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PULSED HIGH-CURRENT ELECTRON SOURCE

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MASTER

I Introduction

Advanced electron beam accelerators have a need for very high-current pulsed electron sources. The Spindt-type field-emission-cathode array, presently under development at SRI International, has been shown to have potential for providing an extremely high current pulse source of electrons. The cathode consists of an array of miniature field emitter tips with a field-forming counter electrode as an integral part of the structure. Because the dimensions of the structure are in the micron and submicron range, only relatively small voltages are required to produce large field emission currents. In addition, the fabrication technology is very similar to that used for integrated circuit fabrication, and lends itself to adaptation to very high tip packing density (e.g. of the order of 1×10^7 tips/cm^2), and to fabrication in arrays covering areas up to about 10-cm in diameter. Furthermore, tests have shown that the emitter arrays are capable of producing cold emission that averages tens or hundreds of microamps per tip over arrays containing several hundred emitter tips. Thus, it may be possible to develop a 10-cm diameter cathode array with 10^7 tips/cm^2, or a total of about 7.8×10^8 emitter tips, and giving currents in the range of 15 kiloamps with an average tip loading of 20-µA/tip.

II Objective

The objective of this investigation was to investigate ways to realize the cathode's potential as a source for high power pulse operation. The questions that needed to be studied were those of large area coverage, maximum emission that the cathode arrays are capable of producing practically, uniformity of emission over large areas, and the ability to operate with high voltage anodes.

III Large Area Arrays

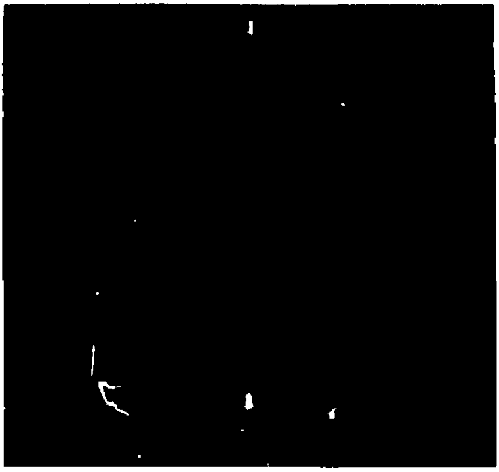
The development of the apparatus required for fabricating cathode arrays over areas much larger than about 1.2-cm square was beyond the scope of this program, however a parallel program in the Physical Electronics Laboratory to develop a flat-panel cathodoluminescent display coincidentally had a requirement for building apparatus to fabricate arrays of matrix addressable emitter tips over a 8.9-cm square area (5-inch diagonal). A phosphor placed 100µm from the cathodes was used to check uniformity of emission from the array by turning on 8.9-cm long by 180-µm wide rows of emitters and observing the emission pattern on the phosphor. The result was that the pattern formed on the phosphor was very uniform in brightness along the entire length of the 8.9-cm long lines showing that the uniformity of emission along the cathode strip was within a few percent. This is an indication that it is possible to form reasonably uniform emitter arrays over an area 5-inches in diameter, however, making a single array covering an area 5-inches in diameter without a short or other disabling fault has not yet been attempted.

IV High Current Density Tests

The potential for very high current density emission is one of the most exciting features of the field-emitter cathode array approach. In exploring the limits of cathode performance we have found that current density is not usually the limiting factor, but rather the total current, or power input to the anode, seems to be the parameter that limits performance.

For example, one of the more common emitter array configurations consists of 10,000 emitters in an array 1-mm in diameter. Cathodes of this kind have been operated up to 100 mA peak emission using a 60-Hz half wave rectified pulse drive on the cathode and an anode or collector biased to +1000 V. The apparatus used to test the cathodes was not designed to operate at high power loadings, so it was necessary to operate at a reduced duty cycle in order to achieve these emission levels. A counting/gating circuit was used to gate the pulses driving the cathode so that the duty cycle was reduced to 2% when operating at 100 mA. The anodes were heated to about 600°C under these conditions, and this has been a limiting factor in investigating high current emission from the cathodes. The current density from the 1-mm diameter cathode operating at 100 mA is about 13-A/cm^2. This is a respectable value, however much higher current densities are expected with this kind of cathode. Demonstrating higher current densities required either an anode system capable of handling higher power input, or simply fabricating cathodes with smaller emitter areas so that higher current densities could be achieved without increasing the power input to the anode.

Because designing and building anode systems capable of handling much higher power without risking occasional electrical breakdown was known to be difficult, the decision was made to investigate high current density operation by fabricating cathodes with smaller emitter areas. The results showed that the power handling capability of the collector system had indeed been a factor in limiting the current density that we were able to demonstrate, and the cathodes were capable of producing current densities of several hundred A/cm^2. Figure 1 is an oscillograph showing the voltage-current relationship for a cathode having 1500 tips in an area 125-µm in diameter. The peak emission current is 13 mA which corresponds to 100 A/cm^2. It is worth noting that the peak gate current is only 8 µm, so the peak power dissipated in the cathode is only 1 mW. It is also interesting that the sense of the gate current is such that there is a net flow of electrons away from the gate. One would expect electrons to



43D-170-2K

0.02 Ω-cm substrate

Horizontal: 50 V/cm

Top trace: 2 mA/cm emission current

Bottom trace: 20 µA/cm gate current

Collector bias: 1200 V

Cathode drive: 60 Hz, half-wave rectified

Cathode area: 125 µm diameter ($1.23 \times 10^{-4} cm^2$)

Number of tips ≈ 1500

Peak current 13 mA

Peak current density = 100 A/cm^2

Figure 1: Oscillograph showing high current density and high current emission.

be flowing to the gate in this kind of structure. The magnitude and sources of gate current can be important, and this is discussed further in the next section.

