Spin-dependent resonant tunneling in ZnSe/ZnMnSe heterostructures

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Abstract

Using the transfer matrix method and the effective-mass approximation, the effect of resonant states on spin transport is studied in ZnSe/ZnMnSe/ZnSe/ZnMnSe/ZnSe structures under the influence of both electric and magnetic fields. The numerical results show that the ZnMnSe layers, which act as spin filters, polarize the electric currents. Variation of thickness of the central ZnSe layer shifts the resonant levels and exhibits an oscillatory behavior in spin current densities. It is also shown that the spin polarization of the tunneling current in geometrical asymmetry of the heterostructure where two ZnMnSe layers have different Mn concentrations, depends strongly on the thickness and the applied bias.

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I. INTRODUCTION

Tunneling and resonant tunneling processes involving electron spin show prominent perspectives for new field spin-dependent fast electronics. Besides important applications in new spin-based multifunctional devices such as spin-field-effect transistor and spin-light-emitting diode, the spin-dependent resonant tunneling (SDRT) effect can also help us to more deeply understand the role of spin degree of freedom of the tunneling electron and the quantum size effects on spin transport processes [1]. In recent years, some attempts have been made to study the effects of SDRT in magnetic tunnel junctions in which the electrons tunnel from one ferromagnetic metal electrode to the other through a nonmagnetic metal layer and a thin insulator layer [2, 3, 4, 5, 6].

On the other hands, spin-injection into semiconductors by using magnetic semiconductors has also been demonstrated, opening the way to new all-semiconductor devices. II-VI diluted magnetic semiconductors (DMSs) [7] are known to be good candidates for effective spin injection into a nonmagnetic semiconductor (NMS) because their spin polarization is nearly 100% and their conductivity is comparable to that of typical NMS. Moreover, II-VI DMSs can be n-type doped, thus avoiding the very fast spin precession that limits the applicability of III-V DMSs as spin injectors. A very promising II-VI DMS for spin injection is (Zn,Mn)Se, which has been previously used for spin injection experiments into GaAs [8], and ZnSe [9]. More recently, Slobodskyy et al. [10] using II-VI semiconductor layers, fabricated a magnetic resonant tunneling diode. Their magnetic device is based on a quantum well made of diluted magnetic semiconductor ZnMnSe between two ZnBeSe barriers and surrounded by highly n-type ZnSe layers.

Recently, Guo et al. [11, 12] and Chang et al. [13] investigated theoretically the spin-dependent transport in ZnSe/Zn$_{1-x}$Mn$_x$Se DMS double barrier structures. The results showed that the spin polarization of the tunneling electrons can be tuned by changing the external magnetic and electric fields. The effect of SDRT on spin transport has also been studied in spin filter tunnel junctions [14, 15, 16, 17, 18] in which a ferromagnetic semiconductor (FMS) such as EuS is used as a magnetic barrier. The large spin polarization achievable using magnetic barriers [19], makes spin filtering a nearly ideal method for spin injection into semiconductors, enabling novel spintronic devices [20].

In Ref. [15], using two FMS layers, we examined the SDRT in a double barrier junction
and in the coherent tunneling regime. In the present work, we study theoretically the effects of SDRT in ZnSe/ZnMnSe/ZnSe/ZnMnSe/ZnSe structures. The left and right ZnSe layers are considered as emitter and collector attached to external leads. We assume that the carrier wave vector parallel to the interfaces and the carrier spin are conserved in the tunneling process through the whole system. The first assumption is well justified for interfaces between materials whose lattice constants are nearly equal; and the second one is also justified in our structure, because the sample dimensions are much smaller than the spin coherence length. Using the transfer matrix method and the nearly-free-electron approximation we will study the effects of resonant tunneling on spin-dependent current densities and the degree of spin polarization.

