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Research Article

Bolometric Properties of a Spin-Torque Diode Based on a Magnetic Tunnel Junction

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Spin caloritronics opens up a wide range of potential applications, one of which can be the thermoelectric rectification of a microwave signal by spin-diode structures. The bolometric properties of a spin-torque diode based on a magnetic tunnel junction (MTJ) in the presence of a thermal gradient through a tunnel junction are discussed. Theoretical estimates of the static and dynamic components of the microwave sensitivity of the spin-torque diode, related to thermoelectric tunnel magneto-Seebeck effect and the thermal transfer of spin angular momentum in the MTJ under nonuniform heating, are presented. Despite the fact that the thermal contribution to the microwave sensitivity of the spin-torque diode is found to be relatively small in relation to the rectification effect related to the modulation of the MTJ resistance by a microwave spin-polarized current, nevertheless, the considered bolometric effect can be successfully utilized in some real-world microwave applications.

1. Introduction

The magneto-Seebeck effect and the thermal initiating spin-transfer torques in MTJ are an important part of spin-caloritronic studies [1–7] and are of a high significance for development of nonvolatile memory and temperature-sensitive devices [8–10]. Spin-torque diode effect in a magnetic tunnel structure is the voltage rectification effect via the microwave modulation of the active component of the MTJ resistance due to the spin-transfer torque [11]. Spin-torque diodes demonstrate extremely high resonant microwave sensitivity [12, 13]. It is worth to note that spin-torque diodes are subject of inhomogeneous heating associated with the temperature drop at the electrodes when the microwave current is applied. Owing to the presence of the tunnel magneto-Seebeck effect and the spin-dependent thermal spin transfer in the MTJ [6], the bolometric effect of thermoelectric voltage rectification arises. The influence of this effect on the microwave sensitivity of the spin-torque diode has not been yet analyzed. In this work the microscopic calculations of the spin-dependent Seebeck coefficients in the MTJ are presented, and the dynamical variation of spin-torque diode sensitivity due to thermally driven spin transport through the tunnel barrier of MTJ is also investigated. The possible advantages of the spin-torque-diode based bolometer in comparison with Schottky semiconductor diodes widely used in microwave applications are discussed.

2. Model

2.1. The MTJ Structure. Let us analyze thermal gradient driven mechanism of spin transport through the MTJ arising because of asymmetric Joule heating of ferromagnetic layers when the electrical current is applied. In general, the applied current, which can be written as $I_e = I_e^{AC}\mathrm{Re}(e^{i\omega t}) + I_e^{DC}$, 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, and 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 Figure 1 and described in detail in an

