Microwave Energy Harvester Based on the Magneto-Tunnel Seebeck Effect in the Nanoscale Spin-Torque Diode

G.D. Demin
Laboratory of Physics of Magnetic Heterostructures and Spintronics for Energy-efficient Information Technologies
Moscow Institute of Physics and Technology (State University)
Dolgoprudny, Russia
demin.gd@phystech.edu

MEMSEC R&D Center
National Research University of Electronic Technology (MIET)
Moscow, Zelenograd, Russia
gddemin@edu.miet.ru

A.F. Popkov
Laboratory of Physics of Magnetic Heterostructures and Spintronics for Energy-efficient Information Technologies
Moscow Institute of Physics and Technology (State University)
Dolgoprudny, Russia
afpopkov@inbox.ru

K.A. Zvezdin
Laboratory of Physics of Magnetic Heterostructures and Spintronics for Energy-efficient Information Technologies
Moscow Institute of Physics and Technology (State University)
Dolgoprudny, Russia
zvezdin.ka@mipt.ru

N.A. Djuzhev
MEMSEC R&D Center
National Research University of Electronic Technology (MIET)
Moscow, Zelenograd, Russia
djuzhev@ntc-nmst.ru

A.V. Popov
Department of Quantum Physics and Nanoelectronics
Functional Electronics Scientific Research Laboratory (NILFE)
National Research University of Electronic Technology (MIET)
Moscow, Zelenograd, Russia
alexcoretex@gmail.com

***Abstract*— At present, there is a growing interest in the field of spin caloritronics, which demonstrates the advantages of using thermoelectric effects when considering spin-transport phenomena. One of its most promising directions are the thermal transfer of the spin-transfer torque and magneto-tunnel Seebeck effect in magnetic tunnel junctions in the presence of a non-equilibrium temperature gradient across the tunnel barrier, which, in combination with the voltage rectification effect driven by the alternating current, can serve as an additional source of microwave energy harvesting and has not been considered before. In this work, we estimated the bolometric properties of a spin-torque diode based on the magnetic tunnel junction under the microwave heating, and also compared the thermal dependences of its sensitivity in comparison with the Schottky semiconductor diode. The thermal contribution to the voltage rectification can be significantly increased in some cases, which plays an important role in the development of new types of microwave energy harvesters operating on the thermoelectric effects.**

Keywords*— spin caloritronics, spin-torque diode, magnetic tunnel junction, magneto-tunnel Seebeck effect, microwave heating, microwave sensitivity

I. Introduction

The possibility of creating both microwave energy harvesters, and microwave detectors operating in the microwave and infrared ranges is of a great interest to many researchers. The effects of spin caloritronics, such as the magneto-tunnel Seebeck effect and thermally-driven spin-transfer torque phenomenon in magnetic tunnel junctions (MTJ) in the presence of a temperature drop across the tunnel barrier, can open the way for creating such devices [1-5]. Earlier, the MTJ was already considered in a number of papers, as the key element of non-volatile magnetoresistive memory and some thermoelectric devices [6-8]. In our work, the MTJ is heated by microwave irradiation.

In other words, MTJ is subjected to non-uniform heating associated with a drop in temperature at the electrodes. when applying microwave current of a given frequency. From recent studies, it was found that MTJs can demonstrate high resonant microwave sensitivity, driven by the current-driven spin-torque diode effect [9, 10]. Due to the magneto-tunnel Seebeck effect and spin-dependent thermally-driven spin-transfer torque in the MTJ, the d.c. voltage in the MTJ can be additionally rectified [11]. Thus, the MTJ can serve as an energy harvester, when it is heated by the incident microwave irradiation. Previously in [12, 13], the advantages of using a spin-torque diode as an energy harvester for microwave applications were demonstrated, which is connected with its good rectification efficiency at μW input power, which becomes a real challenge for a Schottky diode, mainly operating in the mm wavelength range. However, the possibility of thermoelectric energy harvesting by a spin-torque diode was not taken into account before, which in certain cases can additionally increase the rectified voltage signal in the spin-torque diode and its microwave sensitivity. This can serve to the development of a new generation of microwave energy harvesters based on thermoelectric effect.

