OSCILLATORY INTRINSIC PHOTOCONDUCTIVITY OF GaSb AND InSb[†]

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The intrinsic photoconductivity of single-crystal *p*-type GaSb at liquid helium temperature has been found to oscillate with increasing photon energy. The samples studies were *p*-type, grown without intentional doping. The hole concentration in the exhaustion range was about 2×10^{17} cm^{-3}. Three samples from two different ingots were studied. All showed the same effect. Oscillations were observed also in a *p*-type InSb sample. The results are shown in Fig. 1. The positions of the successive minima are plotted in Fig. 2. The lines extrapolate to energies very close to the respective energy gaps. The slopes of the lines give 0.034 eV and 0.026 eV for the separation between successive minima in GaSb and InSb, respectively. In each case, the separation in close to the energy of optical phonons in the material.

Oscillations of photoconductivity associated with the excitation of impurities have been observed previously in InSb[1] and Ge.[2] The effect is entirely different from the effect reported here. The oscillations of the impurity photoconductivity were interpreted as the variation of the optical transition probability with the emission of zero, one, or more phonons. Thus, the effect reflects oscillation in absorption. The structures in the impurity absorption and photoconductivity spectra reported for semiconducting diamond[3] were of similar origin. The effect we observed concerns intrinsic photoconductivity. No oscillations in the intrinsic absorption have been observed in InSb and GaSb. Furthermore, the absorption in the intrinsic region is very high, and all photons entering the sample are absorbed irrespective of possible variations in the absorption coefficient.

Our interpretation of the observed effect is as follows. The energy of the excited electron increases with increasing photon energy according to

$$\epsilon=(h\nu-E_g)/(1+m_e/m_h).$$

The lifetime, τ_e, of the electron is short compared to the time constant, τ_a, of the energy loss

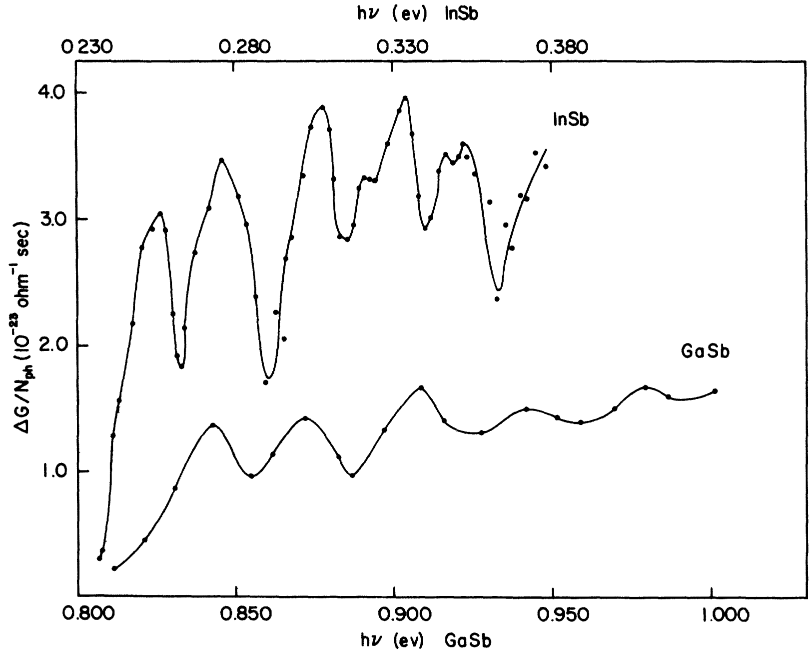

FIG. 1. Spectra of intrinsic photoconductivity of a GaSb and an InSb sample, showing oscillations. N_{ph} is the number of photons absorbed per second and ΔG is the increase of sample conductance.

