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Design and Optimization of an Infrared Pixel based on Seebeck Nanoantennas

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ABSTRACT

Commercial Infrared and Terahertz imaging systems have a focal plane array made of bolometric elements which form the pixels in the imaging system. Bolometers have the disadvantage of being slow and require a bias voltage to operate, which increases the power required to operate the infrared imaging system. The current trend is to transition to small size, weight, and power (SWaP) imaging systems. Seebeck nanoantennas are resonant elements made of two dissimilar thermoelectric materials tuned at a particular wavelength, when this wavelength is incident on the nanoantenna it induces a current that increases the temperature at the feed of the nanaontenna generating a temperature difference that produces a Seebeck voltage. Due to the small size of the antenna and its low thermal mass it makes Seebeck nanoantennas considerably faster than tradition bolometers. Also, since the thermoelectric elements provide an output voltage no bias is needed for operation, reducing the power required by the FPA. In this work an infrared pixel is designed and optimized for detection in the 8-12μm wavelength range, and its thermoelectric voltage is calculated using numerical simulations for different pixel pitch sizes.

Keywords: Seebeck nanoantennas, infrared detector, infrared pixel.

1. INTRODUCTION

Antennas are elements that can be used either to receive or to transmit electromagnetic waves[1], when used in reception mode electromagnetic waves induce currents in the antenna elements that can be later detected and used for various applications[2]. Antennas have several unique advantages such as polarization sensitivity, directivity, small footprint, tunability and the possibility of integration into electronic and photonic circuits[3].

Antenna tunability allows the use of this technology in the detection of radiation at different wavelengths which can go from the visible to the terahertz region of the electromagnetic spectrum[4].

The traditional method to recover information from electromagnetic waves through an antenna is by rectifying the induced current, which travels at the same frequency as the incident electromagnetic wave[5], these devices are also referred as rectennas. Due to the high frequencies these rectennas operate their efficiency is low due to the impedance mismatch of the antenna and the rectifying device[6,7].

By using the thermoelectric effect in a bimaterial antenna (Figure 1) to convert the increase in temperature due to Joule heating at the feed of the antenna will reduce the antenna mismatch increasing the efficiency of the device by at least a factor of 10^3 compared to a rectenna, these devices are also known as Seebeck nanoantennas[8].

In commercial infrared imagers an array of detectors is used to form the infrared image, each one of these detectors covers an area in the image plane of the optical system which will give a picture element (pixel) of the resulting infrared image. The array of detectors is connected to a read-out integrated circuit (ROIC) which reads the amount of electromagnetic power that falls on the detector. The combination of the detector array and the read-out integrated circuit is known as the infrared focal plane array (IR-FPA).

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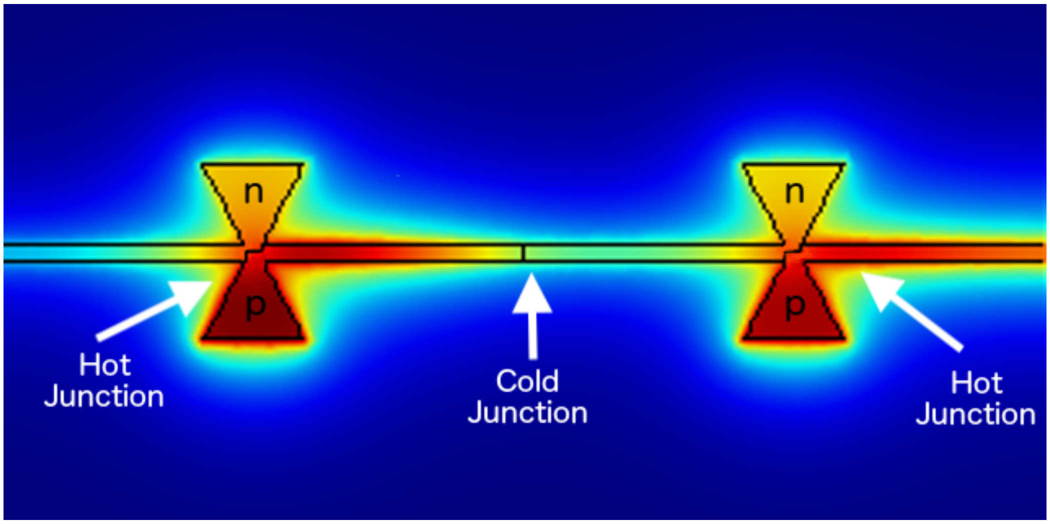

Figure 1. Temperature distribution of thermoelectric antenna under electromagnetic irradiation. Higher temperatures are indicated by red color. Heat is generated by the infrared-induced current in the antenna.

Individual Seebeck nanoantennas may be combined into arrays to create pixel elements if the selected commercial ROICs have sufficiently large dimensions. Multiple nanoantennas may be coupled in series to generate higher voltages, and they may be coupled in parallel to generate higher currents. In this work the thermoelectric voltage of Seebeck nanoantennas connected in series to cover a pixel area is calculated using numerical simulations for different pixel pitch sizes.

