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Field-emission electronic devices offer several advantages over conventional semiconductor devices. However, to operate at low voltages, the cathode of the device must be constructed of small needles that cannot be satisfactorily constructed by current techniques. This research investigated masking and etching techniques, and needles were produced with diameters smaller than the smallest produced by other methods.

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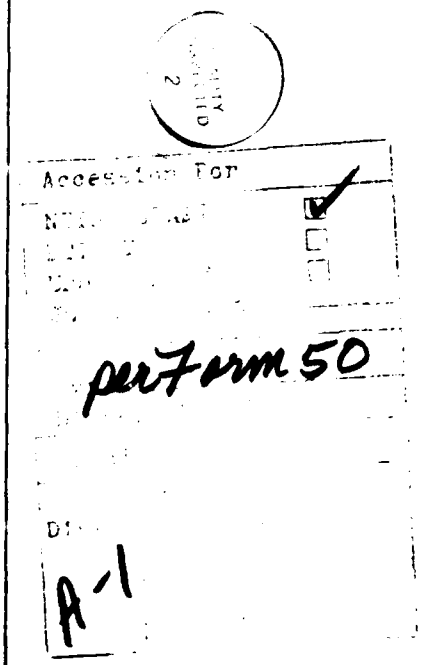
A field-emission electronic device was constructed by forming a cathode consisting of an array of submicron needles on a silicon substrate. The array was placed in close proximity to a silicon anode and tested for field emission. The needle array was formed by depositing masks of silver or polystyrene spheres with diameters less than 100 nm on a silicon substrate and etching the surface not protected by the masks with CF_4 in an RF reactive-ion etching chamber. Several methods of forming the masks and different etching times were explored and the results were documented with scanning electron microscope photographs. The resulting needles were less than 1 μ high and less than .1 μ in diameter, demonstrating that needles could be formed which were substantially smaller in diameter than those commonly produced by other techniques. Different methods were investigated for assembling the device to control the anode to cathode spacing and insulating the anode from the cathode. The devices were tested for field-emission using both ac and dc voltages across the device with potentials to 200 volts. No field-emission was observed. Possible reasons for the negative results are discussed as well as potential advantages and disadvantages of the use of RF reactive ion etching for forming field-emission needles.

Field-emission devices offer the potential of switching speed, insensitivity to high temperatures, and radiation hardness that cannot be obtained with semiconductor devices. Thus these devices address major problems inherent in current technology.



SUBMICRON ELECTRONIC DEVICE USING FIELD-EMISSION TIP

Final Report
SDIO SBIR
Contract # DASG60-87-C-0103

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January 3, 1989

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SUBMICRON ELECTRONIC DEVICE USING FIELD-EMISSION TIP

1. INTRODUCTION

Developers of electronic devices are continually striving for higher performance, and the modern day devices have provided capabilities only dreamed of a few years ago. However, still higher performance equipment is essential for applications in the military, communications, general computing, etc. There are difficult problems to be solved to increase the performance of solid state devices, and thus other technologies are being investigated. From the stand point of the physics involved, one of the most promising technologies is based on field emission.

The operation of the field-emission device is based on the fact that when a cathode is placed near an anode, electrons will under-go quantum mechanical tunneling from the cathode to the anode if the field strength at the cathode is large enough. Since the electrons emitted by the cathode transport through a vacuum, they are not affected by the properties of any materials as they travel from the cathode to the anode. In the case of semiconductor devices, the properties of the materials determine the performance of the device. Three of the major advantages of the field-emission device over conventional semiconductors are:

1. The switching time in the field-emission devices is very fast because the electron travels in free space between the anode and cathode. The transport is said to be ballistic. In the case of semiconductors the electrons generally collide with atoms during transport and are slowed down. The transport velocities may be greater by a factor of 10 or more in a field-emission device.

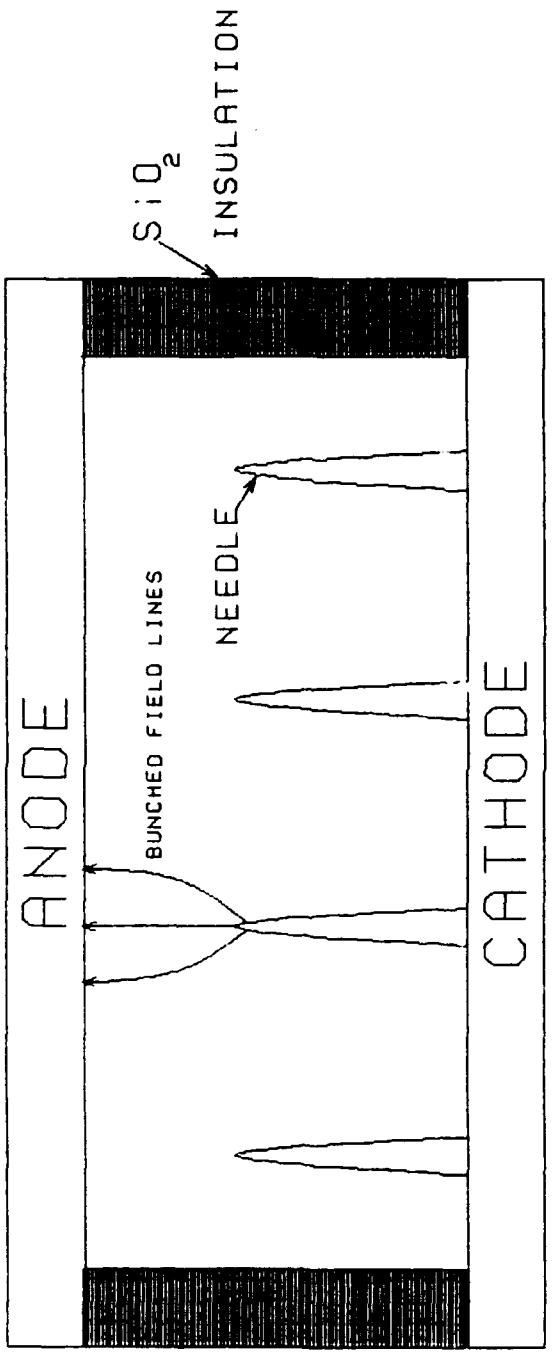
2. The field-emission process is nearly independent of temperature, whereas the current flow in a semiconductor device is a strong function of temperature and limits the operation to a few hundred degrees centigrade. Thus the field-emission device offers an important advantage for high temperature applications.

3. The field-emission device is extremely radiation resistant because the electron transport takes place in a vacuum with the anode and cathode providing conductive paths which are not significantly affected by lattice defects and impurities caused by radiation.

In this research the device studied consisted of a large number of needles forming a cathode placed in close proximity to the anode (see Fig. 1).

