Journal of Magnetics 14(4), 168-171 (2009) DOI: 10.4283/JMAG.2009.14.4.168

Spin Torque Nano-Oscillator with an Exchange-Biased Free Rotating Layer

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(Received 9 November 2009, Received in final form 2 December 2009, Accepted 10 December 2009)

We propose a new type of spin torque nano-oscillator structure with an exchange- biased free rotating layer. The proposed spin torque nano-oscillator consists of a fixed layer and a free rotating layer with an additional anti-ferromagnetic layer, which leads to an exchange bias in the free rotating layer. The spin dynamics of the exchange-biased free rotating layer can be described as an additional exchange field because the exchange bias manifests itself by the existance of a finite exchange bias field. The exchange bias field plays a similar role to that of a finite external field. Hence, microwave generation can be achieved without an external field in the proposed structure.

Keywords : spin transfer torque, microwave oscillator, anti-ferromagnetic layer, exchange bias

1. Introduction

Since the spin transfer torque (STT) has been predicted theoretically and observed experimentally [1, 2], many applications have been proposed, such as STT magnetoresistive random access memory [3], domain-wall-motion-based shift memory [4, 5], and spin torque nano-oscillator (STNO) [6, 7]. The STNO is a promising device for microwave oscillators because it can be integrated with current semiconductor electronic devices [8]. The superior benefits of the STNO, such as small size (< 1 μm^2), wide tunable resonance frequencies in the GHz region, and high quality factor (>1000) compared to conventional microwave oscillators, has prompted active study. Microwave generation can be achieved when the spin direction of the free layer prefers a single direction by an external field, whereas it prefers another direction by STT. When the effects of STT and an external field compete, the free-layer spin oscillates, causing an oscillation of the resistances due to magnetoresistance, which depends on the relative orientations between the fixed and free layer magnetization. Therefore, STT and an external field are essential ingredients for microwave generation [9]. However, in the point of view of integration to current semiconductor electronic devices, the requirement of an external magnetic field is a burden to the STNO. Therefore, the operating mechanism of a STNO without an external field is very important. Recently, Boulle *et al.* [10, 11] proposed a STNO with a wavy angular dependence of the STT, and successfully realized microwave generation without an external magnetic field. However, very careful design of the layer structure is needed to obtain a wavy angular dependence of the STT, and the margins of the possible structure are quite narrow. Other zero-field oscillator ideas have been proposed by employing a perpendicular anisotropy fixed layer with an in-plane free layer [12], and utilizing the vortex structure [13].

This paper proposes a new type of STNO structure, which can generate microwaves without an external magnetic field [14]. The proposed STNO structure consists of a fixed layer and free rotating layer separated by a non-magnetic metal or insulating layer like a conventional STNO structure. The main difference in the new structure is the free rotating layer. The free rotating layer has an additional anti-ferromagnetic (AFM) layer (Fig. 1), the role of which is clear. The spin dynamics of the exchange-biased system can be described by additional unidirectional anisotropy, which is equivalent to the existence of an additional exchange bias field, H_{ex}. This is the main idea of this study. The external magnetic field can be replaced with an exchange bias field when an AFM layer is added to the free rotating layer. This idea was confirmed by solving the macro-spin Landau-Lifshitz-Gilbert (LLG) equations for the given structures.

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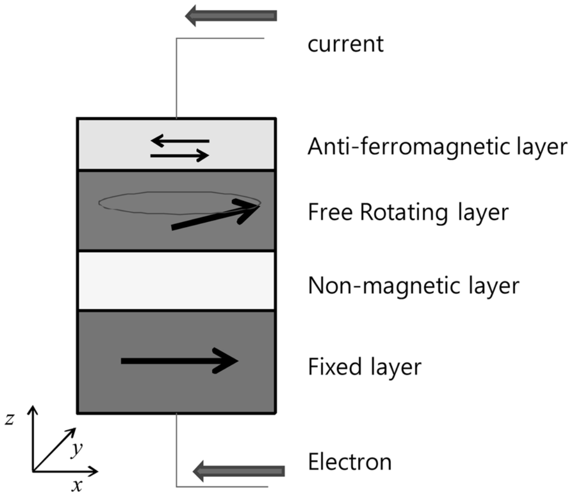

Fig. 1. Schematic diagram of the proposed spin torque nano-oscillator structure with a corresponding coordinate system. The direction of the current is shown with the electron flow.

