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Electron Raman scattering in semiconductor step-quantum well

L.A. Ferrer-Moreno [a,b], Ri. Betancourt-Riera [a], Re. Betancourt-Riera [a,b,*], R. Riera [b]

[a] Instituto Tecnológico de Hermosillo, Avenida Tecnológico S/N, Col. Sahuaro, C.P. 83170 Hermosillo, Sonora, México
[b] Departamento de Investigación en Física, Universidad de Sonora, Apartado Postal 5-88, CP 83190 Hermosillo, Sonora, México

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ABSTRACT

The differential cross section for an electron Raman scattering process in a semiconductor GaAs/AlGaAs step-quantum well is calculated and expressions for the electronic states are presented. The system is modeled considering $T = 0$ K and a single parabolic conduction band, which is split into a subbands system due to the confinement. The gain and differential cross-section for an electron Raman scattering process are obtained. Also, the emission spectra for several scattering configurations are discussed. The interpretation of the singularities found in the spectra is given. The electron Raman scattering studied here can be used to provide direct information about the efficiency of the lasers.

1. Introduction

The development of several experimental techniques, has allowed the nanometer-scale confinements of the band electrons in semiconductor materials, showing a variety of quantum phenomena; such as low-dimensional electron states and modified dynamics of carriers in the systems [1–7]. The Raman scattering is a useful technique to study the electronic structure of semiconductor nanostructures and other materials. Also, electron Raman scattering is one of the most important tools for the specification of the subband structure, the electron density distribution and optical properties of low-dimensional semiconductors [8]. The analysis of the differential cross section of a Raman scattering process allow us to determine the subbands structure of the nanostructured systems by a direct inspection of singularities in the spectra, taking into account the selection rules of transitions of the carriers participating in the interaction with different polarizations of the incident and emitted light.

In particular, semiconductor step-quantum well and multiple quantum wells have aroused great interest because these systems allow the development of light sources such as light emitting diodes and laser diodes in a wide range of the electromagnetic spectrum from terahertz to ultraviolet and far-infrared [9–14], secure communication, genetic analysis, biomedical sensing, explosive and drug detection, security screening, industrial process control, and spectroscopic imaging for astronomy and space physics [15,16]. The structure of the step-quantum well and multiple quantum wells is capable of improving the photoluminescence efficiency due to quantum confinement effect. Compared to nanoparticles, these optoelectronic devices introduces additional barrier layers to provide photoinduced carriers for well layers and thus expecting an improvement in photoluminescence [17].

These devices can be applied in a wide field of technology such as optoelectronics, radar and telecommunications. Step-quantum wells are used because they offer the possibility to create an artificial three-level system given the possibility of controlling the parameters of the quantum well, such as width and height of the potential barrier. The devices are manufactured using various methods [18–23], and various types of materials like InGaAs/AlInAs, GaAs/AlGaAsand InGaN/GaN.

In recent years, several authors have investigated the step-quantum well and multiple quantum wells. For example, the effects of the intense laser field, indium composition and the well width on the Electron Raman Scattering of the strained InGaN/GaN quantum wells, considering which the spontaneous polarization fields caused by the crystal structure can produce a strong internal built-in electric field [24], the coupled quantum wells and the interaction between the interface related Rashba and Dresselhaus spin-orbit interaction [25], the influences of polarization and structure parameters on the intersubband transition frequency within terahertz range and oscillator strength in GaN/AlGaN step quantum well and other factors including doping location and concentration [15], the properties of AlGaN-based multi-quantum-wells designed for intersubband optoelectronics in the THz spectral range. The authors studied the reproducibility issues associated to the current step-QW architecture [26], the intersubband transitions in III-nitride semiconductor [16,17].

In this work, we present a model of electron Raman scattering in step-quantum well, where an electron is in the conduction

* Corresponding author at: Instituto Tecnológico de Hermosillo, Avenida Tecnológico S/N, Col. Sahuaro, C.P. 83170 Hermosillo, Sonora, México. Fax: +52 662 262 0308.
E-mail address: rbriera@gmail.com (Re. Betancourt-Riera).

