Quantum size effects on spin-tunneling time in a magnetic resonant tunneling diode

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We study theoretically the quantum size effects of a magnetic resonant tunneling diode (RTD) with a (Zn,Mn)Se dilute magnetic semiconductor layer on the spin-tunneling time and the spin polarization of the electrons. The results show that the spin-tunneling times may oscillate and a great difference between the tunneling times of the electrons with opposite spin directions can be obtained depending on the system parameters. We also study the effect of structural asymmetry which is related to the difference in the thickness of the nonmagnetic layers. It is found that the structural asymmetry can greatly affect the traversal time and the spin polarization of the electrons tunneling through the magnetic RTD. The results indicate that, by choosing suitable values for the thickness of the layers, one can design a high speed and perfect spin-filter diode.

I. INTRODUCTION

The field of semiconductor spintronics has attracted a great deal of attention during the past decade because of its potential applications in new generations of transistors, lasers, and integrated magnetic sensors. In addition, magnetic resonant tunneling diodes (RTDs) 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]. By employing such a magnetic RTD, an effective injection of spin-polarized electrons into nonmagnetic semiconductors (NMSs) can be demonstrated [2,3]. In this regard, the II-VI diluted magnetic semiconductor (DMS) [4,5] are known to be good candidates for effective spin injection into a NMS because their spin polarization is nearly 100% and their conductivity is comparable to that of typical NMS. A very promising II-VI DMS for spin injection is (Zn,Mn)Se, which has been previously used for spin injection experiments into GaAs [6] and ZnSe [7]. The (Zn,Mn)Se-based RTD with highly spin-polarized electron current has been suggested by Egues [8] and experimentally demonstrated by Slobodskyy et al. [9]. Also, different types of magnetic RTDs have been proposed both theoretically [10-12,13,14,15,16] and experimentally [17,18,19,20,21,22,23].

One of the key parameters in operation of magnetic RTDs is the time aspect of tunneling process, which has been the focus of much research in the past decade, because it is an important parameter for better understanding of the spin-dependent tunneling phenomena in high-speed devices. This quantity may strongly depend on the quantum size of the devices, however, to the best of our knowledge, no theoretical study on the dependence of quantum size on the spin-tunneling time in the magnetic RTDs has so far been reported.

Recently, based on the group velocity concept, several theoretical studies of tunneling time in different magnetic junctions have been done. Guo et al. found obvious features of separation of spin-tunneling time in ZnSe/Zn$_{1-x}$Mn$_x$Se heterostructures [23,24,25]. Zhai et al. [26] studied the tunneling time in magnetic barrier structures consisting of two identical or unidentical magnetic barriers and magnetic wells. Wang et al. [27] investigated tunneling properties of spin-polarized electrons traversing ferromagnetic/insulator (semiconductor) double junctions and reported that the tunneling time strongly depends on the spin orientation of tunneling electrons. The effects of Rashba spin-orbit interaction [28,29] and Dresselhaus spin-orbit coupling [30] on the traversal time of ferromagnetic/semiconductor/ferromagnetic heterostructures have also been investigated. By considering the Rashba spin-orbit coupling in the semiconductor and significant quantum size simultaneously, it has been found that, as the length of the semiconductor increases, the spin-tunneling time will increase with a behavior of slight oscillation, whether for the spin-up electrons or for the spin-down ones [29]. Furthermore, it has been demonstrated that the Dresselhaus spin-orbit coupling, unlike the Rashba spin-orbit interaction that damps the motion of electrons, does not prolong the traversal time of electrons tunneling through the heterostructures [30].

The aim of the present study is to investigate the quantum size effects of a typical magnetic RTD on spin-tunneling time and its dependence on the concentration of magnetic ions. Our device, similar to that used in Ref. [9], is based on a quantum well made of diluted magnetic semiconductor (Zn,Mn)Se between two (Zn,Be)Se barriers and surrounded by highly n-type ZnSe layers. In such a structure, the energy levels of the quantum well states depend on spin direction due to the exchange splitting, meaning that the energy levels of the (Zn,Mn)Se layer for spin-up electrons will be different from that of spin-down electrons. We will show here that this spin splitting of the energy levels, which is controlled by an
applied magnetic field and the value of Mn concentration, enables one to select the resonant condition for the desired spin by adjusting the quantum size of the device. This paper is organized as follows. In Sec. II, we present the model and formalism for traversal time of electrons through ZnSe/ZnBeSe/ZnMnSe/ZnBeSe/ZnSe magnetic RTD. Numerical results and discussions for spin-tunneling time and the degree of electron-spin polarization in both the symmetric and the asymmetric structures are presented in Sec. III. We conclude our findings in Sec. IV.

