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THE OPTICAL ABSORPTION COEFFICIENTS OF THE SUBBAND TRANSITIONS IN LOW CROSS-SECTIONAL DOUBLE QUANTUM WELL WIRES UNDER A LASER FIELD

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Abstract

The electronic and optical properties of a narrow square-cross-sectioned double quantum well wire under laser field are investigated. The quantum states with the corresponding electronic wave functions were calculated within the effective mass-approximation using a finite differences method. The results demonstrated that the laser field strength and the intensity of the incident light strongly influence the absorption coefficients. When a laser field is applied to the system, the maximum values of the total absorption coefficients shift toward higher photon energies.

Keywords: Quantum Well Wire, Energy State, Absorption Coefficients

INTRODUCTION

Intraband optical transitions within the conduction band of a low-dimensional semiconductor structures are of great interest due to the technological applications such as quantum cascade lasers for environmental gas sensing, medical diagnostics, and military countermeasure, and quantum well/dot infrared photodetectors which are widely used in night-vision thermal imaging and remote sensing. Numerous studies exist regarding the variation of absorption coefficients for intraband optical transitions in low-dimensional semiconductor systems [1-4]. A $GaAs/Al_xGa_{1-x}As$ quantum well wire grown as single epitaxial layer induced by Ga ion-beam implantation evidenced low-temperature photoluminescence and photoluminescence excitation spectra [2]. The optical spectra of quantum well wire arrays, accounting for Coulomb interaction and continuum states have been calculated [3]. In the far-infrared (FIR) region, strong, sharp peaks in optical absorption coefficients and significant changes in refractive indices—dependent on the frequency of incident light—have been predicted for $GaAs/AlAs$ parallel quantum well wires [4]. Externally applied fields exert a significant influence on quantum well wires [5-9]. It has been found that the resonant peak values of the linear and third-order nonlinear optical absorption coefficients for a $GaAs/Al_xGa_{1-x}As$ coaxial cylindrical quantum well wire decrease as the magnetic field strength increases [10].

In recent years, advances in technological applications have led to an increase in studies concerning low-dimensional binary semiconductor structures (binary quantum dots, binary quantum wires, and binary quantum wells) [11-15]. These studies have demonstrated the influence of geometry, pressure, temperature, electric fields, magnetic fields, and laser fields on semiconductor structures. The effects of intense laser fields on the electronic structure and nonlinear optical properties of coupled quantum well wires with various

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geometries have been theoretically investigated [16-18]. It has been shown that increasing the intensity of the applied laser field leads to significant distortion of the confinement potential and a splitting at the bottom of the potential wells. This structural change altered the localization of electronic wave functions, thereby increasing the tunneling probability and affecting transitions between subbands.

A structure consisting of two interconnected quantum wires with low cross-sections (LDQWW) was investigated. The electron energy states were calculated when an external laser field was applied to this quantum wire. The effects of the laser field and the optical intensity parameter of the incident photon on the total absorption coefficient—which includes both linear and nonlinear absorption coefficients—were examined for transitions between the first two energy levels of an electron confined within this structure.

THEORY

Let two square cross-sectional $GaAs$ quantum well wires lying along z-axis and enveloped with $Al_xGa_{1-x}As$. The confining wire potential on $x-y$ plane in the absence of any laser field is

$$V(x,y)=\begin{cases}0, & -\frac{L_B}{2}-L\le x\le -\frac{L_B}{2}\ and\ -\frac{L}{2}\le y\le\frac{L}{2}\\ 0, & \frac{L_B}{2}\le x\le\frac{L_B}{2}+L\ and\ -\frac{L}{2}\le y\le\frac{L}{2}\\ V_0, & otherwise\end{cases} \quad (1)$$

where V_0 is the conduction band offset, L is the side length of the each $GaAs$ wire, and L_B is the distance between interconnected two wires.

