INTENSE FIELD EFFECTS ON HYDROGENIC IMPURITIES IN QUANTUM WELLS

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În lucrare prezentăm efectele unei radiații laser de înaltă frecvență asupra energiei de legătură a unei impurități acceptoare pentru diferite poziții ale acesteia în gropi cuantice din GaAs/$Al_{0,3}Ga_{0,7}As$. Calculele au fost efectuate în aproximația masei efective, utilizând o metodă variațională.

In this paper we discuss the effect of the high-frequency laser field and the impurity position on the binding energy of the shallow acceptors in GaAs/$Al_{0,3}Ga_{0,7}As$ quantum wells. The calculations were performed within the effective-mass approximation and by using a variational method.

Keywords: Laser radiation effect, quantum well, shallow acceptor, binding energy, density of states

1. Introduction

In recent years, low dimensional doped structures have attracted much attention, not only for their potential in uncovering some novel phenomena in nanostructured electronics, but also for their technological applications. In GaAs/$Al_xGa_{1-x}As$ quantum wells (QWs), calculations of the hydrogenic impurity levels have been performed for both donor [1] and acceptor states [2]. In the last decade the studies have been extended to semiconductor nanostructures under intense electric fields, created by high-intensity infrared lasers. The laser-dressed binding energy of an on-center donor in QWs with infinite [3] and finite [4] barrier potential has been studied by Fanyao *et al.* within a nonperturbative and high-frequency approximation. They have also calculated the binding energy of an axial donor in a quantum well wire placed in a high-frequency laser field [4].

We recently reported a study of the density of impurity states of shallow donors in a quantum well under intense laser field [5]. Our results point out that a proper consideration of the density of impurity states may be of relevance in the interpretation of the optical phenomena related to impurities in QWs where the effects of an intense laser field compete with the quantum confinement. In this

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paper we consider the laser field effects on the binding energies of simple neutral acceptor in GaAs/$Al_{0,3}Ga_{0,7}As$ quantum wells.

2. Theory

We consider a nonrelativistic electron subjected to a time-independent potential $V(\vec{r})$ and under the action of a laser radiation field. We assume that the radiation field can be represented by a monochromatic plane wave of frequency ω. For linear polarization, the vector potential associated with the radiation field is given by $\vec{A}(t) = \vec{e} A_0 \cos(\omega t)$, where $\vec{e}$ is the unit vector of the polarization. For the monochromatic plane wave one has

$$\vec{\alpha}(t) = \vec{e}\,\alpha_0 \sin(\omega t) \tag{1}$$

where $\alpha_0 = \dfrac{qA_0}{m^* \omega}$ is the laser-dressing parameter and q is the electrical charge. In these conditions the system can be described by the time-dependent Schrödinger equation [6]:

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

where m^* is the electron effective mass.

In the limit $\omega \to \infty$, at fixed value of the parameter α_0, the laser-dressed eigenstates are the solutions of the time-independent Schrödinger equation:

$$\left[-\frac{\hbar^2}{2m^*}\Delta + V(\vec{r},\vec{\alpha}_0)\right]\varphi_0 = E\varphi_0 \tag{3}$$

where

$$V(\vec{r},\vec{\alpha}_0) = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} V(\vec{r}+\vec{\alpha}(t))\,dt \tag{4}$$

is the "dressed" potential. In the Coulomb potential case $V(\vec{r}) = -\dfrac{e^2}{4\pi\varepsilon r}$, the "dressed" potential has the form [4]: $V_C(\vec{r},\vec{\alpha}_0) = -\dfrac{e^2}{4\pi\varepsilon}\left[\dfrac{1}{|\vec{r}+\vec{\alpha}_0|} + \dfrac{1}{|\vec{r}-\vec{\alpha}_0|}\right]$.

The Hamiltonian of a system consisting of a hole bound to an acceptor ion inside a QW in the presence of an intense high-frequency laser field is given by

$$H = -\frac{\hbar^2}{2m^*}\Delta + V_b(z,\vec{\alpha}_0) + V_C(\vec{r},\vec{\alpha}_0) \tag{5}$$

where $V_b(z,\vec{\alpha}_0)$ is the "dressed" confinement potential [4].

Using the variational method, the impurity wave function is chosen as the product of the ground-state wavefunction in the "dressed" confining potential by a field-modulated hydrogenic-like wavefunction

$$\Psi(\vec{r}) = N\Phi_0(z)\exp\left[-\frac{\lambda}{2}\left(|\vec{r}_1| + |\vec{r}_2|\right)\right] \tag{6}$$

Here N is the normalization constant, $|\vec{r}_{1,2}| = \sqrt{\rho^2 + (z - z_i \pm \alpha_0)^2}$ with z_i the position of the impurity in the well and λ is the variational parameter.

The impurity binding energy is given by $E_b = E_0 - \min\limits_{\lambda}\langle\Psi(\vec{r})|H|\Psi(\vec{r})\rangle$ where E_0 is the ground state energy of the dressed well.

