Seebeck bowtie antenna for 2 THz radiation detection

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ABSTRACT

Terahertz imaging systems require small, low cost and low power systems operating at room-temperature. Terahertz Seebeck nanoantennas are room temperature detectors which generate voltage due to incident electromagnetic radiation, they also provide polarization sensitivity, directivity, small footprint, tunability and the possibility of integration into electronic and photonic circuits. In this work a gold bowtie nanoantenna is designed and optimized to detect electromagnetic radiation at 2 THz. The resulting device is a gold bowtie antenna with asymmetric connection lines to optimize the Seebeck voltage. The connection lines are made of Sb_2Te_3 and Bi_2Te_3 to increase the generated voltage due to the incident electromagnetic radiation. Simulation results obtained using COMSOL Multiphysics are presented. The fabrication of the resulting optimized device was performed using photolithography and liftoff. The materials were deposited by sputtering. The fabricated device includes an external heater to measure the effective Seebeck coefficient. Experimental results of the effective Seebeck coefficient of the device as well as response measurements are presented and compared to Multiphysics simulations.

Keywords: Terahertz detector, thermoelectric nanoantennas, Seebeck nanoantennas

1. INTRODUCTION

The Terahertz electromagnetic frequency range is usually considered to be between 0.1 and 10 THz [1]. Electromagnetic radiation at these frequencies has applications in airport security screening, firefighting equipment, gas sensing, medical imaging, pharmaceutical applications, astronomy, communications and material analysis [2].

Terahertz imaging systems require small, low cost and low power systems operating at room-temperature, these systems should be able to provide video-rate speeds and deliver acceptable sensitivity at low-power consumption levels to become attractive for commercial applications [3]. In terms of the readout circuit design, the key challenge is to achieve low power consumption levels which are a characteristic of passive pixel sensors [2].

Antennas have been used as part of the detection mechanism for terahertz imaging systems due to their polarization sensitivity, directivity, small footprint, tunability and the possibility of integration into electronic and photonic circuits [4,5]. The potential of packaging and integration of antennas with silicon chips at THz frequencies, especially arrays of antennas, offers highly promising solutions for commercial applications.

Seebeck nanoantennas convert electromagnetic energy into electrical energy through the thermoelectric effect. These devices have been designed using either a material or geometrical asymmetry that facilitates thermal diffusion of electrons between a hot junction and a cold junction.

When coupled to antennas the electromagnetic energy induces a current in the antenna arms that heats the hot junction of the Seebeck nanoantenna, this hot junction is usually the point of contact between dissimilar materials and is also the feed of the antenna. The choice of materials impacts both the performance of the electromagnetic properties of the antenna and its thermoelectric properties.

In this work the shape and materials of the antenna and the thermoelectric connection of a Terahertz dipole Seebeck nanoantenna are optimized to increase its responsivity.

2. METHOD

In a thermoelectric material, its maximum efficiency is given by its thermoelectric figure of merit

$$,zT = \frac{S^2}{\rho\kappa} \quad (1)$$

where S is the Seebeck coefficient, ρ is the electrical resistivity, κ is the thermal conductivity and T is the absolute point temperature of the material [6].

In an antenna the induced current depends on the conductivity of the fabrication material [7], therefore in a thermoelectric antenna there is a tradeoff between the optimum thermoelectric and antenna materials that will maximize the efficiency of the device.

The devices analyzed are Seebeck dipoles fabricated on a silicon wafer with a silicon dioxide layer for thermal and electrical isolation (Fig. 1(a)). Three configurations are studied, a gap dipole antenna made of gold with the thermoelectric elements made of Bi_3Te_2 and Si connecting at the feed of the antenna (Fig. 1(b)), a gap-less dipole antenna with the thermoelectric elements connected through the gold elements (Fig. 1(c)), and a bimetallic antenna fabricated using the thermoelectric materials (Fig. 1(d)).

