ABSORPTION OF SUB-MILLIMETER RADIATION IN HEAVILY DOPED n-TYPE GERMANIUM

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The absorption of monochromatic radiations of 337 and 311 μm in wavelength has been investigated in Sb-doped Ge single crystals at temperatures below 4.2 K. The concentration ranges from 1.2×10^{16} to 3.6×10^{17} Sb atoms/cm^3. The absorption coefficient measured is substantially independent of temperature and rapidly decreases from 2×10^3 to 1 /cm as the concentration is lowered, showing a hump around $n = 3 \times 10^{16}$/cm^3. The observed hump suggests that the absorption is caused by a transition from the donor ground state to a delocalized conducting state which is supposed to lie between the ground state and the conduction band in the intermediate concentration region, and that the Coulomb interaction between an empty donor and a charge carrier in the delocalized state is appreciable.

1. INTRODUCTION

The purpose of the present investigation is to study the far-infrared properties of heavily doped semiconductors. In germanium samples with antimony concentrations between 1×10^{16} and 1×10^{17} /cm^3, at low temperatures, there is a temperature region where the resistivity is characterized by an activation energy ε_2 [1]. The activation energy ε_2 depends strongly on the impurity concentration [1], magnetic field [2]-[4], deformation [5],[6] and compensation [7] in contrast to the donor ionization energy ε_1 and the activation energy ε_3 [1] for hopping type conduction. These behaviours of ε_2 have been understood in terms of the change in overlapping of donor wave functions, and ε_2 has been supposed to be an energy needed to excite electrons from the donor ground state into an unbound state in which an electric current flows [1],[5]. The present study aims at observing the optical transitions which would occur if this picture is real.

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Most of previous works on the far-infrared properties at liquid helium temperatures have been made in the range of photon energies larger than 6 meV. The value of ε_2 is known to change from 5 meV to zero with increasing concentration [1]. For Sb-doped Ge, the first excited state of an isolated Sb donor lies 5 meV, about a half of ε_1, above the donor ground state. The use of a radiation whose photon energy is not enough to cause the transition between the ground and the first excited states is essential for the present study.

The absorption and reflectivity of monochromatic 337 and 311 μm radiations produced by a CW HCN laser [8] have been investigated in Sb-doped n-Ge single crystals. The excess donor concentration ranges from 1.2×10^{16} to 3.6×10^{17} Sb atoms/cm^3. No compensating impurity was intentionally doped and the compensation ratio was estimated at less than 5 %. The activation energy ε_2 was obtained from the temperature dependence of resistivity at temperatures below 20 K; ε_2 decreases from 5.8 to 0.1 meV as the concentration changes from 1.2×10^{16} to 1.1×10^{17} Sb atoms/cm^3. The metallic type impurity conduction is observed at higher concentrations.

2. EXPERIMENTAL

The samples were bridge or brick shaped and about $10 \times 1 \times (0.05 - 1.0)$ mm^3 in size for the measurements of absorption, and $6 \times 2 \times 1$ mm^3 for the measurements of reflectivity. Both dc and optical measurements were made for each sample. The samples were immersed in liquid helium to avoid the possible temperature rise on illumination. The radiations of 337 or 311 μm from the HCN laser were chopped at 20 Hz. The transmitted or reflected radiations were detected by an n-InSb single crystal. The signal voltage of 20 Hz generated across the detector was fed into a lock-in amplifier. The incident power of radiation was monitored by a Golay cell with a silicon window continuously during the measurements. The photoresponses of the InSb detector were proportional to the power of incident radiation which was below mW level.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 1 shows the absorption coefficient α(337μm) and the resistivity ρ for various samples plotted against the excess donor concentration $N_D - N_A$, temperature being the parameter. The absorption coefficient rapidly increases with $N_D - N_A$ and substantially independent of temperature.

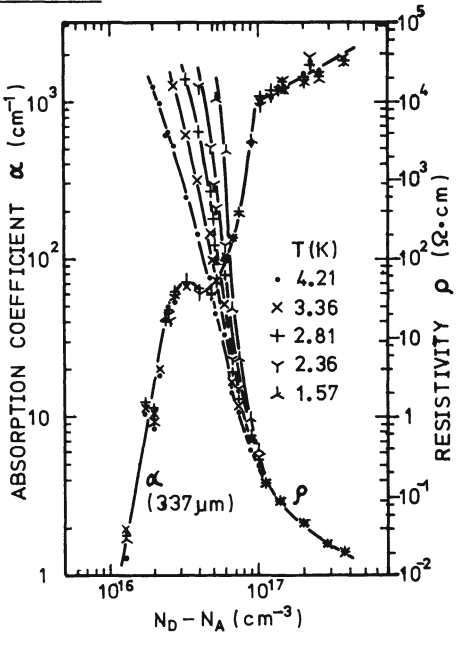

Fig. 1: Absorption coefficient at 337 μm and resistivity as functions of $N_D - N_A$.

