Physica E 77 (2016) 102–107

Contents lists available at ScienceDirect

Physica E

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

Electric field effect on the second-order nonlinear optical properties in semiparabolic quantum wells

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HIGHLIGHTS

- The second order nonlinear optical properties in semiparabolic QW are studied.
- The SHG and OR depend on the direction and the strength of the electric field.
- The blue (or red) shift of the resonance is induced by electric field.

ARTICLE INFO

Article history:
Received 10 October 2015
Received in revised form
4 November 2015
Accepted 10 November 2015
Available online 12 November 2015

Keywords:
Quantum wells
Electronic states
Nonlinear optics

ABSTRACT

Electric field effect on the second-order nonlinear optical properties in semiparabolic quantum wells are studied theoretically. Both the second-harmonic generation susceptibility and nonlinear optical rectification depend dramatically on the direction and the strength of the electric field. Numerical results show that both the second-harmonic generation susceptibility and nonlinear optical rectification are always weakened as the electric field increases where the direction of the electric field is along the growth direction of the quantum wells, which is in contrast to the conventional case. However, the second-harmonic generation susceptibility is weakened, but the nonlinear optical rectification is strengthened as the electric field increases where the direction of the electric field is against the growth direction of the quantum wells. Also it is the blue (or red) shift of the resonance that is induced by increasing of the electric field when the direction of the electric field is along (or against) the growth direction of the quantum wells. Finally, the resonant peak and its corresponding to the resonant energy are also taken into account.

1. Introduction

In the past few years, the study of the optical properties in semiconductor quantum wells (**QWs**) have been so intensively studied [1–5]. This is because the nonlinear effects can be enhanced more dramatically in **QWs** than in bulk materials, which can provide a promising route to the fabrication of semiconductor quantum micro-device, such as high-speed electro-optical modulators, far-infrared photo detectors, and semiconductor optical amplifiers and so on [6–9]. For the bulk susceptibility, the nonlinear effect is not very large because of the symmetry of the crystal structure. For nano materials also with symmetric structure, even-order nonlinear optical effects are usually vanish in theory. Thus the contributions to the second order nonlinear optical susceptibilities are zero for a symmetrical **QW**, but as the symmetry is broken, nonvanishing contributions to second order nonlinear optical susceptibilities are expected to appear [2]. Consequently, in order to obtain the enhanced second order nonlinear optical susceptibilities in **QWs**, externally applied electric fields are used to remove the symmetry [1–3] or the **QWs** structures are produced with a built-in asymmetry using advanced material growing technology [4,5].

Among the nonlinear optical properties, it is attracted much attention to the second order nonlinear optical properties, such as optical rectification (**OR**) and second-harmonic generation (**SHG**). It is because the second-order nonlinear processes are the simplest and the lowest-order nonlinear effects, and the magnitudes of these second-order nonlinear coefficients are usually stronger than that of the higher-order ones, as the symmetry of quantum systems is broken. For example, Karabulut and Baskoutas studied

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http://dx.doi.org/10.1016/j.physe.2015.11.011
1386-9477/

the second and third harmonic generation susceptibilities for the case of spherical quantum dot with parabolic confinement subjected to an external electric field with the presence of an impurity. Their results indicate an increase of the electric field can enhance the peak values of the second [10]. In 2003, Zhang and Xie [1] reported nonzero contributions to **SHG** susceptibilities for both parabolic and semiparabolic **QWs**. However, those pertaining to parabolic **QWs** are completely wrong and contradicts with well-established literature, which had been commented by Karbulut et al. [2]. Karabulut and Safak later [11] studied the nonlinear **OR** in semiparabolic **QWs** with an applied electric field. The nonlinear optical properties in the semiparobolic **QW** have been attracted much attention, such as exciton effect [12], optical absorption [13] and **SHG** [14].Recently, Guo and Du [15] have reported their results for linear and nonlinear optical absorption coefficients and refractive index changes in asymmetrical Gaussian potential **QWs** with applied electric field in the limit $z \ll L$ replaced the potential $-V_0 \exp(-z^2/2L^2)$ with the semiparabolic potential $-V_0(1-z^2/2L^2)$. We find both the energy and the corresponding wavefunction for the low-lying state are wrong to use in works above [16,17]. Unfortunately, these have not been attracted considerable attention by these authors [18–20]. After the other optical properties in the asymmetrical Gaussian potential **QWs** are investigated, such as nonlinear **OR** [18], **SHG** [19] and nonlinear optical absorption via two-photon process [20]. Factually, the direction of the electric field is of importance for studying the nonlinear effect. But there is little literatures for reporting it. Therefore, it is very necessary to investigate the nonlinear optical properties for electron confined in the semiparabolic **QWs** in the presence of the applied electric field where the direction of the electric field is along (or against) the growth direction of the **QWs**.