II. Microwave Heating of a Spin-Torque Diode

A. The MTJ structure

Let us analyze thermal gradient driven mechanism of spin transport through the MTJ arising because of microwave Joule heating of ferromagnetic layers by the 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. current, S_{MTJ} is the cross-sectional area of the MTJ. We suppose that the layer composition of the MTJ stack is

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), as presented in Fig.1 and described in details in an experimental work [14]. 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. At the same figure the spatial profile of potential energy of the electrons $U(z)$ in the CoFeB/MgO/CoFeB structure as active part of the full MTJ stack is presented, where conduction bands are exchange splitted in the ferromagnetic layers.

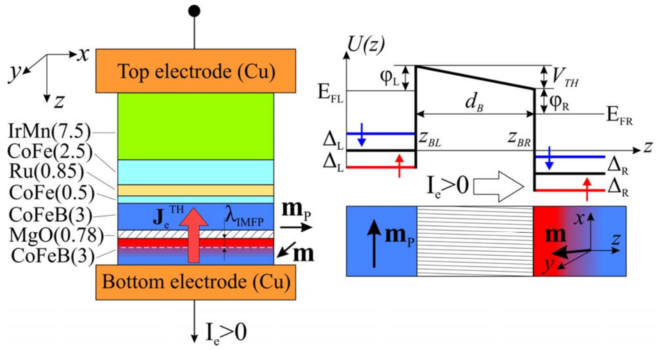

Fig. 1. The concept of heat dissipation along the MTJ under the microwave current $I_e > 0$ passing through it and schematic energy diagram for the potential profile $U(z)$ of the CoFeB/MgO/CoFeB tunnel structure. The red arrow shows the heat flux $\mathbf{J}_e^{TH}$ due to the inhomogeneous Joule heating of the MTJ, where the hear power is generated at the mean free path λ_{IMFP} in the corresponding ferromagnetic layer, close to the right from the boundary of the tunnel barrier, depending on the direction of the external current. The thicknesses of the layers in the MTJ are given in nanometers (color online).

B. Temperature drop across the MTJ induced by asymmetric Joule 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 current 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 dependence of the change in the thermal power density $\wp_{MTJ}^{TH}$ over the thickness of the conducting layers of the MTJ:

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

where $\sigma_J^{(\pm1)} = 0.5\sigma_J(\sigma_J \pm 1)$, σ_J is the polarity of the applied electric current I_e, $z_{BL(R)}$ is the z-coordinate of the left (right) boundary of the tunnel barrier, λ_{IMFP} is electron mean free path in ferromagnetic layer, $P_e^{IN} =< I_e^2 R_{MTJ} >$ is the power of the input signal applied to the MTJ. The resistance of MTJ can be written as:

$$R_{MTJ} = \bar{R}_{MTJ}\left(1 + \rho_0^{MTJ}\mathbf{m}\cdot\mathbf{m}_p\right), \quad (2)$$

where $\bar{R}_{MTJ} = 2\left(1/R_P^{MTJ} + 1/R_{AP}^{MTJ}\right)^{-1}(1-\chi_T < T_{MTJ} >)$, χ_T is the temperature coefficient of the MTJ resistance, $< T_{MTJ} >$ is the average temperature of MTJ, $\rho_0^{MTJ} = \left(R_{AP}^{MTJ} - R_P^{MTJ}\right)/\left(R_{AP}^{MTJ} + R_P^{MTJ}\right)$ is the coefficient of tunnel magnetoresistance, $\mathbf{m}(\mathbf{m}_P)$ is the magnetization unit vector in a free magnetic layer (polarizer), $R_{P(AP)}^{MTJ}$ is the MTJ resistance for parallel (antiparallel) magnetic configuration of the magnetizations of ferromagnetic layers in the CoFeB/MgO/CoFeB. In our calculations we assumed that $\mathbf{m} \perp \mathbf{m}_P$ when there is no bias magnetic field applied. The mean free path of electrons in a ferromagnetic metal is supposed to be of the order of 1 nm, as it is described in [15]. As shown in Fig. 1, depending on the polarity of the applied current I_e, the heat power $\wp_{MTJ}^{TH}$ will be generated either close to the left or close to the right boundary of the tunnel barrier in adjacent layers. This leads both to the appearance of a constant component ΔT_B^C of the temperature drop ΔT_B across the tunnel layer of MTJ, generated by the d.c. current I_e^{DC}, and ensures the presence of the microwave harmonics $\Delta T_B(\omega) = \sum_{\kappa=0...n} \Delta T_{B\kappa}(\omega)\cos\kappa\omega t$, which correspond to the a.c. current I_e^{AC}, i.e. $\Delta T_B = \Delta T_B^C + \Delta T_B(\omega)$, where $\Delta T_{B\kappa} = \Delta T_{B\kappa}(\omega)$ is the amplitude of the $\kappa-$th harmonic, n is the number of harmonics.

