Controllable influence of the photodielectric effect to process of the submillimeter waves spread in quantum dots structures in an external magnetic field

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Abstract – The registration possibility of the excited states for impurity complexes \( \text{A}^+ + e \) (acceptor with an additional hole, which interacts with an electron, localized in the quantum dot ground state) because of their contribution to the dielectric permeability of the semiconductor quasi-zero structure under intraband optical transitions of electrons in an external magnetic field, has been theoretically analyzed. It is shown, that effective control of the photodielectric effect (PDE) by modifying of the electronic adiabatic potential and the electron wave function is possible in an external magnetic field. It is found, that new possibilities for the PDE-control are appeared in an external magnetic field. These effects are important for applications in semiconductive nanoelectronics: for example, for controllable influence on the spread of submillimeter waves in nanostructures; for detectors of infrared - radiation with controllable parameters; for method of the impurities spectroscopic studies in semiconductive nanostructures.

Keywords – photodielectric effect, quantum dot, Zeeman effect, detectors of infrared radiation, submillimeter waves

I. INTRODUCTION

The registration possibility of the excited states for the impurity complexes \( \text{A}^+ + e \) by their contribution to the dielectric permeability of the quasi-zero-dimensional semiconductor structure under intraband optical transitions of electrons in an external magnetic field, has been analyzed in this paper.

Earlier [1] we have shown, that because of the fact, that the effective radius of the excited states for the impurity complex \( \text{A}^+ + e \) in quantum dot (QD) is significantly higher than the effective radius of the ground state, and due to the polarizability growth, the photodielectric effect (PDE) can be realized, i.e. a considerable change in permittivity of the semiconductive quasi-zero-dimensional structure.

New possibilities for the PDE-control are appeared in an external magnetic field, which are important for applications in semiconductive nanoelectronics: controllable influence on the spread of submillimeter waves in nanostructures; detectors of infrared - radiation with controllable parameters; method of spectroscopic studies of impurities in semiconductive nanostructures.

Dichroism of the PDE, associated with the central symmetry violation of the ground state for electronic adiabatic potential as also with the presence of an external magnetic field, has been theoretically investigated in [2]

The aim of this work is a theoretical study of the external magnetic field influence on the PDE, associated with the excitation of impurity complexes in the quasi-zero-dimensional structures, which are transparent dielectric matrix with semiconductive quantum dots synthesized therein.

II. SPECTRAL DEPENDENCE FOR THE LIGHT ABSORPTION COEFFICIENT FOR THE QUASI-ZERO-DIMENSIONAL STRUCTURE WITH \( \text{A}^+ + e \) COMPLEXES IN AN EXTERNAL MAGNETIC FIELD

The photo-excitation process of the impurity complex \( \text{A}^+ + e \) is associated with optical transitions of the electron from the QD - ground state to the excited state of the dimensionally - quantized conduction band in an external magnetic field.

Account of the Coulomb interaction between the electron and hole, localized on the \( \text{A}^+ \) - center, leads to the fact that, as a result of electronic transitions, energy of the hole binding energy will be changed, because of the change for the electron adiabatic potential, which under fixed radius of QD depends only on the initial and final states of the electron.

The interaction of an electron, which is in the
the ground state of QD, with hole, localized on the A'-center, will be considered in framework of the adiabatic approximation. In this case, the electron potential \( V_{a,l,m}(\mathbf{r}) \), acting on the hole, can be considered as averaged over the motion of an electron [3].

In frames of the first-order perturbation theory for the ground state of an electron (\( m = 0, l = 0 \)), potential can be written in the form

\[
V_{a,0,0}(\rho) = -\frac{e^2 \beta}{4\pi\varepsilon_{\rho}} \left[ \frac{m_\rho^*}{2} (\omega^2 + \omega_\rho^2) \rho^2 + \frac{m_\rho^* z^2}{2} \right],
\]

where \( \beta = \gamma_0 - Ci(2\pi n) + \ln(2\pi n) \);

\( \hbar \omega_\rho = \left[ \left( 2\hbar\pi^2 n^2 \varepsilon^2 \right) / \left( 3m_\rho^* R_0^2 4\pi\varepsilon_{\rho} \varepsilon^2 \right) \right]^{1/2} \); \( \varepsilon \) - relative dielectric permeability of the QD material; \( \varepsilon_0 \) - dielectric constant, \( \rho, \varphi, z \) - cylindrical coordinates; \( \gamma_0 = 1, 781 \) - Euler's constant; \( Ci(x) \) - the integral cosine; \( m_\rho^* \) - the hole effective mass; \( \omega_\rho \) - cyclotron frequency, \( m = 0, \pm 1, \pm 2, \ldots \) - magnetic quantum number; \( l = 0, 1, 2, \ldots \) - orbital quantum number.

