Tunneling conductance of a metal-semiconductor heterostructure with Rashba effect

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Abstract. We theoretically studied the in-plane tunneling spectroscopy of the hybrid structure composed of a metal and a semiconductor with Rashba spin-orbit coupling. We found that the energy spacing between two distinct features in the conductance spectrum can be used to measure the Rashba energy of the semiconductor. We also considered the effect that varying the probability of spin-conserving and spin-flip scattering at the interface has on the overall conductance. Surprisingly, an increase in interface scattering probability can actually result in increased conductance under certain conditions. Particularly, in the tunneling regime, an increase in spin-flip scattering probability enhances the conductance. It is also found that the interfacial scattering greatly affects the spin polarization of the conductance in metal, but hardly affects that in the semiconductor.

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1. Introduction

Structural inversion asymmetry of the confining electrostatic potential results in an intrinsic spin-orbit coupling of electrons in a two-dimensional electron gas (2DEG), which can be described by the Rashba Hamiltonian [1, 2, 3]:

$$\mathcal{H} = \frac{\vec{p}^2}{2m^*} - \lambda \hat{j} \cdot (\vec{p} \times \vec{\sigma})$$  \hspace{1cm} (1)

where $\vec{p}$ is 2D momentum, $m^*$ is the electron effective mass, $\hat{j}$ is the direction perpendicular to the plane of motion, $\lambda$ is the spin-orbit coupling parameter, which can be tuned by applying an external gate voltage perpendicular to the 2D plane, and the components of $\vec{\sigma}$ are the Pauli spin matrices. The spin-orbit interaction lifts the spin degeneracy and causes the original parabolic energy spectrum to split into two branches: $E_{\vec{k}, \pm} = \frac{\hbar^2 k^2}{2m^*} \pm \hbar \lambda k$, where $k = |\vec{k}| = \sqrt{k_x^2 + k_z^2}$ (see Figure 1). The density of states of this system is the same as that of the 2D free electron gas for all energies higher than the crossing point of the two branches. However, at the bottom of the band, the density of states has $E^{\frac{1}{2}}$ van Hove singularity because the minus branch has an annular minimum for $k = k_0 \equiv m^* \lambda/\hbar$ instead of a single-point minimum as in the free electron gas. These properties lead to interesting phenomenon, like the spin hall effect (see e.g. Refs. [4] for review), with associated applications in spintronics (see e.g. Refs. [5] for review).

The Rashba effect has been seen in many system like surface alloys and semiconductor heterostructures. There are many techniques that have been used to study the spin-split states in these systems, for example, angle-resolved photoemission spectroscopy [6, 7, 8, 9, 10] and scanning tunneling spectroscopy [11]. The former

![Figure 1](image_url). The energy spectrum of the 2DEG with the Rashba spin-orbit coupling as a function of the magnitude of momentum $k$. "+ branch" and "- branch" refer to the energy branch $E_{\vec{k}, \pm} = \frac{\hbar^2 k^2}{2m^*} \pm \hbar \lambda k$ respectively. The plot of the density of states (in units of $L^2 m^* / \pi \hbar^2$) as a function of energy is shown in the inset.
technique is utilized mainly to obtain the energy dispersion and the Fermi surface map, from which the effective mass, the magnitude of the band splitting, and hence the Rashba spin-orbit coupling energy can be extracted [6, 7, 8, 9, 10]. In the latter technique, the electric current is driven perpendicular to the 2D plane and the differential conductance \( (dI/dV) \) spectrum can be obtained. One can deduct the Rashba energy by fitting the \( dI/dV \) spectrum to the local density of states of the 2DEG [11]. In both cases, to obtain the information about the Rashba spin-orbit coupling, extensive data fitting is needed. In this article, we propose a way to measure the Rashba spin-orbit coupling energy more directly from the experimental data: the in-plane tunnelling spectroscopy. In particular, the energy difference between two features in the conductance spectrum is equal to the Rashba energy \( E_\lambda \equiv \hbar^2 k_0^2/(2m^*) \).

