Spin Polarization through Semiconductor Superlattice in the Presence of Dresselhaus Spin-Orbit Interaction By CPA

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Abstract

The electron tunneling through semiconductor superlattice in the presence of Dresselhaus spin-orbit interaction by coherent potential approximation in the zinc-blende structure is investigated. The effect of indium percent in the impurity layers and the distance between them on the spin polarization, spin up and spin down transparency is evaluated.

Keywords

Spin Polarization, Semiconductor Superlattice, Dresselhaus Spin-Orbit Interaction, Coherent potential approximation.

1. Introduction

In spintronics or spin based electronics, an efficient spin polarized current [Wolf, 2001] is much demanded. There have been a number of researches demonstrating spin injection from dilute magnetic semiconductors [Fiederling, 1999; Jonker, 2000] or ferromagnetic metals [Ohno, 1999; Zhu and Hu, 2001; Hanbicki, 2002] into semiconductors. In recent researches the use of conventional nonmagnetic semiconductors [Voskoboynikov, 2000] at zero magnetic field, has obtained a spin polarized current in resonant tunnelling heterostructure [de Andrada e Silva, 1999]. The conductivity mismatch of the metal and the semiconductor structure causes a fundamental obstacle for electrical injection from ferromagnetic into semiconductor which was first pointed out by Schmidt *et al.* [Schmidt, 2000]. As a result Rashba used the tunneling contact at the metal semiconductor interface [Rashba, 2000]. Also Voskoboynikov, Liu, and Lee [Voskoboynikov, 1998] showed that the spin can be filtered by using only asymmetric nonmagnetic

semiconductor. Perel *et al.* proposed that using a material which lacks the center of inversion as a barrier for electron tunneling can produce a considerable spin polarization, such as zinc-blende structure semiconductors [Perel, 2003]. They showed using a single barrier heterostructure only Dresselhaus spin-orbit interaction makes the spin polarization efficiency of about 20%. Gnanasekar and Navaneethakrishnan used an asymmetrical double-barrier heterostructure and could increase the spin polarization by Dresselhaus spin orbit interaction up to 60-70%, using Rashba spin-orbit interaction caused 75-85% and using both, they achieve a 100% result [Gnanasekar, 2005; Deych, 2003].

In this research the electron tunneling through semiconductor superlattice in the presence of Dresselhaus spin-orbit interaction by coherent potential approximation in the zinc-blende structure is investigated. The effect of indium percent in the impurity layers and the distance between them on the spin polarization, spin up and down transparency is evaluated

2. Method

In this work we calculated spin polarization efficiency and transmission coefficient under spin orbit interaction in zinc-blende structure. The spin dependent part of Hamiltonian, H_D, which is derived from spin orbit interaction, is [Silva, 1997];

$$H_D = \gamma[\sigma_x k_x(k_y^2 - k_z^2) + \sigma_y k_y(k_z^2 - k_x^2) + \sigma_z k_z(k_x^2 - k_y^2)] \ (1)$$

where γ describes the strength of Dresselhaus effect in the barriers, the σ_i are the Pauli matrices and the k_i are the electron wave vector

component. In the Hamiltonian (1) γ is strongly correlated to band structure e.g. for GaAs γ is calculated by eight band Kane theory [Kane, 1957; Rossler, 1984] while for $In_xGa_{(1-x)}$ As is calculated by coherent potential approximation coupled to eight band Kane theory. In CPA, the Green's function for a system of scatterers can be written in operator notation as

$$\tilde{G} = G + GTG \tag{2}$$

where $\tilde{G}$ is the Green's function of real system and G is the average effective Green's function and T is the total scattering matrix of the system. The scattering matrix of the system may be written as

$$T = \sum_{i,j=1}^{N} t_i \delta_{i,j} + \sum_{i,j=1}^{N}\sum_{k \neq j} T_{ik} G t_j \tag{3}$$

where T_{ik} is the scattering-path operator and t_i is the t matrix that describes the scattering from the potential on the i-th site which can be written as

