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# Asymmetry and separation of spin tunneling time in $ZnSe/Zn_{1-x}Mn_xSe$ multilayers

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**Abstract.** We investigate characteristics of spin tunneling time in $ZnSe/Ze_{1-x}Mn_xSe$ multilayers under the influence of both an electric field and a magnetic field. The results indicate that the tunneling time shows complicated oscillations and significant spin separation for electrons with different spin orientations traversing semimagnetic semiconductor heterostructures. It is also shown that the tunneling time exhibits obvious asymmetry in opposite tunneling directions for electrons tunneling through asymmetric heterostructures, which mainly occurs in resonant regions. The degree of the asymmetry of the tunneling time is not only spin-polarization dependent but also external-field induced.

**PACS.** 72.25.-b Spin polarized transport – 75.75.+a Magnetic properties of nanostructures

## 1 Introduction

The last decade brought a revival of the interest in the time scale of tunneling. They are not only of intrinsic interest in quantum mechanics but also clearly important in a wide range of situations where a tunneling entity interactions with additional degrees of freedom, which can adjust to the time development of the tunneling process [1–8]. The new wave of interest was partly due to the need to understand the dynamics of tunneling in the context of high-speed devices based on semiconductor tunneling structures. In spite of the large published literature on the tunneling time, there is still much controversy and no consensus has yet emerged in the academic community regarding the definition of tunneling time because time is not an operator in quantum mechanics; see, for example, the review paper [1] and references therein.

Recently the nascent field "spintronics" has attracted considerable attention [9–23]. The idea of spintronic devices exploit both the charge and spin of an electron for their operation. Experimentally, several groups have been able to demonstrate the efficient electrical injection of spin-polarized electron or hole current into GaAs using semimagnetic semiconductor and ferromagnetic semiconductor epilayers, respectively [11–14]. Jedema *et al.* [15] reported room temperature electrical injection and detection of spin current and observed spin accumulation in an all mesoscopic spin valve. Very recently there has achieved a significant advance towards the realization of multifunctional semiconductor spintronics by Malajovich *et al.* [17]. They studied GaAs/ZnSe heterostructures as building blocks for semiconductor spintronics and found that the efficiency for injecting spin from GaAs to ZnSe is significantly enhanced by applying an electrical bias. Theoretically, Sugakov and Yatskevich [18] examined spin splitting in parallel electric and magnetic fields through a double-barrier heterojunction. Egues [19] investigated spin-polarized transport through a $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure with a single paramagnetic layer and found a strong suppression of the spin-up component of the current density while increasing magnetic fields. We have demonstrated that the electric field can greatly change the status of spin polarization in the semimagnetic semiconductor system [20]. Moreover, we have also investigated spin resonant suppression and enhancement effects [21], quantum size effect and temperature effect on spin-polarized transport in $ZnSe/Zn_{1-x}Mn_xSe$ multilayers [22], as well as spin-resonant splitting in magnetically semimagnetic semiconductor superlattices [23].

In the present paper we explore characteristics of the tunneling time for spin-polarized electrons traversing symmetric and asymmetric semimagnetic semiconductor multilayers. The studies indicated that the tunneling time shows drastic spin-dependent oscillations for electrons tunneling through these kinds of multilayers. In asymmetric multilayers, the tunneling time displays interesting asymmetry in opposite tunneling directions.

## 2 Method

Consider a spin-polarized electron traversing a magnetic-field tunable $ZnSe/Zn_{1-x}Mn_xSe$ heterostructures with