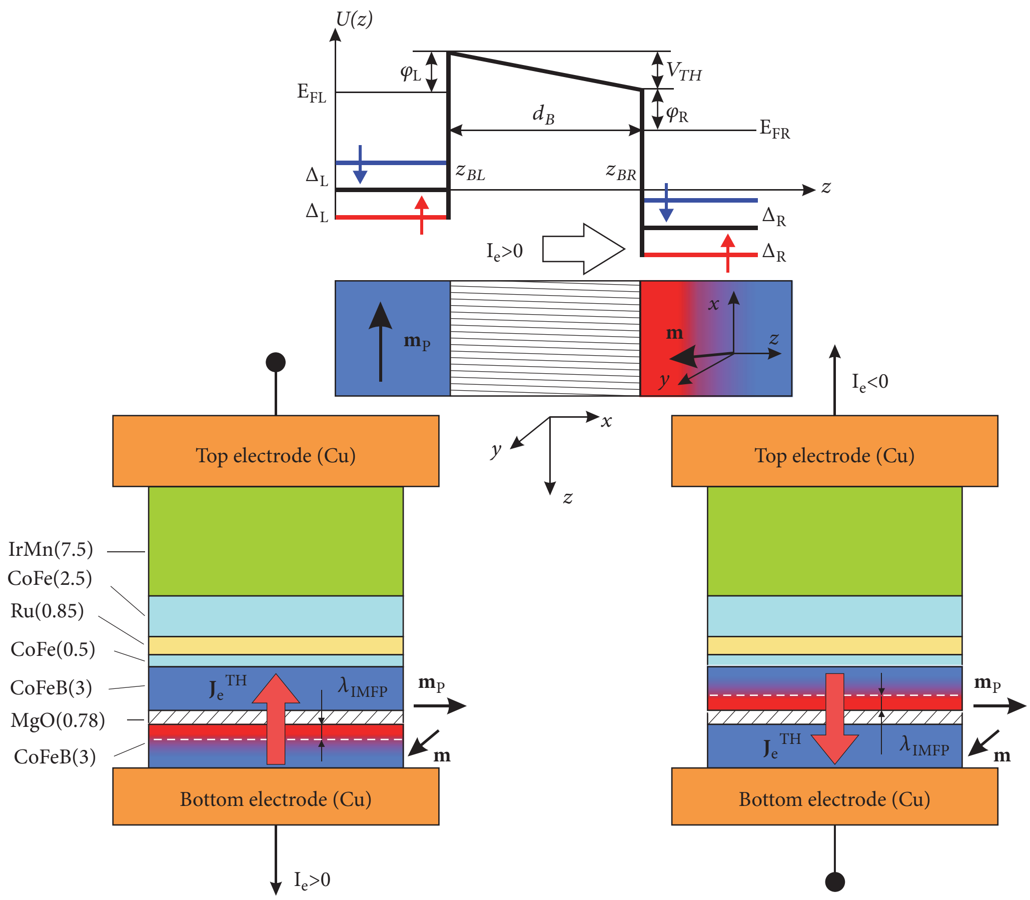

FIGURE 1: Schematic energy diagram for the potential profile $U(z)$ of the CoFeB/MgO/CoFeB structure in the MTJ (top) and the heat dissipation along the MTJ under the microwave current I_e passing through it (bottom). The red arrow shows the heat flux $\mathbf{J}_e^{TH}$ due to the inhomogeneous Joule 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 direction of the external current. The thicknesses of the layers in the MTJ stack are in nanometers.

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 electron $U(z)$ in the CoFeB/MgO/CoFeB structure as active part of the full MTJ stack is presented, where conduction bands are exchange split in the ferromagnetic layers.

2.2. 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:

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

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, and $P_e^{IN} = \langle I_e^2 R_{MTJ}\rangle$ is the averaged power of the input microwave signal applied to the MTJ. The resistance of MTJ can be written as

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

where $\rho_0^{MTJ} = (R_{AP}^{MTJ} - R_P^{MTJ})/(R_{AP}^{MTJ} + R_P^{MTJ})$ is the coefficient of tunnel magnetoresistance, $\mathbf{m}(\mathbf{m}_P)$ is the magnetization unit vector in a free magnetic layer (polarizer), $\overline{R}_{MTJ} = 2(1/R_P^{MTJ} + 1/R_{AP}^{MTJ})^{-1}(1 - \chi_T\langle T_{MTJ}\rangle)$, χ_T is the temperature coefficient of the MTJ resistance, $\langle T_{MTJ}\rangle$ is the average temperature of MTJ [15], and $R_{P(AP)}^{MTJ}$ is the MTJ resistance for parallel (antiparallel) magnetic configuration of the magnetizations of ferromagnetic layers in the CoFeB/MgO/CoFeB. In

