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Macroscopic Model of Current-induced Magnetic Switching Effect in Pseudo-spin-valve Structure

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1. Introduction

The magnetization configuration of a pseudo-spin-valve (**PSV**) is switched conventionally by an external magnetic field. An alternative mechanism to switch the magnetization of a nano-scale PSV (less than 100 nm in diameter) by a spin-polarized current was proposed by Slonczewski [1] and Berger [2] in 1996, which provided a novel proposal of magnetic random access memories operated only by current [3]. Many experiments have confirmed the current-induced magnetic switching (**CIMS**) effect. Slonczewski's early theory [1] believed that **CIMS** originated from the spin dependent reflection at the ferromagnetics/nonmagnetics (**FM/NM**) interface. Heide *et al.* [4] realized the contribution of the spin accumulation in FM. However, recent experiments [5] have demonstrated that both of the two factors contribute to **CIMS** effect. In this paper, we proposed a macroscopic phenomenological model of **CIMS** in a Co/Cu/Co PSV，which incorporates the ballistic spin-dependent scattering and reflection at the Co/Cu interfaces, and the diffusive relaxation of spin accumulation within the free layer. Guo *et al.* believed that only transverse relaxation was the crucial factor in their ballistic-diffusive model [6]. However, we considered that transverse and longitudinal relaxations were indivisible and interdependent and should be considered as a whole. The simulation based on the model was accomplished under four different initial configurations, and the results were consistent with the experiments reported.

2. Model Description

Electron transportation through the spacer layer is assumed to be ballistic, without spin-flip scattering. The free layer is regarded as a single magnetic domain because of its nano-scale elliptic cross section. The origin of **CIMS** is the "*s-d*" interaction between conduction electrons' spins (**m**) and the local moments ($\mathbf{M_L}$) of free layer, which leads to a spin torque on $\mathbf{M_L}$ and consequently a rotation of $\mathbf{M_L}$ [6]. However, what we focused on was the movement and reversal of the whole magnetization, including **m** and $\mathbf{M_L}$. Therefore the complicated details of the internal interaction were not taken into account in our model, and both **m** and $\mathbf{M_L}$ were regarded as an equivalent macro-spin **M**. That is rational because of the single magnetic domain assumption. The variety of **M** can be traced by the dynamic equation as follows,

$$\frac{dM}{dt} = -\frac{\mu_B}{e}(\eta_1 - \eta_2)I - \frac{M - M_0}{\tau} \quad (1)$$

Where M_0 is the initial value of equivalent macro-spin, τ is the spin relaxation time, μ_B is Bohr magneton, η_1 and η_2 are spin current polarization in the spacer layer and top electrode (Cu), respectively. The variety of **M** is resulted from two items, (a) spin relaxation in the free layer, and (b) difference between the spin currents flowing into and out of the free layer, which is proportional to the spin torque. The value of $\eta_{1(2)}$ is not identical when the current direction alters, owing to the spin dependent scattering at two FM/NM interfaces and current polarizing in magnetic layers. $\eta_{1(2)}$ depends on three parameters, β (it is introduced to represent the influence of spin dependent scattering and its value can be inferred from transmission/reflection matrix.), η_0 (intrinsic polarization of FM layers) and $M/|M_0|$ (variety ratio of **M**). The magnetization of free layer is reversed only if the sign of **M** changes under steady state. Steady-state solution of Eq.1 is as follows, under the condition of $dM/dt = 0$.

$$M = M_0 - \frac{\mu_B}{e}(\eta_1 - \eta_2)I\tau \quad (2)$$

At the same time, the critical current I_C is obtained when the magnetization is reversed ($M \le 0$),

$$I_c = \frac{M_0 e}{\mu_B(\eta_1 - \eta_2)\tau} \quad (3)$$

3. Simulations and Discussions

Four different initial configurations (Fig.1) were analyzed for a Co(3nm)/Cu(4nm)/Co(20nm) PSV, with the parameters： η_0=0.3, β=0.24, τ=10^{-9}s and M_s=1.6A/m (saturation magnetic moment of cobalt). Figure 2 denotes the normalized **M** under steady state as a function of applied current. **M** can be reversed only by negative current for antiparallel (**AP**) initial configuration, and $I_C^{AP\text{-}P}$ = -2.15 $\times 10^7$ Acm^{-2}. On the contrary, **M** can be reversed only by positive current for parallel (**P**) initial configuration, and $I_C^{P\text{-}AP}$=2.87$\times 10^7$ Acm^{-2}. The results are in agreement with experiments reported [7].