Another aspect of the study involving 2DEG with Rashba spin-orbit interaction is spin-dependent transport. Many theoretical investigations have shown that both electric and spin transport in hybrid structures between the 2DEG and various materials, like metal [12, 13, 14, 15], ferromagnet [15, 16, 17, 18], and superconductor [19], are affected by the strength of the spin-orbit coupling [12, 13, 14, 15, 16, 17, 18, 19], the inequality of the effective masses [12, 13, 17, 18], and the transparency of the interface [16, 17, 19]. However, in these previous studies, only spin-conserving interfacial scattering was considered. One expects to see interesting consequences of spin-flip interfacial scattering, because the equations describing the spin-up and spin-down spin states are coupled. For instance, in the study of the tunneling conductance spectrum of a semiconductor/superconductor junction [20], the non-spin-flip scattering is found, when present alone, to suppress the Andreev reflection process and hence the subgap conductance as expected. However, when the spin-flip potential scattering is also present at the interface, their combined effect surprisingly enhances the subgap conductance [20].

Here, we consider how the scattering potential barrier affects both the conductance spectrum and the spin polarization of the conductance of a metal/semiconductor junction with Rashba effect. Similar to the previous work by Zutic and Das Sarma [20], the conductance spectrum, which is usually suppressed in the present of the interfacial scattering, can be enhanced by the combined effect of both types of scattering. It is also found that the spin polarizations of the metal and the semiconductor are not equal. The spin polarization in the semiconductor weakly depends on the quality of the interfacial contact, while that in metal is greatly affected.

This article is organized as follows. In the next section, we describe in more detail the theoretical method and assumptions. We then provide the results and discussion in Section 3. The conclusion is given in the last section.

2. Method of calculation and assumptions

We represent our junction by an infinite 2D system which lies on \( xz \) plane, where the metal and the semiconductor occupy the \( x < 0 \) and \( x > 0 \) region respectively. The two regions are separated by a flat interface at \( x = 0 \). The interfacial scattering is modeled
by a Dirac delta function potential [21]. We consider ballistic transport in our junction. In the one-band effective-mass approximation, we describe our system by the following Hamiltonian:

$$\mathcal{H} = \left( \hat{p} + V(x, z) \right) \mathcal{I} + \mathcal{H}_R(x).$$

(2)

Each term is the $2 \times 2$ matrix acting on spinor states. $\mathcal{I}$ is a $2 \times 2$ identity matrix, and

$$\hat{p} = -i\hbar \left( \hat{i} \frac{\partial}{\partial x} + \hat{k} \frac{\partial}{\partial z} \right).$$

The effective mass $m(x)$ is position-dependent, i.e.,

$$\frac{1}{m(x)} = \frac{1}{m} \Theta(-x) + \frac{1}{m^*} \Theta(x),$$

(3)

where $m$ and $m^*$ are effective electron masses in the metal and the semiconductor respectively. $V(x, z)$ is also a position-dependent function and is modeled by the expression

$$V(x, z) = H \delta(x) + E_0 \Theta(x) - E_F \Theta(-x)$$

(4)

where $H$ represents the scattering potential at the interface, $\Theta(x)$ is the Heaviside step function, $E_0$ is the energy difference between the Fermi level and the bottom of the plus branch (see Figure 2), and $E_F = \hbar^2 q_F^2 / (2m)$ is the Fermi energy of the metal. Changing this offset energy $E_0$ will result only in a rigid shift of the conductance spectrum in energy. We assume that $E_F$ is much larger than $E_0$. The diagonal elements of $H$, $H_{11}$ and $H_{1\downarrow}$ correspond to the non-spin-flip scattering potential characterizing the quality of the junction, while $H_{1\uparrow} = H_{\uparrow 1}$ describe spin-flip scattering [20]. The Rashba Hamiltonian is written as [22]

$$\mathcal{H}_R(x) = \frac{\lambda}{2} \cdot \left[ \lambda(x) \left( \hat{p} \times \hat{\sigma} \right) + \left( \hat{p} \times \hat{\sigma} \right) \lambda(x) \right]$$

(5)

where $\lambda(x) = \lambda \Theta(x)$.

