PS-12-1

Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp400-401

Anti-Damping Torque Engineering in Trilayer Spin-Hall System

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Abstract

Anti-damping torque on free-layer and Gain factor has been comprehensively appraised for a trilayer system with perpendicularly magnetized free-layer, heavy metal (HM) with strong spin-hall effect and ferromagnetic insulating substrate. The design optimization has furthermore been discussed. The system is observed to have much larger gain and torque compared to bilayer system (or with non-magnetic substrate), especially for thin HM which would enable faster switching at yet lower current in spin-orbit torque (SOT) devices like SOT-RAM and SOT based non-volatile logic.

1. Introduction

Strong spin-orbit coupling (SOC) in certain heavy metals (HM) enables switching [1] of adjacent perpendicularly magnetized ferromagnetic metals (FM_M) via in-plane spin-polarized current (Rashba-Effect RE) and transverse pure spin-current (Spin-Hall Effect SHE), with much less charge current than required for non-collinear spin-transfer torque (STT) devices [2]. The spin-orbit torque (SOT) is thus an extremely promising technique for next-generation of non-volatile memories and logic. Although both Rashba and SHE produce field-like (Tx) and anti-damping (Ty) torque, former dominates in RE while later one in SHE. The Ty induced by SHE scales directly with the charge current density through HM and its spin-hall angle, while the charge current required for switching and the switching-speed scales with the Gain factor or SHE efficiency [3] (proportional to Ty and $\text{FM-M}_{width}/\text{HM}_{thickness}$). Therefore, improving the torque transferred to FM_M and the gain factor enables switching at even lower currents and /or at higher speeds.

The bilayer system (FM_M-HM) [4] forces spin-current to zero at surface opposite (bottom) to FM_M-HM (top), which for thin HM lowers the spin-current acting on FM_M because of the reflection from the bottom surface. Larger thickness although improves spin-current, lowers the gain because torque scales with HM thickness t_H as $1\text{-sech}(t_H/\lambda_{sf\_HM})$ [5] (λ_{sf_HM} is spin-diffusion length in HM).

In this work, we propose a scheme of engineering anti-damping torque Ty in a trilayer system with magnetic insulating substrate FM_I. The magnitude of Ty, percentage change in Ty with respect to bilayer SHE system (which is equivalent to having trivial substrate) and Gain are comprehensively examined to elucidate the benefits of magnetized substrate, which can be extremely large for thin HM.

2. Methodology

Fig. 1 illustrates the trilayer system with heavy metal (HM) having strong SHE sandwiched between FM_M and FM_I. FM_M would be the perpendicularly magnetized $\mathbf{m_M}$

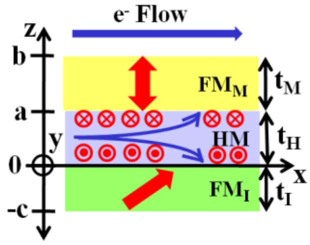

Fig. 1. Schematic of a trilayer spin-hall effect (SHE) system. Heavy metal (HM) with strong spin-hall effect (SHE) is sandwiched between ferromagnetic metal (FM_M) and ferromagnetic insulator (FM_I) substrate with magnetization vectors $\mathbf{m_M}$ and $\mathbf{m_I}$ respectively. Electron current (*Jc*) along x-axis generates spin current (*Js*) along z-axis to switch FM_M magnetization. Boundary Conditions: *Js* is zero at z = *b* and −*c* surfaces, ***Js*** and spin accumulation (***S***) is continuous at z = 0 and *a* surfaces. System is assumed to be homogeneous along x and y-axis, with same length and width for simplicity.

