Laser driven intraband optical transitions in two-dimensional quantum dots and quantum rings

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\textbf{A B S T R A C T}

The intraband optical absorption have been investigated in the presence of hydrogenic donor impurity in GaAs/ GaAlAs quantum dot and quantum ring in the intense laser field. The single electron energy spectrum and wave functions have been found using the effective mass approximation and exact diagonalization technique. Different selection rules are obtained for intraband transitions depending on the direction of incident light polarization. Due to the accidental degeneracy of the laser dressed impurity states the crossings of the curves of the threshold energies and the dipole matrix elements on laser field parameter have been observed. The intraband absorption coefficient is calculated for different locations of hydrogenic donor impurity and different values of intense laser field parameter. The obtained results show that the absorption spectrum can exhibit either a blue- or redshift depending on the impurity location, values of the laser field parameter and direction of incident light polarization. The obtained theoretical results indicate a novel opportunity to tune the performance of new devices, based on the quantum dots and quantum rings and to control their specific properties by means of intense laser and hydrogenic donor impurity.

\textbf{1. Introduction}

In the last two decades, much attention has been devoted to semiconductor nanostructures such as quantum dots (QDs) and quantum rings (QRs) due to the interest in fundamental physics study and potential device applications [1–5]. These nanostructures have a size around a few or a few tens of nanometers, and thus exhibit strong size confinement, resulting in fascinating physical properties and possibly enhanced performance for optical and optoelectronic devices. Droplet molecular-beam epitaxy further referred to as droplet epitaxy (DE) is a technique for producing semiconductor nanostructure arrays on the surface of single crystals. The technique is based on the self-assembly of Group-III metal droplets and subsequent annealing of the droplets in the flux of a Group-V material to crystallize a III–V compound [6,7]. In contrast to the traditional Stranski–Krastanov method, the DE technique provides a means for producing QD and QR ensembles, with ample opportunities for controlling their size, surface density, shape, and composition [8]. In Ref. [9] the authors are dealing with the DE prepared QDs. This technology is not only an alternative way of the strain induced technique to prepare QDs, but it allows to make various shaped nanostructures from various material. The present paper deals not only with the so-called conventional shaped QD but also with the ring shaped dot, with the inverted dot and with dot molecules.

Recently, the intense laser field (ILF) effects on electronic states and optical properties of GaAs-based semiconductor bulk and related nanostructures have been stimulated by the development of high-power tunable laser sources; moreover, interesting physical phenomena have also been revealed in these semiconductor structures [10–14].

On the other hand, the characteristic wavelengths determined by the position of the energy levels of QDs and QRs are very important in many applications. One way to change the position of the levels is to tailor the size of these structures. However, for a given structure the transition energy between two levels is almost fixed (neglecting the fluctuations of temperature and external hydrostatic pressure) in the absence of external fields. The presence of impurities and externally applied ILF alters the potential energy profile of the structure and therefore the energy levels and optical properties [15].

Simultaneous effect of hydrogenic donor impurity and external ILF on single electron states and intraband optical properties of semiconductor QDs have been theoretically investigated in [16–21]. The effects of intense high-frequency laser field on photoionization cross-section...

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and binding energy of shallow-donor impurities in GaAs/GaAlAs square quantum dots have been calculated using variational method with the effective-mass approximation [16]. In Ref. [17] the laser-field dependence of energy levels and donor-related electronic Raman scattering in spherical QD have been investigated by a quasi-analytical approach. The authors have found that the laser field amplitude and confinement strength have an important influence on the Raman scattering. An investigation of the laser radiation effects of a hydrogenic impurity and nonlinear intraband optical properties in a spherical QD has been performed by using the matrix diagonalization method [18]. It was found that the ILF amplitude has an important influence on the binding energies, the linear, third-order nonlinear, and the total absorption coefficients. ILF effects on the impurity states and intraband optical properties of CdS/SiO2 spherical QD under applied electric fields have been studied within the effective mass approximation by using a finite difference method [19–21]. The authors have followed the Floquet method to take into account the dressing effect on the confinement potential and on the electrostatic interaction between the electron and the hydrogenic impurity.

