



Theoretical Investigation of Spin-Dependent Transport Phenomena for Spintronic Electronic Applications

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Abstract

Spin-dependent transport provides an electronic design space in which charge flow is controlled not only by electrostatic potential but also by spin polarization, spin coherence and angular-momentum transfer. This paper develops a unified theoretical study of four transport regimes relevant to spintronic electronic applications: magnetic tunnelling, diffusive spin propagation, gate-controlled Rashba precession and spin-selective resonant conduction. A two-current magnetic-tunnel-junction model is combined with WKB barrier transmission; the one-dimensional spin-diffusion equation is solved for representative diffusion constants and lifetimes; a Datta-Das channel is evaluated as a coherent spin rotator; and a spin-split resonant level is treated with finite-temperature Landauer conductance. For electrodes with polarization 0.65, the calculated parallel-to-antiparallel conductance ratio is 2.463 and the tunnelling magnetoresistance is 146.3%. Increasing a 0.80 eV barrier from 0.8 to 1.4 nm lowers the mean transmission from 9.69×10^{-3} to 2.99×10^{-4} without changing the ideal polarization ratio. At a diffusion constant of $0.010 \text{ m}^2 \text{ s}^{-1}$, spin lifetimes of 25-400 ps give diffusion lengths of 0.5-2.0 micrometres and retain 13.5-60.7% of the injected spin signal after 1 micrometre. For an effective mass of $0.05m_0$, a 1 micrometre channel requires a Rashba coefficient of $2.394 \times 10^{-12} \text{ eV m}$ for a π rotation, yielding an ideal contact-limited on/off ratio of 2.463. A 12 meV spin splitting produces 94.3% resonant conductance polarization at 4 K, but only 2.5% at 300 K. The calculations show that useful spintronic response depends on matching barrier transparency, diffusion length, precession length and thermal broadening to the physical device dimensions.

Keywords: spintronics; spin-dependent transport; tunnel magnetoresistance; spin diffusion; Rashba coupling; spin field-effect transistor; Landauer transport.

I. Introduction

Conventional electronics represents information through charge density and current. Spintronics adds the carrier spin degree of freedom, so the relevant state variable becomes a spin-resolved electrochemical potential or density matrix rather than a scalar carrier population. The early device vision emphasized nonvolatile memory, reconfigurable logic, magnetic sensing and the possibility of separating information transport from net charge displacement [1]. The broader field now includes ferromagnetic metals, semiconductors, antiferromagnets, topological materials and hybrid interfaces, but its central problem remains the same: a spin polarization must be created, transported, manipulated and detected before relaxation erases it [2].

The decisive transport discovery was giant magnetoresistance (GMR). Baibich and co-workers observed a large resistance change in Fe/Cr superlattices and attributed it to spin-dependent transmission between magnetic layers [3]. Binasch and co-workers reported the closely related effect in antiferromagnetically coupled layered structures [4]. These results established the practical two-current picture in which majority and minority carriers experience different scattering rates. Tunnel magnetoresistance (TMR) supplied a complementary geometry. Julliere related the conductance of a ferromagnet/insulator/ferromagnet junction to the spin polarizations of its electrodes [5], and room-temperature thin-film junctions subsequently demonstrated that the effect could support electronic operation [6].

The simple polarization model is not the complete microscopic description. In crystalline Fe/MgO/Fe junctions, transmission depends strongly on the symmetry and decay of electrode Bloch states within the barrier [7]. Experiments on single-crystal MgO junctions then obtained large room-temperature TMR and directly associated it with coherent spin-polarized tunnelling [8]. Spin-dependent resistance is therefore controlled by both magnetic configuration and quantum matching at interfaces.

This study connects that interface physics with transport inside a nonmagnetic channel. Four calculations are used. First, a WKB-Julliere model isolates the barrier-thickness and polarization dependences of a magnetic tunnel junction. Second, a drift-diffusion solution quantifies spatial loss of spin accumulation. Third, Rashba spin-orbit coupling produces a gate-controlled precession angle in a semiconductor channel. Fourth, finite-temperature Landauer transport shows how a spin-split resonance loses filtering selectivity when thermal energy exceeds its spectral separation. The models are intentionally compact: their purpose is to expose device scales and trade-offs rather than reproduce one fabricated sample.

