AZƏRBAYCAN MİLLİ ELMLƏR AKADEMİYASININ XƏBƏRLƏRİ
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RASHBA SPLITTING IN KANE TYPE QUANTUM DISK

F. M.HASHIMZADE, A.M.BABAYEV

Institute of Physics, Azerbaijan Natiomal Academy of Sciences
AZ 1143, Baku, G. Javid ave., 33

Electrons in Kane type semiconductors quantum disk in presence of Rashba spin-orbital interaction and external magnetic field parallel to axis of quantum disk are considered theoretically. A three-level model of the kp theory is used to describe electrons in weak Rashba spin-orbit coupling regimes and external magnetic field, taking into account the main features of the band structure in InSb-type semiconductors: a small energy gap, a strong spin-orbit interaction. We calculated the radii, thickness, coupling strength, and magnetic field dependence of Rashba splitting for electrons. It has been seen that the Rashba splitting of the electrons are decreased with the increasing of radius.

INTRODUCTION

The study of semiconductor quantum dots and nanocrystals in recent years has been of great interest from experimental and theoretical points [1]. The interest originates from an ultimate limit of size quantization in solids in those objects. For an ideal quantum dot the electron spectrum consists of a set of discrete levels. This makes the semiconductor quantum dots very attractive for possible applications in micro and nano-opto-electronics [2].

The electron spin plays an important role in the quantum dot design. Spin-dependent effects that are naturally present in quantum dots are of great importance for the emerging field of spintronics. Spintronics is a new branch of electronics where electron spin is the active element for information storage and transport [3]. An example is Rashba spin-orbit coupling [4], which has recently attracted much attention as it is the basis of a spin-controlled field-effect transistor [5]. In [6,7] found analytic solution to the problem of the Rashba spin-orbit coupling in semiconductor quantum dots and calculated the energy spectrum, wave functions, and spin-flip relaxation times using perturbation theory. The above descriptions treat the case of a simple parabolic energy band.

However, the experimental advantages of using narrow-gap semiconductors for the reduced dimensionality systems make it necessary to account for the real band structure of these materials. To consider the nonparabolicity of the electron dispersion in narrow-and medium gap semiconductors take into account the coupling of the conduction and valence bands. This is purpose of our work. We now calculate the total spin-splitting energy in Kane type quantum disk with hard walls both without and with an applied constant axial magnetic field. It has a contribution due the Zeeman effect and another to the Rashba effect. We consider a three-level model-Kane model of the band structure at k=0 (the Γ point). The Γ_6 level (s type symmetry) is separated by the energy gap E_g from the Γ_8 level (p type), which is in turn split off by the spin-orbit interaction Δ from the Γ_7 level (p type). We also omit the free-electron term in the diagonal part and the Paul spin term, as they give only small contributions to the effective mass and the spin g value of electrons in InSb. The Rashba spin-orbit interaction for conduction band and valence and given by respectively:

$$H_R = R_c(\vec{n}[\vec{k}\vec{J}]) \qquad H_v = R_v(\vec{n}[\vec{k}\cdot\vec{J}]) \qquad H = R_\Delta(\vec{n}[\vec{k}\vec{J}]), \tag{1}$$

where k is the momentum operator, R_c, R_v, R_Δ is the coupling strength for conduction band, valence band, spin-orbit-splitting band respectively, $J=\{J_x, J_y, J_z\}$ are the angular momentum matrices for j=1/2 and j=3/2 [8], n is the unit vector in the growth direction. The Kane Hamiltonian is represented in the Bloch basis [9].

$$1.\, iS\nu_1 \quad 2.\ \boldsymbol{iS}\nu_2 \quad 3. -\frac{1}{\sqrt{2}}(x+iy)\nu_1 \quad 4.\ -\frac{1}{\sqrt{6}}((x+iy)\nu_2 - 2z\nu_1) \tag{2}$$

$$5.\ \frac{1}{\sqrt{6}}((x-iy)\nu_1 + 2z\nu_2) \quad 6.\ \frac{1}{\sqrt{2}}(x-iy)\nu_2 \quad 7.\ -\frac{1}{\sqrt{3}}((x+iy)\cdot\nu_2 + z\nu_1) \tag{3}$$

