

Filtering spin with tunnel-coupled electron wave guides

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We show how momentum-resolved tunneling between parallel electron wave guides can be used to observe and exploit lifting of spin degeneracy due to Rashba spin-orbit coupling. A device is proposed that achieves spin filtering without using ferromagnets or the Zeeman effect.

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Spintronics is an emerging field of electronics where the electron's spin is exploited as well as its charge.¹ Operation of most spintronic devices is based on the ability to create spin-polarized charge carriers in nonmagnetic semiconductors. This requirement has spurred recent interest in the investigation of possible mechanisms and limitations of spin filtering. Simply using Zeeman splitting of spin states is not the most practical way to achieve spin filtering, as needed magnetic-field strengths are often large and on-chip placement of micromagnets is required. More promising approaches employ hybrid structures² with metallic³⁻⁵ or semiconducting⁶⁻⁸ magnetic contacts. However, fabrication of these structures can pose material-science challenges⁹⁻¹¹ and may require rather complicated chip design. Achieving spin filtering by means of intrinsic spin-dependent effects in semiconductors is, therefore, highly desirable and also very intriguing from a fundamental-science point of view. For example, optical excitation from spin-split hole subbands in asymmetric quantum heterostructures can be used^{12,13} to create spin-polarized currents without ferromagnets or magnetic fields. Similarly, resonant transmission through spin-orbit-split quasi-bound states in semiconductor nanostructures is spin selective and may lead to significant polarization of electron current.^{14,15}

Here we propose a spin-filtering device based on the interplay of the Rashba effect^{16,17} and wave-number selectivity due to momentum-resolved tunneling¹⁸ between parallel electron wave guides. Spin-polarized currents are created by applying voltages or small magnetic fields. Switching between opposite spin polarizations is easily achieved. Verification of spin filtering in the device is possible via measurement of the differential tunneling conductance, which would yield the first *direct* observation of Rashba-spin-split electron dispersion curves.

The basic setup, shown in Fig. 1(a), consists of two parallel one-dimensional (1D) electron wave guides (quantum wires) that are coupled via tunneling through a clean, uniform, nonmagnetic barrier of finite length \mathcal{L} . Such a system can be realized, e.g., by quantum confinement of electrons in semiconductor heterostructures using split-gate techniques^{18,19} or cleaved-edge overgrowth.²⁰ Coupling of the quantum wires via the tunneling barrier results in a finite quantum-mechanical probability amplitude $t_{k,k'}$ for electrons to leave a state with wave number k in one wire and occupy a state with wave number k' in the other wire. Translational invariance along an extended uniform barrier implies approximate conservation of canonical momentum in a single

tunneling event. This is seen from the explicit form of the tunneling matrix element,^{21,22} given by

$$t_{k,k'} = 2t \frac{\sin[(k' - k)\mathcal{L}/2]}{k' - k}, \quad (1)$$

whose squared modulus exhibits a delta-function-like peak for $k = k'$ with height $|t|^2 \mathcal{L}^2$ and width $2\pi/\mathcal{L}$. The spin state of tunneling electrons remains unchanged. Hence, tunneling between parallel quantum wires is a highly wave-number-selective but entirely spin-insensitive process.

In our device, wave-number selectivity is utilized for spin filtering by means of an intrinsic coupling of electron spin to its momentum. Such a spin-orbit coupling originates from structural inversion asymmetry^{16,23,24} present in quantum-confined systems. This effect renders the kinetic energy of an electron with canonical momentum $\hbar k$ dependent on its spin state.¹⁷ To illustrate the basic physics, we consider here only

