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Ballistic electron transport in InP observed by subpicosecond time-resolved Raman spectroscopy

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Abstract

Electron ballistic transport in an InP-based p–i–n nanostructure under the application of an electric field has been studied by time-resolved Raman spectroscopy at $T = 300$ K. The time evolution of electron distribution, electron drift velocity has been directly measured with subpicosecond time resolution. Our experimental results show that, for a photoexcited electron–hole pair density of $n \cong 5 \times 10^{16}$ cm^{-3}, electrons travel quasi-ballistically – electron drift velocity increases linearly with time, during the first 150 fs. After 150 fs it increases sublinearly until reaching the peak value at about 300 fs. The electron drift velocity then decreases to its steady-state value.

Keywords: Ballistic transport; Raman spectroscopy; Electron distributions

As the size of semiconductor devices becomes smaller than 1 μm, the time scale important for device operation becomes quite short. In these short time regimes, which is typically in the order of subpicosecond, the transport properties of electrons are known to be very different from those observed under steady-state conditions. One of the interesting phenomena arising is the so-called "electron velocity overshoot", where electron drift velocity overshoots its steady-state value. This potential for greatly enhancing the operating speed of a semiconductor device has attracted a lot of attention [1,2]. With the advent of ultrafast pulsed laser sources, it is now possible to directly observe such a transient electron transport phenomenon in semiconductors. Theoretically, the transient electron transport properties have been extensively studied by Ruch [3], and Maloney and Frey [4] in Si and GaAs. Experimentally, several research groups [5–12] have developed different experimental techniques in an attempt to observe such a novel transient transport phenomenon in Si, GaAs and GaAs quantum wells. Recently, Grann et al. [13] have studied electron velocity overshoot and LO phonon dynamics in a GaAs-based p–i–n nanostructure semiconductor by using subpicosecond Raman spectroscopy. Non-equilibrium electron distributions, LO phonon populations and electron

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drift velocities as a function of electron density and electric field intensity in GaAs were directly measured. In this paper, we demonstrate that time-resolved Raman spectroscopy can also be used to study ballistic electron tranport. We have observed that in InP nanostructures, for electric field intensity of $E = 15$ kV/cm, and electron–hole pair density of $n \cong 5 \times 10^{16}$ cm^{-3}, electrons travel ballistically during the first 150 fs of their transient.

The InP p–i–n nanostructure sample investigated in this work was grown by molecular beam epitaxy on a (0 0 1)-oriented InP substrate. The p-type layer was made up of a 100 Å-thick Be-doped ($\cong 10^{17}$ cm^{-3}) InP layer. The i-type region was a 1 μm-thick intrinsic InP. This was the active volume probed by our experiment. The n-type layer consisted of a 1000 Å-thick Si-doped ($\cong 10^{17}$ cm^{-3}) InP layer. The p-type and n-type layers served as plates of a capacitor which provided a uniform electric field across the intrinsic InP layer. The mesa-like nanostructure p–i–n sample had a circular opening of diameter $\cong 500$ μm. This opening made the light scattering experiments possible.

The laser used in this experiment had a photon energy of 1.51 eV and a pulse width of $\cong 100$ fs. These ultrashort pulses were generated by a cw mode-locked Ti–sapphire laser. The probe pulses consist of a train of pulses having photon energy $\hbar\omega = 1.51$ eV; whereas the pump pulses are derived from their second harmonic, i.e., $\hbar\omega = 3.02$ eV. The photoexcited electron–hole pair density was estimated from the power density per laser pulse, the laser spot size on the sample and the penetration depth of the laser under our experimental conditions. This experimental arrangement is to make sure that no electrons escape from the probe region during the transient measurements.

The single-particle scattering (SPS) experiments were carried out in the backscattering geometry with $Z(X, Y)\bar{Z}$ scattering configurations for the probe pulses; where $X = (1\,0\,0)$, $Y = (0\,1\,0)$ and $Z = (0\,0\,1)$. Since the SPS cross section is inversely proportional to the effective mass of the carriers [14,15], our experiment primarily probes electron transport in the Γ-valley, even though holes are simultaneously present. We note that, under reverse-biased conditions, our backscattering geometry probes the electron distribution along the direction of $-\vec{E}$. All of the experimental data reported here were performed at $T = 300$ K. The scattered light was collected and analyzed by a double spectrometer and a photomultiplier tube. The effective average electric field intensity during the transient was determined by using Franz–Keldysh effect [16].

