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Nonlinear optical absorption via two-photon process in asymmetrical semi-parabolic quantum wells

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ABSTRACT

The nonlinear optical absorption properties via two-photon process of an asymmetrical semi-parabolic quantum well (ASPQW) has been theoretically investigated. The analytical expression for the magneto-optical absorption coefficient (MOAC) is obtained by relating it to the transition probability for the absorption of photons. Meanwhile, the half width at half maximum (HWHM) of the resonant peaks is gained by the profile method. The numerical results are calculated for typical GaAs and GaAs/GaAlAs quantum wells. The obtained results show that MOAC and HWHM are strongly dependent on confinement frequency, magnetic field and temperature in both one- and two-photon processes. The increasing behavior of HWHM on temperature is generally in good accord with the previous reported ones, both theoretically and experimentally.

1. Introduction

The nonlinear optical properties, including the nonlinear optical absorption via two-photon process, of low-dimensional systems have attracted attention in the last few decades. Among these properties, many researchers are interested in the second- and third-harmonic generation [1–4], the optical rectification coefficient [5,6], and the optical absorption coefficient [7–10]. The main aspect of these nonlinearities is the asymmetry in the potential profile of the well [5]. When a static magnetic field is applied to the systems, the energy spectrum in the plane perpendicular to the magnetic field becomes quantized. This leads to the changes of the band structures and the optical properties of low-dimensional systems. Nonlinear optical absorption properties in the presence of magnetic field have been studied in quantum wells [9–12], in quantum wires [13,14], in quantum dots [15,16], in quantum rings [17,18], and in graphene [19]. It can be seen from these research projects that the optical absorption properties are affected not only by the system structure but also by the magnetic field.

It was shown that at the low electron concentration examined in the present work (typically 3×10^{16} cm^{-3} [20,21]), the effect of electron–electron scattering is unimportant [22] and can be neglected [23]. This is acceptable because the electron–electron interaction only leads to a re-distribution in *k*-space what is not so important in most conventional electronic systems [24]. Instead, the electron–phonon interaction plays a very important role in the nonlinear transport as well as the nonlinear optical properties [3,25,26]. Therefore, the nonlinear optical absorption properties due to electron–phonon interaction have been widely investigated. Huang et al. presented an ab initio theoretical study of the electronic, linear and nonlinear optical properties of CdSe [27]. Yu et al. studied the third-order optical nonlinearity of Au nano-bipyramids by using

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optical Kerr effect technique [28]. Khordad and Bahramiyan looked at the optical phonon modes in parallelogram and triangular quantum wires, in which, the polaronic energy shift was calculated for both ground-state and excited-state electron energy levels by applying the perturbative approach [29]. Sota et al. examined the third-order non-linear optical response of a one-dimensional Mott insulator coupled with phonons by using the dynamical density-matrix re-normalization group [30]. In the previous works [31,32], we studied the nonlinear phonon-assisted cyclotron resonance via two-photon process in symmetric parabolic quantum well, but the nonlinear optical absorption in asymmetrical semi-parabolic quantum well (ASPQW) has been left aside. So, it is quite fascinating to study the nonlinear optical absorption properties of an asymmetrical quantum systems.

It is noted that since an even-order susceptibilities become invisible in symmetric systems, the second-order one can be existed only when the symmetry of the confining potential is broken [33]. Because the semi-parabolic quantum well is an asymmetrical system, the linear and nonlinear optical absorption properties in semi-parabolic quantum wells are significantly increased. On the other hand, the study of two-photon absorption process has been admitted to be important for in depth understanding the transient response of semiconductors excited by electromagnetic field. Especially, in applied optics, two-photon absorption in semiconductors has been suggested as a replacement nonlinear process for autocorrelation measurements [34]. In this work, the nonlinear optical absorption via two-photon process due to electron–phonon interaction in ASPQWs is studied. In Section 2, the electronic states in semi-parabolic quantum well and the magneto-optical absorption coefficient are presented. Then, the numerical results and discussion on typical GaAs and $Ga_{1-x}Al_xAs$ materials are performed in Section 3. The threshold energy, MOAC and HWHM as functions of the confinement frequency, the magnetic field, and the temperature are plotted. The results show that MOAC and HWHM are strongly dependent on these factors in both one- and two-photon processes. The increasing behavior of HWHM on temperature is generally in good accord with the previous reported ones, both theoretically and experimentally.

2. Theoretical framework and analytical results

2.1. Electron eigenfunctions and eigenvalues

In this work, we consider a quantum well, where electron is confined in z-direction by an asymmetric semi-parabolic potential. In the presence of magnetic field of magnitude $\mathbf{B} = (0,0,B)$, the Hamiltonian of the system can be written as

$$\mathscr{H} = \mathscr{H}_e + \mathscr{H}_{ph} + \mathscr{H}_{int}, \tag{1}$$

where the first part of Eq. (1) is the electronic Hamiltonian given as

$$\mathscr{H}_e = \frac{1}{2m^*}(\mathbf{p} + e\mathbf{A})^2 + U(z), \tag{2}$$

with $\mathbf{p}$ and $m^* = m_0(0.067{+}0.083x)$ [20] are the momentum operator and the effective mass of a conduction electron, respectively, where m_0 and x are the free electron mass and the alloy concentration. In Eq. (2), $U(z)$ is the semi-parabolic confining potential, which is given by Refs. [6,35,36].

$$U(z) = \begin{cases} m^*\omega_z^2 z^2 \big/ 2 & z \geq 0, \\ \infty & z < 0, \end{cases} \tag{3}$$

where ω_z is the frequency of the semi-parabolic confining potential in the quantum well. The second term of Eq. (1), $\mathscr{H}_{ph}$, is the phononic Hamiltonian, which can be written as

$$\mathscr{H}_{ph} = \sum_q \hbar\omega_{LO} a_q^\dagger a_q, \tag{4}$$

where $a_{\mathbf{q}}^\dagger$ ($a_{\mathbf{q}}$) is the creation (annihilation) operator for the LO-phonon, the energy of the optical phonon is given as: $\hbar\omega_{LO} = 36.25$ meV in the well GaAs, and $\hbar\omega_{LO} = (36.25-6.55x+1.79x^2)$ meV in the barrier $Ga_{1-x}Al_xAs$ [20]. The last term of Eq. (1) representing the electron–LO-phonon interaction part of the Hamiltonian can be written as

$$\mathscr{H}_{int} = \sum_q V_q \left(e^{iq\cdot r} a_q^\dagger + e^{-iq\cdot r} a_q \right), \tag{5}$$

where

$$|V_q|^2 = \frac{e^2 \hbar\omega_{LO}}{\varepsilon_0 V_0 q^2 \chi^*}, \quad \frac{1}{\chi^*} = \frac{1}{\chi_\infty} - \frac{1}{\chi_0}, \tag{6}$$