Spin-torque diode with metamaterial-based absorbing coating for the efficient waste heat energy harvesting from microwave radiation

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***Abstract*— Currently, there is a rapid development of spin caloritronics, an emerging field of physics of the interaction of spin and thermoelectric phenomena in magnetic materials, which is applicable for the development of highly efficient miniature thermal energy harvesters. In this work we propose the concept of a spin-torque diode based on a magnetic tunnel junction combined with metamaterial-based absorbing thin-film coating consisting of a metal-dielectric-metal multilayer structure. The numerical simulation of the coating properties demonstrates near unity absorption of microwave energy in a wide frequency range (from hundreds of MHz to several GHz), which leads to a high temperature gradient through the tunnel spacer of the junction. The inclusion of thermal barriers made of materials with low thermal conductivity into the spin-diode structure provides an increase in the temperature gradient up to hundreds of mK, which, due to the tunnel magneto-Seebeck effect, makes it possible to efficiently utilize heat losses during microwave heating and generate a thermo-voltage at the level of several hundreds of μV. Taking into account the high sensitivity of spin-torque diodes (more than 200 mV/μW), as well as the prospects for their scaling down to 1X nm, it opens up the possibility of creating miniature thermoelectric elements, which enable to supply low-power IoT devices.**

Keywords*— Internet of Things, thermal energy harvesting, spin caloritronics, spin-torque diode, magnetic tunnel junction, metamaterial, tunnel magneto-Seebeck effect, microwave radiation, microwave heating

I. INTRODUCTION

In the context of the current development of the Internet of Things (IoT) market, which consists of a billion interacting smart devices, an important task is to find new technologies for creating miniature and energy-efficient power supplies that can ensure their long-term autonomous operation [1]. Today, conventional battery cells cannot cope with such a task, since they have a limited lifetime and cannot be used for deploying a large-scale IoT network in places where additional recharging becomes impossible, while their regular maintenance requires large financial costs. One of the most promising ways to solve this problem is to scavenge energy from the ambient environment, which can be generated by mechanical vibrations, heat, light, microwave radiation [2]. In a big city, where there are a large number of telecommunications networks (mobile communications, radio communications, Wi-Fi), the use of microwave energy for powering small IoT devices seems to be especially attractive. First of all, this will make it possible to efficiently distribute the energy resources of electromagnetic waves of the microwave range, which are not fully consumed and serve only for wireless data transmission over various communication channels. This approach is expected to significantly reduce the load on the city's electricity grid, as well as its service costs. In this regard, an important role is played by the development of the technology of wireless energy harvesters, which have a high efficiency of conversion of microwave radiation in a given frequency range. The conversion efficiency mainly determines the output power generated by harvester for charging IoT [3]. A magnetic tunnel junction (MTJ) consisting of two ferromagnetic (FM) layers separated by a tunnel layer exhibits a spin-torque diode effect of rectifying the microwave signal coming from the transmission line of the receiving antenna [4]. This effect is caused by the excitation of stable magnetization oscillations in one of the FM layers (free layer) under the action of an alternating current, while the magnetization of the other one (reference layer) remains fixed (for example, by interfacial exchange coupling with an adjacent antiferromagnetic layer). Since the resistance of MTJ depends on the mutual orientation of the magnetizations of the FM layers, it also changes with the frequency of the injected current, which, in turn, generates a rectified d.c. voltage at the output of the MTJ-based spin-torque diode. Table 1 shows the key parameters (operating frequency and output power from the receiving antenna) of the most famous microwave radiation sources operating in the following frequency ranges - FRS / GMRS, GSM900, Bluetooth, Wi-Fi (based on the IEEE 802.11 network protocol), and LTE (including 3G/4G). As follows from this table, the input power of the spin-torque diode generated from these microwave signal sources varies in the range from 4 to 1000 μW [5-9], which meets the conditions for the stable generation of free-layer magnetization oscillations, providing an acceptable level of d.c. output voltage (from hundreds of μV up to tens of mV).

