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Recombination Emission in InSb[†]

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Optically excited recombination emission has been studied for n- and p-type single-crystal samples of InSb at 77 and 4.2°K. Emissions associated with band-to-band transitions, transitions with creation of an optical phonon, and transitions involving acceptor impurities have been observed. The band-to-band emission in the pure samples can be attributed to direct transitions, whereas the emission in samples of high donor concentrations clearly shows transitions violating wave-vector conservation. The emission of phonon-assisted transitions is about 150 times weaker than that of direct transitions; this ratio is consistent with the strength of polar-mode coupling. The n-type as well as the p-type samples show an emission band due to electron transitions from the conduction band to some impurity level at 7.5 meV above the valence band, and the emission is much more prominent in the Zn-doped samples. Germanium-doped p-type samples show a weak emission band associated with an acceptor level at 17 meV above the valence band. Samples of large donor concentrations show the effect of band tailing. The main impurity emission increases linearly while the band-to-band emission increased quadratically with the intensity of exciting light. From the shift and splitting of the emission under applied magnetic field, an electron effective mass of $m_e \sim 0.018m$ and an electron g factor of $|g| = 40$ at 30 kG are obtained. Electroluminescence has been observed in p-type crystals under pulsed electric fields of $\sim$60 V/cm. The observed spectrum appears to be a broadened impurity line. The emission is more than an order of magnitude weaker than optically excited emission corresponding to the same sample conductance.

I. INTRODUCTION

RECOMBINATION emission from indium antimonide was studied by Moss[1] at room temperature using optical excitation. A relatively broad band with a peak at 7–8-μ was observed which was apparently associated with band-to-band recombination. Emission from p-n junctions due to electrical injection was studied by Guillaume and Lavallard.[2] Measurements were made at low temperatures down to 4°K. Recombinations via impurities and phonon-assisted transitions were identified in addition to band-to-band transitions. The effects of an applied magnetic field on the emission spectrum were investigated, and the results were interpreted in terms of spin splittings of a donor impurity level and the lowest Landau level of the conduction band. It was also shown that the spectrum broadened due to electron degeneracy at large concentrations. In a later work using optical excitation,[3] the authors found a narrowing of emission spectrum in pure n-type samples at high levels of excitation and attributed the effect to more efficient thermalization of the excited electrons in the presence of a large concentration of excited holes. Recently, Pehek and Levinstein[4] made studies on n-type and p-type single crystals at various temperatures using optical excitation. Evidence for transitions violating wave vector conservation was found from emission spectra of samples with large electron concentrations. Phonon-assisted recombination and emission involving various impurities were observed. Also, some narrow lines were found to be superimposed on the intrinsic emission band. Beside these few studies, there is a number of publications on stimulated emission in InSb which was first observed from junction diodes with electrical injection.[5–8] It has been obtained also by using electron bombardment[9] as well as optical excitation.[10]

We have studied spontaneous emission from uniform n- and p-type single crystals for the purpose of obtaining further information and better understanding of the emission processes. The results are presented and discussed in the following.[11] Measurements were made at 77 and 4.2°K; a few measurements were made at $\sim$1.5°K. Optical excitation was used for the most part. Measurements were made on samples of various carrier concentrations, the effects of an applied magnetic field, up to 30 kG were investigated, and the dependence of emission on the intensity of exciting light was studied.

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[2] C. Benoit à la Guillaume and P. Lavallard, in *Proceedings of the International Conference on the Physics of Semiconductors, Exeter, 1962* (The Institute of Physics and the Physical Society, London, 1962), p. 875.

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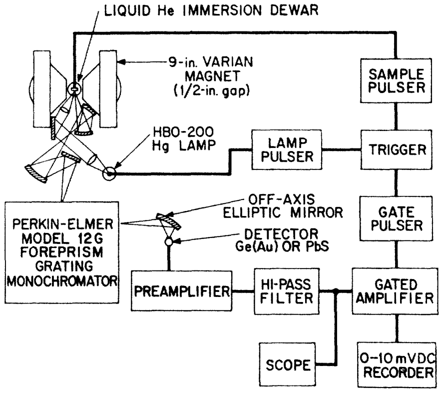

FIG. 1. Schematic diagram of the experimental arrangement. The sample pulser was used in the electroluminescence measurements.

The effects of an applied electric field on the photoexcited emission was also examined. Electroluminescence produced by a pulsed electric field in single crystal samples was observed and studied to some extent.

II. EXPERIMENTAL TECHNIQUES

Samples were prepared by lapping and then etching in a CP_4 solution. The samples were then directly immersed in the coolant and excited optically by a pulsed high-pressure mercury lamp which was operated at 15 pulses per second with 150-μsec pulse duration and 10-kW peak power. Figure 1 shows the experimental arrangement. Recombination emission was collected from the same side of the sample on which the exciting light falls and was analyzed by a Perkin-Elmer single-pass fore-prism grating monochromator. The emission was detected by a p-type gold-doped germanium photoconductive detector operating at 77°K. The output signal from the detector preamplifier was fed to a gated differential amplifier operating as a phase-sensitive detector. During the on time, the gated amplifier passed both signal pulse and noise while the noise was rejected during the off time. The integrated output signal on a dc recorder showed a two-order-of-magnitude improvement in the signal-to-noise ratio. Resolutions better than 5×10^{-4} eV could be used for the strong emissions measured. The glass helium immersion Dewars were able to fit into a $\frac{1}{2}$-in. gap of a Varian 9-in. magnet. The tail piece which held the liquid helium with the immersed sample was made from sapphire or single-crystal magnesium oxide. The arrangement allowed photoluminescence measurements to be extended to 10 μ, 1.2°K, and 30 kG.

In the measurements of the dependence of emission on excitation, the exciting light intensity was varied by using a circular variable neutral density filter. This allowed a uniform reduction of the exciting light intensity without either altering the image pattern on the sample or changing the spectral distribution.

Care was taken to prevent the water vapor absorption bands from affecting the observed spectra. These absorption bands were completely eliminated by flushing the entire closed optical system with dried air obtained by passing compressed air through columns of molecular sieves. Carbon dioxide bands could also be eliminated for a short time with fresh molecular sieves.

III. THEORETICAL BACKGROUND

Intrinsic Emission, Direct Transitions

The exciting light generates electron-hole pairs. The number of excess carriers obtained is determined by the hole-electron recombination rate which is usually dominated by nonradiative processes. We are interested primarily in the radiative recombination produced by optical transitions. Optical transitions in which the sum of electron and photon wave vectors is conserved are called direct transitions as against indirect transitions which violate the wave-vector conservation. In dealing with optical radiation, the photon wave vector may be neglected in this consideration. Only direct transitions are allowed when the effects of lattice imperfections and lattice vibrations are negligible.

The emission spectrum given by direct transitions of hole-electron recombination can be expressed by

$$I(h\nu)\propto\nu^2\int_S |M(\mathbf{k})|^2 f_e(\mathbf{k})f_h(\mathbf{k})\frac{dS}{|\nabla_k(\epsilon_e+\epsilon_h)|}, \qquad (1)$$

where $I(h\nu)$ is the intensity per unit range of photon energy, M is the transition matrix element, $f_e(\mathbf{k})$ and $f_h(\mathbf{k})$ are, respectively, the electron and hole distribution functions, and S is the surface corresponding to the energy $\epsilon_e(\mathbf{k})+\epsilon_h(\mathbf{k})=h\nu-E_g$ in the wave-vector ($\mathbf{k}$) space. In the case where the extrema of the conduction and valence bands coincide at $\mathbf{k}=0$ and have each spherical surfaces of constant energy, the expression reduces to

$$I(h\nu)\propto\nu^2|M|^2f_ef_h\rho, \qquad (2)$$

where ρ is the density of states per unit range of transition energy $h\nu$, and M, f_e, f_h, and ρ are functions of $h\nu$. For energy bands with constant effective masses, $\rho\propto(h\nu-E_g)^{1/2}$. If optical transitions are allowed at the band extrema as it is in our case, $|M|^2$ might be taken approximately as constant, and we get