Figure 2 is an extreme example of what may eventually be possible when we learn how to process our electrodes to handle high power loads. An oscillograph of the voltage-current relationship for a 16-tip array covering an area 10-µm square is shown. The peak emission current of 1.45 mA is 1000 A/cm^2 averaged over the area occupied by the array. This is an average emission current of 90 µA per tip. The same average tip loading on an array with the same packing density but covering an area 1-mm in diameter would produce a peak current of 7.8 A, and with an active area 5 inches in diameter would produce about 125 kA if reasonably uniform emission can be produced over the whole area of the array. Emission uniformity is a very important concern and is one of the two major factors that will eventually determine whether or not the full potential or this cathode technology will be realized. The other is the susceptibility to damage from arcs in the system. These issues are also discussed in later sections.

V Gate Current

The electric field at the surface of the cathode array must be kept at a high enough level to prevent space charge effects from causing emitted

44-234-2Q

0.02 Ω-cm substrate

Horizintal: 50 V/cm

Vertical: 0.2 mA/cm

Collector bias: 1200 V

Cathode drive: 60 Hz, half-wave rectified

Cathode area: $1.44 \times 10^{-6} cm^2$

Number of tips: 16

Peak current: 1.45 mA

Peak current density: ≈ 1000 A/cm^2

Figure 2: Oscillograph showing very high current density from a small array.

electrons to be intercepted by the gate structure. Intercepted current can cause heating, outgassing, and electrical breakdown between the base and gate structure of the cathode, and this usually results in a damaging arc. Figure 3 shows the effects of anode voltage on the gate current for a cathode operating at 5 mA peak emission. At low collector voltage there is a net flow of electrons to the gate [(-) current] due to space charge effects. As the collector voltage is increased, the gate current goes to zero, and then increases to a (+) current [net flow of electrons from the gate]. The positive current is due to reflected primaries from the collector hitting the gate structure and producing secondaries with a secondary emission ratio greater than one. The gate current resulting from reflected primaries is minimized in most of our work by the use of tube-like collector electrodes that have a Faraday cage effect. Most of the primary electrons impact on the inner walls of the tube in a relatively field-free region, and at an angle of incidence that is not conducive to reflection back to the cathode. However, a planar collector directly in front of the cathode will direct many more reflected primaries back to the cathode gate structure, and it is possible that these electrons bombarding the gate may cause desorption that might lead to local high pressure bursts and arcs. It is also evident from an inspection of the gate current that the measured value is the algebraic sum of several sources of current. These are: reflected primaries, secondary emission from the gate to the collector, intercepted emission from the emitter tips due to large angle emission or space charge effects, positive ions formed at the

