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Spin-dependent delay time and the Hartman effect in tunneling through diluted-magnetic-semiconductor/semiconductor heterostructures

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We investigate spin-dependent group delay and dwell time in diluted-magnetic-semiconductor/semiconductor (DMS/S) heterostructures, where the *sp-d* exchange interaction gives rise to a giant spin splitting when an external magnetic field applied along the growth direction of the heterostructures. It is found that both the group delay and the dwell time strongly depend not only on the incident energy and the structural configuration, but also on spin orientations. In the spectra of both the group delay and the dwell time, there are some sharp peaks with larger peak-to-valley ratios for spin-up electrons through the DMS/S heterostructures with a single or double DMS layers, while the curves become more smoothed for spin-down ones through the same heterostructure. The difference of the group delay or of the dwell time between spin-up and spin-down cases reaches its maximum when resonant tunneling occurs. The numerical results indicate that the spin-up and spin-down processes are separated on the time scales. Further, for spin-down electrons, the group delay can be negative at low energy under some magnetic fields.

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I. INTRODUCTION

Recently, considerable progress has been achieved in the nascent field of "spintronics," where spin of an electron or both the charge and spin of it are exploited for device operations (see, for example, the review papers Refs. 1,2 and references therein). Experimentally, several groups succeeded in generating spin-polarized current across nonmagnetic/magnetic semiconductor interfaces, at least at low temperature. Fiederling *et al.*[3] used $Be_xMn_yZn_{1-x-y}Se$ as the spin-aligning diluted magnetic layer while Ohno *et al.*[4] used manganese-doped GaAs. In these two cases, the researchers passed their spin-polarized current into a GaAs-based light-emitting diode with an efficiency of about 90% and 2%, respectively. Jonker and his coworkers[5] have performed similar experiments using paramagnetic ZnMnSe as the spin alingner and observed about 50% optical polarization. Gruber *et al.*[6] proposed and demonstrated the use of magnetic resonant tunneling diodes based on BeTe/ZnMnSe/BeTe structures. Van Dorpe *et al.*[7] demonstrated an electrically injected electron spin polarization in GaAs of 80% at 4.6 K by interband tunneling from the valence band of GaMnAs into an AlGaAs light-emitting diode. In the past few years, tunneling magnetoresistance (TMR) in ferromagnetic semiconductor heterostructures have reserved some progress. Chiba *et al.*[8] reported a TMR ratio of 5.5% at 20 K in a $Ga_{1-x}MnAs/AlAs/Ga_{1-x}Mn_xAs$ trilayer. Tanaka and Higo[9] observed very large TMR in epitaxially grown $Ga_{1-x}Mn_xAs/AlAs/Ga_{1-x}Mn_xAs$ ferromagnetic semiconductor tunnel junctions. However, presently, some doubts remain on the possibility of obtaining a magnetic semiconductor with a high Curie temperature. Another alternative to achieve spin injection in semiconductors (S) is injecting from a ferromagnetic metal F. Although significant effort has been made to incorporate F into S spintronic devices because they offer high Curie temperatures and a ready source of spin-polarized electrons, there exist two difficulties. One is the technical difficulties of combining the growth of F and S, the other is the conductivity mismatch between F and S, which prevent the direct injection from a low-resistive ferromagnetic material.[10] Fortunately, it has been shown that this obstacle can be overcome if the interface resistance dominates, such as when the carriers are injected from F into S by tunneling through a barrier.[11–14] Hanbicki *et al.*[15] observed a net electron spin polarization of 32% in a GaAs quantum well due to electrical spin injection from an Fe/AlGaAs reverse-biased Schottky contact, and pointed out that tunneling is the dominant transport mechanism enabling significant spin injection across the F/S interface.

Theoretically, spin-dependent tunneling through diluted-magnetic-semiconductor/semiconductor (DMS/S) heterostructures has been investigated extensively. Sugakov and Yatskevich[16] examined spin splitting in parallel electric and magnetic fields through a double-barrier heterojunction using the transfer-matrix method. Egues[17] 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. Egues and his coworkers also studied the magnetic-field dependence of exchange-induced energy splittings and spin-flip scattering in digital-magnetic heterostructures[18] as well as spin filtering and magnetoresistance in nonmagnetic/DMS heterostructures.[19] One of us and our coauthors have demonstrated several effects on spin-polarized transport in DMS/S heterostructures, such as the electric field effect, spin-dependent resonant enhancement and suppression effects as well as spin-dependent splitting effect.[20] Béjar *et al.*[21] and Sánchez *et al.*[22] analyzed spin transport and spin dynamics in the similar DMS/S systems. Li *et al.*[23] reported spin-dependent transport through DMS quantum dots.

With the advance on miniaturizing tunneling semiconductor devices, the time aspect of the tunneling process has been the focus of much research in the last decade. Beyond its

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intrinsic quantum mechanics interest, the significance of tunneling time comes from the requirement of understanding the tunneling dynamics in high-speed devices due to the fact that the time is one of key parameters for ultimate performance evaluation of different kinds of electronic devices.[24–39] Therefore, since Condon and Morse[24] posed the question of the alacrity of the tunneling process, even for a simple single-barrier potential, the tunneling time has been studied extensively by various theoretical approaches, such as phase-delay method,[25] dwell time approach,[26] Larmor Clock time and its generalizations,[27] and the wave packets evolvement method.[28] In 1932 MacColl[29] asserted that there is "no appreciable delay" in the transmission of the packet through the barrier. However, Hartman[30] later showed that there is a finite delay but that this delay is shorter than the equal time (the time a particle of equal energy would take to traverse the same distance in the vacuum). This effect was called the "Hartman effect." Up to now, although there exists a great deal of published literature on the tunneling time, there is still much controversy and none of the methods is unanimously accepted in the academic community regarding the definition of tunneling time; see, for example, the review papers Refs. 28,31,32 and references therein. The reason is that time is not an operator in quantum mechanics. The time characteristics introduced in the above-mentioned methods in published works really describe different aspects of electron dynamics and can be extracted from corresponding optical or transport experiments.

