Flexible thermoelectric energy harvesters using bulk thermoelectric materials and low-resistivity liquid metal interconnects

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Advanced Self-Powered Systems of Integrated Sensors and Technologies

(ASSIST) Nanosystems Engineering Research Center

ASSIST vision

Long-term monitoring of personal health & environment enabled by always-on platforms

ASSIST's vision of health and wellness is enabled by its disruptive system features

Motion - Piezoelectric

Heat - Thermoelectric

- Self-Powered/Ultra Low Power
- Wireless
- Hassle-Free/Comfortable
- Medically Validated
- Non-invasive/minimally invasive
- Multi-modal health and environmental sensors

Sophisticated picture of health via correlation of multiple sensors

Enable a pathway towards personalized medicine

ASSIST Roadmap

Health and Environmental Tracker

HET 1


Asthma Management

Long term monitoring of environmental exposures & health

ASSIST Low-Power Sensor Technologies

Ozone | VOC | PPG | ECG

Detection
Wheeze / Cough

Critical Data Correlation
Ozone / Respiratory & Cardiac Health

HET 2

Diet Management & Wound Healing

Non-Invasive Glucose/Lactate & Wound Health Monitoring

ASSIST Zero-Power Extraction and Transportation Technologies

Sweat | ISF | Wound Fluid

ASSIST Low-Power Detection Technologies

Glucose | Lactate | Uric Acid
pH | Breathable Materials

Critical Data Correlation
Food Intake - Glucose / Lactate Levels & Uric Acid - Wound Health

HET 3


Medication Adherence

Non-Invasive Medication Detection

ASSIST Zero-Power Extraction and Transportation Technologies

Sweat | ISF

ASSIST Low-Power Detection Technologies

Monitoring of Medication Intake

Critical Data Correlation
Medication Intake & Physiological Parameters from HET 1.0 & 2.0

Self-Powered Adaptive Platform

SAP 1

Cardiac Health

Vigilant ECG (R-R) and Motion

ASSIST Energy Harvesting and Low-Power Circuit Technologies

Energy Harvesting | Supercapacitors
SoC & Radio | ECG AFE

Critical Data Correlation
A-Fib and Activity Identification Optimized for Low-Power

SAP 2


Cardiac Health, Blood Pressure & Asthma

SAP 1.0 + HET 1.0

ASSIST Energy Harvesting, Sensor & Low-Power CircuitTechnologies

Energy Harvesting | Ozone
PPG | ECG | VOC

Critical Data Correlation
HET 1.0 and Pulsed Transit Time Blood Pressure

SAP 3


Cardio-Metabolic Health

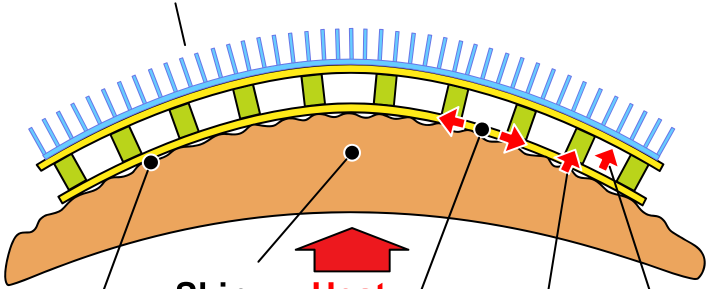
SAP 2.0 + HET 2.0

ASSIST Energy Harvesting, Sensor & Low-Power CircuitTechnologies

Energy Harvesting | VOC | Ozone | BP
Biomarkers < Sweat/ISF | ECG | PPG

Critical Data Correlation
Metabolic Changes & Cardiac Health

Harvesting Heat from the Body

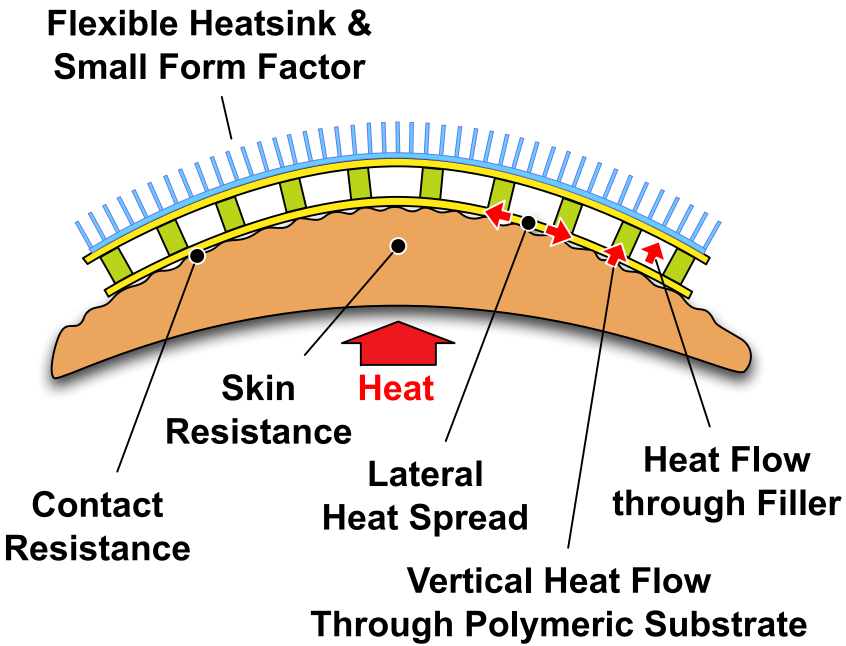


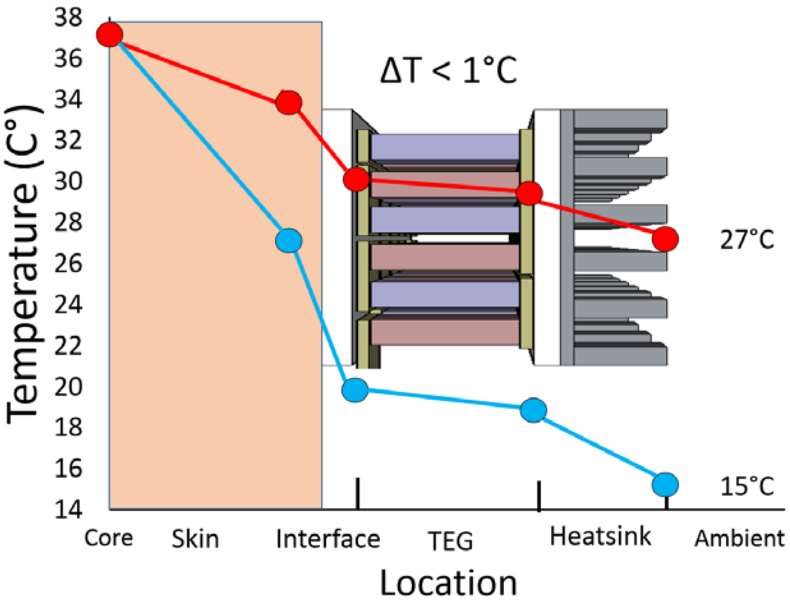
Flexible thermoelectric generators (TEGs) are desirable:

