Visible Light from a Silicon p-n Junction*

ROGER NEWMAN
General Electric Research Laboratory, Schenectady, New York

(Received June 1, 1955)

When low-voltage silicon p-n junctions are biased in the reverse direction to breakdown, visible light is emitted from the junction region. The effects of surface treatment on the phenomenon are discussed. Two typical light output *vs* reverse current curves are shown. A typical spectral distribution curve in the 1.8–3.4 ev range is shown. The observations suggest that the light results from a radiative relaxation mechanism involving the high-energy carriers produced in the avalanche breakdown process.

IT has been observed by R. N. Hall and W. E. Burch of this Laboratory that when low-voltage breakdown (<100 volts) silicon p-n junctions are biased in the reverse direction to breakdown that a weak yellowish light is emitted from the junction region. This paper describes some studies of this effect. Figure 1 shows a photograph of such a junction taken by its own emitted light. Units obtained from both grown and alloyed junctions in which the breakdown voltage ranged from 10 to 70 volts showed the effect. The data quoted in this report are for units cut from a grown junction with a breakdown voltage of about 40 volts.

When freshly etched, the units showed a hard breakdown characteristic, that is, a small reverse current (e.g., $\leqslant 0.01$ μa at 3 volts for units about 0.05 cm^2 in cross section) that increased slowly with voltage to a sharp break.[1,2] In the breakdown region at current levels less than about 100 ma, the etched units showed small spots of light estimated to be about 10μ or less in diameter. A given spot seemed to appear and reach its maximum brightness over a relatively narrow range of current. Different spots would appear at different current levels. One could cycle through various low current levels and see the different spots appear and disappear reproducibly at characteristic currents. At relatively high current levels, (i.e., greater than about 200 ma or 4 amp/cm^2 for the units being discussed) regions would appear of more or less uniform brightness which often extended several mm along the junction. If no attempt was made to limit the temperature rise in the unit, the brightness was a sensitive function of current. However at a constant current the brightness decreased if the sample was cooled by an air blast, indicating a temperature effect. Hence, relative constancy of temperature was an important factor in any attempt at a quantitative experiment.

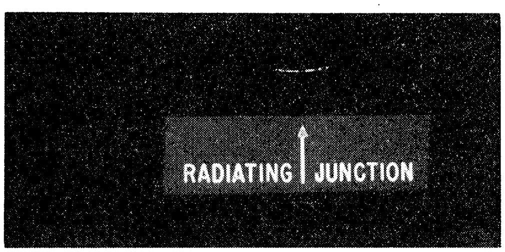

FIG. 1. A photograph of the light emitted from a worked silicon p-n junction unit operating in the breakdown region. The junction is the horizontal bow-shaped curve. Current flows vertically across it.

Attempts at controlling the temperature of the units were not successful. An air blast provided insufficient heat exchange. Immersing the sample in various stirred baths of organic liquids (e.g., silicone oil, mineral oil) was sufficient to hold a temperature, but irreversible changes in the units, presumably surface effects, were produced. This was manifested by the nonreproducibility of quantitative measurements of the light output as a function of current.

It was found that when the surface of an etched unit was lightly worked, spots of light would develop at the points where working had taken place. With sufficient working, almost the whole junction region could be made to emit. However, when examined under a microscope it was seen that the light was being emitted from a large number of closely spaced spots. The photograph in Fig. 1 was of such a worked unit. Working the surface consisted, variously, of grinding the surface with various grades of grinding, or polishing powder, or scratching across the surface with a point of stainless steel, tungsten carbide, or quartz. It was found that passing a point under a few grams load across the junction was sufficient to produce the effect, although in many cases the surface showed no indication of scratching. Working, of course, also softened the breakdown characteristic. A single pass of a point was sufficient to increase the reverse current by a factor of 10 or more (e.g., to ~ 0.1 μa at 3 volts).

In Fig. 2 are shown two plots of reverse current *vs* total light output as measured by an S-4 photomultiplier (EMI 6094). One curve is for a freshly etched unit with junction cross section 1 cm$\times$0.05 cm. The other curve is for the same unit after working it with a quartz point. In both cases, the unit was cooled by an air blast and by conductive cooling through large area Ga-Al paste contacts to copper plates. Below 50 ma, neglibible heating of the silicon occurred.

* A preliminary report of this work was given at the Baltimore American Physical Society Meeting, 1955; Newman, Dash, Hall, and Burch, Phys. Rev. **98**, 1536(A) (1955).

[1] K. G. McKay and K. B. McAfee, Phys. Rev. **91**, 1079 (1954).
[2] K. G. McKay, Phys. Rev. **94**, 877 (1954).

