Scalable Thermal Energy Technologies Seminar

Shannon Yee
Assistant Professor
G.W.W. School of Mechanical Engineering

***S**calable **T**hermal **E**nergy **E**ngineering **L**aboratory*

Shannon Yee

- 2014 Assistant Professor
- 2013 PhD - Mech. Eng.
  - 2010 ARPA-E Fellow
  - 2008 Hertz Fellow
- 2008 MS - Nucl. Eng.
- 2007 BS - Mech. Eng.

Energy Club @ Georgia Tech
Heat Lab @ Georgia Tech
Grand Challenges @ Georgia Tech

Global Electrification

Image from www.constructionweeekonline.com

Fuel Resources

Image from Google Maps Panaramio

Global Cooling

Image from https://energyathaas.files.wordpress.com

Climate Change

Image from www.artic.noaa.gov

Clean Water

Image from www.yosemitehikes.com

Electric Transportation

Image from www.thetorquereport.com

Scalable **T**hermal **E**nergy **E**ngineering **L**aboratory

STEEL *develops scalable* ***thermal energy conversion*** *&* ***transport technologies*** *to better utilize heat*

Seminar Topics:

(choose your own adventure)

Thermal Energy Conversion Technologies

1. Thermoelectric Costs Scaling
2. Organic Thermoelectrics
3. Porous-Si Thermoelectric Cooling
4. Na Thermo-Electro-Chemical Heat Engine
5. Thermo-Electro-Chemical Cooling
6. Betavoltaic Energy Sources

Thermal Transport Technologies

1. Polymer Thermal Conductivity
2. In-Plane FDTR Measurements
3. Thermal Property Gas Sensing
4. Better Building Materials

- Heat Lab @ Georgia Tech
- Energy Club @ Georgia Tech
- Grand Challenges @ Georgia Tech

New Directions with Organic Thermoelectrics

New Directions with Organic Thermoelectrics

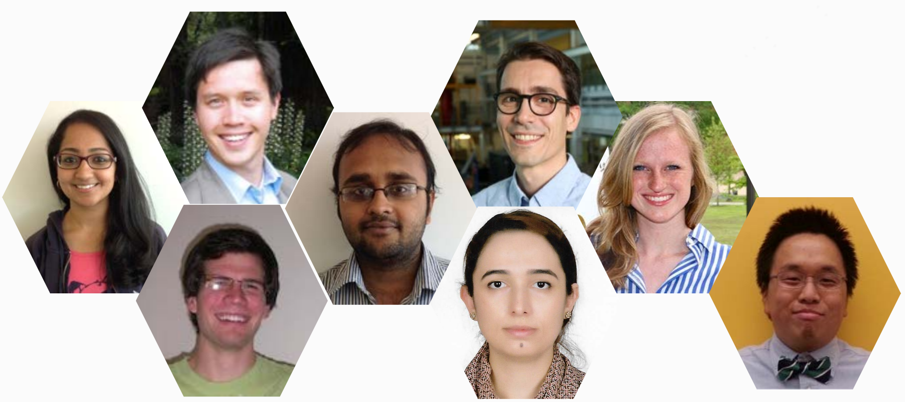
Prof. Shannon Yee
Assistant Professor
G.W.W. School of Mechanical Engineering

***S**calable **T**hermal **E**nergy **E**ngineering **L**aboratory*

Georgia Institute of Technology

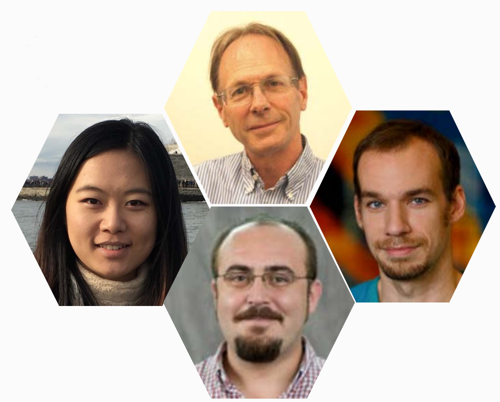
ORGANIC THERMOELECTRICS

Prof. Shannon Yee
Akanksha Menon – PhD Candidate
Rylan Wolfe – PhD Candidate
Sampath Kommandur – PhD Candidate
Dr. Kiarash Gordiz – Colorado School of Mines
Dr. Hend Elmoghunni – Qatar STP
Arnold Eng – PNNL
Olivia Meek – Landis & Gyr



Prof. John Reynolds
Dr. Bing Xu
Dr. Urdal Uzunlar
Dr. James Ponder – Imperial College

Prof. Seth Marder
Dr. Desari “Reddy” Raghunath



Part I

THERMOELECTRIC TECHNO-ECONOMICS

Thermoelectric Figure(s) of Merit

Power Generation

$/W

Electric Cooling

$/kWh$_{th}$

Cost {$} – *Material, Manufacturing, & BOS*

- ***Raw material costs***
- ***Manufacturing costs***
- ***Balance of System (BOS) costs***
  - ***Heat Exchangers***
  - ***Insulating Plates***
  - ***Metallization***

$$G = \frac{C}{P}$$

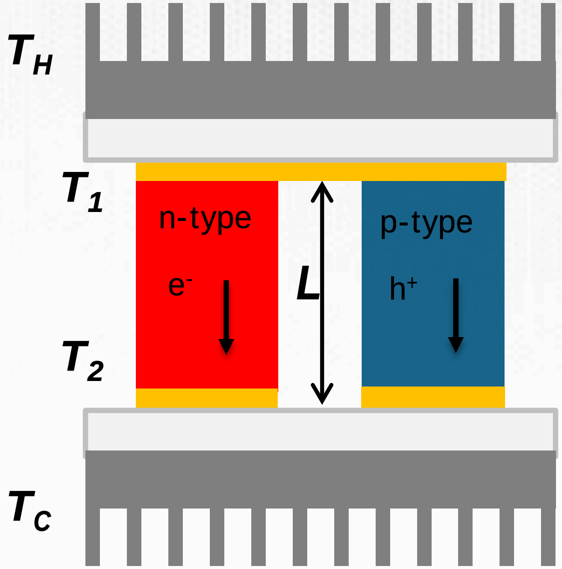
Power {W} – *Device Physics*

"A $/W METRIC FOR THERMOELECTRIC POWER GENERATION: BEYOND ZT"

S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.
S. LeBlanc, S. Yee, *et al.*, *Ren. Sus. Energy Rev.*, **32**, 313-327, 2014.
T. Hendricks, S. Yee, S. LeBlanc, *J. Electron. Mat*. 2015.

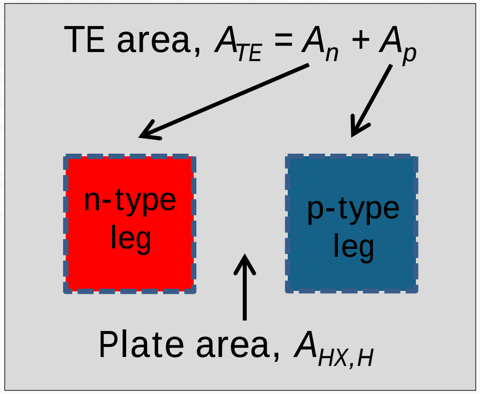
Thermoelectric Device Topology

Design variables – leg length, *L* & fill factor, *F*



Side View

$$F = \frac{A_{TE}}{A_{HX,H}}$$



Top View

<u>Costs:</u> Material, Manufacturing, & Heat Exchangers Costs

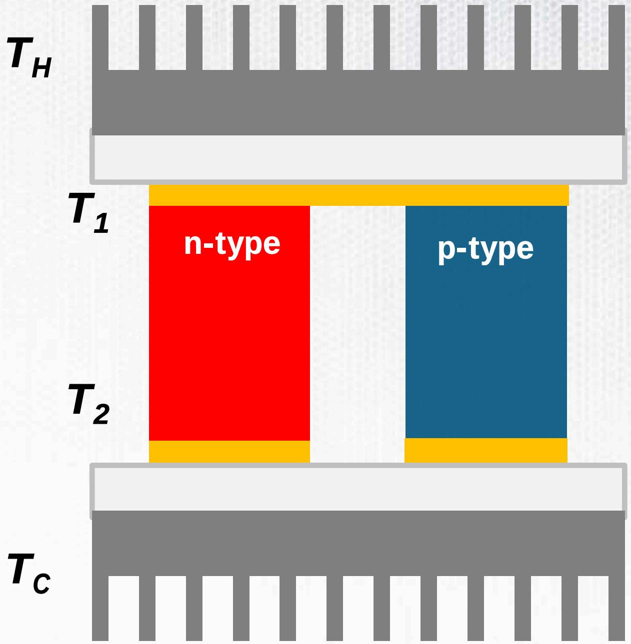
- Volumetric Costs, *C'''* [$/m³]
  - Material costs
  - Manufacturing costs (dicing, cutting, *etc.*)
- Areal Module Costs, *C''* [$/m²]
  - Metallization, metal shunts, *etc.*
  - Manufacturing costs (depositions, assembly, etc.)
- Heat Exchanger Costs, C_{HX} [$/(W/K)]
  - Ceramic plates, plate-and-fin, *etc.*

$$C = \left(C''' L + C'' \right) A F + C_{HX} U A$$

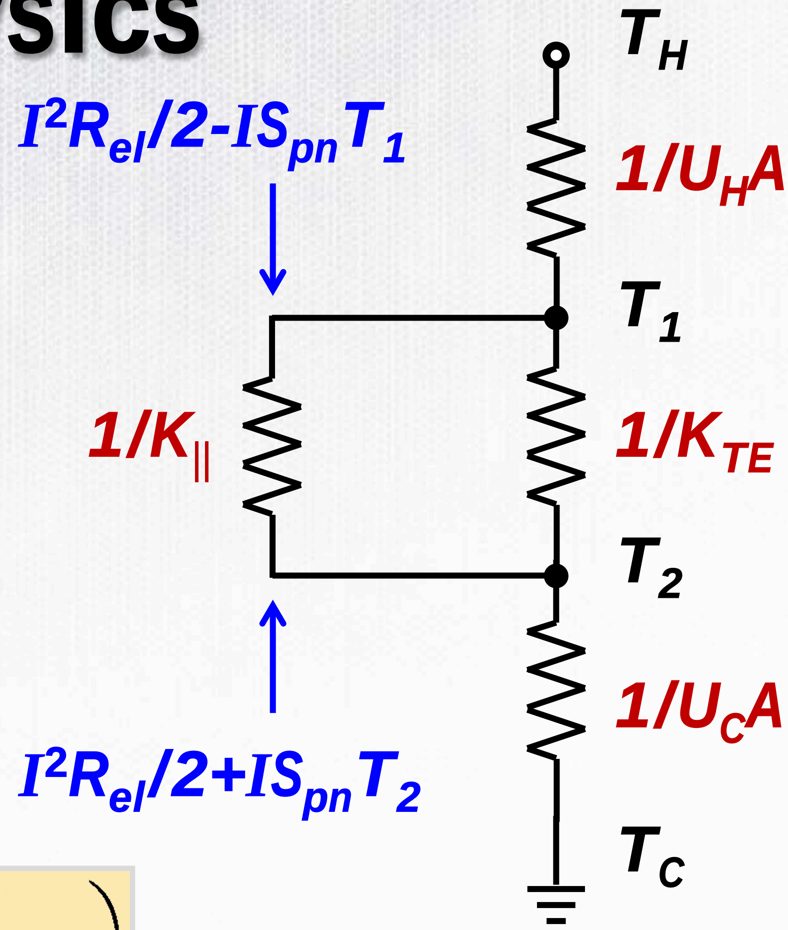
[$] [$/m³] [$/m²] [$/(W/K)]

S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.

Power: Thermoelectric Device Physics



Side View



$$P = \frac{S_{pn}^{\;2}\left(T_1 - T_2\right)^2}{R_{el}}\left(\frac{m}{\left(m+1\right)^2}\right)$$

$$m = \frac{R_L}{R_{el}}$$

S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.

Dimensional and Non-dimensional Terms

Length [m]

$$L_T \equiv \frac{k}{U}$$

Thermal Length

$$L_C \equiv \frac{C''}{C'''}$$

Cost Length

$$L_{HX} \equiv \frac{C_{HX} U}{C'''}$$

Heat Exchanger Length

Dimensionless

$$\tilde{L} \equiv \frac{L}{L_T}$$

$$\tilde{L}_C \equiv \frac{L_C}{L_T}$$

$$\tilde{L}_{HX} \equiv \frac{L_{HX}}{L_T}$$

S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.

