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Ground state normalized binding energy of impurity in asymmetric quantum wells under hydrostatic pressure

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ABSTRACT

We have studied and computed variationally the impurity energy, impurity energy turning points, and ground state normalized binding energy as functions of the impurity position for shallow impurity in asymmetric quantum wells under hydrostatic pressure. We found that the normalized binding energy significantly depends on the asymmetry of the well, besides depending on the impurity position and hydrostatic pressure. Also, the dependence of the positive normalized binding energy on the pressure can be used to find out the degree of the asymmetry of the well or the impurity position in the well.

1. Introduction

The asymmetric quantum well structures without the impurity [1–9] and with the impurity [10–14] have been a subject of extensive investigations in research. When the inverse symmetry of the quantum wells is broken, many new phenomena have been found which can provide potential device applications in future. Zhang et al. [13] have studied the dependence of the ground state binding energy on the impurity position in an asymmetric well in absence of external influences. Akbas et al. [14] have investigated the density of the hydrogenic impurity states for different asymmetric well. Moreover, past studies show that impurities and hydrostatic pressure can obviously effects optical and electronic properties of optoelectronic devices [15]. Hydrostatic pressure effects play an important role in the energy levels in quantum wells without altering the crystal symmetry of these structures [16].

Recently, there has been interest in the determination of the normalized binding energy of impurities within low-dimensional structures [17–23]. Dane et al. [17] first calculated the hydrogenic impurity ground state normalized binding energy in a *GaAs*/*AlAs* spherical quantum dot. Further, Sadeghi [18] have reported the effect of the electric field on the excited states normalized binding energy of an on-center and off-center hydrogenic impurity in a spherical quantum dot. Niculescu et al. [21] have investigated the simultaneous effects of the electric field and hydrostatic pressure on the ground state normalized binding energy of an on-center hydrogenic impurity in an asymmetric quantum well.

In this paper, we mainly study the dependence of the ground state normalized binding energy on the impurity position in $Al_{x_l}Ga_{1-x_l}/GaAs/Al_{x_r}Ga_{1-x_r}$ asymmetric quantum well under hydrostatic pressure. We have concerned with ground state energies and follow a variational calculation with the effective mass approximation.

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2. Theory

In the absence of any impurity, within the effective-mass approximation, the pressure dependence of the Hamiltonian is given by

$$H_0 = -\frac{\hbar^2}{2m^*(P)}\nabla_z^2 + V(z,P) \tag{1}$$

where $m^*(P)$ is the pressure dependent effective mass of the electron at the conduction band minimum [1]. The confining potential for the asymmetric quantum well, is given by

$$V(z,P) = \begin{cases} V_l\ (x_L,P) & for \quad z<0 \\ 0 & for \quad 0 \le z \le L(P) \\ V_r\ (x_r,P) & for \quad L(P)<z \end{cases} \tag{2}$$

where $L(P)$ is width of the quantum well. The confining potential is generated by three layers with different Al contents [5,14],

$$x(z) = \begin{cases} x_l & for \quad z<0 \\ 0 & for \quad 0 \le z \le L(P) \\ x_r & for \quad L(P)<z \end{cases} \tag{3}$$

the parameters x_l and x_r tune the confining potential profile. The eigen function for the ground state within the asymmetric quantum well [14,24] is

$$\psi_0(z) = \begin{cases} B_l e^{\beta_l z} & for \quad 0<L(P) \\ A_c \sin(\beta_c z + \Phi) & for \quad 0 \le z \le L(P) \\ B_r e^{-\beta_r z} & for \quad z \ge L(P) \end{cases} \tag{4}$$

with

$$\beta_{l,r} = \sqrt{2m^*(P)\left(V_{L,r}(P) - E_0(L(P),P)\right)/\hbar^2} \text{ and } \beta_c = \sqrt{2m^*(P)E_0(L(P),P)/\hbar^2} \tag{5}$$

The $E_0(L(P),P)$ is the energy of ground state given by the transcendental equation

$$\tan(\Phi + \beta_c L(P)) = -\frac{\beta_c}{\beta_r} \tag{6}$$

with

$$\sin(\Phi) = \sqrt{\frac{E_0(L(P),P)}{V_l(x_l,P)}} \tag{7}$$

The Hamiltonian for a shallow impurity located at $\vec{r_i} = (0,\ 0,\ z_i)$ in the asymmetric quantum well, in cylindrical coordinates, is

$$H = -\frac{\hbar^2}{2m^*(P)}\left[\frac{\partial^2}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2}{\partial\phi^2} + \frac{\partial^2}{\partial z^2}\right] - \frac{e^2}{\varepsilon(P)\sqrt{\rho^2 + (z-z_i)^2}} + V(z,P) \tag{8}$$

where $\varepsilon(P)$ is the hydrostatic pressure dependent GaAs static dielectric constant. The impurity energy in the presence of pressure is calculated by a variational method. Following trial wave function is adopted for ground-state trial wave function of the form

$$\psi(\rho,z) = N\psi_0(z)\exp\left(-\lambda\sqrt{\rho^2 + (z-z_i)^2}\right) \tag{9}$$

where N and λ are the normalization constant and the variational parameter to be determined. The trial impurity ground-state energy in the presence of pressure is obtained by

$$E_i(L(P),z_i,V(z,P)) = \min_\lambda \frac{\langle\psi(\rho,z)|H|\psi(\rho,z)\rangle}{\langle\psi(\rho,z)|\psi(\rho,z)\rangle} \tag{10}$$

The binding energy, $E_b(L(P), z_i, V(z,P))$, is given as the ground-state energy of the system without the impurity E_0, minus the impurity ground state energy,$E_i(L(P), z_i, V(z,P))$, i.e.,