The effect of Ramsauer type transmission resonances on the conductance modulation of spin interferometers

M. Cahay
Department of Electrical and Computer Engineering and Computer Science
University of Cincinnati, Cincinnati, Ohio 45221

S. Bandyopadhyay
Department of Electrical Engineering
Virginia Commonwealth University, Richmond, Virginia 23284

Abstract

We use a mean field approach to study the conductance modulation of gate controlled semiconductor spin interferometers based on the Rashba spin-orbit coupling effect. The conductance modulation is found to be mostly due to Ramsauer type transmission resonances rather than the Rashba effect in typical structures. This is because of significant reflections at the interferometer’s contacts due to large potential barriers and effective mass mismatch between the contact material and the semiconductor. Thus, unless particular care is taken to eliminate these reflections, any observed conductance modulation of spin interferometers may have its origin in the Ramsauer resonances (which is unrelated to spin) rather than the Rashba effect.

PACS: 72.25.Dc, 72.25.Mk, 73.21.Hb, 85.35.Ds
In a seminal paper, Datta and Das [1] proposed a quasi one-dimensional gate controlled ballistic spin interferometer which is an analog of the standard electro-optic light modulator. Their device consists of a one-dimensional semiconductor channel with ferromagnetic source and drain contacts (Fig.1). Electrons are injected with a definite spin orientation into the channel from the source, then controllably precessed in the channel with a gate voltage which varies the Rashba interaction in the channel [2], and finally sensed at the drain. At the drain end, the electron’s transmission probability depends on the relative alignment of its spin with the drain’s (fixed) magnetization. By controlling the angle of spin precession in the channel with a gate voltage, one can modulate the relative spin alignment at the drain end, and hence control the source-to-drain current (or conductance). This is the basis of the gate controlled spin interferometer.

The work of Datta and Das motivated vigorous research in the field of spintronics. However, to our knowledge, there has never been a complete calculation of the spin interferometer’s conductance as a function of the gate voltage in realistic structures. This would require solving the Schrödinger equation (with the Rashba spin-orbit coupling term in the Hamiltonian) self consistently with the Poisson equation to extract the transmission probability of incident electrons through the channel, and then using the Landauer formula to evaluate the conductance. In this Letter, we provide a mean-field approach to this problem.

In any realistic spin interferometer structure, varying the gate voltage will inevitably move the Fermi level in the interferometer’s channel up or down relative to the conduction band edge. We must therefore consider the following physical mechanism as another potential source of conductance modulation of the spin interferometer. Referring to Fig.2, if we neglect the Rashba effect momentarily, then it is well known that the transmission through the semiconducting channel of the interferometer (barrier region) should peak each time the Fermi level lines up with the resonant energy levels above the barrier between the two
contacts [3]. These levels are given by
\[ E_n = V_0 + \frac{n^2 \hbar^2 \pi^2}{2m^* L^2}, \] (1)
where \( n \) is an integer, \( V_0 \) is the height of the potential barrier between the ferromagnetic contacts and the semiconducting channel (including the effects of quantum confinement in the directions transverse to the channel axis), \( m^* \) is the effective mass in the semiconductor and \( L \) is the length of the channel. As the gate voltage is varied, the Fermi level sweeps through the resonant levels causing the conductance to oscillate. This is the Ramsauer effect. In this Letter, we will show that the Ramsauer effect completely masks the Rashba effect and becomes the primary source of any conductance modulation of the spin interferometer shown in Fig.1.

The quasi one-dimensional spin interferometer is described by the single particle effective-mass Hamiltonian [4]
\[
\mathcal{H} = \frac{1}{2m^*} \left( \vec{p} + e\vec{A} \right)^2 + V(y) + V(z) - \left( g^*/2 \right) \mu_B \vec{B} \cdot \vec{\sigma} + \frac{\alpha_R}{\hbar} \hat{y} \cdot \left[ \vec{\sigma} \times (\vec{p} + e\vec{A}) \right] \] (2)
where \( \hat{y} \) is the unit vector normal to the heterostructure interface in Fig.1 and \( \vec{A} \) is the vector potential due to the axial magnetic field \( \vec{B} \) along the channel caused by the ferromagnetic contacts (this magnetic field was summarily ignored in all previous work, but has important consequences). The Rashba coupling strength \( \alpha_R \) varies with the applied potential on the gate. We will assume that the confining potential \( V(z) \) along the z-direction is parabolic.