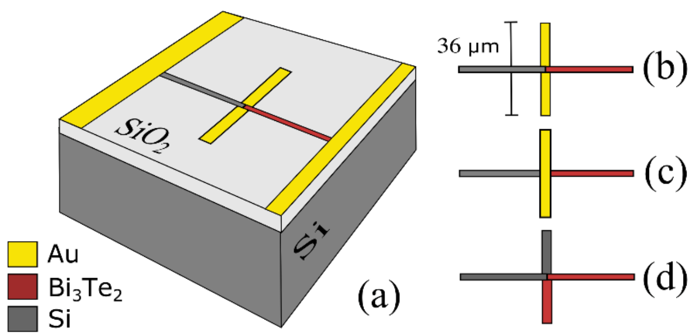

Figure 1. Dipole nanoantenna configurations. (a) Fabrication on silicon-silicon dioxide substrate. (b) Gap dipole antenna with thermoelectric connections. (c) Gap-less dipole antenna with thermoelectric connections. (d) bi-metallic thermoelectric dipole antenna.

The devices were evaluated numerically using COMSOL Multiphysics. The simulation procedure consisted in launching a linearly polarized plane wave with an irradiance of 1000 W/m^2 over the surface of the Seebeck nanoantennas. A parametric simulation was performed by doing a frequency sweep of the incident plane wave from 0.1 to 10 THz. The induced current in the antenna, the increase in temperature due to Joule heating, as well as the output thermoelectric voltage were calculated coupling the electromagnetic, heat transfer, and thermoelectric equations via the multiphysics simulation.

3. RESULTS

Figure 2 shows the thermoelectric voltage generated by three different dipole Seebeck nanoantenna configurations receiving a 1000 W/m^2 plane wave at various frequencies. The thermoelectric voltage generated is plotted as a function of the frequency of the incident terahertz wave.

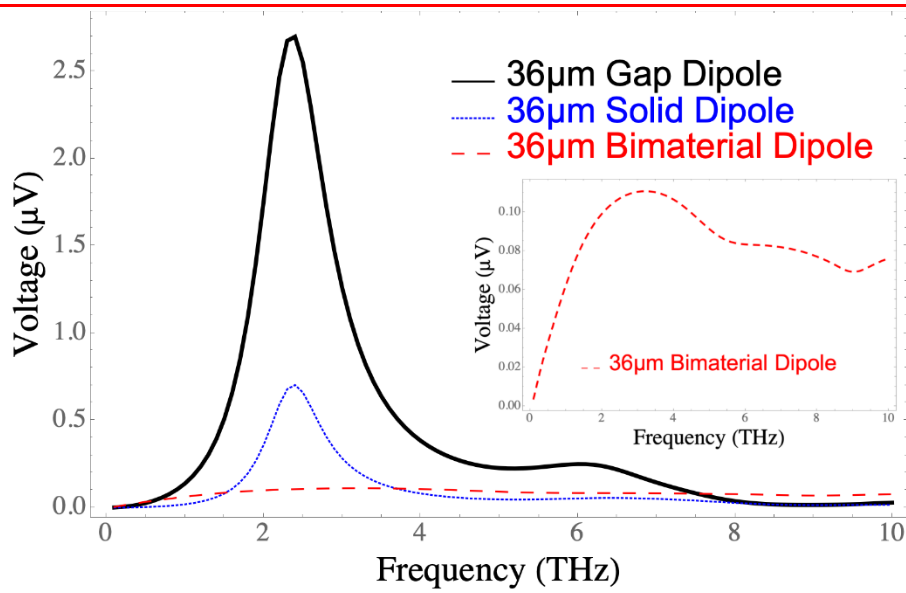

Figure 2. Thermoelectric voltage generated by three different dipole Seebeck nanoantenna configurations receiving a 1000 W/m^2 plane wave at various frequencies.

From Figure 2 it can be seen that a gap antenna made of gold maximizes the induced current and the increase in temperature at the hot junction of the Seebeck nanoantenna device, by using a gap device the thermoelectric voltage is increased by a factor of 5 over a gapless antenna. A bimetallic nanoantenna is the one that showed the lowest performance producing a voltage 25 times lower than a gap antenna.

Figure 3 shows the comparison of three different types of gap antennas, a classical bowtie antenna, a long bowtie antenna and a dipole antenna. The bowtie antenna generates the highest temperature at the thermoelectric hot junction however it shows a larger bandwidth (3.5 THz) than the long bowtie (1.5 THz) and the classical dipole (1THz).