TABLE I. THE MAIN PARAMETERS OF MICROWAVE SOURCES (AT THE OUTPUT OF THE RECEIVING ANTENNA)

№	Source of RF radiation	Frequency, GHz	The RF power, μW	Ref.
1	Walkie-talkie	0.462	6.3	[5]
2	Radiophone	0.923	4.0	[5]
3	Router Wi-Fi (802.11b/g/n/ax)	2.4-2.5	10 (-20 dBm)	[6]
4	Router Wi-Fi (802.11y)	3.6	10 (-20 dBm)	[7]
5	Router Wi-Fi (802.11a/j)	5.5	1000 (0 dBm)	[8]
6	LTE (including 3G/4G)	0.79-0.96; 1.71-2.17; 2.5-2.69	10 (-20 dBm)	[9]

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The maximum experimentally obtained sensitivity of such spin-torque diodes exceeds 200 mV/μW and corresponds to an output voltage of about 20 mV [10]. This value is quite sufficient for a stable supply of low-power sensor nodes as part of an IoT network [11-15], which consume in the region of several tens of nW (Table 2). As an example, it was experimentally demonstrated in [5] that a black phosphorus photodetector can be powered from a spin-torque diode in the case of microwave radiation from such devices as a walkie-talkie (6.3 μW) and a radiophone (4 μW).

TABLE II. The Energy Requirements For The Ultra-Power IoT Sensor Nodes

№	**Type of IoT sensor**	**Power consumption, nW**	**Ref.**
1	Temperature sensor	110	[11]
2	Capacitive sensor	270	[12]
3	Human motion detection sensor	30	[13]
4	Biomedical sensor	450	[14]
5	Actuator	1000	[15]

Table 3 summarizes information about recent work in the field of optimization of spin-torque-diode structures in order to increase the microwave sensitivity [5, 16-20], the value of which is several orders of magnitude higher than the sensitivity of semiconductor Schottky diodes and varies from 0.03 to 210 mV/μW in a wide frequency range (from 0.1 MHz to 9 GHz), covering almost all the bands of ambient RF signals presented in Table 1.

TABLE III. The MTJ-Based Spin-Torque Diode Characteristics From Existing Experimental Works

№	**Type of MTJ structure in a spin-torque diode**	**Freq., GHz**	**Sensitivity, mV/mW**	**Ref.**
GHz frequency range (MTJ with in-plane magnetized free layer)				
1	$Co_{40}Fe_{40}B_{20}/MgO/Co_{40}Fe_{40}B_{20}$	Dual-band, 1.92, 3.56	>8000	[16]
2	$Co_{60}Fe_{20}B_{20}/MgO/Co_{16}Fe_{64}B_{20}$	5-6	280	[17]
3	$Co_{60}Fe_{20}B_{20}/MgO/Co_{60}Fe_{20}B_{20}$	5-9	54	[18]
Sub-GHz frequency range (MTJ with perpendicular magnetic anisotropy (PMA))				
4	$Co_{20}Fe_{60}B_{20}/MgO/Co_{20}Fe_{60}B_{20}$ with canted magnetization	Broad-band, 0.1-1.2	~70	[5]
5	$Co_{20}Fe_{60}B_{20}/MgO/Co_{20}Fe_{60}B_{20}$ MTJ with wedge-shaped free layer and canted magnetization	Broad-band, 0.1-3	~30	[19]
6	$Co_{20}Fe_{60}B_{20}/MgO/ Co_{20}Fe_{60}B_{20}$	0.3-1	$2.1 \cdot 10^5$	[10]
MHz frequency range (MTJ with in-plane magnetized free layer)				
7	$Co_{40}Fe_{40}B_{20}/MgO/Co_{20}Fe_{60}B_{20}$	10^{-4}-0.1	$\sim 0.35 \cdot 10^5$	[20]

