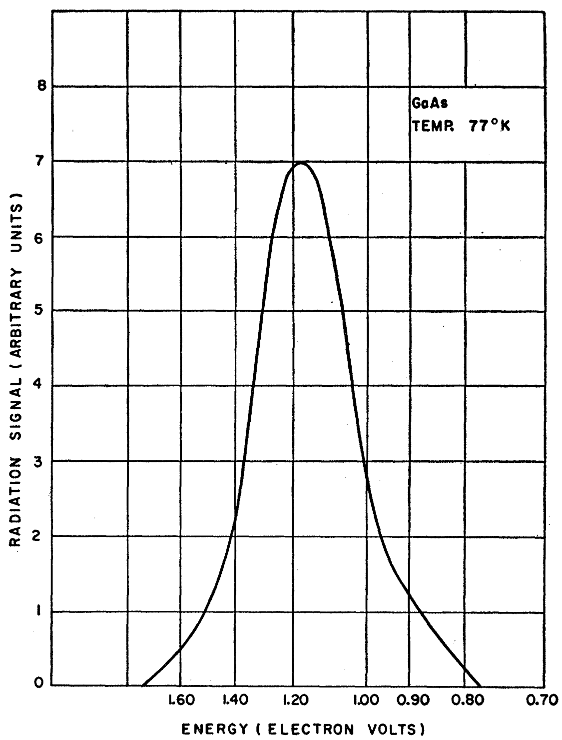

FIG. 3. Spectral distribution of recombination radiation from GaAs at 77°K. This line is to be compared with the line in Fig. 2 taken at room temperature. As the temperature is lowered, the peak intensity of the line increases, the width at half-maximum decreases, and the line shifts to higher energies.

for the room temperature band gap of GaAs as reported by Welker.[4] The absorption or the emission of a phonon can shift a line by only a few hundredths of an electron volt. Self-absorption of the radiation in the sample is also not sufficient to account for the apparent discrepancy. The sample of GaAs was n-type and had a free carrier density of $\sim 10^{17}/cm^3$.

The emission lines of InP and the Ge-Si alloys were not obtained. However, by appropriate filters, the radiation peaks were shown to occur at energies close to the band gaps of these materials.

The intensity of the radiation in all cases was observed to be a linear function of the injection current for the range of forward currents used (up to 1 amp/cm^2). The radiative recombination of electron-hole pairs is a bimolecular process and thus should be proportional to the product of the electron-hole concentrations. However, for the forward currents used, the majority carrier densities remained essentially constant and consequently to a first approximation the radiation will appear to very linearly with the minority carrier densities. In all cases, the integrated intensity of the radiation increased as the temperature of the sample was lowered.

Further results on radiative transitions in semiconductors will be presented at a later date.

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Infrared Absorption in Indium Antimonide*

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THE optical transmission of indium antimonide has been measured from 5 to 150 microns and at different temperatures. A residual ray monochromator was used for wavelengths beyond 35 microns. A number of lattice absorption bands were observed which indicate that there is some ionic binding in the crystal.

Figure 1 shows the transmission curves for a single crystal specimen with an acceptor concentration, N_A, of 10^{15} cm^{-3}. At 297°K, there are two absorption bands at 28.2 and 30 microns. With decreasing temperature these bands shift slightly to shorter wavelength. Measurements on samples of different impurity concentrations varying between 10^{15} to 10^{17} cm^{-3} show that the magnitudes of these bands are independent of carrier or impurity concentrations, indicating that these bands are inherent to the lattice.

Figure 2 shows the reflectivity curves at long wavelength for two temperatures. There is a strong band near 52 microns at both temperatures. While in the 78°K curve the reflectivity drops to 35% at longer wavelengths, the 297°K curve shows another rise of the reflectivity beyond 100 microns. These results show that

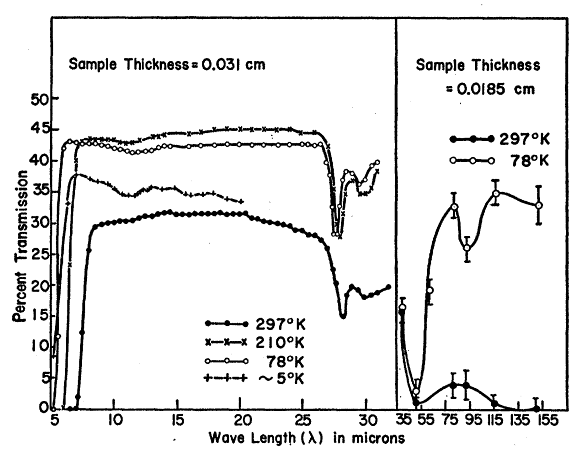

FIG. 1. Transmission as a function of wavelength for an InSb sample; $N_A = 10^{15}$ cm^{-3}.

there is a strong absorption band near 52 microns at both temperatures. Furthermore, there is also high absorption beyond 100 microns at 297°K. This is borne out by the transmission curves shown in Fig. 1. The sample is nearly intrinsic with $n=p=2.4\times10^{16}$ cm^{-3} at 297°K, while $p\sim10^{15}$ cm^{-3} and $n\ll10^{15}$ cm^{-3} at 78°K. The 52-micron band is thus independent of the carrier concentration and is therefore a lattice band. The high absorption beyond 100 microns, observed at 297°K seems to be caused by the carriers,[1] since the absorption becomes small at 78°K.

