Optical-Phonon Emission in Ballistic Transport through Microchannels of InGaAs

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We have observed an oscillatory conductance in electrical transport through In-InGaAs contacts, corresponding to a series of dips in the *I-V* characteristic for both bias polarities at $eV \sim n\hbar\omega_0$, where n are integers and $\hbar\omega_0$ is the LO-phonon energy of InGaAs. We explain the data by successive LO-phonon emission in high-field transport of ballistic electrons through microchannels of InGaAs and point out that the experiment is a solid-state analog of the Franck-Hertz experiment.

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In the course of investigating electrical transport through metal-semiconductor contacts, we observed an oscillatory conductance in the *I-V* characteristic of In contacts to the as-grown, high-mobility InGaAs single crystals. Measurements made at T below the superconducting transition temperature of In demonstrate that electron tunneling plays no role in the transport process. The oscillations are observed in both bias polarities, up to $T \sim 60$ K. While the application of a magnetic field B perpendicular to the InGaAs surface has no effect on the oscillations, the amplitude decreases in the presence of an increasing parallel B and vanishes for $B_{\parallel} \sim 50$ kG. The period of the oscillation varies from junction to junction; nevertheless, the smallest value observed is $\Delta V \sim 33$ meV, which approximates the longitudinal-optical (LO) phonon energy, $\hbar\omega_0 = 32$ meV, of $In_{0.53}Ga_{0.47}As$.[1] These observations suggest that the oscillatory conductance results from successive emission of LO phonons by electrons, accelerated in the electric field applied to the In-InGaAs contacts, reminiscent of the successive inelastic collision of electrons with the gas atoms in the classical Franck-Hertz experiment.[2]

In 1967, Katayama and Komatsubara[3] first reported the observation of an oscillatory conductance in the tunneling of electrons into high-purity *n*-type InSb, with an oscillation period close to the LO-phonon energy of InSb. Subsequently, Cavenett[4] carried out an extensive investigation, which confirmed the results of Katayama and Komatsubara and demonstrated that the oscillation period depended on the junction fabrication, but was always $\geqslant \hbar\omega_0$. More recently, Hickmott *et al.*[5] observed a similar oscillatory conductance in electron tunneling into the lightly doped GaAs electrode of GaAs-AlGaAs tunnel junctions in the presence of B for $B > 40$ kG. All these experiments differ from ours in that the oscillatory conductance is observed only when the tunneling electrons are injected into the high-purity semiconductor electrode.

Recently, Kulik and Shekhter[6] treated theoretically the electrical transport through a narrow semiconductor channel, where the diameter d of the channel is much smaller than its length L and the electron's inelastic relaxation length λ_E (not associated with the phonon-emission process considered in the problem). They predict an *I-V* characteristic showing singularities at $eV = n\hbar\omega_0$, where ω_0 is the optical-phonon frequency of the semiconductor and n are integers. The periodic singularities result from the phonon-emission events, which satisfy $L = nZ_n$, where Z_n is the distance an electron must travel along the channel to gain enough energy to emit a phonon. The commensuration condition is satisfied by those particular events of phonon emission which can cause a sudden drop in the terminal velocity of the accelerating electron, as it reaches the collecting electrode, and consequently give rise to a sudden decrease in the current flow through the channel. The resulting oscillations in the conductance are expected for both bias polarities. We wish to point out that the model, when extended to the ballistic regime, can account for our experimental observation as well as those previous observations made on tunnel junctions. It provides a unified physical picture for the oscillatory phenomena, resulting from LO-phonon emission, in the electron transport through semiconductor constrictions, junctions, and contacts. Indeed, it brings into focus the underlying physics in these experiments and makes it apparent that they are in fact solid-state analogs of the Franck-Hertz experiment.

Our samples are high-quality *n*-type $In_{0.53}Ga_{0.47}As$ single-crystal epitaxial layers, ~ 3 μm thick, grown by trichloride-vapor levitation epitaxy[7] on the (100) surface of heavily doped n^+-InP substrates. Similar samples grown on insulating InP substrates are known to have $n = 1 \times 10^{15}$ cm^3 and $\mu = 10^4$ cm^2/V·sec at 300 K.

The In-InGaAs contact is $\sim 250\times 250\ \mu m^2$ in size, made by thermal evaporation of a thick In film, in a vacuum of $\sim 1\times 10^{-6}$ mm Hg, on the InGaAs crystal, which was precleaned only in organic solvents. Ohmic contacts to the InGaAs are made either directly on the crystal or through the n^+-InP substrate by soldering with In. The data in any case are independent of the Ohmic contacts employed. Two terminal measurements using standard modulation techniques are used to obtain the I-V, (dI/dV)-V, and (d^2I/dV^2)-V characteristics.