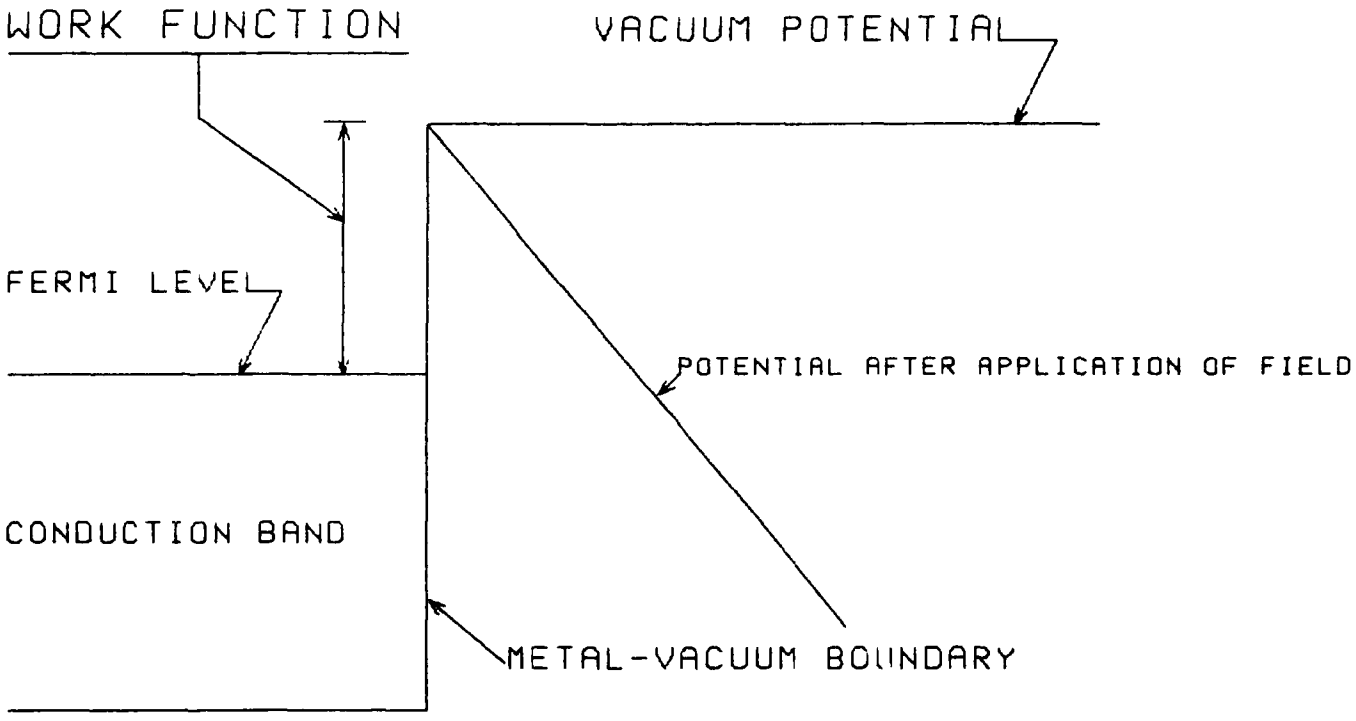
2. THEORY

The electrons in a metal can be described as filling the energy states contained in a potential well (see Fig. 2). The electrons fill the available energy states up to the maximum level known as the Fermi level, μ. The energy required to lift an electron from the Fermi level to the vacuum level, where it becomes a free electron and can leave the metal, is the work function, ϕ. It is not normally energetically possible for an electron to escape from the metal because the vacuum energy is greater than the Fermi energy and such an event would violate the conservation of energy. If, however, a strong electric field is applied, the vacuum energy is modified as shown. If sufficient energy is applied to reduce the potential outside of the metal to the Fermi level at a point 10 to 20 Å from the surface of the metal, then a significant number of electrons will under-go quantum mechanical tunneling



SCHEMATIC OF FIELD-EMISSION DEVICE

FIG. 1



ENERGY DIAGRAM OF METAL-VACUUM BOUNDARY WITH AN ELECTRIC FIELD

FIG 2

through the remaining barrier and escape from the metal. This is known as field emission.

The emission current density is described by the Fowler-Nordheim equation:

$$I=6.2\times10^{6}\{[\mu/\phi]^{1/2}/[\mu+\phi]\}E^{2}\exp[-6.8\times10^{7}\phi^{3/2}/E]\ A/cm^{2},$$

where ϕ and μ are given in eV. Fig. 3 is a plot of the current density as a function of field intensity at the emission surface, and shows that the field intensity must be in excess of 10^{7} volts per cm for significant emission to take place.

In order to obtain these high fields at the surface of the cathode with reasonable voltages between the anode and cathode, the anode to cathode distance is made very small, and the cathode is made like a needle to obtain field bunching at the tip. The closeness of the anode to the cathode causes an image charge to be induced in the anode, which further enhances the field at the surface of the cathode. Estimations show that with an anode-to-cathode spacing of 1μ and a cathode needle approximating a hyperbola of revolution with a ratio of height to diameter of 10:1, a field strength at the cathode of 3×10^{7} V/cm will be achieved with an anode to cathode voltage of 20 V (neglecting the enhancing effect of the image charge in the anode). (For details of this calculation see Ferrell.)

3. DEVICE CONSTRUCTION

A number of techniques have been used to construct field-emission devices in the past (for a brief review of some techniques see Technical Program of The First International Vacuum Microelectronics Conference). A typical device is shown in Fig. 4. Although these processes are able to make uniform arrays of structures, it is difficult to make structures small enough so that field emission will occur at less than several hundred volts between the anode and cathode. This increases the power used by the device and makes them impractical for replacement of low voltage solid state components. Recently, field emission was reported by Makhov (The First International Vacuum Microelectronics Conference) in the 30 volt range. The investigations described here utilize construction techniques which permit smaller needles to be made and closer anode to cathode spacing than with microlithography.

An n-type silicon wafer manufactured for the semiconductor industry was cut into pieces to make the anode and cathode. This wafer material was used for two reasons: 1) silicon substrates are highly polished and furnish a near perfect mechanical surface for the anode and for formation of the cathode structure, 2) since the needles which form the cathode structure are not uniform, the electron velocity saturation which takes place in the silicon will decrease the conductivity in any individual needle and permit needles with less optimal shapes to commence emission.

The method proposed in the original SBIR proposal was to etch the needles, using RF reactive-ion etching, in an SiO_2 layer evaporated on a substrate and then coat the needles formed with gold to provide conductivity. This method was subsequently reevaluated, and the methods described herein of etching the needles directly into a Si substrate appeared to be superior because of the simplicity and the ability to benefit from electron velocity saturation.

The basic method for producing the cathode was to form an etching (consisting of circular areas 1,0000 A or less in diameter) mask on the surface of the silicon and to use CF_4 as an etching gas in a reactive ion etch chamber. A plasma of CF_4 was formed between two parallel conducting plates in the