In the present work we have theoretically investigated hydrogenic donor impurity related intraband optical absorption of two-dimensional cylindrical GaAs/GaAlAs QD and QR in the ILF considering the laser dressed effect on both Coulomb and confining potentials of the electron. The paper is organized as follows. In Section 2 the theoretical model is described. Section 3 is dedicated to the results and discussion, and finally the conclusions are given in Section 4.

2. Theoretical framework

We consider a cylindrical GaAs QD and QR surrounded in the radial direction by a material with a larger energy gap, such as Al,Ga,,,As. Usually, the thickness of the ring along the growth direction is much smaller than the radial dimensions [22,23]. Without loss of generality, our system can be considered as two-dimensional, with the electron confined in the plane z=0 [24]. In this work we have used the method which is based on the non-perturbative theory that was developed originally to describe the atomic behavior under intense, high-frequency laser field conditions [25,26]. We assume the system to be under the action of laser radiation represented by a monochromatic plane wave of frequency \( \omega_0 \). The laser beam is non-resonant with the semiconductor structure, and linearly polarized along a radial direction of the structure (chosen along the x-axis). In the high-frequency regime the particle is subjected to the time-averaged potential [11,12,27]

\[
V_d(x, y) = \frac{\alpha_0}{2\pi} \int_0^{2\pi} V((x + \alpha_0 \sin(\alpha_0 t)i + y)dt,
\]

(1)

where \( \alpha_0 = e A_\text{L}/(m \omega_0) \) denotes the laser field parameter, \( m \) is the electron effective mass, \( A_\text{L} = A_\text{R}i \) is the vector potential, and \( i \) and \( j \) are the unit vectors along the laser polarization and the y-axis respectively. In the case of finite square lateral confining potential well, from Eq. (1) one may obtain a closed analytical form of \( V_d(x, y) \), as in [14]. For the time-averaged laser-dressed hydrogenic donor impurity potential we use the Ehlotzky approximation [28]:

\[
V_d(x, y) = -\frac{e^2}{2\varepsilon} \left[ \frac{1}{\sqrt{\Delta_x^2 + y^2}} + \frac{1}{\sqrt{\Delta_y^2 + y^2}} \right]
\]

(2)

where \( \varepsilon \) is the dielectric constant of the material, which, for simplicity, is taken the same inside and outside the QR. Here \( \Delta_x = x - x_0 \pm \alpha_0 \) and \( x_0 \) is the impurity coordinate. The laser-dressed energies in the presence of hydrogenic donor impurity are obtained from the time-independent Schrödinger equation

\[
\left[ -\frac{\hbar^2}{2m} + V_d(x, y) \right] \phi_d(x, y) = E_d \phi_d(x, y),
\]

(3)

where \( \Delta_2 = \partial^2/\partial x^2 + \partial^2/\partial y^2 \) and \( V_d(x, y) = V_0(x, y) + V_d(x, y) \). The laser-dressed energy eigenvalues and eigenfunctions may be calculated using 2D diagonalization technique. The eigenfunctions are presented as a linear expansion of the eigenfunctions of the rectangle [14,27].

The light absorption process can be described as an optical transition that takes place from an initial state to a final one assisted by a photon. The optical absorption calculations for the intraband transitions are based on Fermi’s golden rule derived from time-dependent perturbation theory [29,30]:

\[
\alpha(\hbar\omega) = \frac{16\hbar^3|\psi_{d0}|^2}{\hbar V N_f |\epsilon_0 E_f - E_i - \hbar\omega|}.
\]

(4)

Fig. 1. The threshold energies between the ground and first two excited states as a function of the laser field parameter \( \alpha_0 \) for QD with R<10 nm. The inset figure shows the first three dressed energies dependencies on \( \alpha_0 \). (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)
where $n_r$ is the refractive index of the material, $V$ is the volume of the sample per structure [31], $\beta_{FS}$ is the fine structure constant, $\hbar\omega_0$ is the incident photon energy and $E_F$ and $E_i$ are the energies of the final and initial states, respectively. $N_f = N_i - N_r$ is the difference between number of electrons in the initial and final states. Since we consider a one-particle problem, we assume $N = 1$ for the ground state and $N = 0$ for all upper states. $M_{fi}$ is the matrix element of coordinate. We calculate the dipole matrix elements for $x$- and $y$-polarizations of the incident light and replace the $\delta$-function by a Lorentzian profile with a full width at half maximum of 0.8 meV.