II. MODEL AND FORMALISM

Consider a spin unpolarized electron current injected into a ZnSe/ZnBeSe/ZnMnSe/ZnBeSe/ZnSe structure shown in Fig. 1, in the presence of magnetic and electric fields along the growth direction (taken as the z-axis). The conduction electrons that contribute to the electric currents interact with the 3d electrons of the Mn ions via the sp-d exchange interaction. Hence, the external magnetic field, $B$, gives rise to the spin splitting of the conduction band states in the Zn$_{1-x}$Mn$_x$Se layer. Therefore, the injected electrons see a spin-dependent potential. 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 $E_n = (n + \frac{1}{2})\hbar\omega_c$, where $n = 0, 1, 2, \cdots$ and $\hbar\omega_c = eB/m^*$. In such a case, the motion of electrons along the z-axis can be reduced to the following one-dimensional Schrödinger equation

$$\frac{\hbar^2}{2m^*} \frac{d^2\psi_{z\sigma}(z)}{dz^2} + U_{z\sigma}(z)\psi_{z\sigma}(z) = E_z\psi_{z\sigma}(z),$$

where the electron effective mass $m^*$ is assumed to be identical in all the layers, $E_z$ is the longitudinal energy of electrons, $U_{z\sigma}(z)$ is the effective potential seen by a transverse electron and is given as $U_{z\sigma}(z) = V_z + U_0 - eV_a z/L$ in the ZnBeSe layers, $0 < z < L_1$ and $L_1 + L_2 < z < L$ where $U_0$ is the height of the ZnBeSe barriers and $U_{z\sigma}(z) = V_z + V_{z\sigma}(z) - eV_a z/L$ in the ZnMnSe layer, $L_1 < z < L_1 + L_2$. Here, $L_1$ and $L_2$ are, respectively, the widths of left and right ZnBeSe layers, and $L_2$ is the width of the ZnMnSe layer ($L = L_1 + L_2 + L_3$); $V_z = \frac{1}{2}g_\mu_B \sigma \cdot B$ describes the Zeeman splitting of the conduction electrons, where $\sigma$ is the conventional Pauli spin operator; $V_{z\sigma}(z)$ is the heterostructure potential or the conduction band offset in the absence of a magnetic field, which depends on the Mn concentration $x$ and is the difference between the conduction band edge of the ZnMnSe layer and that of the ZnSe layer; $V_{z\sigma}(z)$ 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 last two terms can be written as

$$V_z(z) + V_{z\sigma}(z) = \frac{1}{2}\Delta E(x) - N_0 x_0 e_0 S B S \left( \frac{5\mu_B B}{k_B(T + T_0)} \right) \times \Theta(z - L_1) \Theta(L_1 + L_2 - z),$$

where

$$\Delta E(x) = E_0(x) - E_0(0) = -0.63x + 22x^2 - 195x^3 + 645x^4,$$

is the sum of the conduction and valence band offset under zero magnetic field, when the real (effective) Mn concentration is $x$ ($x_{\text{eff}} = x[1 - x]^{12}$). Here, $B_S(\cdots)$ is the Brillouin function and $S = \frac{1}{2}$ is the spin of the Mn ions. $\sigma_z = \pm \frac{1}{2}$ (or [1, 0]) are the electron-spin components along the magnetic field. We should note that this form of Eq. (2) is valid only for $0 \leq x \leq 0.1$ [31]. The last term in $U_{z\sigma}(z)$ denotes the effect of an applied bias $V_a$ along the z-axis on the system.