From the Hamiltonian, one can obtain the eigenstates and eigenenergy for the electrons in each region as follows. In the $x < 0$ region, the energy spectrum is

$$E(q) = \frac{\hbar^2 q^2}{2m} - E_F$$

(6)

where $q = \sqrt{q_x^2 + q_z^2}$ is the magnitude of the 2D momentum of the electrons. In the $x > 0$ region, the eigenenergy is obtained as

$$E^\pm(k) = \frac{\hbar^2 k^2}{2m^*} \pm \frac{\hbar^2 k_0^2}{2m^*} + E_0$$

(7)

where $k = \sqrt{k_x^2 + k_z^2}$ is the magnitude of the 2D momentum and $k_0 = m^* \lambda / \hbar$. Figure 2 shows both energy spectra and both energy contours.

The wave function of the electrons in metal is written as a linear combination of incoming momentum state with equal spin components and a reflected state of the same energy and $k_z$:

$$\Psi_M(x, z) = \left( \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} e^{iq_z x} + \begin{bmatrix} b^\dagger_\uparrow \\ b^\dagger_\downarrow \end{bmatrix} e^{-iq_z x} \right) e^{ik_z z}$$

(8)
Figure 2. The top sketches are the energy contours of the electron in the metal (left) and the semiconductor (right). The angles \( \theta \) and \( \varphi \) are defined as those between the \( x \) axis and the momenta of electrons in the metal and the semiconductor (SC) respectively. The dashed line that crosses both sides shows the momentum states with the same \( k_z \). The dotted line is the line of the maximum value of \( k_z \), which defines the maximum incident angle \( \theta_m \). The lower sketches are the corresponding energy spectra (\( E \) vs the magnitude of momentum). \( E_F \) and \( E_0 \) are the metal Fermi energy and the off-set energy of the semiconductor respectively.

where the \( b_\uparrow, b_\downarrow \) are the amplitudes for reflection of spin-up and spin-down electrons respectively. \( q_x = q \cos \theta \) and \( k_z = q \sin \theta \), where \( \theta \) is the angle between \( \mathbf{q} \) and the \( x \) axis. The magnitude of the momentum, \( q \), depends on energy as

\[
q = \sqrt{\frac{2m}{\hbar^2} (-E + E_F)} \quad (9)
\]

Similarly, in the semiconductor, the wave function is obtained as a linear combination of two outgoing eigenstates of the same energy and \( k_z \):

\[
\Psi_{2DSC}(x, z) = \left( c_+ \left[ \cos \frac{\varphi_{k_+}}{2} \pm \sin \frac{\varphi_{k_+}}{2} \right] e^{\pm ik'_+x} + c_- \left[ \sin \frac{\varphi_{k_-}}{2} \cos \frac{\varphi_{k_-}}{2} \right] e^{ik'_-x} \right) e^{ik_zz} \quad (10)
\]

where \( \varphi_{k_{\pm}} \) are the angles between \( \mathbf{k}_{\pm} \) and the \( x \) axis. For \( E > E_0 \), \( c_+ \) and \( c_- \) are the transmission amplitudes of electrons to plus and minus branch respectively. When \( E < E_0 \), \( c_+ \) and \( c_- \) refer to the transmission amplitudes of electrons to states with smaller and larger \( k \) of the minus branch respectively. The upper and lower signs in the first term of Equation (10) are for \( E \leq E_0 \) and \( E > E_0 \) respectively. \( k'_\pm = k^\pm \cos \varphi_{k^\pm} \) and \( k_z = k^\pm \sin \varphi_{k^\pm} \), where the magnitudes of the momenta, \( k^\pm \), depend on energy as

\[
k^- = k_0 + \sqrt{k_0^2 + \frac{2m^*}{\hbar^2} (E - E_0)} \quad (11)
\]
\[ k^+ = \pm \left( k_0 - \sqrt{k_0^2 + \frac{2m^*}{\hbar^2}(E - E_0)} \right) \]  