Cost Metric for Thermoelectrics

Load Matching

$$\frac{G}{G_0} \approx \frac{1}{4}\left(\frac{(m+1)^2}{m}\right)\left(2F + \tilde{L}\right)^2\left(1 + \frac{\tilde{L}_C}{\tilde{L}} + \frac{\tilde{L}_{HX}}{\tilde{L}F}\right)$$

Three Cost Terms

Fill Factor

Leg Length

Volumetric Cost [$/m³]

Volume [m³]

$$G_0 = \frac{C''' L_T A}{\frac{1}{4} ZT_H \left(\frac{T_H - T_C}{T_H}\right)} \frac{1}{UA\left(T_H - T_C\right)}$$

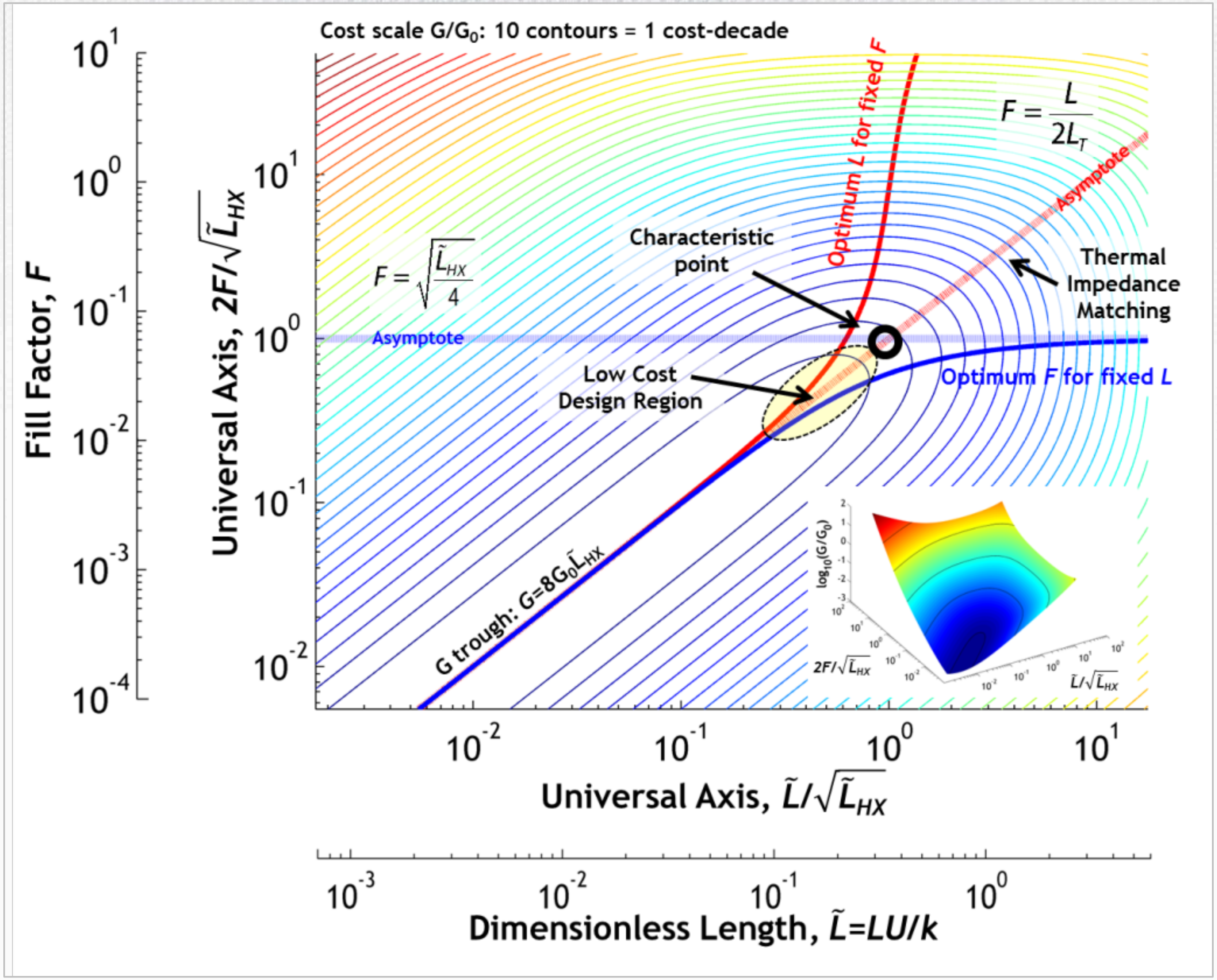
small ZT efficiency

Carnot efficiency

Thermal potential [W]

S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.

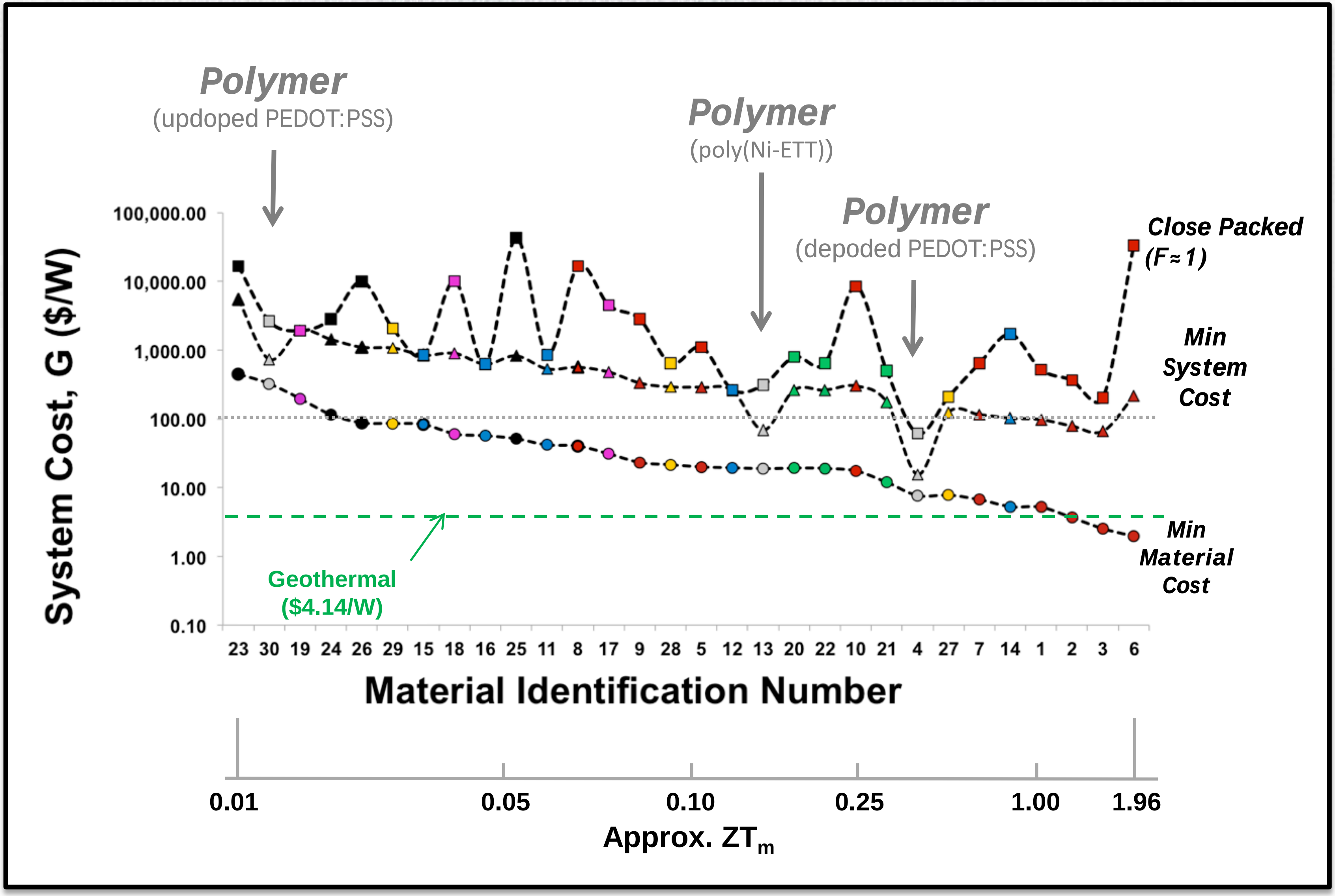
Design Space for G in $/W



S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.

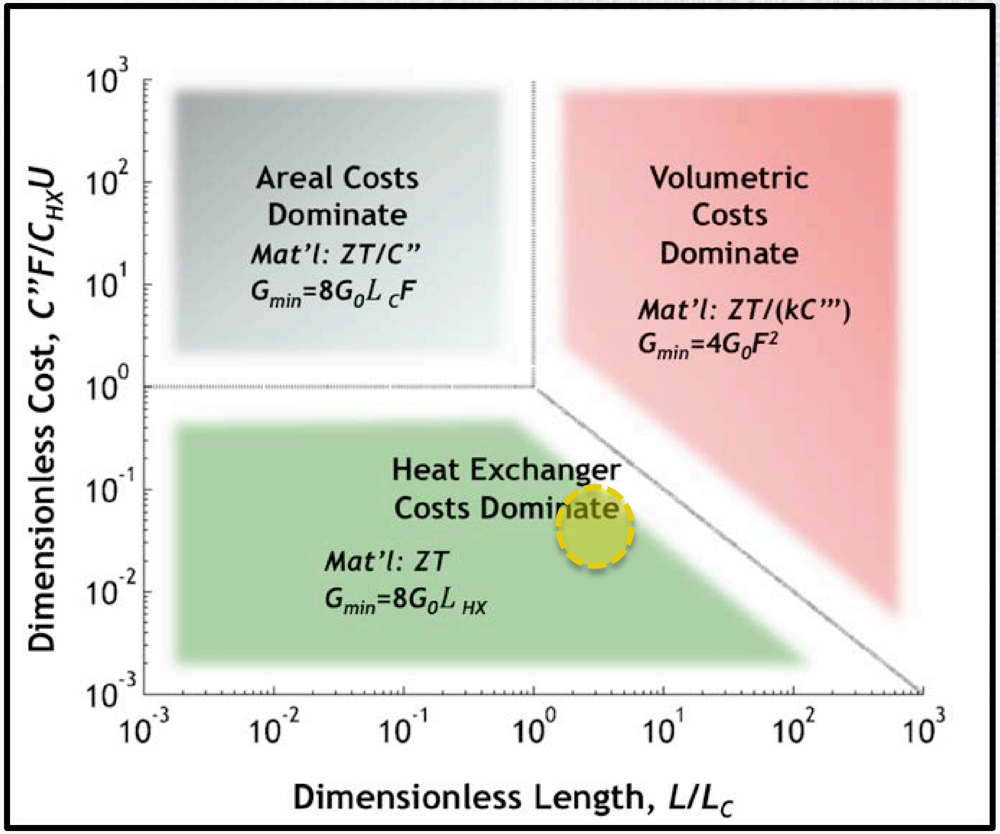
$/W Cost Comparison: Low Temp Waste Heat

$T_H = 100^{\circ}C$, $T_C = 20^{\circ}C$

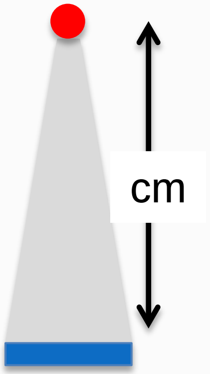


S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.

$/W Cost Minimized Design



- *Heat exchanger costs dominate have dominated in ALL systems to-date*
- *Why not eliminate the heat exchanger and operate with natural convection?*
  - $k_{eff} < 0.5$ W/m-K
  - $L_{opt} \sim 5$ cm
  - $F_{opt} > 1$

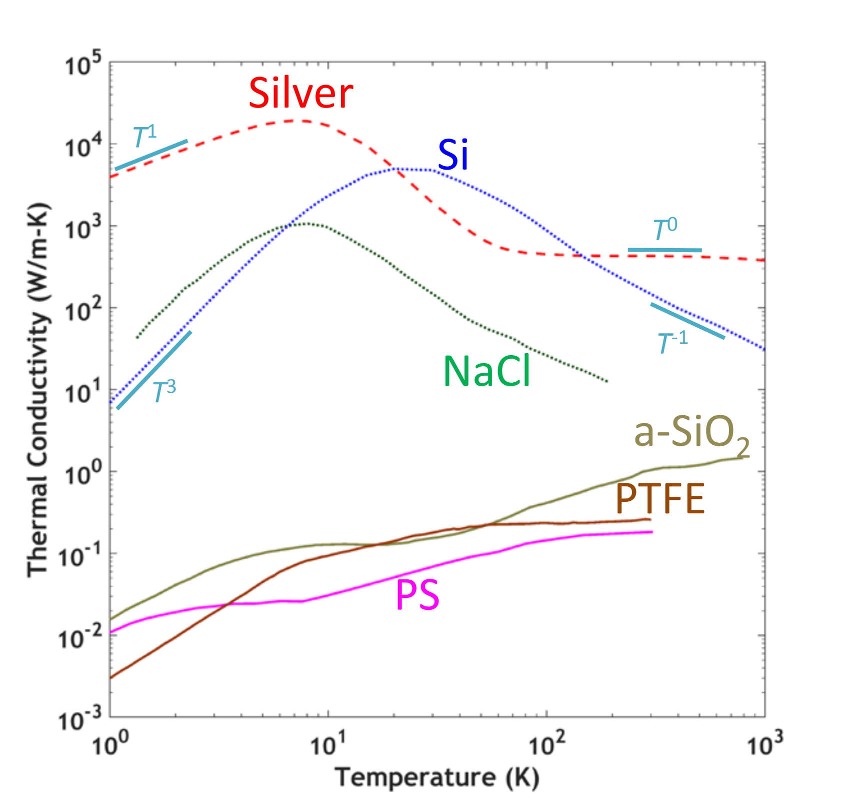


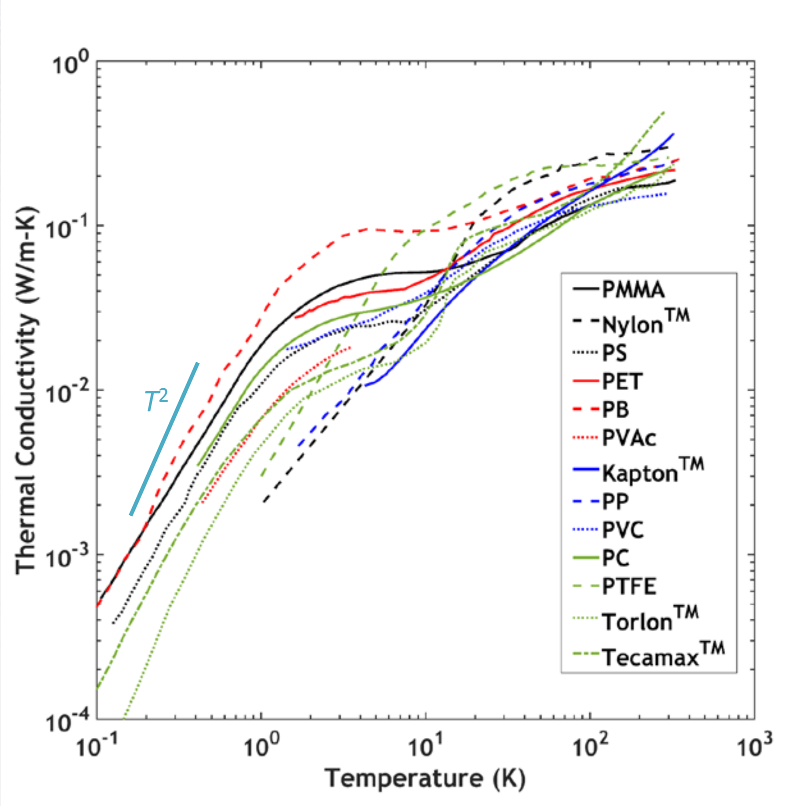
S. Yee *et al.*, *Energy & Environ. Sci.*, **6**, 2561-2571, 2013.

