

**THE USE OF SHARP SILICON TIPS AS PHOTOCATHODES
AND ELECTRON SOURCES FOR X-RAY GENERATION**

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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.

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 towards 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 atmosphere will allow the use of different anodes to obtain different x-ray lines, and will simplify manufacture and use of x-ray diodes.

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.

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 microns thick beryllium window. The aluminium K_{α} line was detected using a Link Si(Li) detector (Fig. 1).

Field emission from p-type silicon can be photosensitive.² A typical current-voltage characteristic curve is shown in Fig. 2. 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 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

Large areas of silicon tips can be fabricated on single crystal silicon wafers using standard lithographic techniques.⁵ We used 15 Ω cm p-type silicon wafers. The main problem with the arrays is the variation of tip diameter. Both over-etched and under-etched 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.

After etching, the wafer is diced to facilitate testing. Each die consists of 10,000 tips and has an area of 16 mm². 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 G Ω internal impedance.

Figure 3 shows current emission at room temperature for the array in the dark (curve a) 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 (Table I). This is expected because the supply function of electrons is being modulated by the laser. Keeping the voltage constant, the temperature of the emitters was lowered to 200K 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 of 2.6×10^{-3} .

When the 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. A similar effect was reported by Dykes *et al.*⁷ This was accompanied by a loss in photosensitivity and soon emission stopped entirely. Subsequent examination of the tips with a scanning electron microscope, showed considerable damage (Fig. 4). 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 Loss of photosensitivity is explained by the increase of the dark current, which becomes large enough to mask the photocurrent.

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

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Figures

FIG. 1. Aluminum $K\alpha$ line. This line was detected using a Link Si(Li) detector. The x-rays were produced by colliding electrons produced by an array of sharp silicon emitters with a thin film aluminum anode.

FIG. 2. Current-voltage characteristics for p-type silicon. Region I: The log of the current and voltage are linear. The current is limited by the barrier transparency. Region II: curve (a) shows the current saturation region (no light); curve (b) shows the effect of light on the current. Region III: the impact ionization region. Region IV: The current is again limited by the barrier transparency and not the supply function of electrons.

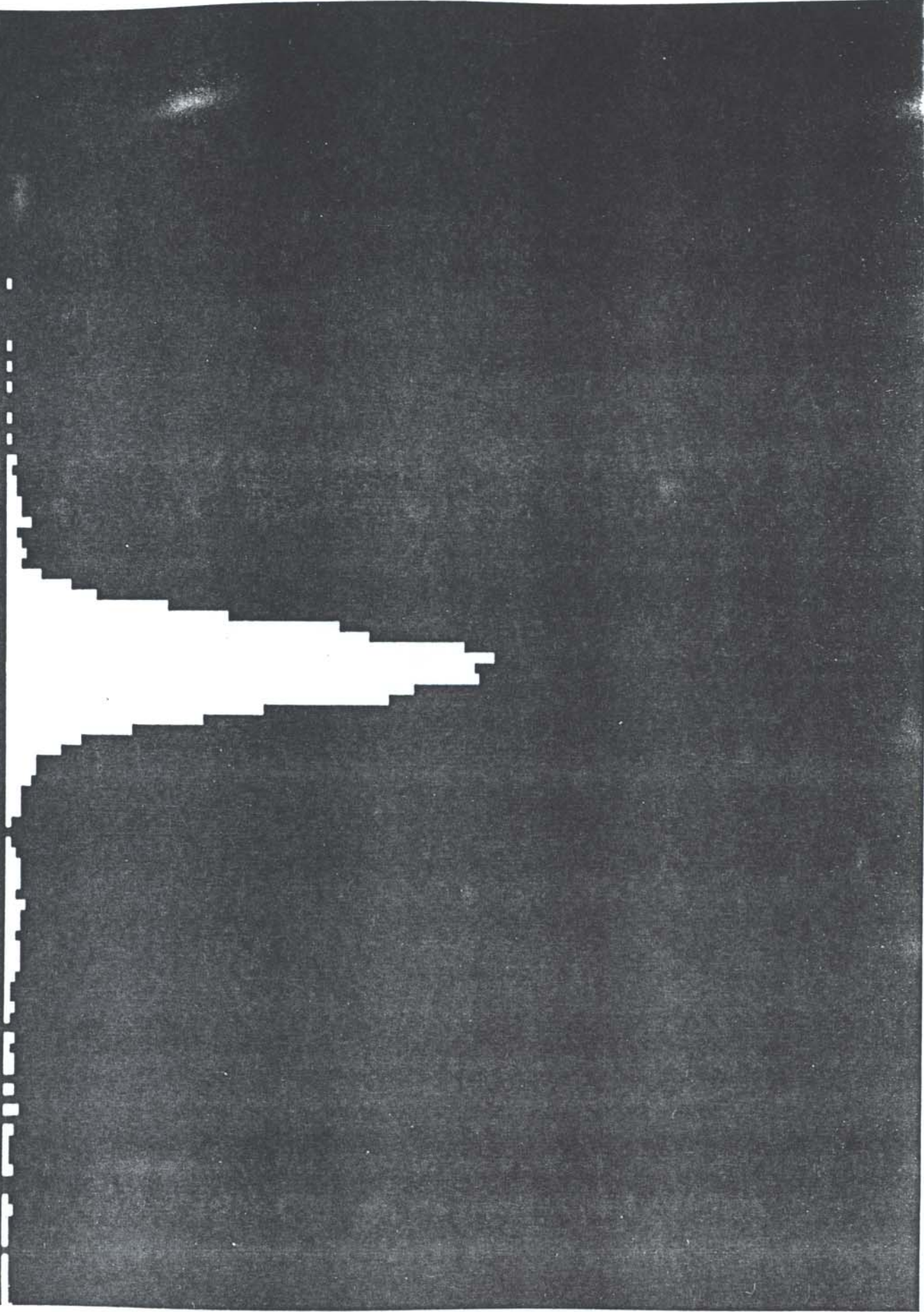
FIG. 3. a) (Lower curve) Current emission for a 15 Ω cm p-type silicon array in the dark. b) (Upper curve) Current emission for the same array while illuminated with a 5 mW, He-Ne green laser.

