Spin-Torque Diode-Based Radio-Frequency Detector by Utilizing Tilted Fixed-Layer Magnetization and In-Plane Free-Layer Magnetization

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We report a novel spin-torque diode (STD) radio-frequency detector by utilizing tilted fixed-layer magnetization and in-plane free-layer magnetization. Through macrospin modeling and numerical simulation, we study both the direct current (dc) dependence and the perpendicular external field dependence of the output voltage of the detector. We systematically investigate both the fixed-layer magnetization tilt angle dependence and the dc dependence of the resonance detection regime of the detector. It is found that an ultrawide resonance detection regime 6.5 GHz can be achieved, which is 1200% higher than the traditional STD magnetic tunnel junction detector with in-plane fixed-layer magnetization.

***Index Terms*—Resonance detection regime, spin-torque diode (STD), tilted fixed-layer magnetization.**

I. INTRODUCTION

SINCE the first discovery of spin-transfer-torque effect in magnetic nanoscale systems, massive studies [1]–[6] related to spin-transfer-induced magnetization dynamics have witnessed desirable progress of spintronic devices, which provides considerable promising solutions to exceed the performance of traditional semiconductor devices. Particularly, in recent 10 years, the spin-torque diode (STD) effect [7]–[11] has intrigued intensive attentions due to its potential application as radio-frequency (RF) detector, which enables one to rectify an alternating current (ac) in nanoscale magnetic tunnel junction (MTJ) through synchronizing the current with the resonant oscillation of the tunnel magnetoresistance. Meanwhile, this effect has also been utilized not only to theoretically explain the nature but also to quantitatively measure the amplitude of the spin torque in MTJs. As one of the several parameters important for the STDs in practical application as RF detectors, the RF detection sensitivity [12]–[16] is widely studied in order to reach or surpass the level of the semiconductor Schottky diode detectors. Representative approaches include the control of magnetic field direction [17], the use of stochastic resonance [18], and the voltage control [19] of the magnetic anisotropy. However, aside from the aforementioned topics, the studies aiming to broaden the resonance detection regime, which are also crucial for STD RF detector into practical application, are still insufficient.

In this paper, we propose a novel STD RF detector structure based on tilted fixed-layer MTJ. The results show that the resonance detection regime could be significantly improved while good RF detection sensitivity is maintained.

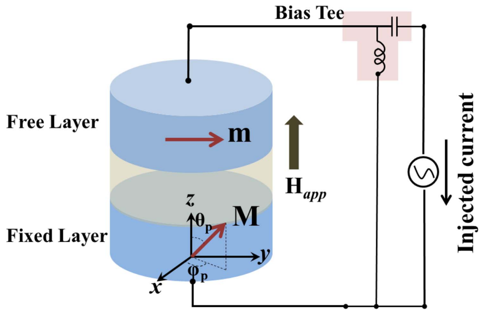

Fig. 1. Schematic of the STD system. The positive current direction is from a fixed layer point to a free layer.

II. MODELING AND COMPUTATION DETAILS

The system considered in this paper is a three-layer MTJ sandwich structure, as presented in Fig. 1(a). Since the size of the MTJ is so small, the magnetic moments in the ferromagnetic layers are uniform and can be analyzed based on the macrospin model. The unit vectors pointing in the direction of the magnetizations of the free and fixed layers are denoted as $\mathbf{m} = (0, 1, 0)$ and $\mathbf{M} = (\sin\theta_p\cos\varphi_p, \sin\theta_p\sin\varphi_p, \cos\theta_p)$, where $\varphi_p = 0$ implies the in-plane pinned layer magnetization.

We numerically obtain the time evolution of the free-layer magnetization through solving the Landau–Lifshitz–Gilbert equation

$$\begin{aligned}\frac{d\vec{\mathbf{m}}}{dt} &= -\gamma\,\vec{\mathbf{m}} \times \vec{\mathbf{H}}_{\mathbf{eff}} + \alpha\vec{\mathbf{m}} \times \frac{d\vec{\mathbf{m}}}{dt}\\ &\quad -\gamma\frac{J\hbar}{2eM_s d}\,\frac{P}{1+P^2\cos(\varphi(t))}\\ &\quad \times [\vec{\mathbf{m}} \times (\vec{\mathbf{m}} \times \vec{\mathbf{M}}) + b_f\vec{\mathbf{m}} \times \vec{\mathbf{M}}] \qquad (1)\end{aligned}$$

where H_{eff} is the effective field, which is comprised of external, anisotropy, and demagnetization fields. γ represents the gyromagnetic ratio, α represents the Gilbert damping parameter, and μ_0 represents the magnetic vacuum permeability.

