Analytic Model of Spin-Torque Oscillators (STO) for Circuit-Level Simulation

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

Abstract—**Spin-torque oscillators (STO) is a new device that can be used as a tunable microwave source in various wireless devices. Spin-transfer torque effect in magnetic multilayered nanostructure can induce precession of magnetization when bias current and external magnetic field are properly applied, and a microwave signal is generated from that precession. We proposed a semi-empirical circuit-level model of an STO in previous work. In this paper, we present a refined STO model which gives more accuracy by considering physical phenomena in the calculation of effective field. Characteristics of the STO are expressed as functions of external magnetic field and bias current in Verilog-A HDL such that they can be simulated with circuit-level simulators such as Hspice. The simulation results are in good agreement with the experimental data.**

Index Terms—**Spin torque oscillator, effective field, analytic model, circuit-level simulation**

I. INTRODUCTION

STO is a nano-sized oscillator based on spintronics technology. Since the predictions by Slonczewski [1] and Berger [2] that the spin-polarized current induces precession of the ferromagnetic thin film's magnetization, various experiments [3-5] have verified that spin torque induced by spin-polarized current generates high frequency auto-oscillation. Microwave in GHz range is generated when external magnetic field and dc-current are applied to an STO. STO has many advantages over conventional oscillators such as easiness of integration, wide tuning range of generated frequency, and energy efficiency.

We have proposed physics-based semi-empirical circuit level model of an STO in our previous work [6]. In this work, we present an improved model which can reflect physical phenomena more precisely than previous model. The characteristics of an STO with respect to the in-plane angle of an external filed can be described more accurately in our new model by enhancing the calculation of the effective field. We analyzed the characteristics of an STO with respect to the external magnetic field, and verified the effectiveness of our model through comparison of simulation results with experimental data. Next chapter explains the modeling procedure. The simulation results with Hspice are given in chapter III.

II. MODEL OF STO

1. Operation of STO

Magnetic multilayered nanostructure used as an STO is composed of three layers: a thick "fixed magnetic layer", a nonmagnetic spacer, and a thin "free magnetic layer" as shown in Fig. 1. The structure is called either a giant magneto-resistance (GMR) spin valve or magnetic tunnel junction (MTJ), in accordance with that the material of nonmagnetic spacer is metal or dielectric.

Initial orientation of magnetization of the free layer is determined when external magnetic field is applied to the STO. Then, the spin polarized current transmits spin

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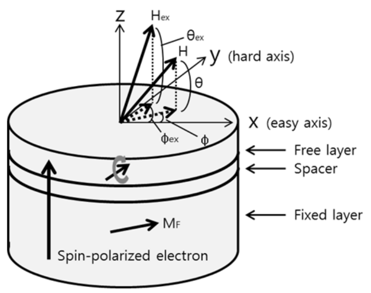

Fig. 1. Structure of an STO.

angular momentum to magnetization of the free layer. Eventually, spin torque acts on the magnetization of the free layer and stationary precession is induced in the free layer. That precession results in generation of microwave signal.

2. Analytic Model of STO Characteristics

Behavior of an STO is described by three characteristics which are generation frequency, linewidth, and power, like general oscillators. In order to obtain these three characteristics effective field should be calculated first. The effective field acts on magnetization of free layer when external magnetic field and current are applied to an STO. Effective field is expressed by three components which are field intensity, in-plane angle φ and out-of-plane angle θ. In-plane angle is the angle between in-plane projection of effective field and easy axis, out-of plane angle is the angle with the plane of film as shown Fig. 1.

In our previous work, three characteristics of an STO are modeled based on Slavin's analytic equations [7]. In the calculation of effective field in our previous model, only external magnetic field and anisotropy field depending on device shape are considered as in Eq. (1).

$$H\sin\theta = H_0 \sin\theta_0 - 4\pi M_0 \sin\theta \quad (1a)$$

$$H\cos\theta\cos\varphi = H_0\cos\theta_0\cos\varphi_0 + H_A\cos\theta\cos\varphi \quad (1b)$$

$$H\cos\theta\sin\varphi = H_0\cos\theta_0\sin\varphi_0 \quad (1c)$$

A fitting parameter δ was introduced in the calculation of mean power $\bar{p}$ to compensate the difference between our simulation results and measurement data as in Eq. (2) [6].

