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COLD ELECTRON PHOTO-INJECTION IN DEGENERATE n-InSb AT 1.8 K

D. G. Seiler and L. K. Hanes

Department of Physics
North Texas State University
Denton, Texas 76203

Laser-induced cooling of the average energy of the conduction electrons is observed with the simultaneous application of a non-ohmic dc electric field and CO laser radiation for photon energies near the bandgap by cold electron photo-injection.

It is well known that a large dc electric field can heat the electron gas in a semiconductor. [1] Heating by optical excitation can also cause an increase in carrier energy by some combination of free carrier, interband, and impurity absorption processes. [2-4] In contrast, by using both electrical and optical excitation together a decrease in the mean carrier energy can be produced by optically injecting electrons into the conduction band at an energy below the unilluminated mean energy of the conduction electrons. This causes a reduction in the average energy that can be observed in both photoconductivity and Shubnikov-de Haas (SdH) measurements. We consider CEPI cooling for photon energies close to (229-234 meV), but less than the bandgap energy (235 meV).

The degenerate electron gas is assumed to be described by a Fermi-Dirac distribution characterized by an electron temperature T_e. Near $T_e = 0$ essentially all states below the Fermi level ε_F are filled while all states above ε_F are empty. The average energy is $\langle\varepsilon\rangle = k_B T_e F_{3/2}(\eta)/F_{1/2}(\eta)$ where k_B is Boltzmanns' constant, F is the Fermi integral, and η is the reduced Fermi energy, $\varepsilon_F/k_B T_e$. The transition probability to a conduction band state depends upon how many states are unoccupied. At energies below $\langle\varepsilon\rangle$ this unoccupied density depends drastically upon the value of T_e, increasing as T_e increases. If the electron distribution can be heated by an applied electric field it should then be possible to optically "inject" carriers below the dark $\langle\varepsilon\rangle$, resulting in an overall decrease in $\langle\varepsilon\rangle$. A decrease in $\langle\varepsilon\rangle$ resulting from this cold electron photo-injection (CEPI) corresponds to a decrease in T_e and any electron temperature dependent property of the crystal should reflect this change in T_e.

The effect of acceptor levels close to the valence band edge on absorption processes near the bandgap is very important in understanding CEPI. These acceptor states produce a tailing of the absorption edge and act as the ground state for saturable absorption at sufficiently high laser intensities. Here they act as additional sources of electrons which can be injected below $\langle\varepsilon\rangle$ by a photon of appropriate energy. The absorption of a photon of energy $\hbar\omega$ by an electron in the acceptor level ε_A creates a photoexcited electron with energy $\Delta\varepsilon = \hbar\omega - \varepsilon_g + \varepsilon_A$ above the bottom of the conduction band. Then for cooling to be observed we must have $\langle\varepsilon\rangle > \Delta\varepsilon$. This absorption model is shown in Fig. (1).

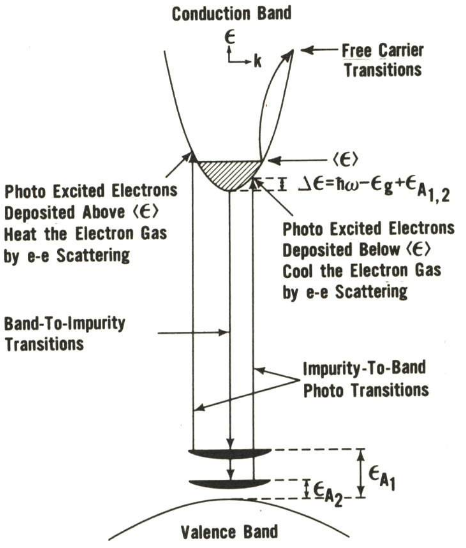

Fig.1 Absorption model showing origin of the heating and cooling

We can model CEPI for 1 or 2 impurity levels by using energy balance considerations. The time rate of change of the average energy per conduction electron in the presence of an electric field E_z and including the effects of optical absorption from the impurity levels can be written as

$$\frac{d\langle\varepsilon\rangle}{dt} = \frac{\langle\langle\varepsilon\rangle\rangle_{dark} - \langle\varepsilon\rangle}{\tau_e} + W_1(\Delta\varepsilon_1 - \langle\varepsilon\rangle) + W_2(\Delta\varepsilon_2 - \langle\varepsilon\rangle) + P_B \quad . \qquad (1)$$