Again, in Equation (12) the upper and lower signs are for \( E \leq E_0 \) and \( E > E_0 \) respectively. The relationship between the angles \( \varphi_{k^\pm} \) and \( \theta \) is

\[ k^\pm \sin \varphi_{k^\pm} = q \sin \theta. \]  

We can obtain the probability amplitudes \( b_\uparrow, b_\downarrow, c_+ \) and \( c_- \) from the following matching conditions that ensure probability conservation [22].

\[ \Psi_M(x = 0, z) = \Psi_{2DEG}(x = 0, z) \equiv \Psi_0, \]

\[ \frac{m}{m^*} \frac{\partial \Psi_{2DEG}}{\partial x} \bigg|_{x=0} - \frac{\partial \Psi_M}{\partial x} \bigg|_{x=0} = \left( 2q_F Z - i \frac{m}{m^*} k_0 \sigma_z \right) \Psi_0 \]  

where \( Z = mH/(\hbar^2q_F) \). The diagonal elements of \( Z \) will henceforth be referred to as \( Z_u \equiv Z_{\uparrow\uparrow} \) and \( Z_d \equiv Z_{\downarrow\downarrow} \), while the off-diagonal element will be denoted by \( Z_F = Z_{\uparrow\downarrow} = Z_{\downarrow\uparrow} \). In what follows the spin flip term \( Z_F \) will be responsible for the enhancement of a feature at the branch-crossing point in the conductance spectrum.

The particle current density along the \( x \) direction is obtained from

\[ j_x^p = \frac{1}{2} \left[ \Psi^\dagger(x) \hat{v}_x \Psi(x) + (\hat{v}_x \Psi(x))^\dagger \Psi(x) \right], \]  

where \( \Psi(x) \) is the spinor wave function, and \( \hat{v}_x = d\hat{x}/dt = i [\mathcal{H}(x), \hat{x}] / \hbar \). From the current density, the reflection and transmission probabilities can be obtained:

\[ R_\uparrow = |b_\uparrow|^2 \]
\[ R_\downarrow = |b_\downarrow|^2 \]
\[ T_+ = \frac{m}{m^*} |c_+|^2 \left( \frac{\mp k_0^+ + k_0 \cos \varphi_{k^+_0}}{q_x} \right) \]
\[ T_- = \frac{m}{m^*} |c_-|^2 \left( \frac{k_0^- - k_0 \cos \varphi_{k^-_0}}{q_x} \right) \]  

where \( R_\uparrow, R_\downarrow \) are the reflection probabilities to spin-up and spin-down states, and \( T_+, T_- \) are the corresponding transmission probabilities. Also, the upper and lower signs in \( T_+ \) are for \( E \leq E_0 \) and \( E > E_0 \) respectively. As mentioned earlier, the matching conditions ensure that \( R_\uparrow + R_\downarrow + T_+ + T_- = 1 \).

Since the current is independent of \( x \), we consider the current density in the metal for simplicity. It can be written as a function of applied voltage \( V \) as follows.

