http://dx.doi.org/10.5573/JSTS.2013.13.6.556 JOURNAL OF SEMICONDUCTOR TECHNOLOGY AND SCIENCE, VOL.13, NO.6, DECEMBER, 2013

Advanced Circuit-Level Model of Magnetic Tunnel Junction-based Spin-Torque Oscillator with Perpendicular Anisotropy Field

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

***Abstract*—Interest in spin-torque oscillators (STOs) has been increasing due to their potential use in communication devices. In particular the magnetic tunnel junction-based STO (MTJ-STO) with high perpendicular anisotropy is gaining attention since it can generate high output power. In this paper, a circuit-level model for an in-plane magnetized MTJ-STO with partial perpendicular anisotropy is proposed. The model includes the perpendicular torque and the shift field for more accurate modeling. The bias voltage dependence of perpendicular torque is represented as quadratic. The model is written in Verilog-A, and simulated using HSPICE simulator with a current-mirror circuit and a multi-stage wideband amplifier. The simulation results show the proposed model can accurately replicate the experimental data such that the power increases and the frequency decreases as the value of the perpendicular anisotropy gets close to the value of the demagnetizing field.**

***Index Terms*—Spin-torque oscillator, magnetic tunnel junction, perpendicular anisotropy, perpendicular torque, circuit-level model**

Manuscript received May. 7, 2013; accepted Oct. 28, 2013
A part of this work was presented in Korean Conference on Semiconductors, Gangwon-do in Korea, Feb. 2013
Department of Electronics Engineering, Ewha Womans University
11-1, Daehyun-Dong, Seodaemun-Gu, Seoul 120-750, Korea
E-mail : hsshin@ewha.ac.kr, slee@ewha.ac.kr

I. INTRODUCTION

A nanoscale STO is suitable for high density integration and it can generate oscillations in several gigahertz ranges. For these reasons, interest in STOs has been increasing. However, their low output power has been a bottleneck for practical use. MTJ-STOs are preferred to giant magneto-resistance (GMR) STOs because they can generate higher power due to their large magneto-resistance (MR) ratio [1]. Also, the bias current to threshold current ratio (I/I_{th}) is another important factor to obtain large power. The threshold current is proportional to the saturation magnetization (M_S). M_S can be decreased by increasing perpendicular anisotropy (M_P) because M_P compensates the demagnetizing field $(H_d = 4\pi M_d)$. Thus, the MTJ-STOs with strong perpendicular anisotropy is gaining high attention for their potential to provide enough power for practical use [2].

In this paper, a circuit-level model of an MTJ-STO with the partial perpendicular anisotropy is proposed. In the proposed model three major characteristics of an MTJ-STO which are generation frequency, power, and linewidth are represented as functions of bias current and applied magnetic field. The model considers the perpendicular torque and the shift field for more accurate calculation of effective field inside the free layer. The MTJ-STO model is written in Verilog-A which is a hardware-description language (HDL) providing full compatibility with circuit-simulators such as SPICE.

Section II presents the analytic model of MTJ-STOs with perpendicular anisotropy. Sections III and IV discuss the simulation results with the HSPICE and the conclusion.

II. ANALYTIC MODEL OF MTJ-STO

The three characteristics of MTJ-STOs - generation frequency (ω_g), mean oscillation power (P_{exp}) and generation linewidth ($2\Delta\omega$), are varied by the bias current and the magnitude and the direction of external magnetic field (H_{ext}). As the three characteristics are directly related to the internal field of the free layer, it is important to calculate the effective field in the free layer accurately. The internal and external magnetic fields that exist in the free layer are shown in Fig. 1. Here the easy-axis and the hard-axis are represented by x and y axes, respectively. The z axis is orthogonal to the $x-y$ plane. In-plane angle φ_0 is the angle between H_{ext} and x axis. Out-of-plane angle θ_0 is the angle with respect to the $x-y$ plane. Shape anisotropy field H_A, the perpendicular torque b_J and the shift field H_{sh} exist in x axis. In GMR-STOs the magnitude of b_J is very small, so it is usually ignored in the GMR-STO model. On the other hand, b_J must be included in the MTJ-STO model because the magnitude of b_J in MTJ-STOs can be as large as 30% of the in-plane torque (a_J) [3]. In previous works, there are a couple of theories on the bias dependence of the b_J [3-5]. In this paper, the bias voltage dependence of b_J is represented as quadratic [6].

$$b_J = C_1 V + C_2 V^2 \tag{1}$$

Here, $C_1 = -20OeV^{-1}$ and $C_2 = 100OeV^{-2}$ have been chosen by comparing calculated data with experimental data [2]. Fig. 2 shows the b_J as a function of bias voltage. For more accurate modeling, H_{sh} should be included in the MTJ-STO model which is composed of dipolar coupling, orange-peel coupling, and inter-layer exchange coupling.