Very recently Winful[33] derived a general and explicit relation between the group delay and the dwell time for quantum tunneling, thus unifying these two approaches to a tunneling time. He found that the group delay is equal to the dwell time plus a self-interference delay, which depends on the dispersion outside the barrier. The Hartman effect in quantum tunneling is explained on the basis of saturation of the integrated probability density (or number of particles) under the barrier, which itself is proportional to the group delay.

How long does an electron with spin tunnel through a DMS/S heterostructures? This question is of much importance both from theoretical and practical points of view. In the present work we extended Winful's theory to spin-dependent process and revealed spin separation during the tunneling process of spin-polarized electrons through DMS/S systems. It is shown that both the group delay and the dwell time are strongly determined not only by the incident energy and the structural configuration but also by spin orientations. For spin-up electrons through DMS/S heterostructures with multiple DMS layers, there appear some very sharp peaks in the spectra of both the group delay and the dwell time, that correspond to the resonant tunneling. For the spin-down electrons of the low energy, however, the group delay can be positive or negative, and its spectrum becomes more smoothed.

II. SPIN-DEPENDENT TIME IN DMS/S HETEROSTRUCTURES

Now we consider electrons with spin tunneling through DMS/S heterostructures with a single or double paramagnetic layers. An external magnetic field is applied to the system along the z direction. The effective Hamiltonian can be written as follows:

$$H = \frac{(\vec{P} + e\vec{A})^2}{2m_e^*} + V_0(z) + V_s + V_{\sigma_z}(z), \tag{1}$$

where m_e^* and $\vec{P}$ are the electron effective mass and the momentum operator, respectively, $\vec{A}$ is the vector potential, $V_0(z)$ is the zero magnetic field potential profile of DMS/S heterostructures, and $V_s=(1/2)g_s\mu_B\vec{\sigma}\cdot\vec{B}$ describes the Zeeman splitting of the electron. 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. In an external magnetic field this interaction gives rise to a giant effective Zeeman effect, which lifts the degeneracy of the spin-up and spin-down electron states.[40] Within the molecular-field approximation, the giant Zeeman term V_{σ_z} has the empirical form

$$V_{\sigma_z} = -N_0\alpha\sigma_z x_{\text{eff}}\langle S_z\rangle. \tag{2}$$

Here $N_0\alpha$ is the electronic sp-d exchange constant, σ_z represents the electron spin components ($\pm 1/2$ or $\uparrow, \downarrow$) along the field, x_{eff} is the phenomenological parameter (reduced effective concentration of Mn). The thermal average of the Mn spin components along the magnetic field, i.e., $\langle S_z\rangle$, can be described by a modified Brillouin function $\langle S_z\rangle = S_0 B_S[g_{\text{Mn}}\mu_B SB/k_B(T+T_0)]$, where $S=5/2$ corresponds to the spins of the localized $3d^5$ electrons of the Mn^{2+} ions, $g_{\text{Mn}}=2.0$ is the g factor of the Mn^{2+} ion, B is the applied magnetic field, μ_B is the Bohr magneton, k_B is the Boltzmann constant, T is the temperature, and T_0 accounts for the reduced single-ion contribution due to the antiferromagnetic Mn-Mn coupling. We introduce the effective potential $U_{\text{eff}}^{\sigma}(z,B)=V_0(z)+V_s+V_{\sigma_z}(z)$, that is both magnetic-field dependent and spin dependent.

In the absence of any kind of electron scattering the motion along the z axis is decoupled from the quantized in-plane one that gives Landau levels with energies $E_n=(n+1/2)\hbar\omega_c$, where $n=0, 1, 2, \ldots$, and $\omega_c=eB/m_e^*$.[17] For simplicity, in this work we assume a single electron mass m_e^* through the heterostructure. Therefore, the Schrödinger equation of the reduced one-dimensional (1D) motion along the z direction can be written as

$$-\frac{\hbar^2}{2m_e^*}\frac{d^2\Psi_\sigma(z)}{dz^2} + U_{\text{eff}}^{\sigma}(z,B)\Psi_\sigma(z) = E_z\Psi_\sigma(z). \tag{3}$$

In the stationary state description, without an applied bias, the wave functions in the left and right ZnSe semiconductor regions are free-electron wave functions, which can be written as follows:

$$\Psi_\sigma^l(z) = e^{ik_l z} + R_\sigma e^{-ik_l z} \tag{4}$$

and

$$\Psi_{\sigma}^{r}(z) = T_{\sigma}e^{ik_{r}z}, \tag{5}$$

where $k_l = k_r = \sqrt{2m_e^* E_z}/\hbar$, and R_σ and T_σ are the spin-dependent reflection and transmission amplitudes, respectively. In the $Zn_{1-x}Mn_xSe$ paramagnetic region $(0<z<L)$, the wave function can be written as

$$\Psi_{\sigma}^{P}(z) = \begin{cases} C_1 e^{ik_2^{\sigma}z} + C_2 e^{-ik_2^{\sigma}z}, & E_z > U_{\rm eff}^{\sigma} \\ D_1 e^{\xi_2^{\sigma}z} + D_2 e^{-\xi_2^{\sigma}z}, & E_z < U_{\rm eff}^{\sigma}, \end{cases} \tag{6}$$

where $k_2^{\sigma} = \sqrt{2m_e^*(E_z - U_{\rm eff})}/\hbar$, $\xi_2^{\sigma} = \sqrt{2m_e^*(U_{\rm eff} - E_z)}/\hbar$, C_1, C_2, D_1, and D_2 are constants. All these constants and R_σ and T_σ can be determined from the boundary conditions by use of the standard transfer-matrix method.