Part II

THERMAL TRANSPORT IN POLYMERS

Experimental Observations of Thermal Conductivity

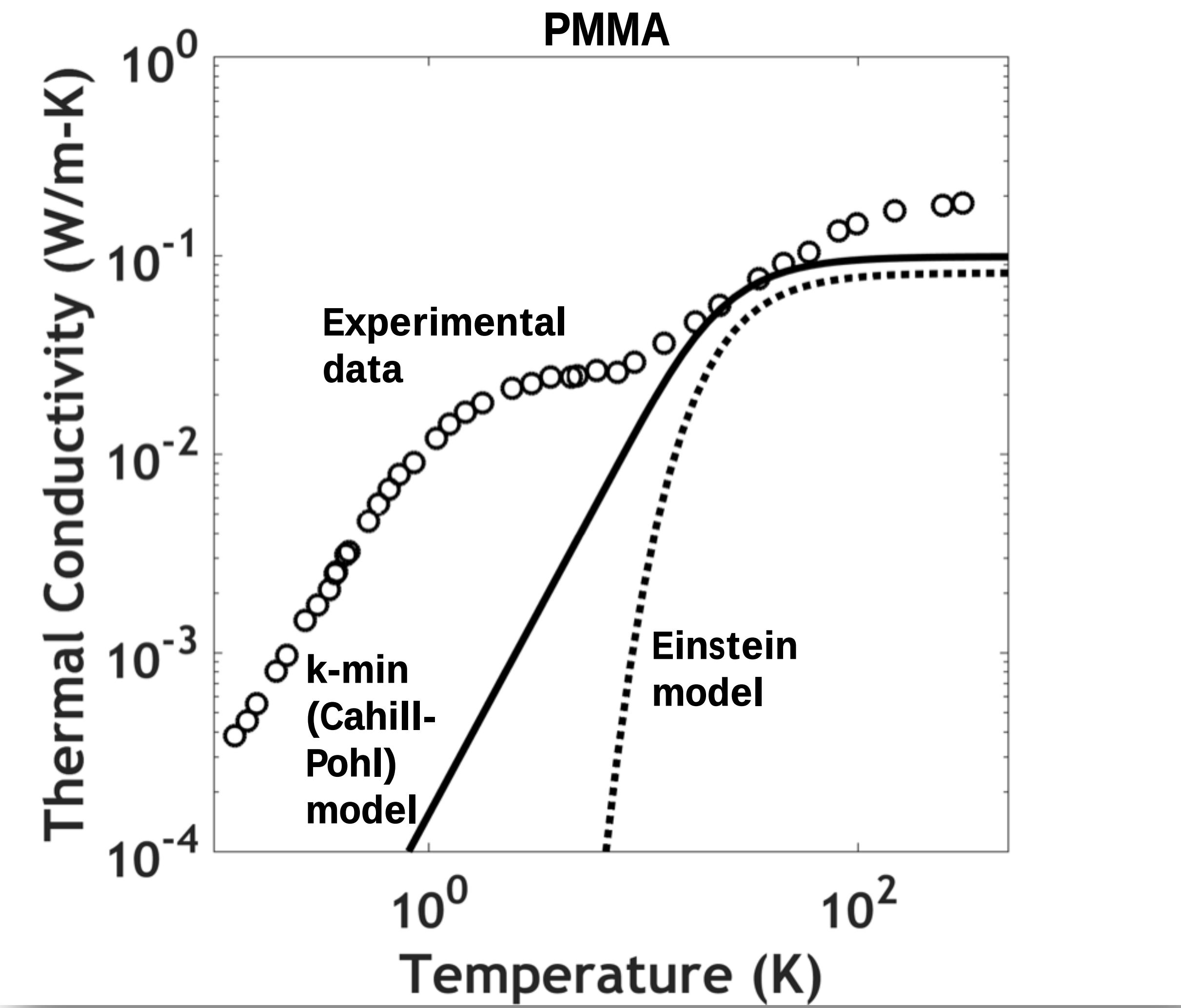




Amorphous polymers exhibit (i) monotonically increasing thermal conductivity trends and (ii) undergo plateau-like transition(s)

E. Toberer et. al., *Ann. Rev. Mater. Res.* **4,** 2012
S. Kommandur and S.K. Yee, *J. Poly. Sci. B* **55**, 2017

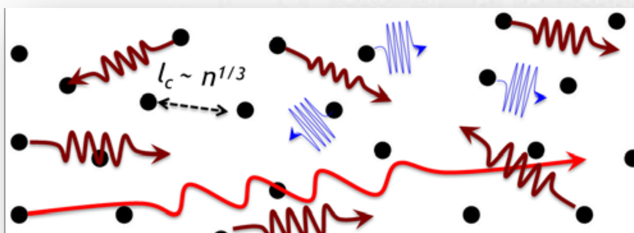
Comparison of experimental data to amorphous thermal conductivity models

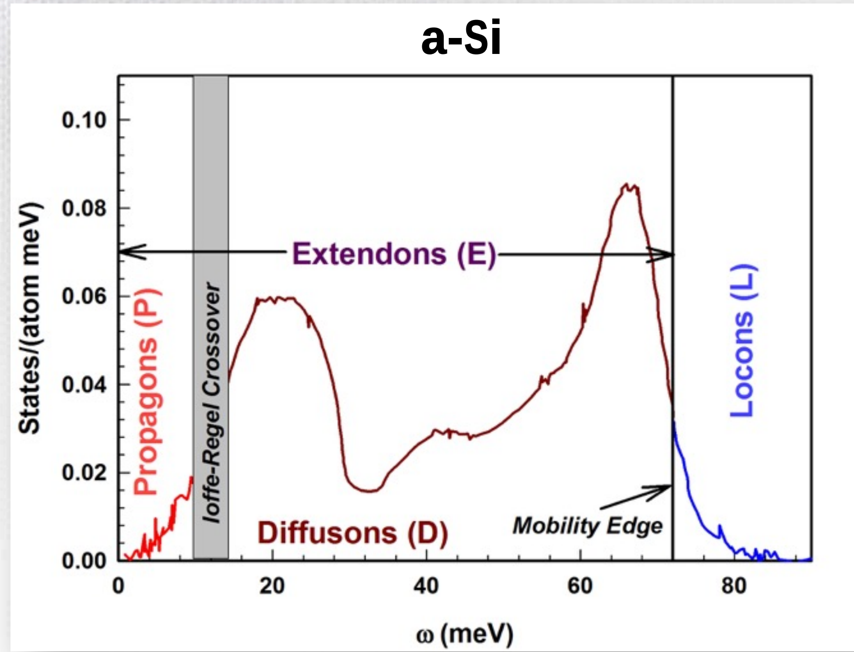


S. Kommandur and S.K. Yee, *J. Poly. Sci. B*, **55**, 2017

Vibrons are vibrational modes in amorphous materials

- Vibrons
  - Extendons
    - **Propagons**
    - **Diffusons**
  - **Locons**





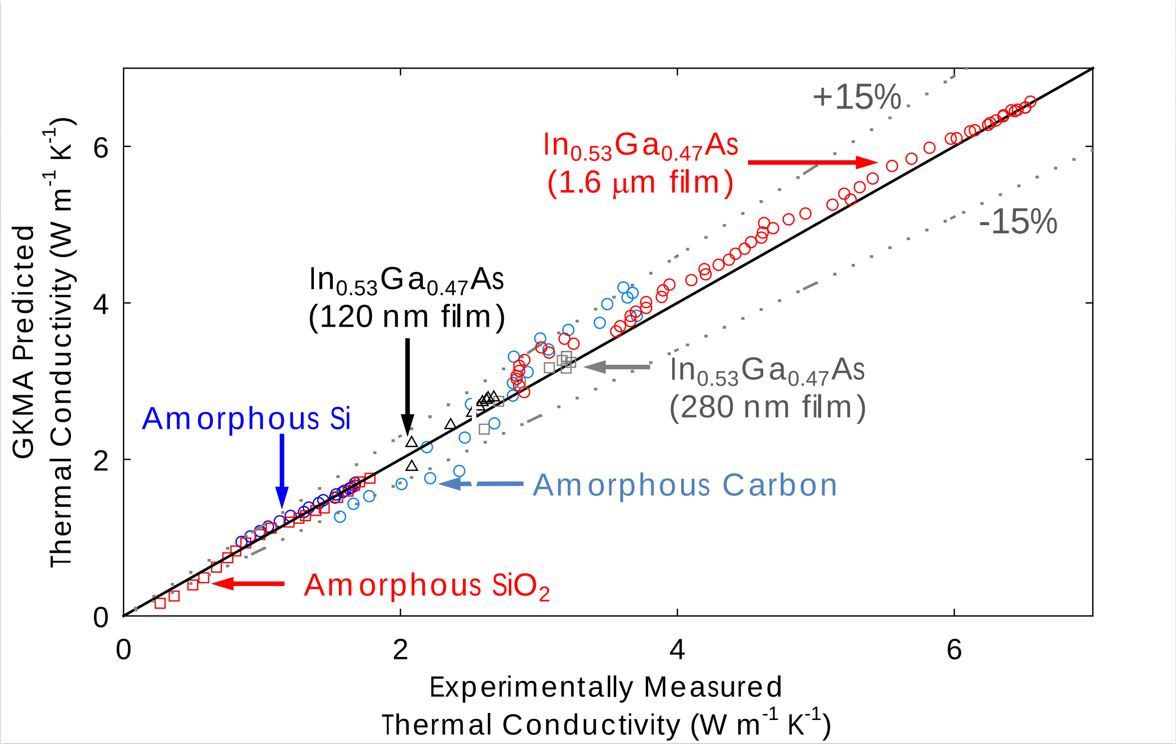
$l_{mfp} > a$ $l_{mfp} \sim a$ $l_{mfp} < a$ $l_{mfp} << a$

The concepts of a mean free path and a wave-vector are less useful for diffusons and locons.

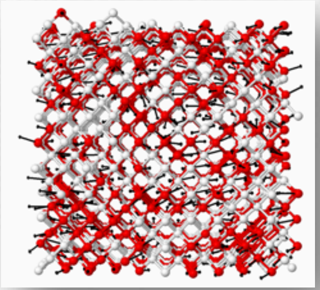
Allen *et. al.*, Philosophical Magazine Part B, **79**, 1999

Green-Kubo Modal Analysis (GKMA)

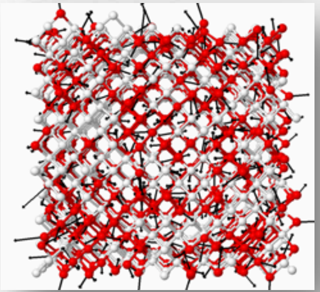
Uses super-cell lattice dynamics (SCLD) with molecular dynamics (MD) to calculate the contributions of phonons in a general way. Can be applied to **amorphous materials**, **polymers**, crystals alloys etc. using one unified formalism. When disorder exists, phonons no longer look like waves.



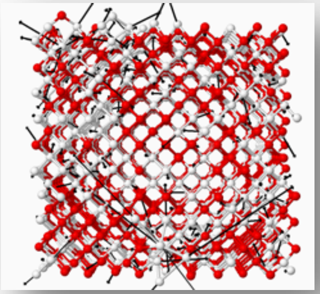
Propagons



Diffusons



Locons



W. Lv, A. Henry, Direct Calculation of Modal Contributions to Thermal Conductivity via Green-Kubo Modal Analysis: Crystalline and Amorphous Silicon, New Journal of Physics, 18, 013028 (2016).

Seyf, Hamid Reza, et al. Rethinking phonons: The issue of disorder, *npj Computational Materials* 3, 1, 49 (2017)

K. Gordiz and A. Henry, A formalism for calculating the modal contributions to thermal interface conductance, New Journal of Physics, 17, 103002 (2015)

Origins of Polymer Thermal Conductivity

$$k = \frac{1}{3} c v l \xrightarrow[\text{Diffusivity}]{D = vl} k = \frac{1}{3} c D$$

- Independent contributions from each vibron

$$\boldsymbol{k = k_P + k_D + k_L}$$

$$k = \frac{1}{3} \sum_i \int_{\omega_{i-1}}^{\omega_i} c(\omega) D(\omega) N(\omega) d\omega$$

Vol. Specific heat

$$c = 3nk_B \frac{x^2 e^x}{\left(e^x - 1\right)^2}$$

Density of states

$$N_i(\omega) \propto \frac{3\omega^2}{2n\pi^2 v_s^3}$$

Diffusivity

$$D_i(\omega) \propto \omega^{-\beta_i}$$

C. Kittel, "Intro to Solid State Physics", *Wiley* (8th Ed.) 2005
J.M. Larkin *et. al*., *Phys. Rev. B*, **89**, 2014

Simplified Model

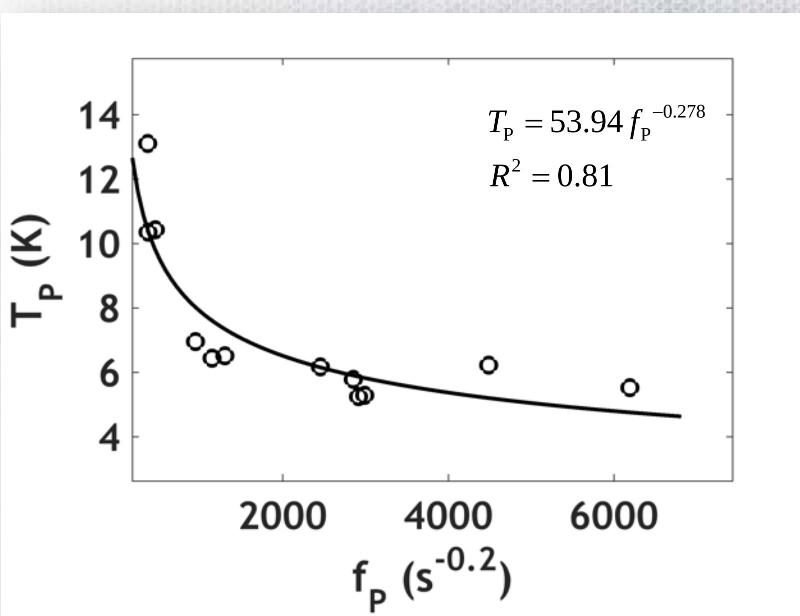
$$k(T) = f_P \frac{k_B}{v_s}\left(\frac{k_B T}{\hbar}\right)^{1.8} \int_0^{x_P} \frac{x^{2.8} e^x}{\left(e^x - 1\right)^2} dx + f_D \frac{k_B}{v_s}\left(\frac{k_B T}{\hbar}\right)^{2} \int_{x_P}^{x_D} \frac{x^{3} e^x}{\left(e^x - 1\right)^2} dx$$

