Dresselhaus spin-orbit effect on traversal time in ferromagnetic/semiconductor/ferromagnetic heterojunctions

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Taking into consideration the Dresselhaus spin-orbit interaction, we study theoretically the transmission coefficients and the traversal time of electrons tunneling through Fe/GaSb/Fe and Fe/InSb/Fe heterostructures. There is a common characteristic for the two different structures, i.e., the transmission coefficients, whether for spin-up spin-down electrons, show obvious resonant features when electrons tunnel through the two heterostructures. We further see that as the length of the semiconductor increases the traversal time of both spin-up and spin-down electrons does not increase linearly but shows steplike behavior: the quantum size effect. Furthermore, we show that the Dresselhaus spin-orbit coupling, unlike Rashba spin-orbit coupling, does not prolong the traversal time of electrons. Because of the different effect of the Dresselhaus spin-orbit coupling on the traversal time of spin-up and spin-down electrons, the difference in the dwell time between spin-up and spin-down electrons can become greater as the length of the semiconductor changes. This is helpful from the device point of view for differentiating spin-up and spin-down electrons and achieving high spin polarizations.

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I. INTRODUCTION

Since the concept of a spin-polarized field-effect transistor was proposed by Datta and Das,[1] based on spin precession controlled by an external electrical field via spin-orbit coupling, the injection of spin electrons from ferromagnetic (F) metals into a semiconductor (S) has attracted considerable attention. As is well known, the lack of inversion symmetry of the trapping wells gives rise to Rashba spin-orbit coupling[2] in semiconductors, which can be effectively modulated by applying a gate voltage. The study of the spin-orbit effects, which link the spin and charge dynamics and open the possibility of spin control by means of electric fields, has attracted much interest and many experimental and theoretical investigations in the last few years. Mireles and Kirczenow[3] have studied coherent quantum transport in ferromagnetic/semiconductor/ferromagnetic junctions theoretically within the Landauer framework of ballistic transport and shown that quantum coherence can have unexpected implications for spin injection. Sun and Xie[4] investigated electron transport through a two-dimensional semiconductor with a nonuniform Rashba spin-orbit interaction and found that a spontaneous spin-polarized current emerges in the absence of any magnetic material or magnetic field, due to the combination of the coherence effect and the Rashba interaction. A single-mode Datta-Das spin field-effect transistor (SFET) was studied by Lee *et al.*[5] in the presence (absence) of impurity scattering and external magnetic fields, and they found interesting mesoscopic effects such as peak splitting, phase locking, and period halving.

Dresselhaus spin-orbit coupling is caused by bulk inversion asymmetry and exists broadly in the widely used III-V compound semiconductors with zinc-blende crystal structures.[6] Recently, Tarasenko and co-workers studied electrons tunneling through a symmetric semiconductor barrier[7] and double-barrier structures[8] based on zinc-blende structure materials, and found that the Dresselhaus spin-orbit interaction couples spin states and the spatial motion of conduction electrons, which leads to spin splitting of the resonance level, depending on the in-plane electron wave vector. Furthermore, Li and Guo[9] investigated the spin-dependent dwell time in double-barrier structures with or without an external electric field, and found that both the transmission and the dwell time of the resonant peaks of the spin-up and spin-down electrons split in the presence of Dresselhaus spin-orbit coupling. Yang and Li[10] calculated the in-plane conductance of a barrier with Dresselhaus spin-orbit interaction, which is sandwiched between two spin-polarized materials aligned arbitrarily, and studied the relationship between the transmitted and reflected currents.

The traversal is characterized not only by the transmission rate but also by the time taken by the transmitted particle to actually traverse the barrier.[11] The question of the "tunneling time" has occupied physicists for decades, and there is still no definitive answer.[12–16] Büttiker[17] presented a reinterpretation of the Baz'-Rybachenko experiment and pointed out that there are three characteristic time associated with the interaction of particles with a barrier: the dwell time,[18] the traversal time, and the reflection time. Many experiments[19–21] have been reported which have observed directly the time involved in optical photon and microwave analogs of quantum tunneling. The tunneling time is a basic characteristic that determines the dynamic range of tunneling devices, and study of the tunneling time is significant because it might enable us to understand the tunneling dynamics in high-speed devices, since time is one of the key parameters for the ultimate performance evaluation of nanodevices. Recently, obvious spin separation features in time have been found by Guo *et al.*[22] in diluted magnetic semiconductor multilayers, where high spin polarization can be obtained.[23,24] Based on the group velocity concept, Wu *et al.*[25] investigated the traversal time of a quasi-one-dimensional waveguide that contains a ferromagnetic/semiconductor/ferromagnetic heterojunction in the presence of Rashba spin-orbit interaction.

