HOSTED BY
ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Progress in Natural Science: Materials International 25 (2015) 258–262
Progress in Natural Science Materials International
www.elsevier.com/locate/pnsmi
www.sciencedirect.com

Original Research

State diagram of spin-torque oscillator with perpendicular reference layer and planar field generation layer

Mengwei Zhang[a], Longze Wang[a], Dan Wei[a,*], Kaizhong Gao[b]

[a]Key Lab of Advanced Materials, School of Materials Science and Engineering, Tsinghua University, Beijing, 100084, China
[b]Advanced Technology Development, Seagate Technology, Bloomington, MN, United States

Received 28 September 2014; accepted 17 February 2015
Available online 9 July 2015

Abstract

The state diagram of spin-torque oscillator (STO) with perpendicular reference layer (REF) and planar field generation layer (FGL) was studied by a macrospin model and a micro-magnetic model. The state diagrams are calculated versus the current density, external field and external field angle. It was found that the oscillation in FGL could be controlled by current density combined with external field so as to achieve a wide frequency range. An optimized current and applied field region was given for microwave assisted magnetic recording (MAMR), considering both frequency and output field oscillation amplitude. The results of the macro-spin model were compared with those of the micro-magnetic model. The macro-spin model was qualitatively different from micro-magnetics and experimental results when the current density was large and the FGL was non-uniform.

Keywords: Spin-torque oscillator; Micromagnetic; Macrospin; External field; MAMR

1. Introduction

Spin-torque oscillator (STO) with perpendicular reference layer (REF) has been proposed to be an efficient way to excite oscillation at low current density [1,2]. A well-controlled STO with stable oscillation can be the basic module for microwave assisted magnetic recording (MAMR) [4]. When the STO is utilized, an external applied field of several kilo-Oe is applied on STO in addition to the applied current [3,4]. MAMR is one of the candidates to achieve extremely high density above 4 Tb/in^2. In MAMR, the STO acts as a generator of the microwave magnetic field. Hence it is important that the STO oscillates stably to generate microwave with proper frequency and large output field. The external applied field and its angle have significant influence to the frequency, amplitude and stability of oscillation. To optimize the STO design, the dependence of STO dynamics on the current, applied field and applied field angle should be analyzed. Many theoretical and experimental studies have been performed for planar REF configuration STO [5–7]. For perpendicular REF geometry, the STO performance under low or zero external field has been studied by both macro-spin and the micromagnetic model [8–11]. However, few detailed theoretical studies have been done on the performance of nano-pillar STO under different external field and different current density.

In this work, the oscillation performance of nano-pillar STO consisted of a planar field generation layer (FGL) and a perpendicular REF, as shown in Fig. 1, has been investigated in detail with the macro-spin model and the micromagnetic model [12]. The dynamics was obtained by solving Landau–Lifshitz–Gilbert equations including the Slonczewski spin transfer torque term [13].

The dependence of STO dynamics on the current density, external field and external field angle was studied. Optimized current and applied field regions were given for suitable frequency and output field magnitude for the STO utilized in microwave assisted magnetic recording (MAMR). In addition, the results of the macro-spin model and the micromagnetic model were compared. The micromagnetic model showed that

*Corresponding author.
E-mail addresses: dreamgreat.zhang@gmail.com (M. Zhang), weidan@mail.tsinghua.edu.cn (D. Wei), Kaizhong.Gao@seagate.com (K. Gao).
Peer review under responsibility of Chinese Materials Research Society.

http://dx.doi.org/10.1016/j.pnsc.2015.05.007
1002-0071/

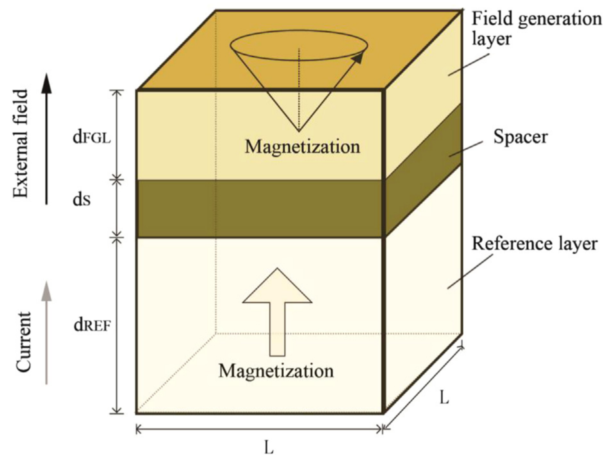

Fig. 1. Geometry of the STO consists of a planar field generation layer (FGL) and a perpendicular reference layer (REF). The parameters of STO in our model are: $L=20$ nm, $d_{FGL}=10$ nm, $d_S=2$ nm and $d_{REF}=10$ nm.

as the current density was large and the moments in FGL were not uniform, the dynamics of STO would be different from the expectation of the simple macrospin model.