$$I(h\nu)\propto\nu^2(h\nu-E_g)^{1/2}f_ef_h. \qquad (3)$$

The distribution function, f_e or f_h, is in general different from the equilibrium distribution for the same concentration of carriers since carriers are generated continuously by a nonthermal process. For simplification, f_e and f_h will be approximated by the thermal distribution which is equivalent to assigning a quasi-Fermi level to each type of carrier. This approximation may be referred to as thermalization of carriers. When the carrier concentrations are sufficiently low for classical distributions to apply, we get

$$I(h\nu)\propto\nu^2(h\nu-E_g)^{1/2}\exp[-(h\nu-E_g)/kT]. \tag{4}$$

The electron effective mass in InSb is very small. In *n*-type samples, the electron distribution is highly degenerate at liquid-helium temperature. This is also true for the *p*-type samples under the intense excitations used. On the other hand, the hole distribution may be considered nondegenerate in most of the experiments. Under such conditions, we have

$$I(h\nu)\propto\nu^2(h\nu-E_g)^{1/2}\exp\left[-\frac{m_e}{m_e+m_h}\frac{h\nu-E_g}{kT}\right]$$
$$\times\left\{\exp\left(\left[\frac{m_h}{m_e+m_h}(h\nu-E_g)-\zeta\right]/kT\right)+1\right\}^{-1}, \tag{5}$$

where ζ is the quasi-Fermi level of the electrons. Since $m_h\gg m_e$, the degenerate electron distribution gives at low temperatures a sharp cutoff for the emission at $(h\nu-E_g)\sim\zeta$. The hole distribution does not influence the emission spectrum strongly unless the electron concentration is so high that $\zeta\gtrsim[(m_h+m_e)/m_e]kT$.

Electrons and holes may recombine via exciton states with the emission peak at a photon energy lower than the energy gap by the exciton binding energy. The exciton binding energy is very small in InSb, and it will be shown that there is no clear evidence of exciton emission in the results obtained. The electron-hole attraction which gives rise to exciton bound states affects, however, the free-carrier states also. In view of this effect, the spectrum should be modified by the factor[12]:

$$\pi\Delta e^{\pi\Delta}/\sinh\pi\Delta,\quad\text{where}\quad\Delta=[(h\nu-E_g)/R_{\text{ex}}]^{-1/2}, \tag{6}$$

and R_{ex} is the exciton binding energy. With the additional factor, $I(h\nu)$ approaches a finite value instead of zero at $h\nu=E_g$, and the emission falls off faster with increasing $h\nu$.

Intrinsic Emission, Indirect Transitions

The emission spectrum due to indirect transitions is given by

$$\epsilon_e=h\nu-E_g\,,$$

$$I(h\nu)\propto\nu^2\int f_e(\mathbf{k}_e)d\mathbf{k}_e\int_S|M(\mathbf{k}_e,\mathbf{k}_h)|^2f_h(\mathbf{k}_h)\frac{dS}{|\nabla_{\mathbf{k}_h}\epsilon_h|}, \tag{7}$$

where S is the surface in $\mathbf{k}_h$ space corresponding to the energy $\epsilon_h(\mathbf{k}_h)=h\nu-E_g-\epsilon_e(\mathbf{k}_e)$. We have in mind mainly indirect transitions due to the presence of impurities or lattice imperfections, since the experimental results show that indirect transitions become important in more impure samples. In the case of indirect transitions due to lattice vibrations, the phonon involved enters into the energy consideration. However, the energy of acoustical phonons involved is small compared to the electron energies. Optical phonons may produce transitions at appreciably smaller photon energies, and this effect will be considered in Sec. IV as phonon-assisted emission. Let $|M(k_e,h\nu)|^2$ be the average value of $|M(\mathbf{k}_e,\mathbf{k}_h)|^2$ over the surface S, and let $|M(\epsilon_e,h\nu)|^2$ be the average value of $|M(k_e,h\nu)|^2$ over the surface of constant ϵ_e in the $\mathbf{k}_e$ space. For the simple model of parabolic energy bands with band edges at $\mathbf{k}=0$, the expression becomes:

$$I(h\nu)\propto\nu^2\int_0^{h\nu-Eg}|M(\epsilon_e,h\nu|^2f_e(\epsilon_e)$$
$$\times f_h(h\nu-E_g-\epsilon_e)\epsilon_e{}^{1/2}(h\nu-E_g-\epsilon_e)^{1/2}d\epsilon_e. \tag{8}$$

Calculation of the matrix element M is the difficult part of the problem. If $|M|^2$ is approximately constant, then the spectrum is simply

$$I(h\nu)\propto\nu^2(h\nu-E_g)^2\exp[-(h\nu-E_g)/kT], \tag{9}$$

in case both the electrons and holes have classical distributions. The spectrum is given by

$$I(h\nu)\propto\nu^2\int_0^{h\nu-Eg}[\epsilon(h\nu-E_g-\epsilon)]^{1/2}$$
$$\times\exp\left[-\frac{h\nu-E_g-\epsilon}{kT}\right]d\epsilon \tag{10}$$

in case the electrons distribution may be considered as perfectly degenerate. Actually, the crude approximation $|M|^2=\text{const}$ cannot be expected to give satisfactory results. This point will be discussed in Sec. IV in connection with the experimental observation.

Impurity Emission

Transitions of carriers from one energy band to impurity levels near the opposite band give rise to emission with $h\nu$ slightly smaller than E_g. Using the effective-mass theory of impurity states, Eagles[13] calculated the emission spectrum for transitions involving the impurity ground state:

$$\begin{aligned}I(h\nu)&\propto\nu^2(X^{1/2}/(1+X)^4)f(h\nu-E_g+E_i)\,,\\X&=(m_1/m_2)(h\nu-E_g+E_i)/E_i\,,\end{aligned} \tag{11}$$

where f is the carrier distribution function, E_i is the impurity ionization energy, m_1 and m_2 are the effective masses of the carrier band and the opposite band, respectively. For electron transitions to acceptors levels near the valence band, $m_1/m_2=m_c/m_v\ll1$, giving

$$I(h\nu)\propto\nu^2(h\nu-E_g-E_i)^{1/2}$$
$$\times\{\exp[(h\nu-E_g+E_i-\zeta)/kT]+\}^{-1}. \tag{12}$$

This expression resembles (5) with a shift of $h\nu$ by E_i.

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[12] R. J. Elliott, Phys. Rev. **111**, 1518 (1958).

[13] D. M. Eagles, J. Phys. Chem. Solids **16**, 76 (1960).

As pointed out before, the extra term representing the hole distribution in (5) does not have an important effect.

Correction for Self-Absorption

The exciting light is absorbed near the sample surface within a depth of less than a micron. The excited carriers diffuse into the sample and recombine within a depth determined by the diffusion. In the case of intrinsic emission, the photons emitted can be strongly absorbed on their way out of the crystal, and correction has to be made in order to obtain the true emission spectrum. With a sample thickness large compared to the diffusion length, the ratio of the observed and true intensities is given by

$$\frac{[I(h\nu)]_{\text{obs}}}{[I(h\nu)]_{\text{true}}}=\int_0^\infty [\Delta n(x)]^p \exp[-\alpha(h\nu)x]dx, \quad (13)$$

where $\Delta n(x)$ is the concentration of excess carriers as a function of distance x from the surface and $\alpha(h\nu)$ is the absorption coefficient for emitted photons of energy $h\nu$. $p=1$ if Δn is small compared to the majority carrier concentration, and $p=2$ otherwise. It can be shown that

$$\Delta n(x)\propto\left[\frac{\alpha' L^2+S\tau}{L+S\tau}e^{-x/L}-e^{-\alpha' x}\right], \quad (14)$$

where α' is the absorption coefficient for the exciting light, L is the diffusion length of the excited carriers, S is the surface recombination velocity, and τ is the lifetime of excess carriers. The expression applies under the condition $\alpha' L\gg 1$ which is valid for our measurements with $\alpha'\gtrsim 10^4$ cm^{-1} and $L\sim 10^{-3}$ cm. Substituting (19) in (18) and using the condition $\alpha' L\gg 1$, we get

$$[I(h\nu)]_{\text{obs}}/[I(h\nu)]_{\text{true}}\propto[\alpha(h\nu)L+p]^{-1}. \quad (15)$$

It should be pointed out that in samples with degenerate electron distributions the absorption edge is shifted to shorter wavelengths, and the absorption coefficient $\alpha(h\nu)$ used should be appropriate for the given condition. Self-absorption becomes important only as the photon energy extends into the shifted absorption edge. Thus, only the high-energy side of the emission spectrum of direct transitions is affected by self-absorption. At liquid-helium temperature, all the n-type samples and also the p-type samples under the exciting light can have degenerate electron distribution.