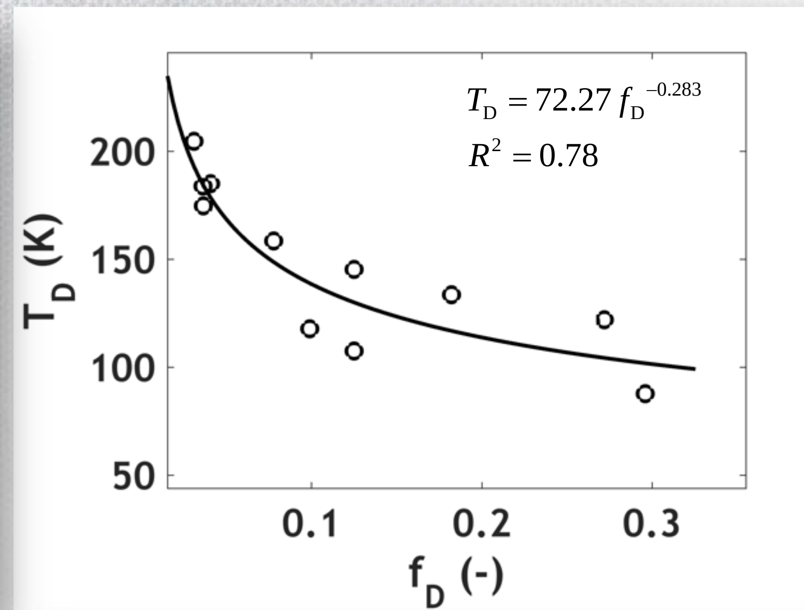
Propagons — Diffusons

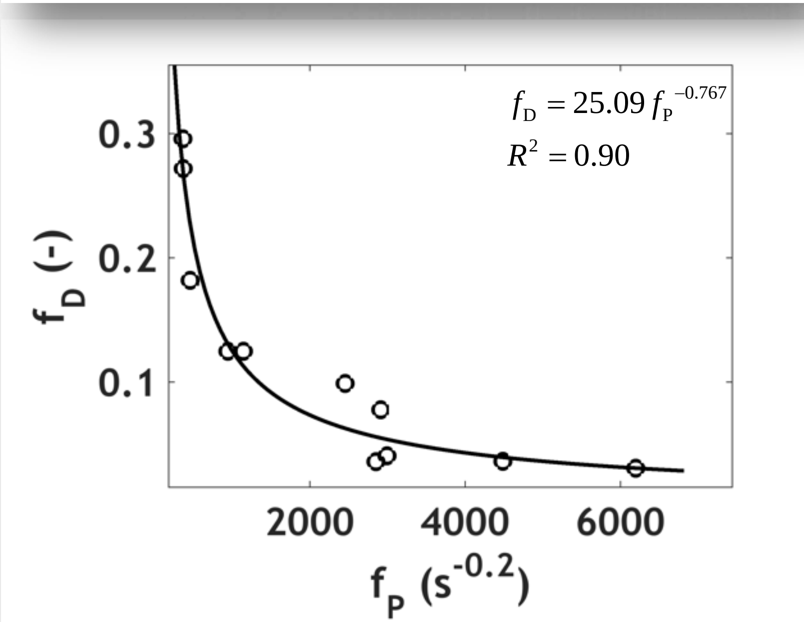
- Considers only propagons and diffusons
  - Neglect locons because polymers degrade/melt/glass-transition as locons contribution becomes significant
- Fixed value of β in the diffusivity relation
  - $T^{1.8}$ has good agreement with experimental data for low T
  - T^2 has good agreement with experimental data for mid T
- Reduces to 4 parameters (T_P, f_P, T_D, f_D)

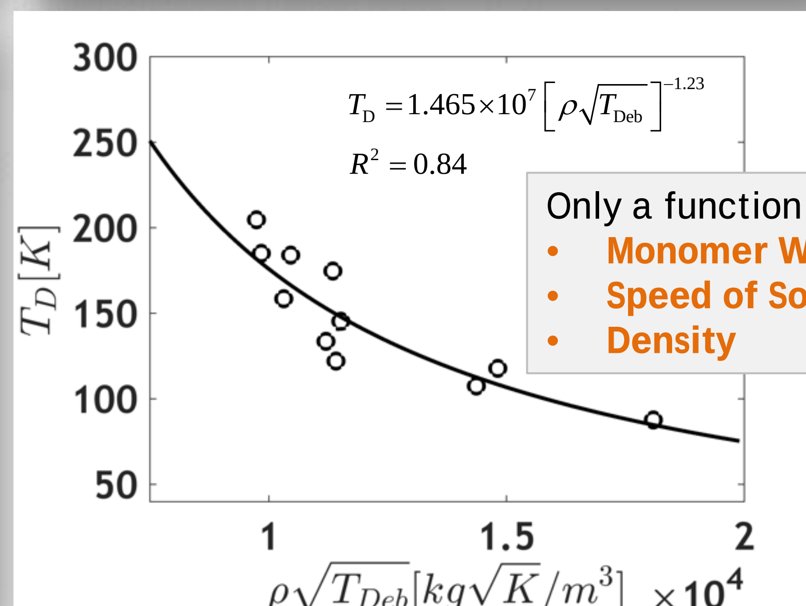
S. Kommandur and S.K. Yee, *J. Poly. Sci. B*, **55**, 2017

Empirical Observations Relating Parameters







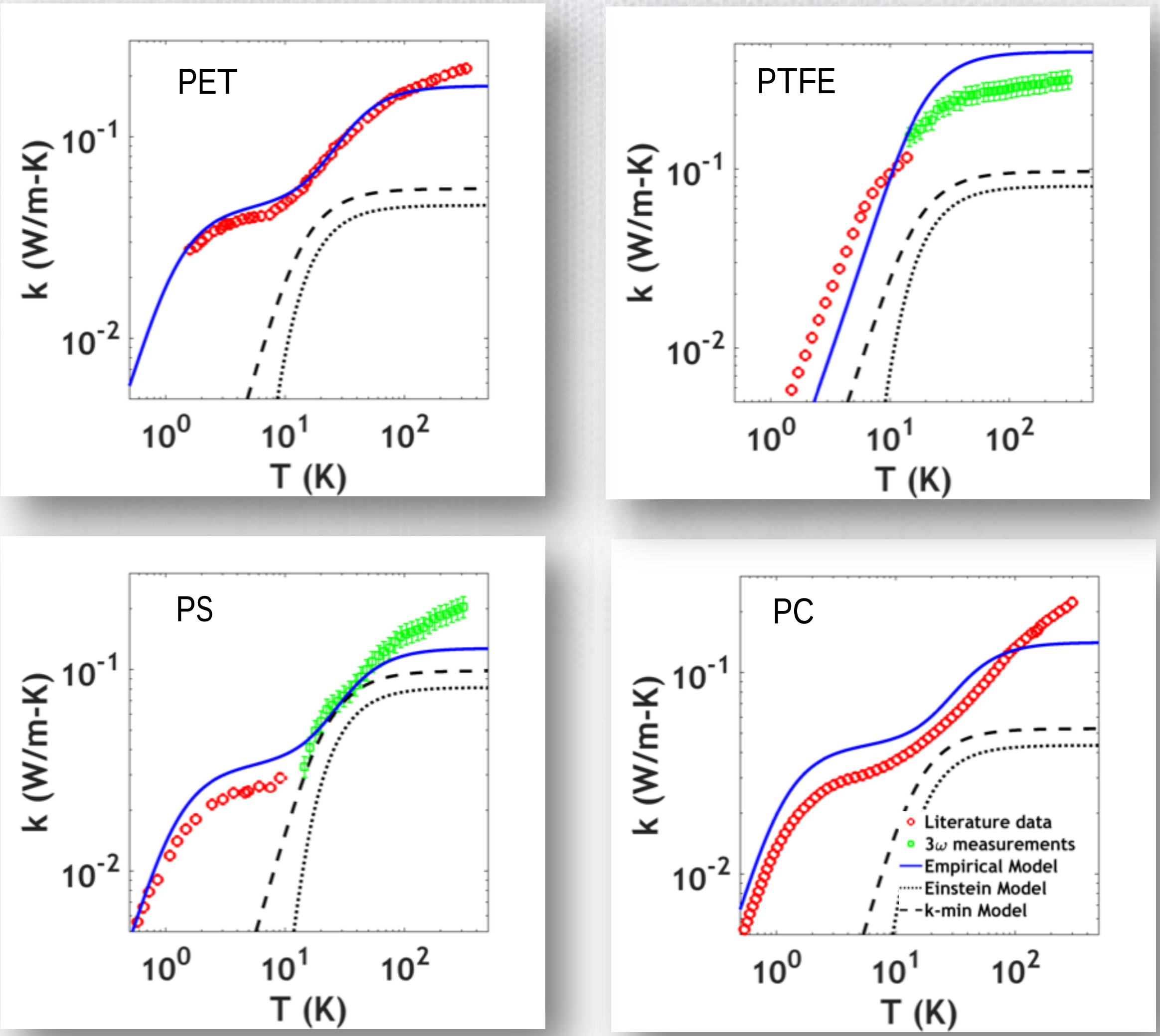


Only a function of

- **Monomer Weight**
- **Speed of Sound**
- **Density**

S. Kommandur and S.K. Yee, *J. Poly. Sci. B*, **55**, 2017

Empirical model predicts the temperature dependent thermal conductivity well



S. Kommandur and S.K. Yee, *J. Poly. Sci. B*, **55**, 2017

Interesting Model Interpretations

- **MFP cross-over between propagons and diffusons**

$$\frac{l_{mfp}}{a} \approx \frac{2\pi v_s n^{1/3}}{\omega_P} \approx 10$$

- **Modal contribution to thermal conductivity**

$$k_P(T) = 1.85 \frac{f_P^{0.5}}{v_s}\left[\frac{1}{x_P^{1.8}}\int_0^{x_P}\frac{x^{2.8}e^x}{(e^x-1)^2}dx\right]$$

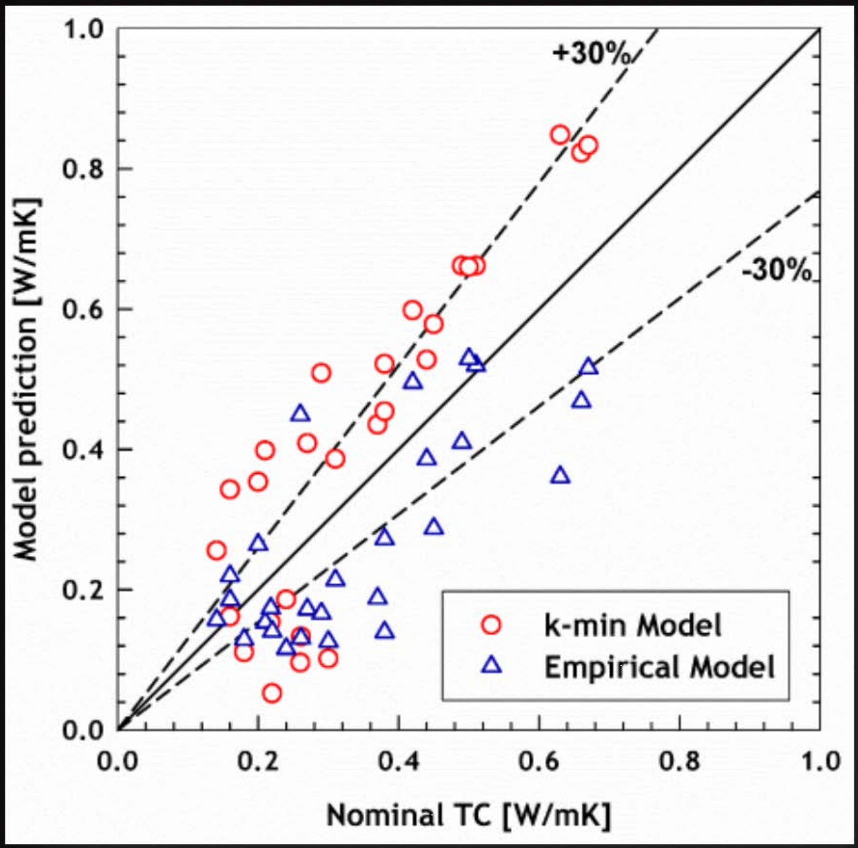
$$k_D(T) = 1226 \frac{f_D^{0.43}}{v_s}\left[\frac{1}{x_D^{2}}\int_{x_P}^{x_D}\frac{x^{3}e^x}{(e^x-1)^2}dx\right]$$