Reflectivity measurements at 297°K on an n-type sample of $n=10^{17}$ cm^{-3} and a p-type sample of $p=10^{17}$ cm^{-3} confirm the above interpretation. The same 52-micron band is present in both samples. Beyond 100 microns, the n-type sample shows an even higher reflectivity than the pure sample at 297°K while the p-type sample has the low reflectivity shown by the pure sample at 78°K. Thus we see that the high reflectivity at long wavelengths is caused by absorption due to the conduction electrons.

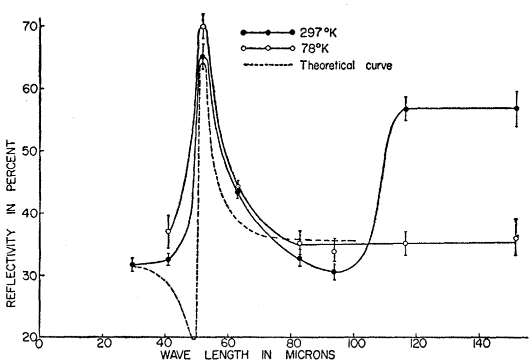

FIG. 2. Reflectivity as a function of wavelength for an InSb sample; $N_A=10^{15}$ cm^{-3}.

The strong lattice band near 52 microns indicates some degree of ionic binding. This absorption gives a contribution to the complex susceptibility,

$$\alpha=\frac{\Delta\epsilon_s}{4\pi}\frac{\omega_0^2}{(\omega_0^2-\omega^2)+i\gamma\omega},$$

where $\Delta\epsilon_s$ is the contribution to the static dielectric constant. By comparing the reflectivities on the short- and long-wavelength sides of this band we estimate $\Delta\epsilon_s<1.5$. The dashed curve (Fig. 2) was calculated with $\omega_0=3.5\times10^{13}$ sec^{-1} and $\gamma=1.3\times10^{12}$ sec^{-1}, and the limiting value $\Delta\epsilon_s=1.5$ was used to get the high reflectivity. The discrepancy between this curve and the curve measured at 78°K may be due to poor resolution. In fact, the measurements at 52 microns were made with three NaCl and an InSb crystals as residual ray plates; with four NaCl plates the measured reflectivity was $\sim$50% instead of 65%. These observations confirm the narrowness of the reflection band in InSb. Using the expression[2]

$$\Delta\epsilon_s=\frac{4\pi Ne^{*2}}{M\omega_0^2}\frac{(n^2+2)^2}{3},$$

where M is the reduced mass of the atoms and n is the short-wavelength refractive index, the effective ionic charge is estimated to be $e^*=0.34e$.

The question arises whether partial ionic binding would be compatible with the high carrier mobilities observed. The formula of mean free path for polar scattering[3] has been derived for $kT\ll\hbar\omega_l$, where ω_l is the frequency of longitudinal waves. At 80°K, $\hbar\omega_l=3.4kT$, this gives a mobility

$$\mu_{\text{polar}}=\frac{e}{m}\left(\frac{3kT}{m}\right)^{-\frac{1}{2}}\frac{6}{\sqrt{\pi}}a_0\frac{n^2(n^2+\Delta\epsilon)}{\Delta\epsilon}\left(\frac{kT}{\hbar\omega_l}\right)^{\frac{1}{2}}$$
$$\times\left[\exp\left(\frac{\hbar\omega_l}{kT}\right)-1\right]\left(\frac{m}{m^*}\right)^{\frac{3}{2}}\simeq15\,000\left(\frac{m}{m^*}\right)^{\frac{3}{2}}\frac{\text{cm}^2}{\text{volt sec}}.$$

This is higher than the mobilities observed around this temperature for holes as well as electrons, the latter having a small effective mass.

It is interesting to note that the transmission up to 35 microns decreased with decreasing temperature within the extrinsic range; at 297°K the sample is intrinsic. As reported previously,[4] in samples with $N_A\geqslant10^{17}$ cm^{-3} the transmission decreases steadily from 297°K down.

This work was stimulated by some preliminary reflection measurements made by E. J. Johnson at the suggestion of Professor K. Lark-Horovitz.

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Experimental Evidence for Dislocations in Crystalline Quartz

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RECENT measurements of well etched, mounted, and contoured AT shear vibrating quartz crystals, shown by Fig. 1, indicate that the Q decreases inversely proportional to the frequency up to 100 Mc/sec. This result is indicative of a relaxation. To verify the existence of such a relaxation, measurements of internal friction of single crystals have been made from 1.5°K to 300°K and in the 5- to 80-Mc/sec frequency region. The results for a 5-Mc/sec crystal are shown by Fig. 2.