Quarterly Technical Report 3 • July 1992

FIELD-EMITTER ARRAYS FOR RF VACUUM MICROELECTRONICS

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A. Rosengreen, Senior Research Engineer
Physical Electronics Laboratory

SRI Project 2743

Prepared for:

Defense Advanced Research Projects Agency
Defense Sciences Office
Virginia Square Plaza
3701 North Fairfax Drive
Arlington, VA 22203-1714

Attn: Dr. Bertram H. Hui

ARPA Order No. 8162

Contract MDA 972-91-C-0029

Covering the Period: 1 April through 30 June 1992

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
July 1992

3. REPORT TYPE AND DATES COVERED
Quarterly Technical 3 (1 Apr. to 30 June 1992)

4. TITLE AND SUBTITLE
Field-Emitter Arrays for RF Vacuum Microelectronics

5. FUNDING NUMBERS

6. AUTHOR(S)
C.A. Spindt and A. Rosengreen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Advanced Research Projects Agency
Defense Sciences Office
Virginia Square Plaza
3701 North Fairfax Drive
Arlington, Virginia 22203-1714

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
SRI International has completed the third quarter of a program to develop field-emitter arrays for vacuum microelectronics. The goals of the effort are 5 mA total current at 5 A/cm2 for at least 1 hour, and demonstrated modulation of the emission at 1 GHz.

PECVD of silicon dioxide films with uniform thickness over a 5-inch-diameter wafer was compared with sputter deposition. Gate aperture holes of 0.8 micrometer diameter were successfully printed and etched. Emission tests on sets of 1000-tip cathodes achieved 7514 hours of operation (4964 hours at 15 mA) with nickel plate anodes.

Mounting apparatus and microstrip lines were completed, and a test vehicle was designed, for microwave measurements for high-frequency testing of low-capacitance cathode structures. Investigations continued on geometry of the close-spaced anode, and simulated electron trajectories show that primary electrons are collected.

Under a new program task to develop a bright light source, preliminary tests were made on a water-cooled phosphor using a standard field-emitter array.

14. SUBJECT TERMS
Field-emitter array, vacuum microelectronics, low-capacitance cathod

15. NUMBER OF PAGES
25

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	None

EXECUTIVE SUMMARY

SRI International has completed the third quarter of Phase I of a research and development program on the SRI Spindt-type field-emitter array cathode with a view toward eventual applications in microwave amplifiers. Goals for this first phase have been set at 5 mA total emission, with a current density of 5 A/cm^2 for at least 1 hour and demonstrated modulation of the emission current at a frequency of 1 GHz. Our approach has been to identify methods of adapting and modifying the basic cathode structure for microwave operation and to experimentally investigate means of implementing those methods.

During the quarter we have accomplished the following, as documented in detail in this technical report:

- Continued research on basic cathode technology as defined by the goals of the DARPA program and related NRL project (Section 1)
- Performed plasma-enhanced chemical vapor deposition of silicon dioxide films with uniform thickness over a 5-inch-diameter wafer, and compared results with sputter and evaporation deposition in our low-capacitance cathode fabrication studies (Section 2)
- Printed and etched 0.8-μm-diameter gate aperture holes in our research toward low-voltage cathode fabrication (Section 3)
- Conducted emission tests on sets of 1000-tip cathodes, achieving 7514 hours of operation (4964 hours at 15 mA) with nickel plate anodes and initiating tests with 200 nickel tube collectors (Section 4)
- Completed fabrication of a mounting apparatus and microstrip lines, designed a test vehicle, and continued microwave measurements for high-frequency testing of low-capacitance cathode structures (Section 5)
- Investigated the geometry of the close-spaced anode and simulated the electron trajectories (Section 6)
- Performed preliminary tests on a water-cooled phosphor using a standard field-emitter array (Section 7)
- Planned activities for the period of 1 July through 30 September (Section 8)

CONTENTS

ILLUSTRATIONS

1. INTRODUCTION

SRI International is participating in an effort of the Defense Advanced Research Projects Agency (DARPA) and the Naval Research Laboratory (NRL) to perform research and development on the SRI Spindt-type field-emitter-array cathode with a view toward eventual applications in microwave amplifiers. The current DARPA program is the vehicle for advancing the basic cathode technology for microwave applications (e.g., reducing intrinsic capacitance and driving voltage requirements), and continues the original program plan to establish the characteristics of the cathode in its preprogram state of development, identify methods of adapting and modifying the structure for microwave operation, and experimentally investigate means of implementing those methods. For the NRL program, which began earlier than the DARPA project, SRI has shifted emphasis to the support of NRL's in-house vacuum microelectronics program by providing NRL with state-of-the-art Spindt-type cathodes and consultation on setting up and using cathodes.

At the beginning of the program, two areas of development required immediate attention. The first was a materials and processing issue related to providing and maintaining a suitable vacuum environment for the cathodes. The second related to the cathode's inherent high capacitance and means for reducing that capacitance to a level that is consistent with the microwave applications envisioned for the cathode.

Our approach has been to research these two issues in parallel, using an easy-to-build, low-frequency-triode configuration fabricated on a TO-5 header as a test vehicle for materials and processing studies, and at the same time designing and researching fabrication techniques for building high-frequency-cathode structures on dielectric substrates (e.g., quartz or glass). Specific tasks that are being addressed on these related programs are:

1. Fabrication of a supply of state-of-the-art cathodes for use in establishing cathode characteristics, and for developing structures, circuits, and procedures for testing the cathodes as triodes.
2. Development of a close-spaced anode test configuration that can be used to investigate triode characteristics at low frequency (kHz to MHz) in order to study the known problems with cathode survival under close-spaced anode conditions.
3. Development of a circuit for driving the cathodes and demonstrating gain, frequency response, and peak emission levels.
4. Studies of advanced cathode structures (geometry, fabrication technology, and processing) for high-frequency operation.
5. Investigations (with NRL) of cathode mounting and connecting procedures using practices that are consistent with the microwave goals of the effort.
6. Consultations with the NRL staff on the experimental results and applications of the cathode technology.

2. LOW-CAPACITANCE CATHODE FABRICATION

Low-capacitance cathode structures were designed and fabricated on the DARPA program, and samples without cones have been delivered to NRL for use in designing mounting structures and contact probes for NRL's in-house testing. As soon as the fabrication technology is developed on the DARPA program, sample working cathodes—for use in establishing NRL in-house experience and evaluation capability for experimental microwave field-emission devices—will be fabricated and delivered on the NRL program.

Characterization of deposition made with several new systems shows that either sputtered or plasma-enhanced chemical vapor deposition (PECVD) films, or some combination of the two, will probably work for the dielectric layer, although we must continue our process development on both methods. The critical test will be the etch patterning of the holes. Achieving a uniform and repeatable etch of the oxide layer depends on obtaining a film with consistent and adequate stoichiometry.

While we develop our in-house processes, we are relying on vendor-supplied atmospheric-pressure chemical vapor deposition (APCVD) glass layers, which are not entirely satisfactory with respect to mechanical properties. Low-capacitance cathodes will be fabricated for mounting on our recently assembled high-frequency test apparatus, which is described in Section 5.