IV. EXPERIMENTAL RESULTS

A. Intrinsic Emission

At nitrogen temperature the observed emission spectra for nondegenerate samples can be interpreted as consisting mainly of intrinsic emission with a long-wavelength tail due to some unresolved impurity emission. Figure 2 shows the observed emission curve for a p-type sample. All p-type samples and n-type samples with $n<5\times10^{15}$ cm^{-3} showed similar spectra as shown by the solid curve in Fig. 2. According to expression (5) for direct transitions and thermalized carriers, the important parameters are the energy gap and the electron effective mass. Because of the large ratio of hole effective mass to electron effective mass, the hole distribution function does not change appreciably in the same energy region as the electron distribution. According to optical-absorption data, the energy gap can be expressed by[14]

$$E_g(T)=0.25-2.8\times10^{-4}T \text{ (eV)},$$

giving a value of 0.2285 eV at 77°K. Although the electron effective mass in InSb is energy-dependent, the variation is small within the energy range of interest.[15,16] The points in Fig. 2 are calculated using $E_g=0.229$ eV. $m_e=0.015$ m, and $m_h=0.45$ m. The dashed curve was obtained from the measured curve by applying a correction for self-absorption. The correction was calculated from (15) using the available absorption data[17] for InSb at 80°K and an estimated value of 3×10^{-3} cm for the diffusion length. The corrected curve fits the calculated points, the long-wavelength tail being given by impurity emission. The fit supports the model of direct transitions and thermalization of excited carriers. Indirect transitions on the other hand should give a peak at a photon energy higher by 10 meV than the calculated points which is clearly incompatible with the observed spectrum.

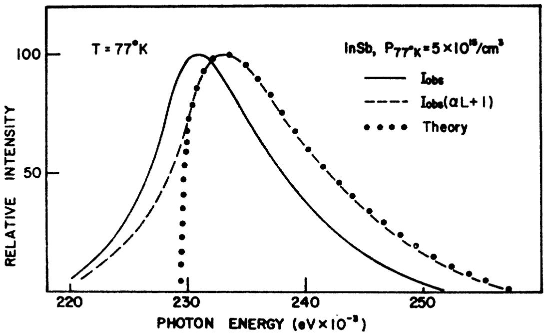

FIG. 2. Normalized emission spectrum for a p-type sample at 77°K. The solid curve is the measured spectrum. The dashed curve is the spectrum after correction for self-absorption. The points are calculated for direct transitions.

For degenerate n-type samples, the measured emission extended to higher photon energies. The intensity fell to half of its peak value at 0.2424 eV in a sample of $n=1.4\times10^{16}$ cm^{-3} and at 0.2556 eV in a sample of $n=5\times10^{16}$ cm^{-3} while the half-intensity in the solid curve of Fig. 2 corresponds to 0.2380 eV. Figure 3

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[14] I. G. Austin and D. R. McClymont, Physica **20**, 1077 (1954).

[15] W. G. Spitzer and H. Y. Fan, Phys. Rev. **106**, 882 (1957).

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[17] G. W. Gobeli and H. Y. Fan, Phys. Rev. **119**, 613 (1960).

shows that emission observed for the sample of $n = 5\times10^{16}$ cm^{-3} fits reasonably the spectrum calculated from (5) neglecting the effect of self-absorption. The sample is degenerate, having a Fermi level $\zeta \sim 30$ meV. The effect of self-absorption should be small at the low-energy end of the spectrum. However, self-absorption would produce an increasing reduction of emission beyond $h\nu \sim E_g + \zeta - 2kT = 0.245$ meV. The observed spectrum does not seem to be sufficiently lower than the calculated curve to account for this effect. The results obtained at liquid-helium temperature show clearly that the model of direct transitions becomes inadequate with increasing carrier or impurity concentration.

At 4.2°K, the emission spectrum sharpened considerably. In the p-type samples, the holes are frozen out at the low temperature. The half-width of intrinsic emission for all the samples was observed to be 3.1 ± 0.4 meV. In the n-type samples with $n < 1\times10^{14}$ cm^{-3} the half-width was <2 meV. The spectrum for the purest n-type sample is shown in Fig. 4. The emission seems to be due to electron-hole rather than exciton transition. The half-width of the emission is several times the exciton binding energy of 0.7 meV, and in n-type samples with larger electron concentrations the width increased without giving an indication of exciton emission in the form of discernible structure. Exciton formation may be weakened by the screening effect of electrons. An electron concentration of 10^{15} cm^{-3} would give a Debye screening length of the order of the exciton Bohr radius. In order to resolve exciton emission, it may be necessary to use weaker excitation to reduce photo-excited electrons and to make measurements at lower temperature.

The observed emission in the p-type samples and in the n-type samples of low-electron concentrations may be attributed to direct recombination of thermalized electrons and holes. An electron concentration in the range 10^{14} to 10^{15} cm^{-3} would give a line width of the order 2-3 meV observed in these samples. This is illustrated in Fig. 4, where the points are calculated for an electron concentration of 3×10^{14} cm^{-3} using (5); a somewhat larger concentration would be needed to obtain the observed width if (6) is used and some allowance for self-absorption is made. It will be shown in Sec. IV. D that electron concentrations of this order were indeed obtained in the p-type samples under excitation. This should be the case in the n-type samples under excitation. This should be the case in the n-type samples also. The spectrum in Fig. 4 indicates that the energy gap has a value close to 0.234 eV as compared to the value (0.2357 ± 0.0005) eV deduced by extrapolation in the analysis of magnetoabsorption data.[18]

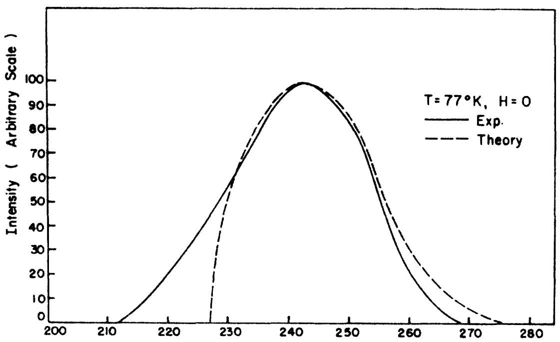

FIG. 3. Normalized emission spectrum for an n-type sample ($n = 5\times10^{16}$ cm^{-3}) at 77°K. The solid curve is measured. The dashed curve is calculated for direct transitions.

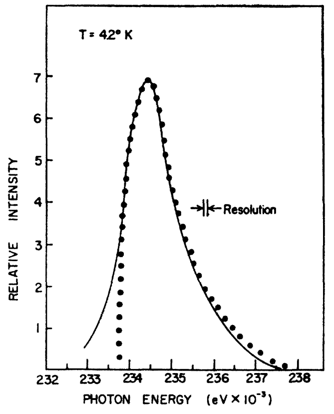

FIG. 4. Band-to-band emission spectrum for a pure n-type sample ($n = 5\times10^{13}$ cm^{-3}) at 4.2°K. The curve is measured. The points are calculated for direct transitions.