The choice of the Landau gauge \( \vec{A} = (0, -Bz, 0) \) allows us to decouple the y-component of the Hamiltonian in (2) from the x-z component. Furthermore, since this Hamiltonian is translationally invariant in the x-direction, the wavevector \( k_x \) is a good quantum number and the eigenstates are plane waves traveling in the x-direction. The two-dimensional Hamiltonian in the plane of the channel (x-z plane) is then given by
\[
H_{xz} = \frac{p_z^2}{2m^*} + \Delta E_c + \frac{1}{2} m^* \left( \omega_0^2 + \omega_c^2 \right) z^2 + \frac{\hbar^2 k_x^2}{2m^*} + \frac{\hbar^2 k_R k_x}{m^*} \sigma_z - \left( g^*/2 \right) \mu_B B \sigma_x - \frac{\hbar k_R p_z}{m^*} \sigma_x \] (3)
where \( \omega_0 \) is the curvature of the confining potential in the z-direction, \( \omega_c = eB/m^* \), \( \mu_B \) is the Bohr magneton, \( g^* \) is the magnitude of the Landé factor of the electron in the channel, \( k_R = m^* \alpha_R / \hbar^2 \), and \( \Delta E_c \) is the potential barrier between the ferromagnet and semiconductor. We assume that \( \Delta E_c \) includes the effects of the quantum confinement in the y-direction.

We now derive the energy dispersion relations in the channel of the interferometer from Equation (3). The first five terms of the Hamiltonian in Eq.(3) yield shifted parabolic subbands with dispersion relations:

\[
E_{n,\uparrow} = (n+1/2)\hbar \omega + \Delta E_c + \frac{\hbar^2 k_x^2}{2m^*} + \frac{\hbar^2 k_R k_x}{m^*}, \quad E_{n,\downarrow} = (n+1/2)\hbar \omega + \Delta E_c + \frac{\hbar^2 k_x^2}{2m^*} - \frac{\hbar^2 k_R k_x}{m^*}, \quad (4)
\]

where \( \omega = \sqrt{\omega_0^2 + \omega_c^2} \). In Eq.(4), the \( \uparrow \) and \( \downarrow \) arrows indicate +z and -z polarized spins (eigenstates of the \( \sigma_z \) operator) which are split by the Rashba effect. These are unperturbed subbands with definite spin quantizations axes along +z and -z directions. Their dispersion relations are shown as dashed lines in Fig. 1.

The sixth and seventh terms in Eq.(3) induce a perturbation and mixing between the unperturbed subbands (+z- and -z-polarized spins). The sixth term originates from the magnetic field due to the ferromagnetic contacts and the seventh originates from the Rashba effect itself. The sixth term was ignored and the seventh was assumed to be negligibly small in ref. [1]. The ratio of the sixth and seventh term can be shown to be of the order of \( 10^4 - 10^6 \) for typical values of the relevant parameters. Therefore, we can neglect the seventh term in comparison with the sixth term.