Figure 3 shows the relations between the critical current and the parameters. The magnitudes of $I_C^{AP\text{-}P}$ and $I_C^{P\text{-}AP}$ depend on η_0 and β, respectively; and the magnitudes of them are both inversely proportional to τ. The absolute value of $I_C^{P\text{-}AP}$ is larger than that of $I_C^{AP\text{-}P}$ because of $\eta_0 > \beta$ in general. Therefore, we inferred that the spin accumulation and relaxation in the free layer played an important role in **AP-P** switching, and the spin dependent scattering at the interface of the fixed layer and the spacer layer is the primary factor in **P-AP** switching. Larger η_0, β and τ are helpful to reduce the critical current.

4. Conclusions

We provided a macroscopic ballistic-diffusive model of **CIMS** effect in a Co/Cu/Co PSV and simulated the movements of free layer's magnetization under four different initial configurations. Our model is consistent with most of the experiments and instructive to improve the device performances. The corresponding experiment studies are being carried out.

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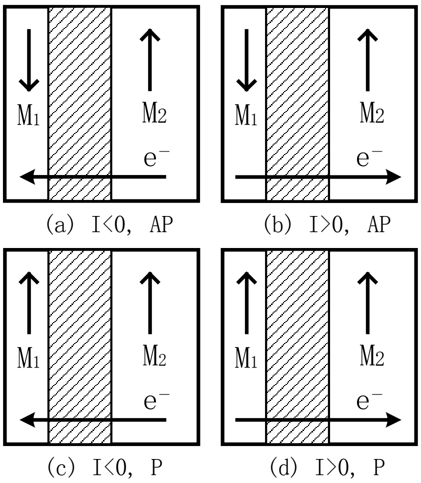

Fig. 1 Four different initial configurations as above were analyzed. $\mathbf{M_1}$ and $\mathbf{M_2}$ denote the initial magnetizations of the free layer and the fixed layer, respectively. The current is defined as positive when electrons flow from the free layer to the fixed layer.

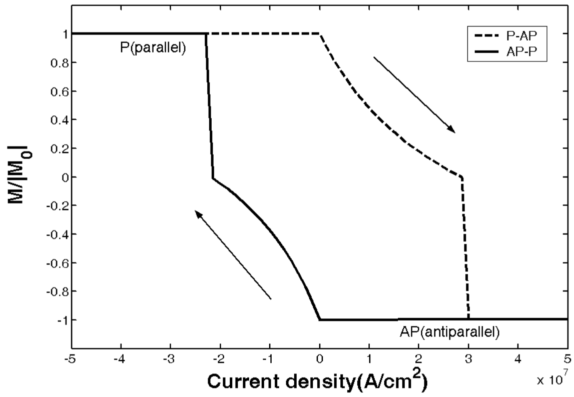

Fig. 2 Normalized equivalent macro-spin of the free layer under steady state, calculated as a function of applied current. **M** is defined as positive when the magnetizations of the free layer and the fixed layer are parallel. **M** reverses when the current exceed the critical value I_C, and $|I_C^{P\text{-}AP}| > |I_C^{AP\text{-}P}|$.

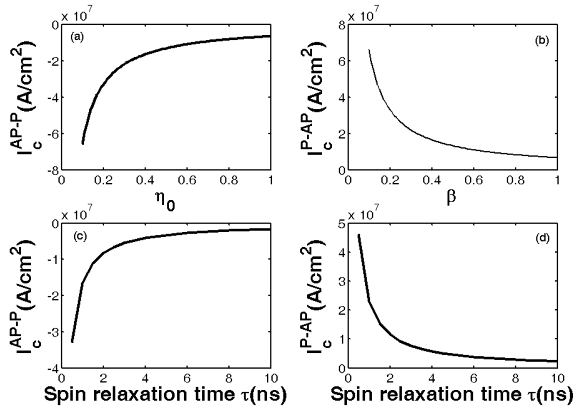

Fig. 3 Relations between the critical current and the parameters: η_0, β and τ.

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