In order to study the tunneling time of electrons through the structure, we adopt the group velocity approach [32, 33], in which the tunneling time of a spin-polarized electron can be defined as $\tau_{z\sigma} = \int dz/v_{z\sigma}(z)$, where the spin-dependent group velocity, $v_{z\sigma}(z)$, is defined as the ratio of the average probability current density $S_{z\sigma} = \text{Re}[\psi_{z\sigma}(z) d\psi_{z\sigma}(z)/im^*]$ to the probability density $|\psi_{z\sigma}(z)|^2$ of the particle [23, 24, 27]. In this regard, the spin-tunneling time can be written as

$$\tau_{z\sigma} = \frac{1}{h} \int_0^L \frac{m^*}{|\gamma_{z\sigma}(z)| \text{Im}[\tan\theta_{z\sigma}(z)]} dz,$$

(4)

where

$$\tan\theta_{z\sigma}(z) = \frac{1}{|\gamma_{z\sigma}(z)|} \left( \frac{1}{\psi_{z\sigma}(z)} \frac{d\psi_{z\sigma}(z)}{dz} \right),$$

(5)

$$\gamma_{z\sigma}(z) = \frac{i}{h} \sqrt{2m^*[E_z - U_{z\sigma}(z)]}.$$

(6)

In the above equations, $\psi_{z\sigma}(z)$ is the spin-dependent wave function of the heterostructure. Since we have considered that the electrons tunnel through the magnetic structure from the left ($z < 0$) to the right ($z > L$), under the influence of the applied voltage $V_a$, the wave functions in each region can be written as

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

(7)

Here, $r_{z\sigma}$ and $t_{z\sigma}$ are the reflection and the transmission amplitudes; $k_{1z\sigma} = \sqrt{2m^* (E_z - V_z + eV_a)}/h$ and $k_{2z\sigma} = \sqrt{2m^* (E_z - V_z + eV_a)}/h$ are the electron momenta; $A_{i\rho_{z\sigma}}(\rho_{z\sigma}(z))$ and $B_{i\rho_{z\sigma}}(\rho_{z\sigma}(z))$ are the Airy functions with $\rho_{z\sigma}(z) = (E_z - U_{z\sigma}(z))/L/(eV_a\lambda)$ and $\lambda = [-h^2 L/(2m^* eV_a)]^{1/3}$. 


we have done our numerical calculations at \(E_F\) the paramagnetic layer.

In the tunneling process at low temperatures, the electrons with energy near \(E_F\), the Fermi energy (asymmetric) if \(j=2\) and \(4\) can be determined from a system of equations formed by \(\psi_{\alpha z}\), and its derivative for the same \(z\) value. Then, we can relate \(\psi_{\alpha z}\) and \(\psi'_{\alpha z}\) at two positions \(z\) and \(z'\) by the transfer matrix \(M\) as follows:

\[
\begin{pmatrix}
\psi_{\alpha z}(z) \\
\psi_{\alpha z}(z')
\end{pmatrix} =
\begin{pmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{pmatrix}
\begin{pmatrix}
\psi'_{\alpha z}(z') \\
\psi_{\alpha z}(z')
\end{pmatrix}.
\tag{8}
\]

Applying the results of Eq. (8) in Eq. (5) the value of \(\tan\theta_{\alpha z}(z)\), which determines the tunneling time at position \(z\), can be written in terms of its value at position \(z'\) as

\[
\tan\theta_{\alpha z}(z) = \frac{1}{|\gamma_{\alpha z}(z)|} \frac{M_{11}|\gamma_{\alpha z}(z')|\tan\theta_{\alpha z}(z') + M_{12}}{M_{21}|\gamma_{\alpha z}(z')|\tan\theta_{\alpha z}(z') + M_{22}}.
\tag{9}
\]

Therefore, using Eqs. (9) and (4) the spin-tunneling time can be calculated for the desired magnetic RTD.