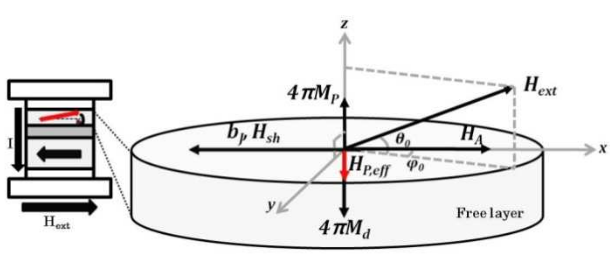

Fig. 1. The internal and external magnetic fields of the free layer.

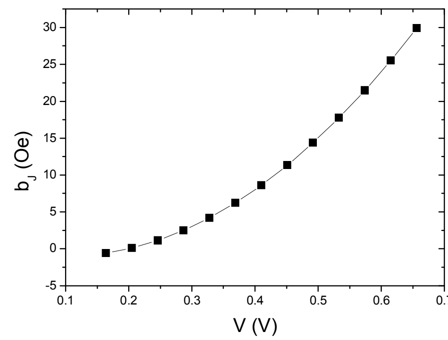

Fig. 2. The perpendicular torque as a function of bias voltage.

For STOs with M_P, it is observed that H_d is compensated by M_P. To consider this effect, the effective perpendicular magnetic field ($H_{P,eff}$) is defined as $H_{P,eff} = 4\pi M_S = 4\pi(M_d - M_P)$ as shown in Fig. 1.

The magnitude H, the in-plane angle φ, and the out-of plane angle θ of the effective magnetic field in the free layer is obtained from (2) [7].

$$H \sin\theta = H_{ext} \sin\theta_0 - H_{P,eff} \sin\theta \tag{2a}$$

$$H \cos\theta \cos\varphi = H_{ext} \cos\theta_0 \cos\varphi_0 + H_A \cos\theta \cos\varphi - H_{sh} - b_J \tag{2b}$$

$$H \cos\theta \sin\varphi = H_{ext} \cos\theta_0 \sin\varphi_0 \tag{2c}$$

Characteristic frequencies and some other coefficients of an MTJ-STO required to calculate ω_g, $2\Delta\omega$, and P_{exp} are determined from H, φ and θ. The more detailed explanation of these parameters can be found in [7].

The three characteristics ω_g, $2\Delta\omega$, and P_{exp} of MTJ-STOs are determined by (3).

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

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

$$P_{exp} = R_{rf} I^2 \psi^2 \tag{3c}$$

In (3), ω_0 and N are ferromagnetic resonance frequency and the coefficient of nonlinear frequency shift, respectively. Also, $\bar{p}$ is dimensionless power and represented as $\frac{Q\eta}{Q+\zeta} \times \left[1 + \frac{\exp(-(\zeta+Q)/Q^2\eta)}{E_\beta((\zeta+Q)/Q^2\eta)}\right] + \frac{\zeta-1}{\zeta+Q}$.. Here,

Q is a nonlinear damping coefficient, η is effective noise power and ζ is a dimensionless supercriticality parameter defined as I/I_{th}. $E_\beta(x) = \int_1^\infty e^{-xt}/t^\beta dt$ is exponential integral function where $\beta = -(1+Q)\zeta/Q^2\eta$. ν is normalized dimension-less nonlinear frequency shift, $\Gamma_+(p_0)$ is positive damping rate, k_B is Boltzmann constant, and T is temperature in Kelvin. $E(\bar{p})$ is oscillator energy and defined as $\lambda\omega_0\bar{p}$ where $\lambda = V_{eff}H_{P,eff}/\gamma$ and V_{eff} is the effective volume of the free layer and γ is gyromagnetic ratio. R_{rf} and ψ^2 are magneto-resistance and the precession angle, respectively, and obtained from (4).

