Dresselhaus spin-orbit coupling effect on dwell time of electrons tunneling through double-barrier structures

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We investigated the effect of the Dresselhaus spin-orbit coupling on the dwell time of electrons tunneling through double-barrier structures with or without an external electric field. The results indicate that obvious resonant features exist in the time domain. In the presence of the Dresselhaus spin-orbit coupling, both the transmission and the dwell time of the resonant peaks of the spin-up and spin-down electrons split. There is a great difference between the dwell time of the electrons with opposite spin orientations, which reaches the maxima at the resonant energies, and becomes greater under a larger in-plane wave vector. The results also indicate that structural asymmetry and external electric fields can greatly affect the dwell time of the electrons.

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I. INTRODUCTION

The physics of spin-dependent tunneling phenomena is one of the most important problems in spintronics. Significant progresses have been made in both theoretical and experimental investigations of spin-dependent tunneling through magnetic junctions.[1,2] Studies of spintronics begin to focus more on the tunneling through nonmagnetic semiconductors after it is pointed out that such tunneling can be spin-dependent because of the spin-orbit coupling (SOC) effect.[3–7] Comparing to the tunneling through magnetic junctions, spin-dependent tunneling through semiconductors has several inherent merits. For instance, it opens the door to orienting, manipulating, and detecting electron spin through electrical ways and avoids the conducting mismatch between magnetic and semiconductor materials that would sharply reduce spin injection efficiency.[8]

Recently, Glazov *et al.*[9] investigated the spin-dependent resonant tunneling through symmetric double-barrier structures grown of noncentrosymmetrical semiconductors in the presence of the Dresselhaus SOC. The dependence of the transmission coefficient on the spin orientations and the wave vector of the electrons was studied, and possible means of generating and detecting spin-polarized electron current were proposed theoretically.

Besides the transmission characteristics, the time scale in mesoscopic systems is another interesting problem. Attempts of finding a simple expression for the tunneling time, which is the time a particle spends to tunnel through a structure, started in the early 30s of last century,[10] but it remains an open question till now. Several time definitions were proposed, and now there is a consensus that different definitions characterize different or complementary aspects of tunneling process, rather than in the narrow sense as the time taken by the particle to tunnel through the barrier region.[11] Among those definitions the dwell time was proposed in the 1960s,[12] and introduced into one-dimensional tunneling by Büttiker,[13] which has now been proved to be an exact statement of the time a particle spends in the structure averaged over all scattering channels.[14]

Time scale investigation was introduced into spin-dependent tunneling in Refs. 15–17, where obvious spin separation features were found in the traversal time through different structures. Very recently, using the time-dependent Schrödinger equation, Romo *et al.*[18] investigated the time scale problem in symmetric double-barrier structures, and proposed that the Dresselhaus SOC causes a nature spin filter mechanism in the time domain.

In this paper, we investigate the dwell time of electrons tunneling through double-barrier structures in the presence of the Dresselhaus SOC and an external electric field. The dependency of the dwell time on the spin orientations and the incident wave vector is presented in both symmetric and asymmetric structures. The same assumptions implied by Glazov *et al.*[9] are followed, namely (1) envelope-function method is used, which has been widely employed in problems of similar dimensions,[7,9,19,20] and (2) a single effective mass is used for the electrons.

II. MODEL AND FORMULA

The Dresselhaus SOC is caused by the bulk inversion asymmetry and exists broadly in the widely used III-V compound semiconductors with zinc-blende crystal structures.[21] The double-barrier structures investigated in the present paper are constructed of layers of GaSb and $Ga_xAl_{1-x}Sb$ which are known to be semiconductors with relatively strong Dresslhaus SOC.[7] When the growing direction is along [001] direction, the Hamiltonian of the Dresselhaus SOC is

$$\hat{H}_D = \gamma(\hat{\sigma}_x k_x - \hat{\sigma}_y k_y)\frac{\partial^2}{\partial z^2}, \tag{1}$$

where γ is a material constant denoting the strength of the coupling, and $\hat{\sigma}_x$ and $\hat{\sigma}_y$ are the Pauli matrices. The coordinate axes x, y, and z are assumed to be parallel to the cubic crystallographic axes [100], [010], and [001], respectively.

