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FIELD-EMITTER ARRAYS FOR RF VACUUM MICROELECTRONICS

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Physical Electronics Laboratory

SRI Project 2743

Prepared for:

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 31 June 1993

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EXECUTIVE SUMMARY

SRI International has completed the sixth 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. We have met the first-phase goals of 5 mA total emission, with a current density of 5 A/cm² for at least 2 hours 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 of 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 ARPA program and related NRL project (Section 1)
- Continued a series of controlled tests with photoresist/developer/stripper combinations to identify the source of a contamination problem in the low-capacitance cathode fabrication technology, and determined that the contamination resulted from sulfur hexafluoride (Section 2)
- Devised a method of shielding the active area of the low-capacitance cathode from the base electrode to eliminate excessive gate interception of the emitted current, and continued studying the effects of processing on cathode performance by experimenting with hydrogen plasma treatment (Section 3)
- Set up four cathodes in our high-frequency chamber in an effort to gain data on the effectiveness of shielding the electrode (Section 4)
- Planned activities for the period of 1 July through 30 September 1993 (Section 5)

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1. INTRODUCTION

SRI International is participating in an effort of the Advanced Research Projects Agency (ARPA) 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 ARPA 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 ARPA 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. We have met the first-phase program goals of 5 mA total emission, with a current density of 5 A/cm² for at least 2 hours and demonstrated modulation of the emission current at a frequency of 1 GHz.

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

A series of controlled tests with glass and silicon substrates and a matrix of photoresist/developer/stripper combinations continued, as we attempted to identify the source of an ongoing and persistent molybdenum contamination problem that began when the photoresist that we had used for many years was no longer available. During the previous quarter we reported five significant observations, and preliminary Auger spectrometry measurements and depth profiling of contaminated and clean molybdenum films have revealed a sixth characteristic:

1. Only the 1375 photoresist has produced contamination in the tests.
2. Once the discoloration has appeared, nothing but sputtering has been able to remove it.
3. All attempts to remove the discoloration with chemicals have made it worse.
4. There appears to be no difference in results with the R-10 stripper and 2001 stripper.
5. The results of these controlled tests have not always been consistent with the observations made during actual cathode processing.
6. Amorphous carbon and molybdenum carbide (Mo_2C) are present on the contaminated gray-brown molybdenum film, while only amorphous carbon is present on the clean, silvery molybdenum sample.

It appeared that the problem could be the result of an ordered sequence of process steps, since our controlled step-by-step experiments had not yet produced precisely the same kind of contamination that we often encounter with the normal fabrication processes. However, our experiments, which were designed to identify the source of the problem, produced inconsistent results and were inconclusive.

Near the end of the quarter, Auger spectrometry showed that small amounts of sulfur were present on the low-frequency cathodes that were performing poorly. Sulfur has been shown to be a poison for field emission in flat-panel display applications where low-voltage sulfide-based phosphors were tried unsuccessfully. This observation was consistent with the notion of residual contamination from the new photoresists, as photoresists contain sulfur compounds. However, we noticed that a group of our standard cathodes fabricated on silicon did not show even traces of sulfur, and that they were patterned with the same resists and at about the same time as the low-capacitance cathodes.

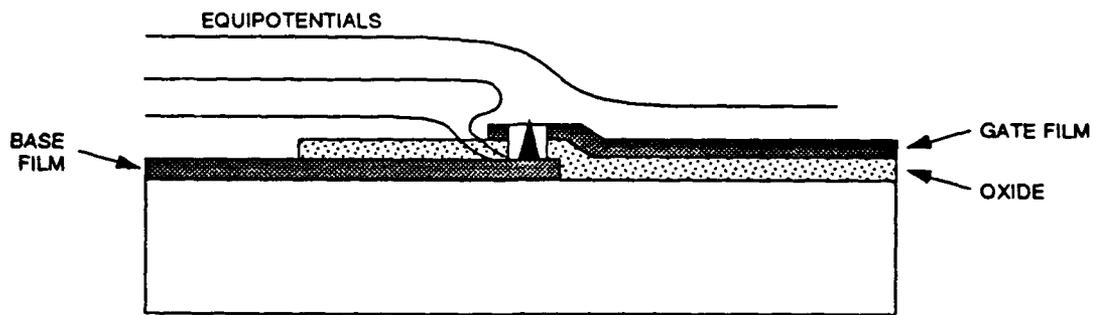
A thorough review of the process steps of the two batches of cathodes showed that the only difference was that the gate film on the low-frequency cathodes had been patterned with reactive ion etching, and the gate film of the standard cathodes had been patterned with wet chemistry. CF_4 has been used for our reactive ion etching of molybdenum; however, the new photoresist does not hold up well to the CF_4 , so SF_6 has been used recently to etch the molybdenum gate film. The SF_6 is about ten times faster than the CF_4 , so the new resist easily withstands the etch.

