Physica B 406 (2011) 1441–1444

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Hydrogenic impurities in quantum dots under intense high-frequency laser field

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ARTICLE INFO

Article history:
Received 28 October 2010
Received in revised form
13 January 2011
Accepted 19 January 2011
Available online 26 January 2011

Keywords:
Photoionizaton
Quantum dot
Impurity
Intense laser field

ABSTRACT

The effects of intense high-frequency laser field on photoionization cross-section and binding energy of shallow-donor impurities in GaAs/GaAlAs quantum dots are calculated using variational method with the effective-mass approximation. From these calculations, it has been concluded that the dependences of the impurity binding energy and photoionization cross-section on the intense laser field are very significant.

1. Introduction

The effects of an intense high-frequency laser field on the physical properties of bulk semiconductors have been a topic of considerable interest. The development of intense high-frequency laser field provided an opportunity to explore the properties of matter in strong electromagnetic fields that greatly exceed the Coulomb binding fields in an atom. There have been numerous investigations about the effects of an intense high-frequency laser field on the physical properties of bulk semiconductors over the past 30 years [1–5]. More recently such studies have been extended to semiconductor nanostructures, where intense electric fields are created by an applied ac voltage or a high-intensity THz laser [6–8]. It was reported that the binding energy of an impurity in low-dimensional systems decreases on increasing the laser field amplitude [9,10].

The photoionization cross-section is mainly used in the characterization of impurities in semiconductors. Several studies have been done on the photoionization cross-section of hydrogenic impurity in low-dimensional structures such as quantum wells, wires and quantum dots [11–17]. Due to their advantages over quantum wells and quantum wires, quantum dots have attracted much interest as an optoelectronic structure [18,19]. The electronic structure in quantum dots is found to be very sensitive to the size quantization effect, and the modification of the effective confining potential in the dots can affect dramatically the optical properties of quantum dots [19].

In this work, we investigated the effects of an intense, high-frequency laser field on the photoionization cross-section and the binding energy of shallow-donor impurities in a semiconductor quantum dot.

2. Theory

The photoionization process is an optical transition that takes place from the impurity ground state as the initial state to the conduction sub-bands, which requires sufficient energy in order for the transition to occur. The excitation energy dependence of the photoionization cross-section associated with an impurity, starting from Fermi's golden rule in the well-known dipole approximation, as in the bulk case is [12–15,20–23]

$$\sigma(h\omega)=\left[\left(\frac{\xi_{eff}}{\xi_0}\right)^2\frac{n_r}{\varepsilon(P,T)}\right]\frac{4\pi^2}{3}\alpha_{FS}h\omega\sum_f\left|\langle\psi_i|\vec{r}\,|\psi_f\rangle\right|^2\delta(E_f\text{-}E_i\text{-}h\omega) \quad (1)$$

where n_r is the refractive index of the semiconductor, $\alpha_{FS}=e^2/\hbar c$ the fine structure constant and $\hbar\omega$the photon energy; $\xi_{eff}/\xi_0$is the ratio of the effective electric field $\xi_{eff}$of the incoming photon to the average field ξ_0 in the medium [24]; $\langle\psi_i|\vec{r}\,|\psi_f\rangle$ is the matrix element of an optical transitions $|\psi_i\rangle$ and $|\psi_f\rangle$, denoted as the impurity ground state and final state; E_f and E_i are the energies of the final and initial states, respectively.

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doi:10.1016/j.physb.2011.01.045

The approach used in the present calculation is based on a non-perturbative theory that was developed originally to describe the atomic behavior under intense, high-frequency laser field conditions [9,10]. We assume that the radiation field can be represented by a monochromatic plane wave of angular frequency ω. For linear polarization, the vector potential of the radiation field in laboratory frame is given as $\mathbf{A}(t)=A_0\cos\omega t\,\hat{e}$, where $\hat{e}$ is the unit vector. By applying the time-dependent translation $\vec{r}\rightarrow\vec{r}+\vec{\alpha}(t)$ the semi-classical Schrödinger equation in the momentum gage, describing the interaction dynamics in the laboratory frame of reference, was transformed by Kramers as follows [25]:

$$-\frac{\hbar^2}{2m^*}\nabla^2\varphi(\vec{r},t)+V(\vec{r}+\vec{\alpha}(t))\varphi(\vec{r},t)=i\hbar\frac{\partial\varphi(\vec{r},t)}{\partial t} \tag{2}$$

where $V(\vec{r})$ is the atomic binding potential and

$$\vec{\alpha}(t)=\alpha_0\sin\omega t\,\hat{e} \tag{3}$$

where the laser-dressing parameter $\alpha_0=eA_0/m^*c\omega$ represents the quiver motion of a classical electron in the laser field and $V(\vec{r}+\vec{\alpha}(t))$ is the 'dressed' potential energy. In terms of the average intensity of the laser, I, α_0 can be written as [25]

$$\alpha_0=(I^{1/2}/\omega^2)(e/m^*)(8\pi/c)^{1/2} \tag{4}$$

where e and m^* are the electric charge and effective mass of an electron, respectively, c is the velocity of light, A_0 is the amplitude of the vector potential and $\omega$is the frequency in cgs units.