To obtain an analytical expression for the dispersion relation corresponding to the first five terms in the Hamiltonian in Eq.(3), we derive the two-band dispersion relation in a truncated Hilbert space considering mixing between the two lowest unperturbed subband states (namely the +z and -z spin states). Straightforward diagonalization of the Hamiltonian in Eq.(3) (minus the seventh term) in the basis of these two unperturbed states gives the
following dispersion relations:

\[ E_1(k_x) = \frac{1}{2} \hbar \omega + \Delta E_c + \frac{\hbar^2 k_x^2}{2m^*} - \sqrt{\left(\frac{\hbar^2 k_R k_x}{m^*}\right)^2 + \left(\frac{g^* \mu_B B}{2}\right)^2}, \quad (5) \]

\[ E_2(k_x) = \frac{1}{2} \hbar \omega + \Delta E_c + \frac{\hbar^2 k_x^2}{2m^*} + \sqrt{\left(\frac{\hbar^2 k_R k_x}{m^*}\right)^2 + \left(\frac{g^* \mu_B B}{2}\right)^2}, \quad (6) \]

where the indices 1 and 2 refer to the lower and upper subbands. Their dispersion relations are plotted schematically as solid lines in Fig. 1.

One can see from Fig. 1 that the magnetic field caused by the ferromagnetic contacts couples the two unperturbed subbands and changes their dispersion relation, lifting the degeneracy at \( k_x = 0 \). While the unperturbed bands are shifted parabolas with single minima at \( k_x = \pm k_R [1] \), the perturbed bands (in the presence of a magnetic field) are not parabolic and are symmetric about the energy axis. One of them has a single minimum at \( k_x = 0 \), and the other has double minima at \( k_x = \pm k_R \sqrt{1 + \left(\frac{g^* \mu_B B}{\delta_R}\right)^2} \), where \( \delta_R = \frac{\hbar^2 k^2}{2m^*} \). The magnetic field not only has a profound influence on the dispersion relations, but it also causes spin mixing, meaning that the perturbed subbands no longer have definite spin quantization axes (spin quantization becomes wavevector dependent). Furthermore, energy degenerate states in the two perturbed subbands no longer have orthogonal spins. Therefore, elastic scattering between them is possible without a complete spin flip.

The energy dispersion relations also show that, in a semiconductor where the Zeeman splitting energy can be made comparable to the Rashba spin-splitting energy \( \delta_R \), the difference \( \Delta k_x \) between the wavevectors in the two subbands at any energy is not independent of energy. Since this difference is proportional to the angle by which the spin precesses in the channel [1], the angle of spin precession is no longer independent of electron energy. Thus different electrons that are injected from the contact with different energies (at finite temperature and bias) will undergo different degrees of spin precession, and the conductance modulation will not survive ensemble averaging over a broad spectrum of electron energy at elevated temperatures and bias.
From Equations (5 - 6), we find that for an electron incident with total energy $E$, the corresponding wavevectors in the two subbands are given by

$$k_{x\pm} = \frac{1}{\hbar} \sqrt{2m^* \left( \frac{B \pm \sqrt{B^2 - 4C}}{2} \right)},$$

(7)

where

$$B = 2(E - \frac{\hbar \omega}{2} - \Delta E_c) + 4\delta R; \quad C = (E - \frac{\hbar \omega}{2} - \Delta E_c)^2 - \beta^2,$$

(8)

with $\beta = g^* \mu_B B/2$.

In Eq.(8), the upper and lower sign corresponds to the lower and upper subbands and are referred to hereafter as $k_{x1}$ and $k_{x2}$, respectively. The corresponding eigenvectors for the two subbands are respectively

$$\begin{bmatrix} C_{1}(k_{x1}) \\ C'_{1}(k_{x1}) \end{bmatrix} = \begin{bmatrix} -\alpha(k_{x1})/\gamma(k_{x1}) \\ \beta/\gamma(k_{x1}) \end{bmatrix},$$

$$\begin{bmatrix} C_{2}(k_{x2}) \\ C'_{2}(k_{x2}) \end{bmatrix} = \begin{bmatrix} \beta/\gamma(k_{x2}) \\ \alpha(k_{x2})/\gamma(k_{x2}) \end{bmatrix}$$

(9)

where the quantities $\alpha$ and $\gamma$ are function of $k_x$ and are given by

$$\alpha(k_x) = \frac{\hbar^2 k_R k_x}{m^*} + \sqrt{\left( \frac{\hbar^2 k_R k_x}{m^*} \right)^2 + \beta^2}; \quad \gamma(k_x) = \sqrt{\alpha^2 + \beta^2}.$$