In this paper, electric-field-induced **SHG** susceptibility and nonlinear **OR** coefficient in semiparabolic **QWs** are investigated theoretically. We find that both the **SHG** susceptibility and nonlinear **OR** depend dramatically on the direction and the strength of the electric field. Numerical results show that the **SHG** susceptibility is always weakened as the electric field increases no matter the direction of the electric field is along (or against) the growth direction of the **QWs**. However, the nonlinear **OR** is weakened (or strengthen) as the electric field increases where the direction of the electric field is along (or against) the growth direction of the **QWs**. Also it is the blue (or red) shift of the resonance that is induced by increasing of the electric field when the direction of the electric field is along (or against) the growth direction of the **QWs**. Finally, the resonant peak and its corresponding to the resonant energy are also taken into account. This paper is organized as follows: Hamiltonian, the relevant wave functions and energy levels are briefly described in Section 2. Also the analytical expressions of the **SHG** susceptibility and **OR** coefficient in semiparabolic **QWs** are presented in this section. Numerical calculations and detailed discussions for typical $Al_xGa_{1-x}Al/GaAs$ materials are given in Section 3. Finally, a brief summary is presented in Section 4.

2. Theory

Within the framework of effective-mass approximation, the Hamiltonian of an electron confined in semiparabolic **QWs** in the presence of electric field along the z axis can be written by

$$H = -\frac{\hbar^2}{2m_e^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)+V(z)+q\eta Fz. \tag{1}$$

with

$$V(z)=\begin{cases}\frac{1}{2}m_e^*\omega_0^2 z^2, & z\geq 0,\\ \infty, & z<0,\end{cases} \tag{2}$$

where, z represents the growth direction of the **QWs**. m_e^* is the effective mass in materials. $\hbar$ is the Planck constant. ω_0 is frequency of the semiparabolic confined potential in **QWs**, F is the strength of the electric field, $\eta=+1$ (or -1) describes the direction of the electric field is along (or against) the growth direction of the **QWs** and q is the absolute value of the electric charge. Under the envelope wave-function approximation, the eigenfunctions $\Psi_{t_n,k}(r)$ and eigenenergies $\varepsilon_{t_n,k}$ are the solutions of the Schrödinger equation for H and are given by [1,19,21,22]

$$\Psi_{t_n,k}(r)=\Phi_{t_n}(z)U_c(\mathbf{r}_\parallel)\exp(i\mathbf{k}_\parallel\cdot\mathbf{r}_\parallel) \tag{3}$$

and

$$\varepsilon_{t_n,k}=E_{t_n}+\frac{\hbar^2k_\parallel^2}{2m_e^*} \tag{4}$$

Here, $\mathbf{k}_\parallel$ and $\mathbf{r}_\parallel$ are the wave vector and coordinate in the xy plane and $U_c(r)$ is the periodic part of the Bloch function in the conduction band at $\mathbf{k}\equiv 0$. $\Phi_{t_n}(z)$ and E_{t_n} can be obtained by solving the following Schrödinger equation

$$H_z\Phi_{t_n}(z)=\left[-\frac{\hbar^2}{2m_e^*}\frac{\partial^2}{\partial z^2}+V(z)+q\eta Fz\right]\Phi_{t_n}(z)=E_{t_n}\Phi_{t_n}(z). \tag{5}$$

The electronic energy levels and corresponding wave functions are given as follows [1]:

$$E_{t_n}=(2t_n+1-\alpha^2\beta^2)\frac{\hbar\omega_0}{2},\quad n=1,2,3\ldots, \tag{6}$$

and

$$\Phi_{t_n}(z)=N_n\exp(-\alpha^2(z+\beta)^2)H_{t_n}(\alpha(z+\beta)), \tag{7}$$

with

$$\alpha=\sqrt{\frac{m_e^*\omega_0}{\hbar}},\quad \beta=\frac{q\eta F}{m_e^*\omega_0^2} \tag{8}$$

where H_{t_n} is the Hermite functions and t_n is real, N_n is the normalization constant. t_n is determined by $\Phi_{t_n}(z=0)\equiv 0$, that is to say, the relation always should be satisfied as $H_{t_n}(\alpha\beta)\equiv 0$. Obviously, $t_n=2n+1$ as the electric field is in absence, where $n=0,1,2\ldots$.

The formulas of the **SHG** susceptibility and the **OR** coefficient in the two models will be derived by using the compact-density-matrix method and the iterative procedure. The system is excited by electromagnetic field $\mathbf{E}(t)=\tilde{E}e^{i\omega t}+\tilde{E}e^{-i\omega t}$. Let us denote ρ as the one-electron density matrix for this regime. Then the evolution of density matrix is given by the time-dependent Schrödinger equation

$$\frac{\partial\rho_{ij}}{\partial t}=\frac{1}{\hbar}[H_0-qz\mathbf{E}(t),\rho]_{ij}-\Gamma_{ij}(\rho-\rho^{(0)})_{ij}. \tag{9}$$

where H_0 is the Hamiltonian for this system without the electromagnetic field $\mathbf{E}(t)$; $\rho^{(0)}$ is the unperturbed density matrix; Γ_{ij} is the relaxation rate.

Eq. (9) is calculated by the following iterative method [1]:

$$\rho(t)=\sum_n\rho^{(n)}(t), \tag{10}$$

with

$$\frac{\partial\rho_{ij}^{(n+1)}}{\partial t}=\frac{1}{i\hbar}\left\{\left[H_0,\rho^{(n+1)}\right]_{ij}-i\hbar\Gamma_{ij}\rho_{ij}^{(n+1)}\right\}-\frac{1}{i\hbar}\left[qz,\rho^{(n)}\right]_{ij}\mathbf{E}(t). \tag{11}$$