most to L.[2] Since we are at the limit of the accuracy of the pseudopotential method, and since GaP, like ZnSe, has a larger antisymmetric potential than GaAs, it could be that in GaP the peak at 3.7 eV arises from transitions close to L rather than transitions along Λ closer to Γ than L. This would then explain the break in the alloy plot. Work is in progress to determine the origin of the 3.7-eV peak.

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FAR-INFRARED ABSORPTION IN N-TYPE SILICON DUE TO PHOTON-INDUCED HOPPING

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In this Letter we report the first experimental observations of far-infrared photon-induced hopping of a charge carrier between impurity centers in a compensated semiconductor. Our results are in good agreement with the recent calculations of Blinowski and Mycielski[1,2] for such a process in n-type silicon.

We have measured the absorption coefficient of compensated n-type silicon at 2.5°K as a function of doping ($10^{17} < N_D < 10^{18}$ cm^{-3}) and compensation ratio ($0.06 < K < 0.4$) in the frequency interval 10-100 cm^{-1}, and have observed a resonant absorption whose maximum, α_{max}, occurs at frequencies between 27 and 45 cm^{-1}, depending upon the donor concentration N_D. The origin of this resonant absorption is the photon-induced hopping of a charge carrier between impurity centers in a compensated semiconductor. This process must be distinguished from the usual phonon-induced hopping mechanism which has been previously studied as a function of the frequency of applied electric field up to 9 Gc/sec.[3-7] In a compensated n-type semiconductor with N_D donors and N_A acceptors ($K = N_A/N_D < 1$) there will be, at low temperatures, N_A negatively charged acceptors, N_A positively charged donors, and N_D-N_A neutral donors. If the compensation is low, $K < 0.2$, and if the concentration is not too high ($N_D \lesssim 8 \times 10^{17}$ cm^{-3}), then it is possible to visualize the absorption process in terms of a localized donor-pair model. In this model one considers an ionized donor and a neutral donor situated in the electric field of a nearby compensating acceptor impurity. The lowest two energy levels of such a system correspond to a localization of an electron on either one or the other of the donors. Under the influence of electromagnetic radiation the electron will be induced to make a transition from one level to the other and thus change its location with respect to the donor atoms. Using such a model Blinowski and Mycielski,[1,2] following the method of Miller and Abrahams,[8] calculated the energy separation of the lowest two electron states of the donor pair ion. The absorption coefficient for photon-induced electronic transitions between these states was calculated by Blinowski and Mycielski,[1] in the interval 10-100 cm^{-1}, for the zero-order process, namely, direct absorption without phonon participation. More recently these authors[2] extended their original calculations to include the first-order process, direct absorption accompanied by the emission of a single longitudinal acoustic phonon. The photon-induced hopping mechanism which gives rise to our observations was first proposed by Tanaka and Fan[5] to explain non-Ohmic behavior in the microwave absorption of p-type silicon. However, to our knowledge the present work is the first instance in which experiments were performed under conditions where the photon-induced hopping process is the dominant loss mechanism. Another useful result of our investigation has been the discovery of heavily doped, uncompensated silicon as a cut-off fil-

ter for high-frequency radiation in the range 10-100 cm^{-1}. This material is usable at helium temperatures, and its threshold for transparency, with respect to frequency, appears to be adjustable by varying the doping level.

Far-infrared absorption of our samples was measured with a Grubb-Parsons Michelson interferometer.[9] In order to correct for phase errors in the recording of interferograms, both sides of the symmetrical interference pattern were recorded, following the technique recommended by Haswell, Martin, and Sharp.[10] Mylar beam splitters of suitable thickness were used in the interferometer in order to concentrate the radiant energy in the region 10-100 cm^{-1}. Since it was essential to remove all radiation of higher frequency to avoid ionization of impurities, and to minimize undue heating of the samples, a combination of cold-soot-ed quartz and black polyethylene disks were used as filters. The reflection loss for all samples was constant over the frequency range 10-100 cm^{-1}. The total uncertainty in the absorption coefficient is estimated to be no more than 10%.