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

The application imposes large thermal resistances

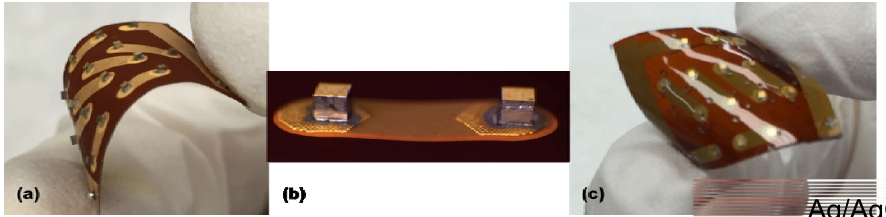
Harvesting Heat from the Body



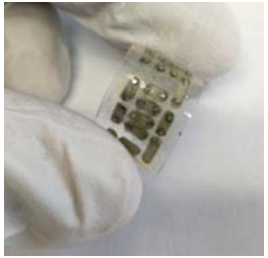


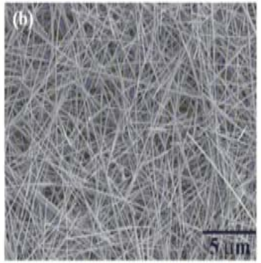
Key Challenge: Small ΔT across the harvester

Our approach to Flexible Thermoelectrics

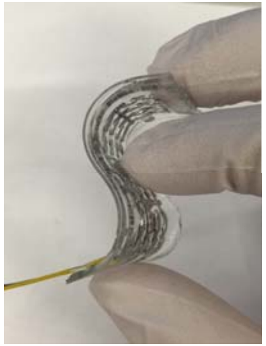


Ag/AgCl





Ag Nanowires



EGaIn

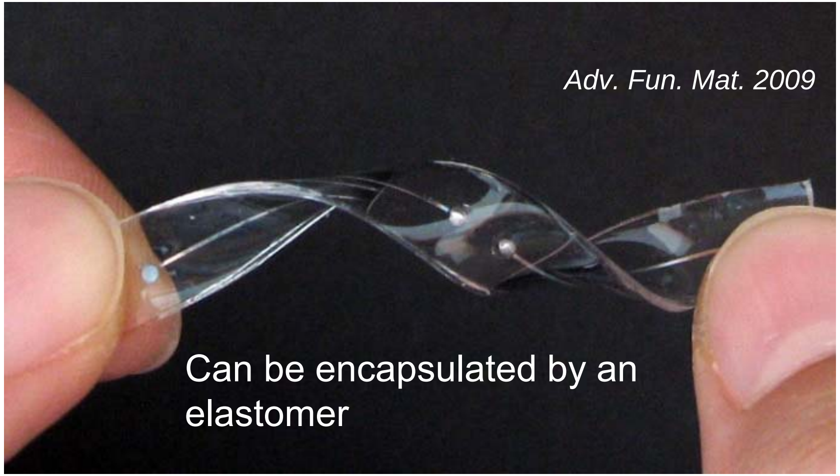
- Bulk thermoelectric materials
  - Best materials used in rigid TEGs
  - No new material development
- Pick-and-Place Tooling
  - Standard technique
- Flexible packaging
  - Material Innovations

A flexible approach with a low cost-of-ownership that can rival the performance of rigid TEGs

Eutectic Gallium Indium (EGaIn)

Gallium		Indium		Liquid
	+		=	
30 °C		157 °C		16 °C

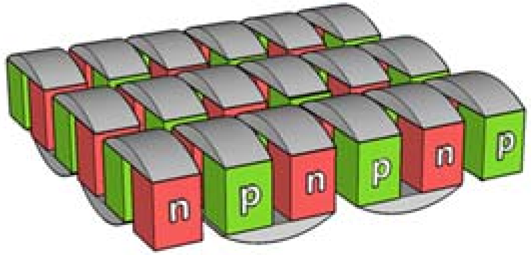
- Low viscosity
- Low toxicity
- Near-zero vapor pressure



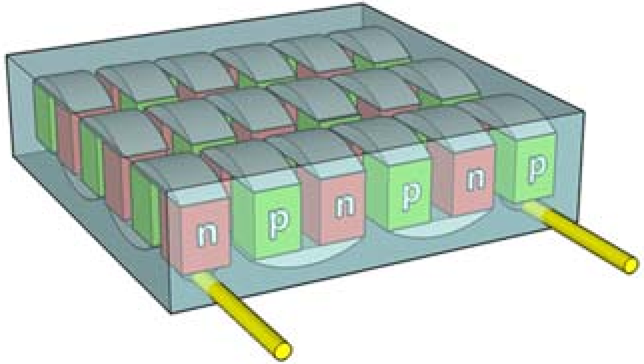
Adv. Mater. 2016

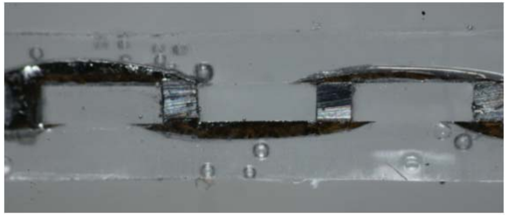
TEG Fabrication with EGaIn Interconnects