Manuscript received March 20, 2015; revised May 14, 2015; accepted May 25, 2015. Date of publication June 1, 2015; date of current version October 22, 2015. Corresponding authors: Y. Zhou and P. W. T. Pong (e-mail: yanzhou@hku.hk; ppong@eee.hku.hk).

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Digital Object Identifier 10.1109/TMAG.2015.2438018

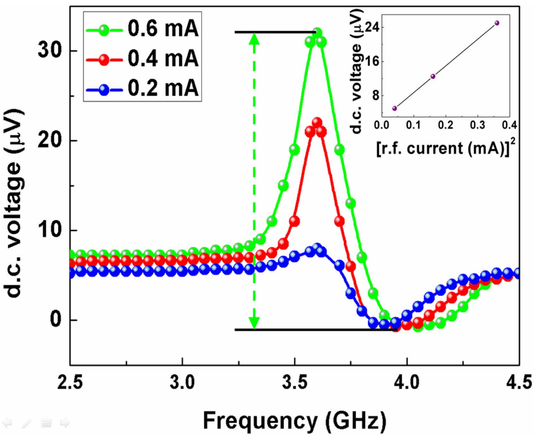

Fig. 2. DC voltage generated by the device in response to the ac when the external field H_{app} is set as 500 Oe and titled angle $\theta_p = 35°$. Inset: linear power dependence of the dc voltage measured from peak-to-valley, as marked by the arrow in the main panel.

The lateral dimension of the NiFe thin film free layer is assumed to be an elliptical shape of 130 × 70 nm^2 with a thickness of 3 nm, while the thickness of the fixed layer FePt is 20 nm. The parameters [21] used in the calculation are as follows: $\alpha = 0.01$, $\gamma = 1.76 \times 10^{11}$ Hz/T, $M_s = 860$ kA/m, $H_k = 0.01$ T, and $H_d = 1$ T. The total spin current density J includes both the ac current density J_{ac} that is to be measured and the direct current (dc) current density J_{dc} that is used to tune the output voltage. P is the spin polarization of the injected current while $\varphi(t)$ is the angle between the free- and fixed-layer magnetization. $b_f = 0.1$ is introduced as the ratio of the magnitudes between the in-plane ST and field-like ST [19], [20].

III. SIMULATION RESULTS AND DISCUSSION

We studied the STD effect by calculating the ferromagnetic resonance (FMR), as shown in Fig. 2. When a relatively weak RF current $I(t) = I_{\text{RF}} \times \cos(2\pi f_{\text{RF}} \times t)$ and a dc is applied to the MTJ simultaneously, the spin torque will excite the free-layer magnetization in an orbit around the equilibrium configuration. A rectified output voltage will be obtained if the time-evolving total current and the time-evolving resistance are phase locked with each other. The rectified output dc voltage obtained from the simulation could be calculated by the ohms law: $V_{\text{output}} = \langle (I_{\text{ac}}(t) + I_{\text{dc}}) \times R(t) \rangle$, where $\langle\ \rangle$ represents the average over the integrated period. From Fig. 2, it is found that when the external field and the tilted angle are fixed ($H_{\text{app}} = 500$ Oe and $\theta_p = 35°$ in this case), the increase in the amplitude of the dc will result in larger output direct voltage (also means larger detect sensitivity). Meanwhile, it is also observed from the inset of Fig. 2 that dc voltage increases linearly with the square of the current. These results are consistent with some previous studies [7]. Furthermore, the spectrum shape in Fig. 2 is symmetric when the injected dc current is relatively large (0.4 and 0.6 mA) while it becomes asymmetric when the injected current is relatively small (0.2 mA). In fact, the shape of the spectrum is largely determined by the parameter b_f that is mentioned in (1). The in-plane ST tends to symmetrically shape the spectrum with a single peak while the field-like ST tends to disperse the spectrum peak [22]. In STD MTJ detector with tilt fixed layer, the in-plane ST overwhelms field-like ST when injected dc current is relatively large (0.4 and 0.6 mA) and thus the spectrum with symmetric Lorentzian distribution is observed [11]. The reason why the asymmetric Lorentzian distribution spectrum is observed when the injected dc current is relatively small (0.2 mA) is still under investigation. This tendency is very different from the phenomenon that observed in STD MTJ detector with in-plane fixed layer.

