Prospects of Electromagnetic Energy Harvesting In a Combined Structure of Broadband Metamaterial Absorber With a Magnetic Tunnel Junction Having Tunnel Magneto-Seebeck Effect

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Abstract

The concept of the electromagnetic energy harvesting by thermoelectric system based on a broadband metal-insulator-metal-based metamaterial combined with a magnetic tunnel heterostructure, exhibiting the tunnel magneto-Seebeck effect, is presented. Based on finite-element calculations, the optimal design of such a broadband metamaterial with conductive TiN layer was selected to ensure maximum adsorption of radiation in a given wavelength range (solar spectrum/microwave region). The microwave heating of the magnetic tunnel heterostructure after passing the electromagnetic wave through the metamaterial and corresponding thermo-voltage response were also evaluated, indicating the possibility of using such system for an effective energy supply of low-power electronic devices.

Introduction

Nowadays, much attention of the scientific community is paid to the search for the most effective technologies in the field of wireless energy harvesting, which is currently a key task for the development of the Internet of Things (IoT) market [1]. More recently, to ensure the standalone operation of IoT low-power devices, a whole list of hybrid structures based on photovoltaic materials combining the accumulation of solar energy and its electrochemical storage was proposed [2]. However, the issue of achieving sufficient durability and low cost of such structures still remains unresolved, while expanding the scope of their applications towards the microwave region for harvesting of ambient electromagnetic energy in the absence of sunlight requires fundamentally new approaches. The use of broadband metal-insulator-metal (MIM)-based metamaterial opens the way to achieving near-unity absorption of incident radiation in a wide frequency spectrum [3]. This energy is mainly distributed to heat up the metamaterial structure in the form of thermal energy, which can be further converted into an electric signal by means of a thermoelectric generator (TEG). Typically, bismuth telluride (Bi_2Te_3) is most often used as a thermoelectric (TE) material in commercial TEG prototypes. As known, Bi_2Te_3 is not fully compatible with semiconductor technology, while, despite the recent success in implementing silicon nanowires in TEG to improve the thermoelectric efficiency (figure of merit is about 0.6), their reproducibility is still a problem [4]. As we shown earlier, the tunnel magneto-Seebeck effect in a magnetic tunnel junction (MTJ) can be effectively used for thermoelectric rectification of a microwave signal in MTJ during its inhomogeneous microwave heating [5]. In this work we propose the concept of a combined device for collecting electromagnetic energy using a broadband MIM-based metamaterial combined with MTJ.

The concept: electromagnetic energy harvester based on a broadband metamaterial absorber combined with MTJ

To increase the efficiency of electromagnetic energy harvesting in thermoelectric energy converters, the use of a broadband electromagnetic absorber in their design seems to be the best solution to solve this problem. The strategy of broadband absorption is based on multi-resonance that, in turn, produces multi-mode absorption. In turn, broadening the bandwidth becomes possible using structure with a metamaterial surface above the ground plane serving as a perfect absorber with dramatically reduced overall thickness. In particular, MIM-based plasmonic metamaterial absorbers (MIM-PMAs) are the most promising and widely studied for a wide range of wavelengths due to their high performance, such as high absorbance, polarization insensitivity, as well as their design flexibility and simple fabrication. Typically, MIM-based PMA consists of three layers: a bottom metal layer, a middle dielectric layer, and a top periodic metal layer of resonator elements or micropatches, as shown in Fig. 1a. Strong absorption in MIM-PMAs is attributed to the localized magnetic and electric dipole resonances, which induce at the boundaries of layers of such a structure by incident electromagnetic radiation, which provide sufficient time to consume light energy by the ohmic losses in the metals. The absorption wavelength is fundamentally defined by the micropatch topology, while the different shapes of micropatches were considered in the literature to tune high absorbance in a wide wavelength spectrum (Fig. 1b).

