Optik 127 (2016) 10519–10526

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Linear and nonlinear magneto-optical absorption in parabolic quantum well

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ARTICLE INFO

Article history:
Received 21 June 2016
Accepted 24 August 2016

Keywords:
Magneto-optical properties
Transport properties
Two-photon process

ABSTRACT

The linear and nonlinear optical absorption via one and two-photon processes in the finite symmetric parabolic quantum well (FSPQW) under the applied magnetic field have been studied numerically for typical $GaAs/Ga_xAl_{1-x}As$. The analytical expression of the magneto-optical absorption coefficient (MOAC) is obtained by relating it to the transition probability for the absorption of photons. The effects of the magnetic field, the temperature, and the well width on MOAC and full-width at half-maximum (FWHM) are investigated. Results reveal that MOAC and FWHM are monotonic functions of these factors in both one and two-photon absorption processes. Obtained results also show that the magneto-optical properties of FSPQW can be controlled by changing these parameters. This suggests a new capacity for magneto-optical device applications.

1. Introduction

The study of linear and nonlinear optical absorption in low-dimensional semiconductor structures is essential for understanding the potential applications in micro-electronic and optoelectronic devices [1–4]. In the presence of magnetic field, the electron–phonon interaction and therefore the optical properties of low-dimensional systems become different because of the quantized energy in the plane perpendicular to the magnetic field [5–7]. The linear and nonlinear optical absorption properties, including the nonlinear optical absorption coefficient, in the presence of magnetic field have been investigated in quantum wells, which have square [8], parabolic [9], graded [10], and V-shaped [11] potential shapes; in quantum dot [12–14]; in a quantum disk [15]; and in quantum rings [16]. Literature review shows that the optical absorption properties depend not only on the structure of the system, but also on the magnetic field.

The two-photon absorption process has been presented in several works due to its importance for understanding the response of semiconductors excited by a laser field. Prudaev et al. reported the results of experiments on terahertz generation from nitride light-emitting diode heterostructures under two-photon excitation by femtosecond laser pulses [17]. Scheibner et al. studied the two-photon absorption by a quantum dot pair [18]. Tanaka et al. presented a novel configuration of a precision laser distance measurement based on the two-photon absorption photocurrent from a silicon avalanche

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http://dx.doi.org/10.1016/j.ijleo.2016.08.070

photodiode [19]. The optical response via two-photon absorption has also been discussed in symmetric quantum well [20], multiple quantum wells [21], quantum wires [22], and quantum dot [23–26]. However, the two-photon absorption process in the presence of electron–phonon scattering in a finite symmetric parabolic quantum well has not been fully considered in previously published reports.

In our previous works, we studied the linear and nonlinear magneto-optical properties of quantum wells with parabolic [9,27] and semi-parabolic [28] infinite potential shapes. It should be noted that the magneto-optical properties of infinite and finite parabolic quantum wells are significantly different. For infinite potential quantum wells, the studies on the linear and nonlinear optical properties are usually based on analytical solution of the stationary Schrödinger equation to find the eigenfunctions and the eigenenergies of electrons in the conduction band. Meanwhile, in the finite potential one, the problem is more complex and there are no analytical solutions of the Schrödinger equation for many types of finite quantum wells. However, the progress in computational program with high accuracy allows us to find these solutions numerically [29–31]; then the results could be used to obtain magneto-optical properties. In this work, we will study the linear and nonlinear magneto-optical properties of finite symmetric parabolic quantum well (FSPQW) via one and two-photon absorption processes. To do this, first, we use the numerical methods to solve the Schrödinger equation for FSPQW. Then the results are used to calculate the magneto-optical absorption coefficient (MOAC). The profile method [32] is used to find the full-width of haft-maximum (FWHM) of resonant peaks. We found out that these magneto-optical properties are significantly different in the finite parabolic quantum well in comparison to those in the infinite systems.

2. Theory

We consider a finite symmetric parabolic quantum well structure where electrons move freely in the x–y plane and a uniform static magnetic field $\mathbf{B}=(0, 0, B)$ is applied to the z-direction. The one-electron eigenfunction $|\alpha\rangle$ and energy eigenvalue $E_{N,n}$ are given by

$$|\alpha\rangle = \frac{1}{\sqrt{L_y}}\exp(ik_y y)\psi_N(x-x_0)\phi_n(z), \tag{1}$$

$$E_{N,n} = \left(N+\frac{1}{2}\right)\hbar\omega_c + \epsilon_n, \quad N=0,1,2,\ldots, \tag{2}$$

where N is the Landau level index, $\omega_c = eB/m^*$ is the cyclotron frequency with $m^* = m_0(0.067+0.083x)$ [33] the effective mass of a conduction electron, where m_0 and x are the free electron mass and the alloy concentration, $\psi_N(x-x_0)$ is the harmonic oscillator wave functions, centered at $x_0 = -\alpha_c^2 k_y$, L_y and k_y are the normalization length and the electron wave vector in the y-direction, respectively, and $\alpha_c = (\hbar/m^*\omega_c)^{1/2}$ is the radius of the orbit in the (x, y) plane. The envelope wave function $\phi_n(z)$ and its corresponding eigenenergies ϵ_n are the solutions of the one-dimensional stationary Schrödinger equation

$$-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2}\phi_n(z) + U(z)\phi_n(z) = \epsilon_n\phi_n(z), \tag{3}$$

where $U(z)$ is the confining potential introduced as

$$U(z) = \begin{cases} 4U_0 z^2/L^2, & |z| < L/2 \\ U_0, & |z| \geq L/2, \end{cases} \tag{4}$$

where U_0 is the potential height between GaAs and $Al_xGa_{1-x}As$, and L is the well width.

After the energies and their corresponding wave functions are obtained, the magneto-optical absorption coefficient (MOAC) due to photon absorption with simultaneous absorption and emission of phonon is given by [34,35]

$$K(\Omega) = \frac{1}{V_0(I/\hbar\Omega)}\sum_{\alpha,\alpha'}\mathcal{W}^{\pm}_{\alpha,\alpha'} f_\alpha(1-f_{\alpha'}), \tag{5}$$

where $V_0 = SL$ is the volume of the system, $I/\hbar\,\Omega$ is the injected number of photons, energy $\hbar\Omega$, per unit area per second with the optical intensity $I = n_r c\epsilon_0\Omega^2 A_0^2/2$. Here, n_r is the refractive index of the material, c and ϵ_0 are the speed of light and the permittivity in free space, respectively, and A_0 is the amplitude of the vector potential for the optical electric field. In Eq. (5), f_α and $f_{\alpha'}$ are the electron distribution functions in the initial and final states. The transition matrix element per unit area for electron–photon–phonon interaction of the 2D carrier [27,36], including ℓ-photon absorption process [37,38], is given by Born second-order golden rule [39]

$$\mathcal{W}^{\pm}_{\alpha,\alpha'} = \frac{2\pi}{\hbar^2\Omega}\sum_{\mathbf{q},\ell}|\mathcal{M}^{\pm}_{\alpha,\alpha'}|^2\left|\mathcal{M}^{\mathrm{rad}}_{\alpha,\alpha'}\right|^2\frac{(\alpha_0 q)^{2\ell}}{(\ell!)^2 2^{2\ell}}\quad\delta(E_{\alpha'}-E_\alpha-\ell\hbar\Omega\pm\hbar\omega_0), \tag{6}$$