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Research Article

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

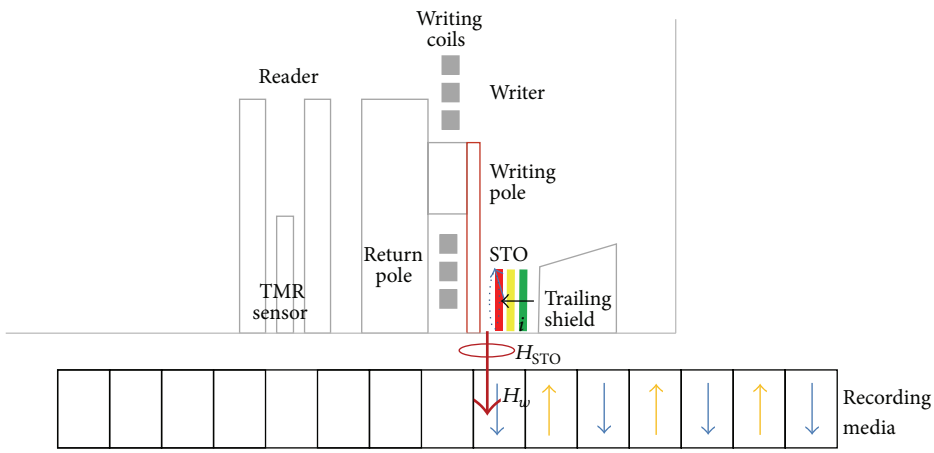

FIGURE 1: Spin torque oscillator in thin film magnetic head.

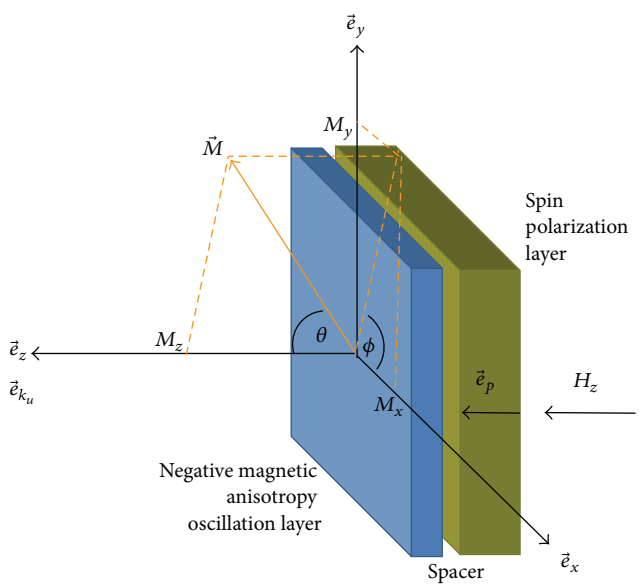

FIGURE 2: Spin torque oscillator with a negative magnetic anisotropy oscillation layer.

(critical for MAMR application), are investigated in detail in this paper.

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:

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

where γ_0 is the gyromagnetic factor, $\vec{H}_{\text{eff}}$ is the effective magnetic field, α is the damping constant, M_0 is saturation magnetization, I_s is the current passing through the STO, $\hbar$ is the reduced Planck constant, μ_0 is the permeability of free space, V is the volume of the oscillation layer, e is the charge of an electron (-1.60×10^{-19} C), $\vec{e}_p$ is current polarization, and $G(\psi)$ is the spin transfer efficiency function given by $G(\psi) = [-4+(1+P)^3\cdot((3+\vec{e}_p\cdot\vec{m})/4P^{3/2})]^{-1}$, 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

$$\frac{d\vec{M}}{dt} = -\gamma_0\vec{M}\times\vec{H}^A_{\text{eff}} + \frac{\alpha}{M_s}\vec{M}\times\frac{d\vec{M}}{dt}, \tag{2}$$

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

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

$$\frac{d\theta}{dt} = \frac{\gamma_0}{1+\alpha^2}\left[h^A_{\text{eff}\phi} + \alpha h^A_{\text{eff}\theta}\right], \tag{3a}$$

$$\frac{d\phi}{dt} = \frac{\gamma_0}{1+\alpha^2}\frac{1}{\sin\theta}\left[\alpha h^A_{\text{eff}\phi} - h^A_{\text{eff}\theta}\right], \tag{3b}$$

where $h^A_{\text{eff}\phi}$ and $h^A_{\text{eff}\theta}$ 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 $h^A_{\text{eff}\phi}$ and $h^A_{\text{eff}\theta}$ can be expressed as

$$h_{\text{eff}\theta} = -\frac{H_{az}}{M_0}\sin\theta - \frac{K_u}{\mu_0 M_0^2}\sin 2\theta - \frac{1}{2}\left(N_x - N_z\right)\sin 2\theta, \tag{4a}$$

