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Static and dynamic spin-torque-diode sensitivity induced by the thermoelectric charge and spin currents in magnetic tunnel junctions

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ABSTRACT

Based on the quantum-mechanical transport calculations of the charge and spin fluxes associated with the inhomogeneous thermal heating of three-dimensional structure of MTJ by the input RF microwave power, finite-element analysis of the thermal contribution to the spin-torque sensitivity of MTJ was carried out in the case of zero bias current. Within the magnon-induced spin-transfer torque model, the amplification of DC rectifying voltage in the spin-torque diode initiated by the spin pumping to the tunnel barrier from magnons was also estimated. The results obtained can be used for the development of new types of microwave detectors based on spin thermoelectric effects in MTJ.

Keywords: Magnetic tunnel junction, spin-torque diode, sensitivity, tunnel magneto-Seebeck effect, microwave detector, microwave power, inhomogeneous thermal heating

1. INTRODUCTION

The search for new applications of spin caloritronics, which determines the relationship between charge, spin and heat currents in the presence of temperature gradient across the tunnel barrier in magnetic tunnel junctions (MTJ), is still of particular interest to researchers [1, 2]. An intersection of this field and the rectification effect of an alternating current, which generates the rectified direct-current (DC) voltage in MTJ-based spin-torque diode [3], can open an original method for the thermal control of the spin-torque-diode sensitivity, caused by the inhomogeneous heating of MTJ during its microwave irradiation (Fig. 1). In the static regime, this contribution to the spin-torque sensitivity can be related to the tunnel magneto-Seebeck effect in MTJ, while in the dynamic regime the sensitivity additive shift is determined by the magnetodynamic response of the free layer of MTJ to the thermal spin-transfer torques due to the non-zero temperature drop ΔT_B across the tunnel barrier [4]. Such spin-torque diodes based on the MTJ demonstrate extremely high resonant microwave sensitivity exceeding that of a semiconductor Schottky diode by an order of value in the presence of the bias current [5, 6]. The passage of the microwave current through the spin-torque diode is additionally accompanied by its inhomogeneous heating associated with the non-zero temperature drop across the MTJ. This drop is primarily due to inelastic electron scattering in the ferromagnetic layer close to the tunnel barrier, into which hot electrons enter and where most of the power dissipation occurs [7]. Thus, both the tunnel magneto-Seebeck effect and the thermal spin transfer generated by the temperature gradient in the MTJ give rise to the thermoelectric effect of voltage rectification [8]. In some cases, the influence of this bolometric effect on the spin-torque diode sensitivity may be important and has not been analyzed previously.

2. MODEL

2.1 The MTJ stack

Let us analyze thermally-driven mechanism of spin transport across the MTJ due to asymmetric Joule heating of ferromagnetic layers under microwave current. In general, the applied current, which can be written as $I_e = I_e^{AC}\,\mathrm{Re}\left(e^{i\omega t}\right) + I_e^{DC}$, includes alternating current (a.c. current) with amplitude I_e^{AC} and direct bias current I_e^{DC} (d.c. current), where $I_e^{AC(DC)} = J_e^{AC(DC)} S_{MTJ}$, $J_e^{AC(DC)}$ is the density of a.c. (d.c.) current, $\omega = 2\pi f$, f is the frequency of a.c.

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current, S_{MTJ} is the cross-sectional area of the MTJ. We suppose that the layer composition of the MTJ stack (Fig.1) is taken from experimental work [9]: IrMn(7.5 nm)/CoFe(2.5 nm)/Ru(0.85 nm)/CoFe(0.5 nm)/CoFeB(3 nm)/MgO(0.78 nm)/CoFeB(3 nm). The metallic current lines with the thicknesses of 250 nm are attached to the top and bottom layers of the MTJ, while the cross-section of the MTJ is of a rectangular shape with a width of 120 nm and a length of 250 nm. The spatial profile of potential energy of the electron $U(z)$ in the CoFeB/MgO/CoFeB trilayer inside the full MTJ stack is also presented in Fig. 2 within the free-electron model, where conduction bands are exchange splitted in the ferromagnetic layers.

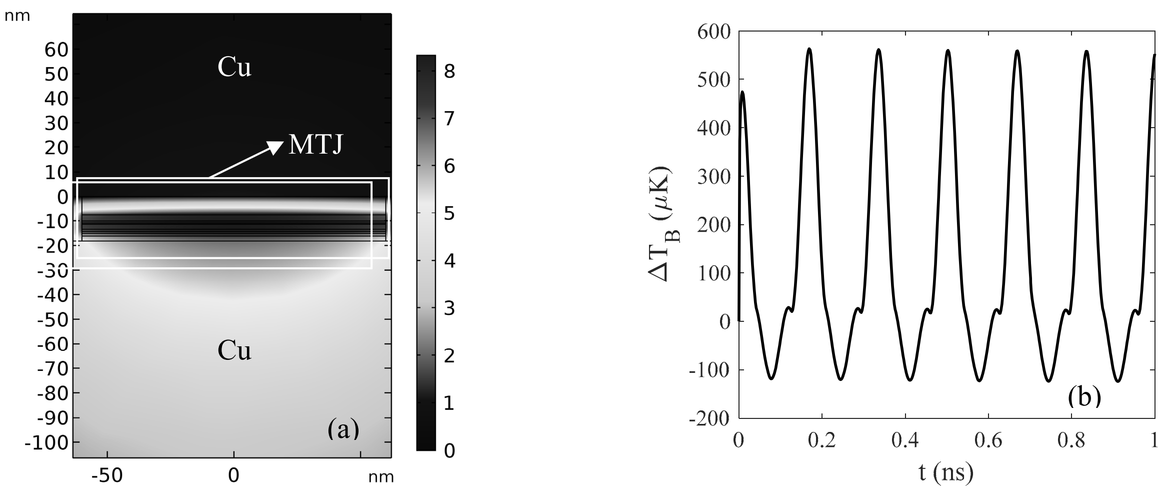

Figure 1. (a) The temperature increment T-T_0 (in mK) of MTJ generated by the input microwave power of 1 μW, where T0=20 K is the room temperature. (b) Time dependence of the temperature drop on both sides of the tunnel barrier of MTJ, induced by the input microwave power of 1 μW at the current frequency of 6 GHz.

