Spin-dependent electron transport in ferromagnetic bilayers: Application to three-dimensional spin detectors

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A general analysis of spin-polarized electron transmission through ferromagnetic bilayers is presented. We calculate the transmitted current through two consecutive layers with in-plane magnetizations and we investigate the particular case where these magnetizations are orthogonal. We show that it is possible to obtain a three-dimensional spin detector for low-energy electrons which is compact and performant.
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INTRODUCTION

Spin-dependent transport experiments have raised a broad interest because of the new physics involved and of their promises of application. Studies on magnetoresistance effects and related phenomena are nowadays an active field of research stimulated by applications to high-density recording, magnetic sensors or "spintronics" devices. Moreover, important improvements have been made in growth processes so that it is possible to associate the properties of ferromagnetic thin films with those of metals, semiconductors or insulators. Nevertheless, the status of the different existing polarimeters is not really satisfactory and spin-resolved electron spectroscopies addressing ballistic electron transport suffer from the low efficiency of the detectors. If, in most cases, spin detectors are based on the spin-orbit coupling in the scattering of electrons from atoms with large atomic number (Mott or LEED detectors), the exchange interaction provides a new way to realize high-sensitivity spin polarimeters.[1] Previous studies have emphasized the relevance of the "spin-filter" concept:[2] due to the asymmetry in the spin d subbands, a ferromagnetic layer acts as a polarizer for an unpolarized beam or can be used as an analyzer for spin-polarized electrons, analogously to an optical polarizer. However, dealing with electrons offers more possibilities because their polarization may have both longitudinal and transverse components. Ferromagnetic multilayers are very promising as several magnetic configurations can be achieved. In this case, the electron intensity transmitted through the multilayer depends both on the beam polarization and on the magnetic configuration. In this paper, we present a general analysis of spin-dependent transport through a bilayer structure where the magnetization states are in-plane, with arbitrary directions. We describe the physical phenomena involved in spin-polarized electron transport and we apply our simple model in the particular case where the magnetizations are orthogonal. We show that such a bilayer constitutes a convenient and performant three-dimensional spin detector for low-energy electrons (about 5 eV above the Fermi level).

SPIN-DEPENDENT ELECTRON TRANSMISSION THROUGH FERROMAGNETIC LAYERS

Spin-dependent electron transport of low-energy electrons in a ferromagnetic metal arises because majority- and minority-spin electrons have different relaxation channels due to different final densities of states.[3] Consider the one-dimensional experiment where an electron beam with a longitudinal polarization (propagating along the **z** axis) crosses a ferromagnetic layer magnetized along **z**. Referring to the initial polarization as P_0, the polarization P of the transmitted beam is $P=(P_0+S)/(1+SP_0)$. In this expression, $S=(t_+-t_-)/(t_++t_-)$ where $t_+(t_-)$ is the spin-dependent transmission coefficient for majority- (minority-) spin electrons.[2] In a mean free path model, $t_\pm=e^{\pm d/\delta}$ where d is the layer thickness and $\delta^{-1}=1/2(\lambda_-^{-1}-\lambda_+^{-1})$ with $\lambda_+(\lambda_-)$ the inelastic mean free path for majority- (minority-) spin electrons. S characterizes the spin selectivity of the layer and is similar to the Sherman function in Mott polarimetry.[4] Oberli and co-workers[5] studied the case where the incident polarization (along the **z** axis, the propagation direction) and the layer magnetization axis (along the **x** axis) are orthogonal. They observed that two kinds of motion are involved in the evolution of the polarization vector: an alignment in the direction of the magnetization due to the spin-filter effect and a rotation around it. The second rotation is the spin precession of the primary electrons, injected at a few eV above the Fermi level (in s-bands), which ballistically cross the magnetic layer. In other words, this rotation is a Larmor precession in the exchange field which splits the s bands. In this case, the emerging polarization can be written as

$$\mathbf{P}=\begin{pmatrix} S \\ P_0\sqrt{1-S^2}\sin\varepsilon \\ P_0\sqrt{1-S^2}\cos\varepsilon \end{pmatrix}. \tag{1}$$

ε is the precession angle and can be written $\varepsilon=\Delta E\tau/\hbar$ where ΔE is the spin splitting of the s-bands and τ the transit time through the layer. More generally, if we consider an electron beam impinging normally onto a ferromagnetic layer, a simple calculation shows that[6]

$$\mathbf{P}=\frac{R_\varepsilon\mathbf{P}_0+\mathbf{S}}{1+\mathbf{S}.\mathbf{P}_0}. \tag{2}$$