$$h_{\text{eff}\phi} = -\frac{I_s \hbar G(\theta)}{2e\mu_0 V M_0^2}\sin\theta, \tag{4b}$$

where H_{az} is total applied magnetic field on the oscillation layer that includes the external applied field 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

$$\frac{d\theta}{dt} = -\frac{\gamma_0 \sin\theta}{1+\alpha^2}\left\{\frac{I_s\hbar G(\theta)}{2e\mu_0 V M_0^2} + \alpha\left[\frac{H_{az}}{M_0} + \frac{2K_u}{\mu_0 M_0^2}\cos\theta + \left(N_x - N_z\right)\cos\theta\right]\right\}, \tag{5a}$$

$$\frac{d\phi}{dt} = \frac{\gamma_0}{1+\alpha^2}\left[-\frac{\alpha I_s\hbar G(\theta)}{2e\mu_0 V M_0^2} + \frac{H_{az}}{M_0} + \frac{2K_u}{\mu_0 M_0^2}\cos\theta + \left(N_x - N_z\right)\cos\theta\right]. \tag{5b}$$

When $d\theta/dt = -(\gamma_0 \sin\theta/(1+\alpha^2))\{I_s\hbar G(\theta)/2e\mu_0 V M_0^2 + \alpha[H_{az}/M_0 + (2K_u/\mu_0 M_0^2)\cos\theta + (N_x - N_z)\cos\theta]\} = 0$, we have

$$H_{az} + \left[\frac{2K_u}{\mu_0 M_0} + M_0\left(N_x - N_z\right)\right]\cos\theta = -\frac{I_s\hbar}{2\alpha e\mu_0 V M_0}\left[-4 + (1+P)^3\cdot\frac{3+\cos\theta}{4P^{3/2}}\right]^{-1}. \tag{6}$$

The oscillation frequency of the STO can be expressed as

$$\omega = \frac{d\phi}{dt} = -\frac{\gamma_0\hbar}{2e\mu_0}\frac{I_s G(\theta_0)}{\alpha V M_0} \quad \text{or} \tag{7a}$$

$$\omega = \frac{d\phi}{dt} = \gamma_0\left[\frac{H_{az}}{M_0} + \frac{2K_u}{\mu_0 M_0^2}\cos\theta_0 + \left(N_x - N_z\right)\cos\theta_0\right], \tag{7b}$$

where the angle θ_0 is the solution of (6); we define $A = (1+P)^3/4P^{3/2}$, $B = -4 + 3A$, $\chi = \hbar/2\alpha e\mu_0 V M_0$, $H_k = 2K_u/\mu_0 M_0 + M_0(N_x - N_z)$, and (6) can be expressed as

$$\left[\cos\theta + \frac{A}{B}\right]\left[\cos\theta + \frac{H_{az}}{H_k}\right] + \frac{\chi I_s}{B H_k} = 0. \tag{8}$$

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

$$\cos\theta_0 = \left(-\left(AH_k + BH_{az}\right) \pm \sqrt{\left(AH_k + BH_{az}\right)^2 - 4BH_k\left(AH_{az} + \chi I_s\right)}\right)\cdot\left(2BH_k\right)^{-1}. \tag{9}$$

For the stable oscillation, the solution of $\cos\theta_0$ is valid only when it is between -1 and $+1$. Inputting the angle θ_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

$$-H_{az} + \left[\frac{2K_u}{\mu_0 M_0} + M_0\left(N_x - N_z\right)\right]\cos\theta = \frac{I_s\hbar}{2\alpha e\mu_0 V M_0}\left[-4 + (1+P)^3\cdot\frac{3-\cos\theta}{4P^{3/2}}\right]^{-1}. \tag{10}$$

Equation (10) can be rewritten as

$$H_{az} + \left[\frac{2K_u}{\mu_0 M_0} + M_0\left(N_x - N_z\right)\right](-\cos\theta) = -\frac{I_s\hbar}{2\alpha e\mu_0 V M_0}\left[-4 + (1+P)^3\cdot\frac{3+(-\cos\theta)}{4P^{3/2}}\right]^{-1}. \tag{11}$$

It is obvious that the solution of (10) is

$$\cos\theta_0' = -\cos\theta_0. \tag{12}$$

Thus θ_0' is equal to $(\pi - \theta_0)$, and the corresponding oscillating frequency is

$$\omega' = \gamma_0\left\{-\frac{H_{az}}{M_0} + \left[\frac{2K_u}{\mu_0 M_0^2} + \left(N_x - N_z\right)\right]\cos\theta_0'\right\} = -\gamma_0\left\{\frac{H_{az}}{M_0} + \left[\frac{2K_u}{\mu_0 M_0^2} + \left(N_x - N_z\right)\right]\cos\theta_0\right\} = -\omega_0. \tag{13}$$

Therefore, the oscillating frequency remains the same, but the oscillating direction reverses after the switching of external magnetic field and the magnetization of spin polarization layer.