II. Theoretical Framework

Spin-resolved conduction and tunnel magnetoresistance

In the collinear two-current approximation, spin-up and spin-down conductances add in parallel. A useful transport polarization is

$$P_G = \frac{G_{\uparrow} - G_{\downarrow}}{G_{\uparrow} + G_{\downarrow}}.$$

For two ferromagnetic electrodes with polarizations P_1 and P_2 , the Julliere conductances are proportional to

$$G_P = G_0(1 + P_1P_2), \quad G_{AP} = G_0(1 - P_1P_2),$$

where P and AP denote parallel and antiparallel magnetizations. Consequently,

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{G_P - G_{AP}}{G_{AP}} = \frac{2P_1P_2}{1 - P_1P_2}.$$

The barrier controls the magnitude of G_0 . For a rectangular barrier of height U , thickness d and effective mass m_b , the low-bias WKB factor is

$$T_0(d) \simeq \exp(-2\kappa d), \quad \kappa = \frac{\sqrt{2m_b(U - E)}}{\hbar}.$$

This scalar factor separates the exponential resistance-area dependence from the ideal polarization ratio. Real MgO junctions require symmetry-resolved complex bands, because majority Δ_1 states and minority interface resonances do not share a single κ [7], [8]. The present WKB result should therefore be read as the envelope on which coherent selection, disorder and bias dependence are superimposed.

Spin accumulation, diffusion and injection

In a diffusive nonmagnetic channel, define the spin accumulation as $\mu_s = \mu_{\uparrow} - \mu_{\downarrow}$. The Valet-Fert treatment links spin-dependent Boltzmann transport to a macroscopic diffusion equation [9],

$$\frac{\partial \mu_s}{\partial t} = D \frac{\partial^2 \mu_s}{\partial x^2} - \frac{\mu_s}{\tau_s}, \quad \lambda_s = \sqrt{D\tau_s}.$$

For steady injection into a semi-infinite channel,

$$\mu_s(x) = \mu_s(0) \exp(-x/\lambda_s).$$

The same exponential controls the separation dependence of an ideal nonlocal detector signal. Electrical injection and detection were placed on an interfacial charge-spin footing by Johnson and Silsbee [10]. A metallic ferromagnet connected directly to a diffusive semiconductor, however, generally suffers conductivity mismatch: most voltage drops in the higher-resistance semiconductor while the low-resistance ferromagnet contributes little spin selectivity [11]. A tunnel contact introduces a spin-dependent interface resistance that can restore efficient injection [12], provided it lies within the resistance window set by channel resistivity, thickness and spin-diffusion length [13]. Thus a barrier can be indispensable for polarization even though excessive barrier resistance suppresses current.

Coherent spin precession and spin relaxation

The Datta-Das transistor proposed that a gate could modulate current by rotating an injected spin before it reaches a magnetic drain [14]. For a two-dimensional electron gas with structural inversion asymmetry, the Rashba Hamiltonian is

$$H_R = \alpha_R(\sigma_x k_y - \sigma_y k_x),$$

where α_R is the controllable spin-orbit coefficient [15]. In a one-dimensional channel along x , the two spin eigenmodes acquire different wave vectors. For a parabolic band, their relative precession angle after length L is

$$\theta = \frac{2m^*\alpha_R L}{\hbar^2}, \quad L_{\pi} = \frac{\pi \hbar^2}{2m^*\alpha_R}.$$

With source and drain polarizations P_S and P_D , an ideal single-mode readout written

$$\frac{G(\theta)}{G_{max}} = \frac{1 + P_S P_D \cos \theta}{1 + P_S P_D}.$$

Bulk inversion asymmetry introduces the Dresselhaus field [16], so the actual rotation axis depends on crystal orientation and confinement. Spin-orbit coupling also produces relaxation. Elliott showed that nominal spin eigenstates acquire opposite-spin admixture, allowing momentum scattering to flip spin [17]. In the D'yakonov-Perel' mechanism, carriers precess about momentum-dependent internal fields between collisions; frequent momentum scattering can then reduce the accumulated precession per free-flight interval [18]. Coherent modulation requires transit time shorter than the relevant dephasing time and sufficiently uniform precession across occupied modes.