Figure 1 is an example of the I-V characteristic and its first and second derivatives taken from an In-InGaAs contact at 4.2 K. The nonlinear behavior, as seen in the dI/dV vs V curve, is similar to that of tunnel junctions with a zero-bias anomaly.[8] However, no superconducting tunneling characteristics[8] are observed as T is lowered below the superconducting transition temperature (~ 3.4 K) of In. This experimental fact shows that electron tunneling plays no role in the transport process and there is no tunnel barrier between In electrode and the InGaAs crystal. The result is consistent with recent findings[9,10] that indicate that contacts of low-work-function metals (e.g., Al and In) to n-type InGaAs do not form Schottky barriers, but they result in ideal Ohmic contacts. In view

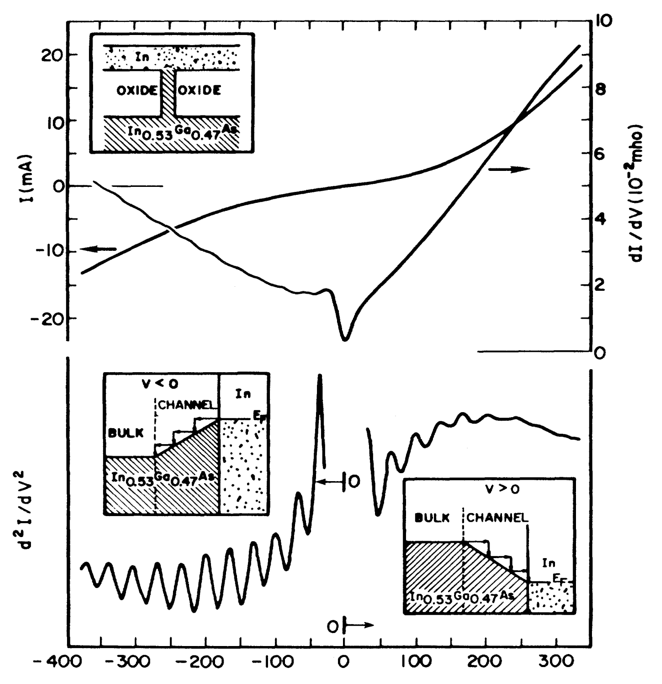

FIG. 1. I-V, dI/dV vs V, and d^2I/dV^2 vs V of an In-InGaAs contact at 4.2 K. The insets show the proposed structure of the contact and the energy-band diagrams under biases.

of the fact that our junction resistance is $\sim 100\ \Omega$, we propose that the electrical contact between the In and the InGaAs is via a large number of thin channels of InGaAs crystal protruding through the insulating oxide layer on the InGaAs surface. The channels must have L of approximately the oxide thickness of several hundred angstroms and d of probably several tens of angstroms, rendering them one-dimensional (1D) wires. This model of the contact and its energy-band diagram under biases are illustrated in the inset of Fig. 1. It should be also noted that the electron mean free path at a velocity of 10^7 cm/sec is expected to be ~ 1000 Å in bulk InGaAs, longer than L. Consequently, the bias dependence of the background conductance may not be simply related to the energy dependence of the electron's elastic scattering time, as in the model for diffusive transport discussed by Shekhter.[11]

The oscillations, already discernible in the dI/dV vs V data in Fig. 1, are apparent in both bias polarities in the d^2I/dV^2 vs V data. In the In negative bias, they are strong ($\sim 7\%$ change in conductance at $V \simeq -0.15$ V) and up to seventeen oscillations have been observed. Similar but weaker oscillations, up to six, are observable in the positive bias in Fig. 1. The peak and valley positions of the first oscillation in both biases are masked and distorted by the zero-bias anomaly. However, the higher-order oscillations are sufficiently well behaved to allow an unambiguous identification of the structures. They correspond to dips in the I-V curve in either polarity at biases equal to integral multiples of ~ 33 meV. Since the LO phonons in $In_{0.53}Ga_{0.47}As$ are known to have $\hbar\omega_0 = 32$ meV,[1] we attribute the oscillations to a series of broadened dips in the I-V characteristic due to emission of InGaAs LO phonons.

Phonon emission is a well-known phenomenon in electron transport via tunneling through tunnel junctions[8] and via injection through point contacts.[12] In both cases, when the injected electron or hole is at a phonon energy away from E_F, it can emit the phonon and cause a peak or dip in the d^2I/dV^2 vs V curve in either bias polarity. However, the probability for multiple phonon emission is known to be small. Extremely weak structures have been observed for emission of two phonons,[13] but higher-order emission is not expected at all. In our data, the strength of the higher-order structure is striking and in fact the amplitude remains approximately constant up to $n=7$ in the negative bias. In our model, this series of structures results from successive events of phonon emission by electrons accelerated in the applied electric field through the microchannels of InGaAs. This process occurs continuously for all biases above the phonon emission threshold, $eV \simeq \hbar\omega_0$. However, when the emission occurs at the end of the channel, the electron