In the application of STO for MAMR, the magnetic field from writing pole is opposite when 0 or 1 is written.

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 $\pm z$ 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_0 is 800 kA/m, the anisotropy energy density K_u is -8×10^5 J/m^3, and the damping constant α is 0.02 for the oscillation layer. The applied magnetic field (including the demagnetizing field from spin polarization layer) H_{az} 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.

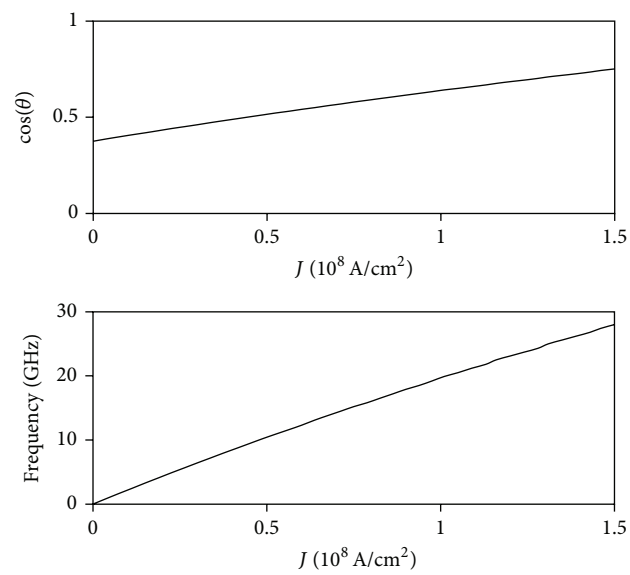

Figure 3: Effects of current on STO.

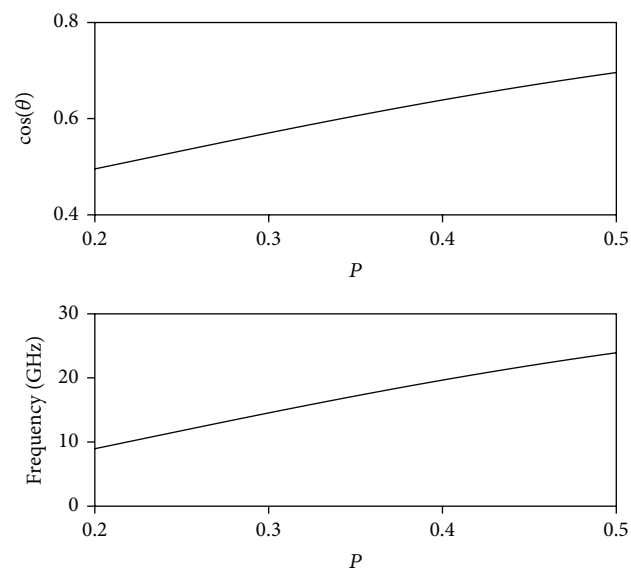

Figure 4: Effects of polarization of conduction electrons on STO.

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

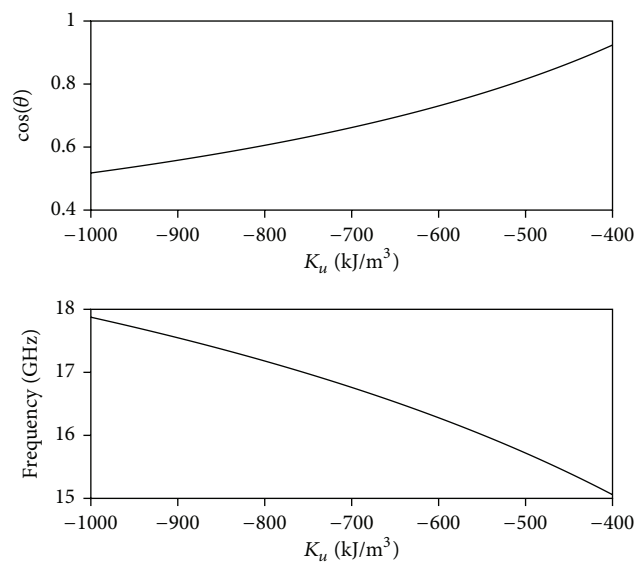

Figure 5: Effects of anisotropy energy density on STO.