\[ j_x^e(eV) = \sum_{q_x>0,q_x} ev_x \left( 1 - R_\uparrow - R_\downarrow \right) \left[ f(E_q - eV) - f(E_q) \right] \]
\[ = \frac{eL^2}{4\pi^2} \int_0^\infty dq \int_{-\theta_m}^{\theta_m} d\theta \frac{\hbar q \cos \theta}{m} \left( 1 - R_\uparrow - R_\downarrow \right) \left[ f(E_q - eV) - f(E_q) \right] \]  

where \( L^2 \) is the area of the metal, \( e \) is the electron charge, \( v_x \) is the \( x \) component of the electron group velocity, and \( f(E) \) is Fermi distribution function, \( \theta_m \) is the maximum angle of the incident electrons from the metal (see Figure 2): \( \theta_m = \sin^{-1}(k^-/q) \).
By changing the integration variable and setting temperature to zero for simplicity, one can obtain the expression for the electric current as

$$j(x) = e \frac{L^2 q_F}{2\pi} \int_0^{eV} dE \int_{-\theta_m(E)}^{\theta_m(E)} d\theta \cos \theta \sqrt{1 - \frac{E}{E_F}} (1 - R_\uparrow - R_\downarrow)$$  \hspace{1cm} (18)$$

Thus, the differential conductance at zero temperature is

$$G(V) \equiv \frac{dj(x)}{dV} = e^2 \frac{L^2 q_F}{2\pi} \int_{\theta_m(V)}^{\theta_m(V)} d\theta \cos \theta \sqrt{1 - \frac{eV}{E_F}} (1 - R_\uparrow - R_\downarrow)$$  \hspace{1cm} (19)$$

The finite temperature will smear the features in the conductance spectrum but will not change their positions (assuming that the strength of the Rashba spin-orbit coupling does not depend on temperature).

The spin polarization of the conductance $P$ is defined as

$$P(E) = \frac{\sum_{q_x>0,q_z} (n_\uparrow v_\uparrow - n_\downarrow v_\downarrow)}{\sum_{q_x>0,q_z} (n_\uparrow v_\uparrow + n_\downarrow v_\downarrow)},$$  \hspace{1cm} (20)$$

where $n_\sigma v_\sigma$ is the number of electrons with spin $\sigma$ that cross a plane of interest per unit time. In terms of the reflection probabilities this spin polarization in the metal can be written as

$$P_M(E) = \frac{\sum_{q_x>0,q_z} (-R_\uparrow + R_\downarrow)}{\sum_{q_x>0,q_z} (1 - R_\uparrow - R_\downarrow)}$$  \hspace{1cm} (21)$$

and the spin polarization in the semiconductor in terms of the transmission probabilities is written as

$$P_{2DEG}(E) = \frac{\sum_{q_x>0,q_z} (T_+ \cos \varphi_{k+} - T_- \cos \varphi_{k-})}{\sum_{q_x>0,q_z} (T_+ + T_-)}$$  \hspace{1cm} (22)$$

As expected, the spin polarization measures the difference in number of the carriers with spin-up and spin-down on each side.

3. Results and discussion

In this section, we discuss the effect of the interfacial scattering on the differential conductance spectra and the spin polarization on each side of the junction. In all plots, we set $m/m^* = 10$ and $k_0 = 0.05q_F$, which corresponds to typical experimental values in metal/semiconductor junctions [20, 23]. In Figure 3, two conductance plots for two values of $E_0$ are shown. Positives values of $E_0$ means the energy spectrum of the semiconductor is unoccupied and the positive $eV$ across the junction will cause the current to flow from the metal to the semiconductor. In the case where the energy spectrum is occupied ($E_0 = -0.075E_F$), the results are identical in shape to those in the unoccupied case ($E_0 = +0.05E_F$), but the applied voltage $eV$ across the junction has to be negative, i.e. changing $E_0$ causes a rigid shift in energy.

There are two main features at the voltage corresponding to the bottom and the branch-crossing of the energy band. The distance between them depends on $E_\lambda$, which
is the quantity of interest. The value of $E_0$ is not important and will henceforth be set equal to zero.

We do not consider the spin filtering interface. That is, we set the non-spin-flip scattering strength $Z_u = Z_d = Z$. It is well-known that the difference in $Z_u$ and $Z_d$ will cause a spin-filtering effect. That is, a higher $Z_u$ will make the transport of the spin-up electrons less favorable and vice versa. This effect cannot be seen in the conductance spectrum and will not be considered in the spin polarization.

