INDIRECT BAND-TO-BAND AUGER RECOMBINATION IN Ge[†]

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A high-energy photon emission from Ge is observed at a photon energy of about $2E_g$. It is concluded from dependence on energy, temperature, and carrier density that a hole is brought into the split-off valence band by indirect band-to-band Auger transition. Here the hole "thermalizes" and is able to recombine with an electron in the conduction band, emitting a photon.

Band-to-band Auger transitions are known in semiconductors with a low, direct energy gap such as InSb. Not known as yet are band-to-band Auger transitions in semiconductors with an indirect, relatively high energy gap such as in the case of Ge. Observation of band-to-band Auger transitions in Ge are reported in this paper.

The thermal activation energy E_a for Auger recombination in InSb[1] may be calculated by means of the theory of Beattie and Landsberg[2] assuming transitions from heavy to light holes.[3] This theory is not applicable in the case of Ge, however, because it assumes a simple band structure. On the other hand, E_a can be estimated from impact ionization; the threshold for this process is known to be 1.1 eV.[4] This energy must be equal to the energy of the Auger particle, namely E_a+E_g. Consequently, E_a is expected to be equal to 0.4 eV. This energy is large compared with the average thermal energy. Hence direct band-to-band Auger recombination in Ge should be a small effect only depending strongly on temperature. The Auger recombination will be demonstrated from observation of high-energy photon emission of Auger particles, since the contribution of Auger recombination to lifetime is small.

Carriers are injected into a slice of Ge by an alloyed p-n junction and photon emission is observed from the side opposite to the p-n junction. The distance between p-n junction and surface is large (50 μm) compared with the penetration depth of the observed 1.2-eV photons. The results presented are obtained using photodiodes from Telefunken type OAP 12 (n-Ge). Qualitatively, the same results are obtained by using p-Ge. A Si microplasma diode is used to detect the radiation[5] because of the low sensitivity of common photomultipliers. Figure 1 shows the energy dependence of the intensity N of photon emission. The exponential dependence shows that this is a high-energy tail of radiative band-to-band recombination. From the dependence on temperature and injection current it is concluded that the emission is not the tail of the well known recombination radiation. From the dependence of photon emission at $h\nu=1.2$ eV on temperature following $\exp(-E_a/kT)$, an activation energy $E_a=0.23\pm0.03$ eV is determined, while for the normal recombination radiation one would expect an activation energy $E_a=h\nu-E_g=0.5$ eV. (The peak intensity of the normal recombination radiation near 0.7 eV was found to be almost temperature independent.) Comparing the dependence of the photon emission at 1.2 eV on injection current in Fig. 2 with that at 0.7 eV, we get no linear connection but a quadratic one. Therefore the intensity at 1.2 eV is proportional to n^2p^2, i.e., two electron-hole pairs are required for the emission of one photon.

The experimental results are explained as follows: By band-to-band Auger recombination a carrier is brought into a higher conduction-band minimum or lower valence-band max-

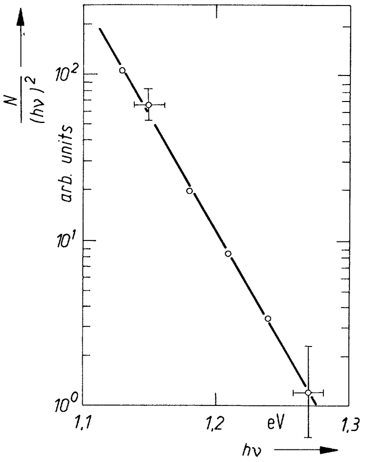

FIG. 1. Dependence of normalized emission intensity on the photon energy at temperature $T=363$°K.

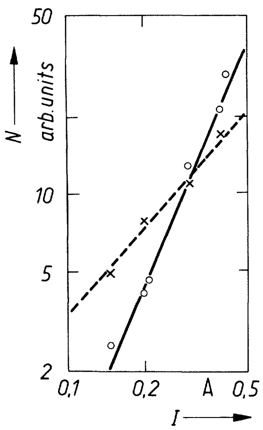

FIG. 2. Dependence of emission intensity on injection current. Straight line, $h\nu = 1.2$ eV; dashed line, $h\nu = 0.7$ eV.

imum. The probability for this event is proportional to n^2p or np^2, respectively. In this band extremum the carrier "thermalizes" and is able to recombine radiatively with a carrier of the opposite sign. Thus the probability of photon emission is proportional to n^2p^2 in agreement with the result given in Fig. 2.

Since the observed activation energy is less than 0.4 eV, we assume that the Auger recombination is not a direct process as described by Beattie and Landsberg, but an indirect one. Momentum conservation is satisfied by participation of a phonon, so that no activation energy is necessary for the Auger recombination. The occurrence of the direct process as observed in impact ionization experiments at room temperature is not in contradiction to our explanation. In these experiments electrical fields are used which cause an electron temperature as high as some thousands of degrees Kelvin.[6] As in the case of radiative recombination in Ge the indirect process is predominant at low temperatures, while at high temperatures the direct process is predominant. Since in the Auger recombination no activation energy is necessary, the observed activation energy should be equal to the energy difference between the observed photon energy and the low-energy limit of the emission band. For this limit we get 0.95 ± 0.03 eV. This value is in good agreement with the energy difference between the absolute conduction-band minimum and the maximum of the split-off valence band. According to Lax and Halpern[7] this value is 0.94 eV. From this result it is concluded that the Auger particle is a hole.

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ANALYSIS OF CRITICAL POINTS OF GRAPHITE FROM TEMPERATURE-MODULATED REFLECTANCE

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The optical properties of graphite are known from absorption and reflectivity experiments[1] over a wide range of wavelengths, though the absolute measurements are not sensitive enough to allow a definite assignment of the observed structure to transitions at critical points in the calculated band structure.

In this Letter we report the differential reflectance of graphite crystals measured in the energy range 4-6.5 eV by modulating the optical constants of the crystals with temperature.[2] The results indicate that the strong peak around