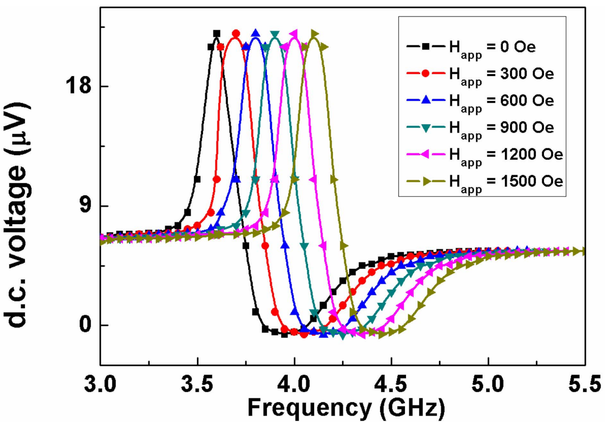

Fig. 3. DC voltage generated by the device in response to the external field when the injected dc current is fixed with 0.4 mA and tilted angle $\theta_p = 0°$ (in-plane fixed layer).

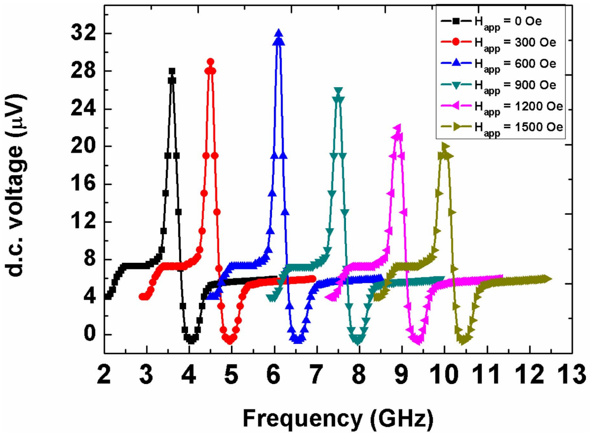

Fig. 4. DC voltage generated by the device in response to the external field when the injected dc current is fixed with 0.4 mA and titled angle $\theta p = 35°$.

In addition to the characteristics of the dc dependence on the output voltage in aforementioned study, we further investigated the external field dependence on the output voltage when both the titled angle $\theta_p = 0°$ (Fig. 3) and $\theta_p = 35°$ (Fig. 4), respectively. As shown in Fig. 3, an STD MTJ detector with perpendicular field tuned resonance is observed. The increase in the external field will achieve the increase in the RF that spin diode MTJ can detect while the external field does not demonstrate any dependence on the output direct voltage. The simulation results indicate that to increase the external field from 0 to 1500 Oe only brings 0.5 GHz

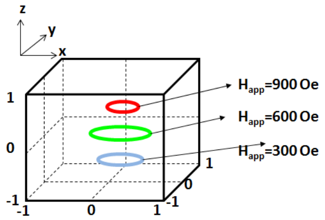

Fig. 5. Trajectory of the magnetization unit vector when the injected dc current is fixed with 0.4 mA and titled angle $\theta p = 35°$.