(10)

Note that the eigenspinors given by Eq.(9) are not $+z$-polarized state $\begin{bmatrix} 1 & 0 \end{bmatrix}^\dagger$, or $-z$-polarized state $\begin{bmatrix} 0 & 1 \end{bmatrix}^\dagger$ if the magnetic field $B \neq 0$. Thus, the magnetic field mixes spins and the $+z$ or $-z$ polarized states are no longer eigenstates in the channel. Equations (9) also show that the spin quantization (eigenspinor) in any subband is not fixed and strongly depends on the wavevector $k_x$. Thus, an electron entering the semiconductor channel from the left ferromagnetic contact with $+x$-polarized spin, will not couple equally to $+z$ and $-z$ states. The relative coupling will depend on the electron’s energy.
We model the ferromagnetic contacts by the Stoner-Wohlfarth model. The spin-up (majority carriers) and spin-down (minority carriers) band energies are offset by an exchange splitting energy $\Delta$ (Fig.2).

Next, we calculate the total transmission coefficient through the spin interferometer for an electron entering from the left ferromagnetic contact (region I) and exiting at the right ferromagnetic contact (region III). A rigorous treatment of this problem would require an accurate modeling of the three- to one-dimensional transition between the bulk ferromagnetic contacts (regions I and III) and the quantum wire semiconductor channel (region II) [9, 10]. However, a one-dimensional transport model to calculate the transmission coefficient through the structure is known to be a very good approximation when the Fermi wave number in the ferromagnetic contacts is much greater than the inverse of the transverse dimensions of the quantum wire [11, 12]. This is always the case with metallic contacts.

In region II ($0 < x < L$), the x-component of the wavefunction at a position $x$ along the channel is given by

$$\psi_{II}(x) = A_I \left[ \begin{array}{c} C_1(k_{x,1}) \\ C'_1(k_{x,1}) \end{array} \right] e^{ik_{x,1}x} + A_{II} \left[ \begin{array}{c} C_1(-k_{x,1}) \\ C'_1(-k_{x,1}) \end{array} \right] e^{-ik_{x,1}x} + A_{III} \left[ \begin{array}{c} C_2(k_{x,2}) \\ C'_2(k_{x,2}) \end{array} \right] e^{ik_{x,2}x} + A_{IV} \left[ \begin{array}{c} C_2(-k_{x,2}) \\ C'_2(-k_{x,2}) \end{array} \right] e^{-ik_{x,2}x}. \quad (11)$$

For a spin-up electron in the left ferromagnetic contact (region I; $x < 0$), the electron is spin polarized in the $[1,1]^{\dagger}$ subband and the x-component of the wavefunction is given by

$$\psi_I(x) = \frac{1}{\sqrt{2}} \left[ \begin{array}{c} 1 \\ 1 \end{array} \right] e^{ik_{x}u_{x}} + \frac{R_1}{\sqrt{2}} \left[ \begin{array}{c} 1 \\ 1 \end{array} \right] e^{-ik_{x}u_{x}} + \frac{R_2}{\sqrt{2}} \left[ \begin{array}{c} 1 \\ -1 \end{array} \right] e^{-ik_{x}d_{x}}. \quad (12)$$

where $R_1$ is the reflection amplitude into the spin-up band and $R_2$ is the reflection amplitude in the spin-down band.
In region III \((x > L)\), the x-component of the wavefunction is given by

\[
\psi_{III}(x) = \frac{T_1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} e^{ik_x u(x-L)} + \frac{T_2}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} e^{ik_x d(x-L)}. \tag{13}
\]

where \(T_1\) and \(T_2\) are the transmission amplitudes into the spin-up and spin-down bands. The wavevectors

\[
k_x^u = \frac{1}{\hbar} \sqrt{2m_0E}, \quad k_x^d = \frac{1}{\hbar} \sqrt{2m_0(E - \Delta)}, \tag{14}
\]

are the x components of the wavevectors in the spin-up and spin-down energy bands, respectively.

