Photon Emission from Avalanche Breakdown in Silicon

A. G. CHYNOWETH AND K. G. MCKAY
Bell Telephone Laboratories, Murray Hill, New Jersey
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Visible light is emitted from reverse-biased silicon *p-n* junctions at highly localized regions where avalanche breakdown is taking place. The emission occurs in both grown and diffused junctions. By using junctions diffused to a depth of only 2 microns below the crystal surface, it was established that the light sources are randomly spaced over the whole area of the junction as well as around the periphery where the junction intercepts the surface. The light sources are too small to be resolved under a high-power microscope. Their sites are reproducible with current cycling and their intensity and color are relatively insensitive to the field distribution, to the junction width, and to temperature. The number of light spots increases with the current rather than individual spots growing brighter. It is concluded that all the breakdown current is carried through the junction by these localized light-emitting spots.

The spectral distribution of the light is continuous with a long tail extending to photon energies greater than 3.3 ev. It is concluded that recombination between free electrons and free holes within the junction region is responsible for the light at the shorter wavelengths, the carrier energies in excess of the energy gap being supplied by the field. At longer wavelengths there appears to be a considerable contribution to the emission from intraband transitions.

A tentative figure for the emission efficiency over the visible spectrum is one photon for every 10^8 electrons crossing the junction. The recombination cross section required is reasonable, being about 10^{-22} cm^2.

INTRODUCTION

It has been reported by Newman, Dash, Hall, and Burch[1] that the passage of a reverse bias breakdown current across a silicon *p-n* junction is accompanied by the emission of visible light. The above authors observed yellowish-white light emerging from the edge of a junction, the junction being formed in the silicon crystal during its growth. The spectrum of the light and the variation of its intensity with current were measured. It was suggested that the light could arise from radiative transitions of the high energy carriers produced at breakdown at the junction though their experiments were unable to decide whether the light originated throughout the junction region or whether it was an effect associated with the surface of the crystal.

It is the purpose of this paper to demonstrate that the light arises from those places in the junction where breakdown occurs, irrespective of surface effects, and to suggest a detailed mechanism for its production.

OBSERVATION OF LIGHT EMISSION FROM GROWN JUNCTIONS

All of the basic experimental facts referred to above[1] have been verified by us. Single-crystal silicon cut into long bars of square cross section were used with the *n-p* junctions bisecting the bars. Carrying breakdown currents of up to 0.5 amp, almost all crystals gave out some light easily visible in a dimly lit room. The breakdown voltages of the crystals varied from 12 to 156 volts with more or less the same behavior in all cases; in particular, the light always appeared yellowish or orange-white in color. At low currents, the light appeared at isolated spots but at higher currents appeared almost continuous along the junction edge. A typical case is shown in Fig. 1. (This photograph was a double exposure: a time exposure was made of the light emission alone followed by a brief exposure with background light to reveal the crystal outline.)

It was clearly desirable to perform a definitive experiment to determine whether a surface effect alone was responsible for the emission, or whether it occurred at the junction throughout the volume of the crystal. The logical step was to use a geometry such that the entire junction lay very close to the surface, i.e., using a junction configuration similar to that of a "solar battery." If light is actually emitted over the whole junction area, it would then have some chance of reaching the surface without suffering too much attenuation.

LIGHT EMISSION FROM DIFFUSED JUNCTIONS

From grown single crystals of high conductivity ($\sim 10^2$ mho/cm), both *n*- and *p*-type, were cut slices 0.03 inch in thickness and about $\frac{3}{4}$ inch in diameter. The slices were then polished on one face. For the first experiments a rough polish only was given, but it was found that to get a sufficiently uniform diffusion into the crystal it was essential that the polish should be of optical quality. Immediately before diffusing in the

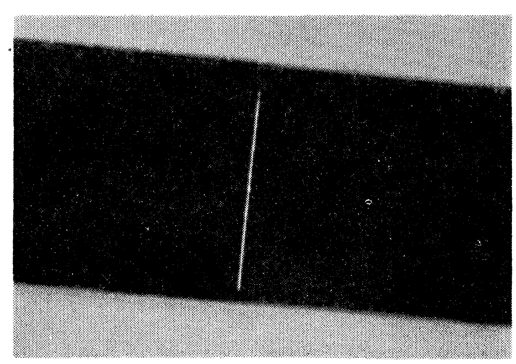

FIG. 1. A photograph of the light emission from a grown junction along the line in which the junction intercepts the surface.

[1] Newman, Dash, Hall, and Burch, Phys. Rev. 98, 1536(A) (1955) and R. Newman, Phys. Rev. 100, 700 (1955).

