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Carrier capture time in T-shaped semiconductor quantum wires

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Abstract

We investigate the capture time from quasi-two-dimensional (2D) electrons to quasi-one-dimensional (1D) electrons in T-shaped semiconductor quantum wires. Two processes are considered: longitudinal-optical-(LO)-phonon emission and quasi-elastic acoustical-phonon scattering. The quasi-1D ground state is a shallow bound state and is separated by less than one LO-phonon from the quasi-2D continuum. This enhances the LO-phonon emission process which largely dominates the capture process. The effects of the modulation of the density probability of the quasi-2D continuum lead only to a weak dependence of the capture time on the structure parameters.

Keywords: Quantum wires; Relaxation; Heterostructures

The high-quality of quantum well (QW) semiconductor lasers has motivated the search for optically active semiconductor quantum wire (QWR) structures. Several methods have been employed to fabricate these structures. A promising class of QWR confinements is obtained through quantum mechanical effects in classically unbound systems. Among these systems are the T-shaped [1], the V-groove [2] and the Wiggled [3] QWRs. The T-shaped and the V-groove QWRs have already shown lasing capabilities. The stimulated emission is strongly modified by the sharp density of states of these structures. In particular, the QWR has a strong exciton binding energy and the lasing seems to be dominated by the excitonic recombination [1].

The QWRs occupy a small volume in the whole structure. Consequently, most of the absorption occurs in the QW which surrounds the classically unbound QWRs. The carriers have to diffuse and relax from the QW to the QWR states. It is therefore of great interest to understand the capture processes of carriers from the QW to the QWR states.

The quantum-mechanical treatment of the carrier capture time from three-dimensional (3D) states to the QW states predicts oscillations of the capture mechanism with the QW width [4]. They originate in the resonant capture through one longitudinal-optical(LO)-phonon emission and in the virtual bound state in the 3D-continuum states. Recently, experimental evidence of resonant capture in QWs has been reported [5].

In this work, we report the results of a quantum-mechanical calculation of the electron capture time from a 2D continuum to the 1D bound state in T-shaped QWR.

We model our system by a single T-shaped GaAs QWR with barriers of $Ga_{0.65}Al_{0.35}Al$. To simplify the

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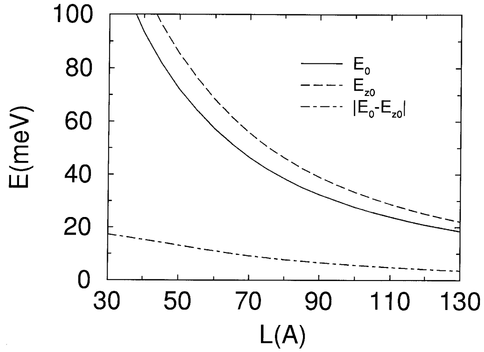

Fig. 1. T-1D-ground state, E_0, and T-leg-QW ground state as a function of $L=L_x=L_z$. The dot-dashed line shows the energy position of the 1D-ground state from the QW ground state.

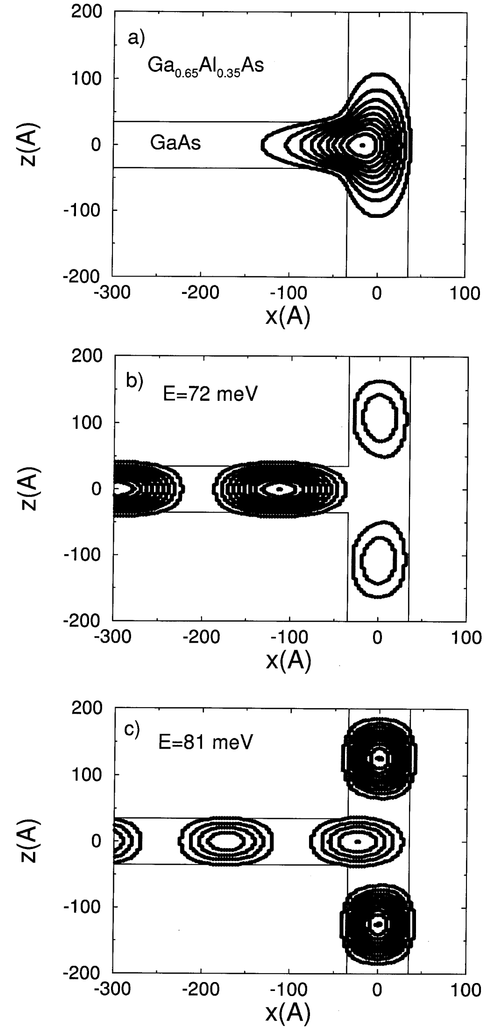

Fig. 2. Contours of constant density of probability for (a) the ground state and the excited states in the 2D-continuum at (b) 72 meV and (c) 81 meV of a $L_x=L_z=70$ Å T-shaped QWR.

