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Ballistic quantum spin separator

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Spin-dependent ballistic transport in a mesoscopic three-terminal Y-shaped setup with a spin-discriminating ferromagnetic membrane in one of the outgoing leads is studied using the Landauer–Büttiker formalism. Our calculations, performed at sufficiently low temperatures when thermal effects and magnon scattering become vanishingly small, predict a strong quantum-interference caused enhancement of a spin-filtering effect originally arising due to the band-structure mismatch between the ferromagnetic metal and the lead. Finally, we discuss its possible applications for an efficient injection of a spin-polarized current into a superconductor and for self-controlled spin currents in quantum spintronic networks.

Keywords: spintronics, quantum charge transport, spin filtering, nanoscale beam splitter, spin separation.

1. Introduction

In contrast to traditional electronics, spintronics (or spin electronics) exploits electron spins as the main degree of freedom, with implications in the efficiency of data storage and transfer. The basic prerequisite for realizing the advantages of spintronics is the design of a controllable source of spatially distributed and highly spin-polarized electron ensembles. By analogy with optics, where this role is played by a birefractive crystal that splits an unpolarized light into two beams with perpendicular polarizations, a spin-discriminating setup should split a charge flow into two spin-polarized currents where electrons with opposite spins are flowing out through different output branches. The ability to control their direction and spin polarization is essential for spintronic circuits.

This task can be performed by a conventional three-terminal Y-shaped device with a charge emitter and two drain wires. In order to create different streams in outgoing channels, some kind of asymmetry should be introduced into the system. In particular, the origin of such asymmetry can exploit manipulations of spin/valley degrees of freedom in two-dimensional crystals of silicon or germanium, honeycomb structural analogs of grapheme [1,2] or a joint effect of a semiconductor quantum-point contact, the spin Zeeman splitting, and the electron transport through the edge states formed in the nanowire at sufficiently high magnetic fields [3]. As was shown in Ref. 4, helical edge states of a two-dimensional topological insulator can be utilized to construct a solid-state Stern-Gerlach spin splitter where magnetic flux creates specific interference effect. In particular, such device with two ferromagnetic leads can be used as a magnetic-field gated spintronic switch [4].

What we propose in the work is a simpler Y-shaped structure with conventional conductors and a spin-filtering nanoscale membrane where electrons are selectively scattered by spin-polarized valence electrons in a magnetic material and which is inserted into one of the branches. It will be shown below that the asymmetrical structure of the device ensures different spin-polarized currents in the two leads and that this polarization can be significantly enhanced due to constructive or destructive interference of coherent electron waves traveling inside ballistic channels. We assume that the charge transmission is mostly governed by the device geometry and external forces since due to the phase-space volume preservation in Hamiltonian systems the ballistic characteristics may be counter-intuitively observable even when the impurity scattering time is much shorter than the characteristic time scale of the ballistic nonlinear dynamics [5]. To keep the presentation simple, we suppose that each lead in the fork-shaped device includes only a single conducting channel and restrict ourselves to zero temperature. The latter assumption makes it possible to use a simple two-current model for the ballistic spin transport which is based on the supposition that electrons of majority and minority spins do not mix in the transfer process due to vanishingly small magnon scattering. If so, then the sample conductivity can be merely expressed as a sum of the contributions from spin-up and spin-down flows. Such a model has been widely used to explain many experimentally observed effects in spintronic devices and, in particular, those related to spin-filtering phenomenon [6].

2. Theory

Our spin-separating device is a Y-shaped quantum beam splitter which consists of a source terminal 1, a drain terminal 2 with a spin filter whose scattering cross-section is spin dependent due to the difference in available phase-space volume of empty states for a particular spin direction, and the second drain terminal 3. The terminals are connected to related reservoirs at certain fixed temperatures and electrical potentials. Traditional approach is based on the electron emitter, a spin filter, and a material into which spin-polarized charge are injected, all connected in series. In such device, transmission of electrons with the required spin direction, selected by the spin filter, into the material under study and retroreflection of electrons with opposite spins into an emitter take place [6]. In our approach it will be a three-arm splitter with a spin-filtering nanometer-thick inset in one of two outgoing leads.