The profile of the structure is shown in Fig. 1. The heterostructure potential $V_0(z)$ equals to V_b for the barriers and $-V_w$ for the well. The thicknesses of the left barrier, the well,

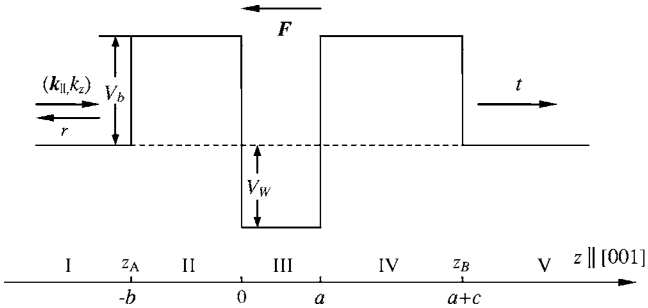

FIG. 1. Potential profile of the [001]-grown double-barrier structure. V_b is the height of the barrier and V_w is the depth of the well. a, b, and c are the width of the well and the thicknesses of the left and right barriers, respectively. $\mathbf{F}$ is the electric field applied to region $[z_A, z_B]$.

and the right barrier are b, a, and c, respectively. In the present work, we choose $V_b=230$ meV, $V_w=200$ meV, $a=30$ Å, $b+c=100$ Å, and assume that in the whole region the Dresselhaus constant $\gamma=76$ eV Å^3 and the effective mass $m^*=0.053m_e$,[9] which are appropriate for the $Ga_xAl_{1-x}Sb$ system. When an external electric field is applied along the $-z$ direction in the structure region, the effective potential becomes

$$V(z) = V_0(z) - eF(z+b)\Theta(z+b)\Theta(a+c-z), \qquad (2)$$

where F is the magnitude of the electric field and $\Theta(z)$ is the step function.

The total Hamiltonian is the sum of the kinetic energy, the effective potential, and the Dresselhaus SOC term, i.e.,

$$\hat{H} = -\frac{\hbar^2}{2m^*}\nabla^2 + V(z) + \hat{H}_D. \qquad (3)$$

Consider electrons tunneling through the structure from the left with initial wave vector $\mathbf{k}=(\mathbf{k}_\parallel, k_z)$, where $\mathbf{k}_\parallel$ is the wave vector in the plane of interfaces and k_z is the wave vector component along the tunneling direction. Under this model, the Dresselhaus SOC term is diagonalized by the spinors[9]

$$\chi_\pm = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ \mp e^{-i\varphi} \end{pmatrix}, \qquad (4)$$

which describe the spin-up ("+") and spin-down ("−") electron eigenstates. In the basis of such spin eigenstates the effective Hamiltonian Eq. (3) has the form[9]

$$\hat{H}_\pm = -\frac{\hbar^2}{2m_\pm}\frac{\partial^2}{\partial z^2} + \frac{\hbar^2 k_\parallel^2}{2m^*} + V(z), \qquad (5)$$

where

$$m_\pm = m^*\left(1 \pm 2\frac{\gamma m^* k_\parallel}{\hbar^2}\right)^{-1}. \qquad (6)$$

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

Under the assumption that $k_\parallel$ is conserved during the tunneling,[7] the wave functions for the electrons with definite longitudinal electron energy (E_z) can be obtained from the Schrödinger equation based on the Hamiltonian given in Eq. (5), and they have the form

$$\psi_\sigma(z) = \begin{cases} e^{ik_{1\sigma}z} + r_\sigma e^{-ik_{1\sigma}z}, & z < -b, \\ \zeta_\sigma(z), & -b \leqslant z < a+c, \\ t_\sigma e^{ik_{5\sigma}z}, & z \geqslant a+c, \end{cases} \qquad (7)$$

where $\sigma=$"$\pm$". ζ_σ denotes the wave functions in Region II–IV. When there is no electric field, ζ_σ can be simply expressed as linear combinations of plane wave functions in each region. When an electric field is applied, ζ_σ in different regions (denoted by n) has the form