The paper is organized as follows. In section II, the model is described and then the spin current densities and spin polarization for ZnSe/ZnMnSe heterostructures with two paramagnetic layers, are formulated. In section III, the numerical results for the symmetric and asymmetric structures are discussed in terms of the thickness of the ZnSe layer, which has been sandwiched between two paramagnetic layers. The results of this work are summarized in section IV.

II. MODEL AND FORMALISM

We consider a spin unpolarized electron current injected into ZnSe/Zn_{1-x}Mn_xSe/ZnSe/Zn_{1-y}Mn_ySe/ZnSe structures in the presence of magnetic and electric fields along the growth direction (taken as z axis). The conduction electrons that contribute to the electric currents, interact with the 3d^5 electrons of the Mn ions via the sp-d exchange interaction. Due to the sp-d exchange interaction, the external magnetic field gives rise to the spin splitting of the conduction band states in the paramagnetic layers. Therefore, the injected electrons see a spin-dependent potential. In the framework of the parabolic-band effective mass approximation, the one-electron Hamiltonian of such system can be written as

$$H = \frac{1}{2m^*}(\mathbf{P} + e\mathbf{A})^2 + V_s + V_0(z) + V_\sigma(z) - \frac{eV_\sigma z}{L},$$

where the electron effective mass $m^*$ is assumed to be identical in all the layers, and the vector potential is taken as $\mathbf{A} = (0, Bx, 0)$. Here, $V_s = \frac{1}{2}g_s\mu_B\sigma \cdot \mathbf{B}$ describes the Zeeman
splitting of the conduction electrons, where $\sigma$ is the conventional Pauli spin operator. $V_0(z)$ is the conduction band offset under zero magnetic field, which is the difference between the conduction band edge of the ZnMnSe layers and that of the ZnSe layer; $V_{\sigma}(z)$ is the sp-d exchange interaction between the injected electron and the Mn ions and can be calculated within the mean field approximation. Hence, the sum of the two terms can be written as

$$V_0(z) + V_{\sigma}(z) = [V_0L - N_0\alpha_L\sigma_z x_{\text{eff}} \langle S_{zL} \rangle] \Theta(z) \Theta(L_1 - z)$$

$$+[V_0R - N_0\alpha_R\sigma_z y_{\text{eff}} \langle S_{zR} \rangle] \Theta(z - L_1 - L_2) \Theta(L_1 + L_2 + L_3 - z), \quad (2)$$

where, $V_{0L(R)}$, $N_0\alpha_{L(R)}$ and $\langle S_{zL(R)} \rangle = SB_S[5\mu_B B/k_B(T + T_{0L(R)})]$ are respectively the conduction band offset, the electronic sp-d exchange constant and the thermal average of $z$th component of Mn$^{2+}$ spin in the left (right) DMS layer. Here, $B_S(x)$ is the Brillouin function and $S = 5/2$ is the spin of the Mn ions. $\sigma_z = \pm 1/2$ (or $\uparrow, \downarrow$) are the electron spin components along the magnetic field, $x_{\text{eff}} = x(1 - x)^{12}$ and $y_{\text{eff}} = y(1 - y)^{12}$ are the effective Mn concentrations due to the antiferromagnetic Mn-Mn coupling, while $x$ and $y$ are real Mn concentrations. $\Theta(z)$ is the step function, $L_1$ and $L_3$ are respectively the widths of left and right DMS layers, and $L_2$ is the width of the middle ZnSe layer. The last term in Eq. (1) denotes the effect of an applied bias $V_a$ along the $z$ axis on the system, where $L = L_1 + L_2 + L_3$ is the total length of the considered structure along the growth direction. It is important to note that, our sample dimensions are much smaller than the spin coherent length in the semiconductors. Therefore we have neglected the effects of spin-flip processes in the Hamiltonian of the system.

