Journal of Magnetism and Magnetic Materials 414 (2016) 132–143

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Optimization of spin injection and spin detection in lateral nanostructures by geometrical means

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ARTICLE INFO

Article history:
Received 5 February 2016
Received in revised form
4 April 2016
Accepted 17 April 2016
Available online 22 April 2016

Keywords:
Spintronics
Spin accumulation
Spin current
Lateral spin devices

ABSTRACT

Lateral spin devices are an important concept in nowadays all-metallic spintronic devices. One of the key problems is to obtain large spin injection and detection efficiency. Several concepts has been envisaged, such as to use half-metallic ferromagnetic electrodes or spin-polarized interface barriers. Within this work, we address the optimization of spin devices (namely optimization of spin current density, spin current and spin accumulation) based on adjustment of the geometry (dimensions) of the lateral device, material selection of spin conductors, jointly with optimization of the interface resistance.

1. Introduction

Spintronics is an important branch of magnetism, with the aim to extend possibilities of current electronics based on charge transfer. As arises from technological limitations, the devices employing spin current are usually build in perpendicular (vertical) or lateral (planar) geometries. In most cases, those devices provide spin current generation, spin propagation, potentially spin manipulation, and finally spin detection. Lateral spin transport provides a large variety of possible geometries and materials, being used to investigate a variety of spin-based phenomena. For example, they have been used to study spin-Hall effect and inverse spin-Hall effect [1,2], spin pumping [3], spin-transfer [4], Hanle effect [5,6], etc. Also, the employed materials range from 3d FM electrodes (e.g. Co [7]) to half-metallic electrodes based on Heusler compounds [8,9], whereas spin-conducting material is either metal (usually Cu or Al), semiconductor [6,10], molecular material [11] or graphene [12].

As spin injection and detection is a crucial feature in spintronics, large effort is taken to increase spin current injection or detection efficiency. This effort is driven in two principal directions. First direction is to increase spin polarization of the FM electrodes, such as using half-metals as FM electrodes [13]. Second approach is to overcome conductivity mismatch between FM electrode and spin conductor, which causes that spin polarization in bulk FM electrode is not transferred into non-FM spin conductor [14]. One approach to overcome conductivity mismatch is to employ tunnel barrier, either built as a thin film of non-conduction material (e.g. MgO) [15], or by using Schottky barrier in case of spin injection into semiconductors [16]. Although often omitted, there is another tricky way to overcome conductivity mismatch based on modified geometry of the lateral spin structure. For example, reduction of spin-injection cross-section area increases spin injection efficiency [17], selection of adjacent material to FM lead can reduce critical switching current [18] or magnetoresistance in lateral device is enhanced by confining laterally the spin accumulation [19].

Within this paper we present theoretical investigation of optimization of spin injection and spin detection in Py/Cu lateral structure, as a function of various cross-sectional areas, and both with and without tunnel barriers between Py/Cu interfaces. First, we derive analytical expression of spin current and spin potentials based on Valet–Fert 1D model [20]. Then, we discuss which geometrical measures provide optimization of spin accumulation, injected spin current or injected spin current density.

2. Valet–Fert model

The spin accumulation and the spin current density in hybrid nanostructures are described by Valet–Fert model, which in one-dimensional case has the following form [20]:

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http://dx.doi.org/10.1016/j.jmmm.2016.04.051

$$\frac{\partial^2 \Delta\mu}{\partial x^2} = \frac{\Delta\mu}{\lambda^2} \tag{1}$$

$$\frac{\partial^2}{\partial x^2}(\sigma_\uparrow \mu_\uparrow + \sigma_\downarrow \mu_\downarrow) = 0 \tag{2}$$

$$j_{\uparrow/\downarrow} = \frac{\sigma_{\uparrow/\downarrow}}{e}\frac{\partial \mu_{\uparrow/\downarrow}}{\partial x} \tag{3}$$

where $\mu_{\uparrow/\downarrow}$ are the spin-up and spin-down electrochemical potentials, their difference $\Delta\mu = \mu_\uparrow - \mu_\downarrow$ is called the spin accumulation. $j_{\uparrow/\downarrow}$ are the spin-up and spin-down current densities, λ the spin-diffusion length and x the lateral dimension. The bulk conductivities of ferromagnetic (F) and non-ferromagnetic (N) materials write