2. Spin Dynamics Model

Consider multilayer stacks with a fixed ferromagnetic layer, non-magnetic layer (NM), and a free rotating ferromagnetic layer (FR), as shown in Fig. 1. The thickness of the FR is d. Here it was assumed that the magnetization direction of the fixed ferromagnetic layer is the $+x$ direction and rigid. Hence, only the spin dynamics of FR were considered. The positive current means the electron flows from the fixed layer to the FR. The FR prefers a parallel configuration with the fixed layer.

First, the conventional STNO without an AFM layer will be discussed. Fig. 2 gives a schematic phase diagram of the spin dynamics for the external current and magnetic field [9]. In the phase diagram, P (parallel) and AP (anti-parallel) denote each stable configuration. The P/AP states are hysteresis regions. Small and large angles indicate the rotation of the FR layer spin with a small and large orbital, as shown in the insets. The out-of-plane region means the spin precesses with full circular motion. The J_c and H_c correspond to the critical current density and coercivity field, respectively. As shown in the phase diagram, microwaves can be generated only when the condition, $H > H_c$, is satisfied.

Consider the STNO with AFM layer, as shown in Fig. 1. The spin dynamics of the FR can be examined by macro-spin LLG equations with STT as follows:

$$\frac{d\vec{M}}{dt}=\gamma\vec{M}\times(\vec{H}_{eff}+b_J\vec{P})+\frac{\alpha}{M}\vec{M}\times\frac{d\vec{M}}{dt}-\frac{\gamma a_J}{M}\vec{M}\times(\vec{M}\times\vec{P})\,. \tag{1}$$

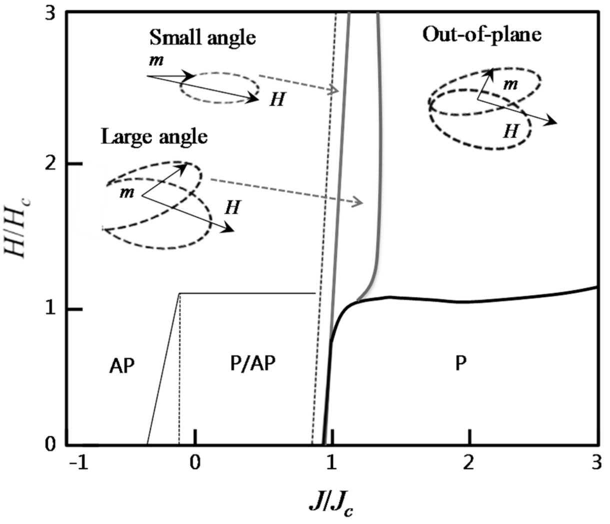

Fig. 2. Schematic phase diagram of the current and magnetic field for a conventional STNO. P (parallel) and AP (anti-parallel) stands for the stable configuration. The P/AP states are the hysteresis region. The small and large angle indicates the rotation of the FR layer spin with a small and large orbital. The out-of-plane region means the spin precess with full circular motion. The J_c and H_c correspond to the critical current density and coercivity field, respectively.

Here, $\vec{H}_{eff}$ is the effective field in the FR including the external, anisotropy, demagnetization, and exchange fields. α, γ and $\vec{P}=(1,0,0)$ are the Gilbert damping parameter for the FR, gyromagnetic ratio, and unit vector of the fixed layer magnetization direction, respectively. a_J is so called the Slonczewski term and is defined as $a_J=\eta_p\hbar J/2e\mu_0 Md$, where η_p, μ_0, e, M, d, and J are the spin torque efficiency, permeability, electron charge, magnetization and thickness of FR, and current density, respectively. b_J is a field-like term. The role of b_J is negligible in fully metallic nanopillars, while it is important in magnetic tunnel junction devices because of the different contributions of the Brillouin zone integral [15]. Therefore, the detailed spin dynamics and switching current density might depend on b_J. Furthermore, the oscillation condition also can be affected. However, it was assumed that the effect of b_J is not important in this study, so b_J was set to 0 for simplicity. If the crystalline anisotropy and magnetostatic coupling between the fixed and free layer is ignored, the effective field can be written as $\vec{H}_{eff}=\vec{H}_{ext}-\vec{N}\cdot\vec{M}+\vec{H}_{ex}$, where $\vec{H}_{ex}$ is the exchange bias field, and $\vec{N}=(N_x, N_y, N_z)$ are demagnetization vectors for the FR layer, and $N_x < N_y << N_z \sim 1$ for a typical free layer geometry. Consider a nanopillar geometry of $100\times 50\times 2$ nm^3, and demagnetization factors of $N_x = 0.0168$, $N_y = 0.0266$, and $N_z = 0.9566$, which were calculated for an corresponding ellipsoid [16]. The typical hysteresis loops without and with exchange bias are sketched in Fig. 3(a) and (b) with the

