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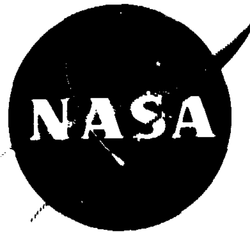

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SPINDT COLD CATHODE ELECTRON GUN DEVELOPMENT PROGRAM

by C.A. Spindt

SRI INTERNATIONAL

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

A project to develop a thin-film field-emission cathode array and an electron gun based on this emitter array is summarized. The work reported covers fabricating state-of-the-art cathodes for testing at NASA and NRL, advancing the fabrication technology, developing wedge-shaped emitters, and performing emission tests. An anisotropic dry etching process (reactive ion beam etching) has been developed that can lead to increasing the packing density of the emitter tips to about 5×10^6 tips/cm² or about 40,000 tips in an area 1 mm in diameter. (The present limit using isotropic wet etching is about 1×10^6 tips/cm²). Tests with small arrays of emitter tips having about 10 tips has demonstrated current densities of over 100 A/cm² several times using cathodes having a packing density of 1.25×10^6 tips/cm². Indications are that the higher packing density achievable with the dry etch process may extend this capability to the 500-A/cm² range and beyond. The wedge emitter geometry has been developed and shown to produce emission. This geometry can (in principle) extend the current density capability of the cathodes beyond the 500-A/cm² level. An emission microscope has been built and tested for use with the cathodes. It will be used for studies during the next phase of the program.

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SUMMARY

The purpose of this phase of the program has been to fabricate, test, and deliver state-of-the-art cathodes to NASA and NRL, advance the fabrication technology, develop a wedge-shaped emitter, and perform emission tests.

A total of 34 cathodes have been delivered to NASA and NRL during the program. A total of 398 cathodes have been tested. Many were tests of new processing techniques or geometries. For example, wedge-shaped emitters have been tested and have shown promise, provided that difficulty with adhesion to the substrate can be solved.

A reactive ion beam etching process has been investigated and shows promise as an anisotropic etch for micromachining hole patterns in the cathode fabrication process. Anisotropic etching will make it possible to increase the packing density of the emitter array, and thus the current density available from the array. With the anisotropic etch process, 40,000 tips can be formed in an area 1 mm in diameter--a packing density of 5×10^6 tips/cm^2. Cathodes formed with the reactive ion beam etching have been tested and shown to work well after some difficulties with contamination had been solved.

Small-area cathodes were fabricated and tested to investigate high-current-density operation without having to deal with large total currents. These tests showed that current densities in excess of 100 A/cm^2 are routinely possible with small arrays of approximately 10 tips and 1.25×10^6 tips/cm^2 packing density.

A test was made of operation with high anode (collector) voltage. A 5000-tip cathode (6.4×10^5 tips/cm^2) was operated at 20 mA peak emission with +3 kV on the anode for nine days; during this time, it was very stable. On the tenth day, a short in the tube terminated the test. Other tests with commercial gun structures were inconclusive because of electrical breakdown in the gun structures.

An emission microscope similar to those built at NRL was fabricated and is ready for testing cathodes during the next phase of the program. The microscope will have a magnification of about 120X, which should be ample to separate tips on 12.7 μm centers.

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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, testing, and delivering state-of-the-art cathodes to the National Aeronautics and Space Administration (NASA), Lewis Research Center (LeRC) and to the Naval Research Laboratory (NRL) for evaluation; other effort has been directed toward improving reliability and increasing the array tip-packing density, thereby increasing the cathode's current-density 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):*

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

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

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

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

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

where V is the voltage applied to the diode structure and

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

*References are listed at the end of this report.

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, we 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 at one end of a sharp point (i.e. small r). The segment is mounted on a

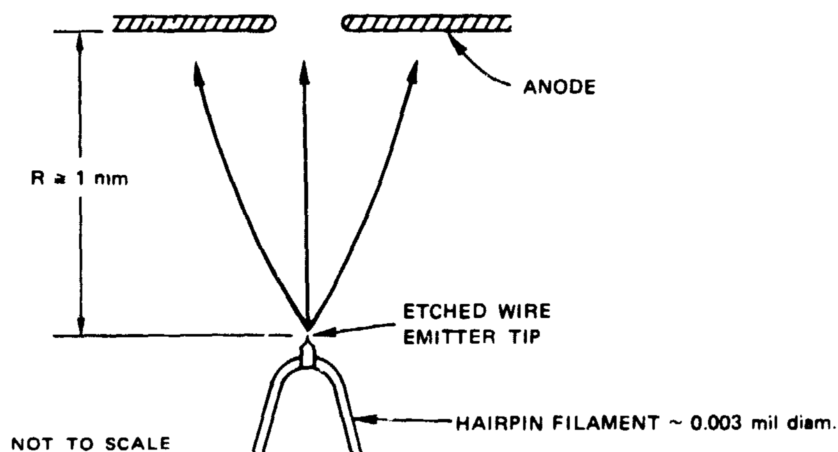

FIGURE 1 CONVENTIONAL FIELD EMITTER AND ANODE

hairpin filament for support and is then cleaned by passing current through the hairpin filament and heating the tip to incandescence. After cooling, the point supplies 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. At the point surface, the electric field required for field emission is on the order of 10^7 V/cm; as a result, with the local field enhancement resulting from the sharpness of the tip, anode potentials of the order of kilovolts are usually required for field emission from a conventional emitter structure. Positive ions formed at the anode or between the anode and the sharp emitter are directed toward the tip by the curved field lines. 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 can be below 150 V; 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 dense arrays neighboring tips would 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 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 per tip for over 65,000 hours from a 100-tip array. The tips are operating at room temperature and unknown pressure, but probably in the 10^{-9}-torr range.

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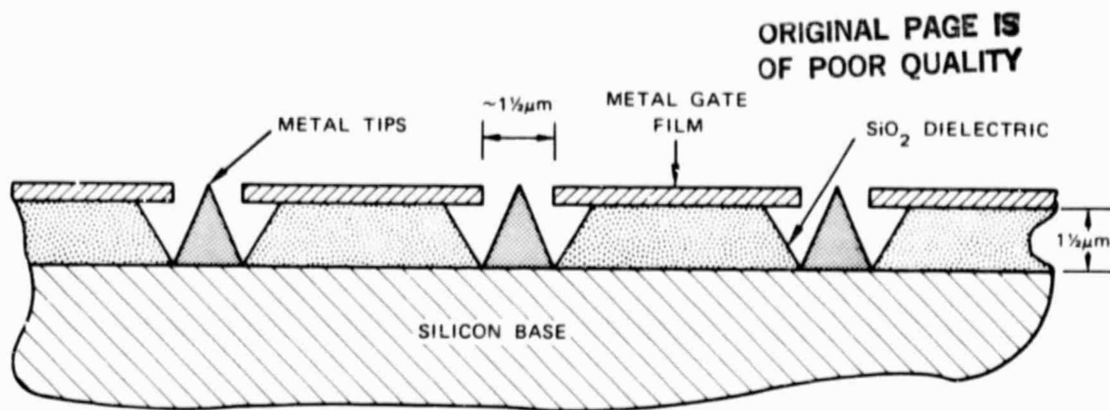
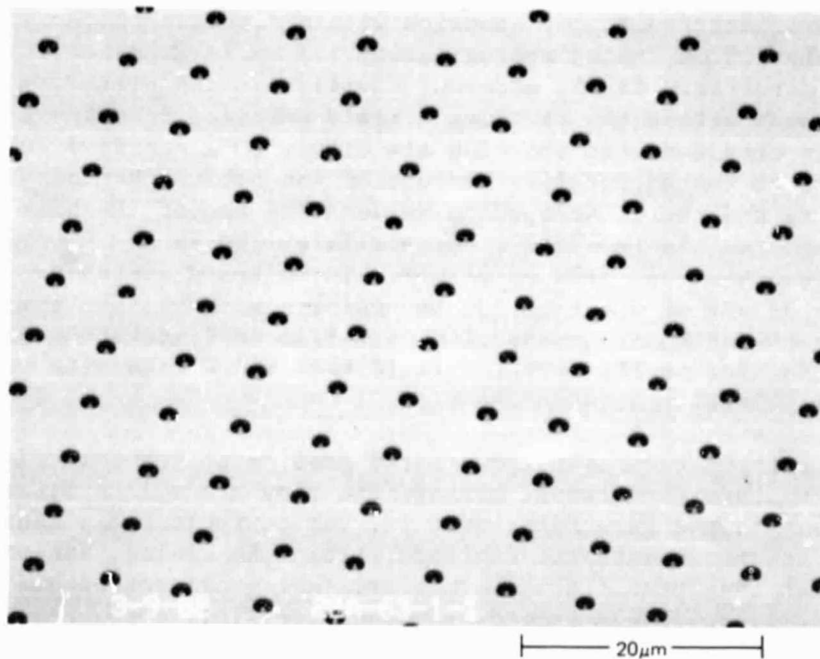
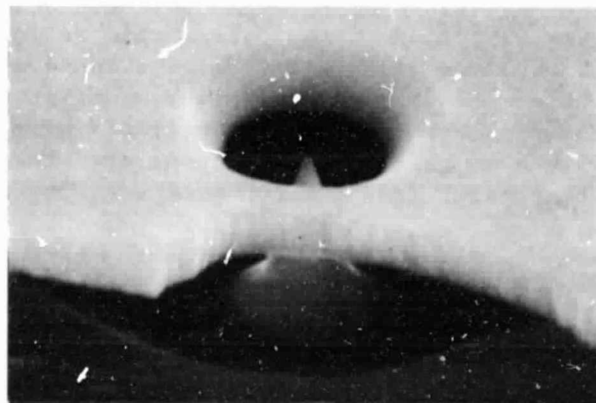


(a) SCHEMATIC OF A THIN-FILM FIELD-EMISSION CATHODE (TFFEC) ARRAY



(b) SEM MICROGRAPH OF TFFEC ARRAY



(c) SEM MICROGRAPH OF TFFEC CATHODE

FIGURE 2 THIN-FILM FIELD-EMISSION CATHODE

II DELIVERY OF STATE-OF-THE-ART CATHODES

The state-of-the-art cathode is defined as a 5000-tip array covering an area 1-mm in diameter on a 2.5-mm square silicon chip. The tip packing density is 6.4×10^5 tips/cm^2. Tip spacing is 12.7 μm between centers. All of the cathodes tested during this phase of the program are listed in the appendix along with the results of the tests. Table 1 lists the 34 cathodes that were delivered to NASA and NRL. Deliveries were made only when requested by NASA or NRL to ensure that all cathodes shipped would be the most up-to-date available.

Cathodes awaiting shipment have been stored in two ways: mounted in TO-5 headers held in aluminum racks and stored in ordinary plastic parts boxes, or unmounted in aluminum trays that are kept in Pyrex glass petri dishes. Until recently, the boxes and petri dishes were stored on a laminar flow clean bench. Near the end of the program, experiments began in which cathodes were stored in desiccators that were evacuated with an oil-free mechanical pump. Early results indicated a possible improvement in performance after storage when the desiccators are used; however, the data base was insufficient for a definite conclusion at the end of this phase of the program.

Before shipping, a protective stainless-steel cover is placed over the cathode and TO-5 header; they are then wrapped in aluminum foil. The foil-wrapped cathode and header are then placed in a glass bottle which is flushed with dry nitrogen before the lid is secured. No cathodes have been mechanically damaged when packed this way; however, this environment may produce surface contamination that can affect cathode operating characteristics. Vacuum containers for shipping are under study.

Table 1

CATHODES DELIVERED DURING REPORTING PERIOD

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Cathode Number	Mount	Gate Current (μA)	Applied Voltage (V)	Emission Current (mA)	Failures		Comments
					Tips Blown	Shorts	
20A-107-10G	TO-5	<1	135	10	0	0	NASA, 27 Jan 1983
20A-110-1D	TO-5	40	178	50	0	0	NASA, 27 Jan 1982
28A-118-3G	TO-5	4	181	20	~75	0	NASA, 27 Jan 1982
20A-111-1F	TO-5	-8	200	20	0	0	NASA, 16 Feb 1982
20A-111-1C	TO-5	-10	207	20	1	0	NASA, 16 Feb 1982
25A-121-5G	TO-5	--	--	--	--	--	NRL (untested), 1 Mar 1982
25A-121-5I	TO-5	--	--	--	--	--	NRL (untested), 1 Mar 1982
20A-107-7I	LeRC	-18	180	25	47	0	NASA, 2 Mar 1982
20A-112-2C	LeRC	--	--	--	--	--	NASA/W-J, 20 Mar 1982
20A-70-1V	TO-5	<1	170	20	6	0	NASA, 7 Apr 1982
20A-82-2Q	TO-5	8	200	20	--	0	NASA, 7 Apr 1982
20A-81-2P	TO-5	10	205	25	--	2	NASA, 7 Apr 1982
20A-110-1B	TO-5	<1	160	20	9	0	NASA, 7 Apr 1982
20A-110-1C	TO-5	<1	160	20	~75	0	NASA, 7 Apr 1982
20A-110-1F	TO-5	<1	160	20	2	0	NASA, 7 Apr 1982
20A-129-1P	LeRC	--	--	--	--	--	NASA/W-J, 18 May 1982
20A-129-1D	LeRC	--	--	--	--	--	NASA/W-J, 18 May 1982
20A-129-1J	TO-5	-7	140	20	0	0	NASA, 7 Jul 1982
20A-129-3L	TO-5	-4	142	20	2	0	NASA, 7 Jul 1982
20A-129-3I	TO-5	-2	135	20	0	0	NASA, 7 Jul 1982
20A-129-4C	TO-5	-10	180	20	1	0	NASA, 7 Jul 1982
28A-129-10C	TO-5	-6	215	25	3	0	NASA, 7 Sep 1982
20A-129-1N	TO-5	-10	140	20	0	0	NASA, 7 Sep 1982
20A-129-4J	TO-5	-9	160	20	1	0	NASA, 7 Sep 1982
20A-129-4X	TO-5	-18	218	20	0	0	NASA, 7 Sep 1982
20A-129-2Q	TO-5	-1[illegible]	19[illegible]	2[illegible]	7	0	NRL, 16 Sep 1982
20A-129-4Y	TO-5	-20	225	20	0	0	NRL, 16 Sep 1982
29A-133-8B	TO-5	<1	222	1.5	0	0	NRL, 1 Oct 1982, 60 A/cm^2
29A-133-8A	TO-5	<1	222	1.5	0	0	NRL, 1 Oct 1982, 60 A/cm^2
20A-129-4T	LeRC	1	203	20	3	0	NASA, 3 Oct 1982
25A-142-4C	TO-5	<1	211	1.3	0	0	NASA, 17 Nov 1982, 50 A/cm^2
25A-142-4D	TO-5	<1	230	1.25	0	0	NASA, 17 Nov 1982, 50 A/cm^2
25A-135-3V	TO-5	-2	195	1.25	0	0	NASA, 16 Dec 1982, 50 A/cm^2
25A-135-3T	TO-5	-2	200	1.25	0	0	NASA, 16 Dec 1982, 50 A/cm^2
20A-110-1F	TO-5	<1	160	20	2	0	NASA, 7 Apr 1982
20A-129-1P	LeRC	--	--	--	--	--	NASA/W-J, 18 May 1982
20A-129-1D	LeRC	--	--	--	--	--	NASA/W-J, 18 May 1982
20A-129-1J	TO-5	-7	140	20	0	0	NASA, 7 Jul 1982
20A-129-3L	TO-5	-4	142	20	2	0	NASA, 7 Jul 1982

III FABRICATION TECHNOLOGY

A. State-of-the-Art Cathodes

The state-of-the-art cathode array during this phase of the program [a 5000-tip array with tips on 12.5-μm centers (6.4×10^5 tips/cm^2)] covers an area 1 mm in diameter on a p-type, 0.01 -cm <111> silicon chip that is nominally 2.5 mm square. This cathode type has been designated "Type 20A" in the cathode series (see Figure 3). Several other configurations that have been made or planned are also described in 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 substrates 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 the SRI-developed screen-lens parallel-beam electron-lithography 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 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, 1981).