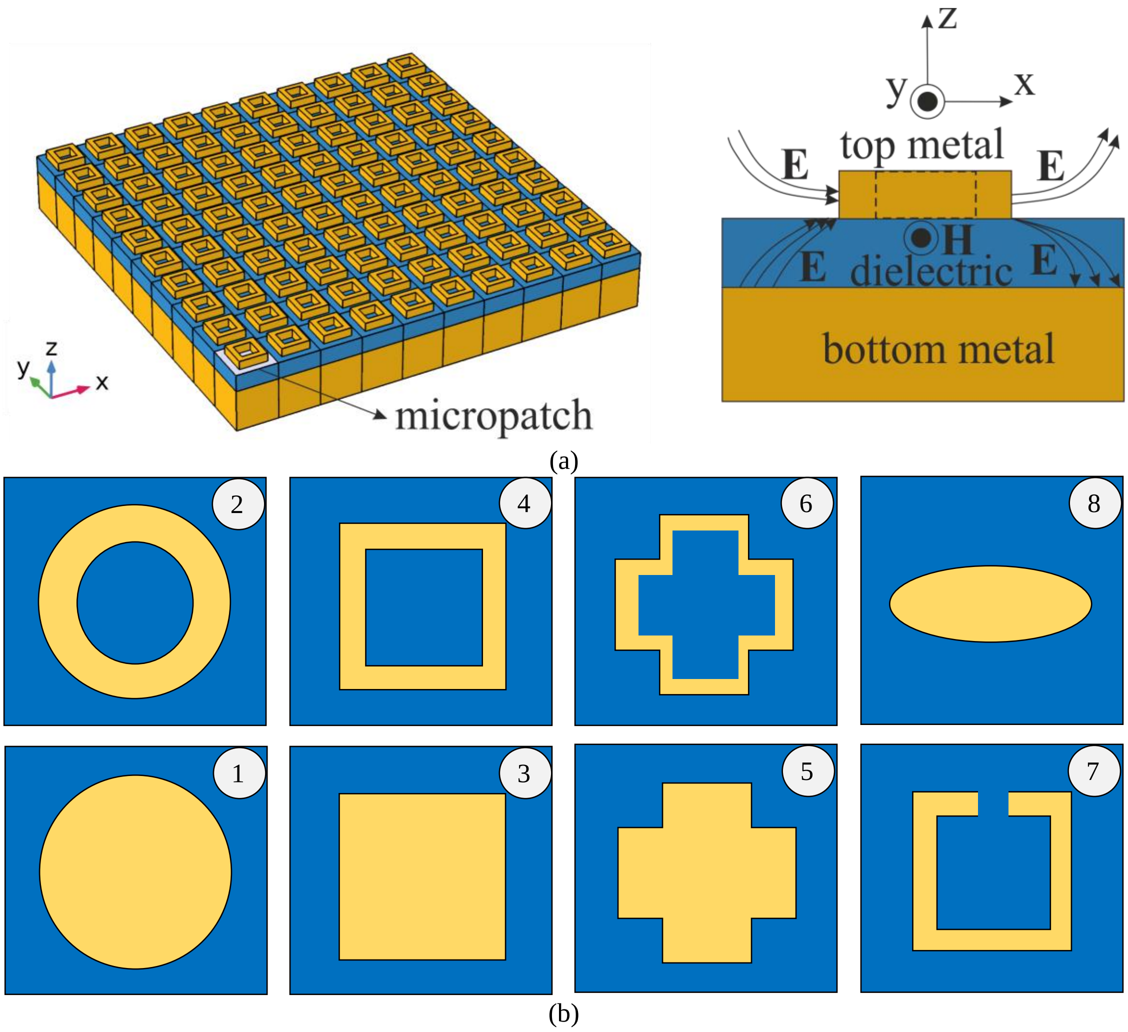

Fig. 1. (a) The schematics of MIM-PMA, where E, H are the electric and magnetic field, respectively. (b) Typical forms of micropatches used to obtain near-unity absorption in MIM-PMA.

The absorption in a such metamaterial structure can be expressed on the basis of S-parameters, as follows: $A(\lambda)=1-R(\lambda)-T(\lambda)$, where λ is the electromagnetic wavelength, $R=|S_{11}|^2$ and $T=|S_{12}|^2$ are reflection and transmission coefficients, respectively.

For a more efficient absorption of transmitted radiation in a wide range of wavelengths, it is effective to use a metamaterial thin film based on a refractory material, such as TiN, which was demonstrated in [6]. The spectral range in which surface plasmons can be excited is very limited, so the best solution is to create the structure shown in Fig. 1a, where part of the energy of sunlight is absorbed by array of micropatches (top layer) due to the excitation of plasmon resonance, while the other part is absorbed by a solid film of titanium nitride (bottom layer).