Transverse spin currents and magnetic torque

Spin-orbit interaction can convert a longitudinal charge current into a transverse spin current. Hirsch formulated the spin Hall effect as the generation of transverse spin imbalance in a paramagnetic conductor [19], and Kerr-rotation imaging later observed the effect in GaAs and InGaAs films [20]. Intrinsic band-structure terms and extrinsic skew or side-jump scattering contribute in different materials and regimes [21]. The inverse process converts an injected spin current into a transverse voltage, providing a nonmagnetic detection route. Absorption of transverse spin angular momentum by a ferromagnet exerts torque. For a polarizer direction p and free-layer magnetization m , the damping-like spin-transfer torque has the form

$$\tau_{STT} = \frac{\hbar \eta I}{2eM_F V} m \times (m \times p),$$

where η is the current polarization efficiency. Slonczewski showed that such current can excite or reverse a magnetic layer [22], and the torque framework now underpins magnetic-memory writing and nano-oscillators [23]. Spin-orbit torques extend the same angular-momentum transfer to inversion-asymmetric magnetic heterostructures [24]. Although torque dynamics are not numerically integrated below, they define the application boundary of the calculated spin currents.

Spin-resolved coherent transport

For a phase-coherent conductor, each spin channel contributes a Landauer conductance [25],

$$G_\sigma(T) = \frac{e^2}{h} \int T_\sigma(E) \left(-\frac{\partial f}{\partial E}\right) dE.$$

For a single spin-split level ε_σ coupled to left and right reservoirs,

$$T_\sigma(E) = \frac{\Gamma_{L\sigma} \Gamma_{R\sigma}}{(E - \varepsilon_\sigma)^2 + (\Gamma_{L\sigma} + \Gamma_{R\sigma})^2/4}.$$

This Breit-Wigner limit is the simplest open-system representation of a resonant spin filter; more elaborate nonequilibrium Green-function treatments add self-consistent electrostatics, multiorbital coupling and scattering self-energies [26].

III. Computational Method

The calculations were performed with four linked models. The magnetic tunnel junction used equal electrode polarizations $P_1 = P_2 = 0.65$. A rectangular 0.80 eV barrier with mass $0.40m_0$ was evaluated from 0.8 to 1.4 nm. The WKB transmission supplied G_0 , while the Julliere factors determined parallel and antiparallel conductance. All conductances in this part are dimensionless because common area, density-of-states and contact prefactors cancel in the comparison.

Table I. Parameters used in the theoretical calculations

Parameter	Symbol	Value	Role or basis
Electrode polarization	$P_1 = P_2$	0.65	MTJ spin asymmetry
Barrier height	U	0.80 eV	WKB tunnel envelope
Barrier effective mass	m_b	$0.40m_0$	Evanescent decay
Barrier thickness	d	0.8-1.4 nm	MTJ sweep
Diffusion constant	D	$0.010 \text{ m}^2 \text{ s}^{-1}$	Nonmagnetic channel
Spin lifetime	τ_s	25, 100, 400 ps	Diffusion-length sweep
Channel effective mass	m^*	$0.05m_0$	Rashba precession
Contact polarization	$P_S = P_D$	0.65	Spin-FET readout

Channel length	L	0.5, 1.0, 1.5 μm	Coherent sweep
Resonant spin splitting	Δ	12 meV	Spin-filter separation
Total level broadening	Γ	4 meV	Contact-induced linewidth
Temperature	T	4, 77, 300 K	Thermal convolution

The diffusive channel used $D = 0.010 \text{ m}^2 \text{ s}^{-1}$ and spin lifetimes of 25, 100 and 400 ps, giving diffusion lengths of 0.5, 1.0 and 2.0 micrometres. Spin accumulation and the normalized nonlocal signal were evaluated over 0-3 micrometres. The coherent channel used $m^* = 0.05m_0$, $P_S = P_D = 0.65$, lengths of 0.5, 1.0 and 1.5 micrometres, and α_R from 0 to $5 \times 10^{-12} \text{ eV m}$.