Despite a huge amount of research on the mechanisms for controlling the efficiency of conversion of microwave radiation in a spin-torque diode, there are relatively few studies of another no less interesting phenomenon observed in the MTJ – the tunnel magneto-Seebeck effect, which arises, by analogy with the ordinary Seebeck effect, in the presence of a non-zero temperature gradient through the tunnel barrier and provides thermo-voltage (or thermo-current) which depends on the magnetization state of the free layer. This effect seems to be very attractive from the point of view of converting thermal energy into electricity and utilization of undesirable heat losses that occur during inhomogeneous microwave heating of the MTJ structure [21] and reduce the overall efficiency of energy harvesting device. The record value of the Seebeck coefficient recently obtained in IrMn-based MTJ, which varies in the range from 0.39 mV/K (at t (IrMn)=3.1 nm and T=310 K) to 1.1 mV K (at t (IrMn)=2.5 nm and T=270 K), opens the way to the practical implementation of thermoelectric elements based on a set of series-connected spin-torque-diode structures [22].The use of absorbing coatings in a structure of spin-torque diode which operate in the GHz frequency range can lead to the maximum absorption of microwave energy [23], as well as to an additional enhancement of the thermoelectric effect due to an increase in the MTJ heating. The inclusion of thermal barriers made of materials with low thermal conductivity on both sides of the tunnel spacer of the MTJ is a promising solution for providing a noticeable difference in temperature between FM layers in order to grow up the output thermo-voltage during microwave irradiation of the spin-torque diode. In this work, we consider the original concept of a spin-torque diode based on MTJ with thermal barriers and an absorbing thin-film coating made of metamaterial, which allows the combined harvesting of both thermal and electromagnetic energy in the microwave frequency range. The following sections provide a detailed description of the proposed structure of the spin-torque diode, the theoretical basis for calculating the spin-dependent thermo-voltage generated in the diode during its microwave heating, as well as the simulation results confirming the usefulness of the proposed approach to the development of a highly efficient thermoelectric and microwave energy converter in one device.

II. The Proposed Design of A Spin-Torque Diode With Metamaterial-Based Absorbing Coating

Figure 1 schematically illustrates a model of an electromagnetic system consisting of the microwave emitter (horn antenna) and the receiver (patch antenna) which is connected to the top electrode of MTJ-based spin-torque diode via transmission line.

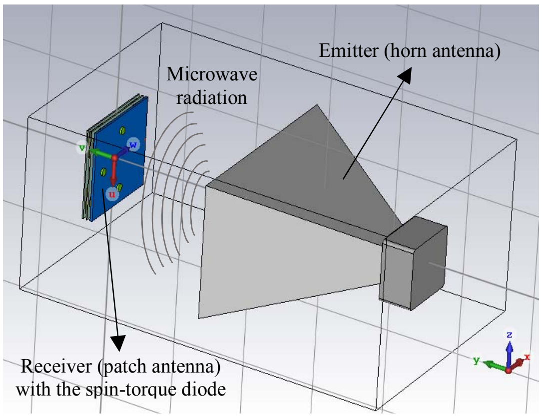

Fig. 1. Schematic illustration of an electromagnetic system «microwave emitter-receiver», where the current from the receiver's transmission line is applied to a spin-torque diode.

To numerically estimate the value of the a.c. current through the transmission line and the corresponding input power supplied to the MTJ in a given frequency range of microwave radiation, the distance between emitter and the receiver was chosen as a variable parameter. Figure 2a shows the proposed design of a spin-torque diode based on MTJ. The MTJ structure contains thermal barriers (made from materials with low thermal conductivity) on both sides of the tunnel

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spacer in order to enhance the temperature gradient across the MTJ during asymmetric microwave heating and a thin-film absorbing coating which provides almost a single adsorption of electromagnetic energy in the GHz frequency range. For the analysis, we chose a magnetic heterostructure of the composition IrMn (7.5 nm) / CoFe (2.5 nm) / Ru (0.85 nm) / CoFe (0.5 nm) / CoFeB (3 nm) / thermal barrier (x nm) / MgO (0.78 nm) / thermal barrier (x nm) / CoFeB (3 nm), which is a modification of the MTJ structure taken from [24]. The top and bottom layer of the MTJ are connected to Cu metal bars with a thickness of 250 nm, while the cross-section of MTJ has a rectangular shape with a width of 120 nm and a length of 250 nm. The absorbing coating is a thin-film metal/dielectric/metal structure based on FR-4 substrate, which is promising candidate for broadband absorption of microwave radiation in the S - band (2-4 GHz) and C-band (4-8 GHz), which was shown in recent work [23].

