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Ferromagnetic resonant tunneling diodes as spin polarimeters

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A method for measuring the degree of spin polarization of magnetic materials based on *spin*-dependent resonant tunneling is proposed. The device we consider is a ballistic double-barrier resonant structure consisting of a ferromagnetic layer embedded between two insulating barriers. A simple procedure, based on a detailed analysis of the differential conductance, allows one to accurately determine the polarization of the ferromagnet. The spin-filtering character of such a system is furthermore addressed. We show that a 100% spin selectivity can be achieved under appropriate conditions. This approach is believed to be well suited for the investigation of diluted magnetic semiconductor heterostructures.
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The operation of spintronic devices[1] requires the availability of efficient techniques to inject and detect spin-polarized currents. In fact, the search for new materials with a high degree of spin polarization today represents an important technological challenge in spintronics. A key parameter in these devices is the spin polarization of the electric current defined as

$$\mathcal{P}=(I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow), \tag{1}$$

where I_σ is the contribution to the current due to σ-spin carriers.[2] Structures containing ferromagnetic materials are obvious candidates as sources of spin-polarized currents. These can be metallic[3] or consist of diluted magnetic semiconductors (DMSs).[4] Two different electric transport methods have been devised for determining this quantity based both on contacting the ferromagnets (F) under investigation to a superconductor (S). In the first one, $\mathcal{P}$ can be estimated by realizing a F/S tunnel junction and Zeeman splitting the superconducting density of states through the application of an external magnetic field.[5] More recently the point-contact Andreev reflection (PCAR) method was introduced. Here the suppression of Andreev reflection (AR) at F/S ballistic junctions is exploited.[6] This method proves most effective for highly transmissive F/S contacts where the AR probability is high,[7] consequently, its application in DMS materials is hindered by the presence of an unavoidable Schottky barrier at the interface.

In this letter, we propose an alternative route to determine the polarization of a ferromagnet (either metallic or DMS) based on a double-barrier resonant structure [see Fig. 1(a)]. The operation principle of this device resides in the fact that, when the resonator is ferromagnetic, the resonant levels of the two spin species occur at different energies whose difference is a function of the exchange field in F (and, therefore, $\mathcal{P}$). The advantage of this method stems from the fact that this energy difference is little dependent on the quality of the barriers (provided their transmissivity is low enough as required for resonant tunneling to occur) and that no direct coupling to a superconductor is necessary, as imposed in PCAR. In addition the same device can be operated as an extremely efficient spin filter.[8,9]

The device consists of a ballistic ferromagnetic layer of thickness L sandwiched between two nonmagnetic barriers connected to electrodes [in Fig. 1(b), the potential profile of the structure is sketched]. In the following, we refer to this structure as to the ferromagnetic resonant tunneling diode (FRTD). (See Ref. 10 for different implementations of magnetic resonant structures). As long as phase coherence in preserved, current through the FRTD can flow via the resonant levels of the quantum well defined by the barriers. Such reso-

