PROCEEDINGS OF THE YEREVAN STATE UNIVERSITY

Physical and Mathematical Sciences 2017, **51**(1), p. 89–92

Physics

LASER DRIVEN IMPURITY STATES IN TWO DIMENSIONAL CONCENTRIC DOUBLE QUANTUM RINGS

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Hydrogenic donor impurity states in the 2D $\mathrm{GaAs/Ga_{0.7}Al_{0.3}As}$ concentric double quantum rings have been investigated under the action of intense laser field. An analytical expression of the effective lateral confinement potential induced by the laser field is obtained. The laser dressed effect has been considered both on electron confining and electron-impurity Coulomb interaction potentials. The single electron energy spectrum and wave functions have been found using the effective mass approximation and exact diagonalization technique. The accidental degeneracy of the impurity states has been observed.

***Keywords*:** concentric double quantum ring, intense laser field, impurity.

Introduction. Among various nanomaterials, quantum rings (QR) show interesting electronic, magnetic, optical properties and attract considerable attention [1]. For example, quantum phase coherence effects, such as the Aharonov–Bohm and Aharonov–Casher effects, have been observed in QRs [2]. The optical Aharonov–Bohm effect has also been predicted and demonstrated, which can be potentially used for applications in quantum information processing systems [3]. In addition, research efforts on quantum rings have also led to various practical applications in the last few years. QR infrared photodetectors have been reported in the mid- and far-infrared spectral range [4]. QRs have also shown promise in high density magnetic memory applications [5] and QR lasers have been reported as well [6].

It is well known that external perturbations are useful tools to manipulate the electronic and optical properties of low-dimensional semiconductor nanostructures. In particular, it was theoretically proved that the nanostructures irradiated by Iintense Laser Field (ILF) exhibit characteristics very different from those of a bulk semiconductor, and the radiation effects are more pronounced as the carriers' confinement is increased by reduction of dimensionality [7–9]. Simultaneous effect of hydrogenic donor impurity and external ILF on single electron states and intraband optical properties of semiconductor QRs have been theoretically investigated.

Present work describes the effects that ILF produces on hydrogenic donor impurity states of $\mathrm{GaAs/Ga_{0.7}Al_{0.3}As}$ 2D concentric double QRs.

Theoretical Framework. The method of investigation of hydrogenic donor impurity states in QRs in the presence of ILF is based on a non-perturbative theory that was developed originally to describe the atomic behavior under intense, high-frequency laser field conditions [10, 11]. We suppose system to be under the action of laser radiation represented by a monochromatic plane wave of frequency ω_0. The laser beam is non-resonant with the semiconductor structure, and linearly polarized along a radial direction of the QR (chosen

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along the x-axis). In the high-frequency regime the particle is subjected to the time-averaged potential [12]:

$$V_d(x,\,y)=\frac{\omega_0}{2\pi}\int\limits_0^{2\pi}V\left(\left(x+\alpha_0\sin(\omega_0 t)\right)\mathbf{i}+y\mathbf{j}\right)dt, \tag{1}$$

where $\alpha_0=eA_0/(cm\omega_0)$ denotes the laser field parameter; m is the electron effective mass; A_0 is the amplitude of laser radiation vector potential; $\mathbf{i}$ and $\mathbf{j}$ are unit vectors along laser polarization x- and y-axis respectively. In the case of finite square lateral confining potential well, one may obtain a closed analytical form for $V_d(x,\,y)$:

$$\begin{aligned}
&V_d(x,\,y)=\\
&=\frac{V_0}{2\pi}\mathrm{Re}\left[\pi-\theta(\alpha_0-x-\Gamma_1)\arccos\left(\frac{\Gamma_1+x}{\alpha_0}\right)+\theta(\alpha_0-x-\Gamma_2)\arccos\left(\frac{\Gamma_2+x}{\alpha_0}\right)-\right.\\
&\quad-\theta(\alpha_0+x-\Gamma_1)\arccos\left(\frac{\Gamma_1-x}{\alpha_0}\right)+\theta(\alpha_0+x-\Gamma_2)\arccos\left(\frac{\Gamma_2-x}{\alpha_0}\right)-\\
&\quad-\theta(\alpha_0-x-\Gamma_3)\arccos\left(\frac{\Gamma_3+x}{\alpha_0}\right)+\theta(\alpha_0-x-\Gamma_4)\arccos\left(\frac{\Gamma_4+x}{\alpha_0}\right)-\\
&\quad\left.-\theta(\alpha_0+x-\Gamma_3)\arccos\left(\frac{\Gamma_3-x}{\alpha_0}\right)+\theta(\alpha_0+x-\Gamma_4)\arccos\left(\frac{\Gamma_4-x}{\alpha_0}\right)\right],
\end{aligned} \tag{2}$$

where $\theta(u)$ is the Heaviside unit-step function and following notations are used: $\Gamma_i=\mathrm{Re}\left(\sqrt{R_i^2-y^2}\right)$, $i=1,2,3,4$.

For the time-averaged laser-dressed hydrogenic donor impurity potential we have used the Ehlotzky [13] approximation:

$$V_c(x,\,y)=-\frac{e^2}{2\varepsilon}\left[(\Delta_+^2+y^2)^{-1/2}+(\Delta_-^2+y^2)^{-1/2}\right], \tag{3}$$

where ε is the dielectric constant of the material, which, for simplicity, is taken the same inside and outside of the rings. Here $\Delta_\pm=(x-x_0\pm\alpha_0)^2$ and in this work the impurity is considered to be in the inner ring on the circle with the distance $x_0=(R_1+R_2)/2$. In the presence of hydrogenic donor impurity the laser-dressed energies are obtained from the time-independent Schrödinger equation:

$$\left[\frac{\hbar^2}{2m}\nabla_\perp^2+V_T(x,\,y)\right]\Phi_d(x,\,y)=E_d\Phi_d(x,\,y), \tag{4}$$

where $\nabla_\perp^2=\dfrac{\partial^2}{\partial x^2}+\dfrac{\partial^2}{\partial y^2}$ and $V_T(x,\,y)=V_d(x,\,y)+V_c(x,\,y)$.

The laser-dressed energy eigenvalues and eigenfunctions are calculated using 2D diagonalization technique [12, 14].

Results and Discussion. Calculations are performed for GaAs/Ga$_{0.7}$Al$_{0.3}$As concentric double QR with parameter values $V_0=256.68$ *meV*, $m=0.067m_0$, where m_0 is the free-electron mass, and the radii of the inner and outer rings are equal to $R_1=10$, $R_2=20$, $R_3=30$ and $R_4=40$ *nm* respectively. In Fig. 1, a–c the laser dressed confinement potential of the concentric double QR for various values of the laser field parameter α_0 are presented. Obviously for the fixed barrier thickness the shape of the potential that affects the carrier confinement is significantly changed by the laser field. With the increase of the laser field the effective length of the confining potential along the laser field polarization (x-direction) decreases in the lower part of the confinement potential.

The electron wave functions is depicted in Fig. 2. The results for different values of ILF parameter α_0 are presented. It is observed that the electron cloud for the ground state is no longer ring-shaped as it must be in the absence of the impurity (see [14]), but it is centered at the impurity site. The laser dressing visibly reduces electron cloud localization around the impurity, by shifting the cloud to the outer ring and also squeezes the cloud in this orbital, thus an increase in energy with α_0 is expected to occur for the ground state. The interring movement of the electron cloud is obtained also for the excited states.

