Robust Heat-Flux Sensors for Coal-Fired Boiler Extreme Environments

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Robust Heat-Flux Sensors for Coal-Fired Boiler Extreme Environments

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Motivation

- Powerplant personnel are reliant on sensors to determine operational parameters during dynamic energy loads.
- Heat flux measurements at the boiler wall or economizer can help determine combustion efficiency or system health.
- Current state-of-the-art heat flux gauges are not compatible with extreme boiler environments.

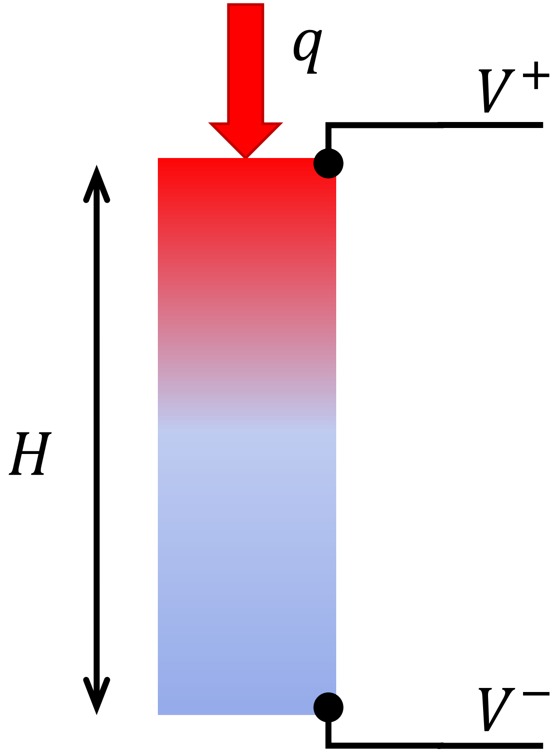
Objectives

- Develop a heat flux measurement system compatible with
  - Operating temperatures in excess of 750°C.
  - Oxidative, corrosive, and erosive environments.
  - Soot or deposition of combustion products.

Measuring Heat Flux

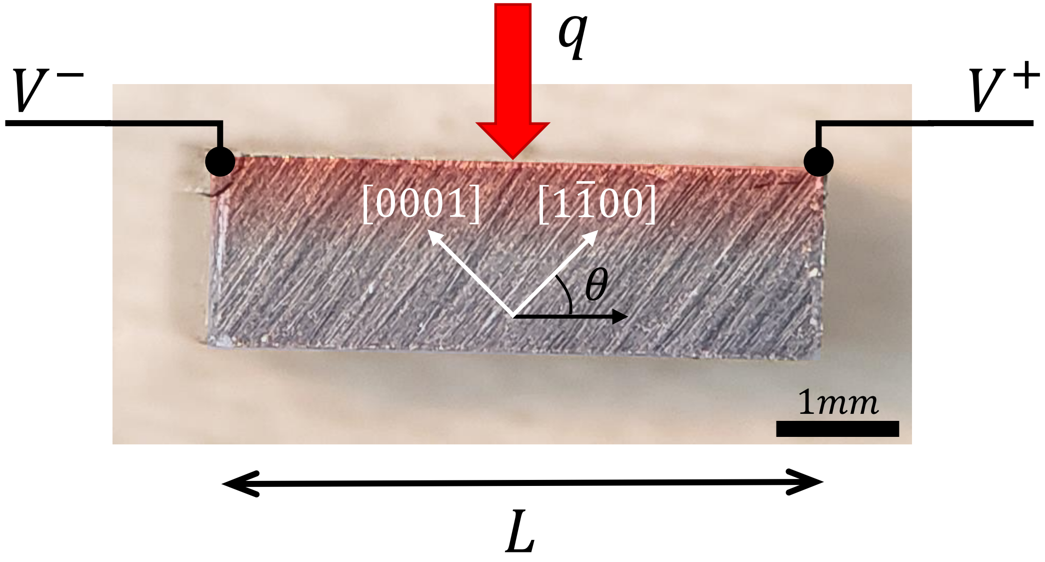
Key

V	*Voltage*
T	*Temperature*
q	*Heat flux*
S	*Isotropic Seebeck coefficient*
k	*Isotropic thermal conductivity*
$f(S_i, k_i, \theta)$	*Constant representing anisotropic material properties and crystallographic orientation*



$$\Delta V = -S\Delta T = \frac{S}{k} H \times q$$

Vs.



