Ballistic Electron Spectroscopy of Quantum Mechanical Anti-reflection Coatings for GaAs/AlGaAs Superlattices

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It is demonstrated that a standard concept for optics, anti-reflection coatings, can be transferred to ballistic electron transport in semiconductor superlattices. This constitutes a further manifestation of the electronic wave nature in nanoscale devices. We demonstrated the counter-intuitive effect that the transmission through a superlattice is increased by a factor of 2.4 if two further barriers are added at both sides of the structure. Additionally we designed a new injector for ballistic electrons which increases the energy resolution of ballistic electron spectroscopy to approx. 10 meV for further studies.

1. Introduction

Ballistic electron spectroscopy is a suitable method to investigate both semiconductor bulk and heterostructure material properties. In Fig. 1 the scheme of a typical application, the spectroscopy of superlattice minibands [1], is shown.

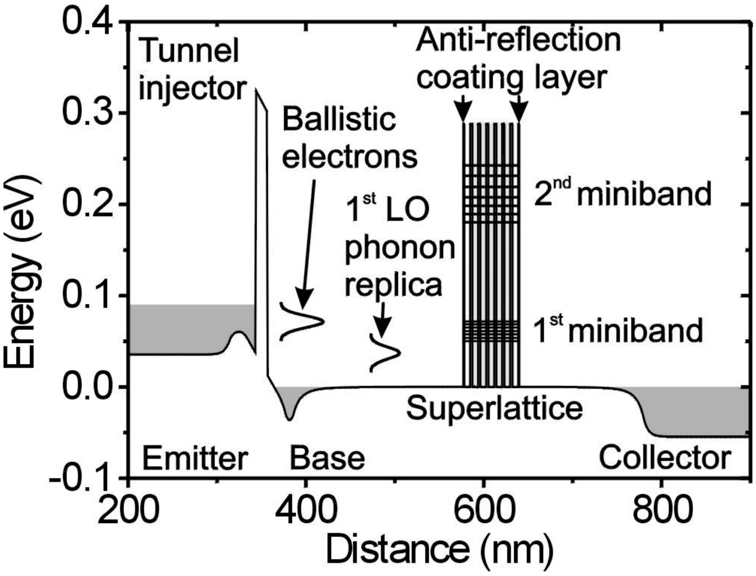

Fig. 1: Schematic bandstructure of a three-terminal device for ballistic electron spectroscopy.

By applying a DC voltage between the emitter and the base contact of a three-terminal device (3TD) hot electrons with a tunable energy are injected through a tunnel barrier into a first drift region. This drift region serves the purpose to reduce quantum-confinement effects originating from the well formed by the injector barrier and the superlattice structure. After traversing the drift region the hot electrons hit the superlattice. In a third contact the electrons which have been transmitted through the superlattice are detected as collector current. From the ratio $\alpha = I_C/I_E$ of the measured currents at T = 4.2 K an energy-resolved spectrum of the superlattice transmission is obtained. The measured transfer ratio $\alpha(V_{BE})$ corresponds to the transmission function T(E) but peaks of T(E) get broadened due to the injected electron distribution, thus limiting the energy resolution of the spectrum.

2. Quantum Mechanical Anti-Reflection Coating

2.1 Theory

A quantum mechanical anti-reflection coating (ARC) for a superlattice (SL) consists in the simplest case of two additional barriers, one in front and one after the superlattice separated from the superlattice by a quantum well. In order to increase the transmission through the superlattice minibands these additional barriers have to be thinner than the barriers forming the superlattice. Using the transfer-matrix method in envelope function approximation including non-parabolicity we studied the transmission through a GaAs/$Al_{0.3}Ga_{0.7}As$-superlattice with five periods (barrier width 25 Å, well width 65 Å) while varying the width of the additional barrier and the distance to the superlattice. As a measure for the transmission we integrate the transmission $T(E)$ over the width of the first superlattice miniband: $T_I=\int T(E)dE$. For the case where the well width between the superlattice and the ARC equals one superlattice well width (65 Å) the maximum of the transmission T_I is achieved when the barrier width equals *half* the width of the barriers constituting the superlattice (12.5 Å). From the calculations of T(E) for both samples shown in Fig. 2, a very strong enhancement of the integrated transmission for the first miniband (by a factor of 3.1) and a significant enhancement for the second miniband (+79 %) due to the additional barriers can be seen.

