Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1466-1467

Physics-based SPICE Model of Spin Torque Oscillators

Hyein Lim, Sora Ahn, Seungjun Lee, and Hyungsoon Shin

Dept. of EE, Ewha Womans University, Seoul 120-750, Korea
Phone: +82-2-3277-3595, e-mail: slee@ewha.ac.kr

1. Introduction

Interest in spin torque oscillators(STOs) is rapidly growing due to its potential use in cell phones, wireless devices and satellite communication. STOs are new devices which are based on the spin-transfer torque effect in magnetic multilayered nanostructures. In these devices, a spin-polarized current can induce precession of the ferromagnetic thin film's magnetization and as a consequence, it creates a frequency tunable microwave source over tens of gigahertz range. There are several approaches to describe highly non-linear characteristics of STOs in analytical equations, and Slavin presented a general analytic model of microwave generation in magnetic nano-structures [1]. However, circuit-level model of STOs hasn't been reported yet, which is essential for verification of the functionality of STOs along with electrical circuit elements.

In this paper, we present for the first time a physics-based empirical circuit-level model of STOs which is compatible with SPICE circuit-level simulator.

2. STO Modeling

Circuit-Level Model of STO

Behavior of an STO is represented by three characteristics: generation frequency ω_g, mean oscillation power $\bar{p}$, and full width at half maximum (FWHM) linewidth $2\Delta\omega$. These characteristics are determined by current flowing through the STO and external magnetic field. Thus, an STO can be modeled as a resistor whose resistance varies periodically according to the current and the external field. The resistance is represented as sum of a DC component which remains constant during excitation and an AC component which reflects non-linear auto-oscillation of an STO as shown in (1).

$$V(top,bottom) = R(t) * I(top,bottom); \quad \text{where } R(t) = R_{DC} + R_{AC}(t) \tag{1}$$

The magnitude of AC component is proportional to the square root of mean power. The center frequency of AC signal is generation frequency of the STO and the fluctuation is related with linewidth. The equation (1) is reproduced as (2) by reflecting those characteristics.

$$\begin{aligned} V(top,bottom) &= R_{DC} * I(top,bottom) \\ &\quad + \sqrt{power} * \cos(\omega_g t + fluctuation(t)); \\ \text{where} \quad fluctuation(t) &= \$rdist\_normal(time\_random, 0, \Delta\omega) \end{aligned} \tag{2}$$

Analytic Models of STO Characteristics

Three characteristics of STO are determined by the current and the external magnetic field (field intensity, in-plane angle, out-of-plane angle). Parameters of internal magnetic field are calculated first using external parameters and then, three STO characteristics can be expressed as in (3) using those internal parameters. Those equations are based on Slavin's analytic model in [1].

$$\bar{p} = \frac{Q\eta}{Q+\zeta}\left[1 + \frac{\exp(-(\zeta+Q)/Q^2\eta)}{E_\beta((\zeta+Q)/Q^2\eta)}\right] + \frac{\zeta-1}{\zeta+Q} + A \tag{3a}$$

$$\text{where } A = a_1 + a_2 * \sin(\pi \frac{I+b_1}{b_2})$$

$$\omega_g = \omega_0 + N\bar{p} \tag{3b}$$

$$2\Delta\omega = (1+\nu^2)\Gamma_+(p_0)\frac{k_B T}{E(p_0)} \tag{3c}$$

$$\text{where } E(p_0) = \lambda\omega_0\bar{p}, \quad \lambda = V_{eff} M_0 / \gamma$$

Q is a nonlinear damping coefficient, η is effective noise power, ζ is supercriticality parameter (I/Ith) and A is a fitting parameter. ω_0 is ferromagnetic resonance (FMR) frequency, N is nonlinear frequency shift coefficient, ν is normalized dimensionless nonlinear frequency shift, $\Gamma_+(p_0)$ is positive damping rate, T is temperature, E is oscillator energy, V_{eff} is effective volume of oscillator and γ is gyromagnetic ratio.

In this model, a sinusoidal component is added to Slavin's original power equation as a fitting parameter to reduce slight discrepancy between the original equation and experimental data. More elaboration on Slavin's model has been made on the equations for generation frequency and linewidth. They reflect the modified power equation such that they are valid seamlessly in whole range of bias current whereas the original model doesn't offer seamless behavior when the bias current increases from below-threshold region to above-threshold.

The linewidth in frequency spectrum is generated by not only phase noise but also frequency fluctuation [2]. Frequency fluctuation means the change of the center frequency of an STO. In our model, the linewidth is expressed as an incremental frequency component having Gaussian random distribution with zero mean and standard deviation proportional to the linewidth. Consequently, the generated frequency of an STO is determined by the sum of the center frequency and the frequency fluctuation component.