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

$$\omega_g = \omega_0 + N\bar{p} \quad (2b)$$

$$2\Delta\omega = (1+\nu^2)\,\Gamma_+(p_0)\frac{k_B T}{E(\bar{p})} \quad (2c)$$

In these equations, ω_0 is ferromagnetic resonance frequency, ζ is supercriticality parameter, Q is nonlinear damping coefficient, ν is normalized dimensionless nonlinear frequency shift, $\Gamma_+(p_0)$ is positive damping rate, $E(p_0)$ is the oscillator energy, and η is effective noise power.

In this work, dipole field and interlayer exchange field are added to calculate the effective field in order to reflect physical phenomena more accurately as in Eq. (3).

$$H_{eff} = H_0 + H_{dip} + H_A + H_{ex} + H_I \quad (3)$$

In this equation, H_0 is external magnetic field, and H_{dip}, H_A, H_{ex}, H_I indicates dipole field, anisotropy field, interlayer exchange field, and Oersted field, respectively.

H_{dip} includes dipolar coupling between fixed layer and free layer. It is either neglected or simply considered as scalar addition of external field intensity in many STO models. However, in accordance with characteristic of a device, direction of magnetization of fixed layer changes considerably depending on in-plane angle of external field. Therefore it is desirable that vector summation of dipolar coupling is applied to calculation of effective field to consider the change of magnetization of fixed layer.

Also, H_I is Oersted field induced by current that acts differently on each internal area of device. Eventually, H_I affects center frequency and linewidth of STO because initial direction and precession trajectory of magnetization of free layer are different in each area. For an accurate analysis, we need micro-modeling which analyzes characteristics by dividing internal area of free layer. In our model, a simple macro-modeling of H_I is adopted for effectiveness of simulation such that a fitting parameter depending on in-plane angle of external field multiplied to parameter N which is nonlinear frequency-shift coefficient as in Eq. (4).

$$N_{modified} = \alpha(\varphi_{ex}) * N_{original\ equation} \tag{4}$$

where

$$\alpha(\varphi_{ex}) = -0.286\sqrt{\varphi_{ex}} + 0.98 \;\; (0 \le \varphi_{ex} \le \tfrac{\pi}{2})$$
$$= -0.286\sqrt{-(\varphi_{ex} - \pi)} + 0.98 \;\; (\tfrac{\pi}{2} \le \varphi_{ex} \le \pi\ )$$

Then, the three characteristics of STO, which are generation frequency ω_g, linewidth $2\Delta\omega$, and mean power $\bar{p}$, are derived by using calculated effective field and bias current along with various internal parameters as in Eq. (5).

$$\omega_g = \omega_0 + N\frac{\zeta-1}{\zeta+Q} \tag{5a}$$

$$2\Delta\omega = (1+\nu^2)\,\Gamma_+(p_0)\,\frac{k_B T}{E(p_0)} \tag{5b}$$

$$\bar{p} = \frac{Q\eta}{Q+\zeta}\left[1 + \frac{\exp(-(\zeta+Q)/Q^2\eta)}{E_\beta((\zeta+Q)/Q^2\eta)}\right] + \frac{\zeta-1}{\zeta+Q} \approx \frac{Q\eta}{Q+\zeta} + \frac{\zeta-1}{\zeta+Q} \tag{5c}$$

As a result, we can get three characteristics of STO without introducing a fitting parameter δ to Slavin's analytic equations by enhancing the calculation of effective field.

3. Modeling of STO in Verilog-A

The behavior of an STO is modeled in Verilog-A which is a hardware description language tailored to mixed-mode circuit design. A flow chart of modeling and skeleton of STO model in Verilog-A are shown in Fig. 2 and Fig. 3.

