# Photoemission from Si Induced by an Internal Electric Field*

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External photoelectric emission from silicon with a threshold of response corresponding to the band gap (1.05 ev) has been observed from a back biased *p-n* junction which had received a cesium surface treatment. This emission current is proportional to the intensity of the incident light. The spectral distribution of this field induced photoemission has been simply related to the spectral distribution of the fundamental absorption of silicon.

ELECTRON emission due to avalanche breakdown in semiconductors has been reported by several workers.[1] Burton has described this effect in silicon, the surface of which had been treated with cesium. Using a system similar to Burton's, we have observed the external emission of photoinduced carriers by means of the internal field across a *p-n* junction. This emission occurs at voltages below those necessary for avalanche breakdown.

The sample, a silicon crystal with a grown *p-n* junction, was mounted in the vacuum tube (as shown in the inset in Fig. 1) for the cesium surface treatment and measurements. The cesium treatment served to reduce the electron affinity of the silicon.[2] After the cesium treatment was completed, a field induced electron emission[3] (with no photoexcitation), similar to that reported by Burton,[1] of several milliamperes could be obtained with a potential drop of about 35 volts in the region of the junction.[2] For the photoemission measurements, chopped light from a monochromator with a band-pass of 0.03 ev or less was used.[4] A collector voltage of 67 v was sufficient to saturate the photoemission in all cases.

Figure 1 shows the spectral distribution of the photoemissive yield with and without an internal field applied. The spectral distribution with no field applied is characteristic of a surface which has received the optimum Cs treatment for hot electron emission (HEE). The application of 9 volts to the Si diode in the reverse direction greatly increases the photoemission and moves the long wavelength limit into the infrared. The threshold of response is moved from 1.4 to 1.05 ev.

The spectral distribution obtained with the internal voltage applied is clearly the sum of the emission due to two separate sources. The first is the field induced photoemission. This completely dominates for photon energies less than about 1.8 ev. At higher energies, a component due to the normal (i.e., that with no internal field applied) photoemissive effect is added. In comparing the two spectral response curves, it is obvious that the normal photoemissive effect dominates in the ultraviolet and that the field induced emission is practically constant for photon energies above 1.8 ev.

Since field induced photoemission would only be expected from the region of the junction, it should be very strongly dependent on the position of the light on the sample. By sweeping our light across the sample, this was found to be the case. However, the width of the light beam was still probably much larger than the region of the crystal from which the field induced photoemission can be obtained. This, of course, results in a reduction of the measured photoemissive yield below the value which could be obtained if all the light were focused onto the emitting area. We do not know what the width of this area is, but it may be fairly small.

One of our Si junctions was activated in an image tube. This allowed the emitted electrons to be focused onto a phosphorescent screen giving an image of the region from which emission originated. For both the HEE and the field induced photoemission, the emission came from a narrow band in the vicinity of the junction. However, the band of emission was not con-

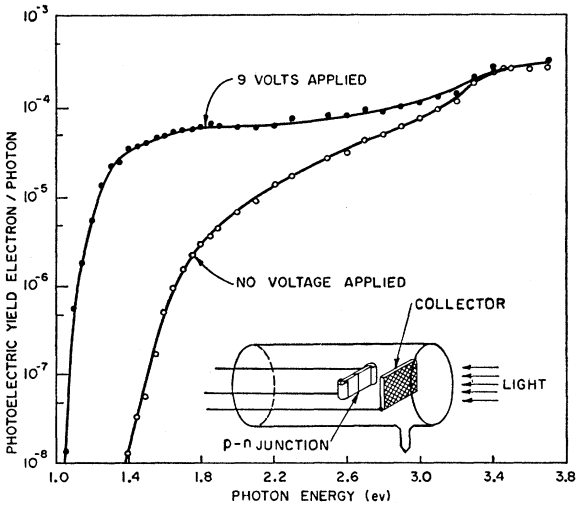


FIG. 1. The increase in the photoemission from cesium treated silicon caused by a potential applied in the reverse direction across the *p-n* junction. Inset shows a schematic diagram of the experimental tube.

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[1] J. A. Burton, Phys. Rev. **108**, 1342 (1957); J. Tauc, Nature **181**, 38 (1958); J. Bok (private communication); L. Patrick and W. J. Choyke, Phys. Rev. Letters **2**, 48 (1959).

[2] W. E. Spicer, Bull. Am. Phys. Soc. **5**, 69 (1960).

[3] For convenience, we will use the term "hot electron emission" (abbreviated HEE) to describe emission both in the avalanche region and at lower voltages.