Thermal regimes of the MTJ heating by a direct current were discussed earlier in a number of papers [7, 16]. Therefore, we give the results of a similar calculation of the amplitudes $\Delta T_{B\kappa}$ ($\kappa = 0,1,2,3$) 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 ($I_e^{DC} = 0$). For simplicity, we further restrict our consideration to only four first harmonics, the frequency-dependent amplitudes $\Delta T_{B0}(\omega)$ and $\Delta T_{B1}(\omega)$ of which most contribute to the temperature drop. Thus, $\Delta T_B(\omega) = \sum_{\kappa=0...3} \Delta T_{B\kappa}(\omega)\cos\kappa\omega t$. The calculation of the non-stationary heating of the MTJ by an a.c. current was performed using the Comsol MultiPhysics software package [17]. The temperature drop ΔT_B across the tunnel barrier due to the current-induced asymmetric Joule heating of the MTJ was calculated as the difference in the average temperatures of the corresponding ferromagnetic layers adjacent to the tunnel barrier, that is $\Delta T_B =< T_L > - < T_R >$, where $< T_{L(R)} >$ is the temperature-averaged temperature of the left (right) ferromagnetic layer. Figure 2 (b) shows the time evolution of the temperature drop ΔT_B across the tunnel barrier of the spin-torque diode at three different frequencies, when the input microwave power is equal to 10 μW. It also was found that the harmonic amplitudes ΔT_{B0} and ΔT_{B2} linearly increase, while the amplitudes ΔT_{B1} and ΔT_{B3} linearly decrease with the input microwave power (Figure 2 (c)). At the same time, as shown in Figure 3, the frequency dependences of the harmonics ΔT_{B0}, ΔT_{B1} and ΔT_{B3} exhibit a strongly non-monotonic behavior at a given frequency range, while the second harmonic ΔT_{B2} have an almost linear dependence on the microwave frequency. As a result, we also can assume that the frequency peak of zero harmonic ΔT_{B0} will lead to the appearance of the resonance of the rectified d.c. voltage of a spin-torque diode observed at the corresponding resonant frequency due to the static magneto-tunnel Seebeck effect, which will be described in the next section.

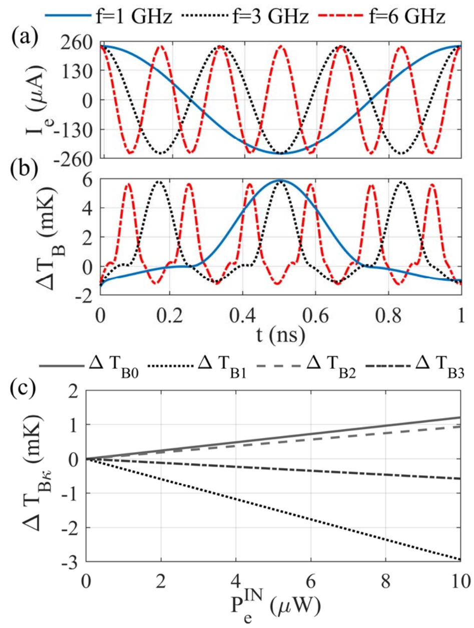

Fig. 2. (a) Time evolution of (a) the microwave current and (b) the temperature drop $\Delta T_B(\omega)$ across the tunnel barrier of MTJ at different frequencies (color online). (c) Dependence of the magnitude of the κ-th harmonic $\Delta T_{B\kappa}$ of the temperature drop on the heating power.