Here, we would like to point out that, due to the absence of any kind of scattering center for the electrons, the motion along the $z$-axis is decoupled from that of the $x$-$y$ plane which is quantized in the Landau levels with energies $E_n = (n + 1/2)\hbar\omega_c$, where $n = 0, 1, 2, \cdots$ and $\omega_c = eB/m^*$. In such case, the motion of electrons along the $z$ axis can be reduced to a one-dimensional Schrödinger equation

$$-\frac{\hbar^2}{2m^*} \frac{d^2\psi_{\sigma}(z)}{dz^2} + \left[V_s + V_0(z) + V_{\sigma}(z) - \frac{eV_a z}{L}\right] \psi_{\sigma}(z) = E_z \psi_{\sigma}(z), \quad (3)$$

where $E_z$ is the longitudinal energy of electrons traversing the heterostructure.
The general solution to the above Schrödinger equation is as follows:

\[ \psi_{j\sigma z}(z) = \begin{cases} 
A_{1\sigma z} e^{ik_{1\sigma z} z} + B_{1\sigma z} e^{-ik_{1\sigma z} z}, & z < 0, \\
A_{2\sigma z} \text{Ai}[\rho_{\sigma z}(z)] + B_{2\sigma z} \text{Bi}[\rho_{\sigma z}(z)], & 0 < z < L_1, \\
A_{3\sigma z} \text{Ai}[\rho_{\sigma z}(z)] + B_{3\sigma z} \text{Bi}[\rho_{\sigma z}(z)], & L_1 < z < L_1 + L_2, \\
A_{4\sigma z} \text{Ai}[\rho_{\sigma z}(z)] + B_{4\sigma z} \text{Bi}[\rho_{\sigma z}(z)], & L_1 + L_2 < z < L, \\
A_{5\sigma z} e^{ik_{5\sigma z} z} + B_{5\sigma z} e^{-ik_{5\sigma z} z}, & z > L, 
\end{cases} \quad (4) \]

where the coefficients \(A_{j\sigma z}\) and \(B_{j\sigma z}\) (with \(j=1-5\)) are constants which can be determined by the boundary conditions, \(\text{Ai}[\rho_{\sigma z}(z)]\) and \(\text{Bi}[\rho_{\sigma z}(z)]\) are Airy functions, and

\[ k_{1\sigma z} = \sqrt{2m^*(E_z - V_s)/\hbar}, \quad (5) \]
\[ k_{5\sigma z} = \sqrt{2m^*(E_z - V_s + eV_a)/\hbar}, \quad (6) \]
\[ \rho_{\sigma z}(z) = -\frac{L}{eV_a \lambda} \left[ V_s + V_0(z) + V_{\sigma z}(z) - E_z - \frac{eV_a z}{L} \right], \quad (7) \]

with

\[ \lambda = \left[ \frac{-\hbar^2 L}{2m^* e V_a} \right]^{1/3}. \quad (8) \]

The wave functions and their first derivatives in the five regions are matched at the interfaces between the regions. The matching results in a system of equations, which can be represented in a matrix form:

\[
\begin{pmatrix} A_{1\sigma z} \\ B_{1\sigma z} \end{pmatrix} = M_{\text{total}} \begin{pmatrix} A_{5\sigma z} \\ B_{5\sigma z} \end{pmatrix}, \quad (9)
\]

where \(M_{\text{total}}\) is the transfer matrix that connects the incidence and transmission amplitudes and has the following form

\[ M_{\text{total}} = M_1^{-1}(0)M_2(0)M_2^{-1}(L_1)M_3(L_1)M_3^{-1}(L_2)M_4(L_2)M_4^{-1}(L_3)M_5(L_3). \quad (10) \]

