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Transition from ballistic to drift motion in high-field transport in GaAs

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Abstract. With strong THz pulses, we measure ultrafast transport of electrons, holes, and an electron-hole plasma in GaAs. The transition from ballistic to drift-like transport is strongly influenced by electron-hole scattering.

In an electric field charge carriers in a semiconductor undergo ballistic transport, i.e., the *acceleration* is proportional to the field, in the absence of scattering. Since any scattering process takes a finite time, every transport will be ballistic on sufficiently short times [1]. If, as is often the case, the most important scattering process is scattering with optical phonons, the relevant time scale is ≈100 fs, determined by the optical phonon frequency. For times considerably longer than these scattering times, transport will be drift-like, i.e., the carrier *velocity* is proportional to the field. On intermediate time scales one expects a gradual transition from ballistic to drift-like transport. Intense femtosecond THz pulses allow for driving carrier transport in semiconductors at very high carrier velocities and provide

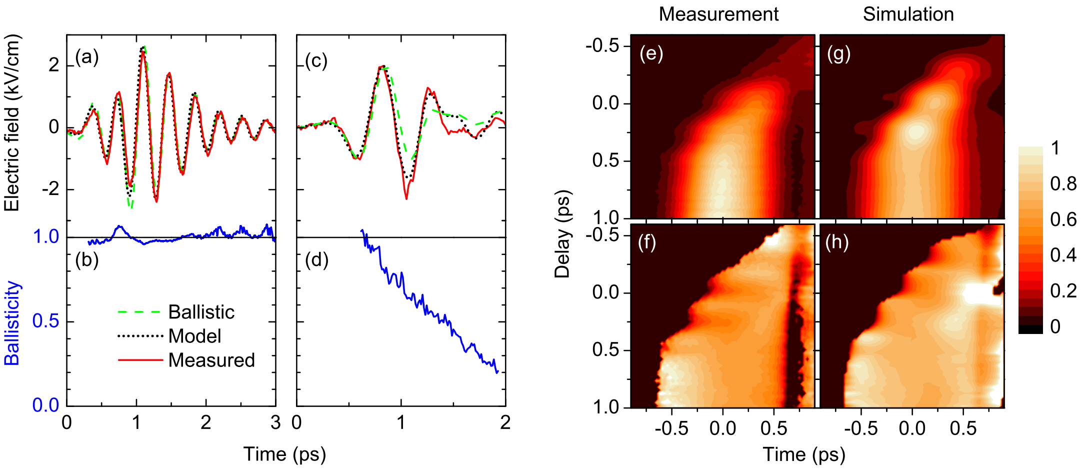

Fig. 1. (a)–(d) Electric fields emitted by the photocarriers for an incident THz field strength of 25 kV/cm. The free carriers were generated with a photoexcitation wavelength of 885 nm and an excitation density of $n = p \approx 2 \times 10^{16}$ cm^{-3}, 1.5 ps before the begin of the THz pulse. The average THz frequency is 3 THz in (a) and 2 THz in (c). (b) and (d) show the time dependence of the ballisticity. (e)–(h) Transport for small delays between photoexcitation and THz pulses. The measured emitted field amplitude (e) and the ballisticity (f) are plotted versus delay and time. For these measurements the photoexcitation wavelength was 800 nm, the density 4×10^{16} cm^{-3}, and the THz field amplitude 50 kV/cm. (g), (h) Corresponding results from our model.

a time resolution below typical scattering times[2]. In this way it is possible to measure the transition from ballistic to drift-like transport, a particularly interesting regime.

To determine the transition between the two types of transport experimentally, both the applied electric field and the current must be measured with a time resolution of at least 100 fs. In our measurements, we use the electric field of a strong THz pulse and determine its time dependence by electro-optic sampling [3]. The time-dependent current leads to the emission of transient electric fields, which can also be measured by electro-optic sampling. If the current is confined to a thin layer, the current $j(t)$ is proportional to the emitted field $E_{\mathrm{em}}(t)$ [4–6],

$$j(t) = -2E_{\mathrm{em}}(t)/(Z_0 d). \tag{1}$$

We obtain the emitted field as the difference between the transmitted and incident fields. To extract the current from the photoexcited carriers we measure the transmitted field transients with and without photoexcitation. The difference between these transients is the field emitted from the photoexcited carriers. The corresponding current is then obtained using Eq. (1).

Knowing both current and field as a function of time, it is easy to distinguish between ballistic ($\pi/2$ phase shift between current and field, ballisticity 1) and drift transport (no phase shift, ballisticity 0). We find that if only electrons are present (n-type sample, no photoexcitation), the transport is ballistic over the whole length of the THz pulse. If only holes are present (p-type sample, no photoexcitation), the current for the same carrier density is essentially zero [7,8]. From this we conclude that the hole current in all measurements is negligible. For an average frequency of 3 THz and photoexcitation at 885 nm (at room temperature this corresponds to the band gap, so that the carriers have nearly no excess energy) of an undoped sample [equal number of electrons and holes, Fig. 1(a)], the transport is ballistic. In contrast, at an average frequency of 2 THz [Fig. 1(c)], there is a transition from ballistic transport at the beginning of the THz pulse to drift transport at later times. The higher the hole density, the faster the transition towards drift transport (comparison of photoexcited n-type, p-type, and undoped samples). Thus, although holes do not contribute appreciably to the current, they influence the electron transport.

For the data in Fig. 1(a) to (d), the photocarriers were generated 1.5 ps before the begin of the THz pulse. If the photocarriers are generated during the THz pulse, the transport depends on the exact timing of the generation relative to the THz field [Figs. 1(e) to (h)]. The reason for this is that the carriers are generated with zero average velocity. Thus, if they are generated at the field extrema, their initial velocity (zero) is equal to the velocity they have for ballistic transport. If, however, the carriers are generated at the zeroes of the field, they start with zero velocity, whereas for ballistic transport they should have a high velocity at this instant of time. This leads to a phase shift between the actual velocity and the velocity for ballistic transport and thus to lower values for the ballisticity [Figs. 1(f) and (h)].

To explain our observations, we have developed a model for high-field carrier transport in semiconductors that correctly describes both the time dependence of transport on ultrashort time scales and steady-state transport [9,1,8]. This is achieved by describing electrons and phonons together as new quasiparticles, polarons, in the form of wavepackets. The wavepacket size determines the amount of scattering. In turn, incoherent energy delivered to the polaron wavepacket will change its size. This model has been used to calculate the data in Fig. 1; they agree very well with the experimental results.

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