Direct measurement of polaron lifetime in degenerate InAs

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We report the first direct measurement of the longitudinal-optical (LO) phonon emission time (τ_{LO}) by electrons in degenerate InAs, using electron tunneling techniques on n-type InAs-oxide-Pb junctions. For a sample having $n = 5.5 \times 10^{17}/cm^3$, we obtain $\tau_{LO} = (5.1 \pm 0.3) \times 10^{-13}$ sec.

InAs is a weakly polar semiconductor and can be doped easily to high carrier densities. In this paper, we report the first direct measurement of the longitudinal-optical (LO) phonon emission time by electrons in degenerate InAs, using electron tunneling techniques on n-type InAs-oxide-Pb junctions. Since the electrons and LO-phonons in InAs interact through polar coupling,[1] this experiment offers a direct test of the theory of polarons in degenerate semiconductors. In the remainder of this paper, we present the experimental results and compare them with the prediction of the polaron theory by Mahan and Duke.[2]

The InAs sample has an electron concentration $n = 5.5 \times 10^{17}/cm^3$ and a bulk Fermi energy $E_F = 98$ meV. Previously, we have described the experimental procedure for junction fabrication and tunneling measurements and have given a detailed account of the tunneling characteristics of the InAs-oxide-Pb junctions.[3] For our purpose here, it suffices to mention that, in the presence of a quantizing magnetic field, the bias (V) dependence of the derivative of the junction conductance (d^2I/dV^2) shows oscillations reflecting the electron Landau levels in InAs. This is illustrated in Fig. 1. Curve (a) shows the d^2I/dV^2-vs-V data at 4.2 °K taken with a magnetic field $H = 22$ kG normal to the plane of the junction. The zero-field data are shown as curve (b), which is taken under identical experimental conditions except for $H \approx 2$ kG (which is needed to quench the superconductivity of the Pb electrode). The structure at $V \approx 10$ mV and at $V \approx 30$ mV seen in this curve arises from tunneling electrons interacting with Pb phonons and with the LO phonons of InAs, respectively. The oscillatory component of curve (a), obtained by subtracting curve (b) from curve (a), is displayed as curve (c). It is clear that the oscillations show a sudden decrease in amplitude at $V \approx 30$ mV, which corresponds to the LO-phonon energy of InAs. This sudden decrease of the oscillation amplitude, which becomes more apparent as we decrease the magnetic field, is our main interest in this paper.

We recall that while the period of the oscillations illustrated in Fig. 1 measures the energy separation of the electron Landau levels in InAs, their amplitude is related to the electron relaxation time.[3] If we regard the tunnel conductance at a bias V as probing the quasiparticles injected into InAs at an energy eV away from its Fermi level (E_F), the amplitude of the oscillations at V reflects the relaxation time of the quasiparticles at an energy eV away from E_F. The observed decrease in oscillation amplitude at $V \approx 30$ mV, therefore, results from the decrease in quasiparticle relaxation time when relaxation by LO-phonon emission becomes energetically possible at $|V| \gtrsim \hbar\omega_0/e$, where $\hbar\omega_0$ is the InAs LO-phonon energy. At $|V| \lesssim \hbar\omega_0/e$, the injected quasiparticles do not have sufficient energy to emit LO phonons.

We have observed that, at a fixed bias, the amplitude A of the oscillations follows an exponential dependence on the magnetic field H, i.e.,

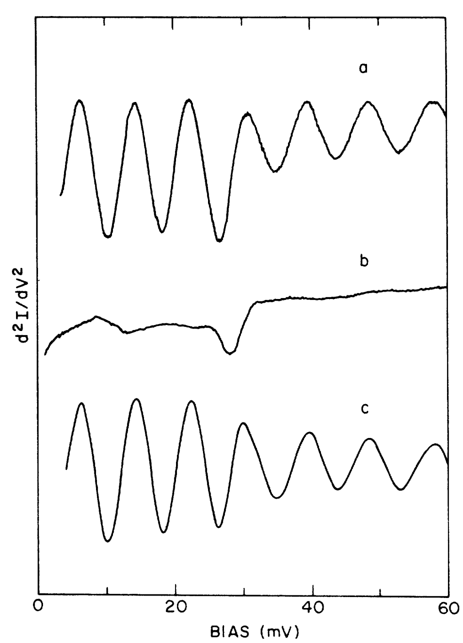

FIG. 1. d^2I/dV^2-vs-V data from an InAs-oxide-Pb junction (the InAs sample: $n = 5.5 \times 10^{17}/cm^3$ and $\mu = 12\,000$ cm^2/V sec) at 4.2 °K. Curve (a) is taken with $H = 22$ kG applied normal to the plane of the junction, curve (b) is taken with H reduced to ≈ 2 kG, and curve (c) is obtained by subtracting curve (b) from curve (a).

