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THERMALLY ENHANCED PHOTO-THERMOELECTRIC MID-INFRARED DETECTION

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1. ABSTRACT

Photo-thermoelectric (PTE) mid-infrared detectors has the potential to empower integrated photonics, microspectrometry, and hyperspectral imaging. By optimising heat transfer and mid-infrared absorption in a microscale thermopile device, a large responsivity is achieved. Resonant optical absorption is directly incorporated in the hot p-n junction of the thin-film thermocouple, therefore reducing complexity and enabling facile fabrication at the microscale. We foresee our detector finding wide application in infrared fingerprinting of pollutants, bioimaging, and security.

2. INTRODUCTION

Mid-infrared photodetectors that are sensitive at room temperature are important to increase the accessibility of mid-infrared technologies [1]. Photodiode detectors boast a high speed and high detectivity, but their spectral response is constrained to visible and near infrared wavelengths by their bandgap. While some photodiodes, like HgCdTe detectors, are specifically designed for mid-infrared wavelengths, they need to be cryogenically cooled to reliably operate, which limits them to lab bench equipment. PTE detectors based on photo-thermoelectric conversion are a broadband alternative to photodiodes, suitable for room-temperature operation. Still, the detectivity of PTE detectors is significantly lower than HgCdTe. We must therefore improve the performance of PTE detectors for demanding applications like spectroscopy, where an array of small cross-sectional detectors is used. Recently, optical resonances have been exploited to improve the PTE conversion [2]. Being a thermal-type detector, however, the performance can be further improved by careful consideration of heat transfer within the device.

The photo-voltage generated by a PTE detector is determined by $V = S\Delta T$, where S is the Seebeck coefficient and ΔT is the temperature difference in the thermoelectric materials. By solving the differential heat balance equation,

$$C_{th}\frac{d\Delta T}{dt} + G_{th}\Delta T = A\Phi,$$

the steady state temperature difference in a PTE device due to an unmodulated optical flux, Φ_0, is given by $\Delta T = \frac{A\Phi_0}{G_{th}}$, where A is the absorptance of the photon absorbing heat source, C_{th} is the thermal capacitance and G_{th} is the thermal conductance from the heat source to a heat sink. The responsivity of a photodetector, $\mathcal{R} =$

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$\frac{V}{\Phi_0}$, is a measure of how much output is produced per input power. Using the heat equation solution from above, the responsivity a thermoelectric detector can then be written as

$$\mathcal{R} = \frac{SA}{G_{th}}.$$

Therefore, to improve responsivity, there are three main points to consider:

1. Choosing good thermoelectric materials with large Seebeck coefficients, S.
2. Optically designing the absorber to maximise absorptance, A.
3. Thermally designing the device to minimise thermal conductance, G_{th}, to the environment.

Typically, point 2 and 3 are achieved by including an external photon absorber, and by fabricating the PTE detector in an air-evacuated environment on a suspended membrane for thermal isolation [3]. However, these solutions introduce complexity to the device design, which constrains miniaturisation efforts demanded by integrated photonics applications.

Here, we introduce a simple yet responsive PTE detector where the thermoelectric and optical functionality is combined in the same materials. The enabling materials are the n-type and p-type narrowband semiconductors Sb_2Te_3 and Bi_2Te_3, which together form a thermocouple. Besides being excellent thermoelectrics, with Seebeck coefficients on the order of 100 µV/K and low thermal conductivities, they are moderately lossy in the mid-infrared due to free carrier absorption. With the aid of a metallic back-reflector, the moderate free carrier losses provide a thin-film resonance to be supported directly in the thermoelectric materials with near perfect absorptance. This absorption of light in the thermocouple directly heats it without any losses due to conduction from an adjacent absorber, which we hypothesised would increase the sensitivity and response of the PTE detector.

3. METHODOLOGY

Prototype PTE detectors were fabricated using direct laser writing photolithography with bilayer photoresists. The active thermoelectric materials Sb_2Te_3 and Bi_2Te_3 were deposited using RF sputtering, and an Au back-reflector was deposited using DC sputtering together with Au electrodes for electrical measurements. The optical resonance was tuned to a wavelength of 3.6 µm by varying the thickness of the thermoelectric materials, and the photo-response was measured at this wavelength using a mid-infrared laser and a source meter. The PTE measurements were complemented by thermal-thermoelectric simulations using the Heat Transfer and AC/DC modules of Comsol Multiphysics.