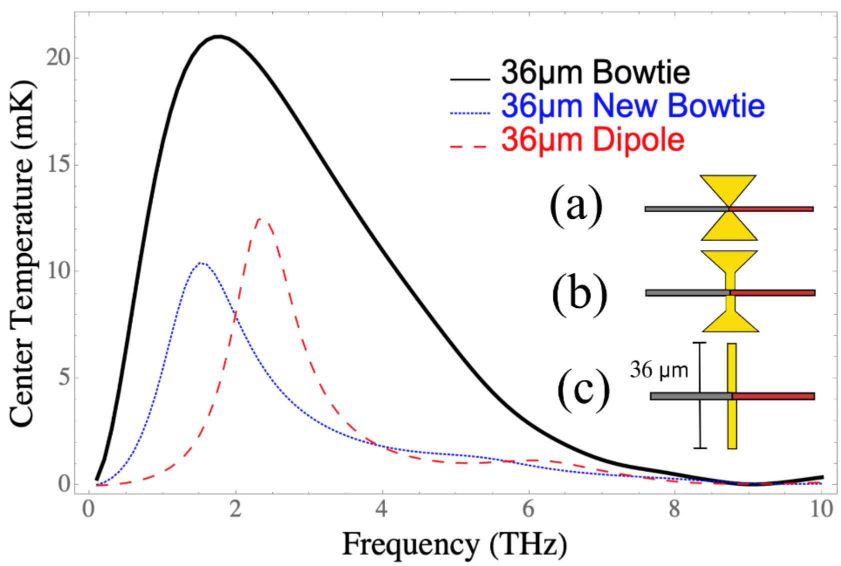

Figure 3. Comparison of three different types of gap antennas, a classical bowtie antenna, a long bowtie antenna and a dipole antenna.

An important part of the thermoelectric device is the thermoelectric connecting elements. Figure 4 shows the thermoelectric voltage as a function of the width of the thermoelectric connection lines. From Fig. 4 it can be seen that there is a best width (0.5 µm) that maximizes the thermoelectric voltage output.

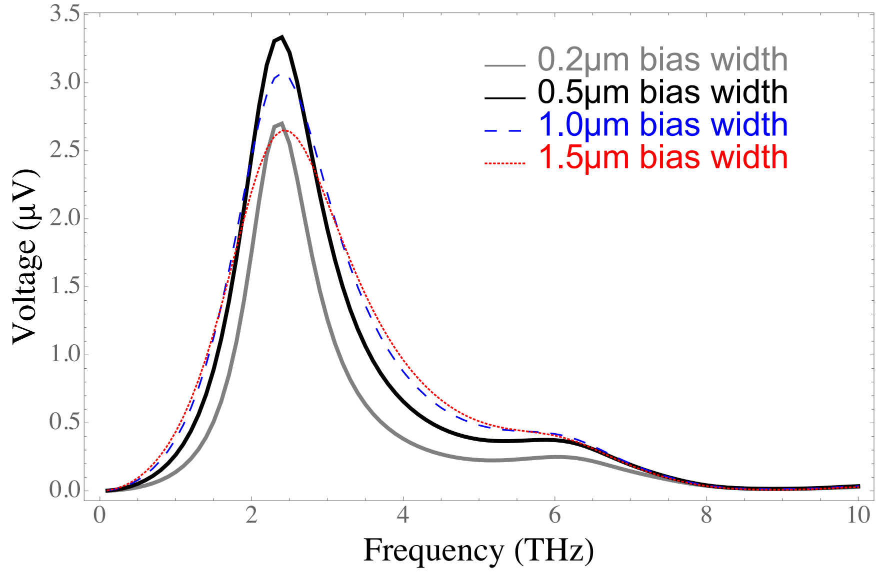

Figure 4. thermoelectric voltage as a function of the width of the thermoelectric connection lines.

Further improvement of the response of Seebeck nanoantennas can be done by increasing its thermal isolation. Figure 5 shows a method of increasing the thermal isolation of the device by creating a free-standing antenna which would decrease thermal losses through the substrate.