[4] H. B. DeVore, RCA Rev. **13**, 453 (1952); H. B. DeVore and J. W. Dewdney, Phys. Rev. **83**, 805 (1951); W. E. Spicer, Phys. Rev. **113**, 114 (1958).

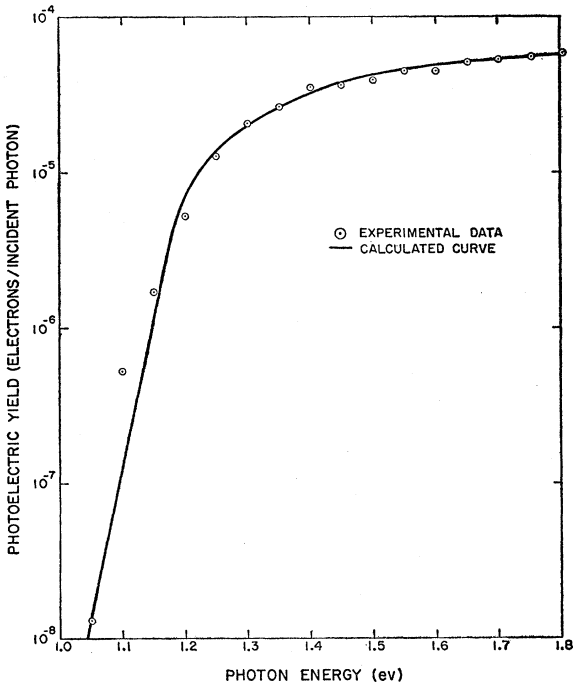


FIG. 2. The calculated curve of photoelectric yield as a function of photon energy fitted to the experimental points.

tinuous but made up of a number of spots indicating a patchy emitting surface. Because of limitations in the electron optical system, we could not be sure of the size of the spots.

The field induced emission has been measured as a function of voltage between four and twelve volts. It increases by about a factor of 80 as the voltage is increased over this range.

The following mechanism is proposed for the field induced photoemission. Light of energy greater than the band gap produced pairs in the silicon thus enhancing the number of minority carriers. In the $p$-type material these are electrons, some of which diffuse into the region of the $p$-$n$ junction near the surface and are accelerated across the junction. In crossing the junction, some of them will receive enough energy to escape from the material and appear as external photoelectrons.

If the above model is correct, the spectral distribution of this emission should be related to the spectral distribution of the fundamental absorption of Si. If we assume a simplified geometry, it is possible to derive an expression for this relationship. Assume that a junction occurs at the emitting surface and that the probability $P(x)$ of a carrier created in the interior of the Si reaching this junction is governed by the diffusion equation:

$$P(x)=e^{-x/L}, \tag{1}$$

where $x$ is the distance from the surface and $L$ is the diffusion length. The number of pairs produced at a depth $x$ per unit time would be:

$$dn/dt=\alpha(h\nu)I_0e^{-\alpha(h\nu)x}dx, \tag{2}$$

where $\alpha(h\nu)$ is the absorption coefficient of Si for a photon of energy $h\nu$ and $I_0$ is the intensity of the incident light in units of photons/sec. Under steady state conditions, the number of electrons reaching the junction will be given by the product of (1) and (2) integrated from zero to infinity. The field induced photoemissive yield will be this quantity multiplied by a factor $C$, the emission efficiency. This is the probability of escape for an electron which reaches the junction. The expression for the photoelectric yield, $Y$, in electrons/photon is:

$$Y=C\frac{\alpha(h\nu)}{\alpha(h\nu)+1/L}. \tag{3}$$

Figure 2 shows this expression fitted to the experimental data in the region where the field induced photoemission is much larger than the emission due to the conventional photoemissive effect. The values of the absorption coefficients of Si were obtained from the data of Dash and Newman[5] and a diffusion length of $2\times10^{-3}$ cm and an emission efficiency of $7\times10^{-5}$ electrons/photon were assumed. The value of $C$ would probably be considerably larger if the light were completely focused on the emitting area and if our boundary conditions had been more realistic. However, the important thing is the good agreement obtained between the experimental data and the calculated curve.

It is clear that this emission is quite closely related to hot electron emission in the voltage range below that at which avalanche breakdown takes place. In HEE one depends on thermally generated minority carriers in the $p$-type material for the emission; in this case, minority carriers are generated by the radiation falling on the sample.

## ACKNOWLEDGMENT

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[5] W. C. Dash and R. Newman, Phys. Rev. **99**, 1151 (1955).