Here τ_e is a phenomenological energy relaxation time, W_1 and W_2 are net transition rates from two acceptor impurity levels which include recombination, P_B is a background term corresponding to the power absorbed due to free carrier absorption and possible absorption from other levels away from the band edge. [5] In the absence of the laser radiation (denoting steady state values by $\langle\langle\rangle\rangle$), $\langle\langle\varepsilon\rangle\rangle_{dark} = eE_z v_d \tau_e + \varepsilon_L$, where ε_L is the average energy of the electrons in thermal equilibrium with the lattice and v_d is the drift velocity. W_1 and W_2 will depend upon the probability of an occupied impurity state and a vacant conduction band state as well as other parameters, such as laser intensity and recombination times. In steady state Eq. (1) becomes

$$\langle\langle\varepsilon\rangle\rangle - \langle\langle\varepsilon\rangle\rangle_{dark} = \tau_e[W_1(\Delta\varepsilon_1 - \langle\langle\varepsilon\rangle\rangle) + W_2(\Delta\varepsilon_2 - \langle\langle\varepsilon\rangle\rangle) + P_B] \quad . \qquad (2)$$

If $W_2 = 0$, we note that $\langle\langle\varepsilon\rangle\rangle$ can be less than $\langle\langle\varepsilon\rangle\rangle_{dark}$ if $[W_1(\Delta\varepsilon_1 - \langle\langle\varepsilon\rangle\rangle) + P_B] < 0$. We can extract $\langle\langle\varepsilon\rangle\rangle$ from the change in the conductivity under illumination and P_B from the low field illuminated conductivity. Thus W_1 can be calculated if a value of τ_e is assumed. W_2 can then be calculated in the same manner as W_1, assuming W_1 is known.

The experimental apparatus is described in more detail elsewhere. [3] The sample ($n \simeq 1.3 \times 10^{15}$ cm^{-3}) is placed within an optical dewar where it can be maintained at 1.8 K while illuminated by chopped pulses of about 20 μs duration from a tunable CO laser at a 3% duty cycle to avoid lattice heating effects. The laser beam is focused to a spot size of ~1 mm. The laser pulses used here are of long enough duration that the electron gas reaches a quasi-equilibrium. Therefore, we assume we can characterize the electrons by a Fermi-Dirac distribution at an electron temperature T_e which is not necessarily the same as the lattice temperature T_L. To find $\langle\langle\varepsilon\rangle\rangle$ as a function of E in the unilluminated case the electrical conductivity was measured as a function of T_L and also as a function of E. A very small electric field was used in the T_L measurements, while T_L was kept at 1.8 K during the electric field measurements of σ. The value of T_e for a given E is then obtained by making a one-to-one correspondence between the two sets of measurements. Knowing T_e then allows the calculation of $\langle\langle\varepsilon\rangle\rangle$ for a given value of E. At E = 0.25 V/cm, where a clearly negative $\Delta\sigma/\sigma$ value is obtained for some photon energies, $\langle\langle\varepsilon\rangle\rangle \simeq 2.8$ meV ($\varepsilon_L = 1.9$ meV).

For a constant sample current I, the photoconductive voltage is $V_p = I\Delta R$, where $\Delta R = R_{ill} - R_{dark}$ is the change in resistance of the sample under illumination. When the incident laser beam causes heating of the electrons the conductivity increases due to the dominance of ionized impurity scattering and a negative value of V_p is observed since $R_{ill} < R_{dark}$. However, we have observed photo-induced positive values of V_p for certain photon energies as the applied electric field is increased, which we interpret as laser induced cooling. In contrast, this behavior has not been observed using a CO_2 laser with much greater incident powers at photon energies ~120 meV. The change in conductivity due to illumination $\Delta\sigma = \sigma - \sigma_o$ can be calculated from V_p, where $\sigma(\sigma_o)$ is the illuminated (unilluminated) conductivity and $\Delta\sigma = ne\Delta\sigma + e\mu\Delta n$. For acceptor level transitions $\Delta n \ll n$ and we assume that $\Delta\sigma$ is predominantly due to the change in mobility, $\Delta\sigma \simeq ne\Delta\mu$. Fig.2 shows a plot of $\Delta\sigma/\sigma$ as a function of electric field. For $\hbar\omega = 229.4$ meV, $\Delta\sigma/\sigma$ decreases but remains positive as the electric field is increased. We attribute this decrease to CEPI cooling produced by an acceptor level 8 meV above the valence band. If the transitions begin here then we have $\Delta\varepsilon_1 = 2.4$ meV which is less than $\langle\langle\varepsilon\rangle\rangle$ for dark high field conditions ($E > .25$ V/cm). Thus, a drop in $\Delta\sigma/\sigma$ with increasing E is expected as the amount of excess energy will drop. For laser illumination at photon energies of 232.8, 233.2, and 233.9 meV, $\Delta\sigma/\sigma$ becomes negative as E is increased, which also is indicative of a laser-induced cooling of the mean energy of the electron gas. However, if we consider the acceptor level at 8 meV above the top of the valence band as a source of these transitions we get $\Delta\varepsilon_1$ to be 5.8, 6.2, and 6.9 meV respectively and heating should result since $\Delta\varepsilon_1 > \langle\langle\varepsilon\rangle\rangle$ in every case. An additional impurity level must be responsible for the observed cooling effects for laser photon energies between 232 and 234 meV. To explain our data, this impurity level must be an acceptor level located ~3 meV above the top of the valence band, as shown in Fig.1. Using this 3 meV level as the starting point for the transitions, we get $\Delta\varepsilon_2 = 0.8$ meV for $\hbar\omega = 232.8$, 1.2 meV for 233.2, and 1.9 meV for 233.9 meV, within our guideline of $0 < \Delta\varepsilon < 2.8$ meV for electron cooling to occur