The eight unknowns \((R_1, R_2, T_1, T_2, A_i(i = I, II, III, IV))\) must be found by enforcing continuity of the wavefunction and the quantity \(\frac{1}{m^*(x)} \left( \frac{d\psi}{dx} + ik_R(x)\sigma_z \psi(x) \right)\) at \(x = 0\) and \(x = L\). The latter condition insures continuity of the current density. This leads to a system of 8 coupled equations for the unknowns which must be solved to extract the transmission amplitudes \(T_1, T_2\) in the spin-up and spin-down energy bands in the right ferromagnetic contact.

For the majority spin carriers, the linear response source-to-drain conductance of the spin interferometer at any temperature \(T\) is given by the Landauer formula

\[
G^\uparrow = \frac{e^2}{4\hbar kT} \int_0^\infty dE |T_{tot}(E)|^2 \text{sech}^2 \left( \frac{E - E_F}{2kT} \right), \tag{15}
\]

where

\[
|T_{tot}(E)|^2 = |T_1(E)|^2 + (k_x^d/k_x^u)|T_2(E)|^2 \tag{16}
\]

is the total transmission coefficient through the interferometer.

Similarly, the conductance of the minority spin carriers \((G^\downarrow)\) is calculated after repeating the scattering problem for electrons incident from the minority spin band in the contacts. Since the up- and down-spin states are orthogonal in the contacts, the total conductance of the spin interferometer is then given by \(G^\uparrow + G^\downarrow\).
We consider a spin interferometer consisting of a quasi one-dimensional InAs channel between two ferromagnetic contacts. The electrostatic potential in the z-direction is assumed to be harmonic with $\hbar \omega = 10$ meV in Eq. (4). A Zeeman splitting energy of 0.34 meV is used in the semiconductor channel assuming a magnetic field $B = 1$ Tesla along the channel. This corresponds to a $g^*$ factor of 3 and an electron effective mass $m^* = 0.036 m_o$ which is typical of InAs-based channels [1]. The Fermi level $E_f$ and the exchange splitting energy $\Delta$ in the ferromagnetic contacts are set equal to 4.2 and 3.46 eV, respectively [5].

The Rashba spin-orbit coupling strength $\alpha_R$ is typically derived from low-temperature magnetoresistance measurements (Shubnikov-de Haas oscillations) in 2DEG created at the interface of semiconductor heterostructures [6]. To date, the largest reported experimental values of the Rashba spin-orbit coupling strength $\alpha_R$ has been found in InAs-based semiconductor heterojunctions. For a normal HEMT $In_{0.75}Al_{0.25}As/In_{0.75}Ga_{0.25}As$ heterojunction, Sato et al. have reported variation of $\alpha_R$ from 30- to $15 \times 10^{-12}$ eVm when the external gate voltage is swept from 0 to -6 V (the total electron concentration in the 2DEG is found to be reduced from 5- to $4.5 \times 10^{11}/cm^2$ over the same range of bias). For a channel length of 0.1 $\mu m$, this corresponds to a variation of the spin precession angle $\theta = 2k_R L$ from about $\pi$ to $0.5\pi$ over the same range of gate bias.