2.1 EVAPORATION DEPOSITION

Early in the quarter, we acquired a CTI Cryogenics Cryo-torr 10 pump as a replacement for the turbomolecular pump in the system on which we depend for evaporation deposition on the 5-inch-diameter wafers required by the photolithography stepper. The evaporation system was recalibrated and the system put back on line.

2.2 ENHANCED CHEMICAL VAPOR DEPOSITION

With the newly operating PECVD system, we have produced silicon dioxide films with good thickness uniformity over a 5-inch-diameter wafer. Very conformal films resulted, with excellent step coverage. Figure 1 shows a scanning electron micrograph (SEM) of a sectioned wafer with PECVD silicon dioxide over a step at the edge of a chromium base film and a molybdenum gate film over that; the continuity of the molybdenum film of the step is quite acceptable.

The index of refraction of the silicon dioxide film was measured as 1.52 (compared to an accepted value of 1.46), suggesting a silicon-rich deposit. However, the breakdown voltage was over 300 V for an 8200-Å-thick film deposited over a step and patterned in the configuration that will be used in the low-capacitance cathode application (breakdown strength = 4.3×10^6 V/cm),

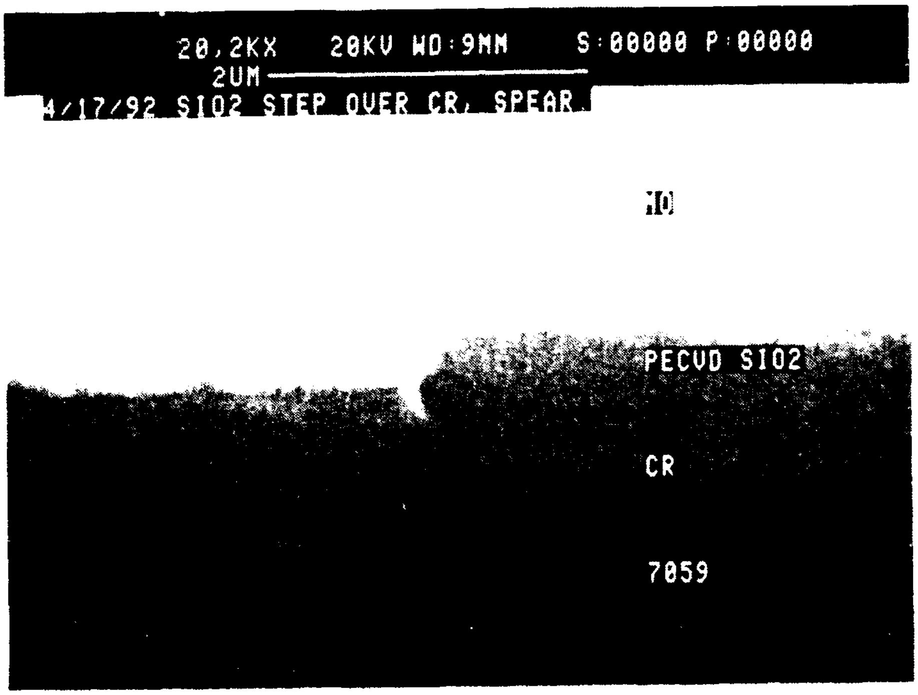


Figure 1. Scanning electron micrograph of a sectioned sample showing molybdenum-coated PECVD silicon dioxide over a chromium step on a glass substrate

which should be very satisfactory. Thus, the only concern with the apparently silicon-rich stoichiometry is the etch properties of the PECVD layer. Etching-test results showed that the PECVD silicon dioxide etched more rapidly than thermally grown oxide, but at acceptable rates in buffered hydrofluoric acid oxide etch (BOE). However, the silicon-rich silicon dioxide did not hold up against potassium hydroxide (KOH), whereas fully oxidized silicon dioxide resists KOH very well. It is essential that the deposited oxide layer withstand exposure to KOH, because KOH is used in subsequent processing of the cathode structure (to etch the sacrificial parting layer used in the cone formation process).

This difficulty with the silicon-rich deposit is most likely the result of insufficient temperature on the substrate during the PECVD process. It is possible that a post-deposition anneal of the film would be helpful, but the temperature for post-annealing might be limited by the chromium base layer or by the substrate when we are working on glass. The PECVD system is being modified for operation at higher temperatures.

2.3 SPUTTER DEPOSITION

Sputtered films (molybdenum/tantalum and silicon dioxide) with the newly operational advanced in-line, four-target, cryopumped system from Circuits Processing Apparatus showed step coverage that was much better than with evaporated films, although not as good as we produced with PECVD films.

The index of refraction was measured as 1.42, suggesting that the film is somewhat porous. The breakdown voltage over a step was measured as 117 V for a 2400-Å-thick sputtered silicon dioxide film (breakdown strength = 4.8 x 10^6 V/cm). The sputtered silicon dioxide films etched at rates slower than those of the PECVD film, but still faster than thermally grown oxide etch rates. In addition, sputter depositing of the molybdenum gate film was unsatisfactory because porosity of the film led to oxide etch and lift-off of the gate film during BOE of the sputtered oxide layer. Because the porosity of sputtered layers is a function of the sputter deposition parameters, it is likely that the porosity of the molybdenum and silicon dioxide layers can be improved by manipulation of the deposition parameters.

3. LOW-VOLTAGE CATHODE FABRICATION

Reduction of voltage requirements for driving our silicon-substrate cathodes in a Spindt-type emitter array has been achieved by reducing the dimensions of the cathode structure. This reduces the energy stored in the parasitic capacitance of the structure and helps to increase the transconductance.

At the beginning of our research program, the typical cathode geometry consisted of 1.1- to 1.25-μm-diameter gate apertures and emitter tips positioned within the plane of the gate film. For one of our standard configurations of a 10,000-tip array in a 1-mm-diameter area, turn-on voltages for the cathodes were typically 80 to 100 V, and 150 to 200 V was required for 20 mA. We are now able to print and etch 0.8-μm-diameter gate aperture holes; with proportionally thinner oxide layers, we can fabricate cones in the cavities with the emitter tips in the plane of the gate film as we did with the larger apertures. The result has been rewarding, with turn-on voltages in the 40- to 50-V range, and around 100 V for 20 mA. In a self-funded effort in which a vendor with the capability of fabricating smaller feature sizes is cooperating, samples are being prepared with 0.5- to 0.75-μm-thick oxide layers, but results have not yet been obtained with gate apertures having diameters of less than 0.8 μm.

Figures 2 and 3 show current-versus-voltage data for a 10,000-tip cathode array (52i-304-1M) with 20 mA of emission being produced at 101 V, and 25 mA at 104 V. Figure 4 is a SEM of a typical emitter tip in the array, showing the gate aperture to be about 0.8 μm in diameter. The emitter tip is not particularly tall, and the tip is rather blunt. We expect even better performance with sharper, taller tips combined with the small gate aperture.