(along z-axis) free-layer in SOT devices, switched via spin-current J_S (y-polarized) generated transverse (along z-axis) to charge current J_C (along x-axis) through HM, while FM_I acts as an insulating substrate to HM which can be trivial (non-magnetic), as in systems studied until now or magnetized $\mathbf{m_I}$ as suggested in this work. FM_I magnetization regulates the torque acting on FM_M by controlling the spin current reflected from HM-FM_I interface. The analytical solution for spin current vector ($\mathbf{J_S}$), spin accumulation dynamics (**S**) and torque (**T**) [4] has been derived and examined for four stable configurations of $\mathbf{m_I}$ i.e. non-magnetic, magnetized along x-axis, y-axis or z-axis.

3. Results and Discussion

Figure 2 shows large improvement in both anti-damping torque Ty (up to ~1500%) and Gain (up to 10 times), especially for smaller thickness of HM. Although, anti-parallel configuration between FM_M and FM_I gives the best results, since $\mathbf{m_I}$ is expected to be fixed in a system while $\mathbf{m_M}$ is switched, it will give asymmetric performance (compare black with dashed olive green line). Hence, FM_I magnetization along transport direction (x-axis) is recommended whose performance is only slightly inferior to anti-parallel but better than parallel configuration. Moreover, it has the symmetric behaviour w.r.t $\mathbf{m_M}$ along + or – z-axis (not shown). **Figure 3** shows that firstly the presence of magnetized FM_I universally improves the performance, and secondly it saturates for larger thickness of magnetic metal FM_M and substrate FM_I indicating the robustness of the suggested scheme which can be extended to thicker materials. **Figure 4** illustrates that the magnitude of torque Ty and hence Gain directly scales with diffusion coefficient of FM_M (see eq. (5) of Ref. FM_M (see eq. (5) of Ref. [4]. It is also observed that relative improvement in Ty w.r.t trivial

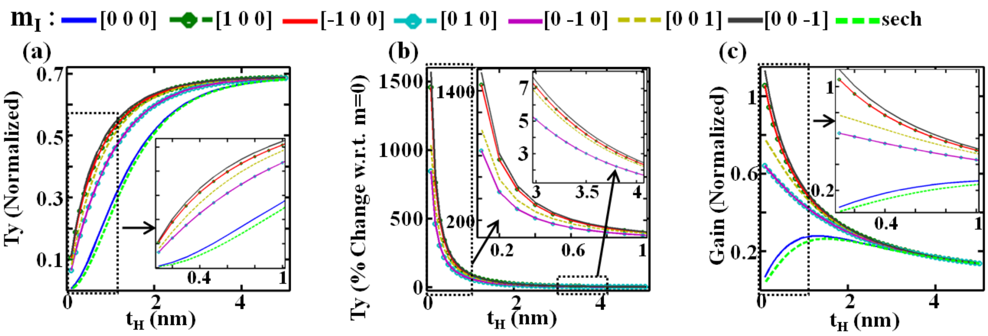

Fig. 2. Effect of HM thickness on anti-damping torque T_y (a), percentage change in T_y with respect to (w.r.t.) trivial substrate (b) and Gain (c) for different $\mathbf{m_I}$ of FM_I stated over the figure. Dashed lime-green line is for 1-sech(tH/λ_{sf}) [5] behaviour of bilayer system and dark blue is numerical solution for trilayer system with trivial substrate for reference. The insets show the zoom-in of region in dashed box. All three regions are assumed to be having same diffusion coefficient i.e. $(D_{FM\text{-}M} = D_{FM\text{-}I})/D_{HM} = 1$ [5].

substrate also improves with the relative diffusion coefficient w.r.t HM. The improvement for small D_{FM}/D_{HM} is still extremely high for very thin HM.