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

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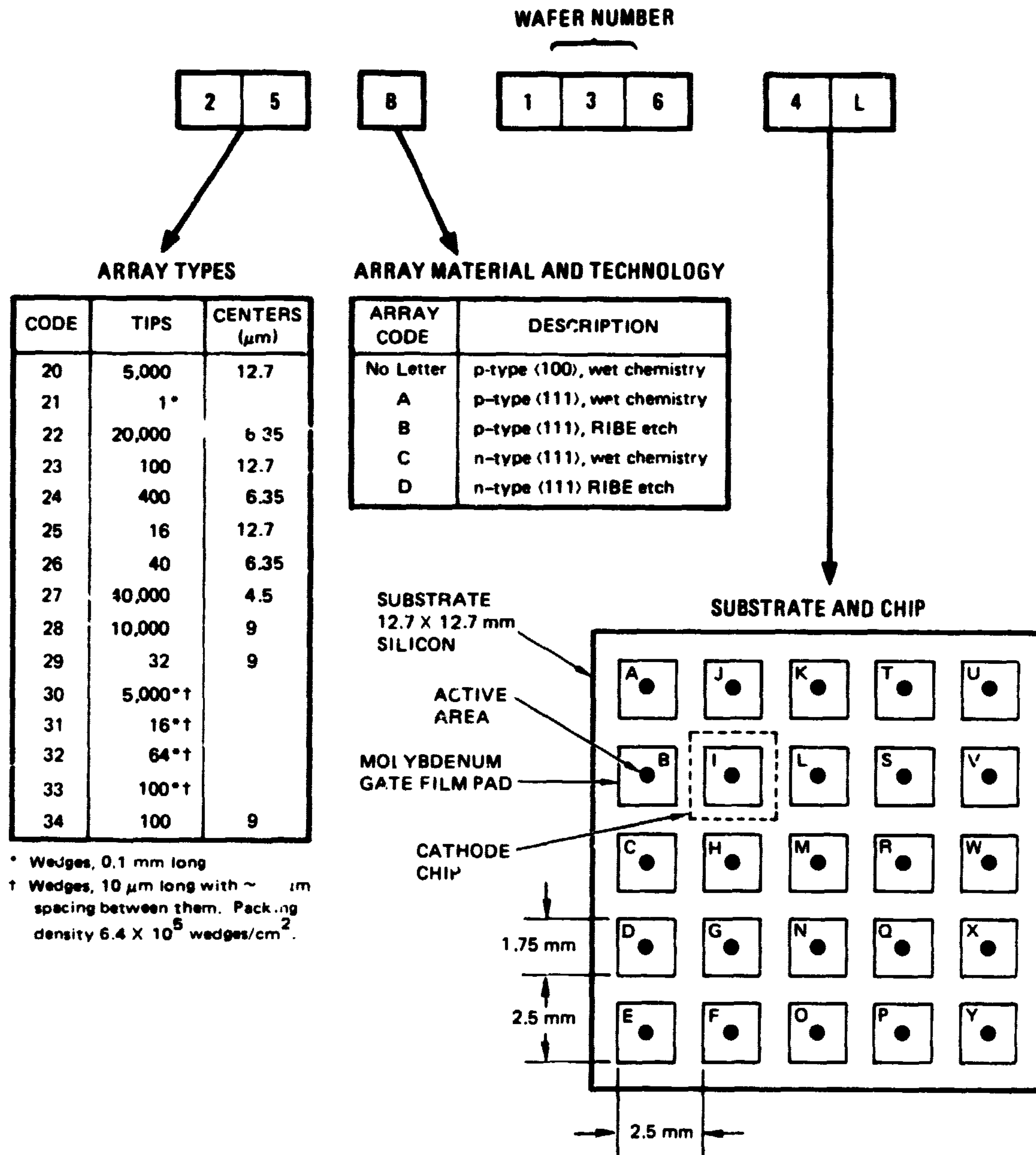

ARRAY TYPES

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*†	
31	16*†	
32	64*†	
33	100*†	
34	100	9

* Wedges, 0.1 mm long

† Wedges, 10 μm long with ~ μm spacing between them. Packing density 6.4×10^5 wedges/cm^2.

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 for testing.

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

B. Advanced Fabrication Processes

During this phase of the program development, work was done on three areas of the cathode fabrication technology:

- Active area patterning
- Arrays of wedge-shaped emitters
- Dry etching techniques.

1. Active Area Patterning

Cathode testing has always been difficult when investigating high-current-density operation of the state-of-the-art cathode (5000-tip arrays covering a 1-mm diameter area): The total emission level can result in power-handling problems at the anode. The most direct solution to this difficulty is to use cathodes with the same packing density but smaller active areas. Thus, the current density can be high, but the total current (and therefore the total power) is reduced.

A double-resist technique was developed to form small-area cathodes without having to modify our electron beam lithography system in any way. A photoresist process is incorporated into Step (5) of the fabrication sequence; after the PMMA is developed a photoresist is spun over the PMMA (e.g. KTI 1350J or 809). A photomask can then be aligned over the hole pattern to expose a pattern in the photoresist and open a window over the holes that are to be etched in the molybdenum gate film. For example, a 50-μm square photomask can be lined up over the 5000-tip array to open a window over a 4 x 4 array of holes on 12.7-μm centers. This is done visually in a standard mask aligner. The photoresist is exposed and developed, leaving the desired area of the PMMA with its hole pattern open for processing. The PMMA is then descummed in an asher (oxygen plasma) and the molybdenum etched through the holes in the PMMA resist. The remainder of the 5000 holes (which are covered by the photoresist) are not etched.

This technique enables us to form any shaped pattern of holes within the 1-mm diameter array without modifying our screen-lens electron-beam lithography system. The process then continues with Step

(6) of the fabrication sequence. Small-area cathodes (e.g. 4 x 4 arrays on 12.7-μm centers) have been fabricated using this technique. The results of their electrical tests are given in the next section.

2. Wedge-Shaped Emitters

One major objective of the fabrication development effort is to maximize the ratio between the actual emission area (A) and the area occupied by the emitter array, or active area (a). Two approaches are being investigated toward this end:

- The obvious tactic of increasing the tip packing density (discussed in Section II-B-3).
- Forming wedge-shaped (rather than cone-shaped) emitters.

If one assumes that each emitter tip in an array has a tip radius (r) of 1000 Å and an emission cone (θ) of up to 30° from the axis of the cone, the emitting area (A) per cone is $A = 2\pi r^2(1 - \cos\theta)$, or about 10^{-10} cm^2. The total emitting area for the state-of-the-art 5000-tip array is thus 5×10^{-7} cm^2, and $A/a = 6.3 \times 10^{-5}$.

Now consider a 5000-slot array with slots 1.5-μm wide, and 10-μm long wedges in the slots. These could be fabricated in the same area that is occupied by the state-of-the-art 5000-tip cathode, and the wedges can be formed by the same technique used for the cones. If each wedge has a radius of curvature (r) of 1000 Å and a length (L) of 10 μm, and if we assume a 30° emitting half angle (θ), the total emitting area (A) per wedge is $A = \theta\pi rL \times 1.1 \times 10^{-2}$, or about 10^{-8} cm^2, for a total emitting area over the 5000 slots of 5×10^{-5} cm^2, and $A/a = 6.3 \times 10^{-3}$. This represents an improvement of two orders of magnitude over the emitting area available with the cone array.

The wedge emitter can be formed by the same technique used to make cone emitters. The only difference in the fabrication process is that slots rather than holes are micromachined in the molybdenum gate film and silicon dioxide layer. To show how a pattern of slots is formed, it is necessary to review the SRI screen-lens/parallel-electron-beam lithography apparatus. The apparatus was originally developed to print arrays of submicron diameter holes in a PMMA resist. The goal was to print arrays of holes with 6.35-μm spacing between centers.

The SRI screen-lens/parallel-electron-beam lithography system (shown in Figure 4) consists of a tungsten hairpin filament cathode, a grid cap, drift space, screen lens, and target. Each hole in the screen functions as an aperture and tiny lens when voltages are applied as shown. The electron optical theory developed for this configuration (Brodie, et al. 1981) predicts that the object (virtual cathode just in front of hairpin) will be (de)magnified in the ratio $M = Z_i/2Z_o$, where M = (image size)/(object size), Z_i is the distance from the screen to the image (target), and Z_o is the distance from the screen to the object

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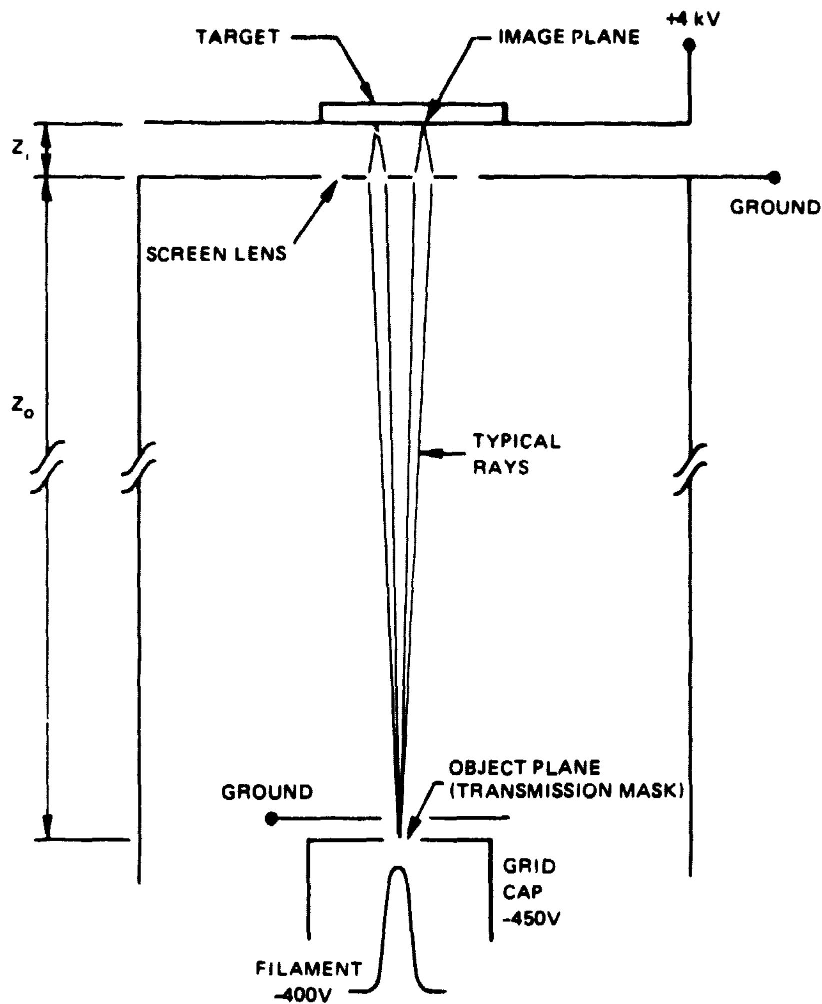

MAGNIFICATION FACTOR: $M = Z_i / 2Z_o$

FIGURE 4 SCHEMATIC OF THE SCREEN LENS

(cathode). Thus, with the configuration used [i.e. Z_o = 24 inches (61 cm) and Z_i = 1/16 inch (1.5 mm)], we have $M = 1.3 \times 10^{-3}$. Then, because the system had a 2000-line/inch screen [i.e. 0.0005-inch (12.7-μm) center-to-center spacing] and we wished to print an array of holes on 0.00025-inch (6.35-μm) centers, we had to do four exposures while moving the image 0.00025 inch (6.35 μm) on the substrate between exposures. Furthermore, we had to move 0.00025 inch (6.35 μm) in directions that are parallel to the orthogonal orientation of the lines on the 2000 line/inch screen.

It is clearly difficult to move the target 0.00025 inch (6.35 μm) between each of four exposures and still get precise positioning of the pattern, especially when the manipulation must be done on the target in

a vacuum chamber. However, we could take advantage of the demagnification factor (M) and move the object (cathode) a distance (d_o) in a direction parallel to one of the sets of screen wires and cause the image to move some proportional distance (d_i) that will be $d_i = Md_o$. Because we know that we wanted d_i to be 0.00025 inch (6.35 μm) and M was calculated to be 1.3×10^{-3} from the system geometry, we could estimate the distance the cathode had to be moved for the first trial as $2.5 \times 10^{-4}/1.3 \times 10^{-3} = 0.1923$ inches (4.88 mm).

The configuration of the screen lens system makes it much easier to move the screen/target combination together than to move the cathode. The screen/target combination was mounted on a microscope stage whose dial indicators were graduated in 0.001-inch (25-μm) increments; the positioning of the image on the target thus could be done to within 1.4×10^{-6} inch (0.03-μm) when the demagnification factor is taken into account.

This manual system worked very well for printing arrays of holes; excellent arrays on 6.35-μm centers ($2.5 \times 10^6/cm^2$) have been formed using this technique. Figure 5 is a scanning electron micrograph (SEM) of such an array made with a four-exposure step-and-repeat process. Because the SEM was taken at an angle of 45° to the surface, the spacing between the holes is distorted in one direction; however, it is clear from the SEM that the positioning of the holes is very good.

Although the manual positioning of the screen/target stage worked well for printing hole patterns with the screen lens, it would not be possible to traverse the stage manually at a uniform rate to print arrays of lines on the target. This obviously requires a controlled motor drive. Stepper motors and associated electronics were purchased and adapted to the screen lens stage drive. The initial setup used a manual multiaxis switch interface to address the motors. (Microprocessor interfacing is also available as an add-on). Figure 6 is a block diagram of the drive system; system parameters are given in Table 2.

Figure 7 shows the pattern that we planned to lithograph using a 2000-mesh screen and traversing the stage an equal distance in the X and Y directions simultaneously. The pattern contains 5000 lines, each 10-μm long and about 1-μm wide; in an area 1-mm in diameter. The exposures take about 320 seconds; 25 separate arrays are lithographed simultaneously in a 1/2-inch square substrate. Figure 8 is an SEM of a portion of a 5000-slot array etched into the molybdenum gate film and the silicon dioxide layer of a cathode structure using the screen-lens exposure scheme described above.

Wedges were formed in the slots using basically the same dual-deposition scheme that is used to form cones in holes. The apparatus, shown schematically in Figure 9, consists of a substrate holder mounted on the shaft of a motor for rotation a substrate heater, two electron beam evaporators, and two quartz crystal deposition-rate monitors. The motor and crystal monitor are mounted on a water-cooled plate to help control temperature. One evaporator is mounted directly in line with

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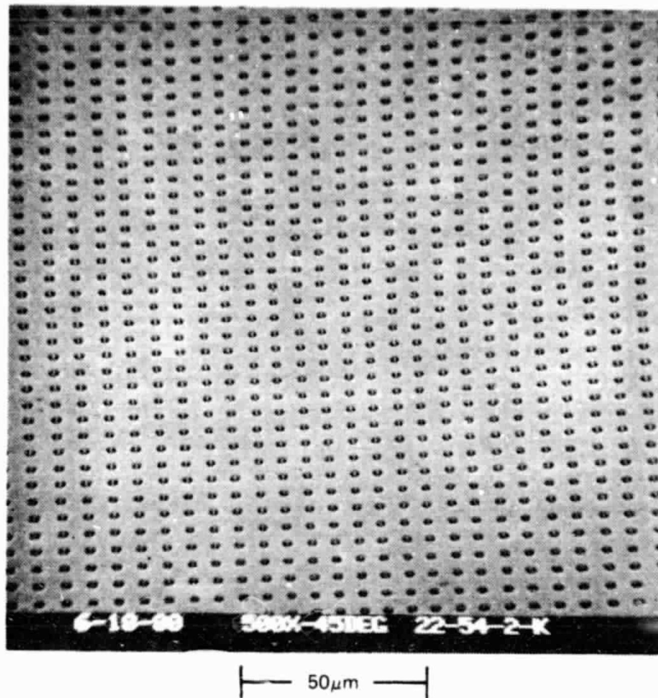

FIGURE 5 PORTION OF A 20,000-TIP ARRAY SPACED ON 0.00025-INCH CENTERS OVER AN AREA 0.040-INCHES IN DIAMETER

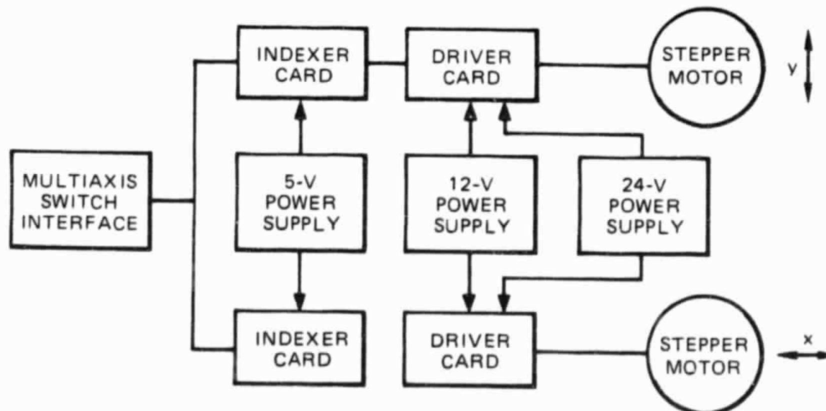

FIGURE 6 STEPPER-MOTOR-DRIVE SYSTEM FOR THE SCREEN-LENS ELECTRON-BEAM LITHOGRAPHY SYSTEM

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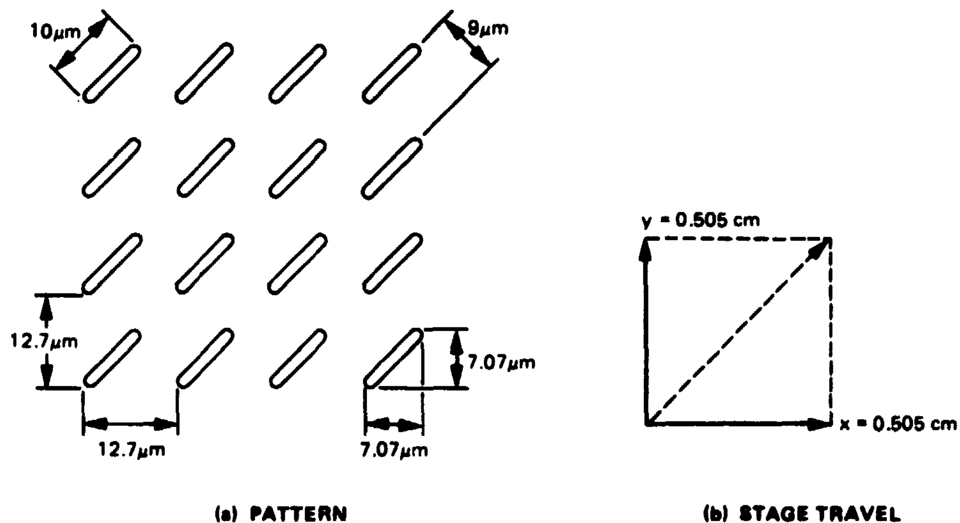
Table 2

OPERATING PARAMETERS FOR LITHOGRAPHING
LINE ARRAYS USING A 2000-MESH SCREEN LENS

Parameter	Value
Step rate (steps/s)	20
Motor travel (degrees/step)	0.9
Stage travel (μm/step)	0.8
Beam spot travel (Å/step)	11
Stage rate (μm/s)	16
Spot rate (Å/s)	220
Spot diameter (μm)	1