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double paramagnetic layers under an external electric field. In Mn-based systems electrons interact with the $3d$ electrons of the localized magnetic moments of the Mn ions *via* the *sp-d* exchange interaction. This interaction gives rise to a giant effective Zeeman effect in an external magnetic field, which lifts the degeneracy of the spin-up and spin-down electron states [24]. Within mean field and for a magnetic field along the $z$-axis, the *sp-d* exchange interaction gives rise to a spin-dependent potential $V_{\sigma_z} = -N_0\alpha\sigma_z x\langle S_z\rangle[\Theta(z)\Theta(L_\mathrm{l}-z)+\Theta(z-L_\mathrm{l}-L_\mathrm{m})\Theta(L_\mathrm{l}+L_\mathrm{m}+L_\mathrm{r}-z)]$ in the Hamiltonian of the system. Here, $N_0\alpha$ is the electron *sp-d* exchange constant, $\sigma_z$ is the electron spin components $\pm 1/2$ (or $\uparrow$, $\downarrow$) along the field, $x$ is the Mn concentration, $\langle S_z\rangle$ is the thermal average of the Mn spin components along the magnetic field (a 5/2 Brillouin functions), $\Theta(z)$ is the Heaviside function, $L_\mathrm{l}$ and $L_\mathrm{r}$ are the widths of left and right paramagnetic layers, and $L_\mathrm{m}$ is the width of the ZnSe layer within two paramagnetic layers. Under an applied bias $V_\mathrm{a}$ along the $z$-axis, an electric-field-induced term $-eV_\mathrm{a}z/L_\mathrm{t}$ ($L_\mathrm{t} = L_\mathrm{l} + L_\mathrm{m} + L_\mathrm{r}$) should be added to the potential $U_\mathrm{eff}(z) = V_{\sigma_z} - eV_\mathrm{a}z/L_\mathrm{t}$. It is important to note that $U_\mathrm{eff}$ is both spin dependent and external electric- and magnetic-field induced.

In the absence of any kind of electron scattering the motion along the $z$-axis is decoupled from that of the $x$-$y$ plane. The in-plane motion is quantized in Landau levels with energies $E_n = (n + 1/2)\hbar\omega_\mathrm{c}$, where $n = 0, 1, 2, \cdots$ and $\omega_\mathrm{c} = eB/m_\mathrm{e}^*$ [19]. In this work we assume a single electron mass $m_\mathrm{e}^* = 0.16m_\mathrm{e}$ through the heterostructure, where $m_\mathrm{e}$ is the mass of a free electron. Therefore, the Schrödinger equation of the reduced one-dimensional (1D) motion along the $z$-direction can be written as

$$-\frac{\hbar^2}{2m_\mathrm{e}^*}\frac{\mathrm{d}^2\Psi(z)}{\mathrm{d}z^2} + U_\mathrm{eff}(z)\Psi(z) = E_z\Psi(z). \tag{1}$$

They are going to be useful for defining the tunneling time if we introduce

$$\tan\theta_{\sigma_z}(z, B, V_\mathrm{a}) = \frac{\mathrm{d}\Psi(z)}{\mathrm{d}z}/|\gamma_{\sigma_z}(z, B, V_\mathrm{a})|\Psi(z), \tag{2}$$

where

$$\gamma_{\sigma_z}(z, B, V_\mathrm{a}) = \mathrm{i}\sqrt{2m_\mathrm{e}^*(E_z - U_\mathrm{eff})}/\hbar \tag{3}$$

is the propagation constant. The average probability current density can be written as

$$S(z) = \frac{\hbar}{m_\mathrm{e}^*}|\gamma_{\sigma_z}(z, B, V_\mathrm{a})||\Psi(z)|^2\mathrm{Im}[\tan\theta_{\sigma_z}(z, B, V_\mathrm{a})]. \tag{4}$$

One of the most intuitive definitions of the tunneling time is based on the group velocity concept, namely $\tau = \int \mathrm{d}z/v_\mathrm{g}(z)$. This definition has been shown to be equivalent to the Bohm definition of the tunneling time [2]. Since $S(z) = v_\mathrm{g}(z)|\Psi(z)|^2$, therefore, the tunneling time becomes

$$\tau_{\sigma_z}(E_z, B, V_\mathrm{a}) = \frac{1}{\hbar}\int_0^{L_t}\frac{m_\mathrm{e}^*}{|\gamma_{\sigma_z}(z, B, V_\mathrm{a})|\mathrm{Im}[\tan\theta_{\sigma_z}(z, B, V_\mathrm{a})]}\mathrm{d}z. \tag{5}$$

Under the influence of an applied bias, the wave functions in each region can be written as

$$\Psi(z) = \begin{cases} \mathrm{e}^{\mathrm{i}k_1 z} + r\mathrm{e}^{-\mathrm{i}k_1 z}, & z < 0, \\ C_{21}A_i(\rho) + C_{22}B_i(\rho), & 0 < z < L_\mathrm{l}, \\ C_{31}A_i(\rho) + C_{32}B_i(\rho), & L_\mathrm{l} < z < L_\mathrm{l} + L_\mathrm{m}, \\ C_{41}A_i(\rho) + C_{42}B_i(\rho), & L_\mathrm{l} + L_\mathrm{m} < z < L_\mathrm{t}, \\ t\mathrm{e}^{\mathrm{i}k_2 z}, & z > L_\mathrm{t}, \end{cases} \tag{6}$$