In following, we extend Winful's theory on the delay time and the dwell time to discuss the characteristics of spin-dependent time in such a reduced 1D potential. Here we restrict our discussion to S/DMS/S systems with a single DMS layer. The obtained results can be naturally extended to the more complex system, such as S/DMS/S/DMS/S systems. As for the system we discussed here, the problem can turn into a particle of energy E_z and momentum $\hbar k_z$ incident from the left upon a reduced 1D spin-dependent potential $U_{\rm eff}^{\sigma}(z,B)$ that occupies the region $0<z<L$ (L is the width of the DMS layer). The group delay (phase time) measures the delay between the appearance of a wave packet peak at the left side $(z=0)$ of the potential and its appearance at the right side $(z=L)$. It is calculated by the method of stationary phase and is given by the energy derivative of the phase shift.[25] As for electrons with spin tunneling through the S/DMS/S system, the group delay becomes spin-dependent due to spin-dependent potential. The group delay in transmission is $\tau_{gt}^{\sigma} = \hbar d\phi_0^{\sigma}/dE_z$, which measures the delay between the appearance of a transmitted wave packet peak and the incoming wave packet peak. Here $\phi_0^{\sigma} = \phi_t^{\sigma} + k_z L$ (ϕ_t^{σ} is the transmission phase shift). $\tau_{gr}^{\sigma} = \hbar d\phi_r^{\sigma}/dE_z$ denotes the group delay in reflection, measuring the delay between the appearance of a reflected wave packet peak and the incoming wave packet peak. ϕ_r^{σ} is the reflection phase shift. For symmetric barriers, there is $\tau_{gt}^{\sigma} = \tau_{gr}^{\sigma}$. For a general asymmetric barrier, it is useful to define a bidirectional group delay as the weighted sum of transmission and reflection group delays

$$\tilde{\tau}_g^{\sigma}(E_z,B) = |T_\sigma|^2 \tau_{gt}^{\sigma} + |R_\sigma|^2 \tau_{gr}^{\sigma}. \tag{7}$$

The dwell time is a measure of the time spent by an electron in the effective potential region $(0<z<L)$ regardless of whether it is ultimately transmitted or reflected. It is defined as the ratio of the number of particles within the barrier (i.e., $N = \int_0^L |\psi_\sigma(z)|^2 dz$) to the flux of the incident particles $j = \hbar k_z / m_e^*$. This definition can be understood from the classic approach. It is given by

$$\tau_d^{\sigma}(E_z,B) = \frac{m_e^* \int_0^L |\psi_\sigma(z)|^2 dz}{\hbar k_z}. \tag{8}$$

From the stationary Schrödinger Eq. (3) and its first derivative with respect to E_z,

$$\left[-\frac{\hbar^2}{2m_e^*}\frac{d^2}{dz^2} + U_{\rm eff}^{\sigma}(z,B) - E_z \right] \frac{\partial \psi_\sigma}{\partial E_z} - \psi_\sigma = 0, \tag{9}$$

one can obtain

$$\frac{\hbar^2}{2m_e^*}\frac{\partial}{\partial z}\left[\frac{\partial \psi_\sigma}{\partial E_z}\frac{\partial \psi_\sigma^*}{\partial z} - \psi_\sigma^* \frac{\partial^2 \psi_\sigma}{\partial E_z\, \partial z} \right] = \psi_\sigma^* \psi_\sigma. \tag{10}$$

Upon integration over the length of the paramagnetic layer we get

$$\left[\frac{\partial \psi_\sigma}{\partial E_z}\frac{\partial \psi_\sigma^*}{\partial z} - \psi_\sigma^* \frac{\partial^2 \psi_\sigma}{\partial E_z\, \partial z} \right]_{z=L} - \left[\frac{\partial \psi_\sigma}{\partial E_z}\frac{\partial \psi_\sigma^*}{\partial z} - \psi_\sigma^* \frac{\partial^2 \psi_\sigma}{\partial E_z\, \partial z} \right]_{z=0} = \frac{2m_e^* \int_0^L |\psi_\sigma|^2 dz}{\hbar^2}. \tag{11}$$

By use of Eqs. (4), (5), and (11) as well as the relation $|T_\sigma|^2 + |R_\sigma|^2 = 1$, we can derive the spin-dependent bidirectional group delay

$$\tilde{\tau}_g^{\sigma}(E_z,B) = \tau_d^{\sigma}(E_z,B) + \tau_i^{\sigma}(E_z,B), \tag{12}$$

where

$$\tau_i^{\sigma}(E_z,B) = -\frac{\hbar Im(R_\sigma)}{k}\frac{dk_z}{dE_z}. \tag{13}$$

The first and second terms in Eq. (12) are the dwell time and a self-interference term, respectively. The self-interference term named by Winful[33] comes from the overlap of incident and reflected waves in front of the barrier. For the S/DMS/S system considered here, both the dwell time and the self-interference term become not only magnetic-field-dependent but also spin dependent. Equation (12) is a general result that unifies two of the major tunneling times and agrees with the wave packet analysis of Hauge, Falck, and Fjeldly.[41] The result of the spin-dependent bidirectional group delay is recovered for the spinless case [see the Eq. (9) in Ref. 33] if we do not consider the spin-dependent effect.