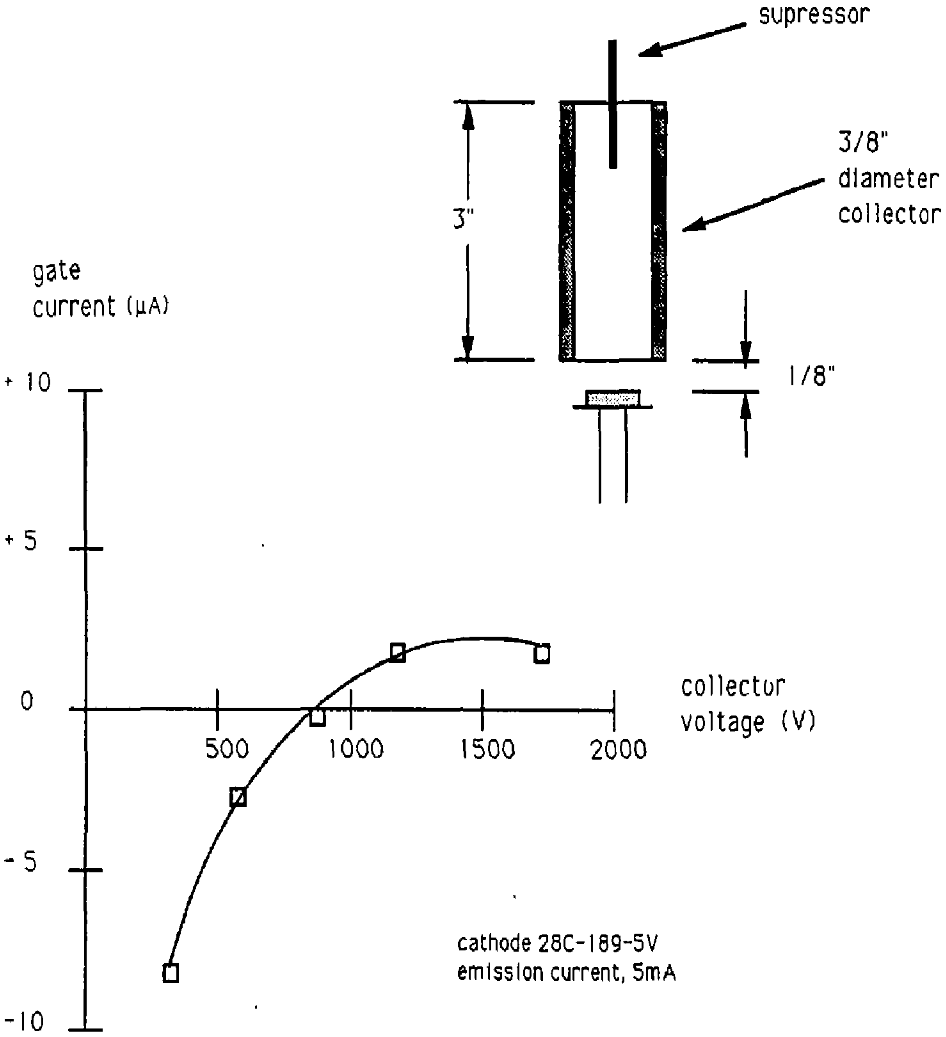


Figure 3. Gate current as a function of collector voltage on a stainless steel tube collector as shown. (-) gate current is a net flow of electrons to the gate, and (+) gate current is a net flow of electrons from the gate to the collector due to secondary electrons flowing from the gate.

anode, and electrical leakage across insulating surfaces or through the bulk. Thus, it is possible for there to be significant gate currents flowing, but for measurements to show little or no net gate current. Specifications on allowable gate current have not been determined for these reasons, however it is obviously good practice to take all reasonable measures to reduce the gate current as low as possible when operating the cathode.

VI Anode Materials and Geometry

The shape, processing, and materials of the anode structures used in testing the cathodes has been found to be very important. The best results to date have been obtained with carefully processed 304 stainless steel tubes of the kind described above. The configuration used most often has been 1/2-inch diameter tubes about 3-inches long. They are thoroughly cleaned chemically and hydrogen fired to 1100°C for 1/2 hour. They are then mounted in an ultra-high vacuum system and heated by electron bombardment to about 1000°C until no change in pressure can be seen on the 10^{-9} torr range when the voltage is turned off for a short time and then turned back on while monitoring the pressure in the chamber.

Cathode arrays are then mounted in the system on axis with the tubes so that the emitted electrons are directed into one end of the tubes and are collected along the inner walls over a large area, and for the most part in a field-free region (figure 3). The entire system is baked at 450^{o}C for about 48 hours and cooled before applying voltage to the cathodes or anodes. Because of the rigorous processing of the tube, there is very little outgassing of the collector during bakeout or operation of the cathode, and very few cathode failures occur up to the power levels at which the anode tubes are heated to incandescence and evaporate chrome from the stainless steel onto the cathode surface. At at these temperatures, the cathode is also heated by radiation from the anode, and sometimes is overheated to the extent that the gate film is cracked due to differential heating and expansion. This usually liberates gas and leads to an electrical breakdown. Obviously, these are extreme circumstances and are usually avoided by limiting the power input to the collector with reduced duty cycle operation, anode cooling, etc.

In general, anode cooling has not been as successful in preventing arcing and damage to the cathodes as one would expect. In particular, we found that high purity copper outgassed by electron bombardment at about 900^{o}C, and water cooled during operation with the cathode arrays, produced more failures due to arcing than the radiation cooled stainless steel collector tubes described earlier. This has been rather disappointing, but not entirely surprising after discussing materials problems with tube manufactures. Copper is a very reactive material, and apparently must be cleaned carefully after each exposure to air to assure best performance. A simple 450^{o}C bake as we had been doing (except for the first cycle when the anodes were heated to $1000^{\circ}C$) apparently is not adequate with copper, but seems to be good enough with the stainless steel anodes. As a result of these experiences we have been using stainless steel anodes processed as described above in most of our tests.

VII High-Resistivity-Silicon Based Emitter Arrays For Uniformity

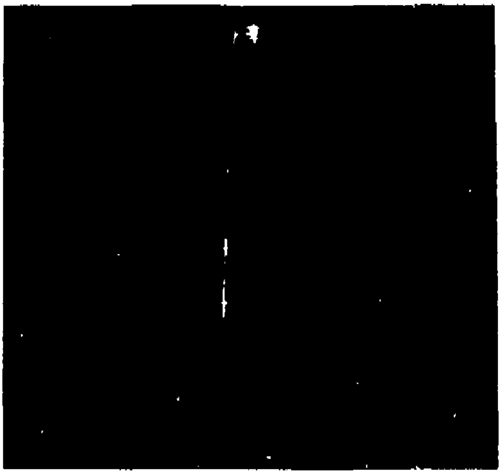
Although many cathodes have been operated at current densities of several hundred amps per square centimeter without damage, it is certain that there have also been many failures due to breakdowns initiated by the cathode. It is also clear that achieving very good uniformity of emission over large areas is difficult even when excellent geometric uniformity has been achieved. This is because the emission process is heavily dependent on the work function of the emitter surface as well as the geometry of the structure, and adsorbates can change the work function significantly. Thus, unless a means of positively cleaning the emitter tips in situ over the entire array can be perfected, it is likely that there will be nonuniformities in the emission over a large array. This will be especially true during early stages of emission and in environments that are less than ultra high vacuum.

An interesting method of improving the uniformity of emission over a large area array is to build the cathode array with a resistor in series with each emitter tip. Then the tips that tended to produce more emission than others would be inhibited by a voltage drop across the series resistor that would have the effect of reducing the voltage applied to that particular tip. Then the tips that are producing less current will have more voltage applied to them than the tips that are more active, and this will tend to make the emission intensity more uniform from tip to tip in the array.