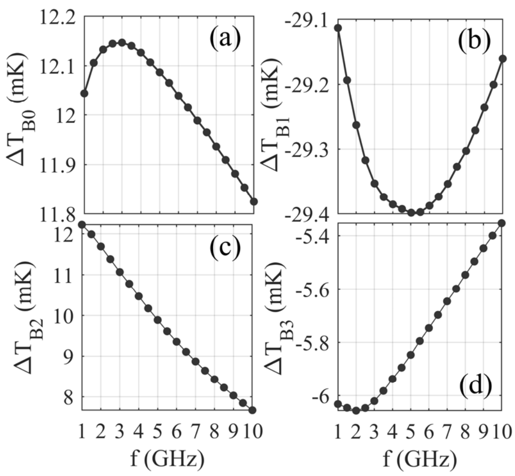

Fig. 3. The dependence of the amplitudes of κ-th harmonics (a) ΔT_{B0}, (b) ΔT_{B1}, (c) ΔT_{B2} and (d) ΔT_{B3} on frequency at the input microwave power of 10 μW.

C. Magneto-tunnel Seebeck coefficient

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 $V_{DC} = V_{DC0}^{TH} + \Delta V_{DC}(\omega)$, where $V_{DC0}^{TH} = -S_{TH}\Delta T_{B0}$, S_{TH} is the frequency-independent Seebeck coefficient, corresponding to the stationary component of temperature drop $\Delta T_{B0}(\omega)$, and $\Delta V_{DC}(\omega)$ is the dynamic component of the d.c. rectified voltage. The latter depends on the microwave part I_e^{AC} of the applied current and frequency-dependent harmonic components $\Delta T_{B\kappa}(\omega)$ of the temperature drop, where $n = 1,2,3$. Our calculations are based on the free-electron model of both spin and charge transport from the heated to the cold electrode as microscopic approach to the theory of thermoelectric phenomena in the MTJ, which was previously used in [18]. In contrast to [18], however, we also take into account the variation of the effective masses in each of the layers, which more correctly describes the electron transport in magnetic structures based on MgO tunnel barrier [19].

From the condition for the balance of the thermal current of electrons to the electric current in an open circuit for small temperature gradients, one can derive a simple expression in the case of a symmetric MTJ for calculating the static Seebeck coefficient:

$$S_{TH} = -\frac{k_B}{e}\frac{\sum_{\sigma,\sigma'}\int_0^\infty P_{\sigma\sigma'(e)}^{(TR_0)}(\varepsilon_x)\left(\ln\left(1+e^{-\bar{\varepsilon}_x^T}\right)+\bar{\varepsilon}_x^T\beta_e^T\right)d\varepsilon_x}{\sum_{\sigma,\sigma'}\int_0^\infty P_{\sigma\sigma'(e)}^{(TR_0)}(\varepsilon_x)\beta_e^T d\varepsilon_x}, \quad (3)$$

where $\bar{\varepsilon}_x^T = (\varepsilon_x - \varepsilon_F)/k_B T_0$, $\beta_e^T = e^{-\bar{\varepsilon}_x^T}/\left(1+e^{-\bar{\varepsilon}_x^T}\right)$, k_B is the Boltzmann constant, ε_x is the longitudinal electron energy, $P_{\sigma\sigma'(e)}^{(TR_0)} = m_{L*}k_{xR}^{\sigma'}\left|T_{\sigma\sigma'}\right|^2 / m_{R*}k_{xL}^{\sigma}$, $k_{xL(R)}^{\sigma(\sigma')}$ 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 $\sigma \to \sigma'$, $m_{L(R)*}$ is the effective mass of the left (right) ferromagnetic MTJ layer, ε_F is the Fermi level of the magnetic system, $T_0 \approx < T_{MTJ} >$ is the average temperature of the magnetic system. Based on the equation (3), we calculated numerically the dependencies of the static Seebeck coefficient S_{TH} on the height U_B of the tunnel barrier and the temperature T_0 for the CoFeB/MgO/CoFeB MTJ with parameters close to the data of [14, 20]. In our simulation we used the following initial parameters of the symmetric MTJ of a rectangular cross-section: $S_{MTJ} = 30\cdot 10^3\,nm^2$, $R_P^{MTJ} = 175\Omega$, $\delta_{MR}^{MTJ} = 0.87$, $E_F = E_{FL(R)} = 2.3eV$ 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 thickness of tunnel barrier (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 layer (CoFeB), m_e is the mass of the electron, and $T_0 = 300K$ corresponds to the average temperature of the MTJ.