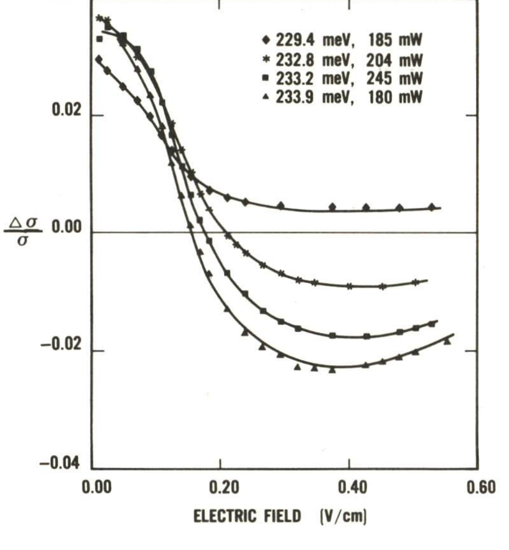

Fig.2 Fractional change in conductivity versus electric field for photon energies near E_g

at high electric fields. Since the laser-induced electron cooling effect relies upon the creation of vacant states by the dc electric field, the smaller the value of $\Delta\varepsilon$ the higher the field necessary to empty the states. That is, at low electric fields all states near the bottom of the band ($\Delta\varepsilon = 0$) are filled. It requires a greater electric field to empty states near $\Delta\varepsilon = 0$ than it does for higher energies in the band. Inspection of Fig.2 shows that this is precisely what is observed. The value of E required for $\Delta\sigma/\sigma < 0$ increases as $\Delta\varepsilon$ decreases.

The net transition rate W_1 for the acceptor level located at 8 meV above the valence band edge can be calculated using Eq. (1) for the 229.4 meV line since in this case it is the only impurity transition allowed. Assuming $\tau_e \simeq 50$ ns [6], we find $W_1 = 1.14 \times 10^6\ s^{-1}$ for $E = 0.24$ V/cm. If the transitions are limited by bleaching of the acceptor states instead of filling of the conduction band states at high electric fields and high laser intensities, then $W_1(\hbar\omega)$ should be relatively constant. Under this assumption for $\hbar\omega = 233.9$ meV we get $W_2 = 8.1 \times 10^6\ s^{-1}$ for $E = 0.24$ V/cm. The fact that $W_2 > W_1$ makes physical sense since more CEPI cooling was obtained from the 3 meV level than the 8 meV level. Thus, it would appear that there are more 3 meV acceptor states than 8 meV acceptor states, or that the absorption cross section is greater for the 3 meV level. This additional level may help explain the transmission in InSb for photon energies between 231 and 235 meV, where the two level absorption model of Miller fails to explain their absorption data. [7,8]

As the electric field is increased when unilluminated, the amplitude of the SdH oscillations will decrease due to the electric field heating of the electrons. [1] At low electric fields the amplitude of the SdH oscillations clearly decreases when illuminated, indicating carrier heating is occuring. [3] However, when the sample is illuminated in the high field region the amplitude of the SdH oscillations increases corresponding to a decrease in T_e. Thus, a laser-induced cooling process is also indicated by SdH measurements, in agreement with the result obtained from the photoconductivity measurements.

The Franz-Keldysh effect can be ruled out as an explanation of these results because the shift in the absorption edge for a dc electric field of the magnitude used in this work is much too small to explain our results.

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