Design Optimization: Large Ty is obtained for thick HM at which the performance benefits of magnetized substrate are nearly lost, but the gain degrades for such large t_H, which is maximum at $t_H \sim 1.5\ \lambda_{sf\_HM}$ for trivial substrate and scales inversely with t_H for magnetized FMI. The search for optimal design complicates further with the effect of thickness on current and current density through HM. Typically conductivity of HM is much higher than of FMM and FMI, holding our assumption of constant current through HM. But for very thin HM t_H has dual effect on current distribution (direct and via conductivity) the analysis of which is strongly material specific, and accounted as a scaling factor for charge current in eq. 2 of Ref. [4]. The optimal design is therefore expected to be one of moderate thickness with x-magnetized substrate that provides much larger Ty and Gain for SHE based switching of FM_M.

4. Conclusion

We have examined the anti-damping torque and gain factor in trilayer spin-hall system with ferromagnetic insulating substrate whose magnetization controls the spin-current through heavy metal and the subsequent torque on free-layer. Extremely large performance improvement has been observed, especially for systems with thin HM.

Acknowledgments: This work at the National University of Singapore was supported by MOE under Grant. R263000B10112 and NRFCRP12-2013-01.

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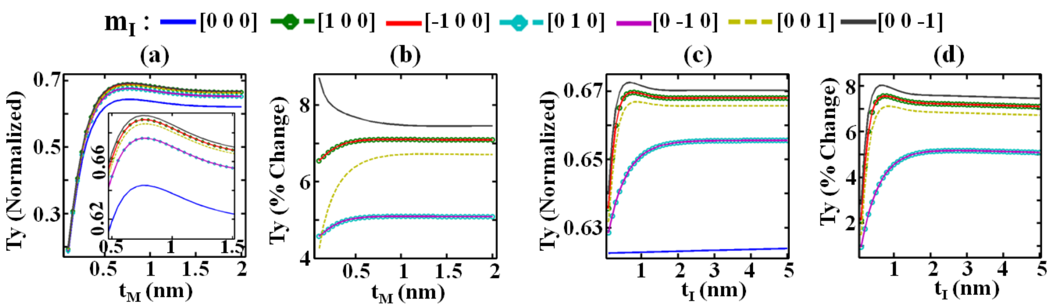

Fig. 3. Effect of FM_M and FM_I thickness on the anti-damping torque T_y (a, c) and on the percentage change T_y (b, d), over a range of $\mathbf{m_I}$. Insets for (a) show the zoom-in for smaller range of t_M.

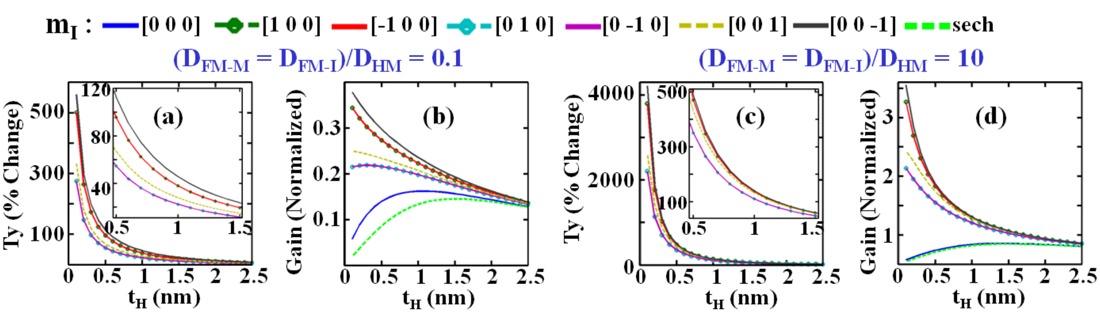

Fig. 4. Effect of Diffusion coefficient of ferromagnetic materials w.r.t D_{HM} (set to one) on the percentage change in anti-damping torque T_y (a, c) and Gain (b, d), over a range of HM thickness (t_H) and FM_I magnetization $\mathbf{m_I}$. For $D_{FM\text{-}M} \neq D_{FM\text{-}I}$ but in range of 0.1 to 10 D_{HM}, the T_y and Gain lie within the range illustrated above. Insets for (a, c) show the zoom-in for smaller range of t_H.