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Resonant spin-torque in double barrier magnetic tunnel junctions

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Abstract

Spin-torque effects were investigated in double barrier magnetic tunnel junctions of the form F1/I1/F/I2/F2 where F is a soft ferromagnetic layer, I1 and I2 are two tunnel barriers, and F1 and F2 are two ferromagnetic layers whose magnetization are pinned in-plane, in either antiparallel or parallel magnetic configuration. We show that for some particular thickness of the F layer, resonant effects take place in the F layer, which enhance the net spin-torque amplitude by more than an order of magnitude. The spin-torque was calculated as a function of distance from the barriers within the F layer. It has an oscillatory behavior with very large amplitude when the resonance conditions are fulfilled.

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Slonczewski already predicted in 1989 that the magnetizations of two ferromagnetic layers separated by a thin tunnel barrier feel an interaction at zero bias voltage resulting from the transfer of spin associated with the symmetric tunneling of spin-polarized electrons through the barrier [1]. Later, the possibility to switch the magnetization of a magnetic nanostructure or to excite spin-waves by a spin polarized current was predicted by Slonczewski [2] and Berger [3]. Due to the relatively large critical current density required to observed these phenomena ($j_c \sim 10^7\ \mathrm{A/cm^2}$), it has long been believed that these phenomena could only be observed in metallic nanostructures. Indeed, magnetic tunnel junctions are voltage-limited since they undergo electrical breakdown when the barrier is exposed to too large bias voltage (of the order of 1 V for a 1 nm thick barrier corresponding to a breakdown electrical field of the order of $10^9\ \mathrm{V/cm}$). Experimentally, it became possible to observe current induced magnetization switching when the technological progress in nanostructuration allowed tailoring magnetic pillars of dimension below 150 nm so that the effects associated with spin transfer were not hidden by the influence of the Oersted field due to the current density. Thus, the first experimental observations of current induced magnetization switching were obtained in 2000 in Co/Cu/Co pillars of lateral dimensions below 150 nm [4,5]. Since then, the phenomenon was observed and studied in many other systems including complex spin-valve stacks used in current-perpendicular-to-plane magnetoresistive heads [6].

More recently, thanks to the progress in the development of low resistance tunnel barriers (resistance area product below $10\ \Omega\,\mu\mathrm{m}^2$) with large TMR amplitude, some experimental groups succeeded to observe spin-torque effects in MTJ comparable to those observed in metallic spin valve pillars [7,8]. The critical current density for switching in MTJ was found to be of the same order of magnitude (5×10^6–$2 \times 10^7\ \mathrm{A/cm^2}$) as in their metallic counterparts. Various schemes are under investigation to try to reduce the critical current density for switching such as by using magnetic material with lower magnetization (for instance CoFeB), or by combining the effects of two reference layers in opposite magnetic states as suggested by Berger [9].

In this Letter, we propose another approach to drastically enhance the spin torque efficiency based on the use of reso-

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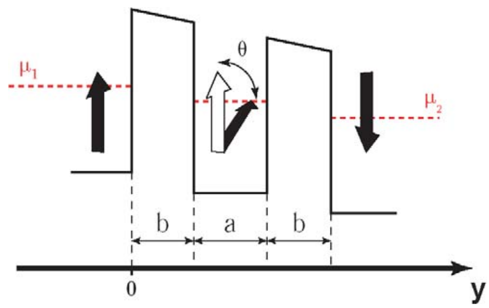

Fig. 1. Schematic representation of energy potential seen by the tunneling electrons in our model system.

nant effect in double barrier magnetic tunnel junctions. The systems we are interested in consist of a central free layer (F) sandwiched between two tunnel barriers (I1 and I2) themselves sandwiched between two ferromagnetic reference layers with in-plane magnetization (F1 and F2). In this geometry, the central free layer forms a spin-dependent quantum well. Under certain resonance conditions, we theoretically show that the electrical current as well as the spin current through the system can be drastically increased, yielding a correlative increase in the amplitude of the spin-torque acting on the magnetization of the F layer.

Our model system consists of two thick (semi-infinite) ferromagnetic electrodes (F1 and F2) connected to reservoirs with chemical potentials μ_1 and μ_2 and two nonmagnetic insulating tunnel barriers (I1 and I2) of thickness b separated by a thin free ferromagnetic layer (F) of thickness a (see Fig. 1). The magnetizations of the outer electrodes are assumed to be pinned in-plane in either antiparallel or parallel alignment and the magnetization of the middle layer makes an angle θ with the direction of the F1 magnetization supposed to be parallel to the z-axis. The y-axis is perpendicular to the plane of the layer. The x-axis is in plane, perpendicular to the y and z axes.