2. METHOD

2.1 Numerical Simulations

The Seebeck nanoantenna pixel was evaluated numerically using COMSOL Multiphysics, the simulation procedure consisted in launching a linearly polarized plane wave on the surface of the Seebeck nanoantenna pixel, this plane wave had irradiance of 1000 W/m^2, simulations were performed by doing a frequency sweep of the incident plane wave from 5 to 60 THz (5 - 60 μm). The induced current and the increase in temperature due to Joule heating were calculated coupling the electromagnetic and the heat transfer behavior through a multiphysics approach.

Previous work showed that the bowtie antenna that showed the maximum responsivity to infrared radiation was a 3 μm gold bowtie nanoantenna with Sb_2Te_3-Bi_2Te_3 thermoelectric connection lines fabricated with an undercut to increase thermal isolation[9] (Figure 2).

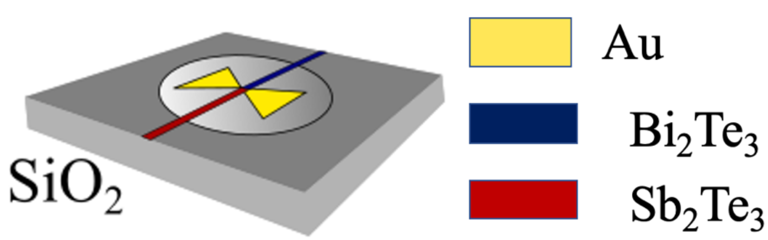

Figure 2. Optimized Seebeck nanoantenna geometry and materials to detect infrared radiation in the 8-12 μm range.

The simulations were performed with a series array of nanoantennas (Figure 3) to cover the whole pixel area in a read-out integrated circuit, different number of serial elements were simulated to investigate the responsivity of different sized arrays that could be used in different pitch ROICs. Square arrays of 2×2, 3×3 and 4×4 of Seebeck nanoantennas were simulated to cover an approximate pixel for a ROIC with pitch sizes of 15, 25 and 35 μm.

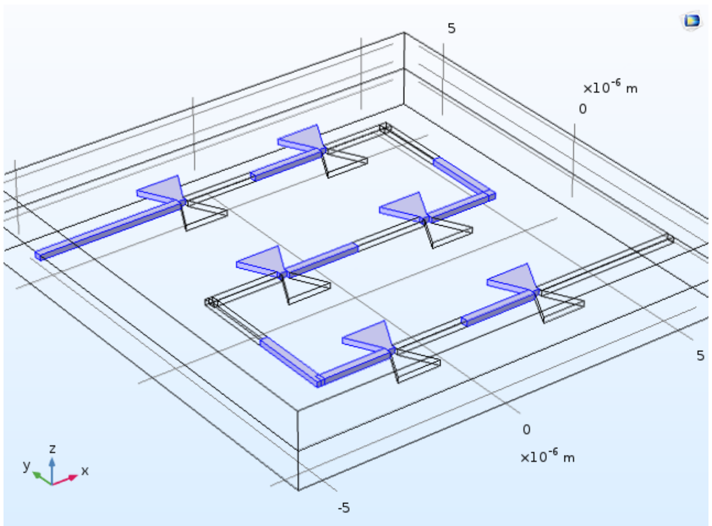

Figure 3. Series array of Seebeck nanoantennas, the optimum length and distance of the bowtie nanoantennas for detection in the 8-12 μm range is 3.5 and 7 μm respectively.

3. RESULTS

Multiphysics simulations of square arrays of 2×2, 3×3 and 4×4 of Seebeck nanoantennas was performed in order to obtain the increase in temperature due to incident electromagnetic waves at different frequencies from 5-60 THz, the irradiance of the incident electromagnetic waves was 1000 W/m^2.

Figure 4(a) shows the temperature pattern of a 4×4 of Seebeck nanoantenna pixel illuminated with 28THz electromagnetic radiation, this arrangement could be used in a 30-35 μm pitch ROIC. Figure 4(b) shows the thermoelectric voltage generated due to the increase in temperature shown in Fig. 4(a).