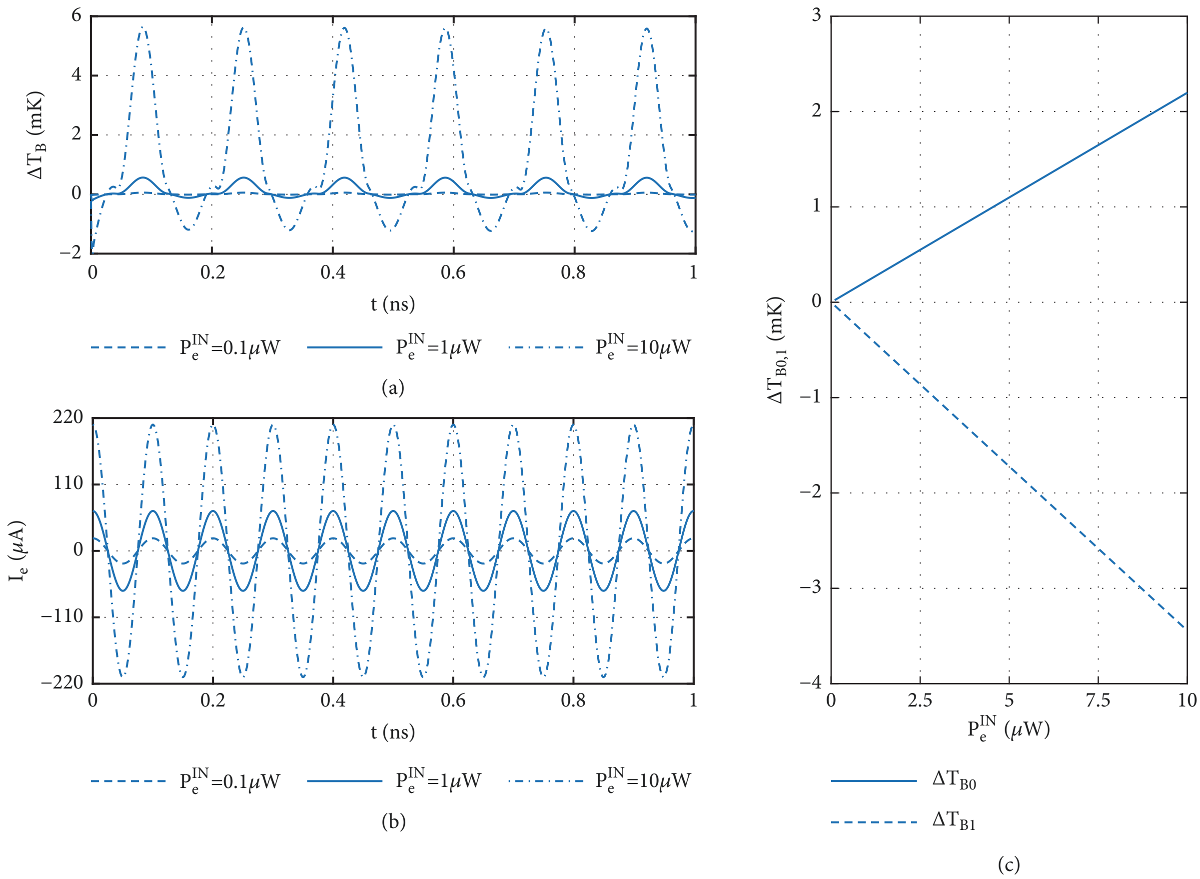

FIGURE 2: (a) Time evolution of (a) the temperature drop $\Delta T_B = \Delta T_{B0} + \Delta T_B(\omega)$ across the tunnel barrier of MTJ and (b) an alternating current with a frequency of 6 GHz at a variable power. (c) Dependence of the magnitude of the constant and variable first-harmonic temperature drops ΔT_{B0} and ΔT_{B1} on the heating power.

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 [16]. As shown in Figure 1, depending on the polarity of the external 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 $\Delta T_B(\omega) = \Delta T_{B0} + \Delta T_{B1} \cos \omega t + \Delta T_{B2} \cos 2\omega t + \ldots$, corresponding to the a.c. current I_e^{AC}, i.e., $\Delta T_B = \Delta T_B^C + \Delta T_B(\omega)$.

Thermal regimes of the MTJ heating by a direct current were discussed earlier in a number of papers [7, 8, 17]. Therefore, we give the results of a similar calculation of the amplitudes ΔT_{Bn} $(n = 0, 1, 2 \ldots)$ 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 ($\mathbf{I}_e^{DC} = 0$). Further we restrict our consideration to only two first harmonics, the frequency-dependent amplitudes $\Delta T_{B0}(\omega)$ and $\Delta T_{B1}(\omega)$ of which completely describe the behavior of the temperature drop. Thus, $\Delta T_B = \Delta T_{B0}(\omega) + \Delta T_{B1}(\omega) \cos \omega t$.

The calculation of the nonstationary heating of the tunnel structure of the MTJ by an a.c. current was performed based on the three-dimensional thermal analysis using the Comsol MultiPhysics software package [18]. 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 $\Delta T_B = \langle T_L \rangle - \langle T_R \rangle$, where $\langle T_{L(R)} \rangle$ is the temperature-averaged temperature of the left (right) ferromagnetic layer. Figure 2(a) 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 for three different microwave power values. With increasing power, the magnitude of the temperature drop ΔT_B also increases, while the steady part of the temperature drop (ΔT_{B0}) and the first harmonic of the temperature drop (ΔT_{B1}) vary linearly with the input power (Figure 2(b)).

As the frequency ω increases, the value of the variable components 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 $\Delta T_{Bn}(\omega) \sim \Delta T_{B0}(\omega)/\sqrt{1 + (n\omega\tau_T)^2}$.

2.3. Frequency-Independent Seebeck Effect. The temperature drop ΔT_B across the MgO barrier in a MTJ due to its nonuniform 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 $\Delta T_{B0} = \Delta T_{B0}(\omega)$, and $\Delta V_{DC}(\omega)$ is the dynamic component of the d.c. rectified voltage. The latter depends on the microwave part of the external current and time-varying component of temperature drop $\Delta T_{B1}(\omega)\cos\omega t$.

Our 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 [19] within the Sommerfeld free-electron model. In contrast to [19], however, we also take into account the variation of the effective masses in each layer of the MTJ, which more correctly describes electron transport in magnetic structures based on MgO tunnel barrier [20].