The resonant model used levels at $\varepsilon_{\uparrow} = -6 \text{ meV}$ and $\varepsilon_{\downarrow} = +6 \text{ meV}$. Symmetric contacts had $\Gamma_L = \Gamma_R = 2 \text{ meV}$, so the total linewidth was 4 meV and each resonance reached unit transmission. The Landauer integral was evaluated on a 0.0025 meV grid from -250 to 250 meV at 4, 77 and 300 K. Table I collects the assumptions.

IV. Results and Discussion

Barrier transparency and tunnel magnetoresistance

Figure 1(a) shows the exponential suppression of both magnetic configurations. The decay constant is $\kappa = 2.898 \text{ nm}^{-1}$. Increasing d from 0.8 to 1.4 nm reduces T_0 by a factor of 32.4; G_P falls from 1.378×10^{-2} to 4.255×10^{-4} , while G_{AP} falls from 5.594×10^{-3} to 1.727×10^{-4} . The parallel state remains more conductive because the product P_1P_2 favours majority-to-majority and minority-to-minority tunnelling.

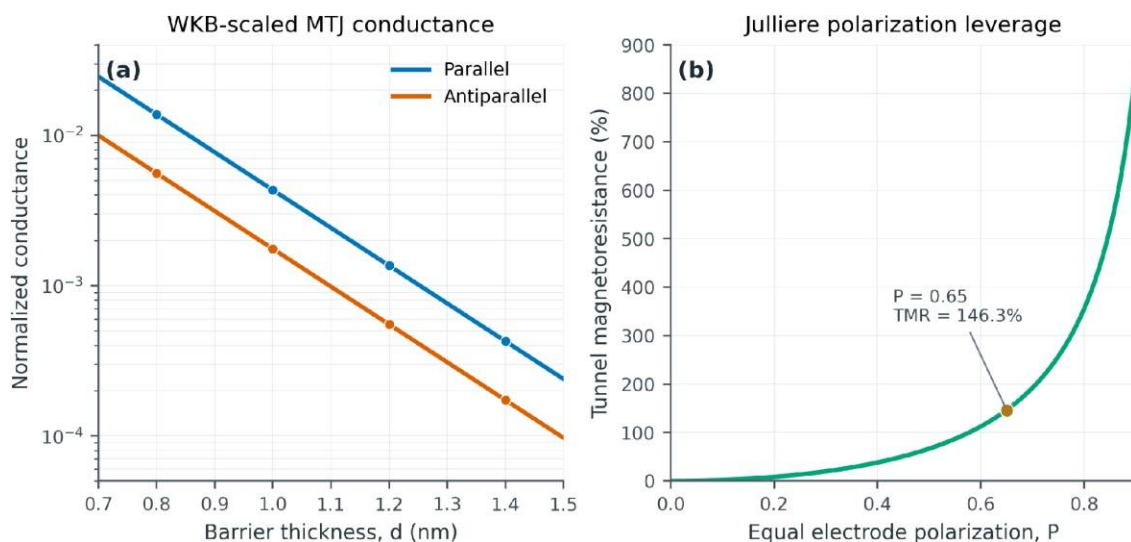


Figure 1. Magnetic tunnel-junction calculation. (a) WKB-scaled parallel and antiparallel conductances versus barrier thickness for $U = 0.80 \text{ eV}$ and $m_b = 0.40m_0$. (b) Julliere TMR versus equal electrode polarization; the marked operating point is $P_1 = P_2 = 0.65$.