$$\zeta_{n\sigma} = C_{n\sigma}\mathrm{Ai}\left(\frac{z+b+u_{n\sigma}/eF}{z_{0\sigma}}\right) + D_{n\sigma}\mathrm{Bi}\left(\frac{z+b+u_{n\sigma}/eF}{z_{0\sigma}}\right), \qquad (8)$$

where Ai(z) and Bi(z) are the Airy functions, $u_{2\sigma}=u_{4\sigma}=E_z-V_b$, $u_{3\sigma}=E_z+V_w$, and $z_{0\sigma}=\left(\frac{\hbar^2}{2m_\sigma eF}\right)^{1/3}$, respectively. In the incident and outgoing regions I and V, the wave functions can be expressed by plane waves with the wave vectors $k_{1\sigma}=\sqrt{2m_\sigma E_z}/\hbar$ and $k_{5\sigma}=\sqrt{2m_\sigma[E_z+eF(a+b+c)]}/\hbar$, respectively. t_σ and r_σ are the transmission and reflection amplitudes, which can be calculated using the transfer-matrix method with the boundary conditions between the regions.

Once the transmission and reflection amplitudes are obtained, it is easy to obtain the transmission and reflection coefficients, using

$$T_\sigma = \frac{k_{5\sigma}}{k_{1\sigma}}|t_\sigma|^2, \quad R_\sigma = |r_\sigma|^2. \qquad (9)$$

The dwell time can be defined as[12]

$$\tau_D^\sigma = \int_L \frac{|\psi_\sigma(z)|^2}{j_{in}^\sigma} dz. \qquad (10)$$

Here $\psi_\sigma(z)$ is the wave function in the interested region L and j_{in}^σ is the incoming flux which equals to $\hbar k_{1\sigma}/m_\sigma$.

Using the 1D time-independent Schödinger equation, the integral of $|\psi_\sigma(z)|^2$ over $[z_A, z_B]$ can be expressed by the value of $\psi_\sigma(z)$ and its derivatives at boundaries of the region[12]

$$\int_{z_A}^{z_B} |\psi_\sigma(z)|^2 dz = \frac{\hbar^2}{2m_\sigma}\left(\frac{\partial\psi_\sigma}{\partial E_z}\frac{\partial\psi_\sigma^*}{\partial z} - \psi_\sigma^*\frac{\partial^2\psi_\sigma}{\partial E_z\,\partial z}\right)\Bigg|_{z_A}^{z_B}. \qquad (11)$$

Winful[22] applied the above equation to zero-bias tunneling and obtained the relationship between the dwell time and the phase time, which provides a way to calculate the dwell time from the transmission and reflection amplitudes. When applying this method to our model, in which the structure region locates at $[z_A, z_B]$, the dwell time becomes

$$\tau_D^\sigma(z_A,z_B;E_z,k_\parallel) = |t_\sigma|^2 \tau_{T\sigma}^\phi(z_A,z_B;E_z,k_\parallel) + |r_\sigma|^2 \tau_{R\sigma}^\phi(z_A,z_B;E_z,k_\parallel) + \frac{|r_\sigma|}{\hbar k_{1\sigma}^2/m_\sigma}\sin(-2z_A k_{1\sigma}+\phi_{R\sigma}), \qquad (12)$$

where $\tau_{T\sigma}^\phi(z_A,z_B;E_z,k_\parallel)=\hbar\, d[(z_B-z_A)k_{1\sigma}+\phi_{T\sigma}]/dE_z$ and $\tau_{R\sigma}^\phi(z_A,z_B;E_z,k_\parallel)=\hbar\, d(-2z_A k_{1\sigma}+\phi_{R,\sigma})/dE_z$ are the transmission and reflection phase time with $\phi_{T\sigma}$ and $\phi_{R\sigma}$ being the phases of t_σ and r_σ. This result agrees with the wave packet analysis of Hauge *et al.*[23]

In more general cases when an external electric field is applied to the structure, we can obtain the expression

$$\tau_D^\sigma(z_A,z_B;E_z,k_\parallel;F) = \frac{k_{5\sigma}}{k_{1\sigma}}|t_\sigma|^2 \hbar \frac{\partial[\phi_{T\sigma}+z_B k_{5\sigma}-z_A k_{1\sigma}]}{\partial E_z} + |r_\sigma|^2 \hbar \frac{\partial(-2z_A k_{1\sigma}+\phi_{R\sigma})}{\partial E_z} + \frac{|r_\sigma|}{\hbar k_{1\sigma}^2/m_\sigma}\sin(-2z_A k_{1\sigma}+\phi_{R\sigma}), \qquad (13)$$

which provides us a way to calculate the dwell time under the electric field from the transmission and reflection amplitudes.