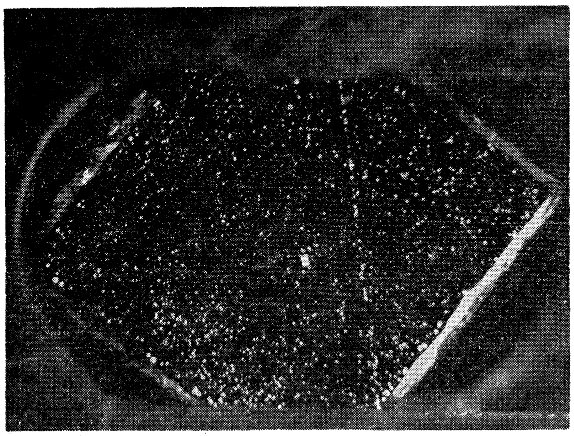

FIG. 2. A photograph of the light emission pattern from a junction diffused to a depth of about 2 microns below the crystal surface, as seen in the direction normal to the surface.

additional impurities, the slices were given a light etch to remove the layers damaged in polishing. To convert the crystal surface to *n*-type or *p*-type, phosphorus or boron, respectively, was diffused into the crystal to a controlled depth at an elevated temperature.

After the above doping treatments, the slices were coated with wax and diced into squares about $\frac{1}{8}\times\frac{1}{8}$ inch. The edges were then given a moderate etch and finally the wax was cleaned off the units.

Owing to the high conductivity of the crystals used for these experiments, satisfactory electrical contacts could be made simply by clamping the crystal between a metal plate and a spring fork-shaped electrode. Reverse currents of up to 0.5 amp were passed through the crystal. A check was made of the rectifier characteristics of the units. It was found that, in general, those slices which had not been optically polished showed "soft" characteristics and varied quite considerably from unit to unit cut from the same slice. Much more uniform results were obtained when a good polish was given and this also resulted in extremely sharp breakdown characteristics. For most of the units used in these investigations the breakdown occurred between 8 and 15 volts.

Optical observations on one series of units, each of which consisted of an *n*-type layer about two microns deep in a *p*-type body were as follows: Breakdown currents of about 100 ma brought out a few white spots around the edges but the most striking feature was a diffuse dull red glow extending over most of the polished face. Scattered in this glow were many local bright spots, though still red in color. Under high magnification, the red glow itself could be resolved into large numbers of very small spots, though the area of an individual spot could not be resolved. Figure 2 is a photograph of the light emitted by such a junction carrying a current of 250 ma. This picture was taken looking down on the upper *n*-type surface of the unit which appears diamond-shaped except for two corners which are masked by the electrodes. The vague continuous light along the edges is from scattered background light while all the spots are from light emitted by the crystal. It will be seen that the density of spots is roughly uniform over the whole surface. It was estimated that the number of spots was about 1000. The particularly intense spots that can be distinguished along the edges of the crystal are in fact the white-light-emitting spots. It should be emphasized here that no white spots were ever found over the polished surface of the crystal—only around the edges where the junction intersected the surface. It will also be noticed in the photograph that there is a strong line of red spots cutting across the surface. This phenomenon was observed quite frequently and in many cases could be correlated exactly with a visible surface marking such as a fine scratch caused during the polishing process. This will be commented on later. Another feature of the pattern of the light spots is that it was exactly reproducible, i.e., the spots always appeared in the same position and time sequence as the current was increased from zero to its maximum value. No flickering was observed.

The interpretation of Fig. 2 is that the emission arises from those sites where breakdown is occurring. The whitish spots along the edge occur just where the junction meets the surface and the light sources are so close to the surface that the light is virtually unattenuated before detection. However, the light from the more central breakdown spots of the junction must penetrate several microns of silicon before detection. Since the absorption coefficient increases rapidly with decreasing wavelength, the effect of absorption is to shift the spectrum towards the red; consequently all the spots in the central region are red in color.

This interpretation was further strengthened by the following experiment. Part of the polished face of a sample like that shown in Fig. 2 was ground and

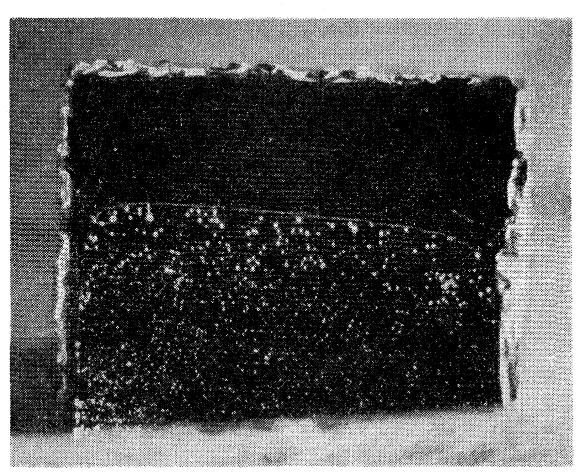

FIG. 3. A photograph of the light emission from a junction similar to that of Fig. 2 except that part of the surface has been ground off at an angle of one degree to the remainder. The sharp white line marking the boundary of the light spots indicates where the junction intercepts the sloping face.

polished at an angle of about one degree to the original surface. The junction thus intercepted this sloping face in a straight line. When a breakdown current was passed through the junction this line stood out as shown in Fig. 3. Under low magnification this line appeared almost continuous. On one side of the line there were no light spots, while on the other side there was a diffuse array of light spots. The color of the emission along the line was blue-white and yellow-white. Proceeding away from the line the colors of the spots went through yellow and orange to red. Thus a very clear qualitative correlation was established between the color of the emission and the thickness of silicon through which the light had to pass, in agreement with the interpretation given above. Results consistent with this interpretation were also obtained when samples with thicker diffused layers were used; for layers about twice as thick as that of the crystal of Fig. 2, the only detectable light arose from the edges.