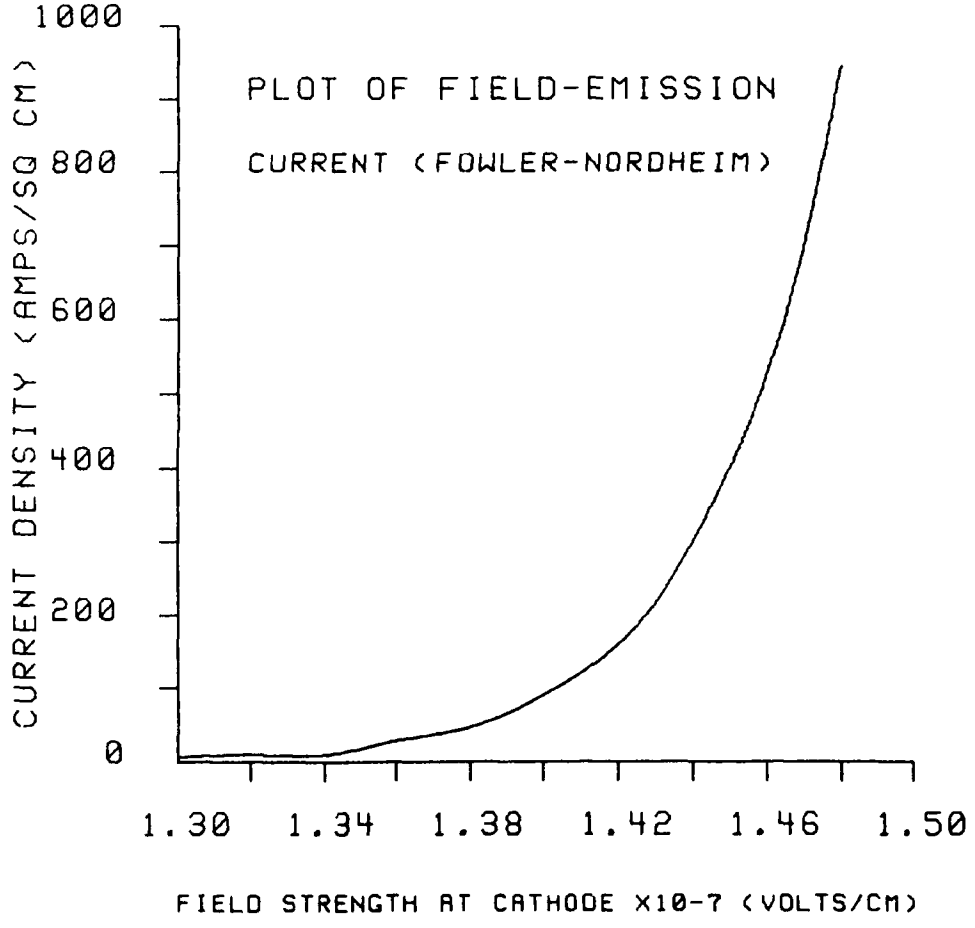
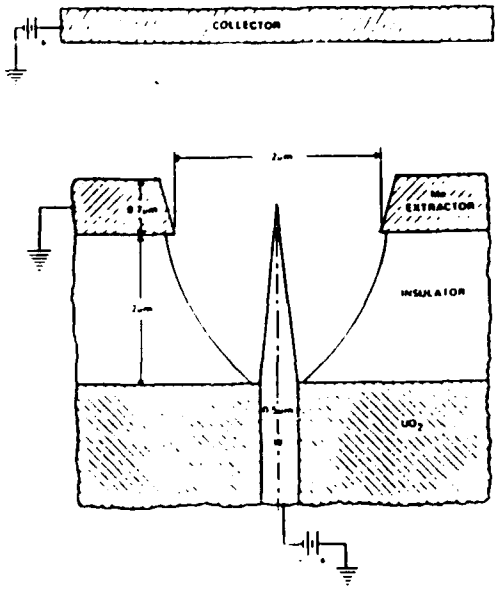
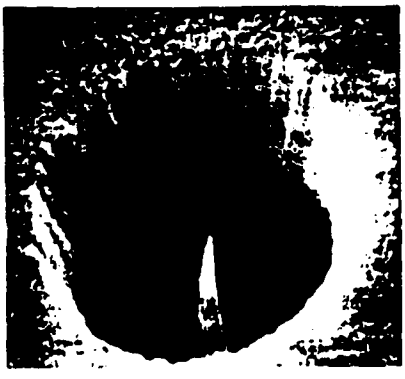

PLOT OF FIELD-EMISSION
CURRENT (FOWLER-NORDHEIM)
CURRENT DENSITY (AMPS/SQ CM)
1000
800
600
400
200
0
1.30
1.34
1.38
1.42
1.46
1.50
FIELD STRENGTH AT CATHODE X10-7 (VOLTS/CM)

FIG 3



(a)



(b)

TYPICAL FIELD-EMISSION DEVICE USING MICROLITHOGRAPHY

FIG. 4

chamber, and a 13 Mhz high-voltage field was applied between the plates. The gas ions followed the field excursions and bombarded the Si substrate placed in the lower horizontal electrode. Since motion of the ions was perpendicular to the surface, the area under each mask was protected, and the etching resulted in posts or needles being formed. The needles continued to increase in height until the mask was finally etched away, and the top of the needle began to etch away also.

A layer of SiO_2 was applied to either the anode or cathode at appropriate locations to provide an insulating separator when the two were sandwiched together to form the device.

4. CONSTRUCTION DETAILS OF CATHODE NEEDLE ARRAYS

The techniques described below were used to make the etch masks for forming the needle arrays.

A. Randomly Deposited Silver Masks. The first technique for generating the masks involved evaporating a 40 Å layer of silver onto the Si substrate, then heating the substrate for 1 min. at 300 °C. The heating caused the uniform silver film to break-up and form small globules or islands on the surface as shown in the scanning electron microscope (SEM) photograph in Fig. 5. Examination of the photograph reveals a random distribution of silver globules with diameters as small as 20 nm (200 Å).

The substrate was then placed in the RF etching chamber and etched for approximately 30 min. with results shown in Fig. 6. Needle diameters of 500 to 1,200 Å were common with maximum heights of 5,000 Å. Since the photograph was taken at an angle of 45° to the substrate, the needle height measured in the microphotograph must be multiplied by 1.4 to obtain the correct height. It is observed that the diameter of the needles varied widely, and that the smaller needles have been etched away from the top after the silver mask was eroded off.

The average spacing of the needles was judged to be too small. This would cause the field to be distributed between adjacent needles rather than concentrating on single needles placed farther apart. Furthermore, the ratio of the height of the needles to their diameter, H/D, was also judged to be too small. If the ratio is too small, field lines which would otherwise terminate on the tip of the needle and add to the field bunching will terminate on the floor of the substrate instead and increase the voltage required for field emission. It was judged that ratios well in excess of 10:1 are desirable with distances between the needles of at least the height of the needle (Gray).

Various etching times were tried throughout these investigations and the maximum ratios obtained neared 10:1. The results of these tests will not be discussed further, but the microphotographs show needles formed using the optimum selection of etching times.

B. Ordered Deposition of Silver Etch Masks.

In order to control the position of the Ag globules formed to produce the etch mask, a closed packed layer of .741 μ diam polystyrene spheres was first applied to the Si substrate. This was done by applying a few drops of a commercially available suspension of the spheres in water on the substrate and then spinning the substrate at 800 to 3,000 rpm, depending upon the size of the substrate, until the substrate was dry. The result was a very imperfect close packed layer of spheres. Although difficult to view because of the lack of detail in the copy, Fig. 7 shows a microphotograph of such a layer. It

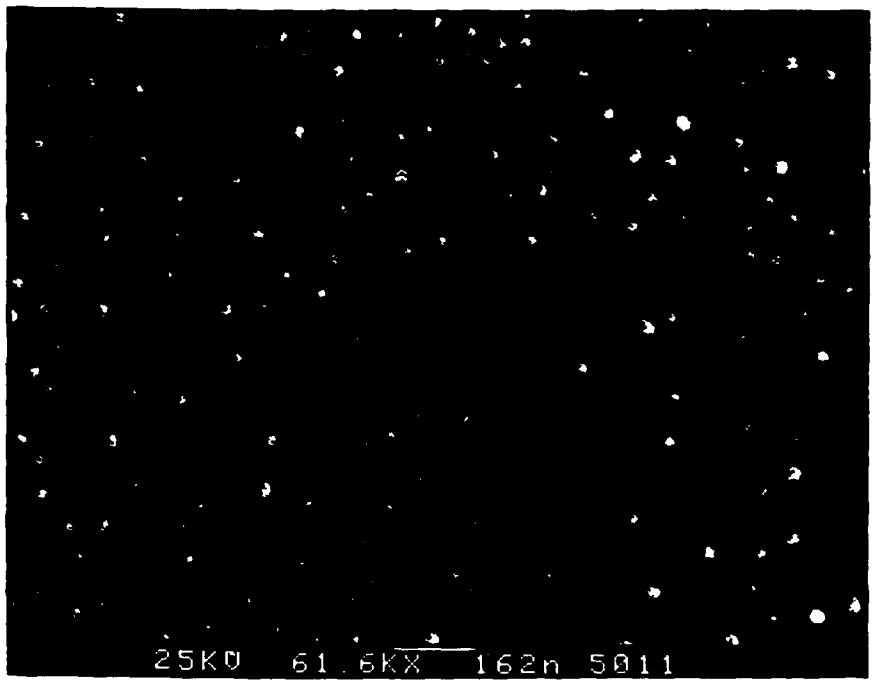


Figure 5. Silver islands.