$$\Delta V = f(S, k, \theta) L \times q$$

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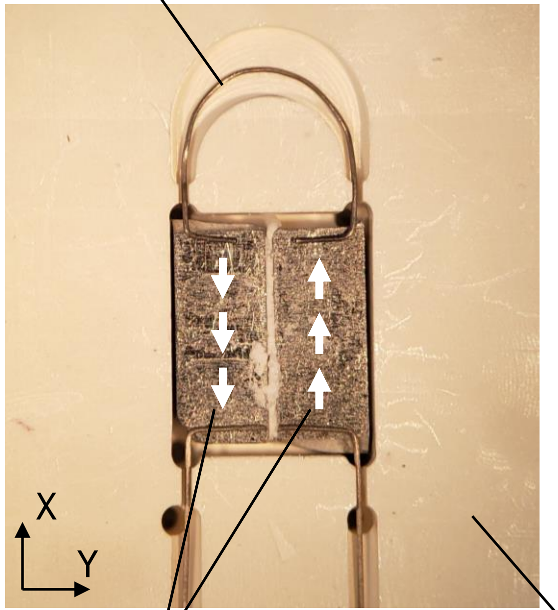
Phase 1 – Antimony crystals
Phase 2 – Rhenium crystals

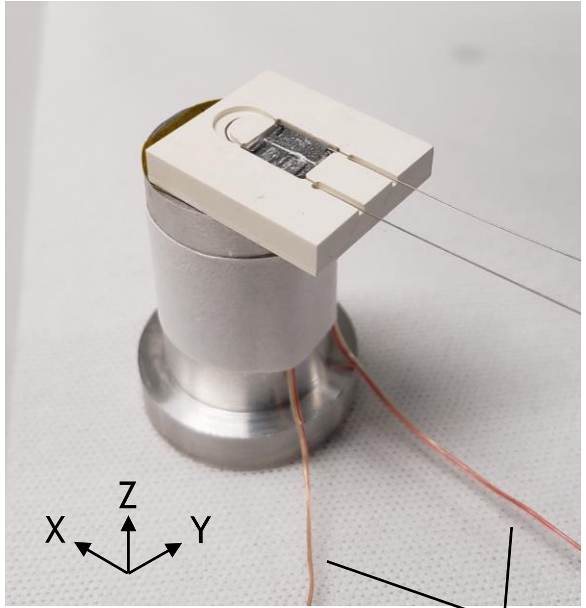
Heat Flux Sensor Design

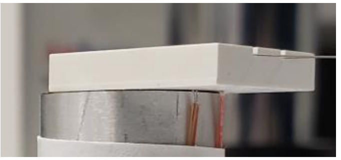
- Transverse Seebeck Effect-based heat flux sensor head.