At first, effective magnetic field is calculated with vector operation by MATLAB. Secondly, complex internal parameters are computed. Then, using these parameters, mean power and center frequency of the oscillation are obtained. After that, random frequency fluctuation is generated to model the linewidth of an STO. Linewidth in frequency spectrum is affected by not only phase fluctuation but also frequency fluctuation which is change of the generation frequency of an STO [8]. In our model, linewidth is expressed as additional frequency component having Gaussian random distribution during random period. Consequently, the generation frequency is sum of center frequency and the frequency fluctuation component, and the generation frequency of STO is swiched to another frequency at random interval. Finally, sinusoidal output of STO is generated as a voltage signal between top and bottom nodes of an STO device to satisfy upper characteristics. The first part of the modeling process is performed in MATLAB because vector operations are not directly supported by Verilog-A HDL.

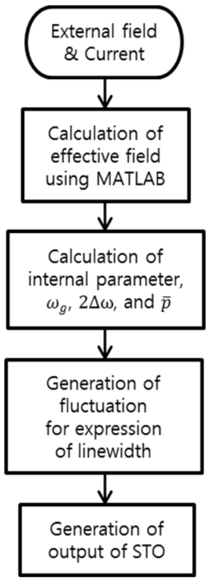

Fig. 2. Flow chart of modeling of STO.

```
Module GMR_STO (top, bottom);
    inout top, bottom;
    electrical top, bottom;
    Itb = abs(I(top, bottom));
    // definition of device parameter & variable
    parameter Heff = ...
    parameter phi = ...
    parameter theta = ...
    ......
    analog begin
        // calculation of internal parameter
        // calculation of three characteristics
        w_g = w0+N*((zeta-1)/(zeta+Q));
        linewidth = ...
        mean_p = ...

        // generation of fluctuation
        @(timer(0, time_random*1n+1.00001n))
        begin
            st=(linewidth/(2*`pi))/const1;
            time_random = abs($random % const2);
            fluctuation
              = $rdist_normal($random%const3, 0.0, st);
        end

        time_signal
          = sqrt(mean_p)*cos(2*pi*(w_g + fluctuation)*$abstime);
        V(top, bottom) <+ Rdc*Itb + time_signal;
    end
endmodule
```

Fig. 3. Verilog-A codes of modeling of STO.

III. CIRCUIT LEVEL SIMULATION

In order to verify operation of proposed STO model, we simulated current mirror circuit connected with an STO as shown in Fig. 4 using Hspice. The voltage of output node is observed by changing external magnetic field with fixed biased current.

The relation between generation frequency and external field intensity is shown in Fig. 5. Both the simulation results with our STO model and measurement data in [4] are shown in the figure. Generation frequency tends to increase with increasing of field intensity, and simulation results fit well with the experiment data. Simulation results with our previous mode are also shown in Fig. 5. In this case when the external magnetic field dominates, our new model does not show noticeable difference from the previous model.

Fig. 6 shows comparison of three characteristics of an STO with respect to in-plane angle of external field. Generation frequency and linewidth of an STO decrease as in-plane angle increases from 0 to 90 degrees. Consequently, they have the minimum value at 90 degrees. On the contrary, the mean power tends to increase as the angle increases, so the power has its maximum value at 90 degrees. Also, results of all three characteristics of an STO are symmetric with respect to the 90 degrees.

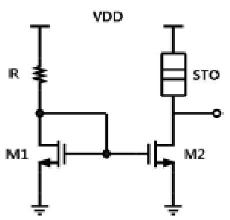

Fig. 4. STO with current mirror circuit.