We concluded that the sulfur contamination was due to the sulfur hexafluoride, but was insidious in that the sulfur did not show up on Auger spectroscopy after the etch until the photoresist had been stripped and the substrate baked. It appears that the sulfur was concentrated on the edge of the molybdenum gate film under the photoresist where the Auger spectrometer could not detect it. It then migrated over the surfaces of the cathode when it was baked for cleaning. We will try combinations of the SF_6 and the CF_4 to determine if the CF_4 can clean off the residual sulfur.

3. EMISSION TESTS

While emission tests with low-capacitance cathodes were suspended during this period pending resolution of the contamination problem, investigations of the basic high-frequency test configuration continued. Earlier tests with low-capacitance cathodes had revealed that these cathodes tend to suffer from excessive gate interception of the emitted current. A study of this effect was carried out in parallel with the ongoing efforts to identify and eliminate the contamination. As a result, it was shown that the very narrow active area that is used to minimize the capacitance between the base and gate electrodes is insufficient to electrostatically shield the emitted electrons from the base electrode, as illustrated by Figure 1. The row of emitter tips is about $2\ \mu\text{m}$ from the edge of the gate film, and the base electrode is, of course, below the gate and spaced about $1\ \mu\text{m}$ from the gate by the silicon dioxide dielectric film.

With the edge of the gate film in such close proximity to the emitter tips, the fringing field from the base electrode deflects the emission current and causes unusually large amounts of the emission to be collected by the gate electrode. This is not a particularly surprising result, as we had previously shown that the fringing base electrode field can be used to produce a shaped (focused) emission beam from a Spindt-type field emitter (Figures 2 and 3, and U.S. Patent 4,874,981). However, we did not anticipate the magnitude of the current flow that would find its way to the gate in this configuration. It appears that the beam is bent to such an extent that it allows space charge effects in the beam to shield some electrons from the influence of the anode field, with the result that these electrons return to the gate film.



DRAWING NOT TO SCALE

DIMENSIONS: OXIDE = 1 μm THICK
 GATE = 0.3 μm THICK
 BASE = 0.3 μm THICK

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Figure 1. Cross section of the low-capacitance cathode showing the shape of the field lines in the vicinity of the active area