In the numerical results below, we calculated the conductance of a spin interferometer with a 0.2 $\mu m$ long channel as a function of the gate voltage. Tuning the gate voltage varies the potential energy barrier $\Delta E_c$. Therefore, we have effectively calculated the interferometer’s conductance as a function of $\Delta E_c$. In our calculations, we vary $\Delta E_c$ over a range of 10 meV which allows us to display several of the Ramsauer oscillations for the selected separation between source and drain. The final energy $\Delta E_c$ is equal to the Fermi energy $E_f$. At that point, the Fermi energy lines up with the top of the potential barrier which corresponds to complete pinch-off of the channel when the carrier concentration falls to zero. Over that range of $\Delta E_c$, we simulated several cases of Rashba spin-orbit coupling strength.
\( \alpha_R \) variation with increasing \( \Delta E_c \) (or increasing gate voltage): **Case 1**: \( \alpha_R \) stays constant and is equal to the largest experimental value reported to date \((30 \times 10^{-12} \text{eVm})\), **Case 2**: \( \alpha_R \) varies from \(30 \times 10^{-12} \text{eVm}\) down to zero, and **Case 3**: \( \alpha_R \) varies from zero to a maximum of \(30 \times 10^{-12} \text{eVm}\), which is the reverse of the previous case. A situation where \( \alpha_R \) actually increases with reduction of the carrier concentration in the channel was reported for inverted InAlAs/InGaAs heterostructures by Schapers et al. [7]. Finally, we consider **Case 4** where \( \alpha_R \) is varied from \(3 \times 10^{-10} \text{eVm}\) (a tenfold improvement over the largest reported experimental result) down to zero. This last case corresponds to a variation of the spin precession angle \( \theta \) from about \(10\pi\) to 0 over the range of \( \Delta E_c \) considered.

The results of the conductance modulation are shown in Fig.3 for the four cases described above at \( T = 2 \text{ K} \). This figure shows that there is very little change between the different curves corresponding to cases 1 through 3 of the \( \alpha_R \) dependence on \( \Delta E_c \). The location of the resonant energy levels was calculated using Eq.(1) and the various quantum numbers \( n \) characterizing the subbands being swept through the Fermi energy are indicated in the figure. The gate voltage variation of the Rashba spin splitting energy modifies slightly the shape and position of the resonant peaks due to electrostatic adjustment of the potential barrier between the two ferromagnetic contacts. Even for case 4, the amplitude of the conductance oscillations are virtually unchanged and merely shifted along the \( \Delta E_c \) axis compared to cases 1 through 3.

Referring to Fig.1, it can be seen that the energy dispersion relations are not parallel as the Fermi level approaches the bottom of the upper subband in the channel, i.e., near channel pinch-off (at larger value of \( \Delta E_c \)). Furthermore, the oscillations in conductance are more closely spaced as the quasi 1D channel approaches pinch-off. These two features make the conductance modulation near pinch-off more sensitive to temperature averaging. As illustrated in Fig.3, the conductance oscillations are washed out completely for \( T = 10 \text{ K} \). This is only shown for Case 2 but similar degradation of the conductance modulation with
temperature is found for all other cases considered above.

In conclusion, we have demonstrated that the conductance modulation of typical electron spin interferometer structures may be primarily due to the Ramsauer effect [3] rather than the Rashba effect. The Ramsauer effect is caused by strong reflections at the contact-channel interfaces which are exacerbated by the large value of $\Delta E_c$ and the significant effective mass differences between the ferromagnetic contact material and the semiconductor. We have also found that the Ramsauer oscillations are accentuated when an insulating barrier is interposed at the ferromagnet-semiconductor interface [13] since it enhances multiple reflections in the channel. Finally, we have studied the effect of elastic scattering in the channel using the scattering matrix technique of ref. [14]. The details will be presented elsewhere, but a few elastic scatterers in the channel do not affect the results significantly. Thus, unless the interferometer is well-designed to eliminate contact reflections, any experiment that purports to demonstrate the spin interferometer needs to pay careful attention to the actual origin of the oscillations.

M. C. dedicates this article to the memory of his father-in-law. The authors acknowledge insightful discussions with S. Datta. The work of S. B. is supported by the National Science Foundation under grant ECS-0089893.
References

[1] S. Datta and B. Das, Appl. Phys. Lett., 56, 665 (1990).

[2] E. I. Rashba, Sov. Phys. Semicond., 2, 1109 (1960); Y. A. Bychkov and E. I. Rashba, J. Phys. C, 17, 6039 (1984).

