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Effect of Spin Memory Loss at Interface of Ferromagnet and Normal Metal on Spin-Transfer Torque

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The spins of conduction electrons are filtered when an electrical current passes through a structure consisting of normal metal (NM) / ferromagnet (FM)/ NM because the reflection probabilities at the interface are spin-dependent. The filtered spin-flow, spin-polarized current, exerts a torque on the noncollinear magnetization of the neighboring second FM, i.e. spin-transfer torque (STT), resulting in a new class of magnetization dynamics [1, 2].The STT attracts a considerable interest because of its rich physics and potential for the applications such as the current-induced magnetization switching, microwave oscillation, and domain wall motion. Both from the fundamental standpoint and, in view of application, it is important to *quantitatively* estimate the magnitude and angular dependence of STTfor a spin valve structure.

Several theoretical models to estimate STThave been proposed; spin diffusion theory [3-7], circuit theory [8, 9], the Boltzmann equation [10, 11], and microscopic quantum mechanical theory [12]. Each theoretical approach has advantages and disadvantages at the same time. For instance, the spin diffusion theory used in this work provides an analytical solution, which is a great advantage, but has shortcomings such as idealization of the Fermi surfaces, impossibility to differentiate the differences between electrons propagating in different directions, and ignoring the spin-flip scattering at interfaces. However, the spin diffusion theory was found to be successful in at least *qualitatively*predicting the angular dependence of STT, verified in the recent experiment corresponding to the so-called "wavy STT" [13].

In spite of the *qualitative* agreement between the experimental result and the present spin diffusion theory, a *quantitative* estimate of STTis highly desired for the application of the current-induced magnetic excitation. To realize this, the shortcomings listed above should be resolved. In this work, we relaxed one of the shortcomings of the present spin diffusion theory related to the spin-flip scattering at interfaces, i.e. spin memory loss. We developed a novel spin diffusion model where interface layers are replaced by *virtual* bulk layers. In our model, it is possible to describe the spin-filp rate at the interface by introducing a finite spin-flip length in the *virtual* bulk layer. We verified our model by comparing with the model used for the "wavy STT" in Ref. [13] assuming no spin memory loss at the interfaces, and found perfect agreement when we also ignored the spin memory loss.

We investigated the effect of spin memory loss on the STT. We found the spin memory loss significantly affects the magnitude and angular dependence of STT. One striking result is that the

STT is not perfectly diminished although the spin memory loss is 90%, i. e. most spins are flipped when passing through the interface. It was found that the spin memory loss modifies the angular dependence of STT. The STT at the parallel magnetic configuration (P) is smaller than that at the anti-parallel configuration (AP) when the spin memory loss is negligible, resulting in the well-known asymmetric switching current density Jc, i.e. $Jc^{P} > Jc^{AP}$. The $STT^{P}(STT^{AP})$ increases (decreases) with increasing the spin memory loss because of a different role of the spin memory loss on the transverse component of the spin accumulation. When the spin memory loss is high, the switching current densities between P and AP state is reversed, i. e. $Jc^{P} < Jc^{AP}$. We compared the Jc^{P}/Jc^{AP} obtained from our model with the experimental results using Cu/Py/Cu/Py spin valve structure at 4 K [14]. A best fit was obtained at the spin memory loss of 31% which is in good agreement with experimentally determined spin memory loss by using giant magnetoresistance (GMR) measurement [15]. Our results evidence the close relation between GMR and STT.

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