$$\sigma_{\mathrm{N}\uparrow/\downarrow} = \frac{\sigma_\mathrm{N}}{2} \tag{4}$$

$$\sigma_{\mathrm{F}\uparrow/\downarrow} = \sigma_\mathrm{F}\frac{1 \pm p_\mathrm{F}}{2} \tag{5}$$

where p_F is the bulk spin current polarization (later called just spin polarization), defined as $p_F = (\sigma_{\mathrm{F}\uparrow} - \sigma_{\mathrm{F}\downarrow})/(\sigma_{\mathrm{F}\uparrow} + \sigma_{\mathrm{F}\downarrow})$.

The spin resistances of N and F materials are defined as [21]

$$R_\mathrm{N} = \frac{\lambda_\mathrm{N}}{\sigma_\mathrm{N} S_\mathrm{N}} \tag{6}$$

$$R_\mathrm{F} = \frac{1}{1 - p_\mathrm{F}^2}\frac{\lambda_\mathrm{F}}{\sigma_\mathrm{F} S_\mathrm{F}} \tag{7}$$

where S_N and S_F are the cross-sectional areas of N and F materials, respectively, and λ_N, λ_F are the spin-diffusion lengths in both materials. Note that the spin resistance for F is defined differently than in Takahashi and Maekawa [21] as our definition provides simplified outgoing relations.

Interface resistances for up and down spin channels are defined as

$$R_{\mathrm{i},\uparrow/\downarrow} = 2R_\mathrm{i}(1 \mp P_\mathrm{i}) \tag{8}$$

where $P_\mathrm{i} = (R_{\mathrm{i},\downarrow} - R_{\mathrm{i},\uparrow})/(R_{\mathrm{i},\uparrow} + R_{\mathrm{i},\downarrow})$ is the spin polarization of the interface and R_i the interface resistance. Note that using this definition, the total resistance of the interface is $R_{\mathrm{i},\uparrow}^{-1} + R_{\mathrm{i},\downarrow}^{-1} = R_\mathrm{i}^{-1}(1 - P_\mathrm{i}^2)^{-1}$.

By solving Eqs. (1)–(3) in a 1D wire the expressions for $\mu_{\uparrow/\downarrow}$ and $j_{\uparrow/\downarrow}$ are

$$\mu_{\uparrow/\downarrow}(x) = \tilde{\mu} + \frac{j_\mathrm{ch} e}{\sigma}x \pm c\frac{\sigma}{\sigma_{\uparrow/\downarrow}}\exp\left[-\frac{x}{\lambda}\right] \pm d\frac{\sigma}{\sigma_{\uparrow/\downarrow}}\exp\left[\frac{x}{\lambda}\right] \tag{9}$$

$$j_{\uparrow/\downarrow}(x) = j_\mathrm{ch}\frac{\sigma_{\uparrow/\downarrow}}{\sigma} \mp c\frac{\sigma}{e\lambda}\exp\left[-\frac{x}{\lambda}\right] \pm d\frac{\sigma}{e\lambda}\exp\left[\frac{x}{\lambda}\right], \tag{10}$$

where $j_\mathrm{ch} = j_\uparrow + j_\downarrow$ is the charge current density. The positive current direction is towards the positive x direction. The energy coefficients c, d are the amplitudes of an exponential damping of $\mu_{\uparrow/\downarrow}$. The electrochemical potential $\tilde{\mu}$ provides an absolute shift of $\mu_{\uparrow/\downarrow}$ being $\tilde{\mu} = (\sigma_\uparrow\mu_\uparrow + \sigma_\downarrow\mu_\downarrow)/\sigma$. The values of $\tilde{\mu}$, c, d for each 1D wire (i.e. each branch of the structure) are determined by the following boundary conditions: everywhere in the structure $\sum_i j_{\uparrow/\downarrow}^{(i)} S^{(i)} = 0$ (current conservation) and $\mu_{\uparrow/\downarrow}^{(i)} = \mathrm{const}_{\uparrow/\downarrow}$ (continuity of electrochemical potential), where $^{(i)}$ denotes the number of a given branch connected to a given cross-section point. Furthermore, at the end points of the structure, $\mu_\uparrow = \mu_\downarrow$, and the values of currents are determined by external charge-currents flow and material polarizations.

