Transport through Wannier-Stark States in Biased Finite Superlattices

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Individual Wannier-Stark states are resolved in a direct current experiment over a wide electric field range for a 5 and 4 period finite superlattice. A hot-electron transistor is used to probe the transmittance of the superlattices at different bias conditions. The energy level positions are used to determine superlattice parameters with high accuracy. 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.

Introduction

In an unperturbed superlattice, the strong coupling of the electronic eigenstates of adjacent wells leads to the formation of minibands that are separated by minigaps. In superlattices with a finite number N of periods, each single miniband is formed by N eigenstates, which are delocalized over the whole superlattice length. Applying an external electric field perpendicular to the layer planes alters the quantum mechanical confinement between the neighbouring wells and leads to a splitting and a localization of the states, which are then given by the Wannier-Stark states. In transport experiments, there are two main problems to determine the Wannier-Stark splitting in a semiconductor superlattice: one is the presence of an inhomogeneous electric field unavoidable in two-terminal superlattice structures; the second 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 Wannier-Stark states.

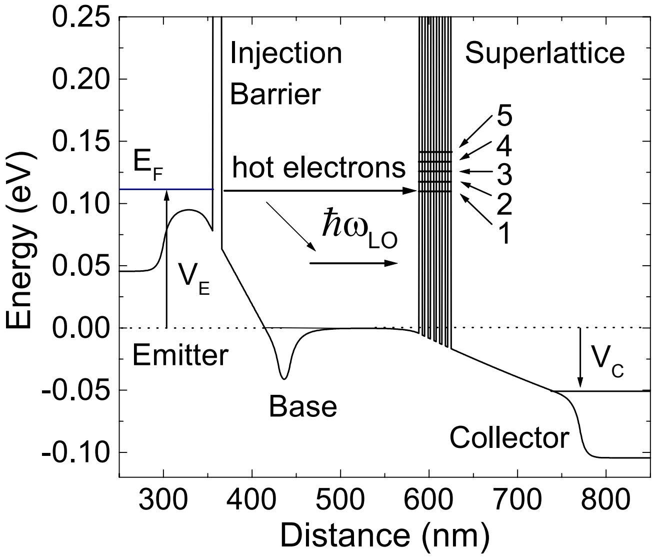

Fig. 1: Conduction band diagram of a hot-electron transistor in growth direction.

In this work, we use the concept of a hot-electron transistor [1] – [4] to study hot electron transport in undoped biased superlattices. The conduction band structure of the device is shown in Fig. 1. An energy tunable electron beam is generated at the tunneling barrier and reaches the superlattice after traversing a highly doped n-GaAs base layer and a slightly n-doped drift region. The static transfer ratio ($\alpha = I_c/I_e$) directly represents the probability of an injected electron to be transmitted through the superlattice. The three terminal device used in this work allows a tuning of the energy of the injected electron distribution independent of the electric field applied to the superlattice.

Experimental

Hot-electron transistors were designed with different undoped superlattice structures between base and collector. The first superlattice consists of 5 periods of 3.5 nm $Al_{0.3}Ga_{0.7}As$ barriers and 3 nm GaAs wells, the second superlattice consists of 4 periods of 4 nm $Al_{0.3}Ga_{0.7}As$ barriers and 3.2 nm GaAs wells. For these superlattice parameters, the lowest miniband is positioned between 122 meV and 158 meV for the 5 period SL and between 120 meV and 143 meV for the 4 period SL. The devices were grown by molecular beam epitaxy and were fabricated by standard photolithographic and wet etching techniques in 30 x 30 μm^2-MESA structures. Standard AuGe/Ni metallization was used to form ohmic contacts. Finally, CrAu pads were evaporated, serving as bonding pads. The emitter and collector currents were measured as a function of negative emitter bias at 4.2 K in a common base configuration using a parameter analyzer.