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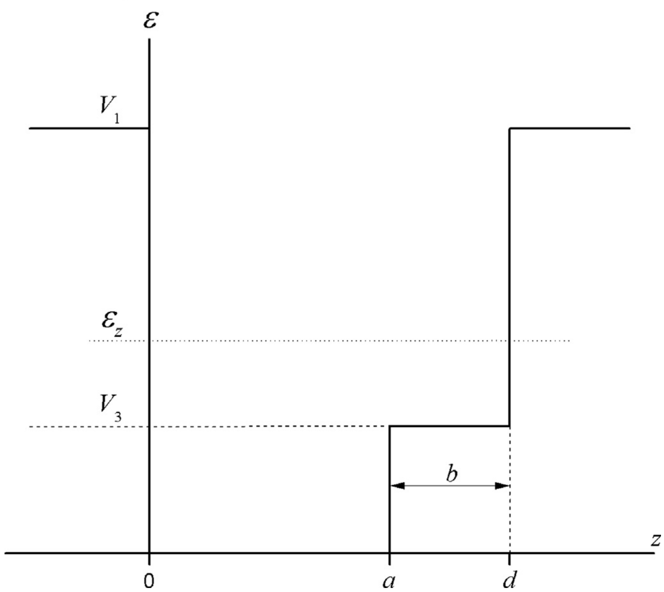

Fig. 1. : Structure of the step-quantum well. The structure of a quantum well is given by two layers A and B with widths l_1 and l_2.

band. The structure of a quantum well is given by two layers with widths l_1 (GaAs) and l_2 ($Al_{0.35}Ga_{0.65}As$), respectively; limited by two barriers (AlAs) as shown in Fig. 1. The intraband Raman scattering processes can be qualitatively described in the following way: first an electron in the conduction band absorbs a photon of incident radiation of energy, $\hbar\omega_l$, then the electron emits a photon of secondary radiation of energy, $\hbar\omega_s$, due to a new intersubband transition [4,29,6]. Thus, the paper is organized as follows: in Section 2 we show the physical model and obtaining of the electron states. The Section 3 is dedicated to determinate the Raman scattering for a semiconductor step-quantum well and the net Raman gain for a three-level system. Finally, in Section 4 a physical discussion of the results obtained is made and some general conclusions are also given.

2. Model and electron states

We must determine the stationary states of an electron in a step-quantum well (QW) system which has a width $d = l_1 + l_2$, where l_1 and l_2 are the widths of the two layers constituting the active region of the QW. The envelope function approximation leads to the solution of the Schrödinger equation [29]. The confinement potential (V_c) and the effective mass (μ) are given by

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

The solution of Schrödinger equation leads to

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

where

$$\varphi_n(z) = \begin{cases} A_1\ \exp(\gamma_1 z), & -\infty < z < 0 \\ A_2\ \cos(\alpha_2 z) + B_2\ \sin(\alpha_2 z), & 0 \le z \le l_1 \\ A_3\ \exp(\gamma_3 z) + B_3\ \exp(-\gamma_3 z), & l_1 < z \le d \quad \text{and} \quad \varepsilon_z < V_3 \\ A_3\ \cos(\alpha_3 z) + B_3\ \sin(\alpha_3 z), & l_1 < z \le d \quad \text{and} \quad \varepsilon_z \ge V_3 \\ B_4\ \exp(-\gamma_1 z), & d < z < +\infty \end{cases} \tag{1}$$

with $u_0(\mathbf{r})$ as the electron Bloch function in the band. The electron energy is given by

$$\varepsilon_n(k_\perp) = \varepsilon_z(n) + \frac{\hbar^2}{2\mu}k_\perp^2 \tag{2}$$

where

$$\alpha_j = \sqrt{\tfrac{2\mu_2}{\hbar^2}\left(\varepsilon_z - V_3\delta_{3,j}\right)} \quad \text{and} \quad \gamma_j = \sqrt{\tfrac{2\mu_1}{\hbar^2}\left(V_j - \varepsilon_z\right)}$$

