X-ray diode using a silicon field emission photocathode

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ABSTRACT

We have produced arrays of 10,000 sharp p-type silicon points using an etch plus oxidation method. These points were used as electron emitters. No high vacuum cesiation or high temperature cleaning was needed to observe the electron emission. These are seen to be photosensitive sources of electrons at 200 K and 300 K. They were also used to produce Al K_α x rays. This constitutes the first use of etched, point arrays for generating electrons for x-ray sources.

1. INTRODUCTION

There is considerable interest in soft x-ray sources which can be modulated temporally and spatially. Such a source has been developed by Stearns at LLNL and is called the x-ray diode.[1] It consists of a photocathode spaced a few millimeters of vacuum from a thin x-ray anode. The photoelectrons emitted from the photocathode are accelerated toward the anode where they produce x rays upon collision. Due to the proximity of the photocathode to the anode, the x-ray output can be modulated temporally and spatially by modulating the light incident on the photocathode. A limitation of this design is the photocathode. It needs ultrahigh vacuum for stable emission. If exposed to the atmosphere its quantum efficiency drops significantly due to contamination. A photocathode that can be vented to the atmosphere will allow the use of different anodes to obtain different x-ray lines and will simplify manufacture and use of x-ray diodes.

2. THEORETICAL BACKGROUND

Field emission from p-type silicon can be photosensitive.[2] A typical current-voltage characteristic curve is shown in Fig. 1. At low voltages, the emission is well described by the Fowler-Nordheim theory (region I).[3] There is no photosensitivity in this region. As the voltage increases, there is a current saturation region (region II). Because the material is p-type, there are few electrons in the conduction band. In the absence of external generation mechanisms, this limited electron supply leads to current saturation (part (a) of region II).[4] By illuminating the photocathode, the electron supply increases. This increases the

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emitted current in the saturation region (part (b) of region II). With further increase in the voltage, the current rises rapidly due to impact ionization (region III).[5] In region IV, the current again becomes limited by the surface barrier transparency and not the electron supply function.[5]

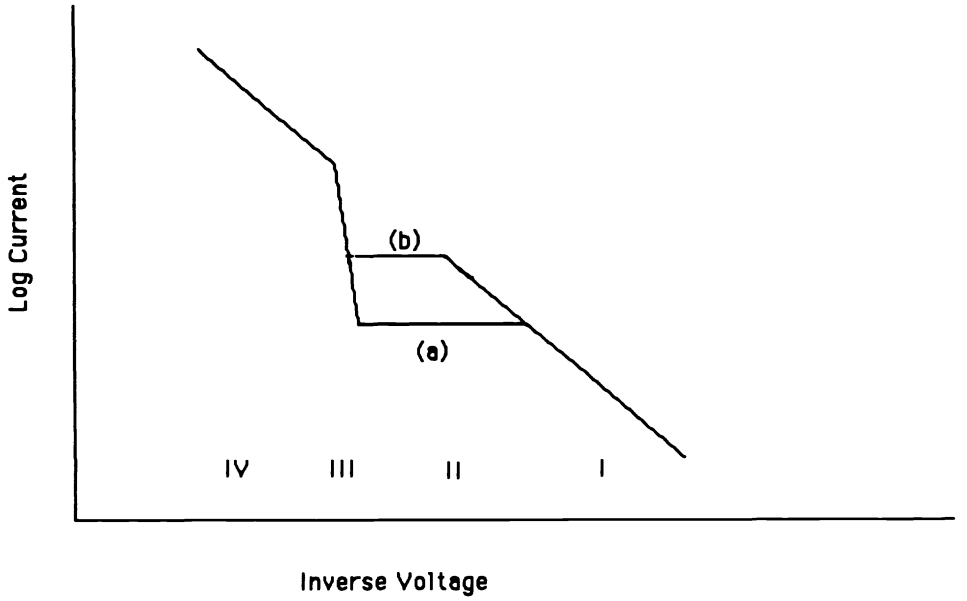


Fig. 1.
Current-voltage characteristics for p-type silicon.

3. EXPERIMENTAL RESULTS

We have recently used an array of sharp p-type silicon points as a photocathode. The electron emission was observed without any high vacuum cesiation or high temperature cleaning. The photocathode was stored in air for several days before testing and was cycle tested several times. Nevertheless, stable emission was detected for several hours.

Large areas of silicon tips can be fabricated on single crystal silicon wafers using standard lithographic techniques (Fig. 2). The wafer has islands of oxide squares on its surface. At this point, it is dipped into the silicon isotropic etch. This etch will attack the silicon, but not the oxide. Undercutting occurs, and sharp points result (Fig. 2). This process is stopped when the silicon points are judged to be in the submicron region. This is done by looking through the transparent oxide top with an optical microscope. The wafer is dipped into buffered HF to remove the oxide squares.

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The main problem with the arrays is the variation of tip diameter. Both overetched and underetched tips do not emit. This problem can be solved by using an anomaly of silicon oxidation which occurs at regions of high curvature.[6] By oxidizing the tips at 950°C in wet or dry oxygen, all the tips asymptotically reach the same end point thickness. Silicon tips less than 1 nm thick have been manufactured using this technique.[6] We used a scanning electron microscope to measure our tip diameters. They were below the microscope's resolution limit of 10 nm.