### 3.1. Differential conductance spectra

In all conductance plots, the conductance is in units of $e^2L^2q_F/(2\pi\hbar)$. The conductance spectra $G$ with different $Z_F$ in different limits of $Z$ are shown in Figure 4 and 5. In general, the conductance is zero until the applied voltage reaches $eV = -E_\lambda$, which is the bottom of the semiconductor band. The conductance increases suddenly with large initial slope that decreases steadily until a second feature: the kink occurring at $eV = 0$, which is the crossing point of the two branches of the band. After this point, the conductance increases approximately linearly.

In the presence of $Z_F$ and $Z$, there occurs a discontinuity in the conductance at $eV = 0$. The height of the jump depends on both $Z$ and $Z_F$. That is, in the presence of the same $Z$ the height of this jump is enhanced by the increase in $Z_F$ up to critical value, after which it begins to decrease. The height of the jump also depends on $Z$ in the same fashion when $Z_F$ is set constant. The energy difference between the onset and the discontinuity in the conductance spectrum can be used to measure the magnitude of the Rashba energy $E_\lambda$. 

**Figure 3.** On the left side is the spectrum in the case where the semiconductor energy band is occupied ($E_0 = -0.075E_F$) and on the right is that where the band is unoccupied ($E_0 = 0.05E_F$). $Z$ and $Z_F$ are set equal to zero. $m/m^* = 10$ and $k_0 = 0.05k_F$. The derivative of the conductance spectrum ($dG/dV$) on the right is shown in the inset.
Figure 4. Differential conductance spectra $G$ for different $Z_F$ in the case where (a) $Z = 0$, (b) $Z = 0.1$, and (c) $Z = 0.5$. 

In addition to the influence on the discontinuity at $eV = 0$, the interfacial scattering affects the overall conductance spectrum as well. For weak non-spin flip scattering ($Z < 0.5$), the spin-flip scattering suppresses the conductance as expected. However, in the intermediate limit and the limit of high $Z$, the results are rather surprising. As can be seen in Figure 4 when $Z = 0.5$, the increase in $Z_F$ from zero to a small value (less than 0.5) does not affect the conductance much. Only when $Z_F$ is increased beyond a critical value, does the conductance get suppressed. When $Z$ is high ($Z \geq 1.0$), the conductance spectrum can be enhanced by the increase in $Z_F$ up to a critical value, after which the spectrum becomes suppressed. The critical value of $Z_F$ depends on $Z$.

One can see the dependence of the conductance spectrum on the spin-flip scattering more clearly by considering plots of the conductance $G$ as a function of $Z_F$ for energies just below and just above 0. In Figure 5 $G^\prec \equiv G(-\delta)$ and $G^\succ \equiv G(+\delta)$, where $\delta/E_\lambda = 0.8$, are plotted as a function of $Z_F$ for different values of $Z$. For small $Z$ (less
than 0.5), both \( G^> \) and \( G^< \) decreases with \( Z_F \). This trend starts to change when \( Z \) is higher than a critical value (around 0.5). That is, both \( G^> \) and \( G^< \) increases with \( Z_F \) and reach a maximum value at a critical value, which increases with \( Z \). This value is smaller for \( G^< \) than for \( G^> \). A similar dependence of both \( G^> \) and \( G^< \) on \( Z \) can also be seen, if one plots \( G^> \) and \( G^< \) as a function of \( Z \) instead.

3.2. Spin polarization

The plots of the spin polarizations in both metal and semiconductor with the Rashba effect as a function of energy are shown in Figure [7]. The spin polarizations of the two sides are very different. In semiconductor, it is always negative, whereas in the metal it is positive when the spin-flip scattering is not strong. This may be understood by considering the density of states of the semiconductor.

