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Electron states and electron Raman scattering in a semiconductor step-quantum well wire

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ABSTRACT

The differential cross-section for an electron Raman scattering process in a semiconductor *GaAs/AlGaAs* step-quantum well wire is calculated and expressions for the electron states are presented. The system is modeled by considering $T = 0$ K and also by a single parabolic conduction band, which is split into a sub-band system due to confinement. The net Raman gain for an electron Raman scattering process is obtained. Also, the emission spectra for several scattering configurations are discussed, and the interpretation of the singularities found in the spectra is given. The results obtained in this study are compared with those obtained for other structures, and so it has been demonstrated that the wire shows greater efficiency.

1. Introduction

The development of new synthesis methods has allowed the construction of a variety of nanostructures, which a few years ago could only be theoretically suggested [1]. Thus, new properties have been discovered that are used in the design of new semiconductor devices; such as lasers [2]. Electron Raman scattering has been used in the research of semiconductor nanostructures since the late 1980s, studying structures such as quantum wells, quantum wires and quantum dots [3]. The study of phonons and electronic structures of materials is of utmost importance because this information makes it possible to determine multiple properties. Light scattering and Raman scattering in particular are among the most important tools for studying the structure of electrons and phonons in different types of materials, especially in nanostructures [3–5]. When analyzing singularities of a Raman emission (excitation) spectrum, where we consider several polarizations of the incident light and scattered light we can determine the energies of the electronic states. However, in order to have a clear understanding of the band structure we must determine the selection rules to be used [6,7].

The Raman scattering has allowed us to study semiconductor nanostructures with different geometries and symmetries from the late 1990s to date. [8–15]. The Raman scattering in a semiconductor quantum well, quantum wire and quantum dot systems considering inter-band and intra-band transitions with and without the participation of confinement phonons, has been the subject of study in multiple works, a summary of this can be analyzed in references [3,16]. The use of semiconductor multiple quantum wells, has been proposed in several works, as well as the semiconductor double quantum well wire and other nanostructures, used as suitable systems for the development of light sources, which can be designed to emit in a wide range of the electromagnetic spectrum from ultraviolet to terahertz [17]. There are several recently conducted studies in various systems with different symmetries such as step-quantum well, double quantum well wire and quantum dots [18,19]. These structures may have different geometries besides the originally treated circular and squared shapes [20–22]. The interest in these systems is due to the fact that they allow the manufacture of a three-level system, where the energy levels can be manipulated up to some extent by controlling a number of parameters such as size and potential barrier [18,21–23]. Examples of these devices are the step-quantum well and the asymmetrical multiple quantum well, manufactured based on a *GaAs/AlGaAs* matrix. Moreover, this technique allows knowing the effect of the electric or magnetic fields on the band structure and on the selection rules of electron transitions [8–15,24–26]. Also, it has been found that Raman scattering is sensitive to the dimensionality and symmetry of systems [3,4]. In these studies, different conditions such as the presence or absence of an external electrical or magnetic field have been chosen; nanostructures with the presence of both fields have also been studied [8–15,24–26]. An important issue is the presence or absence of transitions due to electron-phonon interactions, where phonons may be confined or not, since the study of phonon modes is of great importance for compressing the magnetic and optical properties of surface states [1,8,27].

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The paper's purpose, is to demonstrate that step-quantum well wire gain is superior to other system's, gain, such as the step-quantum well and the multiple quantum wells. Thus, we show the electronic states of a step-quantum well wire, and we describe its fundamental characteristics, showing analytical expressions for the wave function and the electron energy [28]. Furthermore, we will also study the emission and excitation spectra for this system, obtaining the differential cross-section for an intra-band electron Raman scattering process. Finally, a Raman scattering model which fulfills the following conditions is given: first, it considers the presence of a single electron in the conduction band, which is split into a sub-bands system due to confinement; second, we only consider transitions within the conduction band, the reason for this is that we will only use photons of incident radiation with a lower energy than the gap; thirdly, in this case the presence of phonons is not considered; in the fourth determination, the quantum states are used in the envelope function approximation; finally, $T = 0\,\mathrm{K}$ [17,29] is considered. The aforementioned conditions are commonly used in **III-V** and **II-VI** semiconductors, such as *GaAs/AlGaAs* [5].

Therefore, this work is organized in four sections: Section 2 is dedicated to the obtaining of the electron states, in Section 3 we obtain the differential cross-section for an electron Raman scattering process and the net Raman gain for a three-level system, and Section 4 is dedicated to a physical discussion of the results obtained.