Here,

\[ M_j(z_i) = \begin{pmatrix} \psi^+_j(z_i) & \psi^-_j(z_i) \\ \frac{d\psi^+_j(z)}{dz} & \frac{d\psi^-_j(z)}{dz} \end{pmatrix} \quad (11) \]

where, \(\psi^+_j(z)\) and \(\psi^-_j(z)\) are respectively the first and second term of the wave functions in each layer, without considering their coefficients. Since there is no reflection in region 5, the
coefficient $B_{5\sigma}$ in Eq. (4) is zero and the transmission coefficient of the spin $\sigma_z$ electron, which is defined as the ratio of the transmitted flux to the incident flux, can be written as

$$T_{\sigma_z}(E_z, B, V_a) = \frac{k_{5\sigma_z}}{k_{1\sigma_z}} \left| \frac{1}{M_{11}^{total}} \right|^2,$$

where $M_{11}^{total}$ is the left-upper element of the matrix $M_{total}$ defined in Eq. (10). It should be noted that the transmission coefficients depend on the incident energy $E_z$, the magnetic field $B$, the applied bias $V_a$ and the spin orientation. The spin-dependent current density is connected with the transmission coefficients via

$$J_{\sigma_z}(B, V_a) = J_0 B \sum_{n=0}^{\infty} \int_0^{+\infty} T_{\sigma_z}(E_z, B, V_a) \times \{f[E_z + (n + \frac{1}{2})\hbar \omega + V_s] - f[E_z + (n + \frac{1}{2})\hbar \omega + V_s + eV_a]\} dE_z,$$

where $J_0 = e^2/4\pi^2\hbar^2$ and $f(E) = 1/\{1+\exp[(E-E_F)/k_BT]\}$ is the Fermi-Dirac distribution function in which $E_F$ denotes the emitter Fermi energy.

The degree of spin polarization for electrons traversing the heterostructure is defined by

$$P = \frac{J_\uparrow(B, V_a) - J_\downarrow(B, V_a)}{J_\uparrow(B, V_a) + J_\downarrow(B, V_a)},$$

where $J_\uparrow$ ($J_\downarrow$) is the spin-up (spin-down) current density.

### III. RESULTS AND DISCUSSION

From Eq. (13), we can evaluate numerically the spin-dependent current densities as a function of the thickness of the central ZnSe layer for the symmetric and the asymmetric structures, depending on the Mn concentration in both paramagnetic layers. In all of the numerical calculations we use $m^* = 0.16 \ m_e$ ($m_e$ is the mass of the free electron), $T = 4.2 \ \text{K}$, $B = 4 \ \text{T}$, $L_1 = L_3 = 75 \ \text{nm}$, $g_s = 1.1$, and $E_F = 5 \ \text{meV}$. Figs. 1(a) and 1(b) show the thickness dependence of the current densities for spin-up and spin-down electrons respectively, in a symmetric ($x = y = 0.05$) structure. In both figures, $N_0\alpha_L = N_0\alpha_R = 0.26 \ \text{eV}, \ V_{0L} = V_{0R} = 0 \ \text{meV}, \ T_{0L} = T_{0R} = 1.7 \ \text{K} \ [22]$. By applying an external magnetic field, the sp-d exchange interaction gives rise to a giant spin splitting which is much larger than the Zeeman splitting of the conduction electrons. In such case, the degeneracy of the spin-up and spin-down electron states is lifted, thus each paramagnetic layer in our
structure behaves as a potential barrier for spin-up electrons and a quantum well for spin-down ones. Consequently, the spin-up electrons see a double-barrier potential while the spin-down ones see a double-well potential. The barrier potential lowers the current density of spin-up electrons. For these electrons, the central ZnSe layer behaves as a quantum well, thus with increasing the thickness of the central layer, the position of the resonant states formed in the well varies and shifts to the lower energy side. This leads to the oscillations of the current density which decrease exponentially at each applied bias. Our studies have also shown that, with increasing the applied voltage, the transmission coefficients for the energies which are near $E_F$, increase. Since in tunneling process at low temperatures, the electrons with energy near $E_F$ carry most of the current, one can see that the current density increases with the applied bias. On the other hand, as it is clear in Fig. 1(b), the current densities and the amplitude of oscillations for spin-down electrons are much higher than for spin-up ones. This is because the structure behaves as a double-well potential, hence the transmission coefficients are large even at low energy region and the resonant peaks become less sharp. It is important to note that in the spin-down case the resonance is originated from the above-well virtual states.

