Physica B 495 (2016) 89–93

Contents lists available at ScienceDirect

Physica B

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

Charge and spin current oscillations in a tunnel junction induced by magnetic field pulses

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ARTICLE INFO

Article history:
Received 9 February 2016
Received in revised form
10 May 2016
Accepted 13 May 2016
Available online 14 May 2016

Keywords:
Magnetic tunnel junction
Spin current
Tunneling
Spin capacitance

ABSTRACT

Usually, charge and spin transport properties in tunnel junctions are studied in the DC bias regime and/or in the adiabatic regime of time-varying magnetic fields. In this letter, the temporal dynamics of charge and spin currents in a tunnel junction induced by pulsed magnetic fields is considered. At low bias voltages, energy and momentum of the conduction electrons are nearly conserved in the tunneling process, leading to the description of the junction as a spin-1/2 fermionic system coupled to time-varying magnetic fields. Under the influence of pulsed magnetic fields, charge and spin current can flow across the tunnel junction, displaying oscillatory behavior, even in the absence of DC bias voltage. A type of spin capacitance function, in close analogy to electric capacitance, is predicted.

The phenomenon of tunneling is one of the most remarkable features of quantum mechanics [1–4], awakening enormous interest from both scientific and technological perspectives [5–14]. For instance, it has been used in the electronics industry to build high speed devices, such as tunnel diodes and magnetic tunnel junctions (MTJ) [15–25]. A typical tunnel junction consists of two particle reservoirs (metallic, superconducting or semiconducting electrodes) separated by a potential barrier region, which is classically forbidden. Quantum mechanically, however, the particles wavefunctions are evanescent but non-vanishing inside the barrier, leading to a non-zero probability for a particle to traverse the barrier region, provided that the its energy height and spatial thickness are sufficiently small. In an MTJ the so-called tunneling magnetoresistance (TMR) is one or two orders of magnitude larger than the anisotropic MR in materials, leading to immediate applications in hard disks as magnetic reading heads. The time scales associated with electron's spin dynamics in ferromagnetic electrodes composing a MTJ are usually in the picosecond range, which is a few orders of magnitude smaller than the time scales related to the temporal variation of the magnetic fields applied to one or both sides of the MTJ in reading head applications. Nonetheless, a more complete knowledge of the spin dynamics in non-adiabatic regimes is of primary importance for the development of novel devices in spintronics, in which the spin currents will play the principal role [26–30]. The adequate techniques to inject, pump and control spin currents are not fully understood, in comparison with the manipulation of electric currents in semiconductor devices.

Considering the present context, it is our aim to investigate the quantum dynamics of charge and spin transport in a tunnel junction at low bias voltages, under the influence of pulsed magnetic fields applied to one of the sides the junction. The geometry of the proposed nanostructure is illustrated in Fig. 1. Two magnetizable electrodes are separated by a non-magnetic insulating barrier. The left and right electrodes are subjected to constant transverse magnetic fields, which can be set ut to be in parallel or anti-parallel configurations, while at the left side magnetic pulses can be injected. As will be shown, electric and spin currents set up even in the absence of a DC bias voltage, induced by the time-varying magnetic pulses, which unbalance the spin populations of both sides of the tunnel junction near the Fermi level, leading to an effective particle flow across the potential barrier in order to establish a dynamical equilibrium.

As the starting point, consider the simplest form of the tunnel junction hamiltonian, $\hat{H} = \hat{H}_L + \hat{H}_R + \hat{H}_T$, given in second quantized form:

$$\hat{H}_L = \sum_{\mathbf{p},\sigma} E^L_{\mathbf{p},\sigma} a^\dagger_{\mathbf{p},\sigma} a_{\mathbf{p},\sigma} + \sum_{\mathbf{p}} (\Delta_L a^\dagger_{\mathbf{p},\uparrow} a_{\mathbf{p},\downarrow} + h.\,c.\,), \tag{1}$$

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http://dx.doi.org/10.1016/j.physb.2016.05.017
0921-4526/

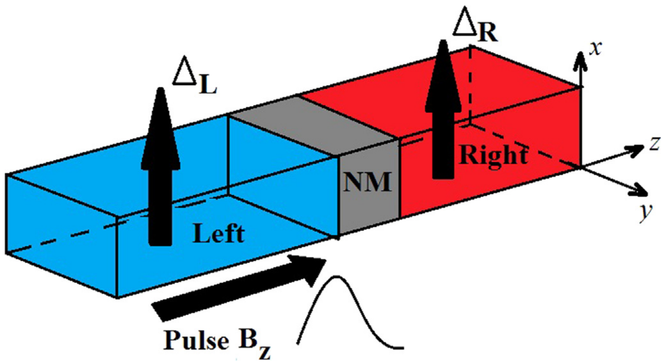

Fig. 1. Geometry of the magnetic tunnel junction to be studied here.