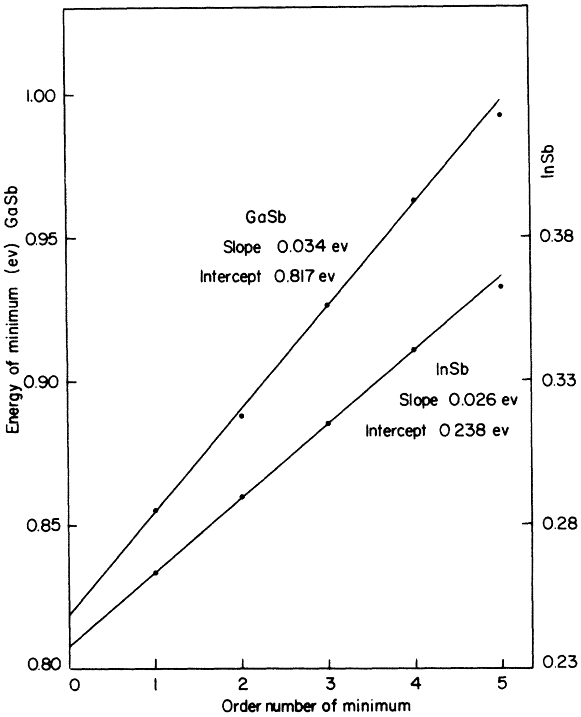

FIG. 2. Energies of successive minima in photoconductivity plotted against the order number of the minimum.

through collision with acoustical phonons. The electron recombines before losing appreciable energy. However, if ϵ exceeds $\hbar\omega_l$ of the longitudinal optical phonon, the electron may lose one or more quanta of $\hbar\omega_l$ very quickly, the polar interaction being very efficient.[4] With increasing photon energy, ϵ oscillates in the range from zero to $\hbar\omega_l$, going through a minimum every time $h\nu$ becomes an integral multiple of $\hbar\omega_l$. At the low temperature, the electron mobility is determined by scattering from ionized centers due to some compensating impurity. The mobility varies with the energy and gives rise to the oscillation. The excited holes should be thermalized and do not contribute to the effect.

The relevant parameters involved are estimated below. The time constant for the energy loss by collision with acoustical phonons is given by[5]

$$\tau_a = (\pi\hbar^4\rho/2^{1.5}m^{2.5}E_1^{\,2})\epsilon^{-1/2},$$

where E_1 is the deformation potential and ρ is the density of the crystal. The estimated values are

$$\tau_a \sim 2\times10^{-8}\epsilon^{-1/2} \text{ sec for GaSb,}$$

$$\sim 3\times10^{-7}\epsilon^{-1/2} \text{ sec for InSb,}$$

where ϵ is expressed in 10^{-2} eV.

The rate of energy dissipation through the emission of optical phonons may be expressed as[6]

$$-\frac{d\epsilon}{dt} = \frac{2\pi(2m)^{1/2}(ee^*)^2}{M\Omega(\hbar\omega_l)^{1/2}} f\left(\frac{\epsilon}{\hbar\omega_l}, \frac{kT}{\hbar\omega_l}\right) \equiv Cf\left(\frac{\epsilon}{\hbar\omega_l}, \frac{kT}{\hbar\omega_l}\right),$$

where M is the reduced mass of the ions, Ω is the volume of an ion pair, and e^* is the effective ionic charge. For $kT/\hbar\omega_l \ll 1$, the function f rises sharply from zero at $\epsilon/\hbar\omega_l \simeq 1$ and is of the order of unity for ϵ more than a few percent larger than $\hbar\omega_l$. The time, τ_{op}, for an electron of sufficient energy to emit an optical phonon is estimated to be

$$\tau_{\text{op}} = \hbar\omega_l/c \sim 3\times10^{-13} \text{ for GaSb, } \sim 10^{-13} \text{ sec for InSb.}$$

From the magnitude of photoconductivity, we get an estimate of $(\mu_e\tau_e + \mu_h\tau_h)$, where μ and τ are the mobilities and lifetimes of the excited carriers. Assuming that the excited electrons contribute a considerable part of the photoconductivity, we get from the measurements

$$\mu_e\tau_e \sim 10^{-4} \text{ cm}^2/\text{V for GaSb,}$$

$$\sim 4\times10^{-5} \text{ cm}^2/\text{V for InSb.}$$

The mobility of p-type InSb and GaSb at low temperatures, just before impurity conduction begins to dominate, indicates that ionized impurity scattering is the determining mechanism. From hole mobility at such temperatures, we estimate the electron mobilities in our samples to be

$$\mu_e \sim 3000\epsilon^{3/2} \text{ cm}^2/\text{sec V for GaSb,}$$

$$\sim 2\times10^5\epsilon^{3/2} \text{ cm}^2/\text{sec V for InSb,}$$

where ϵ is expressed in 10^{-2} eV. The electron lifetimes, τ_e, are therefore of the order of 10^{-9} sec and 10^{-10} sec for the GaSb and InSb samples, respectively.