The above interpretation leads us to expect a narrowing of the emission line with decreasing intensity of excitation. In fact, a narrowing by 1 meV was observed in a p-type sample when the intensity of exciting light was reduced by a factor of 4. An opposite effect has been reported by Guillaume and Lavallard.[3] They found that the emission line in samples of low electron concentrations narrowed under stronger excitation. The effect was explained on the basis that the electrons were not thermalized under the "weak" excitation but became more thermalized with increasing excitation as a result of increased scattering by a larger number of photoexcited holes. In contrast, our experience has been that beginning with the highest excitation intensity obtainable, the emission tended to narrow with decreasing intensity in a range which was limited by the possibility of making measurements with a good constant resolution. The lack of thermalization of photoexcited carriers has been established by the observation of spectral oscillation of photoconductivity in p-type[19] as well as n-type[20] InSb. However, these measurements were made at far less intensities of excitation with monochromatic infrared radiation. We have no clear evidence that nonthermalization of

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[19] M. A. Habegger and H. Y. Fan, Phys. Rev. Letters **12**, 4 (1964); H. J. Stocker, C. R. Stannard, Jr., H. Kaplan, and H. Levinstein, *ibid.* **12**, 163 (1964).

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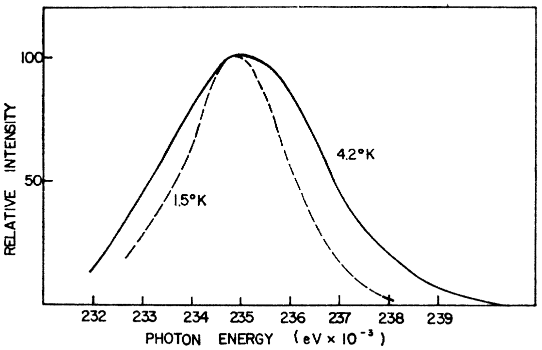

FIG. 5. Band-to-band emission spectra observed from an n-type sample ($n=5\times10^{15}$ cm^{-3}) at two temperatures, showing narrowing of the spectrum at the lower temperature.

excited carriers is important for the emission spectra under the excitations used in our experiments.

Measurements at 4.2°K were made on a number of n-type samples with carrier concentrations ranging from 5×10^{13} to 3.5×10^{17} cm^{-3}. The Fermi level ranges from 0.34 to 70 meV. The measured energy of the peak and the spectrum width at half-intensity are given in Table I. Assuming the holes to be thermalized, the spectrum width of direct transitions for an n-type sample of sufficiently large electron concentration should be limited to $\lesssim 25kT$ or 8.7 meV at 4.2°K. The sample with $n=1.4\times10^{16}$ cm^{-3} has a width of about the maximum value. However, the data for the last two samples in Table I show that the observed width kept increasing with the electron concentration. This is clearly inconsistent with the hypothesis of direct transitions and thermalized carriers. Nonthermalization of excited holes does not appear to be the cause of the large width, since more impure samples may be expected to have shorter thermalization times. The evidence indicates that indirect transitions occur in the highly impure samples. Pehek and Levinstein[4] came to the same conclusion from studies of impure n-type samples at 77°K.

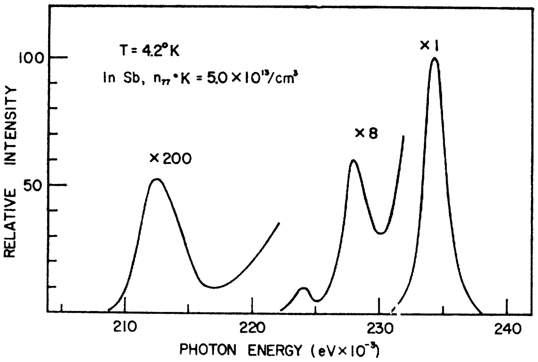

FIG. 6. Emission spectrum of a pure n-type sample ($n=5\times10^{13}$ cm^{-3}) at 4.2°K. The peak at ~234 meV is the band-to-band emission. The peak at 228 meV is the main impurity emission. The peak at 224 meV is due to some unknown impurity. The peak at 212 meV is due to phonon-assisted band-to-band transitions.

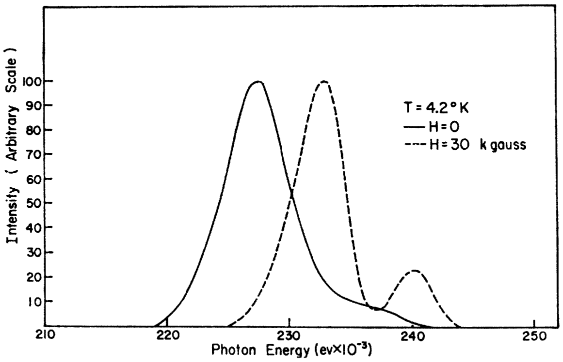

FIG. 7. Emission spectra of a p-type sample ($p=3.5\times10^{16}$ cm^{-3} at 77°K) at 4.2°K, with and without an applied magnetic field, H.

Indirect transitions seem to be important already in the sample of $n=1.4\times10^{16}$ cm^{-3}. At 1.5°K, direct transitions with thermal distribution of holes should have a width limited to ~3 meV. No appreciable narrowing was observed from the width of 8.5 meV when the sample was cooled from 4.2 to 1.5°K, whereas for the next purer sample ($n=4\times10^{15}$ cm^{-3}) appreciable narrowing was actually observed, as shown in Fig. 5.

The two impure samples have Fermi energies of 30 and 70 meV, respectively. The energy spread of holes and the spread of electron distribution near the Fermi level are comparatively negligible. According to (10), the emission should have a width equal to the electron Fermi energy, rising with $(h\nu-E_0)$ to a peak followed by a sharp drop. However, the observed spectrum widths are much smaller than the corresponding Fermi energies (see Figs. 6 and 7). Self-absorption in these highly degenerate samples can be significant only within a few kT of the Fermi energy and cannot be responsible for the discrepancy. The result indicates that the transition probability decreases for electrons of high energies. This conclusion might be expected for indirect transitions resulting from perturbation of the energy bands by impurities. The indirect transitions may be considered as a second-order process consisting of optical transition and carrier scattering by the impurity. The matrix element for impurity scattering is smaller for

TABLE I. The energy of the peak and the spectrum width at half-intensity are given for the intrinsic emission measured at 4.2°K for n-type samples of various electron concentrations.

Electron conc. (77°K)	Energy of peak (meV)	Fermi level (meV)	Linewidth at half-intensity (meV)
1. 5.0×10^{13}/cm^3	234.4±0.15	0.34	1.4
2. 7.0×10^{13}	234.6±0.15	0.42	2.0
3. 1.4×10^{14}	234.8±0.2	0.70	2.5
4. (4×10^{15})[a]	235.2±0.2	(6)	3.5
5. 1.4×10^{16}	236.0±0.5	15	8.5
6. 5.0×10^{16}	244 ±1	30	15
7. 2.5×10^{17}	253 ±2	70	30

[a] Hall value of this sample as given by the supplier was not checked by measurement.

larger $|\mathbf{k}_i-\mathbf{k}_f|$, where $\mathbf{k}_i$ and $\mathbf{k}_f$ are the initial and final wave vectors of the carrier. Furthermore, the probability of the second-order process is inversely proportional to the energy difference in the intermediate state: $(\hbar^2/2m^*)(k_i^2-k_f^2)$. With the holes restricted to small wave vectors, transitions are less probable for electrons of higher energies or larger wave vectors. The fact that the more impure sample had a still broader spectrum indicates that the probability of transitions with large changes of wave vector increases with increasing impurity concentration.

B. Impurity Emission and Band Tailing

It has been mentioned in connection with Fig. 2 that the low-energy tailing of the observed spectrum was due to impurity emission which gave a hump in some of the samples. The impurity emission became well resolved as a distinct band at 4.2°K. The band has a peak near 228 meV in both the *n*- and *p*-type samples as can be seen in Fig. 6 for an *n*-type sample and in Fig. 7 for a *p*-type sample. The band is more prominent in the Zn-doped *p*-type samples; for the sample shown in Fig. 7 the impurity emission is seen to be much stronger than the intrinsic emission. The results indicate that the emission is due to zinc acceptors and the ionization energy of the impurity is 7.5 meV. The ionization energy of the zinc acceptor has been previously estimated to be 8 meV from studies of the Hall effect.[21] Optical absorption[22] due to impurities of approximately such ionization energy has been observed in *p*-type samples as well as in *n*-type samples which were not intentionally doped with acceptor impurities.

