Subband Tunneling and Coulomb Effects in Coupled Quantum Wells

H. Cruz

Departamento de Fisica Basica, Universidad de La Laguna,
38204 La Laguna, Tenerife, Spain
hcruz@ull.es

Abstract. We have solved in space and time the effective-mass non-linear Schrödinger equation for an electron-hole gas in a semiconductor superlattice. Considering a Coulomb interaction between both electron-hole gases and two subbands, we have obtained a time-varying dipole moment in the heterostructure. In this way, we have shown the possibility of having another kind of terahertz electromagnetic radiation emerging from a double quantum dot system.

Keywords: Electron states in low-dimensional structures, Tunneling, Electronic transport phenomena in thin films.

1 Introduction

In recent years, Coulomb effects in semiconductor quantum dots has attracted significant interest in semiconductor physics. [1] Semiconductor quantum dots are nanoestructures which allow confinement of carriers in all directions within dimensions smaller than their De Broglie wavelength. The tunneling dynamics of an electron into a semiconductor quantum dot can be blocked by the classical Coulomb repulsion of the electrons already in the dot. We notice that one remaining key question is to extend the Coulomb effect analysis to a semiconductor superlattice. In principle, photoexited electron-hole pairs can be created in a well-defined superlattice quantum well. We know that if a large number of carriers are localized in a superlattice quantum well, the electrical properties can be strongly modified due to charge-buildup effects. Then, the diffusion process could be modified due to Coulomb effects at high carrier sheet density values. In this work, we study the time-dependent evolution of both wave packets by considering electron-electron Coulomb interactions. The method of calculation is based on discretization of space and time for carrier wave functions. We show that the diffusion process can be strongly modified due to Coulomb interactions.

2 Model

In order to study the charge density dynamics in the structure growth direction, we need to solve the time-dependent Schrödinger equation associated with

A. Sergienko, S. Pascazio, and P. Villoresi (Eds.): QuantumCom 2009, LNICST 36, pp. 258–260, 2010.

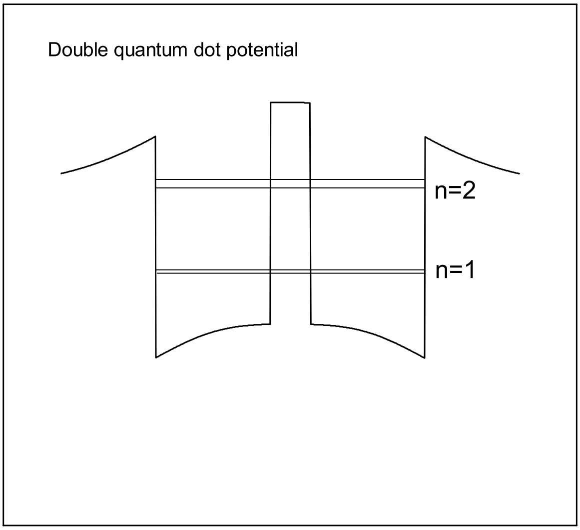

Fig. 1. Double quantum dot potential. It is shown both electron subbands. The level splitting in the first subband is much smaller than in the second subband due to the double quantum dot potential.

a spinless electron in a double quantum well potential. We separate the total electron wave function into the motion along z and the in-plane motion of the electron. The $\psi_{n=1}$ and hole $\psi_{n=2}$ wave functions in the z axis will be given by the nonlinear Schrödinger equations[2]$^-$[4]

$$i\hbar\frac{\partial}{\partial t}\psi_{n=1}(z,t) = \left[-\frac{\hbar^2}{2m_e^*}\frac{\partial^2}{\partial z^2} + V_e(z) + V_H\left(\mid \psi_{n=1}\mid^2, \mid \psi_{n=2}\mid^2\right)\right]\psi_{n=1}(z,t), \tag{1}$$

$$i\hbar\frac{\partial}{\partial t}\psi_{n=2}(z,t) = \left[-\frac{\hbar^2}{2m_e^*}\frac{\partial^2}{\partial z^2} + V_e(z) + V_H\left(\mid \psi_{n=1}\mid^2, \mid \psi_{n=2}\mid^2\right)\right]\psi_{n=2}(z,t), \tag{2}$$

where the subscripts $n = 1, 2$ refer to both subbands, respectively, and $V_e(z)$ is the potential due to the quantum wells. The m_e^* is the electron effective mass. V_H is the Hartree potential given by the electron interaction in the heterostructure region. Such a many-body potential is given by the Poisson's equation[3]

$$\frac{\partial^2}{\partial z^2}V_H(z,t) = -\frac{e^2}{\varepsilon}\left[n_{n=1}\left|\psi_{n=1}(z,t)\right|^2 + n_{n=2}\left|\psi_{n=1}(z,t)\right|^2\right], \tag{3}$$

where ε is the GaAs dielectric constant and $n_{n=1,n=2}$ is the carrier sheet density in each subband.

3 Results and Discussion

The numerical integration in time allows us to obtain the probability of finding both electron and hole charge densities at any time t. We have numerically

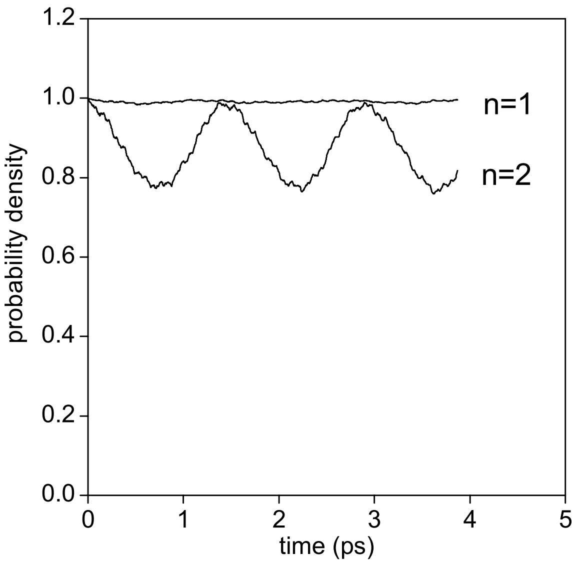

Fig. 2. Probability density versus time. We show tunneling oscillations in the second subband. The tunneling oscillations in the first subband are suppresed due to electron-electron interactions. The level splitting in the first subband is much smaller than the $n = 2$ level splitting. The quantum energy levels in the first subband are easily decoupled with the Coulomb interaction, and then, the tunneling oscillations suppresed.

integrated in space and time the effective-mass Schrödinger equation for an electron gas in a quantum dot. Due to both nonlinear effective mass equations, it is found that the charge dynamically trapped in both wells produces a reaction field that modifies the system resonant condition. In principle, an experimental observation of a such process is possible. In this way, we have shown the possibility of having a different kind of electromagnetic emission emerging from a semiconductor quantum well after an optical excitation of the sample.

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