- **Prediction of room temp. thermal conductivity for amorphous polymers**

$$\boxed{k_{max} = \frac{1}{v_s}\left(f_P^{0.5} + 613 f_D^{0.43}\right)}$$

S. Kommandur and S.K. Yee, *J. Poly. Sci. B*, **55**, 2017

Room Temperature Amorphous Polymer Thermal Conductivity



An upper limit to the thermal conductivity in amorphous polymers

$$k_{\max} = \frac{1}{v_s}\left(f_P^{0.5} + 613 f_D^{0.43}\right)$$

$$f_P \propto \rho^{-0.3} v_s^{-1.7} M^{0.55}$$

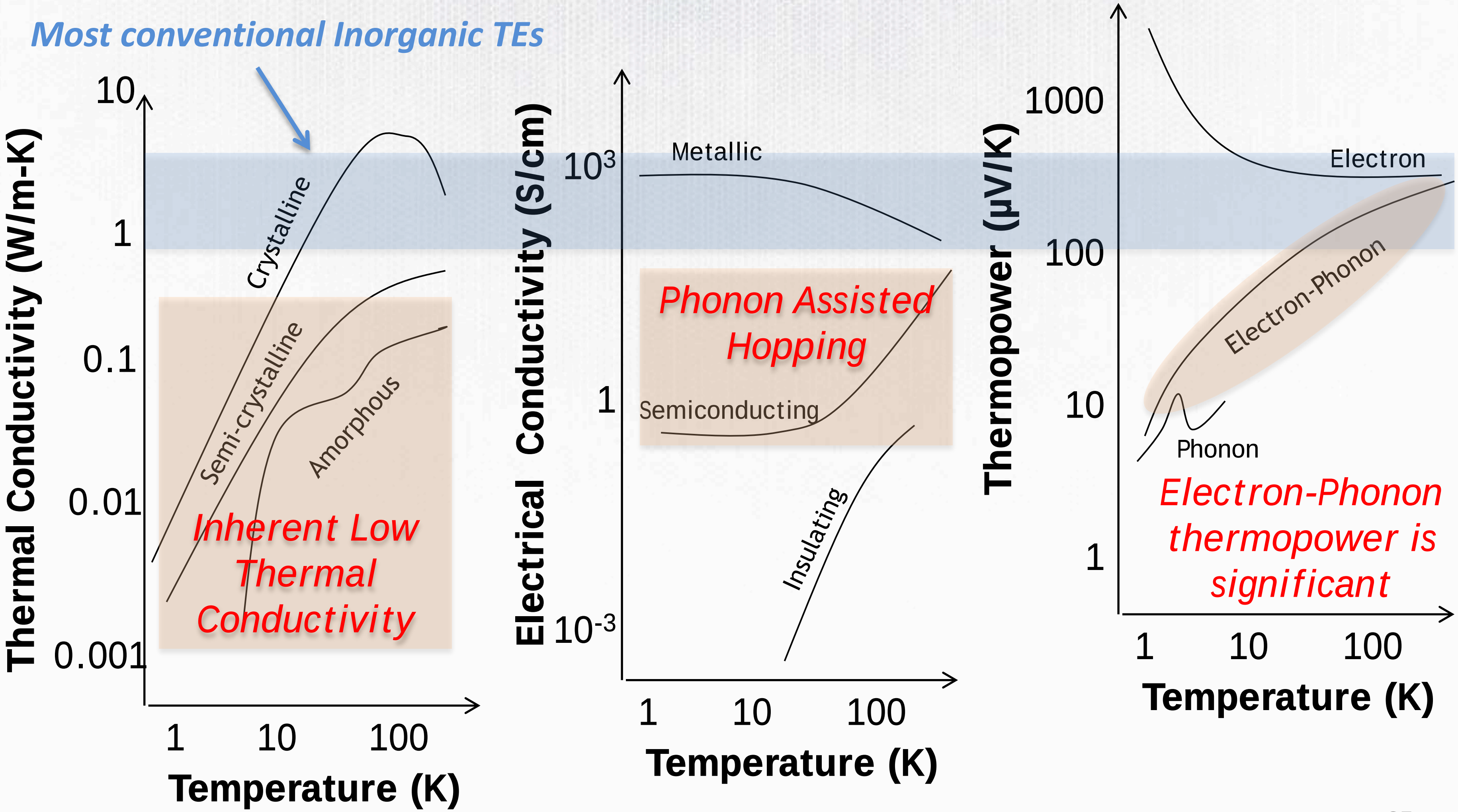
$$f_D \propto \rho^{4.3} v_s^{2.2} M^{-0.7}$$

ρ	Density (kg/m³)
M	Monomer molar mass (kg/mol)
v_s	Speed of sound* (m/s)

* averaged over the two modes

S. Kommandur and S.K. Yee, *J. Poly. Sci. B*, **55**, 2017
X. Xie et al., *Macromolecules*, **49**, 2016
X. Xie et al., *Phys. Rev. B*, **95**, 2017

OTEs offer new directions for improving TE transport

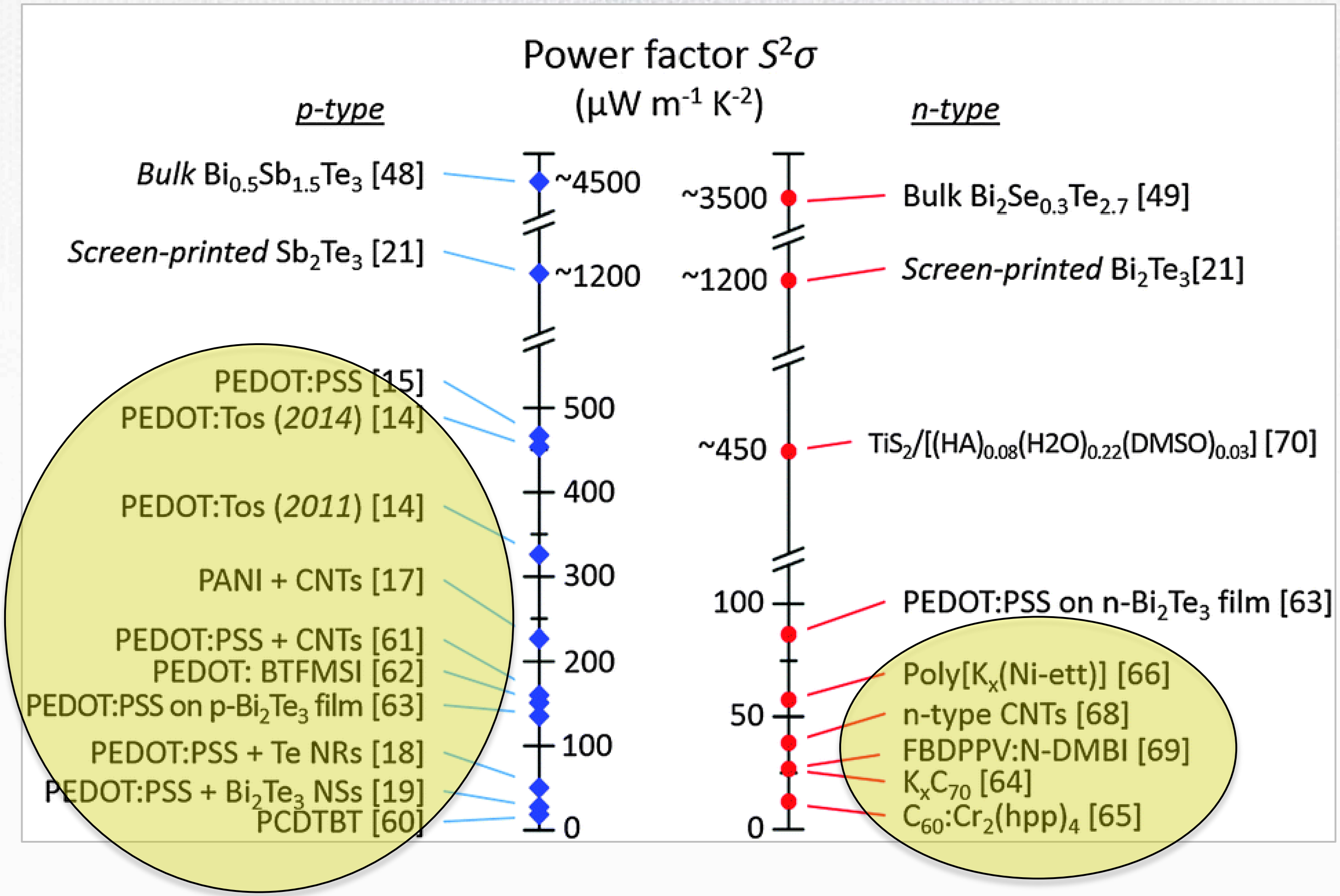


Adapted from: O. Bubnova, and X. Crispin, *Energy Environ. Sci.*, **5**, 9345-9362, 2012.

Part III

POLYMER THERMOELECTRIC MATERIALS

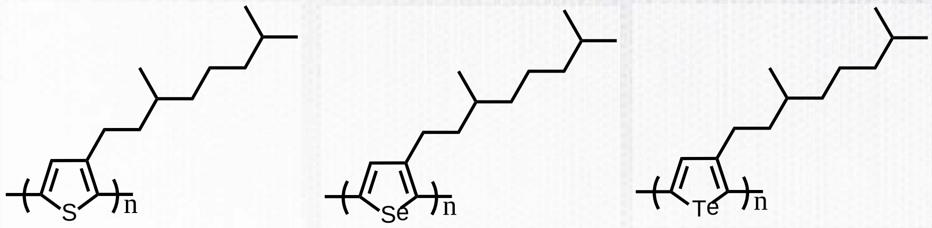
State-of-the-Art Flexible TEs



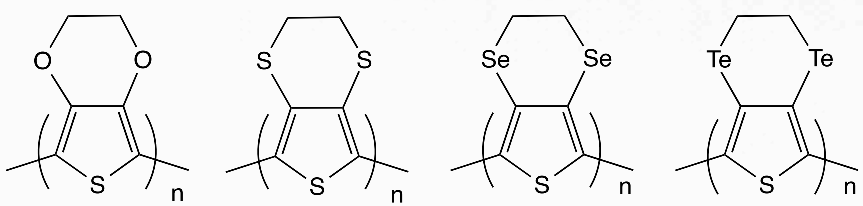
J. Bahk, H. Fang, K. Yazawa, A. Shakouri, *J. Mater. Chem. C*, 2015, **3**, 10362-10374

Thermoelectric Polymers

p-type



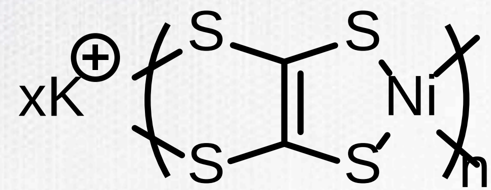
In collaboration with Prof. Dwight Seferos
University of Toronto



PEDOT PEDTT PEDSeT PEDTeT

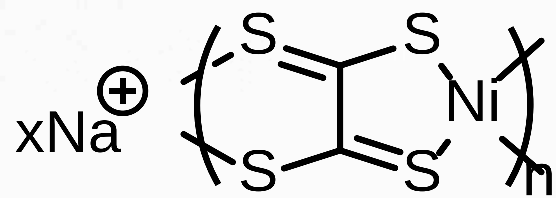
In collaboration with Drs. Peter Bonneson & Kulun Hong
Oak Ridge National Laboratory

n-type



Poly(Ni-ethenetetrathiolate)

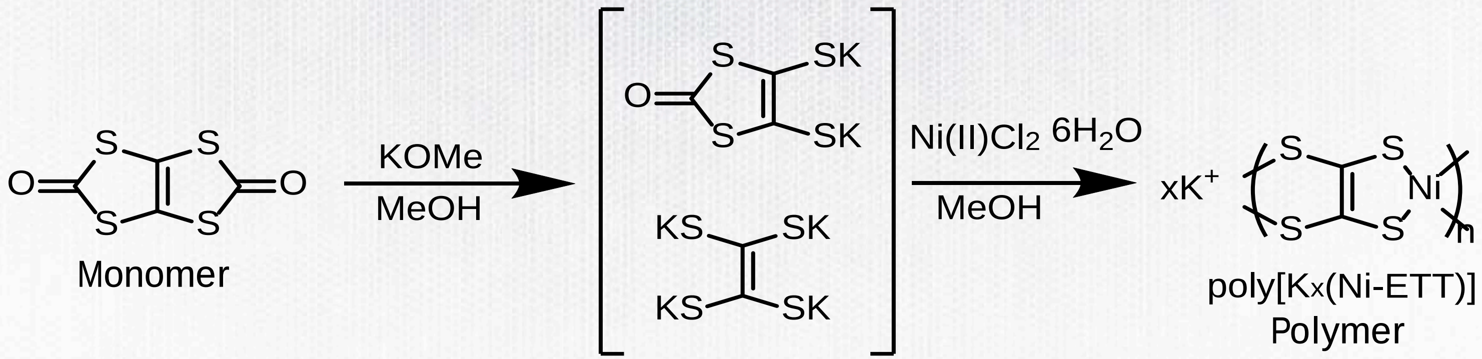
Ni-ETT



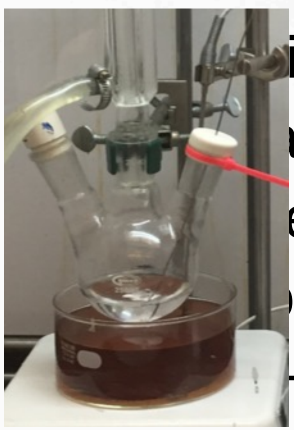
Poly(Ni-tetrathiooxalate)

Ni-TTO

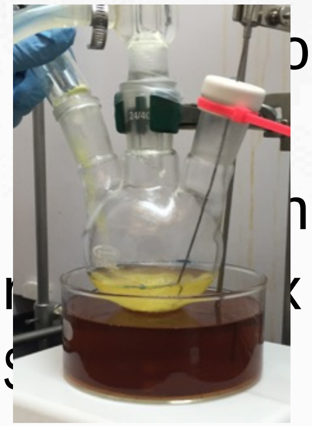
Synthesis of Ni-ETT and Varying the Oxidation Time



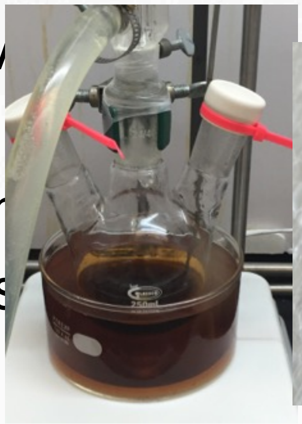
- ir) is o driv
  ation
- er is n com
  an i k is us
  + DMS
- Limited characterization techniques



