energy from the accelerating field, can ionize the lattice and multiply. If this impact ionization becomes a chain reaction, breakdown occurs as a result of electron avalanching.

2. Joule Heating Breakaway. Thermal assisted breakdown is related to the rate of heating and dissipation. With low thermal conductivity and without sufficient heat dissipation, the attendant Joule heating cause the
lattice temperature to rise. In return, Joule heating increases exponentially with temperature as the conduction increases. If the feedback heating sustains, breakdown is bound to occur. However, it is a gradual process and can be detected before failure. In some cases, Joule heating will cause the I-V relation to deviate from the mechanism governing conduction immediately preceding breakdown.

3. Electron-Electron Interaction. Collision between electrons causes the free-electron temperature to rise without limit, a scenario responsible for electrical breakdown in metals. Breakdown due to electron-electron interaction is less likely for materials of low free electron density, such as semiconductors and insulators, since other breakdown mechanism would circumvent.
CHAPTER III

EXPERIMENTAL PROCEDURE

The fabrication of CLFEA cathodes was a complex, multi-step process, which transformed an ingot of the ZrO₂-W composite into a field effect cathode containing arrays of current-limited emitters. The composite was grown from an eutectic melt of the same composition, using a process that is well documented.⁵⁸

The composite ingots were sliced into wafers and diced into the individual chips on which the emitter structure was formed. Each chip was ground and polished, annealed, chemically etched, and placed in a vacuum deposition facility where appropriate thin films were evaporated onto the surface. The chips were further processed, subsequent to film deposition, to form the final emitter structure. Each step of this fabrication process is described in detail.

Following fabrication, each CLFEA cathode was carefully characterized prior to emission testing. The procedures followed in this characterization are outlined, including measurement of the current-voltage (I-V) characteristics of the silicon film, checking of the fiber continuity, and measurement of the pertinent emitter geometric parameters.

Finally, the testing phase of this study is detailed. This includes a description of the techniques for mounting the samples, the vacuum system and the electrical test circuitry, the method of data
collection and reduction, and the post-emission examination of the cathodes.

CLFEA Fabrication

The fabrication of the CLFEA cathode requires a great many processing steps, involving a wide spectrum of technical disciplines. Some of the fabrication techniques are unique, thus necessitating a detailed description. Preparation of the composite substrate, deposition of thin films of different function, and post-deposition processing to yield the final emitter structure are all outlined. In addition, the facilities for chemical etching of the composite, electropolishing of the extractor grid, and thin film deposition are also described. The description is intended to follow the sequence of the fabrication steps as closely as possible. In order to minimize confusion, a schematic overview of key fabrication steps is illustrated in Fig. 3-1.

Substrate Preparation

The yttria-stabilized ZrO_2-W composite from which the emitters were fabricated was sliced, perpendicular to the fiber growth direction, into 0.9 mm thick wafers using a low-speed saw (Buehler Isomet saw, Model 11-1180), equipped with a 0.012 in x 4 in diamond impregnated blade. One side of the composite wafers was sputter-coated with a thin conductive film of Au/Pd to provide electrical contact to one side for testing fiber continuity with a fine multimeter probe from the other side. The wafers that were found to contain a high percentage of continuous fibers were cut into 3 mm
(a) testing the composite chip for fiber continuity with the Au-Pd coating on the other side using a multimeter probe;
(b) polishing both sides of the chip to 0.25 μm finish;
(c) vapor-depositing silicon and Mo on one side of the polished chip;
(d) etching to expose the tungsten fibers;
(e) characterizing the silicon film with a micromanipulator probe through a single fiber;
(f) removing fibers outside a masked area to form the active area;
(g) vapor-depositing Al$_2$O$_3$ and Mo to form the integrated extractor grid;
(h) the finally processed CLFEA after post-deposition processings.

Figure 3-1. Schematic Diagram Depicting Key Steps in CLFEA Fabrication Sequence.
chips. The center region of each individual chip, where the active area was to be located, was again tested for fiber continuity; those that indicated too few continuous fibers were rejected from the lot.

An automatic grinder/polisher (Buehler Minimet Model 69-1000-160) was used to grind and polish the chips with successively finer grades of SiC paper and diamond compound. Ten to twenty chips, glued to a cylindrical polishing holder, could be processed in one polishing routine. Both sides of the chips were polished to a 1/4 μm (10 micro-inch) surface finish.

To provide a stress-free surface for more uniform etching, the polished chips were annealed for one hour at 1500°C in a 4:1 N₂/H₂ atmosphere. In addition to releasing the strain energy stored in the surface layer of the composite chips, annealing also improved the substrate surface by smoothing the microscratches on the tungsten tips, and by reducing any tungstate phases (WOₓ) that might be present in the matrix.

One of the most essential steps in the CLFEA fabrication process was to expose the tungsten fibers by chemical etching to a specified length. Etching studies by Mohr²⁹ indicated that hot phosphoric acid was the only satisfactory etch for the yttria-stabilized cubic zirconia system. The primary etching parameters were determined to be acid concentration, temperature, etching time, and sample surface conditions (i.e., smoothness, stress level, etc.). The effect of the Y₂O₃ stabilizer concentration and the orientation of the oxide cells also played a role in the etching behavior, but their effects were not fully investigated because of the complexity of the interactions.
The composite samples were etched in phosphoric acid in the reflux system diagrammed in Fig. 3-2. The etchant was maintained at 232 ± 5°C with a proportional temperature controller equipped with an iron-constantan (Type J) thermocouple encased in a glass tube. In the reflux system, the equilibrium concentration of the phosphoric acid was 99% at that temperature. Pyrex forceps were used to hold the samples during etching. The length of exposed fibers was determined by the etching time, as shown in Fig. 3-3. To obtain a 1.5 μm fiber height, the etching time was 16 minutes. The etched samples were carefully rinsed in warm distilled water to remove the phosphoric acid.

After the samples were etched, a small area (the active area) was masked on the front surface with an acid-resistant wax (Apiezon wax W) dissolved in trichloroethylene (TCE). The wax mask was applied with a 30 gauge syringe needle, using a zoom stereomicroscope to position the wax dot near the center of the chip, avoiding cell boundaries if possible. The entire back side of the chip was also covered with wax. The size of the active area generally ranged from 50 to 500 μm in diameter, with 200 μm being typical (Fig. 3-4).

When the wax had dried sufficiently, it became inert to most chemicals. An aqueous solution of alkaline ferricyanide (5 gm of NaOH and 15 gm of K₃Fe(CN)₆ in 100 ml of H₂O) was then used to dissolve the fibers everywhere on the front surface of the chip except in the masked area. In 30 minutes the fibers were dissolved to a depth of ~30 μm into the matrix.
Figure 3-2. Schematic Diagram of Apparatus Used in the Reflux Etching System.
Figure 3-3. Plot of Fiber Length vs. Etching Time at Various Temperatures, When Using Phosphoric Acid to Expose Tungsten Fibers in a ZrO₂-W Composite.
Figure 3-4. Photomicrograph of a Typical Active Area of the FEA Cathode (600x, 45° tilt).
Following fiber removal, the samples were rinsed extensively with running tap water for at least several hours to get rid of any traces of ferricyanide that might be trapped in the recessed holes. This was followed by a 10 minute-soak in distilled water, after which samples were dried and stored (with the wax protecting the fibers in the active area) to await the next processing step.

**Deposition Facility**

The thin films comprising the insulator and extractor grids, as well as the resistor film, were deposited by vacuum evaporation. The system was essentially built in-house from commercial components and is diagrammed in Fig. 3-5. It consisted of a vacuum system containing a 1400 l/min mechanical pump and a six inch diameter, 1500 l/min diffusion-pump-(NRC Model 1062-H064). The system was valved such that the mechanical pump could act both as a roughing and a forepump, and the entire vacuum system could be isolated from the chamber with a manual gate valve.

The chamber itself contained a SLOAN multihearth, 180° bent beam system which could divert a 5 KW electron beam into one of four water-cooled, 3.2 c.c. copper hearths. The hearth could be selected by a manual control external to the chamber, permitting up to four different materials to be evaporated in each preparation. A SLOAN model FIVE/TEN A power supply was the power source for the electron gun. An AC component of the electromagnet which directed the beam into the hearth was used to sweep the beam the length of the hearth. An external steering magnet was used to control beam movement orthogonal to the built-in beam sweep. The degree of beam focusing
Figure 3-5. Thin Film Deposition Facility.
could also be controlled. For thermally insulating materials, a
defocussed beam was used to melt a large pool of material for more
stable deposition.

The system was enclosed with a 12 in-diameter Pyrex bell jar.
Stainless steel shields were used extensively throughout the system to
prevent the evaporant from coating the bell jar and to prevent
overheating of the bell jar during the deposition of molybdenum
film. Electrical and cooling water connections were made through
ports of an aluminum collar below the bell jar. A leak valve
(Granville-Phillips model 203) was used to control the atmosphere in
the chamber, bleeding in N₂, O₂, or other gases as appropriate.
System pressure was monitored by two thermocouple gauges (Varian TK
gauge 531), and an ionization gauge (Veeco Model RG-75-P) mounted on
the chamber.

A SLOAN Model MDC 9000 deposition controller was used to control
deposition rate and overall film thickness. The controller formed a
close-circuit control loop with the electron beam power supply to
achieve a constant deposition rate. The deposition rate was measured
with a water-cooled quartz-crystal monitor mounted in the chamber and
looking directly into the hearth. Besides controlling deposition
rate, the microprocessor-based controller could also ramp power up at
start-up, register accumulated film thickness, and shut the system
down when the pre-selected deposition thickness was achieved, or upon
countering system support failures (e.g., crystal failure, loss of
cooling water, power, or vacuum). The controller contained sufficient
memory to pre-program deposition of up to 10 different materials, each
with its own power and rate requirements. In addition to the digital display of deposition rate and thickness, an analog signal to a two-pen recorder was used to produce a simultaneous display of deposition rate and film thickness.

In order to assure adhesion of the films to the substrate, it was necessary to maintain the composite chips at elevated temperature (200-500°C) which varied somewhat depending on the material being deposited. The samples were heated by placing them in recessed slots in a copper block, facing the hearth. A folded Ta strip heater, insulated from the copper block with a BeO plate, was the heat source. Temperature was sensed with a chromel-alumel (Type K) thermocouple, recessed in a hole in the copper block, and was controlled manually by adjusting the heater voltage with a variable auto-transformer.

There were two shutters between the samples and evaporation sources. The first, a sliding shutter mounted in the heater block, was used to shield selected samples from the evaporant stream. A second shutter, located several cm below the sample holder, remained closed until the deposition rate had stabilized.

Deposition Routine

The silicon resistor film was the first thin film to be vapor-deposited on the prepared ZrO₂-W substate. Prior to installation into the vacuum deposition facility, the chips were cleaned by vapor-degreasing in TCE. Twelve chips were placed in the three slots of the sample holder, four chips to a slot. The shields were put in place, the system was sealed and the roughing pump started. When the pressure was sufficiently low, the gate valve was opened, and the
system was allowed to pump on the diffusion pump for a certain period of time before the sample heater was turned on. When the heater reached deposition temperature (usually in 3-4 hours), the hearth containing the silicon source material was rotated into place and the proper deposition program was selected.

The silicon source materials consisted of three-inch-diameter single-crystal ingots, doped with either boron, with a bulk resistivity ranging from 0.01 up to 38 ohm-cm, or phosphorous, with a bulk resistivity of 2234 $\Omega$-cm (the relation between dopant concentration and ingot resistivity is shown in Fig. 3-6). The ingots, which were obtained from the Monsanto Chemical Corporation, were cut into 15 mm cubes with a diamond saw so they would fit easily in the copper hearth. All materials were vapor degreased in TCE before they were placed in the hearth.

After an overnight pumpdown, the deposition chamber would generally reach a pressure of $10^{-6}$ torr, at which point the substrate heater was turned on. The samples were heated at $\sim 150^\circ$C/hr to 500$^\circ$C, after which the chamber pressure usually rose by an order of magnitude. To initiate evaporation, the e-beam power was ramped up at a predetermined rate and held at a critical power level at the evaporation threshold, i.e., just before significant evaporation occurred (at an evaporant vapor pressure of $\sim 10^{-4}$ torr). The threshold level was determined empirically and, of course, varied from one material to another. The material in the hearth was soaked for several minutes at this power level to allow the system to equilibrate and to drive off any contaminants present. The power was then increased until the
Figure 3-6. Resistivity vs. Impurity Concentration for Si at Room Temperature, after Sze et al. [60]
material began to evaporate. When the evaporation rate stabilized to the programmed value, the shutter was opened and the film thickness monitored until the required thickness was reached, at which point the power was shut down.

Unique to the deposition of silicon, the evaporant would frequently erupt and spit from the hearth just before the center region of the ingot was completely melted. Once it was melted, however, the silicon deposition was extremely stable, varying less than ±10% from the programmed rate (2 or 10 A°/sec).

Following the silicon deposition, the silicon film was overcoated with a 0.6 µm-thick Mo film. The Mo overcoat served a two-fold purpose: to protect the silicon film from subsequent chemical etching (to expose the tungsten fibers) and to act as a uniform electron supply electrode for characterization of the resistor film and for activation of the emitters. The Mo source material consisted of single crystals of Mo with a nominal purity of 99.99%, vapor-degreased before its installation in the evaporation facility. The deposition of Mo was done at ~300°C at a programmed rate of 10 A°/sec.

The composite chips coated with Si and Mo were then chemically etched to expose the tungsten fibers. Following etching, the active area was formed and the resistor film characterized. The composite chips with desirable geometry of the tungsten fibers and with satisfactory resistor characteristics were selected for further fabrication.

After the active area had been formed, Al₂O₃ and Mo films, which form the emitter structure on the front side of the composite
substrate, were deposited. The same vacuum facility and deposition procedures were used to make the Al₂O₃/Mo deposition. The Al₂O₃ source material was high purity (99.9%), fine Al₂O₃ powder (Baikowski International, GE6, AS-3). The Al₂O₃ powder was dry-pressed into a pellet (3/4 inch in diameter by one inch long) at 5000 PSI using no lubricants or binders. The pellet was scraped with a spatula to make it conform to the shape of the hearth and also to remove the contaminated skin in contact with the die. The Mo evaporant was the same as that used for the Si/Mo deposition.

The substrate temperature for the Al₂O₃ depositions was held at ~450°C and for the Mo deposition ~300°C. Due to a lagging thermal response of the heater assembly, a temperature fluctuation of 20°C was not uncommon during the long course of the Al₂O₃ deposition (80-160 minutes), and the quoted temperatures are average values.

The thickness of Al₂O₃ (1-2 μm) and Mo (0.6 μm) were programmed according to the average fiber height of the particular group of samples, in order to place the extractor layer at or slightly below the level of the fiber tips. The programmed deposition rate was 2 Å/sec for Al₂O₃ and 10 Å/sec for Mo.

After the depositions (Si/Mo and Al₂O₃/Mo) had been satisfactorily completed, the heater power was turned off. The samples were allowed to cool slowly, in vacuo. It usually took more than 12 hours for the system to reach room temperature, after which the samples were unloaded for post-deposition processing.
Post-Deposition Processing

In order to produce the final emitter structure, i.e., each standing tungsten pin surrounded by a concentric metal aperture, the cone-shape deposits on the tip of tungsten pins had to be completely removed. This was accomplished using a combination of mechanical forces and chemical reaction.

The samples were first etched in 85% phosphoric acid at 100 ± 5°C to dissolve some of the Al₂O₃, thereby undercutting and releasing the cones from the pin tips (Fig. 3-7). The etch rate was estimated to be 0.5 μm/min. The samples were etched for one minute, followed by a rinse in warm distilled water. The chips were then placed in an ultrasonic cleaner (in distilled water) for 5 sec, which served to break off any remaining cones on the pin tips, and to remove loose cones and foreign material from the sample surface. The etch and rinse step was then repeated to insure that all Al₂O₃ was removed from the pin tips. Finally, the samples were soaked for 10 minutes in distilled water to rinse away the last traces of phosphoric acid and possible phosphate products within the cavity surrounding each pin.

The side wall of the insulator hole (Fig. 3-8) was also etched during the cone removal process. This was thought to be beneficial, since it increased the path length for surface leakage current from the base of the pin to the extractor. There was a limit, however, to the degree of undercutting which the extractor film would withstand before it began to fracture.

The extractor film was electropolished to remove sharp protrusions from the edge of the apertures, which might initiate an
Figure 3-7. Photomicrographs of a FEA Cathode at Different Stages of Fabrication, (a) Tungsten Fibers Exposed after Etching, (b) Emitter Sample as Deposited Showing Cone-Shaped Deposits, (c) Final Emitter Structure after Post-Deposition Processings.
Figure 3-8. Photomicrograph of a FEA Cathode, Showing Recessed Holes in Al₂O₃ Film with Extractor Film Partially Removed.
Figure 3-9. Schematic Diagram of Electropolishing Apparatus.
arc between the extractor and the pin tip. The electropolishing apparatus is shown schematically in Fig. 3-9. The electrolyte used was 98% \( \text{H}_2\text{SO}_4 \). The samples were held with a pair of teflon tweezers, while a platinum wire provided electrical contact to the extractor. A cell voltage of seven volts resulted in a material removal rate of 20 nm/sec. Five seconds of electropolishing was sufficient to smooth the extractor, which simultaneously enlarged the diameter of the extractor aperture by 0.2 \( \mu \text{m} \) (Fig. 3-10). The samples were rinsed in distilled water and methanol, and dried with freon spray.

As a precautionary measure, the selected CLFEA cathodes for emission testing were treated with a 5-second rinse in 10% KOH aqueous solution prior to mounting them in the test vehicle to clean the tungsten tips that might have been partially oxidized during previous processing steps.

**Summary of CLFEA Fabrication Procedure**

A step-by-step account of the fabrication procedure of CLFEA is presented here. Because the tiny, exposed tungsten fibers are prone to damaging by any mechanical disturbances inherent to the numerous fabrication steps, the sequence of fabrication procedure was designed to minimize handling samples with exposed fibers. Consequently, the selective etching of the composite was done as late as the procedure allowed.

The fabrication sequence is summarized as follows:

1. Slice \( \text{ZrO}_2\)-W composite into 0.9 mm-thick wafers.
2. Make preliminary test of each wafer for fiber continuity with a multimeter.
Figure 3-10. Photomicrographs of a FEA Cathode, Showing Extractor Film Reduced in Thickness and Extractor Holes Enlarged, (a) After 10 Seconds of Electropolishing, (b) After 15 Seconds of Electropolishing.
3. Dice wafers with continuous fibers into 3 mm-square chips.
4. Perform more extensive continuity tests on each individual chip with a multimeter.
5. Polish both sides of chips with continuous fibers to 0.25 μm surface finish.
6. Anneal the chips in hydrogen for one hour at 1500°C.
7. Vapor deposit Si to the desired thickness, then evaporate a 0.6 μm-thick Mo film over the silicon.*
8. Etch the Si/Mo coated chips to expose the tungsten fibers**
9. Place a wax dot to mask the exposed fibers near the center of each chip under a binocular microscope.
10. Measure the I-V characteristics of the silicon film through exposed fibers using a micromanipulator probe.**
11. Cover the back side of each chip with wax to protect the Mo overcoat.
12. Remove the fibers outside the active area with the alkaline ferricyanide solution.**
13. Remove the wax from the surface to each chip with TCE.**
14. Vapor deposit the Al₂O₃ insulator film and Mo extractor grid.*,**
15. Remove the cones from the tips with phosphoric acid

*This step was preceded by vapor-degreasing in TCE.
**This step was followed by visual inspection in the SEM.
at 100°C.