III. RESULTS AND ANALYSIS

Now we calculated and analyzed the spin-dependent process in two DMS/S configurations. One is S/DMS/S heterostructures with a single paramagnetic layer while the other one is the S/DMS/S/DMS/S system with double paramagnetic layers. The building materials can be $ZnSe/Zn_{1-x}Mn_xSe$ or $Cd_{1-x}Mn_xTe/Cd_{1-y}Mg_yTe$. For the $ZnSe/Zn_{0.95}Mn_{0.05}Se$ heterostructures, $x=0.05$, $x_{\rm eff} = x(1-x)^{12}$, $m_e^* = 0.16 m_e$, $N_0\alpha = 0.26$ eV, $g_{\rm Mn} = 2.0$, $g_s = 1.1$, $T = 4.2$ K, $T_0 = 1.7$ K, and $S = S_0 = 2.5$. For $Cd_{0.93}Mn_{0.07}Te/Cd_{0.938}Mg_{0.062}Te$ heterostructures, $x=0.07$, $x_{\rm eff} = 0.045$, $y = 0.062$, $m_e^* = 0.096 m_e$, $N_0\alpha = 0.22$ eV, $g_{\rm Mn} = 2.0$, $T = 4.2$ K, $T_0 = 3.1$ K, $S_0 = 1.32$, and $S = 2.5$. The conduction band offset under zero magnetic field for $Cd_{1-x}Mn_xTe/Cd_{1-y}Mg_yTe$ system is $V_0 = 0.8(E_g^2 - E_g^1)$, where $E_g^1 = (1.586 + 1.51x)$eV and $E_g^2 = (1.586 + 1.705y)$eV are the

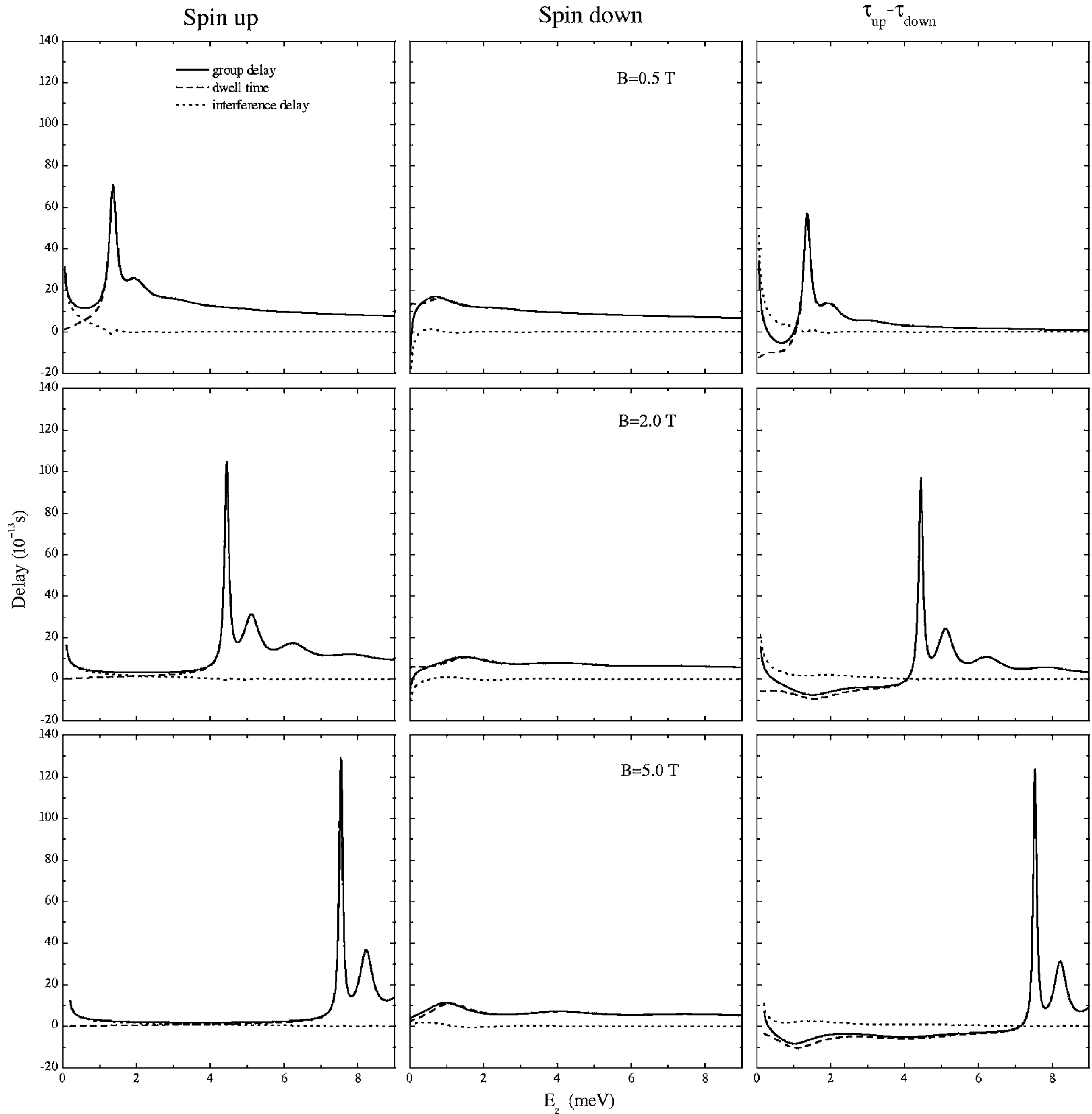

FIG. 1. Spin-dependent phase time (solid line), dwell time (dashed line), and self-interference delay (dotted line) for electrons tunneling through $ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe$ heterostructures.

band gap of $Cd_{1-x}Mn_xTe$ and $Cd_{1-y}Mg_yTe$, respectively. In this section, we mainly consider the effect of spin split on the time scales in DMS/S systems. We consider $V_0=0$ for certain concentrations x and y in the $ZnSe/Zn_{1-x}Mn_xSe$ systems and $Cd_{1-x}Mn_xTe/Cd_{1-y}Mg_yTe$ systems.[23,42]