III. RESULTS AND DISCUSSION

We first investigate the dwell time of electrons tunneling through symmetric structures. Figure 2(b) presents the dwell time τ_D as a function of the longitudinal energy E_z at different $k_\parallel$, from which obvious resonant features and spin splitting are observed. The dwell time is prolonged dramatically around the resonant energies and peaks are formed. When resonance occurs, the electrons are bounced back and forth in the structure for many times before the final escape, and hence the dwell time is prolonged.

Because the Dresselhaus SOC causes the resonant energy of spin-up and spin-down electrons split at nonzero $k_\parallel$, the peak positions of the dwell time split too. Considering the Dresselhaus SOC to be a small perturbation, the resonant energy can be expressed as[9]

$$E_\pm(k_\parallel) = E_0 \pm \alpha k_\parallel, \qquad (14)$$

where E_0 is the resonant energy when the Dresselhaus SOC is absent and α is a constant. For $E_0 \ll V_b$, α becomes

$$\alpha = \frac{2\gamma m^*}{\hbar^2}\frac{V_w}{1+2/\kappa a}, \qquad (15)$$

where $\kappa=\sqrt{2m^*(V_b-E_0)}/\hbar$ is the reciprocal length of the wave function decay under the barrier. Equation (14) indicates that larger $k_\parallel$ causes larger splits between the spin-up and spin-down results; however, the midpoint of the spin-up and spin-down results for any given $k_\parallel$ is basically unchanged. This implies the results in the absence of the Dresselhaus SOC effect can always be estimated backwards as midway between the spin-up and spin-down results in the presence of the Dresselhaus SOC. The widths of the resonant peaks of the dwell time follow similar rules as the transmission coefficient, that is, as $k_\parallel$ increases, the spin-up peak shifts to higher energy region with larger peak width, while the spin-down peak shifts to lower energy region with smaller peak width. For comparison, the transmission coefficient obtained by Glazov *et al.* is presented in Fig. 2(a).

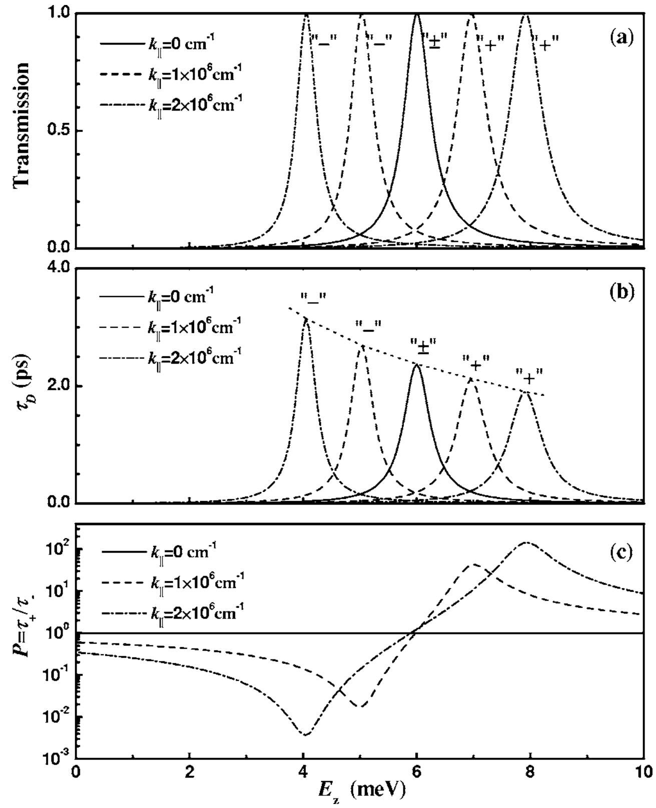

FIG. 2. Transmission coefficients (a), dwell time (b), and $P=\tau_+/\tau_-$ (c) as functions of E_z for electrons with different in-plane wave vectors $k_\parallel$ tunneling through a symmetric structure. $a=30$ Å, $b=c=50$ Å, and $F=0$.