17. Repeat step 5 to remove any remaining Al₂O₃ from the tips of the tungsten fibers.

18. Clean the chips in 10% KOH to remove any oxidized layer on the W tips.

19. Measure the structural parameters of the finished cathodes.

Characterization of CLFEA Cathode

A CLFEA cathode had to be characterized electrically for the current-voltage relationship of the current-limiting series resistor, and morphologically to determine the emitter geometries. Measurement of the silicon series resistors using a micromanipulator probe in a SEM is described first. The results of such measurements can be used directly, because the silicon films are on the same composite substrate that is used for the CLFEA cathode and are measured through a single tungsten fiber. To determine the extent of discontinuous fibers in the active area, which is an extremely important parameter affecting performance, a non-contact examination of fiber continuity is described in detail. The final characterization of the completed CLFEA cathode included measurement of pertinent geometric parameters and the initial capacitance and resistance values, as well as a visual inspection, all of which are performed in the SEM.

Electrical Characterization of the Silicon Film

In order to measure the resistance of the silicon film through
individual tungsten fibers, the probe must be physically small enough that it contacts only one fiber at a time. This also requires the capability of precision movement of the order of several microns. Furthermore, in order to verify that contact was indeed only made with one fiber, all of the measurements were conducted under observation in the SEM.

A micromanipulator was custom-fitted to the SEM specimen chamber and equipped with an electrical probe that could be manipulated from outside of the chamber (Fig. 3-11). The leverage point of the probe was close to the tip, giving a proportional reduction of probe displacement with external movement. The final positioning of the probe on the tungsten fiber could be achieved by adjusting the manipulator or by moving the sample in the SEM with a tilting, rotational, or translational movement.

The probe tip was made of fine gauge tungsten wire, electropolished to a tip radius of less than 2 μm (Fig. 3-12). The shank of the probe was shielded from excessive reaction during electropolishing so that it would remain relatively thick and sturdy, and thus less susceptible to vibration while being positioned and tested.

The sample to be characterized was etched to expose the tungsten fibers to facilitate probe contact, with the silicon film already deposited and overcoated with Mo on the back side. It was bonded to a SEM sample stud, but electrically isolated from it with a thin piece of microscope cover glass in between (Fig. 3-13). Sandwiched between the sample and the cover glass was a sheet of stainless steel which was used to make connection from the sample through an electrometer to
Figure 3-11. Facility Used for Characterization of Thin Film Series Resistors, (a) Micromanipulator Stage Attached to SEM Specimen Chamber, (b) DC Conductivity Measurement Apparatus.
Figure 3-12. Photomicrographs of Micromanipulator, (a) Probe and Part of Emitter Substrate (3X3mm), (b) Probe Making Contact with a Single Tungsten Pin (2500X, 45° Tilt).
Figure 3-13. Schematic Diagram Illustrating the Resistor Characterization Arrangement Showing Emitter Substrate on a Modified SEM Sample Stud.
When the probe contact was made and visually confirmed, the DC power supply was turned on to initiate the test. The voltage drop across the resistor film and the current were recorded as the applied voltage was gradually increased. The voltage was increased in equal increments of $V^{1/2}$. The stability of the current was monitored closely. When signs of current drifting up independently of applied voltage were observed, indicating a Joule heating in the resistor, the voltage was gradually reduced and another set of data taken. The current-voltage (I-V) data were plotted on a log I vs. $V^{1/2}$ scale (Fig. 4-12).

Several fibers in one sample were measured at both positive and negative polarity with respect to ground. One major advantage of this method of measurement was the vast number of fibers available, which provided a broad data base as a means of determining statistical variation from fiber to fiber as well as from one deposition to another.

While the measurements were being made, the primary beam and the signal collecting circuits of the SEM were turned off to provide a noise-free environment inside the chamber for the measurement. The noise level of the measurement was observed to be in the nanoampere range.

**Determination of the Fiber Continuity**

One of the geometric parameters of the CLFEA cathode that needed to be quantitatively determined was the number of working emitters, i.e., the ones with continuous fibers, in the active area. Due to fluctuations during the composite growth process, the continuity of
the tungsten fibers was often interrupted. Oxide-rich bands parallel to the solidification front were not unusual when one examined a longitudinal section of the composite. These bands created tiny gaps in the fibers and caused an open circuit at the gaps (because of the high resistivity of the stabilized ZrO$_2$ matrix), which would prevent the fiber from emitting. Considering the high aspect ratio (2000:1) of a typical fiber in a 0.04 in (1.0 mm) thick substrate, and that the bands occurred irregularly, the crucial knowledge of the percentage of discontinuous fibers could not possibly be predicted. This uncertainty was the largest single source of errors in emission testing.

The size, quantity, and delicate nature of the fibers made it impractical to use a probe to test each individual, exposed fiber. However, a non-contact method of testing the fiber continuity was discovered, which was quite effective in determining the extent of discontinuous fibers in the active area.

The test was accomplished by observing the cathode in the SEM while applying a small positive voltage (+ 10 volt) to the bottom electrode. A CLFEA cathode under emitter continuity observation is schematically diagrammed in Fig. 3-14. The sample was placed in the SEM with its extractor grounded and a power source connected to its base. A positive voltage bias would raise the potential of continuous fibers, making them collectors for low energy secondary electrons. Because the signal composing the SEM image is formed by the same secondary electrons, continuous fibers, when energized, appear darker than the grounded extractor. On the contrary, discontinuous fibers
Figure 3-14. Schematic Diagram Illustrating the Non-Contact Fiber Continuity Examination Using a Biasing Potential Technique in SEM.
float at a negative potential due to charging from the scanning electron beam, since they are electrically isolated. The negatively charged, discontinuous fibers emit more secondary electrons and thus turn brighter when observed in the SEM. The striking contrast produced by the technique is illustrated in Fig. 3-15, which makes identification of discontinuous fibers an easy task. The screening routine for each sample required only a short time (~ 10 minutes) to perform.

**CLFEA Parameters**

All pertinent device parameters of the finished CLFEA were measured and characterized in the SEM, such as the size of active area, the percentage of continuous fibers, the fiber height and shape, and the extractor hole diameter, etc. The results are presented in the next chapter (Table 4.2). The characterization routine also served as the screening process to choose the most ideal CLFEA for subsequent emission testing.

**Emission Testing**

Emission testing of the CLFEA cathodes constituted the final phase of the experimental procedure. The tests were performed in an ion-pumped high vacuum environment. Samples were mounted in a commercial electron gun acquired from Thomas Electronics, Inc., Wayne, NJ. The test vehicle and mounting method, and the vacuum system, electrical testing equipment and pump-down procedure are described in that order. Next the emission test circuitry and cathode activation sequence are presented. Finally, the method of acquisition and
Figure 3-15. Example of the Sharp Contrast between Emitters with Continuous (Dark) and Discontinuous (Bright) Fibers under Fiber Continuity Examination in SEM.
reduction of the emission data is outlined, followed by a brief description of post-emission examination of the samples.

**Test Vehicle**

The emission test vehicle consisted of a commercial electron gun (manufactured by Thomas Electronics, Inc., Wayne, NJ), that was originally designed for a miniature cathode ray tube (CRT), mounted on a 4 1/2" or 2 3/4" Varian ConFlat flange (Fig. 3-16a). The gun was modified by Thomas Electronics, leaving the G1 cup (which normally contained a thermionic cathode) open to accept the CLFEA test cathodes, which was mounted on a modular carrier (Fig. 3-16b).

The module was designed and built locally to mount the CLFEA cathode in the electron gun. The electron gun and cathode module are diagrammed schematically in Fig. 3-17. The ceramic core was custom-made by the Technical Ceramics Division of 3M Company, using a high Al₂O₃ body. External screw threads (1/4-28) were cut into the o.d. of the core and a 0.05 inch (1.2 mm) diameter hole extended along its axis through the entire 0.6 in (15.2 mm) length of the piece. One end of the core was slotted, and metallized with silver ink to receive the cathode chip. A 22 gauge (6.4 mm) Nichrome wire was inserted through the center hole to make electrical contact to the cathode (K). Electrical connection to the extractor (E) was made using a 0.05 in (0.12 mm) thick stainless steel (S.S.) strip, clamped in a groove on the side of the ceramic core with a threaded S.S. cylinder. The end of the S.S. strip also served to mechanically secure the chip to the top of the ceramic core. Before the cathode was seated on the slotted top of the core, a drop of silver ink was used to reinforce mechanical
Figure 3-16. Emission Test Vehicle, (a) Modified Electron Gun on a Feedthru Flange, (b) Electron Gun and Cathode Module.
Figure 3-17. Schematic Diagram of Electron Gun and Cathode Module Used for Emission Testing of CLFEA.
and electrical contact in between. A second threaded S.S. cylinder was screwed on to the core from the opposite end to act as a "jam nut". Both cylinders were machined to provide a snug fit in the Gl cup.

Alignment of the active area of the cathode in the optic axis of the gun was essential for the emission current to reach the collector. Alignment was achieved by centering the active area with respect to the center aperture on G2, observed with a 30X binocular microscope. By sighting down the axis of the gun, the composite chip could be moved around until the active area was centered on the gun axis and then clamped in place.

After aligning the cathode, the mounting fixture was inserted in the Gl cup, the gun was mounted on the ConFlat flange, and electrical connections were made to the appropriate feedthru's. The test vehicle was then bolted to the vacuum chamber and the pump-down sequence was initiated.

 Vacuum System

The vacuum test facility consisted of a stainless steel chamber which contained three 4 1/2" in ports and two 2 3/4" in ports, permitting five samples to be tested in one pumpdown. The chamber and test equipment are pictured in Fig. 3-18. It was evacuated with a 1500 liter/min mechanical pump to approximately one millitorr, followed by a 6-hour bakeout at 250°C. After the chamber cooled, an ion pump (Perkin Elmer Model ULTEK D-1 Pump), equipped with a built-in water-cooled titanium sublimation pump, was turned on. The ion pump reduced the system pressure to the $10^{-8}$ torr range in several hours. An
Figure 3-18. Emission Test Facility, (a) Vacuum Chamber, (b) Electrical Equipment.
additional 24 hours of pumping usually reduced the pressure to the \(10^{-9}\) torr range where emission testing was conducted. System pressure was monitored with a Veeco Bayard-Alpert ionization gauge and controller.

**Test Circuitry**

Emission testing of the CLFEA cathodes was done exclusively in DC mode throughout this investigation. The reason for not testing the samples in pulse mode was because the large resistance of the current-limiting series resistors would seriously distort the output pulses. The emission test circuitry is shown schematically in Fig. 3-19. A Fluke model 415B high voltage DC power supply was connected to the cathode (K) through a resistor box. The resistor box (switchable from 1 to 1000 MΩ) was used to provide short-circuit protection for the cathode and equipment if the cathode failed. Net applied voltage to the cathode was measured with a Hewlett Packard Model 3435A digital voltmeter connected to the cathode side of the resistor box.

The extractor was grounded through a Keithley Model 610CR electrometer. The current in this circuit was monitored as the leakage current. The third electrode, the collector (C), consisted of G2 and G3 which were connected together. A 300 volt dry cell battery was connected to the collector, to provide a positive bias for collection of emitted electrons. The collector current was measured with a second Keithley electrometer. All electrical connections outside the vacuum chamber were made with Type RG-59 coaxial cables. Two sets of testing equipment were available, so that two cathodes could be tested simultaneously.
Figure 3-19. Schematic Diagram of a CLFEA Cathode and Emission Test Circuitry.
CLFEA Activation

Emission testing was initiated by increasing the cathode voltage slowly until an emission current in the nanoamp range was detected. Leakage current was constantly monitored while emission testing was being done. In general, emission current was initially quite noisy, especially at the low current levels. Emission was allowed to stabilize for a brief period (~1 hour) before any further voltage increase was made. Emission I-V data were recorded when the emission current had stabilized and increased to the microamp range. The standard mode of data collection was in the order of decreasing voltage/current, with four to five values of emission current per decade being recorded. Each set of emission I-V data was used to generate a Fowler-Nordheim plot, from which emitter parameters, such as microscopic emitting area, and field enhancement, could be calculated. After collecting the I-V data, the emission current was returned to its original level. At each predetermined current density, several sets of data were obtained sequentially at two intervals to observe the effect of elapsed time on emission. The changes in the Fowler-Nordheim plots, such as slope, intercept, and curvature, etc., were monitored during the data collecting process. When no significant change over a certain period was observed, the cathode was turned up to a higher level of emission. Again, several curves were taken using the procedure just described. This process was repeated until the cathode shorted or testing was terminated for sample examination.
Post-Emission Examination

Emission-tested CLFEA cathodes were examined in the SEM to investigate the extent of failure or structural damage. Typical modes of failure are noted and discussed later in Chapter IV. The I-V characteristics of emission-tested silicon films were measured on two samples, TE6-6 and TE9-2. In order to clear the fibers for probing, the Mo extractor film was stripped by electropolishing in sulfuric acid. Techniques for electropolishing and probing of individual fibers with the micromanipulator were the same as previously described.
CHAPTER IV

RESULTS AND DISCUSSION

In this Chapter the applicability of current-limiting the Field Emitter Array (FEA) cathodes is examined. This is presented by describing the method by which the concept was engineered, i.e., the incorporation of thin film resistors to limit the current. As a consequence of adding a current-limiting component to the Fowler-Nordheim current source (a field emitter), the emission behavior of such a composite device is complex and needs to be derived analytically. The effect of current limiting is discussed with the aid of a mathematical model, which combines the I-V characteristics of both components. Following the theoretical treatment, the experimental results are presented. This includes the measured I-V characteristics of the thin film resistors as well as the emission test results of the CLFEA cathodes.

Formulation of Current-Limiting Resistors

In adopting the current-limiting approach to improving emission uniformity and reliability of the FEA cathodes, it is first necessary to fabricate resistors in series with, and individually dedicated to, each emitter. In addition to the "individuality" requirement, the resistors must also have sufficient resistance to produce the optimum current-limiting effects. Unfortunately, there is no easy method of calculating or estimating the optimum value of resistance needed,
since it depends on many factors such as the total applied voltage, the distribution of emitting tip radii, and most important of all, the magnitude and distribution of emission current.

It is obvious that, even for the same emitters, the operating conditions are likely to change, and hence so is the optimum resistance. The situation is further complicated by the necessity of arriving at a single value of resistance to satisfy the requirements of every emitter. In order to accomplish this, it was necessary to narrow the objectives of current-limiting to within a specific range of operating conditions and physical characteristics of the cathodes. Normally FEA cathodes operate with an applied voltage ranging from 150 to 250 volts. With a goal of obtaining a current density of 5 A/cm\(^2\) reliably, the average emission burden on one emitter would be about 1 \(\mu\)A, assuming an emitter packing density of \(5 \times 10^6/\text{cm}^2\). Hopefully, a voltage difference of not more than 100 volts (40% of the total applied voltage of 250 volts), spread over the high end of the voltage spectrum, would bring the emission current of most emitters to the same order of magnitude. These criteria can be translated into a singular requirement of formulating a resistor with a value of \(10^8\) to \(10^9\) ohm.

It is the structure of the emitter substrate, i.e., the ZrO\(_2\)-W composite, that permits the fabrication of all of the individual resistors with a single thin film of suitable material. Because the matrix (ZrO\(_2\)) is an excellent insulator, only those discrete portions of the film (which is a semiconductor) that are directly beneath the tungsten fibers will be active in the electric circuit. Since the
tungsten fibers are spaced approximately 4-5 μm apart on centers, compared to the fiber diameter of ~ 0.7 μm, the conducting volumes of the film that form the resistors are unlikely to overlap. This condition satisfies the requirement that each resistor influence only the fiber with which it is in direct contact.

Although there are no physical boundaries of the resistor inside the thin film, its conducting path can reasonably be imagined as the volume extension of the fiber through the thickness of the film. It is possible that the diameter of this conducting path may expand as it extends from the base of the metal fiber, the so called "fringing" effect. The effect of fringing could cause overlapping of adjacent resistors if the thickness of the resistor were great enough and the fringing angle sufficiently large. For example, overlapping would occur if the film thickness was greater than 3 μm and the fringing angle was at least 30 degrees.

As yet, it is not certain whether the individuality of the resistors would be hampered by such overlapping; nevertheless, it was deemed prudent to impose a limit on film thickness so that the possibility that neighboring resistors might overlap was kept to a minimum. The limit of the film thickness was set at 3 μm, and was kept at that value with few exceptions. Although this constraint on the thickness was considered necessary, a precise knowledge of the degree of fringing and its effects may not be of crucial importance. By successfully characterizing each individual resistor with a micromanipulator, intermediate data such as the dimensions of the metal fiber and resistor film, the film resistivity, and the fringing
angle are no longer required, because directly measured resistance values as well as and field dependence of resistance become readily available.

To obtain a resistance of $10^8$ to $10^9$ ohm with a resistive material of cylindrical shape having a diameter of 0.7 \( \mu \text{m} \) (same as that of the fiber) and a length of 3 \( \mu \text{m} \), the resistivity of the material must be at least 1000 ohm-cm. Undoped, intrinsic silicon was chosen as the thin film material primarily because it has a suitable resistivity. The choice, however, was not made solely on the basis of resistivity. There are many semiconductors, elemental and compound, intrinsic and extrinsic, whose resistivity is in the usable range. Silicon, however, being the most popular and extensively studied material in solid state research, is unsurpassed in regard to the availability of the material itself and technical information concerning it. It also possesses other qualities, such as chemical inertness, refractoriness, and established methods of microfabrication, that may be required to be compatible with the entire fabrication process of FEA cathodes. A detailed discussion of the series resistors, covering phases such as fabrication, characterization, and measurement, will be presented later in the section titled Silicon Current-Limiting Resistors.

\textbf{Effects of Current-Limiting}

The foregoing discussion of current-limiting the FEA cathode is basically a conceptual one in terms of what might occur qualitatively.
As a field-dependent resistor is added to the already complicated emission circuit of the multiple emitter cathode, the precise "current-limited" emission characteristics can only be obtained with a more rigorous treatment, i.e., through mathematical modeling and simulation. Results of such theoretical calculation are indispensable in predicting, and later interpreting, the outcome of emission testing the CLFEA cathodes.

Mathematical Model of the CLFEA Cathodes

In order to construct a mathematical model, reasonable assumptions and simplifications must be made. Four basic assumptions are described and discussed as follows:

1) The emitters, being otherwise identical, differ on a microscopic scale as to their tip radii, which are assumed to follow a normal distribution.

