Temperature dependence of nonequilibrium transport time of electrons in bulk GaAs investigated by time-domain terahertz spectroscopy

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By using free space terahertz electro-optic sampling technique, the terahertz (THz) waveforms emitted from intrinsic bulk GaAs photoexcited by femtosecond laser pulses under strong bias electric fields at various temperatures were recorded. We clearly observe the velocity of electrons exhibits a pounced overshoot behavior. The nonequiliburm transport time of electrons, τ_ε, has been obtained from the THz waveforms. From the temperature dependence of τ_ε, we find that τ_ε is governed by the polar scattering process of electrons in Γ valley via longitudinal opticalphonon emissions. © *2011 American Institute of Physics*. [doi:10.1063/1.3610472]

With recent progress in miniaturization of electron devices, ultrafast transistors with cutoff frequencies over 500 GHz have been realized.[1] In such devices, carriers drift in channels in a very nonstationary manner and ballistic acceleration rather than steady-state transport properties (mobilities, saturation velocities, etc.) is more essential in determining device performance. Therefore, clarifying of nonequilibrium transport time of electrons, τ_ε, in semiconductors, which is defined as the time of electrons starting to move from the bottom of conduction band to reach the statics-state under extreme nonequilibrium conditions, is, therefore, strongly motivated by the needs to obtain information relevant for designing ultrahigh-speed devices. Furthermore, ultrafast nonequilibrium carrier transport in semiconductors biased under high electric fields is also of fundamental interest in semiconductor physics.[2,3]

Although there have been a number of reports on quasi-static properties of electron motion in biased semiconductors,[4–8] only a few experimental reports have been made on femtosecond carrier dynamics.[2,9–11] Leitenstorfer *et al.* first presented the experimental results on the terahertz (THz) emission from electrons accelerated by high electric fields and showed firm experimental evidence of velocity overshoot in a 10 fs-time scale by utilizing a fact that emitted terahertz fields, $E_{THz}(t)$, are proportional to carrier acceleration.[9,10] Using this technique, clear evidence for velocity overshoot has been experimentally demonstrated. Furthermore, it also provides a unique chance to experimentally investigate the factors that govern the nonequilibrium transport time of electrons, τ_ε, under high electrical fields.

In this work, we have investigated THz radiation emitted from electrons photoexcited by femtosecond laser pulses in bulk GaAs under strong bias electric fields at various temperatures. The nonequilibrium transport time of electrons, τ_ε, has been obtained from the THz waveforms. From the temperature dependence of τ_ε, we find that τ_ε is governed by the time of polar scattering in Γ valley, which is inverse proportional to the emission rate of longitudinal optical (LO) phonons, $\langle N_{LO}+1\rangle$.

The sample used in this experiment was a metal-intrinsic-*n*-type semiconductor (*m-i-n*) geometry with a 1 μm-thick undoped GaAs layer, grown by molecular beam epitaxy. The detail of the fabrication of our sample was described in our previous paper.[2,3] The sample was put in a cryostat whose temperature can be controlled from 4 K to room temperature. The carrie generation condition was same as our previous works together with the experimental setup and condition.[2,3] The internal electric fields, F, in the undoped depletion regions were estimated from the voltage applied to the sample together with the Schottky barrier heights determined from current-voltage measurements, which is ∼0.74 eV at 300 K and ∼0.77 eV at 10 K.

Figures 1(a) and 1(b) show the temperature dependence of THz waveforms, $E_{THz}(t)$, emitted from the sample under 9 kV/cm and 27 kV/cm, respectively. As seen in the figure, $E_{THz}(t)$ has a bipolar feature; i.e., an initial positive peak and a subsequent negative dip. This feature arises from the velocity overshoot[2,9–11] and the initial positive peak is due to electron acceleration in Γ valley, while the subsequent negative dip originates from electron deceleration due to intervalley transfer from Γ valley to L(X) valleys. It should be noted in Fig. 1 that the position of $t = 0$ has been carefully determined by the maximum entropy method (MEM), the detail of which has been published elsewhere.[12] The estimated time error is less than ±15 fs, which is limited by the time interval of the recorded data points. Furthermore, as seen in Figs. 1(a) and 1(b), the time duration of the emitted THz waveforms decreases with increasing temperature, T, under both 9 kV/cm and 27 kV/cm. This indicates that at high T, a short nonequilibrium transport time of electrons, τ_ε (also marked in Figs. 1(a) and 1(b)) should be, which means that the spectrum of $E_{THz}(t)$ is broader. It is consistent with Monte Carlo simulation prediction.[13]

Under applied electric field larger than the Gunn threshold (reported about 3 kV/cm in GaAs), in the ε-*k* diagram, the electrons experience the motion in *k*-space as following: (I) be accelerated from the bottom of Γ valley, (II) relax in Γ valley, (III) go to L(X) valley by intervalley scattering, and then (IV) reach steady state via deformation potential (DP)