2.2 Temperature drop across the MTJ induced by microwave heating

The effect of inhomogeneous microwave heating of the spin-torque diode is associated with the asymmetry of the MTJ and the lead electrodes, as well as with the peculiarity of heat absorption in the MTJ during ballistic transfer of the energy by the charge carriers. A main feature of ballistic heat transfer in the MTJ is the heat power generation near the boundary of the tunnel barrier in the adjacent layers in the direction of which a flow of high-energy electrons enters. It can be taken into account in the following expression of the heat power density $\wp_{MTJ}^{TH}$ dissipated over the thickness of the conducting layers of the MTJ:

$$\wp_{MTJ}^{TH} = \frac{P_e^{IN}}{S_{MTJ}\lambda_{IMFP}}\left(s_I^{(+1)} e^{\frac{z_{BR}-z}{\lambda_{IMFP}}} + s_I^{(-1)} e^{\frac{z-z_{BL}}{\lambda_{IMFP}}} \right), \qquad (1)$$

where $s_I^{(\pm1)} = 0.5 s_I (s_I \pm 1)$, $s_I = s_I(t)$ is the sign of the applied microwave current I_e at given time t, $z_{BL(R)}$ is the z-coordinate of the left (right) boundary of the tunnel barrier, λ_{IMFP} is inelastic scattering mean free path in the receiving ferromagnetic layer, $P_e^{IN} = I_e^2 R_{MTJ}$ is the power of the input signal applied to the MTJ. The MTJ resistance can be written for small deviations $\mathbf{m}$ from $\mathbf{m}_{\mathrm{P}}$ as:

$$R_{MTJ} = \bar{R}_{MTJ} / \left(1 + \rho_0^{MTJ} \mathbf{m}\cdot\mathbf{m}_{\mathrm{P}}\right) \approx \bar{R}_{MTJ}\left(1 - \rho_0^{MTJ}\mathbf{m}\cdot\mathbf{m}_{\mathrm{P}}\right), \qquad (2)$$

where $\mathbf{m}(\mathbf{m}_{\mathrm{P}})$ is the magnetization unit vector in a free magnetic layer (polarizer), $\bar{R}_{MTJ} = 2\left(1/R_P^{MTJ} + 1/R_{AP}^{MTJ}\right)^{-1}\left(1 - \chi_T < T_{MTJ} >\right)$, χ_T is the temperature coefficient of the MTJ resistance, $< T_{MTJ} >$ is the average temperature of MTJ, $\rho_0^{MTJ} = \delta_{MR}^{MTJ} / \left(2 + \delta_{MR}^{MTJ}\right)$, $\delta_{MR}^{MTJ} = \left(R_{AP}^{MTJ} / R_P^{MTJ}\right) - 1$ is the coefficient of tunnel magnetoresistance, $R_{P(AP)}^{MTJ}$ is the MTJ resistance for parallel (antiparallel) magnetization configuration in the MTJ.

In our calculations we assumed that $\mathbf{m} \perp \mathbf{m}_P$, when there is no bias magnetic field applied, and set the bias current I_e^{DC} equal to zero. The inelastic scattering mean free path of electrons in a ferromagnetic metal is supposed to be of the order of 1 nm, as it is described in [7]. As shown in Fig. 2, depending on the polarity of the microwave current I_e, the heat power density $\wp_{MTJ}^{TH}$ will be generated either close to the left or close to the right boundary of the tunnel barrier in adjacent layers. Assuming $I_e^{DC} = 0$, this leads to the harmonic nature of the temperature drop ΔT_B across the tunnel layer of MTJ generated under a.c. part of the microwave current $I_e = I_e^{AC}\,\mathrm{Re}\left(e^{i\omega t}\right)$:

$$\Delta T_B(\omega,t) = \Delta T_{B0}(\omega) + \sum_{\kappa=1\ldots n} \Delta T_{B\kappa}(\omega)\cos(\omega_\kappa t), \tag{3}$$

where $\omega_\kappa = \kappa\omega$, $\Delta T_B(\omega,t) = T_{BL}(\omega,t) - T_{BR}(\omega,t)$, $T_{BL(R)}$ is the temperature on the left (right) boundary of the tunnel barrier of MTJ, $\Delta T_{B\kappa} = \Delta T_{B\kappa}(\omega)$ is the frequency-dependent amplitude of κ-th harmonics, where $\kappa = 0,1\ldots n$. It is well known from the Fourier series analysis that the amplitudes of the corresponding harmonics can be calculated as:

$$\Delta T_{B0}(\omega) = \frac{1}{T}\int_0^T \Delta T_B(\omega,t)\,dt\,,\ \Delta T_{B\kappa}(\omega) = \frac{2}{T}\int_0^T \Delta T_B(\omega,t)\cos(\omega_\kappa t)\,dt \tag{4}$$