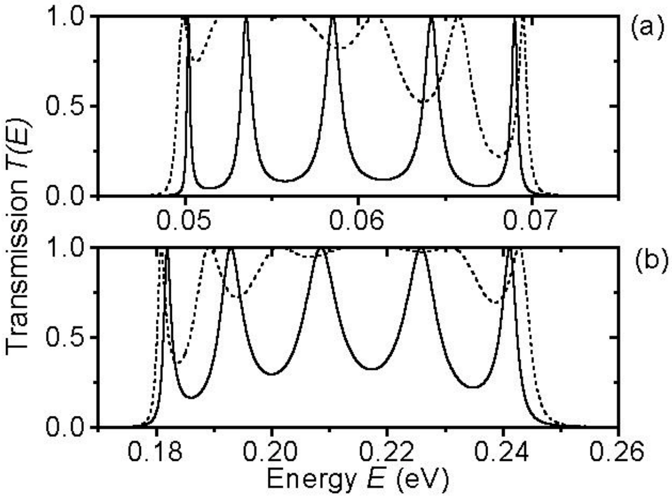

Fig. 2: Calculated transmission T(E) through a superlattice with (dotted line) and without (full line) anti-reflection coating. (a) first miniband, (b) second miniband.

2.2 Experiment

In Fig. 3 the measured transfer ratio α at T = 4.2 K as a function of the applied base-emitter voltage V_{BE}, which specifies the injection energy, is plotted for both structures. In both samples the first peak from the left corresponds to ballistic transport through the first miniband whereas the following peak originates from electrons that have emitted one LO phonon in the drift region in front of the superlattice structure. From the shape of the first peak we deduce that the miniband width and position are not influenced by the anti-reflection coating as is predicted by our calculations. From the peak values an increase of the transfer ratio by a factor of 2.4 is found. This agrees quite well with the average increase of 3.1 estimated from the envelope function calculation, thus showing the validity of the concept of anti-reflection coating for superlattice transport. For the second miniband we measured an increase in the transmission by a factor of 1.35 as can be seen in Fig. 3(b).

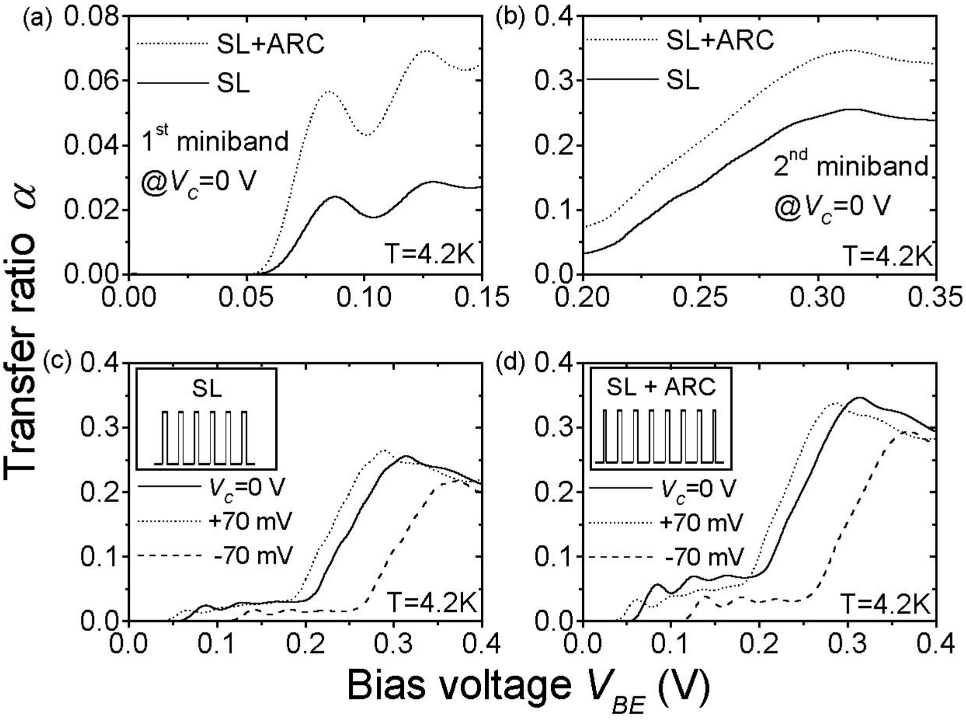

Fig. 3: Measured transfer ratios vs. bias voltage for superlattices with and without anti-reflection coating.

