Optical absorption in core-shell quantum antidot under applied co-directed electric and magnetic fields

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INTRODUCTION

Recently, nanostructures have attracted much attention of scientists due to modern technology of their growth and wide range of their applications in electronic and optoelectronic devices. Today it has become possible to create multilayers spherical quantum dots (MSQD), which are called core-shell, core-shell-shell and others. Based on them, biosensors, fluorescent labels, light emitting devices, solar cells are already being created, and elements for the latest computer technology are being developed [1-2].

Investigation of the electronic energy spectrum, the absorption coefficient and the influence of external fields are important for the creation of new devices for modern nanoelectronics. Therefore, to select the optimal parameters of quantum dot with the required energy spectrum of radiation, and, accordingly, the pre-known characteristics of devices based on them, it is necessary to perform theoretical studies of the external fields influence on energy in spherical nanostructures.

In the present paper, we have calculated electric and magnetic field dependences of electron energy spectra, wave functions and absorption coefficient from intersubband quantum transitions electron in inverted core-shell QD without impurity using matrix method.

THEORETHICAL FRAMEWORK

The semiconductor MSQD $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ consisting of core $Al_{0.3}Ga_{0.7}As$ with the radius r_0, shell-well GaAs with the width and outer shell $Al_{0.3}Ga_{0.7}As$ is under research.

In order to investigate the magnetic field effect on the electron energy spectrum and wave functions in the nanosystem with impurity it is necessary to solve the Schrodinger equation

$$H\psi_{jm}(\vec{r}) = E_{jm}\psi_{jm}(\vec{r}) \tag{1}$$

with the Hamiltonian

$$H = \left(\vec{p} - \frac{e}{c}\vec{A}\right)\frac{1}{2\mu(r)}\left(\vec{p} - \frac{e}{c}\vec{A}\right) + V_F(r,\theta) + V^p(r) + U(r) \tag{2}$$

where $\vec{A}$ is the vector potential, is $V_F(r,\theta)$ the electric field potential, $V^p(r)$ is the self-polarization potential, *U(r)* is the confining potential.

In order to solve the equation (1), the wave functions are expanded over the complete set of exact functions obtained without external fields [3].

$$\psi_{jm}(\vec{r}) = \sum_n \sum_l c_{nl}^{jm} \Phi_{nlm}(\vec{r}) \tag{3}$$

To determine the coefficients c_{nl}^{jm} and energy spectrum E_{jm} we obtain the secular equation

$$\left| H_{n\ell,n'\ell} - E_{jm}\delta_{n,n'}\delta_{\ell,\ell'} \right| = 0 \tag{4}$$

Using the obtained energies and wave functions of an electron, the absorption coefficients can be calculated. For a spherical nanosystem, linear , third-order nonlinear and total absorption coefficients are defined as follows, respectively

$$\alpha^{(1)}(\omega) = \omega\sqrt{\frac{\mu}{\varepsilon_R}}\frac{\sigma_v \hbar\Gamma_{fi}\left|M_{fi}\right|^2}{\left(E_{fi} - \hbar\omega\right)^2 + \left(\hbar\Gamma_{fi}\right)^2} \tag{5}$$

$$\alpha^{(3)}(\omega) = -\omega\sqrt{\frac{\mu}{\varepsilon_R}}\left(\frac{I}{2\varepsilon_0 n_r c}\right)\frac{\sigma_v \hbar\Gamma_{fi}\left|M_{fi}\right|^2}{\left[\left(E_{fi} - \hbar\omega\right)^2 + \left(\hbar\Gamma_{fi}\right)^2\right]^2} \times \left\{4\left|M_{fi}\right|^2 - \frac{\left(M_{ff} - M_{ii}\right)^2\left[3E_{fi}^2 - 4E_{fi}^2\hbar\omega + \hbar^2\left(\omega^2 - \Gamma_{fi}^2\right)\right]}{\left(E_{fi}\right)^2 + \left(\hbar\Gamma_{fi}\right)^2}\right\} \tag{6}$$

The dipole transition matrix element is given by

$$M_{fi} = \left\langle \psi_i \left| e r\cos\theta \right| \psi_f \right\rangle \tag{7}$$

RESULTS AND DISCUSSION

Dependencies of electron energies (at m=0) on electric field intensity F and the distributions of electron probability densities in the ground and first excited states at different values of magnetic field induction (B = 0 T, B = 15 T and B = 30T) in the $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ multilayer spherical quantum dot with core radius r_0=5nm (a) r_0=15nm (b) are presented in Fig. 1. It can be seen that with increasing of the quantum dot core radius the value of energy decreases, instead energy values increase with increasing of the magnetic field induction, one can see the anti-crossing of energy levels (1*f* and 1*d*). It happens due to the taken-off degeneration, which is often observed in nanostructures and studied in detail in [4]..

