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Spin Polarization Efficiency in a Diluted Magnetic Nano-Semiconductor Quantum Well System

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ABSTRACT

Diluted magnetic semiconductors (DMS) in which a fraction of non-magnetic cation is replaced by any transition metal ions. They are considered to have wide potential applications for magneto-optic devices. In the present work, the magnetic field is applied externally in a diluted magnetic semiconductor quantum well to investigate spin transmission properties. The material taken for the study is ZnMnSe/ZnSe quantum well. Rashba spin orbit interaction on the resonant spin polarized transport in this heterostructure quantum well is studied. The plane wave function of the electron is applied to obtain the energy eigen values. The mean field approximation is employed to investigate the interaction of the host electron and the localized magnetic impurities. The large polarization occurs in DMS due to the exchange interaction between the local magnetic impurity and the electrons and this effect lifts the degeneracy of spin-up and spin down electron states. The obtained results, on spin dependent tunneling, may be used in the spin based devices especially in the spin field effect transistors.

1. Introduction

Spin states of a charged particle in reduced dimensional semiconductor systems have given considerable attention for the quantum information processing in quantum computers. Spin dependent properties especially spin degree of freedom can be utilized as qubit. The manipulation of spin degree of freedom of an electron in low dimensional semi-magnetic semiconductor systems is drawing attention both experimentally and theoretically. The manipulation and controlling of charge spin can be achieved by means of spin-orbit coupling and can couple the spin degree of freedom of an electron to its orbital motion [1]. The spin dependent transport properties can be applied in spintronic devices.

The tunneling and the transmission of charged particles through a heterostructure quantum well in physics show wider applications and the application of transfer matrix mechanism is used to study the quantum scattering and bound state problems in the stationary states. The energy eigen values and the corresponding wave functions can be obtained directly by employing this method. This model is solved by means of matching the wave functions at the boundaries of heterostructures in the quantum well and application of the transfer matrix method [2, 3]. Some advanced experimental techniques such as molecular beam epitaxy, chemical vapour deposition and the electron beam lithography exist to fabricate the exact dimension of quantum wells, quantum wires and the quantum dots. The resonant tunneling in multilayered heterostructures based on an exact solution of the Schrödinger equation has been investigated with the combined application of electric field and a magnetic field [4]. The transmission coefficient is found by solving Schrödinger wave equation for $E > 0$ with the application of boundary conditions at the boundaries. The transmission and reflections coefficients are found using transfer matrix method. The proposed model for the calculation of transmission coefficients and the polarization efficiency in the well system with Rashba and Dresselhaus spin-orbit coupling is described in this work.

2. Model and Calculation

The time independent Schrödinger wave equation is employed to investigate the bound states, transmission and reflection. The transmission of electrons with the initial wave vector $\vec{k} = (k_{\parallel}, k_z)$ through an asymmetrical quantum well of heterostructure, ZnSe/Zn_{1-x}Mn_xSe/ZnSe grown along z || [001] is considered and it is as shown in Fig. 1. Here k_{\parallel} is the wave vector in the plane of the interfaces, and k_z is the wave vector component normal to the barrier and pointing in the direction of transmission. The motion of electron in each section of the quantum well is defined by the Hamiltonian and it is given by [5]

$$\hat{H} = -\frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial z^2} + \frac{\hbar^2 k_{\parallel}^2}{2m^*} + V(z) + H_{SO} \quad (1)$$

where m^* is the effective mass of the electron, $V(z)$ is the confined potential of the system and H_{SO} is the spin-dependent contribution to the effective Hamiltonian. It is the addition of H_D (the spin-dependent k^3 Dresselhaus term) and H_R (in-plane Rashba term). They describe the spin splitting of conduction electrons in zinc-blende-lattice semiconductors. Here, we have assumed that the barrier structure is taken in such a way that the kinetic energy is smaller than the confined potential, $V(z)$, the Dresselhaus term [6] is simplified to,

$$H_D = \gamma(\hat{\sigma}_x k_x - \hat{\sigma}_y k_y) \frac{\partial^2}{\partial z^2} \quad (2)$$