2) The work function and microscopic emitting area of the emitters remain constant in a steady state emission process as modeled here.

3) For field emitters having identical structure and tip geometry, the field enhancement at the emitting tip is controlled by tip radius alone. The field enhancement factor (β) is defined as \( \beta = 1/r \) in the model.

4) The Al₂O₃ insulating film and tungsten fibers are assumed to be an ideal insulator and conductor respectively. This assumption permits the finite but negligible amount of current loss due to conduction through the Al₂O₃ insulator, and the voltage drop across the tungsten fiber, to be ignored in the model.
Operation of the CLFEA cathode can be regarded as a group of its constituent emitters operating simultaneously and in parallel with a common source of activation. Experimentally, the emission current can only be measured collectively because of the inability to distinguish between the individual beams of electrons produced by each emitter. Hence it is extremely difficult to study the effects of current-limiting with experimental data consequently compounded, while actually current limitation operates at different levels on an individual basis. The model is devised to assist analyzing the current-limited emission behavior of each elemental emitter separately. The DC model of one of the constituent emitters in steady state operation, is represented by the schematic diagram in Fig. 4-1.

The application of a DC potential (V) to the device, between the grounded extractor and the negatively biased emitting tip, creates an electric field that is sufficiently enhanced by the emitter's sharp tip to produce electron emission. A positive biasing voltage (V_C) is applied to the collector, an electrode placed several millimeters above the emitter to attract the emitted electrons. The emission process is unlikely to be affected by values of V_C of up to 1000 volts across a collector spacing of at least one millimeter, since collector fields of the order of 10^4 V/cm are essentially negligible compared to emission fields at the emitter surface of more than 10^7 V/cm. Therefore, as far as modeling of the emission process itself is concerned, the effect of V_C can be safely ignored.

According to Kirchoff's voltage law, the total applied voltage (V) must equal the sum of the new applied voltage to the exactor (V_E)
Figure 4-1. Schematic Representation of the Mathematic Model of Current-Limited Field Emitters Used in Calculation of Current-Limiting Effects.
and the voltage drop across the resistor \( (V_R) \). The exact values of \( V_E \) and \( V_R \) quite obviously must be determined in order to compute the emission current \( (i_r) \), from an emitter with tip radius \( (r) \), and vice versa. Since \( i_r \) is a one-to-one function of \( V_E \) and \( \beta \), and \( V_R \) a function \( i_r \), the conjugated relation of \( V_E \) and \( V_R \) represents an auto-feedback of the emission process via its own current. For a particular emitter, the balance between \( V_E \) and \( V_R \) would vary not only with \( V \), but also with \( \beta \). To arrive at a solution requires that both functions, \( i_r \) and \( V_R \), be determined in exact terms. At the emitting tip, the value of \( i_r \) (as a function of \( V_E \) and \( \beta \)) can be calculated according to the Fowler-Nordheim (F-N) equation,

\[
i_r = \frac{B \beta^2 V_E^2 \alpha}{\phi t^2(y)} \exp \left( -\frac{C \phi^{3/2} f(y)}{\beta V_E} \right), \tag{4.1}
\]

where \( B \) and \( C \) are numerical constants, \( \phi \) is the work function, \( \alpha \) is the microscopic emitting area, and \( t(y) \) and \( f(y) \) are slowly-varying functions of \( y \), where

\[
y = -3.74 \times 10^{-4} \frac{(\beta V_E)^{1/2}}{\phi} \tag{4-1a}
\]

As the emission process proceeds, electrons are depleted from the emitter circuit and collected at the collector. To sustain emission, the emitter must be replenished with an equal quantity of electrons, which are forced to move through the series resistor. As a result, a voltage drop, \( V_R \), is created across the resistor. Insofar as the magnitude of \( V_R \) is concerned, the resistor should respond in much the
same fashion, regardless of whether $i_r$ is of emission origin or otherwise. This premise allows $V_R$ to be measured directly, i.e., independently of the emission process, using a micromanipulator set up for this purpose. The relation between $V_R$ and $i_r$ can be expressed by the relation,

$$\log i_r = m_t \sqrt{V_R} + C_0$$  \[4-2\]

where $C_0$ and $m_t$ are the intercept and slope of a plot of $\log i_r$ vs. $\sqrt{V}$, for a resistor film of thickness $t$. A more complete discussion of the series resistor and its conduction properties will be presented later. At this point, suffice it to say that $m_t$ is strongly thickness-dependent, i.e., $m_t \cdot \sqrt{t}$ is constant. Utilizing such dependence, a finer tailoring of the resistor's characteristics can feasibly be obtained by carefully controlling the film thickness during the deposition process. In practice, it is easier to achieve the variation of $V_R$ for experimentation by adjusting $m_t$. In the model, the thickness of the resistor film is assigned a value ranging from 0 to 4 \(\mu m\) to generate different values of $R$ for simulation of its effect on emission.

Since $V = V_E + V_R$, eqns. 4-1 and 4-2 can be combined to form a modified, or current-limited, F-N equation,

$$i_r = \frac{B\beta^2[V - (\frac{\log i_r - C_0^2}{m_t})^2]^{\alpha}}{\phi t^2(y)} \exp \left\{ \frac{-C\phi^{3/2}f(y)}{\log i_r - C_0^2} \right\} \cdot \frac{\log i_r - C_0^2}{m_t} \cdot B[V - (\frac{\log i_r - C_0^2}{m_t})^2]$$  \[4-3\]
Equation 4-3 is found to be a transcendental one, since the variables cannot be separated, and can only be solved numerically using an iterative technique with the aid of a computer. A Fortran program written for this purpose is presented in Appendix B. Basically, the computer program performs calculations of \( i_r \) with given values of \( V \) that numerically satisfy eqn. 4-3, for specific combinations of \( \beta \), \( C_0 \), and \( m_e \), by which the emitter and its series resistor are characterized.

To simulate a CLFEA cathode's operation as realistically as possible, the magnitude of \( V \) is varied from 62.5 to 250 volts, a range in which most of the experimental cathodes commonly have been operated. Since the conventional scale of plotting field emission results is \( \log i/V^2 \) vs. \( 1/V \), calculations of \( i_r \) are made at specific values of \( V \), in equally-spaced increments of \( 1/V \), so that the data points are evenly spread over the entire voltage range of interest. Fifty data points are calculated by the program and a smooth curve connecting the discretely spaced points is generated.

The field enhancement factor (\( \beta \)) of an emitter is calculated from its assumed tip radius. For the sake of simplicity the assumed tip radii are divided into eleven groups. The histograms in Fig. 4-2 are graphic representations of the four tip radius distributions used in the CLFEA model. In mathematical form, the tip radius of a particular group (\( r_n \)) can be written as \( r_n = \bar{r} + n \Delta r \), where \( \bar{r} \) is the mean value, \( \Delta r \) is an incremental value, and \( n \) is the group index, ranging from \(-5\) to \(5\). For example, assuming \( \bar{r} = 100 \, \text{A} \) and \( \Delta r = 10 \, \text{A} \), the largest and smallest values of \( r \) would be 150 and 50 A respectively.
Figure 4-2. Histogram of Emitter Tip Radius Distributions Used in Calculation of Simulated Emission, (a)$\sigma = 0.40 \bar{r}$, (b)$\sigma = 0.25 \bar{r}$, (c)$\sigma = 0.20 \bar{r}$, (d)$\sigma = 0.10 \bar{r}$. 

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Typical values of $\bar{r}$ used in the simulation are 90, 100, 110 and 120 A. The incremental value ($\Delta r$) is set at a certain proportion of $\bar{r}$, e.g., $\Delta r = 0.1 \bar{r}$. Since $r_n$'s are assumed to be normally distributed, the frequency for a particular group to occur in the whole population can be determined from standard statistical tables, provided the standard deviation ($\sigma$) of the distribution is known. Four values of $\sigma$, also expressed as fractions of $\bar{r}$, are used to imitate various distributions, ranging from narrow ($\sigma = 0.1\bar{r}$) to fairly broad ($\sigma = 0.4\bar{r}$), with two intermediate values ($\sigma = 0.2\bar{r}$ and $0.25\bar{r}$).

Accordingly, the number of emitters having the same tip radius $N(r)$ can be computed from the total number of the population and its frequency of occurrence.

Systematic Analysis of Current-Limited Emission

The simulated emission results are presented in two formats. In one format the individual emission current ($i_r$) over the spectrum of tip radii ($r$) and reciprocal applied voltage ($1/V$), using a three-dimensional perspective (Figs. 4-3 to 4-6). A supplementary computer program was employed to plot a 3-D diagram of $\log i_r$ vs. $X \cdot r \cdot 1/V$ in arbitrary units. The 3-D plots facilitate visualizing the individual emission current, in a qualitative sense, in response to changes in $r$, $1/V$, or a combination of both. The other format focuses on demonstrating the emission characteristics in the form of F-N plots (Figs. 4-8 to 4-10).

The three dimensional plots of Fig. 4-3 show emission from a single emitter that is not current-limited. The magnitude of $i_r$ increased steadily on a logarithmic scale, with decreasing $r$ and/or $1/V$. 

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Figure 4-3. Calculated Emission vs. Reciprocal Voltage and Tip Radius for a Single Emitter, (a) log $i_r$ vs. $1/V \times r$, (b) log $i_r$ vs. $1/V$, (c) log $i_r$ vs. $r$.

(Arrow Indicates Direction of Increasing Quantity.)
as expected. (The arrows on the axes of the diagrams mark the direction of increase of each quantity.) Accompanying the 3-D plot are two sideviews with the dimensions of $\log i_r$ vs. $1/V$ and $\log i_r$ vs. $r$ to illustrate the dependence of $i_r$ on $1/V$ or $r$ respectively. Plotted in two dimensions, the 3-D topography is transformed into a family of curves that present $i_r$ as a function of $1/V$ or $r$ in a systematic order. The vertical lines in the two-dimensional plots equally graduate the abscissa to show the location of data points actually calculated.

It is interesting to note that the curves plotted as $\log i_r$ vs. $1/V$ are basically the F-N plots for the individual emitters, since their slopes $\left(\frac{\partial \log i_r}{\partial 1/V}\right)$ are inversely proportional to $r$ or $1/\beta$, obeying the F-N equation. It is also evident that, at low emission levels, the value of $i_r$ differed by orders of magnitude between the most and least favorable emitters, since the scale was a logarithmic one. By and large, Fig. 4-3 clearly indicates that the majority of the emission current is produced by the pins having the smallest radius, as one might expect. A similar trend was also observed for an emitter with an appendant series resistor, shown in Fig. 4-4. The hypothetical resistor in this case was adopted to have the characteristics of the resistor film designated Si-23-3, a 3 $\mu$m film that had been thoroughly characterized (to be discussed in detail in the resistor section). As a result of the current-limiting, the overall emission level was reduced significantly.

The most important feature displayed in Fig. 4-4, however, was a pronounced leveling-off of the emission current, which signified a
Figure 4-4. Calculated Emission vs. Reciprocal Voltage and Tip Radius for a single Current-Limited Emitter, (a) log $i_r$ vs. $1/V \times r$, (b) log $i_r$ vs. $1/V$, (c) log $i_r^2$ vs. $r$.

(Arrow Indicates Direction of Increasing Quantity.)
diminishing rate of increase in $i_r$ with decreasing $r$ and $1/V$. The implication was that $i_r$ from a particular emitter might reach a saturation state should a near zero-rate of increase be approached as a result of current-limiting. In that case, a common level of $i_r$ could exist for all emitters regardless of their tip radius variation. Of course such a scenario may remain an ideal case beyond the reach of a real cathode. To a certain extent, nonetheless, this is strong evidence suggesting that, as was originally hypothesized, the emission uniformity should be improved with a current-limiting resistor. Furthermore, there seems to be a real possibility of reducing the risk of emission-induced destruction of some emitters by being able to suppress localized high emission.

As mentioned in the previous section, the emitters in an array were grouped according to their tip radius, with $N(r)$ representing the number of emitters with a common radius, $r$. The group emission current ($I_p$) is simply the product of $i_r$ and $N(r)$. The ensuing 3-D plots (Fig. 4-5 and 4-6) are presented to illustrate the distribution of $I_p$ from an array of emitters whose population could be represented by the histogram in Fig. 4-2, part (d). The reason for choosing such a distribution of tip radii for simulation here is to exaggerate the prevalence of $N(r)$, as opposed to $i_r$, since, in a narrow distribution such as this, $N(r)$ of the emitters having the medium radius is far greater than that of either the sharpest or bluntest radii.

From emitter to emitter, undoubtedly the major emission contributors would be the ones having the smallest tip radius. Among an array of emitters, however, the burden of major emission
Figure 4-5. Calculated Emission vs. Reciprocal Voltage and Tip Radius for an Array of Emitters, (a) log I_r vs. 1/V x r, (b) log I_r vs. 1/V, (c) log I_r vs. r.

(Arrow Indicates Direction of Increasing Quantity.)
Figure 4-6. Calculated Emission vs. Reciprocal Voltage and Tip Radius for an Array of Current-Limited Emitters, (a) log $I_r$ vs. $1/V \times r$, (b) log $I_r$ vs. $1/V$, (c) log $I_r$ vs. $r$. (Arrow indicates direction of increasing quantity.)
contribution could shift to emitters with less favorable geometry due to their greater number. Emission from the few blunt emitters on the high end of the tip radius distribution would not be significant due to the limited emission. It was demonstrated in Fig. 4-3 that the emission current produced by blunt emitters was usually orders of magnitude lower than that from pins with sharper tips.

The distribution of $I_r$ in Fig. 4-5 represents an array of emitters that were not current-limited. Initially, at low emission/activation levels, the major emission contribution was made by the sharpest tips, because larger radius emitters could not have reached the threshold for emission. At higher voltages, the impact of $N(r)$ on $I_r$ and its distribution becomes evident. It is demonstrated by a hump on the current plot, which represented the peaking emission level of the median emitters caused by the large $N(r)$ that prevailed. Nevertheless, the performance of the most favorable emitters appeared to remain unsurpassed in spite of smaller numbers, except at the extreme levels approaching the high limit of $1/V$. This supports the speculation that, for an emitter array which was not current-limited and was as uniform as had been assumed, the burden of emission was carried by only a few emitters throughout most of the operating range. As was mentioned earlier, a situation like this would inevitably result in localized high emission and perhaps premature failure.

In the next set of diagrams, it will be demonstrated that current-limiting can be effective in causing the median radius emitters to assume the burden of emission at moderate levels without resorting to higher voltages. Figure 4-6 demonstrates the
distribution of current-limited emission from the same emitter array as that depicted in Fig. 4-5. The resistor assigned to it was Si-23-3, which was the same one used in the calculation for Fig. 4-4. Apparently, above the midpoint of the 1/V scale, the performance of the median emitters was shown to dominate. Conceivably, this would be a desirable outcome, since it means that the burden of emission was carried by a larger number of emitters in a reasonably wide region within the set limit of 1/V.

**Simulated F-N Plots**

Computer simulated F-N plots were calculated to show the emission characteristics of a hypothetical emitter array. The simulation covers a selected range of the operating conditions in combination with tip radius, radius distribution, and levels of current limiting. Before presenting the F-N plots, differences between field emission for a single tip and an array of emitters will be considered.

According to the F-N equation, the slope of a F-N plot of a single emitter, $-2.97 \times 10^7 \frac{\phi^{3/2}}{s(y)}$, is nearly constant if $\phi$ and $\beta$ remain unchanged during the emission process. For convenience, $\phi$ will be assumed to remain constant. It is worth noting that, for a single emitter, there is a slight deviation from linearity due to the functions $y$ and $s(y)$, particularly at higher fields and/or work function. The magnitude of the deviation, however, should almost be negligible for the field range in this simulation.

For an emitter array, the F-N plot is a composite that is additive for all its constituents. The linearity of such a F-N plot will no longer be spontaneous, since $\beta$ would vary from one emitter to
another. Unless the emitter array is sufficiently uniform in terms of $r$, hence $\beta$, the F-N plot could deviate from linearity depending on how the composition of emission current is structured. It may be postulated that the slope of an apparently linear F-N plot is proportional to $\overline{\beta}$, where $\overline{\beta}$ is weighted average of the field enhancement factors for the preferred emitters which contribute most of the emission current. It is assumed that $\overline{\beta}$ remains constant throughout the operating range. For F-N plots with a changing slope, one possible cause will be derived to assist interpreting the theoretical and experimental emission results.

Using a simplified, two-component emitter array, the slope of a composite F-N plot has been modeled. Let it be assumed there is an emitter array consisting of only two groups of emitters in terms of tip radius, $r_1$ and $r_2$; and respectively the number of emitters in each group is $N_1$ and $N_2$. Thus the field enhancement factor for each group is $\beta_1$ and $\beta_2$ (where $\beta_1 = \frac{1}{r_1}$, $\beta_2 = \frac{1}{r_2}$); the individual emission current is $i_1$ and $i_2$; and the total emission current for each group is $I_1$ and $I_2$ ($I_1 = i_1 \times N_1$, $I_2 = i_2 \times N_2$); and the current density is $J_1$ and $J_2$.

If the actual values of the above are known, then an individual F-N plot can be made for each group of emitters, Fig. 4-7.

Obviously, the individual plots should be linear, only to be raised to a higher level by an amount of $\log N_1$ or $\log N_2$, with the slope, $m_1$ and $m_2$, corresponding to $1/\beta_1$ and $1/\beta_2$. Given that $r_1 < r_2$, the field emission law mandates that $\beta_1 > \beta_2$, $i_1 > i_2$, and $m_1 < m_2$.

Considering a likely case, that $i_1 > i_2$ and $N_1 >> N_2$, the following deductions should hold true for the entire range of $V$; $I_1$
Figure 4-7. Fowler-Nordheim Plots for a Simplified Two-Radius Array,
(a) $I_1 > I_2$, (b) $I_1 > I_2$ in Region $1/V > 1/V_o$, $I_1 < I_2$ in
Region $1/V < 1/V_o$.  

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$> I_2, I \sim I_1$ and $J \sim J_1$ where $I$ is the total emission current and $J$ is the composite array current density of the model emitter array. The composite F-N plot is an algebraic sum of the two individual plots. In the logarithmic F-N plot, $\log \frac{J}{V^2}$ may nearly coincide with $\log \frac{1}{V^2}$, and should remain relatively linear with a slope approximated by $m_1 (m \sim m_1)$ as shown in Fig. 4-7(a), since $J \sim J_1$.