3. Circuit-Level Simulation with STO Model

STO model has been developed in Verilog-A which is a hardware description language tailored for describing behaviors of analog circuit components in continuous time domain. Models written in Verilog-A are compatible with circuit-level simulators such as SPICE. An STO is con-

nected with current mirror circuit as shown in Fig. 1 and simulated using HSPICE and Verilog-A.

Fig. 2 and 3 show the simulation results compared with experimental data [3]. The amount of the current through the STO can be precisely controlled by changing the width of NMOS transistor M2. Fig. 2 shows the red shift of the generation frequency in frequency domain as the current increases. The red shift is also shown in Fig. 3(a). The mean power increases with increasing current in Fig. 3(b). Simulation results of the linewidth show good agreement with experimental data up to ~6mA. The linewidth starts increasing and gets saturated when the current gets very large. This is due to higher-order nonlinear effects and this higher-order effect is not included in our model because there is no theoretical equation available yet which can precisely explain this effect.

The characteristics of STO as a function of out-of-plane angle of external field are presented in Fig. 4 and they also show good agreement with experimental data [4],[5].

The characteristics of STO as a function of field intensity and in-plane angle of external field were also modeled and simulated. The results showed good agreement with experimental data.

4. Conclusions

In this paper, we propose physics-based empirical circuit model of STO which is compatible with the HSPICE. The STO is modeled as a non-linear resistor whose resistance varies periodically at given current and magnetic field. The simulation results of proposed STO model with current mirror circuit show good agreement with experimental data. Proposed STO model is the first attempt as a circuit-level model. As this model is based on general theory of microwave generation in magnetic nano-structure, it can be applied to wide range of STO elements.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology (No. 2011-0016277).

References

[1] A. Slavin, V. Tiberkevich, *IEEE TRANS ON MAGNETICS*, vol.45, no.4, p.1875-1918, 2009.

[2] P. Villard et al., *IEEE J. Solid-State Circuits*, vol. 45, no. 1, p.214-223, 2010.

[3] Q. Mistral et al., *Appl. Phys. Lett.*, vol. 88, p. 192507, 2006.

[4] W. H. Rippard et al., *Phys. Rev. B*, vol. 70, p. 100406, 2004.

[5] W. H. Rippard et al., *Phys. Rev. B*, vol. 74, p. 224409, 2006.

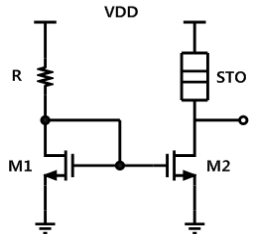

Fig. 1 STO with Current-Mirror Circuit

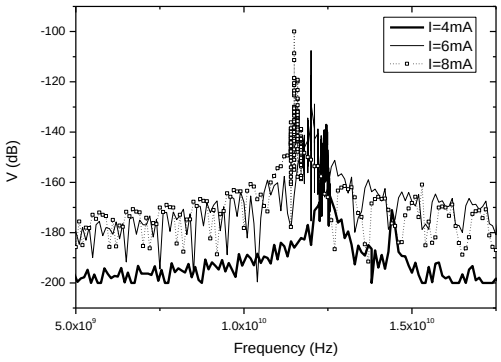

Fig. 2 Frequency Shift with Current

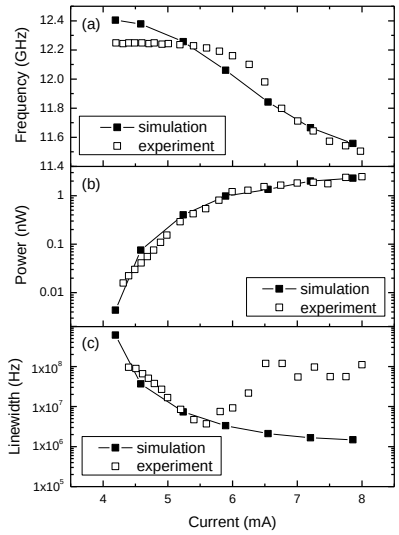

Fig. 3 Comparison of Simulation with Experiment as a Function of Current (a) Frequency (b) Mean Power and (c) Linewidth

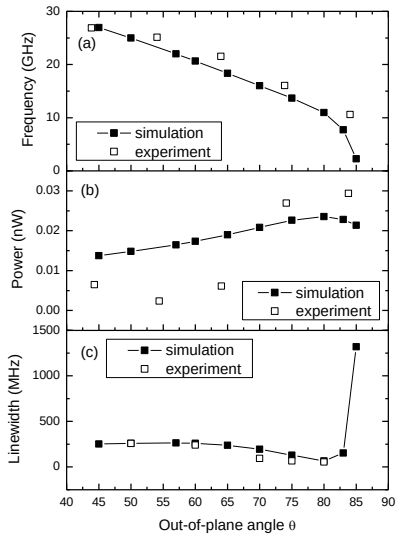

Fig. 4 Comparison of Simulation with Experiment as a Function of Out-of-Plane Angle of Magnetic Field
(a) Frequency (b) Mean Power and (c) Linewidth