CR 174792

DEVELOPMENT PROGRAM ON A COLD CATHODE ELECTRON GUN

Annual Report

January 1985

By: C.A. Spindt, Senior Research Engineer
C.E. Holland, Research Physicist
Physical Electronics Laboratory

Prepared for:

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Contract NAS 3-23776

SRI Project 5723

(NASA-CR-174792) DEVELOPMENT PROGRAM ON A COLD CATHODE ELECTRON GUN Annual Report (SRI International Corp.) 70 p HC A04/MF A01 CSCL 09A

N86-14499

Unclas
G3/33 16292

SRI International
333 Ravenswood Avenue
Menlo Park, California 94025-3493
(415) 326-6200
Telex: 334486

CR 174792

DEVELOPMENT PROGRAM ON A COLD CATHODE ELECTRON GUN

Annual Report

January 1985

By: C.A. Spindt, Senior Research Engineer
C.E. Holland, Research Physicist
Physical Electronics Laboratory

Prepared for:

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Contract NAS 3-23776

SRI Project 5723

SRI International
333 Ravenswood Avenue
Menlo Park, California 94025-3493
(415) 326-6200
Telex: 334486

CR 174792

DEVELOPMENT PR[illegible]AM ON A COLD CATHO[illegible] ELECTRON GUN

Annual Report

January 1985

By: C.A. Spindt, Senior Research Engineer
C.E. Holland, Research Physicist
Physical Electronics Laboratory

Prepared for:

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Contract NAS 3-23776

SRI Project 5723

Approved:

Ivor Brodie, Director
Physical Electronics Laboratory

W.F. Greenman, Vice President
Advanced Technology Division

SRI International

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CR174792		

4. Title and Subtitle	
Development Program on a Cold Cathode Electron Gun	5. Report Date January 1985 6. Performing Organization Code 506-58-22
7. Author's) C.A. Spindt and C. Holland	8. Performing Organization Report No. SRI Project 5723
9. Performing Organization Name and Address SRI International 333 Ravenswood Avenue Menlo Park, California 94025	10. Work Unit No. 11. Contract or Grant No. Contract NAS 3-23776
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	13. Type of Report and Period Covered Annual 14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager - E.G. Wintucky

16. Abstract

During this phase of the cathode development program, SRI improved the multiple electron beam exposure system used to print hole patterns for the cathode arrays, studied anisotropic etch processes, conducted cathode investigations using an emission microscope, reviewed possible alternate materials for cathode fabrication, studied cathode storage techniques, conducted high power operation experiments, and demonstrated high-current-density operation with small arrays of tips.

17. Key Words	18. Distribution Statement
	For General Release

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
U	U	63	

*For sale by the National Technical Information Service, Springfield, Virginia 22161

CONTENTS

ILLUSTRATIONS

PRECEDING PAGE BLANK NOT FILMED

TABLES

SUMMARY

During this phase of the cathode development program, SRI improved the multiple electron beam exposure system used to print hole patterns for the cathode arrays, studied anisotropic etch processes, conducted cathode investigations using an emission microscope, reviewed possible alternate materials for cathode fabrication, studied cathode storage techniques, conducted high power operation experiments, and demonstrated high-current-density operation with small arrays of tips.

- A new multiple-electron beam exposure system has produced packing densities of 10^7 holes/cm^2, with hole size uniformities within about ± 1.5 percent.
- Anisotropic etching using plasma-based dry etching processes has produced good hole geometries, but more work is needed to reduce process-related contamination problems.
- Experiments on the effects of storage on cathode performance suggest that the cathodes should be stored in a good vacuum when not in use.
- Only preliminary tests were made with the emission microscope because of changing mission priorities. Only one cathode was tested; 75 percent of the tips were observed to be contributing to the total emission when the cathode was operating at the 14 A/cm^2 level.
- High-power tests were designed with a goal of 20 mA CW into a 3 kV anode. We achieved 10 mA CW and demonstrated 42 mA peak with a full wave rectified 60-Hz pulsed driving voltage. The average power at this level is equivalent to 20 mA CW.
- We routinely operated small area cathodes at over 50 A/cm^2 CW and 100 A/cm^2 pulsed. A peak emission of 10 mA (60-Hz pulse drive) was achieved with a 29-tip cathode. This is over 400 A/cm^2.

I INTRODUCTION

This report summarizes the past year's work in an ongoing program at SRI International (SRI) to develop a thin-film field-emission cathode (TFFEC) array and a cold-cathode electron gun based on the emitter array. The objective is to produce a microwave-tube gun that uses the thin-film field-emission cathode as an electron source.

During this report period, the project effort has been directed to fabricating state-of-the-art cathodes for evaluation, studying and improving the fabrication technology with a view toward increasing reliability and performance, and demonstrating high emission-current capability.

The TFFEC, which is based on the well-known field-emission effect, was conceived to exploit the advantages of that phenomenon while minimizing the difficulties associated with conventional field-emission structures, i.e. limited life and high voltage requirements. Field emission has been shown to follow the Fowler-Nordheim equation (Fowler and Nordheim, 1928):

$$J = \frac{AF^2}{t^2(y)\phi} \exp - \frac{Bv(y)\phi^{3/2}}{F} \quad , \tag{1}$$

where J is the emission-current density in A/cm^2, A and B are constants, F is the field at the tip, ϕ is the work function in eV, and v(y) and t(y) are slowly varying functions of y, where

$$y = \frac{3.79 \times 10^{-4} F^{1/2}}{\phi} \quad . \tag{2}$$

Both v(y) and t(y) are tabulated in the literature (Burgess et al., 1953). The field at the tip is

$$F = \beta V \text{ V/cm} \quad , \tag{3}$$

where V is the voltage applied to the diode structure, and

$$\beta = f(r,R,\theta)\text{cm}^{-1} \quad . \tag{4}$$

The relationship between β and the tip radius (r), the anode-to-tip spacing (R), and emitter cone half angle (θ) is complex (Dyke and Dolan, 1956) and difficult to determine accurately. For the purpose of our work it is sufficient to note that β increases as r, R, and θ become smaller. Thus, smaller cathode/anode structure reduces the voltage required for a given emission current.

The conventional field emitter, shown in Figure 1, consists of a short segment of fine wire (usually tungsten) etched electrolytically to form a sharp point (i.e. small r). The segment is mounted on a hairpin filament for support and is then cleaned and annealed in vacuum by passing current through the hairpin filament and heating the tip to incandescence. After cooling, the point produces cold electron emission when a positive voltage is applied to a ring or aperture anode spaced at a macroscopic distance (R) (approximately 1.0 mm) from the emitter tip.

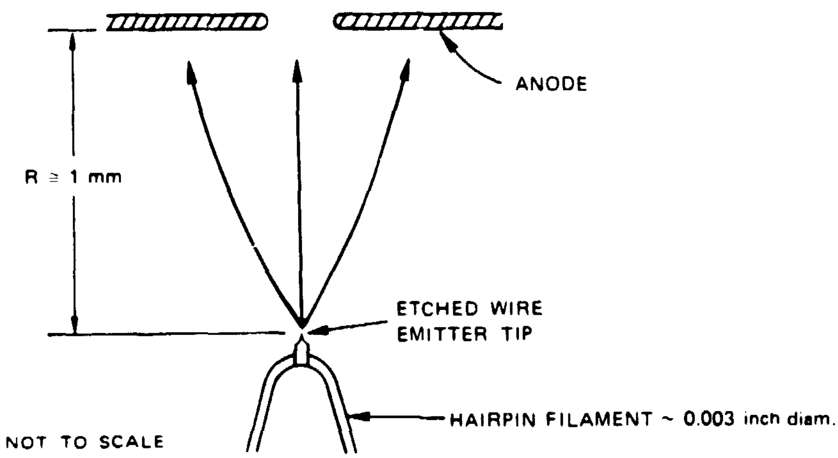


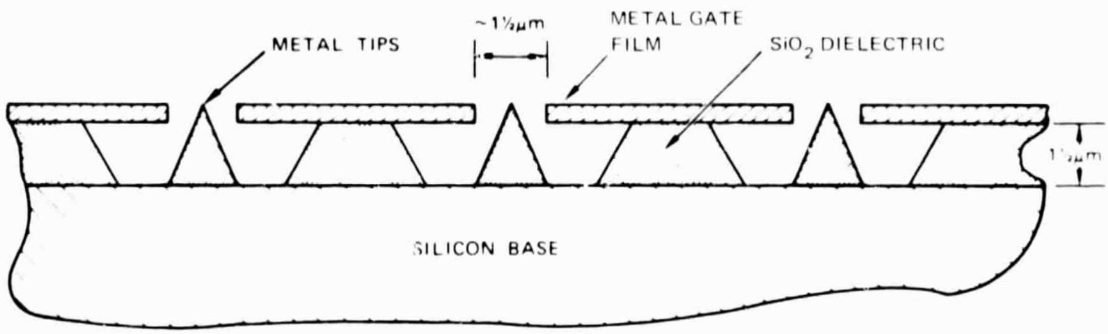
FIGURE 1 CONVENTIONAL FIELD EMITTER AND ANODE

Electric fields of the order of 10^7 V/cm are required for field emission, and with this geometry anode potentials of the order of kilovolts are usually needed to produce the required field. A common difficulty in operating the conventional field emitter cathode arises from the effects of positive ions formed in the interelectrode region being directed toward the emitter tip by the curved field lines that terminate at the tip. Some of these ions have energies in the keV range and can therefore roughen or sharpen the tip by sputtering. [The sputtering rate is determined by the rate of ion formation (which is directly related to the local vacuum pressure and emission current drawn) and by the ion energies (which depend on the applied voltages).] Tip sharpening by ion sputtering during operation increases the local field (for the same applied voltages) and thus progressively increases the emission current and the sputtering rate until an arc or resistive heating of the tip leads to its destruction. Although this effect limits useful lifetimes for conventional emitters, Brodie (1975) has shown that the sputtering effect can be greatly reduced if the emission voltage is below 150 V, and reducing the applied voltage to 50 V might effectively eliminate the sputtering.

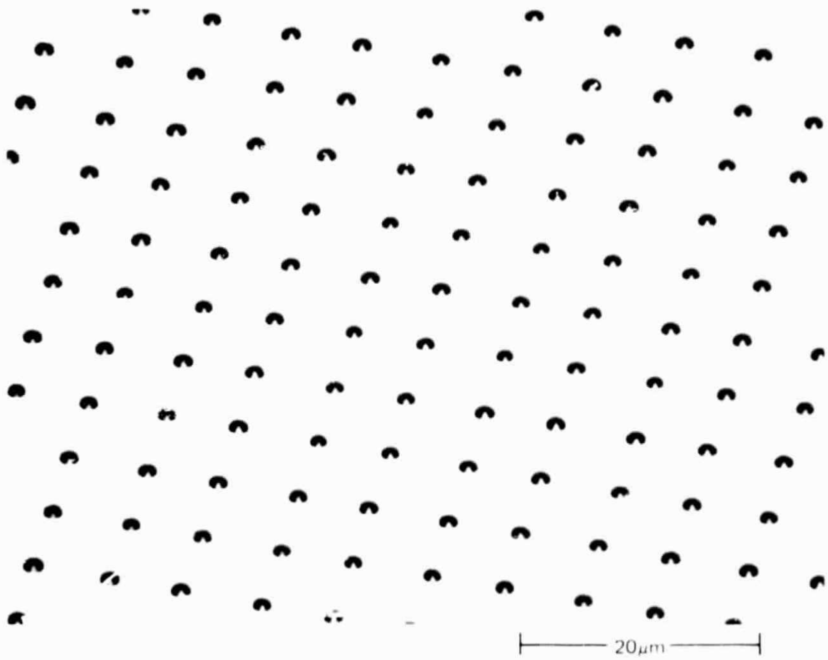
Another difficulty with the etched-wire emitter is that fabricating large arrays of tips for high-current applications would be very difficult, and in densely packed arrays neighboring tips shield each other electrostatically. Thus, large emitter arrays that produce high current densities have not yet been achieved by these means.

In an effort to overcome these difficulties, SRI developed the field emission cathode shown in Figure 2, which consists of a conductor/insulator/conductor sandwich with dielectric thickness of approximately 1.5 μm, holes approximately 1.5 μm in diameter in the top conductor (metal gate film), undercut cavities in the dielectric layer, and metal cones within the cavities. Field emission from the tips of the cones is obtained when the tips are driven to a negative voltage with respect to the gate film. Because of the field enhancement of the tip (small r) and the close spacing between the rim of the hole in the gate film and the tip (small R), potentials as low as 100 V to 200 V across the sandwich can produce large field-emission currents. In addition, dense arrays of the tips can be operated without the tips influencing one another, because the gate film that surrounds each cone prevents reduction of the electric field that would otherwise result from mutual shielding between the tips.

This configuration also reduces the problem of ion bombardment from other high-voltage electrodes, because the tips are well shielded electrostatically by the gate film; that is, the equipotentials contoured about the tip are essentially confined within the cavity, and the potentials between the gate film and other external acceleration electrodes are essentially uniformly spaced and plane parallel. Thus, unlike the single etched-wire configuration, most ions formed between the gate film and an external acceleration electrode are directed toward the gate film, rather than the tip. The ionization volume between the gate film and the tip is very small; any ions formed within this region will have low energies (100 to 200 eV) and will be unlikely to cause significant sputtering damage by striking the tip. This assumption appears to be well-justified: Experimental results show currents averaging over 50 μA peak/tip for more than 65,000 hours from a 100-tip array driven with a 60-Hz pulse. The tips were operating at room temperature and unknown pressure, but probably in the 10^{-9} torr range.



(a) SCHEMATIC OF A THIN-FILM FIELD-EMISSION CATHODE (TFFEC) ARRAY



(b) SEM MICROGRAPH OF TFFEC ARRAY

(c) SEM MICROGRAPH OF TFFEC CATHODE

FIGURE 2 THIN-FILM FIELD-EMISSION CATHODE (TFFEC)

II FABRICATION TECHNOLOGY

A. State-of-the-Art Cathodes

The state-of-the-art cathode for this phase of the program covers an area 1 mm in diameter on an n-type, 0.01 Ω · cm, {111} orientation silicon chip. The silicon chip is nominally 2.5-mm square, and the 1-mm diameter active area consists of 5,000 emitter tips spaced on 12.7-μm centers. This cathode geometry is designated "type 20" in the cathode series (see Figure 3).