One direct result of the splitting is the difference in the dwell time between spin-up and spin-down electrons with the same incident wave vector. The ratio $P=\tau_+/\tau_-$ is introduced to evaluate this difference. Figure 2(c) presents P as a function of E_z. It is clear that the difference is considerably large through the whole energy region and reaches maxima at resonant energies. The difference becomes greater and the peaks become farther apart as $k_\parallel$ increases, which is helpful for differentiating the spin-up and spin-down electrons from the device point of view.

In symmetric structures, the tunneling can reach perfect resonances, i.e., resonances with unity transmission coefficient, at resonant energies. This makes the peak values of the dwell time especially meaningful. The tunneling time, though has not got a general expression till now, is related to the dwell time with[24]

$$\tau_D = T\tau_T + R\tau_R, \qquad (16)$$

where τ_T and τ_R are the tunneling and reflecting time, respectively. The peak values of the dwell time in symmetric struc-

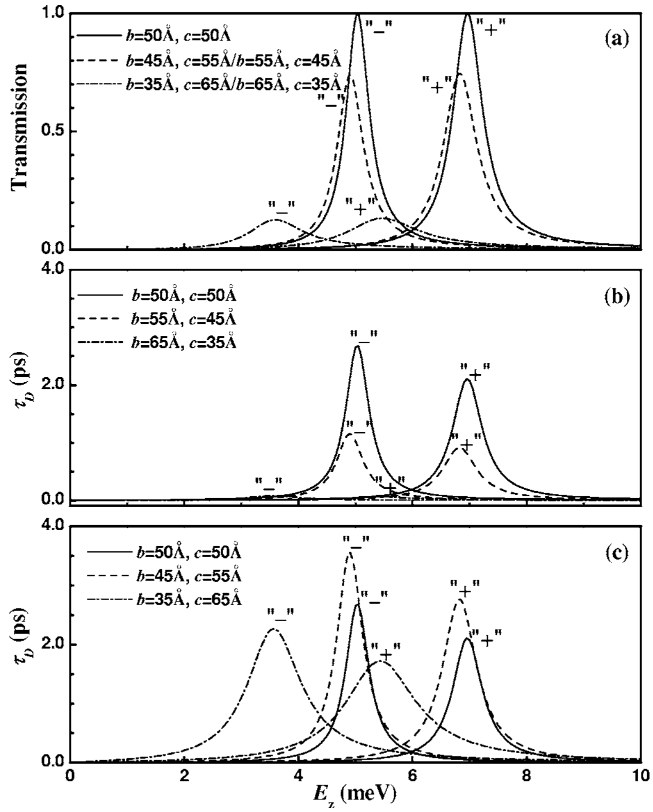

FIG. 3. Transmission coefficients and dwell time as functions of E_z for electrons tunneling through different asymmetric structures at fixed $k_{\|}=10^6\ \mathrm{cm}^{-1}$ and $F=0$. (a) Transmission coefficients; (b) dwell time for thicker-left-barrier structures; (c) dwell time for thicker-right-barrier structures.

tures, which correspond to $T=1$, represent exactly the tunneling time of the electrons in the situation. As shown in Fig. 2(a), the tunneling time, which is on the order of 10^{-12} s, decreases as the resonant energy shifts to higher energy region. From the data presented in the figure, the dependency of tunneling time on E_z can be fitted as

$$\tau_T = C(E_z/\mathrm{meV})^{-\lambda}, \tag{17}$$

where $C=9\times 10^{-12}$ s, $\lambda=0.77$, and $R^2=0.9995$ in the structure investigated. Generally, we would expect $\tau \propto v^{-1} \propto (E_z/m^*)^{-1/2}$. But for here, as $k_{\|}$ increases, the Dresselhaus SOC causes the spin-down electrons resonant at lower energy region with larger effective mass, while the spin-up ones resonant at higher energy region with smaller effective mass [see Eq. (6)]. With the approximation that C is constant, the variation of the effective mass is added to the power of E_z. As a result, λ is greater than 1/2.