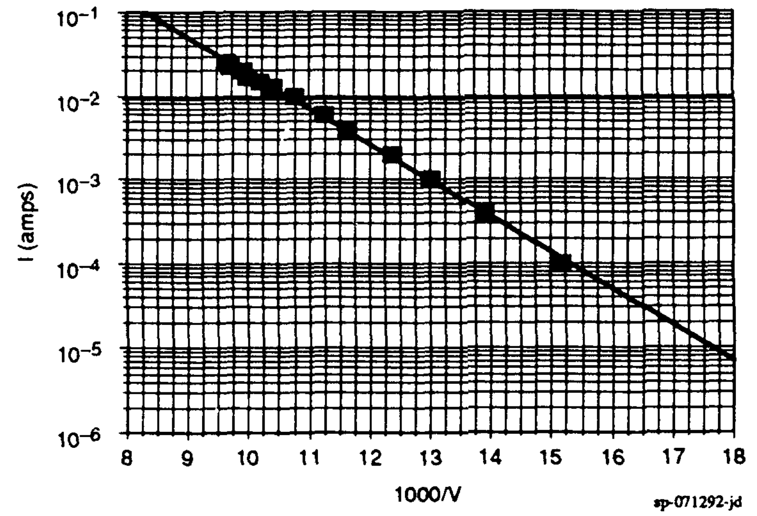


Figure 2. Current vs. 1000 V for cathode 52i-304-1M

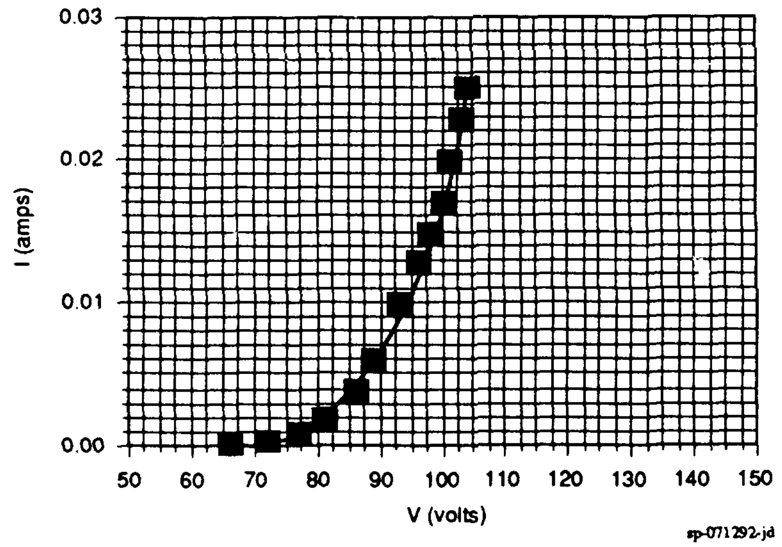


Figure 3. Current/voltage chatacteristics for cathode 52i-304-1M

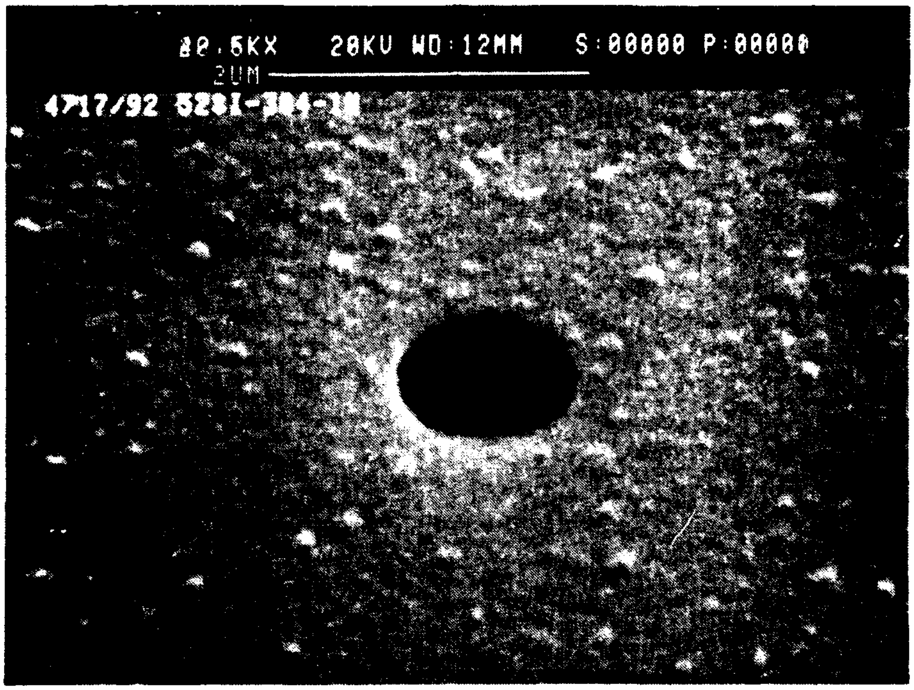


Figure 4. Scanning electron micrograph of cathode 52i-304-1M with aperture diameter of approximately 0.85 µm

4. CATHODE EMISSION TESTS

Silicon-based samples available from work completed before we experienced equipment failures were used for the continuation of tests focusing on anode processing and the effects of geometry on performance. Our principal emission test concentrated on two sets of three 1000-tip cathodes—one set with tube-shaped anodes (originally 304 stainless steel and later changed to nickel) and one set with nickel plate anodes.

4.1 NICKEL PLATE ANODES

Tests on closely spaced (≈1 mm) nickel plate anodes continued with the two (of the original three) 1000-tip cathodes that still operated at the conclusion of the previous quarter. A second cathode failed suddenly while some changes were being made in the gate circuit to compensate for the high gate interception (500 to 800 μA) present throughout the tests because of the need to keep the anode voltage at or below 180 V to prevent overheating of the structure, which results in warpage of the gate contact plate and loss of contact to the gate. We are not certain whether the failure during modification was due to operator error or a cathode fault. As of 10 June, the third cathode (53i+300-7Q) had been operating for a total of 7514 hours, with 4964 hours at 15 mA (15 μA per tip) or more. Figure 5 is an oscillograph showing the current-versus-voltage characteristics of this cathode, and Figure 6 is a plot of the emission current on a log scale versus the inverse of the applied voltage, indicating straight-line performance over four orders of magnitude.

4.2 TUBE-SHAPED ANODES

The 304 stainless steel collectors originally used were changed to 200 nickel tube collectors. During the first test with this setup, the collectors appeared to work very well. Three 10,000-tip cathodes (28C-293-3K, 28C-293-3L, 28C-293-3M) that had been in storage since August 1991 were mounted in the system. Pretests showed the cathodes to require 88, 91, and 89 V respectively to produce 1 mA emission, which is good performance. All three cathodes had severe gate-film stress cracks resulting from the cone formation process, which disfigured the cathodes but had little effect on performance.