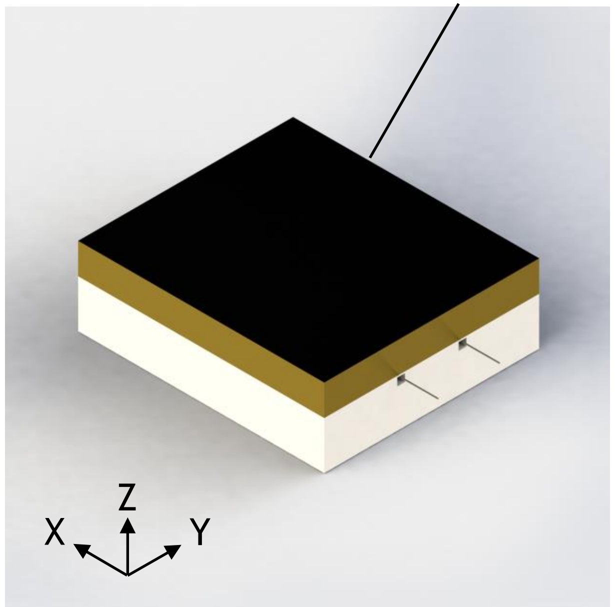
Electrical wiring

Heat flux collector









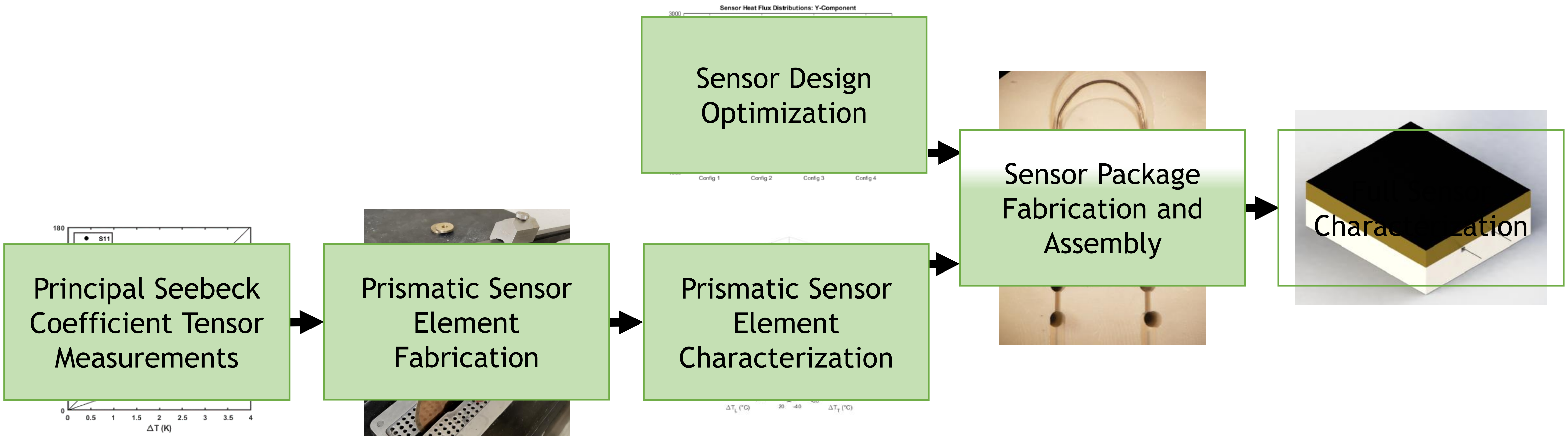
Prismatic crystals

Ceramic package

Auxiliary thermocouples

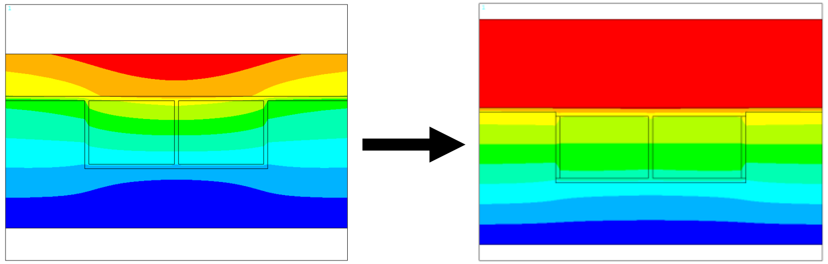
Beta Sensor Development

- Prototype Antimony-based Heat Flux Sensor.



Beta Sensor Development

- Sensor optimization through simulation.