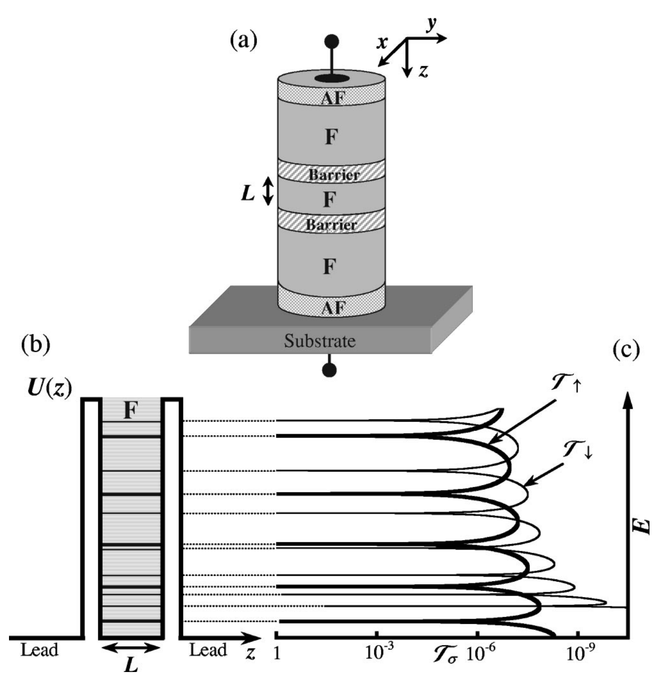

FIG. 1. (a) Scheme of a possible implementation of a ferromagnetic resonant tunneling diode. The magnetic layers (F), separated by insulating barriers, may either consist of metallic ferromagnets or DMSs, and AF denotes antiferromagnetic layers that pin the direction of the electrodes magnetization. (b) Schematic potential profile $U(z)$ of a magnetic double-barrier structure. (c) Qualitative behavior of the transmission probability per spin ($\mathcal{T}_\sigma$) of the structure. The presence of an exchange field in F removes the spin degeneracy of the resonant levels thus changing their energies, as sketched in (b).

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nances show up as peaks in the differential conductance spectrum. Since the resonator is ferromagnetic, the spin degeneracy is lifted and the resonant levels relative to the two electron spin species occur at different energies [see Fig. 1(c)]. By noting that this energy difference depends on the polarization $\mathcal{P}$ of the ferromagnet, it is possible to determine $\mathcal{P}$ from the analysis of the resonance energy position.

In order to clearly explain how the method works, we consider a single-band model as a generic example, and we describe the ferromagnet (or DMS) with an effective exchange field $h_{\rm exc}$ (Stoner model).[11] If the resonator is decoupled from the contacts, the quantum well levels,

$$E_{\sigma}^{n_{\sigma}} = \mathcal{F}(k_{n_{\sigma}}) - \sigma h_{\rm exc}, \tag{2}$$

(characterized by the spin-dependent index n_{σ}) are found from elementary quantum mechanics. In Eq. (2), $k_{n_{\sigma}}$ is the quantized longitudinal quasiparticle wavevector, $\mathcal{F}(k)$ is a generic dispersion relation, and $\sigma = \pm 1$ is the spin index, where the sign $+(-)$ corresponds to $\uparrow(\downarrow)$ spin channel. Note that $\mathcal{F}(k)$ contains a transverse contribution to the total quasi-particle energy. For fixed $h_{\rm exc}$ and L, the requirement that $E_{\sigma}^{n_{\sigma}} > 0$ (i.e., resonant states above the Fermi energy E_F) determines the first resonance index n_{σ}. Due to presence of the exchange field, n_{σ} can, in general, be quite different for the two spin species. By connecting the resonator to the electrodes through weakly transmitting barriers, such bound states acquire a finite width at the energies $E_{\sigma}^{n_{\sigma}}$. As a result, they manifest themselves as peaks in the differential conductance spectrum with a broadening dependent on barrier strength and temperature.

As in the PCAR method, our aim is to determine $h_{\rm exc}$, and therefore $\mathcal{P}$, assuming that the band structure parameters contained in $\mathcal{F}(k)$ are known. Since the exchange field enters the dispersion relation additively, one might think that it can be determined from the energy difference between a spin-up and a spin-down resonance relative to the same index n_{σ}. This however is possible only if $h_{\rm exc}$ is small with respect to such energy difference, a situation that is typically not fulfilled in ferromagnets and DMS. Nevertheless, $h_{\rm exc}$ can still be determined through an analysis of the low-temperature differential conductance spectrum. One can employ the following simple procedure: (i) identify two successive spin-up resonances and measures their energy difference from which the index $\overline{n_{\uparrow}}$ of the first chosen spin-up resonance is determined solving Eq. (2); (ii) perform the same operation on spin-down resonances in order to obtain $\overline{n_{\downarrow}}$; and (iii) measure the energy difference $\delta E_{\uparrow\downarrow}$ between one spin-up resonance of (i) and one spin-down resonance of (ii) so that the exchange field is easily obtained from

$$h_{\rm exc} = \frac{1}{2}[\mathcal{F}(k_{\overline{n_{\uparrow}}}) - \mathcal{F}(k_{\overline{n_{\downarrow}}}) - \delta E_{\uparrow\downarrow}]. \tag{3}$$