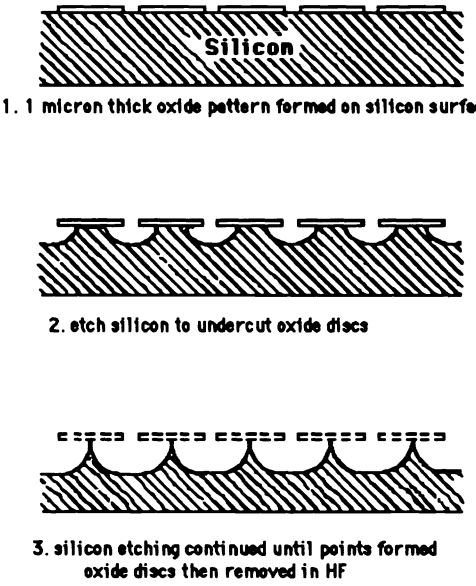


Fig. 2.
Making sharp point field emitters.[5]

After etching, the wafer is diced to facilitate testing. Each die consists of 10,000 tips and has an area of 16 mm^2. The exact number of tips contributing to the current is unknown. The die is then glued to a brass plate using colloidal silver. Using a micrometer, this plate is positioned within a hundred microns of a transparent conductive glass plate which serves as the collecting anode. This facilitates reflective mode photoemission testing. Emission testing was done at a pressure of approximately 10^{-4} Pa. The current is measured as a voltage drop across a known resistor using a Keithley ammeter which has a 10 GΩ internal impedance.

Fig. 3 shows current emission at room temperature for the array in the dark (curve a)

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and under illumination (curve b). At low voltages (region I), the log of the emitted current is linear with the reciprocal voltage. The electron supply is adequate for the emission to be limited only by the barrier transparency. As the voltage increases, the current begins to saturate (region II). By illuminating the emitter array with a 5 mW, green He-Ne laser (543 nm), the emission current increased by as much as a factor of 4 (Fig. 3b). However, the laser showed no effect in region I. Currents with array under illumination were as high as 46 microamperes. This corresponds to a quantum efficiency of 0.02 at 543 nm. The photocurrent was roughly proportional to the power of light incident on the array (Table I). This is expected because the supply function of electrons is being modulated by the laser.

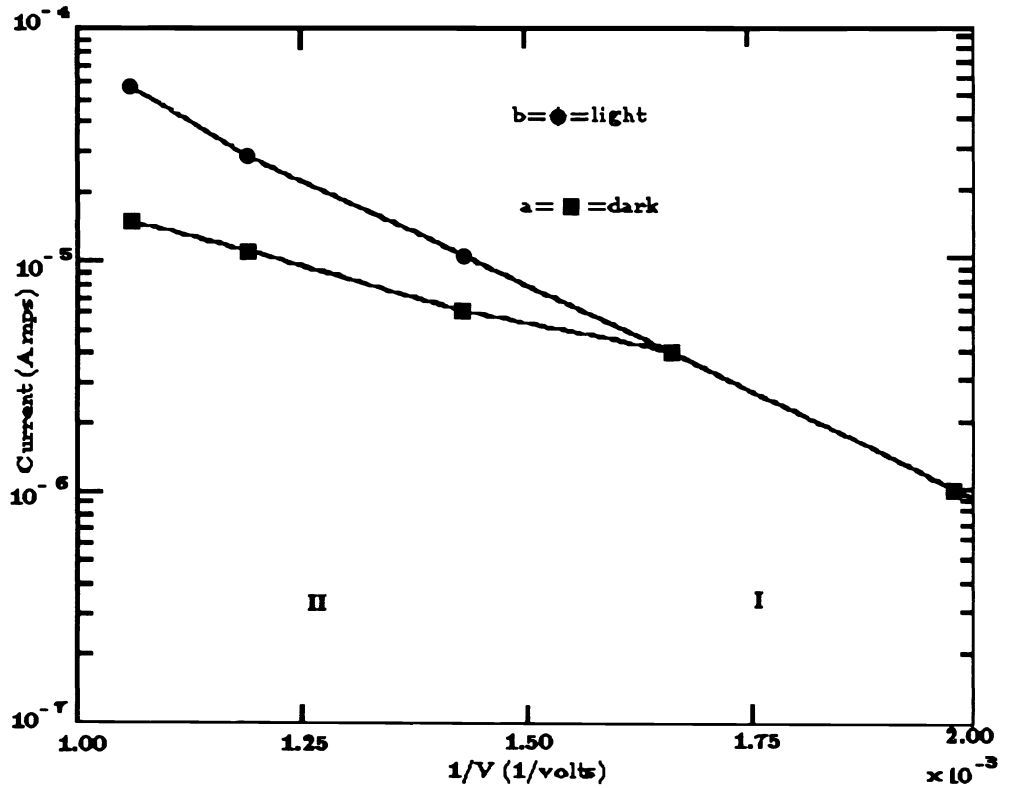


Fig. 3.
Experimental graph of the emitted current versus voltage.