(a) PATTERN

(b) STAGE TRAVEL

FIGURE 7 PATTERN FORMED USING A 2000-MESH SCREEN LENS AND DRIVING x AND y SIMULTANEOUSLY AT 15.7 μm/s FOR 321 SECONDS

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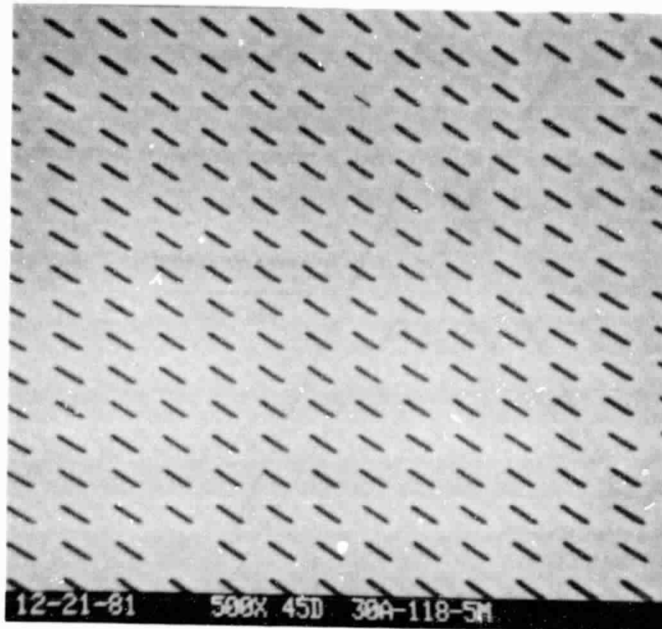
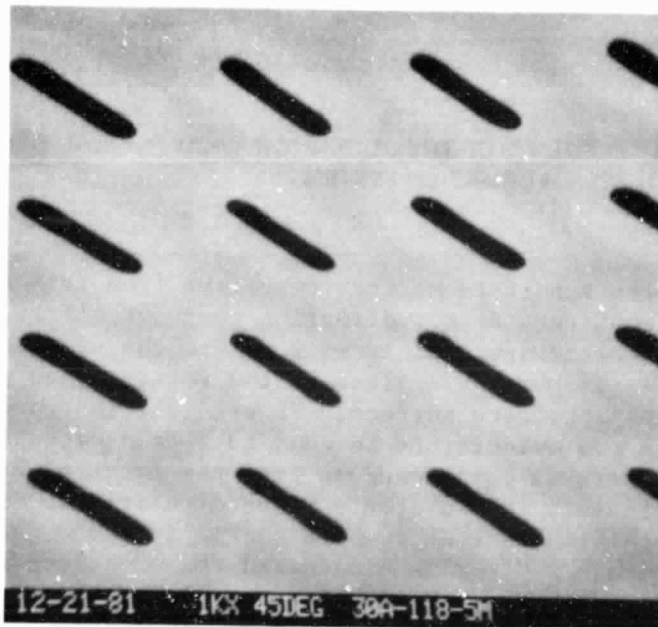


(a) PORTION OF A 5000-SLOT ARRAY (500X)



(b) PORTION OF A 5000-SLOT ARRAY (1000X)

FIGURE 8 SCANNING ELECTRON MICROGRAPH OF SLOTS ETCHED IN MOLYBDENUM GATE AND SiO_2 INSULATING LAYERS

9 μm between rows of lines.

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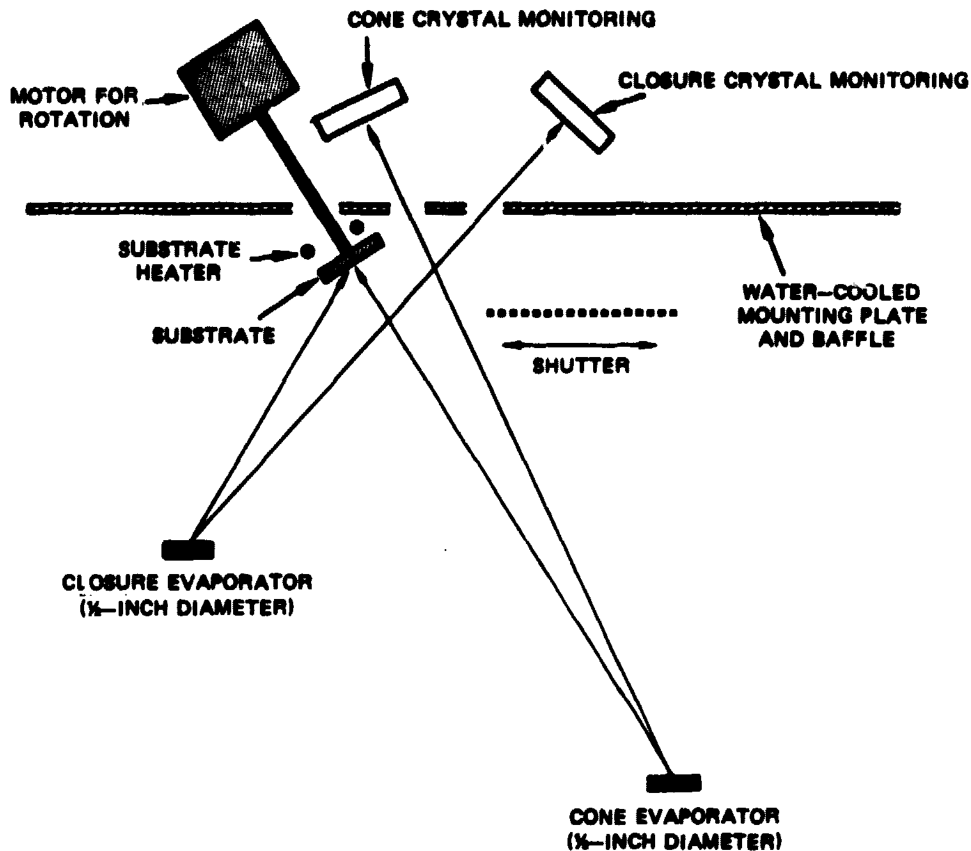

FIGURE 9 ELEMENTS OF THE ULTRAHIGH-VACUUM, DUAL-DEPOSITION CONE-FORMATION SYSTEM

the center of the substrate so that evaporant from this evaporator will arrive at the substrate from a direction perpendicular to the substrate surface. The other evaporator is well off to one side so that the evaporant from this evaporator arrives at the substrate at an angle of about 30° to the substrate surface. Figure 10 illustrates how deposition from these two evaporators is used to form a wedge in a slot. First the substrate is positioned so that the material from the closure evaporator arrives at the substrate perpendicularly to the long axis of the slot. Deposition is then done to partially close the slot from one side, after which a shutter is closed and the substrate is rotated 180° and the deposition is repeated so that the closure of the slot is symmetrical as shown in Figure 10(b). It is necessary to close the shutter while turning the substrate because, as it turns, the slots will pass through an orientation that will briefly expose the silicon in the base of the slots to the evaporant beam; hence, the silicon in the base will then be coated with some of the closure film. This will cause difficulty later because the closure film is also a parting layer. This means that when the parting layer is removed, all structures resting on the parting layer are also removed--in this case the wedges.

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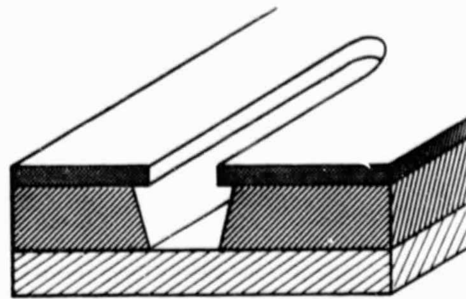
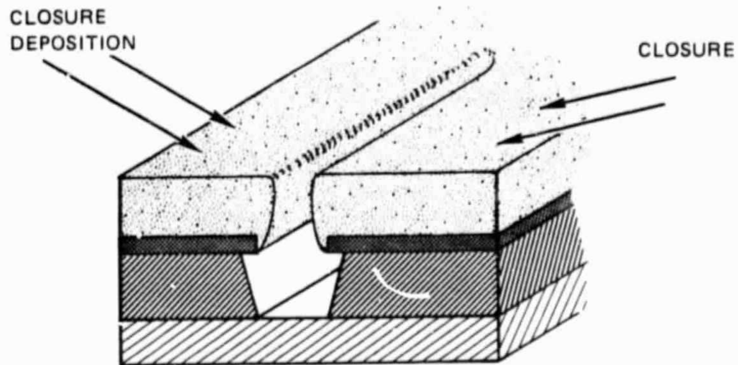
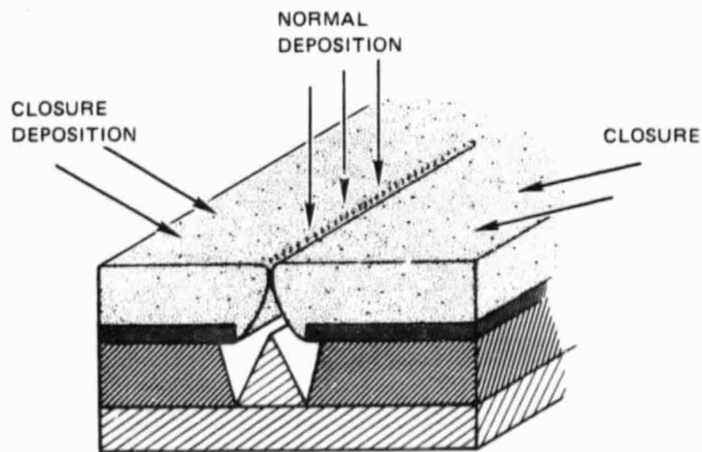


(a) SECTION OF A SLOT



(b) PARTIAL CLOSURE



(c) WEDGE FORMATION

FIGURE 10 WEDGE FORMATION USING DUAL DEPOSITION

After the preclosure layer has been deposited equally from both sides, a brief deposition of molybdenum is made from the normal evaporator. The closure evaporator is then phased back in and rotation of the substrate is initiated. When both evaporators are operating and the substrate is rotating, the closure film is deposited into the slot only when it is lined up in a direction that is line-of-sight to the closure evaporator. This is approximately one fifth of a revolution during the early stages of deposition, decreasing as the film gets thicker and the slot narrows. There is a good indication that this will cause the wedge material to be sufficiently rich in molybdenum to prevent etching during removal of the closure film. The reason for this is the observation that the film on the gate, which is a composite of the closure film and molybdenum wedge formation film, etches cleanly from open areas of the substrate. However, the film that is very close to the edge of a mask or hold-down clamp so that it is shadowed from the closure film for a portion of the rotation cycle (i.e. molybdenum rich) usually does not etch off.

In view of this evidence, the first wedges were formed without protection against depositing some amount of closure film into the wedge. If it is later determined that we would rather not have this situation, we can add fences on the edge of the substrate holder that will shadow the closure evaporator when the orientation favors deposition into the slots. Another solution would be to use a shaped rotating shutter that would shadow the entire substrate during the portion of each cycle that is liable to have unwanted deposition into the slots.

Figure 11 is a scanning electron micrograph (SEM) of a portion of an array of wedges after the wedge formation has been completed but before the closure film has been etched away [as shown in Figure 10(c)]. Figure 12 shows part of a 5000-wedge array and a high-magnification view of a single wedge about 10 μm long. The results of emission tests are given in Section IV.

Careful examination of the wedge arrays showed that many wedges were lifting from the silicon substrate, causing a short to the gate film. It appears that the molybdenum develops tensile stress as it builds up in the wedge structure (as all metal films commonly do). These stresses can be sufficiently large to break the wedge away from the silicon substrate. It was also noticed that the wedges that did work well, however, were high-voltage emitters because they were too short (in height) had very little or no wedge lifting problems. This suggests that the stress problem is a marginal situation, and that the wedges need to be only slightly shorter (in height) in order to be within acceptable limits. Using a cathode structure with a thinner silicon dioxide layer and slots that are proportionally narrower would permit us to make shorter (in height) wedges and probably prevent the tensile stress from becoming high enough to fracture the bond with the silicon substrate.

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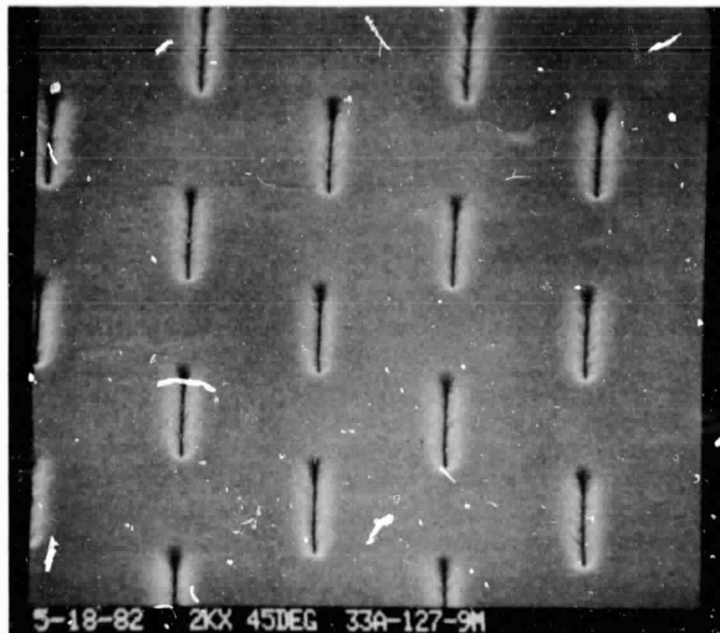

FIGURE 11 PORTION OF A 5000-WEDGE ARRAY WITH
WITH THE CLOSURE FILM STILL IN PLACE

3. Anisotropic Etching

Wet chemistry of the kind that has been used in micromachining the holes in our cathode structures is generally an isotropic etch. The degree of undercut of the gate film that results from etching the silicon dioxide layer [see Figure 2(a) and 2(c)] depends on the silicon dioxide thickness and the adhesion between the molybdenum gate film and the oxide layer. In the best of circumstances, the undercut is approximately equal to the depth of the oxide layer, and at worst it has been as high as four times the oxide depth. In all cases, it is too large because it limits the ultimate packing density. The maximum packing density we have achieved with good results is about 9 μm between centers (~ 1.2×10^6 tips/cm^2). We have printed and etched arrays with packing densities of up to 5×10^6 tips/cm^2 (4.5-μm centers); however, undercutting of the molybdenum made the structures unsuitable as cathodes (too little support is left for the gate film and the structure will not survive the rigors of the cone formation process).

If an anisotropic etch were to be used on the oxide layer, there would (in principle), be no undercut of the molybdenum and we should be able to make cathode patterns with packing densities of 5×10^6/cm^2 and perhaps even higher. Recently, significant developments in dry etching techniques (plasma) and the means of achieving anisotropic etching with dry etching have evolved into a reactive ion beam etch (RIBE) process that has many desirable properties. The process combines the effects of chemical reactions that form volatile products and physical sputtering processes to remove any nonvolatile products. In addition, because an

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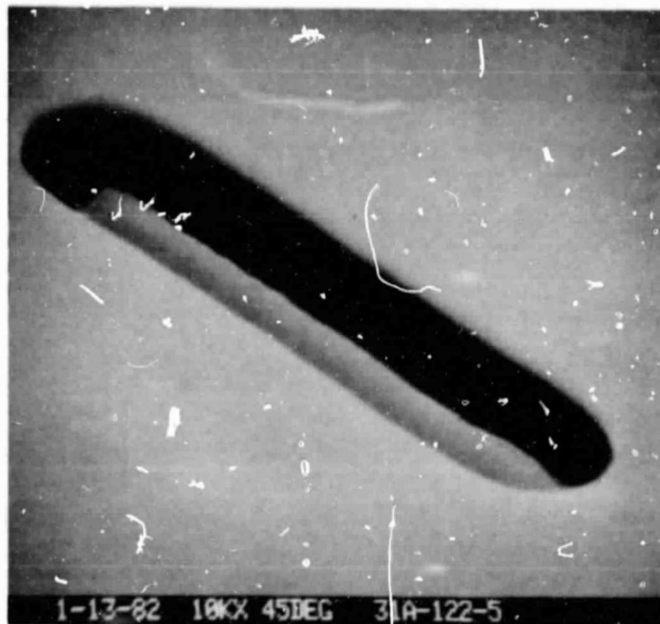
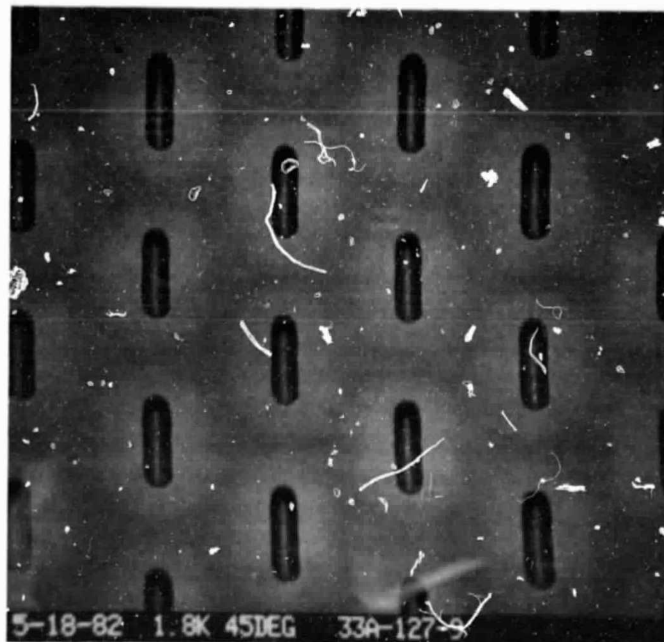


(a) HIGH MAGNIFICATION OF A 10-μm LONG WEDGE



(b) PORTION OF A 5000-WEDGE ARRAY

FIGURE 12 THE WEDGE-SHAPED EMITTER ARRAY

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ion beam is used, the etch can be anisostropic (i.e. the ions can be directed at the work piece in a parallel beam with very little scatter and thus produce an anisotropic etch in the direction of the beam). Clearly many parameters must be controlled to produce the desired effect.

Figure 13 shows a typical RIBE system. The indicated parameters used for etching through a 1.5-μm thick silicon dioxide layer were worked out on a Varian Associates/Extrion Division reactive ion beam etch system (Downey et al., 1981) at the Varian Associates Central Research Laboratories in Palo Alto, California, by Dr. R. Powell.