Assume that the structure is subjected to laser radiation represented by a monochromatic plane wave with frequency w_D.The laser beam is non-resonant with the structure, and is linearly polarized along the x-axis . Under these conditions, the electron experiences a time-averaged laser-dressed potential can be expressed by

$$V_D(x,y)=\frac{w_D}{2\pi}\int_0^{2\pi/w_D}V(x,y,t)dt$$

$$=\frac{1}{2\pi}\int_0^{2\pi}V(x)+\alpha_0 sin\varphi,y)d\varphi \quad (2)$$

where $\alpha_0=eA_0/m^*w_D$ is the laser dressing parameter [19,20].The laser vector potential is given as $\boldsymbol{A}(t)=A_0\cos(\omega_D t)\,\boldsymbol{e_x}$; $\boldsymbol{e_x}$being the unit vector along the x-axis. In the high-frequency limit, the time independent Schrödinger equation is

$$\left[-\frac{\hbar^2}{2m*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)+V_D\right]\psi_n(x,y)=E_n\psi_n(x,y) \quad . \quad (3)$$

The first two energies and eigenfunctions of the electron with and without the laser field is numerically calculated by solving Eq.3 with the bidimensional finite differences method [21-22].

Once the subband states have been calculated, the absorption coefficients for transitions between possible states can be determined using the density matrix method [23–25]. When higher-order harmonic terms are neglected, the linear and third-order nonlinear absorption coefficients can be expressed as

$$\alpha^1(\omega)=\hbar\omega\sqrt{\frac{\mu}{n_r^2\epsilon_0}}\left[\frac{\sigma|M_{if}|^2\tau_{if}^{-1}}{(E_{if}-\hbar\omega)^2+\hbar^2\tau_{if}^{-2}}\right] \quad (4)$$

and

$$\alpha^3(\omega,I)=-\hbar\omega\sqrt{\frac{\mu}{n_r^2\epsilon_0}}\left(\frac{2I}{n_r\epsilon_0 c}\right)x\frac{\sigma|M_{if}|^4\tau_{if}^{-1}}{\left[(E_{if}-\hbar\omega)^2+\hbar^2\tau_{if}^{-2}\right]^2}x\left\{1-\frac{|M_{ff}-M_{ii}|^2}{4|M_{if}|^2}\frac{\left[3E_{if}^2-4E_{if}\hbar\omega+(\hbar\omega)^2-\tau_{if}^{-2}\right]}{E_{if}^2+\hbar^2\tau_{if}^{-2}}\right\} \quad (5)$$

where ε_0 is the electric constant, c is the speed of light in vacum, n_r is the refraction index, I is the optical intensity of the incident radiation, σ is the carrier density,

τ_{if} is the relaxation time, and the transition energy $E_{if} = E_f - E_i$ is the energy difference between the final and initial states. In the electric dipole approximation, for x- polarization of the incident radiation, the dipole transition matrix element between i-th (initial)state and f-th (final) state is given by

$$M_{if} = \left\langle \psi_i \middle| e.x \middle| \psi_f \right\rangle = e\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \psi_i^*(x,y)x\psi_f(x,y)dxdy \quad .(6)$$

The optical total absorption coefficient $\alpha(\omega, I)$ for the (i-f) transition in a quantum wire is given by

$$\alpha(\omega, I) = \alpha^1(\omega) + \alpha^3(\omega, I). \quad (7)$$

RESULTS AND DISCUSSIONS

The calculations were carried out for the two square cross-sectioned $GaAs$ quantum wires, each having $L = 50$ Å side length. The distance between the facing surfaces of two wires, assumed to be positioned parallel to each other, was $L_B = 25$ Å. We also used $m^* = 0.0665m_0$, $V_0 = 228\, meV$, $n_r = 3.2$, $\sigma = 3x10^{22}m^{-3}$, and $\tau_{if} = 0.2ps$ [19, 20].

Fig. 1 shows the first two energy levels as a function of the laser parameter. The energy E_1 is in only slight increase for the small values of laser field, that is $\alpha_0 \leq 10$ Å, while it rises rapidly as α_0 approaches 30 Å, after this value remains constant. The E_2 is nearly constant at low values $\alpha_0 \leq 10$ Å but increases rapidly after up to between this point and $\alpha_0 = 32$ Å. The higher field strengths then that it again becomes nearly constant.

