Multiphysics Simulations for the Design of IR and THz Nanoantennas

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The operating principle of antenna-coupled nanothermocouples (ACNTCs) is based on the wave nature of the IR radiation. A nanoantenna receives the incident radiation, and the radiation-induced antenna currents heat the hot junction of a NTC at the center of the antenna, generating a DC voltage. The thermal response of the devices is inversely proportional to the heat loss to the substrate and the lead lines of the NTC (Fig. 1). In this work, we design thermal insulations for ACNTCs operating at 0.6 THz and 28.3 THz by using COMSOL Multiphysics Simulation Software to reduce these heat losses and increase the device response. The devices are simulated in receiving antenna mode with a unidirectional coupling of the electromagnetic wave module to the heat-transfer module by an electromagnetic-heat-source boundary condition.

Previously, ACNTCs for 0.6 THz were fabricated on a high-resistivity Si wafer [1]. The thermal conductivity of Si is about 100 times larger than SiO_2. By inserting a thin layer of SiO_2 (1 μm to 6 μm) between the antenna and the Si substrate, the heat loss can be significantly reduced (Fig. 2). The resonant antenna length, l, depends on the dielectric constant and the thickness of the material surrounding the antenna. COMSOL simulations were used to determine l for various SiO_2 thicknesses (Fig. 2). The meshing of such simulations is challenging due to the large geometry differences between the antenna and the substrate (Fig. 3a). By varying the antenna length to determine l, the geometry and the mesh changes, resulting in simulation artifacts. We created a geometry independent mesh by constructing the antenna from small domains (Fig 3b), and its length was changed by assigning air or antenna material to each domain. So, the geometry, and hence the mesh, were fixed.

The heat loss to the lead lines can be eliminated by using a primary and secondary antenna structure, as shown in Fig. 4, for a suspended ACNTC operating at 28.3 THz [2]. The thermal resistance around the hot junction is increased because the wider lead lines of the NTCs are located farther away. In addition, both the primary and secondary antennas resonate and heat the hot junction more effectively than a single dipole antenna. Figure 5 shows the resonant antenna length of the primary and secondary antennas obtained by COMSOL simulations. Figure 6 shows the simulated temperature profiles along the antenna. In our presentation, we will discuss the simulation methods and results in detail.

[1] G. P. Szakmany, A. O. Orlov, G. H. Bernstein, W. Porod, IEEE Trans. Terahertz Sci. Technol. **7,** 582 (2017).
[2] G. P. Szakmany, A. O. Orlov, G. H. Bernstein and W. Porod, J. Vac. Sci. Technol., B **36** , 052203 (2018).

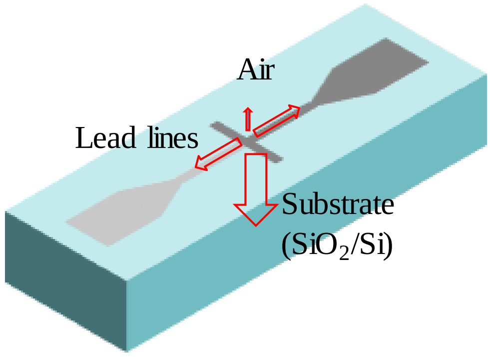

Fig.1: Heat loss of the antenna by air, lead lines, and substrate. The substrate and lead line effects are the strongest, and can be reduced by thermal insulation.

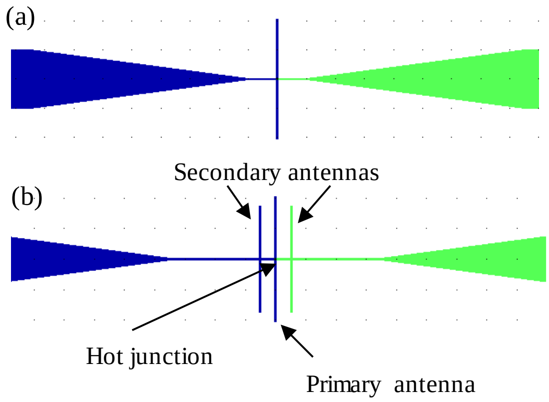

Fig.4:.Schematic of the ACNTC (a) with single dipole antenna, (b) with the antenna structure constructed from a primary and secondary antennas.