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 for the static Seebeck coefficient in the case of a symmetric MTJ:

$$S_{TH} = -\frac{k_B}{e}\frac{\sum_{\sigma,\sigma'}\int_0^{\infty} P_{\sigma\sigma'(e)}^{(TR_0)}(\varepsilon_x)\left(\ln\left(1+e^{-(\varepsilon_x-\varepsilon_F)/k_BT_0}\right)+\left((\varepsilon_x-\varepsilon_F)/k_BT_0\right)\left(e^{-(\varepsilon_x-\varepsilon_F)/k_BT_0}/\left(1+e^{-(\varepsilon_x-\varepsilon_F)/k_BT_0}\right)\right)\right)d\varepsilon_x}{\left(1-\sigma_J\left(\sigma_J-1\right)\right)\sum_{\sigma,\sigma'}\int_0^{\infty} P_{\sigma\sigma'(e)}^{(TR_0)}(\varepsilon_x)\left(e^{-(\varepsilon_x-\varepsilon_F)/k_BT_0}/\left(1+e^{-(\varepsilon_x-\varepsilon_F)/k_BT_0}\right)\right)d\varepsilon_x}, \quad (3)$$

where k_B is the Boltzmann constant, e is the elementary charge of the electron, ε_x is the longitudinal electron energy, $P_{\sigma\sigma'(e)}^{(TR_0)} = m_{L*}k_{xR}^{\sigma'}|T_{\sigma\sigma'}|^2/m_{R*}k_{xL}^{\sigma}$, $k_{xL(R)}^{\sigma(\sigma')}$ 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 $\sigma \longrightarrow \sigma'$, $m_{L(R)*}$ is the effective mass of the left (right) ferromagnetic MTJ layer, ε_F is the Fermi level of the magnetic system, and $T_0 \approx \langle T_{MTJ}\rangle$ is the average temperature of the magnetic system (equal to the ambient temperature for small temperature gradients).

Based on (3), we calculated numerically the dependencies of the static Seebeck coefficient S_{TH} on the thickness d_B and the height U_B of the tunnel barrier for the CoFeB/MgO/CoFeB MTJ (see Figure 3) with parameters close to the data of [14, 21]. In our simulation we used the following 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 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 layer (CoFeB), m_e is the mass of the electron, and $T_0 = 300K$ corresponds to the average temperature of the MTJ.

Figure 3 demonstrates that the maximum calculated value of the Seebeck coefficient S_{TH} varies from 25 to 175 μV/K, depending on the structure parameters and correlates with the corresponding values obtained in [19]. It is also well known that the Seebeck coefficient $S_{TH} = S_{TH}(\mathbf{m}\cdot\mathbf{m}_P)$ of the MTJ has a pronounced dependence on the angle θ_{MTJ} between $\mathbf{m}$ and $\mathbf{m}_P$ and is spin-dependent [1], as it follows from Figure 3. Table 1 summarizes the experimental results from previous studies [22–25] and our theoretical predictions for the Seebeck coefficients $|S_{TH}^P| = |S_{TH}(\theta_{MTJ} = 0)|$ and $|S_{TH}^{AP}| = |S_{TH}(\theta_{MTJ} = \pi)|$ in the case of parallel and antiparallel magnetic configuration of the MgO-based MTJ with Co- and Fe-containing ferromagnetic electrodes, respectively.

It is easily seen from Table 1 that the range of experimental values of $|S_{TH}^{P(AP)}|$ 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 [22] 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 $\Delta S_{TH} = |S_{TH}^P - S_{TH}^{AP}|$ close to 150 μV/K in the case of crystalline MgO-based MTJ [20]. The theoretical estimation of the Seebeck coefficients shows that $S_{TH}^P = -51\mu V/K$ and $S_{TH}^{AP} = -88\mu V/K$ for the given parameters of symmetric MTJ. However, it follows from [26] 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.

2.4. Nonlinear Spin-Diode Rectification Effect Induced by a Microwave Heating of 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, 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 time-varying part of the temperature drop $\Delta T_{B1}(\omega)\cos\omega t$.

Modulation of the magnetoresistance is associated with a dynamic response of $\mathbf{m}$ to the cumulative effect of thermal and electrical 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 Seebeck coefficient due to the