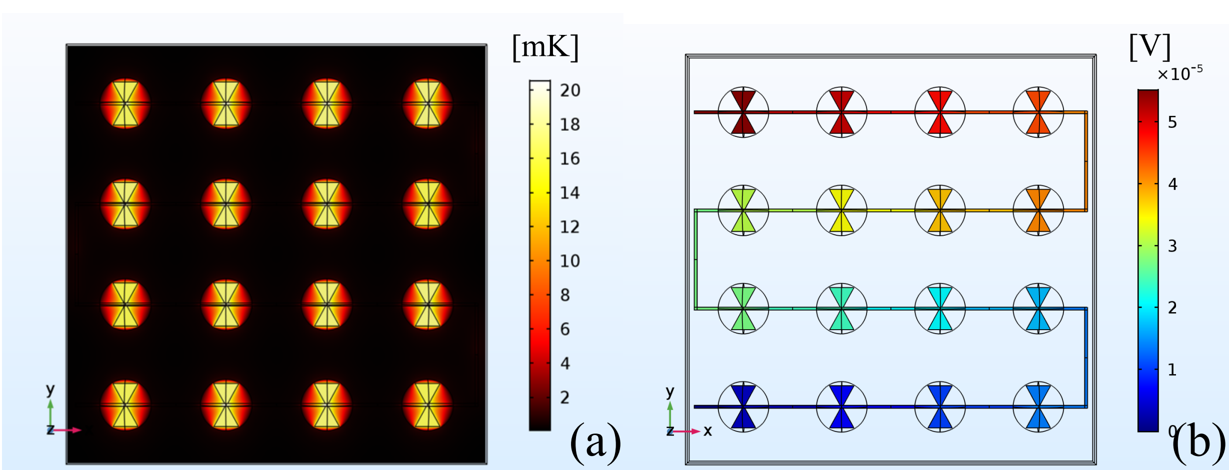

Figure 4. (a) Computer simulation of the increase in temperature of a 4×4 of Seebeck nanoantenna pixel due to 1000 W/m^2 incident 28 THz electromagnetic radiation, (b) thermoelectric voltage generated due to the increase in temperature.

Figure 5 shows the thermoelectric voltage generated by 3 different sized pixels as a function of incident wavelength. The 15 μm pitch pixel is a 2×2 array of Seebeck nanoantennas, the 25μm pitch pixel is a 3×3 array of Seebeck nanoantennas, and the 35μm pitch pixel is a 4×4 array of Seebeck nanoantennas.

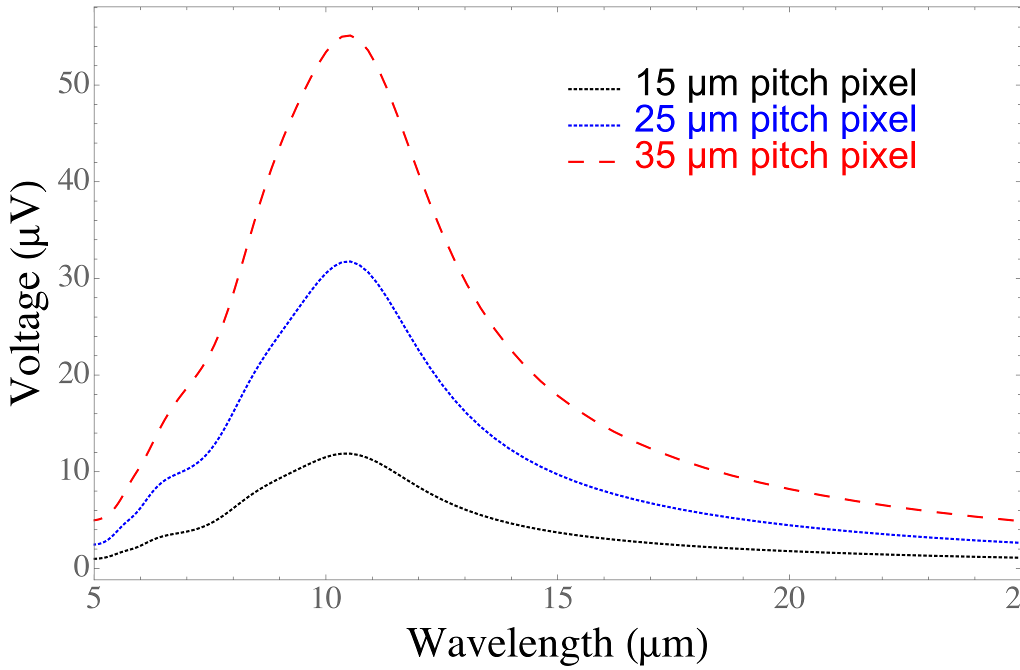

Figure 5. Thermoelectric voltage generated by 3 different sized pixels as a function of incident wavelength.

4. CONCLUSIONS

The maximum thermoelectric voltage obtained for the 3 different sized pixels analyzed (12 μV for the 15 μm pitch pixel, 31 μV for the 25 μm pitch pixel and 55 μV for the 35 μm pitch pixel) indicate that the resulting voltage grows linearly with the number of nanoantenna elements, 4 elements for the 15 μm pitch pixel, 9 elements for the 25 μm pitch pixel and 16 elements for the 35 μm pitch pixel.

The responsivity of the simulated pixels is around 50 V/W, which is lower than the previously reported responsivity for single element detectors[9] (240 V/W), this is because for single element detectors the effective collection area was considered and for a large area pixel the whole area covered by the pixel is taken into account.

From the results presented in this work it can be concluded that serial arrays of Seebeck nanoantennas can be used to cover the pixel area of an infrared focal plane array with the advantage that they do not require a bias voltage.

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