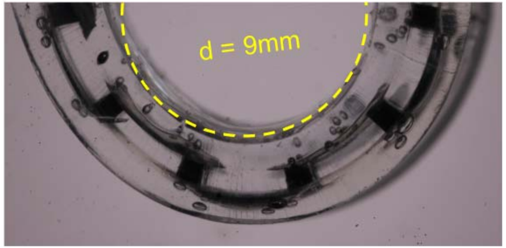
TEG with liquid interconnects

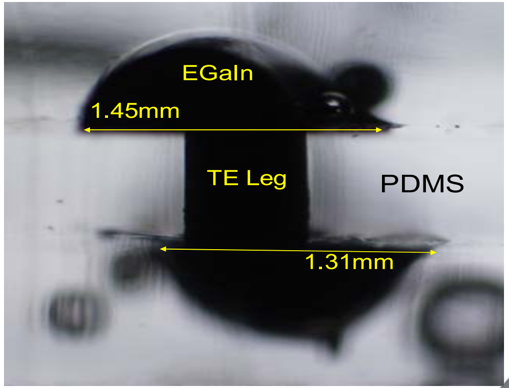


PDMS Encapsulation



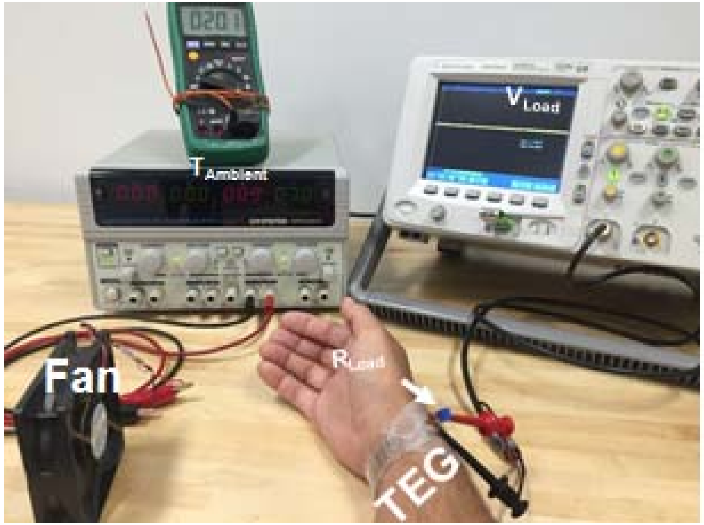


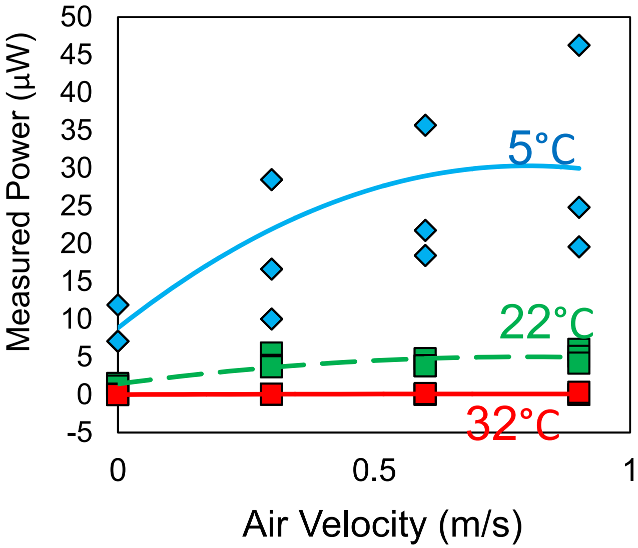


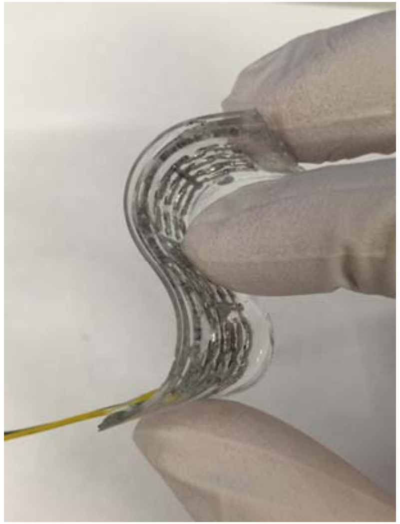


Suarez at. Al, Flexible thermoelectric generator using bulk legs and liquid metal interconnects for wearable electronics, Applied Energy, 2017

Testing on the Human Body



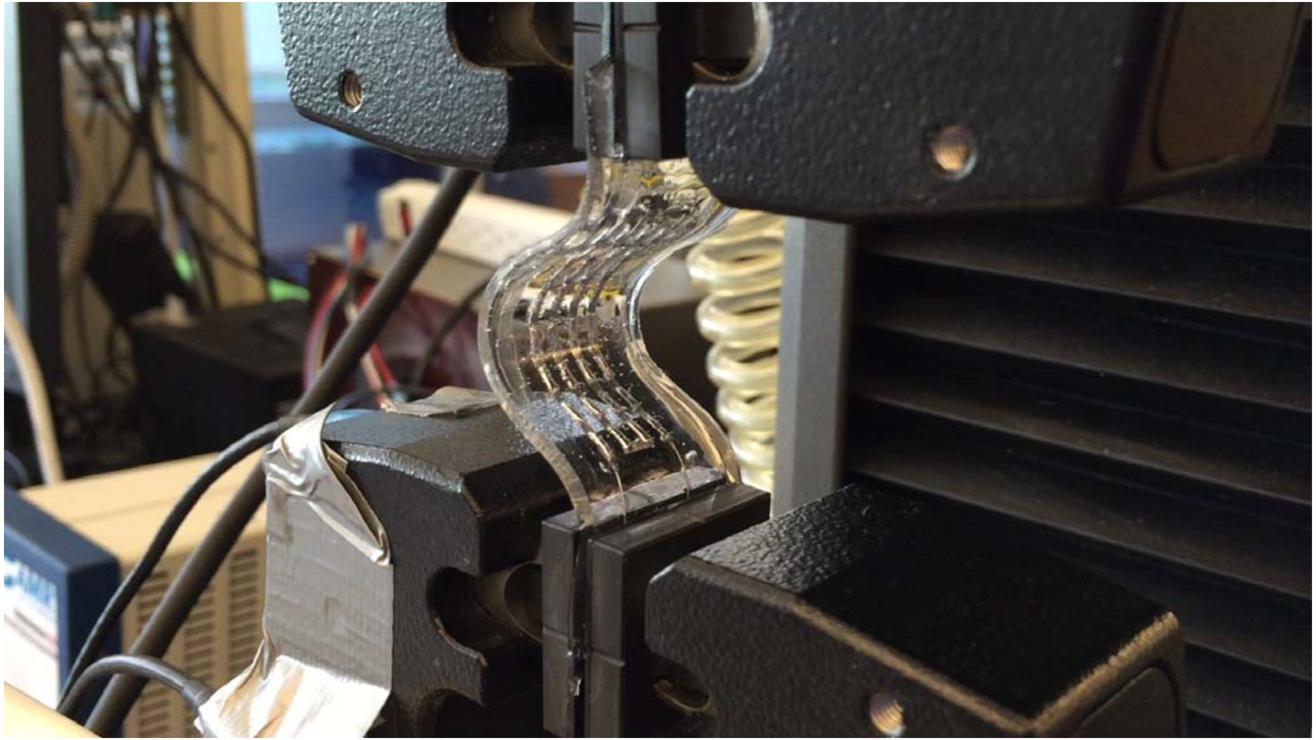




Promising performance despite

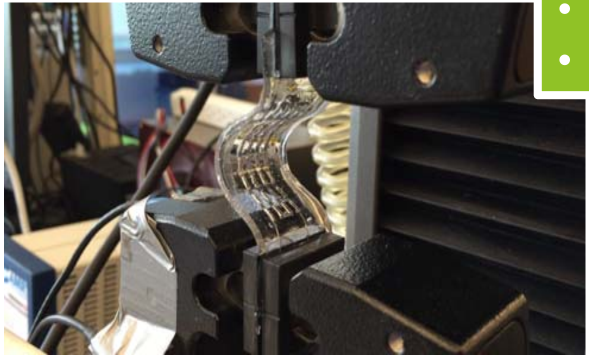
- No heat spreaders
- No heatsink
- Thick PDMS encapsulation