3. Results and discussion

The calculations are performed for a GaAs/GaAlAs QR with parameter values $V_0 = 228$ meV, $n_r = 3.6$, $m^* = 0.067m_0$, where $m_0$ is the free-electron mass. It is well known that for analyzing the optical absorption coefficient it is necessary to understand the behavior of the corresponding threshold energy and matrix element between the corresponding states. For this purpose in Fig. 1 we present the threshold energies associated with the transition between the ground and first two excited states (the red line corresponds to the $1 \rightarrow 2$

Fig. 2. The threshold energies between the ground and first two excited states as a function of the laser field parameter $\alpha_0$ for QR with $R_1 = 5$ nm and $R_2 = 25$ nm. The inset figure shows the first three dressed energies dependencies on $\alpha_0$.

Fig. 3. The matrix elements $|M_{fi}|$ as functions of the laser field parameter $\alpha_0$ for QD with $R=10$ nm. Different light polarizations are considered. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)
Fig. 4. The matrix elements $|M_{ij}|$ as functions of the laser field parameter $\alpha_0$. The results are for QR with $R_1 = 5\, \text{nm}$ and $R_2 = 25\, \text{nm}$. Different light polarizations are considered. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

Fig. 5. Dependence of intraband absorption coefficient (in arbitrary units) on the incident photon energy for different values of laser field parameter $\alpha_0$. Both $x$- and $y$-light polarizations are considered. The results are for QD with $R=10\, \text{nm}$. 
transitions, the blue line corresponds to the $1 \rightarrow 3$ transitions) as a function of ILF parameter $a_0$. The presented results are for the case of QD. Three different positions of impurity were considered: (a) on-center impurity; (b) half-radius impurity; and (c) impurity located at the QD border. We can see that the dependencies of on ILF parameter $a_0$ observe a different behavior (it can be decreasing and increasing function). This fact can be explained by the corresponding behavior of dressed energy levels, which are presented as the inset figures. When the impurity located on the center of QD ($x_0 = 0$, see Fig. 1(a)) the second energy level is double-degenerated as a result of the cylindrical symmetry of impurity and confinement potential. That is why the energies of the first and second excited states are coincide, for this reason both curves of threshold energies start with the same point. When the impurity is located at the half-radius ($x_0 = R/2$, see Fig. 1(b)) and at the border of QD ($x_0 = R$, see Fig. 1(c)) the crossing of threshold energies were observed, due to the accidental degeneracy of the corresponding energy levels.

Fig. 2 shows the dependencies of threshold energies on ILF parameter $a_0$ for different impurity position. The inset figure shows the first three dressed energy dependencies on $a_0$. The results are for QR with fixed values of inner and outer radii $R_1 = 5$ nm and $R_2 = 25$ nm. As it can be seen from figures, in contrast to the previous case the threshold energies always are decreasing functions of ILF parameter $a_0$. It can be explained by the fact that in all cases the ground state energies depend on laser field parameter which always increase faster than the first and second excited states. The last result caused by the fact that in the case of QR the electron probability is shifted from the zero and it is more sensitive to the laser field-induced deformation of the confining potential. On the other hand as it can be seen from the inset figure of Fig. 2(a), the energy levels of first and second excited states are visibly destroyed for more strong laser field (from the value $a_0 = 2$ nm). Therefore the curves of threshold energies for on-center impurity $x_0 = (R_1 + R_2)/2$ almost coincide with* till $a_0 = 2$ nm. When the impurity is located on the outer border of QR the crossing of threshold energies is observed ($x_0 = R_2$, see Fig. 2(c)), which can be explained by the accidental degeneracy of corresponding energy states.