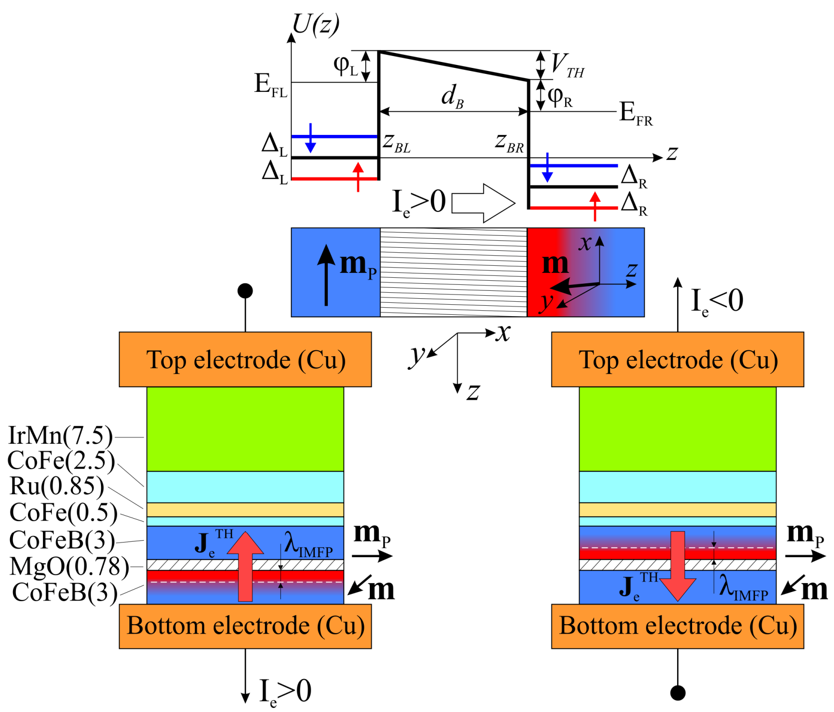

Figure 2. (a) Schematic energy diagram for the potential profile $U(z)$ of the CoFeB/MgO/CoFeB structure in the MTJ (top) and (b) the heat dissipation along the MTJ stack (taken from [9]) under the microwave current I_e passing through it. The red arrow shows the heat flux $\mathbf{J}_e^{TH}$ due to the inhomogeneous Joule heating of the MTJ when the power is generated close to the right (left) from the boundary of the tunnel barrier at the mean free path λ_{IMFP} in the corresponding ferromagnetic layer, depending on the sign of the external microwave current at given time. The thicknesses of the layers in the MTJ stack are in nanometers.

3. RESULTS

3.1 Microwave harmonics of the temperature drop across the MTJ under microwave current

Thermal regimes of the MTJ heating by a direct current were discussed earlier in a number of papers [10-12]. Therefore, we give the results of a similar calculation of the amplitudes $\Delta T_{B\kappa}$ of the harmonic components of ΔT_B that arises when the MTJ is heated by the a.c. current having an input power P_e^{IN} at zero bias current ($I_e^{DC}=0$).

The calculation of the non-stationary microwave heating of the MTJ, shown in Figure 2, by an a.c. current was performed based on the three-dimensional finite-element thermal analysis using the Comsol MultiPhysics software package [13]. In our simulation we used the following parameters of the symmetric CoFeB-MgO-CoFeB-based MTJ with rectangular cross-section, close to experimental data of [9]: $S_{MTJ}=30\cdot 10^3\,nm^2$, $R_P^{MTJ}=175\Omega$, $\delta_{MR}^{MTJ}=0.87$. The temperature coefficient of the MTJ resistance χ_T was set equal to $7.65\cdot 10^{-4}\,K^{-1}$ [14]. The temperature drop ΔT_B was calculated as the difference in the temperature of the CoFeB ferromagnetic leads at the interfaces of the MgO tunnel barrier layer. Figure 1 (a) demonstrates the temperature profile through the CoFeB/MgO/CoFeB trilayer inside the MTJ structure under consideration. Figure 1 (b) shows the time evolution of the temperature drop ΔT_B across the tunnel barrier of the spin-torque diode at a frequency of 6 GHz and a microwave input power equal to 1 μW. It is easy to see from Figure 1 (b) that, since the direction of heat flux in MTJ is reversed as the direction of the current changes, the nature of the temperature drop at the tunnel barrier will depend on the sign of the current.

Further, we can safely restrict our consideration of the temperature drop ΔT_B to only first four harmonics with frequency-dependent amplitudes $\Delta T_{B\kappa}$ ($\kappa=0,1...3$), since only they mainly contribute to the rectifying voltage V_{DC} due to the thermally-driven and the electric-current-driven spin-transfer torques for a given form of a microwave current $I_e=I_e^{AC}\,\mathrm{Re}\left(e^{i\omega t}\right)$. Thus, we suppose that the temperature drop ΔT_B can be approximated as $\Delta T_B\left(\omega,t\right)=\Delta T_{B0}\left(\omega\right)+\sum\limits_{\kappa=1...3}\Delta T_{B\kappa}\left(\omega\right)\cos\left(\omega_\kappa t\right)$. As the frequency $\omega=2\pi f$ increases, the value of the normalized variable components $\Delta\overline{T}_{B\kappa}$ will decrease in accordance with the competition of the oscillation period $T=2\pi/\omega$, which determines the frequency of the change in the microwave signal, with the characteristic time of the heat sink τ_T, in accordance with the relation $\Delta T_{B\kappa}\left(\omega\right)\sim\Delta T_{B0}\left(\omega\right)/\sqrt{1+\left(\omega_\kappa\tau_T\right)^2}$. This amplitude decay is more clearly pronounced for the second harmonic. We also can conclude that the κ-th harmonics of the temperature drop $\Delta T_{B\kappa}$ vary linearly with the power value P_e^{IN}.