Using the "sd model" of free like conduction electrons interacting with localized d electrons responsible for the local magnetization, the one-electron Hamiltonian of the system in layer α can be written in the following form:

$$H^\alpha = \left(\frac{\hat{p}^2(r)}{2m} - U^\alpha\right) - \sum_n J_{\mathrm{sd}}^\alpha (r - R_n)\big(\hat{\sigma}\hat{S}_n^\alpha\big), \tag{1}$$

where $\hat{p}(r)$ is the momentum operator of the conduction electron, J_{sd} is the s–d exchange constant, $\hat{\sigma}$ are Pauli matrices and $\hat{S}_n$ is the operator associated with the localized spin situated at point R_n and responsible for the local magnetization. $J_{\mathrm{sd}}^\alpha = 0$ within the nonmagnetic tunnel barriers and $J_{\mathrm{sd}}^\alpha \neq 0$ inside the ferromagnetic layers. $\alpha = 1, 2, \ldots, 5$ refers to the index of the layers, U^α represents the energy associated with the bottom of the conduction band in the ferromagnetic layers ($\alpha = 1, 3, 5$) and the height of the barriers in the insulating layers ($\alpha = 2, 4$). The ferromagnetic layers are assumed to be in single domain states. The two outer layers (F1 and F2) are in antiparallel (parallel) magnetic configuration whereas the magnetization of the central one makes an angle θ with the F1 magnetization. The z-direction is chosen as the spin quantization axis for the two outer F-layers and the Pauli matrix $\hat{\sigma}$ in the central layer with tilted magnetization ($\alpha = 3$) has to be transformed by the usual matrix of rotation

$$\hat{T} = \begin{pmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}.$$

Finally, we consider that the electrons flowing from left (right) reservoirs are represented by Fermi distributions with chemical potentials μ_1 (μ_2) so that $\mu_1 - \mu_2 = eV$, where V is the applied voltage. The schematic picture of the potentials of the structure is shown in Fig. 1.

In order to calculate the electrical current and the components of the vectorial spin currents, we need to solve the Schrödinger equation and may use the expressions for the currents in terms of the transmission matrix (Landau formalism), which is nondiagonal in spin-space in the case of noncollinear alignment of magnetizations in the ferromagnetic layers.

However a more transparent way to calculate both currents and torques is to use the non-equilibrium Keldysh technique, which allows, in principle, to take into account elastic and inelastic processes of electrons scattering. The result of the investigation of the influence of the scattering on spin torque will be presented in a forthcoming paper. In the present Letter, elastic scattering in the F layer is not taken into account. In the following of the Letter, we will use the mean field approximation for the operator $\hat{S}^\alpha$, so that $\hat{S}^\alpha$ is considered as a classical vector: ($S^z = S_0 \cos\theta$, $S^x = S_0 \sin\theta$, $S^y = 0$).

In the case of absence of scattering processes, the Keldysh Green functions can be calculated in the simple form:

$$G^{-+}(r, r) = \begin{pmatrix} G_{\uparrow\uparrow}^{-+} & G_{\uparrow\downarrow}^{-+} \\ G_{\downarrow\uparrow}^{-+} & G_{\downarrow\downarrow}^{-+} \end{pmatrix}, \tag{2}$$

where

$$\begin{aligned} G_{\sigma\sigma'}(y, y') &= \int_\kappa n_L\big(\psi_L^{*\sigma(\uparrow)}(y,\kappa)\psi_L^{\sigma'(\uparrow)}(y',\kappa) \\ &\quad + \psi_L^{*\sigma(\downarrow)}(y,\kappa)\psi_L^{\sigma'(\downarrow)}(y',\kappa)\big)\,d\vec{\kappa} \\ &\quad + \int_\kappa n_R\big(\psi_R^{*\sigma(\uparrow)}(y,\kappa)\psi_R^{\sigma'(\uparrow)}(y',\kappa) \\ &\quad + \psi_R^{*\sigma(\downarrow)}(y,\kappa)\psi_R^{\sigma'(\downarrow)}(y',\kappa)\big)\,d\vec{\kappa}'. \end{aligned} \tag{3}$$

where n_L (respectively n_R) are the Fermi distribution functions for the left (respectively right) reservoir, $\psi_{L(R)}^{\sigma(\alpha)}(y,\kappa)$ is the spinor (index σ) wave function of the electron when an electron with spin α, energy E and momentum $\vec{\kappa}$ in xz-plane is injected from the left (right) reservoir. y is the coordinate perpendicular to the plane of the layers. We point out that for noncollinear alignment of the magnetizations in the ferromagnetic layers, the indexes σ and α may not coincide. This means that an electron with an initial spin index $\alpha = \uparrow$ (for example) undergoing partial reflection and partial penetration into the F-layer reaches an entangled state in which both $\uparrow$ and $\downarrow$ components are not equal to 0. The system of wave functions $\psi_{L(R)}^{\sigma(\alpha)}(y,\kappa)$ is a full and orthogonal system of eigenfunctions. The latter are normalized to the unit flow.