The impurity emission band in the samples of low-carrier concentrations resembles in shape the intrinsic emission. This is consistent with the similarity of the expressions (12) and (5) pointed out before. Figure 7 shows that the impurity emission band in the *p*-type sample of 3.5×10^{16} cm^{-3} had a width of ~6 meV at half-intensity, which is significantly larger than the width of ~3 meV observed in the purer samples. The larger width may be indicative of a broadening of the acceptor level at large concentrations of the impurity. In *n*-type samples the impurity emission arises from residual acceptors, the concentration of which is not directly related to the concentration of the donor impurity. We may expect the impurity emission to extend to higher photon energy with increasing concentration of degenerate electrons as is the case with intrinsic emission. This is in fact the case, as a result of which the impurity emission increasingly merged with the intrinsic emission. Figure 8 shows that in the sample of $n=1.4\times10^{16}$ cm^{-3} the impurity emission became resolved only under the applied magnetic field. More interesting is the fact that the spectrum extended to lower photon energies with increasing electron concentration of the sample. This can be seen by comparing the spectra in Figs. 8, 9, and 10. It is a clear indication of a tailing of the conduction band due to the effect of donor impurity.

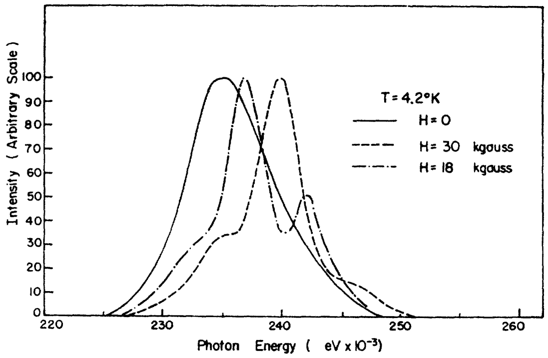

FIG. 8. Emission spectra of an *n*-type sample ($n=1.4\times10^{16}$ cm^{-3}) at 4.2°K measured with different applied magnetic fields *H*. The curves for $H\neq0$ show a hump on the low-energy side which corresponds to the impurity emission.

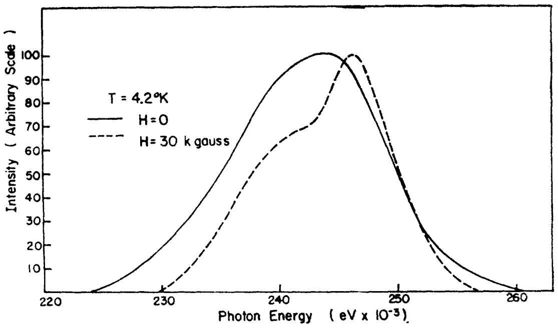

FIG. 9. Emission spectra of an *n*-type sample ($n=5\times10^{16}$ cm^{-3}) at 4.2°K measured with and without an applied magnetic field of 30 kG.

An additional emission peak at 216 meV was observed in samples specially doped with germanium.[23] The peak

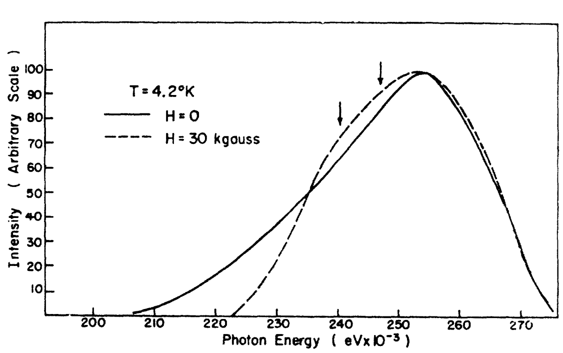

FIG. 10. Emission spectra of an *n*-type sample ($n=2.5\times10^{17}$ cm^{-3}) at 4.2°K. The dashed curve was measured with an applied magnetic field of 30 kG. The arrows indicate the estimated positions of emission from the spin-split first Landau level.

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[21] E. H. Putley, Proc. Phys. Soc. (London) 73, 128 (1959).

[22] E. J. Johnson and H. Y. Fan, Phys. Rev. 139, A1991 (1965).

[23] We are indebted to Texas Instruments for supplying us with this sample.

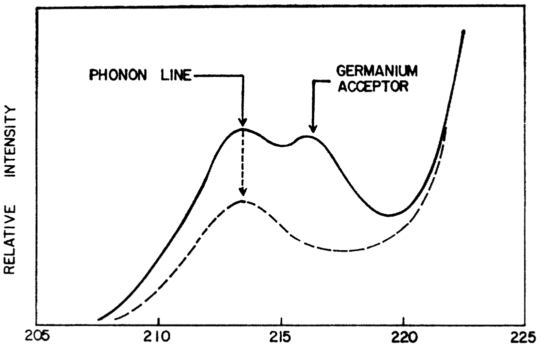

FIG. 11. Comparison of emission spectrum (solid curve) of a Ge-doped sample ($p=10^{14}$ cm^{-3} at 77°K) with that (dashed curve) of a p-type sample not containing Ge.

can be seen in the solid curve in Fig. 11 while it is absent in the dashed curve for a sample without germanium. Germanium can exist either as a donor or an acceptor in InSb.[24] The acceptor level has been estimated from electrical measurements to be about 10 meV above the valence band. The emission peak indicates that the ionization energy of the impurity is ~17 meV.

A line at 224 meV has been reported by other workers[2,4] and was attributed to emission involving an impurity. This line was detected in all the pure samples we measured at 4.2°K (see Fig. 6), and its intensity did not have any regular correlation with any of the other emission lines. We conclude in agreement with the previous workers that this line is due to some impurity or lattice defect which gives a level 11 meV from one of the band edges.

Weak and narrow absorption lines superimposed on the intrinsic emission were observed by Pehek and Levinstein and were attributed to transitions involving bound states which fall within one of the energy bands. We have observed similar features in the emission spectra. However, the observed modulation of emission could be completely eliminated by flushing the entire optical system with air free of water vapor.

C. Phonon-Assisted Emission

The presence of an emission line near 212 meV has been reported. In one case it was attributed to emission involving an impurity[2] while in the other case it was attributed to the electron-hole recombination accompanied by the emission of an optical phonon.[4] We observed the peak at 212.5 meV in all the pure samples at 4.2°K (see Figs. 6 and 11). Its intensity was always about 1/150 the intensity of the intrinsic emission line. The energy separation of about 22 meV between this peak and the intrinsic emission peak is in close agreement with the published[25] values of the optical phonon energy in InSb. Furthermore, the intensity of this line and that of the intrinsic emission had the same dependence on the intensity of exciting light. It appears, therefore, that this line is due to the band-to-band recombination assisted by the emission of an optical phonon from the center of the zone.

The probability for the free-carrier recombination emission to be accompanied by the creation of n optical phonons has been calculated by Hopfield[25]:

$$W_n \sim W_0 \frac{\frac{1}{2}\alpha}{n!}\left(\frac{kT}{\hbar\omega_0}\right)^{1/2}\frac{1}{n}, \tag{16}$$

where α is the heavy-carrier (hole) coupling constant, and $\hbar\omega_0$ is the optical-phonon energy assumed to be much larger than kT. The coupling constant is given by

$$\alpha=\left(\frac{m^*}{m}\right)^{1/2}\left(\frac{R_y}{\hbar\omega_0}\right)^{1/2}\left(\frac{1}{\epsilon_\infty}-\frac{1}{\epsilon_s}\right), \tag{17}$$

where $m^*=0.4m_0$ is the hole effective mass. Using the values $\hbar\omega_0=0.23$ eV, $\epsilon_\infty=15.68$, and $\epsilon_s=17.88$ for the dielectric constants, we get a coupling constant of $\alpha\sim0.11$ for the holes. According to (16), the observed ratio, 1/150, of one-phonon to zero-phonon peak corresponds to $\alpha\sim0.107$, which is in good agreement with the estimated value of 0.11.

