Thermoelectric Energy Harvesting from the Human Body for Self-Powered Wearable Electronics

Mehmet C. Ozturk & Daryoosh Vashaee
Department of Electrical & Computer Engineering

Michael Dickey
Chemical & Biomolecular Engineering

North Carolina State University
Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST) Nanosystems Engineering Research Center


Healthcare Costs → 17% U.S. GDP
75% : Chronic Disease
1 in 3 Americans: Multiple Chronic Diseases
1 in 4 Americans : Poor air quality
Doctor Visits: 4 times a year

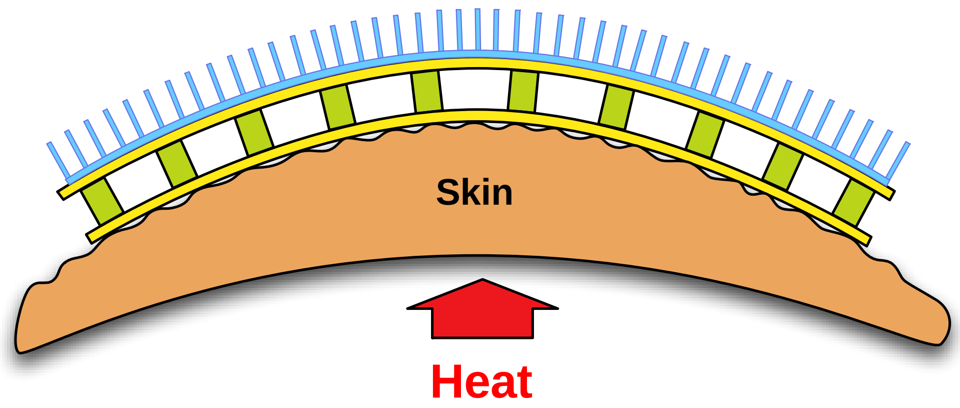
ASSIST vision

- Monitoring of personal health & environment
  - Long-term, continuous monitoring
- Correlation of multiple sensors
- Increased compliance through hassle-free usage
  - Self-powered wearables
  - Small Form-Factor
  - Non-Invasive
  - Textile Integration

Heat - Thermoelectric

Motion - Piezoelectric

Harvesting Heat from the Body

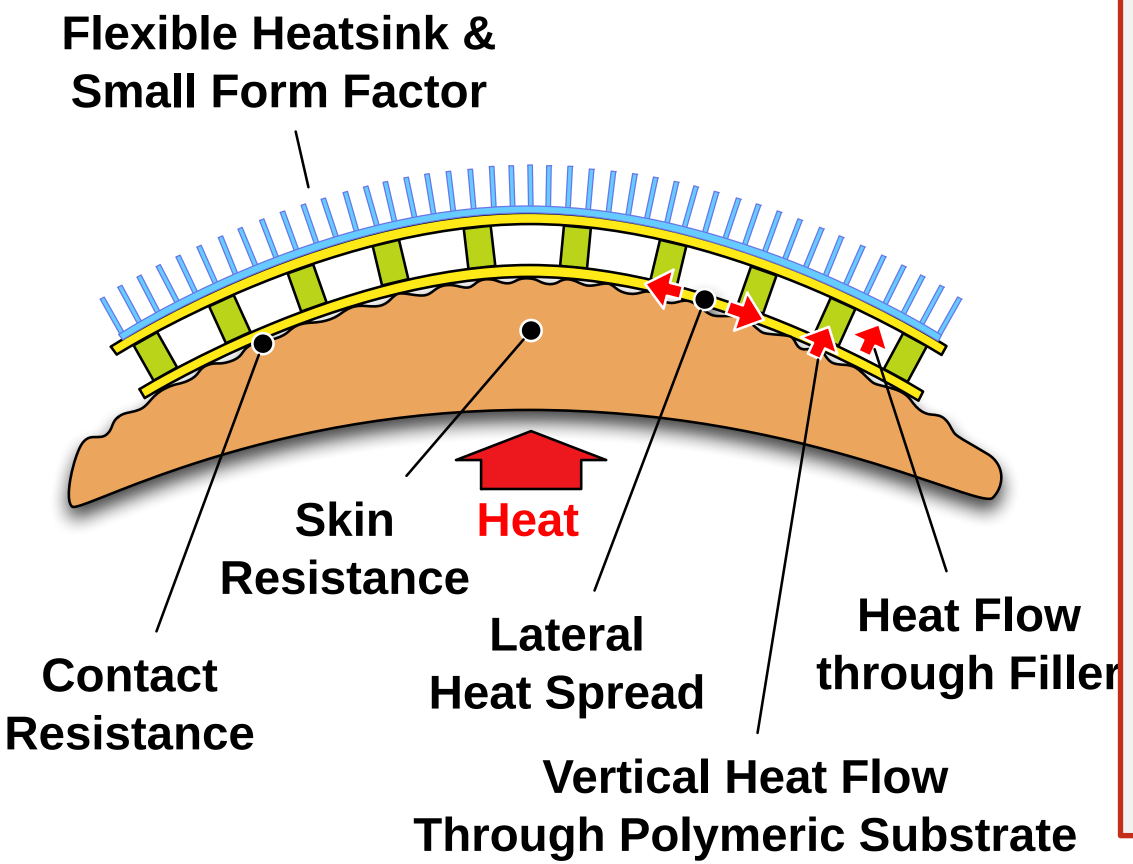


Flexible thermoelectric generators (TEGs) are desirable:

- Conformal to the body
  - Better contact with the skin
- Large area harvesting
  - Simple Integration
  - Electrical resistance
  - Aesthetics

ASSIST

Harvesting Heat from the Body

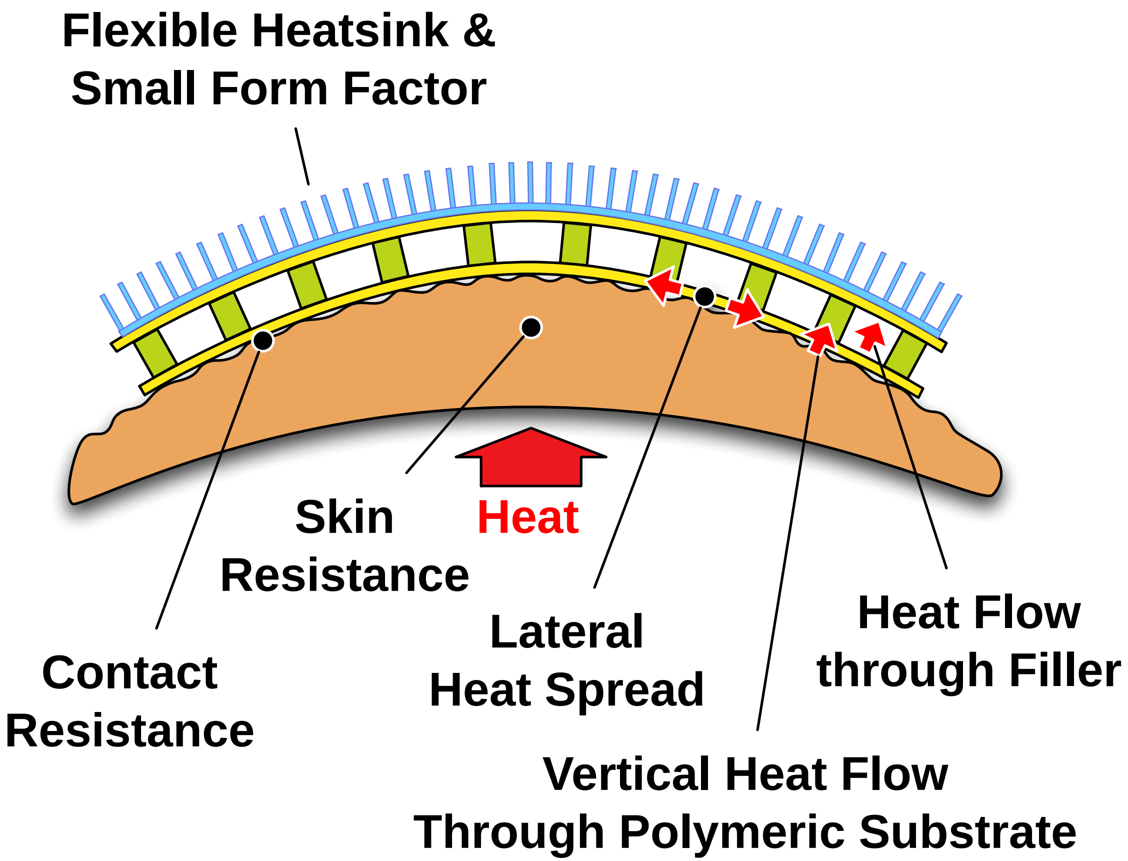


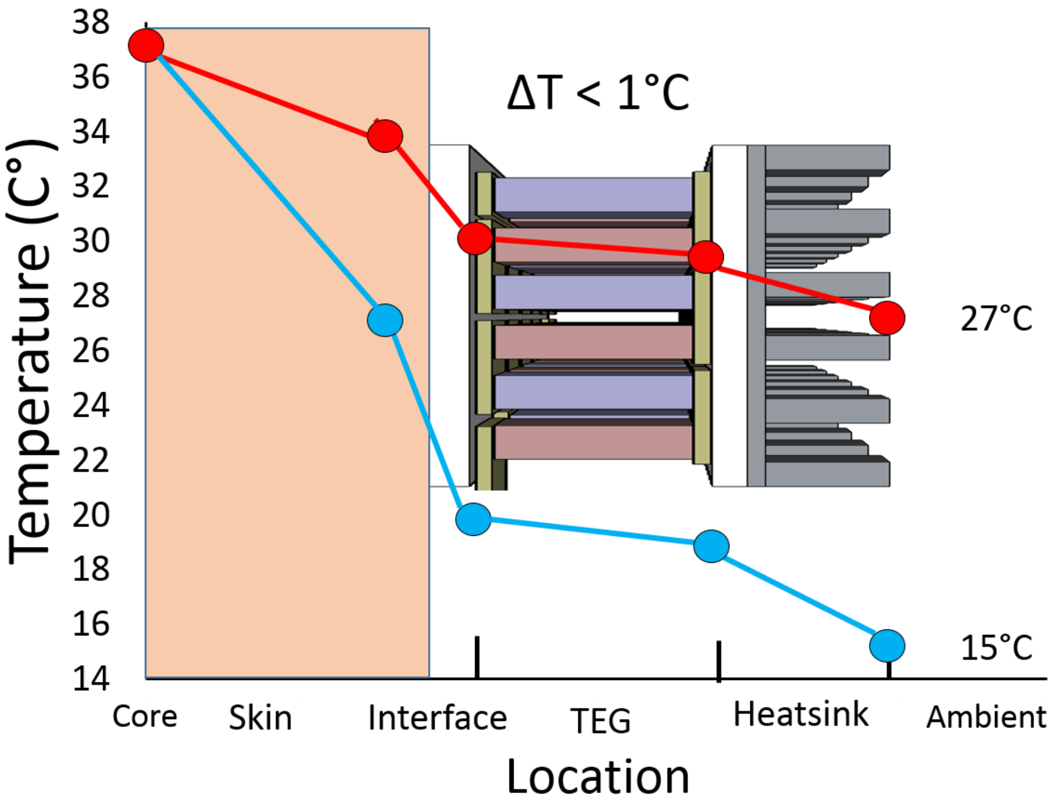
Flexible thermoelectric generators (TEGs) are desirable:

- Conformal to the body
  - Better contact with the skin
- Large area harvesting
  - Simple Integration
  - Electrical resistance
  - Aesthetics

The application imposes large thermal resistances

Harvesting Heat from the Body

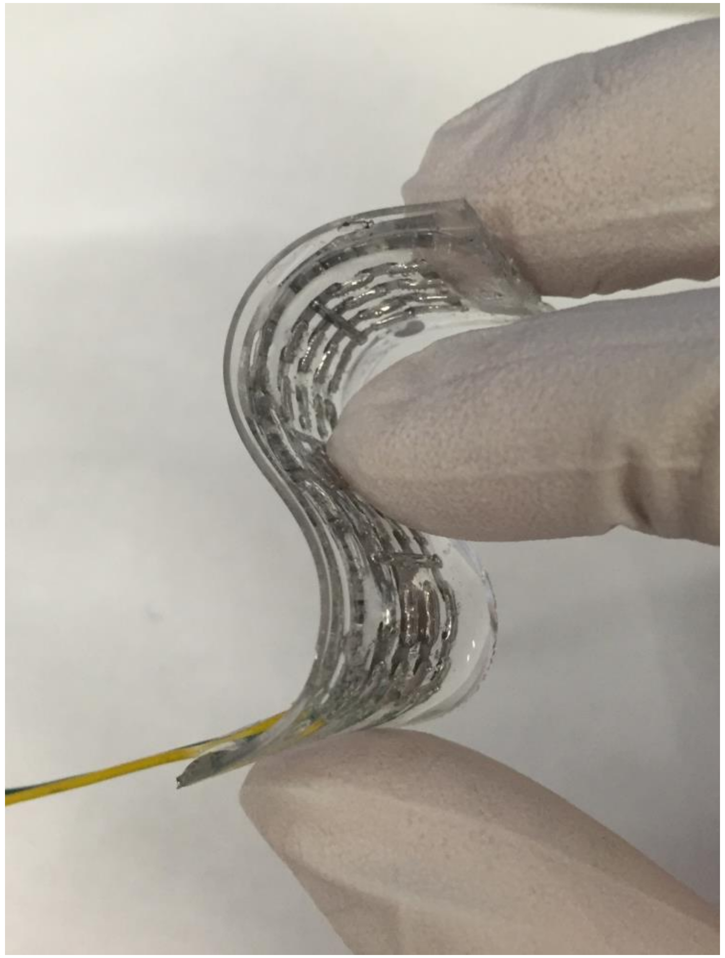




The application imposes large thermal resistances

Key Challenge: Small ΔT across the harvester

Our approach to Flexible Thermoelectrics

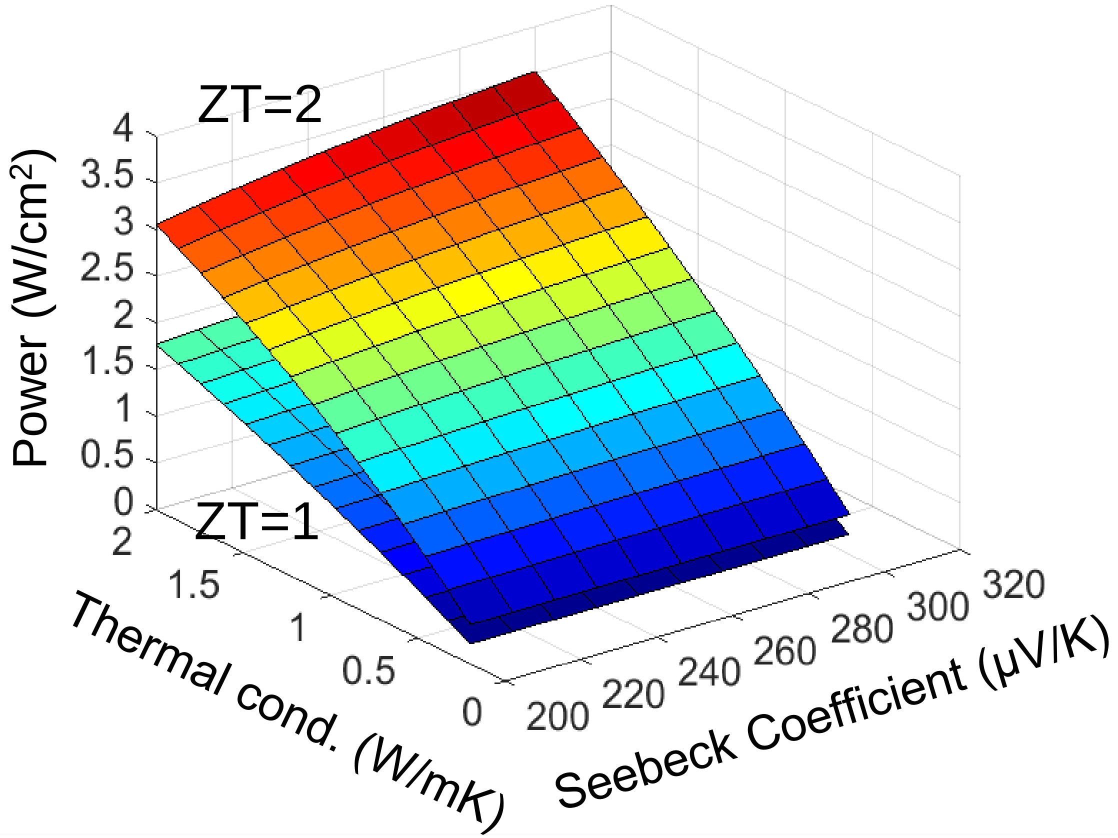


- Bulk thermoelectric materials
  - Best possible materials
  - Pick-and-Place Tooling
- Flexible packaging
  - Material Innovations

Material Optimization - ZT is NOT everything!

