Analysis of Switchable Spin Torque Oscillator for Microwave Assisted Magnetic Recording

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A switchable spin torque oscillator (STO) with a negative magnetic anisotropy oscillation layer for microwave assisted magnetic recording is analyzed theoretically and numerically. The equations for finding the STO frequency and oscillation angle are derived from Landau-Lifshitz-Gilbert (LLG) equation with the spin torque term in spherical coordinates. The theoretical analysis shows that the STO oscillating frequency remains the same and oscillation direction reverses after the switching of the magnetization of the spin polarization layer under applied alternative magnetic field. Numerical analysis based on the derived equations shows that the oscillation angle increases with the increase of the negative anisotropy energy density (absolute value) but decreases with the increase of spin current, the polarization of conduction electrons, the saturation magnetization, and the total applied magnetic field in the \( z \) direction. The STO frequency increases with the increase of spin current, the polarization of conduction electrons, and the negative anisotropy energy density (absolute value) but decreases with the increase of the saturation magnetization and the total applied magnetic field in the \( z \) direction.

1. Introduction

Microwave assisted magnetic recording (MAMR) is one potential technology to overcome the superparamagnetic effect of perpendicular magnetic recording in the hard disk drive. A microwave field matching with the ferromagnetic resonance of recording media excites a large angle precession of magnetization, resulting in a significant reduction in switching field. Using microwave-assisted magnetic switching, it is possible to write data into high magnetocrystalline anisotropy recording media, such as FePt and CoPt, which have sufficient thermal stability at very small grain size.

The angular momentum carried by the spin-polarized current applies a torque on the magnetization vector leading to either precession or reversal through spin-transfer-torque effect [1, 2]. The current-induced magnetization precession enables magnetic nanostructure to be a tunable high-frequency spin-torque oscillator (STO) [3]. The high-frequency magnetization precession in STO can generate localized microwave suitable for the application for MAMR, as proposed in [4, 5]. Furthermore, the fabrication processes of STO are compatible with current thin film perpendicular magnetic recording head and are easy to integrate with the current recording technology.

For the real application of STO for MAMR, the STO should be near the writing pole to avoid field decay with the distance away from STO, as shown in the thin film magnetic head in Figure 1. The STO basically consists of a spin polarization layer, a spacer, and an oscillation layer. The STO is located between the writing pole and trailing shield. The microwave generated by the STO can assist the magnetic field from the writing pole to switch the media.

There is very strong magnetic field in the gap between the writing pole and trailing shield; the STO with the negative magnetic anisotropy oscillation layer can oscillate stably under the very wide range of applied fields and injected spin currents [6]. Therefore, STO with negative magnetic anisotropy oscillation layer is preferred. The oscillation frequency and oscillation angle of the switchable STO, which, together with the saturation magnetization of oscillation layer, determine the microwave frequency and the amplitude...
2. Theoretical Analysis of the Switchable Spin Torque Oscillator

2.1. Theoretical Analysis of the STO Frequency and Oscillation Angle. The basic structure of the STO and the coordinates used for the analysis in this paper are shown in Figure 2. A simple approach to describe current induced magnetization oscillation of the oscillation layer is to fix the magnetization of spin polarization layer and consider the oscillation layer magnetization as a uniform macrospin. The dynamics of the oscillation layer magnetization follows the Landau-Lifshitz-Gilbert (LLG) equation with the Slonczewski’s spin torque term:

$$\frac{d\vec{M}}{dt} = -\gamma_0 \vec{M} \times \vec{H}_{\text{eff}} + \alpha M_0 \vec{M} \times \frac{d\vec{M}}{dt} + \gamma_0 I_s \hbar G(\psi) \frac{1}{\mu_0 V M^2_s 2e} \vec{M} \times (\vec{M} \times \vec{e}_p),$$

where $\gamma_0$ is the gyromagnetic factor, $\vec{H}_{\text{eff}}$ is the effective magnetic field, $\alpha$ is the damping constant, $M_0$ is saturation magnetization, $I_s$ is the current passing through the STO, $h$ is the reduced Planck constant, $\mu_0$ is the permeability of free space, $V$ is the volume of the oscillation layer, $e$ is the charge of an electron ($-1.60 \times 10^{-19} \text{C}$), $\vec{e}_p$ is current polarization, and $G(\psi)$ is the spin transfer efficiency function given by $G(\psi) = \left[-4 + (1 + P)^3 \cdot ((3 + \vec{e}_p \cdot \vec{m})/4P)^{3/2}\right]^{-1}$, where $\vec{m} = \vec{M}/M_s$ and $P$ is the polarization of conduction electrons.