$$t_i = V_i (1 - GV_i)^{-1} \quad . \tag{4}$$

Here, V_i is the extra potential that is caused the scattering i-th site with respect to an effective medium. The effective medium is introduced by the self energy ξ which can be determined by $\langle T \rangle = 0$. Using the CPA, we impose the condition that for any barrier $\langle t_i \rangle = 0$ which means the extra effective scattering due to the atom at site i vanishes and the following self-consistent equations can be achieved

$$G^{(m)\alpha}(E \pm is) = \frac{\Omega}{2\pi N}$$

$$\times \lim_{s \to 0^+} \int_{(m)band} \frac{E \pm is}{(E \pm is)^2 - \left| \sum_{ij\alpha} e^{i\vec{k}.(\vec{R}_i - \vec{R}_j)} \gamma_{i,j}^\alpha \right|^2 - \xi^{(m)}} dk \tag{5}$$

and

$$\xi^{(m)}(E \pm is) = \frac{-1}{2G^{(m)}(E \pm is)}$$

$$+ \left[\frac{1}{4G^{(m)2}(E \pm is)} + \frac{\varepsilon_c}{G^{(m)}(E \pm is)} - \frac{\eta \varepsilon_c}{G^{(m)}(E \pm is)} \right]^{1/2} \tag{6}$$

where ε_c is the effective indium barrier height energy, η is indium barrier percentage, and $\xi^{(m)}$ is the self-energy. We have studied the transmission of an electron through a superlattice which consists of three zinc-blende structured materials A, B and C by the order shown in Fig. 1. In this figure, layer A (InAs) indicates well and layers B (GaAs) and C ($In_xGa_{(1-x)}As$) are the barriers where impurity layers take place on C layers. First the spin polarization and transmission coefficient are calculated for a given heterostructure such as A/B/A and then extended to the whole superlattice using the transfer matrix approach [Kane E. O]. We have considered the transmission of an electron along the growth direction with the initial wave vector k= (k$_\parallel$, k$_z$) through the flat potential barriers of height V periodic along the growth direction ($z \parallel$ [001]) where k$_\parallel$ is the in-plane wave vector and k$_z$ is the wave vector along the growth direction. We have assumed that the kinetic energy of the electron is much smaller than the barrier height V. The Hamiltonian in the barrier of j-th heterostructure is simplified to;

$$H_j = \frac{P^2}{2m_j^*} + V_j(z) + \gamma_j(\sigma_x k_x^j + \sigma_y k_y^j)\frac{\partial^2}{\partial z^2} \tag{7}$$

where m_j^* is the electron effective mass, $V_j(z)$ is barrier potential and the third term is Dresselhaus spin-orbit interaction. In the following, we omit the j indices for convenience. The Dresselhaus term in the Hamiltonian (7) is diagonalized by the spinors;

$$\chi_\pm = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \mp e^{-i\varphi} \end{pmatrix}. \tag{8}$$

These spinors describe the electron states $|+\rangle$ and $|-\rangle$ of the opposite spins directions. In this

notation φ is the polar angle of the wave vector k in the x-y plane, $k = (k_\parallel \cos\varphi, k_\parallel \sin\varphi, k_z)$. The electron spins $s_\pm$ corresponding to the eigenstates "$\pm$" are given by

$$s_\pm(k_\parallel) = \frac{1}{2}(\mp\cos\varphi, \pm\sin\varphi, 0) \qquad (9)$$

Electrons with the eigen spin states $|+\rangle$ and $|-\rangle$ propagate through the barrier, conserving the spin orientation. Since the wave vector in the plane of the barrier $k_\parallel$ is fixed, the wave functions of the electrons can be written in the form

$$\Psi_\pm(r) = \chi_\pm u_\pm(z)\exp(ik_\parallel \cdot \rho)$$

where

$$\begin{cases} u_\pm^A(r) = [\exp(ik_z z) + r_\pm \exp(-ik_z z)] \\ u_\pm^{B\,or\,C}(r) = [A_\pm \exp(q_\pm z) + B_\pm \exp(-q_\pm z)] \\ u_\pm^A(r) = t_\pm \exp(ik_\pm z) \end{cases} \quad (10)$$