### III. RESULTS AND DISCUSSION

In this section, we use the formulas given above to investigate the quantum size effect on the spin-tunneling time and electron-spin polarization in the ZnSe/ZnBeSe/Zn\(_{1-x}\)Mn\(_x\)Se/ZnBeSe/ZnSe heterostructures. In the numerical calculations we have taken the following values: \(U_0 = 92\) meV \(11\), \(T = 2.2\) K, \(T_0 = 1.4\) K, and \(N_0\alpha = -0.27\) eV \(34\), \(E_F = 5\) meV, \(B = 2\) T, \(V_a = 5\) mV, \(g_s = 1.1\), and \(m^* = 0.16\) \(m_e\) (\(m_e\) is the mass of the free electron). In the tunneling process at low temperatures, the electrons with energy near Fermi energy \(E_F\) carry most of the current; for this reason we have done our numerical calculations at \(E_z = E_F\). Also, due to the band-gap bowing of the Zn\(_{1-x}\)Mn\(_x\)Se layer \(31, 34\), we have examined the effects of three values of Mn concentrations \((x = 0.02, 0.04, \text{and } 0.07)\) for the paramagnetic layer.

First, we study the tunneling time in the symmetric and the asymmetric structures, depending on the thickness of the ZnBeSe layers. The structure is called symmetric (asymmetric) if \(L_1 = L_3\) \((L_1 \neq L_3)\). Figure 2 shows the spin-tunneling time as a function of thickness \(L_2\) of the Zn\(_{1-x}\)Mn\(_x\)Se layer. When \(L_2\) is zero, the tunneling time is independent of the spin orientation and hence \(\tau_{\uparrow} = \tau_{\downarrow}\). At \(x = 0.02\) [Fig. 2(a)] and with increasing \(L_2\), the tunneling time oscillates for both spin-up and spin-down electrons; however, the length period of oscillations for \(\tau_{\uparrow}\) is shorter than \(\tau_{\downarrow}\). At this concentration, the paramagnetic layer has its minimum value of band-gap, which is smaller than the band gap of the ZnSe layers \(31\). In the case of \(x = 0.04\) [Fig. 2(b)], the oscillation does not change considerably for spin-down electrons, but the length period significantly increases for the spin-up ones. At \(x = 0.07\), the tunneling time oscillates only for spin-down electrons, as shown in Fig. 2(c). It is important to note that at \(x \approx 0.04\) and under zero magnetic field, the band gap of Zn\(_{1-x}\)Mn\(_x\)Se is nearly the same as that of ZnSe, while for larger values of \(x\) such as \(x = 0.07\), the Zn\(_{1-x}\)Mn\(_x\)Se layer behaves as a potential barrier in comparison with the ZnSe layers \(34\).

The appearance of oscillatory and non-oscillatory behaviors in the tunneling time is due to the effective potential \(U_{\alpha z}(z)\) and reflects this fact that the difference
FIG. 3: (Color online) Spin-tunneling time for electrons traversing the asymmetric structure: $L_1 = 10 \, \text{Å}$ and $L_3 = 90 \, \text{Å}$. The dashed and solid lines correspond to spin-up and spin-down electrons, respectively.

between the position of the Fermi energy and the bottom of the conduction band on the energy axis for each spin orientation in the paramagnetic layer has dominant effect on the behavior of spin-tunneling time. The physical origin of the oscillatory behavior is explained by the quantum well states. As is well known for resonant tunneling through double-barrier structures [35, 36], when the incident energy of electrons coincides with the energy of a quasibound state in the quantum well, a resonance condition is fulfilled and the transmission coefficient of the electrons through the heterostructure strongly increases. On the other hand, the position of the quantum well states, formed in the Zn$_{1-x}$Mn$_x$Se layer, strongly depends on the well thickness $L_2$. Therefore, with continuous variation in $L_2$, the position of the resonant states varies and this leads to the oscillations of the tunneling time. As a remarkable feature in the oscillations, one can see sharp dips in comparison with the broad peaks in the tunneling time curves, which correspond to the narrowing of the width of resonant bands arising from confinement of electrons to the paramagnetic layer. With increasing $L_2$, these narrow bands (levels) quickly cross the energy of incident electrons in the left ZnSe layer on the energy axis, the tunneling time decreases, and the sharp dips appear. In contrast, the peaks are broad, due to the broad gaps between the discrete resonant levels in the ZnMnSe layer.