We next investigate the dwell time in asymmetric structures. In order to simulate the electrons' tunneling from different sides of a device, the structures chosen are all coupled in pairs with exchanged barrier thicknesses. Hence the structures can be classified into two types: thicker-left-barrier structures and thicker-right-barrier structures.

Figure 3 shows the transmission coefficient and the dwell time of spin electrons tunneling different asymmetric structures at a fixed $k_{\|}$. In order to exclude possible influences of a changed structure length and study purely the behavior of the dwell time with increasing structure asymmetry, the structures under investigation are chosen to have equal length. Figure 3(a) presents the transmission coefficient as a function of the longitudinal electron energy, showing that: (i) the transmission coefficients of electrons tunneling the paired thicker-left-barrier and thicker-right-barrier structures are identical, and (ii) as the degree of the structural asymmetry increases, the resonant peaks for both spin-up and spin-down electrons shift to lower energy region, and the peak values of the transmission coefficient decrease.

The dwell time of electrons tunneling through the two types of structures is presented in Figs. 3(b) and 3(c). It is found that electrons tunneling through the thicker-right-barrier structures always have longer resonant dwell time than those tunneling through the thicker-left-barrier structures, although their transmission coefficients are the same. This behavior is intrinsic to one-dimensional asymmetric potentials, and has been reported in an early research in a different context without taking into account of the Dresselhaus SOC effect.[25] The ratio between the two resonant dwell time can be presented as a function of the resonant reflection coefficient $R=1-T$ through[25]

$$\tau_{Dr}^{r\sigma}/\tau_{Dl}^{r\sigma} = (1+R^{1/2})/(1-R^{1/2}), \tag{18}$$

where $\tau_{Dr}^{r\sigma}$ and $\tau_{Dl}^{r\sigma}$ are the resonant dwell time in the thicker-right-barrier structures and the thicker-left-barrier structures, respectively. Our results well agree with the formula.

Physically, the dwell time's behavior can be explained by investigating two factors: the transmission coefficient of the whole structure (T_{st}) and the transmission coefficient of the right barrier (T_{rb}). Larger T_{st} is related to longer dwell time, because the tunneling is closer to the perfect resonance, in which electrons are bounced forth and back many times before escape. Larger T_{rb}, on the other hand, causes shorter dwell time, because the electrons have higher probabilities to tunnel directly through the structure instead of being bounced back. Now the transmission coefficients of the whole structures (T_{st}) are equal in the two types of structures, but the transmission coefficient of the right barrier (T_{rb}) are different. T_{rb} can be simply determined by the change of the height and the thickness of the right barrier for the low energy electrons here. The thicker-right-barrier structures have a smaller T_{rb} and hence a longer resonant dwell time.

As the degree of the structural asymmetry increases, the resonant dwell time decreases monotonically for the thicker-left-barrier structure. For the thicker-right-barrier structure, on the other hand, the resonant dwell time increases at first and then decreases after reaching a maximum value. This can also be explained in the same way as above. The peak values of T_{st} decrease as the degree of the structural asymmetry increases. In thicker-left-barrier structures, as the asymmetry increases, the right barrier becomes thinner and hence T_{rb} increases. As both the decreasing T_{st} and the increasing T_{rb} tend to shorten the dwell time, the resonant dwell time decreases monotonically in Fig. 3(b). In contrast, T_{rb} decreases as the asymmetry increases in the thicker-right-barrier structures. The decreasing T_{st} tends to shorten the dwell time