Dissolve KOMe in methanol



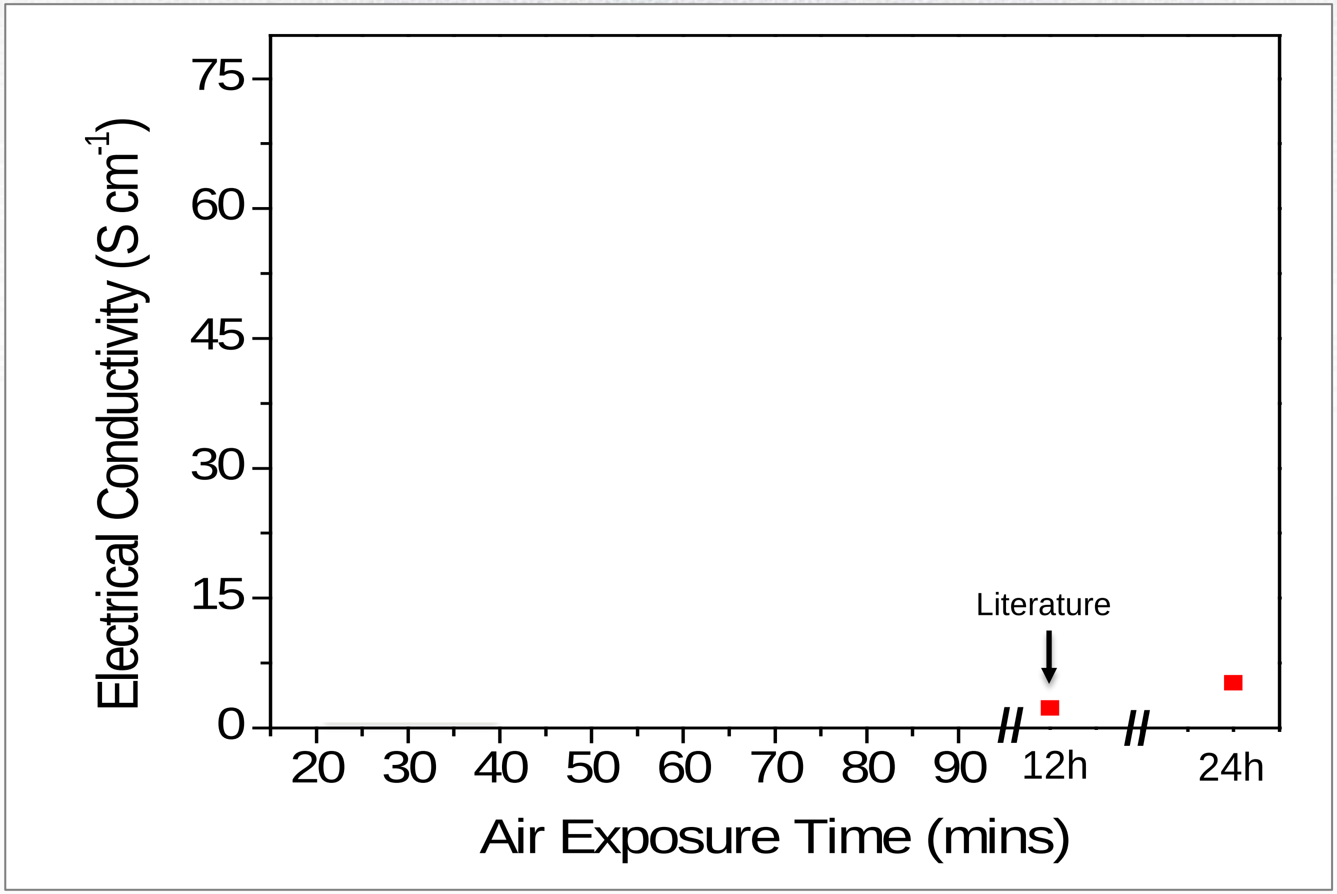
Add TPD monomer



Add $NiCl_2$ and oxidize

Filter and crush into powder

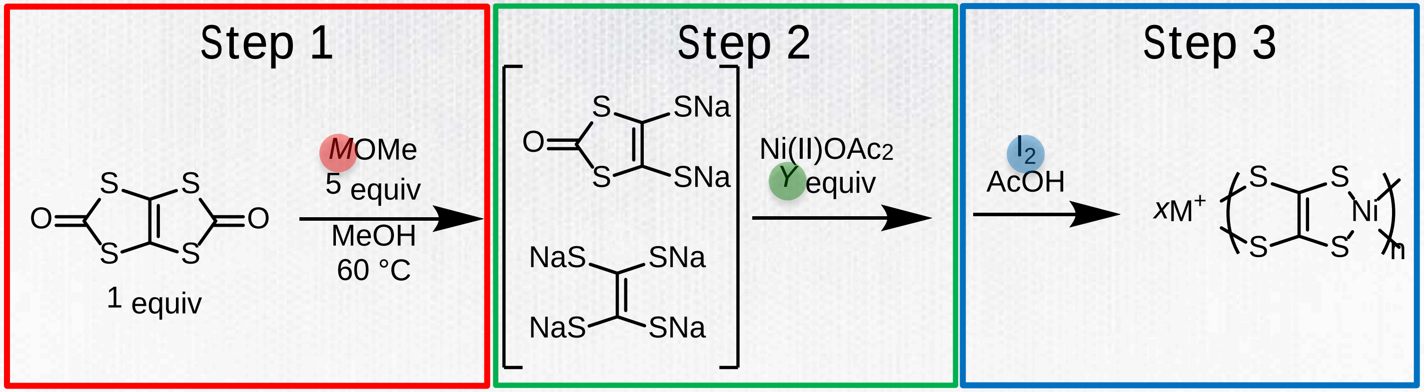
Tuning Electrical Conductivity via Oxidation



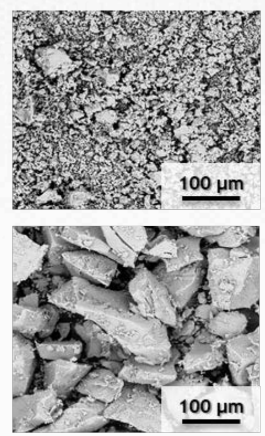
Seebeck coefficient -30 3 μV/K and thermal conductivity is 0.27 0.02 W/m-K remain unchanged

A. Menon et al., *J. Appl. Polym*. Sci, 134, 2017.

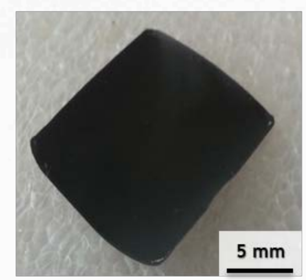
Synthesis of ETT and Film Post-Treatment Allows for Tuning Properties



Sol-gel



SEM of NiETT

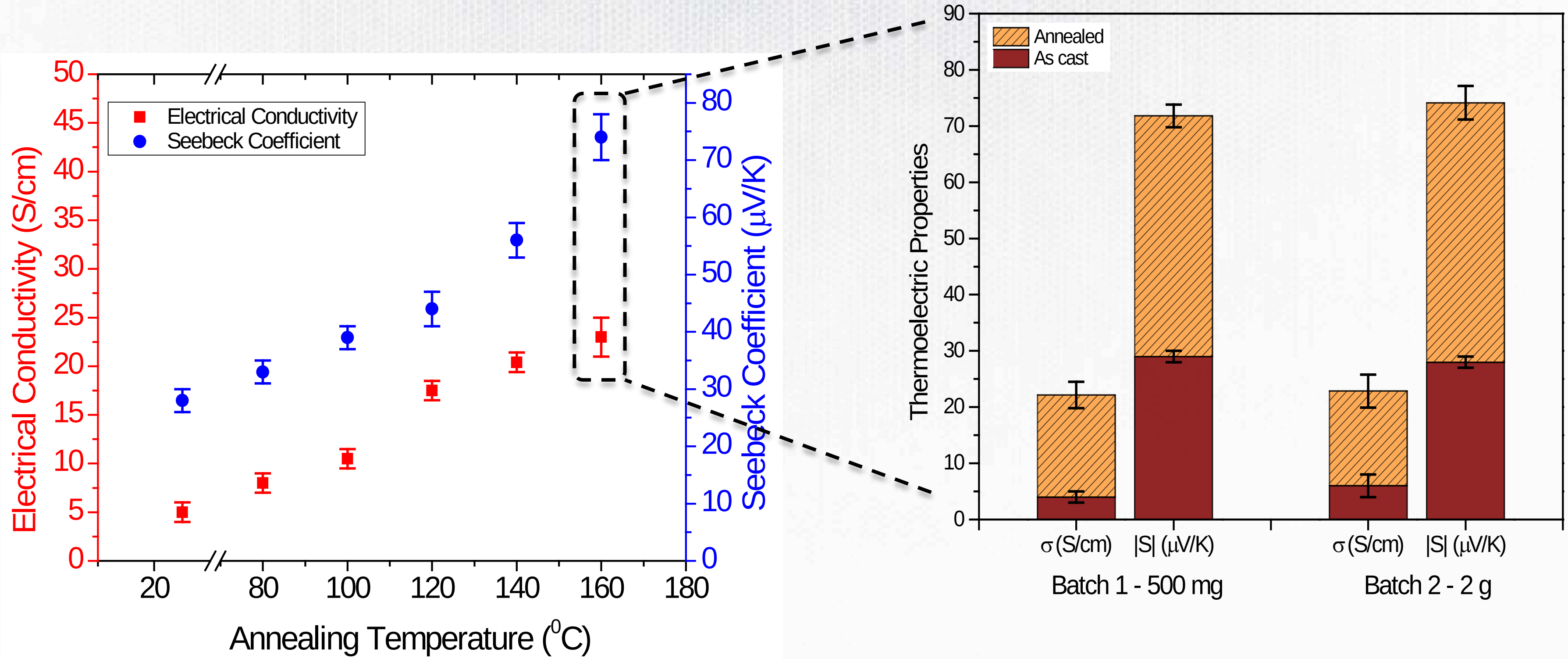


NiETT film with PVDF/DMSO

Measurements at 25 ^{0}C with 4:1 w/w ETT:PVDF/DMSO (matrix is 10 mg/mL).

A. K. Menon, et al., *J. Appl. Polym. Sci*, **134**, 2017.

Film Post-Treatment by Annealing Simultaneously Improves *S* and *σ*

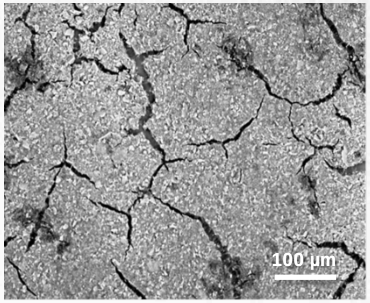


Annealing in air at 160°C for one hour enhances *S* and *σ*.

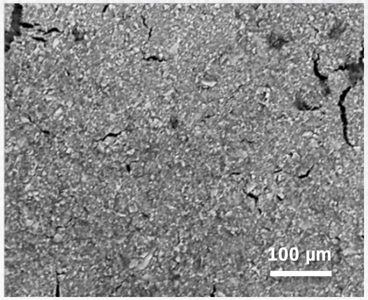
Annealing in air, nitrogen, and vacuum yield similar properties.

Morphological and Compositional Changes occur during Annealing

Morphological changes



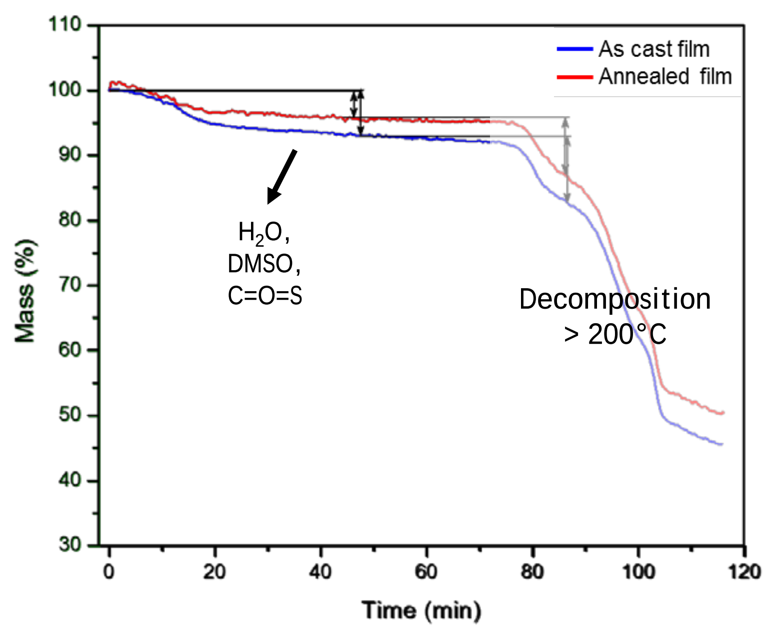
As cast film



Annealed film

Annealing close to the melting temperature of PVDF improves network connectivity, resulting in a higher σ value.

Chemical composition changes



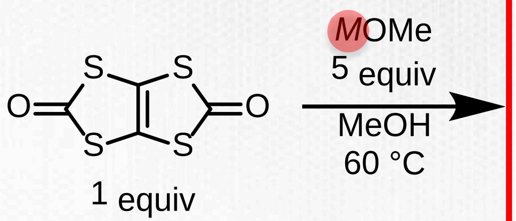
Annealing leads to impurity removal and film densification.