By applying a positive or negative voltage to the collector, the influence of an electric field on the electron transport has been studied. Fig. 3(c) and (d), show the transmission of both samples at collector bias voltages of +70 mV (dotted line), 0 mV (full line), and –70 mV (dashed line), respectively. The absolute value of the transmission of the first miniband (Δ_1 = 20 meV) does not depend on the direction of the applied electric field since the transmission time is much shorter than the dominant interface roughness scattering time ($\tau_I \approx$ 1 ps). This situation is different for the second miniband. Since the miniband width (Δ_2 = 65 meV) exceeds the energy of an LO phonon ($\hbar\omega_{LO}$ = 36 meV), LO phonon scattering becomes the dominant scattering mechanism. For a positively biased superlattice LO phonon enhanced transport leads to an additional current in forward direction. This is the reason for the asymmetric transmission in the second miniband with respect to the applied electric field (peak maximum in the positive bias case is larger than in the negative bias case) as can be seen in Fig. 3 (c) and (d). This effect can be observed in both samples, but is weaker in the sample with anti-reflection coating, although the superlattice is about 33% longer. The LO phonon scattering inside the second miniband leads to a phase loss of the electrons and is therefore the reason why the effect of the anti-reflection coating is reduced for the second miniband.

3. Injector Improvements

The aim of this work is to reduce the width of the ballistic electron distribution by optimizing the layer structure of the electron injector. This was achieved by a special doping profile in the injector. To measure the energetic width of the ballistic electron beam, a three terminal device was designed using a special triple barrier RTD as a narrow energy filter between base and collector. It consists of three $Al_{0.3}Ga_{0.7}As$ barriers and two GaAs wells. To get a transmission of the analyzer that forms a sharp energy filter with a FWHM of 1 meV at 100 meV we choose both well widths to be 4.2 nm and the center barrier (8 nm) twice as thick as the neighboring barriers (4 nm). The complete conduction band structure of the three terminal device is shown in the left part of Fig. 4.

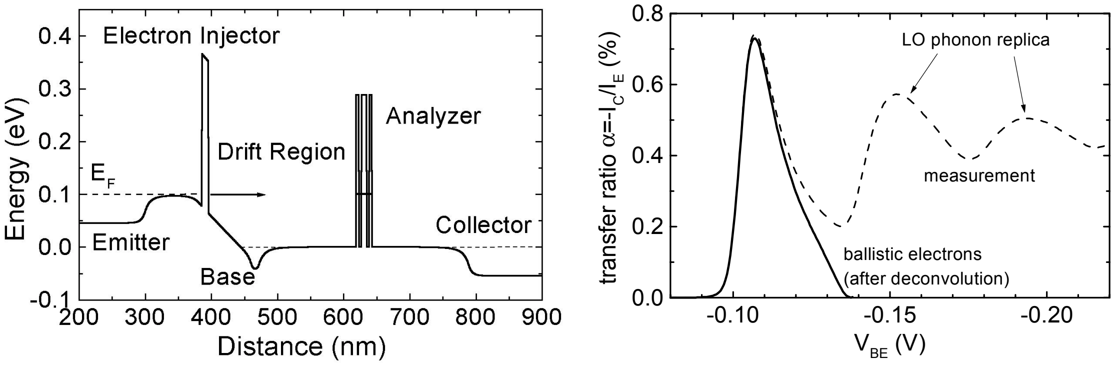

Fig. 4: Schematic bandstructure and transfer ratio for a three-terminal device with optimized injector and analyzer.

The transfer ratio vs. emitter bias is shown in the right part of Fig. 4. Due to the nearly δ-shaped transmission T(E) of the analyzer the first peak of the transfer ratio reflects almost directly the energy distribution of the ballistic electrons. The following peaks in the transfer ratio are due to electrons which are scattered by LO-phonons while traversing the drift region and which have lost 36 meV during the scattering processes. After deconvoluting [2] (thus removing the LO phonon replica) the transfer ratio and estimating the broadening due to the analyzer (≈3 meV) we get a full width at half maximum (FWHM) of the injected electrons of 10 meV.

4. Conclusion

In conclusion, we have demonstrated that the optical concept of anti-reflection coatings is of relevance for electron transport in semiconductor superlattices as well. We have shown that an increase of the transmission by a factor of 2.4 is possible by adding additional barriers of suitable width on both sides of the structure. These concepts will allow for a better design of various devices such as the quantum cascade lasers [3], where the introduction of such anti-reflection coatings may increase the transmission through the injectors significantly. We developed an injector with an ballistic electron distribution with a FWHM of 10 meV to increase the energy resolution for further experiments.

References

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