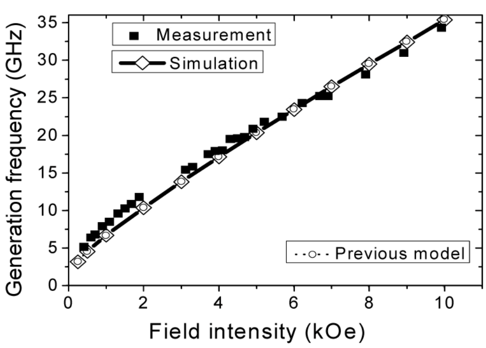

Fig. 5. Comparison of simulation with experiment as a function of the external field intensity. The experimental data are excerpted from [4].

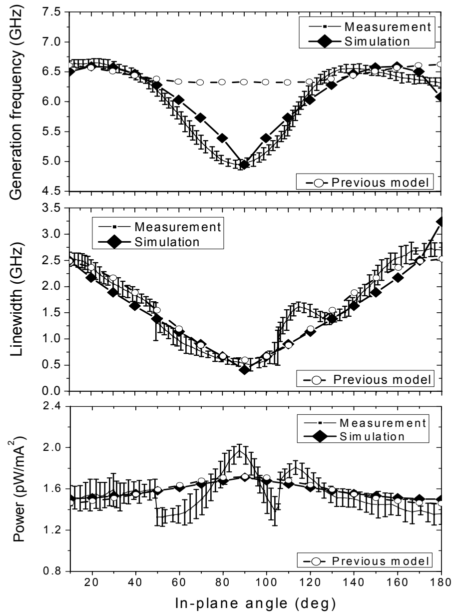

Fig. 6. Comparison of simulation with experiment as a function of the in-plane angle of external field. The experimental data are excerpted from [9].

Simulation results of three characteristics with our advanced model show good agreement with experimental data [9]. Slight discrepancies appear at certain points in the case of linewidth and power. It is mainly due to the fluctuation in measurement data. We expect the validity of our model will be strengthened through comparison with more experimental results.

The top figure in Fig. 6 clearly shows the improvement of the proposed model. Simulation results from our previous model shows large differences from measurement data because it only considers the effects of external magnetic field and anisotropy field. Thus, in the case when either dipole field or exchange field is not small, these fields should be considered to calculate the effective field.

Simulation results with respect to bias current and out-of-plane angle of an external field also fit well to measurement data.

The Fig. 7(a) shows the output of an STO in time-domain when external field is 800 Oe in the direction of hard axis and the dc current is 5.5 mA. The output is sinusoidal signal with given power and frequency. We can also see that the generation frequency shifts from one frequency to another at about 15 ns. That means our

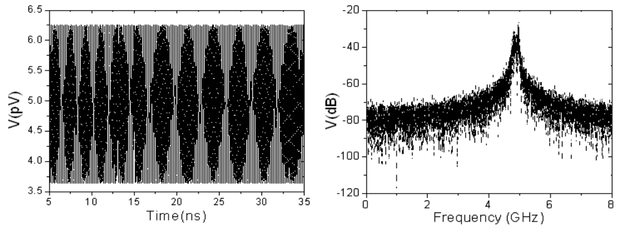

Fig. 7. The output voltage signal in time domain (a) and in frequency domain (b).

model reflects the characteristic of frequency fluctuation of an STO.

Fig. 7(b) shows the frequency spectrum of generated signal. In this example, center frequency is about 5 GHz, and the linewidth due to the frequency fluctuation is about 400 MHz.

IV. CONCLUSIONS

In this paper, a circuit level model of STO based on physical phenomena is proposed. Especially, our previous semi-empirical model is improved to increase the accuracy of our model by enhancing calculation of effective field. Dipole field and interlayer exchange field are added in the calculation of the effective field in order to reflect physical phenomena more accurately. Thus, a fitting parameter that was introduced in our previous semi-empirical model can be safely removed without loss of modeling accuracy. The operation of our STO model is verified through Hspice simulation on a current mirror circuit connected with an STO model written in Verilog-A HDL. Simulation results obtained by changing intensity, in-plane angle and out-of-plane angle of external magnetic field show very good agreement with previously published experimental data.

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