Figure 1 shows the group delay, the dwell time, and the interference delay for electrons tunneling through $ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe$ system with a single DMS $Zn_{0.95}Mn_{0.05}Se$ layer. The width of the DMS layer is $L=1000$ Å. In the panels of the left and middle columns, solid, dashed, and dotted lines correspond to the group delay, the dwell time, and the interference delay, respectively. For lower energy, there is a significant difference between the phase time and the dwell time because of the self-interference delay. In the classical region, however, these two times become equal. It can be easily seen that all physical quantities considered here are strongly dependent on the spin orientations of the tunneling electrons. For spin-up electrons, both the group delay and the dwell time show obvious oscillations. Near the resonant peak, the transmission develops a shoulder whose intensity increases as the magnetic field does (this happens as well in Figs. 2–4). For spin-down electrons, however, both the group delay and the dwell time show weak magnetic-field-dependent and energy-dependent features. It is found that the difference of the group delay or of the dwell time between cases for two different spin orientations can

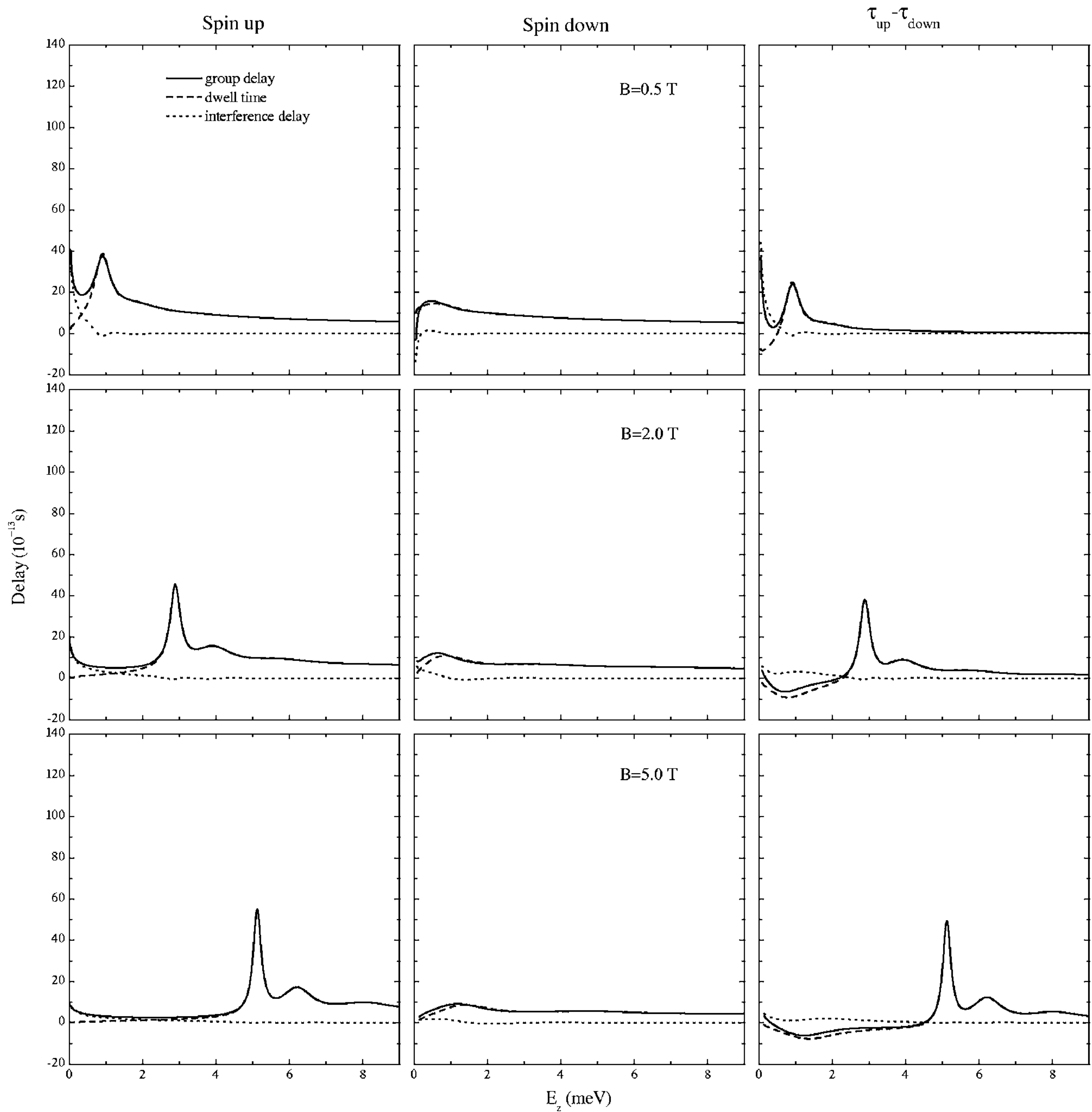

FIG. 2. Spin-dependent phase time (solid line), dwell time (dashed line), and self-interference delay (dotted line) for electrons tunneling through $Cd_{0.938}Mg_{0.062}Te/Cd_{0.93}Mn_{0.07}Te/Cd_{0.938}Mg_{0.07}Te$ heterostructures.

show inhomogenous variations (see the right column of Fig. 1): It becomes maximum at the energy where resonant tunneling occurs. Further, the difference is enhanced for increasing magnetic fields while reduced for increasing the incident energy. The above features strongly indicate that electrons with different spin orientations will spend quite different time through the same heterostructure. Therefore, the tunneling process can be time resolved with respect to the spin orientations. These results can be understood from the following. In an external magnetic field, the paramagnetic layer in the DMS/S heterostructure behaves as a potential well for spin-down electrons and a potential barrier for spin-up ones,[17,20,40] and its depth or height can be tuned by the magnetic field. Thus, as the magnetic field increases, the potential barrier becomes higher while the potential well becomes deeper. When the incident energy of the tunneling electron coincides with the energy of the quasibound states, the resonant tunneling occurs and the electron has the maximal transmission coefficient and longer spin separation time. These features result in obvious magnetic-field-induced spin polarization and spin separation on the time scales in DMS/S systems.