The reciprocal case, in which $N_1 \ll N_2$, is more complicated. The scenarios would be different at different levels of $V$ as the balance between $I_1$ and $I_2$ varies. It is possible that there exists a voltage, $V_0$, where $I_1 = I_2$, below which $(V < V_0) I_1 > I_2$, and above which $(V > V_0) I_1 < I_2$. Such a situation is illustrated in Fig. 4-7(b). As a result of the escalation of $\frac{J_2}{V^2}$, due to the multiplicity of $N_2$, which is deliberately emphasized in the figure, the two individual plots converge at $V_0$ where $I_1 = I_2$. Again a composite plot can be made by adding the two individual plots graphically. The slope at or near the cross-over region can no longer be approximated by $m_1$ or $m_2$ without incurring a significant error, because $m$ would be a complex function of $m_1$, $m_2$ and $V$. The composite slope $m$, should increase with $V$ subject to the boundary condition that $m_1 < m < m_2$. For the extreme cases that $I_1 \gg I_2$ when $i_2 \sim 0$, and $I_1 \ll I_2$ due to prevalence of $N_2 (N_1 \ll N_2)$, $m$ may thus be approximated by $m_1$ at low currents ($m_1 < m$) and $m_2$ at high currents ($m < m_2$).

The physical significance of the change in $m$ described above would be indicative of, but not limited to, the transition of the major emission contributors to the large radius group $r_2$ from the small-radius group $r_1$ with increasing field. Unfortunately, other
real world possibilities exist for similar changes in m, such as a spontaneous increase in emitting sites due to gas adsorption or desorption and/or space charge effects, etc., which are beyond the scope of this study. The situation for a real cathode will be much more complicated than the two-radius model explored above, since there exists an entire spectrum of r and N(r). Nevertheless, the same argument should remain applicable for qualitative analysis of the F-N plots.

After showing the effect of pins of two different tip radii, emission I-V characteristics for the normalized tip radius distributions shown in Fig. 4-2 were calculated. The size of the active area and the emitter density were assumed to be 120 μm in diameter and 5 x 10⁶/cm² respectively, giving 565 as the number of emitters in the array. Based on previous experimental data, the work function was assumed to be a constant one of 8 eV for the oxygenated tungsten surface of the emitters and a microscopic emitting area of 85 Å². The mean tip radius (r) and the standard deviation of the distribution (σ), were alternately varied to provide various combinations of the operating conditions to be tested. These parameters are denoted alongside each figure. In order for the plots to be readily compared, the scales were kept the same for all the plots.

Due to the inherent complexity of the F-N plot that results from incorporating the effects of tip radius distribution and current-limiting, the discussion of the simulated F-N plots will be made by comparison of respective F-N plots graphically. In Fig. 4-8, it was shown that, without being current-limited, the F-N slope remained
Figure 4-8. Theoretical Fowler-Nordheim Plots for an Emitter Array of Various Standard Deviations of Tip Radius Distributions at (a) $\bar{r}=90\text{Å}$, (b) $\bar{r}=100\text{Å}$, (c) $\bar{r}=110\text{Å}$, (d) $\bar{r}=120\text{Å}$.

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relatively constant, especially for those arrays having wider distributions of tip radius ($\delta = .25 \bar{r}$ and $\delta = .40 \bar{r}$). Conceivably, this was the result of emission current from one particular group of emitters being predominant throughout the voltage range.

Referring to the histograms in Fig. 4-2, one could find the number of emitters at both ends of the tip radius spectrum was greater in a broad distribution, if the number of emitters was the same. For effects on emission current, those least favorable emitters at the large end of the distribution could be neglected and the sharpest, small tip radius group would be emphasized. As expected, the overall emission performance of an array with a broad distribution was much greater for a larger number of emitters in the most favorable category, cf. $\sigma = .40 \bar{r}$ to $\sigma = .10 \bar{r}$.

For the array with $\sigma = .10 \bar{r}$, there was a slight up-turning curvature at high levels of emission. This represented the transition of the bulk of the emission current from the most favorable pins to a larger group of emitters having a slightly larger $r$ (smaller $\beta$). In other words, the more populous emitters are gradually providing more emission, but only at the significantly higher levels of activation.

To show the effect of adding a series resistor to a FEA, F-N simulation plots, Figs. 4-9 and 4-10, were calculated for the I-V characteristics of the resistor film designated Si-23. All other parameters were the same as for Fig 4-8. In Fig. 4-9, the effect of current-limiting with successively higher resistance (by means of varying the resistor film thickness) are presented. There was obviously a substantial reduction in the array current density as a
Figure 4-9. Theoretical Fowler-Nordheim Plots for a Current-Limited Emitter Array with a 100Å Mean Tip Radius with Various Resistor Film Thicknesses at (a) $\varrho = 10\varrho$, (b) $\varrho = 20\varrho$, (c) $\varrho = 25\varrho$, (d) $\varrho = 40\varrho$. 

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result of current-limiting. The greatest incremental reduction occurred for the cathode being limited by a resistor with \( t = 1 \ \mu m \).

At 125 volts \((10^3/V = 8.0)\), the emission reduction was approximately one order of magnitude for the first \( 1 \ \mu m \) of resistor film, increasing as \( t \) and \( V \) became larger with increasing \( \sigma \). Again, the same interpretation is offered for the up-turning curvature of the F-N plots. In this case, the curves turned upward at moderate levels of emission, which is an expected result of current-limiting.

Figure 4-10 demonstrates the effects of current limiting with a resistor at \( t = 3 \ \mu m \), but for various distributions in the array. It is interesting to note that all of the F-N plots tend to converge at a common point, meaning, perhaps, that the emission has become dominated by the I-V characteristics of the series resistor. A high enough resistance, capable of absorbing further increases in emission would eliminate the difference in emission from pin to pin. However, this would limit the emission to a level about two orders of magnitude lower than that expected from a non-current-limited array. Other than the unacceptable loss of current, operation in a "saturation" mode could be beneficial in terms of emission uniformity. On the other hand, from a practical standpoint, this is probably too great an emission loss to allow useful operation.

**Silicon Current-Limiting Resistors**

In this section, the results of the experiments performed to characterize the current-limiting resistor films are discussed. First the DC current-voltage (I-V) characteristics of the resistor films
Figure 4-10. Theoretical Fowler-Nordheim Plots for a Current-Limited Emitter Array with a 3µm Resistor Film and Various Tip Radius Distributions at (a) $\bar{r}=90\AA$, (b) $\bar{r}=100\AA$, (c) $\bar{r}=110\AA$, (d) $\bar{r}=120\AA$. 

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made of silicon are presented and described, followed by a brief analysis of the conduction mechanism. The effects of deposition conditions on the electric properties such as the resistance (R) and its field-dependence \( \frac{dR}{dV} \) are also discussed.

**I-V Characteristics of Silicon Resistors**

Characterization of the resistor films was carried out with a micromanipulator attached to a Scanning Electron Microscope (SEM) so that the measurement was made for that portion of the resistor film in direct contact with a probed tungsten fiber. A schematic representation of the measurement arrangement is shown in Fig. 4-11. The set of I-V data is that of a single series resistor, whose effective cross section was similar to the fiber cross sections with diameter (d). Since a direct calculation of the resistance (R) was made with the I-V data, no further determination of the precise dimension of the series resistor was necessary.

Current-voltage relations for nine silicon thin films are shown in Figures 4-12, part (a) through (g), which were designated Si-12 to Si-23, respectively. Using the "Si" prefix, each resistor sample was numbered in the order of the respective deposition run performed, followed by a second number denoting the film thickness in units of micrometers (\( \mu m \)). The I-V characteristics in Fig. 4-12 were presented as \( \log I \) vs. \( V^{1/2} \) to demonstrate the linear dependence of \( \log I \) on \( V^{1/2} \) common to all resistor films. Although the linear region varied from one film to another in both location and extent, it was observed to be preceded and followed by a similar deviation from linearity for all films. Due to the similarity of the curves, the I-V
Figure 4-11. Schematic Diagram Illustrating the Fringing Volume in Resistor Film as a Resistor in Series with a Probed Tungsten Fiber.

d: fiber diameter
D: fiber-fiber separation
t: resistor film thickness
θ: angle of fringing
characteristics will be discussed using Si-13-1.5, Fig. 4-12, part (b), as an example, since it was typical.

Three distinct conduction regions were observed. Region I was usually in a field domain of less than $10^5 \, \text{V/cm}$, i.e., $< 15 \, \text{volts}$ across a 1.5 $\mu\text{m}$ thick film. In this region, current increased rapidly with the applied voltage and the slope ($m_1$) was virtually independent of film thickness. Since the absolute voltage bias was low, the true condition mechanism was likely concealed by a contact resistance at a number of junctions, e.g., probe-to-tungsten fiber, fiber-to-silicon film, and silicon film-to-molybdenum counter electrode. As the contact resistance diminished rapidly with increasing voltage, Region II was observed to span the field domain from $10^5$ to $5 \times 10^5 \, \text{V/cm}$, in which the plot was practically linear. Current in this region was more stable than in either region I or III, and was observed to be thickness-dependent, implying a predictable bulk conduction behavior. The plot could be retraced exactly, regardless of the polarity of the testing arrangement, so that polarity effects of the metal-semiconductor (Mo-Si) junction were negligible. Resistance was calculated to range from $10^8$ to $10^9 \, \text{ohms}$ for each resistor with a 3 $\mu\text{m}$ thickness at 50 volts. This value range was compatible with FEA current-limiting requirements. The resistance ($R$) and its field dependence ($\frac{dR}{dV}$) in Region II will be discussed later. Region III normally began at $\sim 5 \times 10^5 \, \text{V/cm}$, where the trace deviated from linearity with increased voltage. It was termed the breakway region since current tended to rise at an accelerated pace, leading to a breakdown of the resistor. Once breakdown occurred, the resistance decreased many orders of
Figure 4-12. Plots of log I vs. $V^{1/2}$ for Silicon Thin Film Resistors, (a) Si-12-1.5.
Figure 4-12. Cont'd., (b) Si-13-1.5.

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Figure 4-12. Cont'd., (c) Si-14-1, Si-14-2, Si-14-3.
Figure 4-12. Cont'd., (d) Si-15-1, Si-15-2, Si-15-3.
Figure 4-12. Cont'd., (e) Si-16-1, Si-16-2, Si-16-3.
Figure 4-12. Cont'd., (f) Si-17-1, Si-17-2, Si-17-3.
Figure 4-12. Cont'd., (g) Si-20-3, Si-21-3, Si-22-3, si-23-3.
magnitude. However, the breakdown was not usually complete, since a residual resistance of $10^3$-$10^6$ ohms was typical.

For most of the resistor films characterized, the breakdown voltage ($V_B$) correlated well with the film thickness ($t$), Fig. 4-13. Breakdown occurred at a constant field of $5.5 \pm 1.0 \times 10^5$ V/cm. The breakdown field could certainly be regarded as the "apparent" dielectric strength of the silicon films. It was probably not pure dielectric failure, since the breakdown process could have been complicated by the thermal avalanche of charge carriers as a result of Joule heating. This was supported by the observation that, preceding breakdown, current would slowly creep up independently of the applied voltage on many occasions. Presumably, such an effect could at least promote the breakdown process. Consequently, the true dielectric strength would be somewhat higher than $5.5 \times 10^5$ V/cm. It is possible that by cooling the resistor, or by using a good heat sink, the breakdown-limited operating range would be extended to higher voltage.

**High Field Conduction Mechanisms**

For high field conduction in Region II, i.e., at fields exceeding $10^5$ V/cm, the linear dependence of log $I$ vs $V^{1/2}$ is indicative of a Poole-Frenkel (P-F) or Schottky type of conduction mechanism. Because the conductivity in Region II exhibited a bulk-like behavior by being thickness dependent, the conduction mechanism was most likely a P-F process (bulk-limited) rather than a Schottky process (electrode-limited). To separate the two conduction mechanisms requires measuring the temperature dependence, which was beyond the scope of this investigation. For practical purposes, the assumption of a
Figure 4-13. Resistor Breakdown Voltage vs. Film Thickness, Indicating a Constant Breakdown Field.
dominating P-F mechanism was adequate for analysis.

For an ideal, trap-free material in the bulk form, the P-F equation is given by

$$I = I_0 \exp\left[\frac{\beta_{PF}}{2kT} F^{1/2}\right]$$  \[4-4\]

where

$$\beta_{PF} = \frac{e^3}{\pi \varepsilon_0 K^*}$$

$I_0$ is the low-field current,

$\beta_{PF}$ is the P-F coefficient,

$F$ is the applied field,

$\varepsilon_0$ is the free space permittivity,

$K^*$ is the high frequency dielectric constant of the material,

and $k$ is the Boltzmann constant.

The P-F equation can be modified for materials in the form of thin films to become

$$I = I_0 \exp\left[\frac{\beta_{PF}}{kT} \left(\frac{V_R}{t}\right)^{1/2}\right]$$  \[4-5\]

where

$V_R$ is the applied voltage,

and $t$ is the film thickness.

Note that in this case the coefficient of the exponential term is twice as great, since shallow traps in thin films would increase the escape probability of the immobilized electrons as suggested by Mead.\(^1\) A plot of the equation 4-5 on the log $I$ vs. $V^{1/2}$ scale will
be a linear one with its slope \( m_t \) being equal to \[ \frac{B_{PF}}{2,303 KT t^{1/2}} \]
(hereinafter referred to as the P-F plot).

Figure 4-14 is a plot of \( m_t \cdot \sqrt{E} \) calculated from the experimental P-F plots in Fig. 4-12 as a function of silicon film thickness. Broken lines were used to connect data points of samples fabricated in the same deposition run but with varying values of \( t \). The theoretical value of \( m_t \cdot \sqrt{E} \) for Si was calculated (using a dielectric constant of 11.56) to be \( 0.0038 \) \((V/cm)^{-1/2}\), which is represented as a solid, horizontal line. The dielectric constant was obtained from the refractive index of silicon \((n_{Si} = 3.4)\) according to the relation that \( K^* = n_{Si}^2 \). Each data point represented the average of at least five measurements.

It is obvious that most of the experimental values are higher than the theoretical one, ranging from 0.0024 to 0.010 \((V/cm)^{-1/2}\) for the 1.0-\(\mu m\) films, from 0.0037 to 0.7 \((V/cm)^{-1/2}\) for the 2.0 \(\mu m\) films, and from 0.0038 to 0.005 \((V/cm)^{-1/2}\) for the 3.0 \(\mu m\) films. For samples with varying \( t \), with the exception of Si-16 and Si-17, the fairly constant values of \( m_t \cdot \sqrt{E} \) were a good demonstration of the thickness dependence expected of bulk type conduction behavior. For Si-16, Si-17, and other data points with higher than expected \( m_t \cdot \sqrt{E} \) values, the trend of convergence to the theoretical value at \( \sim 3-4 \mu m \) was probably the result of improvement in film quality as \( t \) increased. Due to a higher ratio of volume to surface area for thicker films, the conduction process was believed to be less influenced by the defect-prone surface. Therefore the conduction process would become more directly controlled by the content of the thin film itself, which was
depositions made with only one film thickness

Figure 4-14. Comparison of Normalized Poole-Frenkel Slopes \( (m_t \cdot t^{1/2}) \) of Silicon Thin Film Resistors, Showing a Converging Trend Toward Theoretical Value as Film Thickness Increases.
manifested as $m_t \cdot \sqrt{E}$ gradually approached the theoretical value. Consequently, it is plausible that the data from the thicker films provided more reliable information to be used in assessing the genuine electric properties of the bulk resistor films. Using an average value of $m_t \cdot \sqrt{E}$ for 3-μm films, 0.0048 (V/cm)$^{-1/2}$, a dielectric constant of 6.9 was calculated. This was only 40% smaller than the dielectric constant of silicon in bulk form. Such a discrepancy could be attributed to the fact that the density of evaporated thin films is often less than the theoretical density. The good correlation between the experimental results and the actual value of the P-F coefficient is additional justification for assuming a Poole-Frenkel high-field conduction process.

**Effects of Deposition Conditions**

For incorporation of the resistor film into a FEA, it is necessary to address the effects of desorption conditions on the electric properties of resistance ($R$) and resistance field dependence. Due to the nature of the conduction mechanism, the resistance is subject to a strong field-dependence, which reduces resistance with increasing applied voltage at a rate determined by factors such as $m_t$ and $C_0$. Table 4-1 summarizes the parameters in the deposition process and the measurements of $m_t$ and $C_0$ made from the P-F plots presented in Fig. 4-12.

Some empirical formulae for $R$ and $\frac{dR}{dV}$ in terms of $m_t$ and $C_0$ were delimited through the following mathematical manipulations. First, the I-V relation of a resistor operating in the stable, linear region of the P-F plots can be expressed by
<table>
<thead>
<tr>
<th>Silicon Source Material (dopant/n-cm)</th>
<th>S1-12</th>
<th>S1-13</th>
<th>S1-14</th>
<th>S1-15</th>
<th>S1-16</th>
<th>S1-17</th>
<th>S1-20</th>
<th>S1-21</th>
<th>S1-22</th>
<th>S1-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Substrate Temperature (°C)</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>550</td>
<td>543</td>
<td>561</td>
<td>545</td>
</tr>
<tr>
<td>Pressure During Deposition (10^-5 torr)</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>5</td>
<td>15</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Deposition rate (Å/sec)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>1st thickness (µm)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>4.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>( m^* )</td>
<td>(.600)</td>
<td>(.450)</td>
<td>(.490)</td>
<td>(.340)</td>
<td>(.990)</td>
<td>(.900)</td>
<td>(.200)</td>
<td>(.400)</td>
<td>(.310)</td>
<td>(.250)</td>
</tr>
<tr>
<td>( C_o^* )</td>
<td>(-10.6)</td>
<td>(-10.3)</td>
<td>(-11.0)</td>
<td>(-9.5)</td>
<td>(-9.5)</td>
<td>(-14.0)</td>
<td>(-8.3)</td>
<td>(-10.2)</td>
<td>(-9.60)</td>
<td>(-8.4)</td>
</tr>
<tr>
<td>2nd thickness (µm)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>( m )</td>
<td>(.300)</td>
<td>(.270)</td>
<td>(.500)</td>
<td>(.400)</td>
<td>(.245)</td>
<td>(.230)</td>
<td>(.285)</td>
<td>(.270)</td>
<td>(.735)</td>
<td>(.750)</td>
</tr>
<tr>
<td>( C_o )</td>
<td>(-10.0)</td>
<td>(-9.6)</td>
<td>(-9.7)</td>
<td>(-9.7)</td>
<td>(-9.7)</td>
<td>(-9.7)</td>
<td>(-9.7)</td>
<td>(-9.7)</td>
<td>(-9.7)</td>
<td>(-9.7)</td>
</tr>
<tr>
<td>3rd thickness (µm)</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>( m )</td>
<td>(.245)</td>
<td>(.230)</td>
<td>(.285)</td>
<td>(.270)</td>
<td>(.245)</td>
<td>(.230)</td>
<td>(.285)</td>
<td>(.270)</td>
<td>(.245)</td>
<td>(.230)</td>
</tr>
<tr>
<td>( C_o )</td>
<td>(-9.7)</td>
<td>(-9.5)</td>
<td>(-10.0)</td>
<td>(-9.9)</td>
<td>(-9.7)</td>
<td>(-9.5)</td>
<td>(-10.0)</td>
<td>(-9.9)</td>
<td>(-9.7)</td>
<td>(-9.5)</td>
</tr>
<tr>
<td>CLFEA Fabricated</td>
<td>TE5</td>
<td>TE6</td>
<td>TE7</td>
<td>TE7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>TE8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TE9</td>
</tr>
</tbody>
</table>

\( m^* \) and \( C_o \) are slope and intercept of Log I vs. \( V^{1/2} \) plot.
\[ V = \left( -\frac{C_0}{m_t} \right)^2 \]  \hspace{1cm} [4-6]

where \( m_t \) is the linear slope and \( C_0 \) is the extrapolated intercept at zero bias. Equation 4-6 has been referred to as Eqn. 4-2 earlier, which was virtually the same except the variables were rearranged.