If the spin torque term is included into the effective magnetic field, (1) can be rewritten as

$$\frac{d\vec{M}}{dt} = -\gamma_0 \vec{M} \times \vec{H}_{\text{eff}}^A + \alpha \vec{M} \times \frac{d\vec{M}}{dt},$$

where $\vec{H}_{\text{eff}}^A = \vec{H}_{\text{eff}} + (I_s \hbar G(\psi) / \mu_0 V M^2_s 2e) (\vec{M} \times \vec{e}_p)$, and (2) is the same as the traditional LLG equation in format.

The LLG equation given in the spherical coordinates can be expressed as

$$\frac{d\theta}{dt} = \frac{\gamma_0}{1 + \alpha^2} \left[ h^A_{\text{eff}} + \alpha h^A_{\text{eff}} \right],$$

$$\frac{d\phi}{dt} = \frac{\gamma_0}{1 + \alpha^2} \frac{1}{\sin \theta} \left[ h^A_{\text{eff}} - h^A_{\text{eff}} \right],$$

where $h^A_{\text{eff}}$ and $h^A_{\text{eff}}$ are the normalized total effective field along $\vec{e}_\theta$ and $\vec{e}_\phi$ in the spherical coordinates.

Here the following conditions are assumed: (1) the uniaxial magnetic anisotropy of the spin polarization layer is
along the $z$ axis, (2) magnetization of the spin polarization layer is fixed along the $+z$ axis, (3) the dimensions of STO in the $xy$ direction are the same, and (4) the magnetic field is only applied along the $z$ axis. The effective magnetic field is calculated by the energy variation with magnetization; the $h_{\text{eff}}^A$ and $h_{\text{eff}}^B$ can be expressed as

$$h_{\text{eff}}^A = -\frac{H_{az}}{M_0} \sin \theta - \frac{K_u}{\mu_0 M_0^2} \sin 2\theta - \frac{1}{2} (N_x - N_z) \sin 2\theta,$$

$$h_{\text{eff}}^B = -\int_{\theta} F G (\theta) \sin \theta,$$

where $H_{az}$ is total applied magnetic field on the oscillation layer that includes the external applied fields and the demagnetizing field from the spin polarization layer. $K_u$ is the anisotropy energy density, and $N_x, N_z$ are the demagnetizing factors of the oscillation layer. Thus (3a) and (3b) can be expressed as

$$\frac{d\theta}{dt} = \frac{\gamma_0 \sin \theta}{1 + \alpha^2} \left\{ \frac{1}{2} \alpha \mu_0 M_0^2 \sin \theta \right\} + \alpha \left[ \frac{H_{az}}{M_0} + \frac{2K_u}{\mu_0 M_0^2} \cos \theta + (N_x - N_z) \cos \theta \right] - \frac{1}{2} \alpha \mu_0 M_0^2 \cos \theta,$$

$$\frac{d\phi}{dt} = \frac{\gamma_0 \sin \theta}{1 + \alpha^2} \left\{ \frac{1}{2} \alpha \mu_0 M_0^2 \sin \theta \right\} + \alpha \left[ \frac{H_{az}}{M_0} + \frac{2K_u}{\mu_0 M_0^2} \cos \theta + (N_x - N_z) \cos \theta \right].$$