From the above analysis, we can divide the tunneling process of spin-polarized electrons through a DMS/S heterostrutures into two categories: slow process and quick process. Spin-down tunneling corresponds to the quick process while

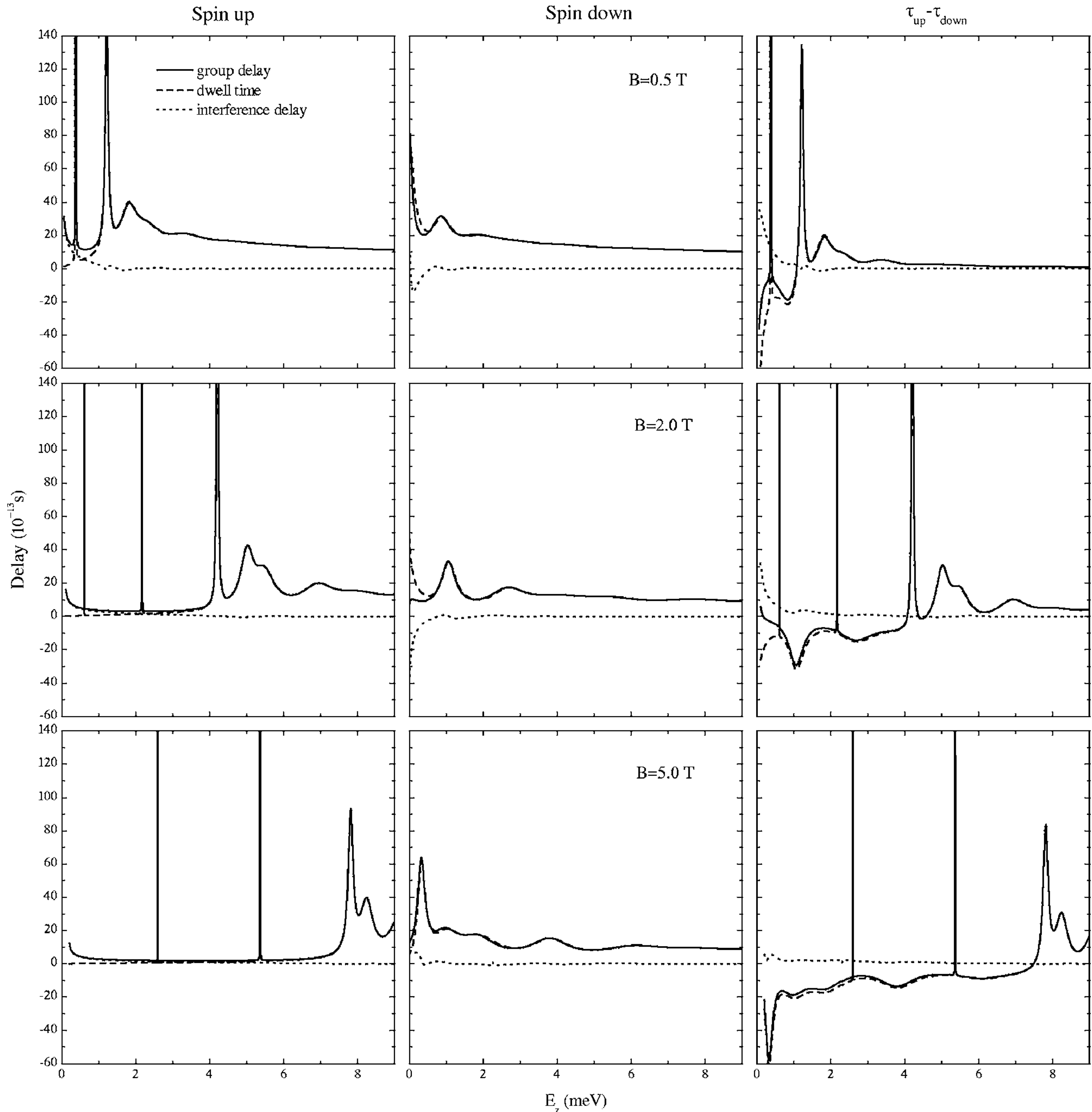

FIG. 3. Spin-dependent phase time (solid line), dwell time (dashed line), and self-interference delay (dotted line) for electrons tunneling through $ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe$ heterostructures.

spin-up tunneling corresponds to the slow one. The two processes are separated on the time scales. Further, these two kinds of processes also show quite different field-dependent features. The quick process weakly depends on the magnitude of the external magnetic field while the slow one sensitively depends on the magnitude of the magnetic field. Associated with spin-polarized characteristics revealed in Refs. 17,20, we see that for the quick process, tunneling has high transmission while for the slow process, the transmission is very small in a certain range of the magnetic field. The results strongly indicate that electrons with different spin orientations not only have quite different transmission but also are separated on the time scales within the same heterostructure.

Figure 2 shows the group delay, the dwell time, and the interference delay for electrons through $Cd_{1-y}Mg_yTe/Cd_{1-x}Mn_xTe/Cd_{1-y}Mg_yTe$ with a single DMS layer. The width of the DMS $Cd_{1-x}Mn_xTe$ layer is $L = 1000$ Å. One can see similar variations of the time versus the energy as that for $ZnSe/Zn_{1-x}Mn_xSe$ system. The typical difference is that the maximum of both the group delay and the dwell time become smaller for spin-up electrons. Therefore, the curves of the time for the $Cd_{1-y}Mg_yTe/Cd_{1-x}Mn_xTe$ case become more smoothed than that for the