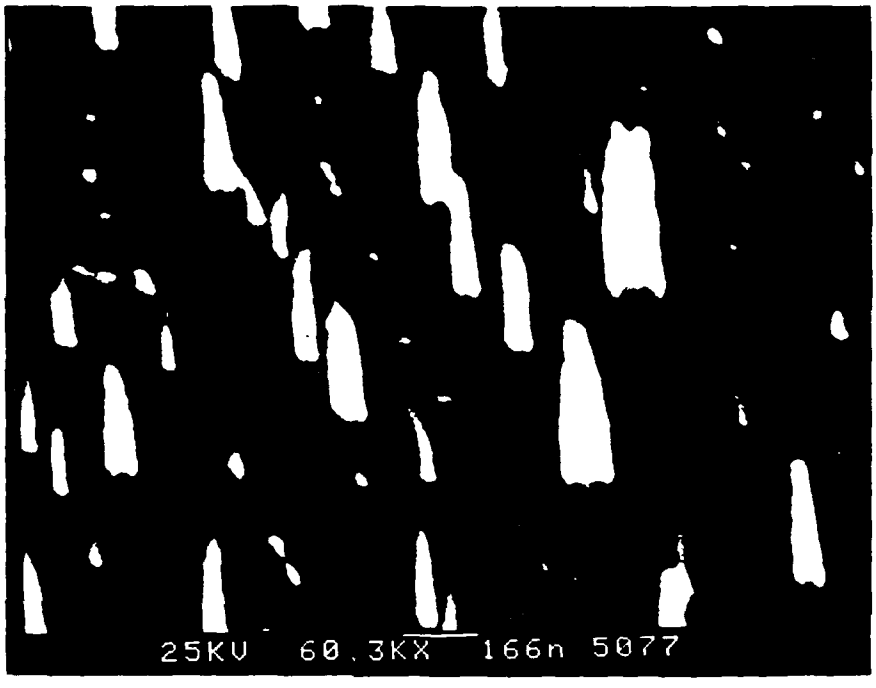


Figure 6. Needles from silver islands viewed at 45°.

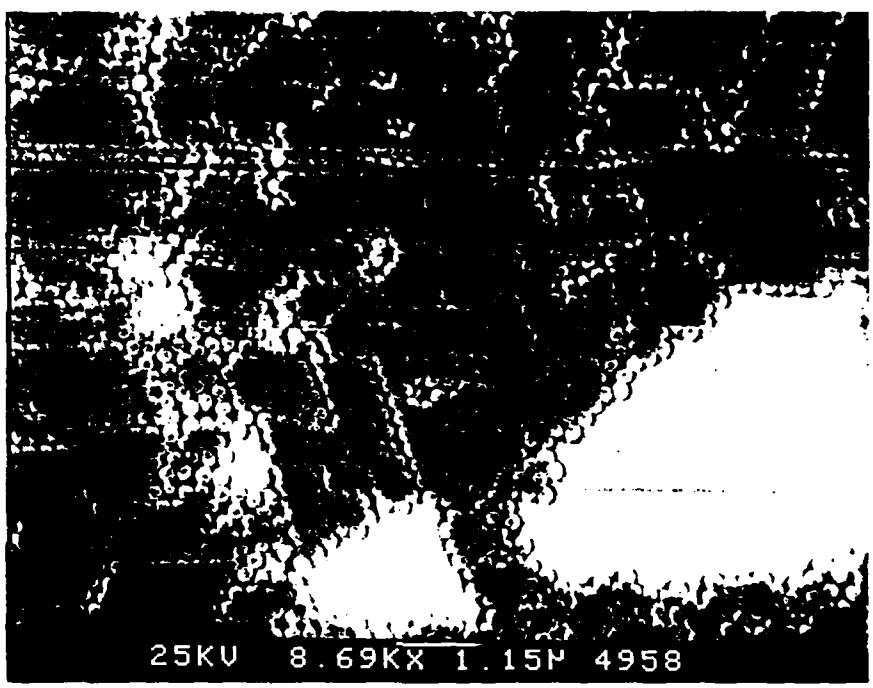


Figure 7. A close - packed monolayer of spheres.

will be noted that there are cell boundary defects, and large areas with no spheres. Not visible are areas of more than one layer of spheres. In the area of close packing each sphere is surrounded by six openings formed between the contact points of adjacent spheres.

The substrate was then placed in an evaporator and coated with 400 Å of silver. The spheres were dissolved away with methylene chloride, leaving an ordered pattern of silver which had been deposited through the holes between the spheres. This substrate was heated to form the silver into globules and then etched as before. The results are shown in Fig. 8. Examination reveals the ordered pattern with a unit cell of six needles. Needle formation was generally poor with low H/D ratios.

Extra large needles are seen which resulted from an excess of silver being deposited through defects in the packing of the spheres. In other areas where more than one layer of spheres existed, there are no needles. These defects can be ignored because only needles with optimum shape are expected to field emit. Large needles will not emit, nor should they interfere with the emission of other needles as long as they are not close by. Of course, areas devoid of needles will not interfere either. Aside from the poor H/D ratio, the needles were still closer together than desired. Larger spheres were available which would result in greater spacing between needles, but no attempt was made to try them because it appeared as though the needle shape degraded as the opening between the spheres increased. This was verified by comparing the superior needles formed with .241 μ diam spheres to those formed with the larger spheres.

C. Randomly Distributed Sphere Masks.

In order to deal with the problem that the silver masks were too large and too close together, substrates were made using polystyrene spheres as the masks. This was accomplished by spin coating a very dilute solution of .087 μ diam (870 Å) spheres on the substrate. The etching was then accomplished as before. Fig. 9 shows the result of this process, and it was judged that these needles were the best obtained. Many needles were far enough apart with shape and H/D equal to or better than the best ratios obtained in the other techniques. Larger H/D ratios were not obtainable because the spheres eroded away and the top of the needles began to etch as they did with silver masks.

5. ANODE-TO-CATHODE SEPARATION

The anode-to-cathode separation technique described in the original SBIR proposal was to coat the cathode needle array with PMMA (an electron resist) which was thicker than the height of the needles. The film would then be exposed at the location of each needle by placing an anode over the film and applying an ac voltage between the anode and cathode. The assumption was that sufficient energy would be deposited in the region of the needles to expose the PMMA and permit the film to be dissolved away in a small region around each needle. Thus each needle would be in a hole, open at the top, over which the anode could be placed with immunity from shorting. This method of exposure failed, and other separation techniques had to be devised. The following is a description of the techniques investigated.