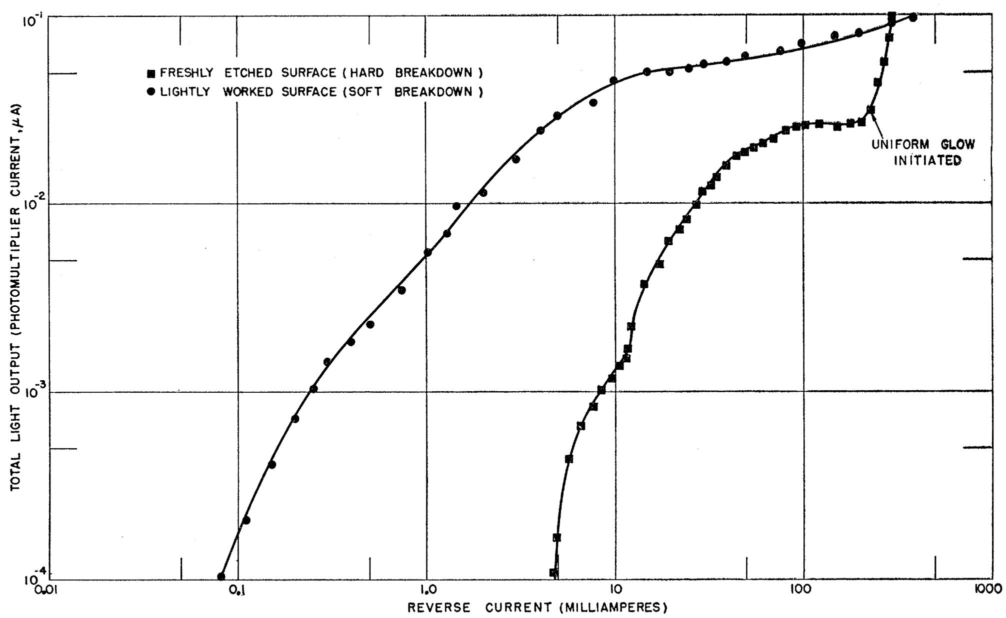

FIG. 2. Two typical reverse current *vs* total light output curves for a silicon p-n junction unit.

The foregoing qualitative observations provide some clue to the interpretation of the curves of Fig. 2. Consider, first, the data for a freshly etched unit. One can suppose that the rapid increase in light output from about 5 to 10 ma corresponds to the development of several bright spots of similar characteristics. Their brightness saturates with increased current corresponding to the break in the curve at about 10 ma. As the current is further increased, a new set of spots start developing in intensity and another rapid increase in light intensity is noted. This process is presumably continued in less discrete steps until by about 100 ma saturation of all the bright spots occurs. Above about 200 ma, a large increase in light output occurs as the relatively large regions of uniform brightness begin to contribute. Ideally one would like to study the characteristics of this uniform brightness region. It is assumed that this effect is associated with the true properties of the junction and not with accidental imperfections in the surface. However, several units were examined using various etching techniques and in no case was a unit obtained which was free from light spots. Consequently it did not appear feasible to obtain a light output *vs* current curve that would relate to one phenomenon alone (i.e., uniform emission) and thus be susceptible to theoretical treatment.

The data of Fig. 2 for the worked unit may be interpreted in terms of a large number of spots, each beginning to contribute its intensity at some different current level. The effects would overlap to give a monotonic appearance to the over-all curve. Curves for units, where the light was emitted over most of the current range from one worked point, resembled the data shown for the worked unit.

It seems pertinent at this point to make some remarks about breakdown in silicon diode units. We have observed that the softness of breakdown and the magnitude of the reverse current can be correlated to intentional imperfections in the surface (e.g., scratches). These, in turn, are manifested as spots of light on the junction when a reverse current in the breakdown range is passed through the unit. It is, therefore, not unreasonable that the spots of light that are observed in etched units may likewise manifest surface imperfections unintentionally produced. Further, the fact that the spots of light appear at different levels of current (or voltage) strongly suggests that a soft breakdown results from breakdown of small patches of material at a spectrum of voltage levels below that required for the breakdown of the bulk material. That is, a spot may be regarded as manifesting a channel for conduction of lower impedance than the main body of material. This suggests the possibility that the reverse currents that are usually measured in silicon units at voltages well below breakdown may be dominated by surface imperfections. These ideas are, of course, not new or particularly surprising. However, it would seem that the present results constitute direct evidence for this view of soft breakdown effects.

It had been hoped that by irradiating the junction with infrared radiation and thus altering the reverse current at constant voltage that an effect could be observed which would definitely associate the light emission with the avalanche breakdown in the silicon.[1] Our experiment was inconclusive in that over the current range where observable changes in reverse current could be obtained no light was detectable.