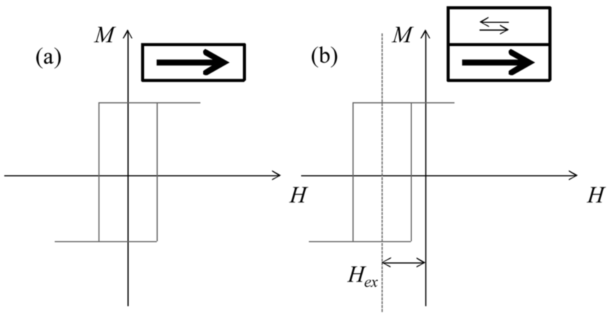

Fig. 3. Schematic hysteresis loops for (a) without and (b) with anti-ferromagnetic layer. The hysteresis loop is shifted to the left by H_{ex} due to the exchange bias.

definition of $\vec{H}_{ex}$ [17]. Fig. 3(b) clearly shows the role of the exchange bias due to the AFM. The detailed physics of the effect of the exchange bias is much more complicated: increase in coercivity, asymmetric switching mechanism, training effect, etc [18, 19]. However, this study focused on the effect of the exchange bias field. The magnitude of $H_{ex}=J_{ex}/Md$ can be controlled by the thickness of the ferromagnetic layer d and J_{ex}, the exchange energy between the ferromagnetic and AFM layer. H_{ex} typically ranges from 10~1000 Oe. The macro-spin LLG equations were solved with $M = 1.1 \times 10^6$ A/m for the FR layer, $\alpha = 0.01$, and $\eta_p = 0.7$. More details of the numerical calculations are reported elsewhere [20].

3. Results and Discussions

Fig. 4(a) shows the dynamics of the normalized M_x as a function of time for zero exchange bias without an external field. At $t = 0$, we set $\vec{M} = M(-1, 0.02, 0)$, and the current pulse was switched on. After switching on the current, the macro-spin LLG equations were solved, and the motion of the FR magnetization dynamics were recorded. In the smaller $J < J_c$ (=1.0×10^{11} A/m^2, critical current density) case, switching did not occur and the magneti-

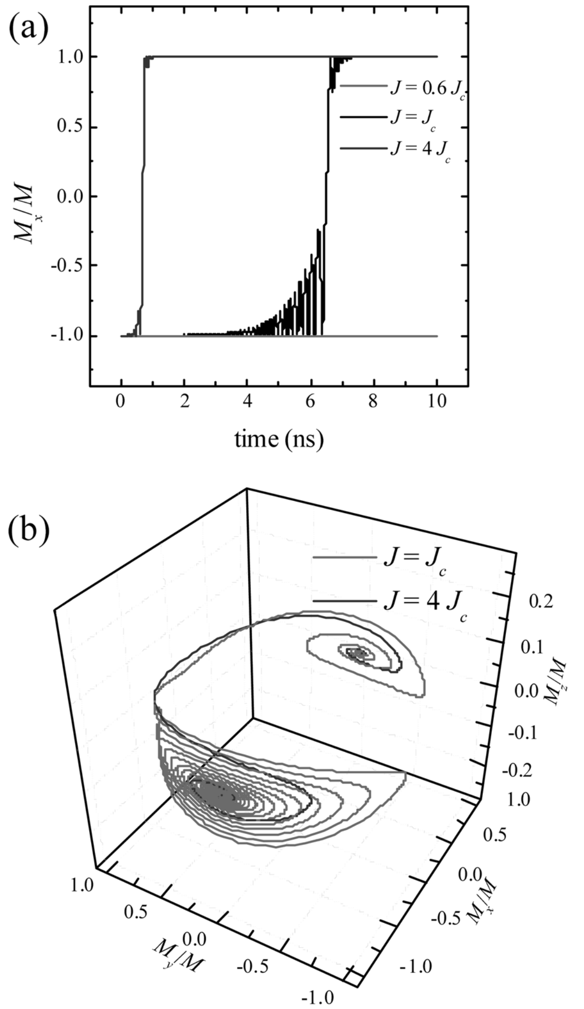

Fig. 4. (a) M_z/M as a function of time for $J = 0.6J_c$, J_c, and $4J_c$ for zero H_{ex} and H_{ext}. (b) Three dimensional trajectories of $J = J_c$ and $4J_c$, respectively.