Comparison shows that $\tau_{\text{op}} < \tau_e < \tau_a$ which is the condition for our interpretation. Photoconductivity was measured with an applied field of ~1 V/cm. In the case of InSb, the excited electrons actually gain energy during their lifetime, except for the emission of optical phonons. However, for a lifetime of ~10^{-10} sec, the gain of energy is negligible. The slopes of the lines in Fig. 2 should correspond to $\hbar\omega_l(1+m_e/m_h)$, giving values of $\hbar\omega_l \sim 0.0272$ eV for GaSb and ~0.0244 eV for InSb which are to be compared with the respective values 0.0290 eV and 0.0228 eV from other measurements.

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MICROWAVE SURFACE IMPENDANCE OF SUPERCONDUCTORS OF THE SECOND KIND: In-Bi ALLOYS

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A superconductor of the second kind allows field penetration at a field H_L while the superconductivity is not destroyed until a field $H_U > H_L$ is reached. The state of the material when $H_L < H < H_U$, the "mixed" state, is thought to consist of a microscopic array of current vortices through which the magnetic field penetrates.[1] Superconductors of the second kind must have small coherence distances which usually result from a small electron mean free path in the normal state. Therefore, pure elements are usually superconductors of the first kind, while alloys are usually superconductors of the second kind.

Microwave studies of superconductors of the first kind are done under extreme anomalous conditions, the microwave skin depth being much smaller than the mean free path in the normal state. When the microwave photon energy becomes comparable to the superconductor energy gap (at high frequencies or at temperatures near the critical temperature), quantum effects due to the excitation of quasiparticles are observed.[2] At lower frequencies and temperatures, extremely complicated magnetic field and temperature dependences have been observed which have yet to be explained.[3] In the present materials the zero-field temperature dependence fits a local two-fluid model quite well. Quantum effects due to the excitation of quasiparticles are masked by the large "free carrier absorption" by the quasiparticles due to the short mean free path. In the mixed state the surface impedance shows a dependence on the angle between the microwave current and $\vec{H}$ which appears to be characteristic of the superconductors of the second kind.

We have measured the dependence on $\vec{H}$ and T of the real part R of the surface impedance of In-Bi alloys at 24 kMc/sec. The specimens were polycrystalline plates of either a 2 or 3 at. % Bi alloy approximately 0.5 in. ×0.5 in. ×0.01 in. The samples were prepared by melting the alloy between CaF_2 plates, or by pressing the material between glass plates. The samples were then annealed for one to three months at 80°C. During this annealing the samples recrystallized leaving the surface slightly irregular. We did not use chemical or electrochemical polishing techniques since they could change the impurity concentration of the surface. The surface impedance of alloys should be affected much less by surface damage than the surface impendance of pure metals, since the mean free path of the alloy is intrinsically very small. The samples formed one wall or part of a wall of a TE_{011} cavity which terminated one arm of a microwave bridge. The change in the power reflected from the cavity was proportional to the change in R.

Temperature dependence. —In Fig. 1 we plot R/R_n, where R_n is R in the normal state, versus the temperature T for samples of In + 2 at. % Bi. We have assumed that $R(T < 1.6, H = 0) = 0$, which seems reasonable on the scale of Fig. 1. The points are experimental. The theoretical curve is calculated for a two-fluid model where we assume a local relationship between the current and electric field. In this case[4]

$$\frac{R}{R_n} = \left[\frac{[(\sigma_1/\sigma_n)^2 + (\sigma_2/\sigma_n)^2]^{1/2} - \sigma_2/\sigma_n}{(\sigma_1/\sigma_n)^2 + (\sigma_2/\sigma_n)^2}\right]^{1/2}, \qquad (1)$$

where σ_1 and σ_2 are the real and the imaginary parts of the conductivity, respectively, and σ_n is the conductivity in the normal state. For σ_1/σ_n we use the Gorter-Casimir relation $\sigma_1/\sigma_n = t^4$