$$R_{rf} = \frac{R_L}{2[R(\theta_0) + R_L]^2} \times \left(\frac{dR}{d\theta}\right)^2 \quad (4a)$$

$$\psi^2 = \arccos^2(1 - 2(1+\varepsilon^*)\bar{p}) \approx 4(1+\varepsilon^*)\bar{p} \quad (4b)$$

In these equations, R_L is the load resistance. ε^* is ellipticity of precession, and it approaches to 0 as the magnetization of free layer becomes orthogonal to the free layer. In previous works, ε^* is limited to in-plane magnetization [8]. In our proposed model, ε^* is realized for both in-plane and out-of-plane magnetizations, and it is represented as (5).

$$\varepsilon^* = \frac{H_{P,eff}\cos\theta}{(2H_{ext} + H_{P,eff})} \quad (5)$$

Threshold current I_{th} required for ζ is defined as (6).

$$I_{th} = \frac{\Gamma_G}{\sigma} \quad (6a)$$

$$\sigma = \mu_0\sigma_0 = \frac{\mu_0\varepsilon g\,\mu_B}{2e(M_d - M_P)LS} \quad (6b)$$

Here, Γ_G is linear damping rate, μ_0 is permeability, ε is dimensionless spin-polarization efficiency, g is spectroscopic Lande factor, μ_B is Bohr magneton, e is the modulus of electron charge, L is the thickness of the free layer, and S is the area of the free layer. It is worth noting that I_{th} decreases as the value of M_P in the free layer increases.

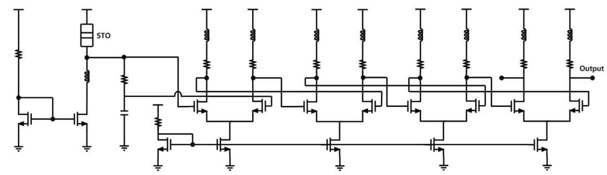

Fig. 3. Circuit schematic of an MTJ-STO with the current-mirror circuit and the 4-stage common source amplifier.

III. SIMULATION RESULTS

1. Characteristics of MTJ-STOs with Bias Current

The proposed MTJ-STO model is written in Verilog-A HDL which provides full compatibility with circuit simulators such as SPICE. In order to verify its accuracy, the model is simulated using HSPICE simulator with a current-mirror circuit and a multi-stage wideband amplifier. The schematic of the circuit is shown in Fig. 3. The dimension of MTJ-STO under simulation is $170\,nm \times 60\,nm$, thickness of free layer is $1.7\,nm$, and H_A is $60\,Oe$. The MR ratio of MTJ-STO is 102 % [2]. The bandwidth of the amplifier in Fig. 3 is about 8 GHz and the power gain is 40 dB.

In Figs. 4 and 5, the simulation results of the three characteristics of the MTJ-STO with the perpendicular anisotropy are compared with the experimental data in [2] for different direction and magnitude of the external magnetic field. The calculated I_{th} from (6) is 0.08 mA which is the same value of I_{th} in [2]. Also, $M_P = 1.1875$ kemu/cm^3 has been chosen by comparing the simulation data with the experimental data which is similar to $M_d = 1.2$ kemu/cm^3 [2]. Although the MTJ-STO has strong perpendicular anisotropy field, it remains in-plane magnetized. As can be seen, the simulation results are in good agreement with the experimental data for both in-plane and out-of-plane fields. In Figs. 4(b) and 5(b), the simulation results of generation linewidth and the experimental data have little discrepancy as I gets close to I_{th}. In this region, STOs operate at thermally excited ferromagnetic resonance (T-FMR) mode [1]. Currently, the proposed model focuses on steady-state oscillation and does not include T-FMR mode because that region is out of normal operating condition in real application.

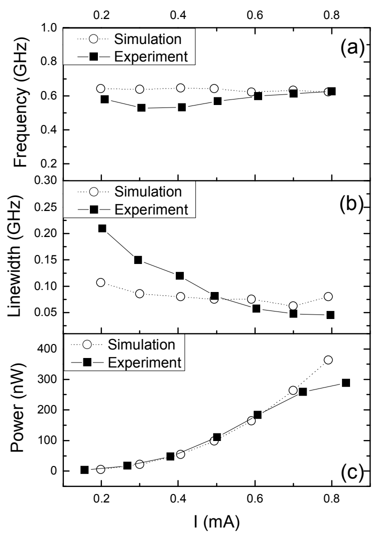

Fig. 4. Characteristics of the MTJ-STO as a function of bias current for in-plane field ($H_{ext} = 220Oe, \theta_0 = 0°$ and $\varphi_0 = -60$ °).

