Ultrafast nonequilibrium transport of electrons and holes in GaAs

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A novel concept based on a bandgap-engineered pin-diode allows for unipolar transport experiments with nm spatial and fs temporal resolution in GaAs. By choosing a modified doping we can probe only electron or only hole properties respectively.

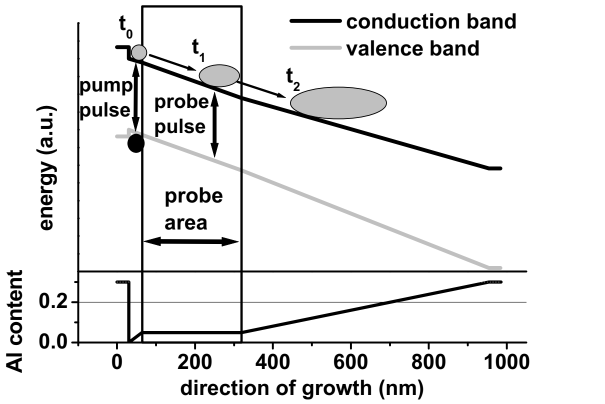

Fig. 1: Upper part: Band diagram with accelerating electrons and stationary holes; lower part: Al-content of the pin-sample

The experiments were carried out between 300K and 4K and fields ranging from 7 to 450kV/cm. In particular dynamic phenomena like the onset of intervalley transfer, velocity overshoot and reduced side valley mobility have been directly monitored on a fs time scale for the ultrafast electron dynamics. For holes an ultrafast acceleration and saturation towards a stationary velocity has been observed. Furthermore due to our on an nm scale defined probe region we were able to extract information about the dynamic changes in the spatial distribution of the accelerated charge carriers.

Also a detailed accompanying Monte Carlo Simulation shows striking agreement to the experimental results and allows for time resolved tracking of many parameters of interest.

The ultrafast transport properties of polar semi-conductors represent a central area of solid state physics and engineering. Previous experiments [1-5] – mostly relying on the emitted THz signal of fs-generated and accelerated carriers in a pin-diode – have in common, that they cannot distinguish between electron and hole transport. In extension they are only sensitive to the center of mass motion.

In our contribution we present a way, to overcome these limitations. The structure suitable for electron transport is depicted in Fig.1. A GaAs injection region and a wavelength adapted pump pulse allows for spatially defined carrier generation (close to the p-contact). The holes do not experience a driving field and remain at their initial position, whereas the electrons are accelerated towards the n-contact. While propagating through the (255nm wide) probe layer, a dipole is built up, partly screening the external field. This results in a modified Franz-Keldysh (FK) absorption, which is detected by a delayed 20fs probe pulse. The transmission change is a measure for the distance the electrons have travelled within the probe layer. When the electrons have left the probe layer, the time resolved transmission changed saturates.

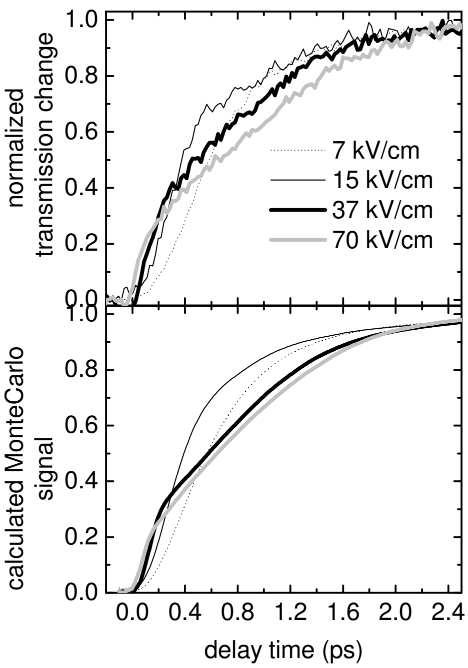

Fig. 2: Upper part: Experimental data for T=4 K, electron transport; lower part results of MC-simulation

Induced field changes before or after the probe layer do not result in significant transmission changes, because of destructive superposition of FK-spectra of a broad continuum of different band gaps (compare Fig. 1, lower part); also shown in [6,7].

The normalized signals for various fields are displayed in Fig 2. The signals are interpreted as follows. At low fields, as expected, it takes much more time before the first (quasi ballistic) electrons to arrive at the probe region (and induce transmission changes) than at high fields. On the other hand, we observe that at the lowest fields the transient transmission changes attain large values much faster than at high fields. This shows that at high fields the carriers already slow down during their path through the probe stretch within a few 100fs, as the ballistic flight becomes drastically impeded by scattering into the L- and X-valleys. The significant change of the signals slope, for fields above 37kV/cm, at about 400fs also indicates this sidevalley transfer, implying a drastic change in the mean velocity.

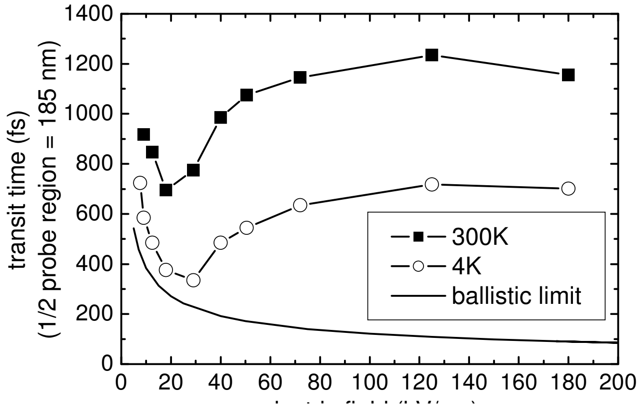

Fig. 3: Transit times for electrons versus fields compared to the pure ballistic limit.

Figure 3 depicts transit times versus field and reflects the behavior mentioned above in comparison to a pure ballistic flight, without any scattering events. The optimum field in terms of highest mean velocity (averaged over time), is reached at about 30kV/cm at 4K, for a flight distance of 185nm and comes quite close to the theoretical value for a pure ballistic flight in the absence of any scattering events including side valley transfer.

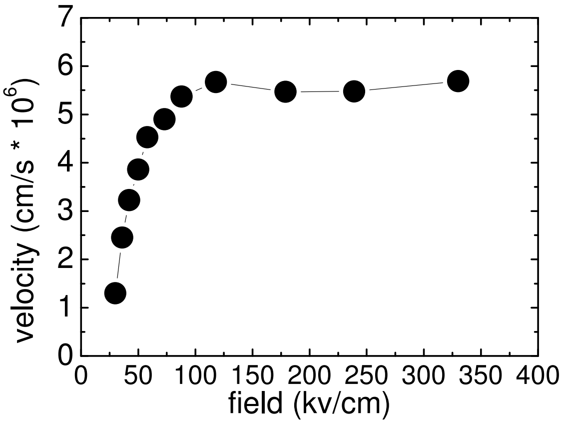

Fig. 4: Hole velocities after 90nm flight versus field at 300K.

Permuting p- and n-contact in Figure 1 leads to a sample appropriate for unipolar hole transport, the same technique as described above is employed. To our knowledge transport properties for holes at these timescales have been previously unexplored, except for theoretical works [8]. Figure 4 depicts hole velocities after a 90nm flight, already close to saturation velocity. Many other dynamic parameters as acceleration, travelled path length and spatial distribution are analyzed in comparison to our Monte Carlo Simulation.

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