A relatively broad emission band with peak at 200 meV has been reported for InSb.[2] It was interpreted as electron-hole recombination accompanied by the emissions of two transverse optical phonons. We have attempted to detect this emission without success. Such a band was seen when the grating monochromator alone was used, but it was eliminated by adding the fore prism. What we saw with grating monochromator alone appears to be given by the double diffraction of the intrinsic emission.

D. Dependence on the Intensity of Excitation

The intensity of emission as a function of the intensity of exciting light was studied for p-type samples at 4.2°K. Both the impurity and the intrinsic emissions were investigated. The monochromator was set for maximum emission signal and maximum slit was used in order to obtain measurements extending to lowest possible intensities. In connection with this study, the increase of conductance, ΔG, of the sample was also measured. The magnitude of ΔG provides a measure of the intensity of excitation.

A representative curve of ΔG is given in Fig. 12, showing that ΔG increased linearly with the intensity of excitation. It indicates that the excited carriers had a constant lifetime throughout this range. The largest

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[24] W. M. Bullis and V. Harrap, in *Proceedings of the International Conference on Semiconductor Physics, Paris, 1964* (Dunod Cie., Paris, 1964), p. 847.

[25] R. N. Hall and J. H. Racette, J. Appl. Phys. **32**, 2078 (1961).

[26] J. J. Hopfield, J. Phys. Chem. Solids **10**, 110 (1959).

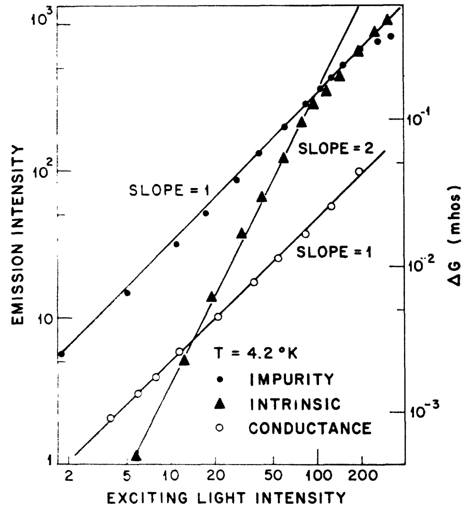

FIG. 12. The sample conductance ΔG and the intensities of the intrinsic and impurity emission as functions of the intensity of exciting light, measured on a p-type sample ($p=2\times10^{14}$ cm^{-3} at 77°K) at 4.2°K.

ΔG obtained with the pulsed exciting light varied between 0.1 and 0.01 mho. The sample was uniformly illuminated over the front surface, and the total number of excited electrons N in the sample may be calculated from the expression:

$$\Delta G=(e/l^2)\mu N, \qquad (18)$$

where l is the sample length and μ is the electron mobility. The contribution of holes to ΔG may be neglected because of their comparatively low mobility. Assuming a diffusion length of the order of 10^{-3} cm, a density of excited electrons within the diffusion layer is estimated to be of the order of 10^{15} cm^{-3} for a ΔG of 0.1 mho.

Figure 12 shows the observed dependence of emission intensity on excitation which is typical of the samples measured. Over most of the range, the impurity emission is proportional to the excitation, whereas the intrinsic emission varies as the excitation intensity squared. The intrinsic emission is proportional to the product of electron and hole concentrations. Since the normal concentration of free carriers is negligible in the p-type samples at low temperature, the concentration of either type of carriers is proportional to the intensity of excitation when the lifetime of excited carriers remains constant, as shown by the results on ΔG. Thus the intrinsic emission is expected to be proportional to the square of excitation. The impurity emission, on the other hand, should be proportional to the concentration of one type of carriers, the electrons, except when the population of the acceptor impurities undergoes a radical change with excitation. Such a change would take place within a limited range of excitation, and it apparently did not occur within the range of measurement.

At the high end of the excitation range, the measured impurity and intrinsic emissions appear to saturate. It is believed that rather than real saturation this result is an indication that the emission became too broad for the full integrated intensity to be measured. The expected emission-excitation relationships discussed in the previous paragraph apply to the case of nondegenerate carrier distributions. With a degenerate distribution of electrons, the emission from the states below the Fermi level would not increase any more with further increase in electron concentration. Consequently, the emission at a given wavelength would only increase as the concentration of nondegenerate holes increases with the excitation. The square dependence of intrinsic emission as well as the linear dependence of impurity emission apply to the integrated intensity, and departure is expected if only a part of the spectrum is measured. As mentioned in Sec. IV. A, the emission in p-type samples at the highest excitation had a width of ~3 meV, which is consistent with the Fermi level corresponding to an electron concentration of ~10^{15} cm^{-3} estimated from ΔG. The results indicate that with the full slit of the monochromator, nearly the integrated intensity was measured over most of the range except for the high-intensity end.

Measurements were made to check whether the saturation at high intensities was caused by sample heating. The time variation of the emission signal was observed with an oscilloscope. It was found that the signal dropped with time during each pulse, caused presumably by sample heating. The emission spectrum was measured for different sections of the pulse by adjusting the timing of the gated amplifier showing that the spectrum was noticeably broader at the end of the pulses than at the beginning. Evidently, the heating effect contributed to the apparent saturation of the data which corresponded to the average signal during each pulse. However, the oscilloscope measurement showed that this contribution accounted only for a minor part of the saturation.

E. Magnetic Field Effects

Photoluminescence was measured under applied magnetic fields up to 33 kG, at temperatures of 77 and 4.2°K. Figure 13 shows the intrinsic emission at 77°K to split and shift to higher photon energies. The observed behavior can be attributed to the shift and spin splitting of the first Landau level of the conduction band. The effect of the field on the valence band may be expected to play a minor role and will be left out of consideration.

Better resolution was obtained at 4.2°K where the impurity emission was also clearly resolved. Several n- and p-type samples were studied (see Figs. 7, 8, and 9). The energies of the peaks associated with the same transitions were found to coincide within experimental error for all the samples studied. Figure 14 shows the combined data for all samples. The median

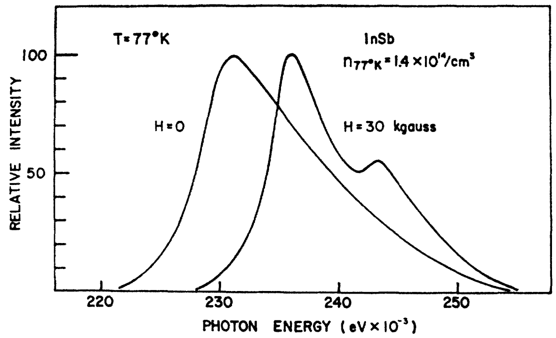

FIG. 13. Emission spectra of an n-type sample ($n=1.4\times10^{14}$ cm^{-3}) at 77°K, with and without an applied magnetic field.

of the two intrinsic peaks denoted by $m=+\frac{1}{2}$ and $m=-\frac{1}{2}$ gives the shift of the lowest Landau level which corresponds to an electron effective mass of $m_c=0.018$ m_0 at 40 kG. The energy difference between the $m=+\frac{1}{2}$ and $m=-\frac{1}{2}$ peaks gives the spin splitting which corresponds to a g factor of 40 at 30 kG. The same value for the g factor was obtained by Phelan[27] from measurements on InSb diodes using electrical injection. The data in Fig. 14 indicate that the splitting at lower magnetic fields corresponds to somewhat larger values of the g vactor. Similar indication was obtained by Zwerdling[18] from magneto-absorption measurements on InSb.

As shown in Fig. 14, the energy of the impurity-emission peak appears to have the same magnetic-field dependence as the lower spin-state intrinsic line. Under a magnetic field, the acceptor state may shift diamagnetically as well as split. In the range of magnetic field used, these effects were apparently negligible. The transition from the upper spin state to the impurity level was difficult to detect because of overlap with the intrinsic emission. This peak was detected in one case at 9 kG, and it is shown in Fig. 14 by an extra point at this field.