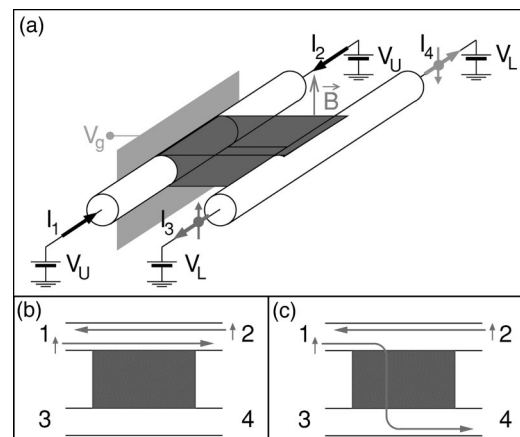


FIG. 1. Schematic picture of spin-filtering device and spin-polarized currents. (a) Two parallel quantum wires, labeled “U” and “L,” are each connected to reservoirs having equal chemical potential V_U and V_L . The wires are coupled via tunneling through an extended uniform barrier. A gate voltage V_g is used to control Rashba spin-orbit coupling in the two wires. (b) Reservoir 1 (2) injects right-moving (left-moving) electrons into the upper wire. Shown is the situation where wave-number selectivity and Pauli blocking prevents tunneling into the lower wire. (c) Interplay of spin-orbit coupling and wave-number selectivity can be used to selectively enable tunneling for right-moving spin-up electrons. Then, a spin-polarized current is flowing from reservoir 2 to reservoir 4.

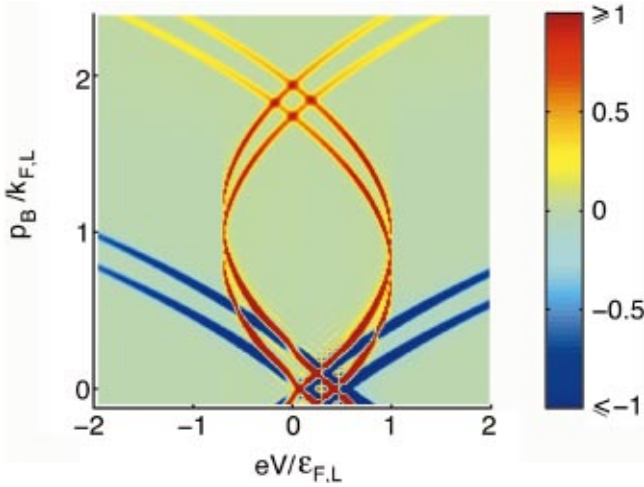


FIG. 2. (Color) Color plot of the differential tunneling conductance, shown in arbitrary units, as function of voltage bias $V = V_U - V_L$ and a magnetic field perpendicular to the plane of the wires. The magnetic-field strength is proportional to the parameter p_B defined in the text. Red and blue resonance features map out electronic dispersion curves in the two wires. Appearance of two sets of identical parabolic curves that are shifted in magnetic-field direction are the unambiguous signature of Rashba spin-orbit coupling of different strength in the two wires. For simplicity, it was assumed in our calculation that the strength of Rashba spin-orbit coupling is finite in the upper wire but vanishes in the lower wire. We then use the lower wire's Fermi wave number $k_{F,L}$ and Fermi energy $\epsilon_{F,L}$ as wave number and energy units, respectively. Parameters used in the calculation are $\Delta E_0 = 0.15 \epsilon_{F,L}$, $k_{so} = 0.1 k_{F,L}$, $\mathcal{L} = 100/k_{F,L}$.

the lowest 1D subband in a quantum wire and neglect subband mixing. Then the electronic dispersion is given by

$$E_{k\sigma} = E_0 + \frac{\hbar^2}{2m} (k - \sigma k_{so})^2 - \Delta_{so}. \quad (2)$$

Here, the spin-quantum number σ distinguishes spin-up ($\sigma = 1$) and spin-down ($\sigma = -1$) electron eigenstates.³¹ The effective mass of electrons is denoted by m , E_0 is the 1D subband energy, and $\Delta_{so} = \hbar^2 k_{so}^2 / (2m)$. The strength of spin-orbit coupling can be expressed in terms of a characteristic wave number, denoted here by k_{so} . Experimental efforts^{25–27} aimed at the realization of an early proposal²⁸ for a spin-controlled field-effect transistor established tunability of k_{so} by external gate voltages. In our device [see Fig. 1(a)], the voltage V_g is used to achieve different strengths of Rashba spin-orbit coupling in the two wires. In that situation, tunneling transport across the barrier provides a direct measurement of the Rashba effect. The differential tunneling conductance, calculated using standard perturbation theory within the tunneling-Hamiltonian formalism,^{22,29} is shown in Fig. 2. It provides a direct image of the spin-resolved parabolic dispersion curves given by Eq. (2). Monitoring the differential tunneling conductance would be the most immediate possibility to observe and study spectral consequences of the Rashba effect in 1D. So far, experimental studies^{25–27} have focused on extracting the value of Rashba-induced zero-field