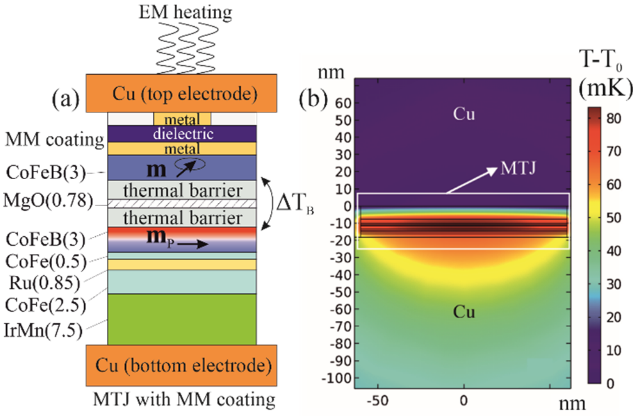

Fig. 2. (a) The proposed design of a spin-torque diode based on MTJ with thermal barriers and an absorbing coating made of metal/dielectric/metal metamaterial (MM), which increases the efficiency of thermoelectric conversion of electromagnetic (EM) radiation in the GHz frequency range. The thicknesses of the layers are indicated in brackets, ΔT_B is the temperature jump through the MgO tunnel spacer, $\mathbf{m}(\mathbf{m}_P)$ is the magnetization vector of the free (reference) FM layer (the heating region is indicated in red). (b) The temperature increment T-T$_0$ (in mK) along the MTJ cross-section (without thermal barriers), resulting from microwave heating with an input power of 1 μW, T$_0$=293 K is the room temperature.

The alternating current $I_e \cos(\omega t)$ flowing from the transmission line of the receiving antenna to the input of the spin-torque diode provides a temperature gradient across the MTJ (Figure 2b). The Joule heating of the MTJ mainly occurs in the region of the FM layer (CoFeB) near the tunnel barrier (MgO), where the spin-polarized current enters, which leads to a nonstationary temperature drop $\Delta T_B(\omega)$ across the spacer [25]. Since this temperature drop linearly depends on the input microwave power, the magnitude of the latter plays a crucial role in the generation of output thermo-voltage. It is well known that the dissipative losses in the transmission line connected to the MTJ exceed 60% (varying from -3 to -5 dB), which does not allow the full utilization of electromagnetic energy. In our previous work [21], we demonstrated the efficiency of using an absorbing nanocoating based on the metamaterial structure TiN (30 nm)/SiO$_2$ (60 nm)/TiN (150 nm) with micropatches having a square-split-ring shape, which allows us to achieve near-unity absorption in a wide range of wavelengths. The use of such a coating as the top trilayer of the MTJ in the proposed design of a spin-torque diode make it possible to obtain the temperature increment up to 80 mK at an input power of 1 μW.

III. THEORETICAL MODEL

To carry out a numerical evaluation of the thermoelectric properties of a spin-torque diode with the proposed design, a physical model of thermo-voltage rectification in MTJ under its inhomogeneous thermal heating by incident microwave radiation was built. It was found that the total voltage generated by the diode during its heating has both constant and variable component, respectively. The constant component of the bias voltage V_{DC0}^{TH} arises due to the presence of a stationary tunnel magneto-Seebeck effect in the MTJ observed in the case of a non-zero temperature drop ΔT_{B0} across the tunnel barrier. At the same time, the microwave heating of MTJ by alternating current leads to the appearance of a frequency-dependent dynamic component of the voltage $\Delta V_{DC}(\omega)$. This contribution comes from the modulation of the MTJ magnetoresistance due to the impact of thermally-induced components of the spin-transfer torque (STT) on the free-layer magnetization in the presence of non-zero frequency-dependent harmonics of the temperature drop:

$$\Delta\tilde{T}_{B\Sigma}(\omega,t) = \sum_{\kappa=1\ldots3} \Delta T_{B\kappa}(\omega)\cos\kappa\omega t \qquad (1)$$