As a test of this principle, several cathode arrays were fabricated on a 300 Ω-cm silicon substrate and tested for emission properties. As expected, there was an obvious buffering effect on the emission due to the IxR voltage drop in the substrate. When a Fowler-Nordheim plot of the voltage/current data was made there was a clear departure from the usual straight line at higher emission levels indicating a significant voltage drop in the silicon substrate.

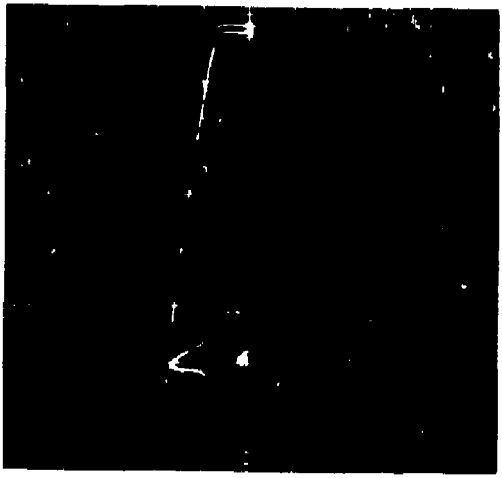
There was also a reduction in the failure rate and the intensity of the damage done locally when an emitter arced to the gate film. Indeed, many cathodes formed on high resistivity silicon performed well at high emission levels without suffering any emitter tip damage at all, including one 10,000 tip array (28E-239-2B) that was operated at 100 mA. On the other hand, there was no change in the devastating effect of an arc to or from the anode as a result of using the high resistivity substrates.

Figures 4, 5, and 6 are oscillographs of the voltage/current relationship



28C-185-2G

0.02 Ω-cm silicon



28E-215-4W

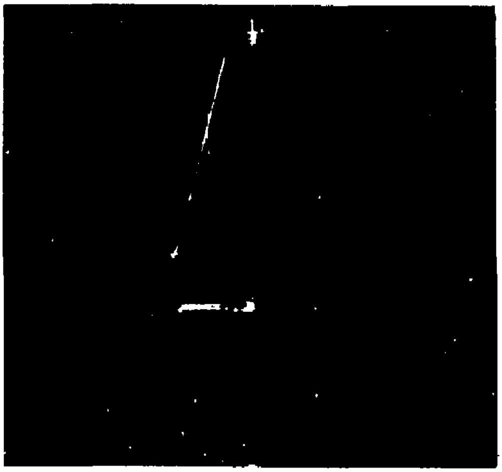
300 Ω-cm silicon

Horizontal: 50 V/div; Vertical: 2 mA/div

Figure 4: Oscillographs showing I-V curves for high and low resistivity silicon bases.

of high resistivity silicon cathodes under various conditions. Figure 4 shows voltage/current curves for two cathodes. One (28C-185-2G) was fabricated on the standard low resistivity silicon (about 0.02 Ω-cm). The other (28E-215-4W) is on about 300 Ω-cm silicon. Both cathodes had been enhanced by the thermal field forming process, and as a result, operated at very low voltages. This has the effect of accentuating the influence of the high resistance substrate because a small ΔV produces as relatively large ΔI. Inspection of the two curves shows that they both turned on at very nearly the same voltage, but the cathode with the high resistance substrate required about twice as much voltage to produce 10 mA of emission as did the low resistance cathode. This is, of course, because of the IxR voltage drop across the high resistance substrate.

Figure 5 shows cathode 28E-215-4W driven to higher levels of peak emission so that space charge effects in the interelectrode region come into play. A clear saturation effect is shown by the decrease in the slope of the emission curve near the peak emission point, and the very sudden and steep increase in gate current at the point where the saturation in the emission first becomes apparent. Obviously this will have to be compensated for in order to drive the cathode to higher levels of emission, because excessive current to the gate electrode will result in overheating of the cathode and eventual breakdown. The remedy is to simply apply a higher electric field to the surface of the cathode by moving the anode closer or increasing the voltage on the anode.



28E-215-4W

≈300 Ω-cm silicon substrate

Horizintal: 50 V/cm

Upper trace: 5 mA emission current

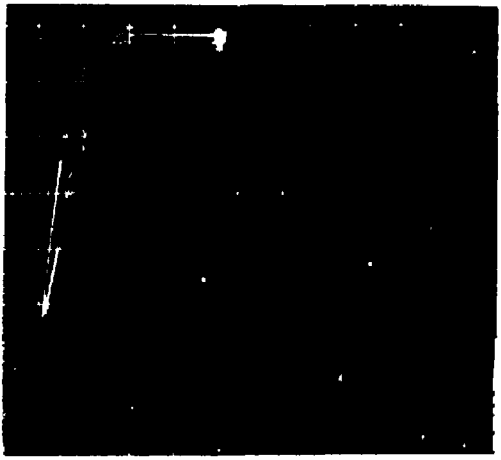
Lower trace: 0.1 mA/cm gate current

Collector bias: 1200 V

Figure 5: Oscillograph showing the effects of space charge at high emission levels. Thermally field formed cathode.