Sensor Design Optimization

Sensor Package Fabrication and Assembly

Full Sensor Characterization

Principal Seebeck Coefficient Tensor Measurements

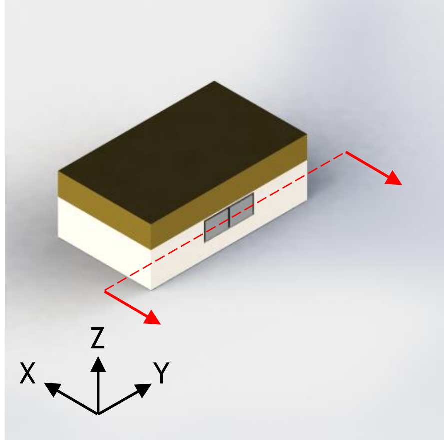
Prismatic Sensor Element Fabrication

Prismatic Sensor Element Characterization

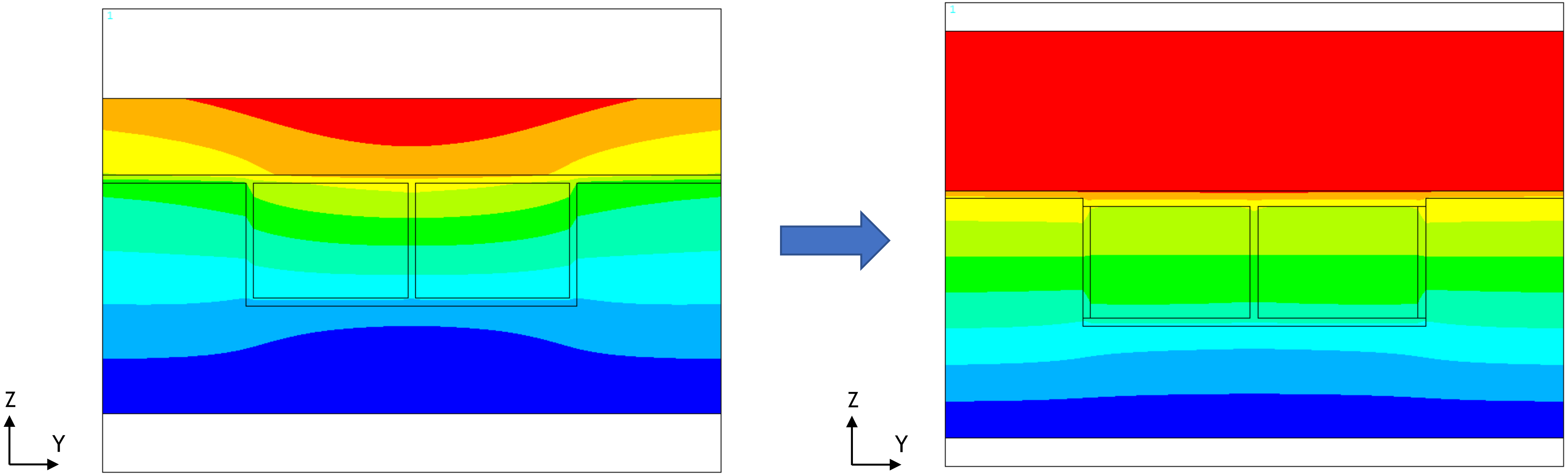
Sensor Design Optimization

- Transduction mechanism $\Delta V = fLq$ is *only* valid if the heat flux in the prismatic crystals is uniform.
- ANSYS thermal simulations were used to optimize the sensor package design to increase heat flux uniformity.

Optimization Through Simulation



- Comparing temperature contours plots demonstrates improvements in heat flux uniformity.

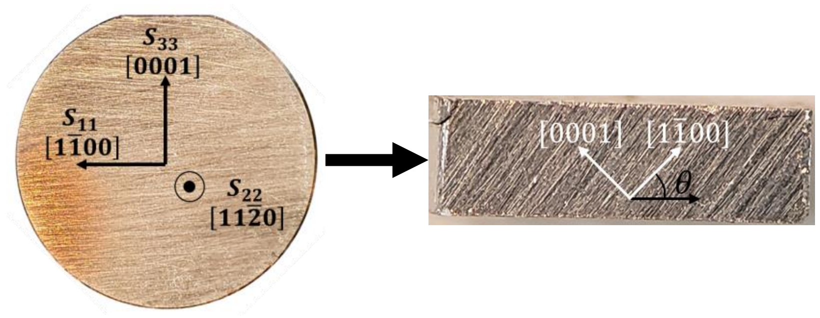


Lessons Learned Through Simulations

- To maximize heat flux uniformity
  - Decrease package – crystal thermal conductivity mismatch.
  - Minimize thermal resistance in heat flux collector.
  - Incorporate insulating features between the side walls of the crystals and the package.
  - Arrange crystals symmetrically across mirror plane with minimal gap.

Beta Sensor Development

- Large single crystal pellet → prismatic crystals.

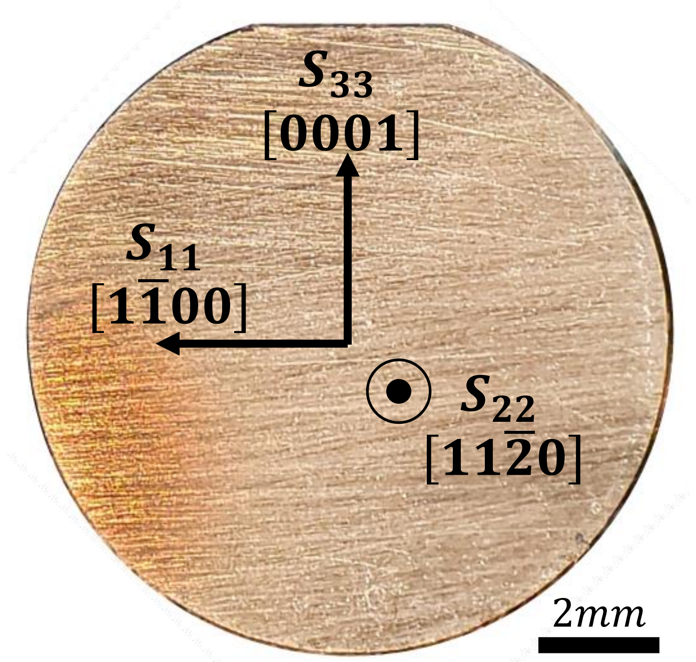


Principal Seebeck Coefficient Tensor Measurements → Prismatic Sensor Element Fabrication → Prismatic Sensor Element Characterization → Sensor Package Fabrication and Assembly → Full Sensor Characterization