The previously described propagation equations and boundary conditions lead to sets of linear equations with unknown variables $\tilde{\mu}^{(i)}$, $c^{(i)}$, $d^{(i)}$, $\mu_{\uparrow/\downarrow}^{(i)}$, $j_{\uparrow/\downarrow}^{(i)}$ at the end of each wire segment. These sets of equations were analytically solved, providing expressions for $\mu_{\uparrow/\downarrow}^{(i)}$, $j_{\uparrow/\downarrow}^{(i)}$ in any point of interest.

3. Numerical example of Cu/permalloy (Py) structure

In following, we discuss the spin polarization and the spin accumulation in various types of lateral spin structures. For those structures, we also provide numerical examples of spin-electrical behavior, which are calculated for permalloy (Py) as F and copper (Cu) as N, at temperature 4 K. Namely, the electrical conductivities are $\sigma_\mathrm{F} = 7.3 \times 10^6\ \Omega^{-1}\,\mathrm{m}^{-1}$, $\sigma_\mathrm{N} = 48.1 \times 10^6\ \Omega^{-1}\,\mathrm{m}^{-1}$, the spin diffusion lengths are $\lambda_\mathrm{F} = 4.3$ nm and $\lambda_\mathrm{N} = 350$ nm and the spin polarization of permalloy is assumed to be $p_\mathrm{F} = 0.4$ [22–24]. If not told otherwise, the cross-section of the lateral structure and the cross-section of the F/N contact are assumed to be $100 \times 100\ \mathrm{nm}^2$, i.e. the cross-section of the conductors and interfaces is $S_\mathrm{F} = S_\mathrm{N} = S_\mathrm{i} = 0.01\ \mu\mathrm{m}^2$. For these materials and geometry parameters, the spin resistances (Eqs. (6) and (7)) of permalloy and copper are $R_\mathrm{F} = 70.1\ \mathrm{m}\Omega$ and $R_\mathrm{N} = 728\ \mathrm{m}\Omega$, respectively (for $S_\mathrm{F} = S_\mathrm{N}$). Hence, $R_\mathrm{F} \ll R_\mathrm{N}$, which corresponds to conductivity mismatch [14], causing an ineffective spin injection. Note that conductivity mismatch happens for most currently used materials in the lateral structures. The charge current passing the structure is $I = 1$ mA. The parameters of the F/N interface, R_i and P_i, are usually free parameters in the numerical calculations. Note that for numerical calculations, the value of the interface resistance R_i is expressed in more common form as an interface specific resistance $AR_\mathrm{i} = S_\mathrm{i}R_\mathrm{i}$, where S_i is the cross section of the interface. In following, we use $S_\mathrm{i} = S_\mathrm{F}$, as the spin diffusion length of F, λ_F, is usually much smaller than typical lateral dimension of the structure. Therefore, the spin relaxation in F is basically an interface effect in the vicinity of the interface and hence the cross-sectional areas of the interface and of F equals.

All the calculations presented here are within one-dimensional approximation. Therefore, the actual values of spin current or spin accumulation can be different, due to potential inhomogeneous flow of spin current through the device. The inhomogeneous flow of charge and spin current is expected in following cases: the interface resistance is small, the cross-sectional area of the contact between F and N is large or the conductivities of F and N in the lateral nanostructures are different. For example, it was demonstrated for Py/Cu device (Py thickness 20 nm, Cu thickness 80 nm, transparent interface) [22] that the spin current is injected from Py to Cu within 30 nm distance from the Py/Cu edge. The currents' flows become more homogeneous when large interface resistance is introduced. The inhomogeneous flow can be approximately described in the one-dimensional approximation by introducing effective cross-section of the interface, defined as a cross-section through which most of the currents' flows.

4. Simple F/N interface

We start the discussion by a simple F/N interface, as sketched in Fig. 1(a). Applying boundary conditions at the interface, the analytical expressions of the spin polarizations and the spin