Applying Ohm's Law \((I = \frac{V}{R})\), the expression for \( R \) will be

\[ R = \frac{V}{m_t \sqrt{V} + C_0} \]  \hspace{1cm} [4-7]

By differentiating \( R \) with respect to \( V \), one obtains the field dependence of \( R \) on \( V \) as

\[ \frac{dR}{dV} = \frac{1 - \frac{2}{2} \frac{m_t}{m_t \sqrt{V} + C_0}}{m_t \sqrt{V} + C_0} \]  \hspace{1cm} [4-8]

The functions in Eqns. 4-7 and 4-8 were plotted in Fig. 4-15, using a typical value of \( m_t \) and \( C_0 \) of .250 and -9 respectively. The plot of \( R \) indicated that it would decrease with increasing \( V \), due to an exponential dependence of the denominator on \( \sqrt{V} \) which outweighed the increase in \( V \), the numerator. At the same time, the plot of Eqn. 4-7 showes that the magnitude of \( \frac{dR}{dV} \), i.e., the rate of change in \( R \), declines with increasing \( V \). However, the rate rate of decrease percentage-wise, i.e., \((\frac{dR}{dV})/R \times 100\%\), was fairly constant, at about -2\% per volt.
Figure 4-15. Plots of $R$ and $\frac{dR}{dV}$ of a Typical Silicon Thin Film Resistor as a Function of Voltage.
Table 4.2 Selected Data of the Thin Film Resistors

<table>
<thead>
<tr>
<th>Si-14</th>
<th>Si-15</th>
<th>Si-16</th>
<th>Si-17</th>
<th>Si-21</th>
<th>Si-22</th>
<th>Si-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(2)$ (50 volts)</td>
<td>4.6</td>
<td>3.7</td>
<td>4.8</td>
<td>4.9</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>$R(2)$ (100 volts)</td>
<td>1.8</td>
<td>1.6</td>
<td>2.1</td>
<td>1.6</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>$R(2)$ (150 volts)</td>
<td>0.8</td>
<td>0.7</td>
<td>0.5</td>
<td>0.6</td>
<td>0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>$\frac{dR}{dV_R}$ (50 volts)</td>
<td>-9.1</td>
<td>-6.5</td>
<td>-12.6</td>
<td>-11.7</td>
<td>-8.1</td>
<td>-4.0</td>
</tr>
<tr>
<td>$\frac{dR}{dV_R}$ (100 volts)</td>
<td>-3.2</td>
<td>-2.6</td>
<td>-3.2</td>
<td>-3.3</td>
<td>-0.6</td>
<td>-0.8</td>
</tr>
<tr>
<td>$\frac{dR}{dV_R}$ (150 volts)</td>
<td>-1.2</td>
<td>-1.1</td>
<td>-1.0</td>
<td>-1.1</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Temp (°C)</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>543</td>
<td>561</td>
</tr>
<tr>
<td>Dopant</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>P</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Deposition Rate (Å/sec)</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Pressure (10$^{-6}$ torr)</td>
<td>8</td>
<td>5</td>
<td>15</td>
<td>8</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

Notes: (1). All data are of 3-μm thick samples.

(2). The unit of $R$ is 10$^9$ Ω.

(3). The unit of $\frac{dR}{dV_R}$ is 10$^7$ Ω/V.
For a selection of the actual resistor films, a list of $R$ and $\frac{dR}{dV}$ calculated for $V$ equal to 50, 100, and 150 volts was tabulated (Table 4-2). The specific values of $V$ were chosen to roughly coincide with the onset, the mid-point, and the end point of Region II on the voltage spectrum so that the selected representations would be adequately comprehensive. Also the data were exclusively of samples with a thickness of 3 μm for reasons disclosed earlier.

Among all the deposition parameters, only temperature had a positive correlation with both $R$ and $\frac{dR}{dV}$. For Depositions Si-14 through Si-17, the temperature was controlled at 475°C, subject to a thermal fluctuation of less than 10°C. This was approximately 75°C lower than that for Deposition Si-21 through Si-23, which were deposited at ~ 550°C on the average. The higher temperature version was more conductive than the low temperature counterpart by a factor of as much as 20 in the extreme case. Depositions Si-21 through Si-23 had values of $\frac{dR}{dV}$ significantly lower than those of Deposition Si-14 through Si-17. However, on a percentage basis, all runs exhibited a $dR/dV$ change of ~ 2% per volt.

Upon closer comparison, there was a slight, but consistent difference separating the two groups of depositions. For the high temperature depositions, a negative resistance coefficient with respect to field of > 2% per volt was always obtained, in contrast to a rate < 2% per volt for the low temperature runs. Hence it is reasonable to conclude that the higher temperature (~ 550°C) resulted in resistor films that were more conductive and slightly more field-dependent. The quantity and type of dopant (B or P) in the silicon
source appeared to have no effect on the properties of the evaporated resistor films. This was attributable to the fact that the conditions of evaporation were suitable for a certain degree of distillation to occur.

Since the evaporation rate of a material is largely determined by its vapor pressure at temperature, a large difference in vapor pressure between any two constituents results in a proportional evaporation rate difference. For example, the vapor pressure of Si at 1600°C is orders of magnitudes lower than that of boron and higher than that of phosphorous. At the silicon evaporation temperature, 1500-1700°C, the minute amount of phosphorous (with its high vapor pressure) would be driven off completely at temperatures lower than that at which Si evaporates so that the evaporated material was pure Si. The same result would occur for the born-doped source, though in opposite sequence, since born would remain entirely in the molten pool of bulk evaporant while Si was being evaporated, due to the low born vapor pressure.

Emission Testing of CLFEA Cathodes

In this section the emission results of the Current Limited Field Emitter Array cathodes (CLFEA) are presented and discussed. For the cathodes tested, their experimental F-N plots are shown in Fig. 4-16 through Fig. 4-23 and operating parameters of those cathodes are summarized in Table 4-3. Current-limited emission effects were observed for two F-N curves, Figure 4-16. These cathodes, designated TE5-1 and TE5-2, were fabricated with a 1.5 μm-thick resistor film.
Table 4.3 Pre-Emission Characterization of Selected CLFEA Cathodes

<table>
<thead>
<tr>
<th></th>
<th>TE5-1</th>
<th>TE5-3</th>
<th>TE6-1</th>
<th>TE9-2</th>
<th>TE9-3</th>
<th>TE9-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Area (µm)</td>
<td>220</td>
<td>182</td>
<td>345</td>
<td>190(1)</td>
<td>33(1)</td>
<td>60(1)</td>
</tr>
<tr>
<td>Continuous Emitters</td>
<td>1900</td>
<td>1300</td>
<td>4670</td>
<td>1420</td>
<td>42</td>
<td>142</td>
</tr>
<tr>
<td>Emitter Height (µm)</td>
<td>2.2</td>
<td>2.3</td>
<td>2.0</td>
<td>2.2</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Emitter Shape(2)</td>
<td>CY</td>
<td>Pointed</td>
<td>CY+HS</td>
<td>HS</td>
<td>IRR+CY</td>
<td>CY+HS</td>
</tr>
<tr>
<td>Substrate Annealing</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Insulator Al₂O₃ (µm)</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Extractor Mo, (µm)</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Extractor Hole Dia. (µm)</td>
<td>2.0</td>
<td>1.75</td>
<td>2.2</td>
<td>2.3</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Resistor Film Si-12</td>
<td>--</td>
<td>--</td>
<td>56</td>
<td>--</td>
<td>66</td>
<td>--</td>
</tr>
<tr>
<td>Initial Capacitance (pF)(3)</td>
<td>--</td>
<td>28.0</td>
<td>2.5</td>
<td>0.007</td>
<td>0.08</td>
<td>--</td>
</tr>
<tr>
<td>Initial Impedance (10^9 Ω) at 10 V(3)</td>
<td>--</td>
<td>0.6 µA</td>
<td>0.4 µA</td>
<td>4 µA</td>
<td>4 µA</td>
<td>--</td>
</tr>
<tr>
<td>Breakdown Threshold</td>
<td>0.6 µA</td>
<td>0.6 µA</td>
<td>0.4 µA</td>
<td>4 µA</td>
<td>4 µA</td>
<td>--</td>
</tr>
</tbody>
</table>

(1) Equivalent size of active area converted from the number of continuous fibers
(2) CY: Cylindrical, HS: hemispherical, IRR: irregular
(3) Readings used for determining whether a proper electrical connection of sample test vehicle is made.

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Figure 4-16. Fowler-Nordheim Plots for Cathodes TE5-1 and TE5-2.
Based on studies of the emitter model, the characteristic feature displayed by the F-N plots for both cathodes was a distinct up-turning curvature which was attributed to the effect of the current-limiting resistor. I-V measurement of the resistor film indicated a resistance at 10 and 50 volts of $1.25 \times 10^9$ and $3.33 \times 10^8$ ohm respectively, with a breakdown threshold of $\sim 0.6 \ \mu A$ at a maximum voltage drop of 64 volts. Failure of the emitters was not prevented, even though the total voltage applied to TE5-1 and TE5-2 was only 118 and 135 volts. The current (or voltage) capability of the resistor did not appear to be sufficient for the intended purpose of making the cathode more reliable. However, there was some indication that the performance of the cathodes might have been improved, judged on the basis of the failure mechanism observed.

Throughout the development program of field emitter array cathodes, failures of emitters were frequently observed. These failures have been classified in three broad categories:

a) Type I: emission-related failures in which a single pin was destroyed, having no appreciable effect on the overall emission current;

b) Type II: emission-related failures in which a group of 2-10 pins were destroyed, frequently causing a measurable loss in emission current;

c) Type III: large-scale failures in which the tungsten pins, extractor film, and matrix were often fused together, resulting in a complete short circuit of the cathode.

Post-emission examination of TE5-1 and TE5-2 in the SEM indicated
Figure 4-17. Example of a Typical Individual Emitter Failure, (a) before Emission Test, (b) after Emission Test. (Deformation of Several Emitters Can be Observed.)
that the failures were exclusively of Type I, i.e., only one emitter was destroyed in a particular failure without direct involvement of its neighbors (Fig. 4-17). This mode of failure is presumably less energetic compared to the larger-scale failures of Type II and III. This was attributed to the effect of the current-limiting resistors, which limited the amount of current dissipated at the site of failure. Even in the case when resistor breakdown was involved, the residual resistance (up to $10^6$ ohm) would prevent a dead short situation. Consequently, the chance of an individual failure escalating into a larger-scale failure would be reduced, and each failure would be isolated, as was observed in this case. Assuming failure of the emitter resulted from excessive current, breakdown of the resistor should have occurred prior to emitter failure because the current capabilities of the resistor (0.6 μA for Si-12-1.5) was less than that of the tungsten emitter. Therefore, the failure could have been a serial event starting with breakdown of the resistor (which removed the resistor current-limitation), followed by a destructive outburst of emission which caused the emitter to fail.

This suggests that failure of the emitter would always be preceded by breakdown of the resistor. However, the converse of the above statement is not necessarily true. For example, in the case of TE5-3, to be discussed soon, the failure of the resistor did not lead to any observable damage to the emitter.

A more complete set of the emission data for cathode TE5-3, also fabricated with Si-12-1.5, is presented in Fig. 4-18. For the curves marked TE5-3-1 through TE5-3-4, there is a gradual shift in their
Figure 4-18. Fowler-Nordheim Plots for Cathode TE5-3.
position from right to left, particularly at the lower voltages. The characteristic upturning curvature is also evident, indicative of the current-limiting effect. From TE5-3-6 through TE5-3-9, there was first an abrupt change in both the shape and position of the F-N plots, and then a gradual shift to lower voltages or higher currents. As is evident, the last three curves became noticeably straighter after a sudden increase in emission current during the course of the tests.

The data for curves TE5-3-1 to TE5-3-4, in which the gradual decline in emission occurred, was taken over a time span of 48 hours. It is likely that rounding or dulling of favorable emitters, presumably the sharpest ones, was responsible for the reduced current. Visual evidence for rounding of the emitter tips was obtained indirect from post-examination of TE5-1, which was subject to current-limiting by the same resistor film (Fig. 4-19). This process was perhaps slowed as a result of current-limiting, so that the change became noticeable. Whereas in previous emission testing of non-current-limited cathodes, the process might have taken place too rapidly at the initial stage of activation to be observed. The same effect was exhibited by cathodes TE9-2 and TE9-3 (Fig. 4-21 and 22), both of which were current-limited with a resistor film designated Si-23-3. The emission data of TE9-8, a cathode of similar emitter geometry to TE9-2 and TE9-3 but not current-limited (Fig. 4-23), provided further support for the conclusion that the current-limiting resistor allowed the emitters to be rounded at a much slower rate. Without current limiting, TE9-8 did not exhibit the slow current decrease observed for
Figure 4-19. Example of a Rounded Emitter Tip after Emission Test.
TE5-1, TE5-3, TE9-2, TE9-3, etc. The gradual rounding of the emitters
could be regarded as a "conditioning" effect, so that an otherwise
catastrophic change could be avoided. As a result of this
conditioning, the tip radius distribution, and hence the distribution
of emission current, might become more uniform as the sharper emitters
became rounded. The degree of rounding remains unknown, since that
determination would have required the almost impossible task of
measuring the tip radius of individual emitters before and after
emission testing.

Approximately 68 hrs into the testing, the sample was operating
at 140 µA of emission (~ 0.5 A/cm²) and 165 volts when an abrupt event
was recorded. The interruption involved a spontaneous increase in
emission current while the net applied voltage actually decreased.
The new reading was 165 µA at 140 volts, an increase of 18 percent in
the emission current, accompanied by a decrease of 15 percent in the
applied voltage. The sudden voltage reduction was clearly due to an
external 1.0 MΩ series resistor, which was used to protect the emission
circuitry in the event of a dead short. Comparing the emission
current at the same voltage level, the increase was actually 450
percent, based on the previous value of 30 µA at 140 volts. This
magnitude of increase in the emission could not be explained as simply
a spontaneous increase in the number of emitters or emission sites
that suddenly became active. If that were the case, then curve TE5-3-
6, taken right after the increase, should have remained subject to
current limiting and should in turn display the characteristic
upturning curvature.
One likely scenario would be shorting or breakdown of the current-limiting resistor under a large number of emitters, relieving them from being current-limited. This would not only explain the increase in emission (since there was no more voltage drop across the resistor and the total voltage was applied to the emitter), but also why the F-N plot became straighter. This is therefore an example of the case in which the current exceeded the breakdown threshold of the resistor but was still within the current-carrying capacity of the emitter, so that only the resistor failed. This unique situation allowed the emission characteristics both with and without current-limiting, represented by TE5-3-1 and TE5-3-9 respectively, to be compared based on identical emitter geometry of the same cathode. The fact that the experimental results were almost identical to those calculated theoretically (shown in Fig. 4-9) was unquestionably helpful for the case to be concluded as discussed.

Once the cause of the spontaneous increase in emission had been determined, it was easy to explain the increasing linearity associated with higher emission (~ 0.9 A/cm²), displayed by curves TE5-3-6 through TE5-3-9. This appeared to be caused by recurrence of the above incident but on a much smaller scale, in which a few remaining resistors continued to fail as testing progressed.

The breakdown of resistor film of TE5-3 was not an isolated case, as a similar event was later observed for TE6-1, Figure 4-20. This cathode was fabricated with Si-13-1.5, having an even lower breakdown threshold of 0.4 µA (although its resistance was higher than that of Si-12-1.5). The evidence of dulling of the emitter tips was present.
Figure 4-20. Fowler-Nordheim Plots for Cathode TE6-1.
in the F-N plots, as was the upturning curvature to be expected with current-limiting. Soon after the data for the curve TE6-1-2 were taken, emission current was observed to increase from 100 \( \mu \text{A} \) to 270 \( \mu \text{A} \). The cathode was left to operate at overnight but, unfortunately, short circuited before a set of I-V data could be obtained for analysis. When the setting on the power supply was switched, the cathode suddenly resumed operation, enabling subsequent data for TE6-1-3 and -4 to be obtained. The performance of the revived cathode appeared to remain unchanged, as far as the peak emission current was concerned.

Because the resistor film could only carry 0.4 \( \mu \text{A} \) as measured, the increased emission for TE6-1 was undoubtedly due to failure of the resistor film, which removed the current limiting resistor from an unknown number of emitters. This was similar to cathode TE5-3, except in this case destruction of some emitters occurred and the cathode subsequently shorted. An explanation of the cathode's revival can only be offered on a speculative basis. It was probably due to the Type I failure of the emitters inherent to a current-limited cathode. Assuming the failed elements were separate, it would be possible for the shorting passage to be opened pin by pin. Because each short circuit could also be limited in the amount of current it could carry due to a small contact area, there existed the possibility that, on reapplication of voltage, either further damage would occur or the short would open. The latter appeared to be the case, made possible by the failure having occurred in an isolated fashion in connection with being current-limited. Although this capability was
not intended for the current-limiting resistor in the first place, it certainly was a beneficial side effect to be realized.

For both cathodes TE9-2 and TE9-3, a less resistive and more current-capable resistor film with a 3 μm thickness was used (Si-23-3). The resistance at 10 and 50 volts was $3.6 \times 10^8$ and $2.0 \times 10^8$ ohms, with a breakdown current of 4 μA. This current level was one order of magnitude larger than that of the previously tested resistor films for TE5's and TE6's. The emitter tip geometry of these two cathodes and a non-current-limited cathode (TE9-8, tested for comparison purpose) was quite similar. The tip geometry consisted of right circular cylinders, with jagged edges on the sides of the emitters.

From the set of F-N plots of TE9-2, Fig. 4-21, the evidence of the emitter's gradual but considerable dulling was demonstrated. The large decrease in the lower portion of the curves, particularly at the initial stage of activation, was perhaps a result of burnishing the jagged edges in addition to normal dulling. In the time between the recording of curves TE9-2-4 and TE9-2-7, this cathode suffered repeated short-circuiting but continually resumed operation when voltage was reapplied. There did not seem to be any appreciable degradation of performance despite its having failed frequently. The lack of a conspicuous upward curvature was probably due to lower resistance of the series resistors. Among the simulated F-N plots shown in Fig. 4-9, there was examples that exhibited emission similar to that observed for TE9-2, Fig. 4-22.