Hereafter, we define the laboratory reference frame by the unit vectors (**x**,**y**,**z**), where **x** is along the magnetization of the layer ($\mathbf{S}=S\mathbf{x}$) and **z** is the propagation direction. R_ε is a matrix of similarity, i.e., the composition of a rotation around **x** (precession motion) with the homothety of a ratio $A=\sqrt{1-S^2}$ (spin-filter effect)

$$R_\varepsilon=\begin{pmatrix} 1 & 0 & 0 \\ 0 & A\cos\varepsilon & A\sin\varepsilon \\ 0 & -A\sin\varepsilon & A\cos\varepsilon \end{pmatrix}. \tag{3}$$

The transmitted current, which is the sum of the up- and down-spin electrons emerging from the layer is $I=I_0(1+\mathbf{S}.\mathbf{P}_0)$ where I_0 is the transmitted intensity for an unpolarized primary beam. Spin-dependent transmission only occurs if $\mathbf{S}.\mathbf{P}_0\neq 0$.

Now consider a ferromagnetic bilayer with arbitrary in-plane magnetizations. To describe the spin-filters we use the direct orthonormal base $(\mathbf{u}_1,\mathbf{v}_1,\mathbf{w})$ with $\mathbf{S}_1=S_1\mathbf{u}_1$ (in the **x** direction), **w** along **z** and we write $\mathbf{S}_2=S_2\mathbf{u}_2$. Since in the absence of quantum interferences the transmitted current in a multilayer is the product of the transmitted current of each layer,

$$I=I_0(1+\mathbf{S}_1.\mathbf{P}_0)(1+\mathbf{S}_2.\mathbf{P}_1) \tag{4}$$

where $\mathbf{P}_1$ is the polarization of the beam emerging from the first layer (i.e., entering the second layer). Using Eq. (4) we obtain

$$I=I_0(1+S_1S_2\mathbf{u}_1.\mathbf{u}_2+S_1(\mathbf{P}_0.\mathbf{u}_1)+S_2(R_\varepsilon\mathbf{P}_0.\mathbf{u}_2)). \tag{5}$$

The contribution $(1+S_1S_2\mathbf{u}_1.\mathbf{u}_2)$ does not depend on the incident polarization but is a function of the relative orientation of the polarizer with the analyzer, $S_1(\mathbf{P}_0.\mathbf{u}_1)$ simply results of spin filtering in the first layer while $S_2(R_\varepsilon\mathbf{P}_0.\mathbf{u}_2)$ is the contribution of the second layer acting on a component of $\mathbf{P}_0$ arising from the precession generated by the first layer. In particular, if $\mathbf{u}_1$ and $\mathbf{u}_2$ are not colinear, a **w** component of the primary beam leads a component along $\mathbf{u}_2$ before entering the second spin filter.

PRINCIPLE OF THE 3-D SPIN DETECTOR

Analyzing performances comparable to those of the best Mott detector have been reported with free-standing Au/Co/Au sandwiches at a few eV above the Fermi level and it was also shown that ultrathin ferromagnetic bilayers act as highly discriminative self-calibrated spin polarimeters.[7] But in this case (spin-valve geometry), only the component of the polarization which is in the magnetization direction was determined. Here, we consider the particular case of a bilayer with perpendicular magnetizations. To extract spin information from intensity measurements, we need to compare the transmitted currents in several magnetic configurations. Assume $I_{\pm\pm}$ to be the transmitted current when $\mathbf{u}_1=\pm\mathbf{x}$ and $\mathbf{u}_2=\pm\mathbf{y}$. With Eq. (5) it is straightforward to see that

$$\frac{I_{++}+I_{+-}}{2}=I_0(1+S_1(\mathbf{P}_0.\mathbf{x}))=I_0(1+S_x(\mathbf{P}_0.\mathbf{x})), \tag{6}$$

$$\frac{I_{++}+I_{-+}}{2}=I_0(1+S_2\sqrt{1-S_1^2}\cos\varepsilon(\mathbf{P}_0.\mathbf{y}))$$
$$=I_0(1+S_y(\mathbf{P}_0.\mathbf{y})), \tag{7}$$

$$\frac{I_{++}+I_{--}}{2}=I_0(1+S_2\sqrt{1-S_1^2}\sin\varepsilon(\mathbf{P}_0.\mathbf{z}))$$
$$=I_0(1+S_z(\mathbf{P}_0.\mathbf{z})), \tag{8}$$

$$I_0=\frac{(I_{++}+I_{--}+I_{+-}+I_{-+})}{4}. \tag{9}$$

Equations (6)–(8) define the Sherman functions S_x, S_y and S_z of the structure in the three measurement directions. Each component of the primary polarization has been isolated by these three combinations (Fig. 1). Because reversing the magnetization of one layer changes the direction of **w**, only two layers are necessary to determine the three components of the incident polarization, as if there were a third "virtual" layer in the **z** direction.