where $k_1 = \sqrt{2m_\mathrm{e}^*E_z}/\hbar$, $k_2 = \sqrt{2m_\mathrm{e}^*(E_z + eV_\mathrm{a})}/\hbar$; $A_i(\rho)$ and $B_i(\rho)$ are Airy functions with $\rho = (2m_\mathrm{e}^*eF/\hbar^2)^{1/3}(z+\eta)$, $\eta = [1/(eF)](E_z - U_\mathrm{eff})$, and $F = V_\mathrm{a}/L_\mathrm{t}$ is the strength of the applied electric field in the ZnSe or $\mathrm{Zn}_{1-x}\mathrm{Mn}_x\mathrm{Se}$ regions [25]; $r$ and $\tau$ are reflection and transmission amplitudes; and $C_{ij}$ are constants. Therefore, to account for propagation through a semimagnetic semiconductor heterostructure, the general form of the wave function at a given $z$ value is $\Psi_i(z) = C_{i1}\Phi_{i1}(z) + C_{i2}\Phi_{i2}(z)$. The constants $C_{i1}$ and $C_{i2}$ can be determined from a system of equations by $\Psi(z)$ and its derivative for the same $z$ value. Once $C_{i1}$ and $C_{i2}$ are determined, a transfer matrix ($s$) can be written that relates $\Psi$ and $\Psi' = \mathrm{d}\Psi/\mathrm{d}z$ at two positions $z$ and $z'$

$$\begin{pmatrix}\Psi'(z)\\ \Psi(z)\end{pmatrix} = \begin{pmatrix}s_{11} & s_{12}\\ s_{21} & s_{22}\end{pmatrix}\begin{pmatrix}\Psi'(z')\\ \Psi(z')\end{pmatrix}. \tag{7}$$

Since $\Psi'/\Psi = |\gamma_{\sigma_z}|\tan\theta_{\sigma_z}$, the value of $\tan\theta_{\sigma_z}$, which determines the tunneling time at position $z$, can be written in terms of that at position $z'$ as follows

$$\tan\theta_{\sigma_z}(z, B, V_\mathrm{a}) = \frac{1}{|\gamma_{\sigma_z}(z, B, V_\mathrm{a})|}\frac{s_{11}|\gamma_{\sigma_z}(z', B, V_\mathrm{a})|\tan\theta_{\sigma_z}(z', B, V_\mathrm{a}) + s_{12}}{s_{21}|\gamma_{\sigma_z}(z', B, V_\mathrm{a})|\tan\theta_{\sigma_z}(z', B, V_\mathrm{a}) + s_{22}}. \tag{8}$$

## 3 Results and analyses

Figure 1 shows the tunneling time as a function of the incident energy $E_z$ under three different magnetic fields. The $\mathrm{ZnSe}/\mathrm{Zn}_{1-x}\mathrm{Mn}_x\mathrm{Se}$ multilayers are symmetric heterostructures with double paramagnetic layers. It can be observed that the tunneling time is strongly dependent on both spin orientations of tunneling electrons and the external magnetic field. As the magnetic field increases, the tunneling time significantly prolongs and displays obvious oscillations for spin-up electrons, while it is essentially decaying and shows complex variations with the incident energy for spin-down ones. The difference of the tunneling time can reach up to several orders of magnitude between the two cases for electrons with different spin orientations. Further, the difference is enlarged with the increasing of the magnetic field while lessened with the increasing of the incident energy. The above features strongly indicate that it takes electrons quite different time if electrons carry