[3] This is a textbook example of one-dimensional tunneling problems. See for instance, H.C. Ohanian, Principles of Quantum Mechanics, Prentice Hall, New Jersey, p. 96 (1990).

[4] A.V. Moroz and C.H.W. Barnes, Phys. Rev. B, 60, 14272 (1999); Phys. Rev. B 61, R2464 (2000).

[5] We use the same values as in F. Mireles and G. Kirczenow, Europhys. Lett., 59, 107 (2002).

[6] J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett., 78, 1335 (1997); Th. Schäpers, J. Nitta, H.B. Heersche, and H. Takayanagi, Phys. Rev. B, 64, 125314 (2001); Y. Sato, T. Kita, S. Gozu and S. Yamada, J. Appl. Phys., 89, 8017 (2001); Y. Sato, S. Gozu, T. Kita and S. Yamada, Physica E, 12, 399 (2002).

[7] Th. Schäpers, G. Engels, J. Lange, Th. Klocke, M. Hollfelder, and H. Luth, J. Appl. Phys., 83, 4324 (1998).

[8] We compute the conductance using the Landauer formula by integrating over an energy range from $[E_f - 4k_BT, E_f + 4k_BT]$. For each temperature, we limit the range of variation of $\Delta E_c$ so that both channels under the gate are conducting for the range of energy considered.

[9] A. M. Kriman and P. P. Ruden, Phys. Rev. B., 32, 8013 (1985).

[10] R. Frohne and S. Datta, J. Appl. Phys., 64, 4086 (1988).
[11] D. Grundler, Phys. Rev. B, 63, 161307(R) (2001).

[12] O. E. Raichev and P. Debray, Phys. Rev. B, 65, 085319 (2002).

[13] E. I. Rashba, Phys. Rev. B, 62, 16267 (2000).

[14] S. Datta, M. Cahay and M. McLennan, Phys. Rev. B, 36, 5655 (1987); M. Cahay, M. McLennan and S. Datta, *ibid*, 37, 10255 (1988).
Figure Captions

Fig. 1: A schematic of the electron spin interferometer from ref. [1]. The horizontal dashed line represents the quasi one-dimensional electron gas formed at the semiconductor interface between materials I and II. The magnetization of the ferromagnetic contacts is assumed to be along the +x-direction which results in a magnetic field along the x-direction. Also shown is a qualitative representation of the energy dispersion of the two perturbed (solid line) and unperturbed (broken line) bands under the gate. The unperturbed bands are given by Equation (4) and the perturbed ones are given by Equations (5) and (6) in the text.

Fig. 2: Energy band diagram across the electron spin interferometer. We use a Stoner-Wohlfarth model for the ferromagnetic contacts. $\Delta$ is the exchange splitting energy in the contacts. $V_o$ is the height of the potential barrier between the energy band bottoms of the semiconductor and the ferromagnetic electrodes. $V_o$ takes into account the effects of the quantum confinement in the y- and z-directions. Also shown as dashed lines are the resonant energy states above $V_o$. Peaks in the conductance of the electron spin interferometer are expected when the Fermi level in the contacts lines up with the resonant states.

Fig. 3: Conductance modulation of the electron spin interferometer (for $T = 2$ K) for different variations of the Rashba spin-orbit coupling strength $\alpha_R$ with the energy barrier $\Delta E_c$. The Fermi energy $E_f$ is designated in the figure. The different $\alpha_R$ vs. $\Delta E_c$ variations are labeled # 1 through #4 corresponding to cases 1 through 4 in the text. The separation between the two ferromagnetic contacts is 0.2 $\mu$m. The confinement energy $\hbar\omega$ is 10 meV. We have indicated the conductance peaks corresponding to different resonant energy levels lining up with the Fermi level in the contacts. The curve labeled $T = 10$ K represents the conductance modulation computed at a temperature of 10 K when $\alpha_R$ varies from $30 \times 10^{-12}$ eVm to 0 as the gate voltage is varied.