The basic cathode-fabrication process has been modified several times during the program. Developments continue as the research progresses and new technologies become available. The basic state-of-the-art cathode-fabrication process at this time is as follows:

(1) Two-inch-diameter silicon wafers are oxidized to a depth of about 1.5 μm in a wet oxygen atmosphere at about 1000°C.

(2) Molybdenum is deposited over the oxide to a thickness of approximately 4000 Å using an electron-bombardment-heated evaporator.

(3) The 2-inch (5-cm) wafer is cut into 1/2-inch (1.27-cm) square substates with a dicing saw.

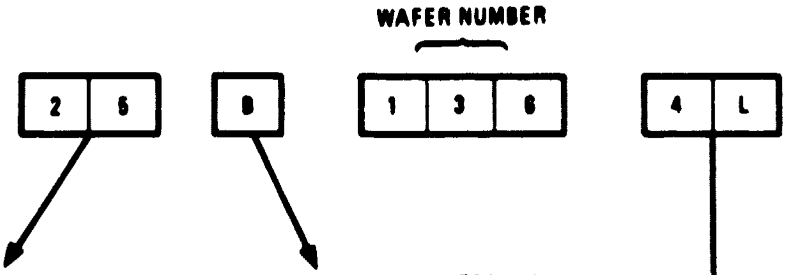
(4) An electron-sensitive resist, poly(methyl-methacrylate) or PMMA, is spun onto the substrates, and the desired pattern of holes is exposed in the PMMA using an SRI-developed multiple electron beam exposure system. Typically, 25 patterns on 0.25-cm centers are formed on the 1.25-cm square substrate.

(5) The PMMA is developed. The molybdenum film is then etched away where it is exposed by the developed holes in the PMMA layer.

(6) The silicon dioxide layer is etched down to the silicon substrate through the etched holes in the molybdenum film; the PMMA is then removed.

(7) Cones are formed in the holes using a dual deposition technique developed at SRI for this purpose (Spindt et al., 1976).

(8) The gate film pattern is etched using photolithography. Typically, this pattern consists of 25 1.78-mm square pads, with a cathode array centered in each pad.



ARRAY TYPES

CODE	TIPS	CENTERS (μm)
20	5,000	12.7
21	1 *	–
22	20,000	6.35
23	100	12.7
24	400	6.35
25	16	12.7
26	40	6.35
27	40,000	4.5
28	10,000	9
29	32	9
30	5,000 †	12.7
31	16 †	12.7
32	64 †	12.7
33	100 †	12.7
34	100	9
35 *	3,500	4.2
36	3,500 ‡	12.7
37	7,000 ‡	9
38	400 †	12.7
39	1	–
40	85,000	2.5
41	200	9

* Wedges, 0.1 mm long
† Wedges, 10 μm long
‡ 0.1 mm X 6 mm array

ARRAY MATERIAL AND TECHNOLOGY

ARRAY CODE	DESCRIPTION
No Letter	p-type (100), wet chemistry
A	p-type (111), wet chemistry
B	p-type (111), RIBE etch
C	n-type (111), wet chemistry
D	n-type (111) RIBE etch

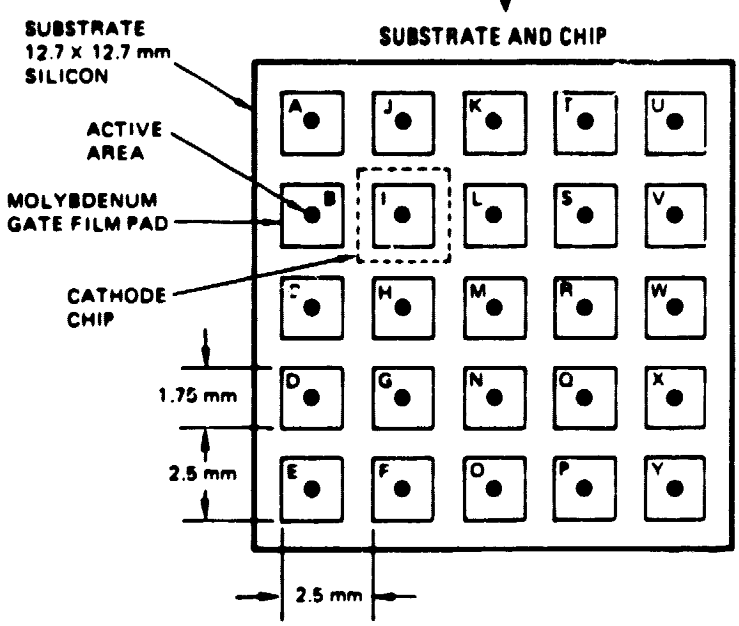


FIGURE 3 CATHODE IDENTIFICATION CODE

Illustrated code indicates 16-tip array on 12.7-μm centers, fabricated on p-type (111) silicon using reactive ion beam etching (RIBE). Wafer is number 136, substrate number is 4, chip is in "L".

(9) The 1.27-cm square substrate is cut into the desired number of cathode chips to correspond with the array pattern. The state-of-the-art cathode is cut into 25 cathode chips, each about 0.25-cm square with the 1.78-mm square molybdenum pad and cathode array centered in it.

(10) The chips are cleaned and mounted ror testing.

These processes have been described in detail in previous reports on this development program (NASA CR-134888, CR-159866, and CR-165401).

B. Advanced Fabrication Processes

During this phase of the program work was done on the multiple electron beam exposure system used for patterning the active area, anisotropic etching techniques, and materials studies for cone fabrication.

1. Active Area Patterning

During the previous report period, SRI modified the multiple electron beam exposure system (MEBES) used for printing arrays of spots in an electron sensitive polymer [poly(methyl-methacrylate) or PMMA] by adding a motor driven stage that could be used to precisely position the beams on the substrate. This system was used to print hole arrays having high packing densities by making a series of step-and-repeat exposures in the PMMA.

During this report period an advanced form of the MEBES (Brodie et al. 1981) became available and was adapted to the cathode fabrication process. Figure 4 is a diagram of the system, which consists of a tungsten hairpin filament, an einzel lens, a beam blanker, an object aperture, first and second deflectors, the screen lens, and the target stage.

The advantages of this system over the original MEBES are many. It has a cryopumped vacuum chamber, which is much cleaner than the oil-pumped system used with the original MEBES. This gives an improved result and reduces downtime for cleaning.

The system also has a well-defined object aperture that is illuminated with a well-defined beam formed by the einzel lens system. The beam blanker can be used to make rapid exposures of short duration and rapid cycle times. The final major improvement is the dual-deflection system that can be used to very accurately position step-and-repeat exposure patterns, or to write patterns such as lines rather than spots.

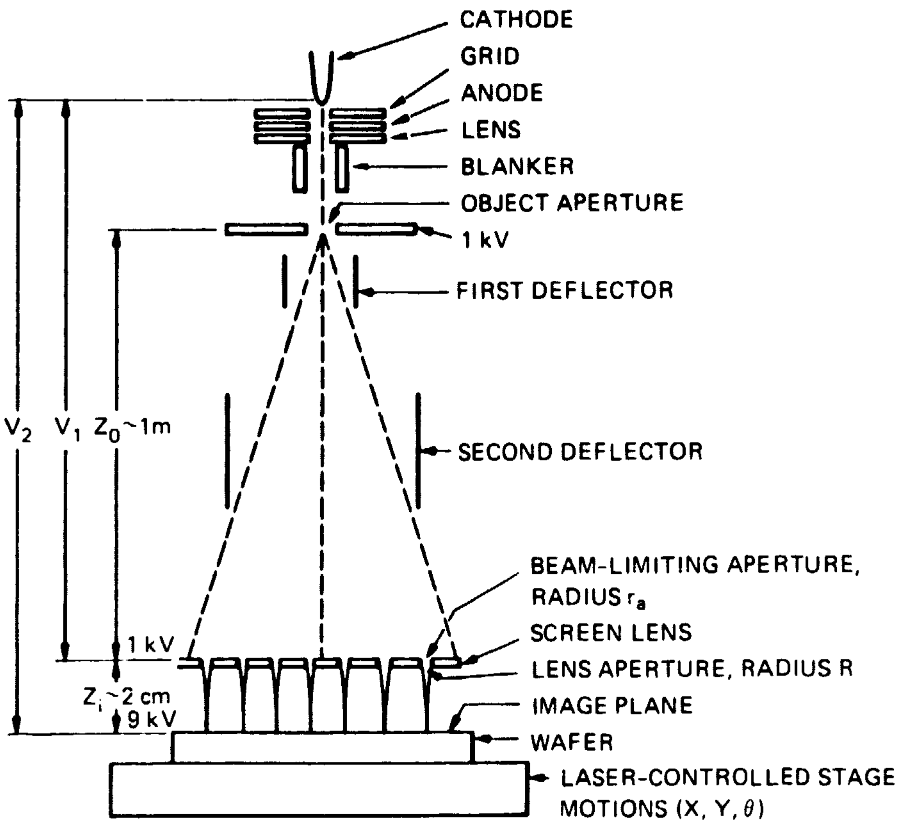
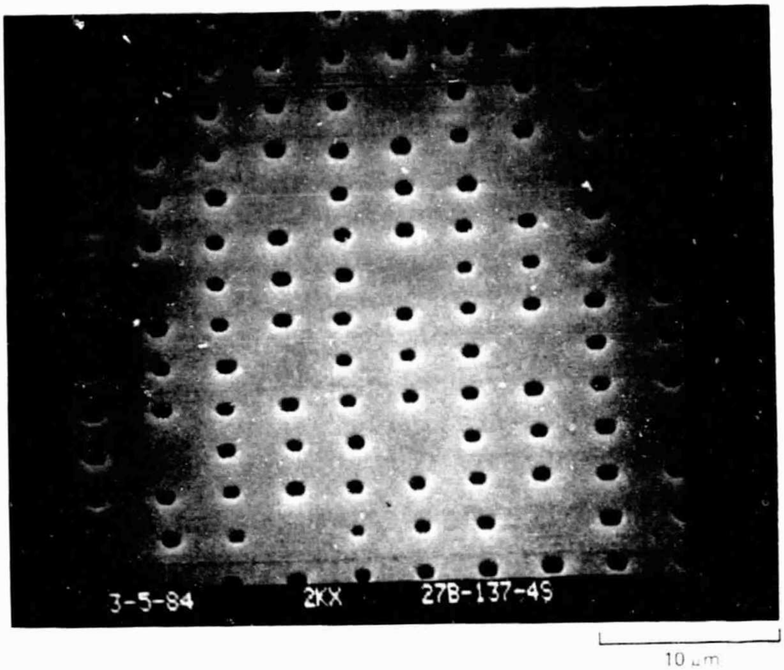


FIGURE 4 MULTIPLE ELECTRON BEAM EXPOSURE SYSTEM (MEBES)

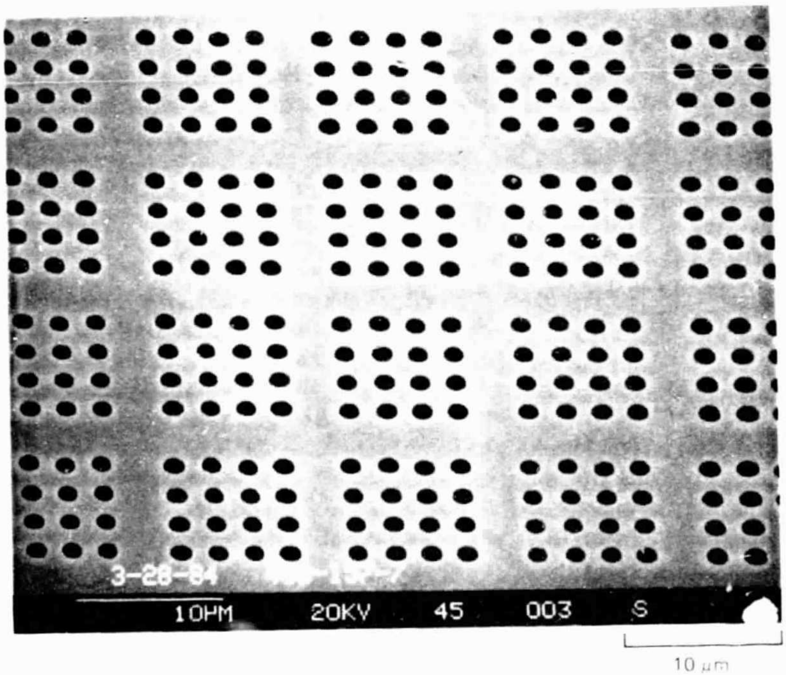
Using deflectors to position the spot on the target rather than mechanically moving the target and screen has the advantage of keeping the target in the same portion of the flood beam during all of the exposures that are made in a step-and-repeat multiple exposure sequence. This improves uniformity because each exposure is more likely to produce the same electron dosage to the polymer film if the flood beam is not moved across the screen.

An illustration of the improved uniformity achieved with the deflector system can be seen in Figure 5. Figure 5(a) is an SEM of a pattern of holes formed with the original screen lens and a step-and-repeat procedure done by mechanically repositioning the screen and target in the flood beam between each exposure. The alignment of the holes is acceptable, but the uniformity of the hole sizes is very poor. Mechanical alignment is not too difficult because the system demagnification factor is about 735 to 1. Thus moving the screen and target 735 μm moves the image only 1 μm, and very precise positioning is possible.

ORIGINAL PAGE IS
OF POOR QUALITY



(a) GENERATED WITH ORIGINAL SCREEN LENS



(b) GENERATED WITH UPGRADED SYSTEM

FIGURE 5 HOLE PATTERNS IN MOLYBDENUM FILMS

But moving the screen and target large distances in the flood beam can lead to nonuniform exposures if the flood beam is not very homogeneous and stable over long periods of time. The result, shown in Figure 5(a), indicates that the beam in the original system was indeed not very uniform or stable; as a result, there is a large variation in the size of the holes that printed (≈ ± 25 percent), and some did not print at all.

Figure 5(b) shows much-improved hole size uniformity, with the hole size variation in the ± 1.5 percent range. With the new MEBES and its dual deflector system, the exposures can be done much more rapidly, and the same portion of the flood beam is used for each exposure. Figure 5(b) is an SEM of a sample fabricated with 16 exposures, each of about 1-1/4 second duration, and a small deflection of the beam between exposures. The spacing between holes is about 2.5 μm between centers, and the groups of 16 holes are spaced on 12.7-μm centers. The packing density is 10^7 holes/cm^2. By filling in the open space between the groups of holes, the packing density can be increased to 1.55×10^7 holes/cm^2. Emitter arrays with these packing densities would require an average current of only about 6.5 μA/tip to produce a current density of 100 A/cm^2.

