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Nonlinear spin-torque microwave resonance near the loss of spin state stability

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A B S T R A C T

The paper analyzes microwave resonant response of the spin-torque diode. The considered spin-torque diode is a magnetic tunnel junction with a nano-pillar structure. The magnetization of the free layer has a tilt caused by an action of the inclined magnetic field in the plane of the structure. Taking into account the effect of spin torque transfer we define stability regions of stationary states of magnetization in the free layer as a function of the azimuth angle of the magnetic field and bias DC current. Microwave volt-watt sensitivity of the spin diode for the obtained stationary states is calculated. It is shown that non-linear frequency shift of the resonance line width limits maximum sensitivity of the spin diode near the critical bias current corresponding to the point of the transition to the self-oscillating mode. Besides that, overlapping of frequency branches occurs in the resonant response as the critical point approach, which is different from the foldover effect in the nonlinear ferromagnetic resonance induced by an alternating magnetic field.

1. Introduction

Magnetic tunnel junction (MTJ), which is promising to create a new generation of non-volatile memory, demonstrates a spin diode rectification effect of the microwave signal [1–10]. Due to the giant magnetoresistance and spin torque transfer effects spin diode, in principle, allows to reach a thermodynamic limit of the volt-watt sensitivity. The effect of the DC voltage occurrence at the MTJ under microwave current has been analyzed for different mechanisms of spin torque effects, bias current values, linear and nonlinear oscillation modes (see. e.g. [5,9,10] and cit. lit.). It was shown that volt-watt sensitivity of the spin-torque diode increases with the increase of a DC bias by more than an order of value for a weak deviation from the mutually perpendicular geometry of magnetization in magnetic layers of the MTJ. The increase may exceed ultimate sensitivity of the semiconductor Schottky diode [5,10]. In Ref. [5] the increase of the microwave sensitivity was associated with the drop of the resonance line width to zero, when the DC bias approaches critical value. The effects of instability have been observed in the vicinity of the transition to the oscillatory regime, mechanisms of which are not entirely clear. Some questions of microwave sensitivity limits for different modes of spin self-oscillation in the supercritical region were considered in [9]. Another mechanism of the sensitivity behavior in the region of spin self-oscillation associated with the injection locking effects was investigated in [10].

The microwave sensitivity limitations of the spin-torque diode before the transition to a self-oscillations mode under the DC bias for different tilted states of its magnetization we analyze below. We have shown that microwave spin diode sensitivity is limited by non-linear shift of the resonance line width near the critical bias current, when the line width of forced oscillations tends to zero in linear approximation. At the same time there is a hysteresis effect near the resonance frequency, which is significantly different from the non-linear effect of overlapping of frequency branches in the ferromagnetic resonance induced by an alternating magnetic field.

2. Basic equations

Let us consider the spin diode with a magnetization tilt in the free layer and fixed magnetization in the reference layer having cylindrical nano-pillar symmetry as shown in Fig. 1. Similar structure was considered in [6] within the framework of the linear theory and without bias current. We assume that nano-pillar diameter D of the spin diode is comparable to the exchange length in its magnetic layers and therefore spin dynamics is described in the macrospin approximation. In this case we can neglect the inhomogeneous modes of spin

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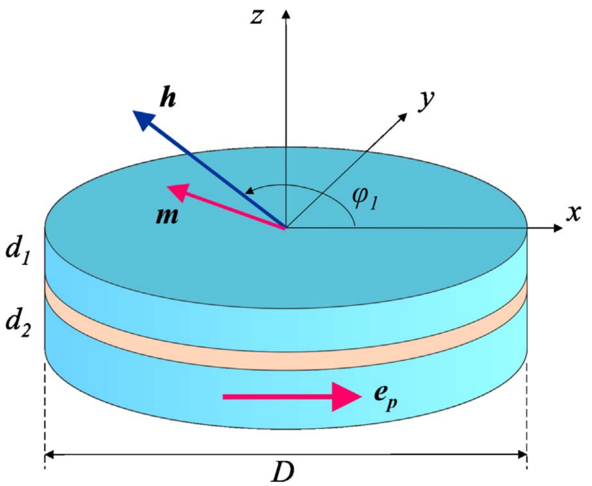

Fig. 1. (Color online) Considered nano-pillar magnetic tunneling diode with the tilt of the magnetization in the free magnetic layer and fixed magnetization in the reference layer.