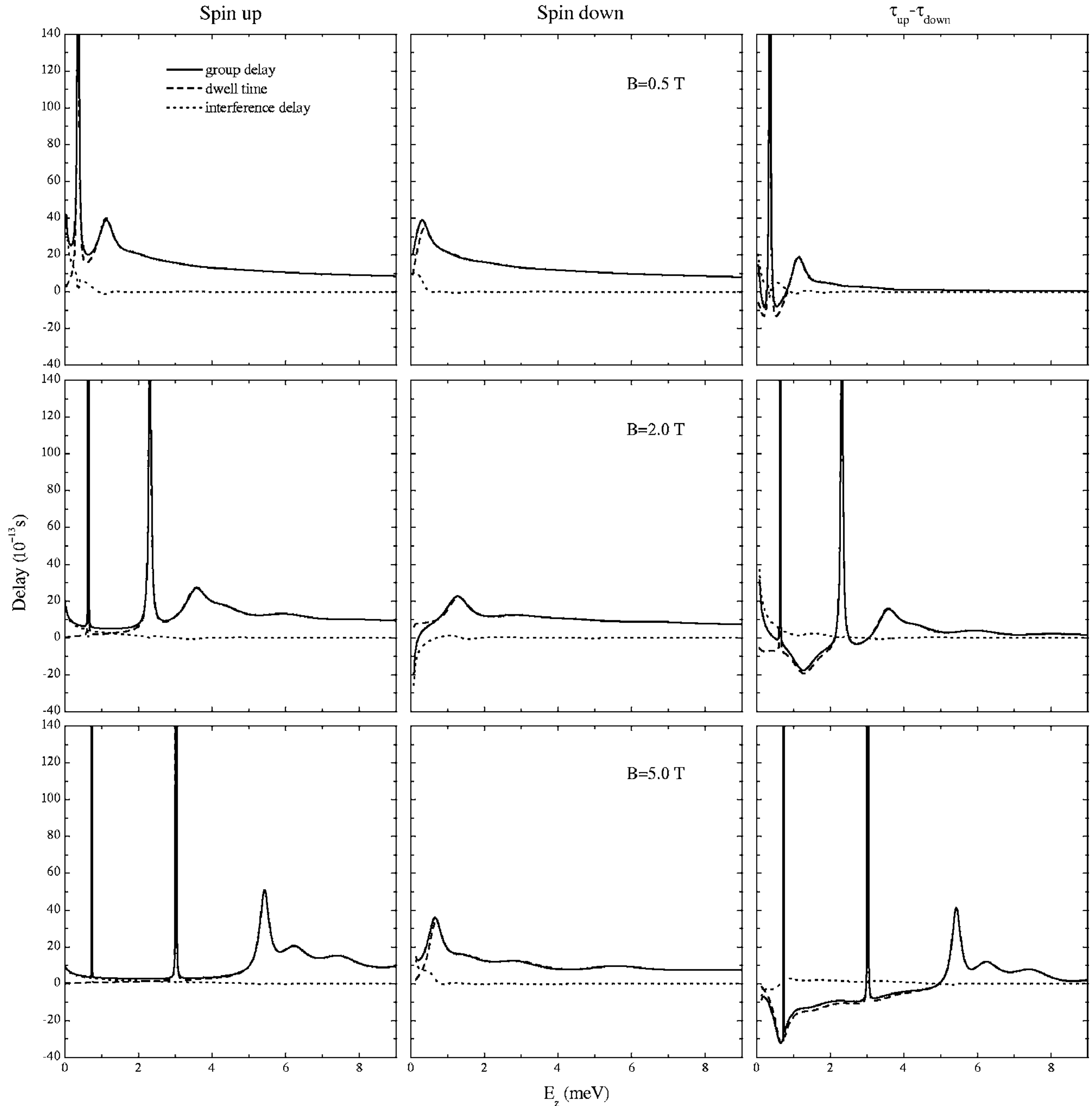

FIG. 4. Spin-dependent phase time (solid line), dwell time (dashed line), and self-interference delay (dotted line), for electrons tunneling through $Cd_{0.938}Mg_{0.062}Te/Cd_{0.93}Mn_{0.07}Te/Cd_{0.938}Mg_{0.062}Te/Cd_{0.93}Mn_{0.07}Te/Cd_{0.938}Mg_{0.062}Te$ heterostructures.

$ZnSe/Zn_{1-x}Mn_xSe$ system. The discrepancies between these two different material systems are caused by different effective potential induced by the giant Zeeman splitting.

Figures 3 and 4 show the time for electrons through $ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe$ and $Cd_{1-y}Mg_yTe/Cd_{1-x}Mn_xTe/Cd_{1-y}Mg_yTe/Cd_{1-x}Mn_xTe/Cd_{1-y}Mg_yTe$ with double DMS layers. Each layer has the same width, i.e., $L_1=L_2=L_3=500$ Å. One can once again see that either the group delay or the dwell time is strongly dependent on the spin orientations and the external magnetic field. There are several sharper peaks in the time spectra for spin-up electrons. However, for the spin-down electrons, the curves are much smoothed, although there are still some mild peaks. The curves for DMS/S systems of double DMS layers become more fluctuant in comparison with that of the DMS/S system of a single DMS layer. At very low energy, the group delay is negative under some magnetic fields. As the magnetic field increases, the tunneling time at its maximum significantly prolongs and displays obvious oscillations for spin-up electrons, while it is essentially decaying with the incident energy for spin-down ones. The dwell time tends to zero as the energy decreases, while the group delay increases. In the third column, we plot $\tau_{\text{up}}-\tau_{\text{down}}$ versus energy. As we can see, at high energy, there is $\tau_{\text{up}}>\tau_{\text{down}}$. However, in the wide region considered here, there is $\tau_{\text{up}}<\tau_{\text{down}}$. The difference of the group delay or of the dwell

