Optical Studies of Injected Carriers. II. Recombination Radiation in Germanium

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The radiation produced by the direct recombination of electrons and holes in germanium is studied. The observed spectral distribution is in fair agreement with theory. For injection into high resistivity, as well as into doped material, the radiation is observed to be a linear function of injection current. Possible explanations for this are discussed. Magnetic concentration of carriers produced changes in the radiation intensity. Polarization of the radiation at oblique angles of emergence is observed.

THE radiation produced by the direct recombination of electrons and holes in germanium was observed by Haynes and Briggs.[1] The present work extends the study of this radiation. As in the preceding paper,[2] studies were made on two types of grown $p-n$ junction diodes cut with plane parallel faces; one in which the injection took place in high-resistivity material (40 ohm cm, n type), the other in which the injection took place in doped material (0.5 ohm cm, p type).

The experimental technique was as follows: The diodes were attached to water-cooled metal blocks which limited temperature rises to less than 10°C for the data quoted in this report. The diodes were pulsed by a 50 percent on-off square-wave generator operating in the vicinity of 350 cps. The radiation from the diodes was detected by a dry-ice-cooled PbS cell used in conjunction with an L-C tuned regenerative feedback amplifier and recording potentiometer. The spectral distribution curves were obtained using a Perkin-Elmer monochromator with a fused quartz prism.

Application of standard radiation theory indicates that the spectral distribution function $I(\nu)$ of recombination radiation from intrinsic material should obey the following relation:

$$I(\nu)\propto \nu^3 e^{-h\nu/kT}[1-e^{-\alpha_\nu d}].$$

Here α_ν is the absorption constant at frequency ν and d, the thickness of the material. Figure 1, shows the observed spectral distribution obtained for a diode and a curve calculated from the above relationship. The absorption data were taken from Briggs.[3] The agreement of observed and calculated curves is probably as good as can be expected. The discrepancy that exists might arise from a spectrometer calibration difference or from errors in the longer-wavelength absorption coefficients. The radiation from thicker diodes than that employed for the figure showed very slight displacements of the distribution curve toward lower frequencies as is to be expected.

If the radiation arises from the direct recombination of electrons and holes, then the intensity of total radiation from a small volume would be expected to be proportional to the $n-p$ product. It was of interest to test this hypothesis by variation of the diode injection current. Before discussing the results in detail, it is worth noting that currents as small as 1 milliampere (~0.03 amp/cm²) produced detectable radiation (signal/noise~4) using an $f/4$ optical system. Presumably, by using larger apertures even smaller currents could be detected.

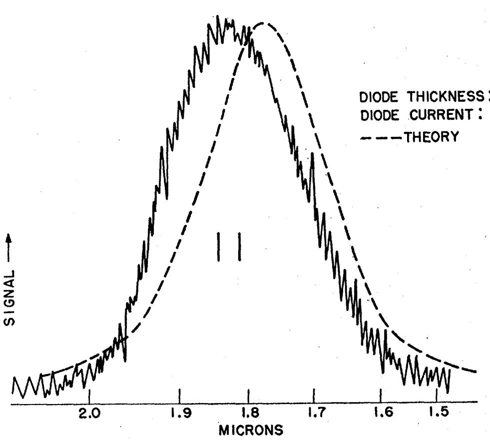

FIG. 1. Spectral distribution of recombination radiation in germanium at 25°C. The theoretical curve was normalized to have the same area under the curve as the experimental curve.

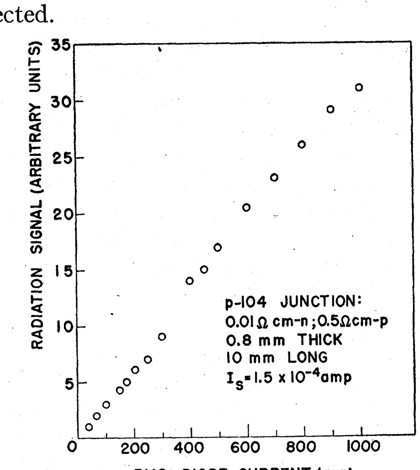

FIG. 2. Radiation signal as a function of diode current for injection into 0.5-ohm cm material.

[1] J. R. Haynes and H. B. Briggs, Phys. Rev. **86**, 647 (1952).
[2] R. Newman, preceding paper [Phys. Rev. **91**, 1311 (1953)]; referred to hereafter as I.
[3] H. B. Briggs, J. Opt. Soc. Am. **42**, 686 (1952).

