Optical absorption in core-shell quantum antidot with applied magnetic field

Volodymyr Holovatsky, Natalia Holovatska, Maryna Chubrei

Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine, y.holovatsky@chmu.edu.ua

INTRODUCTION

Multilayer spherical quantum dots (MSQD) consisting of a core and several shells of semiconductor materials with different bandgap values are intensively studied due to the prospects of their use in various nanoelectronics and nanophotonics devices such as white light sources, high-efficiency photovoltaic devices, fluorescent labels with multimode radiation, various detectors, magneto-optical devices and memory elements for novel computers. The creation of semiconductor devices requires theoretical studies of the MSQD optical properties, the influence of impurities and external fields on their energy spectrum. In this study we report the effect of the outer potential well width of the MSQD with a central donor impurity and magnetic field on the energy spectrum, wave functions, impurity photoionization cross-section (PCS) and intersubband optical absorption coefficient (OAC).

THEORETICAL FRAMEWORK

The multilayer spherical quantum dot investigated in this work consists of a spherical core GaAs and two spherical shells (AlGaAs and GaAs) placed in a wide-gap medium. The core radius is \( r_0 \), the thickness of the spherical layers are \( \Delta_1 \) and \( \Delta_2 \). The MSQD core and the outer spherical shell form two potential wells for the electron, and the inner layer is a potential barrier with height \( V \). The donor impurity is located in the center of the nanosystem core. The scheme of the electron potential energy in MSQD is shown in Fig.1.

The Schrödinger equation for the electron has the form

\[
-\frac{\hbar^2}{2m} \nabla^2\Psi_{nm}(\mathbf{r}) + U(\mathbf{r}) \Psi_{nm}(\mathbf{r}) = E_{nm}\Psi_{nm}(\mathbf{r}),
\]

(1)

where the coordinate dependences of the effective mass, dielectric constant and potential energy are expressed as

\[
m(\mathbf{r}) = m_0 \left( \frac{r}{r_0} \right)^n, \quad \epsilon(r) = \left( \frac{r}{r_0} \right)^n, \quad U(r) = \begin{cases} 0, & r < r_0, \\ V, & r \geq r_0. \end{cases}
\]

(2)

The radial part of wave functions contain the degenerate hypergeometric functions of the 1st and 2nd kind \( F(a, b, x) \) and \( G(a, b, x) \):

\[
R_{nl}(r) = \begin{cases} A_1 r^n e^{-r/2} F(1-n, -2; x), & r \leq r_0, \\ A_2 r^{-n} e^{-r/2} F(1-n, -2; x), & r \geq r_0, \end{cases}
\]

(3)

Based on the energy spectrum and wave functions the effective photoionization cross-section and optical absorption coefficient are calculated by the formulas [1]:

\[
\sigma(h\nu) = \frac{4\pi e^2}{\hbar c} \sum \left| \langle \Psi_{nlm} | \mathcal{E} \Psi_{nlm} \rangle \right|^2 \delta(E_{nlm} - E_{nlm} - h\nu), \quad \alpha(h\nu) = 4\pi r_0^2 \sum \frac{\left| \langle \Psi_{nlm} | \mathcal{E} \Psi_{nlm} \rangle \right|^2}{E_{nlm} - E_{nlm}},
\]

(4)

where \( \delta(E) = \frac{\delta^2}{\delta(E - E_{nlm})^2} \), \( h\nu \) is the photon energy, \( \rho = 0.3 \) is the fine structure constant, the ratio \( F_{1/2}/F_{1/2} = 1, \gamma = 0.4 \) is the carrier density in MSQD, \( r_0 = 0.14 \) ps is the relaxation time. The study magnetic field influence on the optical absorption coefficient needs to solve the Schrödinger equation

\[
\left( \mathcal{H} + \mathcal{M} \right) \Psi_{nlm}(\mathbf{r}) = \left( \mathcal{H} \right) \Psi_{nlm}(\mathbf{r}),
\]

(5)

The electron wave functions \( \Psi_{jm}(\mathbf{r}) \) are calculated by matrix method using the expansion \( \Psi_{jm}(\mathbf{r}) = \sum_{jm} \psi_{jm}(\mathbf{r}) \), where \( \psi_{jm}(\mathbf{r}) = R_{nl}(r)Y_{lm}(\theta, \phi) \).

To determine the coefficients \( c_{jm}^{nl} \) and electron energy spectrum we obtain the secular equation \( \left| H_{nljm} - E_{nl} \delta_{jm} - \delta_{jm} \right| = 0 \).

The eigenvalues \( (E_{jm}) \) and eigenvectors \( (c_{jm}^{nl}) \) of the matrix \( H_{nljm} \) determine the energy spectrum and the wave functions of an electron in MSQD driven by the magnetic field [2].

RESULTS AND DISCUSSION

![Fig. 1. Electron potential energy in GaAs/AlGaAs/GaAs MSQD at Z = 1.](image1)

CONCLUSIONS

The exact solutions of the Schrödinger equation for the electron in a GaAs/AlGaAs/GaAs MSQD with central impurity were obtained. The impurity photoionization cross-section and the intersubband absorption coefficient were investigated on the basis of the energy spectrum and wave function of the electron for various values of the outer potential well size. It was shown that in the region of the energy levels anticrossing the nanosystem is most sensitive to the effect of impurity and external fields on its optical characteristics. A decrease of the outer potential well size of MSQD leads to the shift of PCS and OAC peaks to the high-energy region and to an increase in the contribution of quantum transitions to higher excited states to the optical characteristics. At the absence of impurity in MSQD intersubband absorption occurs mainly through the quantum transition \( 1s \rightarrow 1p \), whereas in the presence of a central impurity the greatest absorption occurs at higher photon energy through the quantum transition \( 1s \rightarrow 2p \). It is shown that the magnetic field with induction of 10-15 T influences the nanosystem optical characteristics as well as the reducing of the outer shell thickness does.

REFERENCES
