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New Hybrid Photoconductivity Technique for the Investigation of CO_2-Laser-Induced Hot-Carrier and Free-Carrier Absorption Effects in Degenerate *n*-InSb at 1.8 K

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(Received 12 April 1978)

Free-carrier absorption of tuned CO_2-laser radiation is shown to be a valuable new tool for the extraction of information on photoheated hot carriers and the free-carrier absorption coefficients in low-concentration, degenerate *n*-InSb at liquid helium temperatures. The technique exploits parallel photoheating and dc-heating experiments conducted in a regime where conductivity changes are unambiguously determined by mobility changes.

Illumination of semiconductors with intense laser radiation leads to carrier heating.[1,2] Studies of hot-carrier distributions are important because they yield information concerning the electron-electron and electron-phonon interactions in semiconductors. Here, we report for the first time free-carrier absorption-induced photoconductivity measurements on degenerate *n*-InSb under optical excitation at CO_2-laser wavelengths that allow extraction of electron temperatures. Furthermore, we present the results of a unique combination of independent electrical and laser experiments carried out at liquid helium temperatures on the same low-concentration sample of *n*-InSb, that allows, in principle, the precision extraction of the free-carrier absorption coefficient as a function of CO_2 laser frequency and laser power. These absorption coefficients are so small at 10 μm that their determination from classical optical absorption measurements alone would prove impractical. Consequently, these novel hybrid experiments and their interpretation result in the *first* reported estimates for the free-carrier absorption coefficient of low-concentration (1.4×10^{15} cm^{-3}) *n*-InSb.

Figure 1 shows a block diagram of the equipment used in this experiment. The sample, immersed in liquid helium in a variable-temperature optical Dewar, was illuminated with a laser pulse produced by mechanically chopping a beam (TEM_{00} mode) from a grating-tuned cw CO_2 laser which provided single-line outputs of several watts from ~9.2 to ~10.9 μm. In the present experiments, a laser pulse with a width of ~20 μsec [FWHM (full width at half-maximum)], a rise and fall time of ~2 μsec, and a repetition rate of ~1700 Hz were employed. The laser pulse was positioned to illuminate the region of the sample between the potential contacts. Calibrated filters of either CaF_2 sheets or sheets of Teflon or some combination of both were used for attenuation.

Figure 2 shows comprehensive results obtained from three separate experiments on how the mobility changes with (1) applied electrical power P_E per electron (obtained from electrical heating

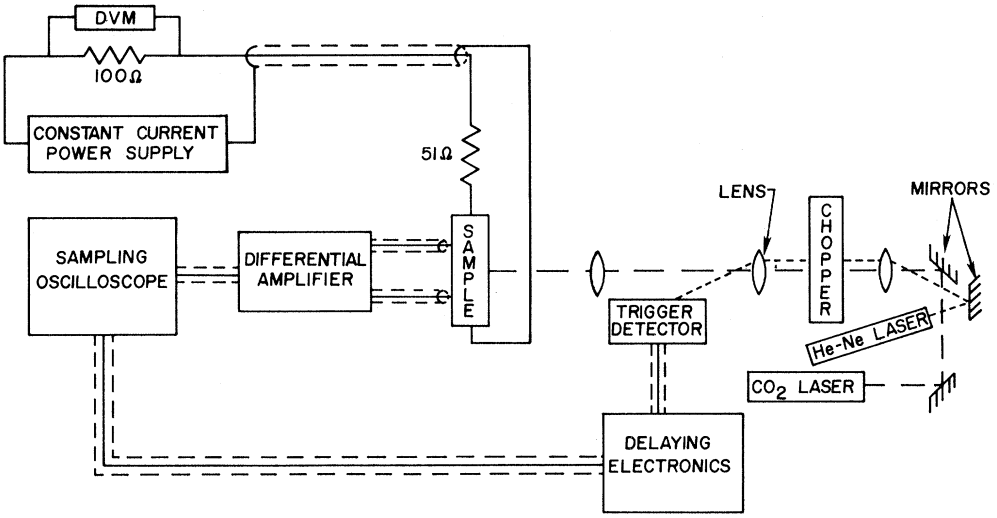

FIG. 1. Block diagram of experimental apparatus.