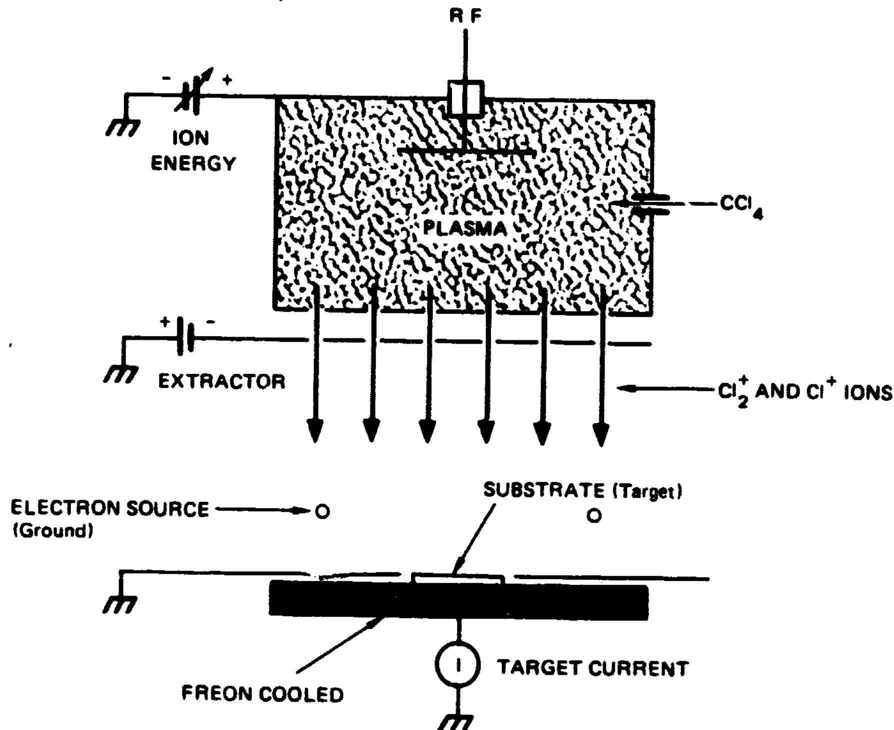

FIGURE 13 REACTIVE ION BEAM ETCH SYSTEM

Typical etch parameters for SiO_2 1.5 μm thick: Ion Energy = 500 eV, Ion Flux ≅ 0.5 mA/cm^2, System Pressure ≅ 10^{-4} torr, Time ≅ 25 min.

The active ion for the work done to date has been chlorine$^+$ extracted from a plasma produced by flowing carbon tetrachloride (CCl_4) into an ion source. The CCl_4 is dissociated and ionized and an ion beam is extracted that consists mainly of Cl_2^+ and Cl^+. Because CCl_4 is thermodynamically unstable at the source temperature, the carbon dissociates from the chlorine before ionization and condenses on the walls of the ionization chamber. Thus, very little carbon is found in the ion beam.

Our first attempts at anisotropic etching of cathode samples were done by preparing a standard cathode substrate up through Step (5) of the process outlined in Section III-A. At this point, the array of

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holes has been etched through the gate film, but the oxide has not been etched, and the PMMA resist is still on the surface. The molybdenum gate film was deliberately made 0.6-μm thick (rather than the usual 0.4 μm) because the selectivity of RIBE is not optimum. As a result, we expect the PMMA and some of the molybdenum to etch away by the time the oxide has been etched down to the silicon base. Etch time is critical for the same reason, because the etch does not stop automatically at the silicon dioxide/silicon interface, as the wet etch does. Therefore, it is necessary to calibrate the process carefully, or to have a monitor that can be used to determine the end point.

Because it is important to have all holes the same depth (so that all cones will have the same height for uniformity of emission), we intend to stop the RIBE just short of the silicon and finish with a light HF wet isotropic selective etch that will give us a slight undercut and stop at the silicon surface.

Figure 14 shows a test sample etched in this way. After the RIBE and wet etch, the molybdenum gate was etched away with selective wet chemistry to afford a better view into the holes. Because we were still unable to determine the extent of the etch into the silicon base, the sample was broken in the hope of getting a cross sectional view of one

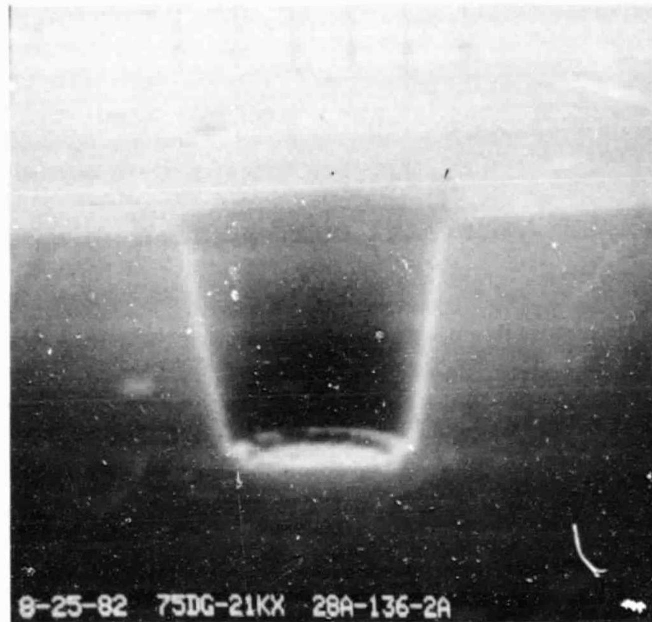

FIGURE 14 ANISOTROPICALLY ETCHED HOLE IN THE SiO_2 LAYER OF A CATHODE STRUCTURE

The molybdenum gate film has been removed.

of the holes. This worked out well, as can be seen in Figure 14. As mentioned, the molybdenum gate has been etched away, but the shape of the hole formed in the silicon dioxide and the penetration into the silicon base are very clear. The side walls of the silicon dioxide are nearly vertical, and the amount of etch-back done with HF is clearly shown. The etch-back is about 0.1 μm, and the penetration into the silicon is about 0.075 μm. The diameter of the hole at the top is about 1.7 μm and the diameter at the bottom of the oxide is 1.25 μm. The side wall is about 10° from vertical. Perhaps more important, the undercut of the molybdenum gate was equal to the etch-back, or 0.1 μm. The importance of this is clear in Figures 15 and 16, which show two fractured cathodes. One was fabricated using wet chemistry and the other with RIBE. Figure 16 is a high-magnification SEM of a single tip, showing the completed cathode structure. Clearly, RIBE will enable us to increase the packing density of the cathodes without weakening the gate film.

These encouraging results show that the RIBE process should eventually give us improved cathodes; however, development of the process has not been without difficulties. In particular, we have experienced contamination problems associated with the process that resulted in very poor emission tests with the first RIBE samples. The first of these had to do with a thermally conductive adhesive that is commonly used in RIBE systems to bond samples to be etched to carrier disks, which also act as heat sinks. The adhesive material was found to be difficult to remove completely and left a residue on the cathodes that caused difficulties with the first emission tests. In addition, because the PMMA did not hold up well, the molybdenum gate film is etched significantly and is left with an "orange peel" surface. Finally, there also seemed to be some residue from the PMMA that could not be removed, probably because of carburization of the PMMA by the heat generated during the RIBE process.

In an attempt to improve the resist situation, a chromium resist for the RIBE was tried in place of the PMMA. In this process, a chromium film about 4000 thick is deposited over the molybdenum gate film; the chromium is then coated with PMMA, the hole pattern in the PMMA exposed, and the pattern etched through the chromium down to the molybdenum surface. The PMMA is then removed, leaving a chromium mask over the molybdenum gate film (Figure 17). Because chromium etches much more slowly in the chlorine ion beam than either molybdenum or silicon dioxide, it is possible to etch through the 0.4-μm molybdenum gate and the 1.5-μm silicon dioxide layer without etching through the chromium mask. In addition, we replaced the heat sink adhesive with PMMA, which we can remove completely when the RIBE process has been completed. Furthermore, the remaining chromium is not removed until immediately before forming cones in the holes; thus, the molybdenum gate film surface is protected throughout the handling associated with the RIBE process. Figure 18 shows a high-magnification SEM of a hole etched with the RIBE process using a chromium resist. Figure 18(a) shows the hole as received from the RIBE process with the chromium resist still in

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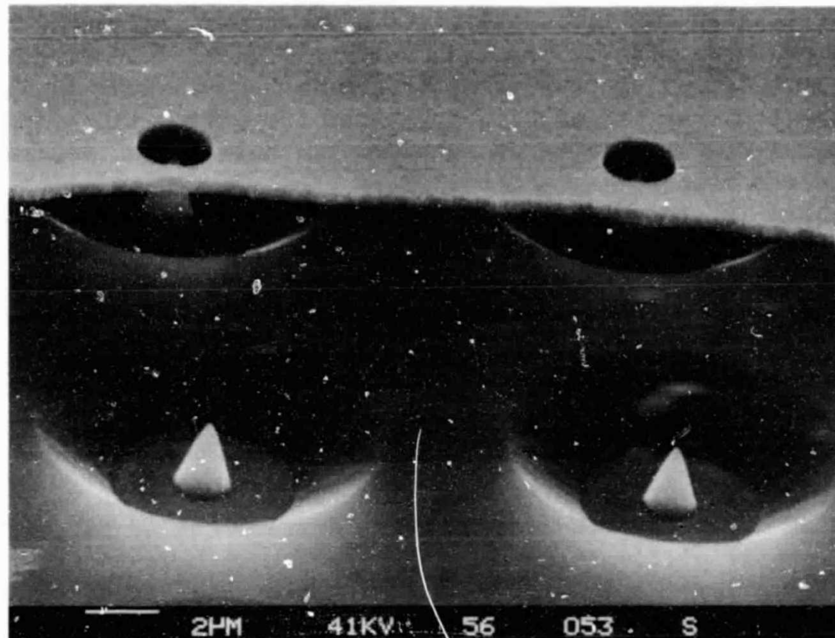

(a) ISOTROPIC WET ETCH OF SiO_2 TIPS ON 12.7-μm CENTERS

(b) ANISOTROPIC DRY ETCH OF SiO_2 TIPS ON 9-μm CENTERS

FIGURE 15 ISOTROPIC AND ANISOTROPIC ETCH OF SiO_2

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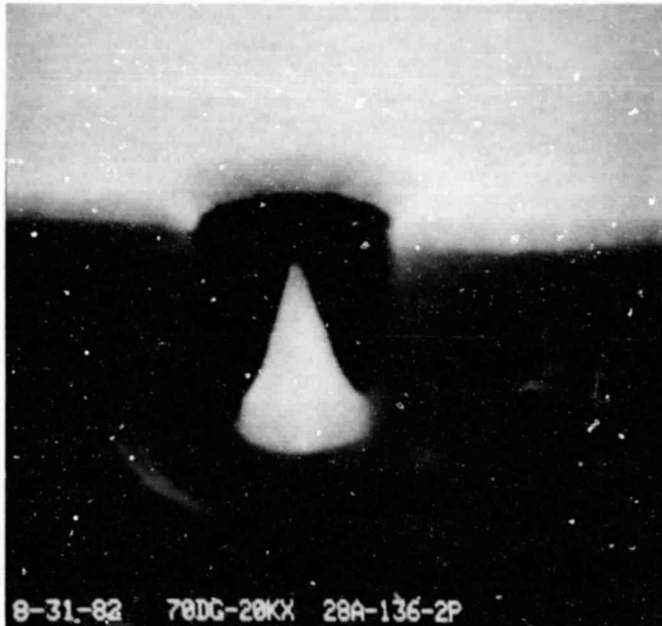

FIGURE 16 FRACTURED CATHODE SHOWING SECTIONAL VIEW OF HOLE ETCHED IN SiO_2 USING REACTIVE ION BEAM ETCHING

Note total absence of undercutting of molybdenum gate film.

place, and Figure 18(b) shows the same hole after a light etch-back of the silicon dioxide layer with HF and removal of the chromium resist film. Cones have been formed in a sample etched with the chromium resist process, and good results were obtained with emission tests using these cathodes. The emission test results are discussed in Section IV.

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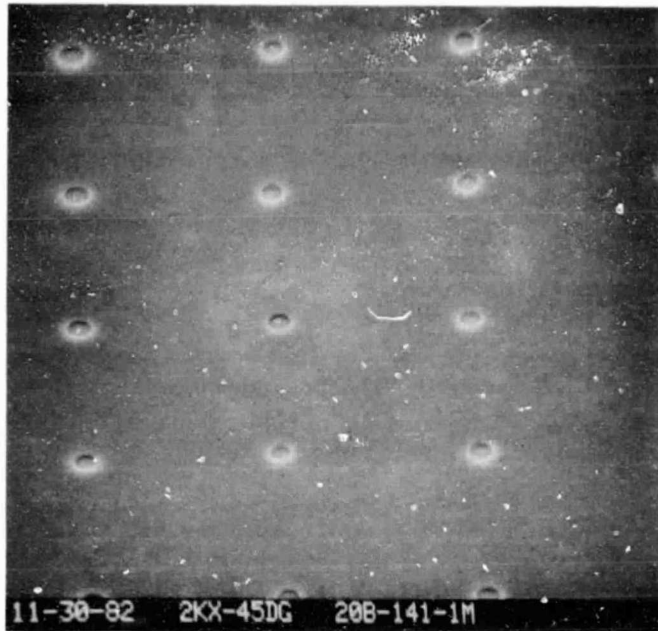

(a) HOLES ON 12.7-μm CENTERS

(b) CLOSEUP OF A SINGLE HOLE

FIGURE 17 HOLES ETCHED IN 4000 Å OF CHROMIUM OVER MOLYBDENUM

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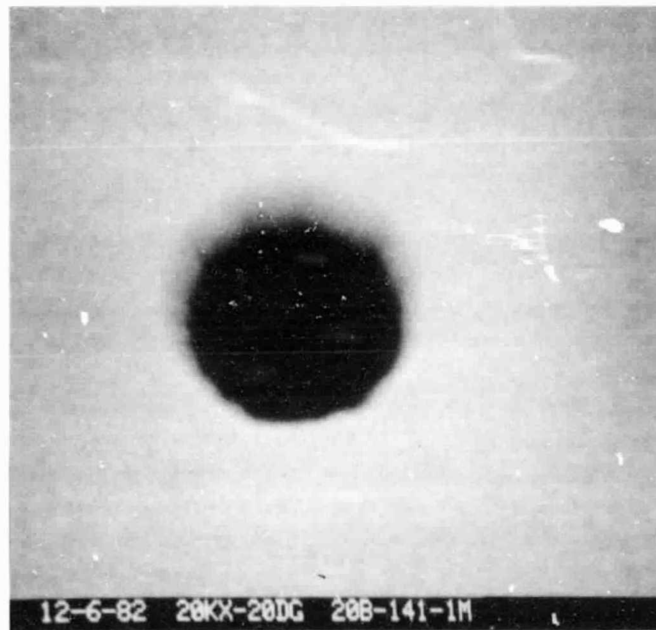
(a) WITH CHROMIUM RESIST



(b) AFTER HF TOUCH-UP OF THE OXIDE AND REMOVAL OF THE CHROMIUM

FIGURE 18 REACTIVE ION BEAM ETCHED HOLE IN MOLYBDENUM AND SiO_2

IV EMISSION TESTS

A. Initial Emission Tests

All cathodes are tested on completion of the fabrication process, except for those that are obviously not worth testing (e.g. with a visible fault) and those that the client requested that SRI deliver untested. The Appendix lists all cathodes that were tested (including those on other programs, to give an large a data base as possible) by test group. The listing includes bakeout temperature, cathode mount, gate current, applied voltage, maximum emission, number of 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 19 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 gentle curve as shown in Figure 19, 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.

The emission process is monitored with a dual-trace oscilloscope, as shown in Figure 19. 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.