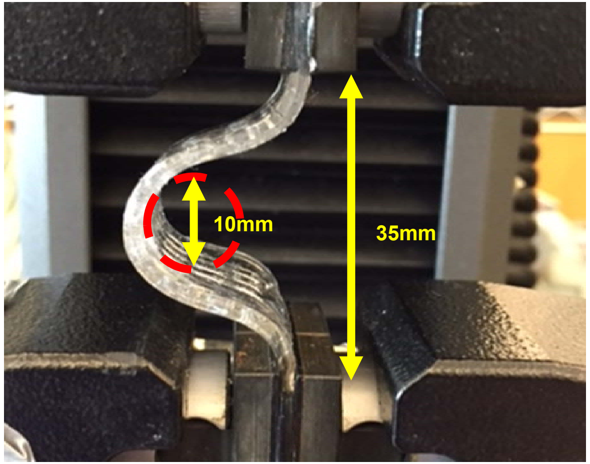
Mechanical Testing

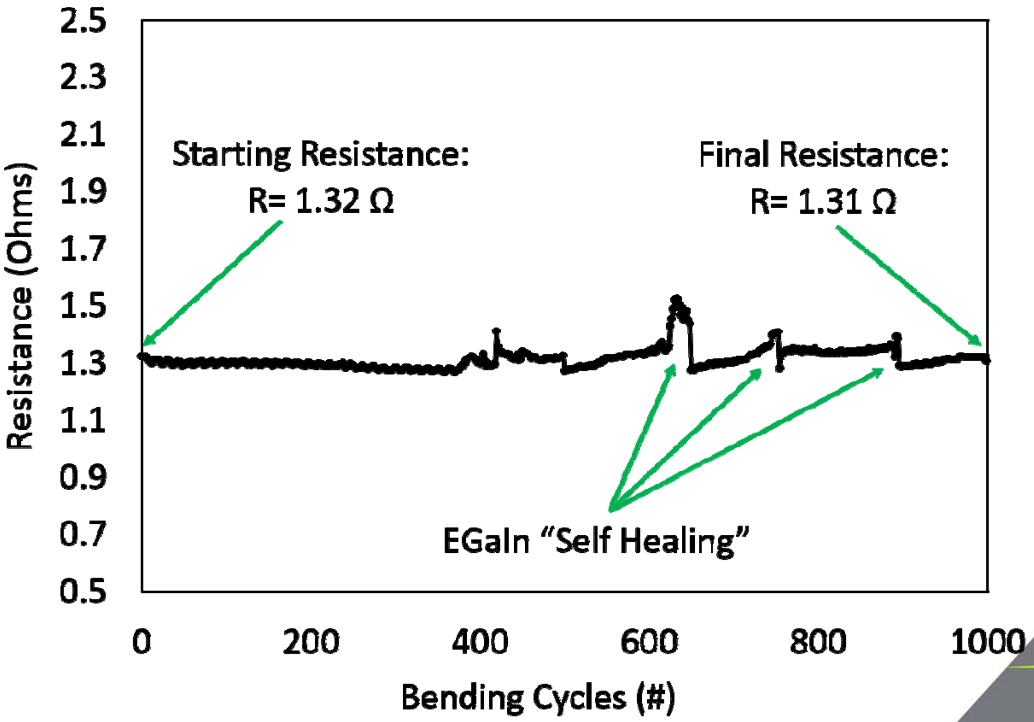


Mechanical Testing

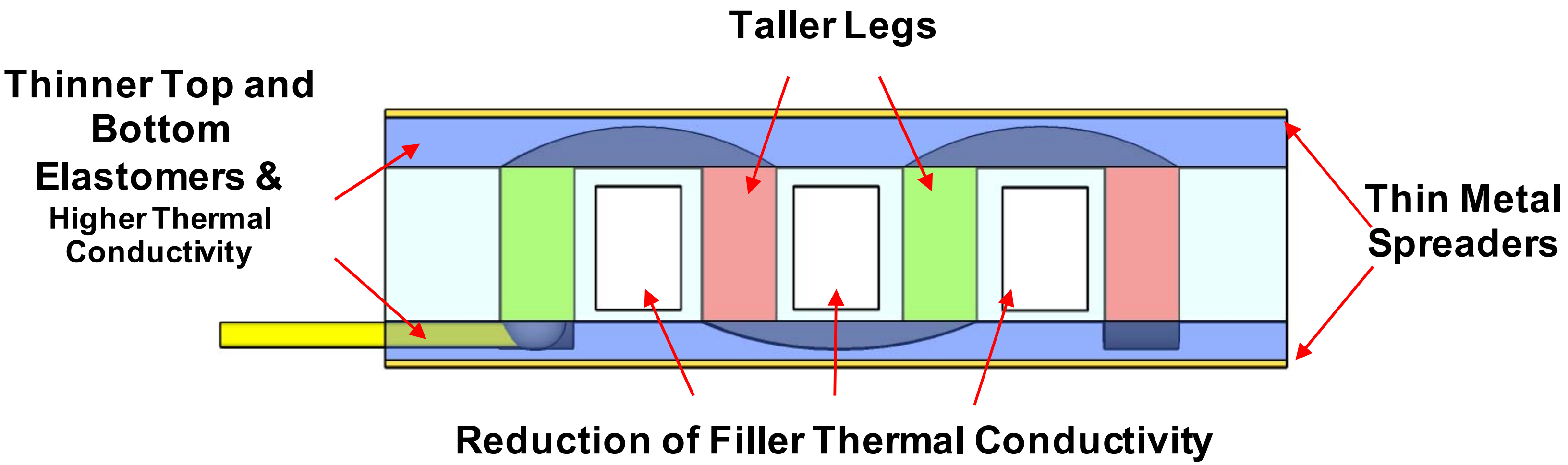
- Low Resistance - negligible contribution from interconnects
- Spikes recovered due to "self-healing" nature of EGaIn