The ratio is independent of thickness in this factorized model: $G_P/G_{AP} = 2.463$ and TMR is 146.3% throughout Table II. Figure 1(b) exposes the nonlinear polarization leverage. Equal polarizations of 0.40 give 38.1% TMR, whereas 0.80 gives 355.6%. Improving effective polarization can therefore raise read contrast more strongly than changing a barrier that multiplies both spin configurations equally. In a coherent MgO device, thickness can also alter effective polarization because different symmetries decay at different rates [7], so the constant-TMR result is a controlled baseline rather than a universal law.

Table II. Calculated MTJ conductance versus barrier thickness

$d \text{ (nm)}$	T_0	G_P	G_{AP}	TMR (%)
0.8	9.687×10^{-3}	1.378×10^{-2}	5.594×10^{-3}	146.3
1.0	3.039×10^{-3}	4.323×10^{-3}	1.755×10^{-3}	146.3
1.2	9.534×10^{-4}	1.356×10^{-3}	5.506×10^{-4}	146.3

1.4	2.991×10^{-4}	4.255×10^{-4}	1.727×10^{-4}	146.3
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The design consequence is a resistance-window problem. A thin barrier improves current but can admit defect-assisted conduction and weaken spin selection. A thick barrier protects polarization yet raises resistance, write voltage and RC delay. Barrier thickness and interfacial order must therefore be optimized together, not treated as interchangeable methods for obtaining a large resistance change.

Spatial survival of a diffusive spin signal

Figure 2(a) quantifies the loss of spin information with distance. At $x = 1 \mu\text{m}$, channels with $\lambda_s = 0.5$, 1.0 and 2.0 micrometres retain 0.135, 0.368 and 0.607 of the injected accumulation. At 2 micrometres, the values fall to 0.018, 0.135 and 0.368. The contour map in Figure 2(b) generalizes the result: a detector placed at $L = \lambda_s$ always receives $e^{-1} = 0.368$ of the interface amplitude, independent of the microscopic combination of D and τ_s .

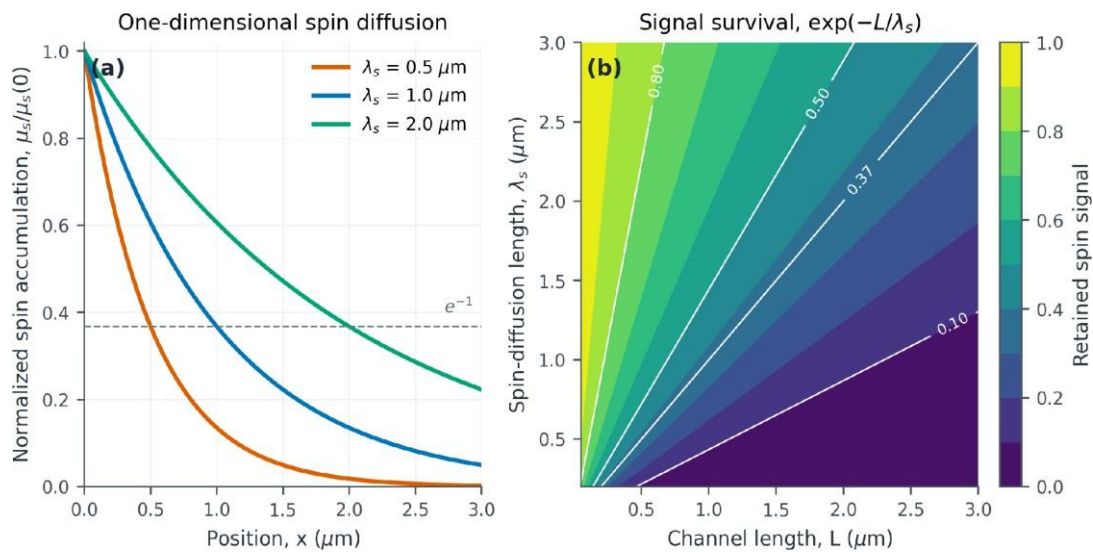


Figure 2. Diffusive spin transport. (a) Normalized spin accumulation for $\lambda_s = 0.5, 1.0$ and $2.0 \mu\text{m}$. (b) Retained nonlocal spin signal $\exp(-L/\lambda_s)$ over channel length and diffusion length; contours mark useful signal fractions.