Keeping the voltage constant, the temperature of the emitters was lowered to 200 K using a liquid nitrogen cold finger. This decreased the dark current by a factor of 10. When the emitters were illuminated with laser light (543 nm) at this temperature, the current increased by as much as a factor of 8. This corresponds to a quantum efficiency

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of 2.6×10^{-3}. All of the above results were acquired by frontal illumination of the array. Transmissive photoemission work is in progress.

$P_0 = 5mW, P = power$

(P/P_0)	$photocurrent(P)/photocurrent(P_0)$
1	1
0.6	0.5
0.1	0.07
0.01	0

Table I. Photocurrent at various illumination powers (P) normalized to the photocurrent at 5 mW illumination. Note that the power ratios and the photocurrent ratios are roughly equal. These measurements were taken at 300 K.

This photocathode was used to produce x rays. It was separated by a few millimeters from a thin aluminum target anode. A potential difference of 5000 volts was applied between the photocathode and the anode. The electrons were extracted using a fine grid about a hundred microns from the photocathode. The x-ray anode consisted of about 100 nm of aluminum evaporated on a 25 micron thick beryllium window. The aluminum K_α line was detected using a Link Si(Li) detector. Photon counts of 3.1×10^4/sec were acquired for dark currents of 10^{-8} amperes.

When the electron extraction voltage is turned on, the dark current increases steadily for several minutes as it asymptotically reaches a steady value for a given voltage. This has been attributed to some form of cleaning by the bombarding ions in the cavity between the photocathode and the anode.[5] The photocathode was cycle tested. Between testing cycles, it was kept in static vacuum. The initial, gradual increase in the current as the voltage is first applied was observed in all cycles. However, the steady current value for each cycle increased. After several cycles the current at a particular voltage increased by as much as an order of magnitude and then abruptly dropped by as much as four orders of magnitude. A similar effect was reported by Dykes *et al.*[7] However, if the extraction voltage is increased, then lowered to the initial value, electron emission is restored to its original value. Subsequent examination of the tips with a scanning electron microscope showed damage. This damage is generally attributed to resistive heating due to the large currents just before failure. Increased surface roughness brought about by the continuous ion bombardment increases the electric field enhancement factor at the rough points leading to an increase in the emitted current.[8] So a plausible explanation would be to say that a few points were emitting, and were damaged, thus decreasing the electron emission current. Upon increasing the extraction voltage, a few new points were cleaned and started emitting. One way to test this theory would be to check the history of damage for the array with a

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scanning electron microscope after each cycle. However, it is very difficult to know which points were emitting electrons and whether they suffered damage or not.

This peculiar effect might also be explained to be due to the charging and discharging of surface states at the silicon-silicon dioxide interface. This would change the electric field value at the surface of the silicon tip, leading to a change in the current emitted. A similar effect was reported by Janesick *et al.*[9] in his work with CCD's.

4. CONCLUSIONS AND FUTURE WORK

We have shown that an array of sharp p-type silicon emitters has the potential to be used as a photocathode. We are continuing to work on characterization of the tip lifetime and the damage mechanisms on the tips. The characterization of the soft x-ray source is also in progress. This includes spatial and temporal modulation. This is the first use of etched sharp point arrays as an electron source for generating x rays.

5. ACKNOWLEDGMENTS

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6. REFERENCES

(1.) D. G. Stearns, "Development of a novel soft x-ray source for laboratory applications," Nuclear Instruments and Methods in Physics Research **A242**, 364-368, (1986).

(2.) R.N. Thomas and H. C. Nathanson, "Photosensitive field emission from silicon point arrays," Appl. Phys. Lett. **21**, 384-386, (1972).

(3.) R. H. Fowler and L. W. Nordheim, Proc. R. Soc. London **A119**, 173 (1928).

(4.) L. M. Baskin, O. I. Lvov, and G. N. Fursey, "On the theory of field emission from p-type semiconductors," Phys. Stat. Sol.(a) **42**, 757-767, (1977).

(5.). N. Thomas, R. A. Wickstrom, D. K. Schroder and H. C. Nathanson, "Fabrication and some applications of large-area silicon field emission arrays," Solid State Electronics, **17**, 155-163, (1974).

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(6.) R. B. Marcus, T. S. Ravi, T. Gmitter, K. Chin, D. Liu, W. J. Orvis, D. R. Ciarlo, C. E. Hunt, and J. Trujillo, "Formation of silicon tips with < 1 nm radius," Appl. Phys. Lett. **56**, 236-238, (1990).

(7.) W. P. Dykes and W. W. Dolan, Advances in Electronics and Electron Physics **VIII**, 89 (1956).

(8.) E. E. Martin, J. K. Trolan, and W. P. Dyke, "Stable, high density field emission cold cathode," Journal of Applied Physics **31**, 782-805, (1959).

(9.) J. Janesick, T. Elliot, T. Daud, and J. McCarthy, "Backside charging of the CCD", SPIE J., Vol. **570**, 46-79 (1985).

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