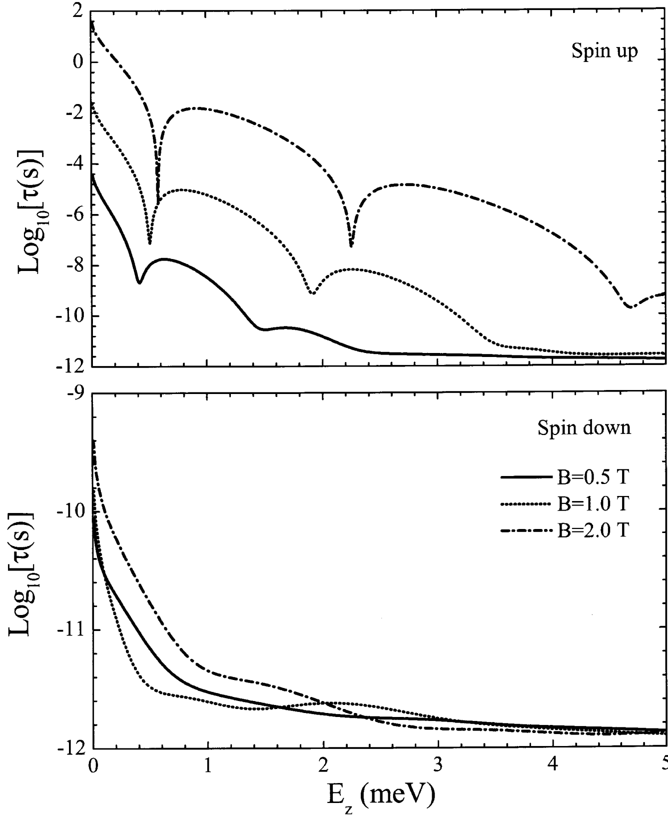


**Fig. 1.** The tunneling time for spin-polarized electrons traversing a symmetric $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure with double paramagnetic layers under three different magnetic fields. $L_l = L_m = L_r = 500$ Å, $V_a = 0$ mV, $B = 0.5, 1.0, 2.0$ T.

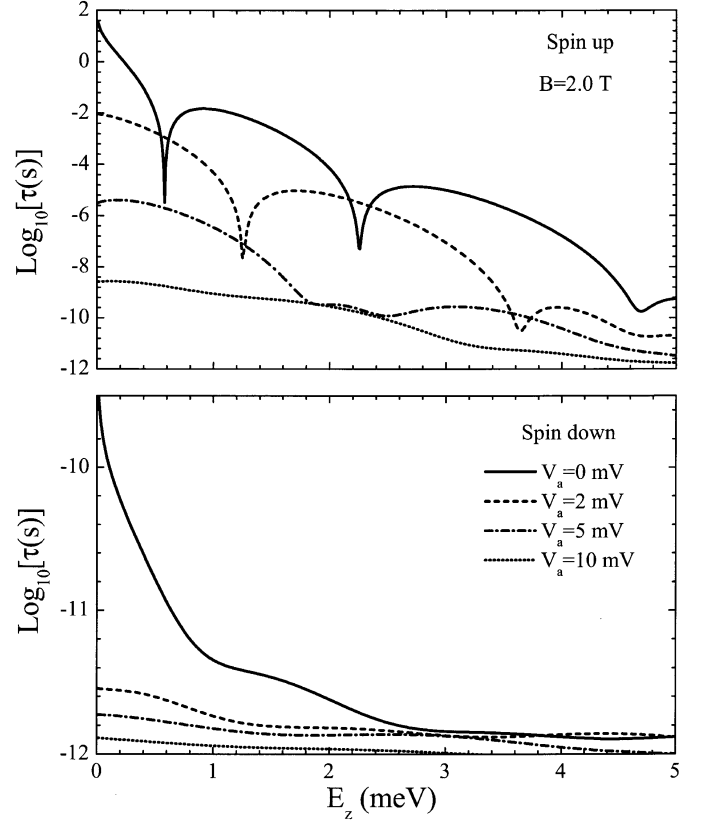


**Fig. 2.** The tunneling time for spin-polarized electrons traversing a symmetric $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure with double paramagnetic layers under zero and three applied biases. $L_l = L_m = L_r = 500$ Å, $V_a = 0, 2, 5, 10$ mV, $B = 2$ T.

different spin orientations through the same heterostructure. If electrons with different spin orientations tunneling through the same structure at the same time, they are separated at the end of the whole tunneling process. It is known that in an external magnetic field, each paramagnetic layer in the band-gap-matched $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure behaves as a potential well for spin-down electrons and a potential barrier for spin-up ones [19–24]. As the magnetic field increases, the potential barrier becomes higher and higher while the potential well becomes deeper and deeper, which result in obvious magnetic-field-induced spin polarization and spin separation in time.