We illustrate the operation of such "ballistic quantum spin separator" starting with a Y-shaped ballistic device formed by three leads intercepted at the junction node (see Fig. 1(a)). In each wire, labeled i ($i = 1, 2, 3$) the coordinate denoted by x_i increases from the node $x_i = 0$. At this point quasiparticle wave functions $\psi_i(x_i)$, linear combinations of plane waves propagating in each quasi-one-dimensional lead are entangled. The charge transport across the structure can be described using a conventional Landauer–Büttiker formalism which was originally proposed as a scattering theory approach for the calculation of transport characteristics of nanostructures [7]. It is based on the concept of three incoming

$$\psi_i^{(\text{in})}(x_i) = \frac{m}{\hbar\sqrt{k_i}} \exp\,(-ik_i x_i)$$

and three outgoing

$$\psi_i^{(\text{out})}(x_i) = \frac{m}{\hbar\sqrt{k_i}} \exp\,(ik_i x_i)$$

wave functions which are carrying unit flux and are parametrized by coordinates x_i. The functions are related to each other by a 3×3 unitary matrix

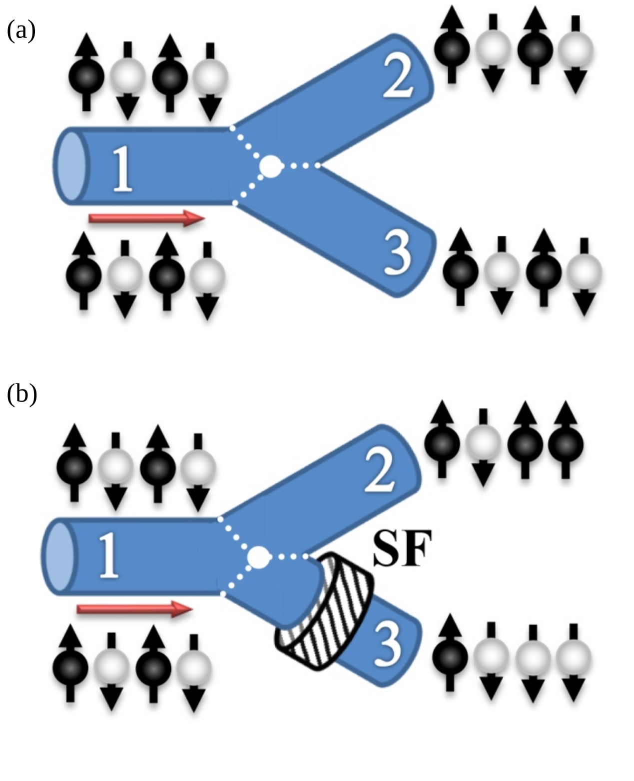

Fig. 1. Schematic view of the proposed ballistic setup with three arms and reservoirs at their ends (not shown). The upper drawing illustrates its operation without a spin filter when the numbers of spin-up and spin-down (black and open circles) electrons coincide in each outgoing leads. The lower drawing demonstrates spin-discriminating effect caused by the spin filter (SF) and quantum interference of coherent electron waves.

$$\mathbf{S} = \begin{pmatrix} r_{11} & t_{12} & t_{13} \\ t_{21} & r_{22} & t_{23} \\ t_{31} & t_{32} & r_{33} \end{pmatrix}$$

with transmission t_{ij} and refection r_{ij} coefficients. To determine its elements, we require the continuity of the wave functions $\psi_1(0) = \psi_2(0) = \psi_3(0) = \psi_0 = \text{const}$ and the conservation of the probability flux $j_1(0) - j_2(0) - j_3(0) = 0$ at the node $x_i = 0$ where [8]

$$j_i(x) = \frac{\hbar}{2mi}\left(\psi_i^* \frac{d\psi_i(x)}{dx} - \psi_i \frac{d\psi_i^*(x)}{dx}\right).$$