Considering Rashba spin-orbit coupling and significant quantum size simultaneously, Zhang and Li[26] examined the properties of the transmission coefficients and the spin-tunneling time in spin tunneling through a ferromagnetic/semiconductor/ferromagnetic heterojunction with a tunnel barrier. Both theoretically and for advances in miniaturizing tunnel semiconductor devices, the traversal time is an important concept for the better understanding and design of quantum devices.

Although the traversal time and other characteristics of two-terminal F/S/F systems with Rashba spin-orbit interaction have been calculated,[25,26] to the best of our knowledge, the traversal time for electrons through these systems with Dresselhaus spin-orbit interaction has never been reported. In the present work, we present the characteristics of the transmission coefficients and the traversal time in Fe/GaSb/Fe and Fe/InSb/Fe heterostructures in the presence of Dresselhaus spin-orbit interaction. InSb and GaSb are known to be semiconductors with relatively strong Dresselhaus spin-orbit coupling, so other possible spin-orbit interaction has been neglected in these cases.[7] This paper is organized as follows. In Sec. II we introduce the Hamiltonian and the boundary conditions for ferromagnetic/semiconductor/ferromagnetic heterojunctions in the presence of Dresselhaus spin-orbit coupling. Numerical results and discussion for the transmission coefficients and the traversal time in heterojunctions are shown in Sec. III. Finally, a brief summary is presented in Sec. IV.

II. MODEL AND FORMULAS

In the one-band effective mass approximation, for the F/S/F structure, the Hamiltonian with exchange interaction in the ferromagnet and Dresselhaus spin-orbit interaction in the semiconductor has the form

$$H = -\frac{\hbar^2}{2}\nabla\frac{1}{m^*(z)}\nabla + H_{ex} + H_D + \delta E_c. \tag{1}$$

$m^*(z)$ is a position-dependent effective mass, $m^*(z)=m_e$ in ferromagnetic regions and $m^*(z)=m^*$ in the semiconductor region, and δE_c models the conduction band mismatch between the semiconductor and the ferromagnets.

The d-band electrons are mainly responsible for the magnetic properties in $3d$ transition metals and their alloys.[27,28] However these electrons exhibit low mobilities. Electron transport is carried by hybridized s-band-like itinerant d electrons at the Fermi level. An imbalance between spin-up and spin-down densities of states can give rise to the exchange interaction. In this case, the Hamiltonian in the ferromagnets can be approximated by an isotropic effective interaction[27,29]

$$H_{ex} = \Delta m \cdot \sigma, \tag{2}$$

where Δ is the exchange splitting energy in the ferromagnets, and the spin-up and spin-down band energies offset is set by an exchange splitting Δ. $\sigma=(\sigma_x,\sigma_y,\sigma_z)$ is the vector of the Pauli spin matrices. The vector m denotes the unit vector of the magnetization in the ferromagnetic electrodes and points in the direction of the minority spins. In this case, the electrode magnetization is chosen along the y direction, parallel to the interface.

The Hamiltonian of the Dresselhaus spin-orbit coupling can be written as[7]

$$H_D = \gamma(\sigma_x k_x - \sigma_y k_y)\frac{\partial^2}{\partial z^2}, \tag{3}$$

where γ is a material constant denoting the strength of the Dresselhaus spin-orbit coupling, σ_x and σ_y are the Pauli matrices, and the coordinate axes x,y,z are assumed to be parallel to the cubic crystallographic axes [100], [010], [001], respectively.