It is worth stressing that for linear or constant dispersion curves, the proposed method fails. In these situations, indeed, the energy difference of points (i) and (ii) would be independent of the resonance index, thus preventing its determination. To identify the spin character of the resonances, we envision the following two possibilities. The first one is to make use of ferromagnetic leads,[12] so that the amplitude of the resonances will be spin dependent [for the same reason for which, for example, the Sharvin conductance of a ferromagnetic point contact of area $\mathcal{A}$ and Fermi wavevector k_{σ}, $G_{\rm Sharvin} = (e^2/h)(\mathcal{A}k_{\sigma}^2/4\pi)$, is different for the two spin species]. The second possibility relies on the application of an external magnetic field which will produce a Zeeman shift of the resonances in opposite energy direction for the two spin species.[13]

So far, we presented an ideal situation. In order to check the actual feasibility of the procedure outlined herein, we have calculated, within a transfer-matrix approach, the differential conductance spectrum of a three-dimensional FRTD with rectangular barriers, assuming translational invariance in the plane of the junctions and large spin–flip length in the ferromagnet with respect to the resonator width.[14] For definiteness, we assumed a parabolic dispersion relation[15] and typical parameters relative to a metallic ferromagnet.[16] The resonator width was chosen in order to show a few resonances per spin within a bias voltage range of one tenth of E_F. Barrier transmissivity ($\approx 10^{-2}$) was taken such that the width of the resonances is small with respect to their relative separation, and a finite temperature was also taken into account in order to make the simulation more realistic. Having computed the differential conductance spectrum, as if obtained directly from a measurement, we have identified the peaks positions and spin character. By applying our procedure, we have determined $h_{\rm exc}$ with a negligible error with respect to the nominal value. This proves the effectiveness of this method. Furthermore, it is remarkable that the method works properly even if the dispersion curve for bias voltages in the range considered is not far from linearity. We wish to remark that all the aforementioned simulations are just an exemplification of how the method works and that some experiments might need to be analyzed employing, for example, multiband models. In this last case, the method is still valid even though the analysis becomes more cumbersome.

Finally, we discuss the spin-filtering action of the proposed structure. For bias voltages such that only the *first* resonance contributes to transport, i.e., for voltages which correspond to the first step in the current–voltage characteristic,[8] the system behaves as an ideal spin filter, providing fully polarized (100%) currents even in the absence of a *half-metallic* (i.e., with $\mathcal{P}=1$) resonator. The spin polarization of the current can be chosen either by varying the diode geometry (the resonator width L) or by selecting an appropriate material (with a given $h_{\rm exc}$). In both situations, the application of an external magnetic field offers an additional way of tuning the spin-filtering character of the structure. To elucidate this property, we show in Fig. 2(a) a contour plot of the zero-temperature differential conductance as a function of resonator width and bias voltage. In this plot of Fig. 2(a), we assumed that the FRTD electrodes are of the same magnetic material as the resonator. Figure 2(a) clearly shows that the spin character of the first resonance (indicated by $\uparrow,\downarrow$ white arrows) can be changed upon variation of L. For example, by choosing $L = 2.2$ nm, the first resonance occurs at eV$=0.08\,E_F$ and is spin up in character, while choosing $L = 2.6$ nm, a spin-down resonance occurs at eV $=0.027\,E_F$ (see red dashed lines in Fig. 2). A similar dependence is observed in Fig. 2(b) where the differential conduc-