V-GATE = 100 V
V-ANODE = 250 V

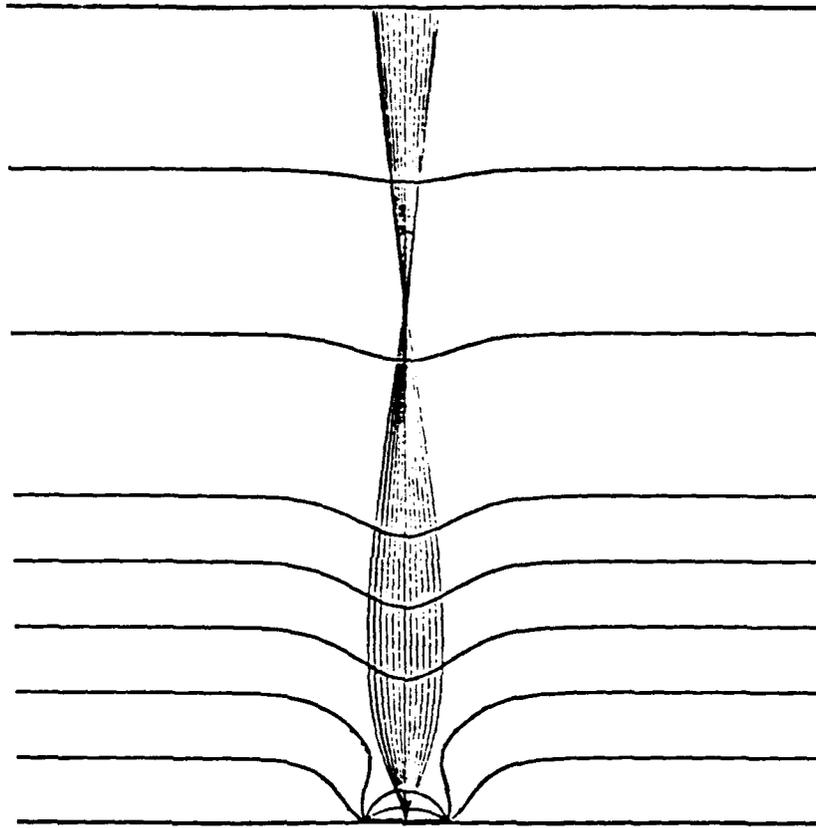


Figure 2. A computer model of trajectories from a single emitter with a small gate film area showing how the fringing fields from the base electrode can focus the beam

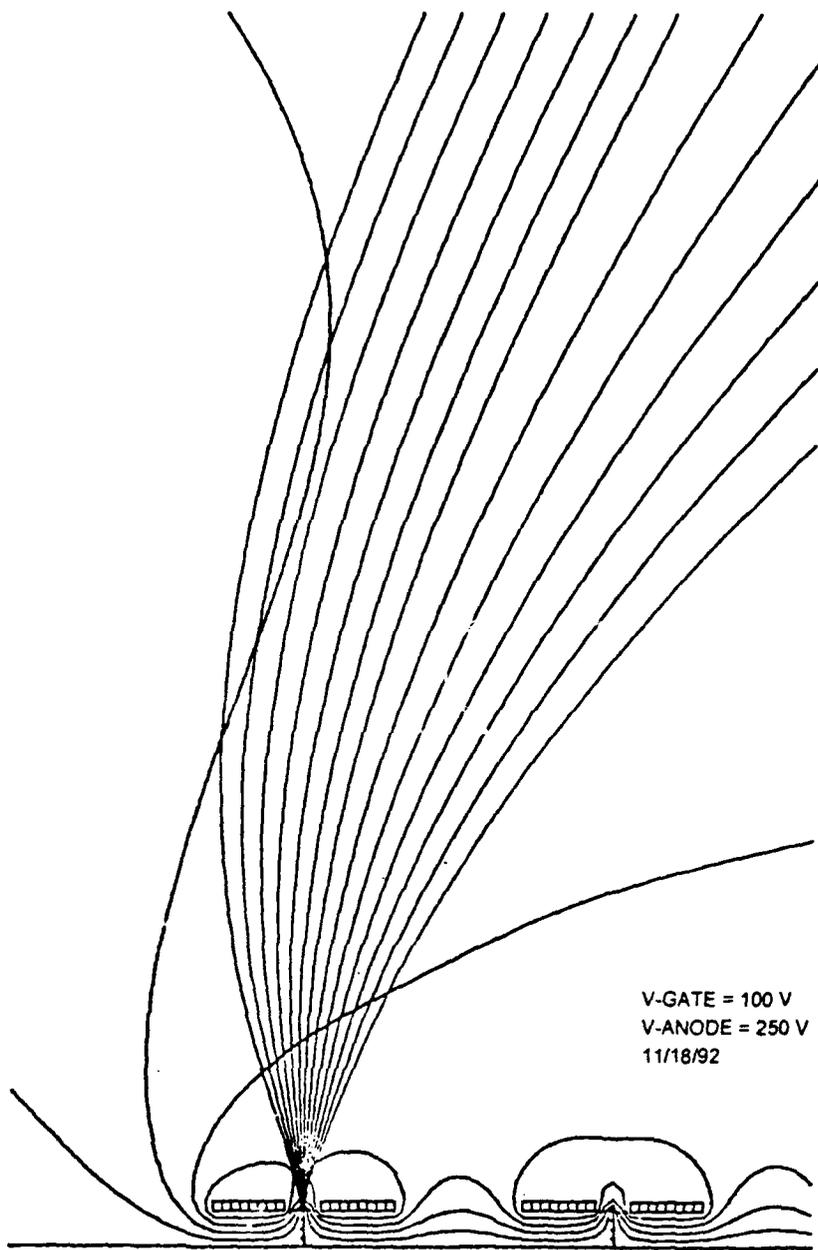
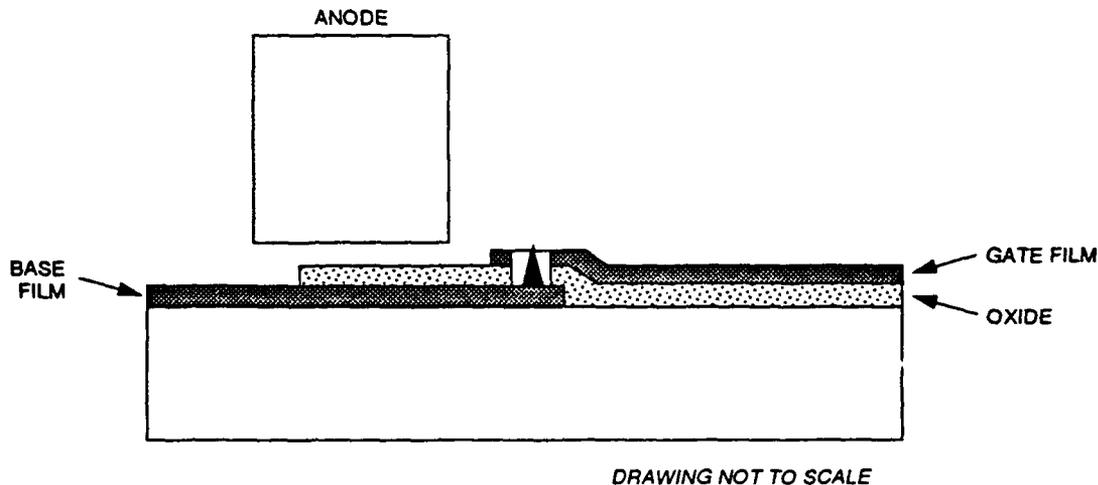