$$8.\ \frac{1}{\sqrt{3}}((\boldsymbol{x}-\boldsymbol{iy})\cdot\nu_1 - \boldsymbol{z}\nu_2) \tag{4}$$

where $\nu_1 = \begin{pmatrix}1\\0\end{pmatrix}, \nu_2 = \begin{pmatrix}0\\1\end{pmatrix}$ spin-up and spin-down functions, respectively as

$$H_K = \begin{bmatrix} -E & & -\frac{Pk_-}{\sqrt{2}} & \sqrt{\frac{2}{3}}Pk_z & \frac{Pk_+}{\sqrt{6}} & 0 & \frac{Pk_z}{\sqrt{3}} & \frac{Pk_+}{\sqrt{3}} \\ & -E & 0 & -\frac{Pk_-}{\sqrt{6}} & \sqrt{\frac{2}{3}}Pk_z & \frac{Pk_+}{\sqrt{2}} & \frac{Pk_-}{\sqrt{3}} & \frac{Pk_z}{\sqrt{3}} \\ \frac{Pk_-}{\sqrt{3}} & & -E_g-E & 0 & 0 & 0 & 0 & 0 \\ \sqrt{\frac{2}{3}}Pk_z & -\frac{Pk_+}{\sqrt{6}} & 0 & -E_g-E & 0 & 0 & 0 & 0 \\ \frac{Pk_-}{\sqrt{6}} & \sqrt{\frac{2}{3}}Pk_z & 0 & 0 & -E_g-E & 0 & 0 & 0 \\ 0 & \frac{Pk_-}{\sqrt{2}} & 0 & 0 & 0 & -E_g-E & & 0 \\ \frac{Pk_-}{\sqrt{3}} & \frac{Pk_-}{\sqrt{3}} & 0 & 0 & 0 & 0 & -E_g-E-\Delta & 0 \\ & \frac{Pk_-}{\sqrt{3}} & 0 & 0 & 0 & 0 & 0 & -E_g-E-\Delta \end{bmatrix} \tag{5}$$

Here P is the Kane parameter, E_g - the band gap energy, Δ- the value of spin-orbital splitting and $k_\pm = k_x \pm ik_y, \vec{k} = -i\vec{\nabla}$. The zero of energy is chosen at bottom of the conduction band.

The Rashba Hamiltonian have the following nonzero elements:

$$\boldsymbol{H}_{12} = -\boldsymbol{i}\cdot\frac{1}{2}\cdot\boldsymbol{R}_c\cdot\boldsymbol{k}_-,\ H_{34} = -i\cdot\frac{\sqrt{3}}{2}\cdot R_v\cdot k_-,\ H_{45} = -i\cdot R_v\cdot k_-, \tag{6}$$

$$\boldsymbol{H}_{56} = -\boldsymbol{i}\cdot\frac{\sqrt{3}}{2}\cdot\boldsymbol{R}_v\cdot\boldsymbol{k}_-,\ H_{78} = -i\cdot\frac{1}{2}\cdot R_\Delta\cdot k_-,\ H_{ij} = H_{ji}^{*}. \tag{7}$$

For Kane model putting R_c=2R, R_v=R, R_d=2R. The effective mass m_n at the band edge defined as [10]:

$$\frac{\hbar^2}{2m_n} = \frac{P^2}{3E_g}\cdot\frac{2\Lambda + 3E_g}{\Delta + E_g}. \tag{8}$$

We are diagonalize the Kane Hamiltonian with the help of unitary transformation $H^d = U^{-1}H_0U$, where U is the matrix of the transformation. For electron states

$$H_0 = \begin{bmatrix} -E - \frac{P^2}{3}(\frac{2}{E+E_g} + \frac{1}{E+E_g+\Delta})k^2 & 0 \\ 0 & -E - \frac{P^2}{3}(\frac{2}{E+E_g} + \frac{1}{E+E_g+\Delta})k^2 \end{bmatrix}. \tag{9}$$

After unitary transformation the Rashba Hamiltonian with providing the terms linear with k will be as follows for the conduction band.

$$H_R = \begin{bmatrix} 0 & -iR\cdot k_- \\ iR\cdot k_+ & 0 \end{bmatrix}. \qquad (10)$$

The spin splitting for electron states it increases linearly with in plane wave vector k, whereas the spin-splitting of heavy hole states can be of third order in k. These results are in agreement with [11].
Following the perturbation approach we present the Hamiltonian H as:

$$H = H_0 + H_R\,. \qquad (11)$$

Where the Hamiltonian H_0 describes the electron states in zero Rashba spin-orbital interaction, and the Hamiltonian describes the effect of a weak Rashba spin-orbital interaction H_R.