Figure 3 shows the spectral distribution of the light

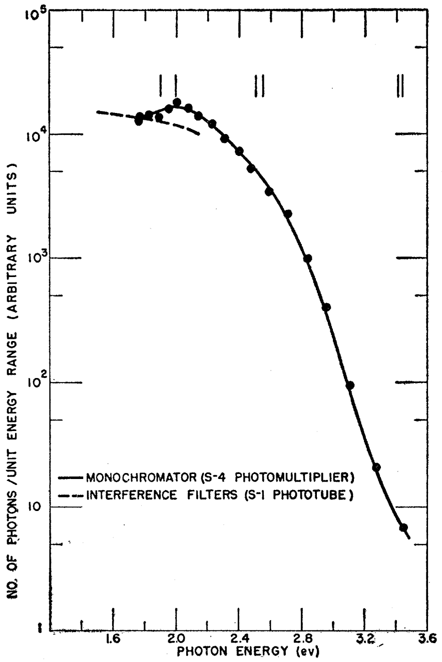

FIG. 3. Spectral distribution curve of the light emitted from a silicon *p-n* junction operated in the breakdown region.

emitted by an etched unit operated in the region of uniform brightness and cooled with an air blast. The measurements were made using a low dispersion quartz monochromator with a photomultiplier detector. The source light was chopped at 450 cps and a Baird phase-sensitive amplifier was used in conjunction with a recording potentiometer. In order to get a sufficient signal/noise ratio it was necessary to operate at an overall band width of about 0.2 cps. The data shown are corrected for the variation in spectral slit width of the monchromator and for the variation in the spectral sensitivity of the photomultiplier. The spectral distribution curve for a worked unit was identical with that shown to within our accuracy of measurement.

Attempts were made to extend the range of the spectral measurements toward lower energies. Vacuum and gas S-1 phototubes and a cooled PbS cell were tried with generally unsatisfactory results. Some data were obtained using interference filters and a cooled vacuum phototube in an electrometer circuit capable of detecting a photocurrent of 10^{-15} amp. These are indicated by the dotted curve of Fig. 3.

The following represent some hypotheses concerning the origin of the effect and the evidence that bears upon them:

I. *Local heating of the silicon.*—Considerations of thermal flow would seem to eliminate this as a possibility. With reasonable estimates of power input densities and estimates of thermal loss, calculations indicate that temperatures characteristic of the emitted light, that is $\sim$2000°K, would not be attainable. Further, even granting that such a temperature were attainable, would be impossible to obtain the temperature gradient necessitated by the observations. That is, the boundary between glowing and nonglowing regions is defined to a few microns, which would imply a gradient of order 10^6–10^7°K/cm.

II. *External gas discharge.*—This was readily eliminated by showing that the effect could be obtained unchanged in a vacuum of a few microns.

III. *A breakdown in the oxide film.*—This possibility cannot be completely discounted. However, it would appear unlikely that a breakdown would occur in the oxide at as low a field as that for which the silicon itself breaks down.

IV. *Breakdown in the silicon itself.*—This possibility seems most likely from the apparently close correlation of the light emission with the breakdown characteristics of the silicon units.

There is some evidence that would indicate that the light is being generated within the silicon and not simply at the surface. For example, occasionally a spot of light will appear colored asymmetrically; that is one side of the spot will appear yellow and the other side of the spot will appear orange or red. This is understandable if the breakdown process at the spot penetrated the silicon nonuniformly. The absorption coefficients are such that the penetration depth for yellow light is $\sim 1.5\mu$ and $\sim 3\mu$ for red light.[3] Occasionally even blue tinted spots could be formed but these would either degrade to yellow or disappear, consistent with a very small penetration depth for blue light (i.e., $\sim 0.3\mu$) and an unstable surface. McKay, using broad area diffused junctions, has also found color variations in the light consistent with emission from the bulk.[4]

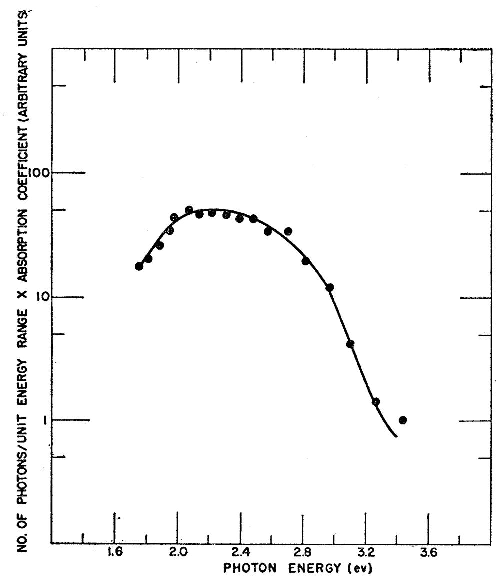

FIG. 4. Data of Fig. 3 corrected for self-absorption of the silicon.