2. Model and electronic states

We must determine the electron states of a semiconductor step-quantum well wire system of cylindrical geometry, with length L and radius r_w, where the active region is composed of two cylindrical layers, the first of radius r_c that we will call “the core” and the second of width d_s that we will call “the shell” [19]. Consequently, we have that $r_w = r_c + d_s$. The confinement potential (V_r) and the effective mass (μ) are given by

$$V_r,\ \mu = \begin{cases} V_0, & \mu_1, & 0 \le r \le r_c \\ 0, & \mu_2, & r_c < r < r_w \\ V_1, & \mu_3, & r_w < r < \infty \end{cases}$$

when considering the envelope function approximation on the solution of the Schrödinger equation leads us to:

$$\Psi_{n,m,k_z}(\mathbf{r}) = \frac{\exp[i(m\theta + k_z z)]}{\sqrt{2\pi L}} u_0(\mathbf{r})\, \varphi_{n,m}(r)\,,$$

the electron energy is given by

$$E_{n,m}(k_z) = E_r(n, m) + \frac{\hbar^2}{2\mu} k_z^2$$

where $u_0(\mathbf{r})$ is the electron Bloch function in the band, E_r is the energy due to the spatial confinement. n and m represent the radial and azimuthal quantum numbers, respectively. Finally, k_z is the electron wave-number in the z direction. Following the method described in reference [3], the following solution is obtained for the radial part

$$\varphi_{n,m}(r) = \begin{cases} A_1 I_m(y), & 0 \le r < r_c \quad \text{and} \quad E_r \le V_0 \\ A_1 J_m(y), & 0 \le r < r_c \quad \text{and} \quad E_r > V_0 \\ A_2 J_m(x) + B_2 N_m(x), & r_c \le r < r_w \\ B_3 K_m(z), & r_w \le r < \infty \end{cases} \tag{1}$$

with

$$x(r) = \sqrt{\frac{2\mu_2 r^2}{\hbar^2} E_r}, \quad y(r) = \sqrt{\frac{2\mu_1 r^2}{\hbar^2} |V_0 - E_r|},$$

$$z(r) = \sqrt{\frac{2\mu_3 r^2}{\hbar^2} |V_1 - E_r|}, \quad \beta_1 = \sqrt{\frac{\mu_2}{\mu_1} \frac{|V_0 - E_r|}{E_r}},$$

$$\text{and} \quad \beta_2 = \sqrt{\frac{\mu_3}{\mu_2} \frac{E_r}{|V_1 - E_r|}}$$

being J_m and N_m the Bessel functions of first and second kind of order m. I_m and K_m the modified Bessel functions of first and second kind of order m. Here, we have used the definitions of Bessel functions according to Abramowitz [30].

To calculate the constants A_2, B_2 and B_3 we must consider the continuity of the function Ψ and the current density $(1/\mu)(\partial\Psi/\partial r)$ at the interface, then

$$A_2 = \frac{A_{21}}{C} A_1,$$

$$B_2 = -\frac{B_{21}}{C} A_1$$

$$\text{and} \quad B_3 = \frac{A_{21}B_{31} - B_{21}B_{32}}{C} A_1,$$

with

$$A_{21} = \begin{cases} I_m(y_c)N'_m(x_c) - \beta_1 I'_m(y_c)N_m(x_c), & E_r \le V_0 \\ J_m(y_c)N'_m(x_c) - \beta_1 J'_m(y_c)N_m(x_c), & E_r > V_0 \end{cases}$$

$$B_{21} = \begin{cases} I_m(y_c)J'_m(x_c) - \beta_1 I'_m(y_c)J_m(x_c), & E_r \le V_0 \\ J_m(y_c)J'_m(x_c) - \beta_1 J'_m(y_c)J_m(x_c), & E_r > V_0 \end{cases}$$

$$B_{31} = \frac{J_m(x_w)}{K_m(z_w)}, \quad B_{32} = \frac{N_m(x_w)}{K_m(z_w)},$$

$$C = J_m(x_c)N'_m(x_c) - J'_m(x_c)N_m(x_c).$$

being $x_k = x(r_k)$, $x_k = x(r_k)$ and $z_k = z(r_k)$.A_1 which can be obtained using the normalization condition

$$A_1 = [I_1 + I_2 + I_3]^{-1/2},$$

where

$$I_1 = \begin{cases} \int_0^{r_c} I_m^2(y) r dr, & E_r \le V_0 \\ \int_0^{r_c} J_m^2(y) r dr, & E_r > V_0 \end{cases}$$

$$I_2 = \frac{1}{C^2} \int_{r_c}^{r_w} [A_{21} I_m(y) - B_{21} K_m(y)]^2 r dr$$

$$I_3 = \left[\frac{A_{21}B_{31} - B_{21}B_{32}}{C}\right]^2 \int_{r_w}^{\infty} K_m^2(z) r dr.$$

Finally, the matching conditions allow us to determine the electron states energies due to the spatial confinement (E_r) from the solution of the secular equation:

$$A_{21}A_{31} - B_{21}B_{32} = 0$$

where

$$A_{31} = J_m(x_w)K'_m(z_w) - \beta_2 J'_m(x_w)K_m(z_w),$$

$$B_{32} = N_m(x_w)K'_m(z_w) - \beta_2 N'_m(x_w)K_m(z_w).$$

Consistently, for each value of m, n energy values are obtained. Therefore the electron states are described by: $m = 0, 1, 2, \ldots$; $n = 1, 2, 3, \ldots$; and k_z (see references [19,21]). It is important to clarify that the main quantum number is n, which denotes the sub-bands;