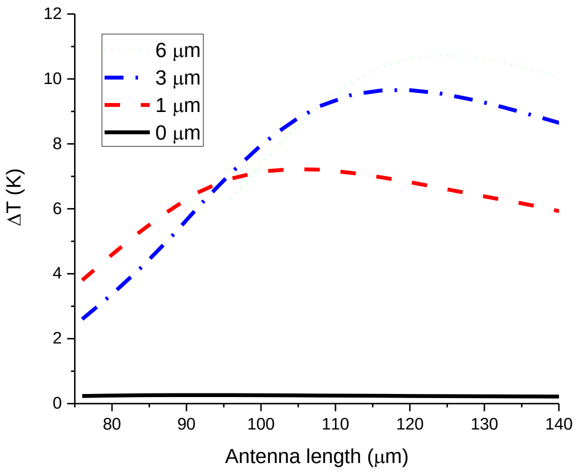

Fig.2: Temperature increase as a function of antenna length for various oxide thicknesses. ΔT on SiO_2 is about 50 times larger compared to devices on a Si substrate. The resonant antenna length changed from 92 µm to 125 µm.

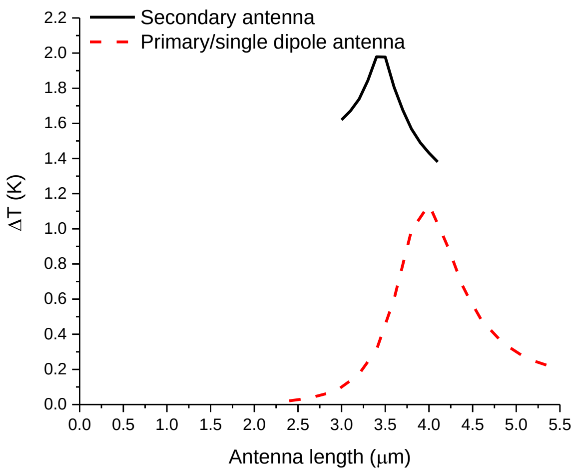

Fig.5. Resonant antenna length of the primary and secondary antennas. The temperature increase at the hot junction is about twice for the antenna structure with primary and secondary antennas as for a single dipole antenna.

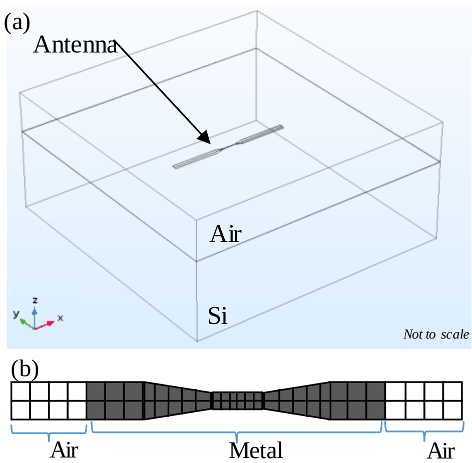

Fig.3: (a) Schematic of the antenna for simulations. (b) The antenna model for geometry-independent meshing. Metal (grey) and air (white) material properties are assigned to each domain to vary the length of the antenna while keeping the mesh the same. .

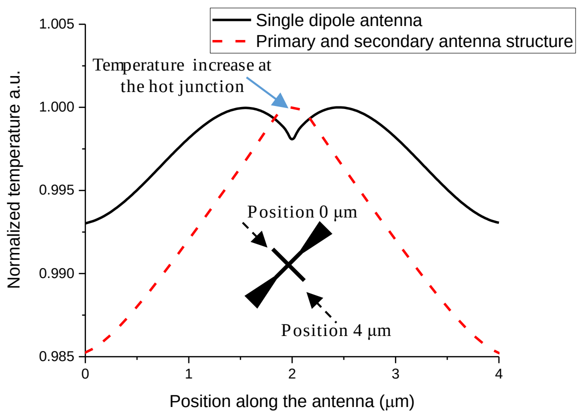

Fig.6: Normalized temperature profiles along the antenna. The heat loss to the lead lines for a single dipole antenna is indicated by the temperature drop at the center, while it is eliminated by using the secondary antenna structure.

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