NDnano Summer Undergraduate Research
2022 Project Summary

1. Student name & home university: Collin Finnan, University of Notre Dame

2. ND faculty name & department: Dr. Gary Bernstein, Electrical Engineering

4. Summer project title: Investigation of Thermoelectrically Coupled Nanoantennas in a Vacuum Setting

4. Briefly describe new skills you acquired during your summer research:

- How to create, optimize, and yield results from complex models within the COMSOL Multiphysics tool.
- How to assemble, operate, and understand a vacuum system starting from the kinematic theory of gasses all the way to pumps and chambers.
- The general ability to quickly read and digest academic papers, specifically those regarding nanofabrication processes.
- An introduction to imaging, starting with electromagnetic waves, refraction, etc. and moving towards applications to larger systems.

5. Briefly share a practical application/end use of your research:

Long-wave infrared detectors can be used for heat tracking of black-body radiators even at room temperature [1]. Applications include target identification [2], solar flare detection, energy harvesting [3], and even biological sensing [4]. Currently, the signal strength of the Thermoelectrically Coupled Nanoantennas (TECNAs) are limited by heat loss due to air. However, other IR detectors like microbolometers use vacuum packaging to avoid this problem [5]. By studying TECNA performance in a vacuum setting, signal strength should improve, resulting in viability for practical applications.

5. 50- to 75-word abstract of your project:

The focus of this project is to explore and quantify the performance improvements of thermoelectrically coupled nanoantennas (TECNAs) while in a vacuum setting. The electrical signal measured on these chips is due to the Seebeck effect, where an open-circuit voltage is generated by a temperature difference between the antenna's hot center and the "cold" substrate, connected by two dissimilar metal lead lines [6]. Heat losses due to air cause a reduction in signal strength, meaning theoretically the TECNAs will improve in the absence of air.

7. References for papers, posters, or presentations of your research:

1. F. J. Gonzalez, B. Ilic, J. Alda, and G. D. Boreman, “Antenna-coupled infrared detectors for imaging applications,” IEEE J. Sel. Topics Quantum Electron., vol. 11, no. 1, pp. 117–120, Jan./Feb. 2005.
2. Cooper, K. B. et al. THz Imaging Radar for Standof Personnel. Screening. IEEE Trans. Terahertz Sci. Technol. 1, 169–182, https://doi.org/10.1109/TTHZ.2011.2159556 (2011).
3. Sanchez, J. E., Yacaman, M. J. & Gonzalez, F. J. Neuromorphic Systems Based on Nanoantennas for Renewable Energy Applications. Microscopy and Microanalysis 24, 1792–1793, https://doi.org/10.1017/S1431927618009443 (2018).
4. Siegel, P. H. Terahertz technology in biology and medicine. IEEE Transactions on Microwave Teory and Techniques 52, 2438-2447, https://doi.org/10.1109/TMTT.2004.835916 (2004).
5. Abdulla, Mahmood & Butler, Donald & Çelik-Butler, Zeynep. (2007). A Device-Level Vacuum-Packaging Scheme for Microbolometers on Rigid and Flexible Substrates. Sensors Journal, IEEE. 7. 1012 - 1019. 10.1109/JSEN.2007.896560.
6. Szakmany, Gergo & Krenz, Peter & Orlov, Alexei & Bernstein, Gary & Porod, Wolfgang. (2013). Antenna-Coupled Nanowire Thermocouples for Infrared Detection. Nanotechnology, IEEE Transactions on. 12. 163-167. 10.1109/TNANO.2012.2236568.
7. Szakmany, Gergo & Orlov, Alexei & Bernstein, Gary & Lin, Matthew & Porod, Wolfgang. (2018). Multiphysics THz Antenna Simulations. IEEE Journal on Multiscale and Multiphysics Computational Techniques. PP. 1-1. 10.1109/JMMCT.2018.2886567.
8. Szakmany, Gergo & Bernstein, Gary & Kinzel, Edward & Orlov, Alexei & Porod, Wolfgang. (2020). Nanoantenna-based ultrafast thermoelectric long-wave infrared detectors. Scientific Reports. 10. 10.1038/s41598-020-70062-6.

One-page project summary that describes problem, project goal and your activities / results:

Thermoelectrically coupled nanoantennas (TECNAs), like other uncooled infrared detectors, generate electrical signals via joule-heating, and therefore have performance improvements in vacuum settings where there are no losses due to air. TECNAs are half-wave dipoles, optimized in length to detect a narrow band of long-wave infrared light. Current, and therefore heat, is at a maximum at the center of the antenna, and by connecting the room temperature substrate to this center "hot junction" via two dissimilar metal wires, a thermocouple is formed. The output signal is caused by the Seebeck effect, and is proportional to the temperature difference between the hot junction and the silicon substrate [6-8]. By rarifying the air surrounding the antenna, heat conduction is limited to the thermocouple metal contacts, theoretically yielding larger signals. The goal of this ongoing project is to understand and quantify the impact of lower-pressure environments on the performance of the TECNAs via simulation and experimentation.

I began the summer by studying a variety of topics useful to the field of micro-electronic mechanical systems (MEMS) but that are not covered in typical electrical engineering undergraduate courses. Basic knowledge in vacuum systems, the kinematic theory of gasses, heat transfer (HT), and blackbody radiation would not only be relevant but necessary to complete my project. In addition to learning background theory, I spent the early weeks of my NURF experience becoming comfortable within the COMSOL Multiphysics tool. By analyzing and dissecting complex E&M and HT models, I not only became competent with the software, but was able to apply the background physics I had learned. Within a month, I had the ability to create my own models of the TECNAs and extract relevant simulated results.

Throughout the summer, I generated a variety of models relevant to the TECNA project; however, the main focus was the vacuum project. As a proof of concept, an introductory simulation was run yielding just two data points - a realistic TECNA in atmospheric pressure air and the same exact TECNA in a perfect vacuum. While in air, the TECNA's hot junction reached a temperature 3.7 K above ambient, consistent with previous results. However, in a perfect vacuum, the very same TECNA climbed to 47.7 K above ambient, a ~12X improvement. From there, a range of vacuum simulations were conducted, including modeling for low and medium (as opposed to perfect) vacuum, transient response in and outside a vacuum, novel spiral TECNAs and their behavior in rarified air, etc. The vacuum simulation work is ongoing, with the hopes to implement new ideas and tools into previously existing models. For example, COMSOL offers a molecular flow module that can more accurately simulate low-pressure environments than bulk material modeling. By integrating this new module, we can be more confident in results and explore more specific questions such as "How many particles hit the TECNA per second?", "How much energy is transferred due to air losses?", etc.

In addition to simulations, physical experimentation is needed to quantify performance metrics of TECNAs. Exploring rarified atmosphere adds several difficulties to taking measurements. The physical vacuum chamber needed for experimentation (see figure 1) was constructed throughout the summer by Dr. Szakmany. A custom, transparent filter was built into the otherwise blind top flange of the chamber, allowing the laser to pass through and excite samples. This flange will be sealed using a reusable o-ring gasket so that samples can easily be swapped and adjusted in between measurements. Due to the poorer seal, experimentation will be limited to the low / medium vacuum regime; however, because of the smaller size of the chamber, pressures will be sufficient to reach molecular flow. The goal is to couple simulation results found this summer with experimental data taken this fall to produce a robust paper. Investigations to be conducted include the effects of pressure on open-circuit voltage and response time for both individual TECNAs and arrays.

Figure 1. Vacuum Chamber for TECNA Experimentation