Following the Floquet approach [9,10], the space-translated version of the Schrödinger equation, Eq. (2) can be cast in the equivalent form of a system of coupled time-independent differential equations for the Floquet components of the wave function φ, containing the (in general complex) quasi-energy E. An iteration scheme was developed to solve this; for the zeroth Floquet component φ_0 the system reduces to the following time-independent Schrödinger equation [8–10]:

$$\left[-\frac{\hbar^2}{2m^*}\nabla^2+V(\vec{r},\vec{\alpha}_0)\right]\varphi_0=E\varphi_0 \tag{5}$$

where $V(\vec{r},\vec{\alpha}_0)$ is the 'dressed' potential, which depends on ω and I only through α_0 [9]. For the Coulomb potential case, $V(\vec{r})=-e^2/(\varepsilon|\vec{r}|)$, the 'dressed' potential has the following approximate form [26]:

$$V_c(\vec{r},\vec{\alpha}_0)\approx-\left(\frac{e^2}{2\varepsilon}\right)\left(\frac{1}{|\vec{r}-\vec{r}_i+\vec{\alpha}_0|}+\frac{1}{|\vec{r}-\vec{r}_i-\vec{\alpha}_0|}\right) \tag{6}$$

where ε is the dielectric constant.

The Hamiltonian of a system consisting of an electron bound to a donor impurity inside a quantum dot in the presence of an intense high-frequency laser field (the laser field polarization is along the z direction) is given by

$$H=\frac{p_x^2}{2m^*}+\frac{p_y^2}{2m^*}+\frac{p_z^2}{2m^*}+V(x,y)+V_b(z,\alpha_0)+V_c(\vec{r},\vec{\alpha}_o) \tag{7}$$

where $V_c(\vec{r},\vec{\alpha}_0)$ is the 'dressed' Coulomb potential. $V(x,y)$ is the two-dimensional confinement potential for x–y and approximately can be written as $V(x,y)=V(x)+V(y)$ [27], where $V(x)$ and $V(y)$ are the confinement potentials for the electron in the x and y directions, respectively:

$$V(x)=\begin{cases}0 & for|x|\le L_x/2\\ V_0 & otherwise\end{cases} \tag{8-a}$$

$$V(y)=\begin{cases}0 & for|y|\le L_y/2\\ V_0 & otherwise\end{cases} \tag{8-b}$$

$V_b(z,\alpha_0)$ is the 'dressed' confinement potential, which is given by the following expression [28]:

$$V_b(z,\alpha_0)=\frac{V_0}{\pi}\left[\Theta(\alpha_0-z-L_z/2)arccos\left(\frac{L_z/2+z}{\alpha_0}\right)+\Theta(\alpha_0+z-L_z/2)arccos\left(\frac{L_z/2-z}{\alpha_0}\right)\right] \tag{9}$$

where V_0 is the conduction band offset at the interface and $\Theta$is the step function.

The specification of the initial ground state and the conduction sub-band state wave functions are required to calculate the photoionization cross-section. Following the variational approach and taking into account the electronic confinement in all the three directions of the dot and the Coulombic interaction between the impurity and the electron we will use for the ground state the trial wave function

$$\psi_i(r)=N\chi(x)\chi(y)\chi(z)\exp\left[-\frac{\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}}{\lambda}\right] \tag{10}$$

where N is a normalization constant, $\chi(x)$, $\chi(y)$ and $\chi(z)$ are the first sub-band wave functions of the electron that are exactly obtained from the one-dimensional Schrödinger equation in the x, y and z directions, respectively and $\lambda$is a variational parameter, which can be determined by minimizing the expectation value $\langle\psi_i|H|\psi_i\rangle$ with respect to that parameter. The ground state impurity binding energy is given by

$$E_B=E_x+E_y+E_z-\min_{\lambda}\langle\psi_i|H|\psi_i\rangle \tag{11}$$

where E_x, E_y and E_z are the lowest donor electron sub-band energies in the x, y and z-directions, respectively.

Due to the electronic confinement in all three directions of the dot without the impurity potential, the eigenstates associated with the Hamiltonian (7) of an electron emitted to the sub-bands n_x, n_y and n_z relative to the x, y and z directions of the dot, respectively, are given by

$$\psi_f(r)=\chi_{n_x}(x)\chi_{n_y}(y)\chi_{n_z}(z) \tag{12}$$

where $\chi_{n_x}(x)$, $\chi_{n_y}(y)$ and $\chi_{n_z}(z)$ are chosen to be solutions of one-dimensional Hamiltonian for electron in the x, y and z-directions of the QD, respectively. To calculate the photoionization cross-section it is necessary to know the conduction sub-bands into which the excited electron is transferred., For an on-center donor impurity and for incident light polarized along the z-direction, the transition that takes place from the impurity ground state to the conduction sub-bands $n_x=1$, $n_y=1$ and $n_z=2$ is first dipole allowed. For an off-center donor impurity and for incident light polarized along the z-direction, the transition that takes place from the impurity ground state to the conduction sub-bands $n_x=1$, $n_y=1$ and $n_z=1$ is first dipole allowed.

In order to obtain an expression for the spectral dependence of the photoionization cross-section as a function of the excitation energy $\hbar\omega$ and the QD dimensions, we have replaced the δ-function in Eq. (1) by narrow Lorentzian with a width equal to 1 meV, [24,29]:

$$\delta(E_f-E_i-\hbar\omega)=\frac{\hbar\Gamma}{\pi[(\hbar\omega-(E_f-E_i))^2+(\hbar\Gamma)^2]} \tag{13}$$

3. Results and discussion

The values of the physical parameters used in our calculations are $m^*=0.067m_0$ (m_0 is the free electron mass), $\xi_{eff}/\xi_0=1$, $\varepsilon_0=13.1$ (the static dielectric constant is assumed to be the same everywhere), $V_0=228$ meV. These parameters are appropriate in