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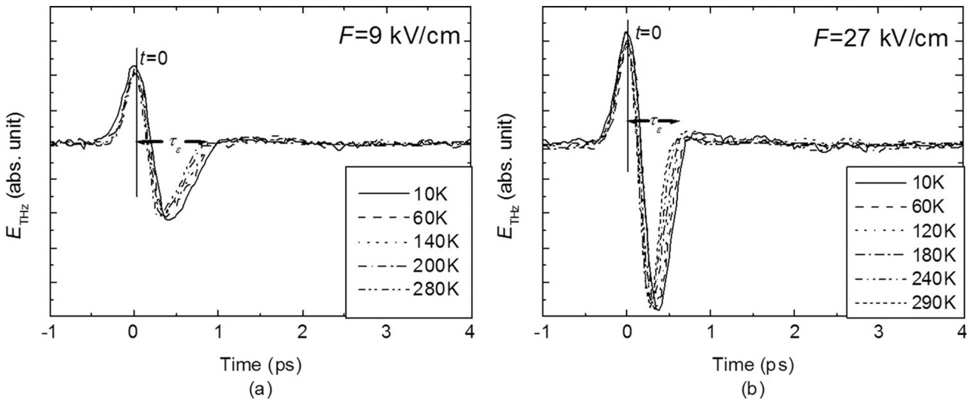

FIG. 1. Temperature dependence of THz waveforms, $E_{THz}(t)$, emitted from an *m-i-n* diode with a 1 μm-thick intrinsic GaAs layer under bias electric fields at 9 kV/cm and 27 kV/cm, respectively.

scattering (part of electrons) in L(X) valleys, (V) be scattered back (part of electrons) to Γ valley, and(VI) relax in Γ valley (part of electrons) via LO phonon scattering, as shown in Fig. 2. Eventually, there is a distribution of electrons in both L(X) and Γ valleys.[14] The longer time of the motion of electrons in *k*-space via I, II, III, and IV or via I, II, III, V, and VI is considered as the nonequilibrium transport time of electrons, τ_ε.

For the order estimation, we first calculate the ballistic acceleration of electrons in Γ valley. From the Newton's law,

$$eF = m_{eff} * \dot{v}, \tag{1}$$

where e, $\dot{v}$, and m_{eff}* are the magnitude of the charge, the acceleration, and the effective mass of electrons, respectively; we can roughly estimate the time for acceleration process. Intervalley scattering from Γ valley to L(X) valleys requires phonon with a large wave vector, and group theoretical selection rules show that the LO phonon is the only one allowed because L(X) valleys minimum lie on the edge of Brillouin zone. Fischetti calculated that the intervalley scattering time from Γ valley to L valley should be about 20 fs and vice versa.[15]

Then, part of electrons experience scattering via DP in side valleys which favors maximum momentum transfer. This scattering can randomize asymmetric momentum distribution that has built up during acceleration from the band minimum, which causes the electrons reaching steady state

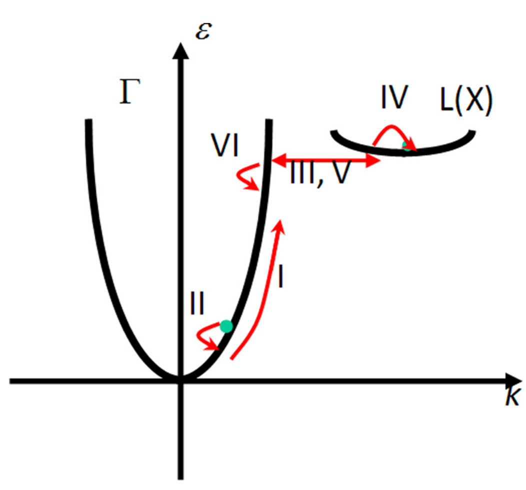

FIG. 2. (Color online) Electrons experience the motion in *k*-space.

in side valleys. By taking account the acoustic and optical phonon scattering via DP, this scattering time can be obtained ~0.3 ps at 300 K and ~0.4 ps at 10 K.[16]

Furthermore, the other part of electrons can be scattered back and relax in Γ valley. In such case, the motion of electrons in *k*-space experience processes I, II, III, V, and VI as shown in Fig. 2. LO phonon emissions are considered as the main scattering for electrons reaching steady state in Γ valley and eventually let the energy of electrons be ~0.15 eV.[14] Therefore, electrons from the edge of Γ valley whose energy is ~0.29 eV should experience ~3 LO phonon emissions in Γ valley.

The scattering rate via LO phonon emission process in Γ valley in bulk sample is expressed[8]

$$\begin{aligned}\frac{1}{\tau_{(e)}(\hat{k})} &= \frac{2\pi}{\hbar}\frac{1}{(2\pi)^3}\frac{e^2\hbar\omega_{LO}}{2\varepsilon_0}\langle N_{LO}+1\rangle\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_s}\right)\\ &\times\frac{m*}{\hbar^2\sqrt{\left|\hat{k}\right|^2-\frac{2m*\hbar\omega_{LO}}{\hbar^2}}}\int_0^{+\infty}\int_0^{\pi}\int_0^{2\pi}|k'|^2\sin\theta\frac{1}{|\hat{k}'-\hat{k}|^2}\\ &\times\delta\left(\left|\hat{k}\right|'-\sqrt{\left|\hat{k}\right|^2-\frac{2m*\hbar\omega_{LO}}{\hbar^2}}\right)d\left|\hat{k}\right|'d\theta d\varphi\end{aligned} \tag{2}$$