A. Evaporated SiO_2 Film and Flexible Bridge Anode.

Since having anode to needle-tip separations of approximately 5,000 Å are desirable, cathodes approximately 1x2 cm were made, and a layer of SiO_2 was evaporated, to a thickness of 1 μ on each end in a band approximately 3 mm wide. An anode of comparable size was then placed so that it was supported at

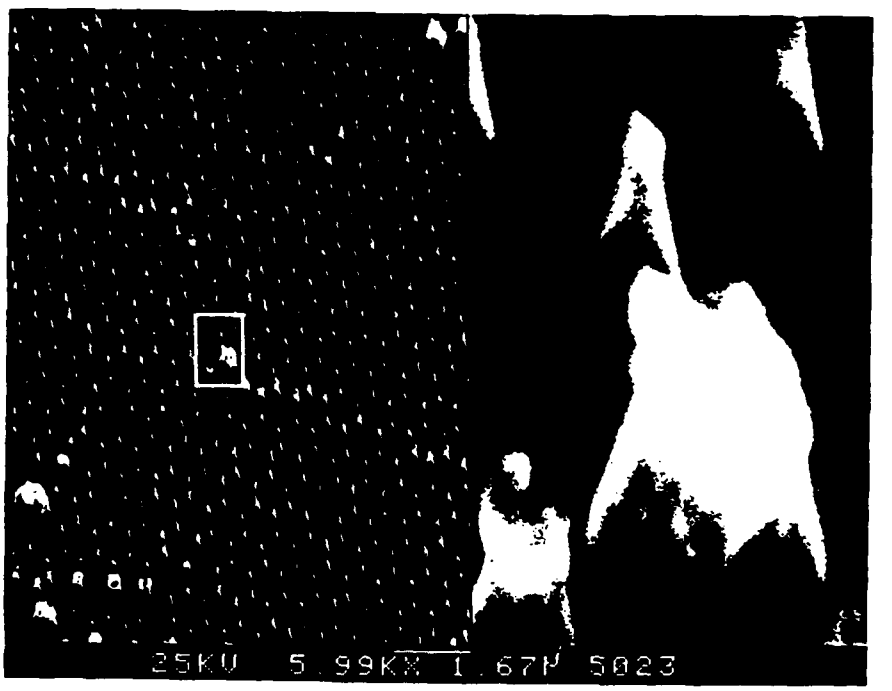


Figure 8. Needles from silver deposited between packed spheres viewed at 45°.

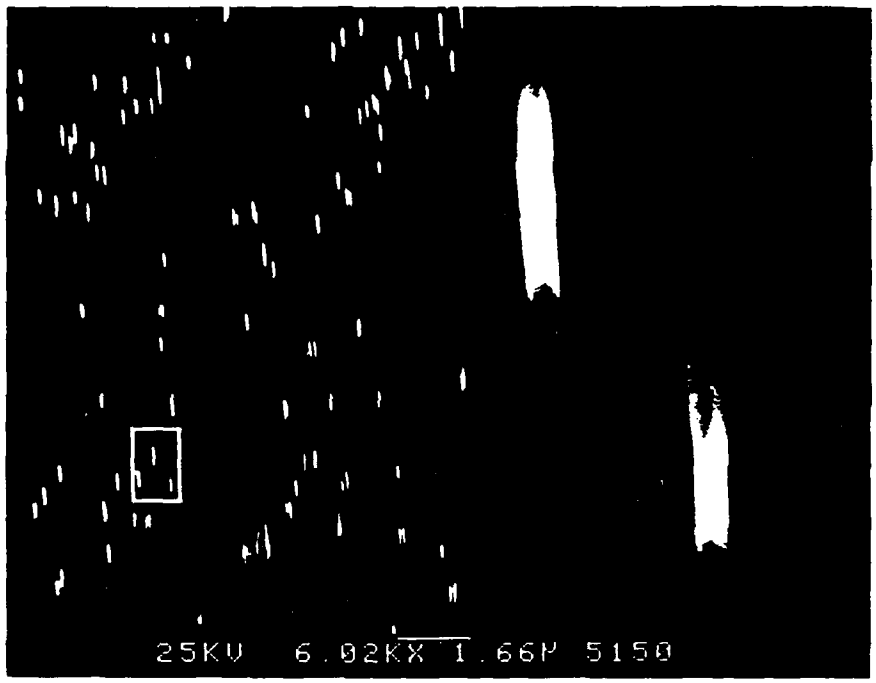


Figure 9. Needles from spheres viewed at 45 °.

each end on the SiO_2 layer, bridging the needle region between. Pressure was applied at the center of the anode using a limber spring attached to a micrometer advance screw. For each 10 μ advance of the screw the anode-to-cathode distance would be reduced by 1/1,000 of that amount, or 100 Å. This method was not adequately controllable, and no suitable way was devised to determine the actual minimum separation. Due to the large areas involved, random dirt particles larger than the desired separation could accumulate on one surface or the other, thus preventing adjustment of the separation.

A further problem with the evaporated SiO_2 layer was that the it flaked-off, indicating that there was an extremely large number of defects. These defects would provide channels for easy electron passage resulting in shorting of the cathode substrate to the anode.

B. Separation With Polystyrene Spheres.

In order to provide a well defined separation between the anode and cathode and to eliminate the problem of conduction through defects in the insulating SiO_2, a layer of .741 μ polystyrene spheres was sparsely coated on the cathode by applying a very dilute water solution of the spheres and spinning. Although this technique should have provided accurate separation provided that there was no dirt or piling-up of the spheres, it was not successful. Electrical break-down of the spheres resulting from the high fields created by the needle points may have been the cause of failure.

C. Air Oxidized SiO_2 Insulating Layer.

To avoid the defects and flaking common to evaporated SiO_2 layers, an air oxidized SiO_2 film was formed on the Si substrate. This was accomplished by heating the substrate on which the cathode was to be formed to 1100° C for 6 to 12 hours. The substrate was then masked on both sides with vinyl tape bearing a hole approximately 2 mm in diameter in the center. The SiO_2 was etched off in the region exposed by the hole with a 25% HF solution. If a silver mask was to be used, the substrate was coated with close packed polystyrene spheres and remasked with tape with a 1.5 mm hole concentric to the first mask. The reason for the smaller hole was to leave a gap between the needle array and the SiO_2 layer. Silver was then evaporated on the substrate and heated. A mask with a 2 mm hole was applied and the RF etching step completed. In the case where spheres were to be used as an etching mask, the spheres were applied and a mask with a 1.5 mm hole was applied before RF etching.

The air oxidized SiO_2 layer did not flake off, and optical microscopic examination revealed few visible defects. Three cycles of interference fringe bands were observed at the etch boundaries, indicating a SiO_2 film thickness of about 3,000 Å. Crude observation of the surface color changes as the oxide layer was slowly etched away also confirmed this conclusion.

6. PREPARATION OF ANODE

Silicon was chosen for the anode, as with the cathode, because it is easily obtainable with a very flat and smooth surface. However, it will develop an oxide coating with a thickness of about 20 Å in one day. Even a very thin layer of oxide will produce an insulating film which will collect the electrons emitted by the cathode needles as a surface charge. The voltage drop between this surface charge and the anode will reduce the field strength at the cathode needle tip. To eliminate this problem, the SiO_2 coating was etched from the surface of the silicon with HF, and it was immediately placed in an evaporator with one boat of chromium and another boat of gold. A layer

of chromium was first evaporated on the silicon to combine with the thin layer of SiO_2 which formed between the etching in HF and placement in the evaporation chamber. The chromium forms a conductive layer with the SiO_2 and provides a base to evaporate a gold layer several hundred A thick which will prevent further oxidization of the silicon and chromium.

7. TEST PROCEDURES

The tests were made by placing the cathode on top of the anode and holding them firmly together with an appropriate spring wire. The design of the set-up for the flexible bridge-type separation was discussed previously; and when sphere spacers or the fixed separation SiO_2 layer was used, a fixed tension spring finger held the cathode firmly against the anode. Before assembly the anode and cathode were cleaned vigorously in a water and soap solution in an ultrasonic cleaner. The cathode was immersed for a few seconds in a 10% HF solution to remove the oxide layer which forms at room temperature. The anode and cathode were then rinsed in distilled water, methyl alcohol, and acetone and dried with a stream of dry nitrogen. These latter processes were carried out in a laminar flow class 100 HEPA filter box to reduce the dirt particle contamination on the surfaces. Once the two electrodes were assembled, dirt could not enter the gap during insertion into the vacuum chamber.