All of the observations and measurements on diffused layer junctions presented in this and succeeding sections refer specifically to a thin *n*-type layer diffused into a *p*-type body. Measurements have also been made on *p*-type layers diffused into an *n*-type body. No significant difference has been observed between the two configurations.

SPECTRAL DISTRIBUTION OF THE EMITTED LIGHT

The emitted light intensity is sufficiently low that special efforts must be made to obtain reasonably accurate spectral distributions. After traversing a Gaertner Type 193 spectrometer, the light impinged on a photomultiplier; either a low-noise type 5819 photomultiplier with an S4 response, or a developmental tube, type C7160, with an S1 response. To reduce cathode emission, the photomultiplier was cooled to liquid nitrogen temperature. Output pulses arising from individual quanta were amplified and counted on a scaling circuit. An adequate heat sink was provided to insure a constant crystal temperature.

The counting rate as a function of wavelength, that is, the emission spectrum, was measured for three different junction sources, using the photomultiplier with the S4 response. The yellowish-white light from a grown junction was measured, using a crystal that emitted more or less uniformly along the line in which the junction intercepted the four faces of the crystal as, in Fig. 1.

Next, the diffused junction of Fig. 3 was used as the source. A current sufficient to produce the bright white line where the junction intercepted the surface was passed through the crystal and the spectrum of this emission was obtained.

Finally, a crystal from the same batch as the previous one was selected for its uniform pattern of red light spots as observed through the surface layer and its emission spectrum was measured.

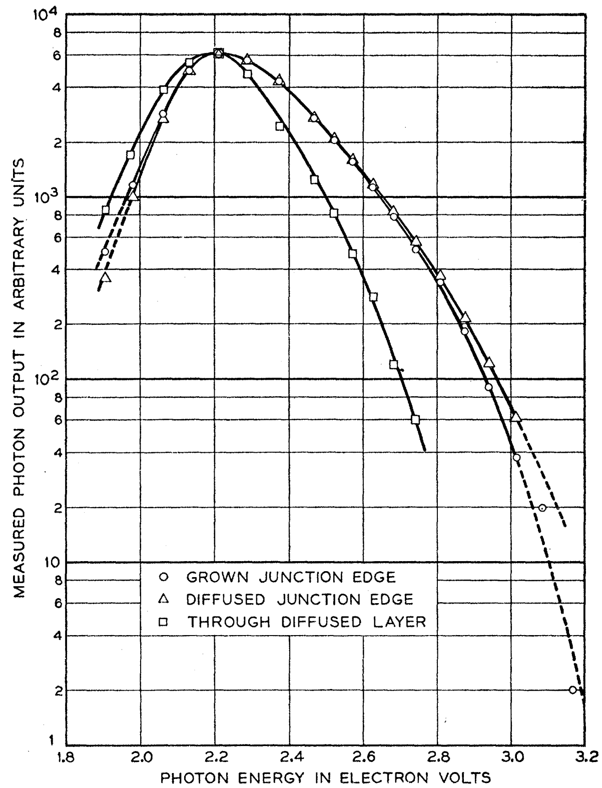

FIG. 4. Spectra of emitted light as measured, i.e., uncorrected for the spectral response of the spectrometer and photomultiplier. The curves are normalized at their peaks.

All three spectra are shown as measured in Fig. 4. They are not corrected for the wavelength variation in the multiplier response, the dispersion of the spectrometer, or its optical efficiency. To make comparisons easy, the spectra were normalized at their peaks. First, it will be noted that the spectra for the grown junction edge and the diffused junction edge are very similar; the slight differences in magnitude that are shown are not regarded as significant. It is also apparent from Fig. 4 that, as expected from the visual color differences, the light from the surface of the diffused junction is relatively deficient in the shorter wavelengths.

The absorption coefficient of silicon as a function of wavelength has been measured by Dash and Newman.[2] By making use of these data it was possible to fit the spectrum of light from the diffused junction edge to that measured after penetration of the diffused layer. We shall make the assumption, later to be justified, that the light observed at the diffused junction edge has suffered negligible absorption throughout the visible spectrum and therefore approximates very closely to the true emission intensity. Let this intensity at a given wavelength be I_0 and let I represent the intensity of the emission through the diffused layer at the same wave-

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

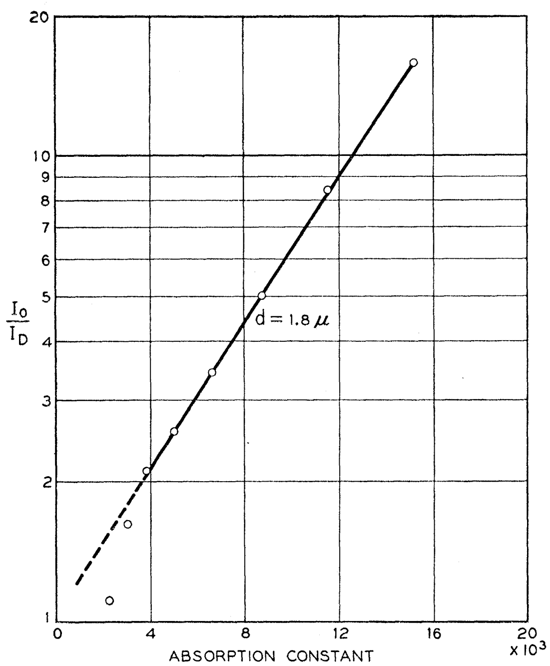

FIG. 5. A plot demonstrating the correlation between the spectra from the diffused junction edge and through surface layers of the crystal. From the slope of this line the depth of the junction below the surface was 1.8 microns.