We have obtained transcendental equation, which describes the binding energy of a hole in the complex \( A^* + e \) for electron in the excited state of QD.

We consider a photo-excitation process for complexes \( A^* + e \) in QD, synthesized in a transparent dielectric matrix in an external magnetic field, when \( \mathcal{E}_k \uparrow B \) and \( \mathcal{E}_k \perp B \). We assume that the \( A^* \) center is localized at the point \( \mathbf{R}_0 = (0, 0, 0) \). The energy spectrum of electrons in a magnetic field in frames of the second-order perturbation theory is given by expression.

\[
E = E^{(0)} + \sum_{n\neq m=0} \frac{R_0^2 |V_{n,l,m,n',l',m'}|^2}{\pi^2 - \bar{X}_{n,l}^2},
\]

(2)

here \( E^{(0)} = \bar{X}_{n,l}^2 E_r / R_0^2 \) - zero approximation to the electron energy in the dimensionally - quantized band; \( \bar{X}_{n,l} \) - root of the half-integer order Bessel function; \( V_{n,l,m,n',l',m'} \) - the matrix element of the perturbation operator:

\[
\begin{align*}
V_{n,l,m,n',l',m'} &= \sum_{s=0}^\infty \left\{ \frac{\hbar \omega_s m}{4\pi \left( \bar{X}_{n,l}^2 - \bar{X}_{n',l'}^2 \right)} J_{l/2} \bar{X}_{n,l} J_{l/2} \bar{X}_{n',l'} \right. \\
& \times \left[ R_0^* \bar{X}_{n',l'} J_{l/2} \left( R_0^* \bar{X}_{n,l} \right) J_{l/2} \left( R_0^* \bar{X}_{n',l'} \right) - \\
& \\
& \left. - R_0^* \bar{X}_{n,l} J_{l/2} \left( R_0^* \bar{X}_{n',l'} \right) J_{l/2} \left( R_0^* \bar{X}_{n,l} \right) \right] + \\
& + \sum_{k=0}^\infty \left( -1 \right)^k m_\rho^* \omega_\rho^2 R_0^2 \left( \bar{X}_{n,l}^3 \right)^{2k+1} \\
& \times \sqrt{(l + k + \frac{5}{2})} \left( 2l + 2 \right)^{2k+1} \left( 2l + 3 \right) \\
& \times \left[ (l - m - 4) \left( l - m + 3 \right) \left( l - m + 2 \right) \left( l - m + 1 \right) \right. \\
& \left. \left( 2l + 1 \right) \left( 2l - 1 \right) \right]^{2k+1} \\
& \times \left( 2l + 2k + 2 \right) \Gamma \left( l + \frac{1}{2} \right) \\
& \times \left[ F \left( -k, -l - k - \frac{3}{2} l + \frac{5}{2} \bar{X}_{n,l}^2 \right) \bar{X}_{n,l} \right] \\
& \times \left( 2l + 2k + 4 \right)^{2k+1} \\
& \left( 2l + 3 \right) \left( 2l - 1 \right) \left( 2l + 1 \right) \right]
\end{align*}
\]

(3)

Where \( R_0^* \) - the QD – radius in the effective Bohr radius units; \( J_s \) (\( x \)) - the first kind Bessel function of arbitrary order \( v \); \( \Gamma \left( x \right) \) - the gamma function; \( F(a, b; c; z) \) - the Gauss hypergeometric function [4].