2. Anisotropic Etching

Referring to Figure 2(c), it is clear that the isotropic wet etch used to form cavities in the silicon dioxide layer produces an undercut of the molybdenum gate film that is much too large for hole spacings of 2.5 μm. Thus, in order to make use of the increased packing density available with the improved MEBES, it will be necessary to develop an anisotropic etch for the silicon dioxide layer. It may be advantageous to have a reduced undercut from a structural point of view as well: The large area of molybdenum overhanging the hole in the silicon dioxide forms a trap for contaminants and is probably more vulnerable to damage in the event of a discharge because it is not supported.

Recently there has been a great deal of effort to develop dry etching systems based on plasma etching. These etching processes can be tailored to produce anisotropic etching in most materials. In an effort to see how this technique could be applied to the cathode structures, SRI established a cooperative effort with the Varian Central Research Labs, so that their sophisticated reactive ion beam etch (RIBE) system could be used to develop an anisotropic etch process for the cathode structure. By the beginning of this report period, we had obtained a good result using CCl_4 in the RIBE system with a chromium resist mask on the sample. This result was described in the preceding report (NASA CR-168212).

During this report period, we made several attempts to repeat this result in the Varian RIBE system. None were successful; and problems with the vacuum system then forced a shutdown of the RIBE system.

Samples were then sent to Plasma Therm's applications laboratory to see how their reactive ion etch (RIE) system would do with the cathode structures. The results were excellent with regard to selectivity of the silicon dioxide etch with respect to molybdenum, and the anisotropy was also excellent. Figure 6 shows SEMs of these results. In Figure 6(a) the substrate was deliberately fractured to provide a view of a hole in cross section. Figure 6(b) shows another cavity viewed at 20° from normal to the surface. This cavity geometry is exactly what we had hoped for. The hole in the molybdenum is nicely tapered; the side wall of the hole through the silicon dioxide is very nearly vertical and does not undercut the molybdenum at all; the etch was stopped right at the silicon/silicon dioxide interface; and the molybdenum has been essentially untouched by the process.

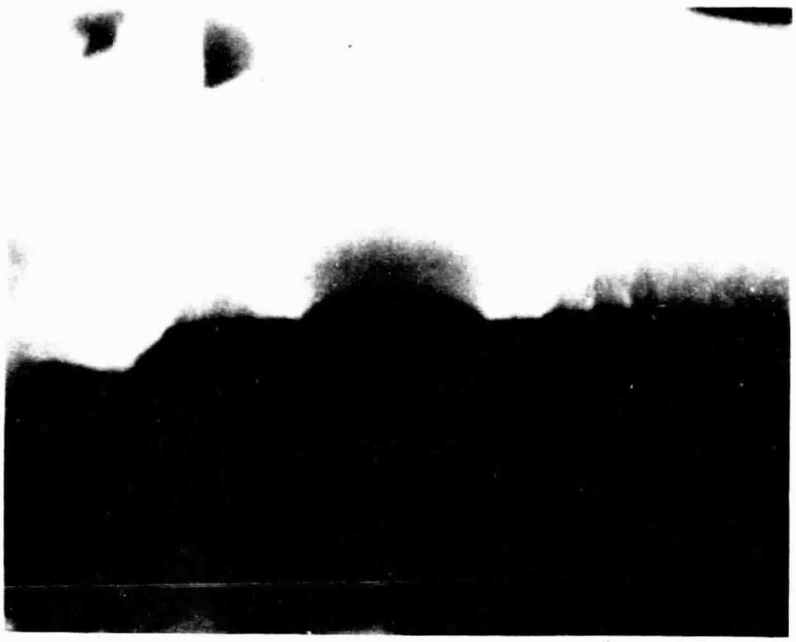
The differences between these samples (with the Plasma Therm RIE) and the samples etched successfully in the Varian RIBE system are that the molybdenum was etched almost all the way through in the Varian RIBE system, and the edges of the holes etched in the RIBE system were not as smooth as those etched with the RIE system.

The Varian RIBE used CCl_4 as the reacting gas and the RIE uses $CHF_3 + O_2$ in the ratio 10:1. The beam energy in the RIBE etch was 500 V; the bias on the target during the RIE etch at Plasma Therm was not reported. Other variables, such as system pressure, are inherent in the differences between the two processes and cannot be meaningfully compared.

Cones have been successfully formed in samples etched in both systems, and emission tests have been made. The results of the emission tests have been very poor with samples from both systems, in that there is always excessive electrical breakdown between the two electrodes (base and gate), frequently even before significant emission can be detected.

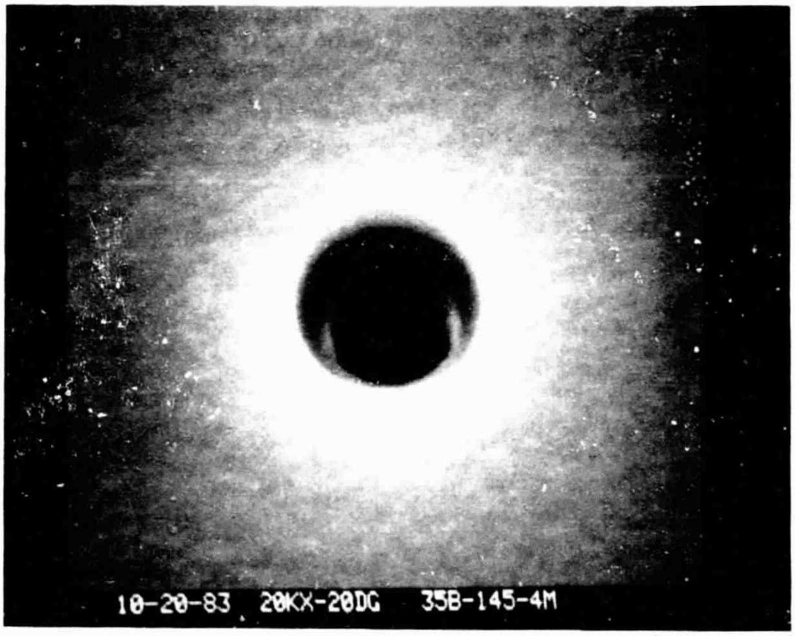
It is known that difficult-to-remove polymers can be formed during reactive ion processes (Flamm, 1981), and it seems very likely that the electrical breakdown is due to contamination of the samples by polymers formed during the etch process. This notion is supported by the good result obtained with the one sample that was coated with chromium during the etch process. The chromium layer was removed in subsequent processing, which would also remove any polymer layers that might have been formed on the chromium during the etch process.

In summary, dry etching processes have been shown to produce ideal structures for the cathode application, but more work needs to be done to eliminate contamination buildup during the etch, protect the surface from polymerized layers with a coating (i.e. chromium), or remove contamination from the surface by subsequent processing that is nondamaging to the cathode structure.



1 μm

(a) CROSS SECTION OF HOLE ETCHED WITH RIE IN SiO_2 (25,000 X)



1 μm

(b) HOLE VIEWED AT 20°, 20,000 X

FIGURE 6 RIE-ETCHED SiO_2 LAYER, MOLYBDENUM TOP LAYER ETCHED WITH WET CHEMISTRY

3. Materials

Field emission is very sensitive to emitter surface conditions because of the strong effect the surface work function and microtopography have on the emission current (see Fowler/Nordheim equation in Section I).

Molybdenum is a convenient material for field emission cathode fabrication because it is refactory; easily evaporated; adheres well to the silicon and silicon dioxide; is selectively etchable with respect to silicon dioxide, silicon, and aluminum oxide; and can be easily etched in a polish-etch mode. Its use is not without drawbacks, however. The most important negative characteristic of molybdenum for this application is that it forms oxides that are unstable and are volatile at relatively low temperatures (800°C), and that oxide formation begins at very low temperatures (200°C). This may be a source of electrical breakdown in some of our tests because of dissociation, migration, and evaporation during operation of the cathode. In addition, the sticking coefficient for gases on metals such as tungsten and molybdenum is much higher than it is for some other materials, such as the carbides (Eisinger, 1958). Thus it would seem that passivating the molybdenum surface with, for example, the transition metals (Davydova, 1979) or coating with stable materials such a titanium carbide which has been reported to yield stable emission (Adachi, 1983), could reduce the incidence of breakdown. A second approach would be to form the entire cone from a more stable material like a carbide. This may be possible because the composition of many carbides is not stoichiometric, and the nonstoichiometric carbides are also very stable (Stroms, 1967). It is reported that titanium carbide can be expressed as TiC_x where x can vary from 0.95 to 0.5 without appreciably changing the stability of the material. This being the case, it should be possible to evaporate $TiC_{0.95}$ and obtain a suitably stable TiC_x.

Other carbides are also interesting in that they are very refactory, chemically stable, have a low capacity for gas adsorption, and have relatively low reported work functions. For example, HFC has a melting point of 3890°C and a reported work function of 2.04 eV (Samsonov and Vinitskii, 1980). This compares extremely well to molybdenum, which has a melting point of 2600°C and a reported work function of at best 4.1 eV (Kohl, 1967). NbC, ZrC, and TaC are also very interesting. Some other materials are interesting but difficult to use for this application because of problems with evaporation or chemical properties (e.g. LaB_6 and TaN).

Experimental investigations of some of these materials will be considered in the next report period.

III CATHODE TESTING

SRI performed a variety of cathode tests during the report period. Routine quality control tests were performed on all cathodes. In addition, SRI tested for the effects of storage environment on the cathode's performance. A brief test was made in an emission microscope to investigate emission uniformity. Tests were also made on high total current operation with large arrays, and on low total current but high-current-density operation using small arrays.

A. Initial Emission Tests

All cathodes that complete the fabrication process successfully are tested in SRI's standard test setup before being subjected to other tests or being shipped to users. This is done to provide a standard level of operation by which the cathodes can be judged and to have a basis by which trends resulting from process changes can be evaluated.

The Appendix lists all cathodes that were tested (including those on other programs, to give as large a data base as possible) by test group. The listing includes bakeout temperature, cathode mount, gate current, applied voltage, maximum emission, number of the tips blown during the test, number of shorts between the base and gate during the test, and final condition of the cathode, [i.e. OK or NG (no good)].

Figure 7 shows the circuit used for the initial tests. It consists of a simple power supply that delivers a 60-Hz half-wave rectified output that is continuously variable between 0 and -500 V peak; a duty-cycle-control gating circuit that is used to operate the cathode at reduced duty cycle (to prevent overheating the collector when operating at emission currents above about 10 mA); and a variable series padding resistor (to prevent excessive emission bursts when the cathode is initially turned on).

The cathode tips are driven to a negative voltage by the power supply, and the gate film is grounded. A collector is biased to about +1200 V with respect to ground to help in overcoming space-charge effects in the emitted beam. The collector is a 316 stainless-steel tube, 3/16 inch in diameter and about 1-1/2 inches long. The tube is bent in a gentle curve, as shown in Figure 7, and the emitted electron beam is directed into one open end of the tube, so as to spread out the landing impact area to reduce the power density at the collector. The tube also acts as a Faraday cage to minimize errors resulting from secondary electron emission. It is open at both ends to pump out any desorbed gases.

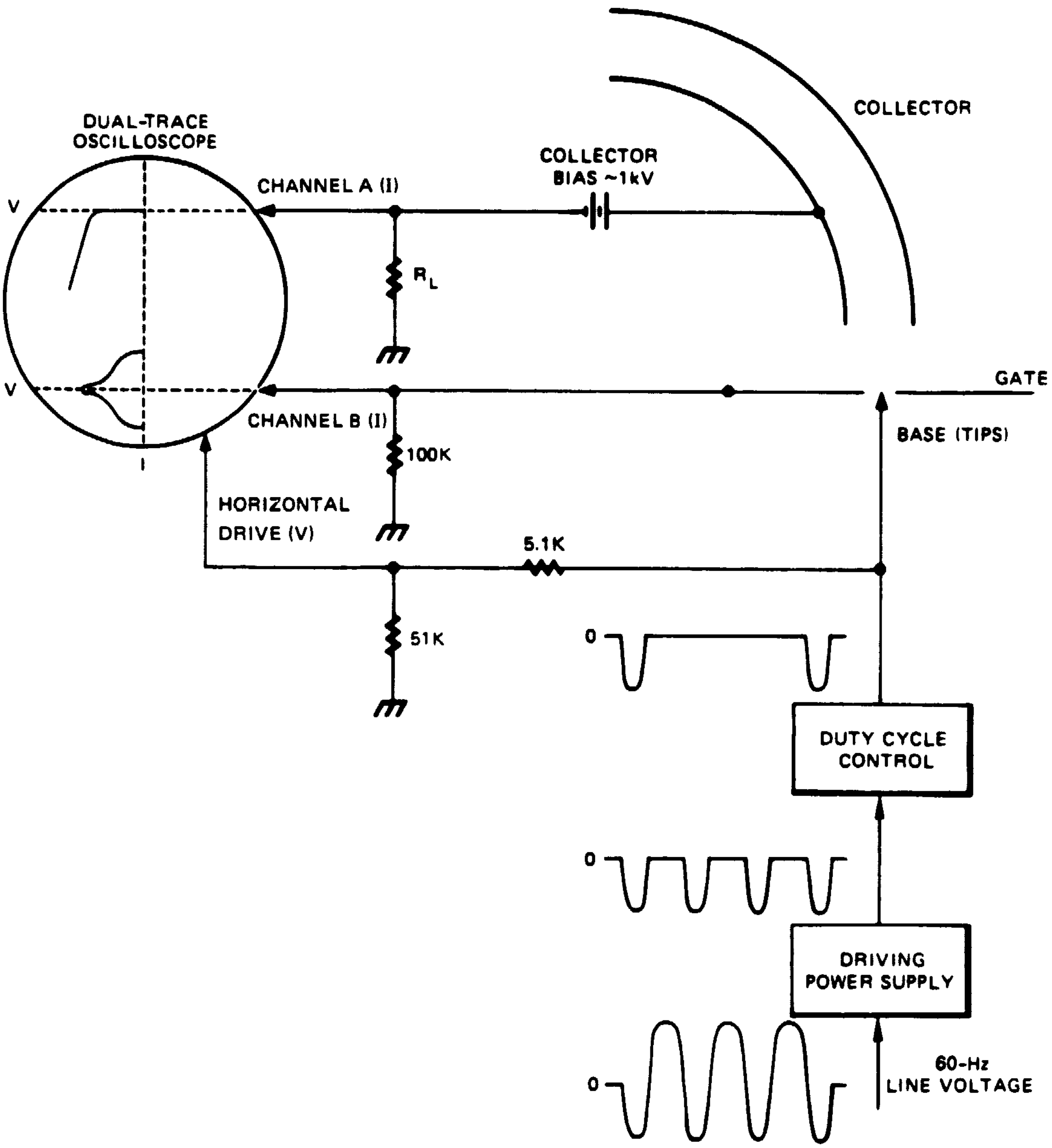


FIGURE 7 STANDARD SETUP FOR EMISSION TEST

The emission process is monitored with a dual-trace oscilloscope, as shown in Figure 7. The voltage applied to the emitter tips is used to drive the horizontal sweep of the oscilloscope through a 100:1 voltage divider; the gate current is monitored by Channel B of the oscilloscope, while the emission current is measured with Channel A. Thus, the applied voltage, the emission current, and the gate current are all monitored simultaneously and can be observed at a glance.