As is well known, which also follows from Figure 4 (a), the Seebeck coefficient has a pronounced dependence on the angle θ_{MTJ} between $\mathbf{m}$ and $\mathbf{m}_P$, and is spin-dependent. Figure 4 (b) demonstrates that the maximum value of the Seebeck coefficient S_{TH} varies from about -19 to 173 μV/K for the given parameters of MTJ and correlates with the corresponding values obtained in [18].

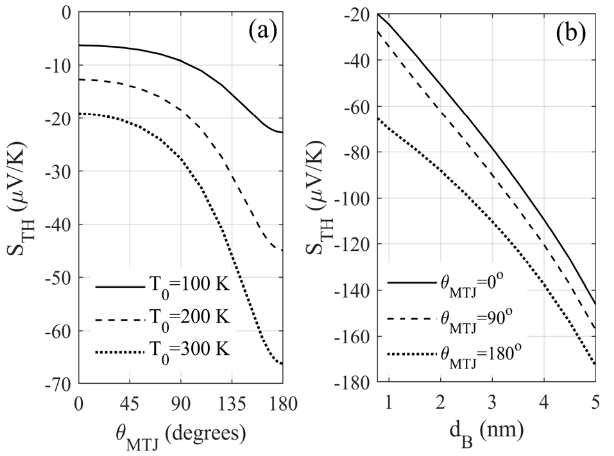

Fig. 4. The frequency-independent Seebeck coefficient S_{TH} as a function of (a) the angle θ_{MTJ} between $\mathbf{m}$ and $\mathbf{m}_P$ and (b) the height d_B of the tunnel barrier of the CoFeB-MgO-CoFeB MTJ.

It is easily seen from [21-24], that the range of experimental values $\left|S_{TH}^P\right| = \left|S_{TH}\left(\theta_{MTJ}=0\right)\right|$ 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 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 [19]. The theoretical estimation of the Seebeck coefficients shows that $S_{TH}^P = -19.1\ \mu\text{V/K}$ and $S_{TH}^{AP} = -66.2\ \mu\text{V/K}$ for the given parameters of symmetric MTJ at 300 K. However, it follows from [25] that ΔS_{TH} is equal to 50 μV/K at the room temperature, which is in consistent with our calculations for the barrier height of about 3 eV.

D. Voltage rectification effect induced by a microwave heating of the MTJ

In addition to the constant component V_{DC0}^{TH} of the voltage drop across the tunnel layer due to the presence of the static Seebeck effect in the case of non-zero ΔT_{B0}, the thermal heating of the MTJ under a.c. current also results in an additional thermal contribution to the frequency-dependent dynamic part of the d.c. voltage $\Delta V_{DC}(\omega)$. This contribution is associated with the rectification effect of the signal due to modulation of the magnetoresistance induced by the thermally induced spin-torque components related to the time-varying part of the temperature drop $\Delta\tilde{T}_{B\Sigma}(\omega,t) = \sum_{\kappa=1\ldots3} \Delta T_{B\kappa}(\omega)\cos\kappa\omega t$. In turn, the modulation of the magnetoresistance is associated with a dynamic response of $\mathbf{m}$ to the cumulative effect of electric and thermal spin torques driven by the electric current through the tunnel barrier and the temperature drop across it as a result of the Joule heating, respectively. According to formula (2), it leads to the variation of the MTJ resistance $R_{MTJ} = R_{MTJ}\left(\mathbf{m}(t)\right)$ and the dynamic renormalization of the Seebeck coefficient due to the nonlinear rectification effect of the microwave signal in the spin-torque diode. Thus, the d.c. voltage $\Delta V_{DC}(\omega)$ is determined as:

$$\Delta V_{DC}(\omega) = \frac{1}{T}\int_0^T dt \Delta R_{MTJ}(\omega)\Delta I_e^{\Sigma}(\omega), \quad (4)$$