length. Then

$$I = AI_0 \exp(-\alpha d),$$

where α is the absorption constant for the chosen wavelength, d is the depth of the junction below the crystal surface, and A is a constant. Thus, a plot of $\log(I_0/I)$ against α, as determined at various wavelengths, should be a straight line whose gradient is d. Such a plot is shown in Fig. 5 and it will be noted that it is very satisfactorily straight save for two points which were taken from the inaccurate measurements at the red end of the spectrum. From the slope of the line, the depth d was found to be 1.8 microns.

The depth of the junction could be measured directly using an interferometric method that has been developed by Bond and Smits.[3] By this method d was found to be 2.0±0.2 microns, in good agreement with the value found by fitting the spectra. This leads to the important conclusion that the light from the diffused junction edge must have arisen from a source which is within 0.2 micron of the surface. Since the absorption in the visible is very small for such a thickness of silicon, this shows that we are here measuring the unmodified spectrum of the light as emitted in the junction. However, this is very close to the spectrum of the light from the edge of the grown junction; consequently, the light from the latter must have arisen from a depth of not more than 0.4 micron from the surface. A probable reason for this somewhat unexpected behavior will be considered in a later section.

To determine the true spectral distribution of the emitted light, it was necessary to calibrate the spectrometer-multiplier system. This was done using a tungsten filament lamp of known filament temperature as a source of black-body radiation. The correction to be applied to the counting rate measurements varied slowly with wavelength for both photomultipliers except at the long wavelength end of their response characteristics. The corrected spectrum for the emission from the edge of the diffused junction is shown in Fig. 6, the data from the two photomultipliers being matched over the range of photon energies, 2.2 to 2.5 ev. For photon energies greater than 2.3 ev, the steady decrease in intensity with wavelength is in general agreement with the data presented by Newman *et al.* for a grown junction edge. At the limit of detectability the photon energy was about 3.3 ev, but it is impossible to extrapolate the curve to an upper limit for the photon energy. In other words, the spectrum exhibits a long, low tail extending to wavelengths shorter than 3900 A.

Throughout the energy range covered by the measurements, the emission intensity varies smoothly. No structure can be unambiguously resolved. At the low-energy end of the spectrum the intensity is still increasing. The fact that this increase was real and not due to errors in the calibrating procedure was confirmed by measuring the spectrum of radiation obtained first, when a breakdown current was passed, and secondly, simply by reversing the leads to the crystal, when carriers were injected into the junction in the forward direction so as to produce recombination radiation.[4] The spectrum of the light obtained when the current was in the forward direction is also plotted in Fig. 6 where it is apparent that there is a rapid cutoff in the emission intensity at the low-energy side of the peak since photons of energy less than the gap width cannot be emitted in interband transition. No such intensity cutoff occurs in the spectrum for the breakdown current and from this fact it is concluded that photons of energy substantially less than the gap width are being emitted in the breakdown mechanism.

EFFICIENCY OF THE LIGHT EMISSION IN THE VISIBLE

The crystal of Fig. 2 was mounted facing the photomultiplier with the S4 response. A current sufficient to produce the uniform red glow but not enough to produce more than a few white peripheral spots was passed through the junction. The emitted photons gave rise to a spread of pulse heights from the photomultiplier. The distribution of pulse heights was determined using a pulse height discriminator and the counting rate was extrapolated to its value at a zero bias on the discriminator. This extrapolation gave the total number of

[3] We are indebted to W. L. Bond and F. M. Smits for the use of their apparatus.

[4] J. R. Haynes and H. B. Briggs, Phys. Rev. 86, 647 (1952).