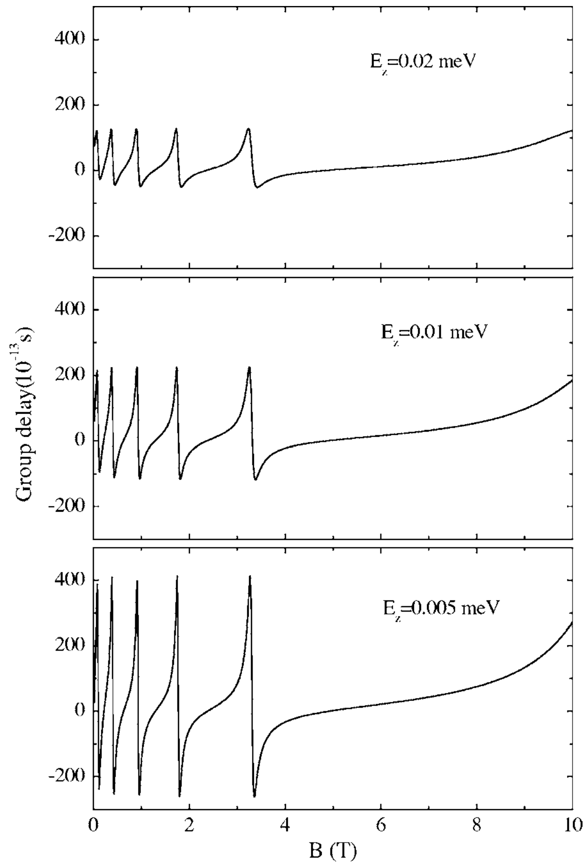

FIG. 5. Group delay as a function of the magnetic field for spin-down electrons tunneling through $ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe$ heterostructures.

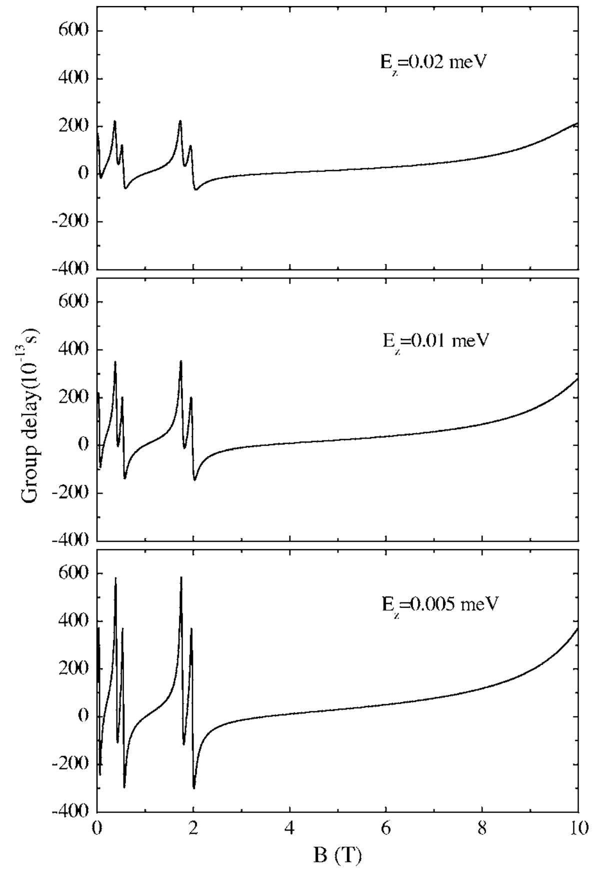

FIG. 6. Group delay as a function of the magnetic field for spin-down electrons tunneling through $ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe/Zn_{0.95}Mn_{0.05}Se/ZnSe$ heterostructures.

time between two different spin orientations also show complex variations. The difference is enlarged with the increasing of the magnetic field. At the low energy limit, the dwell time and the group delay are quite different. However, in the high energy region, these two time scales approach each other. It is known that in an external magnetic field, two paramagnetic layers in the band-gap-matched DMS/S heterostructures behave as double potential wells for spin-down electrons and double potential barriers for spin-up ones. As the magnetic field increases, the double barriers become higher while the double wells become deeper. These features result in obvious magnetic-field-induced spin polarization and separation on the time scales.

From Figs. 1–4, one common feature one can see is that at very low energy the group delay can be negative under some magnetic field. One may wonder under what condition this phenomena can occur. In Figs. 5 and 6 we presented the spin-down group delay versus the external magnetic field for $ZnSe/Zn_{0.95}Mn_{0.05}Se$ systems. The incident energy is set to be $E_z=0.005$, 0.01, and 0.02 meV, respectively. The depth of the effective potential well can be adjusted correspondingly by the magnetic field. As we can see, the spin-down group delay oscillates in the region $B=0-3.7$ T for S/DMS/S configuration and in the region $B=0-2$ T for the S/DMS/S/DMS/S system. The distance between adjacent oscillations become larger for bigger magnetic fields, which corresponds to a deeper effective potential well. Further, one peak for the single quantum well case resolves into two peaks for the double quantum well case. The magnitudes of oscillations become smaller as the incident energy of the electron increases. Beyond the oscillation region, the spin-down group delay increases homogenously. As Büttiker and Landauer pointed out, an incoming peak or centroid does not, in any obvious physically causative sense, turn into an outgoing peak or centroid. So it is not surprising that the peak, or centroid, of the transmitted packet can leave the barrier before the peak, or centroid, of the incident packet has arrived, i.e., group delay can be negative.

IV. CONCLUSIONS

In summary, Winful's theory on the delay time and on the dwell time is extended to deal with the spin-dependent tunneling process through various configurations of juxtaposed DMS and S layers. The results indicate spin tunneling exhibits complex oscillations and separation on the time scales. If electrons with different spin orientations through the same structure at the same time, the spin-up process and spin-down process are separated on the time scales, and the degree of separation strongly depends on the incident energy, the structural configuration, and the external magnetic field. The difference of the group delay or of the dwell time be-

tween spin-up and spin-down electrons can reach by up to several orders of magnitude. The self-interference delay also show obvious spin-dependent features, especially in low energy range. The understanding of the time aspects of spin tunneling processes presented in this work is of fundamental interest to quantum mechanical tunneling. Whether it will have impact on spintronic devices remains to be seen.

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