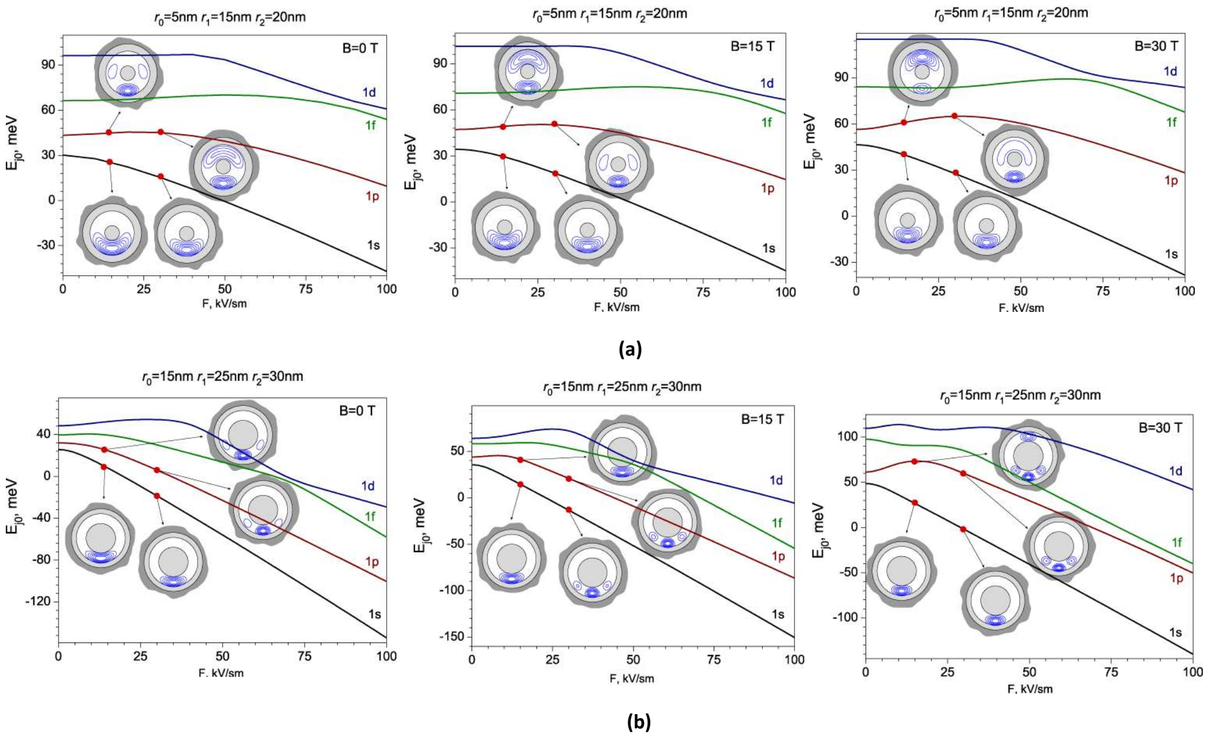

Fig. 1. Dependence of the electron energy spectra on the applied electric field at B = 0 T, B = 15 T, B= 30 T in the $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ multilayer spherical quantum dots with r_0 =5 nm, r_1 =15 nm and r_2 =20 nm (a) and r_0 =15 nm, r_1 =25 nm and r_2 =30 nm (b).

