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Observation of Single-Optical-Phonon Emission

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We report an observation of a single-optical-phonon emission by monoenergetic hot electrons traversing thin n^+-type GaAs and thin undoped AlGaAs layers in times much shorter than the classical phonon period. This was done by injecting ballistic electrons into the thin layers with energy around the threshold for optical phonon emission and monitoring their exit energy. We estimate a scattering time of $\simeq 200$ fsec for electrons with energy of about 85 meV in n^+-type GaAs, and $\simeq 550$ fsec for 40-meV electrons in undoped AlGaAs.

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Among the variety of phonons in GaAs, the longitudinal optical (LO) phonons are coupled most strongly to low-energy electrons. Electrons with wave vector $\mathbf{k}$ will scatter via phonons with wave vector $\mathbf{q}$ to $\mathbf{k}'$ ($\mathbf{q}=\mathbf{k}-\mathbf{k}'$) with a probability proportional to $|\mathbf{q}|^{-2}$ in unscreened material, thus preferring to maintain their original direction. The $\mathbf{q}=0$ LO phonon energy in GaAs has been measured via neutron scattering[1] and inelastic tunneling,[2] and is $\hbar\omega_{\mathrm{LO}} \simeq 36$ meV. At low temperatures, when the phonon occupation number is small, scattering events are mostly due to phonon emission which is possible only when the electron energy exceeds the lowest unoccupied energy state by at least 36 meV. Using energy spectroscopy, Dimaria *et al.*[3] have observed phonon replicas in $\mathrm{SiO_2}$ in electron distributions emerging into vacuum. Multiphoton emission in GaAs was observed by Shaw[4] via photoconductivity experiments, and more recently by Hickmott *et al.*[5] in tunneling experiments. We report here a direct observation of monoenergetic, ballistic, hot electrons that emitted a single LO phonon when traversing very thin layers of n^+-type GaAs and insulating AlGaAs. It is particularly interesting that the transit time of the electrons through the layers is smaller than the phonon classical period ($2\pi/\omega_{\mathrm{LO}}$).

To observe the emission of a phonon by a hot electron, a potential barrier (spectrometer) was constructed; its height was considerably lower than $\hbar\omega_{\mathrm{LO}}$ to enable electrons with energy less than $\hbar\omega_{\mathrm{LO}}$ to pass, but sufficiently high to prevent those hot electrons that lost $\hbar\omega_{\mathrm{LO}}$ from passing. A quasi monoenergetic hot-electron beam was produced by a tunnel barrier (injector), which was made especially wide in order to achieve an energetically narrow hot-electron beam. Our hot-electron structures, described in Fig. 1, were grown by molecular-beam epitaxy, were composed of n^+-type GaAs emitter, undoped AlGaAs tunnel barrier injector, n^+-type GaAs transport region (base), undoped AlGaAs spectrometer barrier, and n^+-type GaAs collector layer.[6,7] The spectrometer barrier, 70 nm thick, with AlAs mole fraction $x=7\%$, had a conduction-band discontinuity of 63 meV. Because of some 1×10^{16}-cm^{-3} unintentional negative charges in all our molecular-beam-epitaxy layers,[8] the measured barrier height was about 73 meV (the additional 10-meV bowing is expected to have a potential maximum at the center of the barrier). With doping of 8×10^{17} cm^{-3} in all n^+-type GaAs layers and Fermi energy of 45 meV at 4.2 K, the spectrometer potential height above the Fermi level in the base was $\Phi_C = 73-45=28$ meV. The barrier height was measured by observing the onset of the collector current as will be shown later. For our thick injector tunnel barrier, 50 nm thick with $x=7\%$, the expected full width at half maximum of the injected energy distribution is about 4 meV.[6,7]

Applying $V_{CB} \gtrsim 30$ meV across the spectrometer barrier, reduces its potential peak to 63 meV (by flattening the bowing potential) and shifts its position to the base side (flat-band conditions as seen in Fig. 1). A further increase in V_{CB} affects Φ_C only slightly. This assures that a large enough window Δ exists between the phonon

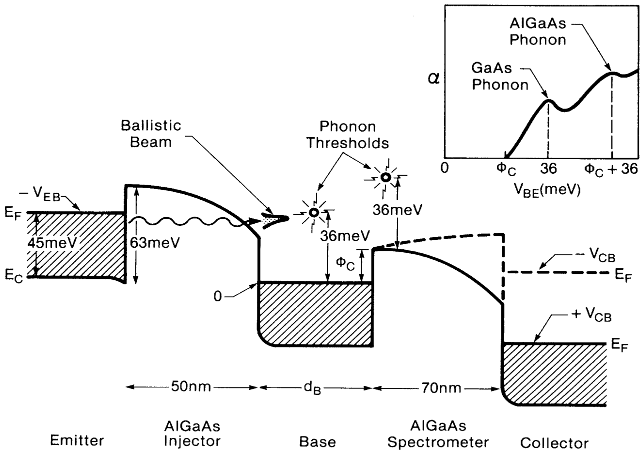


FIG. 1. The conduction band in the hot-electron structure with the expected ballistic electron distribution and the different thresholds for phonon emission. Inset: The expected behavior of α, as a result of phonon emission in GaAs and in AlGaAs.