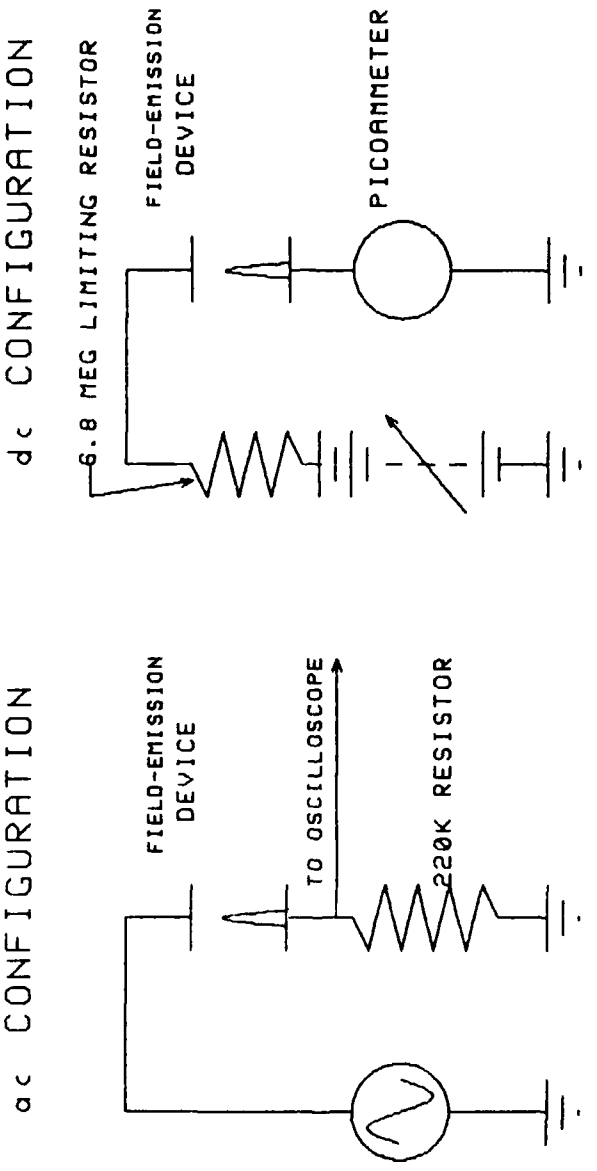
Two test procedures were tried. The first was to place 60 Hz voltage across the electrodes using a Variac and-step up transformer so that up to 500 volts could be applied. The current through the device was monitored with an oscilloscope by measuring the voltage drop across a 220kΩ resistor in series with the transformer and device (see Fig. 10). In addition to providing quantitative measurements, the observation of the ac signal through the device gave a clear view on any rectification which occurred. There were two disadvantages to this method: a) the finite capacitance between the anode and cathode permitted a small ac current to flow through the device, and thus the dc currents of interest would be superimposed on the ac signal, and b) there was high frequency noise of about 20 mV. Although both of these noise signals could have been reduced, more than adequate sensitivity was present to detect field emission, and no further effort was made to do so. For example, a 1 μamp field-emission current would have resulted in a .22 volt signal which would be easily visible.

An alternate way to measure the current through the device is to apply a dc voltage and measure the device current with a picoammeter. This set-up is shown in Fig. 10. The dc measurement eliminated the capacitive current flow, and, additionally, the integration performed by the picoammeter eliminated the high frequency noise. The current resolution was 1 nanoampere. To determine if the device was operating as a rectifier when conduction was observed, the polarity across the device was reversed. A 6.8MΩ resistor was placed in series with the device to prevent destruction of the device when conduction commenced.

In order to prevent an avalanche discharge from forming in the air between the anode and cathode, the assembled device was placed in a vacuum chamber, and the pressure was reduced to about 100 μ. At this pressure the mean free path in air is much larger than the separation between the two electrodes, and an avalanche cannot form.

8. TEST RESULTS

Devices were tested with a combination of cathode construction and anode separation techniques using both ac and dc measurements. Over 15 batches of samples with 4 to 6 samples per batch were produced using the various



TEST CONFIGURATIONS

FIG 10

techniques, and, in almost all cases, at least one sample was examined with the SEM to typify the needle configuration. All samples were tested for field emission at least once, and the most promising looking cathode structures were tested several times with thorough cleaning between the tests. In some cases tests were made using both ac and dc measurement methods and different anodes.

The first tests were made with the evaporated SiO_2 at the ends of the substrate to form the flexible anode structure which was then squeezed together using the spring finger attached to the micrometer advance. Rectification commenced in the 4 to 6 volt region. This result was at first interpreted as field emission, but it was then firmly established that the rectification was just as likely with flow from the cathode to anode as from the anode to cathode. Furthermore, as the voltage was increased, current flow commenced in both directions as clearly shown with the ac measurement. Current flow often occurred in both directions simultaneously, as well as commencing at near zero volts across the device.

Except when conduction commenced at near zero volts, the bias was clearly visible on the oscilloscope display as shown in the rendition of Fig. 11. The off-set was further demonstrated by operating the oscilloscope in the x-y mode and applying a variable ac voltage across the device and to one axis of the oscilloscope and the voltage across the 220kΩ resistor to the other axis. Thus the characteristic current vs voltage device curve was displayed directly and could be viewed in real time. The bias required for conduction and the bidirectional conduction characteristics could be observed.

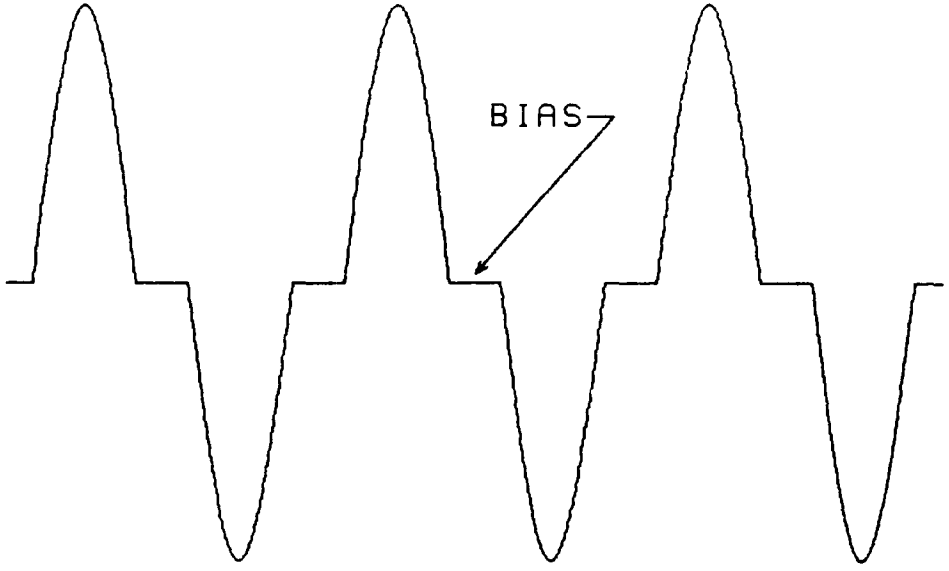
These results appear to be similar to what one would expect from a semiconductor rectifier, and, in the case of bidirectional conduction, the effect is similar to that obtained when two diodes are connected in parallel with the anodes connected to the cathodes.

The conclusion was that the conduction was likely due to conduction through defects in the evaporated SiO_2 coating. Field emission was ruled out because of the bidirectional conduction. Furthermore, when a rectified current did flow between the anode and cathode, the current vs voltage plot did not have a shape predicted by the Fowler-Nordheim equation. At this point in the investigations, the method of forming the SiO_2 insulating coatings by evaporation was replaced by the air oxidization method. Although some of the devices still showed conduction at low applied voltage, many showed no conduction until voltages from 100-200 volts were reached with an air oxidized layer. The results with ac voltages were consistent with those obtained with dc voltages.