oscillations. In general case one should take into account spin time variation in both magnetic layers. However, if the thickness of the upper and lower layers is substantially different, i.e. $d_1 << d_2$, and the exchange bias field in the reference layer is sufficiently large, magnetization oscillations in the reference layer are negligible near the spin-torque resonance for the free layer. In this case it is possible to adopt the approximation in which the magnetization of the second layer is fixed i.e. $\mathbf{m}_2(t) \approx \mathbf{e}_p = const$, where the vector $\mathbf{e}_p$ is directed along the pinning field in the second layer. Dynamical system is simplified and is described by the Landau-Lifshitz-Gilbert -Slonczewski equation for the free layer

$$\dot{\mathbf{m}} = -\mathbf{m} \times \mathbf{h}_{eff} + \alpha \mathbf{m} \times \dot{\mathbf{m}} - \eta_{\parallel}\beta(t)\mathbf{m} \times [\mathbf{m} \times \mathbf{e_p}] - \eta_{\perp}\beta(t)[\mathbf{m} \times \mathbf{e_p}], \tag{1}$$

where $\mathbf{h}_{eff} = k_{eff}(\mathbf{m}\cdot \mathbf{e}_n)\mathbf{e}_n + \mathbf{h} - \kappa \mathbf{e_p}$, $\beta(t) = \beta_0 + \beta_1 \cos(\omega t)$, $\mathbf{m} = \frac{\mathbf{M}}{M_s}$, $\mathbf{h} = \frac{\mathbf{H}}{M_s}$ is the external magnetic field, normalized by the saturation magnetization M_s, $\beta = \frac{J}{J_p}$ is the spin-polarized current, normalized by $J_p = \frac{2edM_s^2}{\hbar}$, where d is the thickness of the free magnetic layer, e is the electron charge, $\hbar$ is the Planck constant, $\eta_{\parallel}$, $\eta_{\perp}$ are the spin-polarized prefactors. The time is normalized by $t_0 = (\gamma\ M_s)^{-1}$, where γ is the gyromagnetic ratio and the frequency is normalized by $[\omega] = \gamma\ M_s$. The spin-polarized prefactors that determine spin-torque components transferred by the current depend on the relative magnetization directions in the layers of the structure according to the relations

$$\eta_{\parallel} = \frac{\eta_{\parallel}^0}{1 + \rho\mathbf{m}\cdot\mathbf{e}_p}, \eta_{\perp} = \frac{\eta_{\perp}^0}{1 + \rho\mathbf{m}\cdot\mathbf{e}_p}, \tag{2}$$

where $\rho = (\eta_{\parallel}^0)^2$, k_{eff}, k_b are the parameters of in-plane and basic anisotropy, $\kappa \sim 2\pi d_2/D$ is the coefficient of the magneto-dipole interaction.

We assume $\beta = \beta_0 + \beta_1 \cos \omega t$, where β_0 is a DC bias current and β_1 is the AC current amplitude, which is proportional to the square root of the input signal power P_{in} according to the relation $\beta_1 = \frac{2\sqrt{2P_{in}Z_0}}{(\overline{R} + Z_0)SJ_p}$, where S is the cross-sectional area of the spin-torque diode, $\overline{R}$ is the diode resistance, $Z_0 = 50$ Om is the impedance of the line.

The sensitivity of the spin diode equals to $\varepsilon = \frac{<\Delta V>}{P_{in}}$, where $<\Delta V>$ is the time-averaged voltage on the spin diode, andP_{in} is the incident microwave power. In the frame of the proposed model the average voltage is determined by the formula

$$<\Delta V(t)> = J_p\overline{R}S\left\langle \frac{\beta_1 \cos(\omega t)}{[1 + \rho\mathbf{m}(t)\mathbf{e}_p]} \right\rangle, \tag{3}$$

where $\overline{R}^{-1} = \frac{R_{\uparrow\uparrow}^{-1} + R_{\uparrow\downarrow}^{-1}}{2}$, $\rho = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\downarrow} + R_{\uparrow\uparrow}}$, $R_{\uparrow\uparrow}$ and $R_{\uparrow\downarrow}$ are the spin-torque diode resistances for parallel and anti-parallel magnetization states correspondingly.