The idea of a microwave energy harvester based on the tunnel magneto-Seebeck effect in nanoscale MTJ was proposed by our group earlier in [7]. Similar to Schottky semiconductor diodes, the MTJ structure, containing two ferromagnetic layers separated by a thin dielectric spacer, exhibit a diode effect, associated with rectification of the output voltage on the MTJ electrodes due to the spin-transfer torque, which is generated when the microwave current is applied [8]. In this case, the peak sensitivity of spin diodes is several orders of magnitude higher than that of semiconductor analogs and varies slightly over a wide temperature range (from 50 to 400 K), while the sensitivity of Schottky diodes has high thermal instability [5]. It was shown in [7] that the microwave response of the MTJ-based spin-torque diode to microwave irradiation (in the GHz frequency range), in addition to the electric contribution, also contains a thermal one associated with the microwave-induced nonuniform Joule heating and the corresponding generation of thermal spin torque through the MTJ structure, as an additional source of microwave energy harvesting. Thus, due to the tunnel magneto-Seebeck effect, caused by the temperature drop across the tunnel barrier, the thermally-induced rectified voltage can be used to collect the absorbed microwave energy.

However, only a small amount of electromagnetic energy is effectively used to heat the MTJ, while much of it is dissipated, resulting in a relatively small thermal contribution to the generated voltage. As is well known, the temperature drop across the MTJ tunnel barrier is directly proportional to the electromagnetic power incident on the MTJ structure. Therefore, to increase the absorbed energy of electromagnetic radiation in a wide spectrum, covering both solar spectrum and microwave region, MIM - PMAs seem especially promising in combination with MTJ, which was not considered previously. This will increase the DC voltage generated by the MTJ during its electromagnetic heating, as well as ensure the efficient use of the Seebeck bolometric effect for energy harvesting.

Thus, it is important to find the optimal design of the TiN-based perfect metamaterial for the broadband near-unity electromagnetic absorption, as well as evaluate the efficiency of increasing the thermally induced voltage in a combined MIM-PMA / MTJ device.

For this purpose, both the optical characteristics of the metamaterial within the solar spectrum and the temperature increment of MTJ related to the microwave heating were calculated on the basis of the finite difference method (FEM) in the COMSOL MultiPhysics software package [9]. To calculate the corresponding thermal distribution in MTJ, a multilayer tunnel structure was selected from the experimental work [10], consisting of a stack of layers IrMn (7.5)/CoFe (2.5)/Ru (0.85)/CoFe (0.5)/CoFeB (3)/MgO (0.78)/CoFeB (3). In turn, absorption in a MIM-based PMA structure was considered for the tri-layer structure TiN (30)/SiO2 (60)/TiN (150), taken from the experimental work [6]. All thicknesses of layers are given in nanometers.

Results and discussion

The absorption of the titanium-nitride-based broadband metamaterial with various designs of micropatches (circles/circle rings, squares/square rings, crosses/cross rings, square split-rings, ellipses) was simulated in the COMSOL MultiPhysics within the solar spectrum related both to the GHz and the THz wavelength ranges, respectively, as presented in Fig. 2. The characteristic size of each micropatch was chosen equal to 250 nm, while the distance between the micropatches was 50 nm.