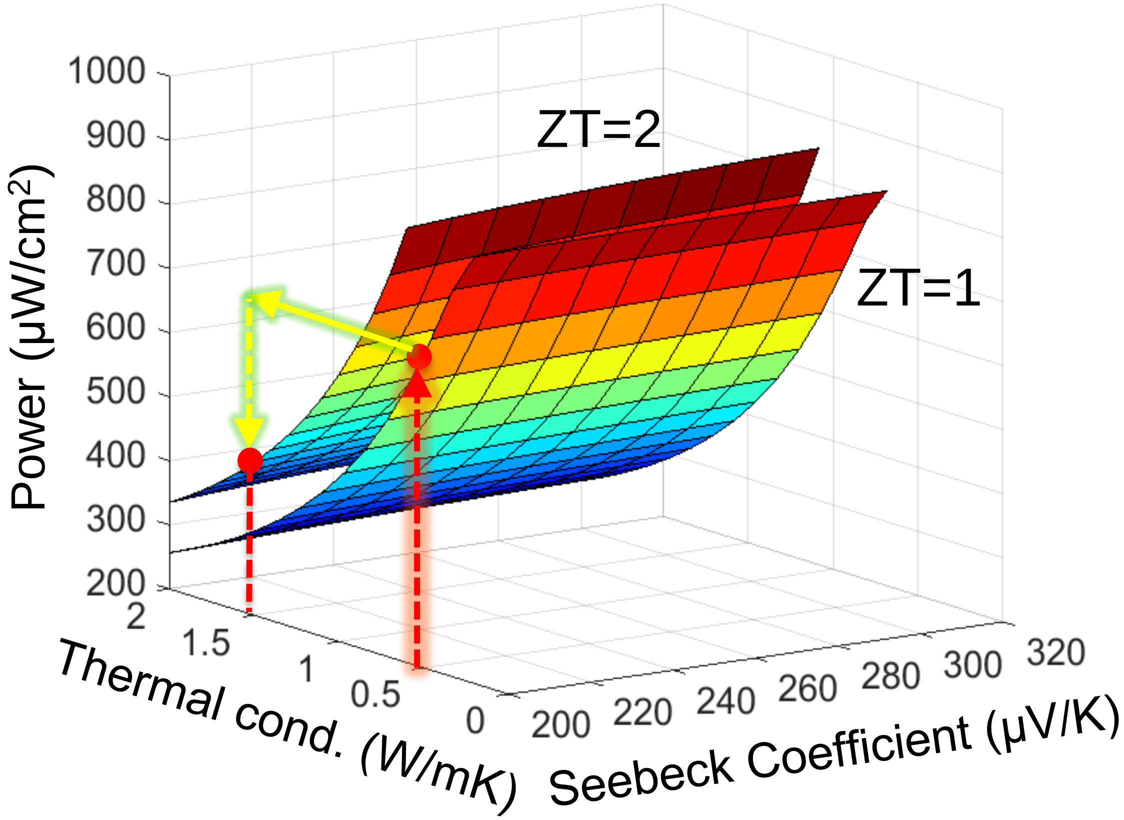
Industrial Energy Harvesting

Higher Power factor is better



Body Heat Energy Harvesting

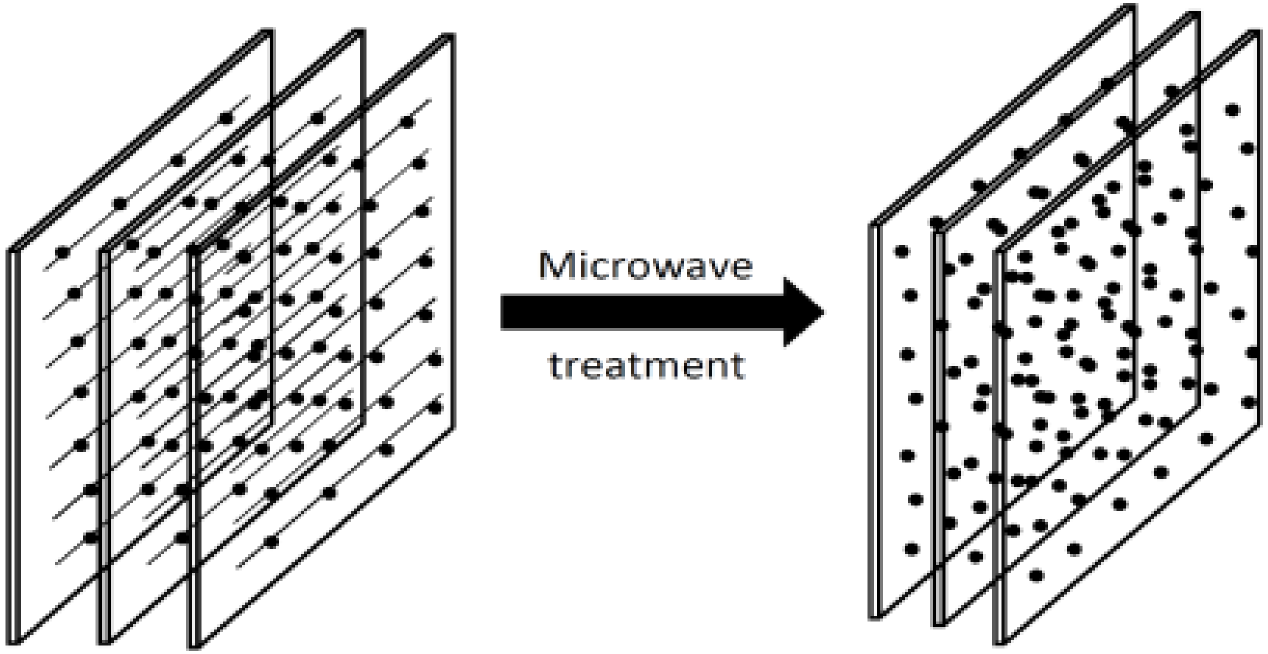
Lower Thermal conductivity is better



Largest gains are achieved by increasing the device thermal resistance

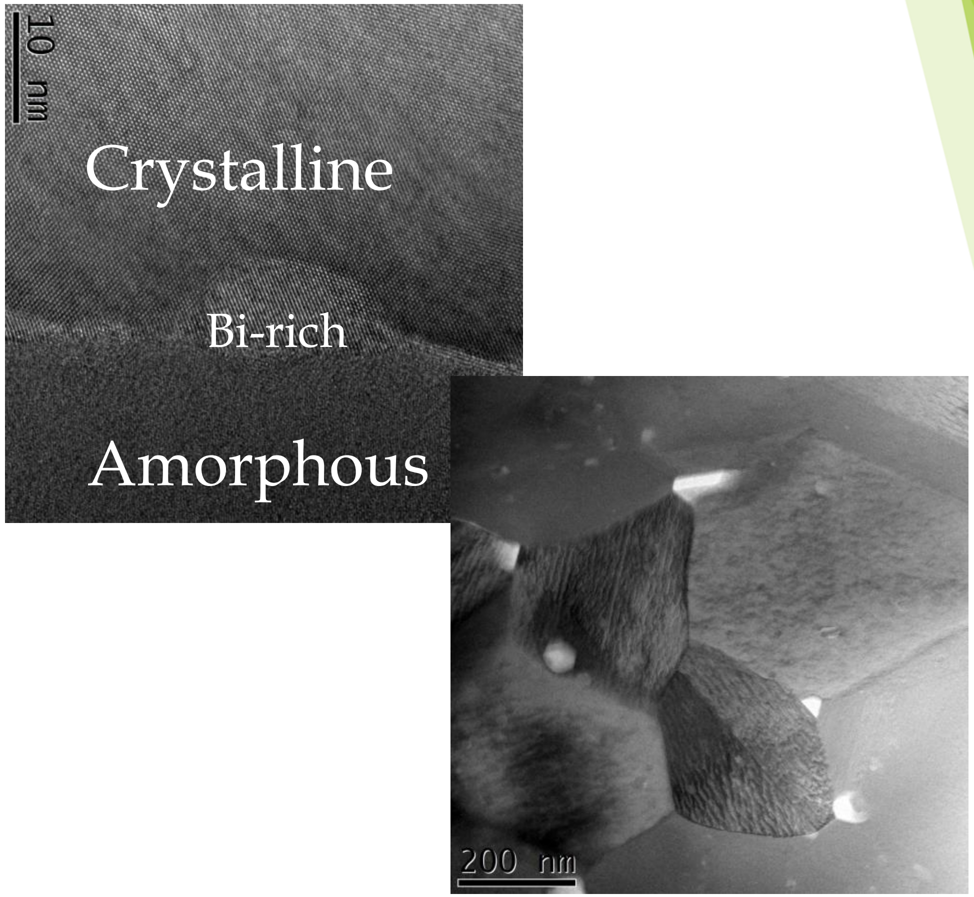
ASSIST

Nanocomposites for Low Thermal Conductivity - **Microwave Sintering**



Crystal planes with atomic arrangement

Amorphous crystal planes

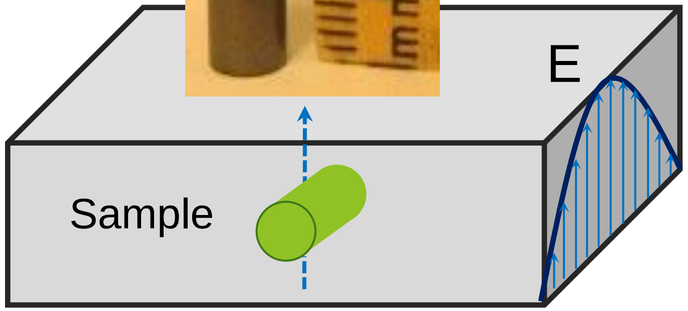


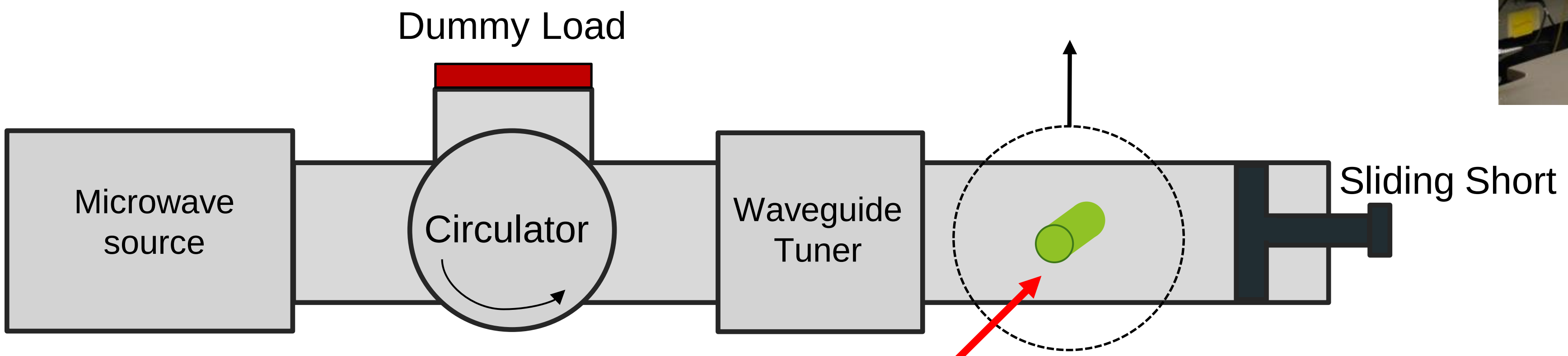
- The sample is exposed to high E-field in a microwave cavity
- High E-field at high temperatures dislodges atoms off the lattice
- Causes randomness in the lattice arrangement

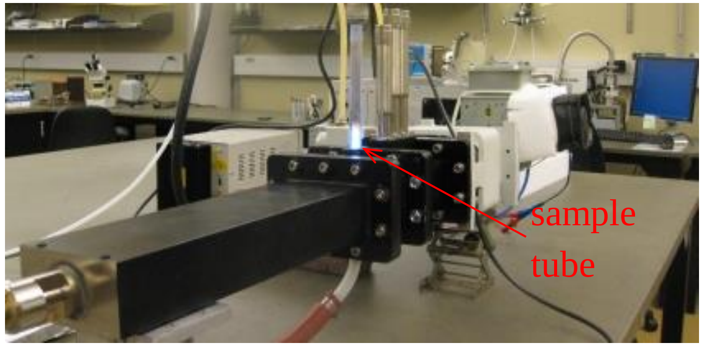
Daryoosh Vashaee, Amin Nozariasbmarz, Lobat Tayebi, and Jerzy S Krasinski, U.S. Provisional Patent Appl. No. 62/260,829 (2015)

