Ballistic Electron Spectroscopy of Wannier-Stark states in short period superlattices

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Ballistic Electron Spectroscopy [1], [2] is used to measure the energy splitting and the progressive localization of the Wannier-Stark states in short period superlattices simultaneously. The main problem to determine the Wannier-Stark splitting in a semiconductor superlattice is the electric field induced localization of the Wannier-Stark states. The localization length inside the superlattice is inversely proportional to the applied electric field which leads to a quenching of the coherent hot electron transport through the individual states. Therefore Wannier-Stark states have been investigated more extensively in optical experiments [3], [4]. In this work we use LO-phonon scattering induced inter-Wannier-Stark state transitions to open up incoherent transmission channels. This way it is possible to overcome the electric field induced quenching of the coherent electron transport through the superlattice. For this purpose two different superlattices with 4 and 5 periods have been designed. The miniband width of the 5 period SL equals the optical phonon energy (36 meV) whereas the miniband width of the 4 period SL (23 meV) is well below the optical phonon energy. For this superlattice LO-phonon assisted transport through the miniband sets in at electric fields where the Wannier-Stark splitting tunes into the optical phonon energy.

The band structure of the device is shown in Fig.1. The transmittance of the superlattice can be measured directly at given superlattice bias V_c by tuning the energy of the injected electron beam generated at the tunneling emitter barrier. The main characteristic thereby is the static transfer ratio $\alpha = I_c/I_e$ which directly reflects the probability of an hot electron to be transmitted through the superlattice. Due to the high resolution [1] of the spectrometer we are able to observe the energy splitting (Fig.2) and the transmission behavior (Fig.3) of the individual Wannier-Stark states separately in transport for both superlattices. The basic transport through Wannier-Stark states is identified to be coherent. Individual transport channels induced by LO-phonon scattering are observed when the Wannier-Stark states spacing tunes into the optical phonon energy (Fig.3).

Another interesting feature appears when applying a magnetic field parallel to the current direction. The magnetic field reduces the phase space for all scattering processes in the device. As a consequence the ballistic electron beam is focused which results in an increase of the resolution of the spectrometer. This effect is directly observed as a decrease in the energetic widths of the individual peaks in the transfer ratios. Moreover we observe a clear magnetic field dependence of the strength of the LO-phonon induced inter-Wannier-Stark state transitions. The transmission of the incoherent part in the measured transfer ratio which directly represents the strength of the LO-phonon scattering process increases with the applied magnetic field.

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[3] E. E. Mendez et al., Phys. Rev. Lett. **60**, 2426 (1988).
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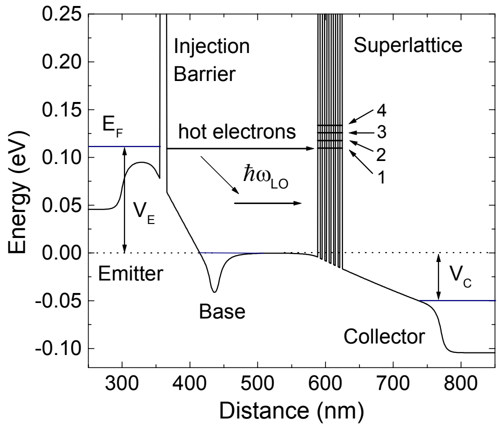

Figure 1: Calculated conduction band diagram of a 3TD with positive bias applied to a 4 period superlattice.

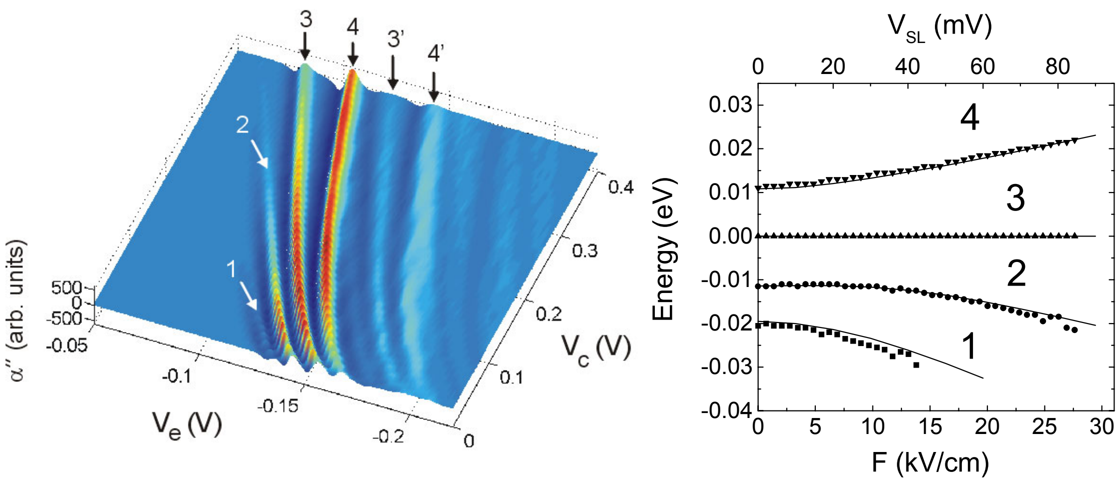

Figure 2: (a) Second derivatives of the transfer ratio vs. emitter bias at different collector biases for the 4 period superlattice. (b) Wannier-Stark states (symbols) of the 4 period superlattice compared to calculations (solid lines).

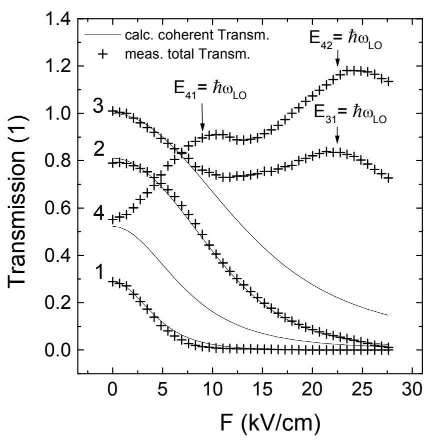

Figure 3: Measured total transmission per states as a function of the electric field (crosses) compared to the calculated coherent transmissions of the individual Wannier-Stark states for the 4 period superlattice (solid lines).