When $\theta = \theta_0$, the oscillation frequency of the STO can be expressed as

$$\omega = \frac{\gamma_0 h L G (\theta)}{2e\mu_0 \alpha V M_0} \text{ or } \omega = \frac{\gamma_0 h L G (\theta)}{2e\mu_0 \alpha V M_0},$$

where the angle $\theta_0$ is the solution of (6); we define $A = (1 + P)^3 / 4 P^{3/2}$, $B = -4 + 3A$, $\chi = h / 2e\mu_0 V M_0$, $H_k = 2K_u / \mu_0 M_0 + M_0 (N_x - N_z)$, and (6) can be expressed as

$$\cos \theta + \frac{A}{B} \left[ \cos \theta + \frac{H_{az}}{H_k} \right] + \frac{\chi L}{BH_k} = 0.$$

It is not difficult to find the solution of (8) as

$$\cos \theta_0 = \left\{ - \left( AH_k + BH_{az} \right) \pm \sqrt{(AH_k + BH_{az})^2 - 4BH_k \left( AH_{az} + \chi L \right)} \right\} \cdot (2BH_k)^{-1}.$$

For the stable oscillation, the solution of $\cos \theta_0$ is valid only when it is between $-1$ and $+1$. Inputting the angle $\theta_0$ into (7a) or (7b), the oscillation frequency of the STO can be found.

2.2. STO Frequency and Oscillation Angle after Switch. If the external magnetic field along the $z$ axis is strong enough, when its direction is changed from $+z$ to $-z$, the magnetization of spin polarization layer will also change from $+z$ to $-z$ (switchable). The demagnetizing field of spin polarization layer also reverses its direction. Therefore, $H_{az}$ becomes $-H_{az}$. The reversal of the spin polarization layer magnetization also causes the current polarization to be reversed. Equation (6) becomes

$$- H_{az} + \left\{ \frac{2K_u}{\mu_0 M_0} + M_0 (N_x - N_z) \right\} \cos \theta$$

$$= \frac{1}{2} \frac{1}{\alpha e\mu_0 M_0} \left[ -4 + (1 + P)^3 \cdot \frac{3 - \cos \theta}{4 P^{3/2}} \right].$$

Equation (10) can be rewritten as

$$H_{az} + \left\{ \frac{2K_u}{\mu_0 M_0} + M_0 (N_x - N_z) \right\} (- \cos \theta)$$

$$= - \frac{1}{2} \frac{1}{\alpha e\mu_0 M_0} \left[ -4 + (1 + P)^3 \cdot \frac{3 + \cos \theta}{4 P^{3/2}} \right].$$

It is obvious that the solution of (10) is

$$\cos \theta' = - \cos \theta_0.$$

Thus $\theta''_0$ is equal to $(\pi - \theta_0)$, and the corresponding oscillating frequency is

$$\omega' = \gamma_0 \left\{ \frac{H_{az}}{M_0} + \left\{ \frac{2K_u}{\mu_0 M_0^2} + (N_x - N_z) \right\} \cos \theta' \right\}.$$
The reverse of the oscillating direction and the unchanged frequency match the needs for the microwave-assisted magnetic switching when 0 or 1 is written. If the STO is not switchable, the external magnetic field applied to STO is different for writing of 0 and 1, which causes a shift of STO oscillation frequency (as shown in the next paragraph) and a mismatch between the STO frequency and the recording media switching frequency, resulting in write-in failures which are the main source of MAMR noise.

For the STO studied in this paper, there is no pinning layer in the polarization layer. However, there is a very strong magnetic field of 5000–8000 Oe along the ±z direction between the main pole and the trailing shield, where the spin torque oscillator (STO) is placed (Figure 1). This field acts on STO, which makes the polarization layer robust enough against other influential forces such as the dipole field from the oscillation layer (which is 100–500 Oe depending on the thickness and \( M_s \) of free layer) or the field from magnetic recording grain (which is about 200–400 Oe at a flying height of 3–5 nm) or the spin torque it experiences when passing through a current (the equivalent spin torque field is about 100–200 Oe).