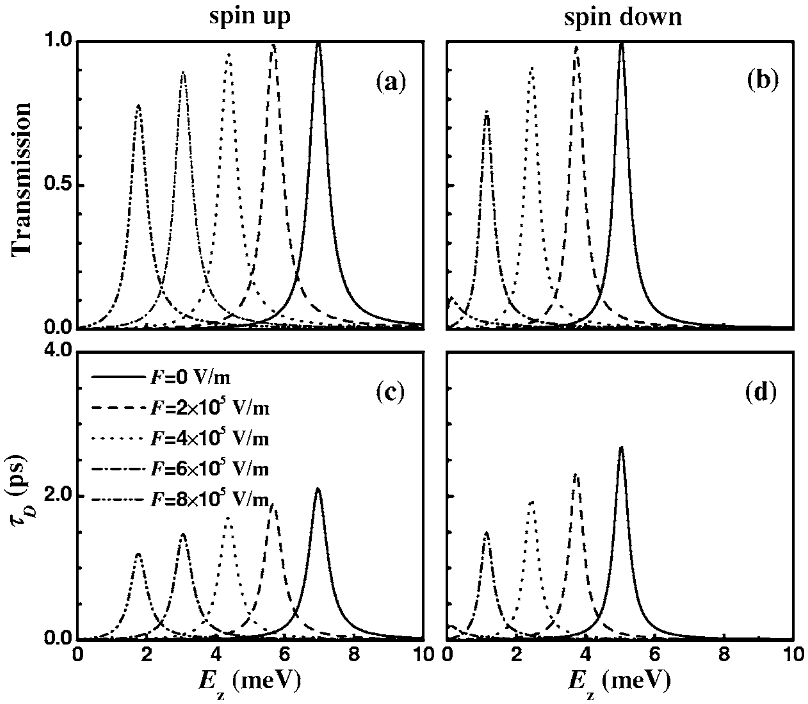

FIG. 4. Transmission coefficients and dwell time as functions of E_z for electrons with fixed $k_{\|}=10^6\ \mathrm{cm}^{-1}$ tunneling through a symmetric structure under zero and series of electric fields. $a=30$ Å and $b=c=50$ Å.

while the decreasing T_{rb} tends to prolong it. The competition between these two factors causes a nonmonotonic change of the resonant dwell time in Fig. 3(c).

Next we apply an electric field to the symmetric structure and see how the electric field affects the tunneling properties. Figures 4(a) and 4(b) present the transmission coefficient as a function of E_z under zero and series of applied bias for spin-up and spin-down electrons, respectively. As the electric field increases, the resonant energies shift to lower energy region, and meanwhile the resonant transmission coefficient decreases, which reflects the asymmetry of the effective potential introduced by the electric field. Figures 4(c) and 4(d) present the dwell time in corresponding cases. It is observed that the resonant dwell time decreases monotonically as the electric field increases. As shown in Figs. 4(a) and 4(b), the resonant peaks of T_{st} decrease as the electric field increases. Furthermore, the increasing electric field causes the right barrier to have lower effective potential and hence larger T_{rb}. Now that both the decreasing T_{st} and the increasing T_{rb} tend to shorten the dwell time, the dwell time decreases monotonically as the electric field increases.

Finally, we examine the effect of the electric field in the asymmetric structures. Figures 5(a)–5(d) present the transmission coefficients of electrons tunneling through a pair of asymmetric structures under zero and series of electric fields. In the thicker-left-barrier structure, the resonant transmission coefficient decreases monotonically as the electric field increases, while in the thicker-right-barrier structure, the resonant transmission coefficient increases at first and yield perfect resonant under a certain electric field. This can be understood as "$-z$" electric fields decrease the height of the right barrier, which can compensate the structural asymmetry caused by the thicker right barrier. Electrons with different spin orientations yield perfect resonance almost under the same electric field, as the same electric field compensates the same asymmetry of the structure, except for a slight difference caused by the split of the modified electron effective masses.

Figures 5(e)–5(h) present the dwell time in the asymmetric structures. In the thicker-left-barrier structure, the resonant dwell time decreases as the electric field increases, which is similar to that shown in the symmetric structure. In the thicker-right-barrier structure, however, the resonant dwell time keeps almost unchanged under the increasing electric field. The origin of the phenomenon can be found in Figs. 5(c) and 5(d), where T_{st} increases first as the electric field increases, which prolongs the dwell time, and thus compensates the increase in T_{rb} that would lead to shorter dwell time. Moreover, in structures with greater degree of asymmetry, $b=40$ Å and $c=60$ Å for example, it is found that the dwell time even increases at first. Therefore, by tuning the electric field and the structural asymmetry, we can obtain different dwell time at the same resonant energy, which is expected to be useful from the device point of view.