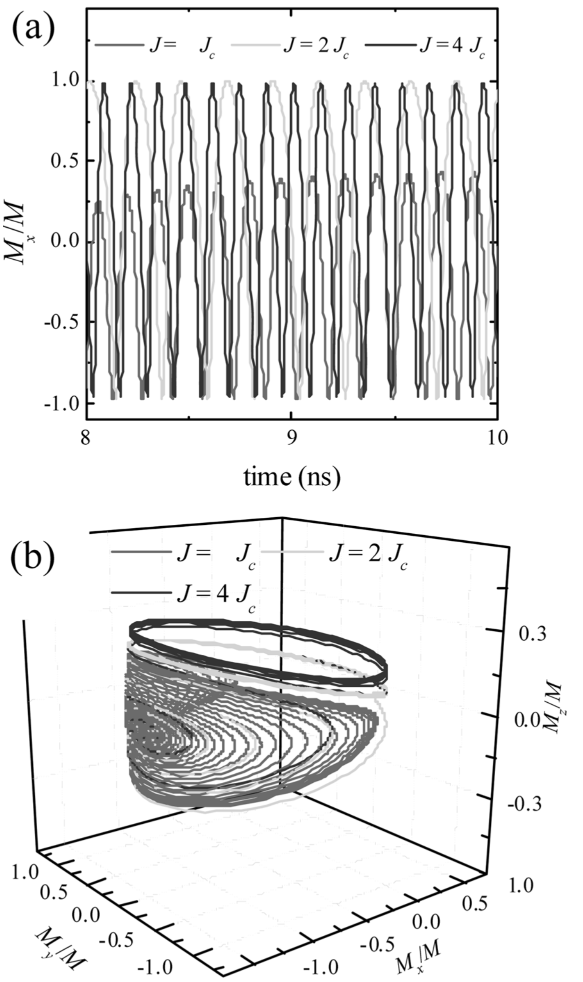

Fig. 5. (a) M_z/M as a function of time for $J = J_c$, $2J_c$, and $4J_c$ for $H_{ex} = -200$ Oe and zero H_{ext}. (b) Three dimensional trajectories of $J = J_c$, $2J_c$, and $4J_c$.

zation damped to the easy axis. When $J = J_c$, the magnetization switched after a few nanoseconds. During switching, the spin precessed for a while, and was finally switched. When $J = 4J_c$ was applied, switching occurred more rapidly with smaller precession. In Fig. 4(b), the three dimensional spin dynamics trajectories are plotted for the $J = J_c$ and 4 J_c cases. As expected, there were no steady precessions without an external field even for a large current density. Only faster switching occurs at a larger J.

Next, the $H_{ex} = -200$ Oe ($> H_c = 140$ Oe) case was considered, where, H_c was determined by a separate macro-spin LLG calculation without STT. Fig. 5(a) shows time dependent normalized M_x dynamics for the $J = J_c$, $2J_c$, and $4J_c$ cases, and (b) shows the same results along with their three-dimensional trajectories. For the $J = J_c$ case, switching does not occur due to the finite H_{ex}, which prefers an anti-parallel state while STT enforces a parallel state. Instead of switching, spin precession with a large angle (see Fig. 2) occurred. At $J = 2J_c$, the spin precesses with a full circular orbit, as shown in Fig. 5(b), which corresponds to the out-of-plane orbit in Fig. 2. For a larger current density, $J = 4J_c$, the overall motion is similar to the $J = 2J_c$ case but the precession frequency increases. Fig. 5(a) clearly shows an increase in precession frequency. It is well known that when J increases, the precession frequency increases in the out-of-plane regions [6]. Therefore, the spin dynamics of the exchange biased free rotating layer is similar to that under an external field without an exchange bias.

4. Conclusions

An STNO structure with an exchange-biased free rotating layer was proposed. We confirm that the proposed STNO could be operated without an external magnetic field with macro-spin LLG. Because the main role of the exchange bias field on the free rotating layer was the same as the external field, the STNO with the exchange-biased free rotating layer can generate microwaves. In addition, the spin dynamics of the proposed STNO were similar to those of the conventional STNO. It should be noted that, only the exchange bias field effect was considered due to the existence of an anti-ferromagnetic layer for simplicity. However, the role of the anti-ferromagnetic layer is much more complex, and other effects must be considered in the experiments, e.g. the increment coercivity, training effect [17], asymmetric switching [21], and STT effect of the AFM itself [22], etc. Furthermore, the efficiency of STT can vary due to the existence of an AFM layer.

Acknowledgements

This study was supported by Nano R&D program (2008-02553) through the Korea Science and Engineering Foundation funded by the Ministry of Science & Technology.

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