The samples were obtained from two ingots of single-crystal silicon with different concentrations of group-V and group-III impurities. The group-V impurity was arsenic and the group-III impurity was boron. The quantity $N_D - N_A$ was obtained from measurements of the Hall coefficient at ~380°K. The boron concentration N_A was simply derived from the amount used to dope the melt, with a minor correction for segregation along the length of the crystal. The uncertainty in determining N_D and N_A is estimated to be about 10%.

The essential features of the resonant absorption due to photon-induced hopping are shown in Fig. 1. The compensation ratios and the concentration of impurities in these samples lie well within the range of validity of the theory of Blinowski and Mycielski. It is clear that the conditions $\hbar\omega \gg kT$, $\hbar\omega > 2E_{LR}$, where $\hbar\omega$ is the photon energy and E_{LR} is the energy of lattice relaxation[1] ($E_{LR} = 8\times10^{-4}$ eV), are fulfilled; that is, the temperature is low enough and the electron-phonon coupling is weak. The resonant absorption occurs at photon energies which are much smaller than the ionization energy of the impurity atoms. At such small photon energies and low temperatures the usual bulk absorption mechanisms are absent. However, it is essential that the spectral intensity

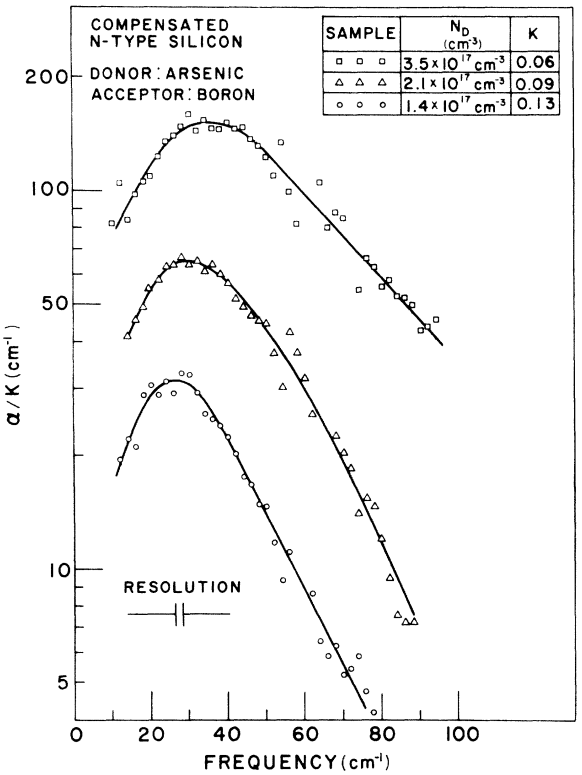

FIG. 1. Far-infrared absorption in lightly compensated ($K < 0.2$) n-type silicon at 2.5°K. Note that the absorption coefficient has been normalized to unit compensation.

be low enough to avoid saturation effects[5] in the population of electronic states. For this reason experiments on the most heavily doped and lightly doped samples of Fig. 1 were repeated with the spectral intensity reduced by a factor of two. No change in the magnitude and shape of the absorption curves, shown in Fig. 1, was detectable. For the three samples in Fig. 1 the absorption maximum increases linearly in magnitude and shifts linearly towards higher frequencies with increasing N_D. This behavior is in accord with the numerical results of Blinowski and Mycielski.[2] The half-widths of the absorption curves in Fig. 1 become larger with increasing N_D, and most of this increase in half-width occurs on the high-frequency side of the maximum.