description of the states, the arms of the T-shaped QWR (z-direction) are limited by infinite barriers at 200 Å from the center of the T. The T-leg direction (x-direction) is left open. In this case, 2D states are formed in the T-leg QW while 1D states are confined in the cross-section of the T. The T-leg QW states behave as a 2D-continuum of states for the 1D T-bound state. The energy levels are calculated starting from the solutions of the T-arm QW. Along the T-leg, the wave-function is written as a combination of plane waves. The eigenstates are found by matching the wave function at the interfaces of the T [6]. Fig. 1 shows the conduction band eigenstates of the T-shaped QWR as a function of the QW width, $L=L_x=L_z$ where L_z is the T-leg QW width and L_x is the T-arms QW width. This situation optimizes the confinement in these structures [7]. We observe only one T-bound state. Because of the open structure, the confined state is a shallow bound state of the QW ground state. Fig. 2 shows contours of constant density of probability for a T-shaped QWR with $L_x=L_z=70$ Å for (a) the ground state and two excited states in the 2D-continuum, at energies (b) 72 meV and (c) 81 meV. For these parameters, the T bound state is at 46.5 meV and the QW ground state is at 55.7 meV. The 2D-continuum states illustrate the modulation of the wave-function in the T cross section induced by the T barrier potential. To quantify these modulations, we calculate a local density-of-states (LDOS) [8] for the 2D-continuum states, defined as

$$\rho_{\mathrm{LDOS}}(E)=\sum_{k_y,k_x} P_{\varepsilon_x}\delta[E-\varepsilon(k_x)-\hbar^2k_y^2/2m_{\mathrm{c}}], \qquad (1)$$

where

$$P_{\varepsilon_x}=\int_{-Lx/2}^{L_x/2}\mathrm{d}x\int_{-L_z/2}^{L_z/2}\mathrm{d}z\,|\Psi(x,z)|^2 \qquad (2)$$

is the integrated probability of finding the carrier in the T cross section. Fig. 3 shows the LDOS as a function of the energy for $L_x=L_z=L$ T-shaped QWR with L equal to 30, 50 and 70 Å. The dashed lines are the energy positions of a bound state plus one LO phonon. We observe sharp increase in the LDOS. This originates from states which are strongly located in the T cross section. Fig. 2 shows the contours of constant density of probability for the state (b) just before the resonance and (c) at the resonance for the $L = 70$ Å T-shaped QWR.

We consider now the electron capture from the 2D-continuum to the 1D state assisted by phonon scattering. The transition probabilities are calculated in the Born approximation. Two processes are considered: the LO-phonon emission and the quasi-elastic acoustical(AC)-phonon scattering both assuming a bulk phonon description. This approximation is expected to give reasonable results when the total scattering rates are calculated [9]. We assume that the electrons are created in the T-leg QW. We normalize the 2D-continuum wave-functions along an extension d of the T-leg from the T-cross section. This distance is of the order of the mean free path and represents the extension of the quantum mechanical wave function that "feels" the T cross section. Beyond this distance, the carriers diffuse semi-classically and their behaviour will not be considered here. The T-shaped QWR is perfectly symmetric in the z-direction. Since in the structure considered here the T-leg QW is rather narrow, we only consider the even states along the z-direction. Fig. 4 shows the capture probability as a function of the incoming electron energy for LO-phonon emission (full line) and quasi-elastic AC-phonon scattering (dashed line) for $L_x = L_z = 70$ Å T-shaped QWR at low temperature (4 K). The LO-phonon emission capture process shows a strong resonance at the threshold energy of the capture process, when the electron is in the 2D-continuum at an energy equal to one LO phonon from the bound state. This is a combined effect of the energy resonant condition *and* the resonance of the LDOS (see Fig. 3), i.e., when the 2D-continuum states show a strong probability in the T cross section. We observe at higher energies a second resonance due to the modulation of the 2D wave function. The AC-phonon scattering process also shows maxima in the capture probability at the resonances of the modulation of the 2D-wave function. The enhancement of the capture probability due to these resonances is, however, not very strong.