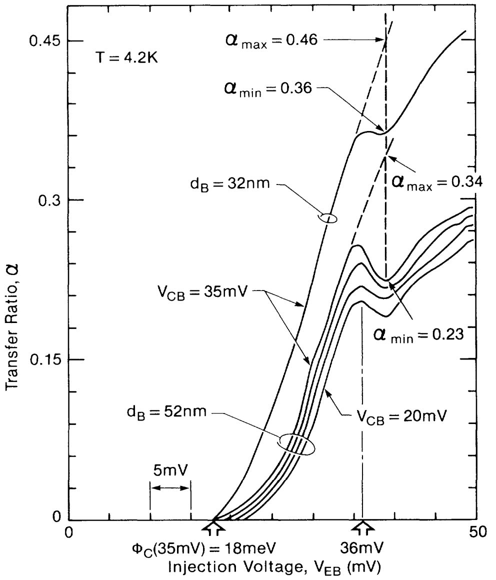
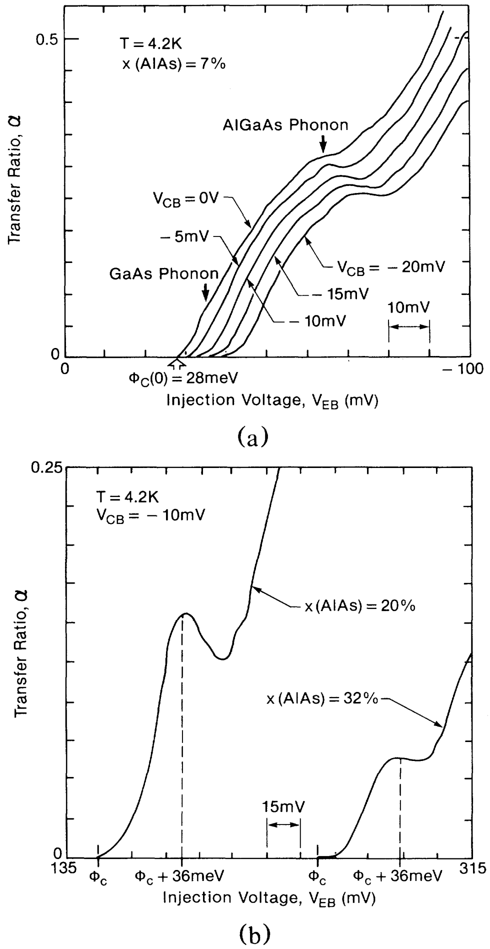


FIG. 2. The transfer ratio α curves for different V_{CB}'s (5-mV steps) in the 52-nm base device. As V_{CB} increases, the window between the phonon emission threshold and the collector barrier height increases and α experiences a stronger dip. The α measured in the 32-nm base device at $V_{CB} = 35$ mV is also shown.

threshold and the barrier top [$\Delta = \hbar\omega_{\mathrm{LO}} - \Phi_C = 36 - (63 - 45) = 18$ meV], allowing the full width of the ballistic distribution, injected by the tunnel barrier, to surmount the spectrometer barrier before emitting a phonon. We have looked at the *differential transfer ratio,* defined as $\alpha = dI_C/dI_E$ for $V_{CB} =$const, where I_C and I_E are the collected and emitted (injected) currents, as a function of the injection voltage, V_{EB}. The quantity α is a good measure of the electron loss since it eliminates constant leakage currents and normalizes the collected current to the injected current (which rises rapidly with the injection voltage).