In Figure 2 we plot the tunneling time as a function of the incident energy under zero and several applied biases $V_a = 0, 2, 5, 10$ mV, where the heterostructure is exactly the same as that examined in Figure 1. The magnetic field is set to be $B = 2.0$ T. One can easily see that as the electric field increases, the tunneling time is drastically shortened, especially for electrons with a smaller incident energy. The magnitudes of the oscillations of the tunneling time for spin-up electrons decrease with the increasing of the electric field. The curves are smoothed out and its dips become shallower. Moreover, the discrepancy of the tunneling time for electrons with different spin orientations is obviously decreased. From Figures 1 and 2 in the present work and Figure 2 in reference [21], one can easily see that the tunneling time has relative minima at those values of the incident electron energy where the transmission coefficient has relative maxima. These features are more obviously revealed in the tunneling time for spin-up electrons. The electric-field dependent features of the tunneling time can be easily understood in terms of usual resonant-transmission picture through titled barriers and wells. In the absence of an applied bias, the effective potential has only one term, *i.e.*, $U_{\mathrm{eff}} = V_{\sigma_z}$, where the spin-dependent potential $V_{\sigma_z}$ is symmetric on the center of the heterostructure. Under an applied bias, the effective potential "seen" by electrons becomes $U_{\mathrm{eff}} = V_{\sigma_z} - eV_a z/L_t$, that is not only spin dependent but also external-field induced, thus the magnetic-field tunable potential and its symmetry can be significantly modulated. Therefore, the configuration of the effective potential becomes titled and its symmetry is broken. Another noticeable fact is that for electrons tunneling through a potential well, the tunneling time weakly depends on the depth of the well, that is determined by the external magnetic field in our considered system. Bear these facts in mind, it is not difficult to understand electric-field dependent features of the tunneling time exhibited in Figure 2.

Figure 3 shows the tunneling time for electrons traversing an asymmetric $ZnSe/Zn_xMn_{1-x}Se$ heterostructures with double paramagnetic layers, where the asymmetry

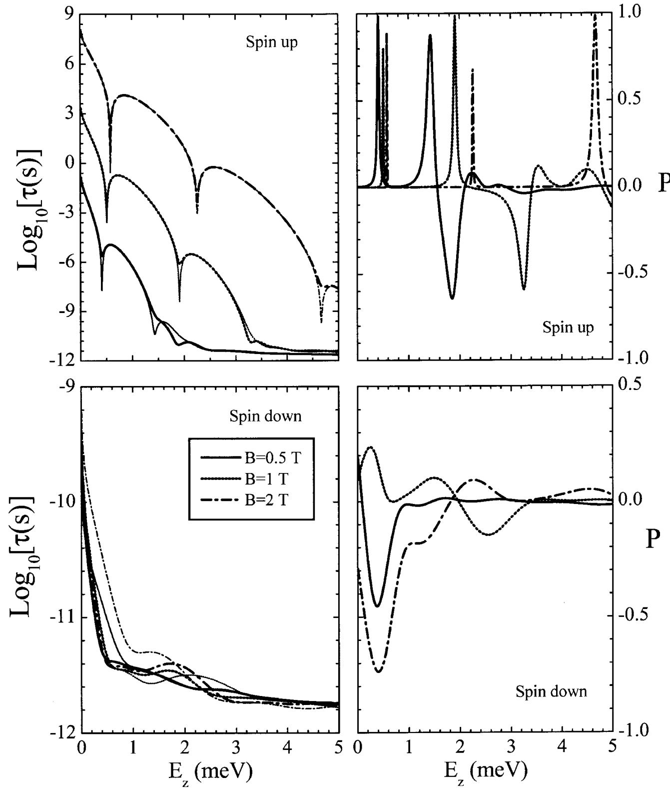


**Fig. 3.** The tunneling time and its degree of asymmetry for spin-polarized electrons traversing an asymmetric $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure with double paramagnetic layers under three different magnetic fields. Thick lines: $L_l = L_m = 500$ Å, $L_r = 1000$ Å; Thin lines: $L_l = 1000$ Å, $L_m = L_r = 500$ Å. $V_a = 0$ mV, $B = 0.5, 1.0, 2.0$ T.