Microwave Sintering

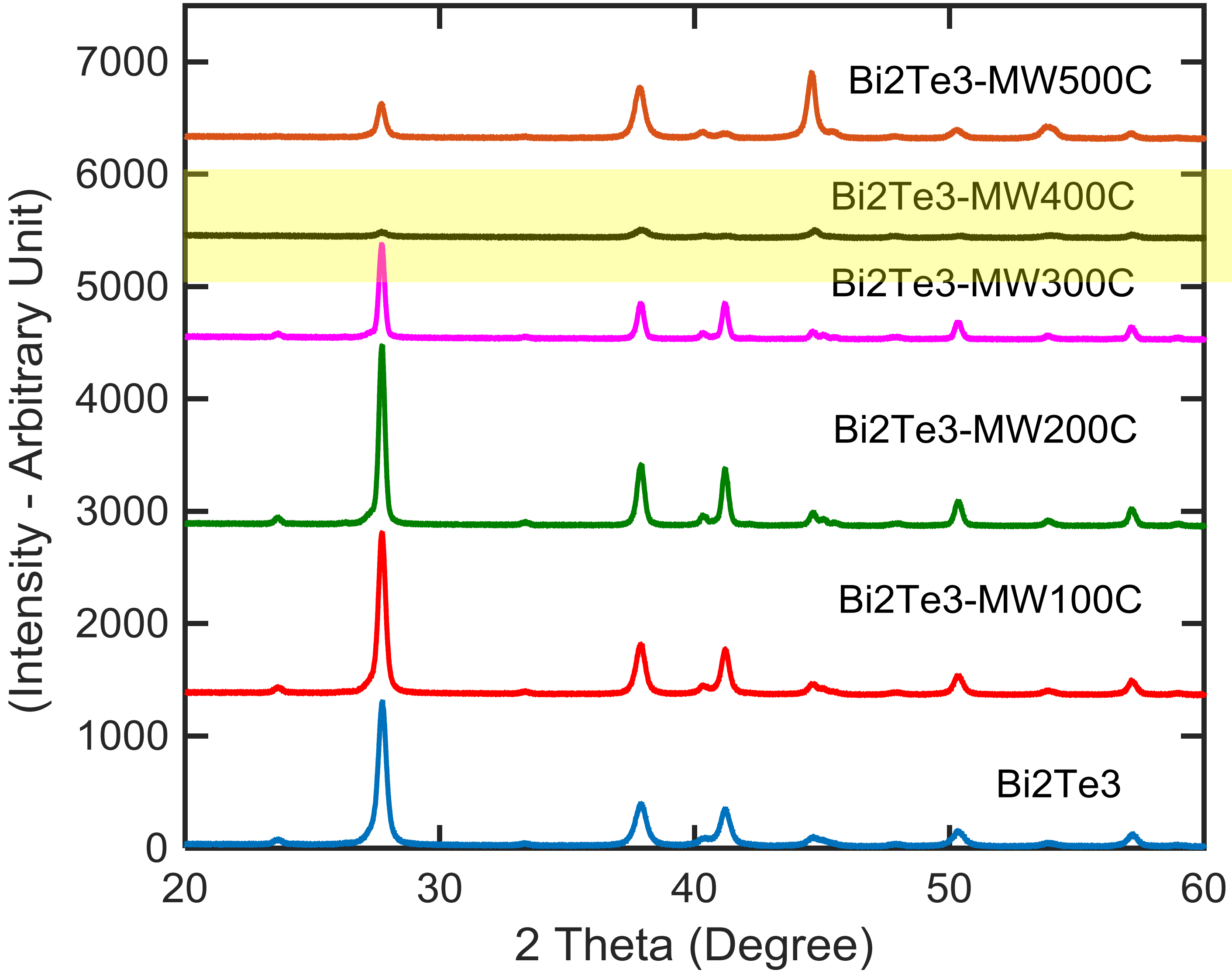
In-situ Decrystallization in MW cavity





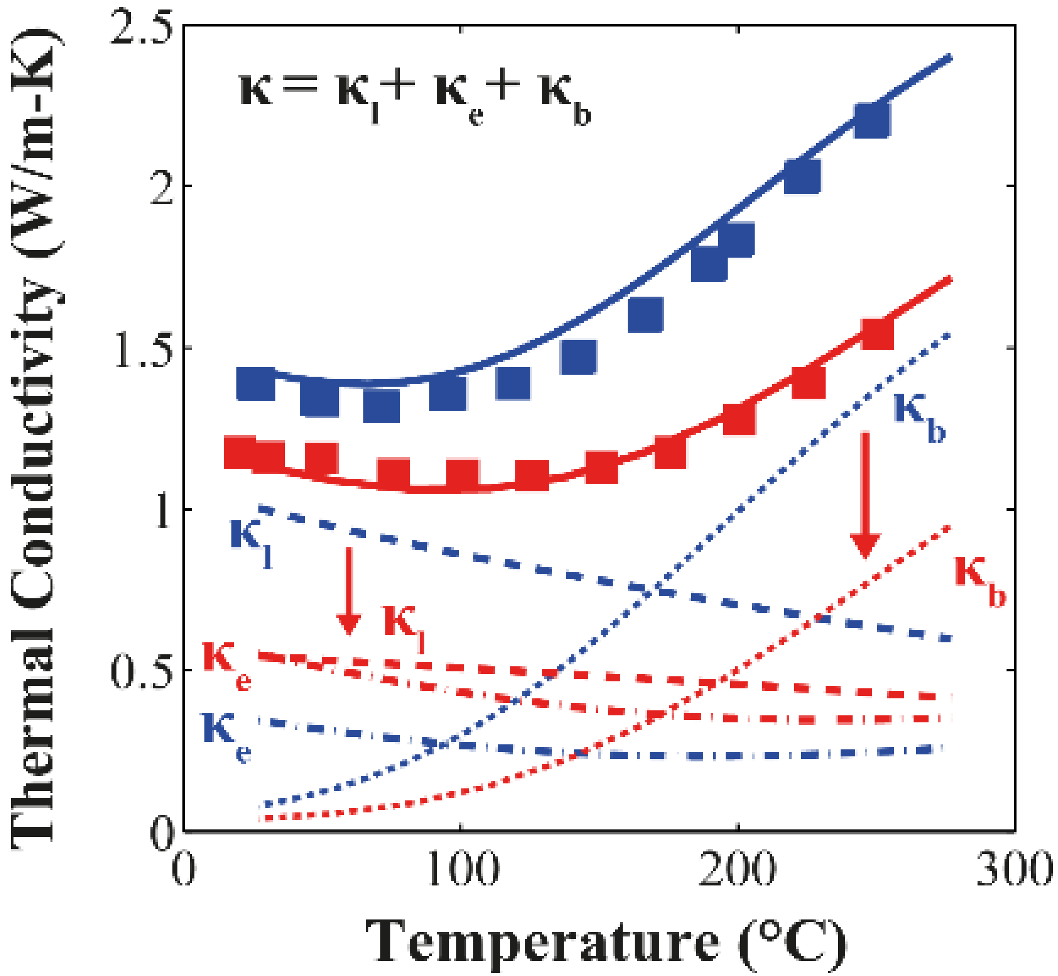


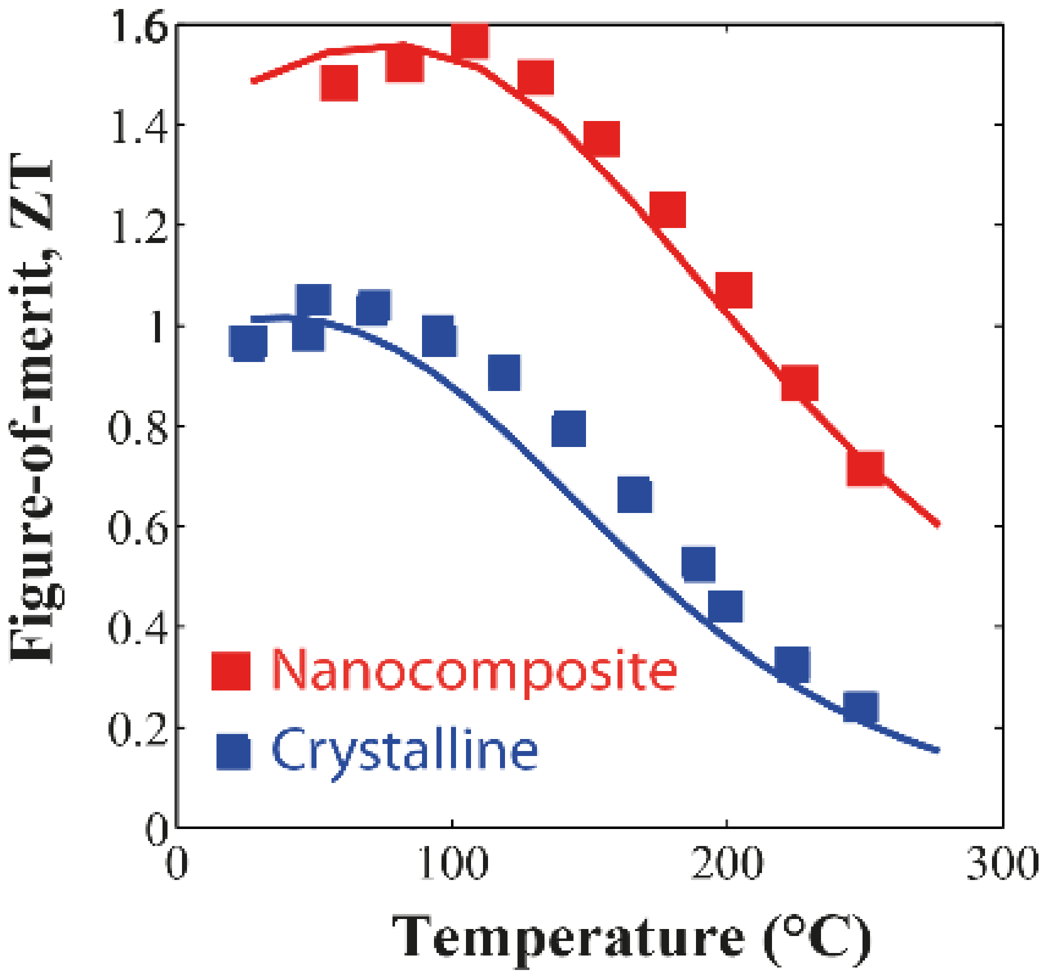
Decrystallization of $(Bi,Sb)_2Te_3$ Ingots