Figure 6 is a double photographic exposure combining the voltage/current curves for two high resistance cathodes fabricated together on the same wafer operating simultaneously in the same vacuum chamber, but under different temperature conditions. Silicon has a negative temperature coefficient of resistivity, and thus the effective series resistance in the base of the cathode will decrease with temperature. This could conceivably be turned into an advantage in the processing of the cathodes. During the first turn-on of a cathode, the cathode is relatively cool and the effective series resistance of the substrate would be large and protective of the emitter tips. Then, as the emission increases, and the tips have been cleaned and stabilized by desorption, it would be safe to warm the cathode and reduce the resistance. Then the cathode could be turned off and on with a reduced ΔV which would make switching easier to manage.

Figure 7 is a graph showing the emission current from a low resistivity substrate cathode and a high resistivity cathode plotted on a log scale versus the applied voltage on a V^{-1} scale. Normally such a plot will be nearly a straight line as shown by cathode 28C1-189-7H in accordance with the well known Fowler-Nordheim theory. However, the high resistivity cathode, 28E-239-2B, exhibits a distinct departure from the projected (dotted) straight line as a result of a significant voltage drop in the silicon substrate.



28E-239-5H (cold)
28E-239-5B (430°C)

≈300 Ω-cm silicon substrates

Horizontal: 20 V/div

Vertical: 2 mA/div

Collector bias: 1200 V

Figure 6: Oscillograph showing the effect of temperature on the cathode emission due to the negative TCR of the silicon substrate.

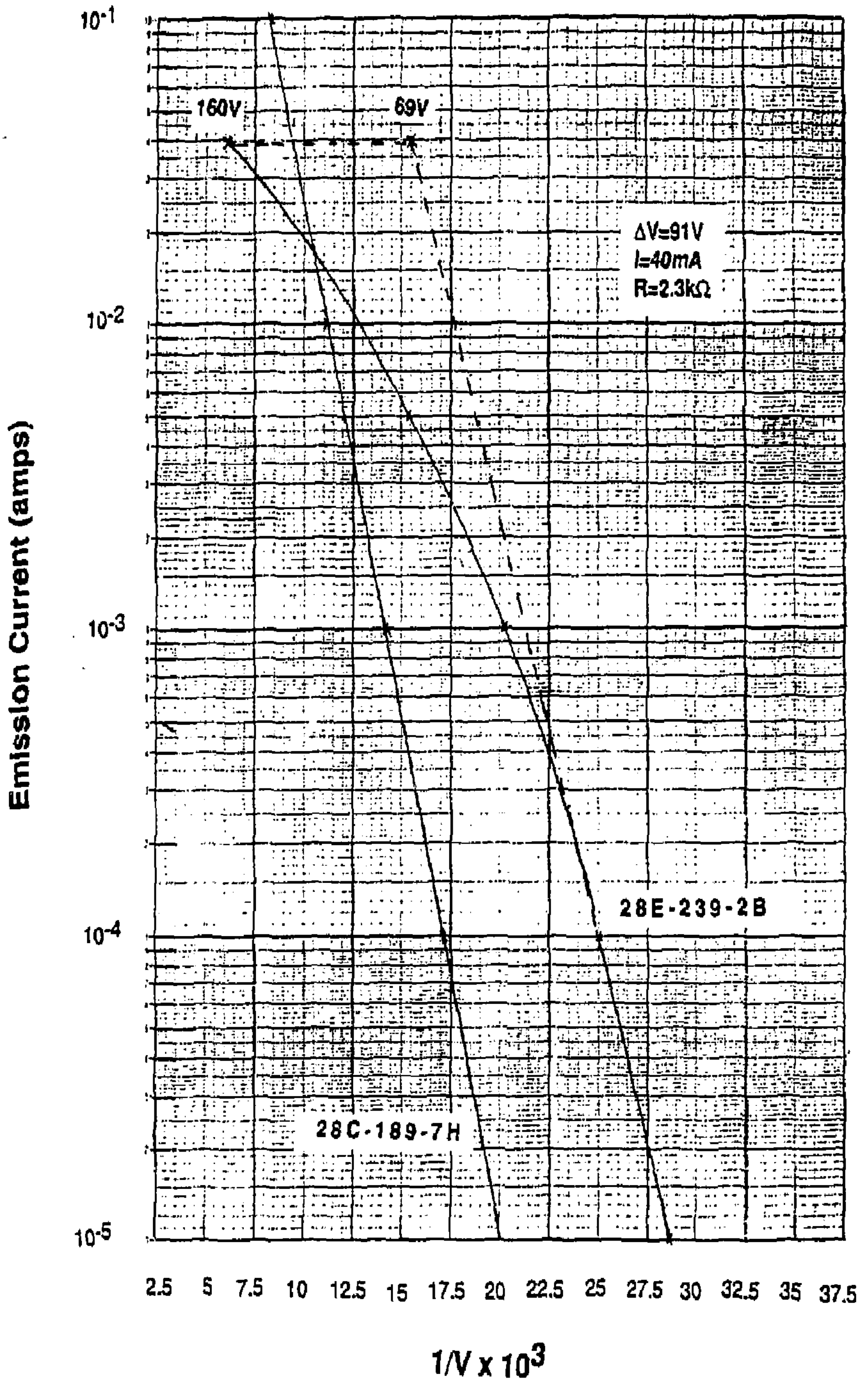


Figure 7: I/V vs I for cathode 28E-239-2B after parital thermal field forming. Effective total series R is about 2.3 kΩ. Cathode 28C1-189-7H on low resistivity silicon is shown for comparison.