To calculate the total capture probability, we have to make some assumptions on the electron distribution in the 2D-continuum states. We consider, in a similar way as in Ref. [4], that the electrons have relaxed to the bottom of the ground state 2D subband through LO-phonon emission. In a simple way, we assume that the electrons are equally distributed in the 2D-continuum states with an energy up to one LO phonon from the bottom of the ground state subband. The states at higher energies are empty. Fig. 5 shows the capture probability as a function of the T-shaped QWR length $L(=L_x=L_z)$. The LO-phonon emission capture probability shows a maximum near $L = 50$ Å. This is associated with the optimization of the combined effects of the energetic resonant condition for the capture and the resonance in the modulation of the 2D-continuum wave function. From Fig. 3 we observe that for $L = 50$ Å the T bound state is at one

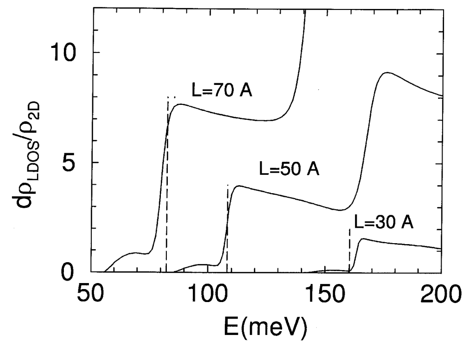

Fig. 3. Local density of states as a function of energy for three different T-shaped QWRs with $L_x = L_z = L$. The dashed lines indicate the energy position of the bound state plus one LO-phonon.

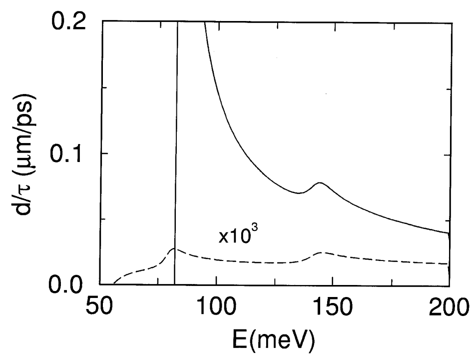

Fig. 4. Capture probability for LO-phonon emission (full line) and AC-phonon scattering (dashed line) processes as a function of the incoming electron energy.

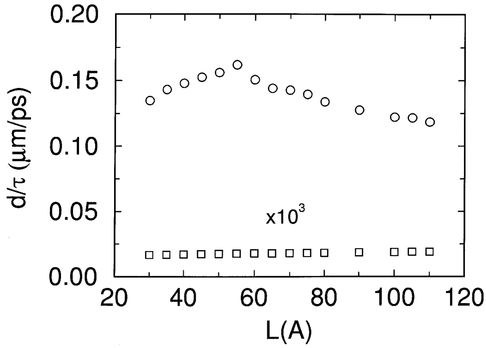

Fig. 5. Capture probability for LO-phonon emission (full line) and AC-phonon scattering (dashed line) processes as a function of the T-shaped QWR length, $L = L_x = L_z$.

LO phonon from the first resonance in the LDOS. However, for the other structures, the two different resonances are only few meV appart, i.e., the T-shaped QWR is always in a near optimal resonance condition. As a consequence, the variation in the capture probability with the T-shaped QWR length, for the parameters considered here, is rather weak. Also, the T-bound state is always within an energy less than one LO phonon from the 2D-continuum. Therefore, for the electron distribution considered here, the resonant LO-phonon emission capture is always present. Consequently, the capture process can be very fast. For instance, if we assume that the 2D-wave functions are extended over 1 μm in the T-leg, the capture time is of the order of a few picoseconds. On the other hand, the AC-phonon scattering process is several orders of magnitude weaker than the LO-phonon emission process and almost structureless.

An alternative channel for the 2D electrons to relax is the formation of a 2D exciton. This process has been calculated [10] and measured [11] and is estimated to be in the range of some tens of picoseconds up to more than a hundred of picoseconds. For 2D-continuum extended over 1 μm, the exciton formation is slower than the electron capture to the T-bound state and the latter process should dominate the carrier dynamics. For 2D-continuum states extended over larger distances, the two mechanisms are of the same order and both relaxation process should compete.

In conclusion, we calculated the LO-phonon emission and the AC-phonon quasi-elastic scattering processes from a 2D-continuum to the 1D state in a T-shaped QWR. The LO-phonon emission process is always in a resonant condition for the capture and the process can be very fast. They dominate the capture process over the AC-phonon scattering process by several orders. The capture time does not show significant variations with the T-shaped QWR length as it was the case in the QW capture times.

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