$$\hat{H}_R = \sum_{\mathbf{p},\sigma} E^R_{\mathbf{p},\sigma} b^\dagger_{\mathbf{p},\sigma} b_{\mathbf{p},\sigma} + \sum_{\mathbf{p}} (\Delta_R b^\dagger_{\mathbf{p},\uparrow} b_{\mathbf{p},\downarrow} + h.\,c.\,), \tag{2}$$

$$\hat{H}_T = \sum_{\mathbf{p},\mathbf{q},\sigma} (\gamma_\sigma a^\dagger_{\mathbf{p},\sigma} b_{\mathbf{q},\sigma} + \gamma^*_\sigma b^\dagger_{\mathbf{q},\sigma} a_{\mathbf{p},\sigma}), \tag{3}$$

where $\hat{H}_L\,(\hat{H}_R)$ is the hamiltonian of the left(right) side of the barrier and $\hat{H}_T$ is the transfer hamiltonian, responsible for the transport of particles across the junction, $a_{\mathbf{p},\sigma}\,(a^\dagger_{\mathbf{p},\sigma})$ is the annihilation (creation) fermionic operator for an electron of energy $E^L_{\mathbf{p},\sigma}$, momentum $\mathbf{p}$ and spin projection $\sigma = \uparrow, \downarrow$ respective to the z-axis at the left electrode (L), $b_{\mathbf{p},\sigma}\,(b^\dagger_{\mathbf{p},\sigma})$ stands for the annihilation (creation) operators at the right side electrode (R), $\Delta_L\,(\Delta_R)$ represents the energy due to the Zeeman coupling with a magnetic field perpendicular to the z-axis at the left(right) electrode, mixing the up and down spin projections, while γ_σ is the effective tunneling amplitude for electrons with spin σ flowing across the tunnel junction. At low bias the relevant physics occurs in the neighborhood of the Fermi level and we can safely assume that the hopping parameter is independent of energy and momentum, but can depend on the spin projection. Also, the transport processes with spin-flip are being neglected, since it is typically one or two orders or magnitude smaller than the spin-conserving tunneling. The electric and spin current operators, $\hat{I}_e$ and $\hat{I}_s$, respectively, are defined in the following way:

$$\hat{I}_e = -\frac{ie}{\hbar} \sum_{\mathbf{p},\mathbf{q},\sigma=\pm 1} (\gamma_\sigma a^\dagger_{\mathbf{p},\sigma} b_{\mathbf{q},\sigma} - \gamma^*_\sigma b^\dagger_{\mathbf{q},\sigma} a_{\mathbf{q},\sigma}), \tag{4}$$

$$\hat{I}_s = -\frac{ie}{\hbar} \sum_{\mathbf{p},\mathbf{q},\sigma=\pm 1} \sigma\,(\gamma_\sigma a^\dagger_{\mathbf{p},\sigma} b_{\mathbf{q},\sigma} - \gamma^*_\sigma b^\dagger_{\mathbf{q},\sigma} a_{\mathbf{p},\sigma}), \tag{5}$$

where $\sigma = +1\,(-1)$ corresponds to the up(down) spin projection. Notice that the charge and spin-polarized currents are being measured in the same physical units, for the sake of comparison.

In order to study charge and spin dynamics induced by Zeeman coupling of the electronic spins to external magnetic fields it is convenient to consider transport at very low DC bias voltage, such that the energies of tunneling electrons are around the Fermi levels and can be written approximately as $E^\alpha_{\mathbf{p},\sigma} \approx E^\alpha_F + \sigma\mu_B B^\alpha_z(t)$, where $\alpha = L, R$ denotes the electrode, $E_F{}^\alpha$ is the Fermi level of the electrode α and $B^\alpha_z(t)$ is the applied magnetic field at the electrode α, μ_B is the Bohr magneton. As a consequence, linear momentum of tunneling particles is nearly conserved, i.e., $\mathbf{p} \approx \mathbf{q}$ in Eqs. (3)–(5), which decouples the spin from the momentum degrees of freedom, leading to the description of a collection of spin 1/2 systems. The sums over momentum quantum numbers, $\mathbf{p}$ and $\mathbf{q}$, in Eqs. (4) and (5), for the charge and spin currents, respectively, can be replaced by the product of number of states calculated at the Fermi levels of both sides of the junction, i.e., $\sum_{\mathbf{p},\mathbf{q}} \to D^L_\sigma D^R_\sigma$. Going further, we drop out momentum quantum numbers from the operators and write down Nambu spinors:

$$\hat{\psi} = \begin{pmatrix} a_\uparrow \\ a_\downarrow \\ b_\uparrow \\ b_\downarrow \end{pmatrix}, \quad \hat{\psi}^\dagger = \begin{pmatrix} a^\dagger_\uparrow & a^\dagger_\downarrow & b^\dagger_\uparrow & b^\dagger_\downarrow \end{pmatrix}, \tag{6}$$

allowing us to rewrite the tunnel junction hamiltonian as follows:

$$\hat{H} = \hat{\psi}^\dagger (\hat{\mathcal{H}}_0 + \hat{\mathcal{V}}) \hat{\psi}, \tag{7}$$

where $\hat{\mathcal{H}}_0$ and $\hat{\mathcal{V}}$ are 4×4 matrices defined below:

$$\hat{\mathcal{H}}_0 = \begin{pmatrix} \mathbf{H}^L_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{H}^R_0 \end{pmatrix}, \tag{8}$$

$$\hat{\mathcal{V}} = \begin{pmatrix} \mathbf{V}^L & \mathbf{H}_T \\ \mathbf{H}^\dagger_T & \mathbf{V}^R \end{pmatrix}. \tag{9}$$

In the above expressions $\mathbf{H}^\alpha_0$, $\mathbf{V}^\alpha$ and $\mathbf{H}_T$ are 2×2 matrices, explicitly given below:

$$\mathbf{H}^\alpha_0 = E^\alpha_F \mathbf{1} - \mu_B B^\alpha_z(t)\sigma_z, \tag{10}$$

$$\mathbf{V}^\alpha = \Delta^\alpha_x \sigma_x + \Delta^\alpha_y \sigma_y, \tag{11}$$

$$\mathbf{H}_T = \gamma \mathbf{1} + \lambda \sigma_z, \tag{12}$$

$(\sigma_x, \sigma_y, \sigma_z)$ are the Pauli spin matrices, $\alpha = L, R$ denotes the electrode, $\Delta_\alpha = \Delta^\alpha_x - i\Delta^\alpha_y$, $\gamma = (\gamma_\uparrow + \gamma_\downarrow)/2$ is the average tunneling amplitude, $\lambda = (\gamma_\uparrow - \gamma_\downarrow)/2$ is the difference of the tunneling amplitude for up and down spins. Making use of one more definition:

$$\mathbf{D} = \begin{pmatrix} D^L_\uparrow D^R_\uparrow & 0 \\ 0 & D^L_\downarrow D^R_\downarrow \end{pmatrix}, \tag{13}$$

where D^α_σ is the number of states of spin σ at the electrode α, we can recast the charge and spin current operators into matrix form, as follows:

$$\hat{I}_e = -\frac{ie}{\hbar} \begin{pmatrix} \mathbf{0} & \mathbf{D}\mathbf{H}_T \\ -\mathbf{D}\mathbf{H}^\dagger_T & \mathbf{0} \end{pmatrix}, \tag{14}$$

$$\hat{I}_s = -\frac{ie}{\hbar} \begin{pmatrix} \mathbf{0} & \mathbf{D}\sigma_z\mathbf{H}_T \\ -\mathbf{D}\sigma_z\mathbf{H}^\dagger_T & \mathbf{0} \end{pmatrix}. \tag{15}$$

Analytical expressions can be obtained using perturbation theory for some particular situations, but they awkwardly fail to predict the correct quantum behavior at long time scales. Therefore, the problem is solved numerically, taking as a first step the calculation of the evolution operator $\hat{U}(t)$, which obeys the Schrödinger equation:

$$i\hbar \frac{\partial \hat{U}}{\partial t} = \hat{H}\hat{U}. \tag{16}$$

Next, the density matrix is calculated directly as $\hat{\rho}(t) = \hat{U}\hat{\rho}_0\hat{U}^\dagger$, being $\hat{\rho}_0 = e^{-\beta\hat{H}}/Z$ the initial condition in the canonical ensemble,