experiments as $e\mu E^2$) as shown in Fig. 2(a); (2) lattice temperature T_L as shown in Fig. 2(b); and (3) peak incident laser power P_I as shown in Fig. 2(c). The electron concentration was determined to be 1.4×10^{15} cm^{-3} from the period of Shubnikov–de Haas (SdH) oscillations and is *constant* at these lattice temperatures and low laser powers where two-photon absorption processes are completely negligible. Consequently,

$$\Delta\sigma/\sigma = \Delta\mu/\mu = \Delta V/V_0, \tag{1}$$

where $\Delta\sigma = \sigma - \sigma_0$, $\Delta\mu = \mu - \mu_0$, and $\Delta V = V - V_0$ are the changes in the conductivity, mobility, and voltage drop across the sample leads, as either T_L, P_I, or P_E is varied while the other two variables are held constant. The values of

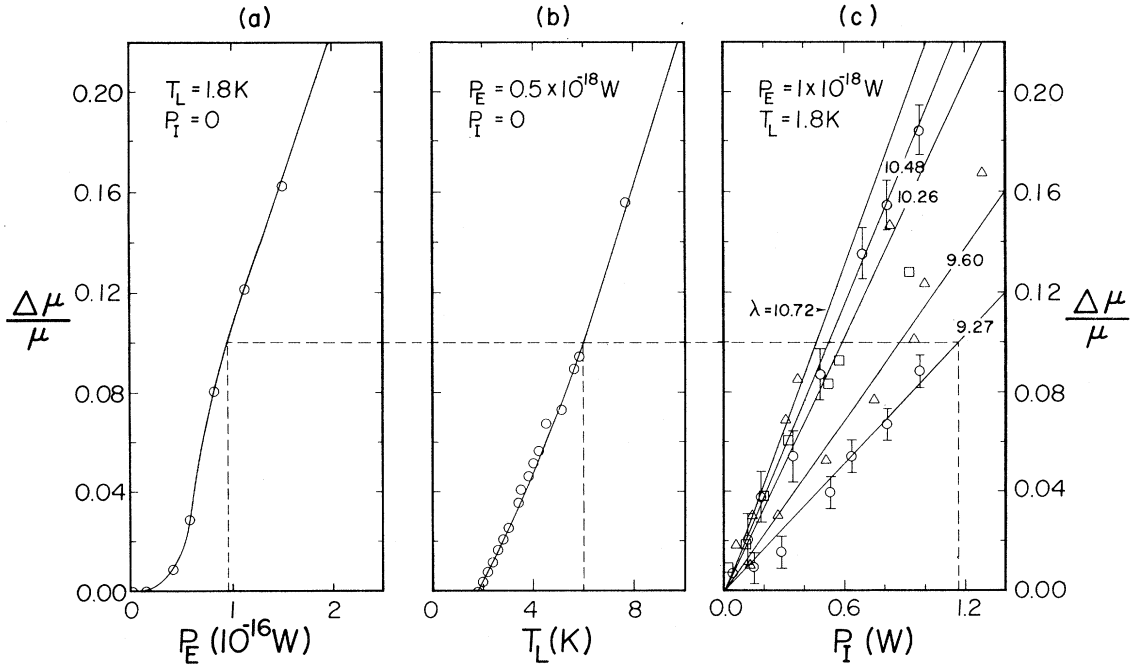

FIG. 2. Mobility changes with (a) applied electrical power per electron P_E (which for a given electric field E is calculated from $e\mu E^2$), (b) lattice temperature T_L, and (c) peak incident laser power P_I. Note that in all cases the mobility increases with either P_E, T_L, or P_I.

σ_0, μ_0, and V_0 are determined at zero laser power ($P_I = 0$) under Ohmic conditions at a lattice temperature of 1.8 K.

As shown in Fig. 2(b), the mobility at $P_I = 0$ obtained using Ohmic electric fields increases with lattice temperature which is consistent with completely dominant ionized-impurity momentum relaxation.[3] We find $\sigma_0 \sim 19.3\ (\Omega\ \mathrm{cm})^{-1}$, $\mu_0 \sim 8.6 \times 10^4\ \mathrm{cm^2/V \cdot sec}$, in agreement with other experimentally determined mobilities with similar electron concentrations and lattice temperatures.[4,5] At 77 K, σ_0 and μ_0 rise to 75 $(\Omega\ \mathrm{cm})^{-1}$ and $3.2 \times 10^5\ \mathrm{cm^2/V \cdot sec}$, respectivley.