4. RESULTS

A temperature map of the microscale PTE detector is shown in Figure 1a, with the central region acting as the photon-absorbing heat source, and the Sb_2Te_3 and Bi_2Te_3 legs extending outwards to establish a temperature gradient. The figure is labelled with the major paths of heat transfer within the device. Optimal device performance was achieved by minimizing the heat transfer away from the hot photon absorber to the environment. Most of the heat generated by the absorber will be lost to the substrate, and therefore greatly enhances the responsivity. We fabricated our device on SiO_2, which has a low thermal conductivity of 1.4 W/m/K; around 100 times lower than that of silicon. Simulations and experiments in Figure 1b validate the superior performance of substrates with lower thermal conductivity. Our fabricated devices present with responsivities on the order of 10 V/W.

Further improvements to the photo-response can be achieved by cascading multiple thermocouple units in series, often referred to as thermopiling. Our simple design is well suited for thermopiling, and by carefully designing the cascaded device, additional thermal benefits can be gained. Importantly, the absorber regions should be placed as close to one another as possible. Firstly, to minimise the photosensitive area for more efficient light collection. Secondly, by concentrating the hot regions together, the cascaded device becomes more thermally effective, as a portion of the dissipated heat is shared between adjacent units rather than being lost to the environment. We see the performance enhancement both computationally and experimentally in Figure 1c, as the responsivity increases with the number of units.

Finally, from a heat transfer perspective, we make an argument that further miniaturisation of the detector will improve its responsivity. Because our microscale device is neither air evacuated nor suspended on a membrane, the heat transfer is dominated by the substrate and surrounding air. We can then assume that the heat is dissipated radially away from the hot absorber in three dimensions. In contrast, the heat generated due to the incident photon flux is dependent on the two-dimensional area of the absorber. Hence, miniaturisation of the device will supress the heat dissipated at a faster rate than the heat generated, resulting in an enhanced responsivity, which is confirmed by the simulations in Figure 1d.

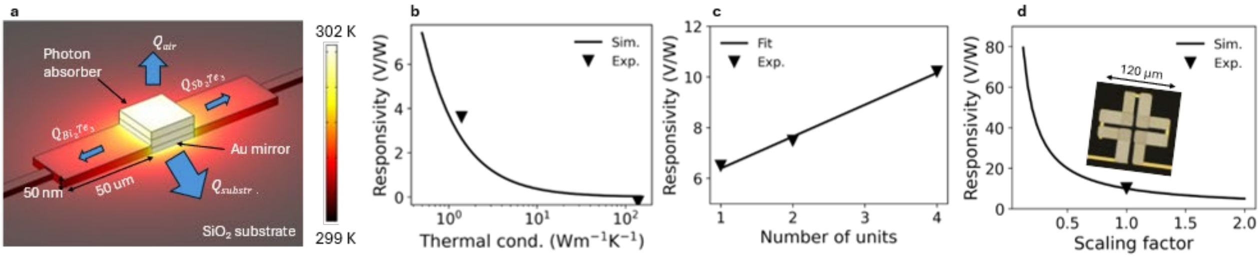

Figure 1 (a) Temperature map of a single unit PTE device. (b) Responsivity as a function of substrate thermal conductivity. (c) Responsivity as a function of number of thermocouple units. (d) Responsivity as the device size is scaled. The reference size is the fabricated four-unit device in the inset, which measures 120 μm across.

5. CONCLUSIONS

A highly responsive prototype PTE detector for narrowband detection of mid-infrared wavelengths has been designed, fabricated and characterised. The novel approach of incorporating a planar resonance cavity directly in the thermoelectric materials enables a compact device with large optical absorptance. Further responsivity enhancements are achieved through careful thermal design. We conclude that Sb_2Te_3 and Bi_2Te_3, with their superior optical and thermoelectric properties, constitute a promising material platform for photo-thermoelectric applications.

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REFERENCES

[1] J. Liu, F. Xia, D. Xiao, F. J. García de Abajo, and D. Sun, ‘Semimetals for high-performance photodetection’, *Nat. Mater.*, vol. 19, no. 8, Art. no. 8, Aug. 2020, doi: 10.1038/s41563-020-0715-7.

[2] K. W. Mauser *et al.*, ‘Resonant thermoelectric nanophotonics’, *Nat Nanotechnol*, vol. 12, no. 8, pp. 770–775, Aug. 2017, doi: 10.1038/nnano.2017.87.

[3] A. Graf, M. Arndt, M. Sauer, and G. Gerlach, ‘Review of micromachined thermopiles for infrared detection’, *Meas. Sci. Technol.*, vol. 18, no. 7, pp. R59–R75, Jul. 2007, doi: 10.1088/0957-0233/18/7/R01.