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Nanoantenna Arrays for Infrared Detection with Single-Metal Nanothermocouples

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***Abstract*—Antenna-coupled nanothermocouples (ACNTC) for infrared detection have been widely studied. It has been shown that dipole antennas receive incident infrared radiation, and radiation-induced antenna currents heat the hot junction of the nanothermocouple, thus producing an electrical potential by the Seebeck effect. We have already demonstrated small thermopiles constructed from the series connection of ACNTCs. Here we study the infrared response of large-scale (N>500) nanoantenna arrays constructed from ACNTCs, where the antennas are spaced over a range of 25% to 300% of the incident wavelength. COMSOL simulations show temperature oscillations, and both simulations and experiments show corresponding open-circuit voltage oscillations as a function of antenna spacing. When the distance between the antennas is less than 2λ, constructive and deconstructive interference leads to an enhancement or attenuation of the antenna currents. Our simulations and experimental results are in excellent agreement, and show that the open-circuit voltage response of the array depends on the inter-column distance of the array and the separation between the hot and cold junctions. Furthermore, we report polarization- and array-size-dependent measurements to confirm that the responses of the arrays are the result of the heating of the hot junction by the radiation-induced antenna currents.**

Keywords—nanoantenna array, nanothermocouple, Seebeck effect

I. INTRODUCTION

Antenna-coupled nanothermocouples (ACNTCs) have been studied for infrared (IR) [1-3] and THz [4] detection. These devices exploit the wave nature of the IR radiation, and are constructed from a receiving and detecting element. The antenna receives the electromagnetic waves, and converts the energy of the irradiation to resonant antenna currents. Through Joule heating, the dissipated antenna currents heat the metallic antenna, and maximum heating occurs where the current is maximum. Where a thermocouple is integrated with the antenna, the thermal energy can be converted to an electrical signal due to the Seebeck effect.

In recent work, we have demonstrated thermopiles for IR detection constructed from individual ACNTCs [5]. We have shown that by connecting several ACNTCs in series, the thermopile follows the thermocouple addition rule, *viz.*, as the number of NTC elements in the thermopile, n, increases, the measured open-circuit voltage increases linearly. We also showed [5] that by connecting n NTCs in series to form a thermopile, the signal-to-noise ratio (SNR) is increased by a factor of $\sqrt{n}$. In that work, the distance between the individual antennas in the thermopile was at least two times larger than the effective wavelength of the IR radiation, so the interference between the antennas was negligible. However, when the distance between the antennas is much less than the effective wavelength of the incident radiation, coupling between the individual devices cannot be neglected. In this paper, we study the infrared response of large-scale ($500 < n < 1400$) antenna arrays constructed from ACNTCs, where the antenna spacing is much less than the effective wavelength of the incident radiation. The antenna array is optimized by COMSOL simulations for maximum open-circuit voltage (V_{OC}) response for a given array area, and is realized by experiment.

It has been demonstrated that large-scale fabrication of antenna-coupled IR detector arrays is possible using nanoimprint lithography techniques [6-8]. However, the fabrication of conventional bi-metal NTC arrays is challenging due to the need for alignment to form an NTC junction, which significantly increases the complexity of the device structure due to the need for critical alignment. Our recent discovery of single-metal NTCs [9] opens the door to large-scale arrays of ACNTCs. We have shown [9] that NTCs can be constructed from a single type of metal, without the need for two different metals, as is required for conventional TCs. Specifically, we have shown that single-metal nanostructures with a cross-sectional discontinuity exhibit a Seebeck effect due to a size-dependence of the Seebeck coefficient [10, 11] for nanometer-scale metallic structures. When a narrow nanowire segment is inserted between two wider wire segments from the same metal, the resulting difference in the absolute Seebeck coefficients (ASC) for these segments results in a measurable relative Seebeck coefficient (RSC). This effect creates NTC junctions at the size discontinuities, and leads to single-metal thermocouple functionality. The fabrication complexity of single-metal NTCs is significantly reduced compared to conventional bi-metal NTCs, since it requires only a single-layer of metal deposition (or imprint) without any alignment.

In order to demonstrate that the experimentally obtained open-circuit voltage response of the antenna array is due to the radiation-induced antenna currents and the Seebeck effect, we also present polarization- and size-dependent measurements of antenna arrays that contain over 1000 individual ACNTCs connected in series.