The total Hamiltonian in the semiconductor is the sum of the kinetic energy, the conduction band mismatch between the semiconductor and the ferromagnets, and the Dresselhaus spin-orbit coupling term, i.e.,

$$H = -\frac{\hbar^2}{2}\nabla\frac{1}{m^*}\nabla + H_D + \delta E_c. \tag{4}$$

We consider that the electrons at the Fermi energy are transported through the ferromagnetic/semiconductor/ferromagnetic heterojunctions along the $z[001]$ direction. Electrons tunnel through the semiconductor with the wave vector $k=(k_\parallel,k_z)$, where $k_\parallel$ is the wave vector in the x-y plane of the semiconductor and k_z is the component wave vector in the direction of tunneling.

The Dresselhaus term can be diagonalized by the spinors[7]

$$\chi_\pm = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\ \mp e^{-i\varphi}\end{pmatrix}, \tag{5}$$

which describe the eigenstates of the spin-up (+) and spin-down (−) electrons. Here φ is the polar angle of the wave vector k in the x-y plane in the semiconductor, where

$$k = (k_\parallel \cos\varphi, k_\parallel \sin\varphi, 0). \tag{6}$$

The orientations of the spins $s_\pm$ corresponding to the eigenstates + and − depend on the in-plane wave vector of electrons in the semiconductor and are given by

$$s_\pm = \frac{1}{2}\chi_\pm^\dagger \sigma \chi_\pm = \frac{1}{2}(\mp\cos\varphi, \pm\sin\varphi, 0). \tag{7}$$

Under this model, $k_\parallel$ is directed along the cubic crystal axis [010] so that the spins are parallel (or antiparallel) to $k_\parallel$. The transmission probabilities for the electrons of eigen spin states + and − (5) are different due to the Dresselhaus spin-orbit term (3). In the basis of such spin eigenstates, the effective Hamiltonian in the semiconductor can be written as

$$H = -\frac{\hbar^2}{2m_\pm}\frac{\partial^2}{\partial z^2} + \frac{\hbar^2 k_\parallel^2}{2m^*} + \delta E_c, \tag{8}$$

where

$$m_\pm = m^*\left(1 \pm 2\frac{\gamma m^* k_\parallel}{\hbar^2}\right)^{-1}. \tag{9}$$

Therefore, the Dresselhaus spin-orbit coupling effect on the spin-up and spin-down electrons is equivalent to a spin-dependent modification of the effective mass.

Given the spin-diagonal nature of Hamiltonian (8), we can write the eigenstates of the whole F/S/F structure in the form $|\Psi_\uparrow\rangle=[\psi_\uparrow,0],|\Psi_\downarrow\rangle=[0,\psi_\downarrow]$.[3,30] The eigenstates in the ferromagnetic region have the form

$$\psi_\sigma^{F,v}=A_\sigma^v e^{ik_{F,\sigma}^v z}+B_\sigma^v e^{-ik_{F,\sigma}^v z}; \quad (10)$$

here $\sigma=\uparrow,\downarrow$ is the spin state of the split band, $k_{F\sigma}$ is the Fermi wave vector with spin state σ in the ferromagnets, and $v=R,L$ denote the right and left ferromangnets. The wave function in the semiconductor region can be written as

$$\psi_\sigma^S=A_\sigma e^{ik_\sigma^S z}+B_\sigma e^{-ik_\sigma^S z}. \quad (11)$$

Here k_σ^S is the Fermi wave vector in the semiconductor for the spin-orbit-split band with spin σ.[30] In the ferromagnetic metal the energy spectrum is

$$E_F^\sigma(k_F)=\frac{\hbar^2}{2m_e}k_F^2+\frac{1}{2}\lambda_\sigma\Delta, \quad (12)$$

and the energy spectrum in the semiconductor becomes

$$E_S^\sigma(k_S)=\frac{\hbar^2}{2m_\pm}k_S^2+\frac{\hbar^2k_\parallel^2}{2m^*}+\delta E_c. \quad (13)$$

Here $\lambda_{\uparrow,\downarrow}=\pm1$, and m^* is the effective mass of the electrons in the semiconductor.