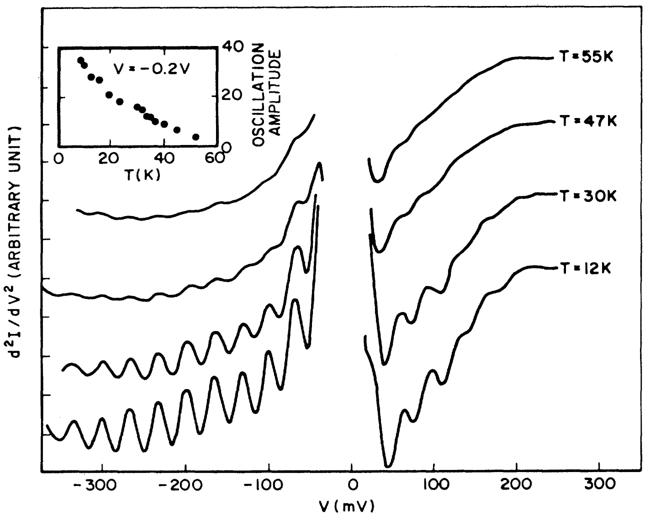

FIG. 2. d^2I/dV^2 vs V for $T=12$ to 55 K. The zeros of the curves are displaced. The inset shows the oscillation amplitude as a function of T.

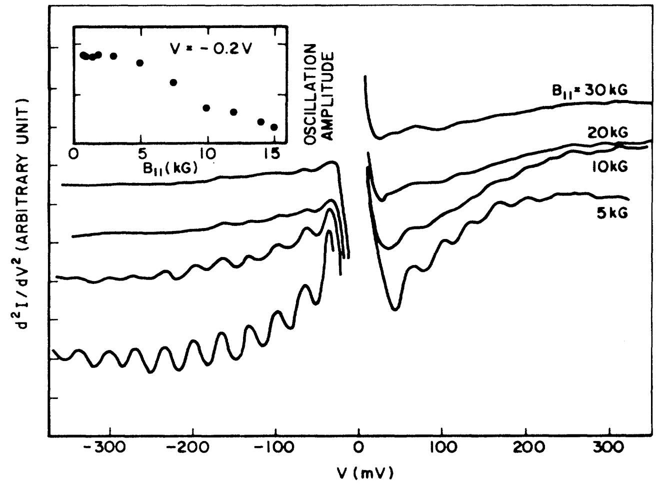

FIG. 3. d^2I/dV^2 vs V for $B_{\parallel}=5$ to 30 kG. The zeros of the curves are displaced. The inset shows the oscillation amplitude as a function of $B_{\parallel}$.

suffers a sudden decrease in its terminal velocity as it approaches the collecting electrode, and causes a drop in the current flow through the channel. Consequently, only when the distance Z_n, which the electron must travel along the channel to gain enough energy to emit a phonon, satisfies $L=nZ_n$ will the emission give rise to a dip in the I-V curve. Since the electric field in the channel is V/L, we expect a series of dips in the I-V characteristic at $eV \sim n\hbar\omega_0$ in both bias polarities. The observed asymmetry in our data reflects the asymmetry of our devices, where the collecting electrodes are the evaporated In in one polarity and the bulk InGaAs in the other.

Several additional observations are relevant. First, the oscillation period increases slightly for large-n oscillations at high bias. Second, it may differ from contact to contact, varying from $\Delta V \sim 33$ to ~ 36 meV, but never less than the LO-phonon energy of $In_{0.53}Ga_{0.47}As$. These two observations illustrate the influence of the series resistance, which can give rise to appreciable voltage drop in the electrodes. They also caution the use of such two-terminal transport measurements for an accurate determination of $\hbar\omega_0$. Third, the oscillations decrease in amplitude with increasing T and remain observable up to ~ 55 K (Fig. 2). These results are consistent with the fact that scattering by acoustic phonons increases with increasing T and, for $T>55$ K, it dominates the transport process and damps out the oscillations, which select specific LO-phonon emission events. Fourth, the application of a B perpendicular to the surface has no observable effect on either the period or the amplitude of the oscillations. On the other hand, the oscillations decrease in the presence of a parallel $B \geqslant 5$ kG and become unidentifiable for $B_{\parallel} \geqslant 30$ kG (Fig. 3).[14] All these observations are consistent with the model. A perpendicular B, directed along the wires, is expected to have no effect on the transport of electrons along them. On the other hand, the effect of a parallel B, which is perpendicular to the wires should depend on the field strength. If $B_{\parallel}$ is sufficiently strong, the bending of the electronic motion by the Lorentz force is expected to smear out the oscillations. Finally, the model can also be employed to understand the oscillatory phenomena in tunnel junctions. As pointed out by Hickmott *et al.*,[5] the oscillations result from phonon emission in the electrode and the role of the tunnel junction is to supply the electrons. It is well known that tunneling is highly directional and the tunnel junction in fact makes the subsequent ballistic transport of the injected electrons one dimensional. In the bias polarity corresponding to the acceleration of electrons out of the semiconductor toward the tunnel junction, the junction acts merely as a blocking contact, and no oscillations are expected from the model.

In summary, we observed an oscillatory conductance in the I-V characteristic of In-InGaAs contacts in both bias polarities. A model based on the work of Kulik and Shekhter[6] explains the oscillatory phenomenon by LO-phonon emission in the one-dimensional transport of ballistic electrons through microchannels of InGaAs bridging the contact. This model also provides an understanding of previous experiments on tunnel junctions and makes it apparent that all the experiments are various versions of the classical Franck-Hertz experiment.

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