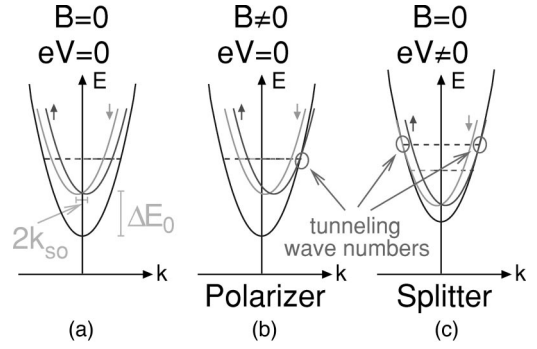


FIG. 3. Illustration of device operation as spin polarizer or spin splitter (a) Due to the Rashba effect, dispersion curves for spin-up and spin-down electrons in the upper wire are shifted horizontally by $2k_{so}$. In the lower wire, where spin-orbit coupling is assumed to be absent, energy dispersions are spin degenerate. (b) Tuning wave-number selectivity by a magnetic field B , tunneling is selectively enabled for right-moving electrons with spin up. (c) At a certain value of voltage V , tunneling becomes possible for left-moving spin-down electrons and right-moving spin-up electrons. Note that parabolicity of electron bands is not essential to achieve coincidences and, hence, spin-polarized currents.

spin splitting in 2D systems from the analysis of beating patterns in the Shubnikov–de Haas oscillations.

When a picture like Fig. 2 is obtained for the differential tunneling conductance, the double-wire system can be used for spin filtering. To simplify the explanation of its basic operational modes as a spin polarizer and a spin splitter, we consider here the special case where Rashba spin-orbit coupling is finite in the upper wire (labeled U) but vanishes in the lower wire (labeled L).³²

Taking into account a finite subband-energy difference $\Delta E_0 = E_0^{(U)} - E_0^{(L)}$, electronic dispersion relations appear as shown in Fig. 3(a). Only states with energies below $E_0^{(U)} + \epsilon_{F,U}$ in the upper wire (below $E_0^{(L)} + \epsilon_{F,L}$ in the lower wire) are occupied by electrons. Due to wave-number selectivity, tunneling can only occur for electron states with wave number close to a point where the dispersion curves of the two wires cross.²² In the case depicted in Fig. 3(a), no such crossings occur for states that are occupied in either one of the two wires, and no tunneling current can flow. All electrons injected into the upper wire from reservoirs 1 and 2 remain in the upper wire [Fig. 1(b)]. This situation can change when a magnetic field B is applied perpendicular to the plane of the two wires. It leads to a relative shift²² of the two wires' dispersion curves in wave-number direction by $p_B = -eBd/\hbar$, where $-e$ is the electron charge, and d the wire separation. For particular values of magnetic field, namely whenever the condition

$$p_B = \frac{\pi}{2} (\gamma n_U - \gamma' n_L) - \sigma k_{so} \quad (3)$$

is satisfied with $\gamma, \gamma' = \pm 1$ and $n_{U(L)}$ denoting electron density in the upper (lower) wire, tunneling is enabled for electrons in spin state σ . Simultaneous tunneling of electrons with opposite spin will be prohibited for high enough wave-number selectivity, i.e., if $\pi/\mathcal{L} \ll k_{so}$. The case corresponding