Similarly, the in-plane Rashba term exists in the asymmetrical quantum wells with non-zero α due to heteropotential asymmetry given by [7]

$$H_R = \alpha(\sigma_x k_y - \sigma_y k_x), \quad (3)$$

where γ is a material constant, $\hat{\sigma}_x$ and $\hat{\sigma}_y$ are the Pauli matrices, and the coordinate axes x, y, z are assumed to be parallel to the cubic crystallographic axes [100], [010], [001], respectively.

The wave functions of the electrons are of the form as plane wave equation as given by

$$\psi_{\pm}(\vec{r}) = \chi_{\pm} u_{\pm}(z) \exp(i\vec{k}_{\parallel} \cdot \vec{\rho}), \quad (4)$$

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where $\vec{\rho} = (x, y)$ is an in-plane coordinate of the barrier and χ_{\pm} is a spinors. The charged particle which propagates through well is explained in the regions as given below [8]

$$u_{\pm i}(z) = \begin{cases} A_i \cos[\gamma_i(z - z_{i-1})] + B_i \sin[\gamma_i(z - z_{i-1})] & \text{for } k_i^2 < 0 \\ A_i \cosh[\gamma_i(z - z_{i-1})] + B_i \sinh[\gamma_i(z - z_{i-1})] & k_i^2 > 0 \end{cases} \quad (5)$$

where $i = 1, 2, 3, \dots, (N+1)$ and $\gamma_i = |k_i|$, $k_i^2 \equiv \frac{2m^*}{\hbar^2}[V_i - E]$

The Dresselhaus term Eq.(2) is diagonalized by the spinors and it is given by

$$\chi_{\pm} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \mp e^{-i\phi} \end{pmatrix} \quad (6)$$

which describe the electron states “+” and “-” of the opposite spin directions. Here ϕ is the polar angle of the wave vector \vec{k} in the plane of the barrier and $\vec{k} = (k_{\parallel} \cos\phi, k_{\parallel} \sin\phi, k_z)$. The eigen spin states “+” and “-” propagate through the well with conservation of the spin orientation.

The electron behavior in the well with the diagonalization of Dresselhaus spin-orbit coupling term is denoted as

$$\frac{d^2 u_{\pm}(z)}{dz^2} - \frac{q_0^2}{\left\{1 \pm \gamma \frac{2m_b k_{\parallel}}{\hbar^2}\right\}} u_{\pm}(z) = 0 \quad (7)$$

Therefore, the wave vector q_{\pm} through the well is given by

$$q_{\pm} = \frac{q_0}{\sqrt{1 \pm \gamma \frac{2m_b k_{\parallel}}{\hbar^2}}} \quad (8)$$

where q_0 is the reciprocal length of decay of the wave function in the well with the omission of spin-orbit interactions and it is given by

$$q_0 = \sqrt{\frac{2m_b V}{\hbar^2} - k_z^2 \frac{m_b}{m_w} - k_{\parallel}^2 \left(\frac{m_b}{m_w} - 1\right)} \quad (9)$$

Here m_b and m_w are the electron effective masses in the barrier and well respectively.

In the present work, the effect of the in-plane Rashba spin-orbit interaction on the spin dependent tunneling through double barrier is designated by diagonalizing the in-plane Rashba term (Eq.3) by the same spinors (Eq.6) and they are used to diagonalize the Dresselhaus term with $\phi = \frac{\pi}{4}$. It is given by

$$\frac{d^2 u_{\pm}(z)}{dz^2} - \left(q_0^2 \mp \alpha \frac{2m_b}{\hbar^2} k_{\parallel} \right) u_{\pm}(z) = 0 \quad (10)$$