Here $r_\pm$ and $t_\pm$ are the reflection and transmission coefficient and $\rho = (x, y)$ is an in-plane coordinate of the electrons propagating through the heterostructure are described in the j-th part of heterostructure A/B or C/A. The wave vector $q_\pm$ through the barrier is given by

$$q_\pm = \frac{q_\circ}{\sqrt{1 \pm 2\gamma\ m_{B\,or\,C}k_\parallel / \hbar^2}} \qquad (11)$$

where $q_\circ$ is the reciprocal length of decay of the wave function in the barrier. When the spin orbit interactions are omitted it is given by

$$q_\circ = \sqrt{\frac{2m_{B\,or\,C}V}{\hbar^2} - k_z^2 \frac{m_{B\,or\,C}}{m_A} - k_\parallel^2(\frac{m_{B\,or\,C}}{m_A} - 1)} \quad (12)$$

Here m_B and m_C are the electron effective masses in the barriers and m_A are in the wells. For calculating transmission through the superlattice as A/B/A/B/… we use the standard

Ben Daniel-Duke boundary condition that obtained two equations at each interface. The coefficient of the last region can be linked to initial coefficients by the transfer matrix. Transmission coefficient is proportional to the ratio of the last coefficient to initial one.

The spin polarization efficiency, P, is determined;

$$P = \frac{|t_+|^2 - |t_-|^2}{|t_+|^2 + |t_-|^2} \qquad (13)$$

The polarization efficiency of the aforementioned heterostructure is plotted in Fig.1.

3. Results and discussion

Our superlattice structure consists of InAs layers (A layers) as wells, GaAs layers (B layers) as barriers and two $In_xGa_{(1-x)}As$ layers (C layers) as disordered layers, one is fixed at the beginning and the other is located on an arbitrary place. The total length of system is 5000 angstrom, width of each barrier or well is equal and the height of each barrier is 320 meV. The temperature regime is 20-77 K.
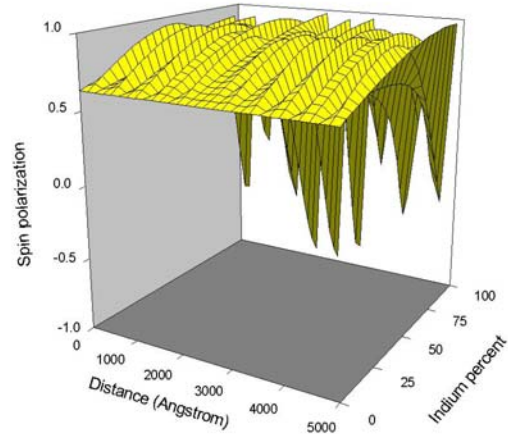

Fig.1. The spin polarization versus Indium (In) percent in disordered layer and the distance between two impurity layers. The energy of the electron is 200 meV.

Fig.1 shows the spin polarization versus Indium (In) percent and the distance between two impurity layers. The energy of the electron is fixed at 200 meV.
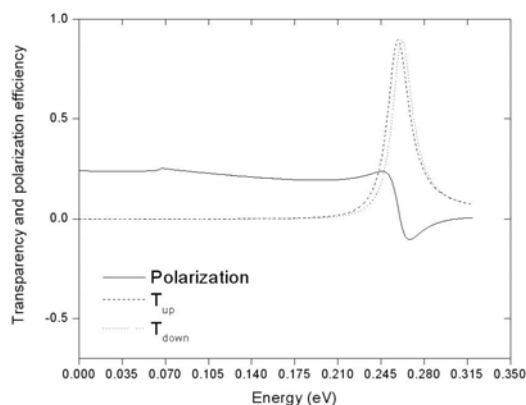
Fig.2. The spin up and down transparency and polarization efficiency as function of the electron energy for InAs/GaSb/InAs/GaSb/InAs double barrier heterostructure in the presence of Dresselhaus spin-orbit coupling. Well width 30 Å, barriers thickness 50 Å and 40Å respectively and the barriers height, V=320 meV.

We restricted our superlattice to a structure of double barriers and no impurity layers with the same well width and barrier thickness. The electron transmission for spin up and down and the polarization efficiency are calculated and the results are plotted as a function of the electron energy in Fig.2 and they are in good agreement with the Gnanasekar reports [Gnanasekar, 2005].

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