Figure 3. A computer model of trajectories from the edge of an array of Spindt-type emitters with very-small-area gate electrodes so that fringing base electrode fields influence the emitted electron beam

In principle, placing the anode very close to the cathode could compensate for the effect of the fringing base field. However, this also has the effect of increasing capacitive coupling to the anode and increasing the power density at the anode to potentially dangerous levels. Our experience with very closely spaced anodes is that they should be avoided if possible. For this reason, we considered alternative anode configurations such as that shown in Figure 4. However, by modeling the structure, we quickly determined that, as a practical matter, the required precision of the placement of the anode for it to be effective is simply not achievable at this stage of the device development.



DIMENSIONS: OXIDE = 1 μm THICK
 GATE = 0.3 μm THICK
 BASE = 0.3 μm THICK

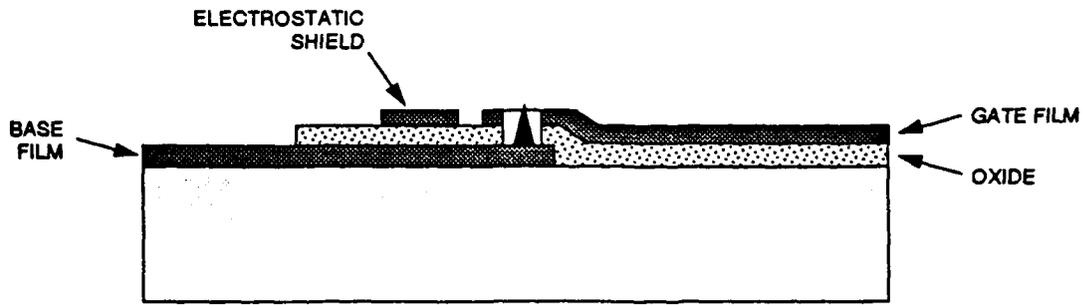
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Figure 4. Cross section of the low-capacitance cathode showing a desirable but impractical anode placement