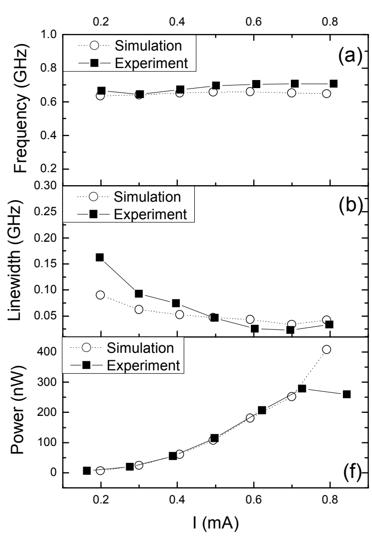

Fig. 5. Characteristics of MTJ-STOs as a function of bias current for out-of-plane field ($H_{ext} = 264Oe, \theta_0 = 40.4°$ and $\varphi_0 = -60$ °).

2. Characteristics of MTJ-STOs with Perpendicular Anisotropy

Fig. 6 shows the three characteristics of an MTJ-STO as a function of bias current for the out-of-plane field with $M_P = 1.1857$ kemu/cm^3 and 1.13 kemu/cm^3. The relation between I_{th} and M_P is shown in Fig. 7. As shown in Fig. 7, the value of I_{th} tends to decrease with increasing of M_P. For example, I_{th} are 0.08 mA and

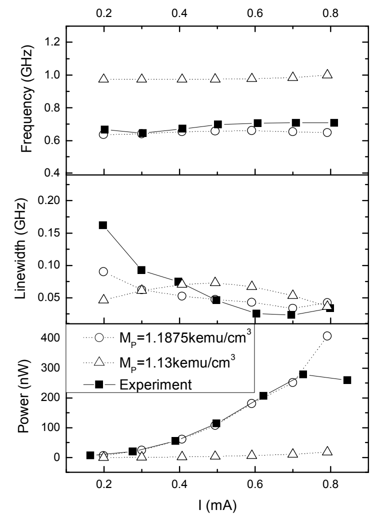

Fig. 6. Characteristics of MTJ-STOs as a function of bias current for different M_P with $H_{ext} = 264Oe, \theta_0 = 40.4°$ and $\varphi_0 = -60$ °.

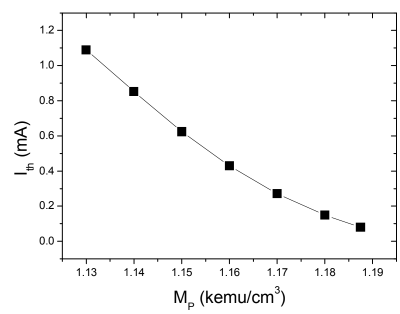

Fig. 7. Threshold current as a function of perpendicular anisotropy.

1.09 mA at $M_P = 1.1857$ kemu/cm^3 and 1.13 kemu/cm^3, respectively. P_{exp} of the MTJ-STO is proportional to ζ. Therefore, as shown in Fig. 6, difference of P_{exp} between two MTJ-STOs is about 0.24 μW at the same value of $I = 0.7$ mA. In addition, ω_g of the MTJ-STO with strong M_P is lower than that with weaker M_P by approximately 0.4 GHz. That is because M_P compensates H_d.

3. Results of Circuit-level Simulation

Fig. 8 shows the simulation results with HSPICE on a circuit shown in Fig. 3. Frequency spectrum of the output signals with out-of-plane field from the current-mirror stage and the 4-stage wideband amplifier are shown. A single frequency peak is shown at 0.65 GHz as expected in Fig. 5. The output signal of the amplifier has about 36

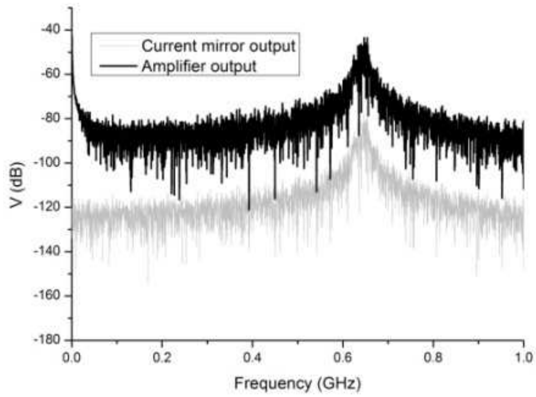

Fig. 8. The frequency spectrum of the output signal from the current-mirror stage and the amplifier stage.

dB power gain over the current mirror output.