Sensor Design Optimization → Sensor Package Fabrication and Assembly

Seebeck Coefficient Measurements

- The crystals used for transverse Seebeck effect-based sensing must have an anisotropic Seebeck coefficient tensor.
- In Antimony crystals $S_{11} = S_{22} > S_{33}$



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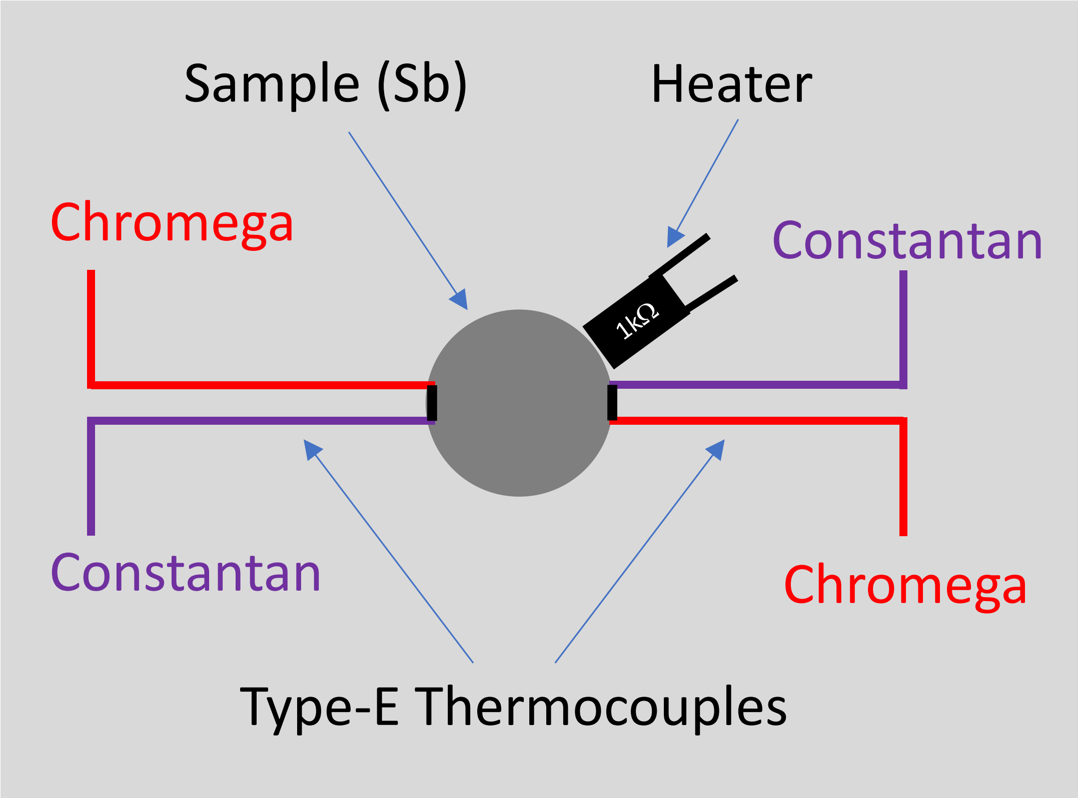
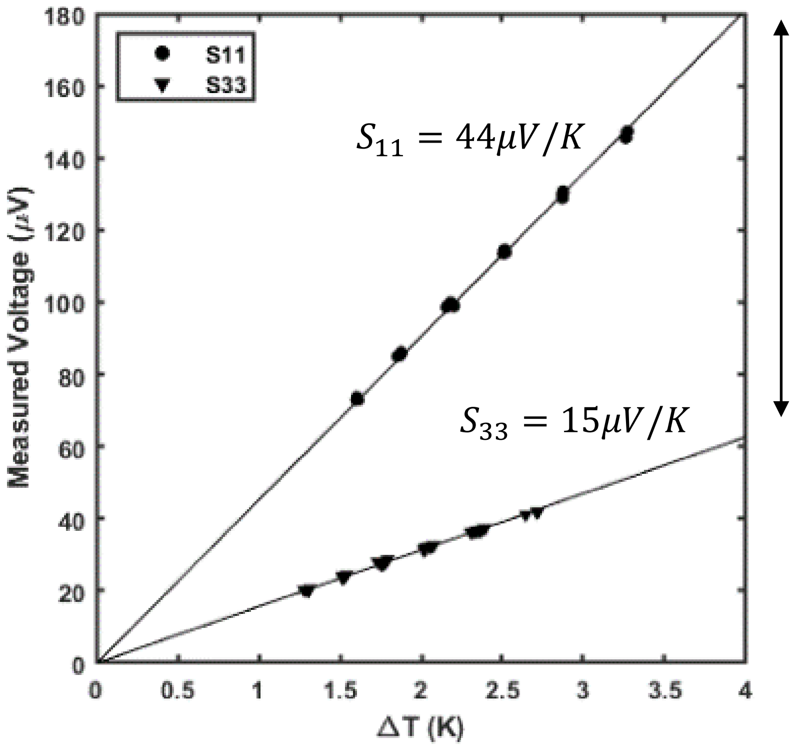
Seebeck Coefficient Measurements