SRI's three test sites, each having space for six cathodes, can all be operated simultaneously; thus, as many as 18 cathodes can be tested at a time. (Usually only 12 are tested at a time because of the characteristics of the vacuum systems and the number of power supplies available.)

Under normal conditions, the cathodes are taken up to 20-mA peak emission with the duty cycle reduced to one pulse in ten through the duty cycle control. Operating at levels much higher than 10 mA with the full 60-Hz driving signal and the usual +1200 V on the collector overheats the collector (and subsequently the cathode, by radiation from the hot collector). Collector temperatures to 900°C have been observed, caused by bombardment from the cathode at peak emission levels of about 20 mA and a 60-Hz driving voltage. These extreme temperatures can be damaging and should be avoided.

B. Cathode Storage and Retesting

Historically the cathodes have been stored in ordinary aluminum trays kept in plastic parts boxes, or wrapped in aluminum foil and placed in glass bottles for shipping. An early test to determine the suitability of these measures by retesting three cathodes that had been stored in the plastic boxes for several months showed no significant change in emission characteristics as compared to the original cathode tests.

Difficulties experienced at NASA with cathodes that had been shipped to the Lewis Research Center led to additional tests of cathodes that had been stored in air. Table 1 shows the results of three successive tests with six cathodes. The cathodes were stored in aluminum trays inside plastic parts boxes between tests. It is remarkable that three of the cathodes showed no change in the second test--the same result as our first three tests, many months before. However, the other three showed significant change, and all six showed significant change after the third test. Clearly a better storage system is needed.

A second test was done with cathodes that had been stored a short time in air, but most of the time in a standard dessicator pumped out with an oiless mechanical pump to ~ 50 millitorr. There was no intentional difference in the way the cathodes were handled, stored, or tested. The time between tests was much longer (6 months) than the time between the tests on cathodes stored in air. The results were again mixed, as shown in Table 2, with four out of nine cathodes that were

Table 1

RESULTS OF RETESTING CATHODES
AFTER LONG PERIODS OF STORAGE IN AIR
(Cathodes were hydrogen fired
at 600°C 1/2 hour before each test)

Cathode	Test Number	Voltage (V)	Emission (mA)	Time Between Tests (mo)	Total Tips Blown
28A-140-2K	1	152	20		5
	2	156	20	1	5
	3	174	20	2	52
28A-140-2M	1	158	20		52
	2	160	20	1	79
	3	166	20	2	>200
28A-140-2N	1	156	20		22
	2	157	20	1	22
	3	160	20	2	70
28A-140-21	1	153	20		10
	2	163	20	1	50
	3	205	20	2	~300
28A-140-1J	1	151	20		9
	2	150	20	1	9
	3	98	0.001	2	10 failed
28A-140-1P	1	160	20		13
	2	164	20	1	35
	3	176	20	2	52

tested giving better performance in the second test and suffering an insignificant loss of tips (three or less). However, the remainder showed either a large increase in the voltage required to reach 20-mA emission or a large loss of tips, or both. In every case except one (where a contact failed that had nothing to do with the cathode), the cathodes reached the 20-mA goal, and this is encouraging. In fact, the same can be said for the group that was stored in air, but the storage times were much shorter, and the one failure was an odd short at very low voltage and with very minimal damage. This is a very rare failure mode.

The data clearly show that, although there are no overwhelming problems, there is a trend toward increased failures with storage time and perhaps also with the number of tests or total operating time.

Table 2

RESULTS OF RETESTING CATHODES AFTER STORING
IN DESSICATOR WITH ROUGH VACUUM FOR SEVERAL MONTHS
(Cathodes were hydrogen fired
at 600°C 1/2 hour before testing)

Cathode	Test Number	Voltage (V)	Emission (mA)	Time Between Tests (mo)	Total Tips Blown
20A-129-3B	1	118	20		0
	2	215	20	10	7
20C-150-1G	1	No contact			0
	2	205	20	6	80
20C-150-1B	1	162	20		0
	2	140	20	6	2
20C-150-1C	1	164	20		1
	2	155	20	6	2
20C-150-1D	1	164	20		4
	2	155	20	6	7
20C-150-1F	1	164	20		28
	2	162	20	6	30
28A-140-20	1	121	20		9
	2	158	20	6	>100
28A-140-2R	1	110	20		65
	2	139	20	6	71
28A-140-2Q	1	110	20		67
	2	No Contact		6	

To help sort some of these variables, a third test was set up in an appendage to our standard test chamber with a bakeable valve on it, so the appendage could be sealed off with the cathodes and kept under vacuum between tests. Of course, it is not possible to examine the cathodes between tests when storing them in this way, but it is possible to do several repeat tests to see if a large number of failures occur.

Table 3 shows the results of these tests. There is a distinct reduction in the total number of tips damaged and improvement in the consistency of performance from one test to the next with regard to the voltage required to achieve a given current. The cathodes were in the chamber for a total of almost 10 months and were taken up to 20 mA three

Table 3

REPEAT TESTS, STORED IN SITU

Cathode	Test Number	Voltage (V)	Emission (mA)	Time Between Tests (mo)	Total Tips Blown
20C-157-3B	1	100	20		
	2	95	20	1	
	3	92	20	1 1/2	
	4	60	0.01	3 1/2	
	5	60	0.01	3	0
20C-157-3C	1	116	20		
	2	109	20	1	
	3	103	20	1 1/2	
	4	60	0.01	3 1/2	
	5	60	0.01	3	5
20C-157-3D	1	90	20		
	2	90	20	1	
	3	91	29	1 1/2	
	4	60	0.01	3 1/2	
	5	62	0.01	3	4
20C-157-3F	1	95	20		
	2	118	20	1	
	3	139	20	1 1/2	
	4	58	0.01	3 1/2	
	5	60	0.01	3	8
20C-157-3H	1	100	20		
	2	90	20	1	
	3	89	20	1 1/2	
	4	Lost contact			
	5				3 (contact repaired)
20C-157-3H	1	109	20		
	2	98	20		
	3	100	20		
	4	68	0.01		
	5	65	0.01		3

times during that period. These cathodes were taken out of the chamber, inspected, and immediately placed in a 1/2-inch-diameter copper pinch-off tube, which was pumped down on a vac-ion system and pinched off for long-term storage in a sealed-off, evacuated container. The tube will be opened and the cathodes will be remounted in the test chamber at a later date to test the effectiveness of this storage technique.

C. The Emission Microscope

An emission microscope has been assembled and tested with good results, following some early difficulties with high-voltage breakdown. The design is shown in Figure 8. The original idea was to mount the entire structure on one flange, including electrical contacts and feedthroughs. In this way, the entire column could be worked on easily by simply removing one flange from the vacuum system. However, this design was troubled with electrical breakdown between the high-voltage flight tube and the leads to the cathode and first lens. The electrical feedthroughs for the first lens and cathode were then moved to a header near the cathode end of the microscope, as shown in Figure 8. This made mounting of the cathode a little more cumbersome; but, more important, it eliminated the voltage breakdown problem.

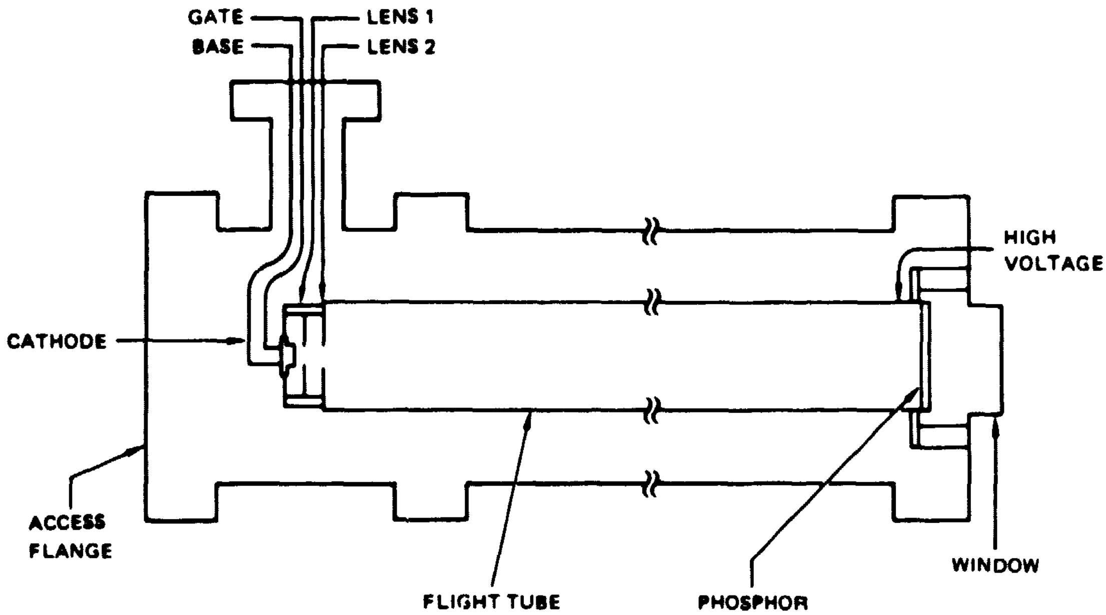


FIGURE 8 EMISSION MICROSCOPE SETUP

Typical values for first trial: Gate: at ground, Base: at -155 V, Emission: 200 μA total, Lens 1: -175 V, Lens 2: + 5 kV, Tube: + 5 kV.

Cathode 25A-156-5T was tested in the emission microscope. This cathode had a 3 x 3 array of tips on 12.7-μm centers. The entire system was baked at 400°C for cleaning prior to turning the cathode on. The cathode was first operated with our standard 60-Hz half-wave rectified power supply and +1200 V on the flight tube and phosphor. The voltage on the flight tube, second lens, and phosphor was then increased to

+5 kV and the cathode emission brought up to 250 μA with the 60-Hz half-wave driving voltage. The cathode was then changed to a CW driving voltage and brought up to emission levels in the 20-μA range. The gate was at ground potential, and the tips were driven negative with the dc power supply.

A dc potential of -130 V applied to the tips produced 20 μA of emission. With 4.5 kV on the phosphor and second lens, -120 V was required on the first lens to focus an image of the cathode on the phosphor. This is undesirable, because a negative voltage on the first lens can create a problem with electrons returning to the positive gate film under the influence of space charge effects when the cathode is operated at high current-density levels. Bombardment of the gate in this way can cause heating, desorption, and electrical breakdown and should be avoided. However, an image was obtained, and a decision was made to carry on as far as possible with this configuration and modify the system later, to see if operation with a positive potential on the first electrode could be achieved.

The first image of the cathode showed three spots, one of which was very bright compared to the other two. There was some radial flaring or "beaconing" from the bright spot, but this effect was not as prominent as has been observed in the NRL emission microscope.

As the driving voltage was raised to increase the total emission level, the original three tips became brighter and others began to appear. The emission was slowly increased to a total of 200 μA, where the gate current reached an excessive level because of the negative potential on the first electrode. At this point, spots could be seen on the phosphor corresponding to seven of the nine tips. The original three remained the most prominent throughout the eight days during which the test was run. The three prominent tips took turns as the brightest emitter of the group. Each tip went through a cycle of low initial brightness, slowly increasing to maximum brightness, followed by a slow decline to an intermediate brightness that seemed to be very stable. Table 4 lists the total current from the cathode at various voltages and the relative intensities of the images of the tips on the phosphor. The intensity ranges from 1 to 10, with 10 being the brightest. The central tip (number 5) was the first dominant tip and was always quite visible. Tips 4 and 8 were also always visible, but not strong at the beginning. All of the others, except 1 and 6, were visible at various times but were not continuously visible. Number 9 was continuously visible after it first appeared, but did not appear until the total current was up to 100 μA. It also continuously improved after first appearing and, much like 4, 5, and 8, gave the impression that it would become dominant if given the time. In other words, it would have eventually scored 10 if the experiment had not been terminated.

As mentioned earlier, the first electrode required a negative voltage to achieve focus. This was unfortunate, because gate current due to space charge effects rose to dangerous levels when the lens was focused, and eventually a breakdown in the gun terminated the

Table 4

RELATIVE BRIGHTNESS OF THE CATHODE TIPS
DURING TESTING IN THE EMISSION MICROSCOPE

Date (1983)	Voltage (Volts)	Total Current (μA)	Tip Number and And Relative Intensity*†								
			1	2	3	4	5	6	7	8	9
6/10	130	20	0	0	0	1	6	0	0	1	0
6/13	140	30	0	1	1	2	6	0	0	2	0
6/14	155	90	0	1	1	6	10	0	0	4	0
6/14	150	100	0	1	1	6	10	0	0	4	1
6/15	150	70	0	1	1	5	8	0	0	4	1
6/15	160	130	0	3	3	8	10	0	1	8	3
6/15	158	160	0	0	3	6	5	0	0	10	3
6/17	158	230	0	0	0	10	5	0	0	5	4
6/18	155	200	0	4	4	10	5	0	0	5	4

*10 = very bright, 5 = moderately bright, 1 = very dim.

†Tip positions:

① ② ③
④ ⑤ ⑥
⑦ ⑧ ⑨

experiment. The lens will be modified to reduce this effect, and additional tests will be made to see if more tips can be brought to maturity on a similar cathode. The impression gained from this first test is that the tips go through a turn-on sequence that goes from very dim first emission to very bright to moderate. If the tip survives the very bright phase, then it will be very stable and long-lived in the moderate stage.

More tests will be done to determine the effects of various treatments on uniformity, stability, and other phenomena such as the "beaconing" or flashing effect seen here and to a larger extent at NRL. However, the time at which this will be conducted is uncertain because of a shift in project emphasis to demonstrating high emission current levels in the CW mode.