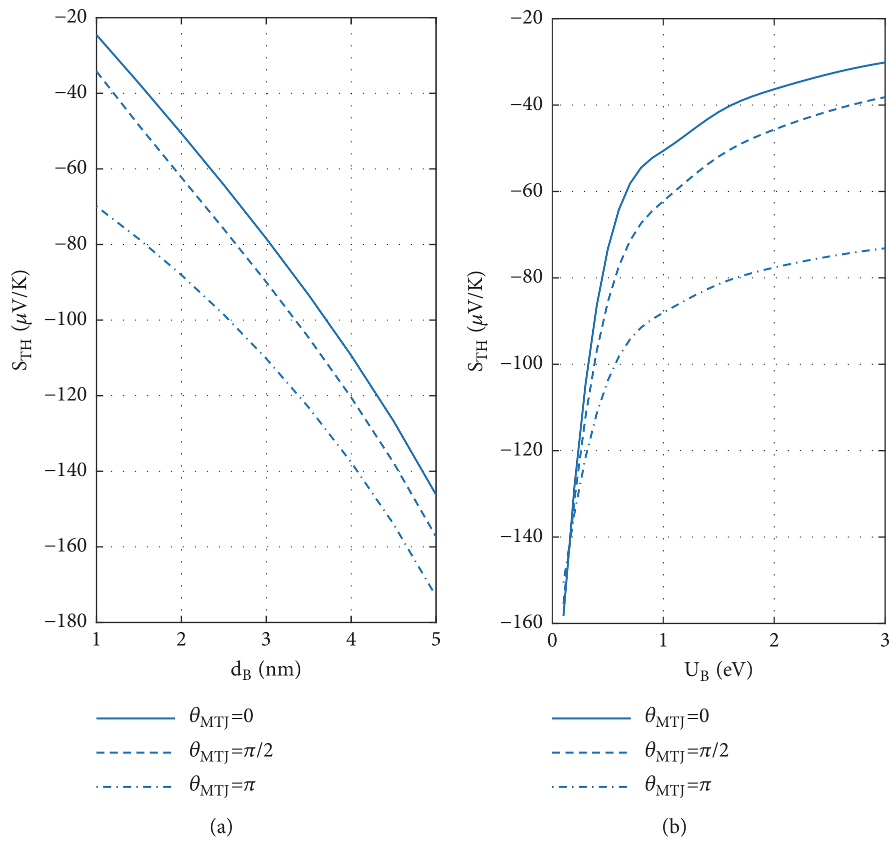

FIGURE 3: Dependence of the frequency-independent Seebeck coefficient S_{TH} on (a) the thickness and (b) the height of the tunnel barrier of the considered CoFeB/MgO/CoFeB MTJ for the varied angle θ_{MTJ} between the unit magnetization vectors $\mathbf{m}$ and $\mathbf{m}_P$.

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)	$\lvert S^{P}_{TH}\rvert$ (μV/K)	$\lvert S^{AP}_{TH}\rvert$ (μV/K)	Ref.
Co_2FeAl(10)/MgO(2)/CoFeB(5)	582	1133	[22]
Co_2FeSi(20)/MgO(2)/CoFe(5)	948	1703	[22]
CoFeB(3)/MgO(1.5)/CoFeB(3)	223	232	[23]
CoFeB(3)/MgO(1.5)/CoFeB(3)	166 (379)	284 (651)	[24]
CoFeB(1.4)/MgO(2)/CoFeB(1.2)	7.3	53.4	[25]
CoFeB(3)/MgO(0.78)/CoFeB(3)	51	88	[14], this work

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 $T = 2\pi/\omega$:

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

where $\Delta R_{MTJ}(\omega) = -0.5R^{P}_{MTJ}\delta^{MTJ}_{MR}(\mathbf{m}\cdot\mathbf{m}_P)$ is the dynamic part of the resistance R_{MTJ}, $\Delta I_e^{\Sigma}(\omega) = I_e^{AC} + \Delta I_{e1}^{TH}$, and $\Delta I_{e1}^{TH} = -S_{TH}\Delta T_{B1}(\omega)/R_{MTJ}$ is the thermal current passing through the tunnel barrier of MTJ under its microwave heating and related to the harmonic component $\Delta T_{B1}(\omega)\cos\omega t$.

Thus, to find the rectified voltage generated in the spin-torque diode, it is primarily necessary to find the dynamic response of the magnetic system to a time-varying component $\Delta T_{B1}(\omega)\cos\omega t$ of temperature drop. 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 (or field-like) components of two spin-transfer torques (thermal and current-induced) created by heat and by external electric current, correspondingly:

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

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, and $\mathbf{e}_\mu$ are the unit vectors in the Cartesian coordinate system, where $\mu = x, y, z$. The total spin-transfer torque $\mathbf{T}_{\parallel(\perp)} = \mathbf{T}^E_{\parallel(\perp)} + \mathbf{T}^T_{\parallel(\perp)}$ 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 [27]. The resulting torques can be written as

$$\begin{aligned}\mathbf{T}_\parallel &= \left(a^E_\parallel I^{AC}_e \cos\omega t - b^T_\parallel S_{TH} \Delta T_{B1}(\omega)\cos\omega t\right) \\ &\quad \cdot \left[\mathbf{m}\times\mathbf{m}\times\mathbf{m}_\mathrm{P}\right] \\ \mathbf{T}_\perp &= -\left(a^E_\perp \left|I^{AC}_e\right| \cos\omega t + b^T_\perp \left|S_{TH}\Delta T_{B1}(\omega)\right|\cos\omega t\right) \\ &\quad \cdot \left[\mathbf{m}\times\mathbf{m}_\mathrm{P}\right],\end{aligned} \tag{6}$$

where $a^E_{\parallel(\perp)} = (\hbar/2eS_{MTJ})\eta^E_{\parallel(\perp)}$, $b^T_{\parallel(\perp)} = (\hbar/2eS_{MTJ}R_{MTJ})\eta^T_{\parallel(\perp)}$, $\hbar$ is the reduced Planck constant, S_{TH} is the static Seebeck coefficient, R_{MTJ} is the MTJ resistance, and $\eta^E_{\parallel(\perp)}$ and $\eta^T_{\parallel(\perp)}$ are the dimensionless electric-current-driven and thermal-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 thermal spin-torque efficiencies.