[3] Dash, Newman, and Taft, Phys. Rev. **98**, 1192(A) (1955).
[4] K. G. McKay and A. G. Chynoweth, Bull. Am. Phys. Soc. **30**, No. 4, 22 (1955).

If the light emission is coming from the bulk silicon, then the spectral distribution curve should be corrected for the self-absorption of the sample. The spectral distribution curve so corrected is indicated in Fig. 4.

If the light is identified with the avalanche breakdown process in the silicon, then two possible processes suggest themselves. The first process involves the radiative recombination of the high-energy electrons and holes produced in the junction region during breakdown. The radiation produced by this process would presumably have a low-energy threshold at about the band gap ($\sim$1 ev) of silicon. Since the probability of carriers having a given energy will decrease with increasing energy the spectral distribution would, of course, show a tailing off at the high-energy end as well.[5] The spectral distribution for this case might resemble the curve of Fig. 4. The results of Wolff's calculation[5] of the carrier distribution function would appear consistent with the observed spectral distribution curve. It would be expected that the light output would increase as the square of the current for this mechanism.

The second process involves an intraband relaxation That is, a high-energy carrier could lose its energy by radiation and drop into a lower level in its own band. Such a process would also produce a tailing off of the emission at high energies (see the foregoing). However, the radiation would presumably, not have a definite low-energy limit. It would be expected that the total light emission would be linear in current.

For both these radiation mechanisms the decay time for light emission would presumably be of order $0.1-0.01$ μsec.[2] Our measurement indicated a decay time that was 4 μsec or less. This result was limited by the instrumentation.

In summary, the evidence suggests that the light emission results from radiative relaxation processes involving high-energy carriers in or near the barrier during avalanche breakdown. However, further study will be required before this conclusion can be made rigorous and a detailed mechanism elucidated.

[5] P. Wolff, Phys. Rev. 95, 1415 (1954).

ACKNOWLEDGMENTS

I am indebted to R. N. Hall for bringing this problem to my attention. I should like to thank W. C. Dash for his help at various stages of the project. E. O. Kane suggested the intraband relaxation mechanism and was very helpful in discussing various phases of this work. I am also indebted to K. G. McKay for his comments on this manuscript.

PHYSICAL REVIEW VOLUME 100, NUMBER 2 OCTOBER 15, 1955

Stark Effect in Rapidly Varying Fields*

S. H. AUTLER† AND C. H. TOWNES
Columbia University, New York, New York

(Received May 31, 1955)

A method is developed for calculating the effects of a strong oscillating field on two states of a quantum-mechanical system which are connected by a matrix element of the field. Explicit approximate solutions are obtained for a variety of special cases, and the results of numerical computations are given for others. The effect of an rf field on the $J=2\rightarrow1$ l-type doublet microwave absorption lines of OCS has been studied in particular both experimentally and theoretically. Each line was observed to split into two components when the frequency of the rf field was near 12.78 Mc or 38.28 Mc, which are the frequencies separating the $J=1$ and $J=2$ pairs of levels, respectively. By measuring the rf frequency, ν_0, at which the microwave lines are split into two equally intense components, one may determine the separation between the energy levels. The measured value of ν_0 depends upon the intensity of the rf field and the form of this dependence has been calculated and found to be in good agreement with the experimental results.

I. INTRODUCTION

1.1 Outline of the Problem

A RELATIVELY weak perturbation varying sinusoidally in time may affect a physical system by causing an occasional transition between quantum states. These transitions are accompanied by the absorption or emission of photons and may be observed spectroscopically. However, if the perturbation is strong enough, transitions are rapidly induced and a variety of other observable phenomena can occur. We shall discuss some of these in the case of a system where relaxation processes are negligible, i.e., where the effects of the sinusoidal perturbation are much more important than those due to processes which dissipate energy. In particular, an experiment will be described which involves the simultaneous effects of two electromagnetic fields on the molecules of gaseous OCS. One field is much stronger than the other and is in the radio-frequency range; the weaker field is in the microwave

* Work supported jointly by the Department of the Army (Signal Corps), the Department of the Navy (Office of Naval Research), and the Department of the Air Force (Air Research and Development Command).

† Present address: Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts.

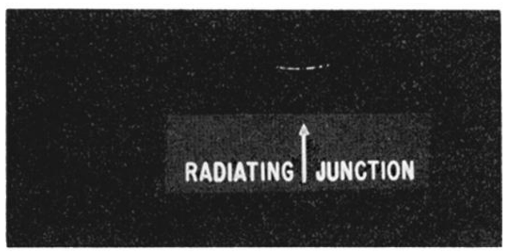

FIG. 1. A photograph of the light emitted from a worked silicon *p-n* junction unit operating in the breakdown region. The junction is the horizontal bow-shaped curve. Current flows vertically across it.