In cylindrical coordinates the eigen function for unperturbed Hamiltonian H_0 is

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} \exp i[(j-1/2)\varphi + k_z z]\cdot J_{j-1/2}(k\rho) \\ \exp i[(j+1/2)\varphi + k_z z]\cdot J_{j+1/2}(k\rho \end{bmatrix}, \qquad (12)$$

where φ is azimuthal angle, ρ is the distance from disk axis, $J_j(\rho)$ the Bessel function of the l-th order. We expand eigenfunction for perturbed Hamiltonian H in the basis of the two lowest spin-resolved eigenstates of the Hamiltonian H_0. Accordingly,

$$\Psi = d_1\cdot\nu_1\cdot C_1 + d_2\cdot\nu_2 C_2\,. \qquad (13)$$

Substituting this result in Eq (11), and using to the standard recurrence relations

$$\left(\frac{d}{dx} + \frac{j\pm 1/2}{x}\right) J_{j\pm 1/2}(kx) = kJ_{j\mp 1/2}(kx)\,, \qquad (14)$$

we get the coefficients $d_{1,2}$ satisfy the eigenvalue equation:

$$\begin{bmatrix} \varepsilon - E & -iRk_- \\ iRk_+ & \varepsilon - E \end{bmatrix}\begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = 0\,, \qquad (15)$$

where ε is the solution of equations:

$$\varepsilon(\varepsilon + E_g)(\varepsilon + \Delta + E_g) - \frac{1}{3}(3\varepsilon + 2\Delta + 3E_g)P^2(k^2 + q^2) = 0\,, \qquad (16)$$

where k, q are wave vector perpendicular and parallel to the quantum disk axis. Equating the determinant of matrix (15) to zero, one obtains for the spectrum of electrons

$$E = \varepsilon \pm iRk\,. \qquad (17)$$

Using equations (16) and (17) found the equation for value of k

$$k^2 \pm kR\frac{3}{(2\Delta + 3E + 3E_g)^2}\left(-\frac{3E(E+E_g)(E+E+\Delta)}{(2\Delta + 3E + 3E_g)} + E(E+E_g) + (2E+E_g)(E+E+\Delta)\right) + \\ + q^2 - \frac{3E(E+E_g)(E+E+\Delta)}{(2\Delta + 3E + 3E_g)P^2} = 0 \qquad (18)$$

The boundary conditions requiring the equality of radial function to zero on quantum disk boundary have the following form:

$$d_1 J_{j-1/2}(k_1 a) + d_2 J_{j-1/2}(k_2 a) = 0 \qquad (19)$$

$$d_1 J_{j+1/2}(k_1 a) + d_2 J_{j+1/2}(k_2 a) = 0\,, \qquad (20)$$

where $k_{1,2}$ are the solutions of the quadratic equation (18).

The spectrum of the electrons in quantum disk is defined from the equality to zero of a determinant of the system (19)-(20):

$$J_{j-1/2}(k_1 a) J_{j+1/2}(k_2 a) - J_{j-1/2}(k_2 a) J_{j+1/2}(k_1 a) = 0 . \qquad (21)$$

The energy is complicated of the disk parameters and the electron angular momentum. The energy system consist of discrete levels enumerated by a set of numbers {n,j}, where n donotes to the nth solution of (21) with fixed j.We have solved this dispersion relations for a JnSb disk for several radii ρ , several thickness d, and several R using the band structure parameters:m_0=0.014m_0, E_g=0.24eV, R=4.10^{-21}eV.cm [12,13].The evolution of the first few energy levels with the parameter $\gamma = R/P$ is shown in Fig.1.The energy scale is in init. of Eg, Eg is band gap energy and the curves are labelled by quantum number (n, j).