3.2 Frequency-independent tunnel magneto-Seebeck effect

The temperature drop ΔT_B across the MgO barrier in a MTJ due to its non-uniform heating by a.c. current leads to the combined effect of static and dynamic rectification of the microwave signal, which is characterized by d.c. voltage $V_{DC}=V_{DC0}^{TH}+\Delta V_{DC}\left(\omega\right)$, where $V_{DC0}^{TH}=-S_{TH}\Delta T_{B0}$, S_{TH} is the frequency-independent tunnel magneto-Seebeck coefficient corresponding to the stationary component of temperature drop $\Delta T_{B0}=\Delta T_{B0}\left(\omega\right)$, and $\Delta V_{DC}\left(\omega\right)$ is the dynamic component of the d.c. rectified voltage. The latter depends on the a.c. part of the microwave current $I_e^{AC}\,\mathrm{Re}\left(e^{i\omega t}\right)$ and time-varying component of the temperature drop $\sum\limits_{\kappa=1...n}\Delta T_{B\kappa}\left(\omega\right)\cos\left(\omega_\kappa t\right)$. Our electron/spin transport calculations are based on a microscopic approach to the theory of thermoelectric transport of a current in the MTJ from a heated electrode to a cold electrode, which was previously used in [4] within the Sommerfeld free-electron model. In contrast to [4], however, we also take into account the variation of the effective masses in each of the layers, which more correctly describes electron transport in magnetic structures based on MgO tunnel barrier [15]. From the condition for the balance of the thermal current of electrons to the electric current in an open circuit for small temperature gradients across the tunnel barrier, one can derive a simple expression for calculating the static Seebeck coefficient in the case of a symmetric MTJ:

$$S_{TH}=-\frac{k_B}{e}\frac{\sum_{\sigma,\sigma'}\int_0^{\infty}P_{\sigma\sigma'(e)}^{(TR_0)}\left(\varepsilon_x\right)\left(\ln\left(1+e^{-\frac{\varepsilon_x-\varepsilon_F}{k_BT_0}}\right)+\frac{\varepsilon_x-\varepsilon_F}{k_BT_0}\frac{e^{-\frac{\varepsilon_x-\varepsilon_F}{k_BT_0}}}{1+e^{-\frac{\varepsilon_x-\varepsilon_F}{k_BT_0}}}\right)d\varepsilon_x}{\left(1-\sigma_J\left(\sigma_J-1\right)\right)\sum_{\sigma,\sigma'}\int_0^{\infty}P_{\sigma\sigma'(e)}^{(TR_0)}\left(\varepsilon_x\right)\frac{e^{-\frac{\varepsilon_x-\varepsilon_F}{k_BT_0}}}{1+e^{-\frac{\varepsilon_x-\varepsilon_F}{k_BT_0}}}d\varepsilon_x}, \tag{5}$$

where k_B is the Boltzmann constant, e is the elementary charge of the electron, ε_x is the longitudinal electron energy, $P_{\sigma\sigma'(e)}^{(TR_0)}=k_{xR}^{\sigma'}\left|T_{\sigma\sigma'}\right|^2/k_{xL}^{\sigma}$, $k_{xL(R)}^{\sigma(\sigma')}$ is the wave vector in the left (right) ferromagnetic MTJ layer with the spin direction $\sigma(\sigma')=\uparrow,\downarrow$, $T_{\sigma\sigma'}$ is the electron transmission coefficient of the spin channel $\sigma\to\sigma'$, ε_F is the Fermi level of the magnetic system, $T_0\approx<T_{MTJ}>$ is the average temperature of the magnetic system (equal to the ambient temperature for small temperature gradients).

Based on the equation (5), we numerically calculated the static tunnel magneto-Seebeck coefficients S_{TH} in the symmetric CoFeB/MgO/CoFeB-based MTJ. The parameters of a such type of MTJ was taken from [4, 16]: $E_F=E_{FL(R)}=2.3eV$ is the Fermi level of ferromagnetic (CoFeB) layers, $\Delta=\Delta_{L(R)}=2.1eV$ is the half of exchange splitting of conduction bands in ferromagnetic (CoFeB) layers, $d_F=3nm$ is the thickness of free ferromagnetic (CoFeB) layer, $d_B=0.78nm$ is the tunnel barrier thickness (MgO), $U_B=\varphi_{L(R)}=1eV$ is the height of tunnel barrier (MgO), $m_{B*}=0.4m_e$ is the effective electron mass in the dielectric layer (MgO), $m_{F*}=1.3m_e$ is the effective electron mass in the ferromagnetic layers (CoFeB), m_e is the mass of the electron, and $T_0=300K$ corresponds to the average temperature of the MTJ. It is also well known that the Seebeck coefficient $S_{TH}=S_{TH}\left(\mathbf{m}\cdot\mathbf{m}_{\mathrm{P}}\right)$ of the MTJ has a pronounced dependence on the angle θ_{MTJ} between $\mathbf{m}$ and $\mathbf{m}_{\mathrm{P}}$, and is spin-dependent [17]. Table 1 summarizes the experimental results from previous studies [18-21] and our theoretical predictions for the Seebeck coefficients $\left|S_{TH}^{P}\right|=\left|S_{TH}\left(\theta_{MTJ}=0\right)\right|$ and $\left|S_{TH}^{AP}\right|=\left|S_{TH}\left(\theta_{MTJ}=\pi\right)\right|$ in the case of parallel and antiparallel magnetic configuration of the MgO-based MTJ with Co- and Fe-containing ferromagnetic electrodes, respectively.

Table 1. Results of experimental measurements and corresponding theoretical estimates for the Seebeck coefficients in MgO-based MTJ at a temperature of 300 K.

Structure (thickness in nm)	$\left\|S_{TH}^{P}\right\|$ **(μV/K)**	$\left\|S_{TH}^{AP}\right\|$ **(μV/K)**	**Ref.**
CoFeB(3)/MgO(1.5)/CoFeB(3)	166 (379)	284 (651)	[18]
CoFeB(3)/MgO(1.5)/CoFeB(3)	223	232	[19]
CoFeB(1.4)/MgO(2)/CoFeB(1.2)	7.3	53.4	[20]
Co_2FeAl(10)/MgO(2)/CoFeB(5)	582	1133	[21]
Co_2FeSi(20)/MgO(2)/CoFe(5)	948	1703	[21]
CoFeB(3)/MgO(0.78)/CoFeB(3)	19.1	66.2	[9], this work

