Superlattices and Microstructures 104 (2017) 428–437

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Electron states and electron Raman scattering in semiconductor step-quantum well: Electric field effect

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ARTICLE INFO

Article history:
Received 21 December 2016
Received in revised form 25 February 2017
Accepted 25 February 2017
Available online 2 March 2017

Keywords:
Electron states
Raman scattering
Quantum well

ABSTRACT

In this work we determine and show the expressions of the electron states of a step-quantum well with the presence of an external electric field, developed in a *GaAs/AlGaAs* matrix. The electron states are obtained using the envelope function approximation. In this work it is only necessary to consider a single conduction band, which due to the confinement is divided into a subband system, with $T = 0K$. Expressions for the electron states and the differential cross-section for an intraband electron Raman scattering process of are presented, the net Raman gain is also calculated. In addition, the interpretation of the singularities found in the emission or excitation spectra is given, since several dispersion configurations are discussed. Furthermore, the effects of an electric field on the electron states and on the differential cross section are studied.

1. Introduction

The nanoscale structures such as quantum wells, dots and wires, have many possible applications, for this reason they have been extensively studied. The introduction of barriers to the movement of charge carriers in semiconductor material gives rise to confinement which causes an enormous amount of quantum effects, especially causing changes in the dynamics of electrons in the system [1–7]. It is widely known that the Raman scattering experiment can be used to investigate different physical properties of semiconductors nanostructures. The electronic structure of nanostructures can be investigated through Raman scattering processes considering different polarizations of incident and emitted radiation. Furthermore, the calculation of the differential cross-section for an electron Raman scattering process remains an essential tool for the study of semiconductor nanostructures, as it allows correct interpretations of experimental Raman spectra.

Nanotechnology allows the creation of devices such as light sources. For instance, light emitting diodes and laser diodes in wide ranges of the electromagnetic spectrum, from terahertz to ultraviolet [8–14]. The applications of these devices cover a wide range of fields in technology, such as optoelectronics, radars and telecommunications [15–17]. One of the semiconductor nanostructures with greater possibilities of development are the multiple asymmetric quantum wells and especially the step-quantum well. The reason for this is that it allows us to have a relatively simple control of the width of the system and the height of the barrier as well as of other physical parameters; and in this way to be able to create a three-levels system which is necessary for the development of several applications. In recent years, research has been conducted on the

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http://dx.doi.org/10.1016/j.spmi.2017.02.049
0749-6036/

step-quantum wells [18] and the asymmetrical multiple quantum wells [19,20], due to the devices that can be designed based on them, partly because of the simplicity of this type of system. Therefore, our aim in this paper is to give a continuation of the work initiated in Refs. [18–20]. Thus, we obtain a model of intraband electron Raman scattering in semiconductor step-quantum well, where an electron is in the conduction band with an external electric field.

In order to show our new contributions, we have organized this work as follows: in Section 2, we show the conditions under which the electron states are obtained and the expressions related to them. Section 3 is dedicated to determine the differential cross-section for a Raman scattering for a semiconductor step-quantum well with the presence of an external electric field and the selection rules for electron transitions, also how to determine the net Raman gain for a three-level system; whereas, in Section 4 physical analysis of the obtained results are presented.

2. Model and electron states

In this section, we will determine the bound states of an electron in the envelope function approximations for a step-quantum well system. Therefore, we must consider that the active region of the system is given by two layers, one of *GaAs* with width l_1 and other of $Al_{0.35}Ga_{0.65}As$ with width l_2 limited by two barriers of *AlAs*, this implies that the width of the system is given by $d = l_1 + l_2$, we also considered the presence of a constant and uniform electric field *F*. The conditions mentioned lead us to the following Schrödinger's equations [19–21].

$$\left\{\nabla^2 + \frac{2\mu}{\hbar^2}\left[\mathscr{E} - V_c(z) - |e|Fz\right]\right\}\Psi = 0. \tag{1}$$

where the confinement potential (V_c) and the effective mass (μ) are given by

$$V_c, \mu = \begin{cases} V_1, & \mu_1, & -\infty < z < 0 \\ 0, & \mu_2, & 0 \le z \le l_1 \\ V_3, & \mu_3, & l_1 < z \le d \\ V_1, & \mu_1, & d < z < +\infty \end{cases}$$

The solution of eq. (1) in the envelope function approximation and considering the continuity of the function Ψ and the current $(1/\mu)(\partial\Psi/\partial z)$ at the interface, leads to

$$\Psi(\mathbf{r}) = \frac{\exp[i\mathbf{k}_\perp \cdot \mathbf{r}_\perp]}{\sqrt{L_x L_y}} u_0(\mathbf{r})\varphi_n(z)$$

where

$$\varphi_n(z) = \begin{cases} A_1\mathrm{Ci}(\eta_{1z}), & -\infty < z < 0 \\ A_2\mathrm{Ai}(\eta_{2z}) + B_2\mathrm{Bi}(\eta_{2z}), & 0 \le z \le l_1 \\ A_3\mathrm{Ai}(\eta_{3z}) + B_3\mathrm{Bi}(\eta_{3z}), & l_1 < z \le d \\ A_4\mathrm{Ai}(\eta_{1z}), & d < z < +\infty \end{cases} \tag{2}$$

$u_0(\mathbf{r})$ is the periodic part of the Bloch function, and Ai and Bi are the Airy's functions. Also, we have

$$\mathrm{Ci}(\eta) = \mathrm{Bi}(\eta) + i\mathrm{Ai}(\eta)$$

and

$$\eta_{jz} = -\left[\frac{2\mu_j}{(eF\hbar)^2}\right]^{\frac{1}{3}}\left[\varepsilon_z(n) - V_c(z) - |e|Fz\right], \tag{3}$$

where $\varepsilon_z(n)$ is the energy due to the spatial confinement, n is the number assigned to the quantum well bound states, and finally $j = 1, 2$ or 3. As it is shown in eq. (1), the potential energy tends to $-\infty$ as z goes to $-\infty$. It is not possible for a system of this type, which is subject to an electric field, to have a genuine stationary state. The reason for this is that, although the electron energy is below the barrier, it can leave the "confinement region" at some point due to quantum tunneling; and if the electric field is different from zero, the electron cannot return to the "confinement region" [19,22]. Another important issue in this system is that the eigenvalues obtained in the solution of the Schrödinger's equation are complex and are written as follows:

$$\varepsilon_z(n) = \varepsilon_n - i\frac{\Gamma}{2},$$

where Γ is the resonance width and is found to be positive, and ε_n corresponds to the quasibound stated energy level, respectively [22]. The total electron energy of the quasibound states is given by