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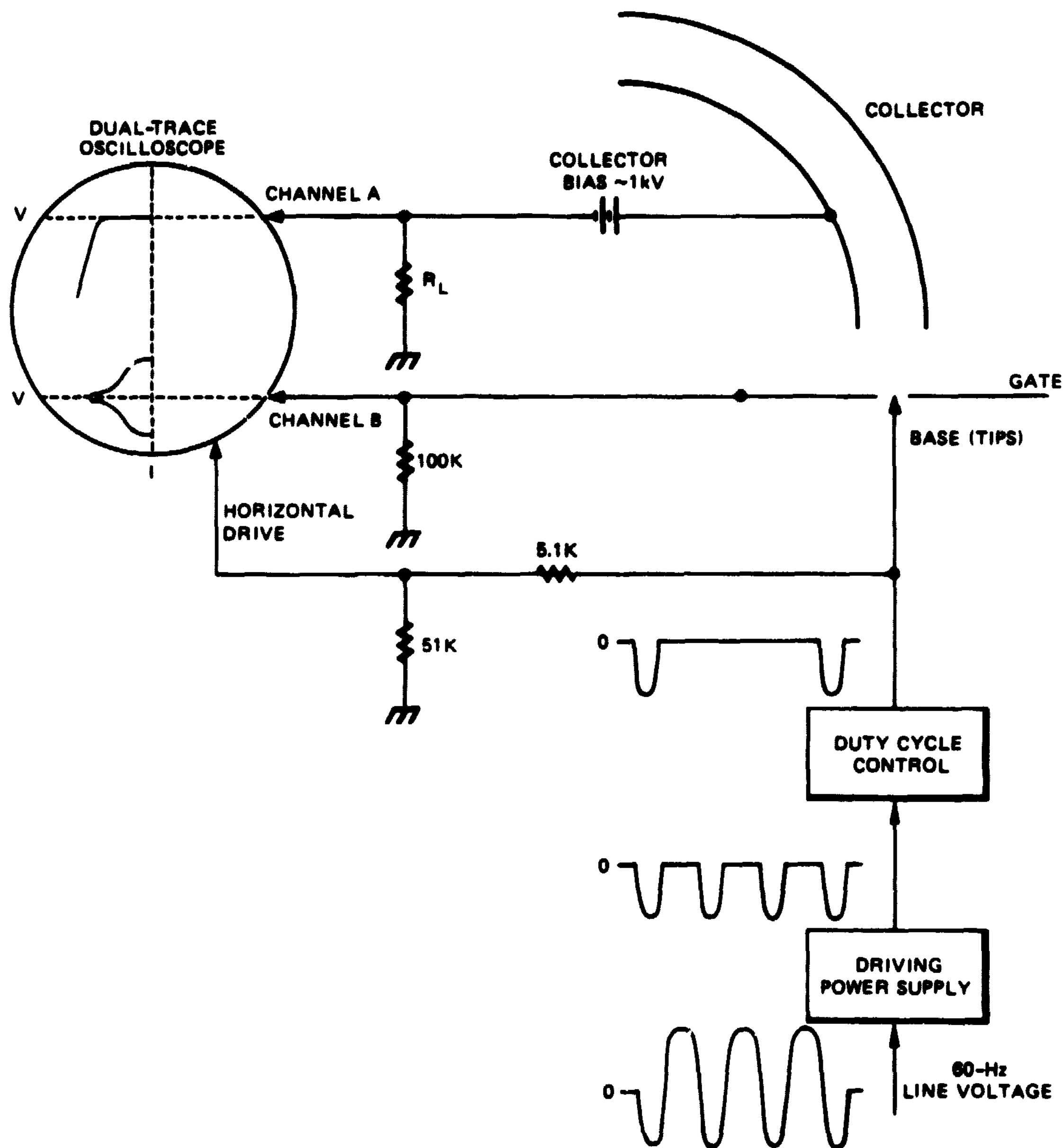

FIGURE 19 STANDARD SETUP FOR EMISSION TEST

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. High-Current-Density Experiments

Most cathode failures fall into three categories:

- Individual tip failures (which only rarely degrade cathode performance or cause a short between the base and gate).
- A damaging electrical discharge between the collector and the gate film.
- A high-energy arc from the cathode structure (base and gate together) to the collector.

Examples of each type of failure are shown in Figures 20. The kinds of damage shown in Figure 20(b) and 20(c) have been seen only when operating our 5000-tip arrays at emission levels of about 15 mA with a 60-Hz cathode driving voltage and 1200 V on the collector. This a peak power input to the collector of 18 W and a peak cathode loading of about 2 A/cm^2. In general, peak emission levels of 10 mA (1.3 A/cm^2) with the 60-Hz driving voltage and 1200 V on the collector (12 W peak) can be achieved comfortably.

Electrical discharges of the kind shown require high gas pressures to support the discharge. Presumably gas to support a discharge is evolved from the cathode or anode structure or both. We may also presume that local high pressures that can support a discharge or an arc are the results of materials outgassing due to heating or desorption arising from ion or electron impact on a surface. If this is the case, it should be possible to remove this gas source by proper selection of materials and adequate processing to outgas the materials before drawing emission from the cathode. If the cathode itself is the source of the gas, many processing variables can be investigated, including materials selection, deposition technology, and post-fabrication processing (e.g. vacuum baking).

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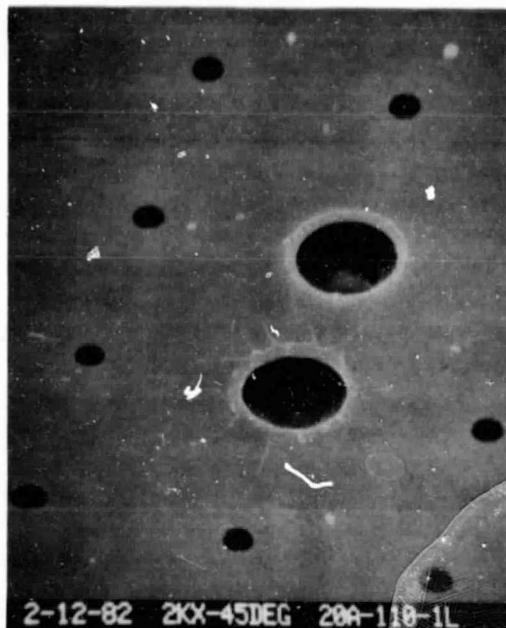
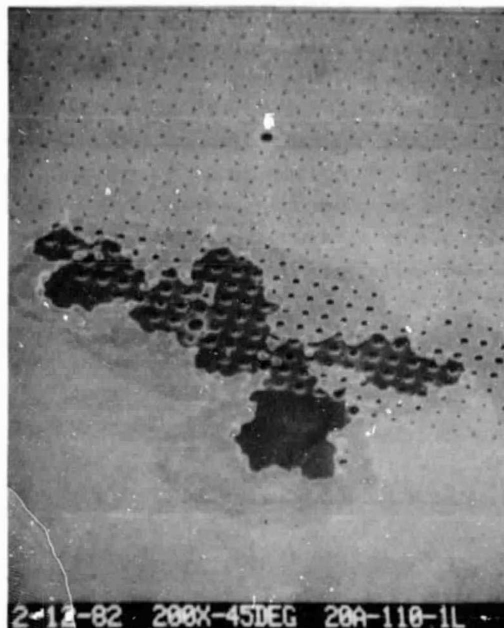
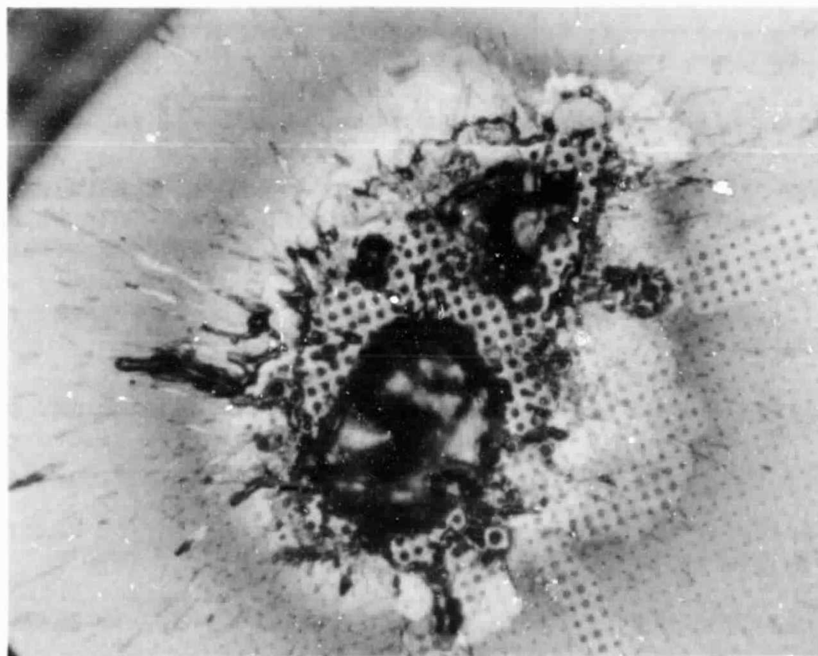


(a) INDIVIDUAL TIP FAILURE (usually does not change cathode performance significantly)



(b) RESULT OF ELECTRICAL DISCHARGE BETWEEN GATE AND COLLECTOR



(c) RESULT OF HIGH-ENERGY ARC BETWEEN CATHODE AND COLLECTOR

FIGURE 20 CATHODE FAILURE MODES

To determine whether the source of gas in the system that results in damaging discharges is because of cathode loading or anode (collector) loading, anode loading was reduced while maintaining a high level of cathode loading by fabricating very-small-area cathodes. Then, if the gas were the result of cathode loading, breakdown would be expected to occur at about 2 A/cm^2 as it does with the large-area cathodes. If, on the other hand, anode loading is the problem, we should be able to achieve much higher current densities with the small-area cathodes.

The small area cathodes were fabricated with the same packing density as the 5000-tip array cathodes, but with only 12 or 16 tips (4 x 4 and 3 x 4 arrays). The small-area cathodes were tested in the same system that is used to test 5000-tip arrays. As mentioned earlier, our experience with the 5000-tip arrays showed that electrical breakdown is common at collector loadings of 18 W peak power and 2 A/cm^2 cathode loading (15 mA total peak emission); however, 12 W peak collector loading and 1.3 A/cm^2 peak cathode loading (peak emission 10 mA) is usually achievable without difficulty. If cathode loading were causing the electrical breakdown, we would expect difficulty with the 16-tip array (4 x 4) at a total current of about 50 μA (2 A/cm^2); however, this was not our experience. Emission tests with the small-area cathodes commonly produced total emission currents of 1 mA and higher. The current density at 1 mA of emission from a 16-tip array with the tips on 12.7-μm centers is about 40 A/cm^2; from a 12-tip array, it is greater than 50 A/cm^2--more than an order of magnitude higher than we have been able to achieve from 5000-tip arrays with having the same tip-packing density as the 16-tip arrays.

In one test, a 12-tip array (25A-121-50) was taken to 6 mA total peak emission using the 60-Hz half-wave-rectified driving voltage. This is an average emission of 500 μA per tip and a current density from the area occupied by the array of 320 A/cm^2. The cathode was operated at this level for three days and then removed from the system and examined. Figure 21 is an SEM of the 12-tip array after operating at 320 A/cm^2; no damage is apparent. Although a Fowler-Nordheim plot of the results (Figure 22) shows no obvious space charge effects, the appearance of some gate current at the peak emission levels suggested that some emission may have been diverted to the gate because of the very high space charge immediately in front of each tip.

Failures that occurred with the small-area cathodes never were of the kind shown in Figure 20(b) and 20(c), but were of the kind shown in Figure 20(a). This suggests that anode loading is responsible for the discharges that result in catastrophic damage, and that the individual tip failures result from local high-pressure discharges owing to cathode tip or gate film heating or local contamination that produces a burst of gas between a single tip and its surrounding gate structure.

Table 3 summarizes the high-current-density tests made during this period with small-area cathodes. Note that the seven cathodes listed from Series 29 all exceeded 100 A/cm^2. This suggests that the Series 28

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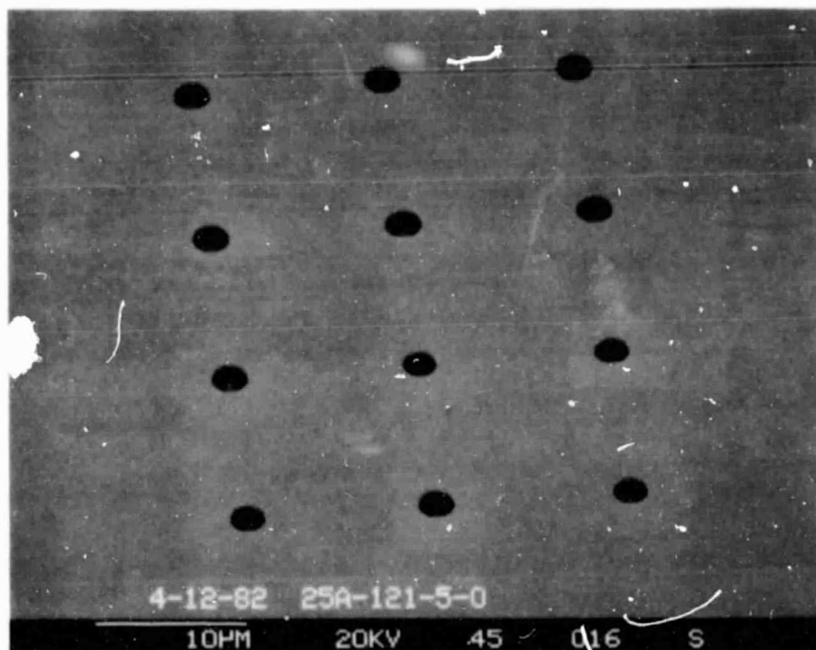

FIGURE 21 SEM OF A 12-TIP CATHODE AFTER OPERATING AT 6 mA PEAK WITH A 60-Hz DRIVING VOLTAGE (320 A/cm^2 peak)

cathodes (1 mm diameter active area) should be capable of producing total currents of about 750 mA routinely if our anode systems could be made to handle such high powers and provided that gate current does not become a problem at these higher currents.

C. High-Anode-Voltage Tests

Some difficulty has been encountered in operating cathodes with anode voltages above our usual +1200 V. Again, the suspicion has been that the problem results from anode heating and outgassing that leads to a discharge, rather than anything to do with the cathode proper. To test this theory, a cathode (20A-107-10-P) was mounted in an SRI-assembled tube with a water-cooled anode. The tube was processed with a 400°C bakeout for 96 hours. The cathode was then turned on with a 60-Hz pulse drive and +1200 V on the water-cooled collector. The emission was brought up to 20 mA over three days and observed to be very stable. The cathode was held at 20 mA for 6 hours and then turned off while the tube was pinched off from the pump station. [The tube had an appendage pump, but the appendage pump was not turned on.]

The cathode was turned on again in the sealed off tube with no pump, and brought up to 20 mA with +1200 V on the collector. Emission was held at this level 4 days and was well-behaved during that time. The emission current was then lowered to 1 mA and collector voltage raised to +3 kV. The emission was then raised to 20 mA over a 30-hour

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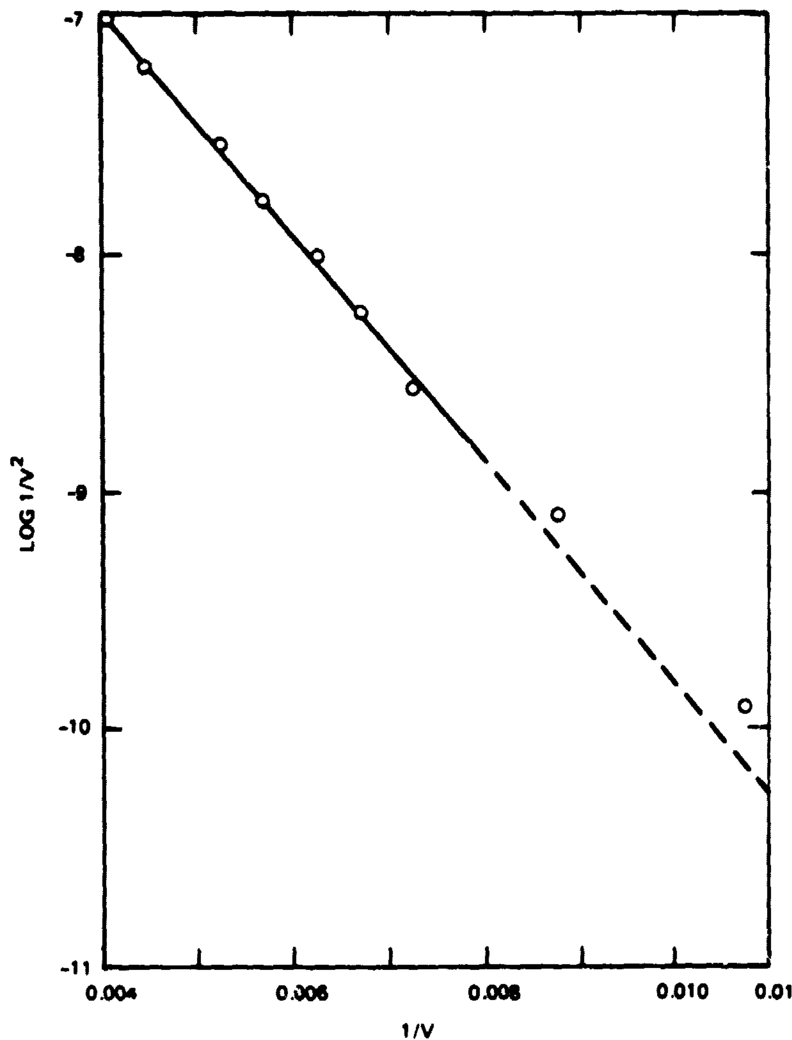

FIGURE 22 FOWLEN-NORDHEIM PLOT FOR 25A-121-50 (12-tip array)
Peak emission 320 A/cm^2 (6 mA).

span and observed to be stable throughout that time. The cathode was held at 20 mA with +3 kV on the collector for 9 days and was quiet and well-behaved; it was found to be shorted in the evening of the tenth day. A chart recording of the emission showed no warning of the short: Emission simply ceased when the cathode shorted. Attempts to clear it with a capacitive discharge were unsuccessful.

The cathode was removed from the tube and examined in a light microscope. Nineteen individual tips were blown. When the cathode was mounted in the tube, it had 13 tips blown from previous tests to 20 mA. There was no other damage, and the cathode appeared to be operable. Electrical measurement showed that the cathode was not shorted. The

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Table 3

SUMMARY OF HIGH-CURRENT-DENSITY TESTS
WITH SMALL-AREA CATHODES

Cathode	V_{max} (V)	I_{col} (mA)	I_{gate}	J_{max}	Tips	Mode	Collector Potential (V)	Remarks
25A-121-5C	247	1.25	-7	50	16	CW	600	3 days at 50 A/cm^2 CW--2 blown
25A-121-5D	245	1	-2	57	12	60 Hz	1200	OK
25A-121-5E	370	1.24	-12	66	12	CW	540	Failed at 66 A/cm^2 CW
25A-121-5F	285	1	<1	70	12	60 Hz	1200	Shorted
25A-121-5L	175	1.25	<1	50	16	60 Hz	5000	High anode voltage test--OK
25A-121-5L	180	1	<1	40	16	CW	5000	Power supply failed (4 days at 5 kV)
25A-121-50	245	6	-5	330	12	60 Hz	1200	3 days at 330 A/cm^2--OK
25A-121-50	195	2.2	-3	125	12	60 Hz	1200	OK
25A-121-50	175	0.64	<1	~ 30	12	CW	3000	5 blown suddenly
29A-128-4D	230	1	+25	300	4	60 Hz	1200	250 μA/tip--OK
29A-128-4F	220	2.5	<1	110	25	60 Hz	1200	2 days at 100 A/cm^2
29A-128-4H	240	2.5	<1	300	10	60 Hz	1200	Blown by power supply accident
29A-128-4I	199	1	<1	100	12	60 Hz	1200	OK
29A-128-4N	212	1.1	+75	100	13	60 Hz	1200	OK
29A-128-40	200	1	<1	120	10	60 Hz	1200	OK
29A-128-4U	225	1.75	+75	230	9	60 Hz	1200	Breakdown out of active area

unanswered question now is, Was the short a fault in the tube rather than the cathode, or was the cathode shorted but inadvertently cleared during demounting and handling? Whatever happened, the cathode did operate at 20 mA, 60 Hz pulse into a +3 kV collector for nine days before the short (or apparent short). The cathode will be remounted and tested. If its performance in unchanged, it is likely that the short resulted from a tube fault, rather than an actual cathode short.