We obtained that for a spin-torque diode on the basis of the MTJ structure under consideration (see Figure 1) the values of thermal-driven and electric-current-driven spin-torque efficiencies at zero temperature are as follows: $\eta^T_{\parallel 0} = 0.35$, $\eta^T_{\perp 0} = 0.26$ and $\eta^E_{\parallel 0} = 0.55$, $\eta^E_{\perp 0} = 0.35$. The effect of temperature on the rectifying voltage should be taken into account also by using temperature-dependent expressions for the spin-torque efficiencies and the saturation magnetization, correspondingly, according to [15]: $\eta^{E(T)}_{\parallel(\perp)}(T_0) = \eta^{E(T)}_{\parallel(\perp)0}(1 - \chi^{E(T)}_P {T_0}^{3/2})$, $M_S(T_0) = M_{S0}(1-(T_0/T_c))^{0.4}$, 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, $\mu_0 M_{S0} = 1.5T$, and $T_c = 1300K$ is the Curie temperature of CoFeB.

Let us assume that the dynamic part of temperature drop across the barrier is determined by the first harmonic $\Delta T_{B1}(\omega)\cos\omega t$ 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 ($\mathbf{I}^{\mathrm{DC}}_\mathrm{e} = 0$), when $I_e = I^{AC}_e \mathrm{Re}(e^{i\omega t})$.

After the linearization of (5), one can find the active part of the small deviation of the magnetization $\delta m_X = \delta m^0_X e^{i\omega t}$ from the equilibrium position and calculate $\Delta V_{DC}(\omega)$ according to (4). Taking into account the linearity of the thermal spin-transfer torques $T^{TST}_{\parallel(\perp)}$ with respect to amplitude $\Delta T_{B1}(\omega)$ of the first-harmonic component of temperature drop, the $\Delta V_{DC}(\omega)$ will be described by the following formula in the case of a small oscillation of $\mathbf{m}$ near $\mathbf{m}_0 = \mathbf{e}_\mathrm{Y}$:

$$\Delta V_{DC}(\omega) = \frac{1}{1+\alpha^2}\frac{\overline{V}^{\Sigma}_{DC}}{2}\rho^{MTJ}_0 \kappa^{MTJ}_1(\omega), \tag{7}$$

where $\overline{V}^{\Sigma}_{DC} = I^{AC}_e \overline{R}_{MTJ} - \overline{S}_{TH}\Delta T_{B1}(\omega)$, $\overline{S}_{TH} = S_{TH}(\theta_{MTJ} = \pi/2)$, and coefficient $\kappa^{MTJ}_1(\omega)$ is determined as

$$\begin{aligned}&\kappa^{MTJ}_1(\omega) \\ &\quad = -\frac{\gamma}{M_S d_F}\frac{\left(\omega^2\Delta\omega\right)T_\parallel - \left(\gamma B\left(\omega_0^2-\omega^2\right)+\alpha\omega^2\Delta\omega\right)T_\perp}{\left(\omega_0^2-\omega^2\right)^2+\left(\omega\Delta\omega\right)^2},\end{aligned} \tag{8}$$

where $T_\parallel = a^E_\parallel I^{AC}_e - \overline{b}^T_\parallel \overline{S}_{TH}\Delta T_{B1}(\omega)$ and $T_\perp = -a^E_\perp |I^{AC}_e| - \overline{b}^T_\perp |\overline{S}_{TH}\Delta T_{B1}(\omega)|$ are the in-plane and perpendicular components of the total spin-transfer torque, correspondingly, $\omega_0 = (1+\alpha^2)^{-1}\gamma\sqrt{B(B+\mu_0 M_S)}$ is the resonant frequency of spin-torque diode, $\Delta\omega = (1+\alpha^2)^{-1}\alpha\gamma(2B+\mu_0 M_S)$ is the resonance line width, and $\overline{b}^T_\perp = (\hbar/2eS_{MTJ}\overline{R}_{MTJ})\eta^T_{\parallel(\perp)}$.

In accordance with (7), 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 4 for the input microwave power of 1 μW, 5 μW, and 10 μW.