The resistance is distributed throughout the substrate, and the effective resistance seen by an individual tips in the emitter array cannot be calculated simply, However, the voltage drop in the substrate can be measured by extrapolating the straight line portion of the curve from the low emission levels and noting the ΔV at a given high emission level. This is shown at the 40 mA level on the curve for cathode 28E-239-2B on figure 7. From the graph, the effective substrate resistance is calculated to be 2275 Ω for the entire 10,000 tip array covering an area 1-mm in diameter. Assuming a homogeneous substrate, and the resistivity of the material to be 300 Ω-cm at the least, and 1000 Ω-cm at the most (manufacture's specifications), the resistance of a 1-mm diameter area in the 275 μm thick substrate would be between 1050 and 3500 Ω which fits very well with the measured value. The effective resistance in series with each tip can be estimated by taking an average current per tip and dividing that into the voltage drop across the substrate. In this case, we have 40 mA from 10,000 emitter tips or an average of 4 μA per tip. Then the effective average resistance in series with each tip is the 91 V drop divided by 4 μA or about 22.5 mΩ. This should be sufficient to provide a significant amount of buffering resistance for the tips.

VIII Apparatus for High Voltage and High Total Emission Current Operation

Arcing from high voltage collector electrodes to the cathode structure has been a major problem when attempting to achieve high total emission current levels from the cathode arrays. Following a suggestion by Dr. Herrmannsfeldt of SLAC, an experimental diode arrangement was constructed as shown in figure 8. The idea behind the design is to provide a large electrostatic field at the surface of the cathode array without having to deal with the problems associated with high electric fields and local outgassing at the anode due to electron stimulated desorption. Our experience has been that electrical breakdown is very common under such conditions, and the cathode is invariably damaged when an arc to the anode occurs. With 10 kV on the collector, and an axial magnetic field of 1 kilogauss the trajectories should be as shown in figure 9, which is a computer simulation generated at LLNL. Under the conditions shown, the emitted electrons are accelerated toward the anode by the electrostatic field, but are turned by the action of the magnetic field so that they do not impact the anode until they are in an area that is under relatively low electrostatic stress. In addition, any positive ions formed at the anode surface cannot find their way back to the field emitter surface. The anode was also water cooled to prevent overheating and outgassing under heavy electron bombardment. The cathode mounting structure was built to accommodate four cathodes so that it would be possible to make at least four trials on each pump down of the tube. The cathodes were

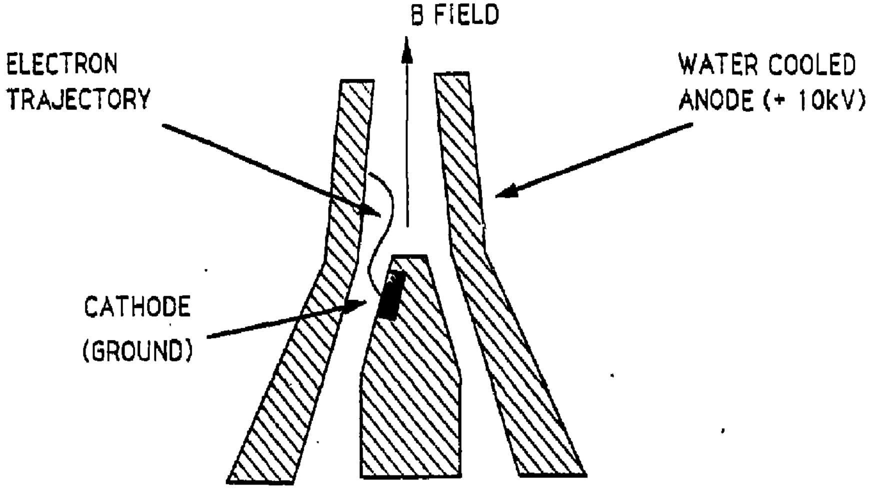


Figure 8: Schematic of the high voltage test apparatus with axial magnetic field.