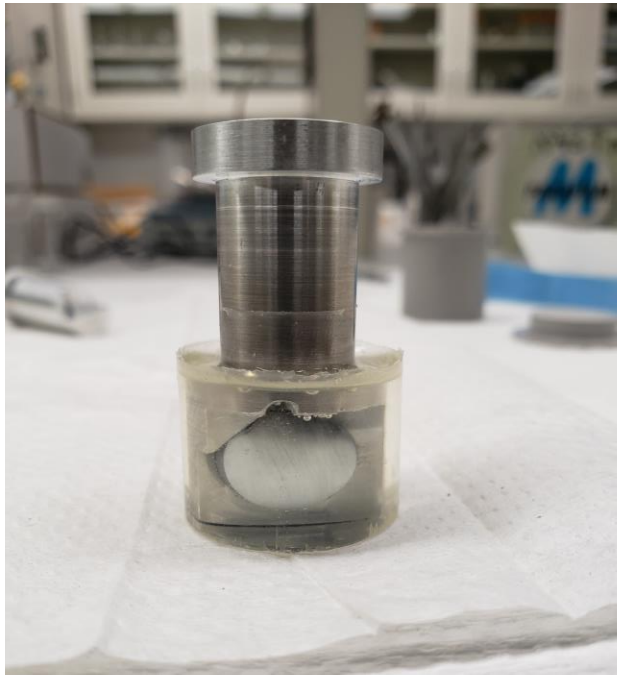


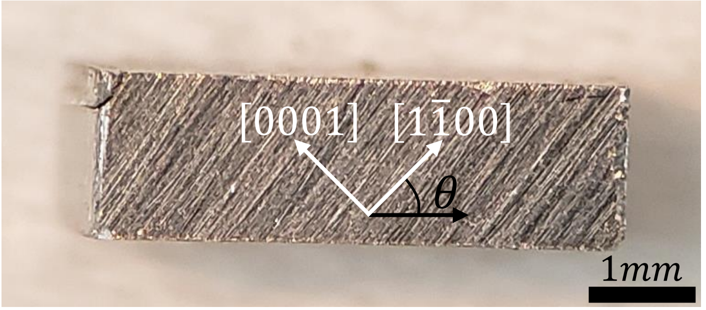


The material displays large, non-equal Seebeck tensor components.

Sensor Element Fabrication

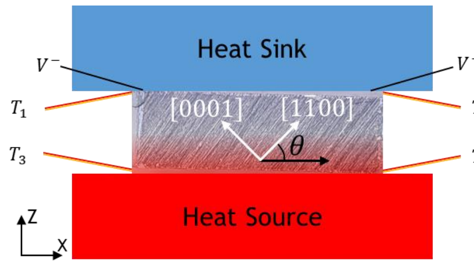
- Sensors were fabricated from large single crystal pellet.