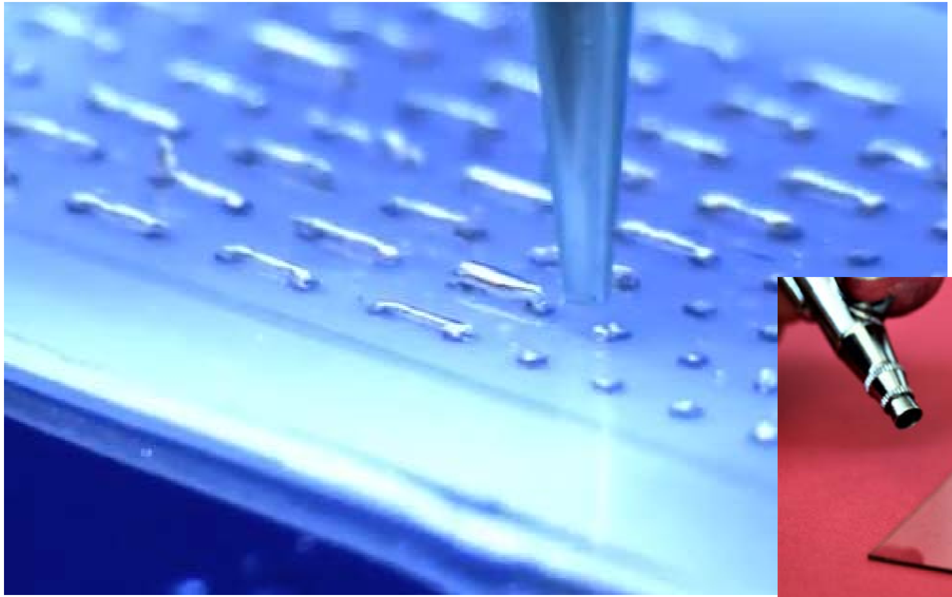


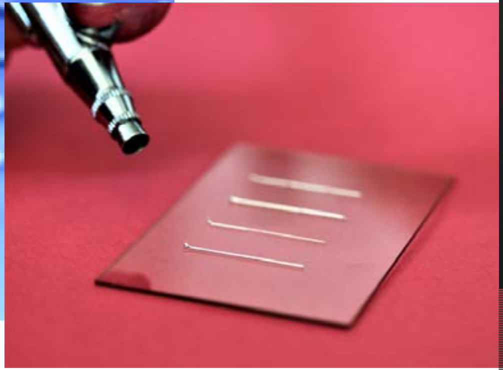


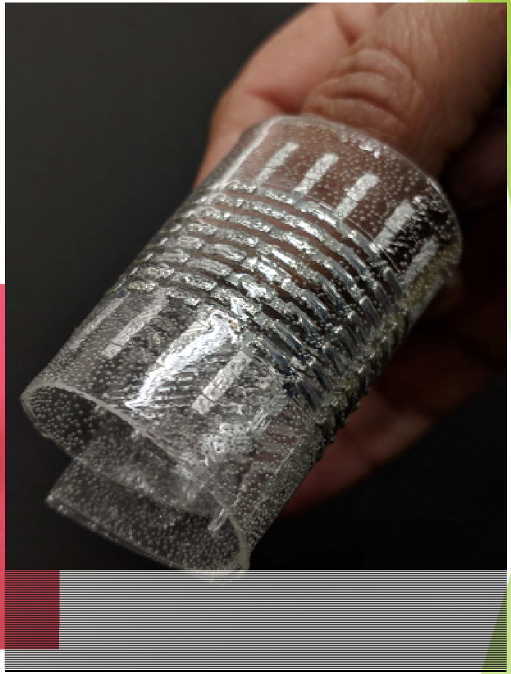
Further Improvements



Printing and Spray Coating of EGaIn







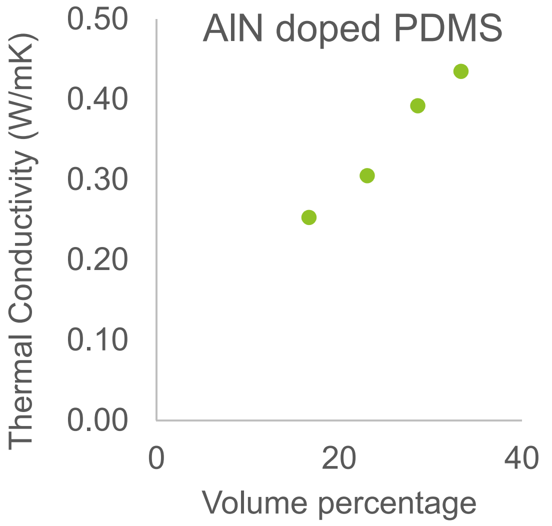
- **Printing provides faster and more reliable interconnects on TEGs with large leg count**
- **Spray coating of encapsulation provides a much thinner encapsulation**

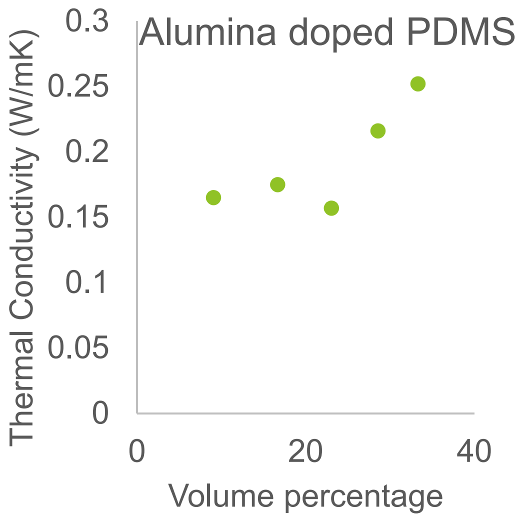
Flexible TEG with 256 legs & Spray Coated Encapsulation

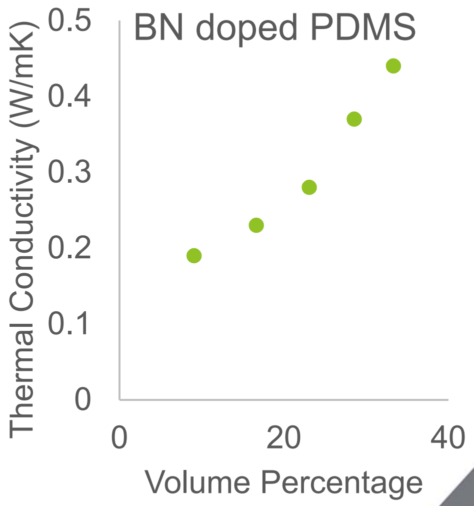
Al_2O_3, AlN, and BN Doped PDMS

Increasing the thermal conductivity of the encapsulating layer

Material	Thermal Conductivity	Powder size
Al_2O_3 Powder	~35 W/mK	≤10 µm
AlN Powder	~150 W/mK	~10 µm
BN Powder	~30 W/mK	~1 µm