2.5. Voltage Rectification and Frequency-Dependent Seebeck Effect. Thus, by rearranging terms of (7), one can write the dc rectified signal $V_{DC} = V^{TH}_{DC0} + \Delta V_{DC}(\omega)$ of the spin-torque diode in a form of the sum of four contributions, $V^{TH}_{DC0}(\omega)$, $\Delta V^{TH}_{DC}(\omega)$, $\Delta V^{CH}_{DC}(\omega)$, and $\Delta V^{TC}_{DC}(\omega)$, which are defined as

$$\begin{aligned}V^{TH}_{DC0}(\omega) &= -\overline{S}_{TH}\Delta T_{B0}(\omega) \\ \Delta V^{TH}_{DC}(\omega) &= -K_{DC}\overline{S}_{TH}\widetilde{B}^T_{c\Sigma}\left(\Delta T_{B1}(\omega)\right)^2 \\ \Delta V^{CH}_{DC}(\omega) &= -K_{DC}\overline{R}_{MTJ}\widetilde{A}^E_{c\Sigma}\left(I^{AC}_e\right)^2 \\ \Delta V^{TC}_{DC}(\omega) &= K_{DC}\left(\overline{R}_{MTJ}\widetilde{B}^T_{c\Sigma} + \overline{S}_{TH}\widetilde{A}^E_{c\Sigma}\right)I^{AC}_e\Delta T_{B1}(\omega),\end{aligned} \tag{9}$$

where the coefficient $K_{DC} = (1+\alpha^2)^{-1}\gamma\rho^{MTJ}_0/2M_S d_f$, $\widetilde{A}^E_{c\Sigma} = c^\omega_\parallel a^E_\parallel + \sigma_J c^\omega_\perp a^E_\perp$, $\widetilde{B}^T_{c\Sigma} = c^\omega_\parallel \overline{b}^T_\parallel \overline{S}_{TH} - \sigma_{\Delta T_{B1}} c^\omega_\perp \overline{b}^T_\perp |\overline{S}_{TH}|$, $c^\omega_\parallel = \omega^2\Delta\omega/((\omega_0^2-\omega^2)^2+(\omega\Delta\omega)^2)$, $c^\omega_\perp = (\gamma(\mu_0 M_S + B)(\omega_0^2-\omega^2) + \alpha\omega^2\Delta\omega)/((\omega_0^2-\omega^2)^2+(\omega\Delta\omega)^2)$, $\sigma^{a.c.}_J$ is the polarity of a.c. current, and $\sigma_{\Delta T_{B1}}$ is the sign of ΔT_{B1}. From (9) it can be seen that $V^{TH}_{DC} \sim \Delta T_{B0}$, and $\Delta V^{TH}_{DC}(\omega) \sim \Delta T^2_{B1}$ are the thermal contribution to the rectified signal due to the static Seebeck effect and the thermal spin-transfer, respectively,

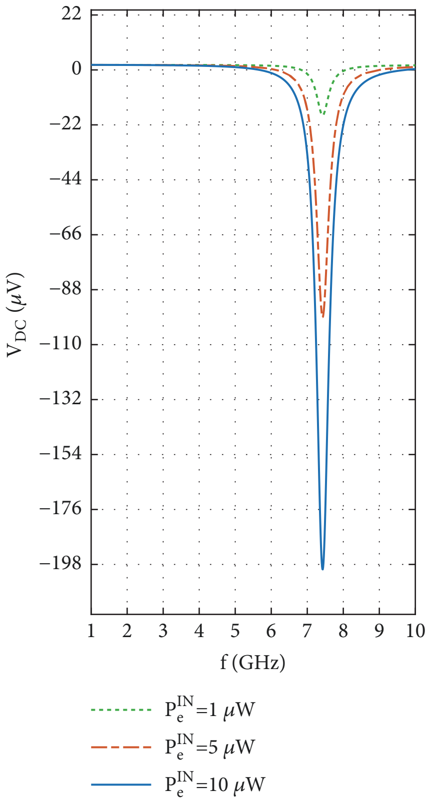

Figure 4: Frequency dependence of the amplitude of rectified signal V_{DC} generated across the MTJ caused by microwave heating of the spin-torque diode at different values of the input microwave power P_e^{IN} and the magnetic field $B = 50mT$, where the parameters of MTJ were taken from [14, 21] and the temperature T_0 is equal to 300 K.

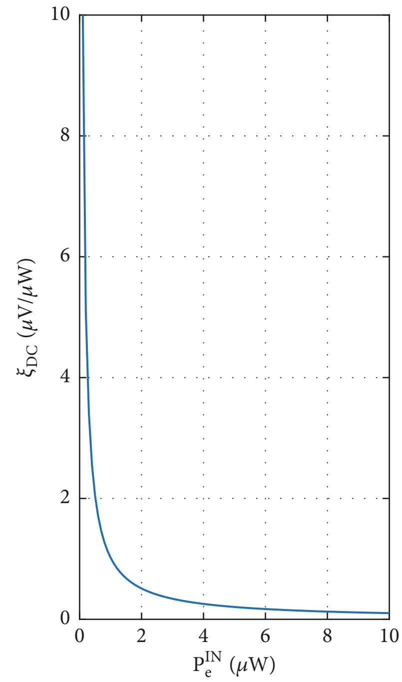

Figure 5: Dependence of the thermal contribution to microwave sensitivity of the spin-torque diode on the microwave input power at the a.c. current frequency of 10 GHz.