IV. CONCLUSIONS

A circuit-level model of an in-plane magnetized MTJ-STO with partial perpendicular anisotropy has been proposed. The MTJ-STO with the perpendicular anisotropy has low threshold current because the effect of the demagnetizing field is decreased. Thus, the MTJ-STO with stronger perpendicular anisotropy produces larger power at the same level of bias current. The simulation results show the proposed model can accurately replicate the experimental data such that the power increases and the frequency decreases as the value of the perpendicular anisotropy gets close to the value of the demagnetizing field. Simulation results also confirmed that the proposed MTJ-STO model is fully compatible with arbitrary CMOS circuits.

ACKNOWLEDGMENTS

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] D. Houssamedine, et al., "Spin Transfer Induced Coherent Microwave Emission with Large Power from Nanoscale MgO Tunnel Junctions," *Appl. Phys. Lett.,* vol. 93, p. 022505, 2008.

[2] Zhongming Zeng, et al., "High-power coherent microwave emission from magnetic tunnel junction nano-oscillators with perpendicular anisotropy," *ACS Nano,* vol. 6 (7), p. 6115, 2012.

[3] J. C. Sankey, et al., "Measurements of the spin-transfer-torque vector in magnetic tunnel junctions," *Nature Phys.,* Vol.4, pp.67-71, 2008.

[4] S. Petit, et al., "Spin-Torque Influence on the High-Frequency Magnetization Fluctuations in Magnetic Tunnel Junctions," *Phys. Rev. Lett..,* vol. 98, p. 077203, 2007.

[5] M. H. Jung, et al., "Bias dependences of in-plane and out-of-plane spin transfer torque in symmetric MgO-based magnetic tunnel junctions," *Phys. Rev. B,* vol. 81, p. 134419, 2010.

[6] Se-Chung Oh, et al., "Bias-voltage dependence of perpendicular spin-transfer torque in asymmetric MgO-based magnetic tunnel junctions," *Nature Phys.,* vol. 5, p. 898, 2009.

[7] A. Slavin, et al., " Nonlinear auto-oscillator theory of microwave generation by spin-polarized current," *IEEE Trans. Magn.,* vol. 45, No. 4, p. 1875, 2009.

[8] Hyein Lim, et al., "A new circuit model for spin-torque oscillator including the perpendicular torque of magnetic tunnel junction," *ICM,* 2012.

Miryeon Kim received the B.S. and M.S. degrees in electronics engineering from Ewha Womans University, Seoul, Korea, in 2011 and 2013, respectively. She is currently working toward the Ph.D. degree at the same university. Her major interest is Spin Torque Oscillators modeling in Spintronics.

Hyein Lim received the B.S. and M.S. degrees in electronics engineering from Ewha Womans University, Seoul, Korea, in 2010 and 2012, respectively. She is currently working toward the Ph.D. degree at the same university. Her major interest is MRAM modeling in Spintronics.

Sora Ahn received the B.S. degrees in electronics engineering from Ewha Womans University, Seoul, Korea, in 2010. She is currently working toward the Ph.D. degree in electronics engineering at the same university. Her major interest is Spin Torque Oscillators modeling in Spintronics.

Seungjun Lee received the B.S. degree in electronics engineering from Seoul National University, Seoul, Korea, in 1986, and the M.S. and Ph.D degrees in electrical engineering and computer science from the University of California at Berkeley, in 1989 and 1993, respectively. From 1993 to 1998 he has worked at Hyundai Electronics Industries. Since 1999, he has been been with the Department of Electronics Engineering at Ewha Womans University, Seoul. His research interests include the design of digital circuits, wireless communication system, and system level design methodology.

Hyungsoon Shin received the B.S. degree in electronics engineering from Seoul National University, Seoul, Korea, in 1982, and the M.S. and Ph.D. degrees in electrical engineering from the University of Texas at Austin, Austin, in 1984 and 1990, respectively. From 1990 to 1994, he was with LG Semicon Company, Ltd., in Korea, where he was engaged in research on the development of DRAM, SRAM, and Flash memory. Since 1995, he has been with the Department of Electronics Engineering, EWHA Womans University, Seoul. His current research interests include new processes, devices, and circuit developments and modeling based on Si, both for high-density memory and RF ICs.