Because another solution for our low-capacitance geometry is necessary, we adopted the approach of shielding the active area from the base electrode by adding an electrode over the base as shown in Figure 5. The photomasks required to fabricate the structure have been designed and ordered from a vendor. Figure 6 is a view of the layout of the low-capacitance cathode, showing the location of the base shield. In use, the shield will be dc biased to gate potential, but the signal will not be applied to the shield. Thus, the capacitance detected by the applied signal will not be significantly increased, but the area of the gate film will in effect be increased for the purpose of shielding the emitting area from the fringing base field.

Cathodes were fabricated using the shield configuration, and tests were made to determine if the relatively large area of the metal/oxide/metal structure formed by the base electrode and the shield will be a problem with respect to defect density (e.g., pinholes) in the plasma-enhanced chemical-vapor-deposited (PECVD) oxide. We found that the oxide held up well to 250 V, a higher level than that at which we expect the cathodes to have to operate.

We also continued to study the effects of processing on cathode performance. Specifically, hydrogen plasma cleaning has been fruitful. A Muller-type emission microscope apparatus was fabricated for studies of cathode processing. The system is capable of operating a

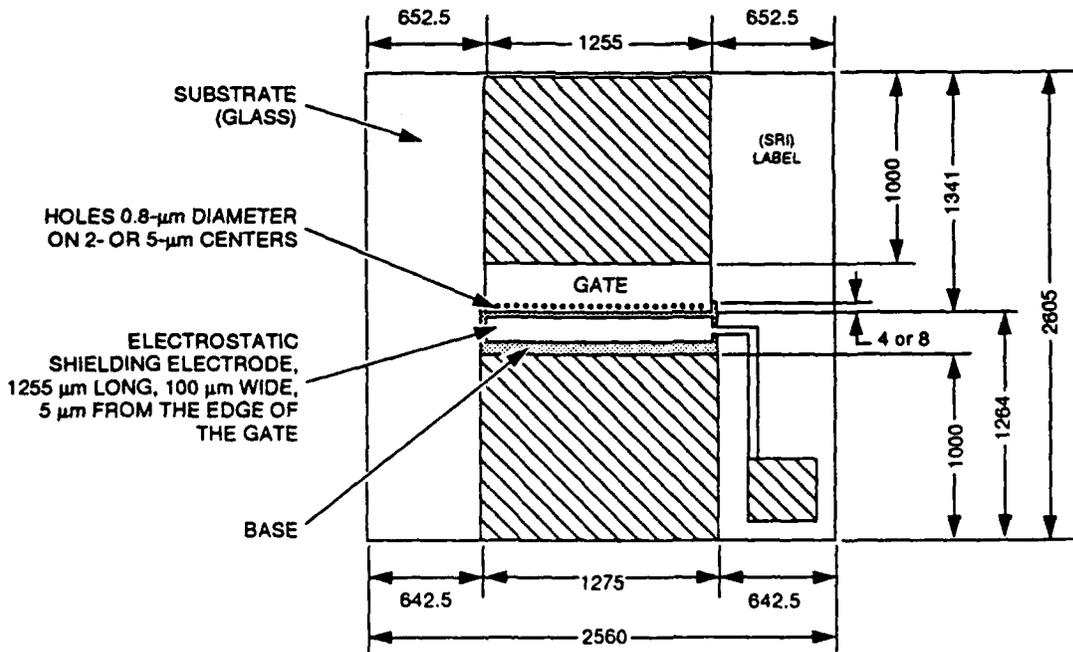


DRAWING NOT TO SCALE

DIMENSIONS: OXIDE = 1 μm THICK
 GATE = 0.3 μm THICK
 BASE = 0.3 μm THICK
 ELECTROSTATIC SHIELD = 0.3 μm THICK, 100 μm WIDE, 5 μm FROM THE GATE

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Figure 5. Cross section of the low-capacitance cathode showing the location of the electrostatic shield



Dimensions in micrometers

Au CONTACT PAD

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Figure 6. Layout of the low-capacitance cathode with a base shield

cathode at temperatures as high as 900 K, or at liquid nitrogen temperature, and has a provision for plasma-treating the surfaces and deposition of material onto the cathodes *in situ*.