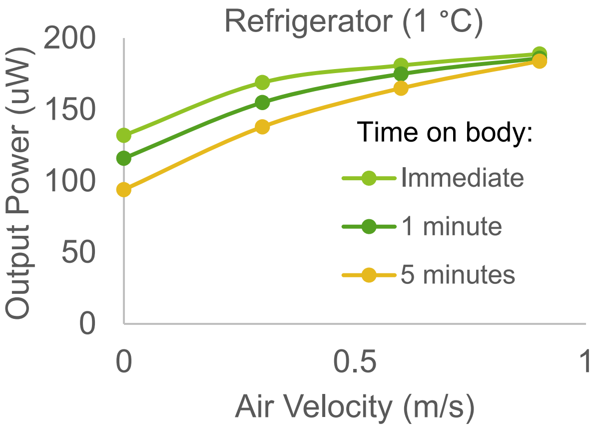


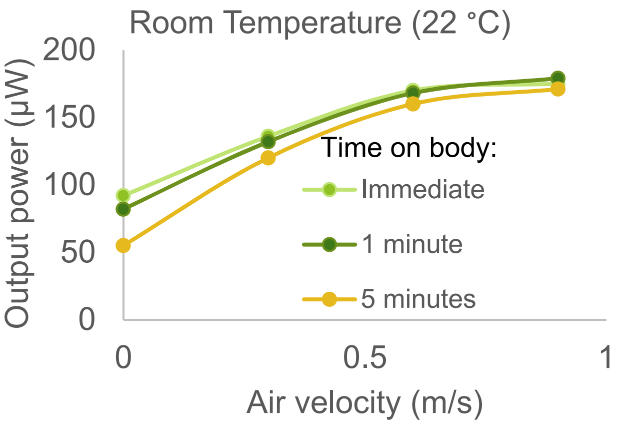


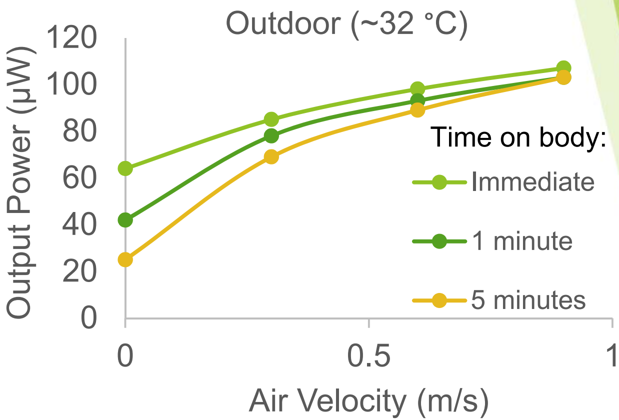


3X enhancement can be achieved in the thermal conductivity of PDMS

Output Power – Device characterization on the wrist – *Impact of time on the wrist*





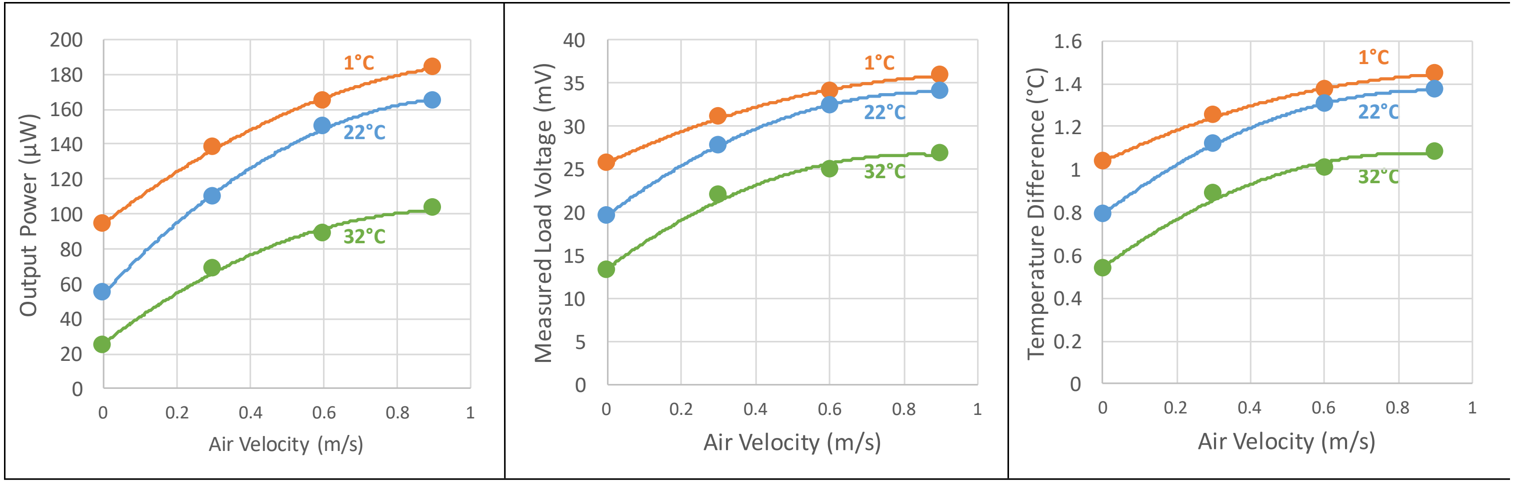


3X improvement in performance with
- Thin PDMS encapsulation
- Al_2O_3 doped PDMS top/bottom layers