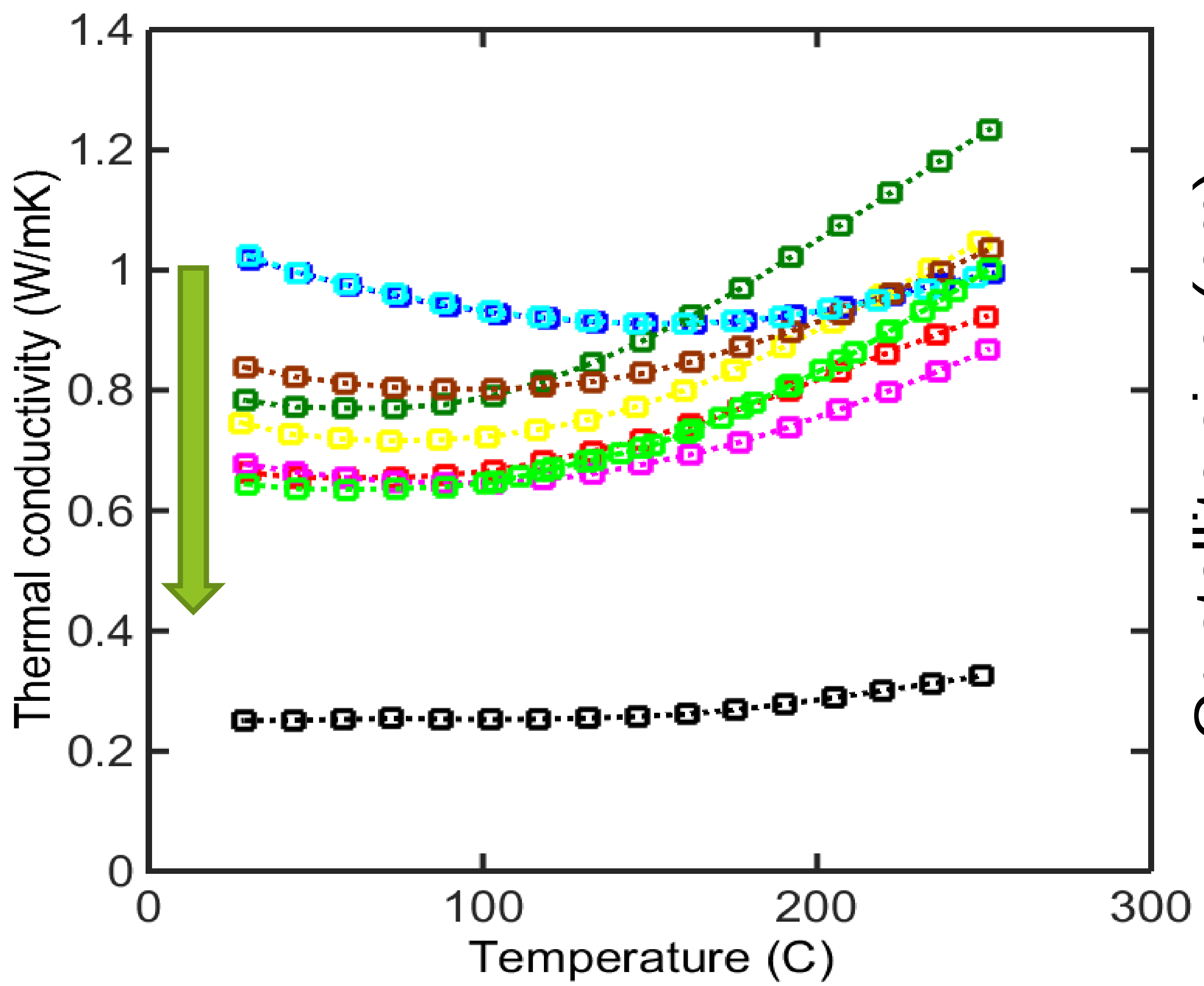
nanocomposite

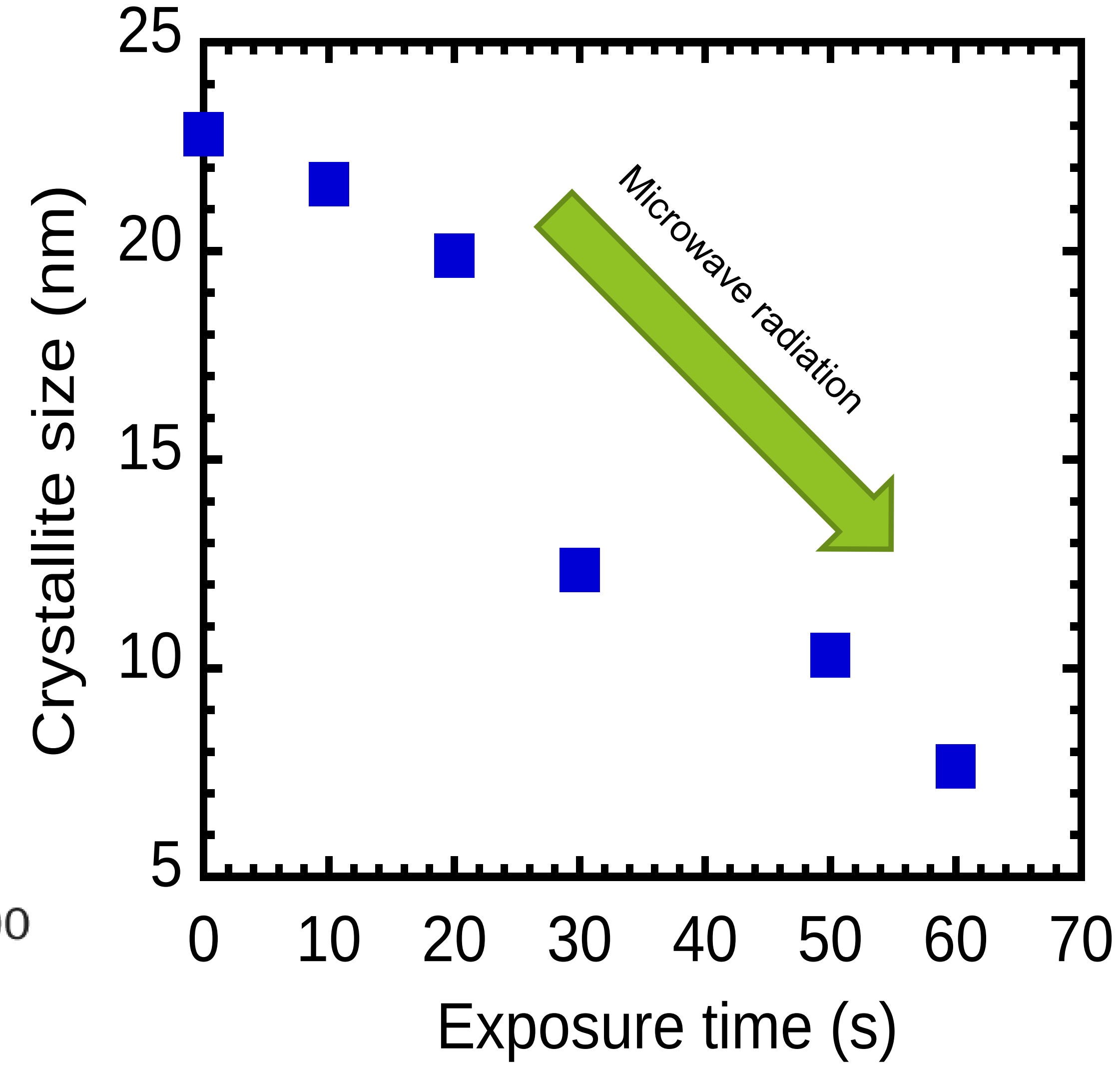
P-type $Bi_{0.5}Sb_{1.5}Te_3$ Nanocomposites



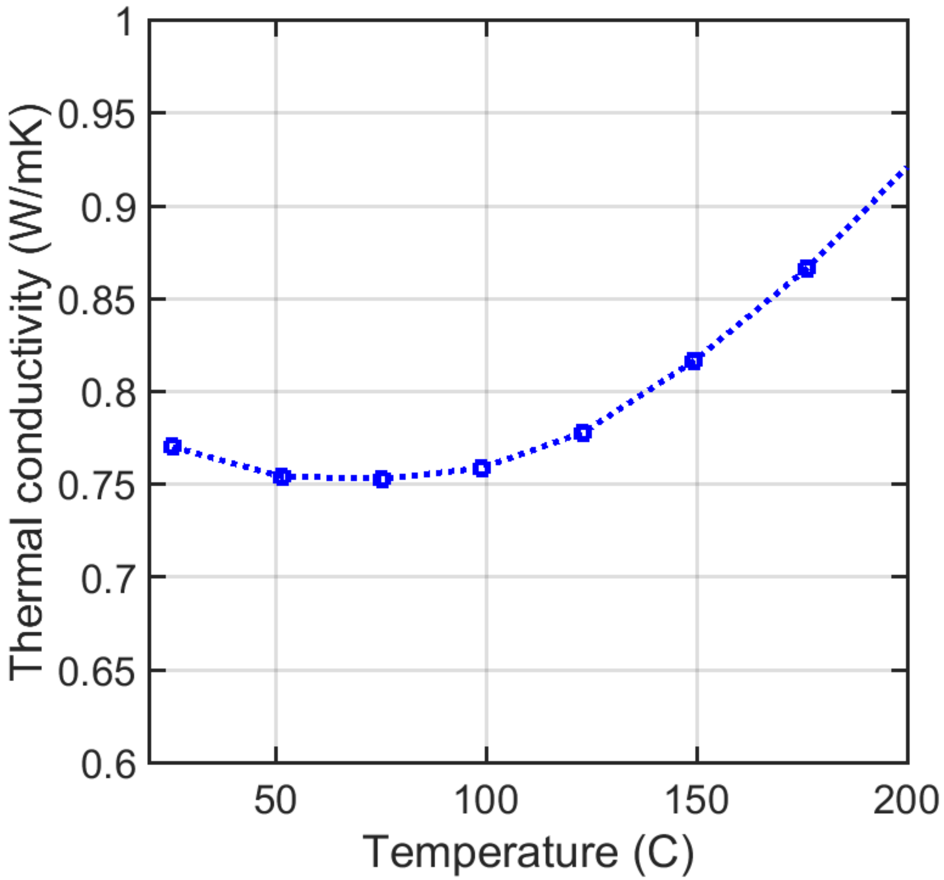


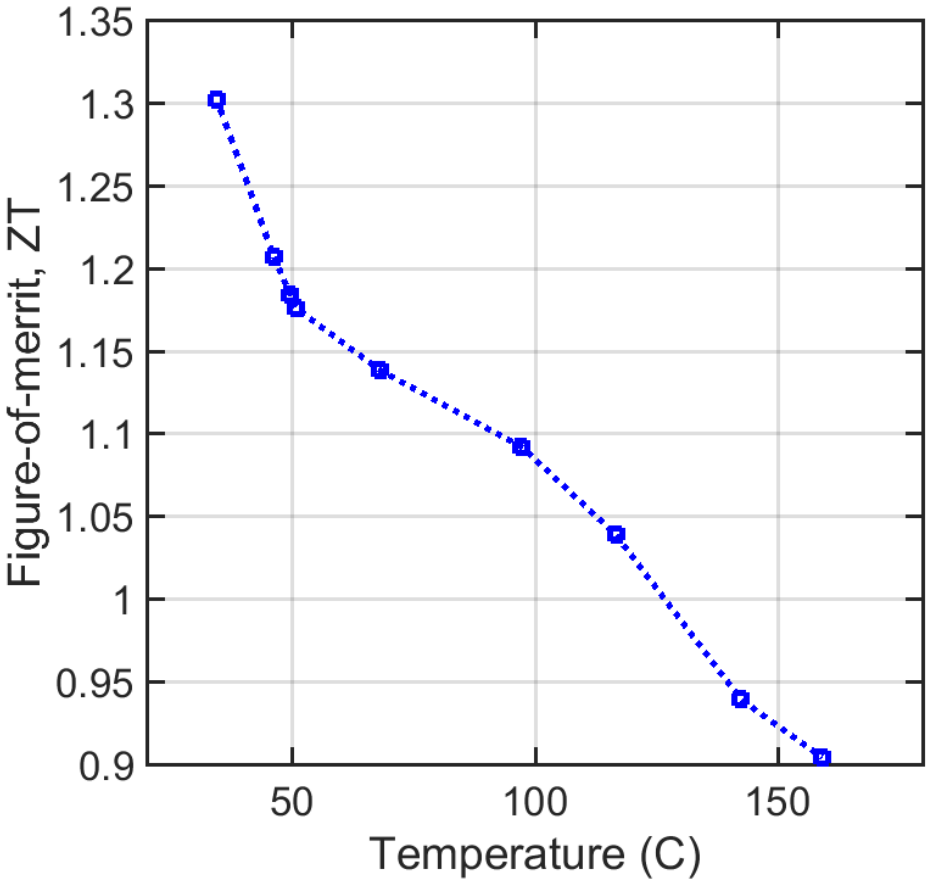
Thermal Conductivity Reduction





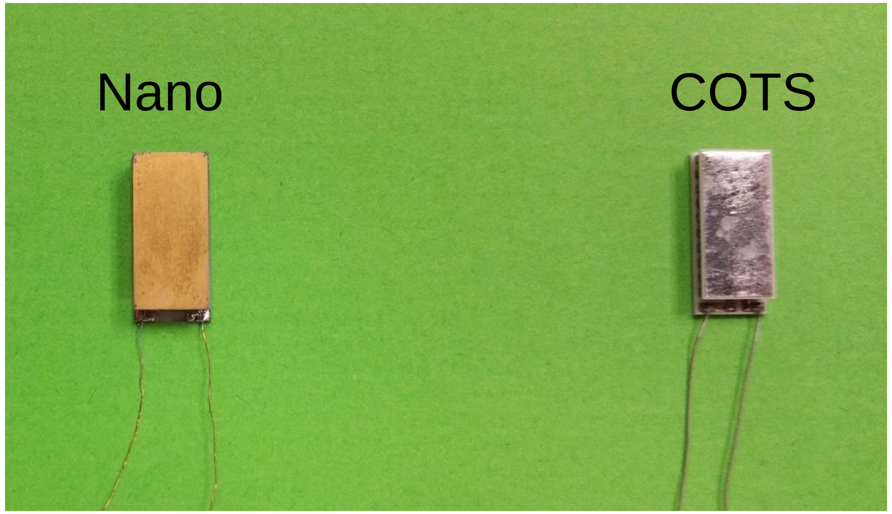
Optimized Material for Body Harvesting





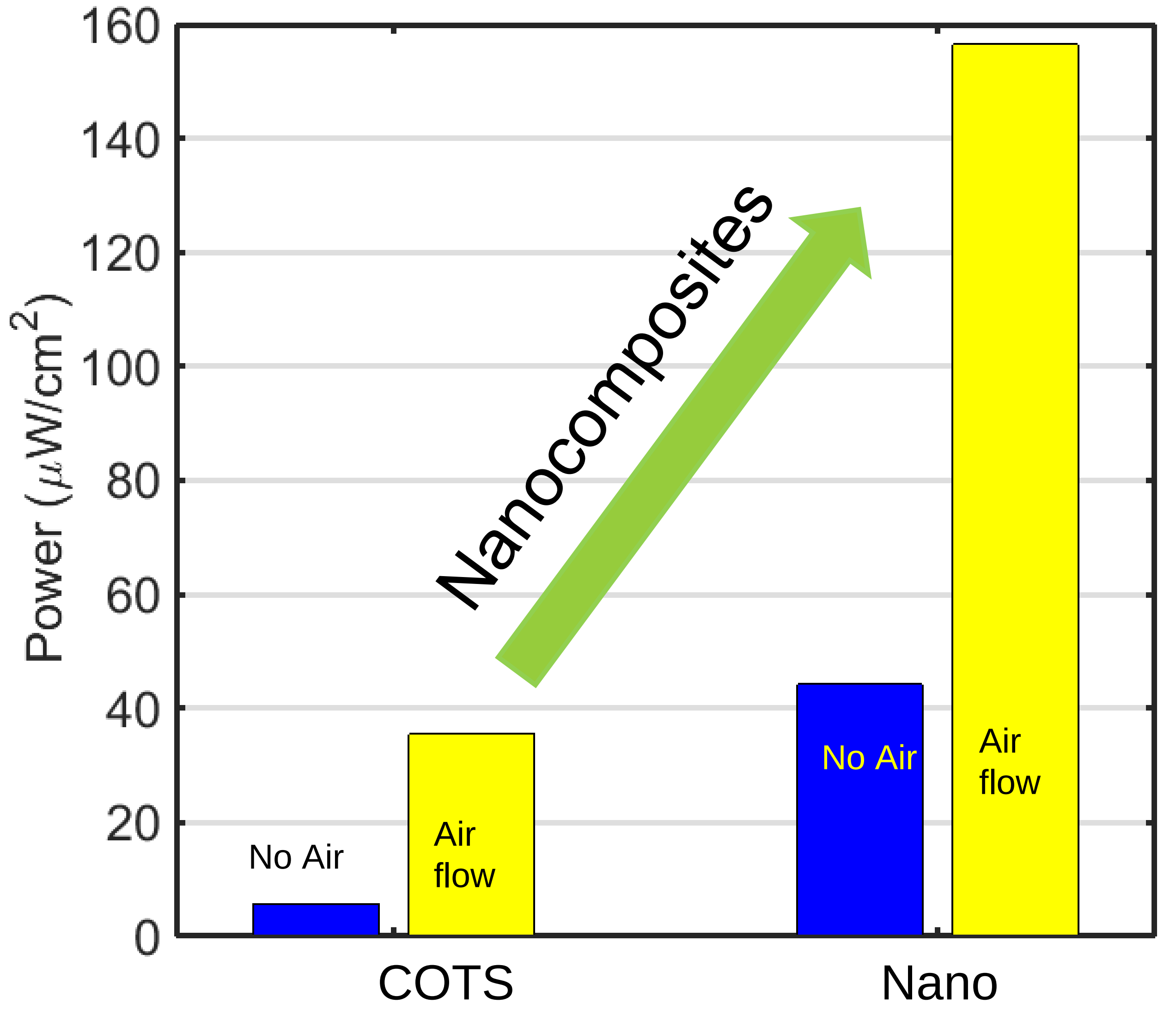
While ZT = 1.6 is possible, we prefer to compromise on ZT for a lower thermal conductivity

Comparison with Commercial TE Devices



	V_{oc} (mV/cm^2)	I_{sc} (mA/cm^2)	P_{out} (µW/cm^2)	
COTS	18.4	1.5	5.7	No airflow
COTS	52.9	3.2	35.5	With Airflow
Nano	49.7	3.9	**44.2**	No airflow
Nano	97.4	7.1	**156.5**	With Airflow

Used 14.3 cm^2 spreader on both sides.