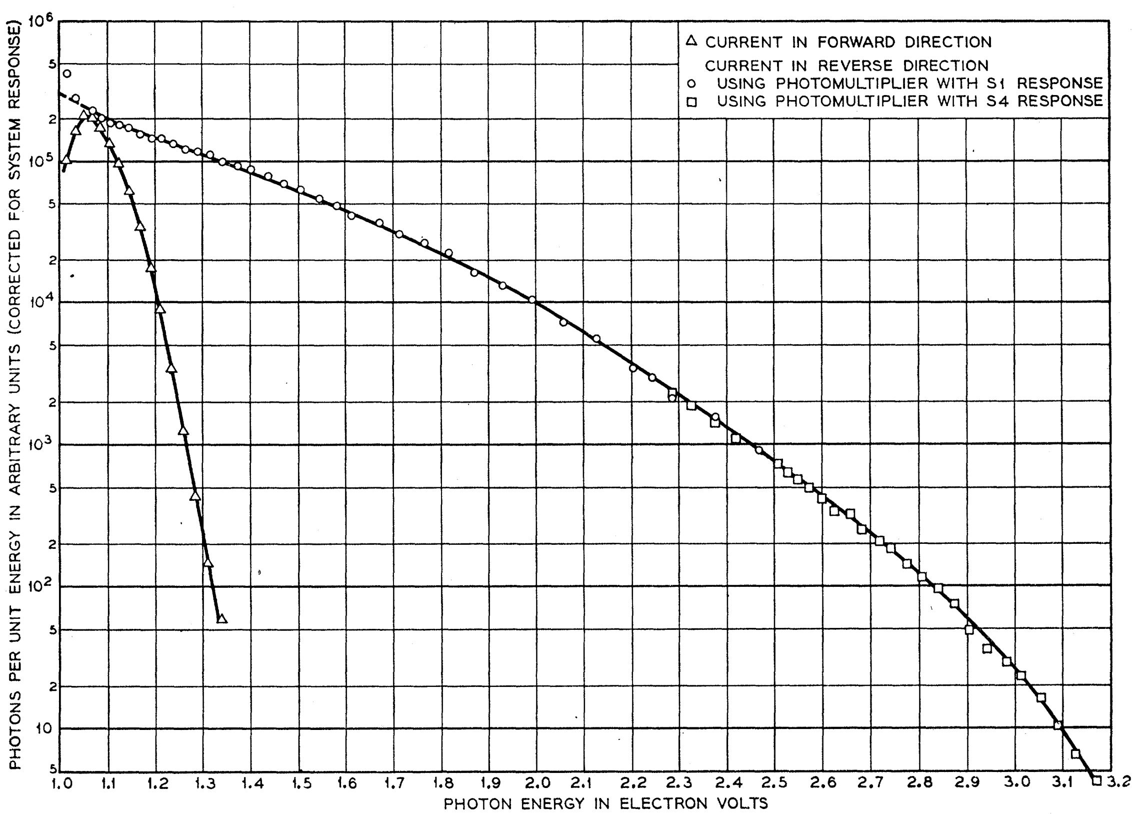

FIG. 6. The emission spectra for both forward and breakdown currents corrected for the spectral response of the spectrometer-photomultiplier system.

photons being detected by the photomultiplier. Knowing the solid angle for photon collection by the photomultiplier, an estimate was made of the total number of photons being emitted at the junction. Corrections were made for the refraction of the light and reflection losses at the crystal surface, for the variation in the spectral response of the photomultiplier, its efficiency, and for attenuation of the light in traversing the two microns of silicon. It was estimated that roughly 7×10^{-9} photons were emitted in the visible part of the spectrum for every electron (or hole) traversing the junction. However, this figure should be regarded as highly tentative in the absence of a direct calibration of the detecting system.

EFFECT OF TEMPERATURE ON LIGHT EMISSION

The temperature studies have been somewhat qualitative but are nevertheless significant. First, the emission from both grown junctions and diffused junctions has been studied at approximately the temperature of liquid nitrogen. There is no observable change in the pattern of the light spots or their color from that observed at room temperature for the same breakdown current. Secondly, a diffused junction, such as that in Fig. 2, was operated at a small constant breakdown current which was sufficient to excite a considerable number of "red spots" but insufficient to heat the crystal appreciably. The crystal was then uniformly heated by an external heat source to approximately 300°C. No change in the pattern or color of the spots was observed. The intensity decreased monotonically until extinction when the junction became intrinsic. Finally, the spectrum was measured at two different temperatures, 30°C and 175°C, using the photomultiplier with the S4 response, the results being shown in Fig. 7. The two spectra are normalized at their maxima so as to demonstrate more clearly the negligible variation of the visible spectral distribution with temperature.

EFFECT OF CURRENT ON LIGHT EMISSION

Observations of the light spots from diffused junctions at low currents, yield a straightforward picture. As the breakdown current is first increased, a few spots appear, either centrally located red spots or peripheral white spots depending on the junction. As the current increases, the number of spots increases. Following its appearance, a given spot does not increase much in intensity. The sequence is entirely reproducible and is not time dependent, i.e., it is a function only of the current. There is no observable change in the spectrum of the light.