Note that the intensity of the intraband optical absorption coefficient determined by the optical transition between the ground and excited states is expressed by the dipole matrix element. In the presence of space anisotropy (impurity and intense laser field) the direction of light polarization will influence on the intraband optical absorption spectrum. Due to the different symmetries of the dressed states for nonzero values of ILF parameter $a_0$ different selection rules are obtained.

In the case of $x$-polarization, transitions from the ground state $j = 1$ to the second excited state $j = 3$ are allowed (see red lines in Figs. 3 and

![Graphs showing the dependencies of threshold energies on ILF parameter $a_0$.](attachment:figure6.png)

**Fig. 6.** Dependence of intraband absorption coefficient (in arbitrary units) on the incident photon energy for different values of laser field parameter $a_0$. Both $x$- and $y$-light polarizations are considered. The results are for QR with $R_1 = 5$ nm and $R_2 = 25$ nm.
and in the case of $y$-polarization, the $1 \rightarrow 2$ transitions are allowed (see blue lines in Figs. 3 and 4). The absolute values of the matrix elements $|M_{ij}|$ are presented in Fig. 3. Different directions of incident light polarization and impurity location are considered. The results are for QD with $R=10$ nm. The red lines correspond to $1 \rightarrow 2$ transitions and blue lines correspond to $1 \rightarrow 3$ transitions. It is clearly seen from Fig. 3 that the absolute values of the matrix elements in dependencies on $a_0$ can be increasing and decreasing functions. It is worth to note that the dependencies of the matrix elements for different polarizations on the impurity positions adopt the same values. This fact can be explained by the degeneracy of corresponding states. The physics behind the behaviors of the matrix elements can be explained by the behavior of wave functions of corresponding states [32]. The distributions of that states for fixed values of the geometrical sizes of the structure depend on the impurity location and ILF parameter. In Fig. 4, we present the absolute values of the matrix elements $|M_{ij}|$. The results are for a case of QR with geometrical sizes $R_1 = 5$ nm and $R_2 = 25$ nm. In this case the matrix elements always are decreasing functions on the ILF parameter which is the result of behaviors of wave functions of corresponding states.

The intraband (linear) absorption coefficient dependence on the incident photon energy for different values of ILF parameter, different impurity location and light polarization direction are shown in Fig. 5. As a consequence of threshold energy in the case of $x$-polarization of the light dependencies in Fig. 5(a) for small $a_0$ we observe a redshift in the absorption spectrum with the increase of $a_0$. When $a_0 > 4$ nm we observe a blueshift in the absorption spectrum. Meanwhile in the case of $y$-polarization when impurity is placed on the border of QD only redshift has been observed (see Fig. 5(d)). On the other hand, changing the location of impurity from the center of QD depending on the value of ILF parameter, in the absorption spectrum we observe both, blue-shift and redshift. As it can be seen from Fig. 6, unlike Fig. 5 in the intraband absorption spectrum only a redshift is observed. This fact is due to the corresponding behavior of threshold energies (see Fig. 2).

4. Conclusions

We have studied the influence of ILF on impurity related intraband optical absorption in GaAs/GaAlAs two-dimensional quantum dot and quantum ring. Also, we have investigated the influence of the light polarization direction on the intraband absorption coefficient. On the one-electron states the laser dressed effect on both electron confining and electron–impurity Coulomb interaction potentials have been considered. The accidental coincidence of the threshold energies and matrix elements of different transitions have been obtained for different values of ILF parameter and different locations of hydrogenic donor impurity. The calculations showed that the intraband absorption spectrum can be effectively controlled by ILF, light polarization direction and hydrogenic donor impurity location. We believe that the effects observed in this work can be used to control physical properties of laser technology devices based on quantum dots and quantum rings.

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