According to the analysis of Blinowski and Mycielski[2] only the zero-order process (direct absorption) and the first-order process (direct absorption and emission of one longitudinal acoustic phonon) play a role in determining the total absorption coefficient. The only numerical results of Blinowski and Mycielski[2] available for

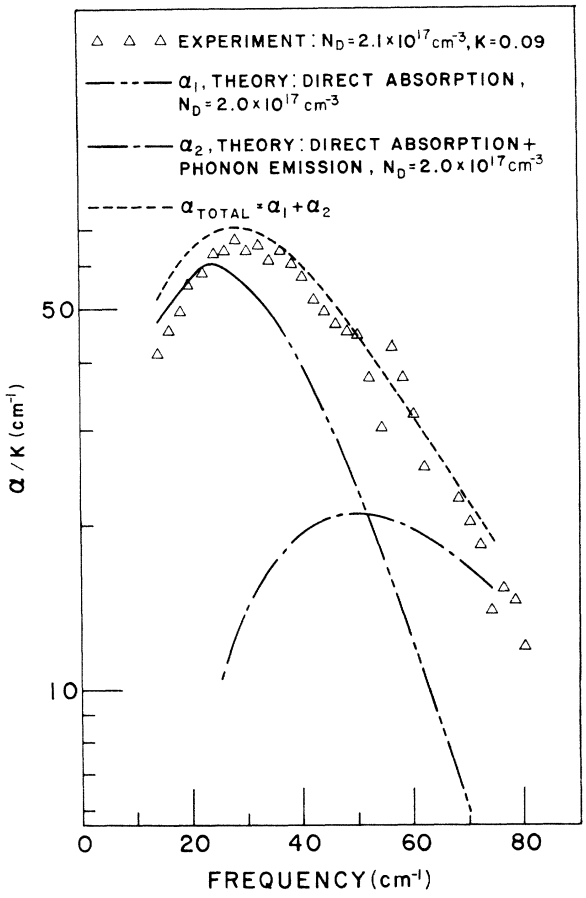

FIG. 2. Comparison of theory and experiment for the sample of Fig. 1 with $N_D = 2.1 \times 10^{17}$ cm^{-3}, $K = 0.09$ The theoretical curves were calculated in reference 2 for $N_D = 2 \times 10^{17}$ cm^{-3}.

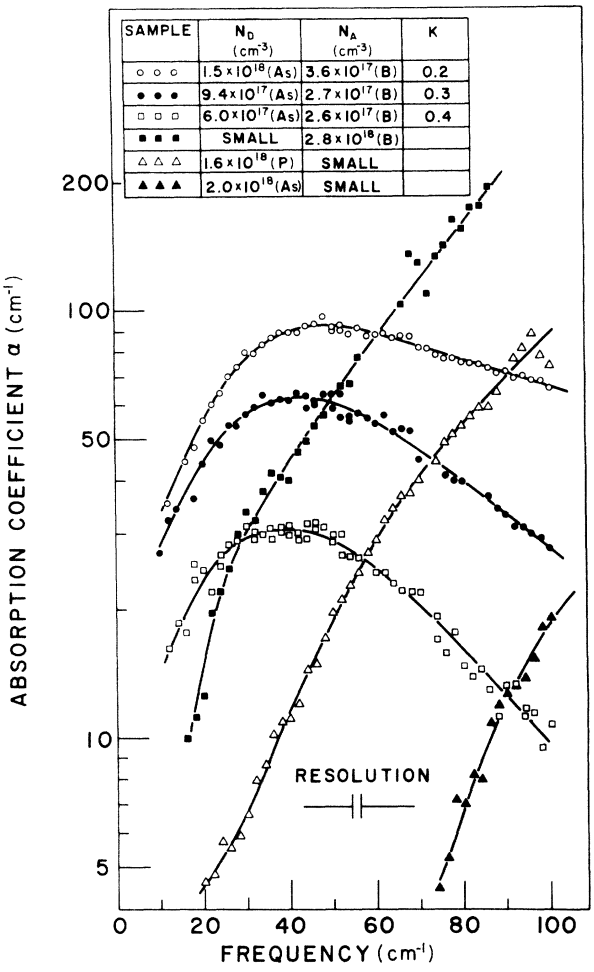

FIG. 3. Far-infrared absorption in highly compensated and uncompensated (n- and p-type) silicon at 2.5°K.

comparison with our data are for a sample with $N_D = 2 \times 10^{17}$ cm^{-3}. This comparison is shown in Fig. 2. The theory does, in fact, predict correct magnitude and shape of the experimental absorption curve within the limits of experimental error, and it thus appears that processes involving emission of two or more phonons are unimportant. The agreement in Fig. 2 is noteworthy because the theoretical curve for the total absorption involves no adjustable parameters, and it was calculated independently of any optical data. However, it would be useful to have available theoretical results for the other two samples of Fig. 1 to test the range of dopings over which this close agreement between theory and experiment exists.