The boundary conditions, which are the continuity of the wave function and the conservation of current density, require that Ψ_σ and $(1/\mu)\partial\Psi_\sigma/\partial x$ are continuous at the interfaces, where $\mu=m_e/m_\pm$. A system of linear equations for A_σ, B_σ, A_σ^v, and B_σ^v can be derived. The probability of an incoming electron in spin state σ at the Fermi energy being transmitted from the left ferromagnet to the right ferromagnet is determined by[30]

$$T_\sigma^P=\frac{k_{F,\sigma}^R}{k_{F,\sigma}^L}\frac{|A_\sigma^R|^2}{|A_\sigma^L|^2}. \quad (14)$$

The tunneling time is a key parameter for ultimate performance evaluations of spin-dependent electrons tunneling through two-terminal F/S/F heterostructures in the presence of Dresselhaus spin-orbit interaction. One of the most intuitive and easiest approaches is based on the group velocity concept, and the traversal time can be defined as follows:[31,32]

$$\tau_\sigma=\int_0^l\frac{dz}{v_{g,\sigma}}, \quad (15)$$

where l is the length of the semiconductor, and $v_{g,\sigma}$ is the group velocity, which is defined as the ratio between the average probability current density and the probability density of the particle. Anwar *et al.*[32] have shown that the real part of the quantum-mechanical wave impedance, at resonance, can be used to calculate the electron traversal time. The average probability current density can be written as

$$S=\mathrm{Re}\left(\frac{\hbar}{im}\psi^*\frac{d\psi}{dz}\right), \quad (16)$$

where ψ is the stationary wave function. Therefore the traversal time of spin-dependent electrons becomes

$$\tau_\sigma=\int_0^l\frac{|\psi|^2}{\mathrm{Re}\left(\frac{\hbar}{im}\psi^*\frac{d\psi}{dz}\right)}dz. \quad (17)$$

This definition has been shown to be equivalent to the Bohm definition of the tunneling time.[33]

III. RESULTS AND ANALYSIS

Now we calculate and analyze the spin-dependent processes in two ferromagnetic/semiconductor/ferromagnetic heterojunctions: the Fe/GaSb/Fe and the Fe/InSb/Fe heterojunctions. In our calculations, the parameters of the ferromagnetic materials are the same in the two different heterojunctions. The exchange splitting energy in the ferromagnets is $\Delta=3.46$ eV. For the ferromagnets, the Fermi wave vectors are $k_{F,\downarrow}=1.05\times10^8\ \mathrm{cm}^{-1}$ and $k_{F,\uparrow}=0.44\times10^8\ \mathrm{cm}^{-1}$, respectively.[30] The effective mass in the ferromagnets is set be m_e. In the Fe/InSb/Fe heterojunction, the effective mass of electrons in the InSb semiconductor is set be $m^*=0.013m_e$, the Dresselhaus constant $\gamma=220$ eV Å^3, and the conduction band mismatch between the semiconductor InSb and the ferromagnets, $\delta E_c=0.23$ eV. In the Fe/GaSb/Fe heterojunction, the effective mass of electrons in the GaSb semiconductor is set be $m^*=0.041m_e$, the Dresselhaus constant $\gamma=187$ eV Å^3, and the conduction band mismatch between the semiconductor GaSb and the ferromagnets $\delta E_c=0.81$ eV.[7]

We first investigate the transmission coefficients of electrons tunneling through the Fe/GaSb/Fe heterostructure. Obvious resonant features can be found from the three dimensional plot in Fig. 1 which presents the transmission coefficients as a function of the length of the semiconductor and the wave vectors in the x-y plane, $k_\parallel$, for the spin-up and spin-down electrons. Although the transmission coefficients of the spin-up and spin-down electrons show resonant features as the length of the semiconductor increases, the transmission coefficients of the spin-up electrons oscillate more rapidly, and the wave peak of the transmission coefficients for the spin-down electrons is sharper than that for the spin-up electrons. This reflects the dominant contribution of the exchange interaction in the ferromagnetic material, where the spin-up and spin-down band energy offset is determined by exchange splitting. Furthermore, one can see that, as the wave vector $k_\parallel$ in the x-y plane increases, the transmission coefficients for the spin-up electrons show obvious resonant features in the peaks; as both the length of the semiconductor and the wave vector $k_\parallel$ in the x-y plane increase, the transmission coefficient oscillates more rapidly, the peaks become sharper, and the intervals between adjacent peaks are narrowed. But the wave vector $k_\parallel$ in the x-y plane has little effect on the transmission coefficients for the spin-down electrons. The results stated above imply that the Dressel-