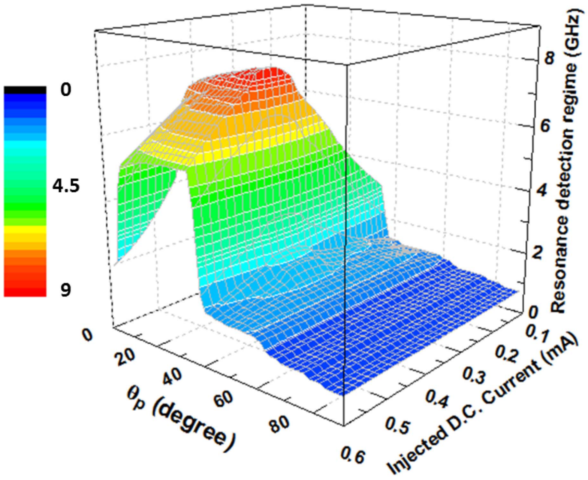

Fig. 6. Influence of fixed-layer magnetization tilted angle θ_p and dc current on the resonance detection regime. $\theta_p \in [0, 90]°$ and the injected dc current $\in [0.1, 0.6]$ mA.

broadening for the RF detection regime, which is not quite efficient.

When we customized the magnetization direction of the fixed-layer magnetization and set the titled angle to $\theta_p = 35°$ as shown in Fig. 4, it is observed that the perpendicular external field could influence not only the RF that spin diode MTJ can detect but also the output direct voltage. On the one hand, the output direct voltage will slightly increase when the external perpendicular increase from 0 to 600 Oe, and then drastically decreases when the external perpendicular field increases from 600 to 1500 Oe. To explain this phenomenon, we plot the trajectory of the magnetization unit vector in Fig. 5 when $H_{\text{app}} = 300$, 600, and 900 Oe, respectively. The magnetization unit vector trajectory suggests that as the perpendicular field increases from 0 to 600 Oe, the precession orbit radius of the free-layer magnetization gradually increases and reaches its maximum value at 600 Oe. When the perpendicular field exceeds 600 Oe, the free-layer magnetization flips and forms a new precession orbit with very small orbit radius, leading to the drastic decrease in the output voltage. On the other hand, it is clear that the increase in the external field from 0 to 1500 Oe will result in a very large frequency detection shift from 3.4 to 9.9 GHz, which brings 6.5 GHz broaden for the RF detection regime. This is around 1200% enhancement compared with the RF detection regime when the fixed layer is in-plane. One reasonable theory to explain this large detection regime is due to the spin-torque FMR (ST-FMR) effect, which has also been reported in [9].

Furthermore, it is systematically explored that how the fixed-layer tilt angle θ_p and the injected dc influence the resonance detection regime in Fig. 6. From Fig. 6. it is intuitively understood that as the tilt angle increases from 0° to 35°, the detection regime also increase and reach its maximum value at 35°. After the tilted angle exceeds 35°, the detection regime will significantly decrease. Meanwhile, under certain tilt angle, the detection regime also exhibits an increase first and decreases with the injected dc. An optimal parameter combination to obtain the maximum resonance detection regime is this paper is $\theta_p = 35°$ and $I_{\text{dc}} = 0.4$ mA.

IV. CONCLUSION

In summary, we successfully modeled the STD RF detector with tilt fixed-layer magnetization using a macrospin simulation model. We analyzed the injected dc influence on the output voltage (detection sensitivity) by employing the discussion of the in-plane ST and the field-like ST. We also obtained the perpendicular field tuned resonance effect for fixed layer with both in-plane magnetization and tilt magnetization. It is revealed that the utilization of the titled fixed-layer magnetization will remarkably enhance the resonance detection regime by 1200%. Finally, the optimal parameter combination of $\theta_p = 35°$ and $I_{\text{dc}} = 0.4$ mA will lead to the maximum resonance detection regime in this paper. These results could be used as a guideline for the fabrication of high performance STD detector with an ultrawide detection regime.

ACKNOWLEDGMENT

This work was supported in part by the Seed Funding Program for Basic Research and Small Project Funding Program of the University of Hong Kong, under Grant ITS/104/13, and Grant ITS/171/13 (Innovative Technology Fund (ITF) Tier 3 funding), in part by the Research Grant Council-General Research Fund (RGC-GRF) under Grant The University of Hong Kong (HKU) 704911P, in part by the RGC-GRF under Grant HKU 17210014, and in part by University Grants Committee of Hong Kong under Contract AoE/P-04/08.

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