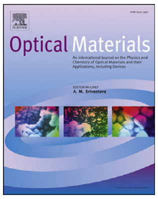
Optical Materials 64 (2017) 496–501

Contents lists available at ScienceDirect

Optical Materials

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



Electron Raman scattering in a double quantum well tuned by an external nonresonant intense laser field

A. Tiutiunnyk [a, b], M.E. Mora-Ramos [a, *], A.L. Morales [b], C.M. Duque [b], R.L. Restrepo [c], F. Ungan [d], J.C. Martínez-Orozco [e], E. Kasapoglu [f], C.A. Duque [b]

[a] Centro de Investigación en Ciencias-IICBA, Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, CP 62209, Cuernavaca, Morelos, Mexico
[b] Grupo de Materia Condensada-UdeA, Instituto de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia UdeA, Calle 70 No. 52-21, Medellín, Colombia
[c] Universidad EIA, CP 055428, Envigado, Colombia
[d] Faculty of Technology, Department of Optical Engineering, Cumhuriyet University, 58140, Sivas, Turkey
[e] Unidad Académica de Física, Universidad Autónoma de Zacatecas, Calzada Solidaridad esquina con Paseo la Bufa S/N, CP 98060, Zacatecas, Zac., Mexico
[f] Faculty of Science, Department of Physics, Cumhuriyet University, 58140, Sivas, Turkey

ARTICLE INFO

Article history:
Received 1 October 2016
Received in revised form
21 December 2016
Accepted 3 January 2017

Keywords:
Intense laser field
Quantum well
Raman scattering

ABSTRACT

In this work we shall present a study of inelastic light scattering involving inter-subband electron transitions in coupled GaAs-(Ga,Al)As quantum wells. Calculations include the electron related Raman differential cross section and Raman gain. The effects of an external nonresonant intense laser field are used in order to tune these output properties. The confined electron states will be described by means of a diagonalization procedure within the effective mass and parabolic band approximations. It is shown that the application of the intense laser field can produce values of the intersubband electron Raman gain above 400 cm^{-1}. The system proposed here is an alternative choice for the development of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ semiconductor laser diodes that can be tuned via an external nonresonant intense laser field.

1. Introduction

Double semiconductor quantum wells have been the subject of investigation for about three decades. Some examples of this interest can be found in Refs. [1–15]. Throughout those years, the attention of the researchers have been mainly focused on electronic and optical -including laser- properties. In particular, GaAs-based double quantum wells (DQW) were proposed as a source of coherent mid-infrared radiation based on electron Raman scattering (ERS), raising the possibility of fabricating intersubband Raman lasers [16–21].

The study of ERS in semiconductor low-dimensional heterosystems started in the 1980s. The initial treatment of electron Raman processes was put forward for interband transitions in bulk systems by F. Comas et al. [22]. A report on the same phenomenon in semiconductor quantum wells appeared a couple of years after [23]. Since then, a collection of research articles on ERS in low-dimensional semiconductor systems have been published [24–31].

On the other hand, the research about the influence of nonresonant intense laser fields (ILFs) on the spectrum of charge carriers in quantum wells has also resulted in a number of papers (see, for example Refs. [32–35]). More recently, some of us participated in the study of nonlinear optical properties in GaAs-Ga_{1-x} Al_xAs DQWs under ILF conditions [15].

The present work is intended to investigate the effect of ILFs on the electron energies and wavefunctions of a GaAs-Ga_{1-x} Al_xAs DQW as well as on the related intersubband ERS and the Raman gain. The study shall be carried out within the effective mass approximation using a spectral scheme to determine the allowed carrier states. The organization of the paper is the following: Section 2 contains the presentation of the theoretical framework. In section 3, we discuss the obtained results and, in section 4, the conclusions are given.

2. Theory

The model potential assumes a GaAs-Ga_{1-x} Al_xAs DQW which dimensions are L_L, L_B, and L_R for the left-well, central barrier, and right-well, respectively. Within the framework of the effective mass

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* Corresponding author.
E-mail address: memora@uaem.mx (M.E. Mora-Ramos).

http://dx.doi.org/10.1016/j.optmat.2017.01.001
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approximation, the Hamiltonian for the electron in the presence of high-frequency ILF (the laser-field polarization is along the z direction) in the DQW is given by

$$H = -\frac{\hbar^2}{2\,m^*}\frac{d^2}{dz^2} + \tilde{V}(z,\alpha_0)\,, \tag{1}$$

where $m^* = 0.0665\,m_0$ is the electron effective mass in the GaAs material (where m_0 is the free electron mass) and z is the coordinate of the electron along the growth direction of the structure. $\tilde{V}(z,\alpha_0)$ is the 'dressed' confinement potential which is given by the following expression [15,34,35].

$$\tilde{V}(z,\alpha_0) = \frac{1}{T}\int_0^T V[z+\alpha_0\,\sin(\omega_0\,t)]\,dt\,, \tag{2}$$

where $\alpha_0 = \frac{e\,F_0}{m^*\,\omega_0^2}$ is the so-called laser dressing parameter, F_0 is the incident field strength, ω_0 is the non-resonant frequency of the laser field, and $V(z)$ is the confinement potential of the heterostructure, in the absence of the ILF, which is zero in the well regions and V_0 in the barrier regions. The value of V_0 is obtained from the band-offset between the well and barrier materials. In this work we take $V_0 = 0.6\,(1155\,x + 370\,x^2)$ in meV, where $x = 0.3$ is the aluminum concentration in the barriers [15].

It is worth mentioning that in a real experiment the effects of nonresonant intense laser field radiation can be achieved, for instance, with the use of an Ar laser with wavelengths in the range of 454.6 nm to 528.7 nm, with electric field strengths sweeping -for $\alpha_0 = 5$ nm- within the range from 3.25×10^5 kV/cm- to 2.07×10^5 kV/cm, respectively.