Results

Figure 2 shows the transfer ratio of the 5 period superlattice in the range of the first miniband as a function of the emitter bias. Below the energy of the first state, we observe no collector current, since the electrons that are injected into the drift region are reflected by the superlattice. This also indicates that no significant leakage current occurs between base and collector. The transfer ratio shows an onset at $V_E = -130$ mV, which indicates electron tunneling through the first resonant state of the miniband. Increasing the emitter bias leads to electron tunneling through the individual resonant states of the miniband. At energies above the first miniband, the ballistic electrons are reflected at the superlattice due to the minigap. In contrast to this behavior, the measured transfer ratio does not drop to zero in this energy range. This is due to the formation of phonon replicas in the drift region and their contribution to the shape of the transfer ratio. To get the energetic positions of the peaks out of the transfer ratios we calculate the second derivatives of the transfer ratios of both samples and take the positions of the corresponding minima. The energetic positions of the 5 (4) individual peaks in the transfer ratio at $V_c = 0$ V fit best to calculated subband energies using superlattice parameters of 3.3 nm AlGaAs barriers and 2.9 nm GaAs wells for the 5 period superlattice and 3.7 nm AlGaAs barriers and 3 nm GaAs wells for the 4 period superlattice. The deviation to the nominal superlattice parameters lies within one monolayer for GaAs and AlGaAs.

Hot electron transport in biased superlattices is investigated as a function of the collector bias up to V_C=400 mV. Figure 3 shows the measured peak positions (symbols) relative to the position of peak 3 for both superlattices as a function of the electric field. The experimental results are in excellent agreement to the theoretical Wannier-Stark splitting (solid lines) up to electric fields of F = 25.9 kV/cm for the 5 period superlattice and F = 27.6 kV/cm for the 4 period superlattice, respectively.

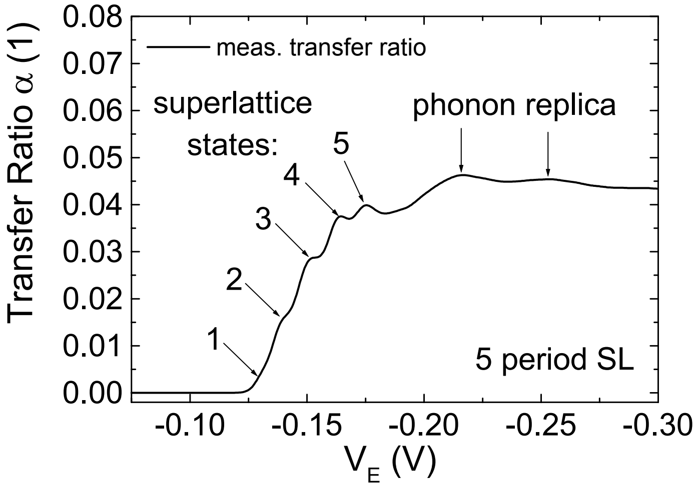

Fig. 2: Measured transfer ratio of the 5 period superlattice as a function of the applied emitter bias V_E.

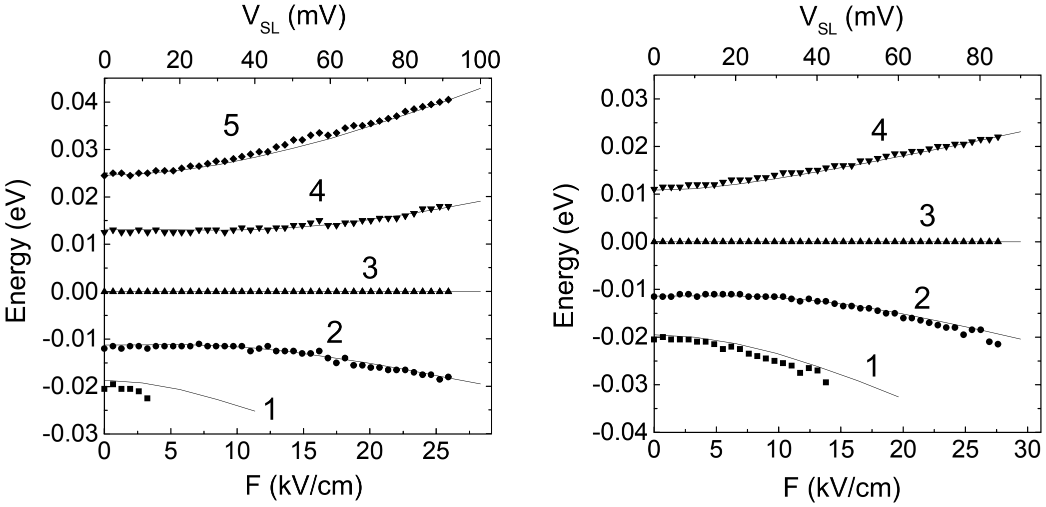

Fig. 3: Measured Wannier-Stark states (symbols) vs. superlattice bias V_{SL} of the 5 (left) and 4 (right) period superlattice compared to the calculated Wannier-Stark splitting (solid lines) vs. electric field F.