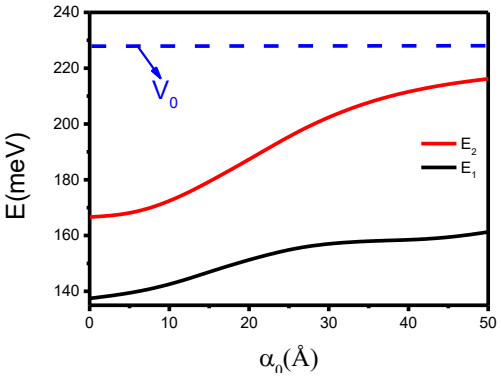


Fig. 1. *Variation of the subband energies with laser field parameter in LDQWW*

To explain the reasons behind these changes in subband energies, the potential energies and the electronic wave functions of the first two energy levels were calculated for three different values of the laser field; the results are presented in Fig 2. It is observed that the application of the laser field transforms the potential profile from a double quantum wire into a triple quantum wire. While the electron wave functions are localized within the GaAs regions in the absence of a laser field, the modification of the potential profile upon the application of the field causes the electron to tunnel toward the center of the structure and reside predominantly there.

Ultimately, the laser radiation transforms the symmetric double quantum wire with a low-aspect-ratio square cross-section into a rectangular quantum-well wire with lower symmetry. This deformation in the quantum wire is expected to give rise to linear and nonlinear absorption of light propagating in the x-y plane.

Fig. 3 displays the total optical absorption coefficient for the (1–2) transition in the LDQWW—in the absence of a laser field—as a function of photon energy for various incident light intensities.

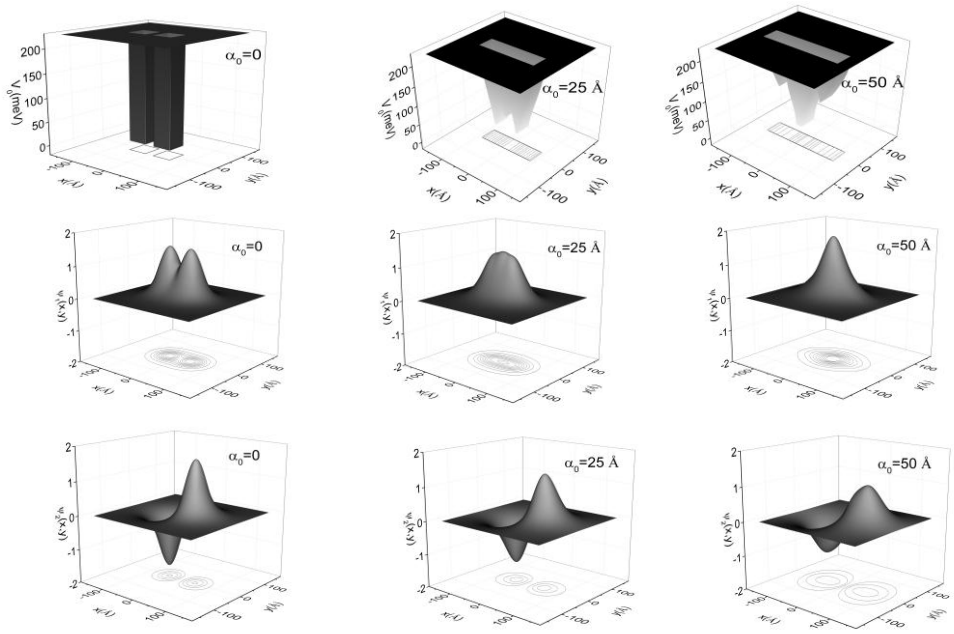


Fig. 2. *Potential energies and bound state electron wave functions in the dressed LDQWW for a_0=0, a_0=25 Å, and a_0=50 Å.*

Fig.3a shows the absorption coefficients as a function of photon energy for the (1–2) transition of x-polarized light at an intensity of $I = 0.1 MW/cm^2$ in the absence of a laser field. This figure demonstrates that the nonlinear term influences the total absorption coefficients. Fig. 3b shows the total absorption coefficients as a function of photon energy for various incident light intensities, in the absence of a laser field, accounting for the third-order nonlinear absorption coefficient. As expected, the peak value decreases with increasing incident light intensity. Notably, at an incident light intensity of $I = 0.3\ MW/cm^2$, the resonance peak splits into two sub-peaks. A strong bleaching effect occurs above this critical value [20].