Nine tips emitting 200 μA CW is an average of about 20 μA/tip CW. This is 5 times greater than the CW emission that would be required to produce 20 mA CW in a 5000-tip array. At this level of average emission (20 μA/tip), about 75 percent of the tips were contributing. More tests should be made to see if this is typical, and to study techniques for improving uniformity if necessary.

D. High-Power Tests

During this report period, there has been an emphasis on demonstrating an emission level of 20 mA in the CW mode with 3 kV on the anode. The standard test system (Figure 7) cannot support power levels of this kind so a new collector/anode structure has been built with water-cooled electrodes to prevent overheating. Figure 9 shows the

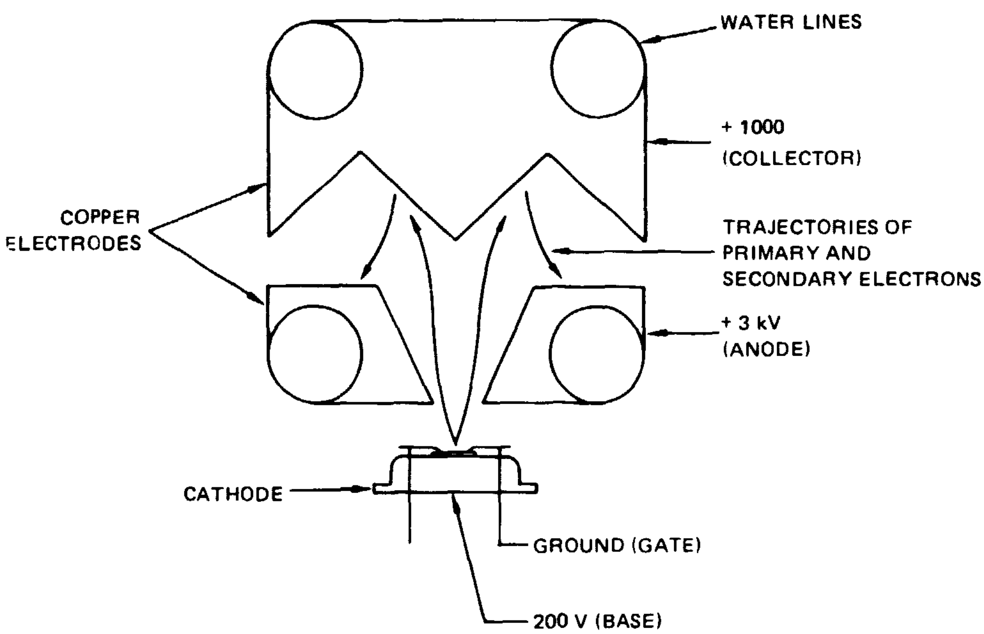


FIGURE 9 SCHEMATIC OF COLLECTOR SYSTEM TO REDUCE POWER HANDLING PROBLEMS AT THE COLLECTOR

The system does not have rotational symmetry. The opening in the anode is rectangular in cross section (a slot), and the "VEE" groves in the collector are long, straight grooves parallel to the slot in the anode.

structure that was built for this purpose. It consists of two electrodes electrically insulated from each other and separately water-cooled. The idea is to accelerate electrons emitted from a cathode to

3000 V through an opening in the first electrode (anode) and collect them on the second electrode (collector), which is at a reduced potential (~ 1000 V). Secondary electrons produced at the collector will return to the back side (collector side) of the anode and be collected there. The electrons impacting the collector, where reflected primaries can return to the cathode, are at 1000 eV of energy, which is no more than is normally seen in the standard test setup with stainless steel collectors. The higher-energy impact of secondaries on the back side of the anode should not cause any difficulty because the impact area is between the two water-cooled electrodes; any ions formed should merely proceed to the other water-cooled electrode and not involve the cathode in any way.

The total power that must be handled is 60 W, which is well within the capabilities of water-cooled copper electrodes of this size. For example, water-cooled electron-beam-bombarded evaporators used in the laboratory routinely handle 1000 W and only rarely suffer a voltage breakdown.

The first high-power tests were with two tubes having these water-cooled electrodes, with the cathodes placed 5/8 inch from the anode. For the initial cathode start-up, 1200 V was applied to both the collector and anode. The plan was to increase the voltage slowly to +3 kV after 20 mA was reached. One cathode (20A-120-3D) had been tested in our usual test setup with stainless steel collector tubes and low-duty-cycle pulsing to 20-mA peak emission. The other (20B-137-2G) was one of the new RIBE etched group and was not pretested. (At this time, none of the RIBE group had been tested, so we were not yet aware of the poor performance of this group caused by contamination problems.)

Cathode 20A-129-3D had performed very well in its initial test and produced 20-mA peak current with 119 V applied between the base and gate. There were no tip failures, and the gate interception was less than 1 μA with 1200 V on the collector. However, the cathode had been stored in a plastic parts box under laboratory air for over a year since its initial test, and, as reported earlier, we have since found that many cathodes do not do well after storage under these conditions. Thus, it is not too surprising that 20A-129-3D shorted at 0.1-mA emission and, although we were able to clear it and achieve 10-mA peak eventually, it never behaved well.

Cathode 20B-137-2G also reached 10 mA, which was probably better than we could reasonably expect in the light of the generally poor performance of that particular group of RIBE cathodes.

For the next trial, two new untested cathodes from a known good group were mounted in the tubes (20C-157-3L and 20C-157-3M). The cathodes were again 5/8 of an inch from the anode, and, for the initial startup, the anode and collector were biased at +1200 V. Both tubes were on the same vacuum system, with valves that could be closed to maintain vacuum in the tubes if the system had to be opened for any reason.

Cathode 20C-157-3L was taken to 5 mA with our usual 60-Hz half-wave rectified driving voltage. The emission was very stable during this time, with no visible fluctuations on the monitoring oscilloscope. The gate current was also very stable and was -7 μA-peak at 10-mA peak emission current. [minus gate current indicates electron flow from the gate to the anode.] The emission was then shut down, and the anode was increased to 3 kV while the collector was left at 1200 V). The emission was then slowly increased.

At 10 mA there was, without warning, a very sharp, loud, arc in the power supply, and the cathode shorted irreparably. Subsequent examination of the cathode showed a large area of the gate film had been melted and blown away, including a large area outside of the active area. There were also discharge marks on the gate hold-down disc. An interesting feature in the damaged area was that many of the tips were undamaged, even though the gate film was melted away. It seemed as though the arc was between the anode and gate, rather than tips and gate.

A special power supply was assembled for slowly increasing the duty cycle at any given peak emission level. Figure 10 is a schematic of the circuit. With the circuit shown, the emission can be brought to the desired level with the usual 60-Hz half-wave rectified driving voltage. Then the second half-wave of a full-wave rectified driving voltage can be slowly brought up to the level of the first half-wave, while the first half-wave is held at the desired value. Finally, a CW voltage can be applied to slowly fill in the valleys between the full-wave rectified driving pulses, and full CW operation can be approached while continually operating at the peak level with the 120-Hz pulse (full-wave rectified) driving voltage.

In the first test with this circuit, cathode 20C-157-3M was taken to 20-mA peak, 60-Hz half-wave emission with 1200 V on both the anode and collector. The voltage on the collector was then increased slowly, while the emission was maintained at 20-mA peak, 60-Hz half-wave and the anode was kept at 1200 V. During this time, the emission was very stable and quiet, but the gate current was higher than we would like (-30 μA). The emission was left at 20-mA peak, 60-Hz half-wave over the weekend for 63 hours, with 3 kV on the collector and 1200 V on the anode, during which time the emission was uninterrupted.

The second half-wave of the 60-Hz full wave supply was then slowly brought up to 20-mA peak. Again, the emission current was very stable, but the gate current was slightly erratic. The full-wave emission is shown on the oscillograph in Figure 11. The emission current was divided between the anode and collector, with 35 percent going to the anode when the collector was at 3000 V and the anode was 1200 V. After two hours of stable emission at 20-mA peak, 60-Hz full-wave emission, CW voltage was applied to the cathode while the full wave emission was held at 20-mA peak.

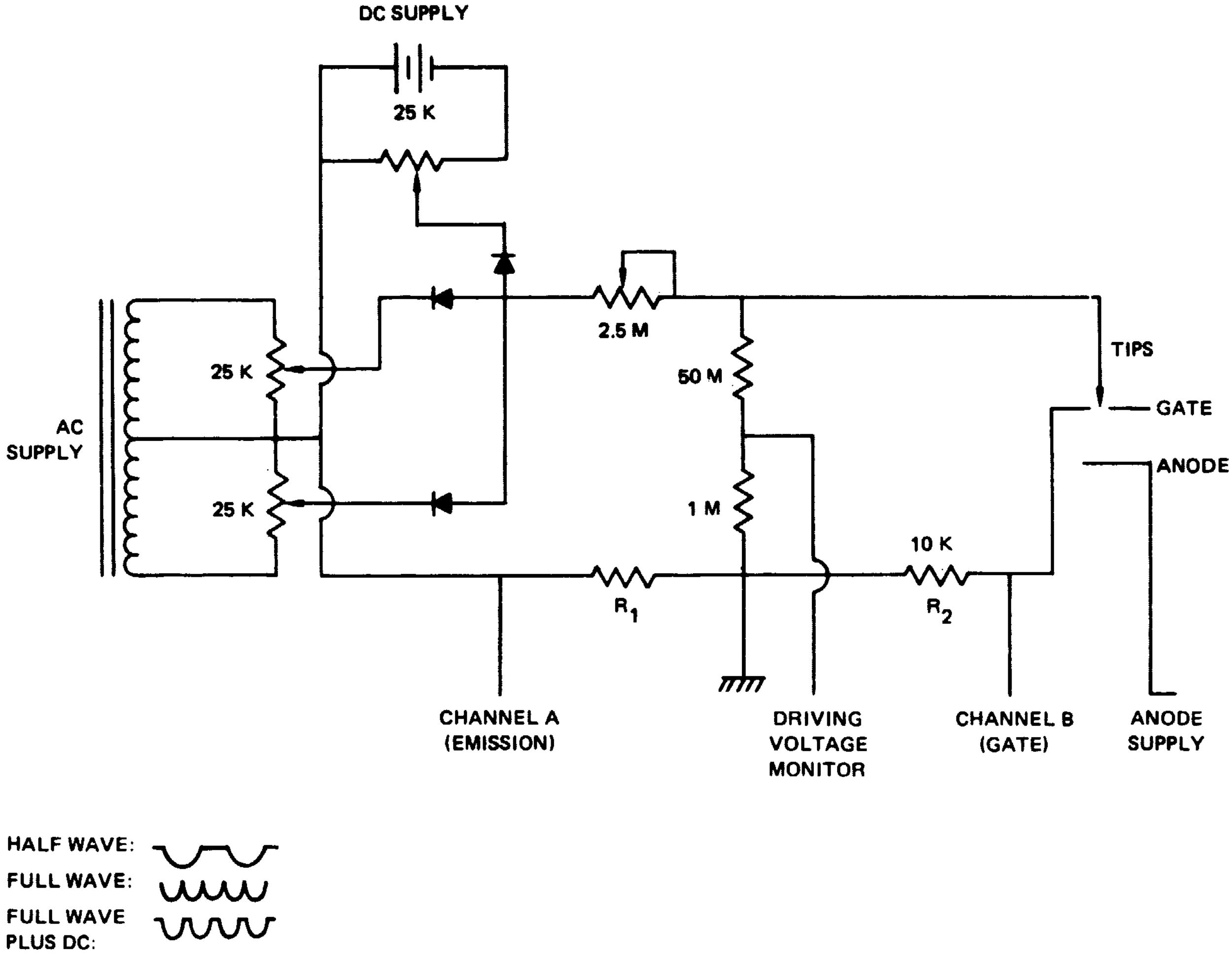


FIGURE 10 COMBINATION HALF-WAVE, FULL-WAVE, AND CW SUPPLY

The amplitude of each half-wave and the CW can be varied independently.

The CW emission was brought up to 1 mA with the full-wave left at 20 mA. For 2-1/2 hours the cathode was stable under these conditions, and then, without warning, it shorted. Examination showed that a devastating arc had left a large crater in the cathode, well into the silicon. The damage was quite different from that seen on 20C-157-3L, which had no damage to the silicon.

Ideally all of the emission should go to the collector, rather than have the large interception by the anode that we measured with these two tubes. Therefore, for the next trial we moved the cathode very close to

ORIGINAL PAGE IS
OF POOR QUALITY

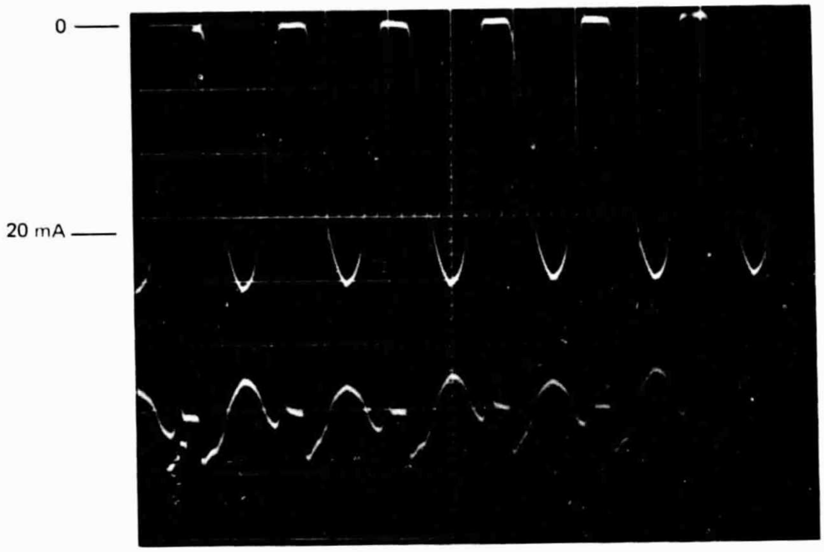


FIGURE 11 FULL-WAVE 60-Hz EMISSION

Top trace (emission): 5 mA/cm vertical, 5 ms/cm horizontal; Bottom trace (gate current): 20 μA/cm vertical, 5 ms/cm horizontal; Cathode 20C-157-3 M; Peak Voltage, 164 V; Anode, 3 kV; Collector 1.2 kV.

the anode (~ 1-1/2-mm spacing) in one tube, and in the second tube, we added lenses to try to shape the beam so that it could miss the anode. For this trial, rectangular-shaped emitter arrays were used, rather than the usual circular array. The arrays are 100-μm wide and 6-mm long and have about 3700 tips. These were used because in earlier experiments this type of cathode had produced 50-mA peak emission with the 60-Hz half-wave driving voltage rather routinely, and the ribbon-like geometry is better suited to the rectangular geometry of the collector system.