In transport experiments, the amplitudes of the current resonances directly resemble the quantum mechanical transmission of the individual states. A comparison of the electric field dependence of the normalized peak amplitudes in the transfer ratios with the expected Wannier-Stark localization amplitudes for the 4 period superlattice is shown in Fig. 4, which directly provides information about the transport mechanisms through each single state. For states 1 and 2, an excellent agreement between measured and calculated transmission is found. For peaks 3 and 4, the experimental findings exceed the coherent predictions: while peak 3 first shows a transmission according to the coherent path an additional contribution to the current starts at 10 kV/cm and becomes larger than the coherent part, passes through a maximum until it decreases at fields above 20 kV/cm. Peak 4 increases above the coherent part already at zero bias and increases in two steps.

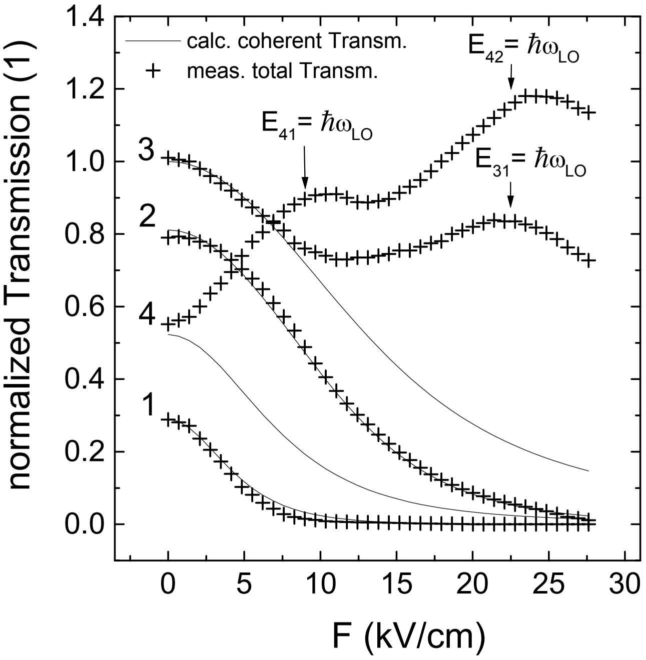

Fig. 4: Measured normalized transmission per states as a function of the electric field (crosses) compared to the calculated normalized coherent transmissions of the individual Wannier-Stark states for the 4 period superlattice (solid lines).

We have previously ruled out interface roughness scattering for a 5 period superlattice [2] as scattering always induces a current component proportional to the electric field which is not observed. Electron-electron scattering can be ruled out due to an extremely low carrier concentration in the device. The only incoherent transmission channel is LO-phonon scattering, which only occurs for transition energies E_{ij} exceeding $\hbar\omega_{LO}$. For the first and second Wannier-Stark state (WSS1, WSS2), LO-phonon scattering can be neglected because the transition energy is much smaller than $\hbar\omega_{LO}$ over the entire bias range. Consequently, transport through these states is purely coherent.

For WSS3 and WSS4, additional current is observed at electric fields where transition energies E_{31}, E_{41} and E_{42} exceed $\hbar\omega_{LO}$ at F_{31} = 21 kV/cm, F_{41} = 9 kV/cm and F_{42} = 22 kV/cm. The increase in the peak amplitude resembles the tuning of the Stark ladder with increasing electric field until the peak of the distribution is resonant with the Stark state splitting of $\hbar\omega_{LO}$. The results clearly show that incoherent transmission channels induced by optical phonons add additional current.

Conclusions

Individual Wannier-Stark states in the first miniband of a 5 (4) period superlattice are resolved up to electric fields of F = 25.9 kV/cm (F = 27.6 kV/cm) in a direct current experiment. From the measured transfer ratios, the exact superlattice parameters are determined. The basic transport through Wannier-Stark states is identified to be coherent. The transport mechanism through higher lying localized states is found to result from an interplay between coherent and incoherent transport as a function of the applied electric field. LO-phonon induced individual channels are found to contribute to the transmitted current. This way we have a method at hand that enables a systematic study of transition rates for different scattering processes in semiconductor heterostructures.

Acknowledgement

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References

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