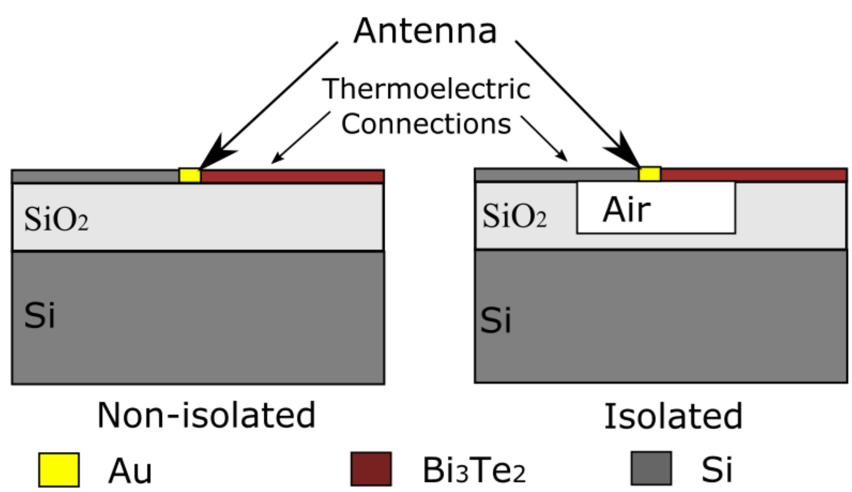

Figure 5. Cross section of a free-standing Seebeck nanoantenna device suspended over air for thermal isolation and a Seebeck nanontenna fabricated on a Si-SiO_2 substrate.

Figure 6 shows simulation results of the free-standing Seebeck nanoantenna structure compared to a Seebeck nanaontenna fabricated on a Si-SiO_2 substrate. Results show that the free-standing Seebeck nanoantenna generates a voltage 10 times higher than a Seebeck nanoantenna on a substrate. It is also worth noting that a shift in resonance frequency is also observed for the free-standing structure where the resonant frequency was at 3.5 THz while the same Seebeck nanoantenna on a substrate has a resonant frequency at 2.4 THz. This change in resonant frequency is due to the change in effective index of refraction of the medium surrounding the antenna which affects the effective length of the antenna and the resonance.

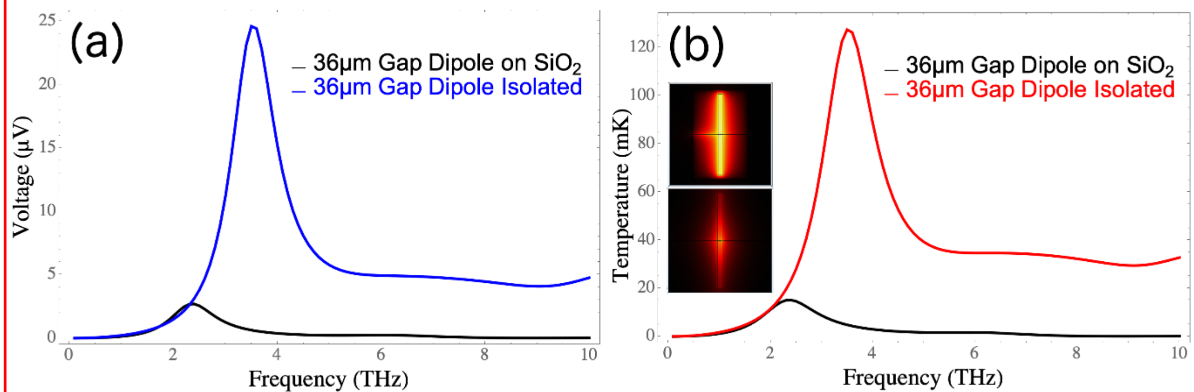

Figure 6. (a) Output Voltage and (b) Temperature at the feed of the antenna for a free-standing Seebeck nanoantenna structure compared to a Seebeck nanoantenna on a Si-SiO2 substrate.

4. CONCLUSIONS

Multiphysics numerical simulations show that for thermoelectric antenna devices the use of high conductivity materials, such as gold, for the antenna and high Seebeck coefficient materials, such as Bi_3Te_2 and Si for the thermoelectric connection lines maximizes the thermoelectric voltage output due to incident electromagnetic radiation.

The maximum voltage output was obtained using a gap gold antenna and 0.5 µm wide thermoelectric connections. Bowtie antennas produce higher thermoelectric voltage than classical dipoles and long bowtie antennas but with lower frequency selectivity.

The approximate collection area for metallic nanoantennas is equal to λ m^2, where λ is the resonant wavelength of the nanoantenna. For nanoantennas tuned at 2 THz the approximate collection area would be equal to 150 µm^2. Therefore the incident electromagnetic power collected by the nanoantenna would be 150 nW. The output voltage of a gold dipole nanoantenna with Bi_3Te_2 and Si thermoelectric connection lines is around 3 µV (Fig. 4) which gives a responsivity of 20 V/W. Free standing structures give a maximum output voltage around 24 µV, which would result in a responsivity of 160 V/W.

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