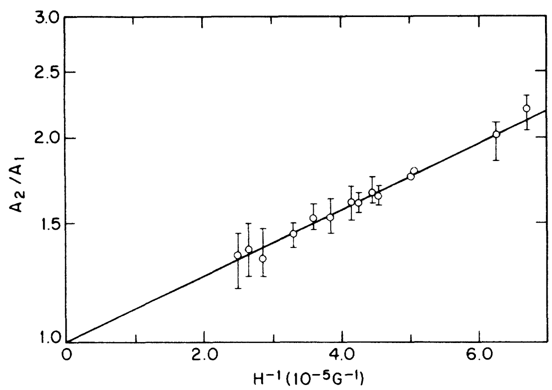

FIG. 2. A_2/A_1 vs H^{-1}.

$$A \propto e^{-H_0/H}. \tag{1}$$

The parameter H_0 is related to an effective Dingle relaxation time τ through $\tau = \pi m^* c/eH_0$,[4] where m^* is the electron effective mass. We let A_1 be the oscillation amplitude at $V = \hbar\omega_0/e$ when relaxation by LO-phonon emission is allowed and A_2 be the oscillation amplitude at $V = \hbar\omega_0/e$ when relaxation by LO-phonon emission is forbidden. If τ_2 is the relaxation time governing A_2, the relaxation time τ_1, governing A_1, is given by

$$1/\tau_1 = 1/\tau_2 + 1/\tau_{LO}, \tag{2}$$

where τ_{LO} is the LO-phonon emission time. The ratio A_2/A_1 is then given by

$$A_2/A_1 = e^{\pi m^* c/\tau_{LO} eH}. \tag{3}$$

It is clear from Eq. (3) that the decrease in oscillation amplitude at $V \approx 30$ mV should be more pronounced at lower H and that τ_{LO} can be determined by measuring this amplitude decrease as a function of H.

In Fig. 2, we plot A_2/A_1, obtained from data in the Pb positive bias at 4.2 °K, on a logarithmic scale as a function of the inverse magnetic field H^{-1}. The quantities A_2 and A_1 are obtained by interpolating the bias dependence of the oscillation amplitude. In other words, A_2 is the oscillation amplitude at $V = 30$ mV as extrapolated from $V < 30$ mV, and A_1 is the amplitude at $V = 30$ mV as extrapolated from $V > 30$ mV. From the slope of the solid line in Fig. 2 and using $m^* = 0.032\, m_0$ (as deduced from the observed oscillation period) we obtain $\tau_{LO} = (5.1 \pm 0.3) \times 10^{-13}$ sec. We note that, within experimental errors, identical results are obtained from data in the Pb negative bias. We should also note that the effective Dingle relaxation times τ_1 and τ_2, deduced from the magnetic field dependence of the oscillation amplitude, are ~4 $\times 10^{-14}$ sec. This fact by itself indicates that $\tau_{LO} \gg \tau_1$ and τ_2 and that we cannot obtain τ_{LO} by measuring the bias dependence of the effective Dingle relaxation time.

The problem of electrons interacting through polar coupling with optical phonons in degenerate semiconductors has been studied by Mahan and Duke, using field-theoretic techniques. The imaginary part of the electron self-energy, $\mathrm{Im}\Sigma$, is related to the phonon emission time τ of the electron through $-\mathrm{Im}\Sigma = \hbar/2\tau$. In order to compare the theory with our experiment, we follow Conley and Mahan[5] and use their approximate expression for the one-phonon self-energy to evaluate the LO-phonon emission time:

$$\tau_{LO} = \frac{\hbar(1 + k_S^2/k_F^2)^2}{2\alpha\hbar\omega_0(\hbar\omega_0/E_F)^{1/2}}, \tag{4}$$

and α is the polar constant given by

$$\alpha = \frac{e^2}{\hbar}\left(\frac{m^*}{2\hbar\omega_0}\right)^{1/2}\left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_0}\right). \tag{5}$$

Here, $k_S = (6\pi n e^2/\epsilon_\infty E_F)^{1/2}$ is the Thomas-Fermi screening constant, $k_F = (3\pi^2 n)^{1/3}$ is the electron Fermi wave vector, and ϵ_∞ and ϵ_0 are the high-frequency and static dielectric constant, respectively. For our InAs sample ($n = 5.5 \times 10^{17}/\mathrm{cm}^3$), we obtain $\tau_{LO} = 5.3 \times 10^{-13}$ sec from Eq. (4) by using $m^* = 0.032 m_0$, $\epsilon_\infty = 12.3$ and $\epsilon_0 = 14.9$, in excellent agreement with the experimental result.

Finally, it should be noted that we expect the polar coupling to LO phonons in our InAs sample most suitable for testing the perturbation theory of Mahan and Duke. Its polar constant ($\alpha \approx 0.05$) is small, its plasma energy ($\hbar\omega_p \approx 50$ meV) is larger than its LO-phonon energy, and, above all, it is a high-density electron gas as indicated by $r_s \approx 0.2$ (here r_s is the interelectron spacing measured in units of the effective Bohr radius). The theory, however, does not take into account of the quantizing magnetic field, which is essential to our experiment. Although we do not expect magnetic quantization to change the result appreciably, it is apparent that a more quantitative test for the theory of polarons in degenerate semiconductors will need an extension of the theory to include the magnetic field.

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[1] O. Madelung, *Physics of III-V Compounds* (J. Wiley, New York, 1964).

[2] G. D. Mahan and C. B. Duke, Phys. Rev. 149, 705 (1966).

[3] D. C. Tsui, Solid State Commun. 8, 113 (1970); and in *Proceedings of the Tenth International Conference on*

the Physics of Semiconductors, Cambridge, Massachusetts, 1970 (U.S. AEC, Oak Ridge, Tenn. 1970), p. 468.

[4]L. M. Roth and P. N. Argyres, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol. I, Chap. 6.

[5]J. W. Conley and G. G. Mahan, Phys. Rev. 161, 681 (1967).