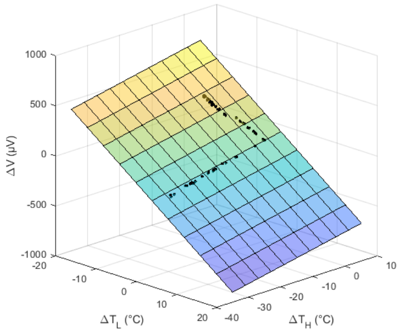




Beta Sensor Development

- Characterization of individual Antimony prismatic sensors.





Sensor Design Optimization

Sensor Package Fabrication and Assembly

Full Sensor Characterization

Principal Seebeck Coefficient Tensor Measurements

Prismatic Sensor Element Fabrication

Prismatic Sensor Element Characterization

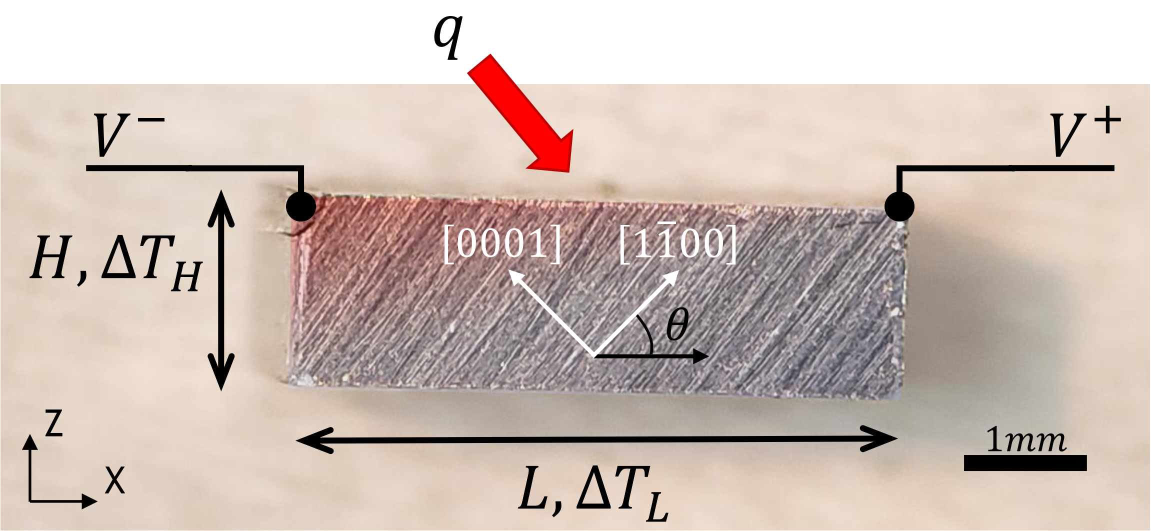
Sensor Element Voltage Response

Key	
ΔT_L	*Temperature difference between right and left prism faces*
ΔT_H	*Temperature difference between top and bottom prism faces*
L	*Prismatic sensor length*
H	*Prismatic sensor height*

- The total voltage response in Sb prismatic sensors can be expressed as

$$\boldsymbol{\Delta V} = C_1 \boldsymbol{\Delta T_L} + C_2 \frac{L}{H} \boldsymbol{\Delta T_H}$$

- Where
  - $\Delta V = V^+ - V^-$
  - $C_1 = -(S_{11} \cos^2 \theta + S_{33} \sin^2 \theta)$
  - $C_2 = -(S_{33} - S_{11}) \sin \theta \cos \theta$