In either case, the water-cooled anode is a significant element, in that stable operation was obtained for several days with 3 kV on the collector and 20 mA peak emission. This had not been possible with uncooled collectors.

D. Gate Current and Collector Voltage

Tests with state-of-the-art 5000-tip arrays usually show the onset of gate current when peak emission levels reach the 10 mA range. The most interesting feature of the gate current is that it is usually of the wrong sense; that is, with the gate film biased positive with respect to the base, one would expect net electron flow to the gate film when gate current is observed. However, the net electron flow usually is from the gate film. Presumably these electrons go to the collector, which is the most positive electrode in the system. One explanation for this behavior is that, as the emission current is increased, space-charge effects in front of the tip cause the electrons to slow down and move sideways. Because the gate is positive with respect to the tips, these electrons are attracted to the surface of the gate, where they strike with a velocity proportional to the voltage applied between the tips and the gate. This is typically in the 150 to 200 V range, which is above the first $\delta = 1$ secondary electron emission crossover point for molybdenum (Bruining 1954), especially when one considers that the impact would probably be at a grazing angle. The secondary electrons generated at the gate would then go to the collector and, if $\delta > 1$, there would be a net flow of electrons from the gate. However, if, the electric field at the surface of the gate is insufficient to accelerate the electrons away from the gate, they will be collected by the gate and there will be a net flow of electrons to the gate.

A second source of electrons to the gate are reflected primaries from the collector. These would strike the gate with the same energy as the emitted electrons, and thus could also give a net flow either to or from the collector, depending on where they impact the gate and what their energy is. Finally, positive ions could cause an apparent electron flow from the gate; however, the number of ions would be proportional to system pressure, and this has not been observed. Thus, the gate current in most cases is probably not attributable to ions.

A test of the effect of collector voltage on the gate current was done with a small-area cathode so that high-current-density observations could be made. Table 4 shows these results. The cathode was first set at just over 1 mA (40 A/cm^2) with -219 V applied to the base, the gate grounded, and the collector biased to +1000 V. The collector was the standard 3/16-inch diameter stainless steel tube with one end of the tube spaced approximately 3 mm from the cathode. The collector voltage was then decreased in steps and the collector current and gate current were recorded. The experiment was then repeated with -150 V applied to the tips and 100 μA (4 A/cm^2) emission. In both cases, the gate exhibited a net electron flow from the gate that increased as collector voltage was decreased, and then suddenly changed sign and produced a net flow to the gate film as the collector voltage was reduced further. This behavior could be explained by either the reflected primary model or secondary emission of primaries from the gate. However, the magnitude from the change makes it appear to be current resulting from electrons from the emitters hitting the gate and then secondaries from the gate going to the collector.

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Table 4

EFFECT OF COLLECTOR VOLTAGE ON GATE CURRENT
AND COLLLECTOR CURRENT AT HIGH CURRENT DENSITY

Cathode 25A-142-4H

Tip and Collector Potential	Gate Current* (μA)	Collector Current† (μA)
Tip Voltage -219V		
+1000V	-1	1080
+900	-2	1080
+800	-2	1080
+700	-2.5	1080
+600	-3	1080
+500	-4	1080
+400	-5	1080
+300	-7	1080
+200	-9	1040
+100	-14	1000
+75	-15	1000
+50	-15	1000
+40	-14	960
+30	-10	960
+20	+1	840
+10	+28	750
Tip Voltage -150V		
+500V	<-0.1	100
+400	<-0.1	100
+300	<-0.1	100
+200	-0.1	100
+150	-0.2	100
+100	-0.2	99
+75	+0.6	98
+50	+1.7	97
+40	+2.0	97
+30	+2.5	96
+20	+3.1	95
+10	+3.8	94
0	+4.1	93

*- indicates electrons leaving gate
 + indicates electrons arriving at gate

†1000 μA collector current = 40 A/cm^2

E. Emission Tests with RIBE Cathodes

Section III-B-3 described the reactive ion beam etching (RIBE) process under development for improving the cathode structures. The first trials using this process produced good results as far as the geometry of the cathodes was concerned; however, as discussed in Section III-B-3, there was a problem with apparent contamination of the samples. Emission tests were tried to determine what could be learned from the attempt. For example, because of the lack of undercutting of the molybdenum gate film by the oxide etch, it was possible that the oxide wall could have been coated with a thin layer of molybdenum (resulting from scatter from the cone as it was formed); if it was not coated, the the possibility existed that oxide charging could occur. Neither effect would be desirable.

The results of this first trial were interesting in that the lack of undercutting seemed to be no problem (as we had hoped), however, the contamination was a severe problem. All but one of the cathodes suffered multiple shorts and hundreds of blown tips. Nevertheless, four of the six tested reached 20 mA peak emission, and the gate currents were quite reasonable. These encouraging results convinced us that the RIBE process should be pursued. These first RIBE test results are tabulated in the Appendix (Group 36).

Additional tests of RIBE cathodes were not attempted until the development of improved processing using a chromium mask as described in Section III-B-3. Group 20B-141-1 performed much better; however, there are still some process improvements required in sample transportation and handling. The RIBE is performed at Varian Central Research Labs and we have yet to establish rigorous control over these steps.

The results of our tests with Group 20B-141-1 are included in the Appendix along with all other cathodes tested. Two highlights are 20B-141-1L (Group 55), which produced 20 mA peak emission with less than 100 V applied, and 20B-141-1J (Group 55), which produced 100 mA peak emission with a 10 percent duty cycle. Unfortunately, this is too high a duty cycle for our collectors, and the collector overheated (observed to be orange) and damaged this cathode.

F. Cathode Storage

In the past, cathodes have been stored in one of two ways

- Cathodes that have completed the fabrication process but have not been mounted in headers for testing are stored in aluminum trays that are kept in Pyrex petri dishes on a laminar flow bench. (Cathodes that have been tested in demountable headers are also stored in the aluminum trays after testing.)

- Most cathodes are permanently mounted in TO-5 headers for testing, and these are stored on aluminum racks that are kept in plastic parts boxes on the laminar flow bench.

In the early stages of the program, a couple of cathodes were retested after having been stored in the plastic parts boxes for several months. They performed well, and as a result it was assumed that this method of storage was acceptable. More recently it has been noted that some cathodes stored for extended periods (years) have discolored and appear to be oxidized. Also, we have noted that some cathodes shipped to the clients after being stored for a period of time did not perform well in emission tests.

These observations led to a review of the storage process and the initiation of new tests. Careful examination of all cathodes in storage showed many have been "stained" by some contamination or corrosion process. On the other hand, many have remained bright and appeared clean, even though they had been stored alongside of some of those that exhibited problems.

The important point is whether cathode performance changes as a result of the storage conditions. As a test of this, a batch of six cathodes of average performance in the initial emission test to 20 mA were remounted in the vacuum system after two weeks of storage on the aluminum racks in plastic parts boxes. All six cathodes were tested side by side in the same test chamber and stored side by side in the same parts box. The cathodes were again tested to 20 mA and then examined. Although all six performed well, three of the six suffered some tip losses, and these three also shorted out at least once during the second test. However, all six operated well at 20 mA once they reached that level. The cathodes were then stored for four weeks in the plastic parts box and tested a third time in the same way. This time one of the six shorted out at only 3 μA of emission and would not clear. Subsequent examination showed only one additional tip had blown, and the damage was very minor and not likely to account for the short. The short probably resulted from a breakdown in the gate film under the holddown disk where it cannot be examined. The other five cathodes all achieved 20 mA of emission, but each suffered at least one short and all lost several tips. These results, given in Table 5, suggest that the storage scheme should be changed, because there is a clear degradation in the cathodes' behavior.

The most obvious solution is to store the cathodes in a vacuum environment; this will be explored in the next phase of the program. In the meantime, a desiccator has been obtained and cathodes are stored in the dessicator under forepump vacuum ($\approx$ 0.1 torr) and cathodes are no longer stored in the plastic parts boxes.

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Table 5

DEGRADATION OF CATHODE PERFORMANCE
AFTER STORAGE IN PLASTIC BOXES

Cathode Number and Test	Gate Current (μA)	Applied Potential (V)	Cathode Emission (mA)	Failures		Storage Time (weeks)
				Tips Blown	Shorts	
28A-140-1I						
1	-3	153	20	10	0	0
2	-3	163	20	50	3	2
3	-6	205	20	~350	4	4
28A-140-1J						
1	-3	151	20	7	0	0
2	-2	151	20	7	0	2
3	<1	98	0.003	8	1	4
28A-140-1P						
1	-3	160	20	11	1	0
2	-6	164	20	22	1	2
3	-3	176	20	49	2	4
28A-140-2K						
1	-3	152	20	4	0	0
2	-4	156	20	4	0	2
3	-10	174	20	49	1	4
28A-140-2M						
1	-3	158	20	52	0	0
2	+7	160	20	79	1	2
3	+13	166	20	~200		4
28A-140-2N						
1	<1	156	20	22	0	0
2	<1	157	20	22	0	2
3	-3	160	20	70	1	4

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G. Tests in Gun Structures

Two gun structures have been assembled on glass stems by Watkins-Johnson Company. As shown in Figure 23, the guns are designed so that the cathode can be changed by sliding back a spring-loaded plunger. The guns and cathodes were pretested before being mounted in a test tube for emission tests. This ensures that the cathode is in good working condition before it is sealed into the tube.

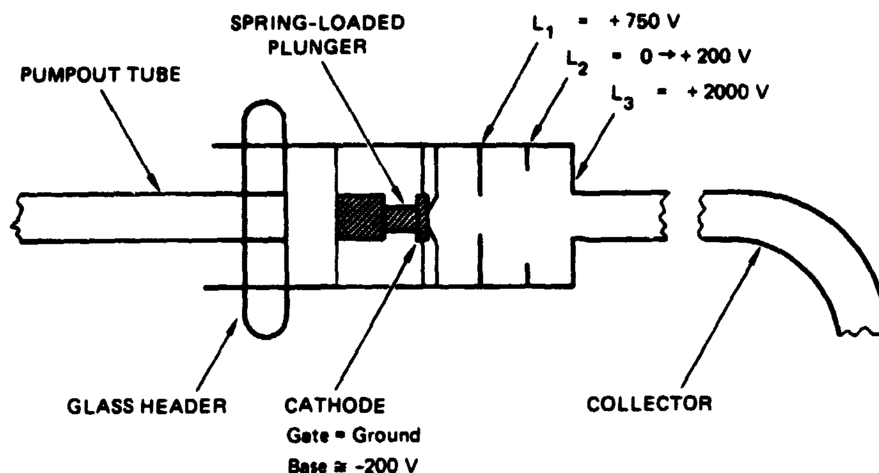

FIGURE 23 WATKINS-JOHNSON GUN CONFIGURATION

Although the first cathodes tested in the guns had been pretested and found to produce the desired current (15 mA), they were not the very best available because we were reluctant to risk our best until we had some experience with the gun structures. In all, five cathodes were tested in each gun. Table 6 summarizes these tests.

After the first cathodes were mounted, the entire gun and glass stem structure was installed in the vacuum system. A stainless steel tube collector of the kind we normally use in our cathode tests was mounted as the anode. The system was pumped down and baked at 430°C for cleaning. A pressure of about 10^{-9} torr was achieved over a weekend of pumping.

The gun voltages were applied and the cathodes turned on slowly. We immediately discovered that the gate of the cathode in Gun 5 (28A-140-2B) was shorted to the first lens elements; thus, we were unable to apply the proper voltages to the lenses of this gun. However, we were able to draw 10 mA peak emission from this cathode using our 60 Hz half-wave driving voltage. The cathode was then removed for examination and found to have blown about 100 tips during the test.

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Table 6

SUMMARY OF CATHODE PERFORMANCE IN WATKINS-JOHNSON GUNS

Cathode Number/ Test Site	Gate Current (μA)	Applied Potential (V)	Cathode Emission (mA)	Failures		Comments
				Tips Blown	Shorts	
28A-140-1G						
SRI system	-4	200	20	53	1	Good cathode.
W-J gun 4	80	150	0.15	~500	3	Emission quiet, but many tips failed and there was a severe arc near edge of gate.
20C-149-2B						
SRI system	-11	182	25	0	0	Excellent cathode.
W-J gun 4	390	190	0.1	~1500	0	Erratic emission. Cathode stored ~6 weeks between tests.
20A-129-1H						
SRI system	<1	175	20	0	0	Excellent cathode.
W-J gun 4	-6	185	1.5	20	1	Failed to a short. Ten failure sites outside of the active area. Stored 11 months between tests.
20C-149-2V						
W-J gun 4	-3	177	0.4	~2000	0	Worked well up to 0.4 mA; then developed 800 μA gate current overnight.
20C-149-2K						
W-J gun 4	110	188	0.06	0	0	Worked well up to 100 μA, then developed 110 μA gate current overnight.
28A-140-2B						
SRI system	12	160	20	~100	0	Good cathode.
W-J gun 5	95	175	10	~200	0	Worked well but L_1 was shorted to the gate lead because of lead wires touching. 4.3 mA to the collector, 5.7 mA to the lenses.
20C-149-2G						
SRI system	-6	166	25	0	0	Excellent cathode.
W-J gun 5	-6	170	1.7	125	1	Performed well until shorted. Stored 5 weeks between tests.
20A-129-1V						
SRI system	-6	162	20	0	0	Excellent cathode.
W-J gun 5	-6	182	1.5	~3000	1	Performed well--sudden failure. Stored 10 months between tests.
20C-149-2R						
W-J gun 5	-106	175	8	~500	6	Worked very well several days at more than 1 mA, then shorted at 0.5 mA after being off overnight. High gate current (because of no axial magnetic field?)
20C-149-2P						
W-J gun 5	35	165	0.1	0	0	Voltage breakdown, especially in electrode lens 3.

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A very good cathode (20C-149-2G) was then mounted in the gun. This cathode had been pretested to 25 mA in our standard test system and had suffered no tip failures. However, in the gun structure, the cathode shorted at 1.7 mA peak emission. The cathode had been very stable and well-behaved until the sudden failure. A second very good cathode was then tested with basically the same result. Then, because of our experiments with the cathode storage, we decided to test a new cathode in the gun. Cathode 20C-149-2R also performed well up to the moment it suddenly failed. No axial magnetic field was used; therefore, about half of the emitted current was hitting the lenses and probably causing a lot of reflected primaries to return to the gate and gate mounting electrode. This of course produces gate current. Figure 24 is an oscillograph of the emission current and gate current for this cathode in W-J Gun 5. Note that both the emission and gate currents are very stable and quiet. Also, the gate current represents a net flow of electrons away from the gate, implying that this current was because of electrons hitting the top surface of the gate film with sufficient energy to cause secondary emission with a secondary emission ratio greater than 1.

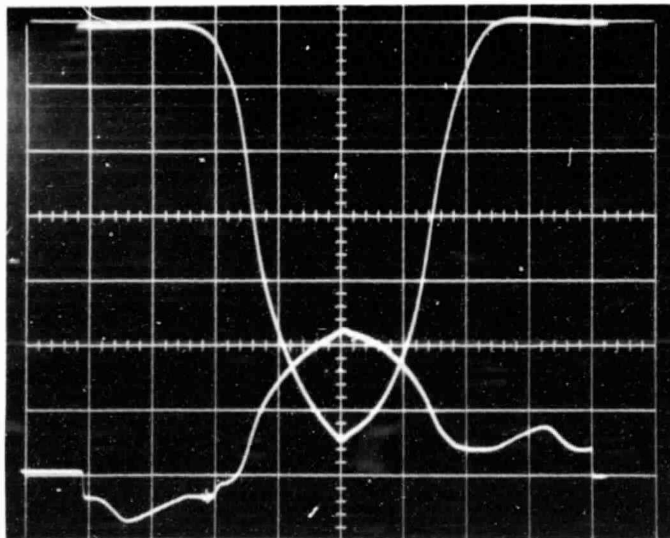

FIGURE 24 EMISSION AND GATE CURRENT FROM CATHODE 20C-149-2R OPERATING IN WATKINS-JOHNSON GUN 5

Upper trace is emission at 0.5 mA/div; lower trace is gate current at 10 μA/cm. Horizontal rate, 1 ms/div. Exposure time, 1 s.

Gun 4 did not perform as well as Gun 5. One cathode (20A-129-1H) went over 1.5 mA and four others failed at much lower currents.

We conclude from these experiments that, because only about half of the emission current was going through the lenses to the collector, breakdown occurred in the gun as the result of having so many electrons hitting the gun electrodes. Thus, it is necessary to have the axial

magnetic field to complete the experiment. This assumption was later supported by the observation that, when voltage was on the gun electrodes, there was an occasional breakdown between them, even with the electron beam off. It is possible that this explains why some of the cathode would perform in a stable and quiet manner, then suddenly short out with no observable warning in cathode behavior. Discharges are one thing that the cathodes do not tolerate well. Further testing with the gun structure has been postponed until a magnetic field can be arranged.