The test vessel was processed in the usual way (baked at 400 °C for 48 hours, ion pumped at 10^{-6} torr or less), and the cathodes were turned on after system cooling to about 80 °C. All three cathodes performed as well as, or slightly better than, they had in the pretest up to 1 mA emission. However, after a short time at 1 mA, cathode 28C-293-3K failed to a short circuit. To test the collectors for damaging effects, the emission on the two remaining cathodes was increased slowly (over 2 weeks time) to 40 mA peak with our standard 60-Hz half-wave rectifier driver and 350 V on the anodes. Under these conditions, the anode tubes were red-orange at approximately 700 °C, and it was impossible for anyone to touch the glass window on the test vessel. At this point, cathode 28C-293-3M failed to a short circuit because of an arc.

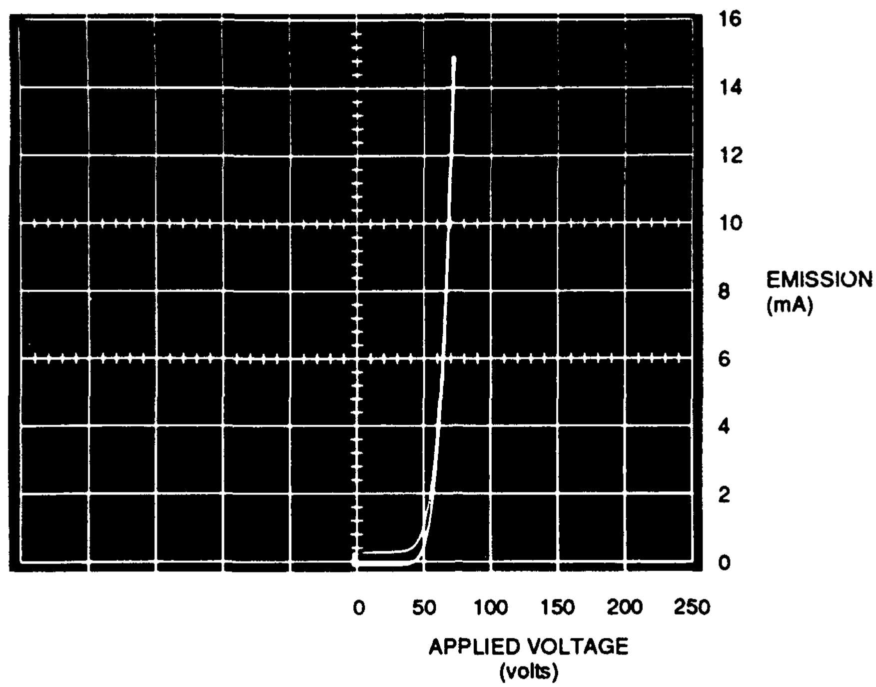


Figure 5. Current/voltage oscillograph for 1000-tip cathode 53i-300-7Q as of 8 June 1992 after 7500 hours of operation with average peak current per tip of 15 μA at 73 V

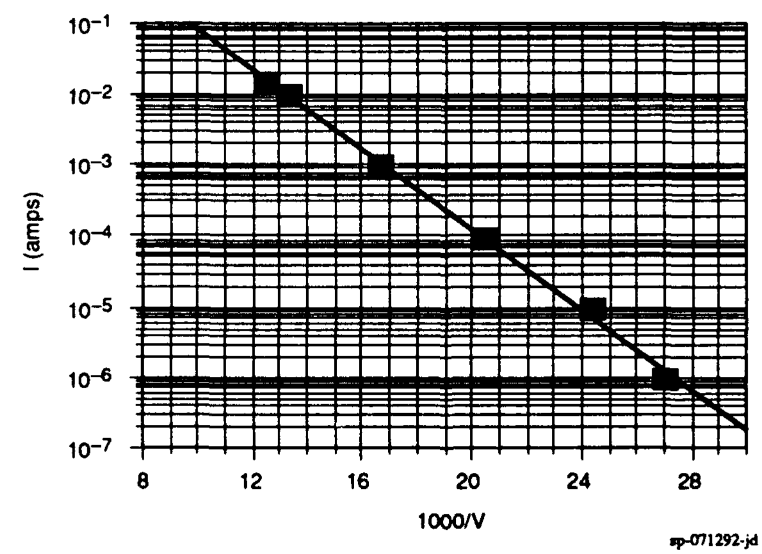


Figure 6. Current vs. 1000 V for cathode 53i-300-7Q after more than 7500 hours of operation

The driving voltage on cathode 28C-293-3L was then changed over to our gating-counting circuit, which allows only every tenth or hundredth 60-Hz pulse to address the cathode, thereby reducing the power into the anode by factors of 10 or 100. This allowed us to increase the emission to 100 mA, and to increase the anode voltage to 800 V without overheating the anode. The increase to 800 V was necessary to overcome the effects of space charge in the gate-to-anode region at the 100-mA emission level. Figure 7 is an oscillograph of the current-versus-voltage curve for this cathode at 100 mA peak emission, and Figure 8 is a Fowler/Nordheim plot of data showing no saturation effects up to that point.

Cathode 28C-293-3L ran for 5 hours at 100 mA without any change, and was left running overnight at that level, even though we normally reduce the emission during the night. The cathode shorted before morning, and a post-operative inspection showed that the gate film had been grossly overheated and was crazed (or mud-cracked) over a large area, much of which was outside the active portion. We suspect that the cathode may have been seasoned or field formed during the night and drew excessive emission, which led to overheating and breakup of the gate film. This is a very unusual failure, since a damaging arc usually occurs before the environment is hot enough to damage the molybdenum gate film, and it implies that the cathode environment is better with nickel anodes than with stainless steel anodes—a fact that we will take into account in our future experiments.

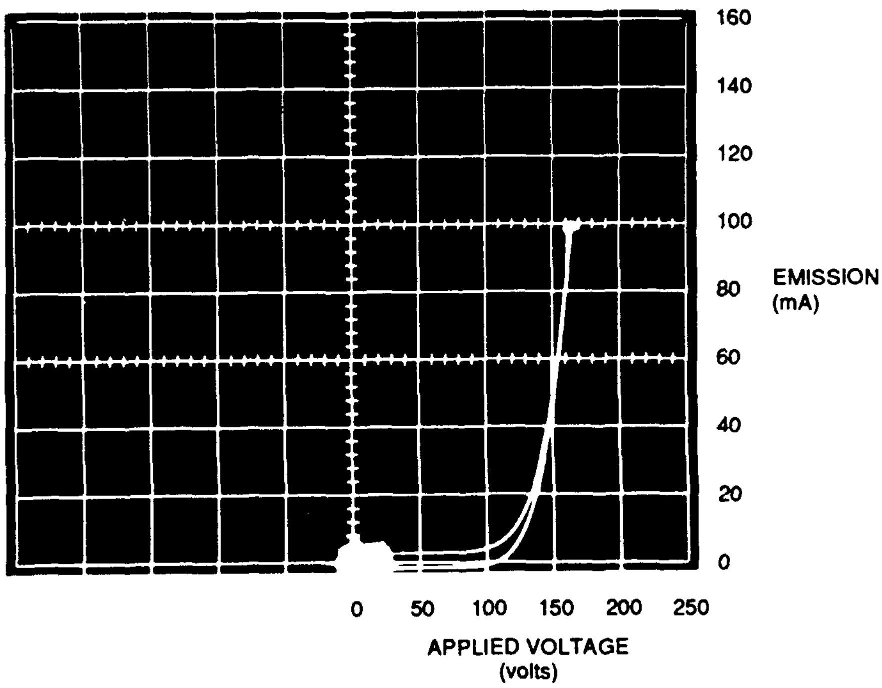


Figure 7. Current/voltage oscillograph for cathode 28C-293-3L operating at a peak emission of 100 mA with a 60-Hz half-wave driving voltage gated at 6 pulses per second

