Analysis of the resonant tunneling diode with the stepped pre-barrier

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Abstract. Resonant-tunneling diodes (RTD) incorporating an emitter stepped pre-barrier are studied both theoretically and experimentally. The simulation of I-V characteristics of modified AlAs-GaAs double barrier RTD grown by molecular beam epitaxy with the stepped pre-barrier is presented. An 1D quantum transport simulator Wingreen based on the nonequilibrium Green functions (NEGF) is used in our case. Our result show that the coupling between energy levels in the emitter quantum-well and the main quantum well leads to the plateau behaviour of the I-V curves. The two plateau regions on the I-V characteristics have been observed in experimental and simulation results.

1. Introduction

In recent years, the resonant tunneling diodes (RTD) have attracted the attention of scientists due to their high frequency performance up to the terahertz region. It is possible to realize oscillators, mixers, switches and various kinds of functional circuits with RTD structures. It is well known that the current-voltage (I-V) curves of the resonant tunneling diodes (RTD) exhibit a characteristic plateau-like behavior and hysteresis. A proper and complete interpretation of the I-V curves is still a controversial issue.

Some groups [1-4] utilized self-consistent solutions of the time-dependent Wigner function equation (WFE) and Poisson equation (PE) for a GaAs-AlGaAs based double-barrier RTD. These simulations revealed intrinsic high-frequency oscillations in the tunneling current. Plateau-like behavior in the I-V curves was obtained from the time-average of the current oscillations. The results showed that the formation of the emitter quantum well (EQW) and the coupling of its quasi-bound state to the state in the main quantum well (MQW) is the physical mechanism responsible for both the hysteresis and the plateau-like behavior.

Other approach is based on the non-equilibrium Green’s functions (NEGF). Gardner, Klimeck and Ringhofer [5-6] performed numerical calculations by the program NEMO based on the NEGF approach. They found that scattering in the emitter reduces hysteresis by broadening the quasi-bound state formed in the emitter as well. Nevertheless, the plateau region did not appear in their results. In our previous work, we presented simulations performed by the NEGF based simulator Wingreen. The plateau region of the same AlAs-GaAs RTD in both experimental I-V curves and those obtained by simulations was portrayed [7].

In this work, we present the simulation of the modified AlAs-GaAs double barrier RTD grown by molecular beam epitaxy with the stepped pre-barrier in the emitter region. The simulation results have
been compared with experimental measurements. Creation of the two plateau regions in negative
differential resistance (NDR) region of the I-V curve is explained by coupling between energy levels
in the emitter quantum-well and the main quantum well.

2. Experiment and simulation
The AlAs-GaAs double barrier RTD with the stepped pre-barrier in the emitter region were
grown by molecular beam epitaxy on semi-insulating GaAs oriented in the [100] direction. The
growth starts with a buffer layer of 250 nm of undoped GaAs. The double barrier quantum well
(DBQW) structures consist of the pair identical 3.4 nm AlAs barriers sandwiching a 5.9 nm GaAs
well. The stepped pre-barrier consist of three 4 nm Al_{x}Ga_{y}As layers with different values of x. 10 nm
u-GaAs spacer layers and 100 nm GaAs:Si supply layers were grown on the both sides of the DBQW.
The n⁺ top and bottom contact layers were 100 nm and 500 nm thick respectively. Ti/Au ohmic
contacts were fabricated on the anode and cathode layers. Mesa structures were formed by
photolithography and etching. The active areas of diodes were 20x20 μm². Schematic cross-sections
RTD with the stepped pre-barrier and the band edge diagram are shown in figure 1(a) and 1(b)
respectively.

The DC I-V characteristics were measured by Hewlett Packard picoampermeter/DC voltage
source 4140B. The measurements were carried out for different temperatures, that have been changed
from 77 to 300K for increasing and decreasing vovtage slopes in both directions [8]. The theoretical
calculations were performed by the Wingreen simulator [9] based on the NEGF approach.

![Schematic cross section (a) and conduction band profile (b) of the resonant tunnelling diodes with the stepped pre-barrier. SPB-stepped pre-barrier, QW-quantum well, TB-tunnelling barrier.](image)

In figure 2 we show comparison of experimental and calculated current-voltage characteristics at
77K. Both experimental and simulation curves show two plateau regions in the NDR region. The
plateau behaviour is restricted to bias voltage between 0.42 and 0.62 V for experimental curve and
between 0.24 and 0.73 V for simulated curve. Since the behaviour of I-V curves outside this voltage
region is well understood, attention is now focused on the behaviour of the curves inside the bistability
region.
Figure 2. I-V characteristics RTD structure with the stepped pre-barrier in the emitter measured (a) and simulated (b) at 77 K

Figure 3 shows the self-consistent potential and the electron density versus bias for the important bias points. These data can be used for the explanation of the plateau region creation. Due to a depletion of electrons in front of the emitter barrier a wide quantum well is formed in the emitter region. With an increase of the bias, energy level in the main quantum well (QW) couples with energy level in the first triangular well in the emitter and the first plateau is observed. The second plateau is formed, when the further triangular well in emitter region is populated.

Figure 3. Electron densities and conduction band profiles of the modified RTD structure with the stepped pre-barrier in the emitter simulated at the bias of the peak current $U_P=0.24$V (a), of the first and second plateau maximum $U_S1=0.32$V (b), $U_S2=0.71$V (c) and of the valley current $U_V=0.73$V (d).

3. Conclusions

We presented both theoretical and experimental studies of resonant tunneling diodes incorporating an emitter stepped pre-barrier. The results showed that the formation of the emitter quantum well and the coupling of its quasi-bound state to the state in the main quantum well is the physical mechanism responsible for plateau-like behaviour. In a forward bias sweep there is a decrease of electron density in the emitter due to the interference between the injected and the reflected electron
waves, and a deep and wide quantum well is formed in the emitter. With an increase of the bias, energy level in the main QW couples with that in EQW. This coupling leads to the plateau-like structure.

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