This dimensionless scaling is directly useful for layout. A nonlocal detector that requires at least 50% of the injected signal must satisfy $L < 0.693\lambda_s$; a 10% threshold permits $L < 2.303\lambda_s$. Increasing lifetime does not guarantee proportional device improvement because λ_s grows only as $\sqrt{\tau_s}$. Quadrupling lifetime doubles the length scale. Contact-induced spin absorption, finite channel width and drift fields can change the prefactor or spatial form, but none removes the basic requirement that the contact separation be commensurate with λ_s .

Gate-controlled Rashba rotation

Figure 3(a) displays coherent drain modulation as α_R is increased. The phase is proportional to $\alpha_R L$, so longer channels oscillate more rapidly. For $L = 1.0 \mu\text{m}$, the first conductance minimum occurs at $\alpha_R = 2.394 \times 10^{-12} \text{ eV m}$. The maximum normalized conductance is 1, the minimum is 0.406, and the corresponding unnormalized on/off ratio is 2.463. Finite contact polarization, rather than spin rotation, limits the ideal contrast: even a pi-rotated spin has a nonzero probability of entering the drain minority channel.

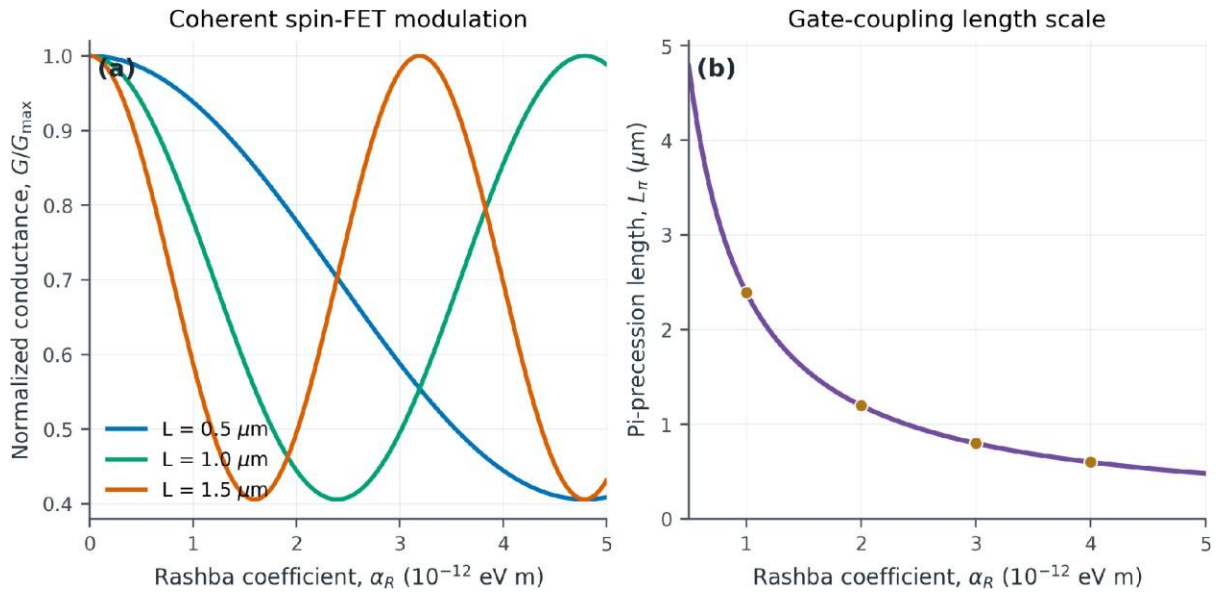


Figure 3. Rashba spin control for $m^* = 0.05m_0$ and $P_S = P_D = 0.65$. (a) Normalized drain conductance for three channel lengths. (b) Pi-precession length L_π versus Rashba coefficient.