The first experiments with cathode processing involved plasma cleaning with hydrogen. A cathode was mounted in the system, baked at 250 °C overnight, and tested to produce Fowler/Nordheim data at a base pressure of 5×10^{-11} torr. The cathode was then exposed to a dose of $\approx 1 \times 10^{18}$ hydrogen ions/cm² from a 300-V, 5×10^{-1} torr plasma in 2.5 minutes. The emitter tips and gate film were connected and formed the cathode in the dc plasma. The anode was approximately 1 cm from the cathode.

After the plasma treatment, the hydrogen was pumped out of the system, and the cathode was again operated to gather Fowler/Nordheim data. The results of measurements made before and after the treatment are shown in Figure 7. Examination of the data shows that an increase in emission current of between one and two orders of magnitude was achieved with an apparent decrease in work function of 1.1 eV as the result of the hydrogen plasma cleaning. In addition, observations of the emission patterns on a phosphor screen showed qualitative improvements in the emission uniformity from the array as the result of the treatment. However, the resolution of the apparatus is not sufficient to obtain quantitative data on uniformity.

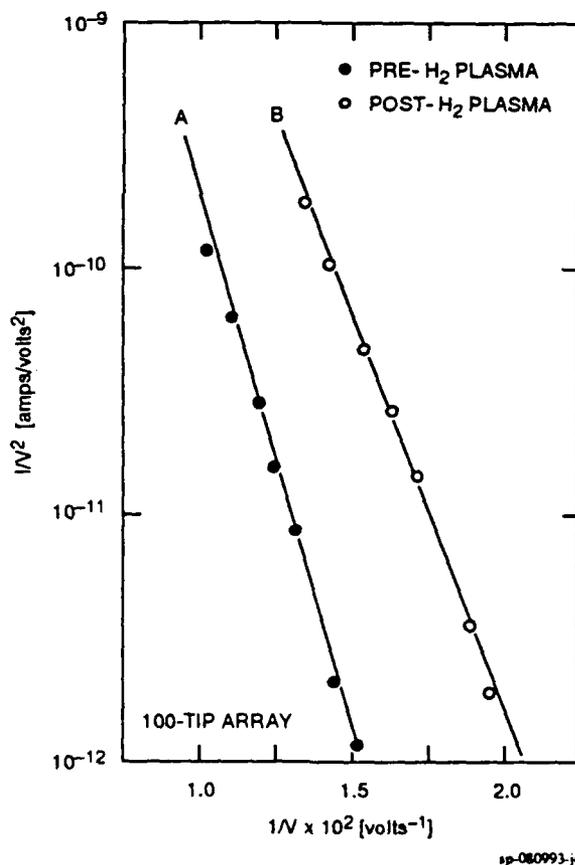


Figure 7. The effect of hydrogen plasma treatment on a 100-tip array. Line A: Fowler-Nordheim data prior to hydrogen plasma treatment, and Line B: Fowler-Nordheim data following hydrogen plasma treatment (dose = 10^{18} ions/cm²). The apparent work function decrease is 1.1 eV.

The emission was stable after the plasma treatment, and unchanged after 100 hours of operation in a vacuum of $\approx 3 \times 10^{-11}$ torr. This is interesting in light of earlier work showing that the emission drifted back to some value between the values before and after plasma treatment when the base pressure was $\approx 3 \times 10^{-9}$ torr. This is further evidence that the emitter arrays tend to come to equilibrium with their operating environment, and once the surfaces are cleaned the environment plays an important role in performance.

4. HIGH-FREQUENCY MEASUREMENTS

No additional high-frequency measurements were made, because we concentrated our efforts on elimination of the contamination problem. However, one group of four cathodes has been set up in the high-frequency chamber in an effort to gain some data on the effectiveness of the shielding electrode. Testing is planned for the next period.

5. WORK PLANNED

We will continue our work to eliminate the molybdenum contamination and to develop a cathode configuration that does not draw excessive gate current due to fringing base fields.