The relative intensity of the two emission peaks associated with a spin split Landau level of the conduction band should vary with the magnetic field. The density of states in the presence of a magnetic field is given by

$$n(E)=\frac{\hbar\omega_c}{8\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}\times\sum_{n=0}^{n_{max}}\sum_{m}\left[E+m\beta gH-(n+\tfrac{1}{2})\hbar\omega_c\right]^{-1/2}, \quad (19)$$

where the summation over $m=\pm\frac{1}{2}$ is for the two spin states of each Landau level denoted by n. The cyclotron frequency ω_c increases with the magnetic field. In a sample of low electron concentration, only the $n=0$ Landau level is populated by electrons at fields sufficiently high for resolution, and we see only emissions from the two spin states of the lowest Landau level. With increasing field, more of the electrons are concentrated in the lower spin state, and the emission associated with the upper spin state becomes progressively weaker. This effect is clearly seen in Fig. 8. The emission corresponding to the upper spin state, the peak at the high-energy end, is seen to be relatively much weaker at the larger field.

For a given magnetic field, the emission peak of the upper spin state may be higher than that of the lower spin state when the electron concentration is sufficiently large, since there is overlapping contribution from the lower spin state in the energy range of emission from the upper spin state. This effect can be seen in Fig. 9, which shows the spectrum for a sample with enough electrons to fill the states up to the second Landau level at the magnetic field used.

Samples of various electron concentrations were measured. With the largest concentration 2.5×10^{17} cm^{-3} the second Landau level should be populated even at the highest field 30 kG used. We were unable, however, to resolve emission peaks associated with the second Landau level in the spectra which covered sufficient energy ranges. Apparently, it is difficult to obtain an adequate $\omega_c\tau$ necessary for getting good resolution. Electron concentrations sufficient for the population of the higher Landau level give relaxation times τ that are too low.

The magnetic field has also a strong effect on the intensity of emission. Figure 15 shows the effect for a p-type sample. The magnetic field was applied in the

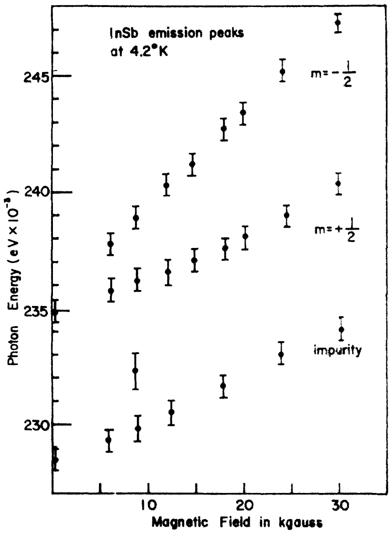

FIG. 14. Photon energy of emission peaks versus applied magnetic field, measured on various samples at 4.2°K. The points constitute three curves. The upper two curves correspond to band-to-band transitions from spin-spilt ($m=\pm\frac{1}{2}$) lowest Landau level of the conduction band. The lowest curve corresponds to transitions from the $m=+\frac{1}{2}$ Landau level to the acceptor impurity.

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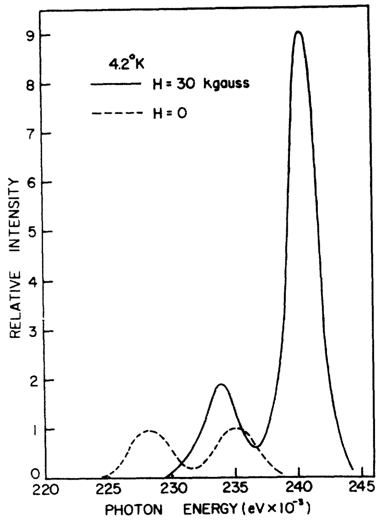
[27] R. J. Phelan, Jr., and R. H. Rediker, in *Radiative Recombination in Semiconductors, Seventh International Conference on the Physics of Semiconductors, Paris, 1964* (Dunod Cie., Paris, 1964),

FIG. 15. Emission spectra of a p-type sample ($p=5\times10^{15}$ cm^{-3} at 77°K) at 4.2°K, showing that the emission peaks shifted and increased in intensity under an applied magnetic field.



plane of the sample surface transverse to the direction in which the emission was observed. Both the impurity and intrinsic emissions were enhanced by the application of the field, but the impurity emission increased by a factor of 2 whereas the intrinsic emission increased by a factor of 9. The following effect may contribute to the strong increase of intrinsic emission. The transverse magnetoresistance decreases the diffusion length, causing the excited carriers to recombine nearer the surface. This effect reduces the self-absorption for the intrinsic emission without significantly affecting the impurity emission. Furthermore, both the impurity and intrinsic emissions compete with the dominant, nonradiative recombination. The dominant recombination and the impurity emission should not be affected by confining the excited carriers to a smaller region with increased concentration. This conclusion follows from the previously discussed observation that the photoconductance and the impurity emission increased linearly with the intensity of excitation. On the other hand, the intrinsic emission which was found to increase as the square of excitation intensity would be increased by the compression of the excited carriers into a narrower region. The factor-of-2 increase of impurity emission may be an actual increase of transition probability produced by the magnetic field.

Phelan[28] studied the intensity of intrinsic emission using magnetic fields parallel and perpendicular to the sample surface. He found that an order-of-magnitude increase of intensity was produced by a transverse field of 25 kG whereas a longitudinal field of 25 kG increased the intensity by only a factor of about 2. This result is consistent with our observation. The longitudinal field should have negligible effect on the diffusion length. The increase of intensity in the case of longitudinal field seems to represent increased transition probability under the field as is the case with impurity emission in our measurement.

F. Electric Field Effects

Some investigations were made on the effect of an applied electric field on the photoluminescence of n-type samples. In these experiments, voltage pulses were applied across the sample in synchronism with the pulses of exciting light. In addition, a dc magnetic field could be applied normal to the directions of the applied voltage and the exciting light. The samples used were about 1 cm long, and the exciting light was focused on a center section of the sample. The curves in Fig. 16 show the variation of the emission intensity with the applied voltage. Attempt was made to detect a broadening of the spectrum which might result from a change of the electron distribution under the applied electric field, but no appreciable change in the shape of the spectrum was detected within the range of the applied voltage. At 77°K, it was possible to extend the observation to fields about 150 V/cm, and no appreciable broadening of the spectrum was seen.

The two curves for $H=0$ show a dropoff of the emission intensity at sufficiently high electric fields. Such an effect would result if the photoexcited carriers were swept out of the sample before they could recombine. On this basis, the field E at which the emission starts to decrease is determined approximately by $E=x/\mu\tau$, where x is the distance from the edge of the illuminated section to the end of the sample, τ is the lifetime of excited carriers, and μ is a mobility associated with the density velocity. μ is of the order of the hole mobility if the concentration of excited holes is small compared

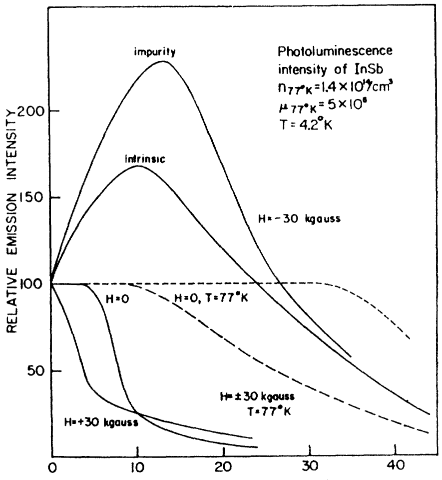


FIG. 16. Intensities of the intrinsic and impurity emissions of an n-type sample ($n=1.4\times10^{14}$ cm^{-3}) versus an applied electric field, with and without a dc magnetic field. The solid curves are for $T=4.2$°K, and the dashed curves are for $T=77$°K. A positive magnetic field deflects the drifting carriers toward the sample surface.

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[28] R. J. Phelan, Jr., M.I.T. Lincoln Laboratory, Progress Report, May, 1965 (unpublished).