In Fig. 2 we show the behavior of α for structures with base widths of 52 and 32 nm, for different spectrometer biasing voltages $V_{CB} > 0$. We see that α rises rapidly when the injection energy eV_{EB} exceeds the barrier height, Φ_C [$\Phi_C(0) = 28$ meV for $V_{CB} = 0$, as seen in Fig. 3(a)]. When $eV_{EB} = 36$ meV, the LO phonon energy α drops sharply, reaching a minimum around 40 meV and thereafter increases again. The drop in α beyond $V_{EB} = 36$ mV is due to those ballistic electrons that emitted a phonon. The overall monotonic rise of α is determined by the energy dependence of all scattering mechanisms, and in particular the quantum-mechanical reflections from the base-spectrometer interface, dominant for energies close to the spectrometer potential height. We define the fractional loss of electrons at energy E due to phonon emission as $\alpha_{\min}(E)/\alpha_{\max}(E)$, where $\alpha_{\min}(E)$ is the measured $\alpha(E)$, and $\alpha_{\max}(E)$ is the extrapolated $\alpha(E)$ as if phonon emission did not occur, as seen in Fig. 2. The different slopes of $\alpha(E)$ before and after threshold indicate an increase in the scattering rate as the electron energy increases. To minimize the error in our estimate for the scattering rates deduced from the extrapolated $\alpha_{\max}(E)$, we measure $\alpha_{\min}/\alpha_{\max}$ at the lowest possible energy above threshold, namely, about a distribution width above the threshold energy. As V_{CB} increases, Φ_C decreases (indicated by the shifting onsets of α in Fig. 2), and the ballistic window Δ increases (up to about 18 meV as shown before), followed in turn by an increase of $\alpha_{\min}(E)/\alpha_{\max}(E)$. We find that increasing V_{CB} above 35 mV does not increase Δ and $\alpha_{\min}(E)/\ \alpha_{\max}(E)$ any more.



(a)

(b)

FIG. 3. The transfer ratio α exhibiting the phonon emission in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$, for (a) $x = 7\%$, and for (b) $x = 20\%$ and 32%. Note in (a) how the phonon-related loss peak in the AlGaAs builds up as V_{CB} becomes slightly negative.

We estimate the mean free path λ from Fig. 2 using $\exp(-d_B/\lambda) = \alpha_{\min}(E)/\alpha_{\max}(E)$, where d_B is the base width. At an energy of about 85 meV we find $\lambda \simeq 126$ nm and $\lambda \simeq 130$ nm for the structures with base width of 52 and 32 nm, respectively. Since at 85 meV the ballistic electron velocity is about 6.1×10^7 cm/sec (assuming a band-edge effective electron mass of $0.067m_e$ and a nonparabolicity parameter $\beta=-0.834/\mathrm{eV}$),[9] the deduced scattering time for phonon emission τ at 85 meV is about 210 fsec in the n^+-type GaAs layers. At slightly higher energies, say 90 meV, we find $\lambda\simeq115$ nm and $\tau\simeq185$ fsec. It is interesting to note that our results are in approximate agreement with experiments done in unscreened GaAs layers.[10] We compare our results with the theoretical predictions for the LO phonon emission rate in undoped GaAs.[11] In mks units,

$$\frac{1}{\tau(E)}=\frac{e^2m^{1/2}\hbar\omega_{\mathrm{LO}}}{4\sqrt{2}\pi\hbar^2E^{1/2}}\left[\frac{1}{\epsilon_\infty}-\frac{1}{\epsilon_{DC}}\right](1+n_{\mathrm{LO}})F(E,E')\,. \tag{1}$$

Here,

$$F(E,E')=\frac{1}{C}\left[A\ln\frac{\gamma^{1/2}(E)+\gamma^{1/2}(E')}{\gamma^{1/2}(E)-\gamma^{1/2}(E')}+B\right],$$

$\gamma(E)=E(1-\beta E)$, $E'=E-\hbar\omega_{\mathrm{LO}}$, n_{LO} is the phonon occupation number, $\epsilon_{\mathrm{DC}}=12.9\epsilon_0$ and $\epsilon_\infty=10.9\epsilon_0$ are the static and optical dielectric constants of GaAs and ϵ_0 is the permitivity of free space, A, B, and C are factors due to nonparabolicity effects (in parabolic bands $A=C=1$ and $B=0$), and $m=0.067m_e$. Substituting in Eq. (1) $n_{\mathrm{LO}}=0$ at $T=4.2$ K, $E=85$ meV, $E'=49$ meV, and calculating[11] $A=5.5$, $B=-0.52$, and $C=5.3$, we find $\tau=240$ fsec.