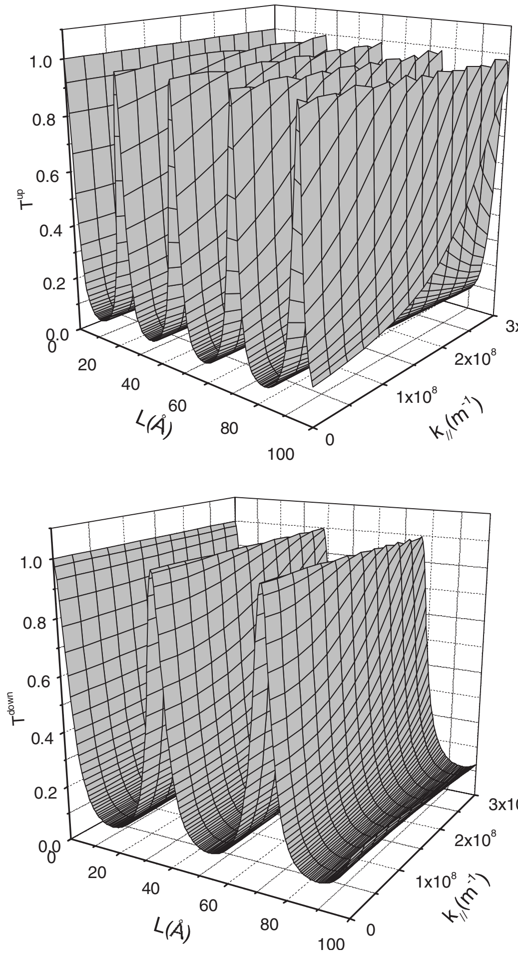

FIG. 1. Transmission coefficients of spin-up and spin-down electrons as a function of the length of the semiconductor and the plane wave vector $k_{\parallel}$ in the x-y for electrons tunneling through an Fe/GaSb/Fe heterostructure.

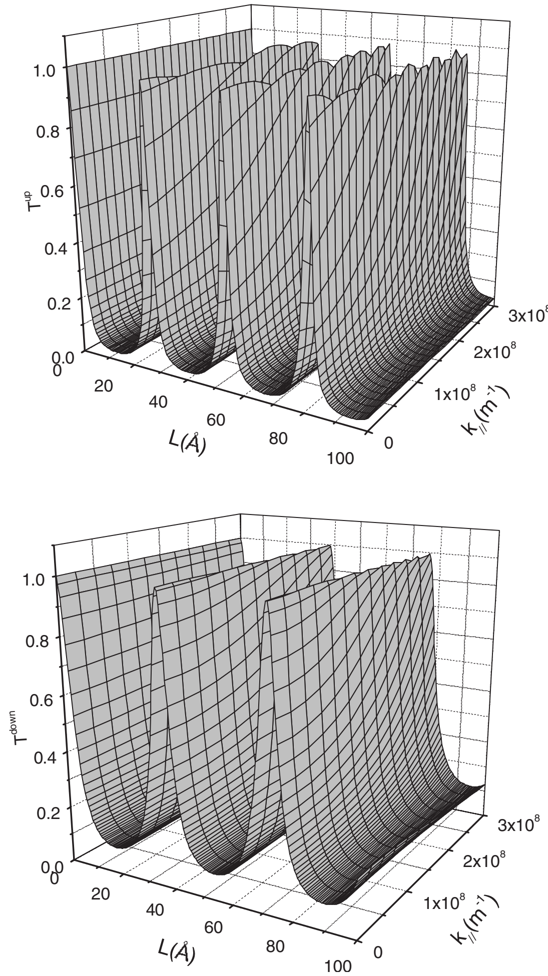

FIG. 2. Transmission coefficients of spin-up and spin-down electrons as a function of the length of the semiconductor and the wave vector $k_{\parallel}$ in the x-y plane for electrons tunneling through Fe/InSb/Fe heterostructure.

haus spin-orbit coupling causes the resonant peaks for the spin-up and spin-down electrons to split when the in-plane wave vector is not zero. In this way, spin splitting can be achieved at the resonant peak via tuning the x-y plane wave vector $k_{\parallel}$. Therefore, we conclude that the transmission for spin-up electrons and spin-down ones can be separated, and their degree of separation depends not only on the length of the semiconductor but also on the strength of the in-plane wave vector. In other words, the zinc-blende structure does not have a center of inversion, so that we can have a spin splitting of the electron states at nonzero wave vector $k_{\parallel}$ even for a magnetic field $B=0$, which is expected to be useful from the device point of view. Here, we would like to point out that one method to control the in-plane wave vector was reported recently with sidegate resonant devices in a prototype sidegated asymmetric resonant interband tunneling device.[34] The results may be useful for understanding and designing quantum spintronic devices.