The density of states of the minus branch is larger than that of the plus branch. As we can see from Figure [8], because the spins of the transmitted states of the minus branch are mostly pointing down, it is not surprising that the spin polarization in the semiconductor is negative. As for the metal side, because more spin-down states are transmitted into the semiconductor, the spin polarization is positive.

The interfacial scattering does not affect the spin polarization in the semiconductor as much as in the metal. The increase in either \( Z \) or \( Z_F \) seems to slightly change the magnitude of the spin polarization. However, in metal the interfacial scattering potential
Figure 7. The plots of the spin polarization of conductance in metal and semiconductor (SC) with the Rashba effect as a function of energy when $Z$ is (a) 0 and (b) 0.5.

affects the spin polarization a great deal. For a particular value of $Z$, the increase in $Z_F$ can cause the spin polarization in metal to change sign.

One can look at the influence of the spin-flip scattering in more detail by plotting the spin polarization at different energies: $P^< = P(-\delta)$, $P^0 = P(0)$, and $P^> = P(+\delta)$, as a function of $Z_F$. Again, in all plots $\delta/E_\lambda = 0.8$. In metal, when $Z$ is small, $P^<$ is decreased with $Z_F$. When $Z$ is large, $P^<$ is converged to zero for all $Z_F$. $P^0$ and $P^>$ are also converged to zero, when $Z$ is large. However, for small $Z$, $P^0$ and $P^>$ decreases with...
Figure 8. Density of states of each branch of the 2DEG with the Rashba effect. The contour plots on the left and on the right are those in the case where $E < E_0$ and $E > E_0$ respectively. When $E > E_0$, the outer contour is that of - branch and the inner one is that of + branch. When $E < E_0$, both energy contours belong to the - branch. The arrows represent the spin direction of the states with positive $v_x$.

$Z_F$. Both of them become zero at almost the same values of $Z_F$, and as $Z_F$ increases $P^0$ and $P^>$ turn negative. Their magnitudes increase and reach a maximum value at a critical value of $Z_F$. With further increase in $Z_F$ after this value, the magnitudes of $P^0$ and $P^>$ become smaller and converged to zero.

In the semiconductor, $P^0$ has a bigger magnitude than $P^<$ and $P^>$, and is least affected by the scattering potential at the interface. The dependence of $P^<$, $P^0$, and $P^>$ are similar. For small $Z$, they increase with $Z_F$. For large $Z$, they decrease with $Z_F$ until $Z_F$ reaches a critical value, after which it increases with $Z_F$. This critical value of $Z_F$ increases with $Z$. The polarization on the semiconductor is always present and can be unexpectedly higher in the tunneling regimes (large $Z$) than in the metallic regimes (small $Z$).

4. Conclusions

According to the results on our simple model, one can directly use in-plane tunneling conductance spectrum of a metal/semiconductor junction to measure the Rashba energy of the semiconductor. The energy difference between the onset and the discontinuity in slope of the conductance spectrum is equal to the Rashba energy. In the presence of interfacial spin-flip scattering, the conductance is not always suppressed by the increase in spin-conserving scattering characterizing the quality of the interface. Specifically, in
Figure 9. Spin polarization $P(E)$ in (a) metal and (b) semiconductor (SC) plotted as a function of the spin-flip barrier height $Z_F$ at a constant energy slightly below [upper panel, denoted by $P^< (Z_F)$], at [middle panel, denoted by $P^0 (Z_F)$], and slightly above [lowest panel, denoted by $P^> (Z_F)$)] the energy corresponding to the crossing of the Rashba-split bands. $Z$ is (a) 0 and (b) 0.5.
the tunneling regimes, the conductance can be higher than that in the metallic regimes.

As the current is driven through the metal/semiconductor junction, an imbalance in spin in both sides also occurs. We found that the spin polarization of the conductance in metal depends very strongly on both types of the interfacial scattering and can disappear in the tunneling regimes. On the contrary, in the semiconductor the spin polarization is always present and only slightly affected by the interfacial scattering. Moreover, it has even higher magnitude in the tunneling limits.

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