Increasing the current still further, however, fre-

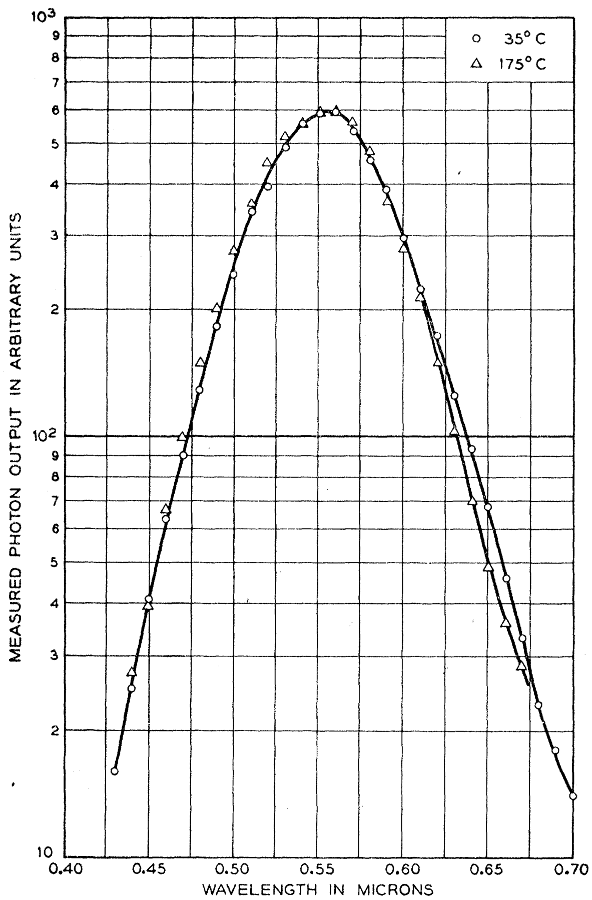

FIG. 7. Uncorrected emission spectra at two different temperatures, normalized at their peak values.

quently develops a more complex situation. The red spots near the crystal center may fade out while the number of white spots around the edges of the crystal increases. Finally the only light from the crystal may be the white emission from the junction edge which now looks almost continuous. If an air jet is now directed at the crystal to provide more cooling, the edge emission reduces and the red spots reappear. Similarly, if a high-level current step function is passed through a crystal which is initially at room temperature, the entire sequence is followed, the continuous white edge emission requiring several seconds to appear.

It seems evident that the high-current behavior is intimately associated with a temperature rise in the crystal. However, the behavior is different from that observed under the more controlled conditions considered in the previous section. It is believed that when the junction is heated by its own breakdown current, the heating is not uniform. The ionization rate decreases with increasing temperature[5] and the breakdown voltage goes up. If the temperature increases more in the interior of the crystal than around the edges, then the observed behavior should follow.

These experiments have a profound bearing on the interpretation of the current dependence of light emitted from the edge of grown junctions such as shown in Fig. 1. In measurements similar to those earlier reported,[1] we had also observed an increase in light from a grown junction as the current increased. However, when placed on a transient basis, it was evident that the light was time-dependent in the same manner as the edge emission from diffused junctions.

In deciding upon the detailed mechanism responsible for the light emission, it is desirable to fix the functional relationship between breakdown current and emission density. However, this cannot be determined unless the current change occurs without any change in the pattern of the light emission. Therefore measurements on the edge of grown junctions can never be so used since the whole of the junction is not accessible for observation. In fact, even with a diffused junction, it is seen that a current change is nearly always accompanied with at least a change in the number of emission spots and thus the relation between emission and current in a given spot has not yet been ascertained.

This often observed shift of the breakdown regions to the surface at high currents, resolves one problem posed by the grown junctions. Let us assume that about 100 μa flows through each breakdown region or microplasma,[5] and that with 100-ma crystal current the resultant 100 microplasmas are randomly (or uniformly) distributed throughout the junction. Since we can see light emission only from those spots that lie, say, within 5 microns of the surface, we should then be able to see on one side of a typical junction such as that of Fig. 1, about three spots. Actually we observe a nearly continuous line of microplasmas. We believe that this is independent evidence for a concentration near the surface of breakdown regions at high currents which is consistent with the spectral measurements of the previous section.

DETAILED MECHANISM

The above experiments determine that the observed light arises from within or extremely close to the junction itself. As previously understood, the breakdown at a *p-n* junction occurs at many highly localized spots rather than uniformly over the whole junction, with each of these spots carrying a current of from 50 to 100 μa. From the spot count of Fig. 2, the current per light spot was of the order of 100 to 200 μa and this reasonable agreement with the above figure makes it almost certain that in these junctions the light arises only from those spots where breakdown is occurring.

The studies of the light emission provide essential clues to the detailed mechanisms of its production. These mechanisms must account for the observed spectrum (and especially the emission of quanta of energy ≥ 3.3 ev, and ≤ 1.05 ev), the virtual insensitivity

[5] K. G. McKay, Phys. Rev. 94, 877 (1954).

of the emitted light to temperature variations, to junction width and to field distributions, the efficiency of the light emission and the size of the emitting spots.

The hypothesis that all the emission is due to local lattice heating does not stand up to critical inspection. As was pointed out in reference 1, considerations of thermal flow seem to eliminate this as a possibility. The color temperature of the light source appears to be $\sim 3000°K$ and as the boundary between light and dark regions is less than a few microns, the temperature gradient would be of the order of 10^6–10^7°K/cm. Furthermore, at temperatures of a few hundred degrees centigrade the crystal would become intrinsic making it impossible to maintain the normal breakdown potential whereas in fact, the latter was maintained.