The dissipated power P_0 on the resistance $\overline{R}$ is

$$P_0 = \overline{R}S^2J_p^2 \left\langle \frac{\beta_1^2 \cos^2(\omega t)}{[1 + \rho\mathbf{m}(t)\mathbf{e}_p]} \right\rangle, \tag{4}$$

On the other side, the input power is related to the dissipated power by the well-known matching ratio $P_0 = P_{in}\frac{4Z_0\overline{R}}{(Z_0 + \overline{R})^2}$. Taking into account this expression, the microwave sensitivity of the spin diode becomes

$$\varepsilon = \frac{<\Delta V>}{P_{in}} = A\frac{\left\langle \frac{\beta_1 \cos(\omega t)}{[1 + \rho\mathbf{m}(t)\mathbf{e}_p]} \right\rangle}{\left\langle \frac{\beta_1^2 \cos^2(\omega t)}{[1 + \rho\mathbf{m}(t)\mathbf{e}_p]} \right\rangle}, \tag{5}$$

where $A = \frac{1}{J_pS}\frac{4\overline{R}Z_0}{(\overline{R} + Z_0)^2}$.

We take the following parameters of the spin diode structure. $d = 2$ nm, $D = 140$ nm, $S = \pi 70 \times 70$ nm^2 $= 1.5\cdot 10^4$ nm^2, $M_s = 10^6$ A/m, $S\overline{R} = SdV/dI = 10\ \Omega$ μm^2, $\overline{R} = 700\ \Omega$,$\Delta R/R = 130\%$, $\eta_{\parallel}^0 = 0.63$, $\eta_{\perp}^0 = 0.3$, $\rho = (\eta_{\parallel}^0)^2 = 0.4$,$\alpha = 0.01$, $d = 2\pi d_2/D = 0.27$, $k_{eff} = -4\pi N_z = -12$, $k_b = 4\pi(N_y - N_x) = 0$.

Chosen resistive parameters are close to those of the spin-torque diode structure investigated in [10], but for different anisotropy parameters. For these parameters the frequency is normalized by $[\omega] = 3.2$ GHz, current density is normalized by $J_p = 6.4\cdot 10^{11}$ A/m^2, sensitivity is normalized by the factor $A = 26$ mV/mW. The magnitude of the external magnetic field is regarded as fixed and equal to $H = 3.98\cdot 10^4$ A/m, or in normalized units $h = 0.5$. Magnetic field direction in the first magnetic layer is fixed in the layer plane, and the azimuth angle ϕ_1 is varied. The direction of the magnetization in the second layer is fixed in the layer plane by $\phi_2 = \phi_p = 0$.

3. Stability regions of magnetization states in the angle-current plane in the absence of microwave irradiation

Based on the fact that the microwave sensitivity maximum is reached near the critical lines of loss of stationary states stability, it is necessary to choose the optimal angle of inclination of the magnetic field in accordance with the “angle - current” diagram of the transition to the self-oscillating mode. In this connection we first perform linear dynamic analysis of the system in the absence of an external alternating current, i.e. for $\beta_1 = 0$. Qualitative analysis of the dynamic system described by Eq. (1) is carried out by classification of the stationary equilibrium points types after considering characteristic equation for the linearized system near stationary points. Fig. 2 presents the result of the bifurcation analysis of the dynamical system considered for the selected account parameters. It shows stability regions and critical lines on the “angle-current” diagram. It is seen that there are regions in which macro spin equilibrium points are absolutely absent (region II), and only macrospin self-oscillations are possible. The line width of spin-torque resonance tends to zero near the critical lines of transition from the static to the self-oscillating mode (between regions I and II, see e.g. Ref. [5]), and therefore the sensitivity of the microwave excitation should have a maximum. Note that there is no region of the spin precession in the vicinity of angles close to 90°, where microwave sensitivity at zero DC bias reaches a maximum in the frame of linear theory. On the other hand, microwave response will decrease due to the fall of the magnetoresistance amplitude[1] to zero when approaching a state of magnetization of layers to the collinear geometry. In this connection the optimum angle of inclination corresponding to the maximum sensitivity is close to either left border of the upper region of instability or right edge of the bottom region. We

[1] It is easy to show that the microwave sensitivity ε for zero DC bias of spin diode having the tilt of the magnetization in the free layer by an angle ϕ in the linear theory is proportional to $\sin^2\phi$.