where $\Delta R_{MTJ}(\omega) = -0.5 R_{MTJ}^P \delta_{MR}^{MTJ}\left(\mathbf{m}\cdot\mathbf{m}_P\right)$ is the dynamic part of the MTJ resistance R_{MTJ}, and $\Delta I_e^{\Sigma} = I_e^{AC}\cos\omega t - S_{TH} R_{MTJ}^{-1}\Delta\tilde{T}_{B\Sigma}(\omega,t)$ is the total current as a sum of the electric current and thermal current passing through the tunnel barrier of MTJ under its microwave heating. To determine the dynamic response of the magnetic system of an MTJ to a time-varying part of the frequency-dependent temperature drop $\Delta T_B(\omega)$, we linearized the Landau-Lifshitz-Gilbert equation describing the 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 components of the total spin torque:

$$\dot{\mathbf{m}} = -\gamma\left[\mathbf{m}\times\mathbf{B}_{\text{eff}}\right] + \alpha\left[\mathbf{m}\times\dot{\mathbf{m}}\right] - \frac{\gamma}{M_S d_F}\left(\mathbf{T}_\parallel + \mathbf{T}_\perp\right), \quad (5)$$

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 in-plane (perpendicular) spin torque $\mathbf{T}_{\parallel(\perp)} = \mathbf{T}_{\parallel(\perp)}^E + \mathbf{T}_{\parallel(\perp)}^T$ is the sum of two components $\mathbf{T}_{\parallel(\perp)}^E$ and $\mathbf{T}_{\parallel(\perp)}^T$, responsible for the electrical and thermal mechanism of spin transfer, respectively:

$$\begin{cases} \mathbf{T}_\parallel = \left(a_\parallel^E I_e^{AC}\cos\omega t + b_\parallel^T \Delta\tilde{T}_{B\Sigma}(\omega,t)\right)\left[\mathbf{m}\times\mathbf{m}\times\mathbf{m}_P\right] \\ \mathbf{T}_\perp = -s_I\left(a_\perp^E I_e^{AC}\cos\omega t - b_\perp^T \Delta\tilde{T}_{B\Sigma}(\omega,t)\right)\left[\mathbf{m}\times\mathbf{m}_P\right] \end{cases}, \quad (6)$$

where $a_{\parallel(\perp)}^E = \left(\hbar/2eS_{MTJ}\right)\eta_{\parallel(\perp)}^E$, $\hbar$ is the reduced Planck constant, $b_{\parallel(\perp)}^T = \left(\hbar/2eS_{MTJ}R_{MTJ}\right)\left|S_{TH}\right|\eta_{\parallel(\perp)}^T$, S_{TH} is the static Seebeck coefficient, $\eta_{\parallel(\perp)}^E$ 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. In agreement with our previous study of the spin-torque diode on the basis of the MTJ structure under consideration [26], we obtained that the values of electric-current- and thermal-driven spin-torque efficiencies at zero temperature are as follows: $\eta^E_{\parallel 0} = 0.63$, $\eta^E_{\perp 0} = 0.3$, and $\eta^T_{\parallel 0} = 0.35$, $\eta^T_{\perp 0} = 0.26$. It should be taken into account that the effect of temperature on the rectifying voltage is described by the following expressions [27]: $\eta^{E(T)}_{\parallel(\perp)}(T_0) = \eta^{E(T)}_{\parallel(\perp)0}\left(1 - \chi^{E(T)}_P T_0^{3/2}\right)$, $M_S(T_0) = M_{S0}\left(1 - (T_0/T_c)\right)^{0.4}$, where we take that $\chi^{E(T)}_P = 1.7 \cdot 10^{-5} K^{-3/2}$ is the temperature coefficient of spin polarization of electric (thermal) spin current in the MTJ, $\mu_0 M_{S0} = 1.5T$ is the demagnetization field of the CoFeB at zero temperature, $T_c = 1300K$ is the Curie temperature of the CoFeB.