H. Tests with Wedge Emitters

Arrays having 5000, 100, and 16 wedges were tested. The wedges were all of the pattern shown in Figure 8. All of the 5000- and 100-wedge arrays tested shorted several times and had high leakage current. Three of the 16-wedge arrays (Group 6 in the appendix) produced current densities of 35 A/cm^2 or more and had no shorts. These were all relatively short (in height) wedges however, and the voltages required for emission were very high. For example, 31A-121-6D required 440 V to produce 1 mA (50 A/cm^2).

No additional emission tests were done with the wedges because of the wedge-lifting problem discussed in Section III-2. New wedge structures will be fabricated with thinner oxide layers so that low-tensile-stress short (in height) wedges can be made with the gate films close enough to produce emission at comfortable voltage levels (200 V).

I. Emission Microscopy

The uniformity of emission from tip to tip and the stability of the emission from each tip have been two long-standing questions that can best be answered with the aid or an emission microscope. Following the approach taken by NRL, SRI assembled an emission microscope with the cathode at ground, and the drift tube and phosphor at high voltage. Figure 25 is a schematic of the first form of the microscope. The lens assembled was modeled on a computer, and the results indicate that we should expect a magnification of about 120x with the dimensions and voltages shown. Higher magnifications are achievable; however, a magnification of 120 will give about 1/16-inch separation between tips on our state-of-the-art cathodes. This should be adequate considering each spot size will be in the 0.001-inch range. We plan to install an aperture and Faraday cage in place of the phosphor for future high-current measurements. When operating in this mode, a deflector system will be used to scan the array across the aperture. The current to the Faraday cage can then be used to plot a profile of the current intensity from the array of tips. This technique is more complicated than viewing the image on a phosphor, but should be a more convenient and informative way of studying high current operation. First tests, however, will be done with the phosphor and small-area cathodes. The cathodes will be driven with a pulse supply so that higher levels of emission can be explored without damaging the phosphor.

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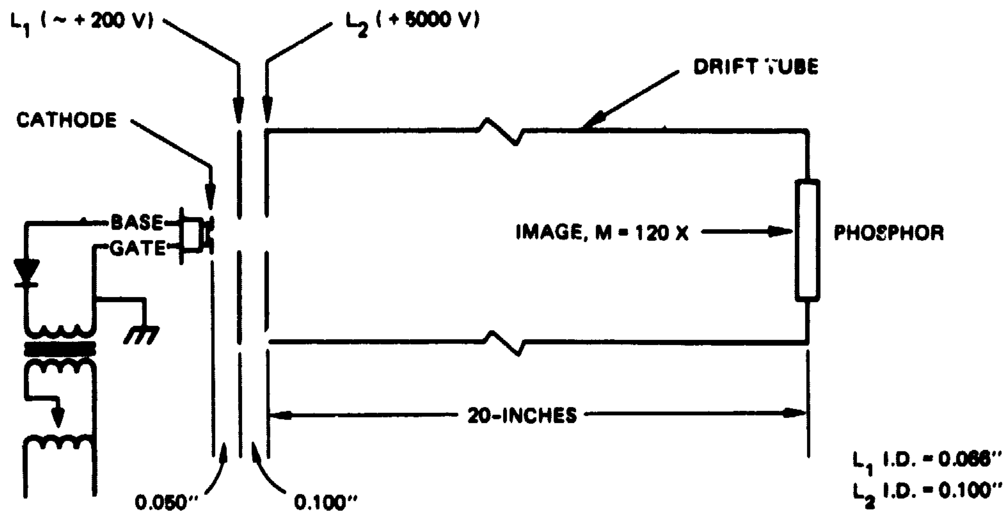

FIGURE 25 CONFIGURATION OF A SIMPLE EMISSION MICROSCOPE

V SUMMARY AND CONCLUSIONS

The purpose of this phase of the program has been to:

- Fabricate, test, and deliver state-of-the-art cathodes to NASA and NRL
- Advance the fabrication technology
- Develop wedge-shaped emitters
- Perform emission tests.

A total of 34 cathodes have been delivered to NASA and NRL during the program. All but two were pretested before delivery and found to be working well; two were delivered to NRL untested at their request.

During the entire program, a total of 398 cathodes of 12 different types have been tested; these are listed in the Appendix. The cathodes were mounted in either a commercial TO-5 header consisting of gold-plated Kovar with glass insulators or in "R&W" headers, which are custom-made from alumina and molybdenum and are demountable. Most of the cathodes were of four types:

- The 20A series (5000 tips in a 1-mm diameter area on <111> p-type silicon).
- The 28A series (10,000 tips in a 1-mm diameter area on <111> p-type silicon).
- The 25A series (16 tips on 12.7-μm centers on <111> p-type silicon).
- The 20C series (5000 tips in a 1-mm diameter area on <111> n-type silicon).

In the 20A series, 152 cathodes were tested, of which 110 were working after testing. This was by far the largest group, and is the state-of-the-art cathode. However, many of the cathodes tested were involved with tests of various kinds, such as changes in storage conditions, and cleaning procedures. The other three series that had a fair number tested were even more successful. Series 20C had 68 tests, of which 54 were working after the test, Series 28A had 73 tested of which 56 were working, and Series 25A had 35 tested with 21 working after the tests. The 25A series is particularly interesting because these were all tested up to approximately 50 A/cm^2.

Advanced fabrication technology has been devoted mostly to developing an anisotropic etch for the hole patterns and to the development of the wedge-shaped cathode. The anisotropic etch has been shown to give

very good straight-walled holes, and cathodes have been made using this process. Tests demonstrated very good emission from several of these cathodes with 100 mA total emission being achieved in one case. A problem with contamination remains in the processing, but this should be resolved in the near future.

Wedge-shaped emitters have been formed and tested. Most suffered problems with adhesion to the silicon substrate; however, some short wedges produced high current densities (~50 A/cm^2) from small-area arrays. The adhesion problem seems to be associated with wedge height, and it appears that scaling the structure down will eliminate the difficulty.

High-current-density tests have been made using small-area arrays, and in excess of 100 A/cm^2 was observed several times. One 12-tip array produced a peak current of 6 mA. This is an average current per tip of 500 μA and a current density of 320 A/cm^2.

Tests on the effects of collector voltage on gate current have shown that the effect is small for emission levels of up to 40 A/cm^2. Collector voltages of less than 300 V could be tolerated without any strong effect on gate current.

Storage conditions have been found to be more important than earlier tests had led us to believe. A group of six cathodes stored in a plastic parts box, as we have normally done, showed a clear degradation after a total of six weeks of storage. Only one cathode failed completely, but all suffered increasing numbers of tip failures as the storage time increased. The voltage required to produce a given emission level also increased. Alternate storage procedures are under investigation.

An emission microscope has been built and will be used for uniformity studies during the next phase of the program.

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Appendix

CHARACTERISTICS OF EMITTERS FABRICATED ON THIS PROJECT

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
1	20A-112-2B	R & W	380°C	-.003	170	22	~500	0	NG
	C	↓	↓	-.003	165	20	1	0	ok
	G			-.005	163	20	26	2	ok
	H			-.001	166	20	4	0	ok
	I			+.040	165	20	250	0	ok
	20A-110-1 N			-.010	153	25	—	arc	NG
2	31A-122-5B	R & W	390°C	+.009	450	.012	all	arc	NG
	M	↓	↓	.250	460	—	all	arc	NG
	N			—	—	—	all	arc	NG
	O			<.001	400	.0005	all	arc	NG
	P				340	.0002	all	arc	NG
	S			—	—	—	all	arc	NG

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
3	30A-118-5 B	TO-5/wire	390°C	<.001	350	.008	15	3	NG
	C	↓	↓	<.001	170	.028	8	2	NG
	D	↓	↓	<.001	305	.001	9	3	NG
	F	↓	↓	<.001	180	.015	~130	5	NG
	G	↓	↓	<.001	240	.002	17	5	NG
	H	↓	↓	<.001	273	.005	11	4	NG
4	20A-104-2 B	R & W	380°C	-.003	210	5	~700	2	NG
	D	↓	↓	+.600	200	1.2	~100	0	NG
	F	↓	↓	+.200	250	10	~700	0	OK
	G	↓	↓	<.001	230	5	~700	1	NG
	H	↓	↓	+.075	220	5	~300	0	OK
	I	↓	↓	+.130	240	6	~700	1	NG

GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
5	20A-110-1 L	TO-5/disc	380°C	+.003	125	40	36	arc	NG
	M	↓	↓	+.006	86	30	17	1	NG
	N			-.010	153	25	1	1	NG
	P			+1.5	52	25	0	1	NG
	2S			<.001	239	.031	35	2	hair line cracks in gate film
	2T			+.030	300	.030	300	1	NG
6	31A-122-6B	R&W	450°C	-.009	435	.700	11	1	NG
	C	↓	↓	+.270	440	.220	8	1	NG
	D			-.003	440	1.0	0	0	OK 50A/cm²
	F			<.001	460	.750	0	0	OK 38A/cm²
	H			~-.003	445	.700	0	0	OK 35A/cm²
	I			<.001	400	.050	12	1	NG

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
7	25A-121-5A	TO5/DISC	450°C	<.001	250	.008	2	0	OK
	B	↓	↓	<.001	235	.060	6	1	NG
	C			~.001	248	1.4	2	0	OK
	D			~-.002	245	1	0	0	OK
	E			-.012	370	1.15	4	0	OK
	F			<.001	285	1	4	1	NG
8	20A-112-5K	TO-5/DISC	400°C	Aborted OMIT					
	M	↓	↓						
	–								
	Q								
	L			+.012	120	1.15	–	–	ERRATIC
	–								

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS		
8	20A-114-1B	TO-5/disc	400°C	-.024	170	20	0	0	OK	
	C	↓	↓	-.020	175	20	4	0	NG	Mechanical Dim. (Guide rims)
	D			-.020	170	20	24	2	OK	
	F			<.001	170	1	50	1	OK	
	G			-.004	180	10	13	0	OK	
	H			-.030	200	22	12	1	OK	
9	20A-122-3A	TO-5/disc	400°C	<.001	110	1	200	1	NG	ARC when base unplugged.
	B	↓	↓	-.002	108	1	~300	2	NG	
	C			-.060	145	5	-	4	OK	
	D			-.015	119	3	~1000	4	NG	
	F			<.001	78	.015	~300	2	NG	
	G			+.010	70	.025	~200	2	NG	

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
10	20A-111-1 I	R & W	425°C	+.002	216	3	~500	1	← Power failure OK
	J	↓	↓	-4	250	1	~500	1	OK
	K	↓	↓	-.250	217	2.5	~500	1	NG
	121-3A	↓	↓						
	B	↓	↓						
	D	↓	↓						
12	25A-121-6G	TO-5/DISC	435°C	<.001	300	—	Looks OK	but emits	Nothing. possible crack thru chip or gate
	M	↓	↓	<.001	400	—	wired	wrong	VISUAL OK. RETEST
	N	↓	↓	<.001	300	—			VISUAL OK
	V	↓	↓						
	W	↓	↓						
	X	↓	↓						

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
11	25A-121-5N	R&W	410°C	<.001	250	.150	6	0	NG
	O	↓	↓	-.090	248	6	0	0	OK
	Q	↓	↓	<.001	345	.002	1	0	NG
	S	↓	↓	<.001	305	.002	3	0	NG
	U	↓	↓		350	—			~~nothing~~ NO CONTACT
	V	↓	↓	<.001	335	.06	4	0	OK
12	20A-122-3H	TO-5	425°C	<.001	171	2	all	0	NG
	I	↓	↓	-.006	200	20	100	1	OK
	J	↓	↓	-.007	208	20	17	0	OK
	L	↓	↓	<.001	NA	—	~1000	1	NG
	M	↓	↓	-.010	234	20	200	0	OK
	N	↓	↓	-.006	218	13	~200	0	OK

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
13	20A-122-30	TO-5/DISC	410°C	-.005	163	10	0	0	OK
	P	↓	↓	-.005	155	10	5	0	OK
	Q			-.004	150	10	23	0	OK
	R			-.002	165	10	~100	0	OK
	S			-.010	175	10	0	0	OK
	T			-	250	-	-	-	[illegible] NO CONTACT
14	20A-107-11A	TO5/DISC	440°C	-.014	190	20	~500	2	OK
	B	↓	↓	-.004	200	20	33	1	OK
	C			-.006	196	20	10	0	OK
	D			-.020	219	10	19	0	OK
	F			-.010	200	20	6	2	OK
	G			-.007	196	20	14	0	OK

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
15	20A-129-1B	R&W	440°C	-.002	130	20	2	0	OK
	C	↓	↓	-.125	156	20	1	0	OK
	D			-.002	161	20	3	0	OK
	F			-.013	194	25	—	5	NG extensive runs
	H			<.001	175	22	0	0	OK
	I			-.004	149	25	25	0	OK
16	20A-129-1G	TOE (DISC	410°C	-.012	158	20	0	0	OK 3 CRACKS IN GATE (MECHANICAL)
	J	↓	↓	-.007	140	20	0	0	OK
	K			<.001	135	20	3	1	OK
	L			-.002	140	20	2	0	OK
	M			-.004	150	12	0	0	OK
	N			-.010	140	20	0	0	OK

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GROUP	# [illegible]	MOUNT	BASE TEMP	[illegible] MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
	20A-107-11	TO-5/DEC	450°C	-.006	185	10	8	0	OK
	I	↓	↓	<.001	185	10	13	0	OK
17	J	↓	↓	-.003	174	10	3	1	OK
[illegible]	K	↓	↓	-.008	178	10	12	0	OK
	L	↓	↓	-.012	200	10	6	0	OK
	M	↓	↓	-.004	184	10	1	0	OK
	20A-129-1P	R&W	450°C	-.005	153	20	0	0	OK
	G	↓	↓	-.004	147	20	0	0	OK
18 20	R	↓	↓	<.001	170	.400	25	arc	NG
	S	↓	↓	-.004	180	20	1	0	OK
	T	↓	↓	<.001	155	1	6	1	NG
	V	↓	↓	-.006	162	20	0	0	OK

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GROUP	CATHODE	MOUNT	[illegible] TEMP	[illegible] MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
19 ~~24~~	33A-128-5T3	TPS | PSG	440°	+.030	240	.015	17	3	NG (~~ERRATIC~~)
	C	↓	↓	<.001	240	.020	4	2	NG
	D			+.001	125	—	0	2	NG (~~won't clear~~)
	G			+.007	232	1.5	~50	4	NG
	H			.003	199	.150	~70	5	NG
	I			<.001	200	—	0	0	NG ~~VISUAL OK LOOKS LIKE NO CONTACT~~
63									
20 ~~22~~	25A-121-5T	R & W	420°C	<.001	270	.030	4	0	OK
	V	↓	↓	<.001	335	.060	4	0	OK
	20A-129-2L			<.001	170	.500	34	0	OK
	M			-.004	183	.350	—	1	NG
	N			<.001	166	.500	23	0	OK
	O			+.002	152	.500	3	0	OK

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21	20A-129-2D	TO-5/DBC	420°C	+.055	238	10	~500	0	OK
	F	↓	↓	<.001	199	3	6	0	OK
	H	↓	↓	-.001	230	3	~100	1	OK
	I	↓	↓	-.014	232	10	5	0	OK
	J	↓	↓	-.009	229	10	8	0	OK
	K	↓	↓	-.080	260	10	~500	4	OK
22	33A-127-9A	TO-5	480°C	+.018	200	.050	33	5	NG
	B	↓	↓	+.030	200	.300	20	4	NG
	C	↓	↓	+.020	255	.200	13	5	NG
	D	↓	↓	<.001	215	.025	31	4	NG
	F	↓	↓	<.001	240	.600	4	1	NG
	H	↓	↓	+.024	210	.020	18	2	NG

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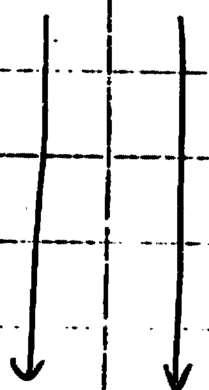
GROUP	[illegible]	MOUNT	[illegible] TEMP	[illegible] MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
2	29A-128-40								
	F								
	I								
	L								
	N								
	O								
23	20A-114-1 I	TO-5/DISC	450°C	-.005	262	10	58	3	NG
	J	↓	↓	+.300	228	3	~3000	3	NG
	L			+.100	200	5	~500	3	OK
	N			-.012	222	15	9	0	OK
	O			+.035	225	10	~200	1	OK
	P			+.020	232	20	25	0	OK



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GROUP	CATHODE	MOUNT	BASE TEMP	GATE MA	VOLTS	EMISSION MA	TWO BLOWN	SHORTS	
24	20A-129-3B	TO-5	410°C	<.001	118	20	0	0	OK
	D	↓	↓	<.001	119	20	0	0	OK
	H	↓	↓	<.001	120	20	0	0	OK
	I	↓	↓	-.002	135	20	0	0	OK
	L	↓	↓	-.004	142	20	2	0	OK
	N	↓	↓	–	250	–	–	–	NG NO CONTACT
25	20A-129-4B	TO-5/DISC	400°C	<.001	200	–	–	–	NO CONTACT
	C	↓	↓	-.010	180	20	1	0	OK
	D	↓	↓	-.001	170	20	3	1	OK
	F	↓	↓	-.009	172	10	4	0	OK
	H	↓	↓	+.400	230	20	~500	0	OK
	I	↓	↓	-.008	200	20	2	0	OK

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
26	29A-128-4D	R&W	400°C	+.025	230	1	0	0	OK
	H	↓	↓	<.001	240	2.5	9	0	NG (accidental 1200V BURST)
	J			<.001	280	.020	1	0	OK
	L				visual OK			1	NG (SHORT WON'T CLEAR)
	O			<.001	200	1	0	0	OK
	P			~.020 erratic	275	1.75	ALL	1	NG
27	20A-129-2P	TO-5/Disc	410°C	-.015	189	20	3	0	OK
	Q	↓	↓	-.010	194	20	7	0	OK
	R			-.012	208	20	2	0	OK
	129-4J			-.009	160	20	1	0	OK
	N			-.037	191	20	4	0	OK
	O			<.001	200	NO CONTACT		0	NG