Cathode 36C-149-5F was mounted in the tube with a lens meant to keep the beam from hitting the anode. The lens system was not entirely satisfactory, because when sufficient voltage was applied to the focus electrode to steer the beam through the anode aperture, current to the extractor electrode (closest to the cathode) and gate increased sharply. Thus we were again forced to accept what turned out to be about 35 percent interception by the anode. Nevertheless, the cathode was well behaved and gave very stable emission up to 20-mA peak, with the half-wave 60-Hz driving voltage. There was one short at 12-mA peak, which came without warning and was cleared easily. After clearing, the cathode returned to the emission current voltage characteristic that it had exhibited before the short. The cathode was operated for 5 days at 20-mA peak emission with the half-wave 60-Hz driving voltage. The emission was very quiet and stable, but the gate current varied from -14 μA to -20 μA and had periods of noisy behavior. The second half-wave was then phased in while the first was held at 20-mA peak. With both half cycles at 20-mA peak, the emission was still very quiet and stable, but the gate current was disturbingly erratic: The peak value varied from -18 μA to -26 μA. After eight hours, the emission had not changed and was still very stable. The cathode was left at this level overnight and was found to be shorted in the morning. Attempts to clear the short were unsuccessful.

Subsequent examination showed that a group of about 150 tips had blown, with large areas of gate film blown away, including a section out of the active area. There was little damage to the silicon base or silicon dioxide.

The second tube had cathode 36C-149-5E mounted 1/16 inch from the anode. This cathode was started with +1200 V on both the anode and collector. (Only one 3-kV supply was available, and it was being used on the first tube at this point.) The cathode was brought up to 10-mA peak with the half-wave supply. The anode was then increased to +3 kV, and the second half-wave was phased in, while holding the first at 10-mA peak. After the second half-wave reached 10-mA peak, the voltage was increased on both half-waves together to increase the peak full-wave emission to 20 mA over a period of two days. The emission was very quiet and stable during this time, and the gate current was also stable at -9 μA when the peak emission was 20 mA.

At this time the decision was made to attempt to achieve a power level equivalent to 3 kV and 20 mA CW in the full-wave mode. The feeling was that this would be a good way to condition the tube at the desired power level without having to introduce untried power supplies. The area under the emission trace on the oscilloscope (Figure 11) was used to determine a pulsed equivalent of 20 mA CW power current level. This turned out to be 42-mA peak full wave. The emission from cathode 36C-149-5E was then increased from 20-mA peak full wave to 42-mA peak full wave over a period of four days. Again, the emission and gate current were very quiet and stable. When the emission was at 42-mA peak, the gate current was -20 μA as shown in Figure 12. The anode was +3 kV and the collector was at +1200 V. The equivalent CW emission was calculated to be 47 percent of the peak or about 20 mA.

While operating at 42-mA peak full-wave, a partial power supply failure caused the anode voltage to drop to 1200 V. This, in turn, caused the gate current to go from -20 μA to -50 μA because of the effects of space charge at the cathode with the reduced accelerating field. Fortunately there was no evidence of damage, and the emission remained stable at 42-mA peak with 196 V applied to the cathode when the +3 kV anode supply was restored. The anode supply failed again on the next day, and shortly thereafter the cathode shorted. The emission was stable and quiet up to the time of the sudden failure. The gate current was also stable except during the anode supply failures.

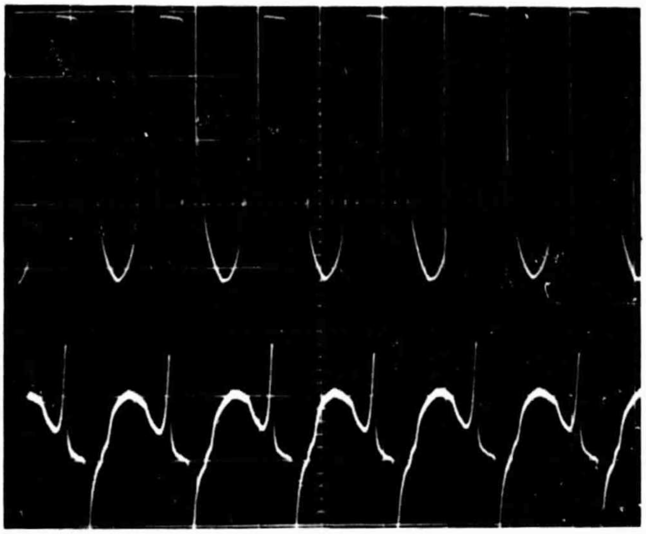


FIGURE 12 FULL-WAVE 60-Hz EMISSION; AVERAGE CURRENT EQUAL TO 20 mA CW

Top trace (emission): 10 mA/cm vertical, 5 ms/cm horizontal; Bottom trace (gate current): 20 μA/cm vertical, 5 ms/cm horizontal; Cathode, 36C-149-5E; Peak voltage, 196 V; Anode, 3 kV; Collector 1.2 kV.

This result is very encouraging: The cathode produced the average power required with peak current and power levels well in excess of the CW goals. However, the fact that there was a sudden discharge after several days of operation is disappointing, and at this time we still do not know if we are dealing with a discharge that is initiated at the cathode or at the anode.

We conducted additional trials with the usual 5000-tip arrays in different configurations in the tubes with no different results. The highest level of CW emission that has been achieved was with two cathodes placed about 1/4 inch from the anode. The cathodes were 20C-171-6C and 20C-171-6F. Both were baked at 310°C for 36 hours and then turned on after cooling to room temperature. 20C-171-6C was brought up to 10-mA peak 60-Hz pulse with +1200 V on the anode and collector. At that point, the gate current was observed to be -38 μA, which was judged to be higher than we would like.

The only way to reduce the gate current was to increase the collector voltage. We also want to operate in the CW mode, so the decision was made to increase collector voltage to +2000 V and reduce the emission current to 1 mA CW. This is approximately the same power level that we had with the 10-mA peak 60-Hz pulse, and 1200 V on the collector. The water was also turned on at this time. The cathode was slowly brought to 10 mA CW with +1200 V on the collectors and found to be very stable. However, the gate current was again high, -27 μA.

The decision was made to slowly increase the voltage on the collector in order to reduce gate current while maintaining 10 mA CW. This was done by increasing the collector voltage in 200-V increments and leaving it at each level for a few hours to see if any changes occurred. The gate current diminished with each increase in collector voltage, and at +2800 V on the collector the emission was unchanged at 10 mA CW and gate current was down to -11 μA. The emission was left at 10 mA CW with +2800 V on the collectors overnight, with a chart recorder monitoring the emission. At about 22:00 hours, the emission suddenly ceased and the cathode was found to be shorted in the morning. Figure 13 shows the chart recording of the emission while the cathode was operating at 10 mA CW and the voltage on the collector was being increased. The emission was very stable and no sign of trouble could be detected from the emission current or the gate current. The emission had been at 10 mA CW for about 30 hours when the short occurred, and the collector voltage had been at +2800 V for about 10 hours.

The cathode (20C-171-6F) in the other water-cooled system was also taken to 10 mA CW with +2000 V on the collector and left at that level for 63 hours over the weekend. It had low gate current (~ -3 μA at 10 mA CW with +2000 V on the collector), and the plan was to increase the emission to 20 mA CW, or until the gate current increased to an uncomfortable level, before increasing the collector voltage. Unfortunately, this cathode also shorted without apparent warning after about 40 hours of emission at 10 mA CW. Figure 14 shows the chart recording of cathode 20C-171-6F operating at 10 mA CW prior to shorting. It was even more stable than 20C-171-6C and gave no sign of difficulty before failure. There were some problems with the power supply and one of the amplifiers used for the chart recorder, but the cathode was very well behaved. The oscillographs in Figure 15 show the stability of the emission from the cathode under these conditions.

Both cathodes were cleared of shorts by the usual technique of discharging a 1 μf capacitor charged to 20 V through the short. They were operated only briefly after clearing because it seemed important to see what had happened, and additional operation could result in more damage that might obliterate important evidence.

Examination of the cathodes showed that the damage was relatively limited compared to most of our prior failures at high power levels. Cathode 20C-171-6C had four failure sites, involving a total of 51 tips. Thirty-eight of the failures were within a single failure site, and it was probably this area that resulted in the short. Cathode 20C-171-6F had a total of seven failure sites--the largest of which involved about 16 tips (~ 50 μm square).

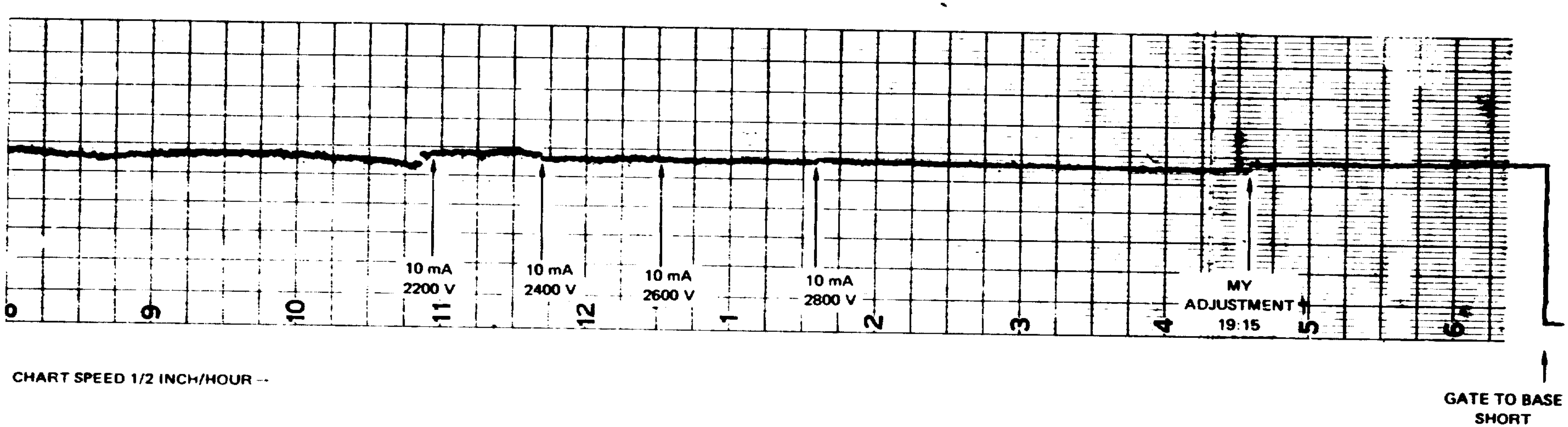


FIGURE 13 20C-171-GC OPERATING AT 10 mA CW
WITH INCREASING COLLECTOR VOLTAGE

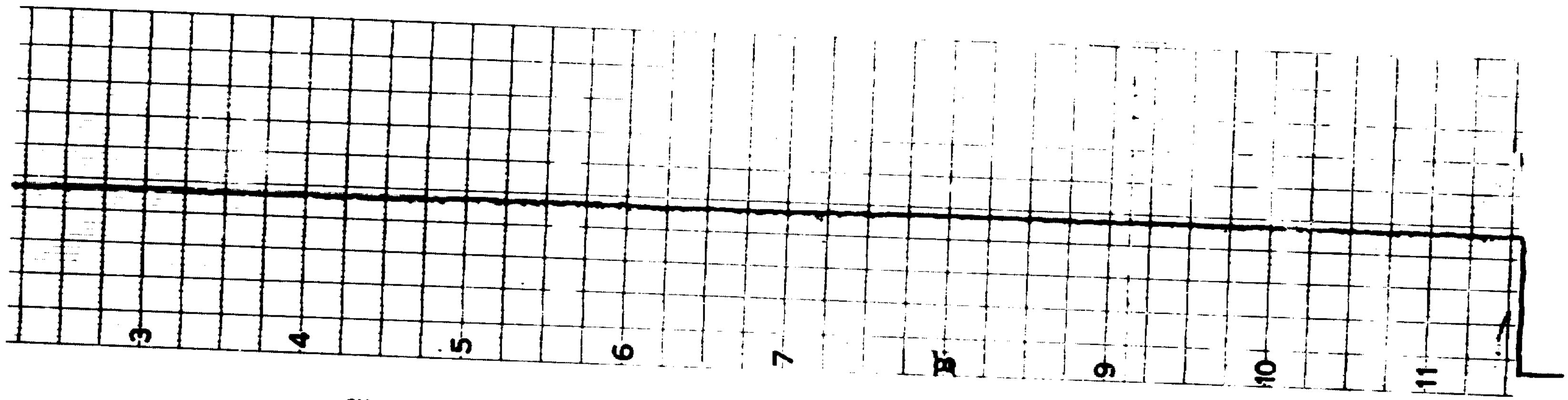
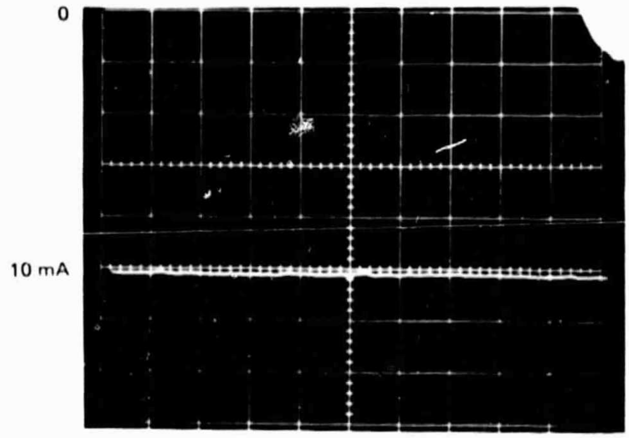
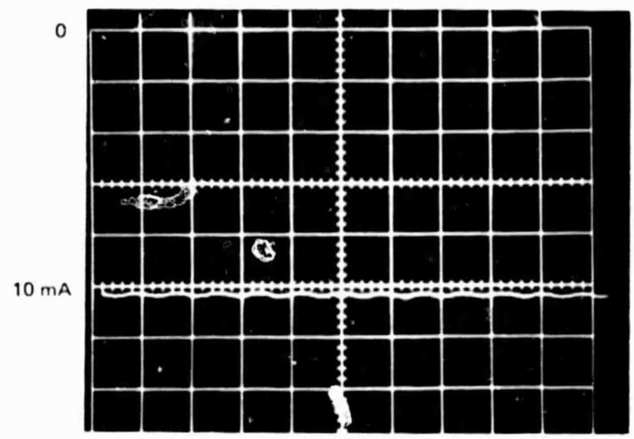


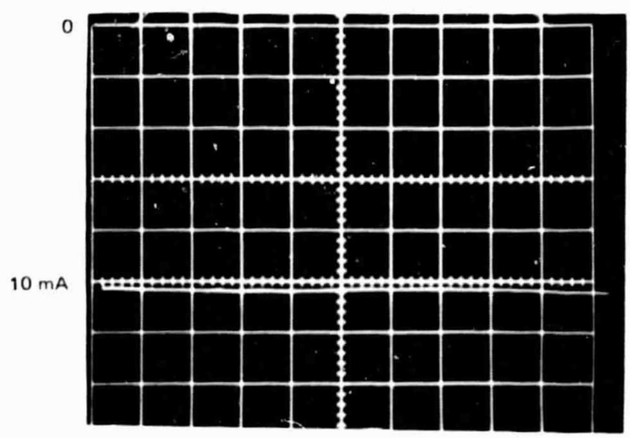
FIGURE 14 EMISSION LEVEL OF CATHODE 20C-171-6F OPERATING AT 10 mA CW WITH +2000 VOLTS ON THE ANODE



(a) HORIZONTAL 10 s/cm



(b) HORIZONTAL 20 ms/cm



(c) HORIZONTAL 2 ms/cm

FIGURE 15 EMISSION LEVEL AS A FUNCTION OF TIME FOR CATHODE 20C-171-6F

Note very low low-frequency noise and essentially no high-frequency noise.