Of various possible mechanisms, the one that best fits the above conditions at the high-energy end of the spectrum is direct recombination between essentially free holes and electrons in the breakdown microplasma itself. The mechanism of avalanche breakdown requires that some electrons and holes be accelerated up to energies sufficient to "ionize." Wolff[6] has concluded that the threshold for electron-hole pair production in silicon is about 2.3 ev and within the approximations used, is equal for electrons and holes. Thus, considering the light that arises from the radiative recombination of energetic electrons with holes in equilibrium with the lattice, the spectrum should equal the electron distribution function multiplied by the transition function. Similarly, for recombination between energetic holes and electrons in equilibrium with the lattice, the emitted spectrum is the product of the hole distribution function and the transition function. For both these processes, the maximum photon energy will be the sum of the "pair-production" energy and the energy gap since there is a negligible probability for the existence of carriers of energy in excess of 2.3 ev from the bottom of the energy band. Thus, the maximum photon energy will be $2.3+1.1=3.4$ ev, in agreement with observation.

It is also possible for recombination to occur between energetic electrons and energetic holes. Such interactions could produce, in theory, photons up to a maximum energy of $(2\times 2.3)+1.1=5.7$ ev; the probability of the occurrence of the highest energy photons should be vanishingly small.

To predict the shape of the spectrum to be expected on the basis of the above mechanisms would require a detailed knowledge of the transition probability functions and the distribution functions for both free electrons and holes. Since none of these functions are known at present we can say only that the observed spectrum is quite consistent with the above picture.

At the low-energy end of the spectrum, the above mechanism would require a rapid drop in the intensity at energies close to the energy gap since the minimum possible photon energy for interband recombination is the energy gap itself. Such a decrease in intensity cannot be discerned in the spectrum. In fact, the intensity increases continuously right through the gap energy of about 1.1 ev. To account for this it seems most likely that radiative intraband transitions by energetic electrons and holes are occurring. For such a process, one would expect a maximum photon energy of about 2.3 ev while there would be no measurable lower limit. At this stage it is not possible to predict the exact spectrum resulting from the superposition of the two mechanisms though one would expect, at least, an inflection point at some energy slightly higher than the energy gap. Our experiments failed to show the effect conclusively owing to the low intensity of the emitted light. It is intended to make more accurate measurements than were possible with the equipment used in the above experiments in the hope of resolving some structure in the spectrum.

The processes as described are essentially independent of temperature and also of junction width and field distribution. This is because avalanche breakdown is believed to be essentially unstable and the final state of the microplasma is primarily dependent on the properties of the silicon itself rather than on the distribution and concentration of impurities, donors, and acceptors.

To estimate the recombination cross section σ_r (integrated over the visible region of 2.0 ev to 3.4 ev), we have that

$$\sigma_r = Rv_d/\rho l v_r,$$

where R is the number of visible photons emitted per electron transit across the junction, ρ is the electron (or hole) density in the microplasma, l is the length of the microplasma, v_d/v_r is the ratio of drift velocity to random velocity of an electron in the microplasma. Although the details will not be presented here,[7,8] some simple assumptions lead to values of $\rho \simeq 10^{18}/\text{cm}^3$, $l \simeq 500$ A, and $v_d/v_r \simeq 0.25$. Hence, with $R \simeq 7\times 10^{-9}$ photons per electron transit, we obtain $\sigma_r \simeq 4\times 10^{-22}$ cm^2. As befits a rather improbable process, this is a satisfactorily small cross section. The fact that the spots are of less than 1 micron in diameter is consistent with the assumption that a microplasma is a few hundred angstroms in diameter.

CONCLUSIONS

The identification of the emitted light with radiative recombination between free holes and free electrons, and intraband transitions of energetic carriers in the breakdown region, is not only consistent with the known facts about the light, but also leads to further insight into the breakdown process. Pictures such as Fig. 2 provide striking evidence that breakdown occurs at many separate places. Once started, the microplasma (as the breakdown region has been called) does not

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

[7] See D. J. Rose and K. G. McKay, Phys. Rev. 99, 1648(A) (1955).

[8] D. J. Rose (to be published).

spread laterally through the junction but remains localized and a further current increase is accommodated by the incidence of more microplasmas. The occasional tendency for breakdown to occur preferentially along scratches (Fig. 2) suggests an effect of lattice damage on junction width; however, this has not been definitely established.

The light emission studies afford direct proof that under certain conditions of high current, the breakdown current in both grown and diffused junctions is confined to an extremely shallow surface layer.

It should be observed that the efficiency of energy transport by photon emission is here so low that photon emission does not play any appreciable role in the breakdown mechanism itself.

ACKNOWLEDGMENTS

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Intersection Faulting Mechanism Theory of Flow and Fracture of Face-Centered Cubic Metals

Robert B. Green
Research Laboratory, Baker & Company, Newark, New Jersey

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The intersection of any dislocation avalanche with a stationary dislocation having a Burgers vector component normal to the slip plane is shown to produce a close-packed partial plane of vacancies or interstitials in the slip plane, intrinsic or extrinsic faults for {111} slip planes. These faults have high energy in non-close-packed planes, consistent with observed slip plane preference. The mechanism gives improved understanding of recent x-ray results. Metallographic slip observations are consistent with the hypothesis that the etch indications are occurring at faults produced by the present mechanism. Fracture is postulated as resulting from the growth of "head-on" faults until transition occurs to the Griffith mechanism. Fault correction by partial slip produces additional dislocations, some potentially active as Frank-Read sources in the other slip planes. For copper, intrinsic or extrinsic faults are estimated to have energies of 40 ergs cm^{-2} and maximum widths of 400 A.