The modulation process occurs due to the dynamic response of the free-layer magnetization to the alternating electric current from the transmission line of the receiving antenna and the thermal current flowing in the opposite direction, which is described by macrospin Landau-Lifshitz-Gilbert equation with the Slonczewski-Berger STT terms:

$$\dot{\mathbf{m}} = -\gamma[\mathbf{m}\times\mathbf{B}_{\text{eff}}] + \alpha[\mathbf{m}\times\dot{\mathbf{m}}] - \frac{\gamma}{M_S d_F}(\mathbf{T}_\parallel + \mathbf{T}_\perp), \qquad (2)$$

where γ is the gyromagnetic ratio, α is the Gilbert damping constant, $\mathbf{B}_{eff} = \mathbf{B}_a + \mathbf{B}_d$ is the effective magnetic field, $\mathbf{B}_a$ is the external magnetic field, $\mathbf{B}_d$ is the demagnetization field, M_S, d_F are the magnetization and the thickness of free layer, respectively. The STT $\mathbf{T}_{\parallel(\perp)} = \mathbf{T}_{\parallel(\perp)}^E + \mathbf{T}_{\parallel(\perp)}^T$ is represented as the sum of two components, which are responsible for the electrical ($\mathbf{T}_{\parallel(\perp)}^E$) and thermal ($\mathbf{T}_{\parallel(\perp)}^T$) mechanism of spin transport in MTJ. Linearization of the equation (2) near the equilibrium position of the magnetization $\mathbf{m} = \mathbf{m}_0$ allows us to obtain an analytical expression for the dynamic part of the generated bias voltage $\Delta V_{DC}(\omega) = \Delta V_{DC}^{TH}(\omega) + \Delta V_{DC}^{CH}(\omega) + \Delta V_{DC}^{TC}(\omega)$ which was described in detail in [25], where $\Delta V_{DC}^{TH}(\omega) \sim \bar{S}_{TH} \sum_{\kappa=1\ldots3} \bar{B}_c^\kappa (\Delta T_{B\kappa}(\omega))^2$ is the purely thermal contribution due to the stationary Seebeck effect and thermally-driven spin transfer, $\bar{B}_c^\kappa = c_\parallel^{\omega_\kappa} \bar{b}_\parallel^T + c_\perp^{\omega_\kappa} \bar{b}_\perp^T$, $c_{\parallel(\perp)}^{\omega_\kappa}$ is the frequency-dependent variable parameter, $\omega_\kappa = \kappa\omega$, $\bar{b}_{\parallel(\perp)}^T = (\hbar / 2eS_{MTJ}\bar{R}_{MTJ})|\bar{S}_{TH}|\eta_{\parallel(\perp)}^T$, $\hbar$ is the reduced Planck constant, e is the electron charge, S_{MTJ} is the area of the MTJ cross-section, $\eta_{\parallel(\perp)}^T$ is the dimensionless coefficient of the thermally-induced STT efficiency, $\bar{S}_{TH}$ is the average value of the frequency-independent stationary Seebeck coefficient. The term $\Delta V_{DC}^{CH}(\omega) \sim (I_e)^2$ is the purely electrical contribution associated with the voltage rectification under the impact of an alternating electric current, while $\Delta V_{DC}^{TC}(\omega) \sim I_e \Delta T_{B1}(\omega)$ is the interference term describing the total contribution of the electric and thermal STTs to the temperature drop across the tunnel spacer due to the Joule heating of the MTJ under the microwave irradiation. In this case, the constant voltage $V_{DC0}^{TH} = -\bar{S}_{TH} \Delta T_{B0}$. In contrast to the previous theoretical works, we took into account the variation of effective electron mass in each layer of the MTJ stack, which more correctly describes electronic transport in the MgO-based MTJs within the Sommerfeld free-electron model. The absorption properties of a thin-film coating of a spin-torque diode design of which is described in the previous section can be calculated based on the evaluation of the S-parameters obtained from the full-field electromagnetic simulation of a metal/dielectric/metal metamaterial operating in a given frequency range.