Dividing both sides of the latter expression by the constant value $|\psi_0|^2 \neq 0$, we obtain that

$$\text{Im}\left(\frac{1}{\psi_0}\frac{d\psi_2(x)}{dx}\bigg|_{x=0} + \frac{1}{\psi_0}\frac{d\psi_3(x)}{dx}\bigg|_{x=0} - \frac{1}{\psi_0}\frac{d\psi_1(x)}{dx}\bigg|_{x=0}\right) = 0.$$

Hence, the expression in brackets is a real constant K characterizing the waves coupling at the point $x_i = 0$ and

$$\frac{d\psi_1(x)}{dx}\bigg|_{x=0} - \frac{d\psi_2(x)}{dx}\bigg|_{x=0} - \frac{d\psi_3(x)}{dx}\bigg|_{x=0} = K\psi_0.$$

Note that for two-terminal junctions it is just a derivative boundary condition appropriate for an arbitrary dimensionless δ-functional potential barrier at the interface [9]. In the junction shown in Fig. 1(a), the barrier is replaced by a node with sizes less than inelastic scattering length in the wires (note that even in the disordered node region the quantum transport can be realized due to the presence of quantum-percolating trajectories [10]). Therefore, the only free parameter K may be interpreted as an "effective potential barrier" at the interception point $x_i = 0$.

After some algebra, for three identical leads discussed below we get $t_{ij} = 2k/(3k+iK)$, $i \neq j$, and $r_{ii} = -(k+iK)/(3k+iK)$. From these results it is evident that a non-zero backscattering effect $r_{ii} \neq 0$ exists even for totally symmetric structure with three alike wires and without any node scattering. For example, for three identical quantum channels and $K = 0$ a carrier incident into the first wire is partly rejected back with the probability $|r_{11}|^2 = 1/9$ and partly transferred to reservoirs 2 and 3 with probabilities $T_{12} = |t_{12}|^2 = T_{13} = |t_{13}|^2 = 4/9$. This counter-intuitive conclusion arises due to the wave functions entanglement at the setup node.

Let us now transfer to the same device but with a nanoscale spin filter (SF) in the lead 2 (see Fig. 1(b)). As was argued in the Introduction, there could be different physical realizations of the spin-filtering action. The simplest one is a single interface between a ferromagnetic metal (FM) and an electronic conductor possessing elastic scattering spin-discriminating properties arising due to the band-structure mismatch between the two contacting metals. As is known, the simplest way for interpreting metallic ferromagnetism is the Stoner model with a shift of the two spin bands (proportional to magnetization) whose shape is supposed to be unchanged. It means that in ferromagnetic systems spin-up and spin-down states are occupied asymmetrically by electrons. Because of it, it is possible to drive spin-polarized electron current across the interface between a ferromagnet and a nonmagnetic material. However, if this material is semiconducting, the interface is low transparent and only weak signatures of the spin-polarized electrons injected from ferromagnetic metals into semiconductors have been reported. At the same time, the mismatch of Fermi wave numbers in the conducting wires k and the ferromagnetic inset $k_{FM,s}$ can lead to transmission $t_{SF,s}$ and backscattering $r_{SF,s}$ probability amplitudes different for two spin orientations $s = \uparrow,\downarrow$ [11,12]. But the mismatch of two metals is usually too low and the main aim of our work has been to enhance this spin-separating effect using quantum interference phenomenon.