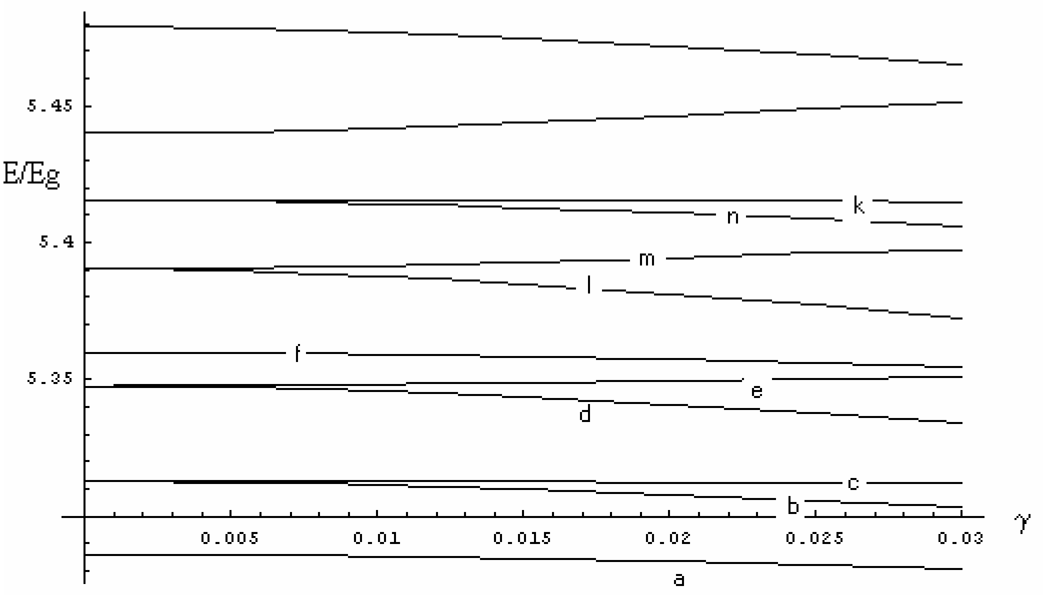

Fig.1

Rashba splittings:

energy as a function of $\gamma = R/P$ for the states (1/2,0)(a), (3/2,0)(b), (1/2,1)(c), (5/2,0)(d), (3/2,1)(e), (1/2,2)(f), (7/2,0)(l), (5/2,1)(m), (3/2,2)(n), (1/2,3)(k)

In Fig.2.show Rashba splitting (Energy differences E(1/2,1)-E(3/2,0)) as a function of ρ for thickness of quantum disk d=20A. It has been seen that the Rashba splitting are decreased with the increasing of radius.

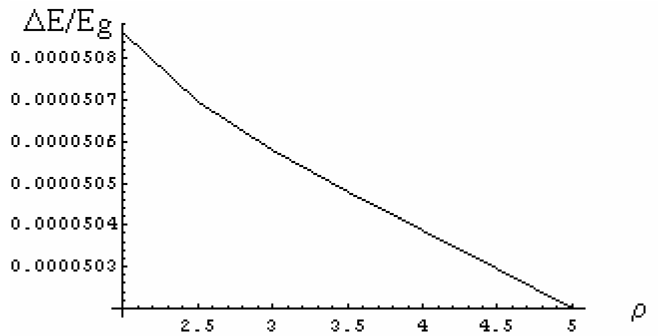

Fig.2.

Energy differences (E(1/2,1)-E(3/2,0))/E_g as a function of ρ for thickness of quantum disk d=20A.

The thickness dependence of Rashba splitting calculated for JnSb quantum disk is shown in Fig.3.for ρ =200A. It has been seen that the Rashba splitting are decreased with the increasing of thickness.

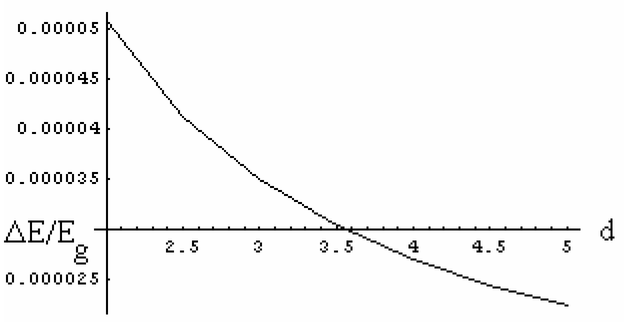

Fig.3.