This excellent agreement with our measured τ is somewhat surprising since at our equilibrium electron concentration of 8×10^{17} cm^{-3} the $\mathbf{q}=0$ LO phonons and plasmons have similar energies ($\hbar\omega_p\simeq38$ meV), and thus interact strongly, resulting in two coupled modes: a plasmonlike mode with $\mathbf{q}=0$ energy $\hbar\omega_+(0)=43$ meV and a phononlike mode with $\hbar\omega_-(0)=28$ meV (Ref. 12). The lowest possible $|\mathbf{q}|$ modes for which scattering is most dominant in unscreened GaAs is

$$q_{\min}=|\mathbf{k}(85\ \mathrm{meV})|-|\mathbf{k}'(49\ \mathrm{meV})|\simeq1\times10^6\ \mathrm{cm}^{-1}\,,$$

and $q_{\min}/k_F\simeq0.35$, where k_F is the Fermi wave vector. Because of dispersion, we would expect to observe two thresholds, one at $\hbar\omega_+(0.35)\simeq57$ meV and the other at $\hbar\omega_-(0.35)\simeq31$ meV (Ref. 12), both are not observed. Screening might be rather important since $k_0>|\mathbf{q}_{\min}|$, where $1/k_0$ is the Thomas-Fermi screening length. Then emission of higher $\mathbf{q}$ LO phonons with $\hbar\omega_{\mathrm{LO}}\simeq36$ meV can dominate due to their high density, explaining the 36-meV peak. Since the coupling to the plasmon branch is expected to be strong,[12] the absence of an observed threshold at 57 meV is not clear. The higher $\mathbf{q}$, higher frequency, plasmons modes, however, are heavily damped by single-electron excitations, and thus not observable. Quantization effects in the narrow base are less likely to affect our observations due to the similarity of the results found in the 52- and 32-nm-wide bases. However, the possibility of an emission of an unscreened, uncoupled, LO phonon, in agreement too with our observations should not be ruled out.

The same structure enabled us also to observe single-phonon scattering events in AlGaAs. In the spectrometer barrier, when the ballistic hot electrons lose energy and relax to the bottom of the conduction band, they can "roll back" to the base or "roll forward" to the collector, depending on the potential shape in the barrier. Indeed, for $V_{CB}>0$ it is difficult to verify the existence of electron scattering in AlGaAs, since both the ballistic electrons and the ones that scatter reach the collector. However, when a small negative bias is applied across the barrier (-10 to -20 mV), a clear peak in α is observed near $eV_{EB}=\Phi_C+36$ meV,[13] as we show in Fig. 3(a) (the GaAs-like LO phonon is 35.5 meV in AlGaAs with $x=7\%$). Here the estimate for λ is cruder since it is more difficult to determine accurately the traversal region in the AlGaAs barrier (see dotted line in Fig. 1). At higher negative bias, the threshold voltage is not unique and the phonon threshold broadens and shifts to higher energies. We have used the same method as before to estimate λ. Using an estimated length to the potential peak of 45 nm for $V_{CB}=-10$ mV (via a Poisson solution) and an excess energy in the AlGaAs of $\simeq40$ meV, we find $\lambda\simeq230$ nm. With an estimated average ballistic velocity of 4.2×10^7 cm/sec in the barrier, we arrive at $\tau=550$ fsec. Using in Eq. (1) $E=40$ meV, $E'=4$ meV, and the appropriate parameters for $\mathrm{Al}_{0.07}\mathrm{Ga}_{0.93}$-As,[14,15] we find $\tau\simeq490$ fsec, which is in good agreement with our measurements.

Phonon emission can also be observed in AlGaAs layers with higher AlAs mole fractions. We have fabricated similar hot-electron structures but with $x=20\%$ and 32% in the barriers. Here, an electron energy in the GaAs base must be at least some 180 and 290 meV, respectively, to enter the AlGaAs spectrometer; however, in AlGaAs the electron energy can be near the phonon emission threshold. Figure 3(b) shows the α of these two devices for a small negative spectrometer voltage, $V_{CB}=-10$ mV. Again, the peaks in α are very near 36 meV above Φ_C, resolving clearly the GaAs-like LO phonons (which are about 35 and 34.3 meV in AlGaAs with $x=20\%$ and 32%, respectively[14,15]). The AlAs-like phonons, being 44.6 and 47 meV, respectively, are difficult to resolve since the ballistic distributions at high injection energies in these structures are much broader ($\simeq60$ meV, Ref. 7). Since the energy width of the ballistic distributions here is wider than the window $\Delta\simeq36$ meV, and its width requires an extrapolation too long for an accurate determination of $\alpha_{\max}(E)$, the validity of α as a quantitative measure of electron loss is questionable. If we assume the dominant scattering to be due to the GaAs-like LO phonons and $E=40$ meV, Eq. (1) predicts $\tau=400$ fsec in AlGaAs with $x=25\%$, and a λ of about 150 nm.

In summary, we have directly observed electrons that emitted a single longitudinal optical phonon in n^+-type GaAs and in undoped AlGaAs layers. In both layers a clear single threshold at 36 meV (the LO phonon energy) was observed, and we have estimated the phonon-related scattering time near threshold to be $\simeq 200$ fsec in n^+-type GaAs.

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