The emission performance of cathode TE9-3, Fig. 4-22, had a
Figure 4-21. Fowler-Nordheim Plots for Cathode TE9-2

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Figure 4-22. Fowler-Nordheim Plots for Cathode TE9-3.
Figure 4-23. Fowler-Nordheim Plots for Cathode TE9-8.
maximum emission of 0.2 A/cm^2 while operating under current limiting effects. This cathode also suffered breakdown of the series resistor. A ten-fold increase in current density to 2 A/cm^2 was measured after resistor-film shorting, which removed current limitations. Also shown by Fig. 4-21 was the gradual shift in the lower portion of curves TE9-3-1 through TE9-3-5, signifying dulling of the sharpest emitters.

Space-charge-limited emission was observed for this cathode after resistor breakdown occurred. The downward curvature exhibited by TE9-3-6 through TE9-3-8 is believed to result from space charge due to high localized emission from a few of the favorable emitters. These emitters would have been producing high emission currents before the resistor failed, which would explain why even a resistor film with a 4 μA current capability per emitter could not avoid breakdown at a time the average emission was only 0.04 μA. This observation indicated that even with a resistor film, the variability of emission from site to site for this cathode was too great to allow the current limiting series resistors to normalize emission across the array.

For the time dependence changes in F-N plots observed, i.e., their gradual shift to higher voltages/lower currents, degradation or changes in the series resistor itself cannot be totally ruled out as possible causes. In order to determine whether resistor degradation had occurred and in fact modified the emission results, the extractor film on several cathodes was stripped off to let the series resistor be remeasured with the micromanipulator. For most of the reprobed resistors, their I-V characteristics were not significantly different from the original measurements. This demonstrated that the resistor
either should function as indicated by the I-V data, or could fail to become a complete short circuit, the occurrence of which was observed on many occasions. Therefore, the time dependent changes in the emission characteristics would be solely produced by processes involving the emitters alone, although current-limitation was undoubtedly a rate-determining factor for the effects that were observed.
CHAPTER V

CONCLUSIONS

1. From calculations of emission for an array of field emitters limited by series resistors, an upturning curvature of the Flower-Nordheim plots was predicted. Such behavior was observed in experimental emission from most current limited cathodes. This effect was attributed to increased relative emission from less favorable but more populous emitters.

2. The silicon series resistors, deposited by a vacuum evaporation technique on ZrO₂-W substrate, exhibited a Poole-Frenkel type conduction behavior at high fields (> 10⁵ V/cm) as indicated by a linear dependence of log I on \( V^{1/2} \) in addition to bulk-limited conduction characteristics.

3. The slopes of Poole-Frenkel plots for the silicon thin films, or their Poole-Frenkel coefficients, generally decreased and approached the theoretical value of bulk silicon with increasing film thickness, indicating that thicker films (>3 μm thick) were less subject to enhanced conduction from defects at the W fiber/resistor interface.

4. A dielectric strength of ~ 5 x 10⁵ V/cm was measured for the silicon thin films, which appeared to be degraded by an attendant Joule heating of unknown magnitude.
5. Most of the series resistors investigated were ineffective in maintaining current-limitation at high emission currents due to (a) low current capabilities (<1 μA), (b) high field-dependence of resistance at high fields (a negative field coefficient of resistance of -2% per volt). This led to reduced current limiting resistance and emitter failure due to excessive emission.

6. Although the current-limiting resistors did not prevent emitter failure, the failures were limited to the extent that each single failure involved only a single emitter (Type I failure), because of limited energy dissipation at the site of failure under current-limitation.

7. Because failure occurred in an isolated fashion, the CLFEA cathodes, after short-circuiting, could be induced to resume operation. This was believed to be the result of having a small contact area short between the tungsten fiber and the extractor film that subsequently opened on reapplicatin of voltage. In these cases substantial degradation of performance was not observed.

8. A slow temporal decline of emission current at low voltages, signifying emission-induced dulling of the sharp emitters, was observed for CLFEA's but not for non-current-limited FEA's. This led to the conclusion that current-limitation caused the dulling rate to be reduced significantly so that its effect became recognizable.

9. The fact a cathode (TE9-3) suffered breakdown of its resistors with a 4-μA current capability indicated that emission from at
least some emitters had exceeded this level. Coupled with another fact that the average emission per pin was only 0.04 μA, the variability of emission from site to site for this cathode appeared too great to allow the current-limiting series resistor to normalize emission across the array at a moderate reduction of emission.
CHAPTER VI

RECOMMENDATIONS

For future study of similar field emission devices, it is highly desirable to have some tests performed in a high magnification Field Emission microscope (FEM), capable of resolving emission from individual emitters, so that quantitative measurements of emission uniformity are possible.

Power loading on the thin film series resistor could be quite significant because of its small size. Thus, aging effects in the resistor due to Joule-heating induced thermal annealing or oxidation needs to be investigated in a rigorous manner. This would ascertain whether there was any change in the resistor's I-V characteristics throughout the course of emission testing that might have been responsible for emission changes observed.

Utilizing non-resistive devices could be a viable alternative to achieving current limitation. For example, if a device possesses a negative differential conductance (NDC) region in a compatible operating range of I and V with the emitter, it should provide current limitation at higher voltage drops. A tunnel diode is a good example of such a device (Fig. 6-1), and should be easily incorporated on the emitter substrate as a two-layer structure of degenerately-doped semiconductor films. Better still, operating with the saturation current of a reverse-bias p-n junction diode should allow current to be
Figure 6-1. I-V Characteristics of a Tunnel Diode.

Figure 6-2. I-V Characteristics of a P-N Junction Diode Illustrating the Rectification Property. (Note the Change of Scale between First and Third Quadrants.)
limited at a fixed value. Figure 6-2 is a plot of current vs. voltage of a typical p-n junction diode, illustrating the rectification property. A typical value of reverse current density is $10^{-5}$ A/cm$^2$ for silicon, which is too low to be compatible with current-limiting requirements for the emitter. Hence a "leaky" junction diode made of Ge, PbS, or InSb, of which the energy gap is much smaller than that of Si, would provide a larger saturation current, $I_S$, because

$$I_S \sim \exp(-E_g/KT)$$  \hspace{1cm} [6-1]$$

A simple order-of-magnitude calculation of $I_S$ for Ge ($E_g = 0.65$ eV) indicates a current density of $\sim 1.0 \times 10^3$ A/cm$^2$. This would allow emission to be limited at about 2 µA per pin until the reversible breakdown occurs. Presumably a p-n junction diode would be a better approach than the resistor film employed, but satisfying the limitations of breakdown, operating temperatures, and successful fabrication of such a junction would be formidable. Even if the junction property was used in lieu of the resistor, the resistor might still be necessary to function as a potential gradient layer to insure individuality of emitter array operations.
APPENDIX A

SYMBOLIC NOMENCLATURE AND PHYSICAL CONSTANTS

The purpose of this appendix is to provide a summary of the nomenclature and physical constants used in this dissertation. The values of the physical constants are given in Table A-1; the symbols and their meanings are listed in Table A-2. Symbols that appear infrequently are defined in the text.

Table A-1. Physical Constants

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Electron Charge</td>
<td>$1.60210 \times 10^{-19}$ coulomb</td>
</tr>
<tr>
<td>m</td>
<td>Electron Rest Mass</td>
<td>$9.10959 \times 10^{-28}$ gram</td>
</tr>
<tr>
<td>h</td>
<td>Planck's Constant</td>
<td>$6.62520 \times 10^{-27}$ erg·sec</td>
</tr>
<tr>
<td>K</td>
<td>Boltzmann's Constant</td>
<td>$1.38054 \times 10^{-16}$ erg/deg</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Permittivity of Free Space</td>
<td>$8.84194 \times 10^{-12}$ coul$^2$/N·m$^2$</td>
</tr>
</tbody>
</table>

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Table A-2. Symbolic Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Numerical constant of F-N equation, 1.54x10^{-6}</td>
</tr>
<tr>
<td>C</td>
<td>Numerical constant of F-N equation, 6.83x10^{-7}</td>
</tr>
<tr>
<td>C₀</td>
<td>Intercept of log I vs. √V plot</td>
</tr>
<tr>
<td>D</td>
<td>Emitter-emitter separation</td>
</tr>
<tr>
<td>d</td>
<td>Diameter of tungsten pin</td>
</tr>
<tr>
<td>E</td>
<td>Electric field in the normal direction</td>
</tr>
<tr>
<td>f(y)</td>
<td>Image potential correction function of F-N equation</td>
</tr>
<tr>
<td>h</td>
<td>Planck's constant</td>
</tr>
<tr>
<td>ĥ</td>
<td>h/2π</td>
</tr>
<tr>
<td>I</td>
<td>Field emission current</td>
</tr>
<tr>
<td>I₆_r</td>
<td>Emission current from emitters with tip radius r</td>
</tr>
<tr>
<td>I₉_r</td>
<td>Emission current from an emitter with tip radius r</td>
</tr>
<tr>
<td>J</td>
<td>Emission current density</td>
</tr>
<tr>
<td>m</td>
<td>Slope of log I vs. √V plot</td>
</tr>
<tr>
<td>N(r)</td>
<td>Number of emitters with tip radius r</td>
</tr>
<tr>
<td>N(W)dW</td>
<td>Supply function of electrons in a metal</td>
</tr>
<tr>
<td>R</td>
<td>Resistance of current-limiting resistor</td>
</tr>
<tr>
<td>r</td>
<td>Emitter tip radius</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>( r )</td>
<td>Mean tip radius</td>
</tr>
<tr>
<td>( s(y) )</td>
<td>Image potential correction function of F-N equation</td>
</tr>
<tr>
<td>( t )</td>
<td>Resistor film thickness</td>
</tr>
<tr>
<td>( t(y) )</td>
<td>Image potential correction function of F-N equation</td>
</tr>
<tr>
<td>( U )</td>
<td>Total potential energy of electrons in a metal</td>
</tr>
<tr>
<td>( U(x) )</td>
<td>Image potential of electrons outside a metal</td>
</tr>
<tr>
<td>( V )</td>
<td>Total applied voltage to emitter</td>
</tr>
<tr>
<td>( V_A )</td>
<td>Voltage applied to anode</td>
</tr>
<tr>
<td>( V_E )</td>
<td>Net applied voltage to emitter</td>
</tr>
<tr>
<td>( V_R )</td>
<td>Voltage drop across current-limiting resistor</td>
</tr>
<tr>
<td>( V(x) )</td>
<td>Potential function of a bound electron</td>
</tr>
<tr>
<td>( W )</td>
<td>Energy of electrons in the normal direction</td>
</tr>
<tr>
<td>( x )</td>
<td>Distance to surface in the normal direction</td>
</tr>
<tr>
<td>( y )</td>
<td>Variable of image potential correction function, ( (e^3E \frac{f}{\phi}) )</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Microscopic emitting area</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Field enhancement factor for an individual pin tip</td>
</tr>
<tr>
<td>( \beta_{PF} )</td>
<td>Poole-Frenkel coefficient</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Work function</td>
</tr>
<tr>
<td>( \Delta \phi )</td>
<td>Reduction in potential barrier</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Standard deviation of tip radius distribution</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Wave function of electrons</td>
</tr>
</tbody>
</table>

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APPENDIX B

FORTRAN PROGRAMS FOR CALCULATION OF FOWLER-NORDHEIM DATA

The computer programs used to generate the theoretical Fowler-Nordheim plots (Program TFNP) and to plot the experimental Fowler-Nordheim plots (Program FNP) are presented here. The calculations performed by TFNP are based on Equation 4-3, discussed in Chapter IV.
This program is used to generate theoretical Fowler-Nordheim plots for an array of current-limited emitters based on the field emission theory. The emitters are assumed to have a normal distribution of tip radii. I-V characteristics of the current-limiting resistors are that of Si-23. Field dependence of resistance is approximated in an exponential form. To run this program, an input data file "datain" is required. A sample input data file is attached at the end of this Program. Additional data will be requested through interactive keyboard dialogue.

12-15-82
CHANGED PIN RESISTANCE FORMULA

12-16-82
MODIFIED PROGRAM TO MAKE MULTIPLE PLOTS

12-17-82
CHANGED PIN RESISTANCE FORMULA AGAIN PER J. LEE

12-17-82
MODIFIED PROGRAM TO PERMIT VOLTAGE/CURRENT PLOTS

12-29-82
MINOR FORMAT CHANGES

12-29-82
MODIFIED TO PLOT ARRAY CURRENT DENSITY

12-31-82
INPUT & FORMAT MODIFICATIONS

1-12-83
CHANGED "NUM" VARIABLE TO INTEGER

1-12-83
CORRECTED DISTRIBUTION FUNCTION

8-31-83
CORRECTED ERRORS IN PLOT ROUTINES

4-16-84
******************************************************************************
* MODIFICATIONS MADE BY J. LEE *
* TO 1. ACCEPT MULTIPLE I/O'S *
* E.G., LOG1,*,DATAIN,AUX,DUMP,EIV3D *
* *(DEFAULT): KEYBOARD DIALOGUE *
* DATAIN: INPUT DATA FILE *
* AUX: FORMATTED OUTPUT, I.E., F-N TABLES *
* DUMP: INTERMEDIATE MONITORING OUTPUT *
* EIV3D: EMISSION I-V DATA TO BE USED AS *
* INPUT DATA FILE FOR 3D PLOT *
* 2. SELECT EMITTER TIP RADIUS AND *
* ITS DISTRIBUTION *
* 3. INCORPORATE FIELD DEPENDENCE OF *
* SI THIN FILM RESISTORS *
* 4. CHANGE SIMULATION CONDITIONS *
******************************************************************************

4-19-84
CHANGED INPUT STRUCTURE, TIP RADIUS AND ITS DISTRIBUTION TO BE READ FROM "DATAIN"-3RD LINE

4-20-84
MELTED EMITTERS WERE MADE ACCOUNTED FOR

REAL JAY1(50), J(50), JAY(11,50), IPIN(11,50), IPINC(11,50), 
$ LOG1(50), LOGJAY1(50)
INTEGER U, CAPTION(5)

DIMENSION V(50), X(50), W(50), Z(50), DAT(10), E(11,50)
DIMENSION XX(50), IBUF(512), IP(2), WM(50), Z2(50), V3(11,50)
DIMENSION IDENT(3), INC(11,50), V1(12,50), V2(11,50), Y(50), SY(50)
DIMENSION FY(11), TY(11), VFIF(11), R(11), NUM(11)
DIMENSION PC10(11), PC20(11), PC25(11), PC40(11), PC1(11)
DIMENSION DIA(11), RAD(11), BETA(11), AFIB(11), RFIB(11)
DIMENSION BASEDIA(11), ABASE(11), AEQUIV(11), RTRIAL(11,50), PC100(11)
DATA C/1.54E-5/, B/6.83E7/, PHI/8.0/, N/11/0/
DATA XPAGE/2.0/, YPAGE/-4.0/, N/10/, PI/3.1415927/
DATA I-MARK/2.0/, THETA/30.0/
DATA PC10/0.001, 0.02, 0.60, 0.06, 24.17, 38.30, 24.17, 6.06,
$ 0.60, 0.02, 0.001/
DATA PC20/0.92, 2.76, 6.55, 12.10, 17.47, 19.38, 17.47, 12.10,
$ 6.55, 2.76, 0.92/
DATA PC25/2.20, 4.49, 7.79, 11.56, 14.64, 15.86, 14.64, 11.56,
$ 7.79, 4.49, 2.20/
DATA PC40/4.57, 6.05, 7.52, 8.79, 9.64, 9.95, 9.64, 8.79,
$ 7.52, 6.05, 4.57/

C
KEYBOARD ENTRY OF SI FILM BREAKDOWN, IF SO CHOSEN

BDFIELD=500.
K=0
WRITE (8,999)
READ (7,X) XMMMM
IF(XMMMM.EQ.0) GO TO 60
IF(XMMMM.NE.2.) GO TO 1999
WRITE (8,999)
READ (7,X) BDFIELD

C
READ FORMATED INPUT DATA

C

1999 READ (5,104) CAPTION
1 READ (5,100) ICODE, (IDENT(J), J=1,3)
IF (IIF (5)) 58.2
2 READ (5,X) TIPA, SIGMA
READ (5,X) ALFA, A
READ (5,X) RHO, RESIST, THICK

C
SELECT TIP RADIUS DISTRIBUTION ACCORDING TO
STANDARD DEVIATION ENTERED

C

1000 DO 1111 J=1,11
1111 PC100(J)=PC10(J)*0.01
GO TO 1010
2000 DO 2222 J=1,11
2222 PC100(J)=PC20(J)*0.01
GO TO 1010
2500 DO 2525 J=1,11
2525 PC100(J)=PC25(J)*0.01
GO TO 1010
4000 DO 4444 J=1,11
4444 PC100(J)=PC40(J)*0.01
1010 DD 101 J=1,11
101 PC(J)=PC100(J)*100.
IF (IIF (5)) GO TO 419
CALL PLOTS (1BUFF, 512, 2, 40)
CALL FACTOR (1.0)
CALL LIMIT (1.0, 9.0, -3)

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CALL SYMBOL (-0.75,-1.0,0.14,CAPTION,270.,50)

CONTINUE

CONVERT TIP RADIUS FROM ANGSTROM TO CM

TIP=TIPA*1.0E-8
RAD(I)=TIP/2.
CORRECT=TIP/100.
SIGMA=SIGMA*CORRECT*1.0E8
RADINCR=10.*CORRECT

K=0

THICKUM=THICK*1.0E4
BRKDOWN=DFIELD*THICKUM
WRITE(5,916) TIPA,SIGMA,PC(6),THICKUM
WRITE(8,916) TIPA,SIGMA,PC(6),THICKUM
N=40

KK=N-1
XX(1)=4.0
DO 4 J = 1,KK

CALCULATE 1/V IN THE RANGE 62.5-250 VOLTS

4 CONTINUE
U = 0
NN=N+2
IF (11.GT.0) GO TO 18
IF (ICODE.EQ.5.OR.ICODE.EQ.6) XPAGE = 9.0

18 D1 = X * 4.0/P1
D = SQRT(D1)
DIA(1) = 0.55E-4
DO 3 J = 1,11
3   DIA(J+1) = DIA(J) + 0.01E-4
DO 5 J = 1,11
NUM(J) = RHO * A * PC100(J)
IF (NUM(J) .EQ.0) NUM(J)=1

CALCULATE THE LOW FIELD RESISTANCE

THETA = THETA/57.29578
BASEDIA(J) = DIA(J) + 2. * THICK * TAN(THETA)
RFIB(J) = 4.0 * RESIST * THICK/(PI * DIA(J))
$ = (2.0 * THICK * TAN(THETA) + DIA(J))
R(J)=RFIB(J)
RAD(J)=RAD(1)+(J-1)*RADINCR
BETA(J) = 1./RAD(J)
5 CONTINUE