Two main approximations have been considered: i) a constant effective mass along the whole heterostructure and ii) parabolic conduction bands, or what is the same energy-independent effective masses [36,37]. The justification for such a simplification mainly comes from the rather large value of the effective length of the heterostructure which is further enhanced by the intense laser effects. As can be later seen, the ILF causes the reduction of the intermediate barrier height, which tends to disappear for intense enough laser radiation.

The energies and wave functions of the confined states are obtained by diagonalization of the Hamiltonian using the eigenfunctions of an infinite confinement potential quantum well of length L [15]:

$$\phi(z) = \left(\frac{2}{L}\right)^{1/2}\sum_{m=1}^{\infty} C_n\,\sin\!\left(\frac{m\,\pi\,z}{L}+\frac{m\,\pi}{2}\right), \tag{3}$$

where the expansion coefficients C_n are obtained from the diagonalization of the Hamiltonian in Eq. (1). In this particular computation we use 50 terms in sum and $L = 50$ nm that ensures the convergence for the computed energy levels.

The general expression for the electron Raman differential cross section (DCS) is given by Refs. [22,38,39].

$$\frac{d^2\sigma}{d\Omega\,d\nu_S} = \frac{V^2\,\nu_S^2\,n(\nu_S)}{8\,\pi^3\,c^4\,n(\nu_L)}\,W(\nu_S,\hat{u}_S), \tag{4}$$

where c is the speed of light in vacuum, $n(\nu)$ is the refraction index as a function of the radiation frequency, $\hat{u}_S$ is the polarization vector for the emitted secondary radiation field with frequency ν_S, $V = A\times L$ is the volume of the DQW (A is the transversal section of the structure), and ν_L is the frequency of the incident radiation (with polarization vector $\hat{u}_L$). Considering that the Raman process involves the DQW states in the way $|0\rangle\rightarrow|2\rangle\rightarrow|1\rangle$, the transition rate $W(\nu_S,\hat{u}_S)$ is given by

$$W(\nu_S,\hat{u}_S) = \frac{2}{\hbar}\left|\frac{T_{021}}{E_S+E_1-E_2+i\Gamma_a}\right|^2\frac{\Gamma_f}{(E_L-E_S+E_0-E_1)^2+\Gamma_f^2}, \tag{5}$$

where $T_{021} = P_{02}^L \times P_{12}^S$ with $P_{ij}^k = \langle i|H_k|j\rangle$ (H_k with $k = S, L$).

We have chosen a fixed value for the broadenings of the intermediate and final states, i.e., $\Gamma_a = \Gamma_f = 2$ meV [38,39].

Bearing in mind that the growth direction in the heterostructure is along the z-axis, and considering the polarization of both the incident and the emitted secondary radiation to be oriented along the z-axis as well (that is, we choose $\hat{\mathbf{u}}_L = (0,0,1)$ and $\hat{\mathbf{u}}_S = (0,0,1)$, for the polarization unit vectors), the photon-electron interaction operators involved in the matrix elements appearing in the transition rate (H_k with $k = S, L$) will be given by

$$H_k = -\frac{i|e|}{m_0}\sqrt{\frac{2\pi\hbar^3}{V\nu_k}}\,\frac{d}{dz}. \tag{6}$$

The nonlinear dielectric susceptibility due to the electron-Raman scattering is [16].

$$\chi^{(3)}(E_S;E_L,E_S,-E_L) = -i\,\frac{(N_0-N_1)e^4\left|M_{02}\right|^2\left|M_{12}\right|^2}{\varepsilon_0\left(\delta^2+\Gamma^2\right)\Gamma}, \tag{7}$$

where $M_{ij} = \langle i|z|j\rangle$ and $\delta = E_2 - E_0 - \hbar\,\omega_L$.

The Raman gain is a quantity that characterizes the efficiency of the Raman scattering process for obtaining a coherent emerging radiation. At the frequency ω_S it will be given by Ref. [16].

$$G_R = -\frac{\omega_S}{n\,c}\,\mathrm{Im}\left(\chi^{(3)}\right)\left|E(\omega_L)\right|^2, \tag{8}$$

where $\left|E(\omega_L)\right|^2$ is the squared amplitude of the pumping field from which we obtain the pumped intensity $I_L = 1.0\times10^{10}$ W m^{-2}. Besides, we have $N_0 - N_1 = 2/V = 2.0\times10^{23}$ m^{-3} as the three-dimensional density of carriers in the process (The number 2 comes from the two electrons with opposite spin in the ground state). The linewidth Γ is assumed to have the value 1.5 meV in all cases. For the incident photon we took $\hbar\,\omega_L = 150$ meV and for the refractive index $n = 3.5$ [38,39].

3. Results and discussions

Two different samples have been considered in this work. The sample 1 (S1) has two quantum wells of 8 nm and 4 nm separated by a central barrier of 2 nm. The sample 2 (S2) has two quantum wells of 8 nm and 6 nm separated by a central barrier of 2 nm.

The features of the Raman response to be analyzed below can be better understood if we previously discuss the properties of the electron spectrum as a result of the changes in the intensity of the laser field.

The DQW potential profile, for six values of the α_0 ranging from 0 to 5 nm in 1 nm steps, is presented in Fig. 1(a) − (f). For $\alpha_0 = 0$, Fig. 1(a), it is observed that the ground state is mainly confined to the left well, of larger width, while the first excited state is more localized in the right well, with smaller width. The second excited state, which energy is close the barrier height, is more localized in the left well. A small percentage of the probability density of the mentioned three states is localized in the secondary well. It should be noted that the well dimensions and barrier height allow only the