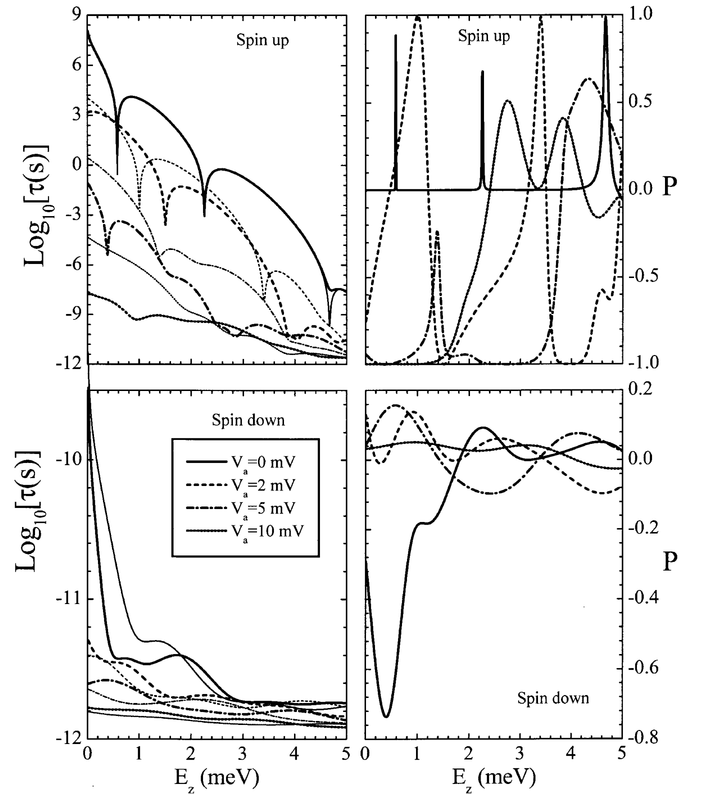


**Fig. 4.** The tunneling time and its degree of asymmetry for spin-polarized electrons traversing an asymmetric $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure with double paramagnetic layers under zero and three applied biases. Thick lines: $L_l = L_m = 500$ Å, $L_r = 1000$ Å; Thin lines: $L_l = 1000$ Å, $L_m = L_r = 500$ Å. $V_a = 0, 2, 5, 10$ mV, $B = 2.0$ T.

is introduced by the difference of the widths of the two paramagnetic layers. The thick lines in Figure 3 refer to the left-to-right direction of tunneling while the thin ones correspond to the right-to-left tunneling direction. An obvious difference of the tunneling time between these two situations can be observed. For spin-up electrons, the difference mainly occurs in the vicinity of dips, where the transmission coefficient has relative maxima. In order to see clearly to what extent the asymmetry of the tunneling time is, we define the degree of the asymmetry as $P_\sigma = (\tau_{l\to r} - \tau_{r\to l})/(\tau_{l\to r} + \tau_{r\to l})$, where $\tau_{l\to r}$ and $\tau_{r\to l}$ are left-to-right and right-to-left tunneling time. We see that the degree of asymmetry shows spin-polarization dependent and field-induced oscillations. $P_\uparrow$ has several sharper peaks and deeper valleys in the vicinity of the dips of the tunneling time, while $P_\downarrow$ shows oscillations with smaller magnitudes. The latter are decreased with the increasing of the incident energy. Under an applied bias, the tunneling time decreases and its dips become shallower (see Fig. 4). As the electric field increases, $P_\downarrow$ is further decreased, while $|P_\uparrow|$ can be larger values in the wide region of the incident energy. It is found that there are several values of the energy for which the tunneling time in both directions become equal. Under $V_a = 0$, $P_\uparrow$ almost keeps zero except several sharp peaks. For these energy values the geometric asymmetric structure becomes symmetric with respect to the tunneling time. The fact that the tunneling time from left to right and from right to left are different while the transmission coefficient is the same can be explained as follows [3,26]. The tunneling time for a symmetric structure at resonance is given by $\tau = 2\hbar/\Gamma$, where $\Gamma$ is the decay width of the resonant energy level. In general, $\Gamma = \Gamma_1 + \Gamma_2$, where $\Gamma_1$ and $\Gamma_2$ are the partial widths for decay to left and right. The transmission coefficient at resonance depends only on $\Gamma$, while the tunneling time from left to right and from right to left depend on $\Gamma_1$ and $\Gamma_2$, respectively. In an asymmetric structure, $\Gamma_1 \neq \Gamma_2$, so that at resonance the transmission coefficient is the same while the tunneling time is different.

## 4 Concluding remarks

In summary, the tunneling process exhibits complex oscillations and significant spin separation in the time scales for electrons with different spin orientations traversing semimagnetic semiconductor multilayers. The process of spin-up tunneling is slow and has low transmission, while that of spin-down tunneling is quick and has high transmission. For electrons tunneling through asymmetric

multilayers, the tunneling time shows obvious asymmetry. The degree of the asymmetry is not only spin-polarization dependent but also external-field induced. The results obtained in the present work might shed some light on understanding and designing spintronic optoelectronic devices.

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