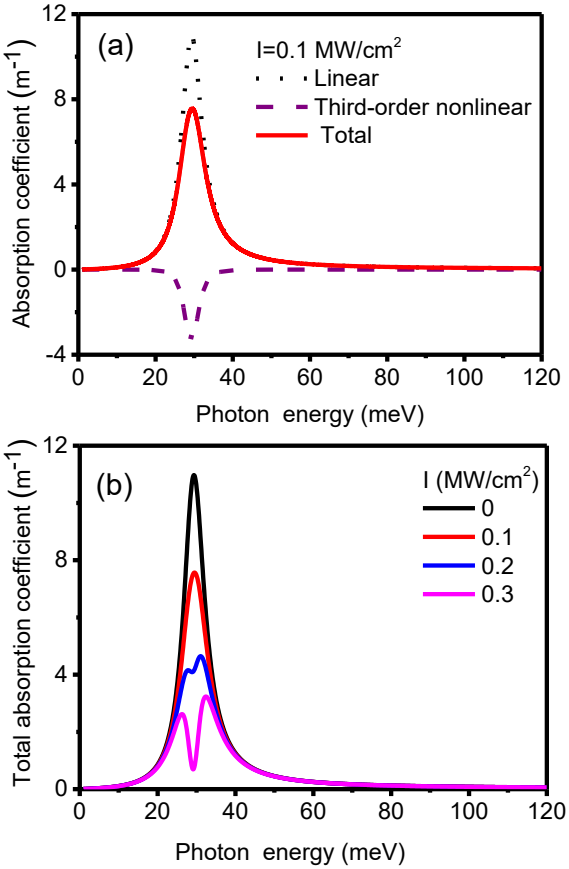


Fig. 3. *(a) Linear, third-order nonlinear and total optical absorption coefficients as a function of the photon energy for I=0.1MW/cm^2 and (b) total absorption coefficient as a function of the photon energy for different values of optical intensity of incident wave for (1-2) transition in the undressed LDQWW.*

Fig. 4 shows the total absorption coefficient as a function of photon energy for the (1–2) transition—using light polarized along the x-axis—at various incident light intensities and laser field values. We observe that the absorption peaks shift toward higher photon energies as the laser amplitude increases. This behavior stems from the energy levels in the dressed structures; the larger the laser parameter, the greater the separation between the two energy levels. Consistent with the energy level behavior shown in Figure 1, the position of the resonance peak for the (1–2) transition exhibits a strong dependence on the laser amplitude.

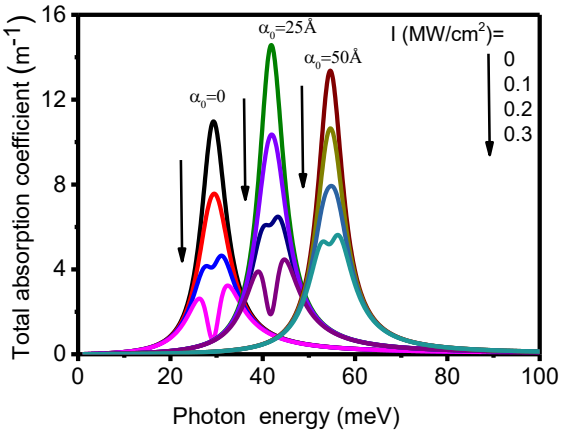


Fig. 4. *Total absorption coefficient as a function of the photon energy for different values of optical intensity of incident wave for (1-2) transition in the dressed LDQWW for a_0=0, a_0=25 Å, and a_0=50 Å.*

CONCLUSIONS

We present a theoretical study of linear and nonlinear inter-subband optical absorption coefficients in an LDQWW under a laser field. Subband levels and corresponding wave functions were obtained within the framework of the effective-mass approximation using the two-dimensional finite-difference method. The laser-dressing effect was taken into account for the finite confinement potential.

Our results demonstrate the significance of laser parameters regarding energy levels and total absorption coefficients. It is observed that total absorption coefficients depend not only on laser intensity and frequency but also on the intensity of the incident light. Interesting behaviors in absorption peaks are observed when both the laser field intensity and the incident light intensity are increased simultaneously. These parameters could be proposed as mechanisms for optical tuning.

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