<u>Manuscript under preparation:</u>

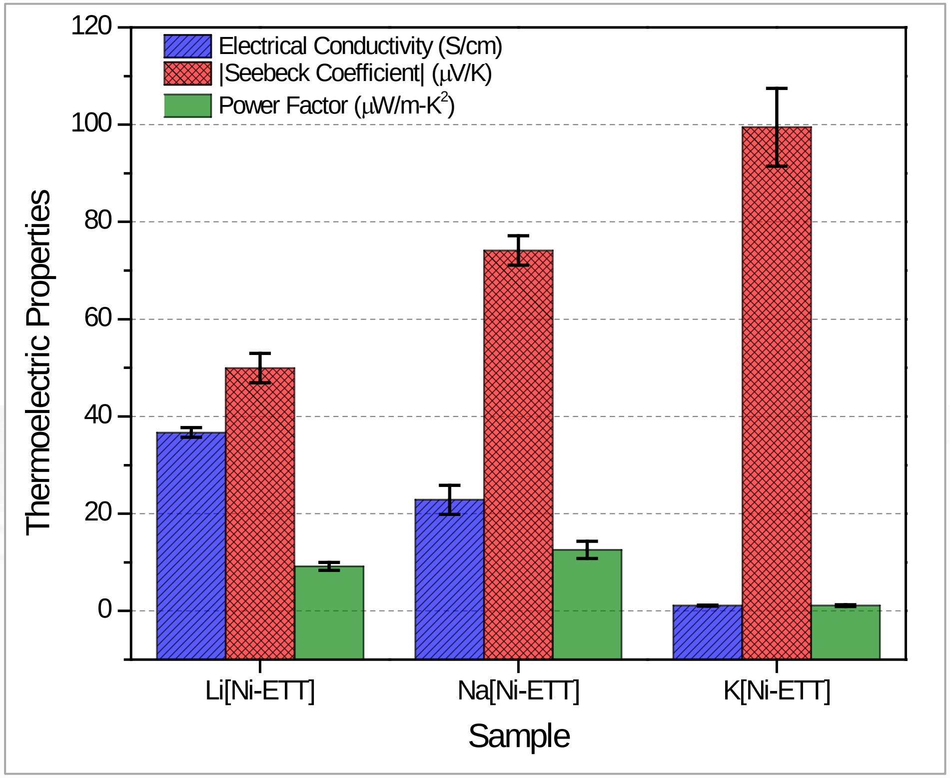
R. M. Wolfe, A. K. Menon, J. R. Reynolds and S. K. Yee, *"Simultaneous Enhancement in Thermoelectric Properties of NiETT Films by Annealing."*

Synthesis Modifications (Step 1): Varying the Counterion

Step 1



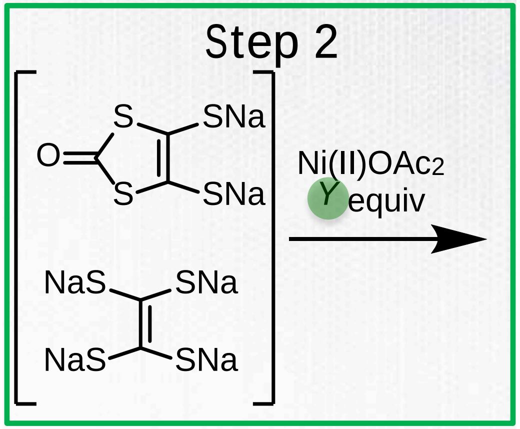
Size of the counterion changes TE properties: Na(NiETT) shows the highest performance



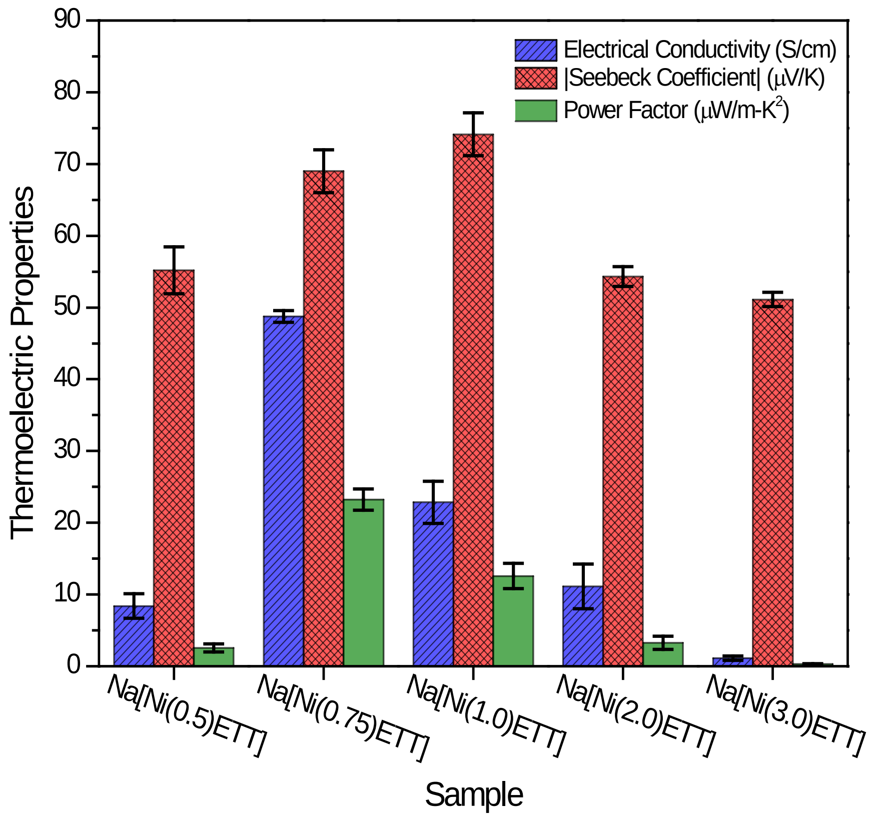
Smaller metal counter-ion = Larger conductivity

Larger metal counter-ion = Larger Seebeck

Synthesis Modifications (Step 2): Optimizing Ni(II) Amount



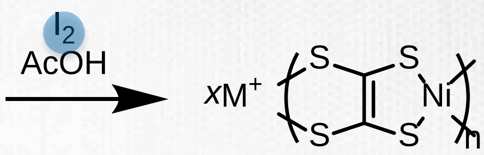
Sub-stochiometric amounts of Ni(II) result in enhanced performance: 0.75 Ni(II) yields highest properties



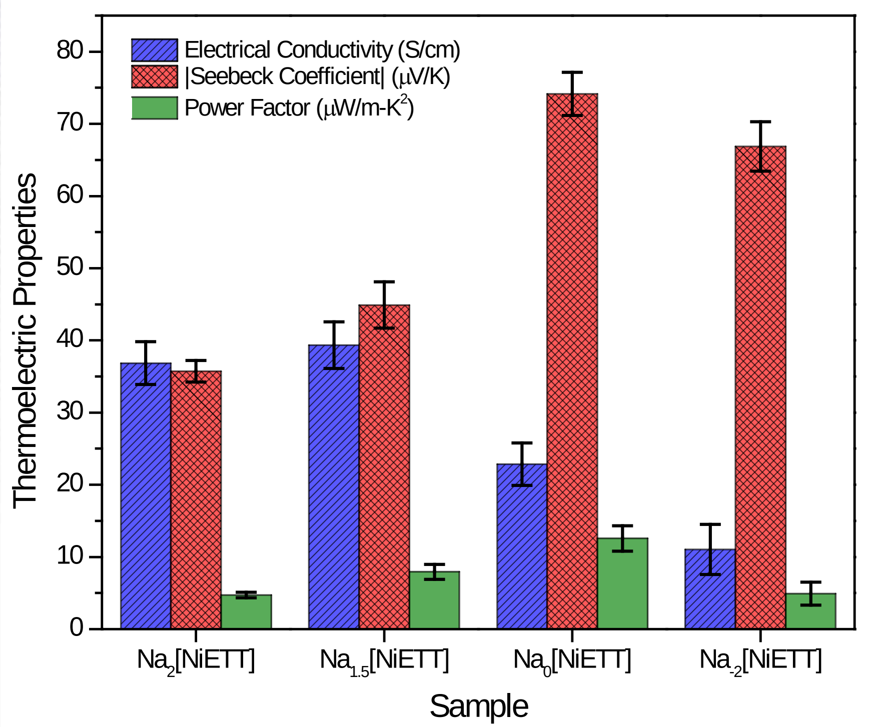
XPS reveals that the presence of excess Ni results in the formation of secondary products such as $NiSO_4$ and $Ni(OH)_2$.

Synthesis Modifications (Step 3): Tuning the Oxidation Level

Step 3



Iodine can tune the oxidation level by extracting electrons from the polymer backbone

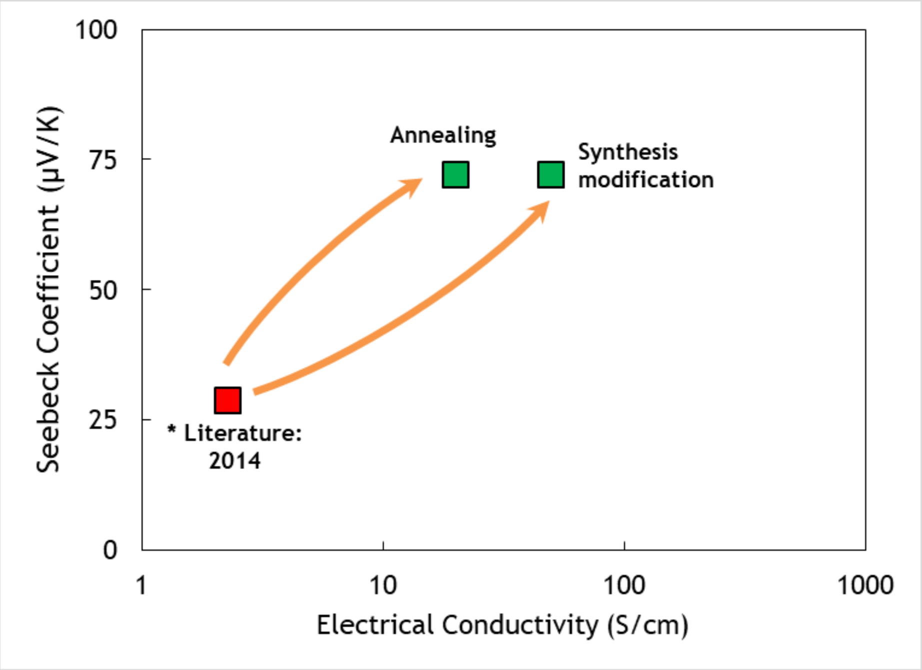


XPS reveals that the oxidation is a ligand-centered process.

Manuscript under preparation

A. K. Menon, R. M. Wolfe, J. R. Reynolds and S. K. Yee, *"Systematic Power Factor Optimization in n-type NiETT/PVDF Composite Films."*

Development of a High Performance and Air Stable n-type Polymer

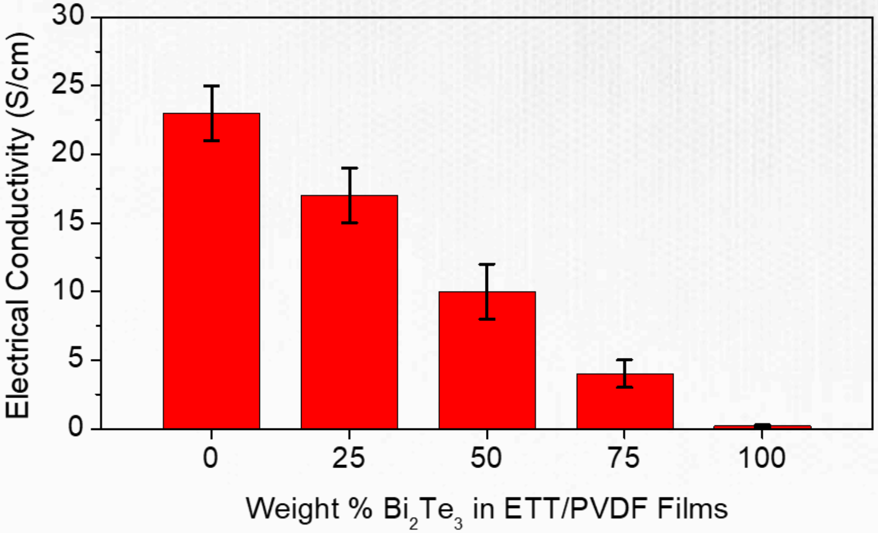


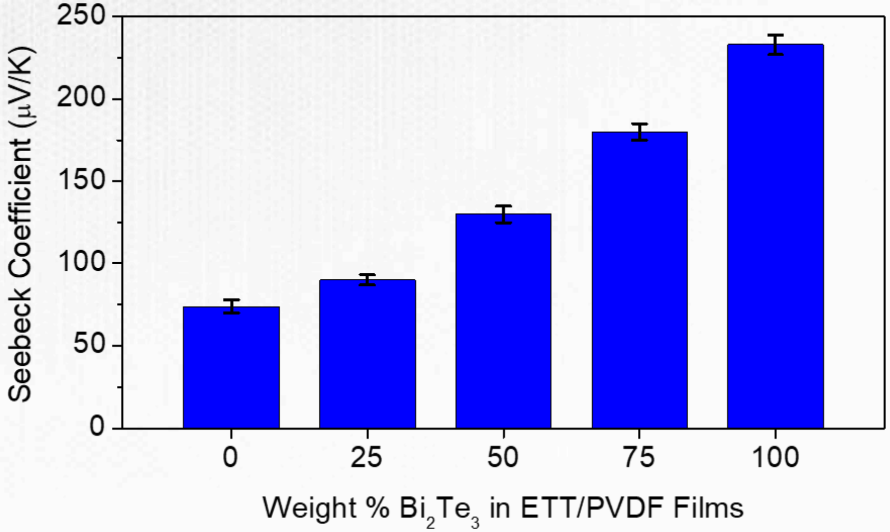
* F. Jiao et. al., *Phil Trans R Soc A*, **372**, 2014.

Highest σ for a solution processed n-type film, maintains air stability, tunable viscosity for printing applications.

Enabling Organic – Inorganic Composites

Development of an air stable n-type polymer with high conductivity enables composites with a high σ (from NiETT) and high S (from Bi_2Te_3)





50 wt.% n-type Bi_2Te_3 in ETT/PVDF films results in

σ = 10 S/cm and S = -130 μV/K.

This enables printable organic-inorganic composites.

Part IV

THERMOELECTRIC DEVICES

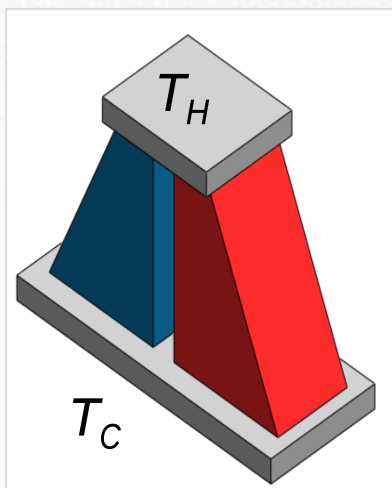
New Architectures for Polymer TEGs

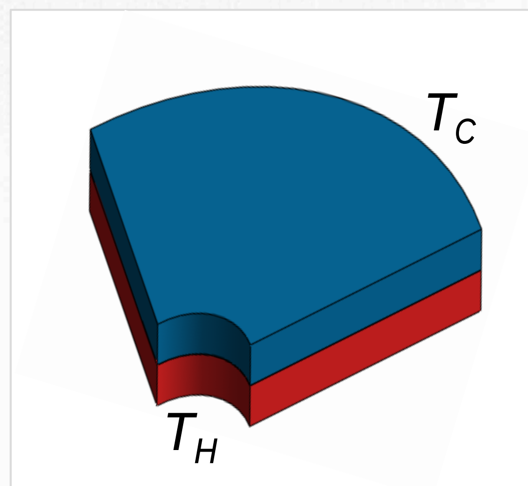
$/W → F > 1

Yee et. al., *Energy Environ. Sci.*, **6**, 2013.