The inverse relation in Figure 3(b) gives $L_\pi = 2.394, 1.197, 0.798$ and 0.598 micrometres for $\alpha_R = 1, 2, 3$ and 4×10^{-12} eV m, respectively. A shorter device therefore requires stronger gate-controlled spin-orbit coupling. Conversely, making the channel longer reduces the required α_R but increases exposure to diffusion, dephasing and multimode phase averaging. The coherent condition is not simply $L = L_\pi$; it is simultaneously $L \lesssim \lambda_s$ and a sufficiently narrow distribution of precession angles.

Thermal broadening of a resonant spin filter

The two unit-transmission resonances in Figure 4(a) are separated by 12 meV, three times their total linewidth. At 4 K, $k_B T = 0.345$ meV, so the Landauer derivative samples one resonance at a time. With the Fermi level at the spin-up resonance, $G_\uparrow = 0.926e^2/h$, $G_\downarrow = 0.027e^2/h$, and the conductance polarization is 0.943. The sign reverses at the spin-down resonance.

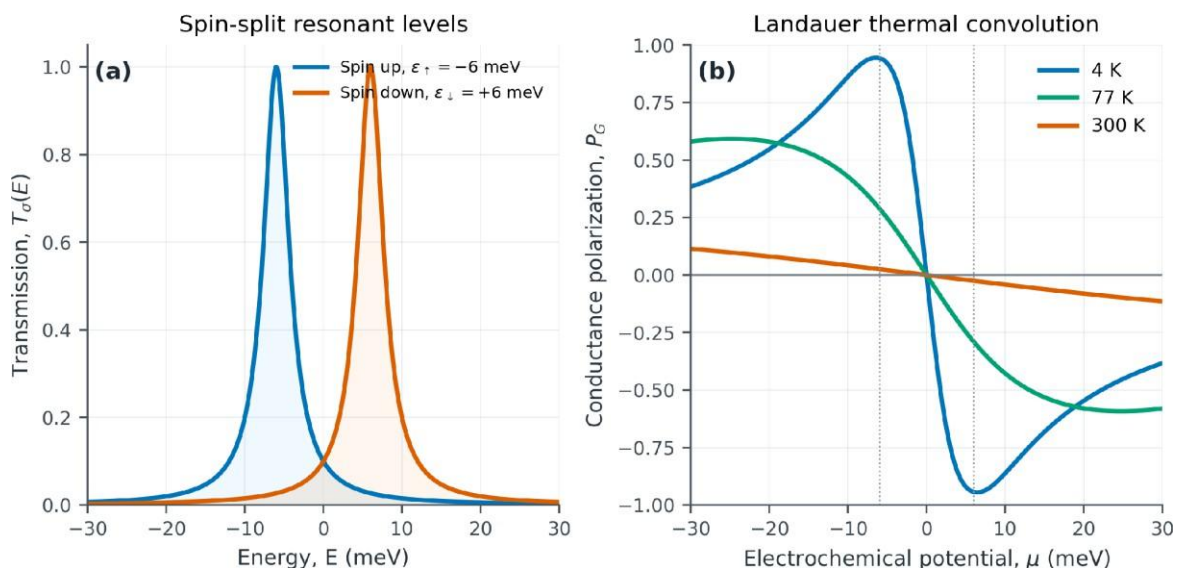


Figure 4. Spin-selective resonant conduction. (a) Breit-Wigner transmissions for levels split by 12 meV with total linewidth 4 meV. (b) Linear-response conductance polarization at 4, 77 and 300 K after Landauer thermal convolution.