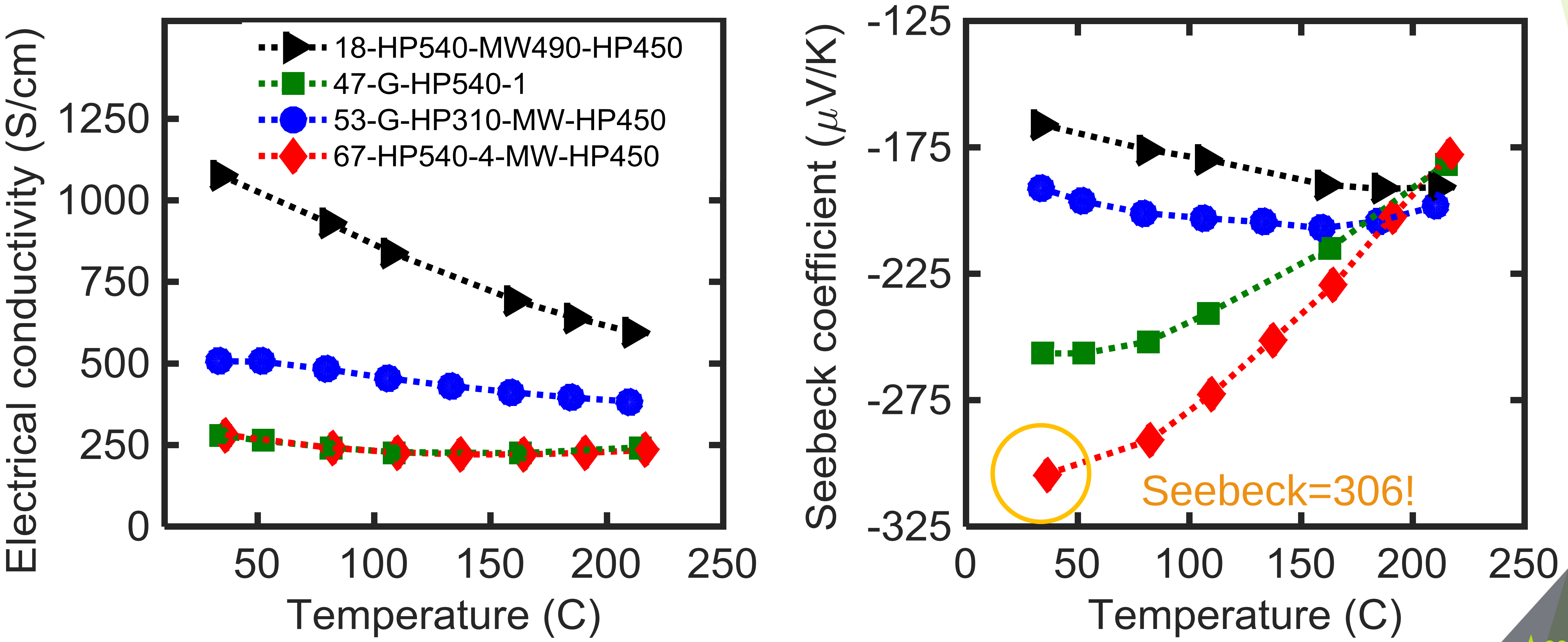


Suarez et al., Energy & Environmental Science, 2016, DOI: 10.1039/C6EE00456C

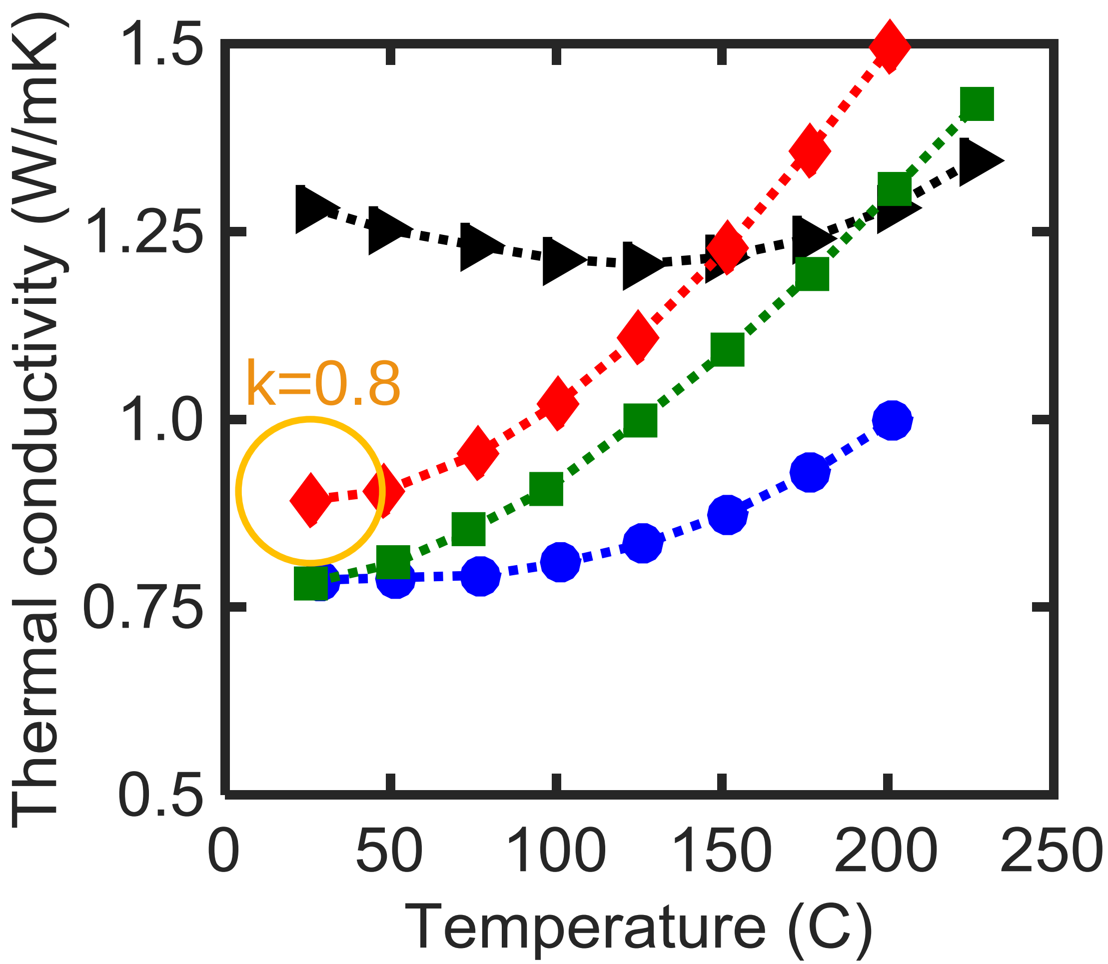
N-type Bi_2Te_3 Nanocomposites

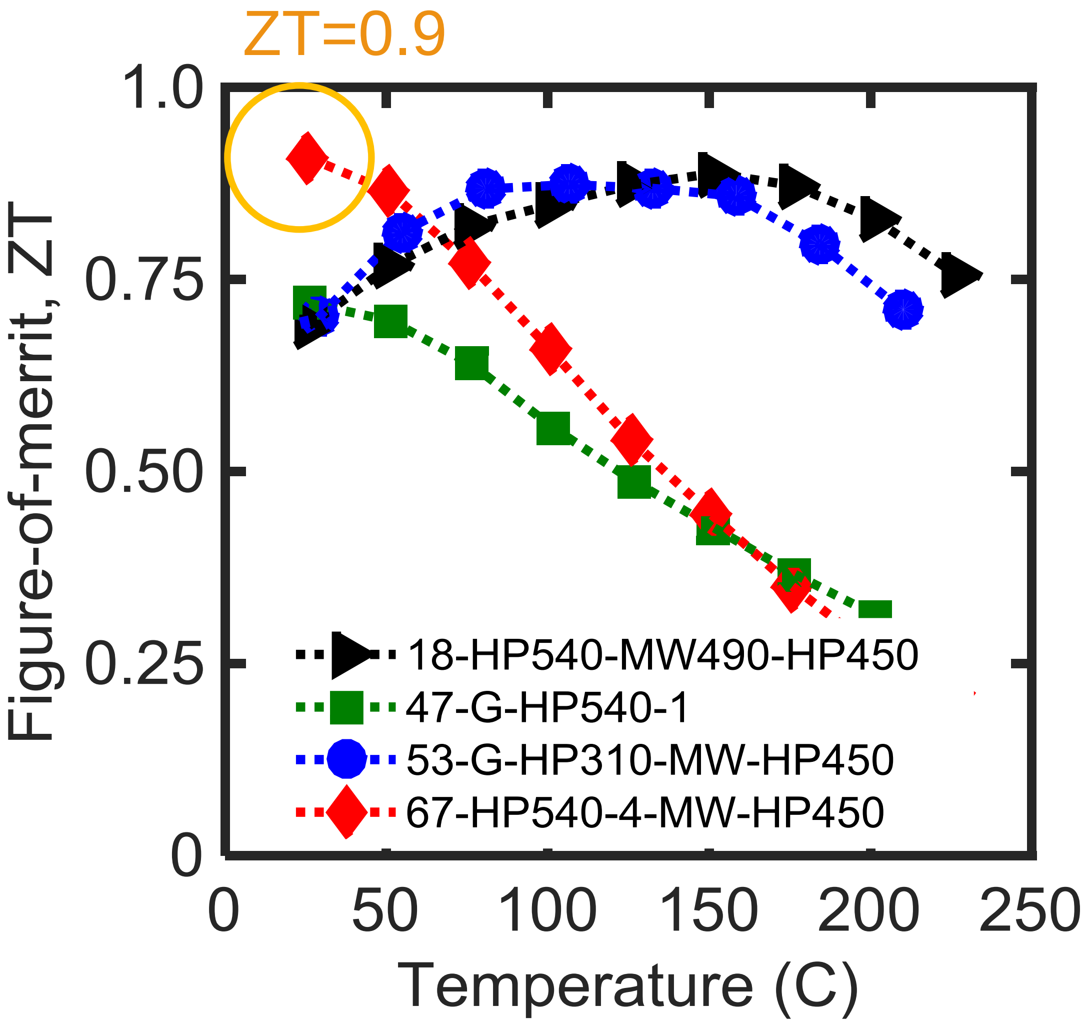
- Doping Optimization
- Optimize sintering parameters
  - Press temperature, pressure, soak time
- Glass Inclusions
  - Sintering aid, reduced thermal conductivity
- Microwave Assisted Decrystallization
- Annealing Optimization
  - ~ 200oC for 40 hrs – to improve electrical conductivity

Comparison of Our Best N-type Samples So Far

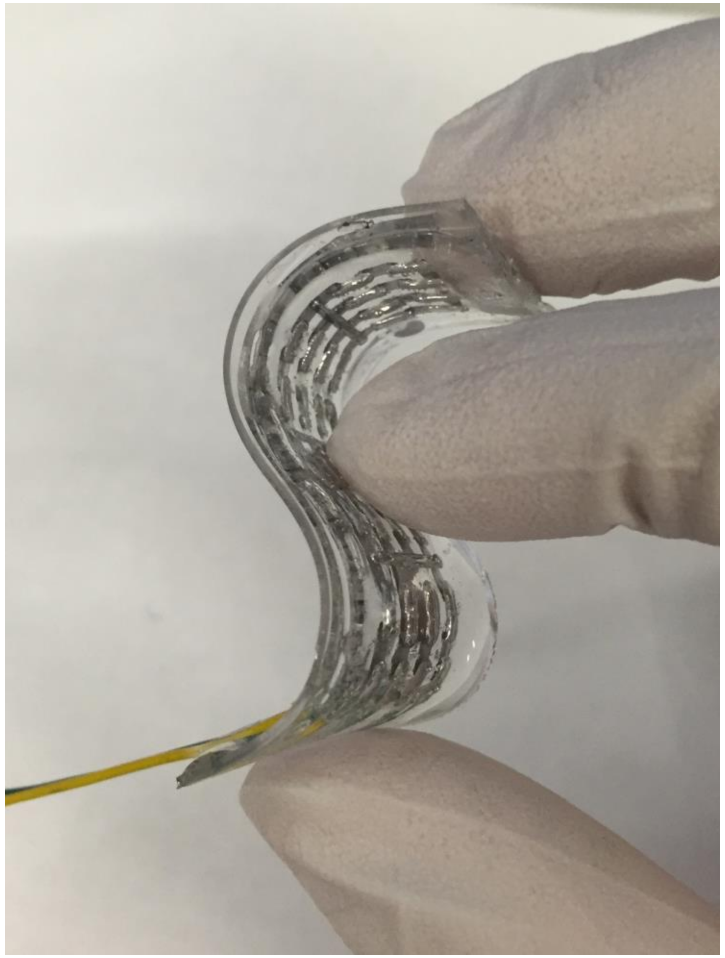


Comparison of Our Best N-type Samples So Far





Our approach to Flexible Thermoelectrics



- Bulk thermoelectric materials
  - BiTe Nanocomposites ✓
  - Pick-and-Place Tooling
- Flexible packaging – New Materials
  - Optimized elastomers
  - Stretchable interconnects

ASSIST

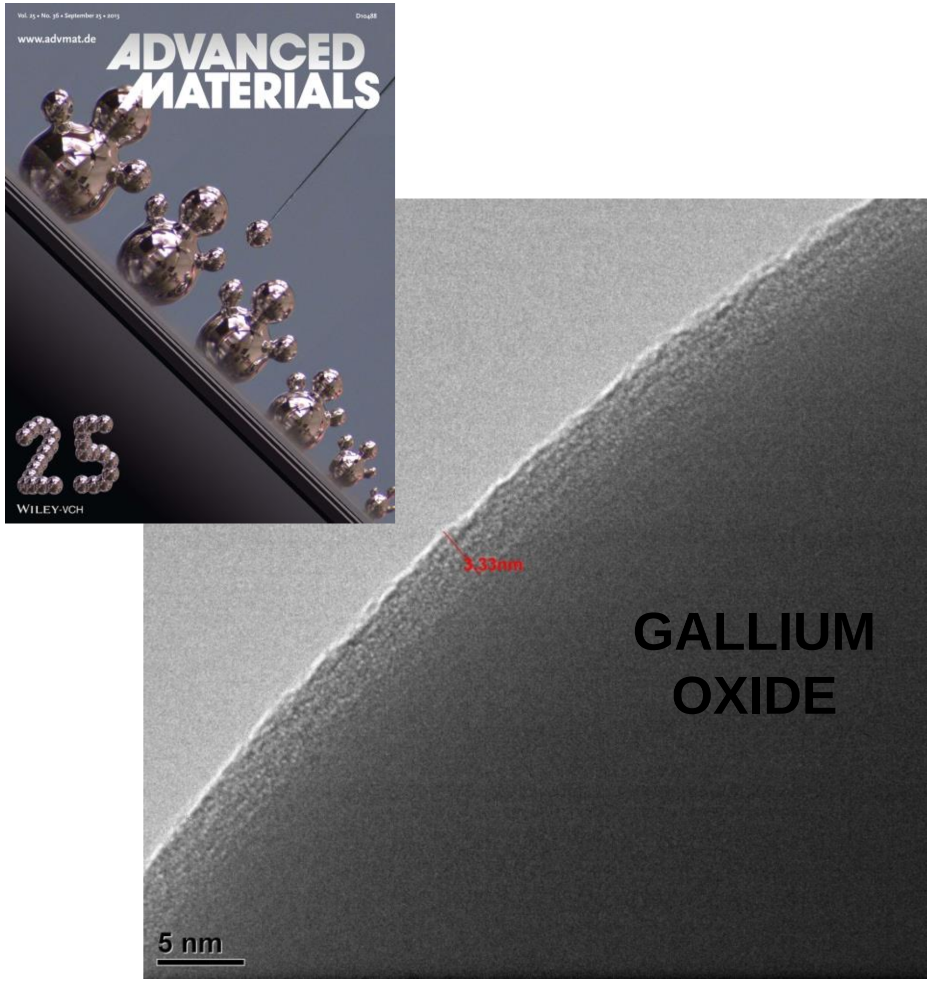
Eutectic Gallium Indium (EGaIn)

Gallium		Indium		Liquid
	+		=	
Melting point: **30 °C**		**157 °C**		**16 °C**

Properties:

- Water-like viscosity
- Low toxicity
- Near-zero vapor pressure

Stretchable EGaIn Interconnects

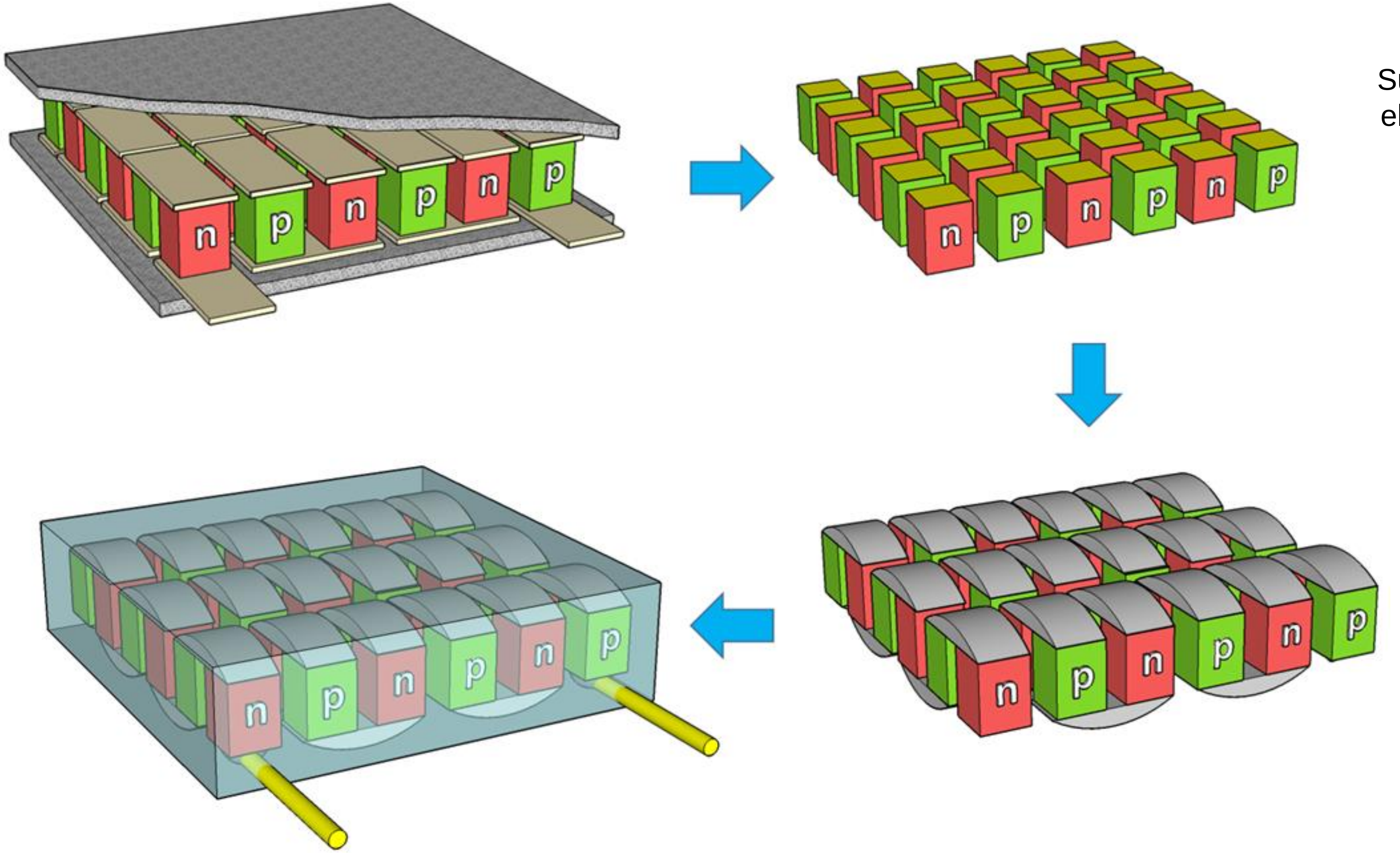


- Behavior dominated by a skin oxide
- Can be encapsulated by an elastomer

TEGs with EGaIn Interconnects

Conventional TEG

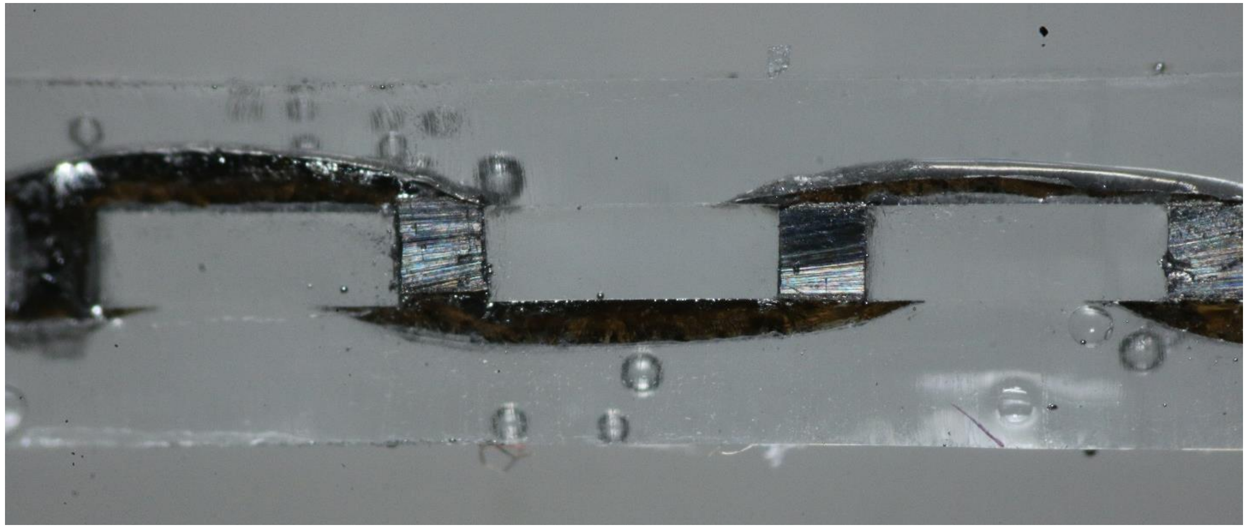
Substrates eliminated

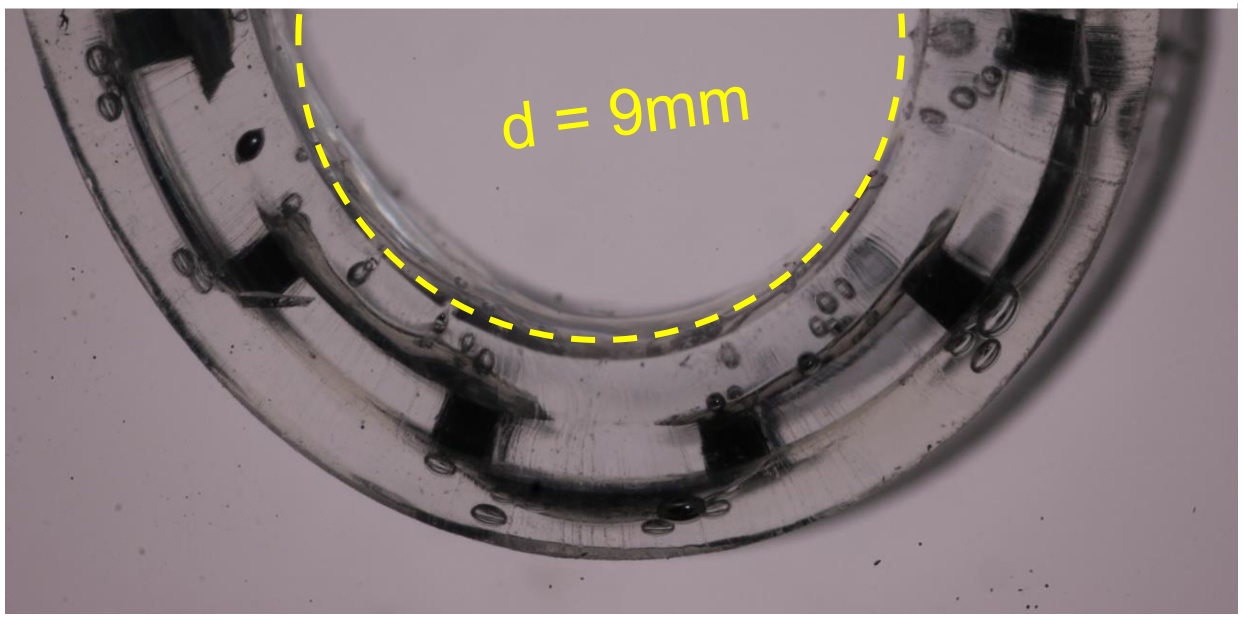


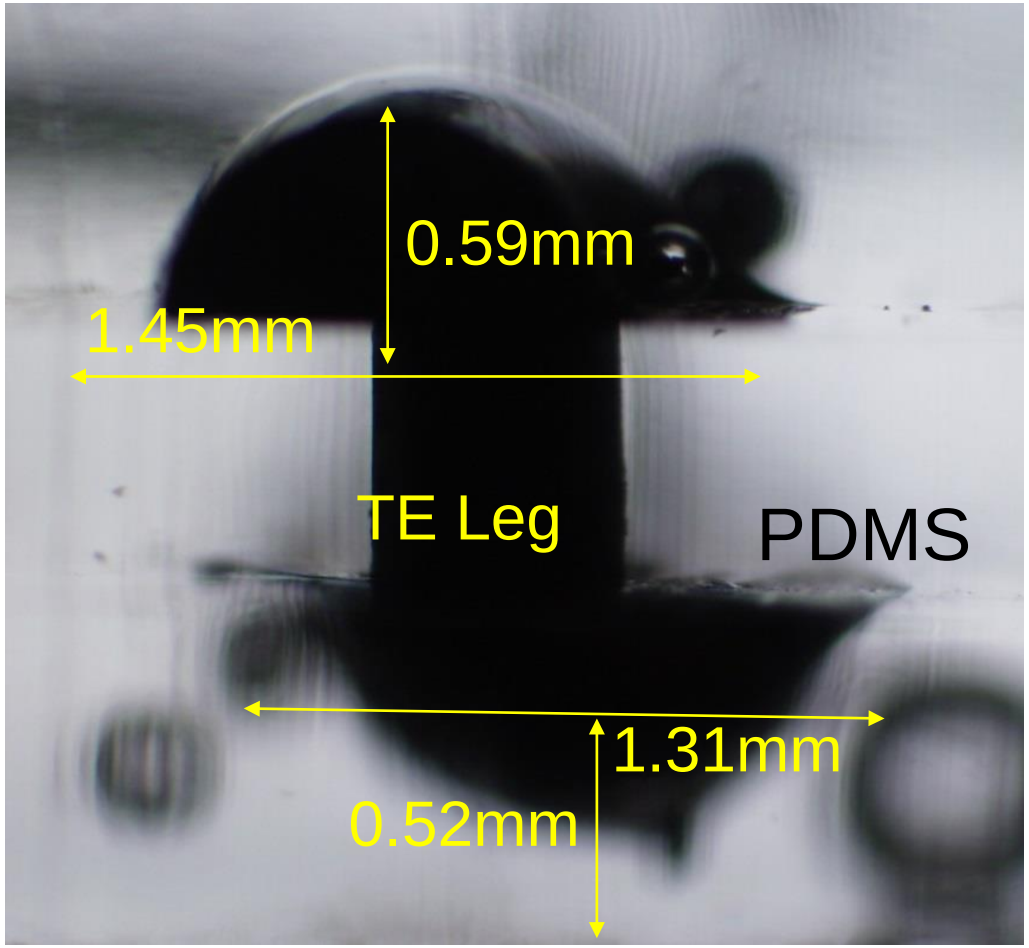
PDMS Encapsulation

Liquid Metal Interconnects

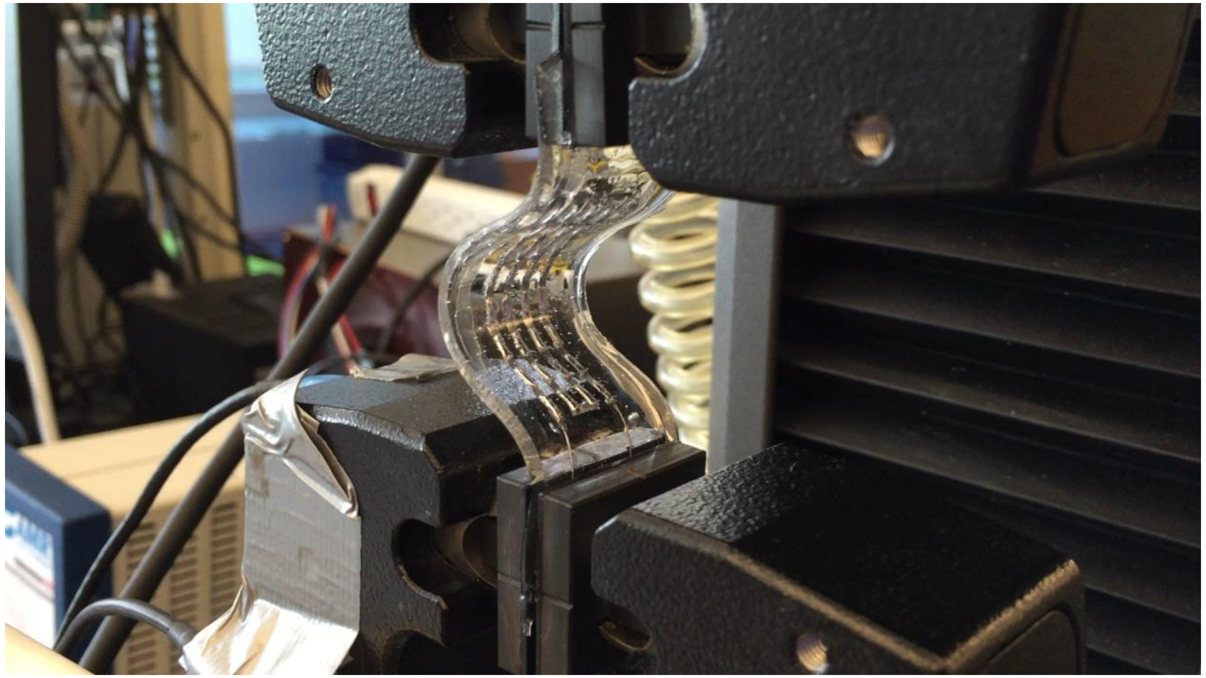
Stretchable interconnect: EGaIn