ε_z is the energy due to the spatial confinement. Taking the continuity of the function Ψ and the current density $\frac{1}{\mu(z)}\frac{\partial\Psi}{\partial z}$ at all the quantum well interfaces as boundary conditions, we can calculate the constants A and B of Eq. (1); also we can determinate energy levels ε_r from the following transcendental equation, for $\varepsilon_r \le V_3$

$$\left(1 - \tfrac{\mu_3\gamma_1}{\mu_1\gamma_3}\right)\left[\left(1 - \tfrac{\mu_3\gamma_1}{\mu_1\gamma_3}\right)\cos\alpha_2 l_1 + \left(\tfrac{\mu_2\gamma_1}{\mu_1\alpha_2} + \tfrac{\mu_3\alpha_2}{\mu_2\gamma_3}\right)\sin\alpha_2 l_1\right]\exp\left[-\gamma_3 l_2\right] =$$
$$\left(1 + \tfrac{\mu_3\gamma_1}{\mu_1\gamma_3}\right)\left[\left(1 + \tfrac{\mu_3\gamma_1}{\mu_1\gamma_3}\right)\cos\alpha_2 l_1 + \left(\tfrac{\mu_2\gamma_1}{\mu_1\alpha_2} - \tfrac{\mu_3\alpha_2}{\mu_2\gamma_3}\right)\sin\alpha_2 l_1\right]\exp\left[\gamma_3 l_2\right]$$

for $\varepsilon_z > V_3$

$$\left[\bar{A} - \frac{\mu_2\gamma_1}{\mu_1\alpha_3}\bar{B}\right]\sin\alpha_3 d = \left[\bar{B} + \frac{\mu_2\gamma_1}{\mu_1\alpha_3}\bar{A}\right]\cos\alpha_3 d$$

where

$$\bar{A} = \left[\cos\alpha_2 l_1 \cos\alpha_3 l_1 + \frac{\mu_3\alpha_2}{\mu_2\alpha_3}\sin\alpha_2 l_1 \sin\alpha_3 l_1\right]$$
$$+ \frac{\mu_2\gamma_1}{\mu_1\alpha_2}\left[\sin\alpha_2 l_1 \cos\alpha_3 l_1 - \frac{\mu_3\alpha_2}{\mu_2\alpha_3}\cos\alpha_2 l_1 \sin\alpha_3 l_1\right]$$

and

$$\bar{B} = \left[\cos\alpha_2 l_1 sin\alpha_3 l_1 - \frac{\mu_3\alpha_2}{\mu_2\alpha_3}\sin\alpha_2 l_1 \cos\alpha_3 l_1\right]$$
$$+ \frac{\mu_2\gamma_1}{\mu_1\alpha_2}\left[\sin\alpha_2 l_1 \sin\alpha_3 l_1 + \frac{\mu_3\alpha_2}{\mu_2\alpha_3}\cos\alpha_2 l_1 \cos\alpha_3 l_1\right]$$

As it can be observed, n is the number assigned to the quantum well bound states.

3. Raman cross-section and net Raman gain

The Raman differential cross-section in a volume per unit solid angle for incoming light of frequency ω_l, and scattered light of frequency ω_s, is given by Refs. [29,30], and it can be written as

$$\frac{d^2\sigma}{d\omega_s d\Omega} = \frac{V^2\omega_s^2\eta(\omega_s)}{8\pi^3c^4\eta(\omega_l)}W(\omega_l,\mathbf{e}_l,\omega_s,\mathbf{e}_s) \tag{3}$$

$\eta(\omega_r)$ is the refraction index as a function of the radiation with frequency ω_r; $\mathbf{e}_r$ is the light polarization unit vector; the subindex