In Figs. 2(a) and 2(b) we have shown the thickness dependence of the current densities for spin-up and spin-down electrons respectively, in an asymmetric ($x = 0.04, y = 0.05$) structure. Here, for $x = 0.04$, $N_0\alpha_L = 0.27$ eV, $V_{0L} = -3$ meV, $T_{0L} = 1.4$ K, and for $y = 0.05$, $N_0\alpha_R = 0.26$ eV, $V_{0R} = 0$ meV, $T_{0R} = 1.7$ K [22]. At low applied bias, the current density and the amplitude of oscillations for spin-up electrons slightly increase when the thickness of $L_2$ increases, while with increasing the applied bias a reverse behavior appears. An important point to note is that the values of current density for the spin-up electrons in the asymmetric structure is three orders of magnitude higher than the symmetric one, while in the spin-down case, the values do not change considerably relative to those obtained in the symmetric structure. However, the behavior of current density for the two spin subbands is completely different in both structures as shown in Figs. 1 and 2. In the asymmetric structure and in the spin-down case, with increasing the applied bias and the thickness of the central ZnSe layer, the current density increases, which is important for possible technological applications. This is a direct consequence of the effect of conduction band offset and the difference in the magnetic impurity concentrations in the paramagnetic layers.
In order to further see the effects of the resonant states in our system, we have shown in Figs. 3 and 4 the degree of spin polarization as a function of $L_2$ under several applied voltages in the symmetric and the asymmetric structures, respectively. One can easily see in Fig. 3 that, the output current of the symmetric structure exhibits high values of spin polarization, which can reach 100% when $L_2$ increases. Therefore, the results display obvious behavior of spin filtering effect in the symmetric structure, which is independent of the applied voltage. The spin polarization in the asymmetric structure has been shown in Fig. 4. The results show that (in contrast with Fig. 3) in the asymmetric structure the spin polarization strongly depends on the applied voltage. In such structure at fixed $L_2$ the high (low) values of spin polarization correspond to low (high) applied voltages. As the thickness $L_2$ increases, the degree of spin polarization for the low voltages decreases slowly, while the amplitude of oscillations increases. However, the system for the high voltages exhibits a reverse behavior. The results once again indicate that the spin-dependent resonant states which are responsible for the oscillations in spin currents, strongly depend on the external electric field and the geometrical structure.

Therefore, the obtained results in the asymmetric structures clearly illustrate that the current density and hence the degree of spin polarization can be tuned by changing the applied voltage and/or the thickness of the central ZnSe layer.

IV. SUMMARY

Based on the transfer matrix method and the effective-mass approximation, we have investigated the effect of resonant states on spin transport in ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-y}$Mn$_y$Se/ZnSe heterostructures. The numerical results show that the symmetric structure enables the generation of spin-polarized injection currents, since the heterostructure for each value of the applied bias and the thickness of the central ZnSe layer, filters out the contribution of spin-up electrons in the total current density. On the other hand, our numerical calculations indicate that the asymmetric structure can be a good spin filter, if we adjust the applied voltage and the thickness. Such behaviors are originated from the enhancement and suppression in the spin-dependent resonant states. These interesting features are relevant for devising tunable spin-dependent electronic devices such as spin switches, tunable lasers [23, 24], magnetic resonant tunneling
diodes [10], and also useful to study fundamental effects involved in the spintronic field.

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FIG. 1: (a) Spin-up and (b) spin-down current densities as a function of the thickness $L_2$ for ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe heterostructures.
FIG. 2: (a) Spin-up and (b) spin-down current densities as a function of the thickness $L_2$ for ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-y}$Mn$_y$Se/ZnSe heterostructures.
FIG. 3: Degree of spin polarization as a function of the thickness $L_2$ for ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-y}$Mn$_y$Se/ZnSe heterostructures.

FIG. 4: Degree of spin polarization as a function of the thickness $L_2$ for ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-y}$Mn$_y$Se/ZnSe heterostructures.