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GROUP	PART NO./[illegible]	MOUNT	CASE TEMP	[illegible]E MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
28	28A-129-11K	TO-5 /DISC	410°C	<.001	170	20	50	0	OK
	L	↓	↓	-.012	186	20	~100	1	OK
	P			-.010	190	20	1	0	OK
	129-10B			-.013	240	20	1	0	OK
	C			-.006	215	25	3	0	OK
	F			-.008	190	20	8	0	OK
29	28A-129-10G	R&W	410°C	-.006	200	20	2	0	OK
	H	↓	↓	-.010	210	20	8	0	OK
	I			<.001	220	20	0	0	OK
	J			-.030	160	20	~150	2	OK
	K			<.001	184	1	1	1	NG (won't clear)
	11N			-.006	182	20	50	1	OK

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
30 ~~33~~	20A-114-1G	~~TO-5~~/DISC	400°	-.025	180	10	12	2	OK
	F			-.011	192	20	23	1	OK
	107-11C			-.012	233	10	12	0	OK
	D			-.020	219	10	19	0	OK
	129-2L			-.007	230	10	34	0	OK
	N			<.001	228	10	23	0	OK
31 ~~29~~	34A-133-3D	R&W	450°C	<.001	210	1	9	3	NG
	E			-.004	223	5	9	1	OK
	F			<.001	249	4	14	1	OK
	G			-.050	220	4	ALL	1 big one	NG
	H			-.007	219	5	-	1	NG
	I			+.010	229	5	3	0	OK

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SPARKS	
32 (~~35~~)	20A-129-1W	R&W	450°	-.022	230	20	4	0	OK
	X	↓	↓	-.012	227	20	3	0	OK
	20A-129-4T	↓	↓	-.001	203	20	3	0	OK
	U	↓	↓	-.008	188	20	0	0	OK
	V	↓	↓	-.002	200	20	1	0	OK
	S	↓	↓						
33 (~~36~~)	20A-129-4W	TO-5	440°C	-.002	204	20	0	0	OK
	X	↓	↓	-.018	218	20	0	0	OK
	Y	↓	↓	-.020	225	20	0	0	OK
	28A-129-10L	↓	↓	-.001	240	20	6	0	OK
	P	↓	↓	-.008	210	15	~30	1	(won't clear, but should)
	Q	↓	↓	-.012	218	15	~100	1	NG (accident)

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
34 (~~37~~)	34A-133-2B	TO-5	420°C	<.001	203	.400	ALL	1	NG
	e	↓	↓	<.001	230	.700	MOST	1	NG
	H	↓	↓	<.001	200	.200	~1/2	2	NG
	8A	↓	↓	<.001	220	1.5	0	0	OK
	B	↓	↓	<.001	220	1.5	0	0	OK
	C	↓	↓	<.001	283	.700	6	1	OK
35 (~~38~~)	34A-133-2I	R&W	420°C	–	–	–	–	1	NG
	J	↓	↓	–	–	–	–	1	NG
	K	↓	↓	–	–	–	–	1	NG
	29A-133-8D	↓	↓	-.013	232	2	0	0	OK
	F	↓	↓	-.002	209	1.2	6	0	OK
	28A-129-10C	↓	↓	-.010	203	20	4	0	OK

GROUP	[illegible]	MOUNT	BASE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS [illegible]	SPOTS	
36 39.	28B-136-2B	TO5/DISC	450°C	-.027	170	20	~500	6	OK
	C	↓	↓	-.008	162	20	6	0	OK
	D			-.004	125	20	~500	4	OK
	F			-.010	168	20	~100	4	OK
	G			~.001	144	1	~100	5	NG
	H			<.001	140	1	~300	3	NG (won't clear)
37 40	29A-133-8I	TO-5	420°C	—	—	—	—	1	NG
	J			<.001	355	1	—	1	NG
	M			—	—	—	—	1	NG
	P			<.001	240	1	—	0	OK
	Q			<.001	240	0.15	—	1	NG
	R			<.001	270	0.2	—	1	NG

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GROUP	CATHODE	MOUNT	BASE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SPOKES	
38 [illegible]	28A-140-1B	TO-5	400°C	-.005	170	20	5	0	OK
	C		↓	-.002	172	20	10	0	OK
	D		↓	-.004	171	20	4	0	OK
	2G		↓	-.006	168	20	20	0	NG (mechanical)
	I		↓	-.150	150	4.5	~500	0	OK
	J		↓	-.002	160	20	~300	1	OK
39 [illegible]	28A-140-1F	R&W	400°C	+.030	171	20	~300	1	OK
	G	↓	↓	-.004	200	20	53	0	OK
	H	↓	↓	<.001	145	20	5	0	OK
	2B	↓	↓	+.010	160	20	~100	0	OK
	C	↓	↓	+.020	159	20	7	0	OK
	F	↓	↓	+.007	130	.500	–	4	NG (obvious mech. damage)

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GROUP	CATHODE	MOUNT	BASE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS FIRING	SPIKES	
40	27B-137-4B	TO-5/DISC	410°C	+.060	200	.040	3000	2	NG
	C	↓	↓	+.060	195	.700	MANY 1000's	1	NG
	D	↓	↓	+.004	108	.100	~200	1	NG
	20A-135-3B	↓	↓	-.005	173	20	4	0	OK
	C	↓	↓	-.008	177	20	3	0	OK
	D	↓	↓	-.004	160	20	3	0	OK
41	28A-140-1 I	TO-5/DISK	400°C	-.003	153	20	10	0	OK
	J	↓	↓	-.003	151	20	7	0	OK
	P	↓	↓	-.003	160	20	11	1	OK
	2K	↓	↓	-.003	152	20	4	0	OK
	M	↓	↓	-.003	158	20	52	0	OK
	N	↓	↓	<.001	156	20	22	0	OK

GROUP	CATHODE	MOUNT	BAKE TEMP	[illegible] MA	VOLTS	EMISSION MA	[illegible]	[illegible]	
42 ~~45~~	28A-140-1G	R&W	400°c	-.004	200	20	53	1	OK
	S	↓	400°c	+.060	180	12	~300	2	OK
	T	↓	↓	~.002	120	.200	~300	6	BAD
	2-0	↓	↓	≈.004	121	20	9	0	OK
	R	↓	↓						
	G	↓	↓	-.006	168	20	20	0	OK possible mechanical damage
43 ~~46~~	20A-135-3F	TO-5/disc	430°c	-.005	171	20	31	1	OK
	G	↓	↓	-.006	176	20	5	0	OK
	H	↓	↓	-.008	192	20	5	0	OK
	I	↓	↓	-.010	200	20	0	0	OK
	J	↓	↓	-.010	200	23	1	0	OK
	K	↓	↓	–	200	22	9	0	OK

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GROUP	[illegible]	MOUNT	[illegible] TEMP	[illegible] MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
44 (~~49~~)	28B-136-2I	TO-5/DISC	450°C	<.001	121	6	~500	1	NG
	J	↓	↓	—	—	—	0	1	SHORTED NEVER CLEARED
	K	↓	↓	+.010	122	3	~300	5	NG
	25A-142-4A	↓	↓	—	—	—	0	1	SHORTED NEVER CLEARED
	B	↓	↓	~+.002	180	1	0	0	OK
	C	↓	↓	<.001	210	1	0	0	OK
76									
45 (~~48~~)	20A-110-2P	R&W	380°C	<.001	210	8	19	2	NG (LOOKS OK)
	Q	↓	↓	+.170	245	20	9	0	OK
	R	↓	↓	+.041	235	22	1	0	OK
	20-57-1P	↓	↓						
	20A-64-2C	↓	↓						
	45-2T	↓	↓						

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GROUP	[illegible]	MOUNT	CASE TEMP	GATE MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
46 (~~49~~)	25A-142-4D	TO-5/disc	430°C	<.001	230	1.25	0	0	OK
	F	↓	↓	+.030	300	1.25	2	2	NG
	G	↓	↓	<.001	211	1.3	0	0	OK
	20B-131-6B	↓	↓						
	C	↓	↓						
	D	↓	↓						
47 (~~50~~)	25A-135-3S	R&W	480°C	<.001	200	.400	4	1	NG
	T	↓	↓	~.002	200	1.25	0	0	OK
	U	↓	↓	<.001	205	.600	2	1	NG
	V	↓	↓	~.002	195	1.25	1	0	OK
	20A-64-2C	↓	↓						
	20B-137-6F	↓	↓	+.140	150	1.5	~200	7	NG

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GROUP	[illegible]	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SHORTS	
48	28A-1401I	TO-5/DISC	400°	-.003	153	20	10	0	OK
	J	↓	↓	-.003	151	20	7	0	OK
	P	↓	↓	-.003	160	20	11	1	OK
	2K	↓	↓	-.003	152	20	4	0	OK
	2M	↓	↓	-.003	158	20	52	0	OK
	N	↓	↓	<.001	156	20	22	0	OK
49	25A-135-3N	TO-5	490°C	<.001	260	0.5	16	1	N.G.
	O	↓	↓	<.001	185	1.25	0	0	OK 50A/cm²
	P	↓	↓	<.001	220	1	16	1	N.G.
	W	↓	↓	<.001	204	1.35	0	0	OK 60A/cm²
	X	↓	↓	+.005	220	1.35	2	0	OK 60A/cm²
	Y	↓	↓	<.001	191	1.3	0	0	OK 60A/cm²

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GROUP	[illegible]	MOUNT	BASE TEMP	[illegible] MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
50 58	20A-135-4B	Al_2O_3	450°C	-0.013	191	20	2	0	OK
	C			—	—	—	—	1	N.G
	F			-0.025	213	20	8	0	OK
	25A-142-3B			+0.012	235	1.25	2	0	OK 50A/cm²
	C			—	—	—	—	—	NO CONTACT
	D			<.001	171	1.25	0	0	OK 50A/cm²
51 59	20C-144-1B	TO-5	450°C	-0.007	180	20	0	0	OK
	C			-0.008	180	20	0	0	OK
	D			-0.008	173	20	1	0	OK
	F			-0.008	175	20	0	0	OK
	G			-0.006	172	20	1	0	OK
	H			—	—	—	—	—	NO CONTACT

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TWO CHANNEL	SPOTS	
52	20B-141-1-B	TO-5	450°C	-.004	114	20	14	0	OK
	C			+.004	116	20	~200	1	OK
	D			-.002	135	20	31	0	OK
	G			+.002	115	20	5	0	OK
	H			-.005	109	25	5	0	OK
	NO CATHODE								
53	20C-149-2-A	Al_2O_3	450°C	-.058	210	20	0	0	OK
	B			-.011	182	25	0	0	OK
	C			-.010	190	25	0	0	OK
	D			-.008	197	25	5	0	OK
	F			—	—	—	—	—	NO CONTACT
	G			-.006	166	25	0	0	OK

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GROUP	CATHODE	MOUNT	BASE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS [illegible]	SHORTS	
54	208-141-1-J	TO-5	450°C	-.048	140	110	ALL	1	SEVERE ARC
	N			-.005	125	25	23	2	OK
	O			-.007	128	25	13	0	OK
	S			-.006	113	25	2	0	OK
	V			+.020	125	25	~200	0	OK
	W			—	—	—	—	—	NO CONTACT
55	208-141-1 I	TO-5	430°C	—	—	—	—	—	NO CONTACT
	K			-.001	99	20	0	0	OK
	L			-.012	91	45	51	0	OK
	M			-.001	120	20	~250	1	OK
	Q			-.001	110	20	7	0	OK
	R			+.00?	105	20	6	0	OK

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GROUP	[illegible]	MOUNT	BASE TEMP	GATE MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
56	25A-142-4 H	TO-5	430°C	-.001	210	—	0	0	OK
	I			-.002	297	—	0	0	OK
	J			+.014	295	—	0	0	OK
	L			<1	290	.25	2	1	N.G.
	M			—	—	—	—	1	N.G.
	N			—	—	—	—	0	NO CONTACT
57	20C-149-1 I	Al_2O_3	400°C	—	—	—	—	1	MECHANICAL DAMAGE N.G.
	K			+.170	220	20	~150	0	OK
	L			<.001	149	0.1	7	1	N.G ARC
	20C-149-2 H			-.001	210	20	0	0	OK
	[illegible]			-0.022	205	20	7	0	OK
	I			-0.003	200	20	1	0	OK

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GROUP	CATHODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	[illegible] MA	TIPS [illegible]	SPOTS	
58	28A-140-1 I	TO-5	450°C	-0.006	205	20	~300	4	OK RETEST EXPERIMENTAL GROUP AIR STORAGE
	J			<0.001	98	0.0008	8	1	N.G.
	P			-0.003	176	20	49	2	OK
	28A-140-2 K			-0.01	174	20	30		OK
	M			-0.013	166	20	~200	1	OK
	N			-0.003	160	20	70	1	OK
59	28A-129-2 S	TO-5	450°C	-.005	220	6	13	2	N.G.
	T			-0.04	240	20	2	0	OK
	Y			-0.03	240	20	40	0	OK
	W			<0.001	190	2	46	4	N.G.
	X			-0.016	275	20	44	0	OK
	28A-129-10 T			-0.14	250	20	37	1	OK

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GROUP	TRIODE	MOUNT	BAKE TEMP	GATE MA	VOLTS	EMISSION MA	TIPS BLOWN	SPOTS	
60	28A-129-10 U	TO-5	450°C	+0.004	140	2	~100	3	N.G.
	V			-0.068	245	20	~100	0	OK
	W			<0.001	140	0.3	45	1	N.G.
	X			-0.023	200	20	25	0	OK
	20A-135-3 L			-0.07	220	20	36	0	OK
	M			-0.02	200	20	~150	0	OK
61	20-150-I B	TO-5	450°C	[illegible]	[illegible]	20	[illegible]	0	OK
	C			-0.007	164	20	1	0	[illegible]
	D			[illegible]	164	20	4	0	OK
	F			-0.010	164	20	23	0	OK
	G			-	-	-	-	-	NO CONTACT
	H			+1	120	10	~300	1	N.G. - SEASONED

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GROUP	[illegible]	MOUNT	BASE TEMP	GATE MA	VOLTS	[illegible] MA	TIPS [illegible]	SHORTS	
62	20C-150-4B	Al_2O_3	450°C	+0.02	300	20		0	OK
	C			+0.07	220	20		0	OK
	D			0	185	20		0	OK
	F			-0.006	200	20		0	OK
	G			-0.010	181	20		0	OK
	I			-0.003	202	20		0	OK
63	20C-149-3A	TO-5	430°C	+0.016	160	20	~500	0	OK
	B			-0.008	145	20	2	0	OK
	F			-0.009	162	20	2	0	OK
	G			+0.030	220	1	~500	4	SILICON COATED N.G.
	J			+0.030	230	1	>1000	3	SILICON COATED N.G.
	M			+0.033	235	3	~200	1	SILICON COATED N.G

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GROUP	CATHODE	MOUNT	BAKE TEMP	[illegible] MA	VOLTS	[illegible] MA	TIPS [illegible]	[illegible]	
	20C-149-3H	TO-5	430°C	0	72	20	N/A	0	RETEST EXPERIMENT-VACUUM STORAGE DESTROYED
	I	-	-	-	-	-	-	-	NO CONTACT
64	K			-0.006	142	20	N/A	0	RETEST EXPERIMENT-VACUUM STORAGE
	L			-0.002	127	20	N/A	0	RETEST EXPERIMENT-VACUUM STORAGE
	N			-0.011	132	20	N/A	0	RETEST EXPERIMENT-VACUUM STORAGE
	O			-0.010	130	20	N/A	0	RETEST EXPERIMENT-VACUUM STORAGE
	20A-144-2 B	TO-5	450°C	-	-	-	~200	-	NO CONTACT TO COLLECTOR
65	C			+0.25	130	0.06	~2000	1	N.G. VACUUM TROUBLE
	D			+0.01	143	1	~1000	1	N.G. "
	F			-0.001	145	10	~70	0	OK "
	G			+0.025	168	8	~300	3	N.G "
	28A-140-3 B			0	149	0.4	60	2	N.G "

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GROUP	[illegible]	MOUNT	BASE TEMP	[illegible] MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
69 / 66	28A-140-3 C	Al_2O_3	450°C	+0.001	90	15		0	OK SEASONED VACUUM TROUBLE
	D			-0.006	120	15		1	OK VACUUM TROUBLE
	F			-0.0?4	179	15		0	OK "
	G			0	148	0.3		2	N.G. "
	H			0	115	0.01		1	N.G. "
	I			+0.005	110	0.01		2	N.G "
67 / 70	20C-150-1 J	TO-5	430°C	-0.009	215	10	3	0	
	K			—	—	—	—	1	N.G. DAMAGED BY VOLTAGE ACCIDENT
	L			-0.010	220	10	36	0	
	M			-0.006	190	10	24	0	
	N			+0.050	185	10	~100	0	
	O			-0.002	190	10	8	0	

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GROUP	# NOVE	MOUNT	BAKE TEMP	[illegible] MA	VOLTS	[illegible] MA	[illegible]	[illegible]	
68	20A-140-2 O	Al_2O_3	430°C	-0.005	158	20	~100	0	RETEST-VACUUM STORAGE
	R			-0.001	139	20	71	0	RETEST-VACUUM STORAGE
	Q			—	—	—	—	—	RETEST-VACUUM STORAGE NO-CONTACT
	20C-149-3 P			-0.013	190	20	0	0	"
	Q			—	—	—	—	1	SHORTED FROM START
	R			-0.012	200	20	9	0	OK
8									
69	20C-150-1 B	TO-5	430°C	-0.004	140	20	2	0	RETEST-VACUUM STORAGE (SEE GROUP 64)
	C			-0.009	155	20	2	0	"
	D			<0.000	155	20	7	0	"
	F			-0.010	162	20	30	0	"
	G			+0.010	205	20	80	0	"
	20A-129-3 B			+0.010	215	20	7	0	RETEST-AIR STORAGE