In both cathodes, roughly half of the tips that were damaged blew out with a fairly energetic discharge that damaged both the gate and the silicon substrate. The others seemed to be rather mild events and were probably secondary failures resulting from the more violent events that damaged their neighbors. The thing that is puzzling is that both cathodes were very stable for weeks and at 10 mA CW for many hours and then suffered damage without warning.

Three points are encouraging in reviewing these results:

- Both cathodes operated at 10 mA CW for many hours.
- The failure damage was less severe than with any previous high-power test--even though this is the highest CW level we used.
- If each of the damaged areas was the result of a single tip failure triggering an event, about 99.9 percent of the tips operated without failure.

E. High-Current-Density Tests

Small-area cathodes have been fabricated and tested for use in the emission microscope and to test high cathode loading without having to deal with high power to the anode and collector system. Two geometries have been used: an array of approximately 16 tips spaced on 12.7-μm centers (6.4 tips/cm^2) and an array of approximately 32 tips spaced on 9-μm centers (1.2×10^6 tips/cm^2). (The number of tips on an individual cathode often varies from 16 or 32 due to small differences in the diameter of masks used to define the active areas.)

Both geometries have consistently produced much higher cathode loading than we have ever achieved with the more common 5000-tip arrays. Table 5 shows the results of tests with a recent group of cathodes fabricated for high-cathode-loading tests on another program. Eighteen cathodes were tested in three groups: One group of six had a goal of 1 mA total emission; the other two groups had a target of 2.7 mA, which is a current density of 100 A/cm^2 for a 32 tip array with 9-μm spacing between tips.

Ironically, the group that was meant to go to only 1 mA had twice the failure rate of the two groups that were taken to 2.7 mA. All of the cathodes are from the same substrate and were processed together. A significant difference, however, was that the two groups that were taken to 2.7 mA were placed in the test chamber the day after processing was completed, while the group that only went to 1 mA was stored for 18 days in an aluminum tray enclosed in a glass petri dish (before being placed in the test chamber). The petri dish was kept in a desiccator that was pumped out with an oilless mechanical pump, but was opened several times during the storage time. This is additional evidence that the cathodes should always be stored in vacuum, such as in the pinch-off tubes described in Section III-B.

Table 5

EMISSION TESTS WITH SMALL AREA EMITTER ARRAYS USING 60 Hz PULSE

Cathode Number*	Number of Tips	Peak Emission (mA)	Peak Voltage (V)	Peak J (A/cm^2)	Final Result
29C-177-3A	32	0.45	175	17	Shorted
29C-177-3B	32	2.7	250	100	OK
29C-177-3E	35	2.7	280	92	OK
29C-177-3F	24	2.7	290	135	OK
29C-177-3F	24	1.7 CW	260 CW	85 CW	OK
29C-177-3G	43	2.7	270	75	OK
29C-177-3H	32	2.7	300	100	OK
29C-177-3I	37	2.7	310	87	OK
29C-177-3J	20	1.0	185	60	OK
29C-177-3K	31	1.0	192	39	OK
29C-177-3L	32	1.0	210	38	OK
29C-177-3M	32	0.01	140	0.4	Shorted
29C-177-3N	32	1.0	190	38	Shorted
29C-177-3O	40	1.0	210	30	Shorted
29C-177-3Q	32	2.7	292	100	OK
29C-177-3R	32	0.5	219	19	Shorted
29C-177-3S	20	0.5	246	30	Shorted
29C-177-3T	29	11.5	368	475	OK
29C-177-3V	32	2.7	294	100	OK

*Cathode 29C-177-3F operated at 85 A/cm^2 CW and 29C-177-3T operated at 475 A/cm^2 with a pulse drive.

Two of the cathodes in the group that was taken to a minimum of 2.7 mA were subjected to extraordinary tests. One (29C-177-3F) was tested up to 135 A/cm^2 peak with the usual 60-Hz pulse drive, and then switched to CW and taken to 1.7 mA CW, which is 85 A/cm^2 CW. The cathode had 24 tips, so it was operating at a tip loading of

70 μA CW/tip. This is almost 20 times higher than the tip loading that would be required to produce 20 mA CW with a 5000-tip array. These tests were done in the standard stainless-steel tube collector apparatus, so it was not possible to check performance at 3-kV accelerating voltage.

A second cathode (29C-177-3T) was taken to 11.5 mA in the 60-Hz pulse mode. This is a peak current density of 475 A/cm^2, and is the highest loading level measured to date. The cathode has 20 tips, so the average tip loading was about 575 μA/tip. The 11.5-mA peak 60-Hz pulse is the maximum level that can be reached with the 3/16-inch diameter stainless-steel collector system, and the collector was hot enough at this point to cause a temperature rise measured on the outside wall of the vacuum vessel from 24°C to 30°C.

Figure 16 is an oscillograph of the applied voltage and the emission current as a function of time for the cathode, and Figure 17 shows the data plotted on a Fowler/Nordheim plot. There are no obvious nonlinearities that can be attributed to the very-high-current-density operation of the cathode. The voltage on the collector during the test was +1200 V.

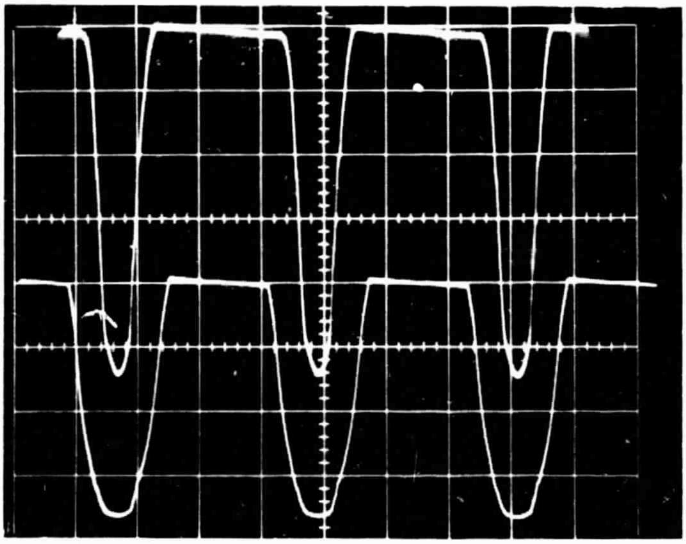


FIGURE 16 CATHODE 29C-177-3T OPERATING IN THE 60-Hz PULSE MODE AT 10.8-mA PEAK EMISSION CURRENT (450 A/cm^2)

Collector voltage was + 1200 V. Total number of tips on the cathode is 29. Top: 2 mA/cm, Horizontal: 5 ms/cm, Bottom: 100 V/cm.

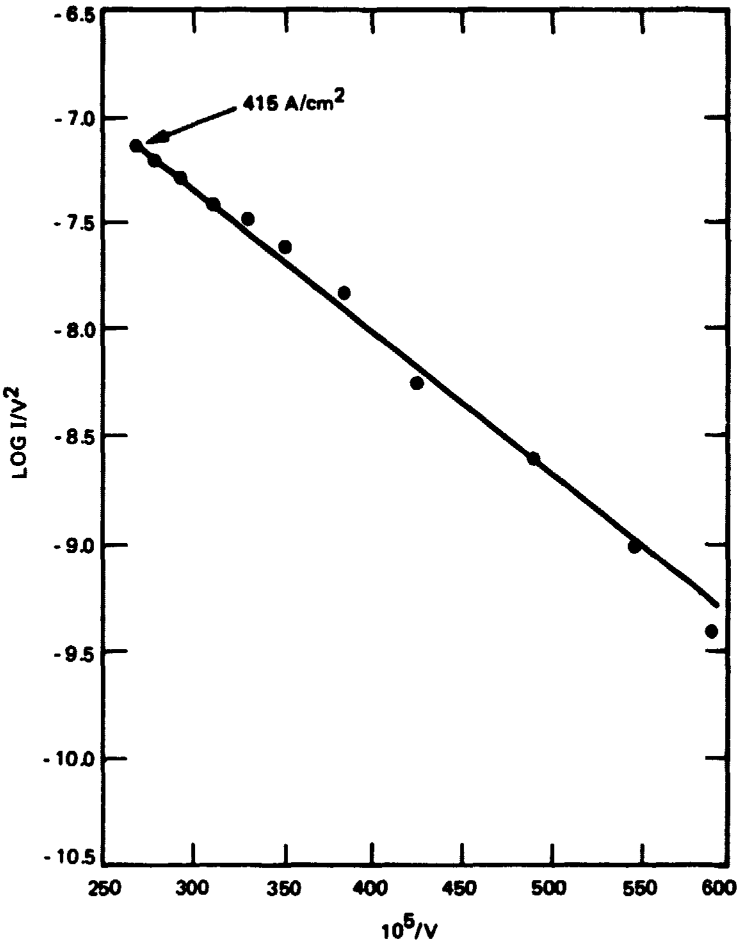


FIGURE 17 FOWLER/NORDHEIM PLOT OF EMISSION DATA FOR CATHODE 29C-177-3T OPERATING UP TO 10-mA PEAK EMISSION (415 A/cm^2)

It is remarkable that these small-area cathodes can operate at total emission levels of 10 mA, which is equivalent to that obtained with the 5000-tip arrays. It is especially interesting when one considers that many 5000-tip arrays have suffered damaging arcs at the 10-mA level of emission. Again it seems that total power into the collector is the major limiting factor in the results, rather than a limit on the cathode loading capabilities.

IV SUMMARY AND CONCLUSIONS

This phase of the cathode development program has been directed toward increasing cathode array uniformity, improving cathode hole geometry, conducting preliminary studies of alternate cathode materials, performing emission microscope studies, studying storage techniques, testing high-power CW performance, and conducting high-cathode loading tests.

An upgraded multiple electron beam exposure system has been adapted to the cathode fabrication process and has produced arrays of holes with improved uniformity of size and increased packing density. Arrays having 1.0×10^7 holes/cm^2 were demonstrated and hole size variation was about $\pm$ 1.5 percent.

Anisotropic etching techniques based on reactive ion etching have been shown to produce holes in the silicon dioxide layer with no detectable undercutting of the molybdenum gate film layer. This produces a more robust structure because of greatly improved gate film support and allows us to fabricate higher hole packing densities.

A materials study has shown that several metal carbides are very attractive cathode materials. Of these TiC, ZrC, NbC, HfC, and TaC are particularly interesting because they have very high melting points, low vapor pressure, and low work functions relative to molybdenum. They also tend to have a low capacity for gas adsorption, which is important for electrical discharge prevention.

The conditions under which the cathodes are stored have been shown to have an important effect on their performance. Storage in vacuum, preferably in sealed-off tubes, has been shown to be the best method for long-term storage.

An emission microscope has been assembled and tested. The tests demonstrated that the lens should be modified so that an accelerating field is formed at the surface of the cathode to prevent excessive gate current during operation. A nine-tip cathode array was imaged with a total emission current of 200 μA CW. This is an average tip loading of about 20 μA/tip, which is five times the tip loading required to produce 20 mA CW with a 5000-tip array. Seven of the nine tips were seen to form images on the phosphor: about 75 percent of the tips were contributing to the total emission.

High-power tests with 5000-tip arrays were made with a goal of 20 mA CW into an anode at 3 kV. Water-cooled electrodes were fabricated for the tests. The 20-mA CW goal has not been achieved, but 42-mA peak, 120-Hz (full-wave rectified 60-Hz) pulse emission was demonstrated with collectors at 3 kV. The 42-mA peak emission at 120 Hz is equivalent in power to 20 mA CW. When using pulsed driving voltages, 20-mA peak current is routine, but the highest CW current that has been achieved to date is 10 mA.

Very high cathode loadings have been demonstrated using small arrays of tips (~ 10 to 30 tips). With these small arrays, pulsed currents averaging 100 μA/tip are common and current densities averaged over the total area of the array are commonly in excess of 100 A/cm^2. CW emission current densities of 50 A/cm^2 have been achieved many times. These values are more than an order of magnitude greater than what is needed to achieve 20 mA with the 5000-tip arrays.

References

Adachi, H., et al. 1983: "Stable Carbide Emitter," Appl. Phys. Lett., Vol. 43, No. 7, p. 702.

Brodie, I., 1975: "Bombardment of Field-Emission Cathodes by Positive Ions Formed in the Interelectrode Region," Int'l J. Electron., Vol. 38, No. 4, pp. 541-550 (April).

Brodie, I., E.R. Westerberg, D.R. Cone, J.J. Muray, N. Williams, and L. Gasiorek, 1981: "A Multiple Beam Exposure System for High-Throughput Direct-Write Submicrometer Lithography," IEEE Trans. Electron. Devices, Vol. ED-28, pp. 1422-1428.