Except for the higher voltages required for conduction, the characteristics with an air oxidized insulating layer were identical to those observed with the evaporated SiO_2 insulating layer. Generally, a current started to flow in one direction as the voltage was increased, and then bidirectional conduction began as the voltage across the device was further increased. Once bidirectional flow occurred, hysteresis was evidenced by the fact that the voltage often had to be reduced to near zero before bidirectional conduction ceased. A near ohmic relation between current and voltage was observed. In many cases, removing the device from the vacuum chamber and repositioning the anode relative to the cathode was necessary before the "short" was removed. The onset of conduction in the 100-200 volt range was consistent with the expected breakdown voltage of a 3,000 Å thick SiO_2 layer.

9. CONCLUSIONS

Close examination of the data conclusively demonstrated that no field emission



TYPICAL OSCILLOSCOPE DISPLAY SHOWING BIAS

FIG. 11

was observed. The results were consistent with conduction through defects in the insulating oxide layer or shorting due to contamination. Based on the needle configuration observed in the SEM microphotographs and the expected anode-cathode separation, field emission was anticipated at 100 volts across the device. The reasons for the failure to observe field emission are speculative, but these speculations are discussed below.

The detailed shape of the cathode needle is important. The tip must be pointed to produce a significant increase in the field intensity, and the needle must have sufficient height to prevent the near field from being distributed to the floor of the substrate. Based on the experience of previous investigators, an H/D ratio well in excess of 10:1 is desirable. This was not achieved in this investigation. The maximum ratio here was about 10:1. Attempts to increase the ratio failed, primarily due to the fact that the masks eroded the top off of the needles and tip points, then etched at a faster rate than the floor of the substrate.

A second possible problem is that, due to contamination the anode was separated from the cathode much further than anticipated based on the thickness of the insulating oxide layer. For example, a single 1 μ particle could increase the separation by an unacceptable amount. Although the final cleaning took place in a clean area, there is no guarantee that sufficient cleanliness was obtained; and, if a particle was imbedded in the oxide layer during the oxidization process, the particles would not be removed during the cleaning process.

10. DISCUSSION

Although field emission was not detected, several observations can be made about the general applicability of the techniques investigated for producing field-emission arrays.

1. The use of RF reactive ion etching for producing field-emission needles showed promise. The technique, when compared to some of the more conventional methods, offered the potential for low cost and smaller and thus lower voltage needles. Suitable needles could be etched if sufficient research was put into the etching process and methods of producing the masks. With regard to improving the etching process, there are numerous parameters which may affect the needle formation. These parameters include gas pressure, voltage, frequency, and gas type.

2. Random-sized needles resulted from the method of coating the substrate with silver and heating to form mask globules. The smallest of these needles eroded and produced shorter ones at random locations. This approach would not appear to have the characteristics necessary to develop a practical technique for mask construction.

3. The method of using close packed spheres distributed the silver masks in an ordered array, but defects and the closeness of the spacing caused serious problems which would be difficult to overcome in a production environment.

4. The use of the polystyrene spheres produced the most uniform needles and might form the basis for developing a random needle pattern for low cost field-emission arrays for electron sources. Producing needles with diameters less than 500 Å was clearly demonstrated, suggesting that RF etching should be pursued more vigorously than in the past for producing field emission configurations.

11. SUPPLEMENTAL STUDIES

Two additional investigations were made in fulfillment of requirements negotiated for contract extensions. The results of these efforts are discussed below:

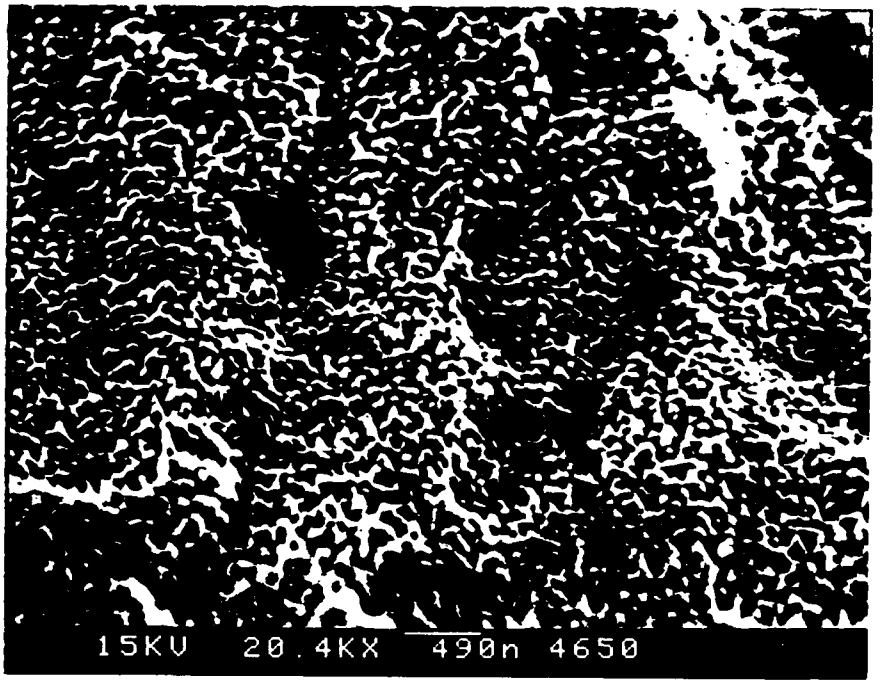
A. Formation of Cathode Needles on Tungsten Substrates.

In order to circumvent the rectification which was encountered in these investigations and attributed to effects of conduction through the oxide layer placed on a semiconductor, formation of cathode needles on a tungsten substrate was attempted. Silver was evaporated on a tungsten surface and heated as described above to form silver mask globules. The substrate was then RF ion etched as were the Si substrates. The results of this effort are shown in the SEM photomicrograph of Fig. 12. The basic problem was that the tungsten surface was extremely rough, and it was not possible to form needles. No source of polished tungsten is known which equals that of Si, and any further efforts were abandoned.

B. Investigation of Tunneling From Cathode Needles in Scanning Tunneling Microscope (STM).

The operation of the STM is based on the principle that if an extremely small negatively biased conducting tip is placed in close proximity to a conducting surface, electrons will tunnel from the tip to the conducting surface. Since the tunneling current is a strong function of the distance between the tip and surface (near exponential), the tunneling current is used in a feed-back circuit which keeps the tip to surface distance constant. Hence, the tip traces out, in high resolution, the surface irregularities of the surface as it scans over it. The difference between tunneling and field-emission should be noted. In tunneling, the electron goes from the potential well in the tip to the potential well in the surface and is never "free". In the case of field emission, the electron becomes free.

In spite of this difference, investigating the tunneling current from cathode tips appeared instructive. To make this investigation, one of the cathode needle arrays was placed in the STM, and a blunt scanning tip was installed on the STM. The STM needle was brought close to the cathode array, and the tunneling current was measured as a function of the bias between the tip and the array (a positive bias means that the STM tip is at a positive potential with regard to the cathode array). The results (see Fig. 13) show that three times more tunneling current flows when the STM tip is biased positively than when it is biased negatively, indicating enhancement of current from the cathode tips. For comparative purposes, a Si substrate with no cathode tips was also investigated, and the results are shown in Fig. 14. In this case, there was only about 10% as much current as when the cathode needles were present, demonstrating clearly the enhancement of the tunneling current from the cathode tips.