Figs. 3 and 4 show the spin-tunneling times in two asymmetric structures: (i) case $L_1 < L_3$ where $L_1 = 10 \, \text{Å}$ and $L_3 = 90 \, \text{Å}$; (ii) case $L_1 > L_3$ where $L_1 = 90 \, \text{Å}$ and $L_3 = 10 \, \text{Å}$. In the case of $L_1 < L_3$ (Fig. 3), the spin-tunneling times are almost increasing functions of $L_2$ and there is no oscillation between $\tau_\uparrow$ and $\tau_\downarrow$ in all three Mn concentrations. In contrast, for the case of $L_1 > L_3$ (Fig. 4), the spin-tunneling times show oscillatory behavior very similar to those of the symmetric structure ($L_1 = L_3$). The reason for discrepancy in the tunneling time of two asymmetric structures is that the voltage drop within the ZnBeSe and ZnMnSe layers depends on the position $z$ [see the last term in $U_{\sigma_z}(z)$], and hence, the depth of quantum well in the paramagnetic layer strongly depends on the position of the layer with respect to the origin. Therefore, in the case of $L_1 > L_3$, the incident electrons see a deeper quantum well with respect to the the case of $L_1 < L_3$, and this affects the features of the resonant states. If we increase the bias voltage, the oscillatory behavior in the asymmetric structures with $L_1 < L_3$ appears, too. These results may be important from experimental point of view and indicate that special care must be taken during sample growth in order to make a magnetic RTD with low power consumption, high speed, and greater spin-filter efficiency [14].
is necessary to point out that the effects of the width of the paramagnetic layer on the spin-dependent current densities in such a magnetic RTD have been studied and the oscillatory behaviors in the current-voltage characteristics reported [11].

Now, for further understanding of the quantum size effects of the system on the spin-tunneling times, we calculate the degree of spin polarization of the tunneling electrons, which can be defined as
\[ P = \frac{(\tau_\uparrow - \tau_\downarrow)}{(\tau_\uparrow + \tau_\downarrow)}. \]
The results are plotted in Fig. 5 for both the symmetric and the asymmetric structures. It is clear that the value of spin polarization can be greatly changed by the Mn concentration, the thickness of the ZnMnSe layer as well as the status of structural symmetry. At \( x = 0.07 \) and with increasing \( L_2 \), the spin polarization retains positive and its value increases almost linearly and reaches nearly 100\%, indicating an excellent spin filtering effect. This means that for this value of \( x \) and in all the structures, the tunneling process of spin-up (spin-down) electrons is always a slow (quick) process. In the cases of \( x = 0.02 \) and \( x = 0.04 \), however, the spin polarization can change sign for particular ranges of \( L_2 \) in the structures with \( L_1 = L_3 \) and \( L_1 > L_3 \). Therefore, the case of \( \tau_\uparrow > \tau_\downarrow \) or \( \tau_\uparrow < \tau_\downarrow \) may strongly depend on the thickness of the paramagnetic layer.

According to the above results, the tunneling process of the spin-polarized electrons through the magnetic RTD can be divided into slow and quick processes. However, we cannot say which one of the spin orientations of the tunneling electrons always corresponds to the slow process and which one corresponds to the quick process. Such a feature occurs for Mn concentration \( x \leq 0.04 \) in both the symmetric and the asymmetric \( (L_1 > L_3) \) structures. We would like to point out here that our calculations have been performed under the assumption of a phase-coherent tunneling process, which applies to heterostructures with narrow wells and barriers. When the heterostructures become thicker, we should replace the phase-coherent tunneling by a sequential process and these features will change.

### IV. CONCLUSION

Using the group velocity concept and the particle current conservation principle, we have shown how the geometry and the size of the device affect the spin-tunneling time and the degree of spin polarization of tunneling electrons in a (Zn,Mn)Se-based magnetic RTD. The tunneling time for spin-up and spin-down electrons and hence the degree of spin polarization may strongly depend on the width of the paramagnetic layer and the Mn concentration. We found that, due to the oscillatory behavior of spin-tunneling time with increasing thickness of the (Zn,Mn)Se layer, special care should be taken for designing a magnetic RTD with high efficiency. Furthermore, the present results may open a new way to control the degree of spin polarization and design the high speed magnetic devices.

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