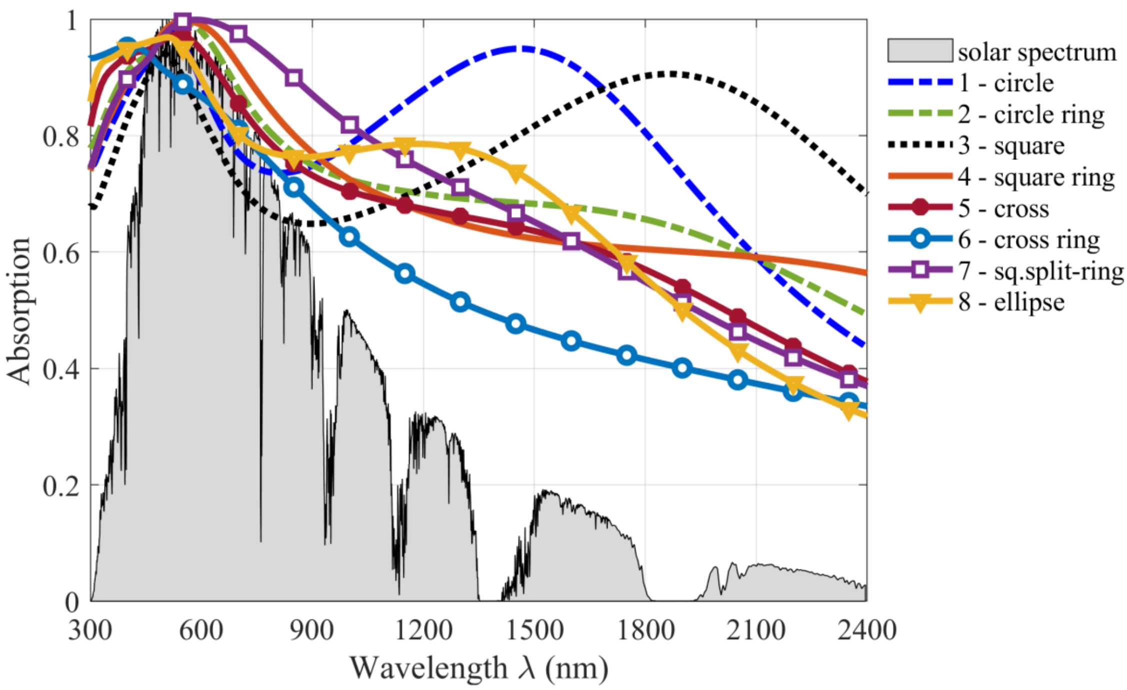

Fig. 2. Calculated absorption for the broadband metamaterial with TiN conductive layers as a function of wavelength (within solar spectrum) for different shapes of micropatches.

As can be seen from Fig. 2, the most effective absorption is obtained for micropatches with holes (in particular, the best one are for square ring and square split-ring, which is in agreement with [6]), covering the entire solar spectrum with a maximum near the boundaries of visible light, while for the remaining forms of the micropatch without holes (circles/ellipses and squares) the curves intersect the spectrum, having two resonant peaks located far enough apart from each other. In turn, cross-shaped micropatches, with or without a hole, have a single resonant peak and exhibit poor adsorption in the given solar spectrum.

A near-unity absorption of electromagnetic energy in the metamaterial leads to a high temperature gradient (up to several mK) through MTJ due to its electromagnetic heating (Fig. 3), which allows one to obtain an output power (from μW to mW) sufficient to provide energy for the operation of low-power IoT devices.

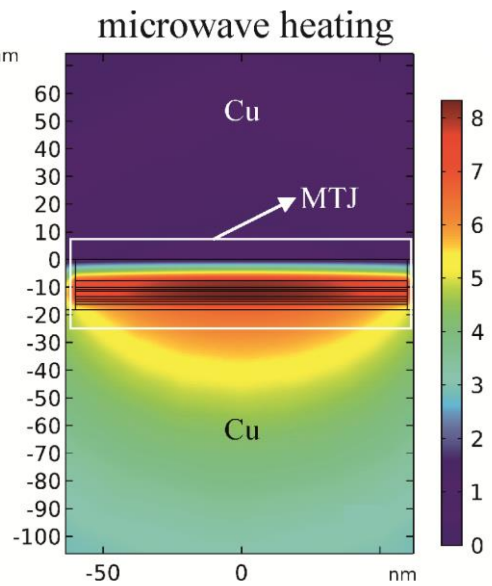

Fig. 3. Temperature increment of MTJ due to its microwave heating (in mK).

As can be seen from the Fig. 3, the main heating is concentrated in the region of the tunnel layer of MTJ. Additionally, to enhance the output voltage caused by electromagnetic heating, thermal barriers (BiTe, GeSbTe) near the tunnel spacer should be used, since they significantly contribute to an increase in the spin-dependent Seebeck coefficient of MTJ.

Summary

It has been shown that titanium nitride (TiN) based metamaterial structures with the holes inside the single micropatches (in particular, with square-ring or square-split-ring shape) are the most promising for efficient absorption of radiation in a wide range of wavelengths. The use of metamaterial in a combined device, including a photocell and an MTJ as thermoelectric element heated by incident electromagnetic wave, allows achieving an additional increase in the absorption of electromagnetic energy. It allows to increase the thermally-induced rectified voltage in MTJ induced by the tunnel magneto-Seebeck effect, which may play an important role in the development of electromagnetic energy harvesters based on spintronic technology.

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