Further let us assume that the magnetization unit vector in the polarizer $\mathbf{m}_P = \mathbf{e}_X$. After the linearization of equation (5), one can find the active part of the small deviation $\delta m_X = \sum_{\kappa=1\ldots n} \mathrm{Re}\left(\delta m^0_{X\kappa} \exp(i\omega_\kappa t)\right)$ of the magnetization $\mathbf{m}$ from the equilibrium position $\mathbf{m}_0$ and obtain, according to (4), that the dynamic part of the d.c. voltage $\Delta V_{DC}(\omega) = \Delta V^{TH}_{DC}(\omega) + \Delta V^{CH}_{DC}(\omega) + \Delta V^{TC}_{DC}(\omega)$, where each contribution to $\Delta V_{DC}(\omega)$ can be expressed as:

$$\begin{cases} \Delta V^{TH}_{DC}(\omega) = -K^{DC}_V \bar{S}_{TH} \sum\limits_{\kappa=1\ldots 3} \bar{B}^\kappa_c \left(\Delta T_{B\kappa}(\omega)\right)^2 \\ \Delta V^{CH}_{DC}(\omega) = -K^{DC}_V A^1_c \bar{R}_{MTJ} \left(I^{AC}_e\right)^2 \\ \Delta V^{TC}_{DC}(\omega) = K^{DC}_V \left[A^1_c \bar{S}_{TH} - \bar{B}^1_c \bar{R}_{MTJ}\right] I^{AC}_e \Delta T_{B1}(\omega) \end{cases}, \qquad (7)$$

where $A^\kappa_c = c^{\omega_\kappa}_\parallel a^E_\parallel - c^{\omega_\kappa}_\perp a^E_\perp$, $\bar{B}^\kappa_c = c^{\omega_\kappa}_\parallel \bar{b}^T_\parallel + c^{\omega_\kappa}_\perp \bar{b}^T_\perp$, $\bar{b}^T_\parallel = \left(\hbar / 2eS_{MTJ}\bar{R}_{MTJ}\right)\left|\bar{S}_{TH}\right| \eta^T_{\parallel(\perp)}$, $c^{\omega_\kappa}_\parallel = \omega^2_\kappa \Delta\omega / \Delta_{\omega_\kappa}$, $c^{\omega_\kappa}_\perp = (\alpha\omega^2_\kappa \Delta\omega + \gamma(\omega^2_0 - \omega^2_\kappa)(\mu_0 M_S + B)) / \Delta_{\omega_\kappa}$, $\omega_\kappa = \kappa\omega$, $\bar{S}_{TH} = S_{TH}(\theta_{MTJ} = \pi/2)$, $\Delta_{\omega_\kappa} = (\omega^2_0 - \omega^2_\kappa)^2 + (\omega_\kappa \Delta\omega)^2$, $\omega_0 = \left(1+\alpha^2\right)^{-1} \gamma \sqrt{B(B + \mu_0 M_S)}$ is the resonant frequency of the spin-torque diode, $\Delta\omega = \left(1+\alpha^2\right)^{-1} \alpha\gamma(2B + \mu_0 M_S)$ is the resonance line width, $K^{DC}_V = (1+\alpha^2)^{-1}\gamma\rho^{MTJ}_0 / 2M_S d_F$. Thus, the d.c. rectified voltage V_{DC} has four components - $V^{TH}_{DC0} \sim \Delta T_{B0}$ is the voltage due to the static Seebeck effect, $\Delta V^{TH}_{DC}(\omega) \sim \left(\Delta T_{B\kappa}\right)^2$ is the voltage due to purely thermal spin current, $\Delta V^{CH}_{DC}(\omega) \sim \left(I^{AC}_e\right)^2$ is the voltage due to purely electric spin current, and $\Delta V^{TC}_{DC}(\omega) \sim I^{AC}_e \Delta T_{B1}$ is the interference term describing the cumulative effect of the thermally-driven and electric-current-driven spin-transfer torques on the rectified voltage. Figure 5 presents the frequency dependence of rectified signal V_{DC} for the thickness of the tunnel barrier $d_B = 0.78nm$ and the magnetic field $B = 50mT$ for the input microwave power of 1 µW, 5 µW and 10 µW.