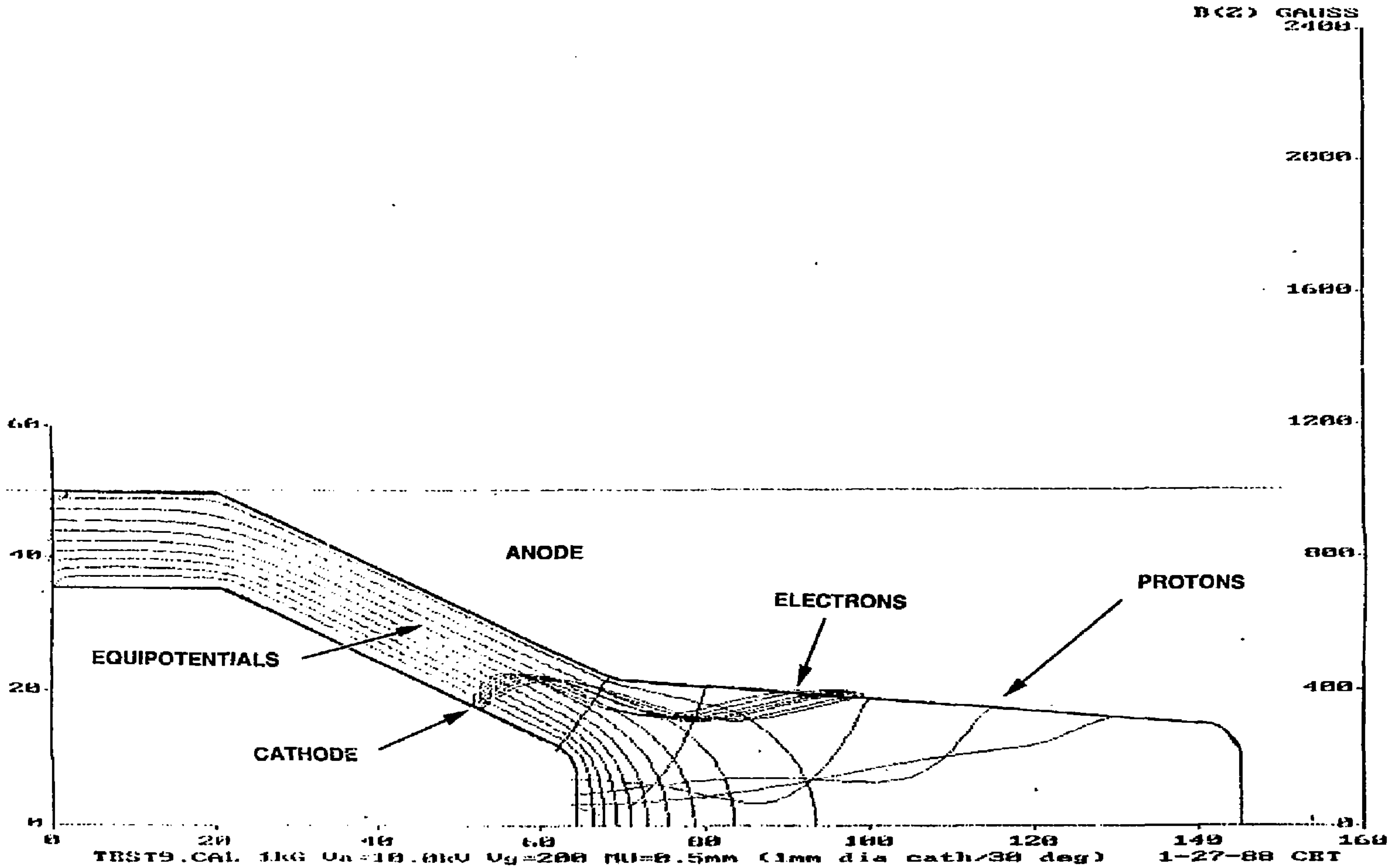


Figure 9: Computer model of trajectories in the experimental tube.

demountable so that the tube could be opened and the cathodes replaced as necessary. The tube was as shown in figure 10, and was dimensioned to fit into a typical SLAC solenoid. The cathodes were first tested by connecting the tube to an ion pumped chamber at SRI via a copper pinch-off tube, evacuating and baking the tube at 450^{0}C, and turning the ion pump on. The cathodes were then brought up to a few hundred microamps with a 60 Hz pulse drive and 500 V on the anode to assure that they were operating properly. The cathodes were then turned off, and the anode was "spot knocked" by slowly applying voltage up to a level of 13 kV with a low current power supply. Several low energy arcs were noted, but after about an hour at 13 kV the tube appeared to be stable. The cathodes were then turned back on with 500 V on the anode to test for any damage that might have occurred during the spot knocking. All four cathodes appeared to be unaffected by the arcs and were operating just as they had been before the spot knocking procedure.

The tube was pinched off from the vacuum chamber while monitoring the pressure in the ion pump to assure that a successful seal was made. The ion pump was then turned off, and the tube was taken to SLAC and installed in a solenoid. A high current, 10 kV power supply was connected to the anode, the solenoid was turned on and set to 1 kilogauss, and the anode voltage was slowly increased. At about 8.5 kV there was an arc that damaged the power supply and all four cathodes. The cathodes were not operating at the time of the arc.

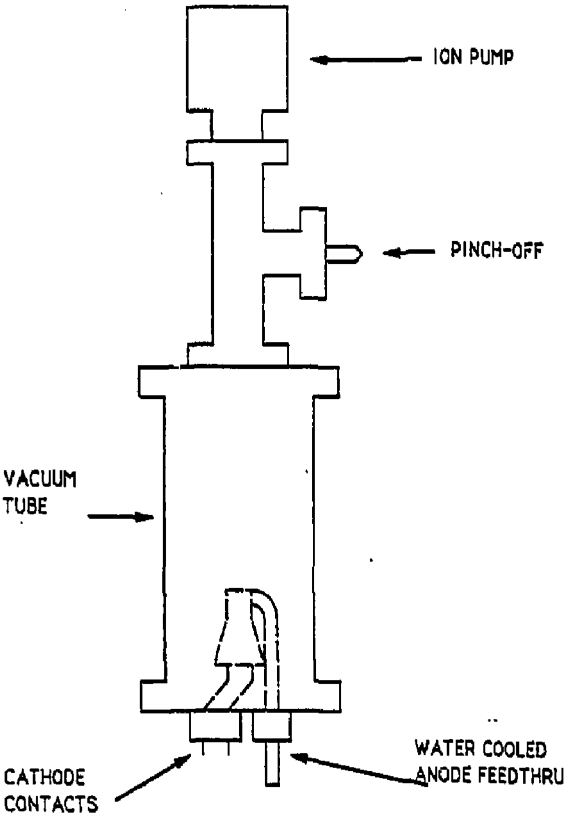


FIGURE 10: VACUUM TUBE FOR HIGH VOLTAGE TESTS IN THE SLAC SOLENOID.