The absorption coefficients of compensated and uncompensated samples are compared in Fig. 3. The uncompensated material exhibits a threshold frequency for transparency, and this behavior makes such material suitable for far-infrared transmission filters at liquid-helium temperatures. From Fig. 3 it is evident that the presence of the compensating boron acceptor is essential for the observation of a resonant absorption. The calculation of Blinowski and Mycielski is applicable to material with $K < 0.2$, and hence only the sample with $N_D = 1.5 \times 10^{18}$ cm^{-3}, $K = 0.2$ can be compared with the theory. When normalized to unit compensation the value of α_{max}/K for this sample is a factor of two less than predicted by theory. It may be that at such concentrations the simple donor-pair model is no longer valid. One possible reason for the breakdown of this model may be the presence of molecule-ion traps.[5] These traps consist of those donor pairs with very small interatomic spacing and therefore

large resonance energy, such that the photon energy is insufficient to excite the charge carrier. The effect of large compensation may also be seen in Fig. 3 in the case of $N_D = 6.0 \times 10^{17}$ cm^{-3}, $K = 0.4$. Here too the maximum absorption observed experimentally is less than calculated[2] for a sample of similar doping but with $K < 0.2$.

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EFFECT OF SPIN RESONANCE ON HOT ELECTRONS BY SPIN-ORBIT COUPLING IN n-TYPE InSb†

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We have observed the magnetic resonance of conduction electrons in n-type indium antimonide, by the "heating" of the electron kinetic-energy temperature via the electron spins. This is the first direct evidence suggesting a contribution of spin-orbit coupling to relaxation in this system. In a steady-state spin-resonance experiment, a power $P_S = (M_0 - M_z)H/T_1$ is transferred to the systems (reservoirs) towards which the spins relax. Here, M_0 is the equilibrium magnetization, M_z the component of the magnetization along the magnetic field H, and T_1 the relaxation time. The reservoir of interest in our case is the kinetic energy of the electrons coupled to the electron spins by spin-orbit interaction. The power fed from the spins increases the kinetic temperature of the electrons, and this is detected by an increase in the mobility μ.[1] To our knowledge, this is the first observation of the power flow, due to relaxation, from the spins to a reservoir, applied to the detection of magnetic resonance of conduction-electron spins. It differs in principle from usual spin-resonance observation methods, which are based on electromagnetic interactions of the spin system, such as the voltage induced in a resonator by the rotating magnetic moment, or again such as power absorption $P_S = M_y H_x$ from the rotating field H_x by the out-of-phase component M_y. Besides providing information on the relaxation mechanism, the present method (that we call "relaxation" method) should also in some cases by much more sensitive than the usual "electromagnetic" detection methods.

The order of magnitude of the sensitivity of the method[2] can be estimated as follows. Let N be the number of spins, $\omega/2\pi$ the resonance frequency, T the temperature. For a nondegenerate electron gas and not too large a polarization (high-temperature approximation), the power absorbed by the spins is

$$P_S = N(\hbar\omega/kT)(\hbar\omega/T_1)(\tfrac{1}{4}S), \qquad (1)$$

where S is the saturation factor $(M_0 - M_z)/M_0$. The power Π transferred to the kinetic energy of the electrons is only a fraction αP_S of this power. The coefficient $\alpha = (1/T_1)_{S.O.}/(1/T_1)$ measures the contribution of the spin-orbit coupling to the spin-relaxation rate and can vary between zero and unity. Now, we measure the resistance R (hence the mobility μ) of the sample by passing a constant current I and measuring the voltage $V = RI$ across the sample. The dc power $P_0 = RI^2$ raises the kinet-