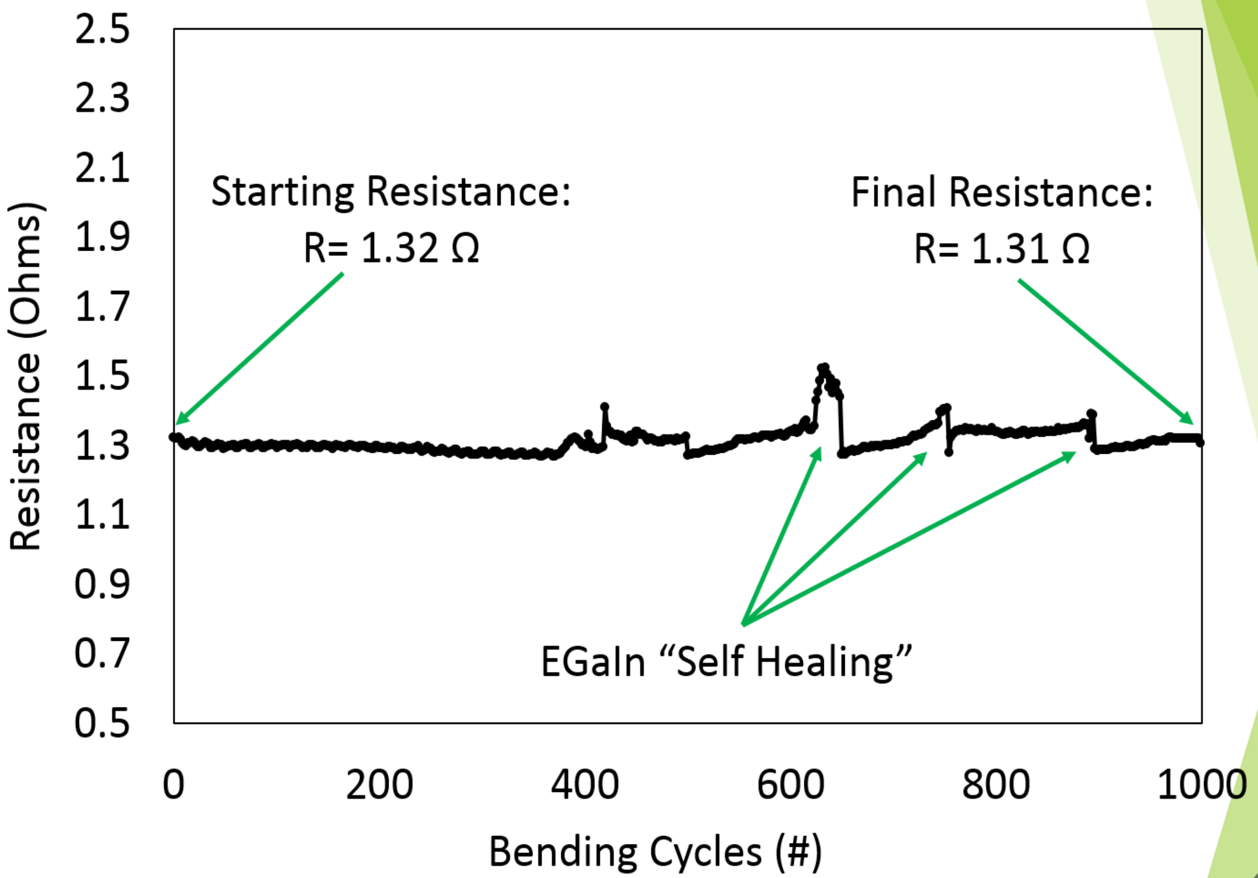






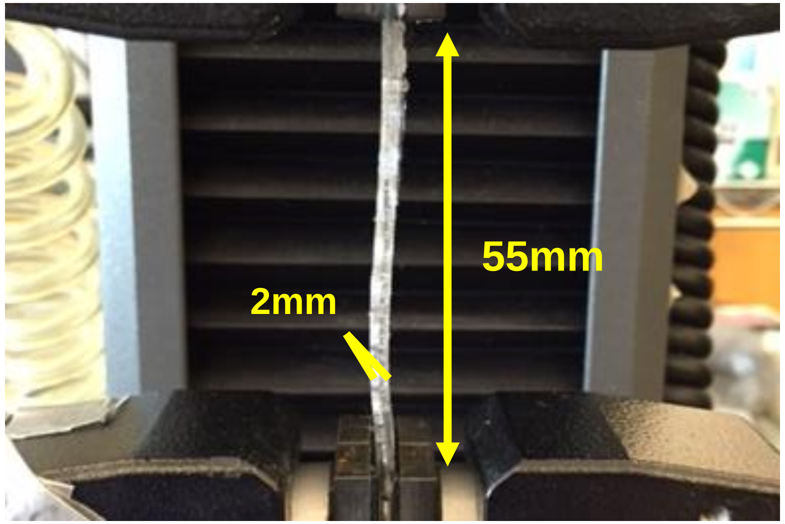
Mechanical Testing

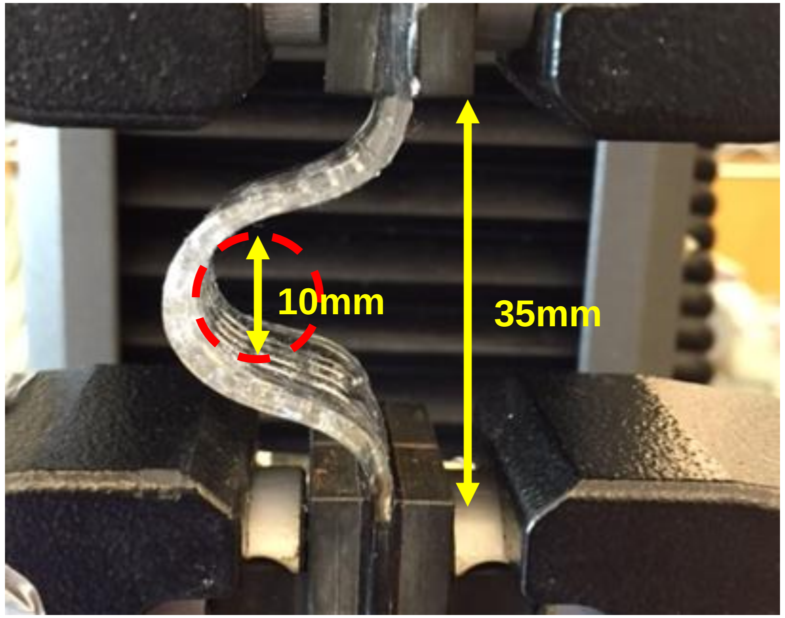




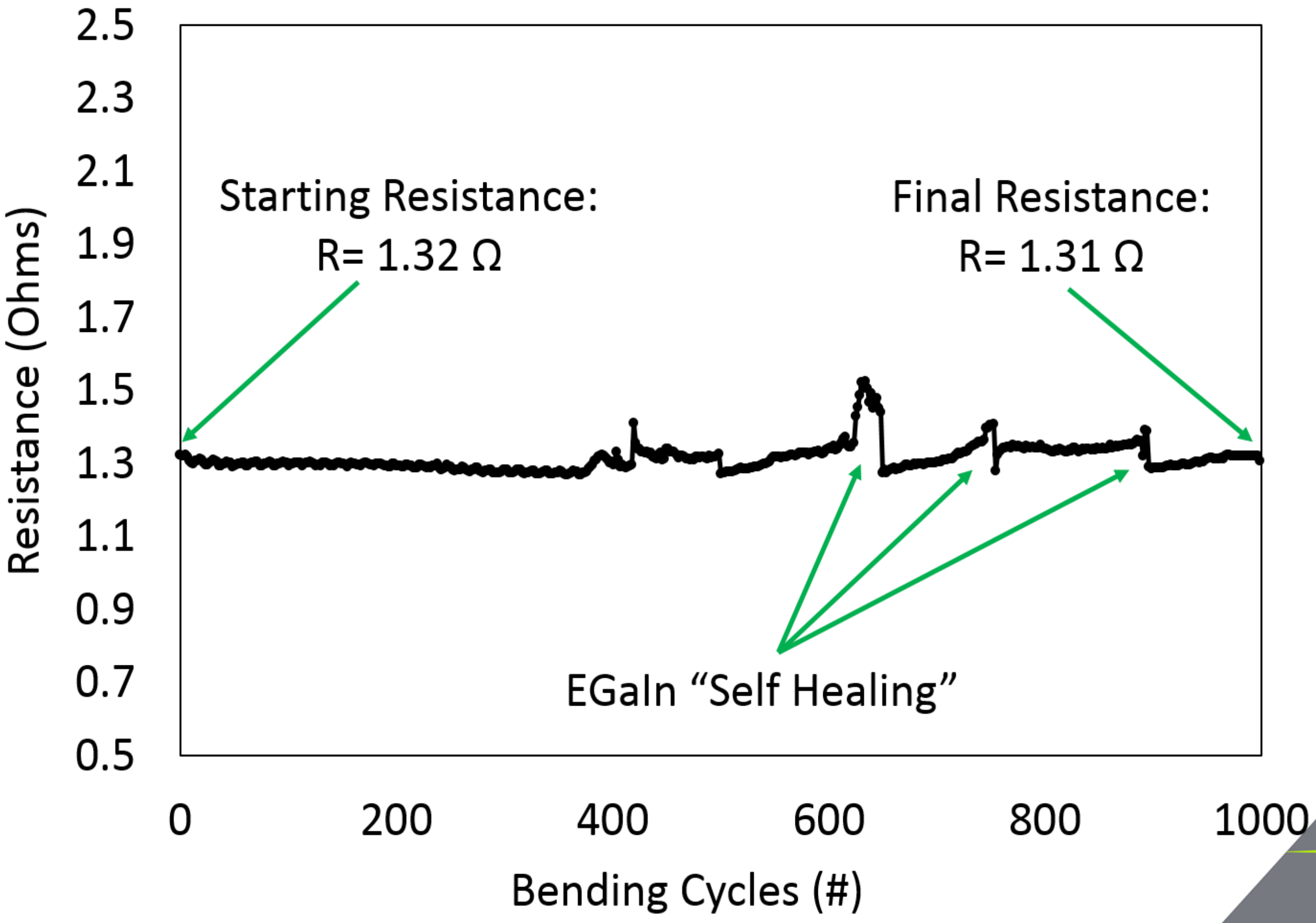
- Low Resistance – negligible contribution from interconnects
- Spikes recovered due to "self-healing" nature of EGaIn

Mechanical Testing

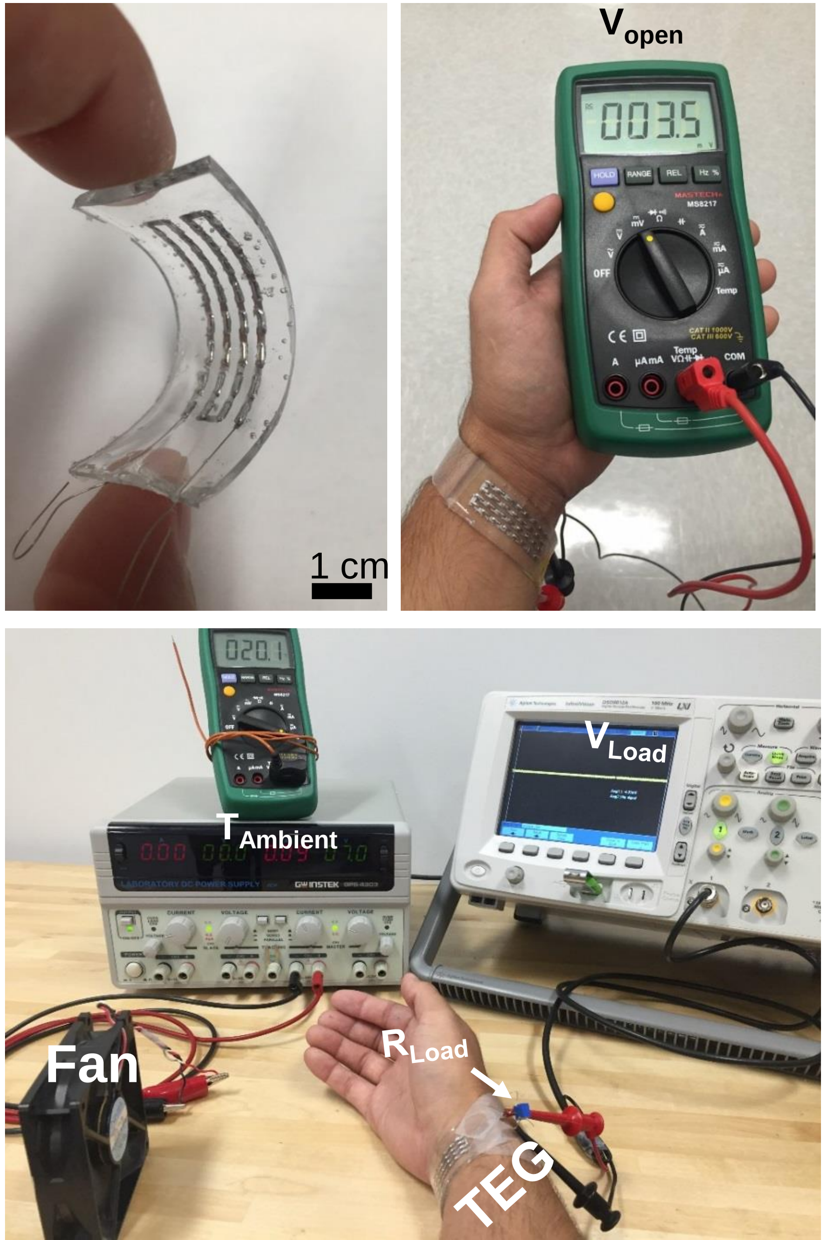




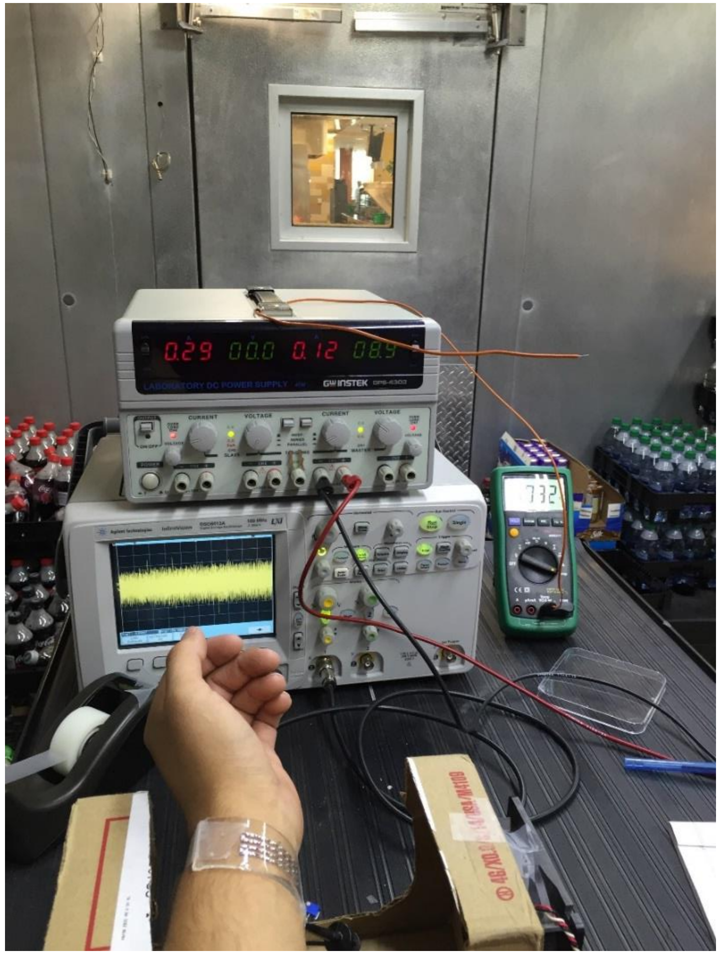
- Low Resistance – negligible contribution from interconnects
- Spikes recovered due to "self-healing" nature of EGaIn