The tube was taken back to SRI, opened, and the cathodes removed for inspection. All had severe arc damage that extended well into the silicon substrate. No damage could be seen on the anode structure, however it was not possible to examine the anode surface with the same optical magnification as was used on the cathodes because of the geometry of the structure.

The power supply was repaired and tested successfully to 10 kV with no load. The cathodes were then replaced and the tube was evacuated and spot knocked in the same way as had been done for the first test. Again the cathodes behaved well at low anode voltage without the magnetic field, and the tube was pinched off, taken back to SLAC, and installed in the solenoid. The cathodes were checked for emission and found to be operating normally, producing 0.5 mA with about 100 V applied to the cathodes and 800 V on the anode. They were then turned off, and the B field was increased to 1 kilogauss. Voltage was then applied to the anode slowly. At about 4 kV there was an arc that was nondamaging to the power supply. The decision was taken to try to operate at 8 kV in view of the previous devastating at 8.5 kV, and the lesser momentary breakdown and 4 kV. The 8 kV level was reached successfully and the cathodes were again turned on with the usual 60 Hz pulse driver. One shorted with an audible snap with only 30 V applied to the gate. (Moments before it had operated stably at 0.5 mA with 100 V applied at the gate and 800 V on the anode). Two of the three remaining cathodes were slowly brought up to 0.5 mA and operated normally at that level. It was decided to keep the third remaining cathode turned off so that if another arc occurred there might still be the possibility of another try.

The emission current was slowly advanced while monitoring it carefully for any signs of instability. Both cathodes produced stable emission up to 0.8 mA. The drive voltage required was the same as it had been at low anode voltage. After five minutes at 0.8 mA, an arc occurred without warning and both cathodes shorted. Attempts to clear them were unsuccessful, and the experiment was terminated. The tube was returned to SRI, and the fourth cathode was turned on with the usual 60 Hz driving supply and 500 V on the anode, but of course, without a B Field. In this configuration the emitted electrons impact the anode directly in front of the cathode, and therefore it is important to keep the field stress as low as possible to minimize the chances for a breakdown. The emission was slowly increased while monitoring the gate current for any signs of effects due to space charge which could cause emitted electrons to return to the gate. The anode voltage was increased only as needed to minimize gate current. When the emission level reached 13 mA, the anode voltage required was 700 V. At this point the duty cycle was reduced to six 60-Hz pulses per second to avoid overheating the anode locally where the emission was concentrated due to the proximity of the cathode.

This procedure of periodically increasing the emission, and as necessary, the anode voltage, was continued until a level of 50 mA peak with a gate drive pulse of 132 V peak was reached. The emission was left at 50 mA, and the anode voltage was slowly increased while watching for any signs of instability. The increases in anode voltage had no effect on the level emission from the cathode up to 3 kV which was the limit of the power supply that was available for the experiment. The cathode was left at 50 mA with 3 kV on the anode while arrangements were made with LLNL to obtain a 10 kV power supply so that the anode voltage could be increased to higher levels. After five days of stable operation at 50 mA with 3 kV on the anode, the cathode shorted without warning.

The tube was opened, and the cathodes removed for inspection. The cathodes were numbered one through four according to their position in the tube. Number one had arced with only 30 V applied after the high voltage had been set at 8 kV with the B field on. Number two was not operated at 8 kV with the B field, but was operated for about a week at 50 mA peak (60 Hz) emission with up to 3 kV on the anode. Numbers three and four arced at 8 kV with the B field on in the test at SLAC. Three and four had very large craters blown into the silicon that extended well beyond the active area. There was no question that they both suffered a direct arc between the gate and anode. Cathode number one had two moderate craters and one small one in the gate film that resulted from an obviously much gentler arc to the anode. Cathode number two, which was operated at 50 mA for several days with 3 kV on the anode was quite different in appearance. There was one very small crater of the kind that were found in the other three cathodes, but most of the damage was confined to the gate film and was in the form of cracking and lifting from the silicon dioxide with some areas having melting of the gate film around the edges of the missing areas of gate film. The silicon dioxide was not damaged in these areas indicating that there must have been a discharge between the gate and the anode that damaged the gate film.

IX Summary

Cathode arrays having several hundred emitter tips have been shown to be capable of producing current densities of hundreds of A/cm^2 when working into anodes biased to one or two kV. Very small arrays (16 tips) have been shown to operate at 1000 A/cm^2. Very large area cathodes have been fabricated on a separate program, and this work has shown that it is possible to produce uniform emission over areas about 10 cm in diameter. Emitter arrays have also been fabricated on high resistivity silicon substrates, and tests have shown that the series resistance provided by the substrate greatly reduces the incidence of emitter tip breakdown. More work on this effect is needed to determine the optimum resistivity for a given cathode loading. These results are very encouraging, and show that the field emitter cathode array has promise as a very high current pulsed electron source. Tests intended to reproduce these results with larger area cathodes using water cooled anodes designed to handle high power levels were unsuccessful. Cathodes that tested well in experiments with l kV anodes failed at relatively low emission levels when tested in a high voltage environment. The failures were always sudden and catastrophic and usually without warning. Because the anode voltage was the only thing changed between successful and unsuccessful tests, electrical discharges due to the high voltages applied to the anode are suspected to be the source of the problem. Indeed, some cathodes were damaged before being turned on, by arcs that occurred as the anode voltage was applied. It appears that a study of electrode processing with a view toward preventing arcing would be helpful, and that if anode initiated arcing can be prevented then it may well be possible to realize the full potential of these cathode arrays.