### 3. Numerical Analysis of STO Frequency and Oscillation Angle

For microwave assisted magnetic recording (MAMR), STO generates microwave, which is used to reduce the switching field of recording media during writing process. In order to sufficiently reduce the media switching field, the microwave frequency should be tuneable to match the natural precession frequency of the media magnetization and the oscillating amplitude of microwave (i.e., AC magnetic field) should be large enough (about 10% of the media \( H_k \)). Therefore, the microwave frequency and the AC magnetic field are two key parameters for MAMR. In our STO design, the AC magnetic field strength is determined by the STO oscillation angle. Therefore, the discussion on the STO oscillation angle is critical for the application of STO in microwave assisted magnetic recording. Based on the equations above, the relationship between STO oscillation angle/frequency and the relative parameters is numerically analysed below. The dimension of the oscillation layer of STO is 40 nm × 40 nm × 10 nm.

#### 3.1. Injected Spin Current

In our simulation we assume that the saturation magnetization \( M_s \) is 800 kA/m, the anisotropy energy density \( K_u \) is \(-8 \times 10^5 J/m^3\), and the damping constant \( \alpha \) is 0.02 for the oscillation layer. The applied magnetic field (including the demagnetizing field from spin polarization layer) \( H_{ax} \) is 10000 Oe, and the polarization of the conduction electrons \( P \) is 0.35 [7]. We vary the current density \( J \) from 0 to 1.25 × 10^8 A/cm^2. The numerically calculated results of \( \cos \theta \) and frequency are shown in Figure 3. The increase of the spin current results in a decrease in the oscillation angle and an increase in the oscillation frequency. This trend is easily understandable because the larger current injects more spin torque to the oscillation layer and makes the oscillation layer oscillate faster.

#### 3.2. Polarization of the Conduction Electrons

The simulation parameters are the same as those in Section 3.1, except for a fixed current density of 1 × 10^8 A/cm^2 and a varied polarization of the conduction electrons \( P \) from 0.2 to 0.5. The numerically calculated results of \( \cos \theta \) and frequency are shown in Figure 4. Similar to the spin current, the increase in the polarization of conduction electrons results in a decrease in the oscillation angle and an increase in the oscillation frequency because more spin torque is injected to the oscillation layer.

#### 3.3. Anisotropy Energy Density

The simulation parameters are the same as those in Section 3.1, except for a fixed current density of 1 × 10^8 A/cm^2 and a varied anisotropy...
3.4. Saturation Magnetization. The simulation parameters are the same as those in Section 3.1, except for a fixed current density of $1 \times 10^8 \text{ A/cm}^2$ and a varied saturation magnetization $M_s$ from 400 kA/m to 800 kA/m. The high saturation magnetization results in a low magnetic anisotropy field and a high demagnetizing field, which result in a low oscillation angle (high $\cos(\theta)$) and a low value of the spin transfer efficiency function $G(\theta)$. Besides the $G(\theta)$, the STO frequency is inversely proportional to the $M_s$ as shown in (7a); thus the oscillation frequency decreases with the increase of the saturation magnetization as shown in the numerically calculated results in Figure 6.

3.5. Total Applied Magnetic Field. The simulation parameters are the same as those in Section 3.1, except for a fixed current density of $1 \times 10^8 \text{ A/cm}^2$ and a varied total applied magnetic field $H_{\text{az}}$ in +z direction from the 0 to 10000 Oe. The high $H_{\text{az}}$ results in a low oscillation angle and a low value of the spin transfer efficiency function $G(\theta)$. Therefore, the oscillation frequency decreases with the increase of the $H_{\text{az}}$ as shown in the numerically calculated results in Figure 7.

4. Conclusions

Using modified LLG equation, we derived formulas to solve the oscillation frequency and oscillation angle for the switchable spin torque oscillator (STO) with negative magnetic anisotropy oscillation layer. The STO keeps the same oscillation frequency, while its oscillation direction reverses after the flip of applied external field in the $z$ direction. The oscillation angle increases with the increase of the negative anisotropy energy density (absolute value) but decreases with the increase of spin current, the polarization of conduction electrons, the saturation magnetization, and the total applied magnetic field in the $z$ direction. The STO frequency increases with the increase of spin current, the polarization of conduction electrons, and the negative anisotropy energy density (absolute value) but decreases with the increase of the saturation magnetization and the total applied magnetic field in the $z$ direction. The findings in this paper offer guidelines
for STO design for microwave assisted magnetic recording at ultrahigh density.

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this paper.

**References**