We wish to state that the electron transport across ferromagnetic/semiconductor/ferromagnetic double junctions is carried by two independent spin systems. And since the spin orientation in the semiconductor is aligned to the ferromagnetic drain electrode, the electrons can flow into the ferromagnetic drain electrode. The Dresselhaus term in a semiconductor can rotate the spins of incident electrons and current flow is modified by the spin precession angle. The parallel magnetization configuration of the electrodes is considered in our model.

Figure 2 shows the transmission coefficients as a function of the length of the semiconductor and the wave vector $k_{\parallel}$ in the x-y plane for the spin-up and spin-down electrons tunneling through an Fe/InSb/Fe heterostructure. In the region considered, the transmission coefficients for spin-up electrons have four periods, but only three periods for spin-down ones. These features strongly indicate that the electrons with different spin orientations will be separated when they tunnel through the same F/S/F heterostructures. In Figs. 1 and 2, one can see a common feature, i.e., the transmission coefficients whether for spin-up or for spin-down electrons show obvious resonant features. However, the transmission coefficients for electrons tunneling through Fe/InSb/Fe heterostructures are very different from those for electrons tunneling through Fe/GaSb/Fe heterostructures due to the different strength of the Dresselhaus spin-orbit coupling and the conduction band mismatch in the two different building materi-

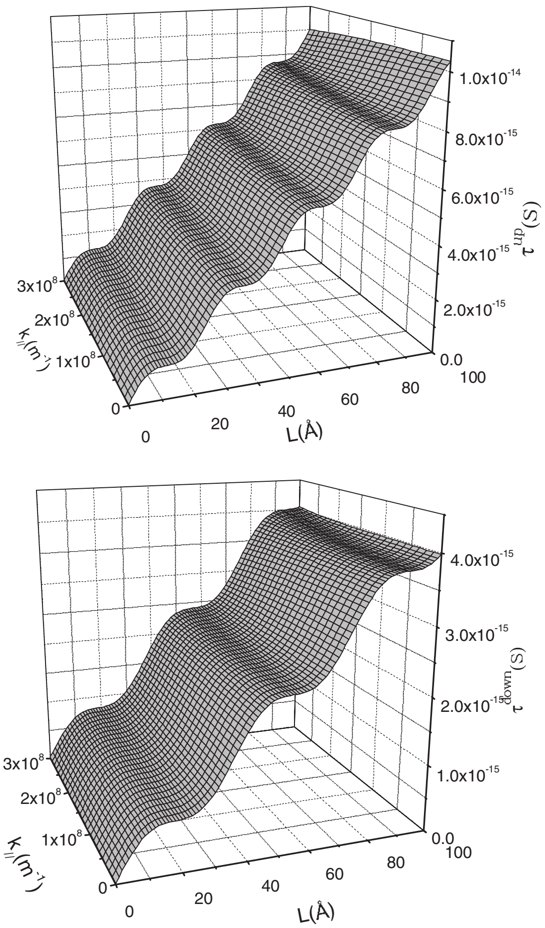

FIG. 3. Traversal time of spin-up and spin-down electrons as a function of the length of the semiconductor and the wave vector $k_\parallel$ in the *x*-*y* plane for electrons tunneling through an Fe/GaSb/Fe heterostructure.

als of the semiconductor. As the length of the semiconductor increases, the transmission coefficient for electrons tunneling through the Fe/GaSb/Fe heterostructure oscillates more rapidly than that for electrons tunneling through the Fe/InSb/Fe heterostructure. Also, as the strength of the in-plane wave vector increases, there is almost no change in the transmission coefficients for a spin-down electrons tunneling through the Fe/GaSb/Fe heterostructure, but for spin-down electrons through the Fe/InSb/Fe heterostructure the transmission coefficients show a slight vibration. These features strongly indicate that the transmission coefficients are determined not only by the length of the semiconductor and spin orientation but also by the strength of the Dresselhaus spin-orbit coupling and the building materials of the semiconductor.