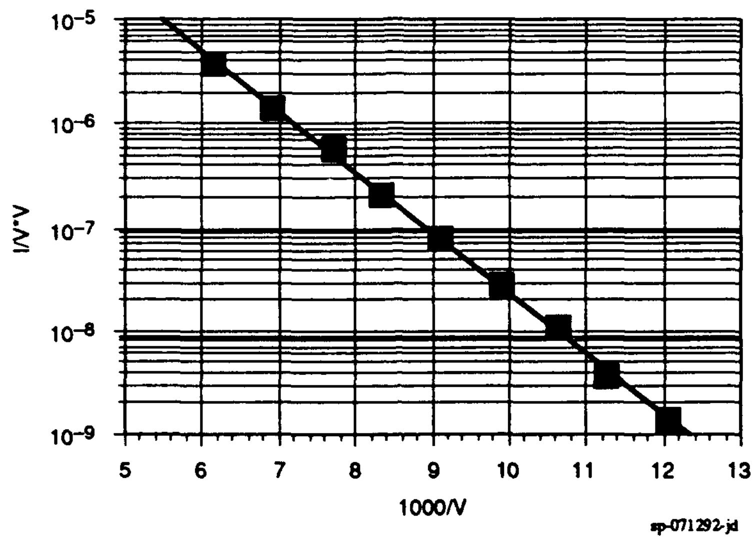


Figure 8. Data for cathode 28C-293-3L at a peak current of 100 mA

5. MICROWAVE MEASUREMENTS WITH LOW-CAPACITANCE CATHODE STRUCTURES

The fabrication of mounting apparatus and microstrip lines required for testing low-capacitance cathodes at high frequencies was completed. Figure 9 is a schematic cross section of the cathode and anode structure, and Figure 10 is a schematic plan view of the cathode, anode, microstrip lines, and SMA coaxial connectors mounted on a support structure that also provides a ground plane for the cathode and microstrip lines.

To evaluate the microstrip lines and the bonds to them and to the SMA connectors, two microstrip lines were bonded together and their other ends bonded to SMA connectors, thus forming a single microstrip line. The S-parameters of this line were measured from 0.5 to 1.5 GHz. The results were excellent. The voltage standing wave ratio (VSWR) at 1.0 GHz was 1.0225, corresponding to a reflection coefficient of 0.0111 and a return loss of -39.2 dB. The maximum loss was -36.0 dB at 1.5 GHz.

In the fabrication of the microstrip line, the metal film forming the metal ground plane is applied to the microstrip-line wafer before it is cut to size. During the cutting, this film tends to peel. This raised the question of whether the film is necessary, since both the metal surface on which the microstrip line rests and the surface of the microstrip line wafer are optically flat. To investigate this, the measurement described above was repeated for microstrip lines without the back metal film. The VSWR at 1.0 GHz was 1.071, corresponding to a reflection coefficient of 0.0343 and a return loss of -29.3 dB. The loss at 1.5 GHz was -25.5 dB. Although these results are not as good as those obtained with a metal film on the backside of the microstrip lines, they are within acceptable limits. The bond between the two microstrip lines was not as good as the first one and may account for some of the added return loss.

As was mentioned in Quarterly Technical Report 1, the S-parameters of the microwave triode will be measured under a pulsed condition to avoid heating problems. The instrumentation for these measurements was set up and tested. Instead of a direct connection from the network analyzer to the gate of the triode, a switch is inserted. The bias to the triode is supplied via two bias tees, and the gate voltage is pulsed synchronously with the switch that provides the signal from the network analyzer. The setup was tested on a passive element, since the triode will not be ready before this summer. The tests were performed with 1-second pulses at a duty cycle of 10%. No problems were encountered.

To process the S-parameter data, a small Fortran program was written to calculate the various gain terms and stability conditions discussed in Quarterly Technical Report 1. The program provides convenient output files for plotting.

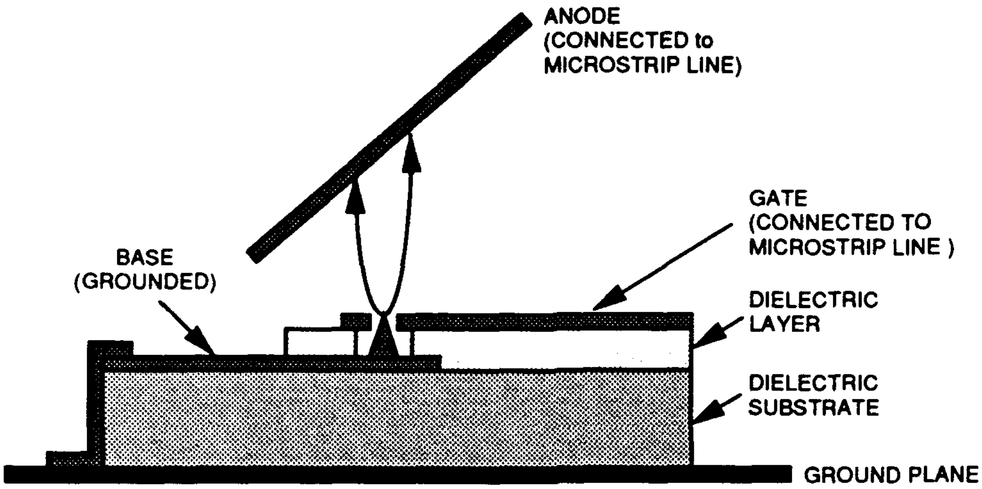
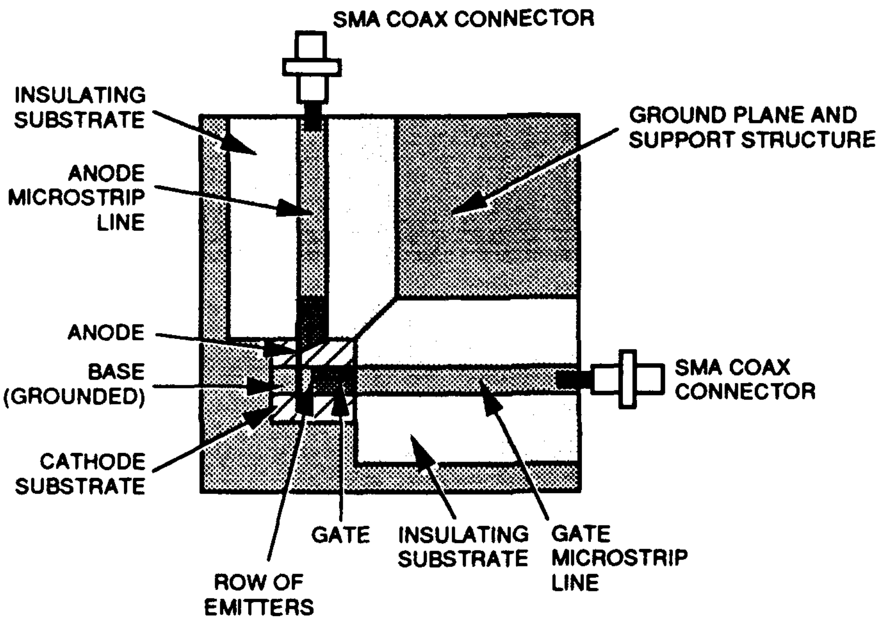