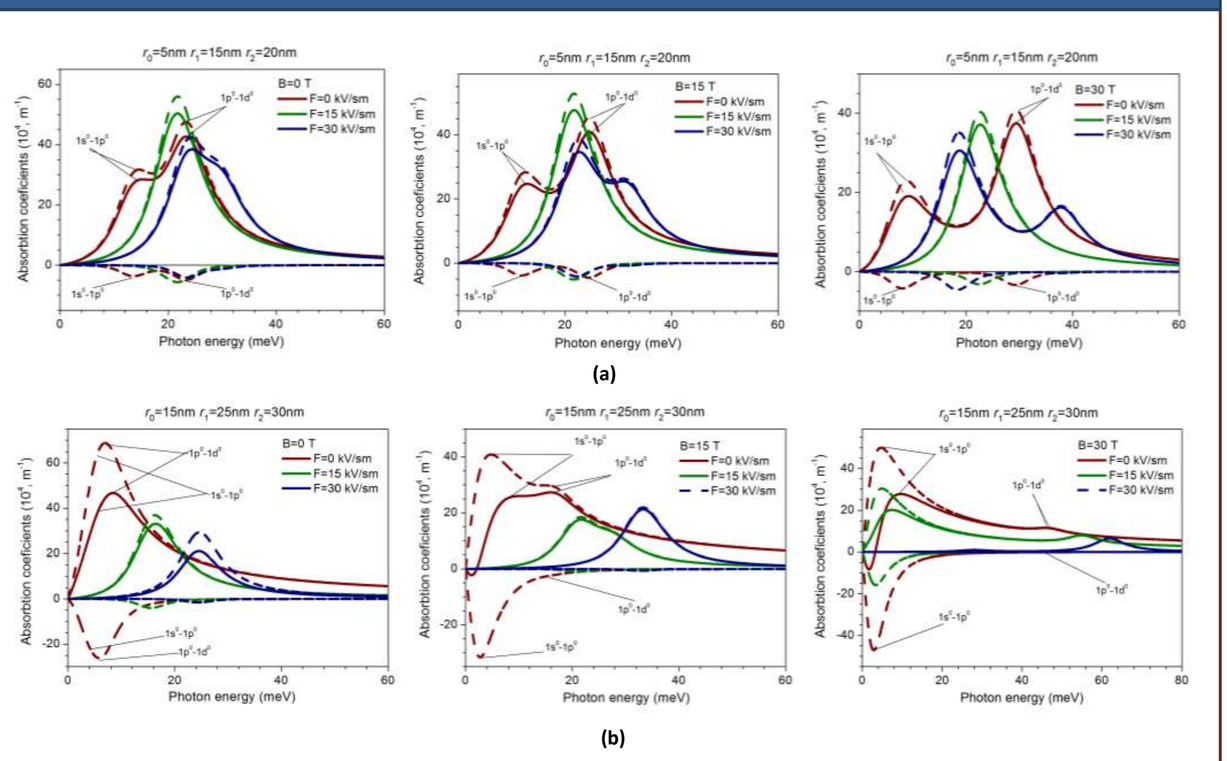

Fig. 2. Dependence of absorption coefficient on the applied magnetic field in the $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ multilayer spherical quantum dots with r_0 =5 nm, r_1 =15 nm and r_2 =20 nm (a) and r_0 =15 nm, r_1 =25 nm and r_2 =30 nm (b).

Fig. 1. indicates the linear, third-order nonlinear and total OACs in the MSQD with core radius r_0=5nm (a) r_0=15nm (b) without impurity as function of the incident photon energy. Two peaks are formed by quantum transitions 1s-1p and 1p-1d correspondently. The energy distance between peaks is bigger at bigger magnetic field induction. As the electric field intensity increases, the peaks shift to the region of higher energies. The third-order nonlinear OAC is much smaller than linear OAC at r_0=5nm (Fig.2a). The value of nonlinear OAC increases with the growth of the core radius and the magnetic field induction. Therefore, at some region of photon energies, the total OAC becomes negative (Fig.2b). In this case, contribution of the quantum transition 1s-1p is much greater than 1p-1d.

CONCLUSIONS

In order to obtain the electron energy spectrum and its density distributions in semiconductor $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ driven by electric and magnetic field, the stationary Schrodinger equation is solved within the method of wave function expansion over the basis of electron wave functions obtained for the nanostructure without the external field. The approximation of effective mass and finite rectangular potential barriers model are used. The dependences of electron energies, density distributions and absorption coefficient on external fields intensity are obtained. It is shown that with increasing of the quantum dot core radius the value of energy decreases, instead energy values increase with increasing of the magnetic field induction. Is obtained that absorption coefficient peaks shift to the region of higher energies with electric fied intensity increasing, the energy distance between peaks is bigger at bigger magnetic field induction, for r_0 =5 nm linear OAC is much bigger than third-order nonlinear OAC.

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