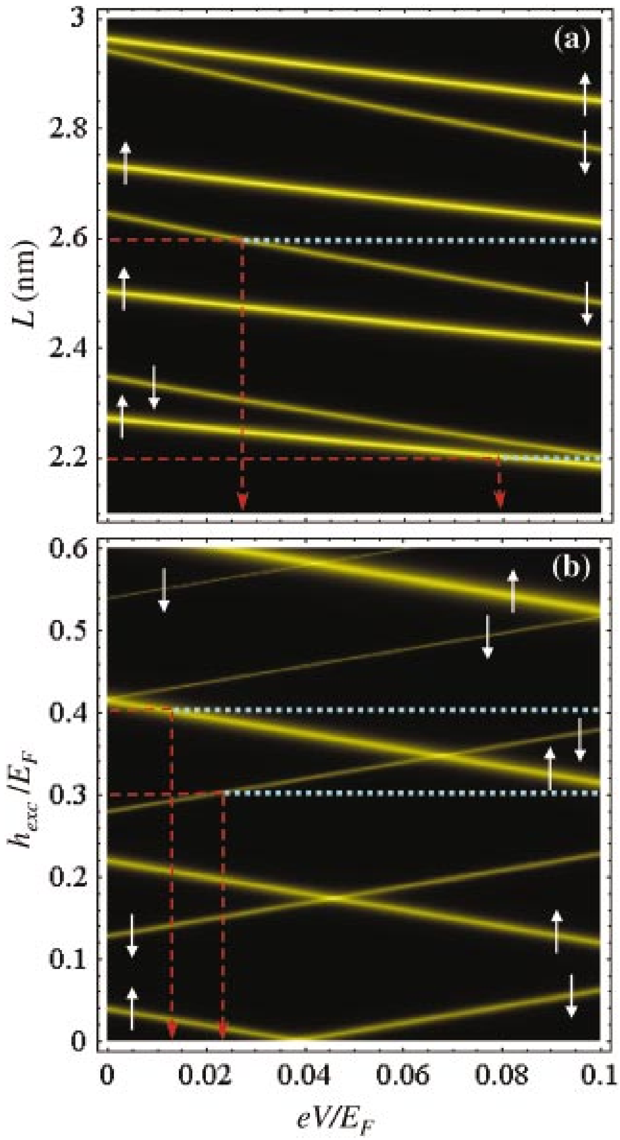

FIG. 2. (Color) Contour plot of the zero-temperature differential conductance spectrum (arbitrary units) vs bias voltage and resonator width (a), and vs exchange field (b). White arrows indicate the spin character of the resonances and the blue dashed lines show examples of possible bias ranges in which a 100% spin-polarized current is achieved for chosen L (a), or fixed $h_{\rm exc}$ (b). In these simulations, we used $E_F = 5.7$ eV, barrier transmissivity of 10^{-1}, $h_{\rm exc} = 1.425$ eV (a) and $L = 3$ nm (b). The color scale ranges from black to yellow indicating a variation of conductance from zero to maximum, and yellow brightness is proportional to the resonances amplitude.

tance is plotted versus the exchange field for fixed resonator width ($L = 3$ nm).

We conclude by elaborating on the actual realization of the FRTD as a spin polarizer. Figure 1(a) shows a FRTD where the magnetization direction of the two ferromagnetic electrodes (F) is pinned through their contact with antiferromagnetic layers (AF), and the magnetization of the resonator can be changed from the parallel to antiparallel direction upon the application of weak magnetic fields. The device could be engineered through the sequence of metallic (for example Ni_xFe_{1-x} alloy) or III–V DMSs (typically $Ga_{1-x}Mn_xAs$) stacked layers, and taking advantage of the x dependence of their exchange field in order to tune the spin filter.

In summary, we have proposed a general method which exploits a FRTD for determining the degree of polarization of a ferromagnet. The spin-filtering character of such a structure was additionally addressed and ideal spin selectivity proven. The proposed procedure seems to be more appropriate than PCAR for the case of DMSs, where the formation of a transmissive contact with the superconductor is expected to be difficult due to the presence of an unavoidable Schottky barrier at the interface with the metal. On the contrary, the technology for the fabrication of magnetic resonant tunneling diodes, both metallic[8,17] and consisting of DMSs,[18] is nowadays already available.

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[12] Due to the small value of the involved coercitive fields, a small magnetic field is sufficient to make sure that the magnetization of all layers are parallely aligned.

[13] The magnetic field values required to produce an appreciable energy shift depend on the resonator material through the g factor.

[14] The presence of spin–flip scattering does not alter the energy position of the resonances. When using ferromagnetic electrodes, it simply alters the relative amplitude of resonances belonging to different spin species.

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