The effective Hamiltonian for interaction \( \tilde{H}_{\text{int}}(\mathbf{r}) \) with field of the light wave in case, when \( \mathcal{E}_k \uparrow B \), is written as

\[
\tilde{H}_{\text{int}}(\mathbf{r}) = -i\hbar \lambda_0 \sqrt{\frac{2\pi \hbar^2 \alpha^*}{m^2 \omega}} I_s \exp \left( i \mathbf{q} \cdot \mathbf{r} \right) \left( \mathbf{\hat{e}}_s \mathbf{\nabla}_s \right),
\]

(4)

where \( \lambda_0 \) - the local field coefficient; \( \alpha^* \) - the fine structure constant, with taking into account the static relative dielectric permittivity \( \varepsilon \); \( I_s \) - intensity of light with frequency \( \omega \), wave-vector \( \mathbf{q} \), and the unit vector of polarization \( \mathbf{\hat{e}}_s \); \( \mathbf{\nabla}_s \) - the Hamilton operator.

The matrix element \( M^{(i)}_{l',l} \), which determines the value of oscillator strength for the dipole optical transitions of electron and hole from the ground state \( \Phi_{\text{in}}(\mathbf{r}_e, \mathbf{r}_h) \) of the impurity complex to the excited state \( \Phi_{\text{ex}}(\mathbf{r}_e, \mathbf{r}_h) \) of QD can be written as

\[
M^{(i)}_{l',l} = i \sqrt{\frac{2\pi \alpha^* I_s}{\omega}} \left( E_{l',l} - E_{l,0} \right) \left( E_{l,0} - E_{s,0} \right) \Phi_{\text{in}}(\mathbf{r}_e, \mathbf{r}_h) \Phi_{\text{ex}}(\mathbf{r}_e, \mathbf{r}_h)
\]

\[
= i \sqrt{\frac{2\pi \alpha^* I_s}{\omega}} \left( E_{l,0} - E_{l,0} \right) \left( E_{s,0} - E_{s,0} \right) \Phi_{\text{in}}(\mathbf{r}_e, \mathbf{r}_h) \Phi_{\text{ex}}(\mathbf{r}_e, \mathbf{r}_h)
\]
The coefficient of the light impurity absorption under photo-excitation of impurity complexes $A^+ + e$ in the quasi-zero-dimensional structure in an external magnetic field, $K^{(0)}_W (\omega)$, with taking into account dispersion of the QD- radius, is determined by the next formula (in the Bohr units)

$$K^{(0)}_W (X) = \frac{2\pi N_e}{\hbar^2 E_k} \sum_{j\epsilon_{\perp}} |M^{(0)}_{j'j}|^2 \times$$

$$\times \delta \left( \frac{k (X_{\perp} - \pi^2)}{(\tilde{R} u)^2} - (\eta_{j\alpha} - \eta_{j\alpha}^-) - X +$$

$$+ \tilde{R} u^2 \sum_{s_{+}\perp\perp} \frac{|V_{s_{+}\perp\perp}^{\lambda\lambda} e^{-\pi^2} - V_{s_{+}\perp\perp}^{\lambda\lambda} e^{-\pi^2}|^2}{(\pi^2 - \tilde{X}^2_{e,j}) E_k} \right) P(u) du ,$$

where $N_e$ – the QD concentration in a dielectric matrix; $\delta (x)$ – the Dirac delta function.

For the case, when $\tilde{e}_\perp \perp \tilde{B}$, for transversal light polarization, the effective Hamiltonian of interaction $\hat{H}^{(0)}_{\perp\perp}$ with field of the light wave, which is characterized by the wave vector $\tilde{q}$, and by the unit polarization vector $\tilde{e}_\perp$, can be written as:

$$\hat{H}^{(0)}_{\perp\perp} = -i \hbar \lambda_0 \sqrt{2 \pi \hbar^2 \alpha} I_0 \times$$

$$\times \exp (i \tilde{q} \cdot \tilde{r}) \left[ (\tilde{e}_\perp \cdot \nabla ) - i \frac{|\tilde{q}| B}{2 \hbar} [\tilde{e}_\perp , \tilde{r}] \right] .$$