IV. RESULTS AND DISCUSSION

The simulation of the microwave radiation pattern from a horn antenna in the frequency range from 0 to 12 GHz, which was carried out in the CST Microwave Studio software package, shows that its main part reaches the receiver with a spin-torque diode (Figure 3a). Figure 3b shows the frequency dependence of the amplitude of the alternating current at the input of the spin-torque diode at different distance dmw between the emitter and the receiving patch antenna. As can be seen from the figure, the diode in close proximity to the emitter (at a distance of 5 mm) generates a large alternating current with main peaks at a frequency of 3.8 GHz, 7-9 GHz, while at a distance of 100-500 mm, the amplitude of the current is about several hundred μA, which is enough to obtain the constant voltage in a spin-torque diode.

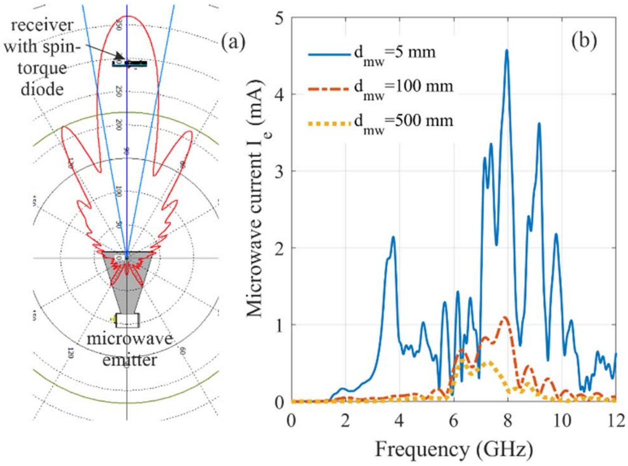

Fig. 3. (a) Radiation pattern of microwave radiation from a horn antenna (at a frequency of 6 GHz) coming to a patch antenna with a spin-torque diode. (b) The alternating current in the microstrip line as a function of the radiation frequency at different distances between the emitter and the receiver.

Figure 4a shows the time dependence of the temperature drop ΔT_B across the MTJ tunnel spacer at a current frequency of 6 GHz. According to (1), the temperature drop changes with the same frequency as the microwave current and can be expanded into a series of individual harmonics, the main of which (zero and first) increase linearly with the microwave power. With an increase in the frequency of the current, the amplitude of the harmonic components $\Delta T_{B\kappa}(\omega) \sim \Delta T_{B0} / \sqrt{1+(\kappa\omega\tau_T)^2}$ decreases, which is associated with the competition of two factors affecting the temperature drop - the period of the microwave current $T = 2\pi/\omega$ and the characteristic time of heat removal τ_T. The resonant frequency at which the peak of the zero harmonic ΔT_{B0} is observed corresponds to a rise in the generated thermo-voltage V_{DC0}^{TH}, which is provided by the influence of the stationary spin-dependent Seebeck effect.

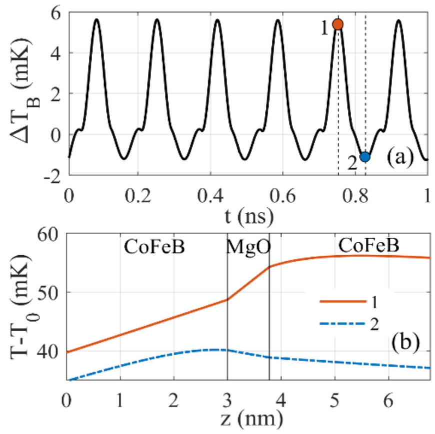

Fig. 4. (a) The time evolution of the temperature drop ΔT_B across the tunnel spacer of MTJ (without thermal barriers) induced by a.c. current with an amplitude of 250 μA (with input power of about 1 μW) and a frequency of 6 GHz. (b) The MTJ temperature increment $T - T_0$ along the direction of thermal spin transport, where 1 (2) - the state of parallel (antiparallel) mutual orientation of the magnetizations $\mathbf{m}$ and $\mathbf{m}_P$, T_0 is the room temperature.

