Developing a Novel Platform for Characterizing Thermoelectric Materials for Uncooled Detectors for Land Imaging Applications

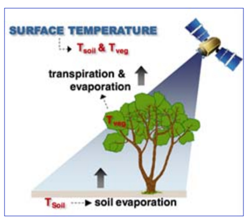
Riley A. Reid[1], Emily M. Barrentine[2], Brendan Bramman[3], Ari D. Brown[2], Steven Cagiano[2], Nicholas P. Costen[2,4], Vilem Mikula[2,5], Alicia T. Joseph[2]
[1]North Carolina State University, Raleigh NC, [2]NASA Goddard Space Flight Center, Greenbelt MD, [3]University of Waterloo, ON Canada, [4]SGT, Inc., Greenbelt, MD, [5]American University Department of Physics, Washington DC

Introduction

Geosynchronous thermal land imaging is an essential tool for understanding and managing Earth's freshwater resources. Doped-Si materials materials integrated into uncooled detectors could vastly improve this instrument technology by saving on mass, power, and cost. In this study, **we aim to design a testing platform to accurately characterize the thermoelectric properties of thin-film doped-Si materials.**

Thermal Imaging Application

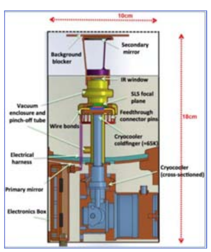
- By incorporating thermal imaging data, data (at ~10-11 micron wavelengths), one can estimate evapotranspiration (ET) from soil and vegetation to monitor land moisture at field-scales.
- These data are relevant to:
  - Irrigation management
  - Food and water security
  - Impacts of urban development and deforestation
  - Affects of climate change



Courtesy of Alicia T. Joseph

Uncooled Detector Technology

- Although quantum well infrared detectors used in the TIRS-2 instrument [5] have outstanding signal to noise characteristics, they operate at T<50K, which necessitates the use of complex, massive cryocoolers. Uncooled detector technologies don't have these complex, massive, and power consuming components.



Courtesy of Alicia Joseph

- We aim to focus on novel doped-Si thermopiles [6] for several reasons:
  - **Room temperature operation does not require cryocoolers**
  - No bias power required for readout
  - Ability to **optimize** Seebeck coefficient
  - Si is strong, lightweight, and thermally robust

Thermoelectric Figure of Merit

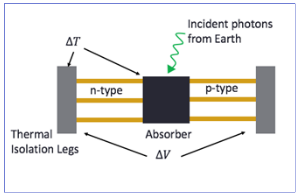
- Because doped-Si has been shown to have among the highest thermoelectric figure of merit at room temperature on bulk samples [6], it has motivated us to make microfabricated doped-Si thermopiles.
- Doped-Si material can be assembled into a thermopile detector because it exhibits the thermoelectric Seebeck effect in which a temperature difference (ΔT) is converted into a voltage differential (ΔV).
- Using the Seebeck coefficient (S), resistivity (ρ), and thermal conductivity (σ), the Figure of Merit (Z) can be calculated [1].

$$S = \frac{\Delta V}{\Delta T}$$

Seebeck Coefficient

$$Z = \frac{S^2}{\rho\sigma}$$

Figure of Merit

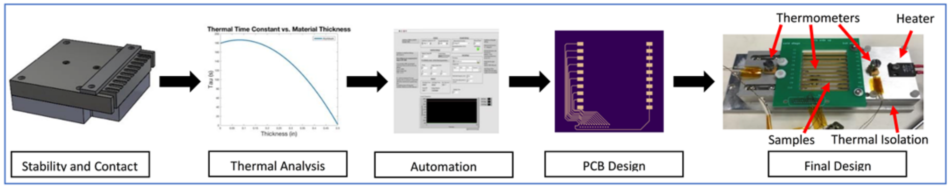


- To optimize this material, we aim to measure thermoelectric figure of merit in ultra-thin (450 nm) doped-Si and compare different dopant concentrations in a consistent characterization platform.