In the dipole approximation, the matrix element $M^{(0)}_{j'j}$ for considered optical transitions can be represented as the sum of two terms:

$$M^{(0)}_{j'j} = M_1 + M_2 ,$$

where

$$M_1 = i \lambda_0 \sqrt{2 \pi \hbar^2 \alpha} I_0 \left( E_{j'j} - E_{j\alpha} - (E_{j'\alpha} - E_{j\alpha}) \right) \times$$

$$\times \left[ (\tilde{e}_\perp , \tilde{r}) \frac{\nabla \Phi^{(0)}_{\perp\perp}}{\Phi^{(0)}_{\perp\perp}} \right] (\tilde{r}, \tilde{r}) .$$

$$M_2 = -\lambda_0 \sqrt{2 \pi \hbar^2 \alpha} \frac{\hbar \omega}{2} \times$$

$$\times \left[ (\tilde{e}_\perp , \tilde{r}) \frac{\nabla \Phi^{(0)}_{\perp\perp}}{\Phi^{(0)}_{\perp\perp}} \right] (\tilde{r}, \tilde{r}) .$$

Figure 1 shows curves of the spectral dependence for the light absorption coefficients under photo-excitation of impurity complexes $A^+ + e$ in the quasi-zero-dimensional structure with InSb - QDs in an external magnetic field for the case $\tilde{e}_\perp \perp \tilde{B}$ (curve 2) and $\tilde{e}_\perp \perp \tilde{B}$ (curve 3).

It is seen, that shift for the absorption band edge occurs in a magnetic field to shorter wavelengths spectrum (compare curves 1 and 2, 1 and 3), that is connected with dynamics of the Landau levels.

In the case, when $\tilde{e}_\perp \perp \tilde{B}$, the absorption band is splitted into the Zeeman doublet (compare curves 1 and 3) in accordance with selection rules for the magnetic quantum number $m = \pm 1$. It is expected, that these features of the spectral curves in a magnetic field will be appeared in the PDE spectra.
Figure 1. Spectral dependence of the light absorption coefficient (in relative units) under photoexcitation of the impurity complexes \( A^+ + e \) in the quasi-zero-dimensional structure with InSb-QDs in an external magnetic field at \( E_\parallel = 5 \) meV; \( R_0 = 50 \) nm for different values of \( B \): 1 - \( B = 0 \); 2,3 - \( B = 5 \) T (2 - \( \vec{e}_\parallel \parallel \vec{B} \), 3 - \( \vec{e}_\parallel \perp \vec{B} \)).

III. CALCULATION OF THE RELATIVE DIELECTRIC PERMEABILITY

Under relatively small changes in the relative dielectric permeability \( \varepsilon (\Delta \varepsilon \leq 3\varepsilon) \), change of the \( \varepsilon \) value under photoexcitation in the dipole approximation with account of the QD radius dispersion is determined from the following formula (see also [6])

\[
\Delta \varepsilon (\omega) = \frac{4\pi N \omega I_0}{\hbar \omega} \sum_\sigma \int_0^{\beta} \sigma_\alpha (\omega) r_\alpha P(u) du,
\]

(13)

where \( I_0 \) - the radiation intensity; \( \omega \) - frequency of the incident light; \( \alpha \) - polarizability of the excited states for electron in the quantum dot; \( \tau \) - the lifetime of the excited electronic states; \( \sigma_\alpha (\omega) \) - the partial cross-section of the photon absorption by QD with complex \( A^+ + e \).

Figure 2 a,b shows dependence of the relative change in dielectric permeability (RCDP) for the quasi-zero-dimensional structure with InSb-QDs from the external magnetic field value for cases \( \vec{e}_\parallel \parallel \vec{B} \) (Fig. 2a) and \( \vec{e}_\parallel \perp \vec{B} \) (Fig. 2b).

IV. CONCLUSION

Influence of an external magnetic field on the PDE, which is connected with excitation of impurity centers \( A^+ + e \) in the quasi-zero-dimensional structure, has been investigated in frames of the zero-range potential model in the adiabatic approximation. It is shown, that effective control of the PDE by modification of the electron adiabatic potential and the electron wave function, is possible in an external magnetic field. It is very important for controllable influence to process of the submillimeter waves spread in nanostructures because of purposeful variation in refractive index.

REFERENCES