2. Simulation model

The STO configuration considered here is shown in Fig. 1. The STO was comprised of a perpendicular REF, a planar FGL, and a spacer between them. The sizes of this layers were $L \times L \times d$, where $L=20$ nm and the thicknesses were $d_{REF}=10$ nm, $d_{FGL}=10$ nm, and $d_S=2$ nm. In the micromagnetic model, REF and FGL are 3D discretized by a regular mesh, with a cell size of 2 nm × 2 nm × 2 nm. This structure was simulated by the Landau–Lifshitz–Gilbert equations including the Slonczewski spin transfer torque (STT) term [13]:

$$\left(\frac{\partial \boldsymbol{m}_F}{\partial t}\right)_{STT} = \frac{\hbar\gamma_0 J}{eM_s d_F}\frac{1}{f_P(\boldsymbol{m}_F\cdot\mathbf{m}_R)+b_P}\boldsymbol{m}_F\times(\boldsymbol{m}_F\times\boldsymbol{m}_R) \quad (1)$$

where γ_0 is the gyromagnetic ratio, J is the current density, d_{FGL} is the FGL thickness, $\circ\mathbf{m}_{FGL}$ and $\circ\mathbf{m}_{REF}$ are the normalized magnetizations of a cell in FGL and REF, respectively. $f_P=(1+P)^3/4P^{3/2}$ and $b_P=3f_P-4$, and P is the spin polarization of the conduction current.

The REF and FGL are coupled by magnetostatic interaction and STT of tunneling spin-polarized current. The REF has a large perpendicular anisotropy and FGL has an in-plane anisotropy. The FGL has a large saturation magnetization so as to generate large microwave field. The parameters used in our simulation are as follows: Saturation magnetizations of FGL and REF were $M_{FGL}=1700$ emu/cm^3 and $M_{REF}=1100$ emu/cm^3, respectively. Anisotropy energy constants of FGL and REF were 5×10^4 erg/cm^3 and 2.2×10^7 erg/cm^3, respectively. The Gilbert damping constant α was set as 0.02 in both layers. The spin polarization P is set as 0.45. When the oscillation of STO is simulated by the micromagnetic model, the exchange constant between neighbor cells was set to be 2×10^{-6} erg/cm. The current density varied from 10 to 400 MA/cm^2. The current flowing from the REF to the FGL was defined as the positive current. An external magnetic field H_{ext}, and perpendicular current, were applied to the STO. The H_{ext} in this work was the order of the external field applied on the STO in MAMR. The magnitude of external magnetic field varied from 5000 to 15000 Oe with a step of 1000 Oe. The angle of external field varies from perpendicular (0°) to 45° with a step of 9°.

3. Results and discussions

3.1. Macrospin model

The frequency dependence of current density and external field magnitude is shown in Fig. 2, where the external field angles are 0°, 9° and 18° for Fig. 2(a), (b) and (c), respectively. When the external field angle was above 27°, the oscillation in FGL will disappear. The color shows the frequency. In deep blue area the frequency is zero, indicating that the magnetization of FGL is fixed at some direction without oscillation. In each plot of Fig. 2, there are three regions. When the current density was below the bottom threshold (upper bound of the colored region), the magnetization of FGL was fixed in the direction of external field. On the contrary, as current density was above the upper threshold (lower bound of the colored region), the magnetization of FGL switched to the REF moment direction. Between two thresholds, the FGL oscillated under a specific frequency.

It can be obtained from Fig. 2 that the frequency increases as the current density increases until the magnetization of FGL switches to the REF magnetization direction. The oscillation frequency decreases slowly as the external field magnitude increases. Both the oscillation upper and bottom threshold increase as the external field magnitude increases. However, the frequency continuous growth feature does not match experimental result [2]. We will show later the micromagnetic model does predict that the frequency saturates as current density is large enough. Comparing the state diagram with different external field angle, it can be seen that the bottom threshold increases as the angle increases. In addition, the width of oscillation region shrinks as angle becomes larger.

3.2. Micromagnetic model

When a more complete micromagnetic model was used for the STO, the frequency dependence of current density and external field magnitude is shown in Fig. 3,where the external field angle are 0°, 9°, 18°, 27°, 36° and 45° for (a), (b), (c), (d) , (e) and (f), respectively. The features of these state diagrams are different from the result of the macrospin model in Fig. 2. The bottom threshold in Fig. 3 qualitatively coincides with that of the macrospin result. However, it can be observed from in Fig. 3 that when the current density is large, the oscillation region for FGL is much wider and the frequency saturates. This feature coincides with experiments result [2]. This saturation feature is mainly caused by the nonuniformity in FGL which will be discussed later. In addition, under a larger external field, the oscillation frequency increased. Moreover, with higher external field, the saturation frequency was larger. Hence, the frequency of STO was highly affected by the external field magnitude and the current density.