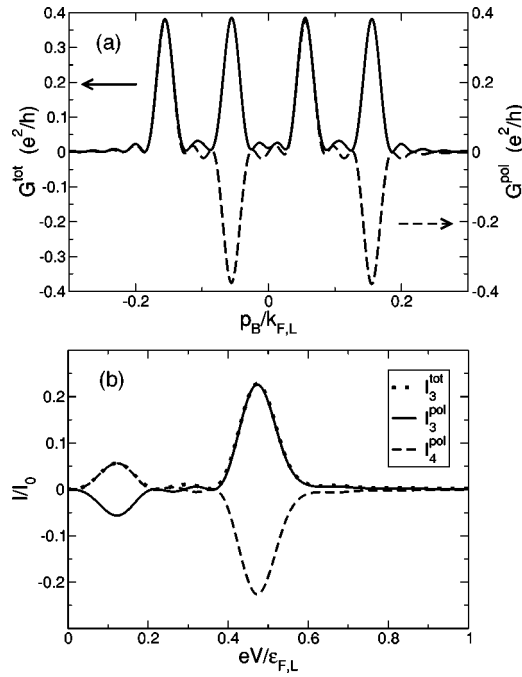


FIG. 4. Tunneling transport calculated exactly using scattering theory (a) and perturbatively (b) as explained in Ref. 22(a) Total linear tunneling conductance through the barrier $G^{\text{tot}} = G_{\uparrow} + G_{\downarrow}$ (left axis) and spin-polarized conductance $G^{\text{pol}} = G_{\uparrow} - G_{\downarrow}$ (right axis) vs magnetic field B . Resonances with definite spin polarization occur at values of the magnetic field determined by Eq. (3). Data shown are for $\Delta E_0 = 0.1\epsilon_{F,L}$, $k_{so} = 0.05k_{F,L}$, $\mathcal{L} = 200/k_{F,L}$, $|t| = \epsilon_{F,L} \cdot \pi/1000$. (b) Currents in all the leads are spin polarized when operating the device in spin-splitting mode [Fig. 3(c)]. Total and spin currents entering lead j are denoted by $I_j^{\text{tot}} = I_j^{\uparrow} + I_j^{\downarrow}$ and $I_j^{\text{pol}} = [I_j^{\uparrow} - I_j^{\downarrow}] \text{sgn}(I_j^{\text{tot}})$, respectively. In the spin-splitter mode, we have $I_4^{\text{tot}} = I_3^{\text{tot}} = -I_2^{\text{tot}} = -I_1^{\text{tot}}$. We show I_3^{tot} vs bias voltage $V = V_U - V_L$ (dotted curve). It is appreciable only in finite ranges of voltage where states near points of coincidence for the wires' dispersion curves are occupied in one wire but empty in the other one. Within these voltage intervals, total current in each lead is practically 100% polarized. This is seen from comparing I_3^{tot} with I_3^{pol} (solid curve) and I_4^{pol} (dashed curve). Data shown are calculated for $\Delta E_0 = 0.15\epsilon_{F,L}$, $k_{so} = 0.1k_{F,L}$, $\mathcal{L} = 100/k_{F,L}$, $|t| = \epsilon_{F,L} \cdot \pi/1000$, $B = 0$. Current unit is $I_0 = 2e\pi|t|^2\mathcal{L}^2/(\hbar^3v_{F,U}v_{F,L})$, where $v_{F,U}$ ($v_{F,L}$) is the Fermi velocity in the U (L) wire.

to $\gamma = \gamma' = +1$ is depicted in Fig. 3(b). In that situation, a spin-polarized current of electrons from reservoir 1 reaches reservoir 4. As shown in Fig. 1(c), it is compensated globally by the current of spin-up electrons from reservoir 2 that can only reach reservoir 1. Using the standard scattering-theory formalism³⁰ for calculating electron transport, we have obtained the linear conductance for tunneling across the barrier. Our results, given in Fig. 4(a), show the four resonances determined by solutions of Eq. (3), which exhibit almost perfect spin polarization of the tunneling current. We emphasize that the applied magnetic field, used here simply to tune wave-number selectivity, is typically much smaller than the field required to achieve spin-filtering from Zeeman splitting. Tuning between the four resonances allows the double-quantum-wire system to be used as a switchable spin polar-

izer. Analyzing the resonance condition given by Eq. (3) from a fundamental point of view, we realize that this is possible because Rashba spin-orbit coupling enters the single-particle Hamiltonian like a spin-dependent vector potential.