Fig. 1 shows a typical electron distribution function for an InP nanostructure taken at $n \cong 5 \times 10^{16}$ cm^{-3}, an electric field intensity of $E = 15$ kV/cm and at a time delay of $\Delta t = 120$ fs. Electron distribution shifts toward $-\vec{E}$ direction, as expected. A sharp cut-off in the velocity distribution around 1.4×10^{8} cm/s is observed, indicating the onset of electron intervalley scattering processes in InP. The distribution clearly cannot be fit by a shifted Fermi–Dirac function which reflects the extremely non-equilibrium nature of electron distribution under the application of an electric field. The electron drift velocity for a given electron distribution function was calculated in a straightforward way by taking a weighted average over the electron velocity distribution.

Fig. 2 shows electron drift velocity as a function of the time dealy for an InP nanostructure taken at $n \cong 5 \times 10^{16}$ cm^{-3} and at an electric field intensity of $E = 15$ kV/cm. We have found that, for a

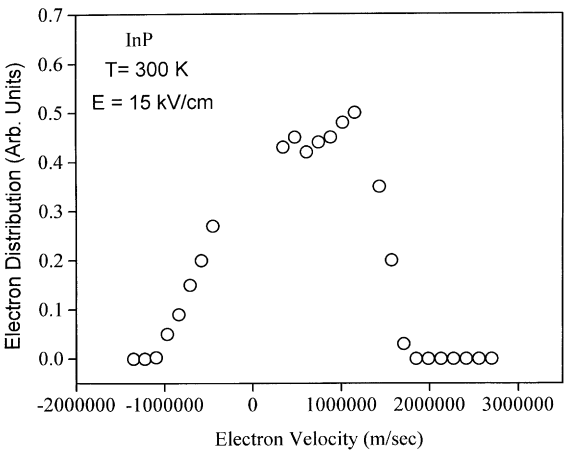

Fig. 1. Electron distribution for an InP nanostructure taken at $T = 300$ K, $n \cong 5 \times 10^{16}$ cm^{-3}, an electric field intensity of $E = 15$ kV/cm and at a time delay of $\Delta t = 120$ fs.

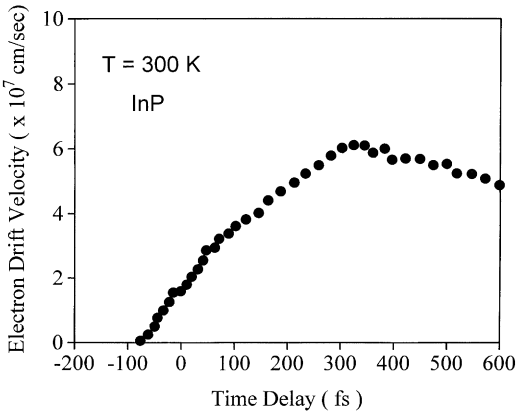

Fig. 2. Electron drift velocity as a function of the time delay for an InP nanostructure. The linearly increased velocities between 0 and 150 fs were attributed to the ballistic transport of electrons during the transient.

photoexcited electron–hole pair density of $n \cong 5 \times 10^{16}\,\mathrm{cm}^{-3}$, electrons travel quasi-ballistically – electron drift velocity increases linearly with time, during the first 150 fs. After 150 fs it increases sublinearly until reaching the peak value of about 8×10^7 cm/s at about 300 fs. The electron drift velocity then decreases to its steady-state value. Apparently, for the first 150 fs of the transient, electrons suffer very minimal scattering. As a result the drift velocity increases linearly with the elapsed time.

In conclusion, we demonstrate that time-resolved Raman spectroscopy can also be used to directly study ballistic electron tranport. We have observed that in InP nanostructures, for electric field intensity of $E = 15$ kV/cm, and electron–hole pair density of $n \cong 5 \times 10^{16}\,\mathrm{cm}^{-3}$, electrons travel ballistically during the first 150 fs of their transient.

Acknowledgements

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