Table III. Derived spin-control and filtering metrics

Phenomenon	Setting	Derived scale	Calculated readout
Spin diffusion	$\tau_s = 25$ ps	$\lambda_s = 0.500$ μm	$S(1 \mu\text{m})/S_0 = 0.135$
Spin diffusion	$\tau_s = 100$ ps	$\lambda_s = 1.000$ μm	$S(1 \mu\text{m})/S_0 = 0.368$
Spin diffusion	$\tau_s = 400$ ps	$\lambda_s = 2.000$ μm	$S(1 \mu\text{m})/S_0 = 0.607$
Rashba rotation	$L = 0.5$ μm	$\alpha_\pi = 4.788 \times 10^{-12}$ eV m	On/off = 2.463
Rashba rotation	$L = 1.0$ μm	$\alpha_\pi = 2.394 \times 10^{-12}$ eV m	On/off = 2.463
Rashba rotation	$L = 1.5$ μm	$\alpha_\pi = 1.596 \times 10^{-12}$ eV m	On/off = 2.463
Resonant filter	4 K, $\mu = -6$ meV	$k_B T = 0.345$ meV	$P_G = 0.943$
Resonant filter	77 K, $\mu = -6$ meV	$k_B T = 6.64$ meV	$P_G = 0.290$
Resonant filter	300 K, $\mu = -6$ meV	$k_B T = 25.85$ meV	$P_G = 0.025$

Thermal convolution rapidly weakens the filter. At 77 K, $k_B T = 6.64$ meV and the polarization at the spin-up resonance falls to 0.290 because the injection window covers both levels. At 300 K, $k_B T = 25.85$ meV and it is only 0.025. Table III places this spectral constraint beside the diffusion and Rashba length scales. Room-temperature resonant filtering therefore requires a spin splitting substantially larger than both Γ and several $k_B T$, or an additional spin-selective contact that suppresses the unwanted channel.

V. Electronic Applications and Model Boundaries

The four calculations describe different application functions. The MTJ is a two-terminal magnetic state reader, suitable for nonvolatile memory and sensors. Its decisive figures of merit are TMR, resistance-area product, bias stability and switching compatibility. The diffusive channel is a spin interconnect or nonlocal logic element; its geometry must be shorter than the spin-diffusion length and its contacts must avoid conductivity mismatch. The Rashba channel is a voltage-controlled spin modulator, but useful gain requires strong and uniform spin-orbit coupling, polarized contacts and preserved phase coherence. The resonant structure is an energy-selective spin filter whose room-temperature operation demands large spectral splitting.

These transport mechanisms also supply spin angular momentum for writing. A high-polarization MTJ current can exert spin-transfer torque [22], [23], whereas a heavy-metal or inversion-asymmetric layer can generate a transverse spin current and spin-orbit torque [21], [24]. Read and write optimization need not coincide: a barrier that maximizes TMR may raise the voltage required for torque switching, and strong spin-orbit coupling that enables efficient torque can shorten spin lifetime in a coherent channel.

The numerical values must be interpreted within the stated approximations. The WKB model neglects detailed complex bands, interface resonances, roughness and voltage-induced barrier deformation. The diffusion model is one-dimensional and assumes constant D and τ_s with no contact backflow. The Rashba result is single-mode and neglects Dresselhaus coupling, disorder and energy-dependent contact transmission. The resonant model omits Coulomb blockade, inelastic scattering and self-consistent level shifts. Quantitative design of a specific stack would require measured or first-principles interface parameters, multidimensional electrostatics and spin-dependent nonequilibrium Green functions. The compact models remain valuable because they show which ratios must be controlled before such detail can improve performance.

VI. Conclusion

Spin-dependent electronic response is governed by a hierarchy of coupled length, energy and resistance scales. In the tunnel junction, polarization fixes the ideal magnetic contrast while the barrier thickness controls current exponentially. In the diffusive channel, the ratio L/λ_s determines how much injected spin survives. In the coherent spin transistor, the product $m^* \alpha_R L$ fixes the rotation angle, but the contact polarization limits readout contrast. In the resonant filter, spin splitting competes with linewidth and thermal broadening.

For the parameters studied here, the MTJ gives 146.3% TMR, a 1 micrometre diffusive link retains 13.5-60.7% of its injected signal as lifetime increases from 25 to 400 ps, and a 1 micrometre Rashba channel reaches pi rotation at 2.394×10^{-12} eV m. A 12 meV resonant splitting is highly selective at 4 K but ineffective at 300 K. These results show why spintronic components cannot be optimized by maximizing polarization, spin-orbit coupling or lifetime separately. Effective electronic applications require a matched design in which contact resistance, channel dimensions, coherence and operating temperature support the same transport regime.

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