Energy differences (E(1/2,1)-E(3/2,0))/E_g as a function of d for radii of quantum disk ρ=200A.

APPLIED MAGNETIC FIELD

For a uniform magnetic field, H directed along the z axis, the vector potential may be chosen in the form

$$\vec{A} = \left(-\frac{Hy}{2}, \frac{Hx}{2}, 0 \right) \tag{22}$$

$k_{\pm}$ have the forms

$$k_{\pm} \to k_{\pm} \pm i\frac{1}{2}\lambda_H r_{\pm}, \tag{23}$$

where
$$r_{\pm} = x \pm iy, \quad \lambda_H = \frac{eH}{\hbar c} \tag{24}$$

We want to transform Hamiltonian (5) into an effective equation for electron states that depends only on the conduction band spinor components of the eight-component envelope function. By eliminating the valence band components from the (5) for we obtain:

$$\left(-E + \frac{P^2}{3}\left(\frac{2}{E+E_g} + \frac{1}{E+E_g+\Delta}\right)\left(-\nabla^2 + \lambda_H L_z + \frac{1}{4}\lambda_H^2\rho^2\right) \pm \frac{P^2\lambda_H}{3}\left(\frac{1}{E+E_g} - \frac{1}{E+E_g+\Delta}\right) \right) C_{1,2} = 0, \tag{25}$$

where L_z z component of angular momentum operator L and $\rho^2=x^2+y^2$. The Rashba spin-orbit Hamiltonian for conduction band

$$H_R = R(\vec{n}[\vec{\sigma}\vec{k}]), \tag{26}$$

where σ are Pauli spin-matrices.

Taking into account the Rashba spin-orbit terms Eq.(25) can be written in the matrix form:

$$\begin{pmatrix} H_{11} - E & -iRk_- \\ iRk_+ & H_{22} - E \end{pmatrix} \cdot \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = 0, \tag{27}$$

where

$$H_{11} = \frac{P^2}{3}\left(\frac{2}{E+E_g} + \frac{1}{E+E_g+\Delta}\right)\left(-\nabla^2 + \lambda_H L_z + \frac{1}{4}\lambda_H^2\rho^2\right) - \frac{P^2\lambda_H}{3}\left(\frac{1}{E+E_g} - \frac{1}{E+E_g+\Delta}\right), \tag{28}$$

$$H_{22}=\frac{P^2}{3}\left(\frac{2}{E+E_g}+\frac{1}{E+E_g+\Delta}\right)\left(-\nabla^2+\lambda_H L_z+\frac{1}{4}\lambda_H^2\rho^2\right)+\frac{P^2\lambda_H}{3}\left(\frac{1}{E+E_g}-\frac{1}{E+E_g+\Delta}\right). \quad (29)$$

We consider a disk with the radius ρ and the thickness d in the cylindrical coordinates (ρ,φ,z).In cylindrical coordinates $k_\pm$ have the form:

$$k_\pm = -i\exp(\pm i\varphi)\cdot\left(\frac{\partial}{\partial\rho}\pm\frac{i}{\rho}\frac{\partial}{\partial\varphi}\mp\frac{\rho}{2\alpha^2}\right), \quad (30)$$

where α is the magnetic length.

The origin of the system lies at the centre of the disk and z-axis being chosen along the rotation axis. Since the system is cylindrically symmetric, the wave function can be represented as:

$$\begin{pmatrix} C_1 \\ C_2 \end{pmatrix}=\begin{pmatrix} \exp(im\varphi+ik_z z)\exp\left(-\frac{x}{2}\right)x^{\frac{|m|}{2}}Y(x) \\ \exp(im\varphi+ik_z z)\exp\left(-\frac{x}{2}\right)x^{\frac{|m+1|}{2}}Z(x) \end{pmatrix}. \quad (31)$$