where ε_0 is the dielectric permittivity of vacuum, ε_s is the static dielectric constant, $\varepsilon_\infty$is the high frequency dielectric constant, N_{LO} is the thermal equilibrium phonon population in per unit volume, and k, k' are the wave vector of electrons before and after scattering, respectively. As shown in Eq. (2)), because the probability of LO phonon emission is proportional to $\langle N_{LO}+1\rangle$ and expressed as

$$\langle N_{LO}+1\rangle = \frac{1}{exp(\hbar\omega_{LO}/k_BT)-1}+1, \tag{3}$$

which is temperature dependent; we expect this polar scattering time is shorter at higher temperatures. By using Eq. (3), the time for single scattering via LO phonon emission in Γ valley can estimated to be 0.15 ps at 300 K and 0.2 ps at 10 K, and the calculated results are consistent with the experimental results reported by Betz *et al.*[17]

From this order estimation, by comparing the time of electrons motion in *k*-space via I, II, III, and IV or via I, II, III, V, and VI, it is concluded that the time of polar scattering by LO phonon emissions in Γ valley governs the nonequilibrium transport time of electrons, τ_ε. The estimated τ_ε at 10 K, is

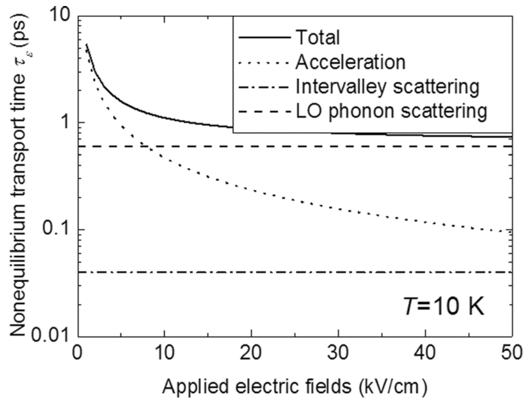

FIG. 3. The estimated results of nonequilibrium transport time of electrons in bulk GaAs are plotted as a function of bias electric field, F_0 at 300 K (solid line). The dot line is the calculated time for the electrons accelerated in Γ valley under various electric fields. The dash dot line is the intervalley scattering time of electrons between Γ and L(X) valleys. The dash line is the time of polar scattering process via LO phonon emissions in Γ valley.

plotted in Fig. 3 [ballistic acceleration process (dotted line), intervalley scattering processes (dashed dotted line), 3 LO phonon emissions process in Γ valley (dashed line), and the total (solid line)] as a function of applied electric fields.

Figure 4 plots the temperature dependence of τ_ε, which gradually decreases with increasing T under both 9 kV/cm and 27 kV/cm. We can clearly see that the trend of temperature dependence τ_ε agrees with that of the estimated results (dashed line for 9 kV/cm and solid line for 27 kV/cm). The agreement between the experimental and estimated results strongly suggests that the nonequilibrium transport time of electrons, τ_ε, is governed by the polar scattering process of

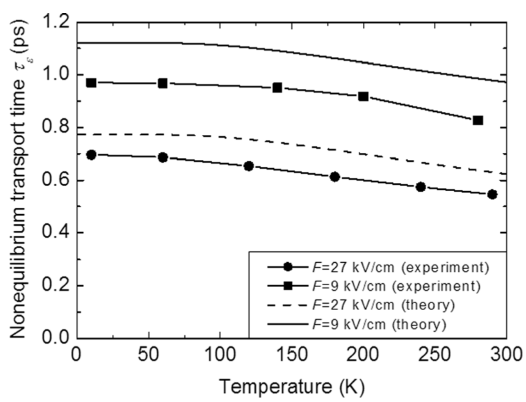

FIG. 4. The experimental results of nonequilibrium transport times of electrons in bulk GaAs are plotted as a function of temperature under $F = 9$ kV/cm (squares), 27 kV/cm (circles). The dash line (9 kV/cm) and solid line (27 kV/cm) show the temperature dependence of τ_ε from the calculation.

electrons in Γ valley via LO phonon emissions. At lower temperature (10 K), LO phonon emission rate (Eq. (4)) decreases and a longer polar scattering time is expected, which results in a longer nonequilibrium transport time of electrons than that at 300 K, under both 9 kV/cm and 27 kV/cm.

The difference between the experimental data and estimated results under both electric fields as shown in Fig. 4 mainly comes from the neglect of acoustic phonon scattering in Γ valley.

In summary, we have investigated temperature dependence of THz radiation emitted from electrons photoexcited by femtosecond laser pulses in bulk GaAs under strong bias electric fields. We clearly observe the velocity of electrons exhibits a pounced overshoot behavior. From the temperature dependence of nonequilibrium transport time of electrons, τ_ε, obtained from the THz waveforms, we find that τ_ε is governed by the polar scattering process of electrons in Γ valley via LO phonon emissions.

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