Figure 9. Schematic cross section of the microwave-triode test geometry



NOTE: THE ANODE IS ACTUALLY DIRECTLY OVER THE EMITTERS, BUT IS SHOWN TO ONE SIDE TO AFFORD A VIEW OF THE POSITION OF THE ROW OF EMITTERS.

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Figure 10. Schematic plan view of cathode, microstrips and connectors

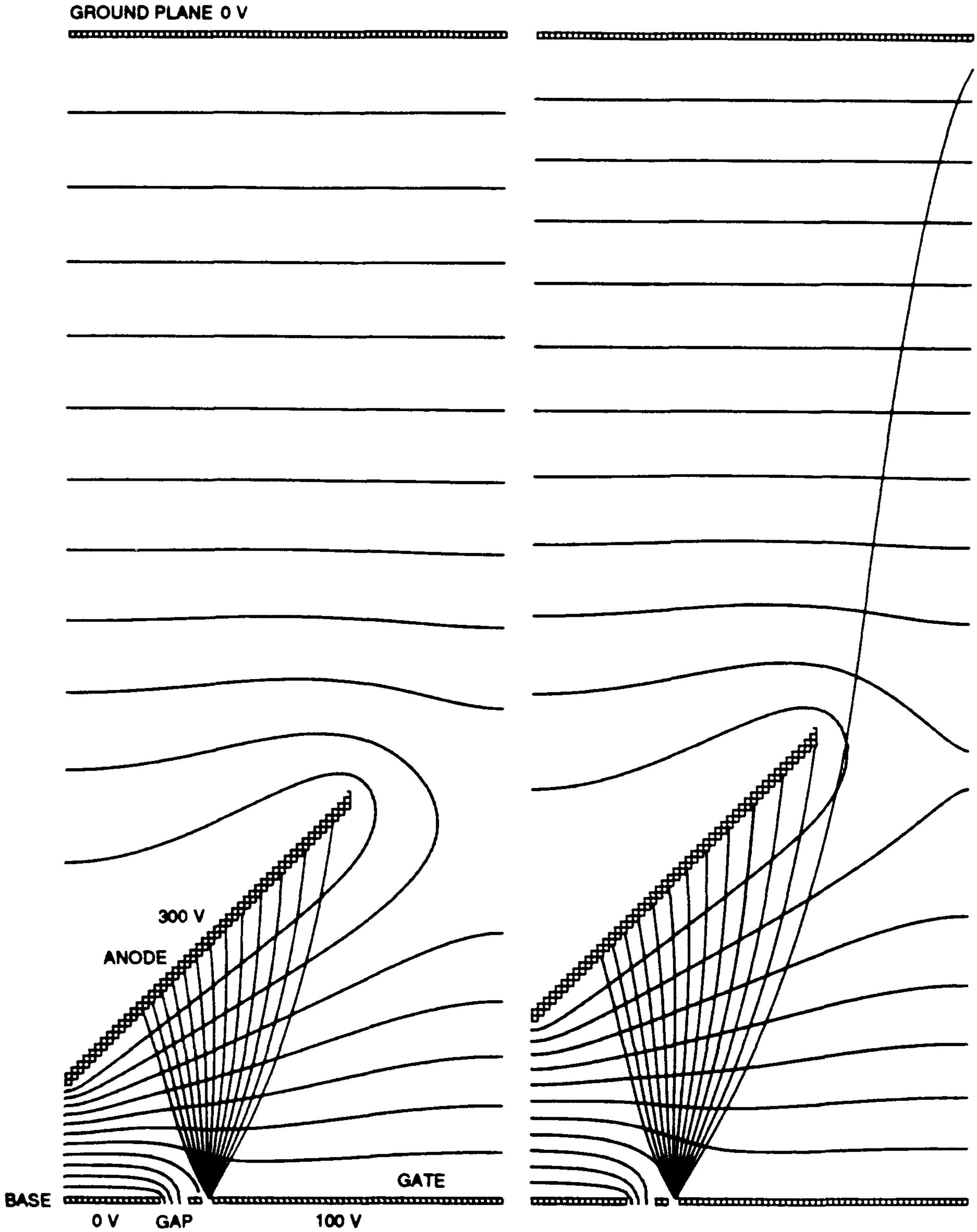
The vacuum test vessel will have provisions for testing four cathodes per pumpdown, so that the probability is reasonable of having at least one cathode working well enough to produce good data on each pumpdown cycle. The cathodes and anodes are addressed by the microstrip lines and SMA coaxial connectors that in turn couple to a Hewlett-Packard network analyzer for measuring the S-parameters.

6. CLOSE-SPACED ANODES

The geometry of the close-spaced anode and its position relative to the field-emitter tip were discussed in the first quarterly report. To get a better understanding of how the surrounding electrodes and the position and size of the anode affect the collection of the electrons, we performed a simple simulation of the electron trajectories using the program Simion 5.0. The geometry that was investigated is similar to that shown in Figure 9. Because the simulation allows the use of only 16,000 mesh points, it was impossible to simulate the details around the field-emitter tip. Instead, the emitter was simulated with a point in an opening of the gate film from which electrons with an energy of 100 eV were started at angles 5 degrees apart in the range of -30 to 30 degrees. The base, gate, and anode voltages were set at 0, 100 and 300 V, respectively. Because of the small thickness of the oxide layer that separates the gate and base planes, these two electrodes are all in the same plane in Figure 11. To avoid affecting the potential in front of the tip, a small gap was inserted between the gate and base electrodes. The bottom edge of the anode was placed 20 mils above the gate-base plane and has a length of about 70 mils. At the very top of Figure 11 is a ground plane 200 mils above the gate-base plane presenting the surroundings.

Figure 11(a) shows that all the primary electrons are collected. However, reflected secondary electrons may escape, and ions generated by the electron bombardment of the anode will be collected by the gate. Figure 11(b) shows the case where the anode has been raised by 10 mils. In this case, electrons emitted at angles from about 25 to 30 degrees escape.