For the samples with $N_D - N_A > 1 \times 10^{17}/cm^3$, the resistivity is independent of temperature; the conduction is known to be of the metallic type. The absorption is roughly interpreted as due to free carriers in the conduction band.

For the samples with $N_D - N_A < 1 \times 10^{17}/cm^3$, the absorption coefficient rapidly decreases from 1×10^3 to 1 cm^{-1} as the concentration is lowered, showing a pronounced hump around $N_D - N_A = 3 \times 10^{16}/cm^3$. The resistivity exibits strong temperature and concentration dependences; the conduction is known to be of the nonmetallic type. These facts suggests that the rapid decrease in α seen in the range of $7 \times 10^{16} < N_D - N_A < 1 \times 10^{17}/cm^3$ is not associated with the free carrier absorption but is understood in terms of the transitions from the donor ground state into the conduction band whose bottom is lowered [9] due to the interaction between donors. The hump corresponds to the absorption associated with the activation energy ε_2 as will be discussed below.

The absorption of 311 μm radiation shows almost the same dependence on the concentration as that seen in Fig. 1, but the hump shifts to the lower concentration side.

In Fig. 2 is shown the reflectivity of 337 μm radiation

for various samples as a function of $N_D - N_A$. The reflectivity depends little on temperature. For the samples with $N_D - N_A < 1 \times 10^{17}/cm^3$, the reflectivity is constant; the value is approximated to that of pure crystalline germanium. For the samples with $N_D - N_A > 1 \times 10^{17}/cm^3$, the reflectivity increases up to about 0.75 with increasing $N_D - N_A$. The observed concentration dependence of reflectivity indicates that the absorption by free carriers is negligible for the samples with $N_D - N_A < 1 \times 10^{17}/cm^3$.

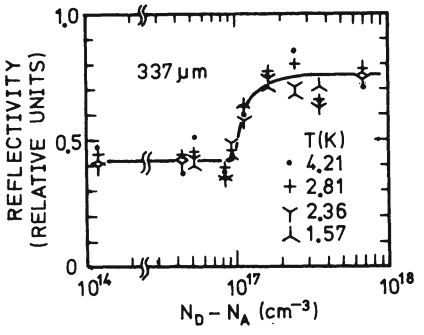

Fig. 2: Reflectivity at 337 μm of various samples expressed in terms of that of an Al mirror.

Figure 3 shows the absorption cross-section of 337 and 311 μm radiations plotted vs the activation energy ε_2 for respective samples. The absorption cross-section σ is obtained from the relation $\sigma = \alpha/N_D$, where the donor concentration N_D is replaced by $N_D - N_A$ in the present case because $N_A \ll N_D$. The vertical dashed lines indicate the photon energies of 337 and 311 μm radiations, $\hbar\omega = 3.7$ and 4.0 meV respectively.

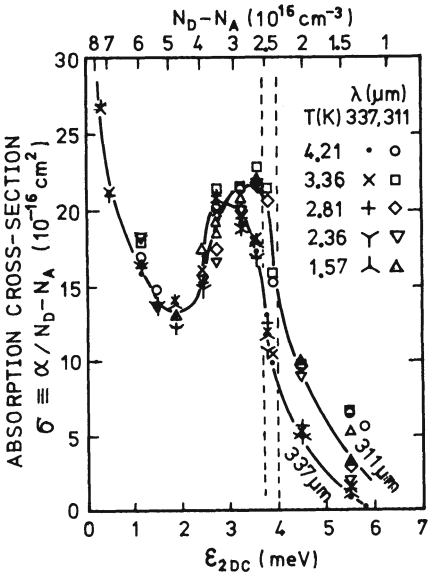

Fig. 3: Absorption cross-section vs ε_2 for various samples.

For the samples with ε_2 larger than $\hbar\omega$, σ falles rapidly with increasing ε_2. This fact suggests that the absorption is associated with the optical transition from the donor ground state to a delocalized state which lies between the ground state and the conduction band, and that ε_2 is the energy needed to cause the transition.

For ε_2 smaller than $\hbar\omega$, σ passes through a maximum, which

corresponds to the hump in Fig. 1, and then decreases to about 60 % of maximum value showing a minimum as ε_2 is reduced, followed by a rapid increase. The fact that σ is not a monotonic increasing function of $N_D - N_A$ is difficult to be explained in terms of the transitions associated with tail states extended below the conduction band, since the absorption caused by the tail states shows an exponential dependence on the photon energy [10].

The width of the peak of σ vs ε_2 curves is about 1 meV. If for the delocalized state a rigid band model is valid in the narrow concentration range around the peak, and the Coulomb interaction between an empty donor and a charge carrier in the state is negligible, σ should reflect the density of states; the width should correspond to the band width. But the observed width appears too small to assure the one-electron interpretation. The narrow width indicates an appreciable effect of Coulomb interaction in the delocalized conducting state [11].

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