Burgess, R.B., H. Kroemer, and J.M. Houston, 1953: "Corrected Values of Fowler-Nordheim Field Emission Functions v(y) and t(y)," Phys. Rev., Vol. 90, No. 4, pp. 173-181 (May).

Darydova, E.I., et al., 1979: Sov. Phys. Tech. Phys., Vol. 49, No. 11, p. 1307.

Dyke, W.P., and V.W. Dolan, 1956: Advances in Electronics and Electron Physics, Vol. 8, p. 98 (Academic Press, New York).

Eisinger, J., 1958: J. Chem. Phys., Vol. 20, p. 1154.

Flamm, D.L., and V.M. Donnelly, 1981: "Design of Plasma Etchants," Plasma Chemistry and Plasma Processing, Vol. 1, No. 8, pp. 317-362 (December).

Fowler, R.H., and L.W. Nordheim, 1928: "Electron Emission in Intense Electric Fields," Proc. Royal Soc. (London), Vol. A119, pp. 173-181 (May).

Kohl, W.H., 1967: Handbook of Materials and Techniques for Vacuum Devices, (Reinhold, New York).

Samsonov, G.V., and I.M. Vinitskii, 1980: Handbook of Refractory Compounds (IFI/Plenum, New York).

Spindt, C.A., I. Brodie, L. Humphrey, and E.R. Westerberg, 1976: "Physical Properties of Thin-Film Field Emission Cathodes with Molybdenum Cones," J. Appl. Phys., Vol. 47, No. 12, pp. 5248-5263 (December).

Stroms, E.D. 1967: The Refractory Carbides (Academic Press, New York).

Appendix

EMITTER CHARACTERISTICS AND TEST DATA

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
1	25A-156-5G	TO-5	410	-0.002	225	1	0	0	OK
	H			-0.002	219	1.1	0	0	OK
	I			-0.002	205	1.05	0	0	OK
	J			-0.002	195	1	0	0	OK
	K			-0.001	195	1	0	0	OK
	L			-0.001	190	1.1	0	0	OK
2	25A-156-5M	Al_2O_3	410	-0.001	190	1		0	OK
	N			-	-	-	-	-	No contact
	28A-140-2Q			-0.003	133	10		0	OK (Retest)
	25C-151-3B			-	-	-	-	-	No contact
	C			-	-	-	-	-	No contact
	D			-0.001	255	1		0	OK

PRECEDING PAGE BLANK NOT FILMED

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
3	25A-156-5A	TO-5	410	0.005	185	1	0	0	11 tips, 56 A/cm^2, OK
	B			< 1	183	1	8	1	14 tips, 44 A/cm^2, shorted
	C			-0.002	200	1	1	0	14 tips, 44 A/cm^{2}OK
	D			< 1	148	1	0	0	9 tips, 69 A/cm^2 OK
	E			< 1	155	1	0	0	15 tips, 41 A/cm^2 OK
	F			< 1	193	0.8	9	1	9 tips, 55 A/cm^2 shorted
4	25A-156-5G	TO-5	410	-0.002	225	1	0	0	9 tips, 69 A/cm^2 OK
	H			-0.002	210	1.1	0	0	12 tips, 57 A/cm^2 OK
	I			-0.001	205	1	0	0	15 tips, 41 A/cm^2 OK
	J			-0.002	195	1	0	0	16 tips, 39 A/xm^2 OK
	K			-0.001	195	1	0	0	12 tips, 52 A/cm^2 OK
	L			-0.001	195	1.1	0	0	11 tips, 62 A/cm^2 OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
5	25A-156-5M	$Al_2)_3$	410	0.001	190	1	0	0	15 tips, 41 A/cm^2 OK
	N			-	-	-	-	-	No contact
	28A-140-2Q			-	-	-	-	-	No contact
	25C-151-3B			-	-	-	-	-	No contact
	C			-	-	-	-	-	No contact
	D			0.001	240	1	0	0	11 tips, 62 A/cm^2 OK
6	20A-144-2H	TO-5	420	-	-	-	-	-	Shorted from start
	I			0.02	140	0.15		0	Aborted
	J			0.11	120	0.08		1	Aborted
	K			0.006	122	0.06		1	Shorted
	L			< 1	133	0.15		1	Aborted
	M			0.006	130	0.25		)	Aborted

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
7	20A-144-2N	TO-5	420	-0.002	153	20	~500	0	OK
	O			< 1	175	20	~500	0	OK
	P			0.004	168	16	~ 1000	0	Poor
	20C-149-2K			-0.01	210	20	~500	0	OK
	L			0.05	170	1.5	1	1	OK
	M			0.002	195	20	~500	0	OK
8	20C-149-2N	Al_2O_3	420	-	-	-	-	-	No contact
	20A-135-3N			-	-	-	-	-	No contact
	O			< 1	185	0.014	3[illegible]	0	Aborted
	P			< 1	185	0.015	2	0	Aborted
	R			-	-	-	-	-	No contact
	S			< 1	135	0.001	2	0	Aborted

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
9	20C-150-3B	TO-5							
	C								
	D								
	E								
	F								
	G								
10	20C0157-1B	TO-5	450	-0.012	232	10	22	0	OK
	D			-	-	-	-	-	No contact
	F			-0.015	230	10	11	0	OK
	G			-0.008	195	10	5	0	OK
	H			-0.008	199	10	14	0	OK
	J			-0.01	210	10	1	0	OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
11	25C-151-2B	Al_2O_3	450	< 1	250	0.9	1	0	8 tips, 77 A/cm^2 OK
	C			< 1	222	1.2	0	0	9 tips, 83 A/cm^2 OK
	D			-	-	-	-	-	Shorted from start
	E			-	-	-	-	-	Shorted from start
	F			0.013	205	1	0	0	9 tips, 69 A/cm^2 OK
	G			< 1	205	1	0	0	9 tips, 69 A/cm^2 OK
12	25C-151-2H	TO-5		< 1	222	1.2	0	0	9 tips, 83 A/cm^2 OK
	I			< 1	200	1	0	0	9 tips, 69 A/cm^2 OK
	J			< 1	182	1	0	0	9 tips, 69 A/cm^2 OK
	L			-	-	-	-	-	No contact
	M			< 1	195	1	0	0	10 tips, 62 A/cm^2 OK
	N			< 1	202	1	0	0	12 tips, 52 A/cm^2 OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
13	20C-157-3J	TO-5	450	0.001	130	20	8	0	OK
	K			-	-	-	-	-	No contact
	L			-0.004	118	20	0	0	OK
	M			-0.006	115	20	7	0	OK
	N			-0.002	129	20	9	0	OK
	P			< 1	116	20	6	0	OK
14									
	20C-157-3B								
	C								
	D								
	F								
	H								
	I								

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
15	20A-166-2B	Al_2O_3	450	-0.01	150	20	0	0	OK
	C			-0.006	140	20	3	0	OK
	D			0.006	149	20	2	0	OK
	H			-0.005	142	20	3	0	OK
	L			-0.006	140	20	0	0	OK
16	27B-137-3B	TO-5	400	-0.006	150	10	~ 300	1	Shorted
	C			< 1	130	0.4	~ 500	1	Shorted
	D			0.007	99	20	16	0	Seasoned, OK
	E			0.007	114	20	13	0	Seasoned, OK
	F			< 1	145	0.1	~ 700	2	Shorted
	G			-	-	-	-	-	Shorted from start

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
17	20B-137-2C	TO-5	400	0.065	149	0.15	22	1	Shorted
	H		-	-	-	-	-	-	No contact
	I		-	-	-	-	-	-	No contact
	J			< 1	152	0.6	2	1	Shorted
	K			4	47	20	25	0	Seasoned
	27B-137-3H								
18	20C-157-1K	Al_2O_3	400	7	43	20	5	0	Seasoned
	L			-0.014	200	8	27	1	Shorted
	P			-0.025	225	20	1	0	OK
	R			0.175	100	30	~ 2000	1	Seasoned - Shorted
	S			6	49	20	~ 250	0	Seasoned
	T			-	-	-	-	-	No contact

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
19	20C-150-1Q	TO-5	400	0.75	75	20	~ 500	1	Seasoned - Shorted
	S			1.2	143	13	~ 500	1	Seasoned - Shorted
	T			1.4	141	15	~ 500	1	Seasoned - Shorted
	V			-0.03	160	20	7	0	OK
	W			-0.008	188	20	4	0	OK
	X			0.06	170	0.2	5	1	Shorted
20	20B-137-2R	TO-5	430	-	-	-	-	-	No contact
	S			< 1	180	0.02	15	2	Shorted
	T			< 1	170	0.01	18	4	Shorted
	V			-0.008	178	20	30	2	OK
	L			-	-	-	-	-	No contact
	M			-	-	-	-	-	No contact

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
21	35B-145-1B	TO-5	410	1.2	41	0.005	~ 1000	3	Shorted
	35B-145-1C			0.6	45	0.003	~ 1000	3	Shorted
	38A-146-5F			0.007	235	0.5	16	3	Shorted
	G			< 1	135	0.001	0	1	Shorted
	38A-148-4E			< 1	200	0.15	21	4	Shorted
	F			0.002	205	0.4	~ 100	2	Shorted
22	35B-145-1E	Al_2O_3	420	0.5	40	0.01	~ 1000	2	Shorted
	F			0.5	25	0.001	~ 1000	2	Shorted
	H			-	-	-	-	-	Shorted from start
	38A-146-5H			< 1	180	0.025	-	0	Aborted
	38A-148-4G			0.005	210	0.025	-	0	Aborted
	H			-	-	-	-	-	No contact

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
23	20C-169-3B	TO-5	420	< 1	170	10	5	0	OK
	C			< 1	165	10	1	0	OK
	F			< 1	140	10	20	0	OK
	G			< 1	130	10	2	0	OK
	K			-0.001	131	10	4	0	OK
	M			< 1	130	10	12	0	OK
24	20C-157-3H	TO-5		< 1	140	20	~ 100	1	OK
	I			< 1	140	20	3	0	OK
	20C-149-1Q			-	-	-	-	-	No contact
	20B-137-20			0.001	185	15	~ 200	1	Shorted
	W			0.06	180	20	~ 80	o	OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
25	20C-169-2B	TO-5	450	-0.002	180	10	11	0	OK
	G			-0.003	200	10	21	0	OK
	H			-0.003	195	10	6	0	OK
	I			-0.004	190	10	0	0	OK
	J			0.002	225	10	9	0	OK
	K			-0.002	170	10	5	0	OK
26	20C-169-2L	Al_2O_3		0.003	152	10	0	0	OK
	M			-0.005	180	10	0	0	OK
	N			-0.004	180	10	3	0	OK
	O			-0.004	160	10	1	0	OK
	P			0.009	160	10	0	0	OK
	R			< 1	184	10	1	0	OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
27	35B-145-4B	TO-5	430	0.12	120	0.3	~ 500	6	Shorted
	C			0.025	100	0.014	~ 100	2	Shorted
	I			< 1	135	0.15	~ 1500	5	Shorted
	J			0.005	115	5	~ 250	4	Shorted
	L			0.022	84	0.001	~ 200	5	Shorted
	M			0.020	85	0.001	~ 1000	5	Shorted
28	20C-169-3J	TO-5	450	-	-	-	-	-	Shorted from start
	L			-0.003	173	10	55	0	OK
	N			-0.001	160	10	13	0	OK
	20-169-4C			-0.01	168	10	3	0	OK
	D			0.001	169	10	40	0	OK
	E			0.4	75	20	20	0	Seasoned OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
29	39C-168-6D	Al_2O_3	450	< 1	320	0.1	0	0	V. high voltage
	F			< 1	320	0.03	1	1	Shorted
	G			< 1	260	0.07	1	0	Not emitting
	H			< 1	250	0.1	0	0	V. high voltage
	I			0.015	290	0.1	0	0	V. high voltage
	J			< 1	245	0.1	0	0	V. high voltage
30	20C-170-4B	TO-5	430	0.004	130	10	5	0	OK operated at 2 mA cw
	C			-	-	-	-	-	Shorted from start
	D			0.002	125	10	1	0	OK
	20C-169-2S			0.001	200	10	25	0	OK
	T			-0.006	195	10	14	0	OK
	V			-.005	173	10	12	0	OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
31	2-C-170-1B	Al_2O_3	400	-0.003	190	10	0	0	OK
	D			-0.002	171	10	1	0	OK
	F			-01004	190	10	3	0	OK
	G			-0.008	185	10	0	0	OK
	H			0.015	193	10	4	0	OK
	I			-0.003	162	10	3	0	OK
32	20C-171-3B	TO-5	400	-0.004	181	10	0	0	OK
	D			-0.005	189	10	7	0	OK
	F			-0.004	172	10	1	0	OK
	G			-0.006	180	10	30	0	OK
	H			-0.004	190	10	4	0	OK
	I			-0.004	200	10	3	0	OK

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
33	20C-170-4F	TO-5	400	-0.002	150	10	0	0	OK
	G			0.003	160	10	0	0	OK
	H			< 1	155	10	1	0	OK
	I			-0.001	140	10	0	0	OK
	L			-	-	-	-	-	Shorted from start
	M			-0.001	140	10	0	0	OK
34	20C-169-4F	Al_2O_3							
	G								
	H								
	I								
	U								
	V								

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
35	20C-169-30	TO-5	400	-0.006	160	13	40	2	OK
	P			-0.005	180	11	10	1	OK
	Q			-0.005	170	12	2	0	OK
	T			-0.004	100	20	~200	0	Seasoned, OK
	V			< 1	11C	17	7	0	Seasoned, OK
	W			-0.004	130	15	9	0	OK
36	20C-172-5B	TO-5	400	< 1	165	1	18	3	Shorted
	C			-0.006	218	10	1	0	OK
	F			-0.005	230	10	5	0	OK
	G			< 1	160	1	5	0	Lost contact
	H			-0.001	223	10	1	0	OK
	J			< 1	190	4	~100	1	Shorted

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
37	20C-169-3 O	TO-5	400°C	-0.006	160	13	40	2	OK
	P			-0.005	180	11	10	1	OK
	Q			-0.005	170	12	2	0	OK
	T			-0.004	100	20	~200	0	Seasoned, OK
	V			<1	110	17	7	0	Seasoned, OK
	W			-0.004	130	15	9	0	OK
38	20C-172-5 B	TO-5	400°C	<1	165	1	18	3	Shorted
	C			-0.006	218	10	1	0	OK
	F			-0.005	230	10	5	0	OK
	G			<1	160	1	5	0	Lost contact
	H			-0.001	223	10	1	0	OK
	J			<1	190	4	~100	1	Shorted