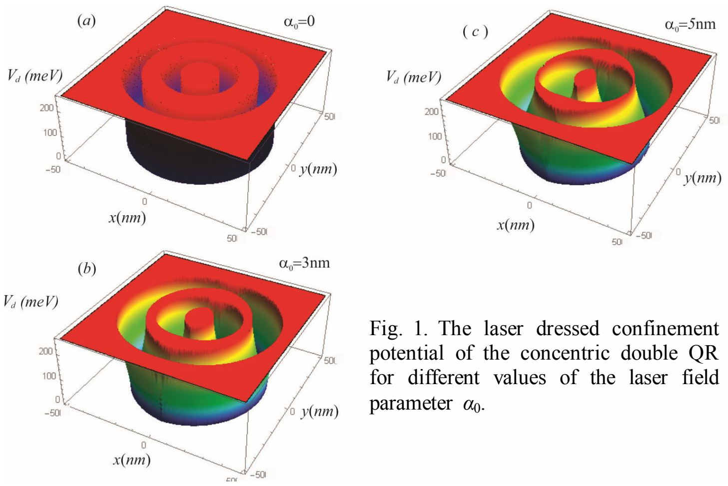

Fig. 1. The laser dressed confinement potential of the concentric double QR for different values of the laser field parameter α_0.

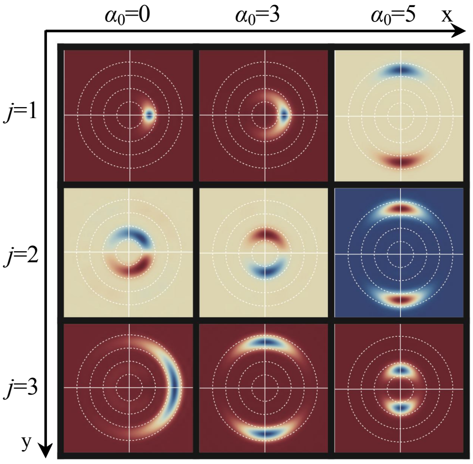

Fig. 2. The wave functions of the first 3 levels for different values of laser field parameter α_0.

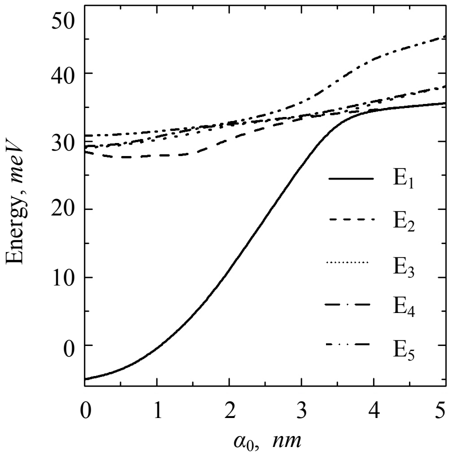

Fig. 3. The first 5 dressed energy levels of the electron as functions of laser field parameter α_0.

Fig. 3 shows the electron energies of the first five impurity states in a concentric double QR as the functions of the laser dressing parameter α_0. The energy of the ground state has relatively low values, due to the good spatial overlapping of the impurity potential and ring-like wave function of the electron in the absence of the impurity. Ground state energy increases very rapidly with the laser parameter going from $\simeq -5$ *meV* (for $\alpha_0 = 0$) up to $\simeq -35.5$ *meV* (for $\alpha_0 = 5$ *nm*), as a result of the laser-induced shifting of the wave function to the outer ring. In Fig. 1 we saw laser field dressed potential to have non-equal sizes of the quantum well widths along the x- and y-axes. This inequality affects the probability density of all the states, but more clearly it is demonstrated in non-monotone variations of the energies of excited states seen in Fig. 3. On the other hand, the strengthening of laser field creates new degeneracy: 1st state with the 2nd, and 3rd with the 4th. To understand the latter, on should refer to the forms of wave functions in Fig. 2 that, for example, clearly shows similar distributions of the 1st and 2nd states.

Conclusion. In the paper is shown that the hydrogenic donor impurity states in 2D $\mathrm{GaAs/Ga_{0.7}Al_{0.3}As}$ concentric double quantum rings can be totally controlled by the external intense laser field. Laser field affected single-electron states show a tendency to be shifted between the rings, thus laser field has in impact on the interring coupling. As a result, energy spectrum shows non-monotone variation tendency with the increment of laser field parameter. In addition, this shifting modifies the energy spectrum in an unexpected way, resulting in a new laser dressed accidental degeneracy.

The author thank prof. A.A. Kirakosyan and H.M. Baghramyan for useful discussions.

This work has been supported by SCS of MES RA, in the frame of the research project №15T-1C331

Received 22.12.2016

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