MICROPHOTOGRAPH OF ATTEMPT TO FORM NEEDLES ON TUNGSTEN

FIG. 12

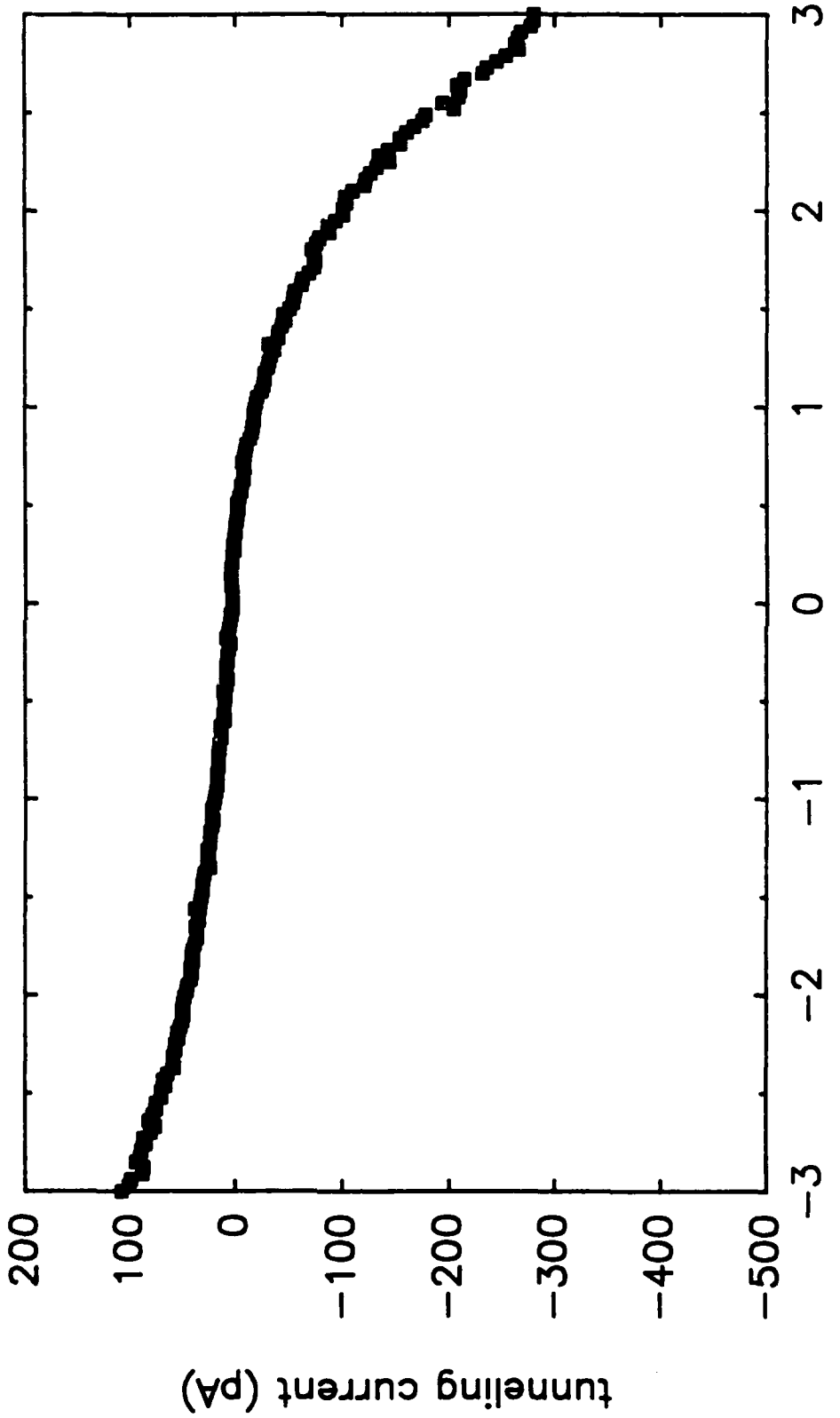


FIG. 13 STM CURRENT FROM SILICON NEEDLES

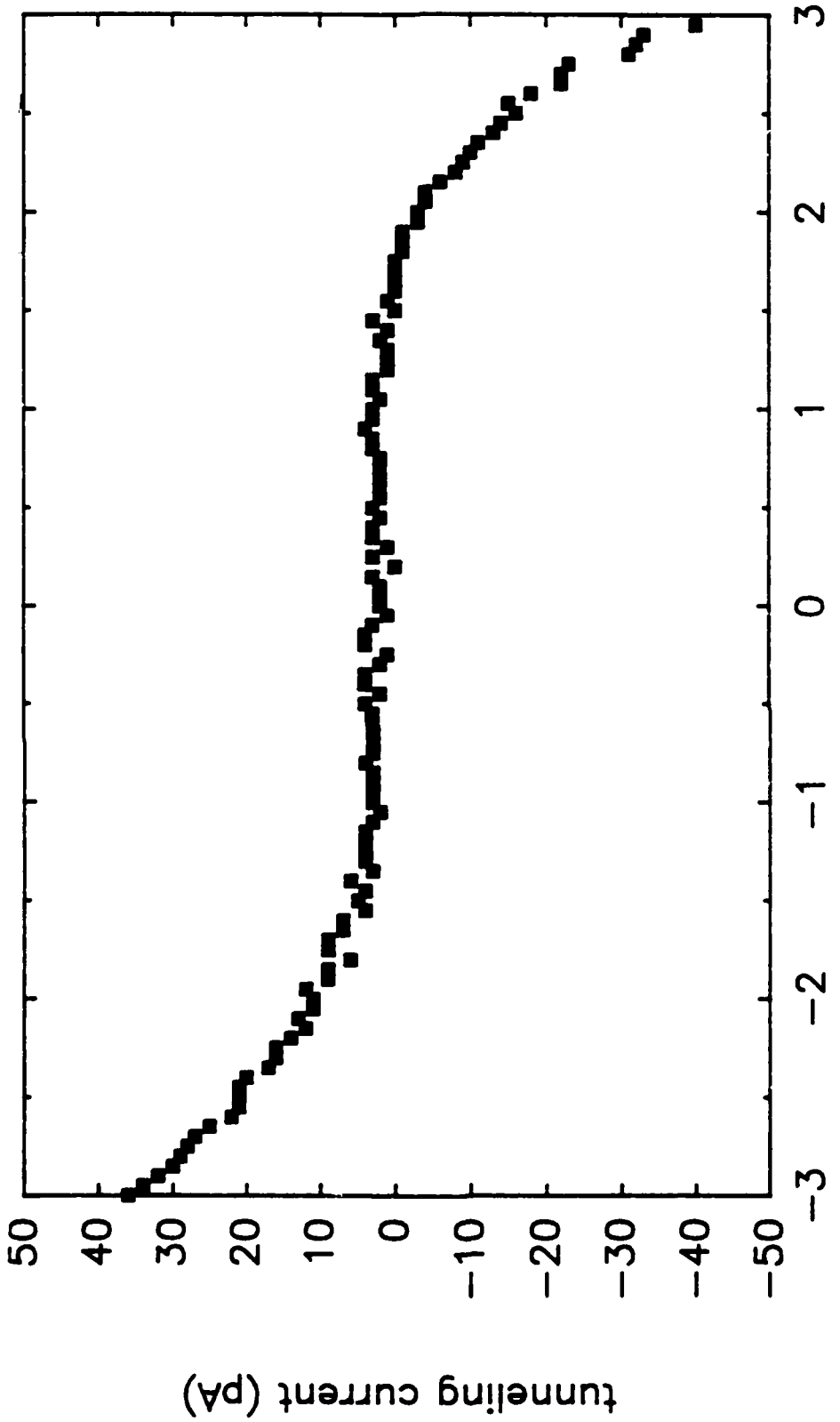


FIG. 14 STM CURRENT FROM SILICON WITHOUT NEEDLES

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