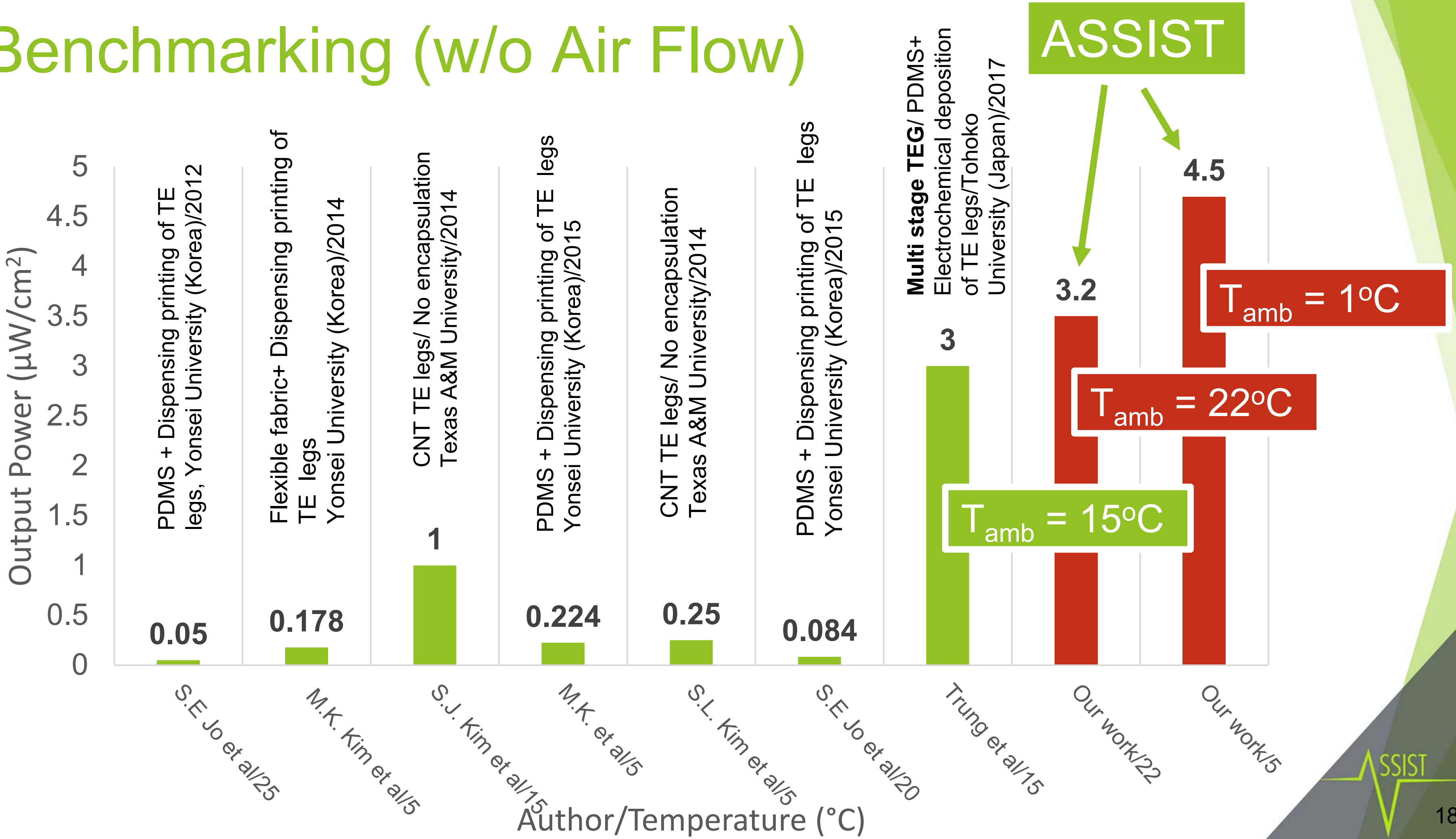
Still… No heatsink or heat spreaders

Device characterization on the wrist

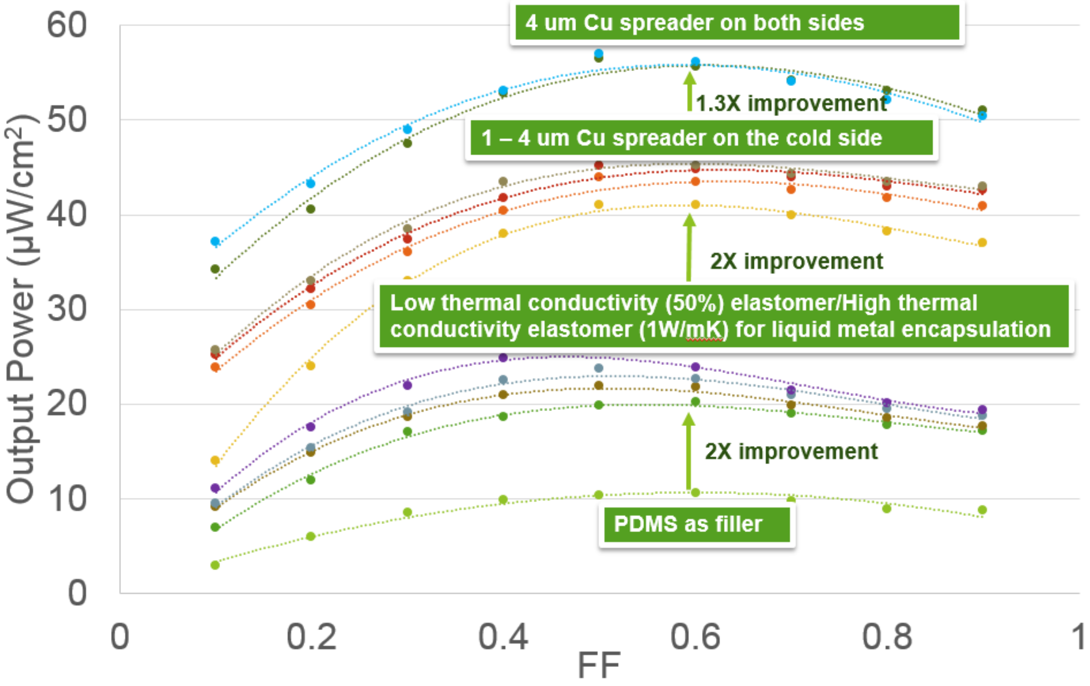
Voltage, Temperature Differential and Power

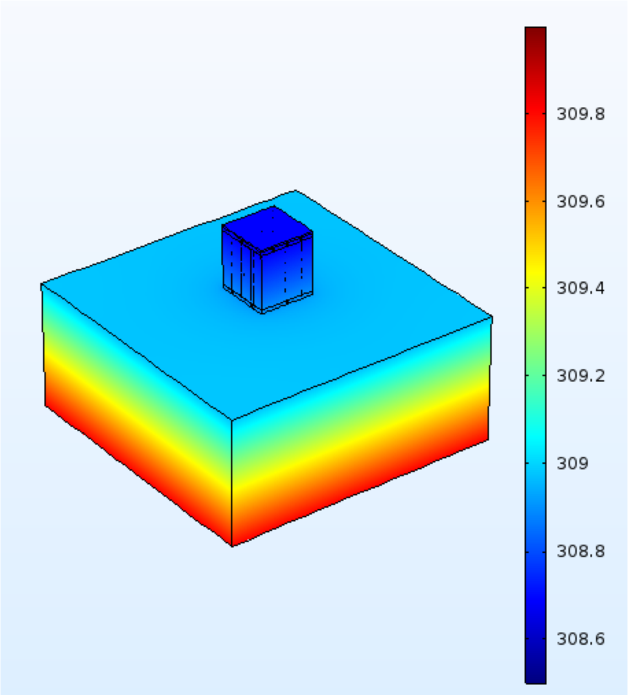


Benchmarking (w/o Air Flow)