Substituting these functions into Eq.(27), we obtain second-order differential equations for the radial functions:

$$\begin{aligned} &x\frac{d^2Y(x)}{dx^2}+(-x+1+|m|)\frac{dY(x)}{dx}-\frac{1}{2}\left(1+|m|+m-h\alpha^2-\alpha^2k_t^{\,2}\right)Y(x)+ \\ &+\frac{\alpha\beta}{\sqrt{2}}x^{\frac{1+|m+1|-|m|}{2}}\left(\frac{dZ(x)}{dx}+\frac{1}{2}\frac{1}{x}\left(1+|m+1|+m\right)Z(x)\right)=0 \end{aligned}, \quad (32)$$

$$\begin{aligned} &x\frac{d^2Z(x)}{dx^2}+(-x+1+|m+1|)\frac{dZ(x)}{dx}-\frac{1}{2}\left(2+|m+1|+m+h\alpha^2-\alpha^2k_t^{\,2}\right)Z(x)- \\ &-\frac{\alpha\beta}{\sqrt{2}}x^{\frac{1+|m|-|m+1|}{2}}\left(\frac{dY(x)}{dx}+\frac{1}{2}\frac{1}{x}\left(|m|-m-2x\right)Y(x)\right)=0 \end{aligned}. \quad (33)$$

In Eq.(33) the following notations are used:

$$h=\frac{\lambda_H\left(\frac{1}{E+E_g}-\frac{1}{E+E_g+\Delta}\right)}{\left(\frac{2}{E+E_g}+\frac{1}{E+E_g+\Delta}\right)}, \quad (34)$$

$$k_t^{\,2}=\frac{3E}{P^2\left(\frac{2}{E+E_g}+\frac{1}{E+E_g+\Delta}\right)}-q^2, \quad (35)$$

$$\alpha=\sqrt{\frac{\hbar c}{eH}},\ \beta=\frac{3R}{P^2\left(\frac{2}{E+E_g}+\frac{1}{E+E_g+\Delta}\right)},\ x=\frac{\rho^2}{2\alpha^2}. \quad (36)$$

We have introduced parameters a_1 and a_2 which is related to the equations following form:

$$x\frac{d^2Y(x)}{dx^2}+(-x+1+|m|)\frac{dY(x)}{dx}-a_1Y(x)=0\,, \quad (37)$$

$$\boldsymbol{x}\frac{\boldsymbol{d}^2\boldsymbol{Z(x)}}{\boldsymbol{dx}^2}+\boldsymbol{(}-\boldsymbol{x}+1+|\boldsymbol{m}+1|\boldsymbol{)}\frac{\boldsymbol{dZ(x)}}{\boldsymbol{dx}}-\boldsymbol{a}_2\boldsymbol{Z(x)}=0\,. \quad (38)$$

Equations are the canonical form of Kummer's equations for the confluent hypergeometric function [14]. Taking into account Eqs.(37)-(38), Eqs.(32)-(33) can be written as:

$$\begin{aligned}&(a_1-\frac{1}{2}\left(1+|m|+m-h\alpha^2-\alpha^2k_t^2\right))Y(x)+\\&+\frac{\alpha\beta}{\sqrt{2}}x^{\frac{1+|m+1|-|m|}{2}}\left(\frac{dZ(x)}{dx}+\frac{1}{2}\frac{1}{x}\left(1+|m+1|+m\right)Z(x)\right)=0\end{aligned}\,, \quad (39)$$

$$\begin{aligned}&(a_2-\frac{1}{2}\left(2+|m+1|+m+h\alpha^2-\alpha^2k_t^2\right))Z(x)-\\&-\frac{\alpha\beta}{\sqrt{2}}x^{\frac{1+|m|-|m+1|}{2}}\left(\frac{dY(x)}{dx}+\frac{1}{2}\frac{1}{x}\left(|m|-m-2x\right)Y(x)\right)=0\end{aligned}\,. \quad (40)$$