VI(1,1) = 0.
V2(1,1) = 0.
VDEF(I) = 0.
INC(1,1) = 0
WRITE(8,*)'N:"VOLTAGE STEPS"
PRINT(9,*) "********************************************************************
C C C C C
C C C
C C C
C C C
C C
C C
C C
C C
C C
C C
C C
C C
C C
CALCULATE EMISSION CURRENT BASED ON F-N EQN.
C
DO 6J = 1, J
P AS 50.
INC(J,L)=0
V1(J,L)=50.
7 E(J,L) = BETA(J) * (V(L) - V1(J,L))
Y(J) = 3.79E-4 * SQRT(E(J,L))/PHI
SY(J) = 1.0 - 0.15 * Y(J) ** 1.9047
FY(J) = 1.0 - Y(J) ** 1.7
TY(J) = 1.0 + (0.1107 * Y(J) ** 1.43)
JAY(J,L) = (C * (E(J,L)*E(J,L)/(PHI * TY(J) * TY(J))))
S * EXP( (-B * PHI ** 1.5) /E(J,L) ) * FY(J)
IF (E(J,L) .GT. 1.0E7) GO TO 22
JAY(J,L) = 0.0
22 IP IN (J,L) = JAY(J,L) * ALFA
IP INC (J,L) = IP IN (J,L) * FLOAT(NUM(J))
C
C
DETERMINE R(J) AT CORRESPONDING FIELD
C
IF (THICK.LE.0.) GO TO 3053
RT RIAL(J,L) = R(J) * 10. ** (-0.0186*V1(J,L)/(THICK*10000.))
GO TO 4053
3053 R T R I A L(J,L) = 0.
4053 V2(J,L) = IP IN (J,L) * R T R I A L (J,L)
IF (V2(J,L) .GT. V(L)) V2(J,L) = V(L)
V3(J,L) = V(L) - V2(J,L)
INC(J,L) = INC(J,L) + 1
IF (1111.GT.0) GO TO 515
VD IF (J) = V1(J,L) - V2(J,L)
GO TO 525
515 VD IF (J) = V2(J,L) - V1(J,L)
WRITE OUTPUT FILE: DUM P
525 WRITE (9, 1052) J, L, R T R I A L(J,L), V1(J,L), VD IF (J)
IF (VD IF (J).LE. 0.) GO TO 335
1111 = 1111
PASS = PASS + 0.5
535 IF (ABS (VD IF (J)). LE. 0.2) GO TO 6666
V1(J,L) = V1(J,L) * PASS
V(J,L) = V1(J,L)
GO TO 7
6666 IF (XMMM.NE.2.) GO TO 6
11 IF (V1(J,L) .LT. BRIDWM) GO TO 6
PRINT (9, #) " /PINS MELTED DUE TO HIGH FIELD BREAKDOWN OF SI FILM!"
V1(J,L) = 0.
RT R I A L(J,L) = 0.
IP IN (J,L) = IP IN (J,L) * 1.0E-20
IP INC (J,L) = IP INC (J,L) * 1.0E-20
6 CONTINUE
9 CONTINUE
DO 17L = 1, N
  I (L) = 0
DO 15J = 1, I1
  I (L) = I (L) + 1
  IF (I (L) .LE. 0.) GO TO 26
  LOG1 (L) = ALOG10 (I (L))
15 CONTINUE
GO TO 28
26 N = L + 1
NN = N + 1
28 DO 20L = 1, N
  JAY1 (L) = I (L) / A
  LOGJAY1 (L) = ALOG10 (JAY1 (L))
  X (L) = 1. / V (L)
  W (L) = 1. / X (L) ** 2
  Z (L) = ALOG10 (W (L))
  SW (L) = JAY1 (L) * X (L) ** 2
  ZZ (L) = ALOG10 (W (L))
DO 3721 J = 1, I1
  IF (IPIN (J, L) .GT. 1.0E-11) GO TO 3721
  IPIN (J, L) = 0.
  IPININC (J, L) = 0.
3721 CONTINUE
20 CONTINUE
C WRITE HEADINGS
C
WRITE (6, 110) (IDENT (J), J = 1, 3)
IF (ICODE .EQ. 7 .OR. ICODE .EQ. 10) GOTO 11
11 WRITE (6, 161)
WRITE (6, 162)
WRITE (6, 163)
WRITE (6, 164)
GO TO 14
12 WRITE (6, 120)
C
14 ND = N - (K-1)
C 14 ND = 30
C
16 DO $GL = 1, N
  WRITE (6, 130) L, V (L), I (L), X (L), LOG1 (L), Z (L),
$ LOGJAY1 (L), ZZ (L), JAY1 (L), IMARK
46 CONTINUE
WRITE (6, 200)
WRITE (6, 201)
WRITE (6, 202) (J, PC (J), NUM (J), DIA (J), RAD (J), BETA (J), RFIB (J),
$ RTRIAL (J, I), J = 1, 11)
WRITE (6, 214) D, RWD
WRITE (6, 216) THICK, RESIST
WRITE (6, 217) RAD (6), SIGMA
WRITE (6, 218) ALFA
WRITE (6, 204) RAD (1)
WRITE (6, 205)
WRITE (6, 206) (V (L), V2 (1, L), V3 (1, L), E (1, L), JAY (1, L),
$ IPIN (1, L), IPININC (1, L), INC (1, L), L = 1, N)
IF (ICODE .EQ. 3 .OR. ICODE .EQ. 4) GOTO 56
62 WRITE (6, 208)
WRITE (6, 210) (RAD (J), J = 1, 11)
WRITE (6,212) (V(L), (I(PIN(J,L),J=1,11),L=1,N)
C
C CALL SUBROUTINE TO PLOT DATA POINTS AND DRAW
C LINEAR REGRESSION LINE THRU SPECIFIED POINTS.
C
56 CALL SYMBOL(XPAGE+.07,YPAGE,.14,.11,0.,-1)
CALL SYMBOL(XPAGE,YPAGE-.3,.0,.14,IDENT,270.,30)
IF (ICODE.EQ.5,.OR.,ICODE.EQ.6) 55,57
55 CALL FN PLOT(N,ND,K,NN,XX,ZZ,IBUF,V,11,U,ICODE)
GO TO 59
57 CALL VIPLOT(N,ND,K,NN,V,LOGJAY1,IBUF,11,U,ICODE)
C
59 K = K+1
54 LI=L+1
XPAGE = XPAGE - 0.21
C GENERATE EIV3D: EMISSION I-V DATA AS 3D PLOT INPUT
C
PRINT (10,4) 11, "#################################################################################
WRITE (10,1901) (CAPTION(JJ),JJ=1,5)
WRITE (10,1902) (IDENT(JJ),JJ=1,3)
WRITE (10,1903) (NUM(JJ),JJ=1,11)
PRINT (10,4) "#################################################################################
GO TO 1
C
1901 FORMAT(1X,5A10)
1902 FORMAT(1X,3A10)
1903 FORMAT(1X,11I4)
1904 FORMAT(1X,12E10.3)
999 FORMAT(/1X,"ENTER NON-ZERO VALUE TO CONTINUE ",
$ /1X,"ENTER 2 TO ACCOUNT FOR MELTED EMITTER TIPS",
$ /1X,"ENTER ZERO TO ABORT")
2999 FORMAT(/1X,"ENTER BREAKDOWN FIELD OF SI FILM",
$ /1X,"TYPICAL VALUE IS 35-60 VOLT PER UM")
C 999 FORMAT(/1X,"ENTER MEAN TIP RADIUS AND STANDARD DEVIATION"),
C $ IN FREE FORMAT"
C $/1X,"FOR 10\%, 20\%, 25\% & 40\% OF TIP RADIUS .")
1052 FORMAT(1X,"RTRIAL(",12,"),"",E9.1,
$ "V1(J,L)= ",F7.1," VDIF(J)="",F7.2)
100 FORMAT (12,3A10)
102 FORMAT (10A10)
104 FORMAT (5A10)
109 FORMAT ("*N")
110 FORMAT (1H1/17X, *FOWLER-NORDHEIM DATA FOR *, 3A10/)
120 FORMAT (T1O,"DIODE",5X,"EMISSION",T4I,"LOG OF",T6O,
$ "LOG OF",T8I,"CURRENT"/1X,"POINT",2X,"VOLTAGE",4X,
$ "CURRENT",5X,"1000",4X,"EMISSION",2X,"LOG OF",4X,
$ "CURRENT",3X,"LOG OF",5X,"DENSITY"/2X,"NO","3X,
130 FORMAT(1X,12,OPF10.1,1P13.2,3PF8.2,OPF4.2,1PF12.2,3PF8.2)
161 FORMAT (T6O,"AVERAGE",3X,"ENHANCED",3X,"MICROSCOPIC")
162 FORMAT (1X,"POINT",3X,"DIODE",5X,"EMISSION",3X,"1000",5X,
163 FORMAT (2X,10D4.1,3X,"VOLTAGE",4X,"CURRENT",6X,"V")
CALL LIMIT(12.0,0.0,-3)
CALL LIMIT(12.0,0.0,999)
60 STOP
END

C
SUBROUTINE FNPLOT(N,ND,K,NN,VINV,IVSQ,IBUF,V,11,U,ICODE)
DIMENSION X(50) ,Y (50) ,V IN V (50), IVSQ(50), IBUF (512) ,V (50)
REAL IVSQ,LOGB,M,LOGC,LOGD
INTEGER U
DATA A A /2 ./,B B /- 1 .2/,C C /-5 ./,D D /.1 /,E E /8 ./,F F /1 1 .2/

C ADJUST AXES OF F-N PLOT
06 IF (ICODE.EQ.6) 7 .8
7 BB=B8

DD=DD+1
CC=CC+1
IF(11.EQ.0) 15,17
08 IF(11.GT.0) GO TO 17
09 IF(IVSQ(N).LT.CC) 10,11
10 CC=CC+1.
GO TO 9
11 GG=CC+DD*FF
IF(IVSQ(1).GT.GG) 13,14
13 DD=DD+.1
GO TO 11
14 HH=AA-BB*EE
IF(VINV(N).GT.HH) 16,15
16 BB=BB-.1.
GO TO 14

DRAW AXES FOR F-N PLOT

15 CALL FACTOR(1.0)
CALL LIMIT(0.,0.,3)
CALL AXIS(0.,0.,10000,-6,EE,270.,AA,-BB)
CALL AXIS(0.,0.,0.,"LOG (J/V%2)",11,FF,0.,0.,CC,DD)

17 CALL LIMIT(0.,0.,3)
VINV(N+1)=AA
VINV(N+2)=BB
IVSQ(N+1)=CC
IVSQ(N+2)=DD
X(3)=AA
X(4)=BB
Y(3)=CC
Y(4)=DD
CALL LINE(IVSQ, VINV, 0, 1, 11)
5 RETURN
END

SUBROUTINE VIPLLOT (N,ND,K,NN,V,LOGJ,IBUF,11,U,ICODE)
DIMENSION X(50),Y(50),V(50),LOGJ(50),IBUF(512)
REAL LOGJ,LOGB,N,LOGC,LOGO
INTEGER U
DATA AA/50.,BB/-20.,CC/-1.,DD/.1,EE/8./,FF/11./
DATA BB/-20.,CC/-3.,DD/0.5/

ADJUST AXES OF I-V PLOT

06 IF(ICODE.EQ.2.OR.ICODE.EQ.4.OR.ICODE.EQ.6) 7,8
07 BB=BB+1
DD=DD+.1
CC=CC+1.
IF(11.EQ.0) 15,17
08 IF(11.GT.0) GO TO 17
09 IF(LOGJ(N).LT.CC) 10,11
10 CC=CC+1.
GO TO 9
11 GG=CC+DD*FF
IF(LOGJ(1).GT.GG) 13,14
13 DD=DD+.1
GO TO 11
14 HH=AA-BB*EE
IF(V(1).GT.HH) 16,15

16 BB=BB-10.
GO TO 14

C
C DRAW AXES FOR I-V PLOT

C 15 CALL FACTOR(1,0)
CALL LIMIT(0.,0.,3)
CALL AXIS(0.,0.,"VOLTAGE (<VOLTS>"",-17.,EE.270.,AA.,-BB)
CALL AXIS(0.,0.,0.,"LOG OF ARRAY CURRENT DENSITY (A/<CM%2>"",
$ 39.,FF.0.,0.,CC.,DD)

C 17 CALL LIMIT(0.,0.,3)
V(N+1)=AA
V(N+2)=BB
LOGJ(N+1)=CC
LOGJ(N+2)=DD
X(3)=AA
X(4)=BB
Y(3)=CC
Y(4)=DD
XP = (V(1)-AA)/BB
YP = (LOGJ(1)-CC)/DD
CALL LINE(LOGJ,V,NB,1,1,11)

C CALL SYMBOL(XP,YP-.2,.07,1.DENT,270.,30)
5 RETURN
END

C
C sample input data file "datain"

C
C 123456789012345678901234567890
C
C 3UM SI-23, VARIOUS TIP RADIUS, SIGMA/TIP=.40
C 6TIP RADIUS= 90 ANGSTROM
C 30,40
C 6.45E-15,2.84E-5
C 5.0E6,2.55E4,3.0E-4,
C 6TIP RADIUS= 100 ANGSTROM
C 100,40
C 6.45E-15,2.84E-5
C 5.0E6,2.55E4,3.0E-4,
C 6TIP RADIUS= 110 ANGSTROM
C 110,40
C 6.45E-15,2.84E-5
C 5.0E6,2.55E4,3.0E-4,
C 6TIP RADIUS= 120 ANGSTROM
C 120,40
C 6.45E-15,2.84E-5
C 5.0E6,2.55E4,3.0E-4,
PROGRAM FNP (INPUT, OUTPUT, TAPES=INPUT, TAPES=OUTPUT)

C 1-3-80 COMPLETED OUTPUT FORMAT HEADINGS
C 3-12-80 REVISED OUTPUT FORMAT
C 3-13-80 CORRECTED BUGS IN OUTPUT FORMAT
C 3-14-80 MORE CHANGES TO OUTPUT FORMAT
C 3-19-80 ANOTHER CHANGE TO OUTPUT FORMAT
C 10-20-80 CHANGE INPUT TO NON-FORMATTED READ STATEMENT
C 11-6-80 MAJOR REVISION - CHANGED PLOT SUBROUTINE
C TO ADJUST AXES TO PROPER VALUES
C 11-7-80 REVISED INPUT FORMAT TO ALLOW EITHER FORMATTED
C OR NON-FORMATTED DATA INPUT.
C 2-24-81 REVISED FNPLT SUBROUTINE
C 03-06-82 MAJOR REVISION - ADDED SUBROUTINE TO
C CALCULATE AVERAGE PIN CURRENT

C THIS PROGRAM READS RAW V-I DATA FROM A DATA FILE.
C ALONG WITH THE AREA OF THE ACTIVE AREA IN SQ CM, AND
C CALCULATES VALUES OF LOG(I/V**2) & 10**3/V. IT THEN
C PERFORMS A LINEAR REGRESSION ANALYSIS ON THESE VALUES,
C DETERMINING THE SLOPE & INTERCEPT OF THE REGRESSION
C LINE, THE STANDARD ERROR OF ESTIMATE FOR THE SLOPE AND
C INTERCEPT, & THE CORRELATION COEFFICIENT. THE FIELD
C ENHANCEMENT FACTOR IS CALCULATED FROM THE SLOPE OF THE
C REGRESSION LINE, USING AN ASSUMED VALUE FOR THE WORK
C FUNCTION. THE AVG ELECTRIC FIELD AT 100 VOLTS IS CALC-
C ULATED, & FROM THIS THE AVG MICROSCOPIC CURRENT DENSITY
C AT THE PIN TIPS. THE CURRENT AT 100 VOLTS IS DETERMINED
C FROM THE REGRESSION EQN & USED WITH THE CURRENT DENSITY
C TO CALCULATE THE TOTAL EMITTING AREA. THE VALUE OF THE
C ARRAY CURRENT DENSITY J IS CALCULATED FOR EACH VALUE OF
C I AND THEN LOG(J/V**2) IS PLOTTED AS A FUNCTION OF 10**3/V
C USING THE CALCOMP PLOTTER. MORE THAN ONE PLOT CAN BE
C PLACED ON A GIVEN AXIS.

C DATA INPUT INSTRUCTIONS

C COLUMN(S) EXPLANATION

C LINE 1

C 1   CODE NO. (SEE CODE KEY BELOW)
C 2-16 PLOT NUMBER
C 17-18 NO. OF DATA POINTS
C 21-27 SIZE OF ACTIVE AREA (SQ CM), ENTERED IN
      "E" FORMAT TO TWO DECIMAL PLACES
C 30-34 PIN DENSITY, ENTERED IN "E" FORMAT
      TO ONE DECIMAL PLACE

C LINE 2

C 1-140 PERTINENT EXPERIMENTAL DATA

C LINE 3 - (N+2)

C 1-6 EXTRACTOR VOLTAGE FOLLOWED BY DECIMAL POINT
C 7-14 EMISSION CURRENT IN "E" FORMAT, WITH MAX.
      OF TWO DECIMAL PLACES. **RIGHT JUSTIFIED**
C 21-28 LEAKAGE CURRENT IN "E" FORMAT, MAX. OF TWO
      DECIMAL PLACES. **RIGHT JUSTIFIED**

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#NOTE# IF LEAKAGE CURRENT IS ENTERED, COLUMN 1, LINE 1
MUST BE LEFT BLANK, THEREBY SELECTING THE
FORMATTED READ STATEMENT. IF NO LEAKAGE VALUES,
CODE 1 MAY BE SELECTED AND THE VOLTAGE AND CURRENT
VALUES CAN BE ENTERED SEPARATED BY A COMMA OR SPACE (S).