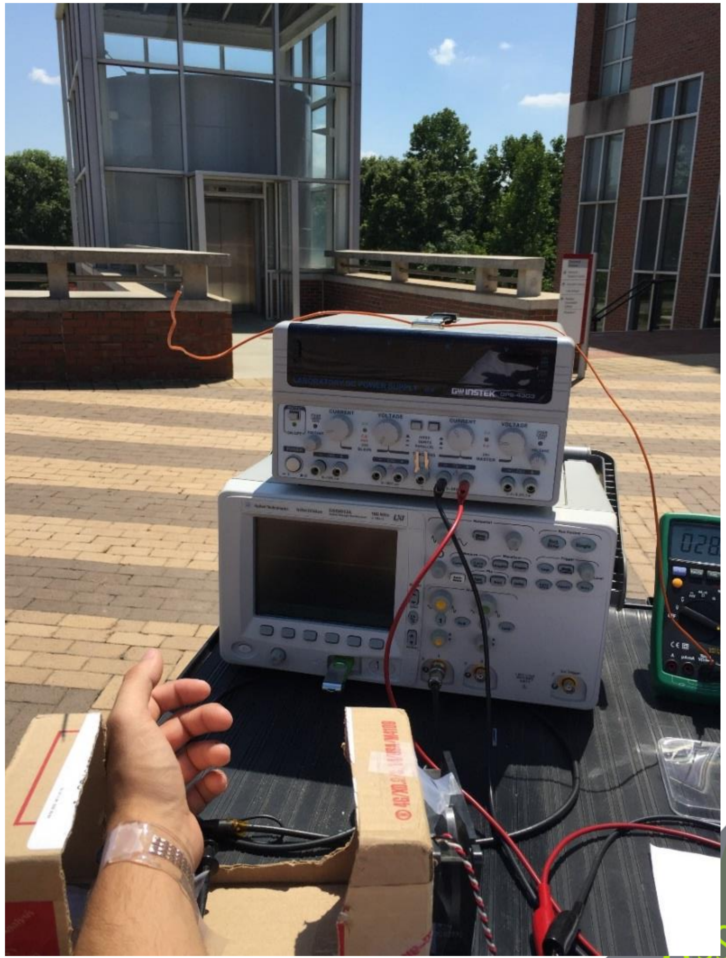
Testing Flexible TEG



TEG tested on the wrist at 3 distinct temperatures:
35 , 24 and 5°C

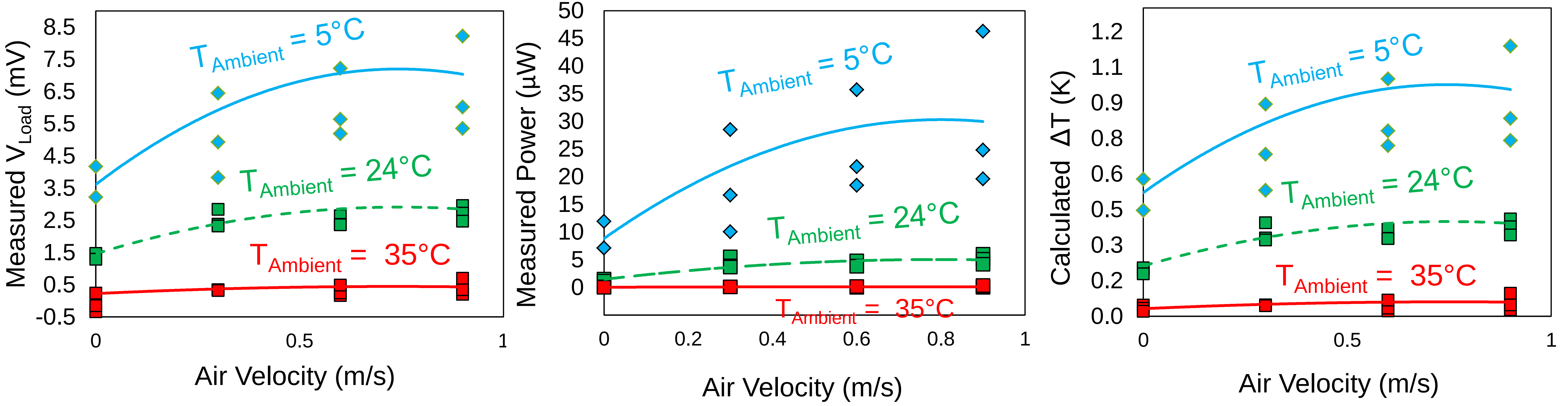


(5°C)



(35°C)

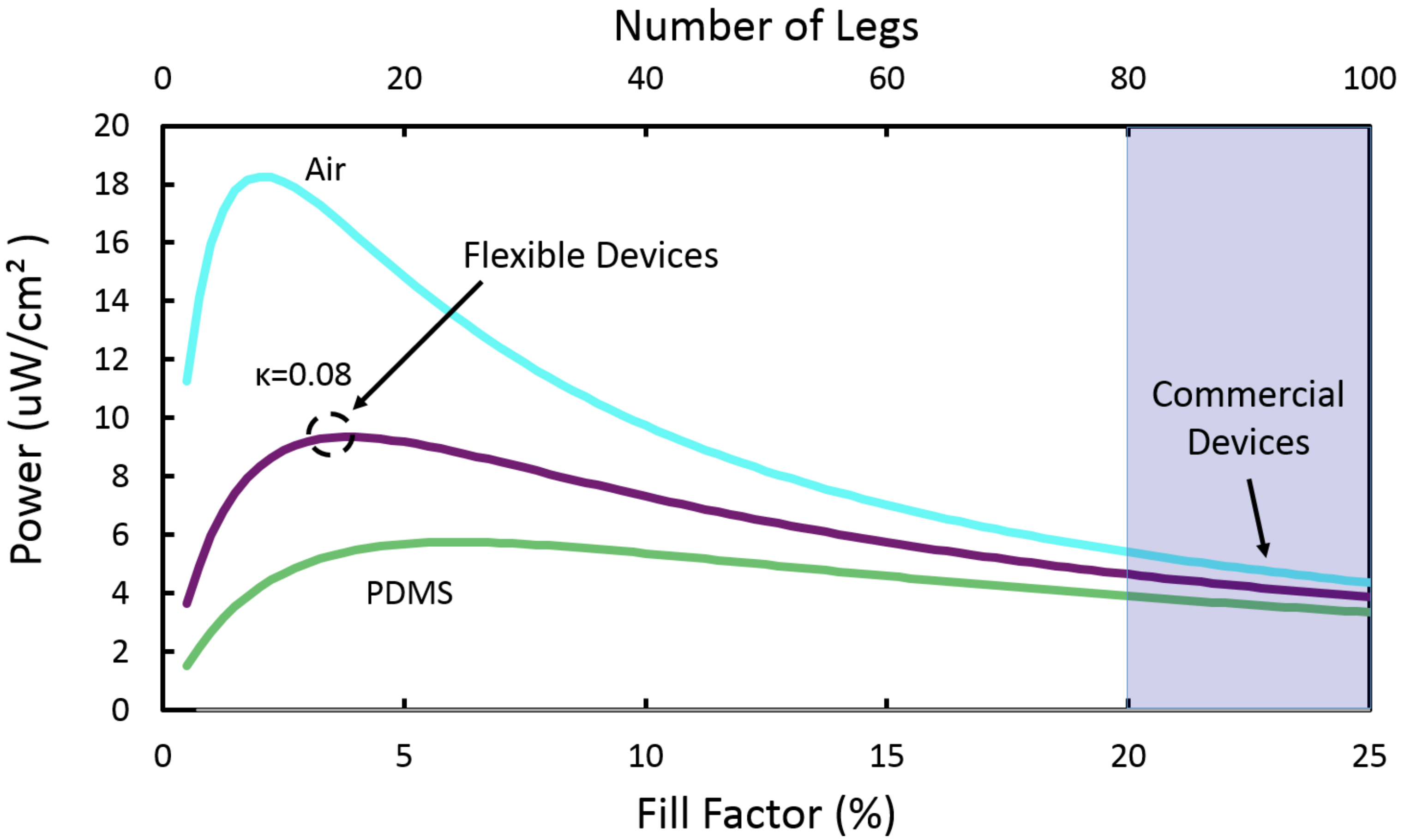
Testing Flexible TEG



- The performance is expected to improve significantly with
  - Stretchable heatsinks
  - Metal spreaders
  - Thinner EGaIn encapsulation
  - Lower thermal conductivity filler

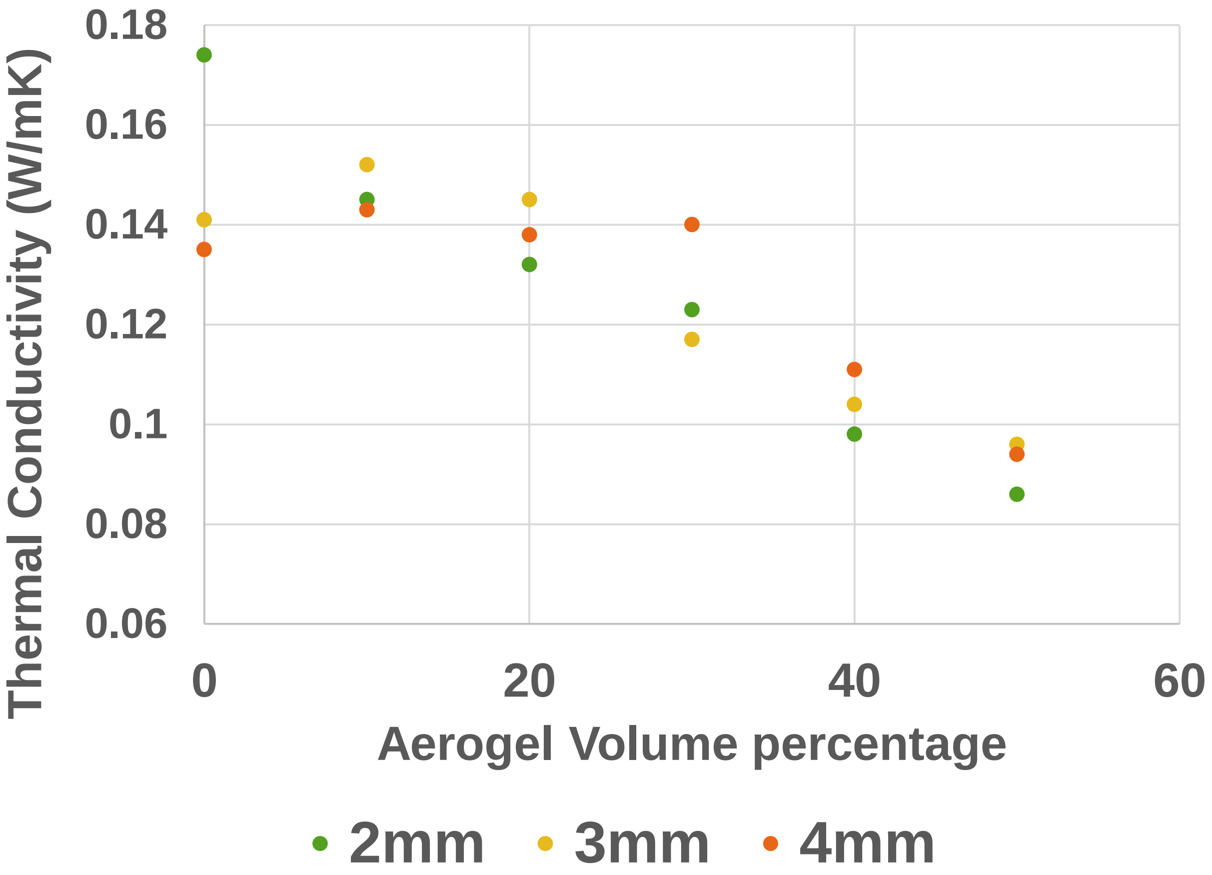
SSIST

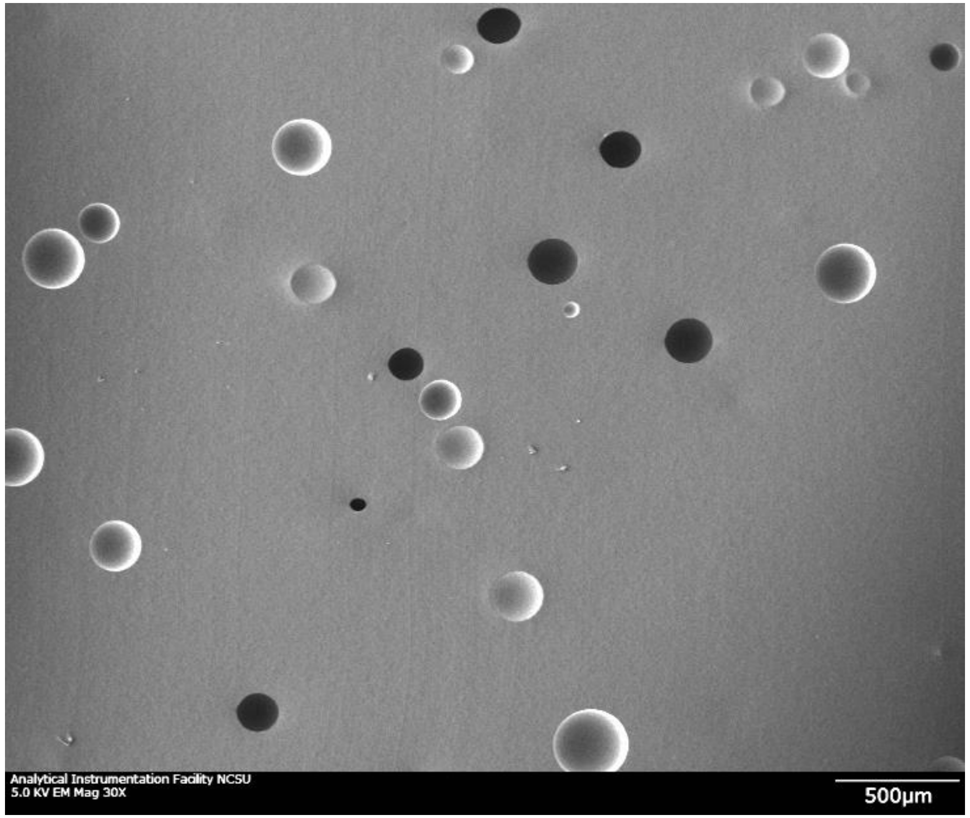
Impact of the Filler Material



Reducing the thermal conductivity of the filler material can be instrumental in producing flexible TEGs

Aerogel Doped PDMS





Significant reduction in elastomer thermal conductivity is possible via aerogel doping

Conclusions

- Low thermal conductivity may be more important than ZT for body worn thermoelectric devices
- Microwave sintering can be used to produce nanocomposites
- EGaIn provides a low-resistivity, stretchable interconnect
- Improved device packaging and materials have the potential to yield flexible TEGs comparable to or better than their rigid counterparts