Design, Fabrication, and Testing

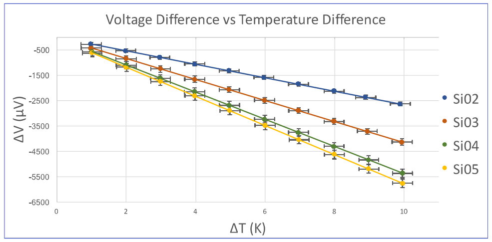
- We designed and fabricated a novel platform through the following stages of development:
  - 3D modelling of stages with optimized thickness for thermal time constant and insulation
  - Integration of BeCu spring clips to improve electrical and thermal contact of the samples
  - Cohen-Coon PID tuning algorithm to improve temperature control loop
  - LABVIEW program for increased testing efficiency
  - Implementation of shielding and PCB design to strengthen signals and reduce electrical noise
- We used this platform to measure the Seebeck coefficient of doped-Si samples. The samples consisted of phosphorus ion implanted 450 nm thick silicon membranes epoxy bonded to aluminum oxide substrates.

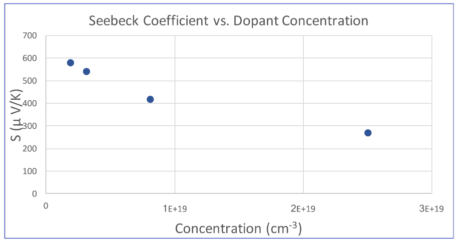
Sample	N- Dopant Concentration [cm^{-3}]
Si02	2.51E+19
Si03	8.18E+18
Si04	3.18E+18
Si05	1.95E+18



Characterization Results

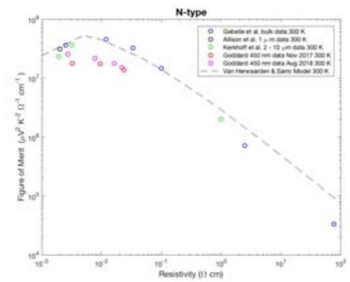
- We increased the temperature difference from 1 to 10K and recorded the voltage difference.
- We repeated this for each sample, and used linear regression to find the Seebeck coefficient vs. dopant concentration.





Conclusions

- By eliminating the need for cryocoolers in thermal imaging instruments, doped-Si thermopile detectors present a compelling alternative for future instruments.
- We have designed, fabricated, and tested a platform to accurately characterize doped-Si samples at room temperature.
  - This platform provides mechanical stability, consistent electrical contact, and reduced electrical noise.
  - Using PID tuning and automation, we improved temperature stability and produced more consistent readings at a higher frequency.
- Seebeck coefficient results show less deviation from bulk literature than previous measurements with old platform.
- Characterization results are closer to bulk literature expectations of peak figure of merit for doped-Si material:



Courtesy of Emily Barrentine, [2] [3] [4]

Future Steps

- Complete thermal conductivity measurements to calculate full Figure of Merit.
- Use these results to guide our thermopile detector design to provide an optimal and competitive detector alternative for future thermal imaging instruments.

References & Acknowledgements

- [1] A. Graf et al., Measurement Science and Technology, 18, R59 (2007).
- [2] T. H. Geballe & G. W. Hull, "Seebeck Effect in Silicon," Phys. Rev., 98, 940 (1955).
- [3] Allison et al. "A bulk micromachined silicon thermopile with high sensitivity", Sensors and Actuators A, 104, 32-39, (2003).
- [4] A. W. Van Herwaarden, and P. M. Sarro. "Thermal sensors based on the Seebeck effect." Sensors and Actuators 10.3-4, 321-346, (1986).
- [5] M. Jhabvala et al. "Performance of the QWIP focal plane arrays for NASA's Landsat Data Continuity Mission." Infrared Technology and Applications XXXVII. Vol. 8012, (2011).
- [6] Lakew, B. et al, "Concept Doped-Silicon Thermopile Detectors for Future Planetary Thermal Imaging Instruments." AAS/Division for Planetary Sciences Meeting Abstracts, 48 (2016).

- I would like to thank NC State University's Office of Undergraduate Research for providing travel funding.