In Figure 12, the anode has been rotated 180 degrees around a vertical axis through the emitter. In comparison with the results shown in Figure 11, the effect of the base potential on the electron trajectories is clearly shown leaving more margin for an effective collection. This structure has the added advantage that the ions from the anode will be collected by the base electrode. An anode structure similar to that in Figure 12 has been fabricated and will be used in the triode. However, for safety its length has been increased to 100 mils.



(a) ANODE SEPARATION FROM GATE-BASE PLANE EQUAL TO 20 MILS

(b) ANODE SEPARATION INCREASED TO 30 MILS

Figure 11. Calculated equipotentials and electron trajectories of triode

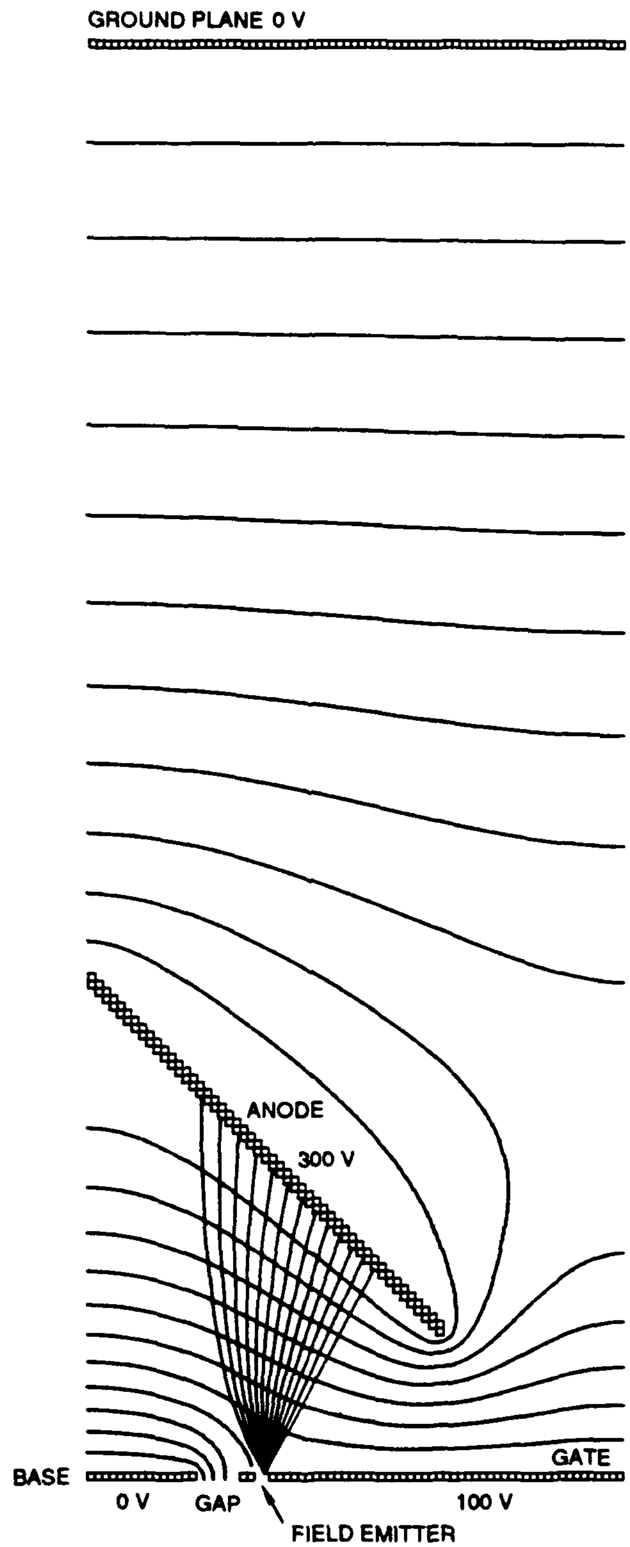


Figure 12. Calculated equipotentials and electron trajectories of triode, with anode rotated 180 degrees from position in Figure 11

7. BRIGHT LIGHT SOURCE DEVELOPMENT

A new task has been added to the program, with the goal of developing a new bright light source using a phosphor screen driven by an electron field emitter cathode. This will provide ample current density for obtaining a high brightness. To demonstrate the feasibility of such an approach, the test vehicle shown in Figure 13 will be constructed and tested. The bottom part consists of a water-cooled copper block with a layer of phosphor. Above is a field-emitter array on a transparent substrate with transparent indium tin oxide electrodes.

We have studied some of the literature on phosphors for high-intensity applications and performed preliminary tests on a water-cooled phosphor using a standard field-emitter array.

7.1 PHOSPHORS FOR HIGH-INTENSITY APPLICATIONS

High-intensity phosphors are required for tubes used in high-definition television (HDTV) and for projection tubes. The latter application requires very special phosphors because the power density is about 100 times that in direct-view tubes.[1] The main problem with phosphors in these applications is their lifetime. The half-life is usually expressed in coulombs/cm^2. This means that the lifetime is inversely proportional to the current density (A/cm^2). Use of large current densities has the added problem of transitory or lasting decrease in luminescence efficiency. However, the current density used in the proposed light source will be significantly lower than that in a TV projection tube, where the current density must be large because of the very short dwell time of the electron beam on each pixel.

Hase et al.[2] have discussed the properties of phosphor materials for cathode-ray tubes. Of the effects mentioned as a cause for reduction of the luminescence efficiency, the following is of particular interest:

1. Presence of "killer centers" such as lattice imperfections, surface states, and impurity-related centers
2. Thermal quenching, increasing the probability for nonradiative transitions and providing energy for formation of "killer centers"
3. Too high a level of excitation, causing brightness saturation as a result of thermal quenching

Clearly, thermal quenching is an important parameter, and cooling the phosphors as shown in Figure 13 achieves significant improvement.

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1 Yamamoto, H., and H. Matsukiyo, *Journal of Luminescence*, **48 & 49**, pp. 43-48, 1991.

2 Hase, T., T. Kano, E. Nakazawa, and H. Yamamoto, *Advances in Electronics and Electron Physics*, **79**, pp. 271-373, 1990.