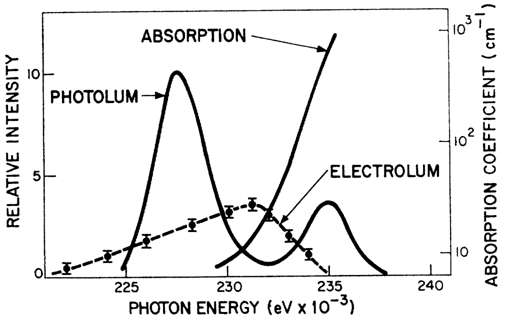

FIG. 17. The dashed curve gives the electroluminescence spectrum measured on a p-type sample ($p=2\times10^{14}$ cm^{-3} at 77°K) at 4.2°K. Optically excited emission spectrum of similar p-type samples is shown by the solid curve with two peaks, band-to-band and impurity emission. A different scale is used for each spectrum. The absorption coefficient of pure InSb at 4.2°K is shown by the solid curve rising with energy.

to the normal concentration of electrons. The curves for the two temperatures indicate that the hole mobility is several times larger at 4.2°K than at 77°K.

In the presence of an applied magnetic field, the carriers drifting under the electric field are driven either toward or away from the surface depending on the direction of the magnetic field relative to the direction of the electric current. We shall take the magnetic field to be positive when the carriers are driven toward the surface. With $H=+30$ kG, both the impurity and the intrinsic emissions decreased with the application of voltage, without waiting for the voltage to reach a certain value as in the case of $H=0$. A high surface recombination velocity could produce such a result. In fact the curve for $H=-30$ kG shows emissions to increase at first with the applied voltage. After reaching a maximum, the emissions started to decrease due presumably to the sweepout effect. The fact that the mobility should be reduced in the presence of the magnetic field could be responsible for the sweepout effect to be felt at a larger voltage than for $H=0$. In the case of $H=+30$ kG, the sweepout effect may be expected to be delayed to still larger fields as the effective carrier lifetime is reduced by increased surface recombination. At 77°K, the emission in the presence of magnetic field started to decrease at a smaller voltage than for $H=0$. In contrast to the results for 4.2°K, there was no initial increase with negative H: One of the reasons for this behavior may be self-absorption, which is more important at 77°K where the electrons are nondegenerate. Self-absorption would reduce the observed emission when the carriers are driven away from the surface. It is not clear however, why there is no appreciable difference in the emission for opposite directions of the magnetic field.

The above discussion gives a plausible, qualitative explanation of the observations. More detailed investigations are needed in order to obtain a thorough understanding.

G. Electroluminescence

Emission produced by the application of a pulsed electric field was observed in p-type single crystals at 4.2°K. The samples had hole concentrations about $(1\text{–}2)\times10^{14}$ cm^{-3} and were cut to a length of ~2 mm. Emission was detected at applied fields in the neighborhood of 600 V/cm. The spectrum is shown by the dashed curve in Fig. 17.

At 77°K, the samples had similar current-voltage characteristics as reported previously in the literature.[29] The current rose rapidly when the applied field became sufficiently high. The field at which this occurred varied from 20 to 80 V/cm and changed with resoldering of the current leads, indicating that carrier injection from the contact took place. At some field >400 V/cm, the current-voltage curve rose vertically with a sharp break, signifying band-to-band breakdown. Luminescence from the band-to-band breakdown has been observed by other workers.[30,31] At 4.2°K, measurements made by Salomon in this laboratory showed a sharp rise of current characteristic of breakdown which occurred at fields ~15 V/cm. This effect is apparently produced by the impact ionization of neutral acceptors. The emission we observed was probably produced by carrier injection following the acceptor ionization. Injection which might be difficult with the normal high resistivity of the sample could be facilitated by the greatly increased hole concentration resulting from acceptor ionization. The fields at which the emission was observed appears to be too low for band-to-band breakdown.

Figure 17 shows that the observed electroluminescence appears to be impurity emission. The spectrum shown by the dashed curve is broader and peaks at a higher photon energy than the impurity peak of photoluminescence from the same sample. This could be caused by hot-carrier effect of the injected electrons. The energy distribution of the electrons can be deduced from the spectrum. However, it must be borne in mind that the high-energy end of the spectrum might have been cut short by self-absorption. The effect of self-absorption is much more important in electroluminescence where emission takes place throughout the sample rather than near the surface as in the case of photoexcitation. This may be one of the reasons for the absence of an intrinsic emission peak in the observed electroluminescence. Another possible reason is the fact that the intrinsic emission in photoluminescence increased proportional to the square of intensity. It follows that uniform distribution of excess carriers is much less favorable than the concentration of carriers in a thin layer.

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[29] B. Ancker-Johnson, in *Proceedings of the International Conference of the Physics of Semiconductors, Exeter, 1962* (The Institute of Physics and the Physical Society, London, 1962), p. 141.

[30] B. D. Osipov and A. N. Khvoshchev, Zh. Eksperim. i Teor. Fiz. 43, 1179 (1962)[English transl.: Soviet Phys.—JETP **16**, 833 (1963)].

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In a typical case, the sample resistance was about 1000 Ω at 77°K where the acceptors were ionized, and it was 10 Ω at 4.2°K under the pulsed field used for electroluminescence. Thus, the conductance under the pulsed field is a measure of the amount of injected carriers and the contribution from acceptor ionization should be small. The observed impurity emission in electroluminescence was, however, weaker by about two orders of magnitude than that for the same sample conductance under photo-excitation. The absorption is low near the peak of the emission (see Fig. 17), and the impurity emission has been found to be linear with excitation in photoluminescence. Therefore, the weakness of emission with electrical injection cannot be attributed to a wider distribution of excess carriers in the sample. Two possible explanations can be suggested. First, the electron mobility should be considerably higher under the large field in electrical injection, hence the same conductance corresponds to a much lower concentration of excess carriers. Secondly, the impact ionization of acceptors taking place with electrical injection could suppress the emission involving the impurity.

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Hot-Carrier Hall Mobility and Magnetoresistance in n-Type Germanium of Large Carrier Concentration

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Hot-carrier galvanomagnetic phenomena in n-type germanium are studied for the case when the carrier concentration is large enough to ensure a Maxwellian energy distribution, displaced in the momentum space, in each valley. Numerical values of Hall mobility as obtained from the present theory agree quite closely with the earlier theory developed for low carrier concentration. Values of magnetoresistance, however, differ considerably, thus suggesting that a study of hot-carrier magnetoresistance in n-type germanium samples of varying carrier concentrations would enable one to find out the critical carrier concentration above which the concept of a displaced Maxwellian energy distribution is valid.

1. INTRODUCTION

THE energy distribution of carriers in a semiconductor under hot-carrier condition is theoretically expected to be dependent on the carrier concentration. Frohlich and Paranjape[1] have shown that for carrier density greater than a critical value, intercarrier collisions would predominate, enforcing a Maxwellian distribution on the carriers corresponding to an effective carrier temperature determined by the applied field. For lower concentrations, however, collisions with the lattice vibrations predominate and the distribution of the hot carriers, in this case, is non-Maxwellian.[2] However, numerical values of conductivity mobility as obtained from the two theories agree quite closely and it has also been experimentally observed by Prior[3] that for n-type Si and both types of Ge, the hot-carrier mobility is independent of carrier concentration. Hence, it is not possible to verify the distinctions in the distribution functions from conductivity measurements.

Hot-carrier galvanomagnetic phenomena in many-valley semiconductors have been studied by Conwell,[4] Budd,[5] and Das and Nag.[6] Numerical values of Hall mobility have been given by Das and Nag; Das[7] and also Nag and Paria[8] have calculated the electric field dependence of magnetoresistance in n-Ge. In these works, the carrier concentration has been assumed to be below the critical value so that the theory of non-Maxwellian energy distribution would apply. The purpose of the present paper is to study the Hall mobility and magnetoresistance of a many-valley semiconductor in which the carrier concentration is greater than the critical value and ensures a Maxwellian energy distribution in each valley. The concentration, however, is not so large as to make intervalley electron-electron collisions important.[9] In Sec. 2, the steady-state energy and momentum-balance conditions are utilized to give expressions for the Hall mobility. The theory is extended in Sec. 3 to obtain magnetoresistance as a function of field. Numerical results as obtained for n-Ge are discussed in Sec. 4.

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