The solutions of (39), (40) that is bounded is $Y(x)=d_1\ M(a_1,b_1,x)$ and $Z(x)=d_2\ M(a_2,b_2,x)$
Where

$$a_1=\frac{m+|m|}{2}-\varepsilon_0\,,b_1=|m|+1\,, \quad (41)$$

$$\boldsymbol{a}_{21}=\frac{\boldsymbol{m}+1+|\boldsymbol{m}+1|}{2}-1-\varepsilon_0\boldsymbol{,b}_{21}=|\boldsymbol{m}+1|+1\,, \quad (42)$$

$$\varepsilon_0=\frac{1}{2}\cdot\left(2\cdot\gamma^2+2\cdot\varepsilon-1\pm\sqrt{1-4\cdot\boldsymbol{s}+4\cdot\boldsymbol{s}^2+\gamma^2+2\cdot(2\cdot\varepsilon+1)}\right), \quad (43)$$

$$\alpha^2\cdot\boldsymbol{k_t}^2=2\cdot\varepsilon+1\boldsymbol{;}\alpha^2\cdot\beta^2=2\cdot\gamma^2\boldsymbol{;}\,\boldsymbol{h}\cdot\alpha^2=-2\cdot\boldsymbol{s}\,. \quad (44)$$

The wave function can be written:

$$R^{+}(x)=c_1\cdot d_{1+}\cdot M(\frac{m+|m|}{2}-1-\varepsilon_{0+},b_1,x)+c_2\cdot d_{2+}\cdot M(\frac{m+1+|m+1|}{2}-1-\varepsilon_{0+},b_2,x), \quad (45)$$

$$R^{-}(x)=c_1\cdot d_{1-}\cdot M(\frac{m+|m|}{2}-1-\varepsilon_{0-},b_1,x)+c_2\cdot d_{2-}\cdot M(\frac{m+1+|m+1|}{2}-1-\varepsilon_{0-},b_2,x)\cdot \quad (46)$$

In a nanocrystal with an infinite potential barrier the wave function must vanish at the the quantum disk surface gives the dispersion equation for the electron quantum size levels:

$$\begin{aligned}&\frac{d_{1+}}{d_{1-}}\cdot\frac{d_{2-}}{d_{2+}}\cdot M(\frac{m+|m|}{2}-\varepsilon_{0+},b_1,x)\cdot M(\frac{m+1+|m+1|}{2}-1-\varepsilon_{0-},b_2,x)-\\&M(\frac{m+|m|}{2}-1-\varepsilon_{0-},b_2,x)\cdot M(\frac{m+1+|m+1|}{2}-1-\varepsilon_{0+},b_2,x)=0\end{aligned}\,. \quad (47)$$

This equation provides all the information about the energy spectrum of electrons. The energy is complicated function of the disk parameters ρ, d and the electron angular momentum m. The energy system consist of discrete levels enumerated by a set of numbers {n,m}, where n donotes to the n-th solution of (47) with fixed m. Equation (47) can be useful for analysing the influence of nonparabolicity on the energy spectrum of electrons in a quantum disk.

CONCLUSION

Analytic solutions of the Kane equations have been presented for a quantum disk in the presence of Rashba spin-orbit interaction and external magnetic field. The nonparabolicity of the spectrum of light holes, electrons and spin-orbit splitting valence band were taken into account. The spin splitting for electron states it increases linearly with in plane wave vector $k_{\square}$, whereas the spin-splitting of heavy hole states can be of third order in $k_{\square}$.

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KEYN TİPLİ NANODİSKDƏ RAŞBA PARÇALANMASI

F.M.HƏŞİMZADƏ, A.M.BABAYEV

Keyn spektrinə malik yarımkeçirici nanodiskdə elektronların enerji spektrləri Raşba spin-orbital qarşılıqlı təsiri nəzərə alınmaqla hesablanmışdır. Raşba parçalanmasının nanodiskin radiusundan və qalınlığından asılılığı öyrənilmişdir. Göstərilmişdir ki, nanodiskin radiusu və qalınlığı artdiqca parçalanmanın qiyməti azalır.

СПИН-ОРБИТАЛЬНОЕ РАСЩЕПЛЕНИЕ РАШБЫ В КЕЙНОВСКОМ КВАНТОВОМ ДИСКЕ

Ф.М.ГАШИМЗАДЕ, А.М.БАБАЕВ

Найдены энергетический спектр носителей заряда в квантовом диске с учетом спин-орбитального взаимодействия Рашбы. Найдены зависимости расщепления Рашбы от радиуса и толщины квантового диска. Показано, что при возрастании радиуса и толщины диска расщепление уменьшается.

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