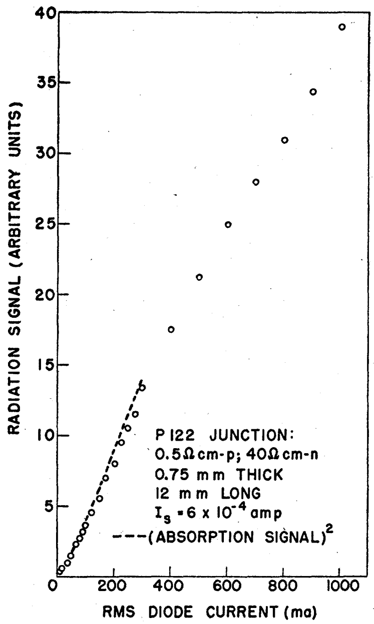

FIG. 3. Radiation signal as a function of diode current for injection into 40-ohm cm material. The dotted curve is the normalized square of the absorption signal obtained from the same diode.

Figure 2 shows typical radiation signal *vs* current data for a diode in which injection took place into doped material. It is essentially a linear relationship. This is understandable on the basis of simple diode theory. A calculation based on the observed reverse saturation current indicates that for forward currents up to the order of 1.5 amperes (rms) the majority carrier density will remain essentially constant. In other words, using the language of chemical kinetics, the expected bimolecular reaction, which produces the radiation, will operationally appear as first order in the minority carrier density, which is indeed what is observed.

In contrast to this case, it was anticipated that a study of the radiation *vs* current curve for injection into almost intrinsic material might yield more direct evidence for the bimolecular process. However, as Fig. 3 shows, the radiation *vs* current data for this case again gives an essentially linear relationship. As pointed out in I, simple diode theory can not be expected to apply for the range of currents used here. If the interpretation of the data for the absorption of injected carriers is correct, then a nonlinear relationship between injected carrier density (equals total carrier density for regions of interest) and current is indicated. As was suggested in I, empirically, the square of the carrier density, as observed by optical absorption, is linear with current. This is shown as the dotted curve of Fig. 3. In consequence, the radiation would then be expected to be also linear with current if it arises from the bimolecular process. For both classes of injection, negative departures from linearity would be expected at higher-current levels.

As an interesting sidelight to the recombination problem, it has been observed that changes in the radiation signal could be produced by introducing a large magnetic field (20 kilogauss) perpendicular to the direction of current flow. When the magnetic field deflected carriers away from the surface seen by the detector, increases in radiation signal as large as 30 percent could be observed. Conversely, when the field deflected carriers toward the surface seen by the detector, decreases as large as 40 percent could be observed. The percent changes in signal showed a dependence on the current level. However, because the effect was rather poorly reproducible in its quantitative detail, this dependence was not studied as fully as would have been desirable. The experiment may be considered an optical analog of the Suhl effect. The changes in signal level presumably result from changes in the ratio of radiative to nonradiative recombinations.

Germanium has a refractive index of approximately 4. This implies that all radiation seen external to a plane surface was originally directed within a cone whose axis is the surface normal and with a 14.5° half-angle. All other radiation is totally reflected. Using Snell's Law, one can calculate how the radiation within the cone is dispersed on passing through the surface. The intensity of radiation in a given plane of refraction and at a fixed distance from the radiating diode should be proportional to $\cos\psi/\cos\phi(T_p+T_s)$, where ψ is the angle of external refraction, ϕ the angle of interior incidence, and T_p and T_s are the transmission coefficients for light polarized, respectively, parallel and perpendicular to the plane of incidence. The experimental data are satisfactorily fitted by this relationship.

Radiation emerging from the germanium at angles of refraction differing from 0° is polarized by the refraction. At the Brewster angle ($\sim$75°) the ratio T_p/T_s is calculated to be 4.5. For a diode which, just prior to measurement had received a metallographic polish, the value 3.3 was observed as the ratio of the intensities of parallel and perpendicular components at the Brewster angle. The discrepancy between the observed and calculated ratio is perhaps the result of the visible slight imperfections which remained in the surface after the polishing. No great pains were taken to see how high a ratio could be obtained. It is of interest to note that the polarization ratio for a diode that had been lying around the laboratory for several weeks could be raised from 1.3 to 2.5 by chemical etching. This implies the presence of a surface film of at least 1000A thickness prior to the etch. The film may have been accidentally acquired. Rank and Cronemeyer[4] report a related phenomenon.

It is a pleasure to acknowledge the assistance of R. L. Watters, who designed the amplifier used in this work and that of the preceding paper. Dr. R. N. Hall was an agreeable source of samples and ideas, both of high quality.

[4] D. H. Rank and D. C. Cronemeyer, Phys. Rev. **90**, 204 (1953).