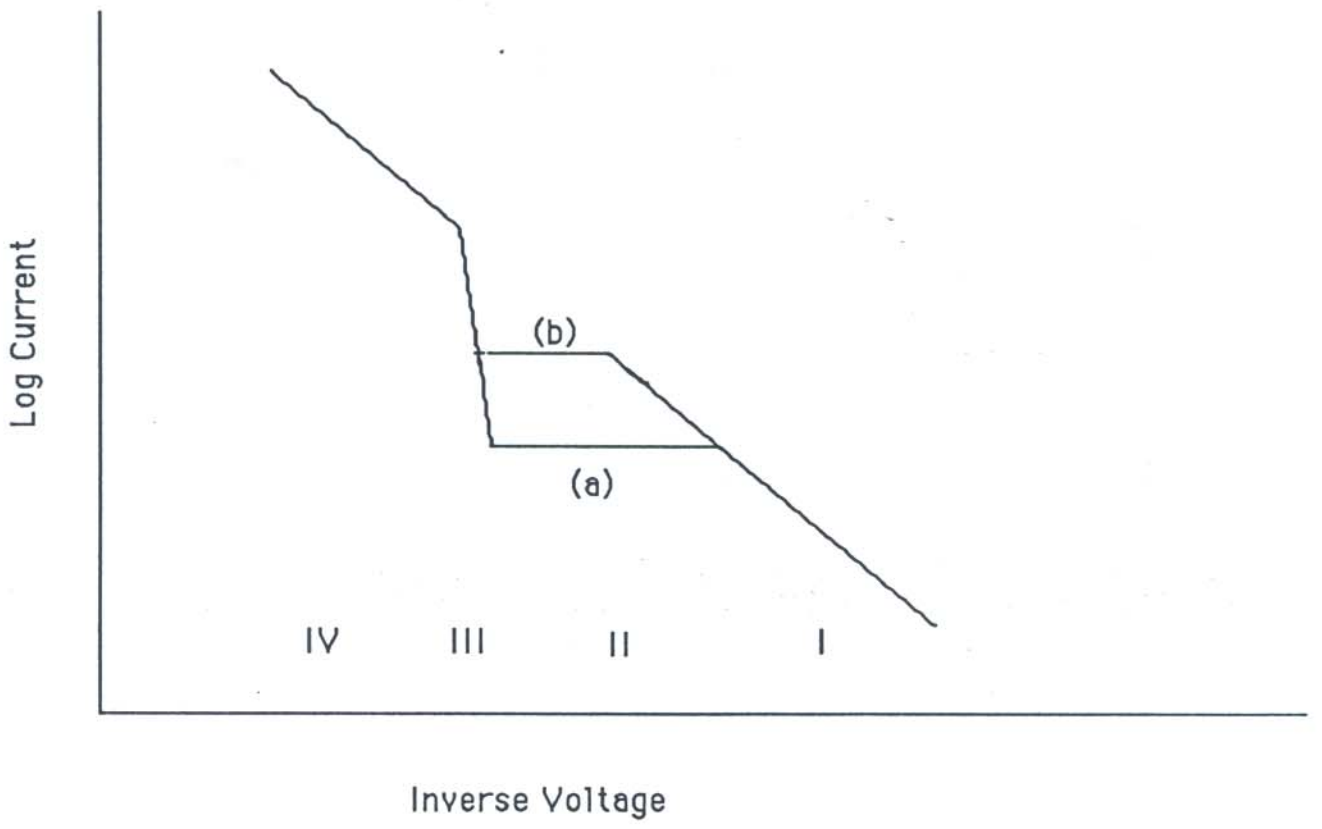
FIG. 4. a) A closeup of a damaged silicon emitter. Marker=1micron. b) A number of silicon emitters at different stages of damage. Marker= 10 microns

< .9

1.492 KeV

2.1 >





$$P_0 = 5mW, P = \text{power}$$

(P/P_0)	$\text{photocurrent}(P)/\text{photocurrent}(P_0)$
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 300K.