$\Delta V_{DC}^{CH}(\omega) \sim (I_e^{AC})^2$ is a purely electric contribution related to the rectification of the signal by means of electric spin transfer [12], and $\Delta V_{DC}^{TC}(\omega) \sim \Delta T_{B1}$ is the interference term describing the cumulative effect of the two spin-transfer torques to the dynamic response of the magnetic system, which are due to both the thermal and electric current of the microwave signal in the absence of heating.

According to (9), 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:

$$S_{TH}^{eff} \approx \overline{S}_{TH}\left(1 - \frac{1}{1+\alpha^2}\frac{\hbar}{4e}\right.$$
$$\left.\cdot \frac{\gamma\rho_0^{MTJ}\Delta\overline{j}_e^{TH}}{M_S d_f}\left(c_\parallel^\omega \Delta\overline{J}_{e1}^{TH}\eta_\parallel^T - c_\perp^\omega \left|\Delta\overline{J}_{e1}^{TH}\right|\eta_\perp^T\right)\right), \quad (10)$$

where $\Delta\overline{j}_e^{TH} = \overline{J}_{e1}^{TH}/\overline{J}_{e0}^{TH}$, $\Delta\overline{J}_{e0(1)}^{TH} = -\overline{G}_{MTJ}\overline{S}_{TH}\Delta T_{B0(1)}(\omega)$ is the thermal current density for corresponding harmonic components of the temperature drop, and $\overline{G}_{MTJ}$ is the MTJ conductance per unit area in the case when $\mathbf{m} \approx \mathbf{m}_0 = \mathbf{e}_y$. As it follows from Figure 2, the amplitudes $\Delta T_{B0}(\omega)$ and $\Delta T_{B1}(\omega)$ 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 $\Delta R_{MTJ} = (dR_{MTJ}/dT)\Delta T_B$ is negligibly small.

3. Microwave Sensitivity

The microwave sensitivity of a spin-torque diode is defined as the ratio of the rectified signal to the input power, i.e., $\xi_{DC}^{MTJ} = V_{DC}/\overline{P}_{eZ_0}^{IN}$. 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 $\overline{P}_{eZ_0}^{IN} = P_e^{IN}(\overline{R}_{MTJ} + Z_0)^2/4Z_0\overline{R}_{MTJ}$, where $P_e^{IN} = (I_e^{AC})^2\overline{R}_{MTJ}/2$ is the average input power incident on the spin-torque diode. Hence, according to (7), we get that

$$\xi_{DC}^{MTJ} = -\frac{8Z_0}{\left(I_e^{AC}\left(\overline{R}_{MTJ} + Z_0\right)\right)^2}\left(\overline{S}_{TH}\Delta T_{B0}(\omega) - \Delta V_{DC}(\omega)\right), \quad (11)$$

where $\Delta V_{DC}(\omega) = \Delta V_{DC}^{TH}(\omega) + \Delta V_{DC}^{CH}(\omega) + \Delta V_{DC}^{TC}(\omega)$ is calculated according to (9).

Figure 5 shows the spin-torque diode sensitivity ξ_{DC}^{MTJ} as a function of the input power of microwave signal (at low temperature $T_0 < 10K$). As can be seen from this figure, the microwave sensitivity gradually increases with increasing power input. 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 nonmonotonic and may have a peak character, which is associated with the thermal drift of the resonant frequency. In turn, the peak sensitivity of a spin-torque diode monotonously changes in a given temperature range (from 50 to 400 K) by 9%, while in the Schottky diode the sensitivity changes about 6 times.

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_{DC}^{MTJ} 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 $\omega \sim \omega_0$. In turn, the thermoelectric resonance contribution can be observed at the second harmonic at frequency $2\omega \sim \omega_0$ 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 [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 for operation 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 in which spin pumping occurs, instead of a spin-polarizing conducting electrode [29].

In addition, it is well known that, in the presence of a bias current in a spin-torque diode, the width of the resonance line for the rectification effect of the microwave signal associated with the current transfer of the spin changes and approaches zero in the vicinity of the critical value of the transition of the diode to the self-oscillation state. In this case, the resonant contribution to the microwave sensitivity can increase by more than two orders of magnitude [30, 31]. This can also be expected for the dynamic contribution to the bolometric effect due to the thermal current for the inhomogeneous heating of the MTJ. Discussion of this issue, however, is beyond the scope of this article.

Data Availability

The article is purely theoretical; thus all the parameters used to support the study are included within the article or available in the prior studies which are cited at relevant places in the text as references.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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