DISCUSSION AND CONCLUSION

To evaluate the performances of such a 3-D spin detector, we must choose a particular material and estimate S_x, S_y and S_z. Nevertheless, the data concerning magnetic materials are scarce and only few measurements are available in the low-energy range. Moreover, we have to determine the thick-

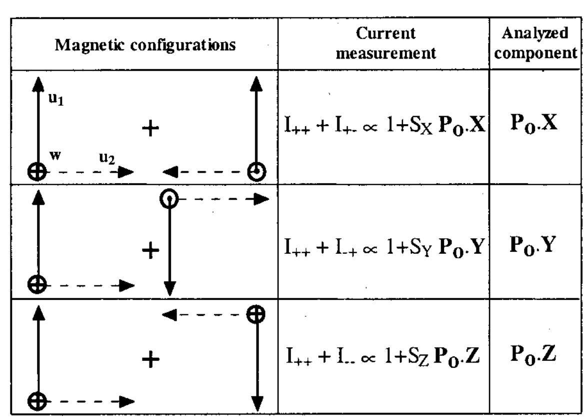

FIG. 1. Schematic representation of the pairs of magnetic configurations used to isolate each component of the primary polarization vector in Eqs. (6)–(8). $\mathbf{u}_1=\pm\mathbf{x}$ is the direction of the first magnetization seen by the electron beam while $\mathbf{u}_2=\pm\mathbf{y}$ is the direction of the second. **w** is defined as $\mathbf{w}=\mathbf{x}\times\mathbf{y}$. The second column recalls the polarization dependence of the transmitted current. This scheme makes intuitive the analyzing direction, where a unit vector is common to the two configurations.

TABLE I. Materials parameters. In the first line, the layer thickness is indicated in nm. λ_+ (λ_-) is the mean free path for majority- (minority-) spin electrons. The precession angle ε is calculated after Ref. 10. The Sherman functions in the three directions are calculated from Eqs. (6)–(8) using the expression $S=\tanh[(d/2)(1/\lambda_- - 1/\lambda_+)]$ given in Ref. 2, d being the layer thickness. The line T indicates the electron transmission from the relation $T=\exp(-d/\lambda)$ where $1/\lambda=1/2(1/\lambda_+ + 1/\lambda_-)$ is the spin-averaged mean free path.

<table>
<tr><th></th><th>Au
(1.5)</th><th>Co
(1.8)</th><th>Au
(4.5)</th><th>Co
(3.5)</th></tr>
<tr><td>λ_+ (nm)</td><td>4.5</td><td>2.0</td><td>4.5</td><td>2.0</td></tr>
<tr><td>λ_- (nm)</td><td></td><td>1.1</td><td></td><td>1.1</td></tr>
<tr><td>ε (deg)</td><td></td><td>34</td><td></td><td></td></tr>
<tr><td>S_X</td><td colspan="4">0.6</td></tr>
<tr><td>S_Y</td><td colspan="4">0.6</td></tr>
<tr><td>S_Z</td><td colspan="4">0.4</td></tr>
<tr><td>T</td><td>0.7</td><td>0.08</td><td>0.4</td><td>0.007</td></tr>
</table>

ness of the ferromagnetic metals to obtain high electron transmission, in-plane magnetizations and different coercive fields, allowing to realize the different magnetic configurations. We suggest a structure consisting in two Co layers (1,8 nm, 3,5 nm) separated by a 4,5 nm Au spacer, a well-known system, which leaves the Co layers only weakly coupled by indirect exchange.[8] The first Co layer (1,8 nm) should be covered by 1,5 nm of Au to prevent oxydation.[2] Relevant parameters for Au and Co are given in Table I, after Ref. 9 for the inelastic mean free path in Co and Au and after Ref. 10 for the precession angle. Finally, the overall thickness of the detector is of 11 nm with a transmission of the order of 10^{-4} mostly due to the Co layers, which means that the structure is not far from optimum. The collection efficiency, i.e., the ratio of the number of detected electrons over the number of injected electrons, is comparable to that of a typical Mott scatterer, and even the lowest Sherman function S_z compares to that of the best Mott polarimeter. This result paves the way to the development of compact and sensitive spin detectors. Obviously, to obtain a practical device, the spin-sensitive film has to be grown on a solid-state collector. The ultimate performance will be limited by the collection efficiency. We are presently investigating several possibilities, based on our experience in ferromagnetic layer deposition on semiconductor.[11]

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