Matching the wave functions, we obtain that $t_{SF,s} = 2\sqrt{kk_{FM,s}}/(k+k_{FM,s})$ and the scattering from an FM surface amplitude $r_{SF,s} = (k_{FM,s}-k)/(k+k_{FM,s})$. Next, by summarizing all possible charge paths within the lead 2 which include scatterings from the junction node r_{22} and the interface with a ferromagnet (see, as an example, Ref. 13), we find probability amplitudes for the charge transmission from a terminal 1 into the spin filter $\tilde{t}_{1SF,s} = \dfrac{t_{12}t_{SF,s}}{1-r_{22}r_{SF,s}}$ modified by scattering processes within the lead 2. Then an electron can transfer the nanometer-thin SF membrane and appear in the reservoir 2. The total probability of the scattering pathway for an electron which starts its route in the terminal 1, transfers the SF membrane of the thickness d_{FM}, and ends in the reservoir 2 can be calculated in a similar way:

$$T_{12,s} = 0.5\left|\frac{\tilde{t}_{1SF,s}\exp\left(ik_{FM,s}d_{FM}\right)t_{SF,s}}{1-(-r_{SF,s})\exp\left(2ik_{FM,s}d_{FM}\right)\left(-r_{SF,s}+\dfrac{t_{SF,s}r_{22}t_{SF,s}}{1-r_{22}r_{SF,s}}\right)}\right|^2. \tag{1}$$

Here the product of $k_{FM,s}$ and the thickness of the FM inset $d_{FM,s}$ is the phase shift acquired by an electron during its way between two sides of the spin filter. Next, we present results for the transmission amplitude $T_{13,s}$ and the backscattering amplitude $R_{11,s}$:

$$T_{13,s} = 0.5\left|\tilde{t}_{12,s}\left(r_{SF,s}+\frac{t_{SF,s}\exp\left(2ik_{FM,s}d_{FM}\right)\left(-r_{SF,s}\right)t_{SF,s}}{1-r_{SF,s}\exp\left(2ik_{FM,s}d_{FM}\right)r_{SF,s}}\right)t_{23,s}+t_{13,s}\right|^2, \tag{2}$$

$$R_{11,s} = 0.5\left|r_{11}+\tilde{t}_{12,s}\left(r_{SF,s}+\frac{t_{SF,s}\exp\left(2ik_{FM,s}d_{FM}\right)\left(-r_{SF,s}\right)t_{SF,s}}{1-r_{SF,s}\exp\left(2ik_{FM,s}d_{FM}\right)r_{SF,s}}\right)t_{21,s}\right|^2. \tag{3}$$

Of course, the sum of the three probabilities should be equal to unity

$$\sum_s \left(R_{11,s} + T_{12,s} + T_{13,s} \right) = 1.$$

3. Numerical results and discussion

The figure of merit for a spin-splitting device is the spin polarization of the transmission coefficients $T_{1i,s}$, defined as $\gamma_{1i} = \dfrac{T_{1i\uparrow} - T_{1i\downarrow}}{T_{1i\uparrow} + T_{1i\downarrow}}$ with probabilities (1) and (2) for charge transmissions from a terminal 1 to the drain reservoirs 2 and 3. These values should be compared with the spin-filtering efficiency of a single interface between the lead 2 and the FM $\gamma_{SF} = \dfrac{\left|t_{SF\uparrow}\right|^2 - \left|t_{SF\downarrow}\right|^2}{\left|t_{SF\uparrow}\right|^2 + \left|t_{SF\downarrow}\right|^2}$.

From the formulas above it is clear that the final result strongly depends on the signs of reflection amplitudes $r_{SF,s}$, i.e., on the interrelation between $k_{FM,s}$ and k for two spin orientations. Below we consider two possibilities $k_{FM\downarrow} < k < k_{FM\uparrow}$ and $k < k_{FM\downarrow} < k_{FM\uparrow}$, see Figs. 2(a) and 2(b), respectively, with fixed ratios $k_{FM\downarrow}/k$ and varying $k_{FM\uparrow}/k$ values. As can be seen, the presence of a scattering node strongly enhances the separation efficiency of the three-arm setup comparing to that of the SF membrane (solid lines in Fig. 2) which is controlled by the $k_{FM\downarrow}/k$ ratio. The oscillating character of the $\gamma_{1i}(k_{FM\uparrow})$ dependences arises due to the quantum interference of electron waves within the nanoscale FM inset. The presence of backscattering effects at the node ($K \neq 0$) results in the intensification of the spin-polarized phenomenon for electrons leaving the lead 2 raising it to a near ideal magnitude $\gamma_{12} \leq 1$ when only electrons with a certain spin orientation are transmitted into the reservoir 2 at the Fermi energy. At the same time, finite K values significantly suppress the spin-polarized effect in the lead 3.