To calculate the density of the impurity states we assume that the quantum well is not too thin so that one may treat the impurity position as a continuous random variable. In this case, the density of impurity states per unit energy is given by $g(E_B) = \frac{1}{L}\sum\limits_{\{z_i\}}\left|\frac{\partial E_B}{\partial z_i}\right|^{-1}$ where $\{z_i\}$ are all impurity positions with the same binding energy [1].

3. Results and discussion

For numerical calculations, we take $m^* = 0.36\, m_0$ (m_0 is the free electron mass), $\varepsilon_r = 12.5$ and the hole barrier height $V_0 = 149.64\,\text{meV}$.

In Fig. 1 we plot the variation of the binding energy of a simple neutral acceptor in an $L = 2b = 100$ Å GaAs/$Al_{0,3}Ga_{0,7}As$ QW as a function of the laser-field parameter α_0, and for different impurity positions. The dashed line indicates the impurity band center of gravity [1].

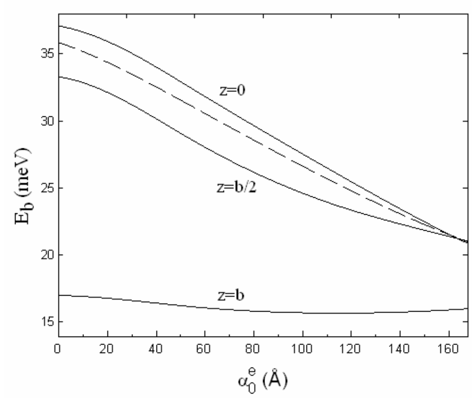

Fig.1

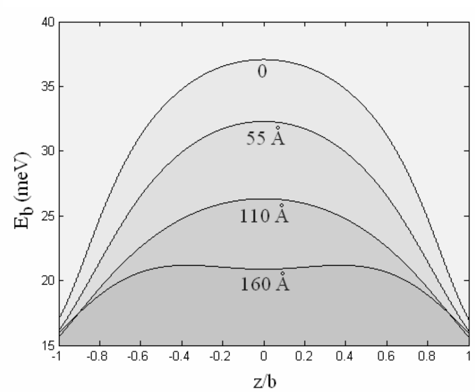

Fig.2

Fig.2 presents the binding energy dependence on the impurity position z_i within the quantum well for following values of the laser parameter: α_0 = 0, 55, 110, and 160 Å. We observe that the effect of the laser field on the binding energy becomes less pronounced as the impurity ion approaches the boundary of the quantum well due to the increase of *p*-like character of the wave function.

In Fig. 3 we plot the dependence of the acceptor peak energy (transition from the first conduction subband to 1s-like state of an acceptor) on the laser-field parameter.

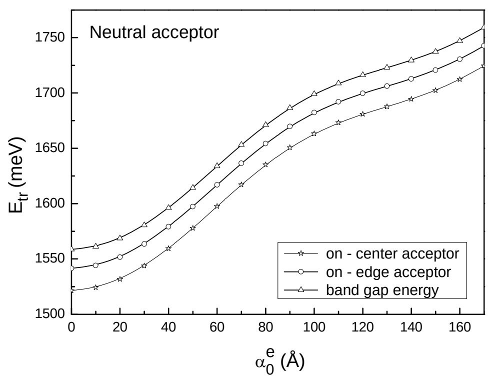

Fig.3

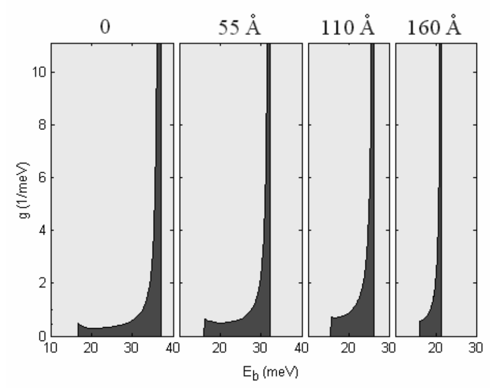

Fig.4

The density of impurity states for a hydrogenic acceptor in an $L = 100$ Å GaAs/$Al_{0,3}Ga_{0,7}As$ QW is plotted in Fig. 4 for some values of the laser parameter: α_0 = 0, 55, 110, and 160 Å. One observes that at small α_0 values, $g(E_b)$ presents two peaks related to on-center and on-edge impurities, respectively. In an intense laser field, the impurity - related absorption spectrum presents one red-shifted peak associated with on-center impurities.

As a summary, we have studied the effect of the high-frequency laser field and the impurity position on the binding energy of the shallow acceptors in GaAs/AlGaAs QWs. The calculations were performed within the effective-mass approximation by using a variational method. The above predictions could be observed for instance in the optical spectra of acceptors in QW materials.

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