The CO_2-laser radiation is partially absorbed via free-carrier absorption processes and subsequently leads to a mobility increase as observed in Fig. 2(c) where $\Delta\mu/\mu$ is plotted versus P_I, the peak incident laser power at a constant lattice temperature of 1.8 K. An electron temperature T_e^0 can be determined for each wavelength and value of P_I by making a one-to-one correspondence between the mobility changes in the two cases shown in Figs. 2(b) and 2(c). For example, Fig. 2(c) shows that for a peak incident power of about 1.16 W, $\Delta\mu/\mu \approx 0.10$, which corresponds to a temperature $T_e^0 \sim 6$ K.

The lines shown in Fig. 2 are the "best fit" lines through the data points. Consequently, a plot of T_e^0 versus P_I can be made as shown in Fig. 3. Provided the steady state is controlled by intercarrier collisions, the carrier distribution will be a heated Fermi-Dirac distribution with a true electron temperature T_e which may be identified with T_e^0 if the carrier heating maintains the system within the regime dominated by ionized-impurity–limited mobilities. The steady-state remnant excitation pulse at $\epsilon \sim \hbar\omega + \epsilon_F$ will have negligible effect on the mobility at our low excitation rates: The low-energy carrier assembly is only minutely depleted by photoexcitation.

The procedure may be repeated at zero laser power ($P_I = 0$) with $T_L = 1.8$ K but instead using a pulsed dc electric field of 20-μsec duration to heat the carriers into the warm-electron regime. These pulsed-current techniques were used to avoid sample lattice heating at high electric fields. Figure 2(a) shows the resultant mobility change versus applied electrical power P_E for the same sample. The extracted effective electron temperatures $T_e^E(P_E)$ may be again identified with the true electron temperature T_e under appropriate conditions. In such a case, we may invert the functional relations $T_e^0 = T_e^0(P_I)$ and $T_e^E = T_e^E(P_E)$ to deduce the thermodynamic relationship $P_E = P_a(P_I)$ under the constraint $T_e^0 = T_e^E = T_e$, where P_a is the portion of absorbed optical power per electron transferred to the carrier assembly via intercarrier collisions prior to dissipation to the lattice. The *extreme* case (*Model I*) occurs when the intercarrier energy-loss rate Γ_{ee} (scattering-out term) exceeds all other energy-loss rates $\Gamma_{e\,\mathrm{ph}}$ due to photon scattering at all energies up to and exceeding the photoexcitation energies ($\sim \epsilon_F + 4k_B T_e + \hbar\omega$). In this instance $P_a = \alpha(\lambda) d P_i$, where $\alpha(\lambda)$ is the steady-state free-carrier absorption coefficient, d is the sample thickness, and P_i is the incident laser power per illuminated electron. It follows that $\alpha(\lambda, T_e)$ may be extracted exactly as the ratio

$$\alpha(\lambda, T_e) = \frac{P_E(T_e)}{P_i(T_e, \lambda)} \frac{1}{d}, \tag{2}$$

where we make explicit the wavelength (λ) and electron temperature (T_e) dependences.

Our estimates of the critical carrier concentration n_c for which the condition that $\Gamma_{ee} \gg \Gamma_{e\,\mathrm{ph}}$ ensures a valid electron temperature model are based on similar calculations due to Stratton[6] but for relaxation against a *degenerate* distribution in the presence of Thomas-Fermi screening. While the present sample concentration satisfies $n \gg n_c$ for energies $\epsilon \lesssim \epsilon_F + \hbar\omega_L$, where ϵ_F is the Fermi energy and $\hbar\omega_L$ the LO phonon energy, we