III. SPIN-TORQUE DIODE SENSITIVITY

The microwave sensitivity of a spin-torque diode is defined as the ratio of the rectified signal to the input power, i.e. $\xi^{MTJ}_{DC} = V_{DC} / \bar{P}^{IN}_e$. The input power of the spin-torque diode with the resistance Z_0 of the transmission line is given by the expression $\bar{P}^{IN}_e = \bar{P}_e(\bar{R}_{MTJ} + Z_0)^2 / 4Z_0\bar{R}_{MTJ}$, where $\bar{P}_e = \bar{R}_{MTJ}(I^{AC}_e)^2/2$ is the average input power incident on the spin-torque diode. Hence, we obtain that:

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

where $\Delta V_{DC}(\omega)$ is calculated according to (7).

Figure 5 (a) presents the frequency dependence of rectified signal V_{DC} for the thickness of the tunnel barrier $d_B = 0.78nm$ and the magnetic field $B = 50mT$ for the input microwave power of 1 µW, 5 µW and 10 µW.

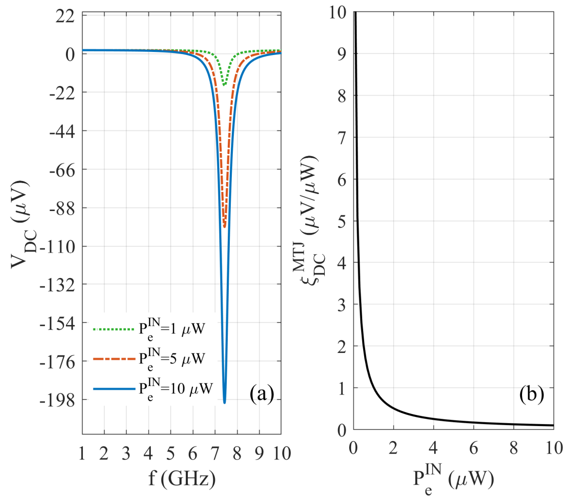

Fig. 5. (a) The frequency dependence of the d.c. voltage V_{DC} for varied input microwave power at a temperature of 300K (color online). (b) Dependence of the thermal contribution to microwave sensitivity ξ^{MTJ}_{DC} of the spin-torque diode on the microwave input power at the a.c. current frequency of 10 GHz. The magnetic field B is equal to 50 mT and the parameters of MTJ were taken from [14, 20].

It is clearly seen from Figure 5 (a) that the d.c. voltage V_{DC} linearly increases with the applied power and has a resonant peak at frequency of about 7.4 GHz. Figure 5 (b) shows the spin-torque diode sensitivity as a function of the input power of microwave signal (at low temperature $T_0 < 10K$), where the microwave sensitivity gradually decreases with increasing input power. It should be note that the temperature dependence of the microwave sensitivity of a spin-torque diode is very different from the similar dependence of a semiconductor Schottky diode at a fixed frequency. This dependence is non-monotonic and may have a peak character, which is associated with the thermal drift of the resonant frequency. The peak sensitivity of a spin-torque diode monotonously changes in a given temperature range (from 50 to 400 K) by 9%, while the sensitivity of the Schottky diode changes about 6 times. It should be note, that the thermally-driven part of the microwave sensitivity is much less than the microwave sensitivity due to the current-induced rectification effect. Nevertheless, the thermoelectric resonance contribution can be observed at the second harmonic, which is far from the main resonance peak.

IV. SUMMARY

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. 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 electric spin torque in the MTJ at the main resonance frequency, the Seebeck bolometric effect can be used for energy harvesting at the second harmonic of thermal heating. It also may be used for detection and microwave visualization of objects at not too great distances [28]. It was also found that the variation of the peak sensitivity of a spin-torque diode with a temperature is significantly less than that of a Schottky semiconductor diode, which may be applicable in conditions of large temperature variations. 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 [29]. In addition, it is well known that in the presence of a bias current in the spin-torque diode, the width of the resonance line changes and approaches zero near the transition to the self-oscillation state [26]. In this case, the resonant contribution to the microwave sensitivity can increase by more than two orders of magnitude [30], which is attractive for energy harvesting applications. However, experimental confirmation of the proposed concept of a microwave energy harvester based on the thermoelectric effect in the spin-torque diode is a subject for further study and is beyond the scope of this paper.

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