$\phi = \frac{\pi}{4}$ is taken throughout our computation and it is due to spin mixing of Rashba and Dresselhaus spin interaction terms. It can be attained experimentally. The Eq.(10) describes the electron behavior in the barrier with the in-plane Rashba spin-orbit coupling with the wave vector q_{\pm} through the well is given by

$$q_{\pm} = \sqrt{q_0^2 \mp \alpha \frac{2m_b}{\hbar^2} k_{\parallel}} \quad (11)$$

Hence, the combined effect of Dresselhaus and Rashba spin interactions on the spin dependent transmitting through the quantum well is given by,

$$\frac{d^2 u_{\pm}(z)}{dz^2} - \frac{\left(q_0^2 \mp \alpha \frac{2m_b}{\hbar^2} k_{\parallel} \right)}{\left\{ 1 \pm \gamma \frac{2m_b k_{\parallel}}{\hbar^2} \right\}} u_{\pm}(z) = 0 \quad (12)$$

The wave vector q_{\pm} through the well including both Dresselhaus and in-plane Rashba spin-orbit interactions are obtained as

$$q_{\pm} = \frac{\sqrt{q_0^2 \mp \alpha \frac{2m_b k_{\parallel}}{\hbar^2}}}{\sqrt{1 \pm \gamma \frac{2m_b k_{\parallel}}{\hbar^2}}} \quad (13)$$

The transmission coefficient t_{\pm} is calculated by transfer matrix mechanism [9] and the spin polarization efficiency P that determines the difference of transparency for the spin states “+” and “-” through the barrier is

$$P = \frac{|t_+|^2 - |t_-|^2}{|t_+|^2 + |t_-|^2} \quad (14)$$

3. Results and Discussion

Fig. 1 shows the transparency T_{up} , T_{down} , and the polarization efficiency P, of the ZnSe/Zn_{1-x}Mn_xSe/ZnSe asymmetrical well hetero structure with the function of the electron energy at fixed $k_{\parallel} = 2 \times 10^8 \text{ m}^{-1}$ with Dresselhaus spin-orbit term. It is seen that both the spin-down and spin down electrons are transmitted completely and show resonant transmission. At a given initial wave vector of electrons, k, the polarization efficiency decreases slightly with the strength of the Dresselhaus spin-orbit coupling up to the first discrete energy value 0.16 eV and then increases (Eq.8) slightly. Also, it is observed that both the spin-up and spin down charged particles are transmitted completely showing resonant transmission. As spin-down electrons see shallower well compared to spin-up electrons, the spin down electron shows the lower transmission coefficients than the transmission coefficients of spin-up electrons. However there occurs a drastic increase in polarization efficiency with both the spin orbit coupling terms are included (Eq.13). Eventually this figure shows the enhancement of the efficiency of polarization with both the spin orbit terms are involved in the Hamiltonian [10].

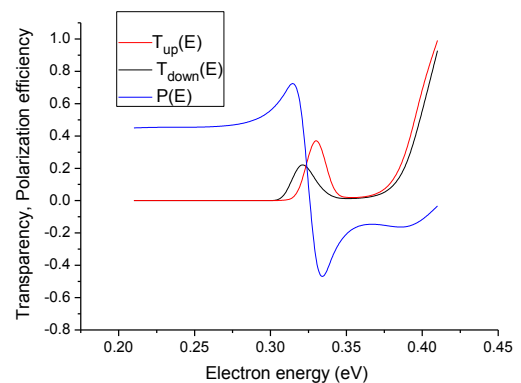


Fig. 1 Transparency T_{up} , T_{down} , and the polarization efficiency P, of the ZnSe/ZnMnSe/ ZnSe quantum well heterostructure

4. Conclusion

In conclusion, the calculations which are depicted in the present model bring out the resonant transmission structures through an asymmetry heterostructure with a simple one electron band approximation with spin-orbit coupling. Here, the external magnetic field is not applied in the heterostructure but it includes the spin-orbit coupling. It is projected that a spin-polarized current spontaneously arises in this heterostructure of ZnSe/Zn_{1-x}Mn_xSe/ZnSe quantum well and it can be applied for spin based devices in near future.

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