In order to reveal the tunneling properties more thoroughly, we calculate the traversal time of electrons tunneling through the F/S/F heterostructures. In Fig. 3 we show the tunneling time of spin-up and spin-down electrons tunneling through the Fe/GaSb/Fe heterostructure. It is interesting to note that, as the length of the semiconductor increases, the traversal time for both spin-up and spin-down electrons does not increase linearly but shows steplike behavior. These features are agreement with the results of Ref. 25, in which the traversal time of a quasi-one-dimensional waveguide that contains a ferromagnetic/semiconductor/ferromagnetic heterojunction was studied in the presence of Rashba spin-orbit interaction. The results indicate that the steplike behavior for the traversal time of electrons tunneling through F/S/F heterostructures is a quantum size effect. We can further see that, as the length of the semiconductor increases, the difference between the spin-up and spin-down states becomes more obvious in the time domain. Moreover, we can see that the split of the traversal time of spin-up and spin-down electrons can be caused by the Dresselhaus spin-orbit coupling at nonzero $k_\parallel$. The split of the electron spins can be achieved via the change of the in-plane $k_\parallel$ in the presence of Dresselhaus spin-orbit coupling, which is helpful for differentiating the spin-up and spin-down electrons from the device point of view. From Fig. 3 it is clear that the tunneling process of electrons with different spin orientations through a Fe/GaSb/Fe heterostructure can be divided into a slow and a quick process. The tunneling process of spin-up electrons corresponds to the slow process while the tunneling process of spin-down electrons corresponds to the quick process. The tunneling process is similar to the spin-dependent electron tunneling process in diluted-magnetic-semiconductor/semiconductor heterostructures.[12] The results strongly indicate that electrons with different spin orientations not only have quite different transmission coefficients but also are separated in time within the same heterostructure. Here we want to point out that our calculations and discussion are under the assumption of a phase-coherent tunneling process, which applies to heterostructures with narrow wells and barriers. When the heterostructures become longer, the phase-coherent tunneling should be replaced by a sequential process and these features will be changed.

To further understand the effects of the strength of Dresselhaus spin-orbit coupling and the building materials of the semiconductor on the traversal time, we calculate the traversal time of spin-up and spin-down electrons tunneling through an Fe/InSb/Fe heterostructure. The numerical results are plotted in Fig. 4. Similarly, it can be seen that the traversal time for both spin-up and spin-down electrons shows steplike behavior, and the difference between the spin-up and spin-down states becomes more obvious in the time domain as the length of the semiconductor increases. Due to the differences in the building materials of the semiconductors and the strength of the Dresselhaus spin-orbit coupling, in the same range of change for the semiconductor length, the traversal time for electrons tunneling through Fe/InSb/Fe heterostructure has three steplike behaviors, and the traversal time in Fe/GaSb/Fe heterostructure has four steplike behaviors. According to the analysis of Wu *et al.*[25] the transmission coefficient and the traversal time have the same length period. From Figs. 1–4, our results are in agreement with theirs. Moreover, at a given initial wave vector of electrons, the traversal time does not drastically increase with the strength of the Dresselhaus spin-orbit coupling γ. However, the Rashba spin-orbit effect on the traversal time in a ferromagnetic/semiconductor/ ferromagnetic heterojunction with a tunnel barrier has already been presented.[26] It is shown that the Rashba spin-orbit term can damp the motion of electrons, decrease the device response velocity, and increase the tunneling time of electrons. Therefore, we can say