Intriguingly, spin-polarized currents can be created in our device without applying any magnetic field at all. Instead, a finite bias voltage $V = V_U - V_L$ can be used to induce a relative shift $-eV$ of the two wires' dispersion curves in energy direction.³³ This way, coincidences are created for electron states with spin σ and wave number k satisfying

$$eV = \Delta E_0 - \frac{\hbar^2}{m} k_{so} \sigma k. \quad (4)$$

If such a state is occupied by an electron in one wire and empty in the other one, it will contribute to the tunneling current. A situation where current flow is made possible by the applied voltage is depicted in Fig. 3(c). Tunneling is simultaneously enabled for electrons having opposite spin and wave number, which will end up in opposite leads of the wire they have tunneled into. For large enough wave-number selectivity, tunneling for a particular spin species turns out to occur, if at all, only for wave numbers of one sign. As a result, currents flowing in the leads of the double-wire device are fully spin polarized. This is seen in Fig. 4(b) for a particular set of parameters. Currents in leads 1 and 3 have the same spin polarization, which is opposite to that in leads 2 and 4. Selection of spin-up or spin-down polarization for currents in leads 1 and 3 (2 and 4) is possible simply by adjusting the voltage. While no global spin imbalance is created, wave-number selectivity leads to a redistribution of spin-polarized currents between the four leads. Thereby, spin filtering is possible without any magnetic or exchange fields. Note that wave-number selectivity provides the most direct way to utilize the Rashba effect for spin filtering. Hence, besides opening up an interesting alternative to previously suggested energy-selective mechanisms,¹⁵ our device offers certain advantages that may be important for application in spintronics.³⁴

Three mechanisms limit functionality of a real double-wire system as a spin-filtering device. First, wave-number selectivity is reduced by disorder. However, the successful measurement of 1D dispersion curves for parallel quantum wires in GaAlAs heterostructures²⁰ demonstrates the possibility to achieve sufficient wave-number selectivity using present-day technology. While this particular system cannot be used for spin filtering due to its negligible Rashba effect, similar structures could be created in more suitable materials. Second, quantum wires are really multichannel 1D wave guides for electrons. Spin-orbit coupling induces mixing between these channels (subbands), which was neglected in our discussion so far. Detailed analysis²⁸ shows that subband mixing can be safely neglected as long as the energy difference between consecutive quasi-1D subbands is much larger than Δ_{so} . In present-day samples, this requirement is easily met for realistic values²⁵⁻²⁷ of k_{so} . Finally, our conclusions apply at temperatures T low enough such that smearing of the Fermi function does not substantially decrease wave-

number selectivity. The relevant criterion $k_B T \lesssim \hbar^2 k_{so} k_{F,L} / m$ translates, for typical sample parameters, into $T \lesssim 10$ K. This temperature range is routinely accessible in semiconductor-research laboratories where our basic design for a spin-filtering device could be demonstrated.

Experimental tests for the successful operation of our device as spin polarizer or spin splitter could be based on the usual spin-detection mechanisms, applied to currents leaving or entering any of the four leads. For example, ferromagnetic contacts can serve as spin analyzers, or spin polarization of charge carriers could be measured optically.^{5–8} Results of such experiments will be determined not only by the efficiency of spin filtering in the double-wire system but also by

spin-equilibration processes in the leads. An equally significant test is provided by measurement of the differential tunneling conductance as a function of magnetic field and transport voltage. Clearly resolved Rashba-split dispersion curves, as shown in Fig. 2, prove sufficient wave-number selectivity for addressing different spin states and constitute, therefore, the decisive experimental demonstration of spin filtering in our device.

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- ³¹The spin quantization axis is fixed in the direction perpendicular to the quantum wire and the growth direction of the 2D quantum well where it is created.
- ³²A finite difference $\Delta k_{so} = k_{so}^{(U)} - k_{so}^{(L)}$ and sufficient wave-number selectivity ensure functionality of the device. Subsequent formulas remain valid when k_{so} is replaced by Δk_{so} .
- ³³In general, charging and exchange-correlation effects in the wires renormalize the voltage-induced shift of their dispersion curves. This can be taken into account straightforwardly and does not alter functionality of our device as a spin splitter.
- ³⁴The most important advantage is that spin filtering occurs in our setup when the transmission into output channels is maximal. This is different in the *T*-junction device of Kiselev and Kim (Ref. 15) where resonance with quasi-zero-dimensional bound states is essential to achieve appreciable spin filtering but, at the same time, results in almost complete backscattering.