A DISLOCATION intersecting a stationary dislocation with a Burgers vector component normal to the slip plane receives a jog equal to that component. (For brevity, since such stationary dislocations produce a spiral ramp in the lattice, they will be called spiral-ramp dislocations in what follows.) In further motion, the jog trails vacancies (or interstitials, implied as an alternative when vacancies are discussed in what follows), spaced at intervals of $\csc\beta$ atomic spacings, where β is the angle between the trail and the Burgers vector of the moving dislocation.[1,2]

Fisher[3] has noted that when many identical screw dislocations consecutively intersect a perpendicular stationary crew dislocation, the trails of vacancies produced, each close-packed in this case, form a complete layer of vacancies, which, he proposes, with suitable normal tensile stress may act as a crack and propagate by the Griffith criterion.[4]

The Fisher suggestion may be generalized to include all dislocation intersections in which the stationary dislocation has a Burgers vector component normal to the slip plane. Each passing dislocation of Burgers vector b displaces the crystal on one side of the slip plane by a distance $b \sin\beta$ normal to the trail of its jog. This is also the distance between consecutive trails. The slip plane area per vacancy, proportional to the product of vacancy spacing, $\csc\beta$ atomic spacings, and trail width, $b \sin\beta$, is a constant, independent of the trail angle β. Regardless of the trail direction, when any series of identical moving dislocations consecutively intersects a stationary spiral-ramp dislocation, a complete, close-packed vacancy layer is produced.

Each vacancy trail may be treated as the extensions of the two sides of the moving dislocation back to the intersection point, one line above the other by the distance of the stationary-dislocation Burgers vector component normal to the slip plane, or may be considered as the line of parting, during slip, of the spiral-ramp crystal plane which characterizes the stationary dislocation. Taking the second view, Fig. 1 shows how repeated slip intersecting a spiral-ramp dislocation

[1] W. T. Read, Jr., *Dislocations in Crystals* (McGraw-Hill Book Company, Inc., New York, 1953), p. 87.
[2] F. Seitz, *L'Etat Solide*, edited by R. Stoops (76–78, Coudenberg, Bruxelles, 1952), p. 377.
[3] J. C. Fisher, Acta Metallurgica 3, 109 (1955).
[4] A. A. Griffith, Trans. Roy. Soc. (London) A221, 163 (1921).

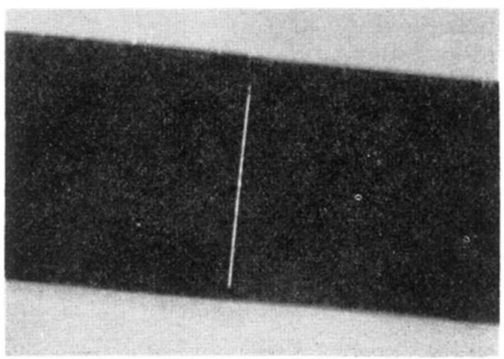

FIG. 1. A photograph of the light emission from a grown junction along the line in which the junction intercepts the surface.

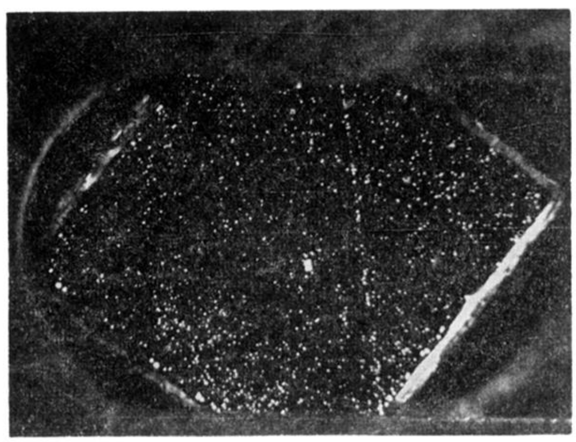

FIG. 2. A photograph of the light emission pattern from a junction diffused to a depth of about 2 microns below the crystal surface, as seen in the direction normal to the surface.

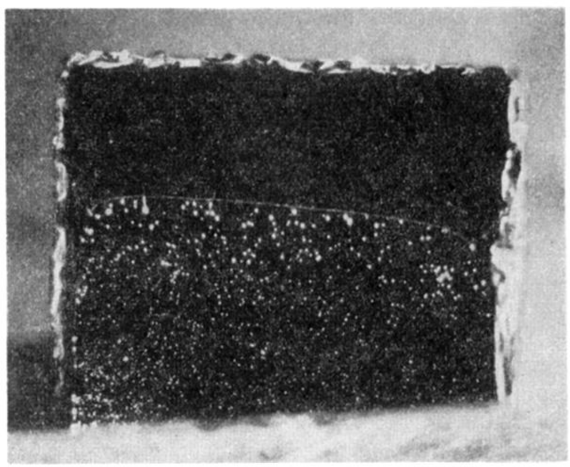

FIG. 3. A photograph of the light emission from a junction similar to that of Fig. 2 except that part of the surface has been ground off at an angle of one degree to the remainder. The sharp white line marking the boundary of the light spots indicates where the junction intercepts the sloping face.