Due to this effect, the temperature distribution over the MTJ cross section, as well as the temperature drop across the spacer strongly depends on the orientation of the magnetizations of the FM layers (Figure 4b). Since ΔT_B is proportional to the input power, it increases by a factor of 10 when the power changes from 1 to 10 μW (see Figure 5).

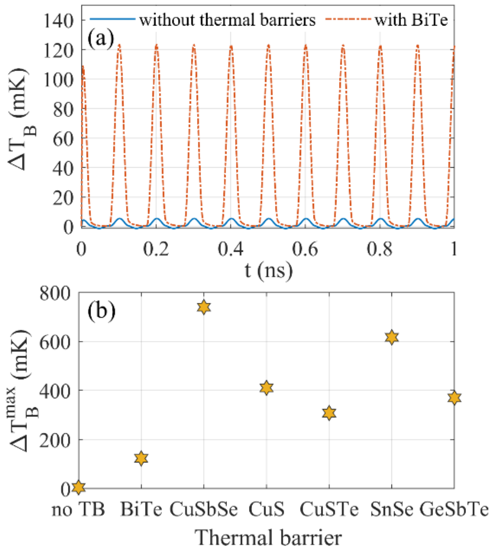

Fig. 5. (a) Time dependence of the temperature drop ΔT_B in the absence of BiTe thermal barriers and in the case of their inclusion in the MTJ composition. (b) The variation of the maximum temperature drop $\Delta T_B^{\max}$ depending on the material of the thermal barriers. The thickness of thermal barriers in the MTJ is equal to 3 nm and the input radiation power is 10 μW.

The simulation has shown that the inclusion of thermal barriers in the MTJ structure of spin-torque diode on both sides of the tunnel spacer enhances ΔT_B by hundreds of times compared to the usual MTJ. Its peak value increases from 5 to 123 mK when the commonly-used BiTe thermal barriers are added to the MTJ (Figure 5a). In this case, the temperature drop ΔT_B increases inversely with the thermal conductivity of the material of thermal barriers. To achieve the maximum amplification of the thermally-induced voltage, materials with the lowest thermal conductivity should be used – chalcoaltimonates CuSbSe (0.25-0.3 W/m K), copper chalcogenides CuS (0.45 W/m K), CuSTe (0.6 W/m K), tin selenides SnSe (0.3-0.35 W/m K), germanium and antimony tellurides GeSbTe (0.5 W/m K). According to Figure 5b, the most promising material, CuSbSe, leads to an increase in the temperature drop by almost 150 times (up to 739.7 mK). Taking into account the Seebeck coefficient in MTJ, which can reach more than 300 μV/K [22], the thermo-voltage will vary in the range of hundreds μV, which is enough to charge low-power IoT sensors.

V. CONCLUSION

The simulation of the thermoelectric properties of a spin-torque diode based on MTJ with an absorbing coating demonstrates the possibility of using it as a thermoelectric element for converting microwave energy in a wide frequency range, which is associated with achieving a relatively high temperature gradient (from tens to hundreds of mK) through the tunnel structure during its microwave heating. It was shown that the inclusion of thermal barriers made of materials with low thermal conductivity (BiTe, CuS, CuSbSe, SnSe, GeSbTe) on both sides of the MTJ spacer allows increasing the amplitude of the temperature jump by several orders of magnitude, which proportionally increases the thermo-voltage generated by the spin-torque diode. The results obtained can be useful in the design and development of a new class of microwave energy harvesters based on the MTJ.

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