Note that above we have ignored the phase shifts acquired in the leads while took it into account inside the SF membrane that is applicable, as an example, for separating setups made of doped semiconductors with small Fermi wave numbers comparing to strong ferromagnetic metals with large $k_{FM\uparrow}$ values for majority spin bands.

One of possible applications of the proposed quantum spin separator can be injection of spin-polarized electrons into a superconductor placed at the end of the lead 3. Simultaneous presence of the macroscopic phase coherence in superconductors and spin-sensitive effects in magnetic materials is of considerable value for studying conceptually new issues in superconductors and as a playground for cooperation and interference of different forms of ordering in condensed matter, see the reviews [14–16]. Proposed Y-shaped device permits to eliminate direct proximity effects between

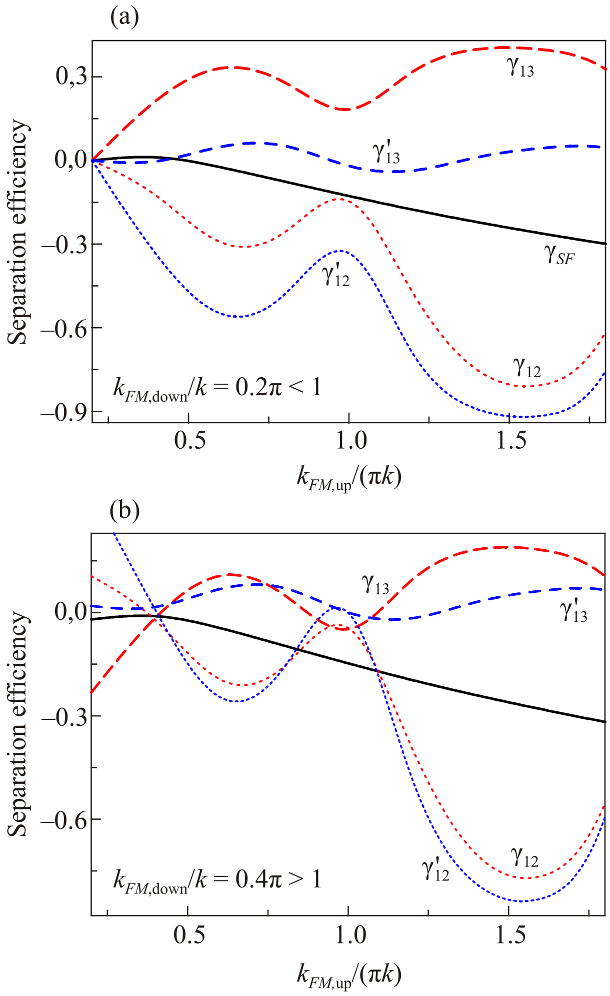

Fig. 2. Effect of the $k_{FM\uparrow}/k$ parameter on spin-separation efficiencies γ_{12} and γ'_{12} for electrons transmitted from a terminal 1 to the reservoir 2 at the end of the lead 2 (two dotted lines) as well as γ_{13} and γ'_{13} for those transmitted from a terminal 1 to the reservoir 3 (two dashed lines) compared with the spin-filtering efficiency of a single interface between the lead 2 and the FM γ_{SF} (a solid line). Left and right graphs differ by fixed $k_{FM\downarrow}/k$ values shown in the figures whereas unprimed and primed curves correspond to the node scattering parameter K equal to zero and $5k$, respectively.

superconducting (S) and magnetic films which take place in conventional spin-filter/superconductor bilayers where stray fields can strongly affect superconductivity in a spatially nonuniform manner. Three-arm devices with FM and S insets can be also exploited for creating significant energy dependence of the spin-separating effect which can be used, in particular, for the realization of self-controlled spin currents in quantum spintronic networks as it was proposed recently for charge flows [17]. We expect to discuss this issue elsewhere.