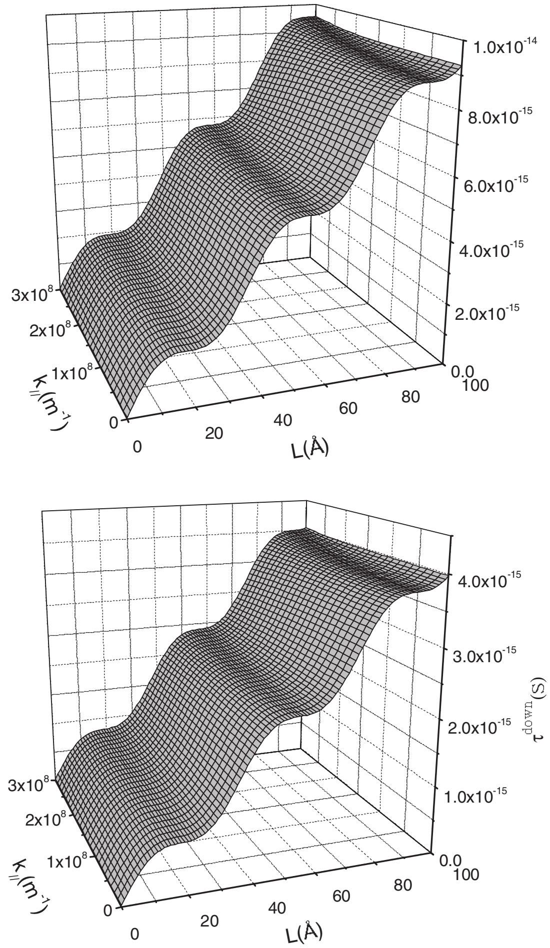

FIG. 4. Traversal time of spin-up and spin-down electrons as a function of the length of the semiconductor and the wave vector $k_{\|}$ in the *x-y* plane for electrons tunneling through an Fe/InSb/Fe heterostructure.

that not only the length of the semiconductor and the spin orientations but also the strength of the Dresselhaus spin-orbit coupling and the building materials of the semiconductor have important effects on the traversal time of electrons tunneling through F/S/F heterostructures.

By a comparison between Figs. 3 and 4, it is learned that the traversal time of the spin-up electrons tunneling in an Fe/GaSb/Fe heterostructure shows more obvious steplike behaviors than that in an Fe/InSb/Fe heterostructure, but the traversal time does not change in Fe/GaSb/Fe and Fe/InSb/Fe heterostructures whether for spin-up or spin-down electrons when the length of the semiconductor is 100 Å. This indicates that Dresselhaus spin-orbit coupling, unlike Rashba spin-orbit coupling, does not prolong the traversal time of electrons. Further, one can see that the traversal time of the spin-down electrons tunneling in Fe/GaSb/Fe heterostructures is very similar with that in Fe/InSb/Fe heterostructures, i.e., the difference of strength of Dresselhaus spin-orbit coupling has little effect on the traversal time of spin-down electrons. These results are different from our previous results,[26] where Rashba spin-orbit coupling damps the motion of the spin-up and spin-down electrons and increases the tunneling time of the spin-up and spin-down electrons. Because of the different effect of the Dresselhaus spin-orbit coupling on traversal times of spin-up and spin-down electrons, the difference in the dwell time between spin-up and spin-down electrons can become greater as the length of the semiconductor changes. This is helpful from the device point of view for differentiating the spin-up and spin-down electrons and achieving high spin polarizations.

IV. SUMMARY

In summary, we study theoretically the transmission coefficients and the traversal time of electrons tunneling through Fe/GaSb/Fe and Fe/InSb/Fe heterostructures in the presence of Dresselhaus spin-orbit interaction. One common feature is that the transmission coefficients whether for spin-up or spin-down electrons show obvious resonant features. One can see that the length of the semiconductor and the strength of the in-plane wave vector will produce different effects on the spin-up electrons and spin-down electrons. So the Dresselhaus spin-orbit interaction can lead to spin splitting, depending on the in-plane electron wave vector. We also calculate the traversal time of electrons tunneling through the Fe/GaSb/Fe and Fe/InSb/Fe heterostructures. The traversal time is qualitatively different from that in the classical region and has steplike behavior. Due to the different effect of the Dresselhaus spin-orbit coupling on the traversal time of the spin-up and spin-down electrons, the difference in the dwell time between spin-up and spin-down electrons can become greater as the length of the semiconductor increases. The results strongly indicate that electrons with different spin orientations not only have quite different transmission but also are separated in the time domain within the same heterostructures. The results may be useful for the understanding and design of quantum spintronic devices.

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