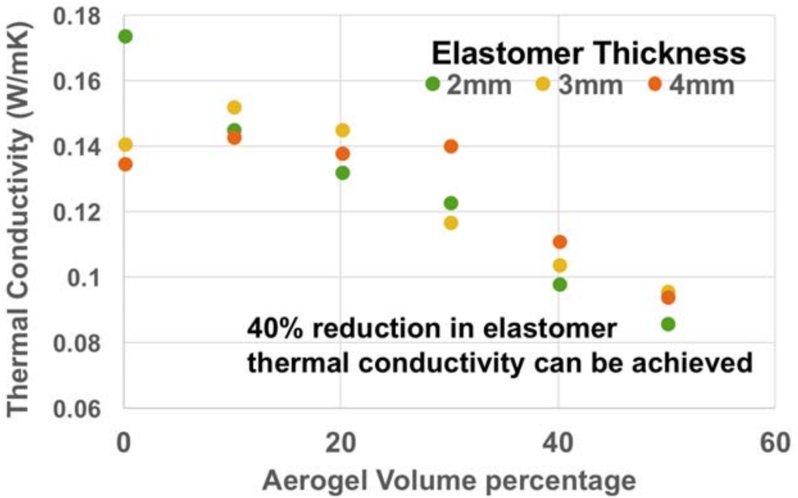


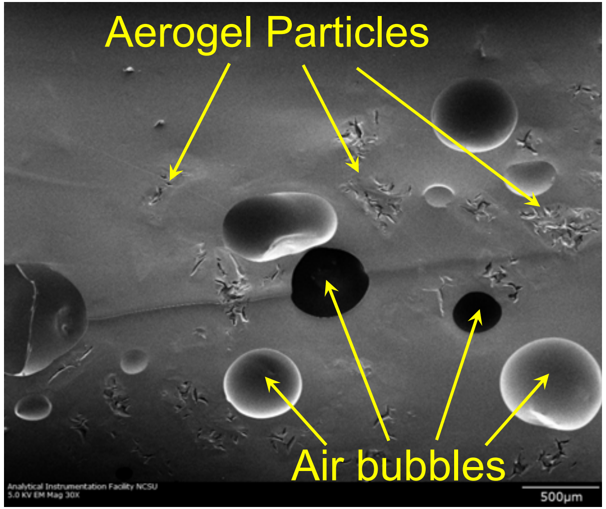
Further Improvements – COMSOL simulation

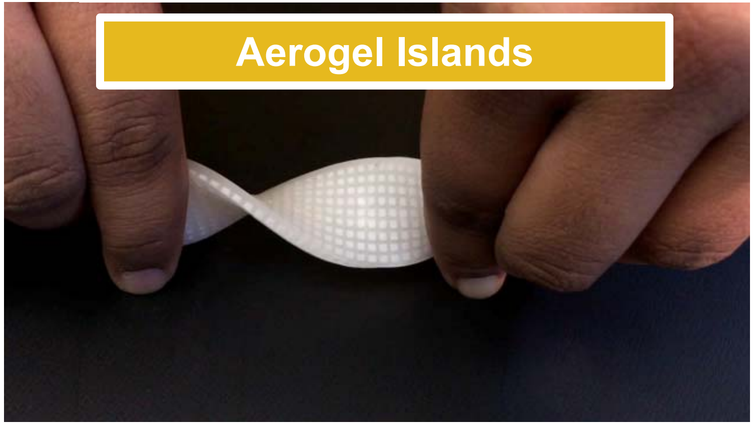




Low Thermal Conductivity Elastomer



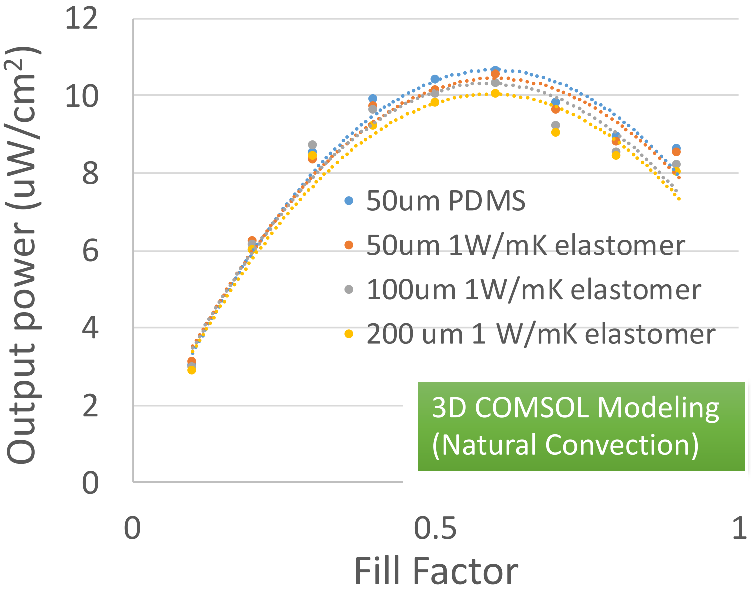




A low thermal conductivity elastomer between the legs can increase the power by ~ 2X

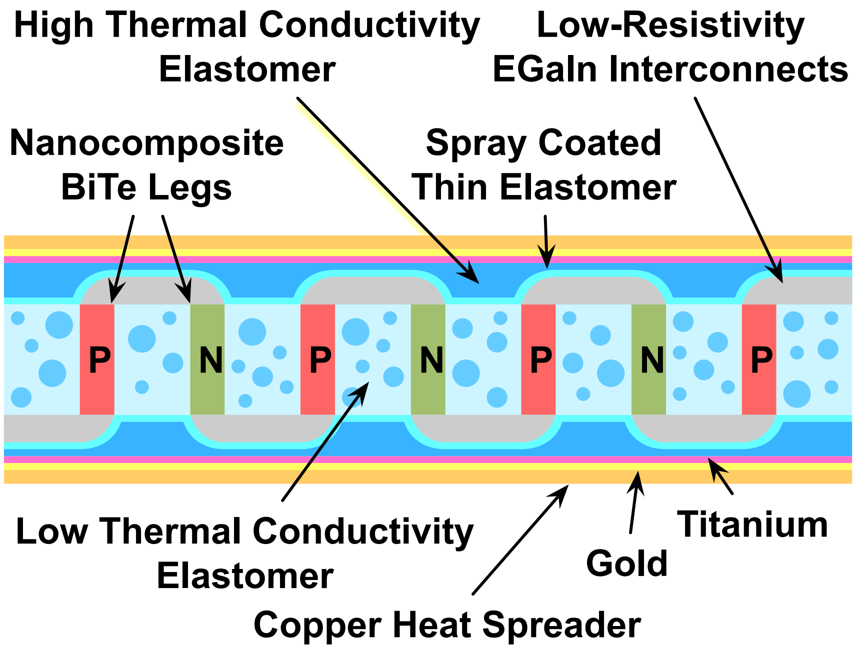
Graphene/EGaIn Doped Elastomer

Graphene percentage	PDMS + Graphene	PDMS + EGaIn + Graphene
2.2%	0.602 W/mK	0.838 W/mK
4.3%	0.652 W/mK	0.853 W/mK
6.3%	Cannot measure	0.871 W/mK



- Our approach was elastomer doping with high thermal conductivity particles
- We have tried
  - Al2O3, AlN, BN, Graphene and EGaIn
- Best results were obtained with EGaIn + Graphene Doping
  - 0.85 W/mK (5.6X improvement)
- We can increase the encapsulating thickness to 200 um without paying significant penalty

Improved TEG design



Conclusions

- EGaIn provides
  - Printable, low-resistivity, stretchability
  - Self-healing, reliability
  - Room-temperature bonding to TE legs
- There is still much room for improvement
  - Thermal management - Device packaging and materials

There is potential for producing flexible TEGs that rival the performance of rigid TEGs materials

Invitation to submit

Wearable Energy Harvesting and Storage Devices

Guest Editor

Prof. Dr. Mehmet C Ozturk

Deadline

30 September 2018

Special Issue