`CODE KEY`

<table>
<thead>
<tr>
<th>CODE NO.</th>
<th>EXPLANATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (BLANK)</td>
<td>F-N PLOT WILL BE PLOTTED GIVING ONLY SYMBOLS UNLESS CORRELATION COEFFICIENT IS GREATER THAN &quot;RTEST&quot; (SET IN PROGRAM), IN WHICH CASE A LEAST SQUARES LINEAR REGRESSION LINE WILL BE PLOTTED THRU THE DATA POINTS. IF SPACE CHARGE IS SUSPECTED, THE VALUE OF &quot;K&quot; CAN BE RESET IN THE PROGRAM, CAUSING IT TO LOOP THRU THE SPECIFIED NUMBER OF TIMES, DROPPING HIGH-CURRENT DATA POINTS UNTIL THE CORRELATION COEFFICIENT IS EQUAL TO &quot;RTEST&quot;.</td>
</tr>
<tr>
<td>1</td>
<td>SAME AS 0, EXCEPT NON-FORMATTED READ STATEMENT IS SELECTED.</td>
</tr>
<tr>
<td>2</td>
<td>SAME AS 0, EXCEPT THAT LINEAR REGRESSION LINE IS PLOTTED REGARDLESS OF THE CORRELATION COEFFICIENT.</td>
</tr>
<tr>
<td>3</td>
<td>SAME AS 0, EXCEPT THAT THE WORK FUNCTION IS ADJUSTED TO KEEP THE FIELD WITHIN THE LIMITS OF THE F-N EQUATION.</td>
</tr>
<tr>
<td>4</td>
<td>SETS THE AXES OF THE FN PLOT.</td>
</tr>
<tr>
<td>5</td>
<td>CALCULATES 6 PLOTS AVERAGE PIN CURRENT</td>
</tr>
<tr>
<td>6</td>
<td>COMBINATION OF 4 &amp; 5</td>
</tr>
</tbody>
</table>

```c
REAL I(25), M, INT, INTJ, JAY(25), LOGB, LOGC, MEANX, MEANZ,
$ JAY1(25), LOGD, LOGI(25), LGJAY1(25), LGBAR(25)
INTEGER U
DIMENSION V(25), X(25), W(25), Z(25), DAT(16), E(25)
DIMENSION XX(25), IBUF(512), IP(2), WW(25), ZJ(25)
DATA C/1.54E-6/, B/6.83E7/, PHI/8.0/, RTEST/0.999/
DATA XPAGE/9.5/, YPAGE/-4.0/
DATA IMARK/"I"/
CALL PLOTS(1BUF, 512, 2, 40)
CALL FACTOR(1, 0)
CALL LIMIT(1, 0, 9.0, -3)
WRITE (6, 109)
```

READ CODE NO, PLOT NO, NO OF DATA POINTS, SIZE OF
ACTIVE AREA, ADDITIONAL DATA

```c
5 READ (5, 99) ICODE, (IP(K), K=1, 2), N, A, RHQ, (DAT(J), J=1, 16)
   IF (EOF(5)) 58, 4
4 IF (ALE.0 OR A.GT.1.0) 8, 6
```

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READ VALUES OF VOLTAGE AND CURRENT

IF (ICODE.EQ.1) GO TO 2
READ (5,*) (V(J), I(J), J=1,N)
GO TO 9

READ (5,10) (V(J), I(J), J=1,N)
IF (N.LE.1) GO TO 50
U = 0
K = 1
NN = NN+2
IF (11.GT.0) GO TO 7
IF (ICODE.EQ.7.OR.ICODE.EQ.8) XPAGE = 2.0

CALCULATE VALUES OF LOG((1/V**2) & 1/V)

DO 10 J = K, M
IF (V(J).LE.0.0 OR I(J).LE.0) GO TO 51
X(J) = 1/V(J)
XX(J) = 1000.*X(J)
W(J) = I(J)*X(J)*X(J)
Z(J) = ALOG10(W(J))
LOG1(J) = ALOG10(X(J))
CONTINUE

WRITE HEADINGS
WRITE (6,110) (IP(K), K=1,2)
IF (ICODE.EQ.5.OR.ICODE.EQ.6) 11,12
WRITE (6,161)
WRITE (6,162)
WRITE (6,163)
WRITE (6,164)
GO TO 14
WRITE (6,119)
WRITE (6,120)
WRITE (6,121)
WRITE (6,122)

PERFORM LINEAR REGRESSION ANALYSIS ON DATA

NO = N - (K-1)
CALL STAT (K,N,ND,X,Z,SUMX,SUMSQX,MEANX,SUMXZ,SDXSQ)
CALL STAT (K,N,ND,Z,X,SUMZ,SUMSQZ,MEANZ,SUMXZ,SOZSQ)

LOGB = (SUMX*SUMZ - SUMSQX*SUMZ) / (SUNX+SUMX) - FLOAT (ND) *SUMSQX
LOGC = LOGB - ALOG10(A)
IF (ICODE.EQ.5.OR.ICODE.EQ.6) 16,18

LOGD = LOGB - ALOG10(RHO)
INT = 10.0*LOGB
INTJ = 10.0*LOGC
N=(SUMX*SUMZ-FLOAT (ND)*SUMXZ) / (SUNX+SUMX) - FLOAT (ND) *SUMSQX
EV=(1.0/(FLOAT (ND-2))) *(SUMSQZ-LOGB*SUMZ-K*SUMXZ)
VARM = ABS (EV) /SDXSQ
SEEM = SQRT (VARM)
VARB = EV*(1.0/FLOAT (ND)) + (MEANX*MEANX/SDXSQ)
SEEB = SQRT (VARB)
TB = ABS (LOGB/SEEB)
\[
\begin{align*}
T & = \text{ABS}(M/\text{SEEM}) \\
R & = (\text{FLOAT}(ND) \times \text{SUMXZ} - \text{SUMX} \times \text{SUMZ}) / \\
& \quad \text{SORT}(\text{FLOAT}(ND) \times \text{SUMSQX} - \text{SUMX} \times \text{SUMX}) \\
& \quad \text{SORT}(\text{FLOAT}(ND) \times \text{SUMSQZ} - \text{SUMZ} \times \text{SUMZ}) \\
R' & = \text{ABS}(R) \\
\text{ZED} & = 0.5 \times \text{ALOG}\left(\frac{1.0+R}{1.0-R}\right) \\
\text{SIG} & = 1.0 / \text{SORT}(\text{FLOAT}(ND-3)) \\
\text{TR} & = \text{ABS}\left(\frac{\text{ZED} - 2.64665}{\text{SIG}}\right)
\end{align*}
\]

CALL WORK FUNCTION SUBROUTINE IF DESIRED

\[
\begin{align*}
\text{IF}(\text{ICODE.EQ.3}) & \quad 15,40 \\
15 & \quad \text{CALL WFUNC(PHI,V,H,N,K)}
\end{align*}
\]

CALL SUBROUTINE TO DETERMINE FIELD ENHANCEMENT FACTOR AND TOTAL EMITTING AREA

40 CALL AREA(PHI,M,LOGB,ALFA,V1,BETA)

CALL SUBROUTINE TO DETERMINE FIELD ENHANCEMENT FACTOR AND TOTAL EMITTING AREA

40 CALL AREA(PHI,M,LOGB,ALFA,V1,BETA)

CALCULATE AVERAGE PIN CURRENT, IF DESIRED

\[
\begin{align*}
\text{IF}(\text{ICODE.EQ.5} \text{ OR } \text{ICODE.EQ.6}) & \quad 42,45 \\
42 & \quad \text{IF}(\text{RHO.LT.1.0E5} \text{ OR } \text{RHO.GT.1.0E8}) 43,44 \\
43 & \quad \text{WRITE}(6,177) \\
44 & \quad \text{CALL PINCUR(N,V,1,X,Z,WW,ALFA,BETA,} \\
& \quad \text{RHO,E,JAY,1BAR,1G1BAR,1MARK}) \\
45 & \quad \text{GO TO 58}
\end{align*}
\]

CALCULATE ARRAY CURRENT DENSITY, LOG(J/V**2)

\[
\begin{align*}
& \quad \text{DO} 46 \text{J} = \text{K,R} \\
& \quad E(J) = \text{BETA} \times \text{V(J)} \\
& \quad \text{JAY(J)} = 1(J) / \text{ALFA} \\
& \quad \text{JAY1(J)} = \text{W(J)} / \text{ALFA} \\
& \quad \text{LGJAY1(J)} = \text{ALOG10}((\text{JAY1(J))} - \\
& \quad \text{MW(J)} = \text{JAY1(J) \times X(J)} - \text{X(J)} \\
& \quad \text{ZZ(J)} = \text{ALOG10}(\text{MW(J)}) \\
& \quad \text{WRITE}(6,130) \text{ J, V(J), 1(J), X(J), Z(J),} \\
& \quad \text{JAY(J), JAY1(J), E(J), JAY(J), 1MARK} \\
& \quad \text{CONTINUE}
\end{align*}
\]

50 \text{WRITE}(6,165) \\
51 \text{WRITE}(6,170) \\
55 \text{WRITE}(6,135) \text{ A} \\
56 \text{WRITE}(6,142) \text{ LOGB, SEE, PHI} \\
57 \text{WRITE}(6,144) \text{ R, ALFA} \\
58 \text{IF}(\text{RHO.NE.0}) 61,62 \\
61 \text{WRITE}(6,145) \text{ RHO} \\
62 \text{WRITE}(6,160) (\text{DAT(J), J=1,14})
\]

TEST TO SEE IF CORRELATION COEFFICIENT IS HIGH ENOUGH. IF NOT, LOOP THROUGH SPECIFIED NO OF TIMES (VALUE OF K), DROPPING DATA POINTS UNTIL R IS AS LARGE AS SPECIFIED.
IF (ICODE.EQ.2) 76, 70
70 IF (R1.GE.RTEST.AND.K.EQ.1) 71, 72
71 U = 1
GO TO 56
72 IF (R1.LT.RTEST.AND.K.EQ.1) 73, 74
73 U = 0
GO TO 56
74 IF (R1.LT.RTEST.AND.K.GT.1) 75, 76
75 IF (R1.GE.RTEST.AND.K.GT.1) 76, 58
76 U = 2
GO TO 57

CALL SUBROUTINE TO PLOT DATA POINTS AND DRAW
LINEAR REGRESSION LINE THRU SPECIFIED POINTS.

CALL SYMBOL (XPAGE+.07, YPAGE-.14, 11, .0, -.1)
CALL SYMBOL (XPAGE, YPAGE+.34, 11, 0, 15)
IF (ICODE.EQ.7 OR ICODE.EQ.8) GO TO 64

57 CALL FNPLT (N, ND, K, NN, XX, ZZ, IBUF, M, $ LOG, LOGC, LOGO, V, 11, U, ICODE)
IF (ICODE.EQ.2) GO TO 5
IF (U.EQ.1 OR U.EQ.2) GO TO 54

53 K = K + 1
IF (K.GT.1) GO TO 54
GO TO 7
64 CALL VIPLOT (N, ND, K, NN, V, LG, JAYI, IBUF, 11, U, ICODE)
54 N = N + 1
XPAGE = XPAGE -.21
GOTO 5

99 FORMAT (11, A10, A5, 12, E9.2, E7.1/16AB)
101 FORMAT (F6.0, E8.2)
109 FORMAT ("N")
110 FORMAT (111//27X, "FOWLER-NORDHEIM DATA FOR ", A10, A5//)
119 FORMAT (T61,"ARRAY", 4X, "ENHANCED", 3X, "MICROSCOPIC")
123 FORMAT (1X, "Intercept: ", 0P2F6.2, "$ T39, "FIELD ENHANCEMENT FACTOR: ", 1PE7.1/
125 FORMAT (1X, "PIN DENSITY: ", 1PE7.1, "$ PINS/SQ CM")
126 FORMAT (1X, "ADD. TEST DATA: ", 7A8/T18.9A8)
127 FORMAT (1X, "AVERAGE", 3X, "ENHANCED", 3X, "MICROSCOPIC")
128 FORMAT (1X, "APOI, 3X, "DIODE, 5X, "EMISSION, 3X, "1000", 5X, $ A", 7X, "LOG", 6X, "CURRENT")

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SUBROUTINE WKFUNC(PHI, VH, N, K)
DIMENSION V(25)
REAL M, JAY
DATA C/1.54E-6/, B/6.83E7/

VHAX = 0.
DO 2 J = K, N
   V2 = V(J)
   IF (V2 GT VMAX) VHAX = V2
2 CONTINUE
SY = 1.0
5 BETA = ABS(B * PHI**1.5 * SY/(2.303 * M))
E = BETA * VMX
Y = 3.79E-4 * SQRT(E)/PHI
SSY = 1.0 - 0.167 * Y**1.9047
P = SY - SSY
IF (P.LT.0.005) GOTO 10
SY = SY - (SY-SSY)/2
GOTO 5
10 EMAX = 6.94E6 * PHI * PHI
IF (E.LE.EMAX) GOTO 15
PHI = PHI + 0.2
GOTO 5
15 RETURN
END

SUBROUTINE AREA (PHI, M, LOGB, A, VI, BETA)
REAL M, KK, LOGB, JAY
DATA B/6.83E7/, C/1.54E-6/
VI = 100.0
5 BETA = ABS(B * PHI**1.5 * SY/(2.303 * M))
E = BETA * VI
Y = 3.79E-4 * SQRT(E)/PHI
SSY = 1.0 - 0.167 * Y**1.9047
P = SY - SSY
IF (P.LT.0.005) GOTO 10
SY = SY - (SY-SSY)/2
GOTO 5
10 FY = 1.0 - Y**1.7
TY = 1.0 + (0.1107 * Y**1.43)
JAY = (C + (E**E/(PHI**TY * TY)))
A = MEXP(((-B / PHI**1.5)/E) * FY)
IF (JAY.EQ.0.0) STOP
KK = M/VI + LOGB
A = ((VI*VI)/JAY)**10.0**KK
SUBROUTINE STAT (K, N, N2, U, V, SUM, SUMSQ, MEAN, SUMUV, SDSQ)

REAL MEAN

DIMENSION U(25), V(25), W(25)

SUM=0.0
SUMSQ=0.0
SUMUV=0.0
SDSQ=0.0

DO 10 J=1,K
  SUM = SUM + U(J)

10 CONTINUE

MEAN = SUM/FLOAT(N)

DO 20 J=1,K
  SUMUV = SUMUV + U(J)*V(J)

20 CONTINUE

RETURN

END

SUBROUTINE FNPLOT (N, ND, K, NN, VINV, IVSQ, IBUF, M, LOGB, LOGC, LOGD, V, II, U, ICODE)

DIMENSION X(5), Y(5), VINV(25), IVSQ(25), IBUF(512), V(N)

REAL IVSQ, LOGB, LOGC, LOGD
INTEGER U

DATA A/2., B/-2., C/-1., D/.1./, E/7./, F/n./

DATA B/-t./, C/l./, D/0.5/.

C ADJUST AXES OF F-N PLOT

06 IF (ICODE.EQ.2. OR ICODE.EQ.4. OR ICODE.EQ.6.) 7, 8
07 BB=BB4
    DD=DD4
    CC=CC4
08 IF (11.EQ.0) GO TO 17
09 IF (IVSQ(N) .LT.CC) 10, 11
10 CC=CC-1.
    GO TO 9
11 DD=DD4
    IF (IVSQ(N) .GT.GG) 13, 14
12 DD=DD+.1.
    GO TO 11
13 HH=AA-BBEE
    IF (VINV(N).GT.HH) 16, 15
14 BB=BB-1.
    GO TO 14
15 CALL FACTOR (1.0)
    CALL LIMIT (0., 0., 3)
    CALL AXIS (0., 0., 61003/V, -.EE.27, AA, BB)
    IF (ICODE.EQ.5. OR ICODE.EQ.6.) 18, 19
17 CALL AXIS (0., 0., 0., 11HLOG (1/V32), 11, FF, 0., 0., CC, DD)
    GO TO 17
```fortran
18 CALL AXIS(0.0,0.0,11HLOG (J/V/2),11,FF,0.0,CC,DD)

17 CALL LIMIT(0.0.,0.,3)
VINV(N+1)=AA
VINV(N+2)=BB
IVSQ(N+1)=CC
IVSQ(N+2)=DD
X (3)=AA
X (4)=BB
Y (3)=CC
Y (4)=DD
IF (U.EQ.2) GOTO 2
CALL LINE (IVSQ, VINV, HD,1.,-1.,11)
2 X(1)=1.0
X(2)=300.
DO 4 J=K,N
IF (V(J).GE.X(1)) X(1)=V(J)
IF (V(J).LE.X(2)) X(2)=V(J)
4 CONTINUE
IF (ICODE.EQ.5.OR.ICODE.EQ.6) 22,24
22 Y(1)=M/X(1)+LOGD
Y(2)=M/X(2)+LOGD
GOTO 26
24 Y(1)=M/X(1)+LOGC
Y(2)=M/X(2)+LOGC
26 X(1)=1000./X(1)
X(2)=1000./X(2)
IF (U.EQ.0) GOTO 5
CALL LINE (Y,X,1,1,0,1)
5 RETURN
END

C SUBROUTINE PINCUR(N,V,X,Z,ZZ,WW,ALFA,BETA,
$ RHO,E,JAY,IBAR,LAGIBAR,MARK)
 REAL L(25),IBAR(25),JAY(25),LAGIBAR(25)
 DIMENSION V(25),WW(25),ZZ(25),Z(25),E(25)
 DIMENSION X(25)
 DO 10 J=1,N
 E(J)=BETA*V(J)
 JAY(J)=I(J)/ALFA
 IBAR(J)=I(J)/RHO
 LAGIBAR(J)=ALOG10(IBAR(J))
 WW(J)=IBAR(J)*X(J)*X(J)
 ZZ(J)=ALOG10(WW(J))
 WRITE (6,100) J, V(J), I(J), X(J), Z(J),
 $ ZZ(J), IBAR(J), E(J), JAY(J), MARK
10 CONTINUE
100 FORMAT (2X,12,OPF10.1,1X,1PE12.2,SPF8.2,OPF10.3,
 A OPF10.3, 1PE10.2, 1PE12.2,1PE13.2, T106, A1/)
 RETURN
END

C SUBROUTINE VIPLOT (N,ND,K,NN,V,LOGJ,IBUF,II,U,ICODE)
 DIMENSION X(50),Y(50),V(50),LOGJ(50),IBUF(512),V(N)
 REAL LOGJ,LOGB,N,LOGC,LOGD
 INTEGER U
 DATA AA/20.,BB/-10.,CC/-1.,DD/-1,E/E/8.,FF/10./
 DATA BB/-40.,CC/-5.,DD/-0.6/

C ADJUST AXES OF I-V PLOT
```
C 06 IF(ICODE.EQ.4.OR.ICODE.EQ.6.OR.ICODE.EQ.8)7,8 07 BB=BB4 08 DD=DD4 09 CC=CC4 10 IF(11.EQ.0)15,17 11 IF(11.GT.0)GO TO 17 12 IF(LOGJ(N).LT.CC)10,11 13 CC=CC-1. 14 GO TO 9 15 GO=CC+DD*FF 16 IF(LOGJ(1).GT.GG)13,14 17 DD=DD+.1 18 GO TO 11 19 HH=AA-BB*EE 20 IF(V(1).GT.HH)16,15 21 BB=BB-10. 22 GO TO 14 23 24 C DRAW AXES FOR I-V PLOT 25 26 CALL FACTOR(1.0) 27 CALL LIMIT(0..0..3) 28 CALL AXIS(0.,0.,"VOLTAGE (<VOLTS)",16,EE,.270..AA,-BB) 29 CALL AXIS(0.,0.,0.,"LOG OF ARRAY CURRENT DENSITY (A/<CM%2)",& 30 $ 38,FF,0.0,CC,DD) 31 32 CALL LIMIT(0..0..3) 33 V(N+1)=AA 34 V(N+2)=BB 35 LOGJ(N+1)=CC 36 LOGJ(N+2)=DD 37 X(3)=AA 38 X(4)=BB 39 Y(3)=CC 40 Y(4)=DD 41 XP=(V(1)-AA)/BB 42 YP=(LOGJ(1)-CC)/DD 43 CALL LINE(LOGJ,V,ND,1,1,1) 44 CALL SYMBOL(XP,YP,-.2,.07,IDENT,.270,.30) 45 RETURN 46 END 47
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Major: Ceramic Engineering
Minor: Electrical Engineering

Vacuum Science and Technology
Scanning Electron Microscopy
Fine Power Characterization
Ceramic Processings
Microfabrication
Thin Solid Films
Magnetron Devices
Ion Assisted Depositions