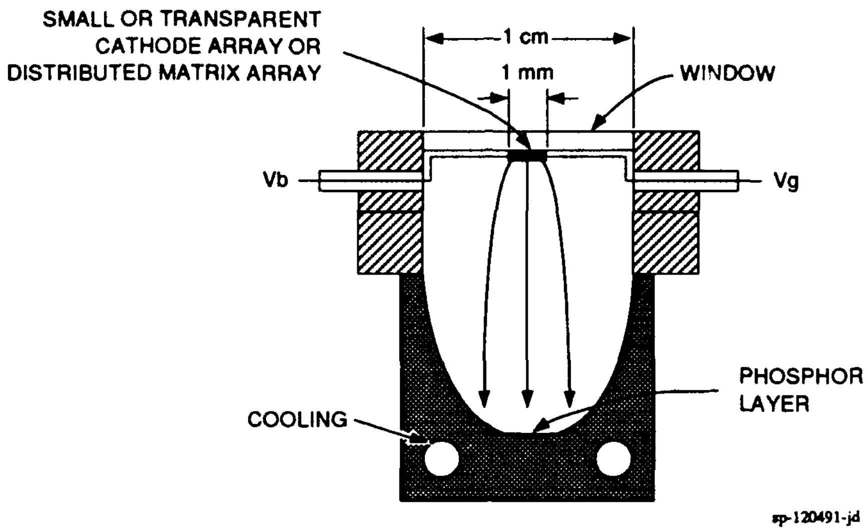

Figure 13. Proposed test vehicle for bright light source

The performance of the phosphors is a strong function of their composition and the method used for fabrication. Klaassen et al.[3] have made a study of the degradation of several phosphors at low current densities in the range of 10^{-4} to 10^{-3} A/cm^2. In the case of monocrystalline Zn_2SiO_4:Mn, the experiments indicated that the loss of radiative efficiency was due to surface losses by an oxygen-deficient surface layer created by the electron bombardment. Annealing the crystal in pure oxygen for 4 hours at 1100 °C returned the efficiency. Experiments with $Sr_2Al_6O_{11}$:Eu indicated that the degradation is caused by absorption of the generated luminescence by color centers in the host lattice. In our case it would be beneficial to find a phosphor with a long lifetime, where the major cause of degradation was due to thermal effect since this can be controlled by water cooling. This, of course, assumes that the thermal conduction of the phosphor layer is adequate, and may require a very densely packed layer or a thin-film phosphor.

7.2 PRELIMINARY EXPERIMENTS

Preliminary experiments have been conducted, employing the arrangement shown schematically in Figure 14. Here, a conventional field-emitter array is mounted in an ultra-high vacuum chamber opposing a phosphor layer deposited on a water-cooled, copper anode assembly. The window allows for direct viewing of the light output with a luminosity meter. Studies of luminosity versus electron current density, electron energy, and time can thus accomplished.

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[3] Klaassen, D.B.M., D.M. de Leeuw, and T. Welker, *Journal of Luminescence*, 37, pp. 21-28, 1987.

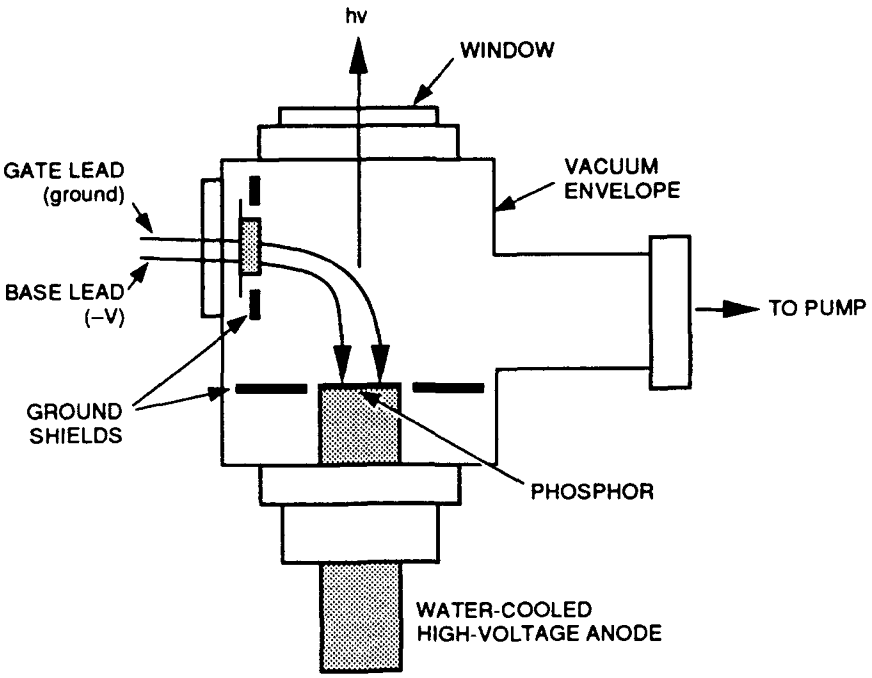

Figure 14. Schematic of the water-cooled phosphor experiment using a Spindt-type cathode

Initial light output studies were made with powdered manganese activated zinc-silicate crystals (Zn_2SiO_4:Mn, designated P1) as the phosphor for several reasons. Not only is P1 generally well characterized as to its phosphorescent properties, but it is efficient (30 lumens output/watt input), and has one of the better half-lifes known (> 100 C/cm^2). In addition, it was on hand in our laboratory.

We have observed brightness levels of 10^3 foot-lamberts at electron energies of 10 keV and current densities of 10 mA/cm^2. This brightness level is roughly that required for heads-up display applications. At this current density, the light output of P1 is beginning to saturate, which is equivalent to a decrease in efficiency.

The most serious decrease in efficiency arises from degradation of the phosphor by the introduction of defects into the phosphor crystals, due to electron radiation damage. At 10 keV and 10 mA/cm^2, decreases in light output of 50% are observed in approximately 100 hours of operation. Other investigators[4] have shown that in the case of P1, this degradation in light output is the result of oxygen depletion in the surface layer(s) of the P1 crystal. As the electron energies employed in cathodoluminescent displays far exceed the binding energies between atoms/molecules in solid-state materials, radiation damage is inevitable. It appears that in most, if not all, known phosphors such damage eventually leads to a significant deterioration in efficiency. Thus, particularly in dc lamp applications, restoration of the efficiency of the phosphor, preferably by an *in-situ* method, might be necessary if near-peak performance is to be maintained over reasonable time periods.

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[4] *I bid.*

With regard to P1, it is known that reoxidation of degraded crystals occurs at temperatures on the order of 1000 °C. As such temperatures are not feasible to achieve in most practical tubes, we have initiated an investigation of *in-situ* reoxidation employing a low-pressure oxygen gas discharge. Preliminary experiments have shown improvements in efficiency of between 50 and 300% resulting from reoxidation of a depleted P1 phosphor by exposing it to an oxygen gas discharge. Of course, oxygen and oxygen discharges are not the best of environments for the field-emission cathode array; however, in principle, such a procedure could be implemented periodically in a working light source, thereby extending the life of the phosphor almost indefinitely.

Such plasma oxidation could also be used more generally for regenerating oxygen-depleted phosphors in tubes or on substrates that cannot withstand temperatures required for thermal oxidation.

8. WORK PLANNED

During the next quarter, we will improve our tools for the fabrication and testing of advanced low-capacitance cathodes by assembling and debugging the recently completed high-frequency test apparatus. We will also work to establish routine PECVD silicon dioxide depositions on 5-inch wafers, and to achieve good adhesion between these films and the evaporated molybdenum gate layer. In addition, we will continue our research on silicon-substrate cathodes.

Experiments will include the further investigation of the reoxidation of phosphors by oxygen plasma techniques, studies of light output from several other powdered phosphor materials, particularly YAG phosphors (P53), and the initiation of thin-film phosphor studies.