At the end of this section, we would like to point out that all the discussions above are based on electrons having fixed in-plane wave vector $\mathbf{k}_{\|}$. One method to control the in-plane wave vector was demonstrated recently with side-gate resonant devices in a dc regime.[26] The resultant transmission coefficient can be measured through the electric current detection. The dwell time can be measured by making the barrier weakly absorbing.[27]

IV. SUMMARY AND CONCLUSION

In summary, we investigated the effect of the Dresselhaus SOC on the dwell time of electrons tunneling through double-barrier structures under the influence of an external electric field. It is found that obvious resonant features exist in the time domain, and the Dresselhaus SOC causes the

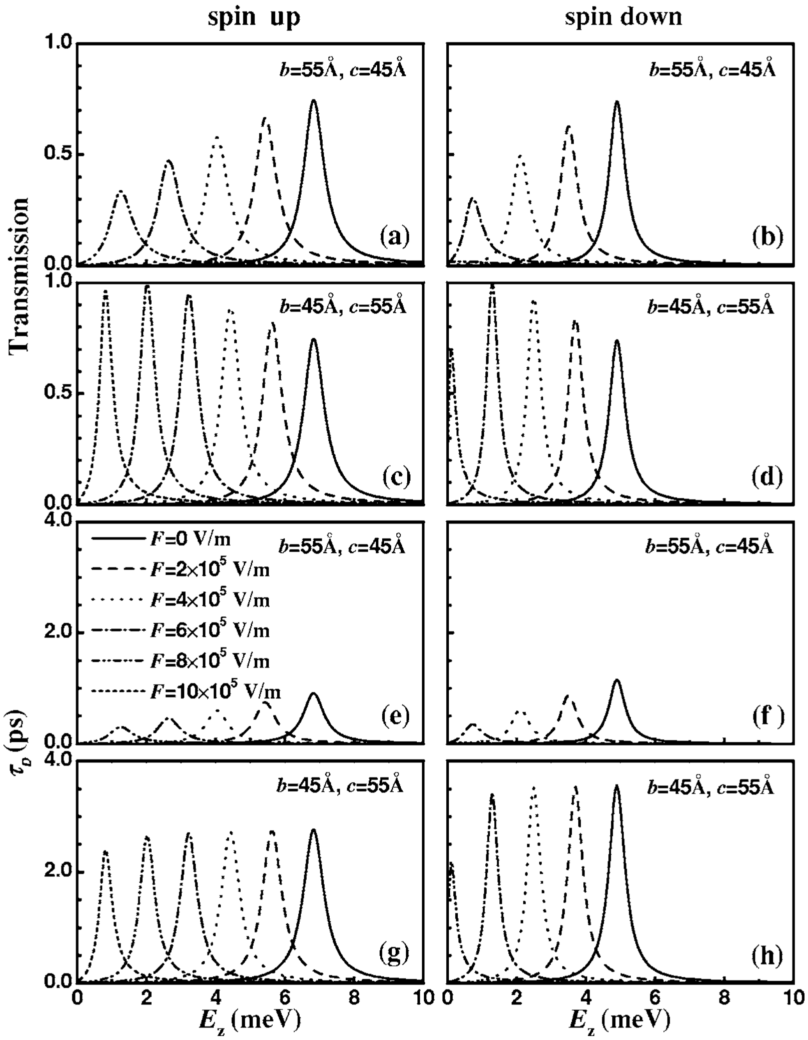

FIG. 5. Transmission coefficients and dwell time as functions of E_z for electrons with fixed $k_{\|}=10^6\ \mathrm{cm}^{-1}$ tunneling through asymmetric structures under zero and series of electric fields.

resonant peaks for the spin-up and spin-down electrons split when the in-plane wave vector is not zero. The difference in the dwell time of opposite spin electrons is found to reach its maxima at the resonant energies and become greater under larger in-plane vectors. Neither the structural asymmetry nor the electric field changes the main features of the resonance and spin splitting, but they are found to shift the resonant peaks and change the peak values significantly. At zero bias, though the transmission coefficients are exactly the same for the electrons tunneling through an asymmetric structure from opposite directions, the dwell time is quite different. We point out that by simultaneously tuning the in-plane wave vector, the asymmetry of the structure, and the electric field, it is possible to make the spin-up and spin-down electrons resonant at given energies with appointed resonant dwell time.

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