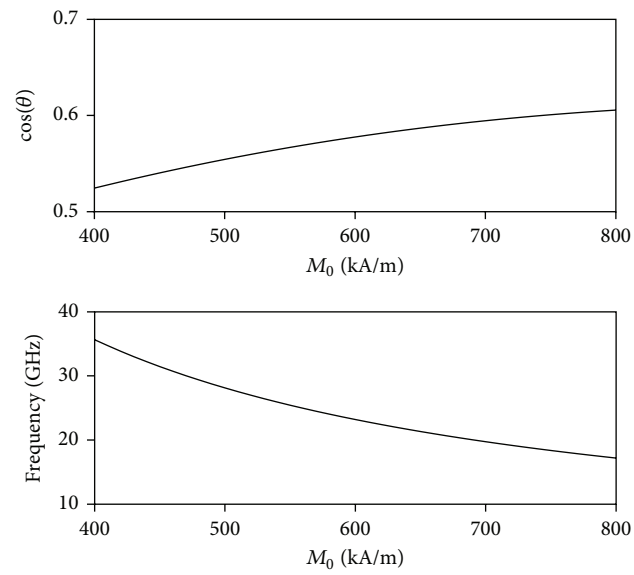

Figure 6: Effects of saturation magnetization on STO.

energy density K_u of the oscillation layer from $-1000\,\mathrm{kJ/m^3}$ to $-400\,\mathrm{kJ/m^3}$. A high negative anisotropy energy density (absolute value) results in a high oscillation angle (low $\cos\theta$) and a high value of the spin transfer efficiency function $G(\theta)$; thus the oscillation frequency increases with the increase of the anisotropy energy density (absolute value) as shown in the numerically calculated results in Figure 5.

3.4. Saturation Magnetization. The simulation parameters are the same as those in Section 3.1, except for a fixed current density of $1 \times 10^8\,\mathrm{A/cm^2}$ and a varied saturation magnetization M_0 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 $1 \times 10^8\,\mathrm{A/cm^2}$ and a varied total applied magnetic field H_{az} in $+z$ direction from the 0 to 10000 Oe. The high H_{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_{az} as shown in the numerically calculated results in Figure 7.

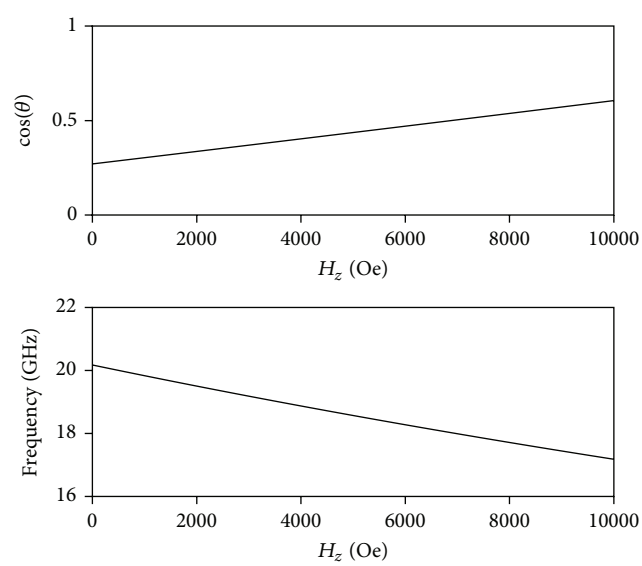

Figure 7: Effects of applied magnetic field on STO.

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.

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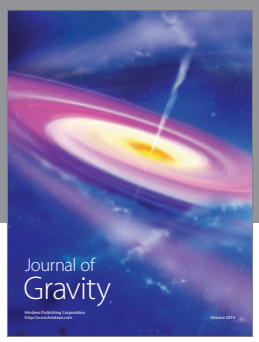

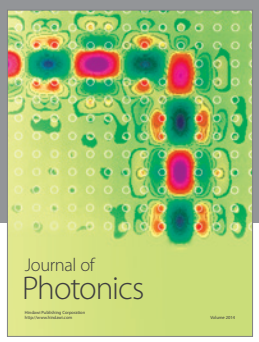

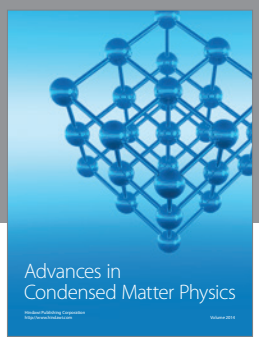

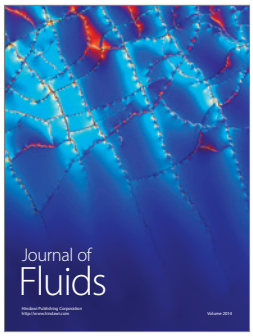

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