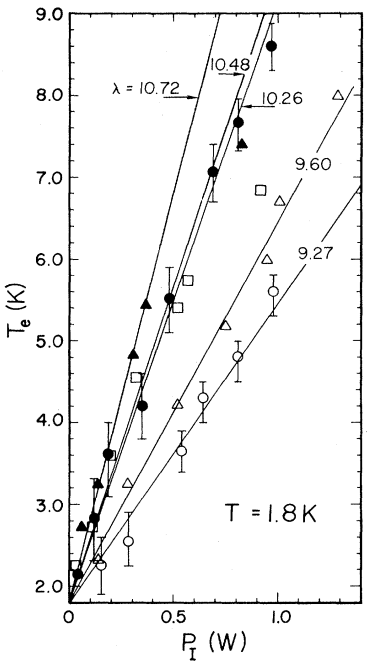

FIG. 3. Electron temperature T_e vs peak incident laser power P_I for various CO_2-laser wavelengths.

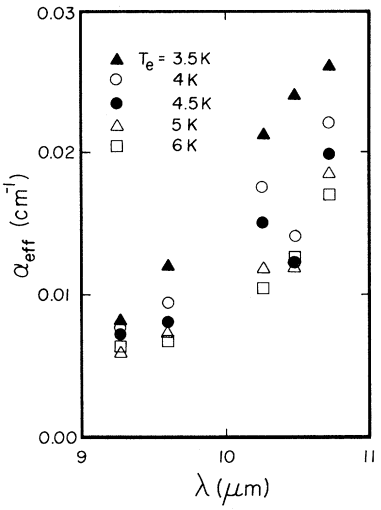

FIG. 4. Effective free-carrier absorption coefficient, α_{eff}, vs wavelength of the CO_2 laser at various electron temperatures T_e.

find $n<n_c$ for higher energies where energy loss to the lattice is controlled by fast polar-mode optical-phonon emission processes. In these circumstances (*Model II*) we might anticipate that a substantial fraction β of the optically absorbed power per electron, $P_a^0=\alpha d P_i$, is transferred to the lattice by optical-phonon cascading as the photoexcited electrons scatter to energies below the threshold for which $\Gamma_{e\,ph}>\Gamma_{ee}$. The residual power, $P_a=[1-\beta(\lambda)]P_a^0$, will then be effective in heating the carriers into a Fermi-Dirac distribution with electron temperature T_e via intercarrier collisions. The subsequent quasithermalized distribution will then lose energy to the lattice via predominantly acoustic phonon processes at the rate $[1-\beta(\lambda)]P_a^0$. In this case we find

$$[1-\beta(\lambda)]\alpha(\lambda, T_e)=\frac{P_E(T_e)}{P_i(T_e,\lambda)}\frac{1}{d}. \quad (3)$$

The analysis of Models I and II may be summarized by the general expression

$$\alpha_{eff}(\lambda, T_e)=P_E(T_e)/P_i(T_e,\lambda)d, \quad (4)$$

which relates an *effective* free-carrier absorption coefficient $\alpha_{eff}=\alpha(1-\beta)$ to experimentally accessible quantities. Model I involves $\beta=0$. Experimentally, as shown in Fig. 4, we find values for α_{eff} in the range 0.005–0.03 cm^{-1} for the electron temperature and wavelength ranges 3.5–6 K and 9.27–10.72 μm, respectively. We note that at 10.6 μm typical values for α have been reported in the range 0.3 to 0.6 cm^{-1} for a higher concentration of $\sim 10^{16}$ cm^{-3} at low temperature.[7]

Plots of α_{eff} versus λ^2 for the range of available wavelengths indicate an approximately linear variation with values extrapolated to zero wavelength of order -0.03 cm^{-1}. These nonzero *negative* extrapolated values are consistent with a *nonzero* loss factor $\beta(\alpha)$. The finite width of the excitation pulse $\Delta\epsilon\sim\epsilon_F+4k_BT_e$ precludes a strong oscillatory photoconductivity effect $[\beta(\lambda)\sim 1]$. Indeed, the presently available spread of photoexcitation energies $\Delta\epsilon<\hbar\omega_L$ is not sufficient to expose any definite oscillatory structure although a minimum in α_{eff} may be indicated at $\lambda=10.49$ μm. Further experiments are in progress on other concentration samples to investigate the physical origin of the nonzero loss factor β.

The authors gratefully acknowledge the partial support of this research by the U. S. Office of Naval Research and helpful discussions with A. L. Smirl.

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