It is easily seen from Table 1, that the range of experimental values of $\left|S_{TH}^{P(AP)}\right|$ in magnetic tunnel structures varies widely. In comparison with the CoFeB/MgO/CoFeB structure, a significant increase in the tunnel magneto-Seebeck effect was observed in [21] for the MTJ with half-metallic Fe-based Heusler (Co_2FeAl and Co_2FeSi) electrodes. In turn, the first-principle calculations lead to maximum values of the spin-dependent Seebeck coefficient $\Delta S_{TH}=\left|S_{TH}^{P}-S_{TH}^{AP}\right|$ close to 150 μV/K in the case of crystalline MgO-based MTJ [22]. The theoretical estimation of the Seebeck coefficients shows that $S_{TH}^{P}=-19.1\mu V/K$ and $S_{TH}^{AP}=-66.2\mu V/K$ for the given parameters of symmetric MTJ. However, it follows from [22] that ΔS_{TH} is equal to 50 μV/K at the room temperature, which is quite consistent with our calculations.

3.3 Spin-torque diode effect induced by a microwave heating of MTJ

In addition to the constant component $V_{DC0}^{TH} = -S_{TH}\Delta T_{B0}$ of the voltage drop across the tunnel layer due to the presence of the static Seebeck effect, the thermal heating of the MTJ under a.c. current also results in a frequency-dependent constant voltage $\Delta V_{DC}(\omega)$. This voltage is associated with the rectification effect of the signal due to modulation of the magnetoresistance induced by the spin-torque components related to the a.c. current $I_e^{AC}\,\mathrm{Re}\left(e^{i\omega t}\right)$ and time-varying part of the temperature drop $\sum_{\kappa=1...n}\Delta T_{B\kappa}(\omega)\cos(\omega_\kappa t)$. Thus, this modulation is associated with a dynamic response of $\mathbf{m}$ to the cumulative effect of thermally- and electric-current-driven spin-transfer torques. According to formula (2), the time-modulation of the spin-transfer torques creates the corresponding spin-orientation modulation of the MTJ resistance $R_{MTJ} = R_{MTJ}(\mathbf{m}(t))$ and, as a consequence, the dynamic renormalization of the tunnel magneto-Seebeck coefficient due to the nonlinear rectification effect of the microwave signal in the spin-torque diode.

As a result, the signal $\Delta V_{DC}(\omega)$ is determined by averaging the oscillations of the variable thermoelectric voltage over the oscillation period $T = 2\pi/\omega$:

$$\Delta V_{DC}(\omega) = \frac{1}{T}\int_0^T dt\Delta R_{MTJ}(\omega)\Delta I_e^{\Sigma}(\omega), \tag{6}$$

where $\Delta R_{MTJ} = -\bar{R}_{MTJ}\rho_0^{MTJ}(\mathbf{m}\cdot\mathbf{m}_\mathrm{P})$ is the dynamic part of the resistance R_{MTJ}, and $\Delta I_e^{\Sigma} = I_e^{AC}\cos\omega t + \Delta I_e^{TH}(\omega)$, $\Delta I_e^{TH} = -S_{TH}R_{MTJ}^{-1}\sum_{\kappa=1...n}\Delta T_{B\kappa}(\omega)\cos(\omega_\kappa t)$ is the thermal current passing through the tunnel barrier of MTJ under its microwave heating and related to the time-varying harmonic components of a temperature drop. Thus, to find the rectified voltage $\Delta V_{DC}(\omega)$ generated in the spin-torque diode, it is primarily necessary to find the dynamic response of the magnetic system to the combined effect of a.c. current and time-varying harmonic part of the temperature drop with the frequency-dependent amplitudes $\Delta T_{B\kappa}(\omega)$, where $\kappa = 1...n$. For this purpose we linearized the Landau-Lifshitz-Gilbert-Slonczewski equation describing the spin-transfer-torque induced magnetization dynamics of a free ferromagnetic layer near the equilibrium position $\mathbf{m} \approx \mathbf{m}_0 = \mathbf{e}_y$, taking into account both in-plane and perpendicular (or field-like) components of two kinds (electric-current-driven and thermally-driven) of spin-transfer torques created by an a.c. current and by non-zero time-varying harmonics of the temperature drop ΔT_B across the MTJ, correspondingly:

$$\dot{\mathbf{m}} = -\gamma\left[\mathbf{m}\times\mathbf{B}_{\mathrm{eff}}\right] + \alpha\left[\mathbf{m}\times\dot{\mathbf{m}}\right] - \frac{\gamma}{M_S d_F}\left(\mathbf{T}_\parallel + \mathbf{T}_\perp\right), \tag{7}$$

where γ is the gyromagnetic ratio, α is the Gilbert damping constant, $\mathbf{B}_{eff} = \mathbf{B} + \mathbf{B}_d$ is the effective magnetic field, which includes the external magnetic field $\mathbf{B}\parallel\mathbf{e}_y$ and the demagnetization field $\mathbf{B}_d = -\mu_0 M_S \mathbf{m}_z$, μ_0 is the vacuum permeability, M_S is the saturation magnetization of free layer, $\mathbf{e}_\mu$ are the unit vectors in the Cartesian coordinate system, where $\mu = x, y, z$. The total spin-transfer torque $\mathbf{T}_{\parallel(\perp)} = \mathbf{T}_{\parallel(\perp)}^E + \mathbf{T}_{\parallel(\perp)}^T$ has two components which correspond to electric and thermal mechanisms of spin transfer. By analogy with the current-induced field-like torque term, the presence of thermally-driven field-like spin torque in the MTJ in the case of asymmetric Joule heating was confirmed experimentally in [23]. The resulting spin-transfer torques can be written as:

$$\begin{cases} \mathbf{T}_\parallel = \left(a_\parallel^E I_e^{AC}\cos\omega t + b_\parallel^T \sum_{\kappa=0,1...n}\Delta T_{B\kappa}\cos(\omega_\kappa t)\right)\left[\mathbf{m}\times\mathbf{m}\times\mathbf{m}_\mathrm{P}\right] \\ \mathbf{T}_\perp = -s_I\left(a_\perp^E I_e^{AC}\cos\omega t - b_\perp^T \sum_{\kappa=0,1...n}\Delta T_{B\kappa}\cos(\omega_\kappa t)\right)\left[\mathbf{m}\times\mathbf{m}_\mathrm{P}\right] \end{cases}, \tag{8}$$

where $a_{\parallel(\perp)}^E = (\hbar/2eS_{MTJ})\eta_{\parallel(\perp)}^E$, $b_{\parallel(\perp)}^T = (\hbar/2eS_{MTJ}R_{MTJ})|S_{TH}|\eta_{\parallel(\perp)}^T$, $s_I = \mathrm{sgn}\left(I_e^{AC}\cos\omega t\right)$, $\hbar$ is the reduced Planck constant, S_{TH} is the static Seebeck coefficient, R_{MTJ} is the MTJ resistance, $\eta_{\parallel(\perp)}^E$ and $\eta_{\parallel(\perp)}^T$ are the dimensionless electric-current-driven and thermally-driven spin-torque efficiencies (spin-polarized coefficients), correspondingly, determined from microscopic quantum-mechanical calculations of corresponding spin fluxes in the MTJ.

Similar to the calculation of spin-transfer torques from a spin-polarized current, we carried out microscopic calculations of the amplitudes of the in-plane and perpendicular components of thermal spin-transfer torque in the absence of bias voltage by solving the quantum-mechanical problem of spin transport through the MTJ and the subsequent thermodynamic averaging of the spin fluxes. This torque is due to the thermal transfer of spin in the presence of temperature drop ΔT_B across the tunnel barrier which is caused by the microwave heating of the MTJ structure. The results of such calculations allow us to estimate the temperature dependencies of thermally-driven spin-torque efficiencies correspondingly for the MTJ structure under consideration (see Figure 2).

According to our previous study [24], we also set the electric-current driven spin-torque efficiencies at zero temperature equal to $\eta_{\parallel}^{E}(0)=0.63$, $\eta_{\perp}^{E}(0)=0.3$. To take into account the effect of temperature on the rectifying voltage, one also should take into account the thermal dependences of the spin-transfer torque efficiencies and the saturation magnetization, which are determined, respectively, as $\eta_{\parallel(\perp)}^{E(T)}\left(T_0\right)=\eta_{\parallel(\perp)}^{E(T)}\left(0\right)\left(1-\chi_P^{E(T)}T_0^{3/2}\right)$, $M_S\left(T_0\right)=M_S\left(0\right)\left(1-\left(T_0/T_c\right)\right)^{0.4}$, where $\chi_P^{E(T)}$ is the temperature coefficient of spin polarization of electric (thermal) spin current in the MTJ, T_c is the Curie temperature of free ferromagnetic layer. For the magnetodynamic calculations we take the following parameters of MTJ from [14]: $\chi_P^E=\chi_P^T=1.7\cdot 10^{-5}K^{-3/2}$, $\mu_0 M_S(0)=1.5T$, $T_c=1300K$ for CoFeB magnetic layer.

Let us assume that the dynamic part of temperature drop across the barrier is determined by the sum of κ-th harmonics $\Delta T_{B\kappa}\left(\omega\right)\cos\left(\omega_\kappa t\right)$, where $\kappa=1...n$, and the magnetization unit vector in the polarizer $\mathbf{m}_{\mathrm{P}}=\mathbf{e}_{\mathrm{X}}$. Further analysis will be carried out for the case of zero bias current, when $I_e=I_e^{AC}\,\mathrm{Re}\left(e^{i\omega t}\right)$.

After the linearization of equation (7), one can find the active part of the small deviation $\delta m_X=\sum_{\kappa=1...n}\mathrm{Re}\left(\delta m_{X\kappa}^0\exp\left(i\omega_\kappa t\right)\right)$ of the magnetization $\mathbf{m}$ from the equilibrium position $\mathbf{m}_0$ and calculate $\Delta V_{DC}\left(\omega\right)$ according to (6). Taking into account the linearity of the thermal spin-transfer torques $T_{\parallel(\perp)}^{TST}$ with respect to the amplitudes $\Delta T_{B\kappa}\left(\omega\right)$ of the κ–th harmonic components of temperature drop, the rectified voltage $\Delta V_{DC}\left(\omega\right)$ will be described by the next formula in the case of small oscillations of $\mathbf{m}$ near the equilibrium $\mathbf{m}_0=\mathbf{e}_{\mathrm{Y}}$:

$$\Delta V_{DC}^{MTJ}=\frac{1}{1+\alpha^2}\frac{\rho_0^{MTJ}\bar{R}_{MTJ}}{2}\left(\tau_1 I_e^{AC}+\sum_{\kappa=1...n}\tau_\kappa\Delta\bar{I}_{e\kappa}^{TH}\right), \tag{9}$$

where $\Delta\bar{I}_{e\kappa}^{TH}=-\bar{S}_{TH}\bar{R}_{MTJ}^{-1}\Delta T_{B\kappa}$ is the κ-th harmonic of thermoelectric current, $\bar{S}_{TH}=S_{TH}\left(\theta_{MTJ}=\pi/2\right)$, $\tau_\kappa=\tau_{\parallel\kappa}+\tau_{\perp\kappa}$ is the dimensionless total spin-transfer torque ($\kappa=0,1...n$), the corresponding components $\tau_{\parallel\kappa}$ and $\tau_{\perp\kappa}$ of which can be expressed as:

$$\begin{cases}\tau_{\parallel\kappa}=-\gamma\left(M_S d_F\right)^{-1}\left(a_{\parallel}^E I_e^{AC}\delta_{\kappa 1}+\bar{b}_{\parallel}^T\Delta T_{B\kappa}\right)c_{\parallel}^{\omega_\kappa}\\ \tau_{\perp\kappa}=-\gamma\left(M_S d_F\right)^{-1}\left(-a_{\perp}^E I_e^{AC}\delta_{\kappa 1}+\bar{b}_{\perp}^T\Delta T_{B\kappa}\right)c_{\perp}^{\omega_\kappa}\end{cases}, \tag{10}$$

where $\delta_{\kappa 1}$ is the Kronecker delta, $c_{\parallel}^{\omega_\kappa}=\omega_\kappa^2\Delta\omega/((\omega_0^2-\omega_\kappa^2)^2+(\omega_\kappa\Delta\omega)^2)$, $c_{\perp}^{\omega_\kappa}=(\alpha\omega_\kappa^2\Delta\omega+\gamma(\omega_0^2-\omega_\kappa^2)(\mu_0 M_S+B_a))/((\omega_0^2-\omega_\kappa^2)^2+(\omega_\kappa\Delta\omega)^2)$, $\omega_\kappa=\kappa\omega$ is the frequency of κ-th harmonic, $\omega_0=\left(1+\alpha^2\right)^{-1}\gamma\sqrt{B\left(B+\mu_0 M_S\right)}$ is the resonant frequency of the spin-torque diode, $\Delta\omega=\left(1+\alpha^2\right)^{-1}\alpha\gamma\left(2B+\mu_0 M_S\right)$ is the resonance line width, $\bar{b}_{\parallel}^T=\left(\hbar/2eS_{MTJ}\bar{R}_{MTJ}\right)\left|\bar{S}_{TH}\right|\eta_{\parallel(\perp)}^T$.

In accordance with (9), in the case when n=3, the frequency dependence of the rectified signal V_{DC} for the thickness of the tunnel junction $d_B=0.78nm$ and the magnetic field $B=50mT$ is shown in Figure 3 for the input microwave power of 1 μW, 5 μW and 10 μW.

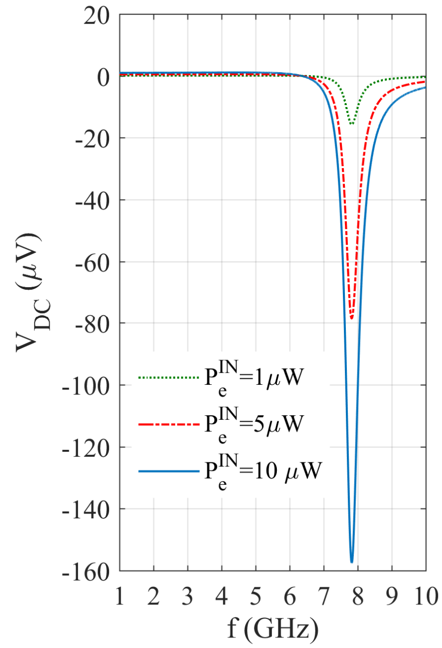

Figure 3. Frequency dependence of the amplitude of rectified signal V_{DC} generated across the MTJ caused by microwave heating of the spin-torque diode, calculated for the considered MTJ structure with parameters taken from [19], when the input power $P_e^{IN} = 10\mu W$ and the magnetic field $B = 50mT$.

Thus, by rearranging terms of equation (9), one can write the dc rectified signal $V_{DC} = V_{DC0}^{TH} + \Delta V_{DC}(\omega)$ of the spin-torque diode in a form of the sum of four contributions – $V_{DC0}^{TH}(\omega), \Delta V_{DC}^{TH}(\omega), \Delta V_{DC}^{CH}(\omega), \Delta V_{DC}^{TC}(\omega)$, which can be expressed as:

$$\begin{cases} V_{DC0}^{TH}(\omega) = -\overline{S}_{TH}\Delta T_{B0}(\omega) \\ \Delta V_{DC}^{TH}(\omega) = -K_V^{DC}\overline{S}_{TH}\sum\limits_{\kappa=1\ldots n}\left[c_{\parallel}^{\omega_\kappa}b_{\parallel}^{T} + c_{\perp}^{\omega_\kappa}b_{\perp}^{T}\right]\left(\Delta T_{B\kappa}(\omega)\right)^2 \\ \Delta V_{DC}^{CH}(\omega) = -K_V^{DC}\left[c_{\parallel}^{\omega_1}a_{\parallel}^{E} - c_{\perp}^{\omega_1}a_{\perp}^{E}\right]\overline{R}_{MTJ}\left(I_e^{AC}\right)^2 \\ \Delta V_{DC}^{TC}(\omega) = -K_V^{DC}\left[\left(c_{\parallel}^{\omega_1}b_{\parallel}^{T} + c_{\perp}^{\omega_1}b_{\perp}^{T}\right)\overline{R}_{MTJ} - \right. \\ \left. -\left(c_{\parallel}^{\omega_1}a_{\parallel}^{E} - c_{\perp}^{\omega_1}a_{\perp}^{E}\right)\overline{S}_{TH}\right]I_e^{AC}\Delta T_{B1}(\omega) \end{cases}, \tag{11}$$

where the coefficient $K_V^{DC} = (1+\alpha^2)^{-1}\gamma\rho_0^{MTJ} / 2M_S d_F$. From (11) it can be clearly seen that $V_{DC0}^{TH} \propto \Delta T_{B0}$, and $\Delta V_{DC}^{TH}(\omega) \propto (\Delta T_{B\kappa})^2$ are the thermal contribution to the rectified signal due to the static Seebeck effect and the thermally-driven spin transport, respectively, $\Delta V_{DC}^{CH}(\omega) \propto \left(I_e^{AC}\right)^2$ is a purely electric contribution to rectification of the signal related to the electric-current-induced spin transfer [5], and $\Delta V_{DC}^{TC}(\omega) \propto I_e^{AC}\Delta T_{B1}$ is the interference term describing the cumulative effect of the thermally-driven and electric-current-driven spin-transfer torques on the rectified voltage. According to (11), the presence of a dynamic contribution $\Delta V_{DC}^{TH}(\omega)$ to the rectified signal V_{DC} associated with the inhomogeneous heating of the MTJ leads to the renormalization of Seebeck coefficient:

$$S_{TH}^{eff} \approx \overline{S}_{TH}\left(1 + \frac{1}{1+\alpha^2}\frac{\hbar}{4e}\frac{\gamma\rho_0^{MTJ}}{M_S d_F}\sum_{\kappa=1\ldots n}\Delta\overline{j}_e^{TH}\left(c_{\parallel}^{\omega_\kappa}\eta_{\parallel}^{T} + c_{\perp}^{\omega_\kappa}\eta_{\perp}^{T}\right)\Delta\overline{J}_{e\kappa}^{TH}\right), \tag{12}$$

where $\Delta\bar{j}^{TH}_{e\kappa} = \Delta\bar{J}^{TH}_{e\kappa} / \Delta\bar{J}^{TH}_{e0}$, $\Delta\bar{J}^{TH}_{e\kappa} = \Delta\bar{I}^{TH}_{e\kappa} / S_{MTJ}$, $\kappa = 0,1...n$. As it follows from our calculations, the amplitudes $\Delta T_{B\kappa}(\omega)$ are determined by the value of the input microwave power P_e^{IN}. Thus, the renormalized contribution to the Seebeck coefficient depends on the power and frequency of microwave signal, and has a resonant form. It also should be noted that the contribution from the temperature dependence of the MTJ resistance $\Delta R_{MTJ} = \left(dR_{MTJ} / dT\right)\Delta T_B$, is negligibly small. The microwave sensitivity of a spin-torque diode is defined as the ratio of the rectified signal to the input power, i.e. $\xi^{MTJ}_{DC} = V_{DC} / \bar{P}_e^{IN}$. The power at the input of the waveguide to the spin-torque diode with the resistance Z_0 of the transmission line is given by the expression $\bar{P}_e^{IN} = \bar{P}_e(\bar{R}_{MTJ} + Z_0)^2 / 4Z_0\bar{R}_{MTJ}$, where $\bar{P}_e = \bar{R}_{MTJ}(I_e^{AC})^2 / 2$ is the average input power incident on the spin-torque diode. Hence, according to equation (9), we get that:

$$\xi^{MTJ}_{DC} = -\frac{8Z_0}{\left(I_e^{AC}\left(\bar{R}_{MTJ} + Z_0\right)\right)^2}\left(\bar{S}_{TH}\Delta T_{B0}(\omega) - \Delta V_{DC}(\omega)\right), \tag{13}$$

where $\Delta V_{DC}(\omega) = \Delta V^{TH}_{DC}(\omega) + \Delta V^{CH}_{DC}(\omega) + \Delta V^{TC}_{DC}(\omega)$ is calculated according to the equations (11).

Figure 4 shows the spin-torque diode sensitivity ξ^{MTJ}_{DC} as a function of the input power of microwave signal at a given temperature $T_0 = 300K$. As can be seen from this figure, the microwave sensitivity gradually increases with increasing power input.

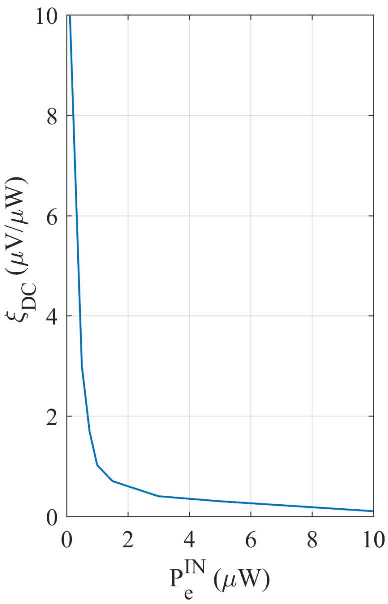

Figure 4. Dependence of the thermal contribution to microwave sensitivity of the spin-torque diode on the microwave input power at the a.c. current frequency of 10 GHz.

However, the thermal contributions (from the static Seebeck effect and from the nonlinear rectification caused by the thermal spin –transfer torques) to the microwave sensitivity ξ^{MTJ}_{DC} is much less than the microwave sensitivity due to the spin-polarized current-induced rectification effect. Namely, their ratio at an irradiation power of 1 μW is approximately 10^{-4} at the resonance on the main frequency $\omega \approx \omega_0$. In turn, the thermoelectric resonance contribution can be observed at the second harmonic at frequency $2\omega \approx \omega_0$ which is far from the main resonance peak.

4. CONCLUSIONS

Thus, the analysis performed shows that microwave sensitivity of the spin-torque diode to the microwave irradiation along with the electric contribution contains the thermal one. The latter in turn, in addition to the ordinary contribution due to the static Seebeck effect caused by the constant temperature drop, also contains a dynamic contribution originating from the thermal transfer of the spin angular momentum modulated at the frequency of microwave irradiation. The thermal contribution to the microwave sensitivity is small in comparison with the resonance response due to the spin-polarized a.c. current, but it contains both weakly frequency-dependent part, which is absent in the purely electric contribution, and also the resonant contribution from the second harmonic. In combination with the nonlinear effect of rectifying the microwave signal due to the electrical component of the spin-transfer torque in the MTJ at the main resonance frequency, the Seebeck bolometric effect can also be used for microwave applications at the second harmonic of thermal heating, i.e. when $2\omega \sim \omega_0$. For example, it may be used for detection and microwave visualization of objects at not too great distances by external heating of one of the electrodes of the spin-torque diode. The dynamic contribution to the microwave sensitivity can be greatly increased by magnon transfer of the spin flux in a magnetic heterostructure with a heated dielectric in which spin pumping occurs, instead of a spin-polarizing conducting electrode.

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