It is clear that the spin-polarization degree can be influenced by spin-flip scattering if that occurs inside the leads or at the interface. One of the main origins of this effect is spin-orbit coupling. Thus it is desirable to choose materials in which spin-orbit coupling of the relevant states is minimal, either because of the low atomic numbers of the constituent elements or due to the material band structure.

Conclusions

In summary, we have proposed a three-terminal quantum device whose purpose is to separate two spin polarizations from the incoming lead 1 into one running to the reservoir 2 and the other running into the wire 3. We have shown that it can be realized by inserting a nanometer-thick membrane made of a ferromagnetic metal into one of the outgoing leads. Its inherent spin-filtering efficiency, which originates from band-structure mismatch between the ferromagnetic metal and the lead, is rather small but the spin-separation outcome can be strongly enhanced due to quantum interference effects within the spintronic device. Let us emphasize that in our setup the spin separation takes place even for a nonmagnetic emitter 1. If it is ferromagnetic, the effect is clearly more pronounced. Addition of resistive-switching effects [18,19] would allow controlling transport processes in the proposed device.

Finally, our study demonstrates great potential for manipulating and controlling spin degrees of freedom using three-terminal quantum heterostructures. The above analysis definitely calls for experimental evidence in support of the theoretical predictions. At the same time, transporting ensembles of electrons over long distances without losing their spin polarization as well as direct demonstration on the ballistic nature of the charge flows across nanowire devices remain challenging and largely unexplored issue.

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It is our pleasure, and an honor, to contribute to this issue dedicated to Professor Boris Verkin on the occasion of his 100th birthday. Professor Boris Verkin was among the founders of the Ukrainian low-temperature physics school, now well known in the world. His contributions to magnetism, superconductivity, cryogenic medicine and biology remain valuable nowadays and the best monument to Professor Boris Verkin is the Institute for Low Temperature Physics and Engineering created by him.

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Балістичний квантовий спіновий сепаратор

О. Житлухіна, М. Білоголовський, P. Seidel

За допомогою формалізму Ландауера–Буттікера досліджено спін-залежний балістичний транспорт крізь мезоскопічну трьохтермінальну Y-подібну структуру з чутливою до спіну феромагнітною мембраною в одному з вихідних провідників. Розрахунки, виконані при досить низьких температурах, коли тепловими ефектами і розсіюванням на магнонах можна знехтувати, передбачають істотне посилення ефекту спінової фільтрації, обумовленого неузгодженістю між зонними структурами феромагнітного металу та провідника. На закінчення обговорюються можливі застосування цього явища для ефективної інжекції спін-поляризованого струму в надпровідник і саморегульованих спінових струмів квантових спінтронних мережах.

Ключові слова: спінтроніка, квантове перенесення заряду, спінова фільтрація, нанорозмірний сплітер, спіновий сепаратор.

Баллистический квантовый спиновый сепаратор

Е. Житлухина, М. Белоголовский, P. Seidel

С помощью формализма Ландауэра–Буттикера исследован спин-зависимый баллистический транспорт через мезоскопическую трехтерминальную Y-образную структуру с чувствительной к спину ферромагнитной мембраной в одном из исходящих проводников. Расчеты, выполненные для достаточно низких температур, когда тепловыми эффектами и рассеянием на магнонах можно пренебречь, предсказывают существенное усиление эффекта спиновой фильтрации, обусловленного рассогласованием между зонной структурой ферромагнитного металла и проводника. В заключение обсуждаются возможные применения этого явления для эффективной инжекции спин-поляризованного тока в сверхпроводник и саморегулируемых спиновых токов в квантовых спинтронных сетях.

Ключевые слова: спинтроника, квантовый перенос заряда, спиновая фильтрация, наноразмерный сплиттер, спиновый сепаратор.