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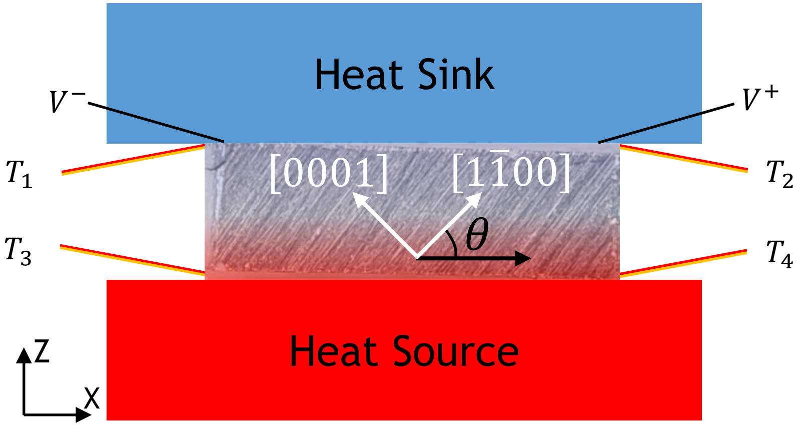
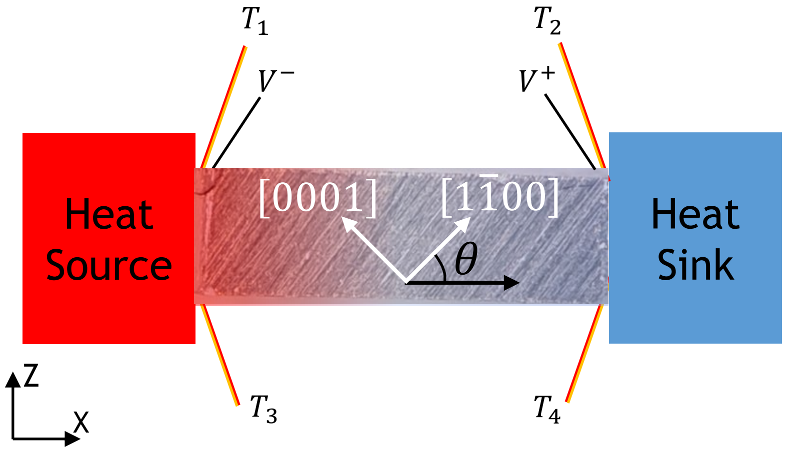
Characterizing Antimony Sensors

- The thermoelectric parameters of the sensor element (C_1 and C_2) were determined by subjecting the crystal to multiple heating scenarios.



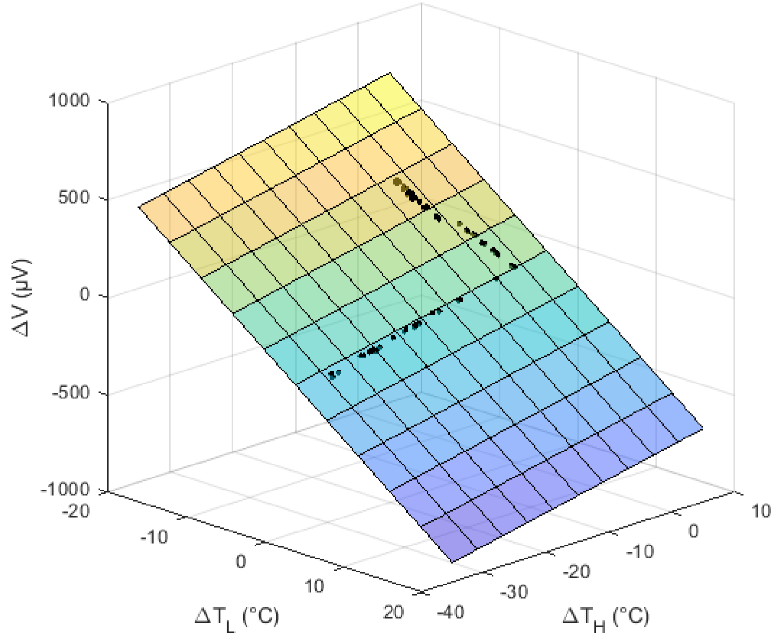


Prismatic Antimony Sensor Response

- The voltage response can be represented as a planar surface.

$$\boldsymbol{\Delta V} = C_1 \boldsymbol{\Delta T_L} + C_2 \frac{L}{H} \boldsymbol{\Delta T_H}$$

- For Antimony prismatic sensing elements
  - $C_1 = -32.8\ \mu V/K$ → Matches predictions
  - $C_2 = 2.12\ \mu V/K$ → Smaller than predicted



Conclusions

- Have produced single crystal Antimony sensing elements and characterized full anisotropic thermoelectric response.
- Demonstrated optimization of package configuration tailored towards heat flux uniformity.
- Have begun assembly of transverse Seebeck effect-based heat flux sensor (Beta version).

Milestones (performance period 0-15 months)

- One-dimensional Heat Flow – Demonstration of a sensor head design for which heat flow through the thermoelectric sensing element is one-dimensional.
  - Status: 100% complete
- Transverse Seebeck Prototype – Demonstration of analog electrical signal generation by the single crystal chain. The signal shall be a monotonic function of the heat flux.
  - Status: 80% complete

Future Work

- Demonstrate the voltage response of a fully assembled Antimony-based heat flux sensor.
- Fabricate and characterize the thermoelectric response of Rhenium prismatic sensing elements.
- Demonstrate high-temperature heat flux sensing capabilities.

Questions?