Cooled by natural convection alone

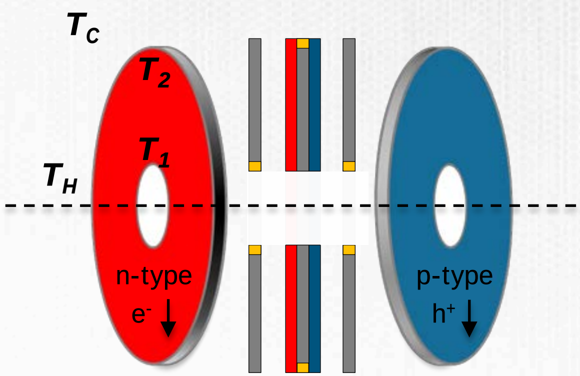
Heat spreading



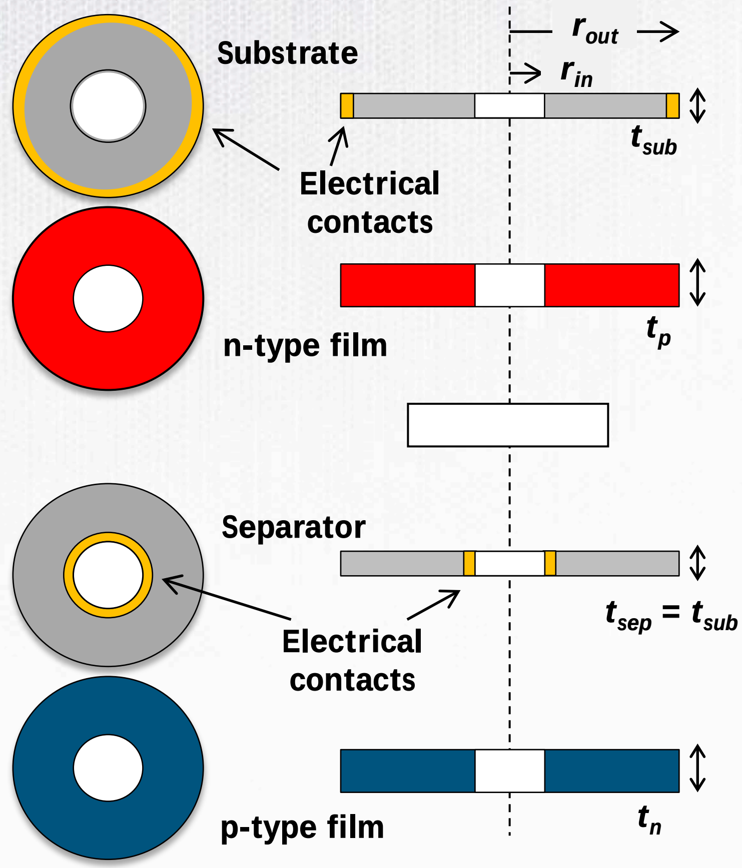


Menon & Yee. J. of Appl. Physics, 119 (055501) 2016

Radial TEG Concept



$$F = \frac{A_{TE}}{A_{HX,H}} = \frac{2\pi r_{out}(t_p + t_n)}{2\pi r_{in}(t_p + t_n)} \approx \frac{r_{out}}{r_{in}} > 1$$



Menon & Yee. J. of Appl. Physics, 119 (055501) 2016

Conditions for Maximum Efficiency and Module *ZT*

- Relates device geometry with material properties
- Maximizes *ZT* and device efficiency

Module *ZT*

$$ZT = \frac{S_{pn}{}^{2}T}{R_{el}K_{th}}$$

	Flat-plate	Radial
Electrical Resistance, R_{TE}	$\frac{L_p}{\sigma_p A_p} + \frac{L_n}{\sigma_n A_n}$	$\frac{\ln\left(r_{out,p}/r_{in,p}\right)}{2\pi\,\sigma_p t_p} + \frac{\ln\left(r_{out,n}/r_{in,n}\right)}{2\pi\,\sigma_n t_n}$
Thermal Conductance, K_{TE}	$\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n}$	$\frac{2\pi k_p t_p}{\ln\left(r_{out,p}/r_{in,p}\right)} + \frac{2\pi k_n t_n}{\ln\left(r_{out,n}/r_{in,n}\right)}$
Geometry Matching Condition	$\frac{A_n l_p}{A_p l_n} = \sqrt{\frac{k_p \sigma_p}{k_n \sigma_n}}$	$\frac{t_n \ln\left(r_{out,p}/r_{in,p}\right)}{t_p \ln\left(r_{out,n}/r_{in,n}\right)} = \sqrt{\frac{k_p \sigma_p}{k_n \sigma_n}}$

Menon & Yee. J. of Appl. Physics, 119 (055501) 2016

Optimum Leg Length for Maximum Power Density

Includes heat exchangers to obtain temperature distribution across device

	Flat-plate	**Radial**
Thermal Impedance Matching Condition L_{match}	$L = 2FL_T$	$\ln\left(\frac{r_{out}}{r_{in}}\right) = \left(\frac{L_T}{r_{out}}\right)$
Optimum Leg Length L_{opt}	$L \approx 2FL_T$	$\ln\left(\frac{r_{out}}{r_{in}}\right) \approx \left(\frac{L_T}{r_{out} - 2L_T}\right)$

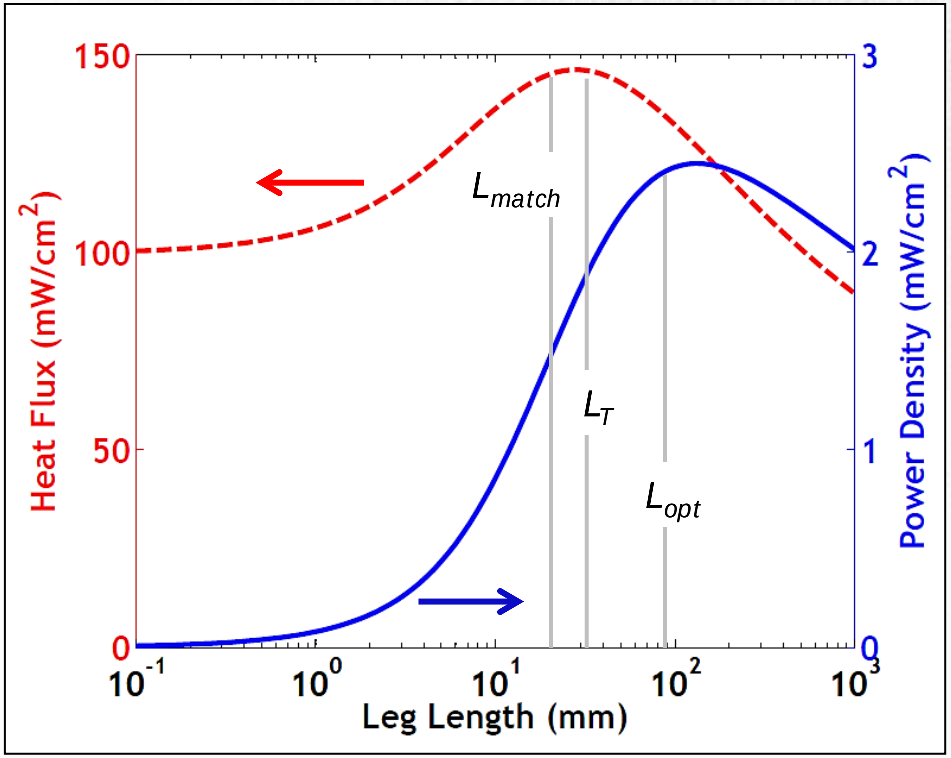
For radial TEG, $L_{opt} > L_{match}$ making it advantageous to operate under natural convection

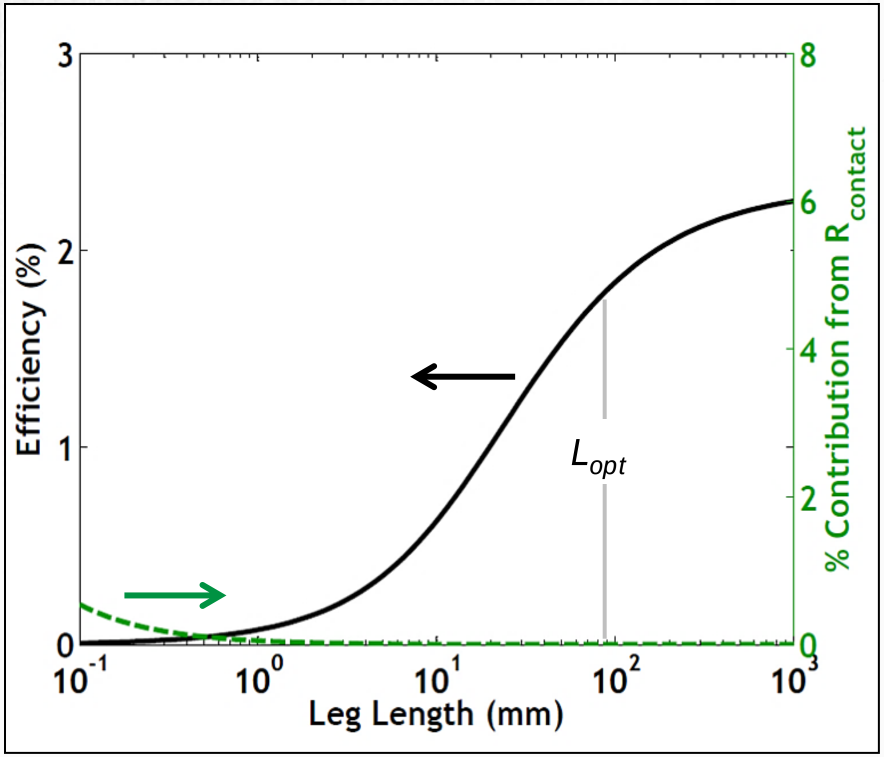
Menon & Yee. J. of Appl. Physics, 119 (055501) 2016

Radial TEG is Advantageous for Thin-Film Devices

*Dedoped DMSO-mixed PEDOT:PSS

S = 72 µV/K, σ = 890 S/cm, and k = 0.33





Negligible electrical contact resistance due to larger area of contact

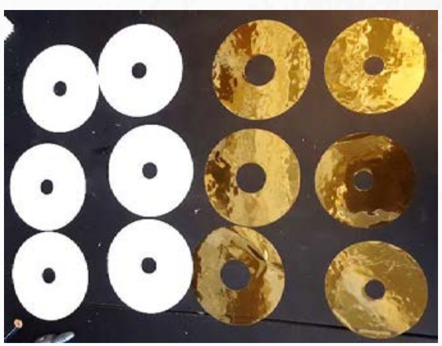
* Kim et. al., *Nature Materials*, **12**, 2013.
Menon & Yee. J. of Appl. Physics, 119 (055501) 2016

Radial TEG Proof-of-Concept

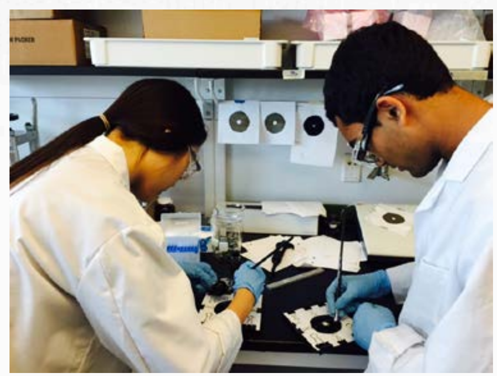
- **p-type[1]** - PEDOT:PSS with Te nanowires
- **n-type[2,3]** – Poly[K_x(Ni-ett)] blended with PVDF/DMSO

p-type zT values at 300 K	
Polymer Thin-Film[1]	0.1
Paper composite	0.15×10^{-3}

n-type zT values at 300 K	
Polymer Thin-Film[3]	0.2
Paper composite	0.3×10^{-3}



Substrates: copy paper
Separators: polyimide



Paint p- and n-type polymers

Paint electrodes (silver ink)

[1] Yee et. al., *Phys. Chem. Chem. Phys.*, **15**, 2013. [2] Sun et. al., *Adv. Mater.*, **24**, 2012. [3] Jiao et. al., *Phil. Trans. R. Soc. A*, **372**, 2014.

Menon, Meek, Eng, & Yee. J. of Appl. Polymer Sci,, 134, 3, (44060), 2016

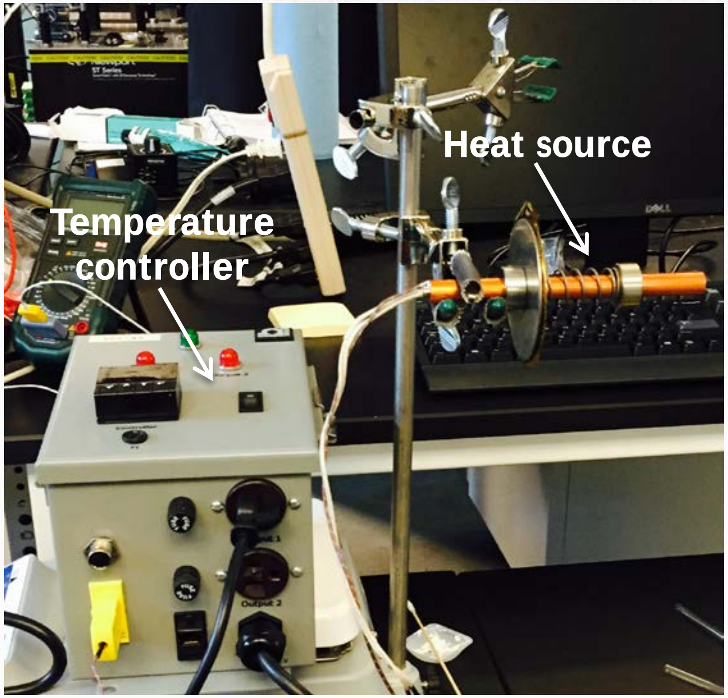
Experimental Setup

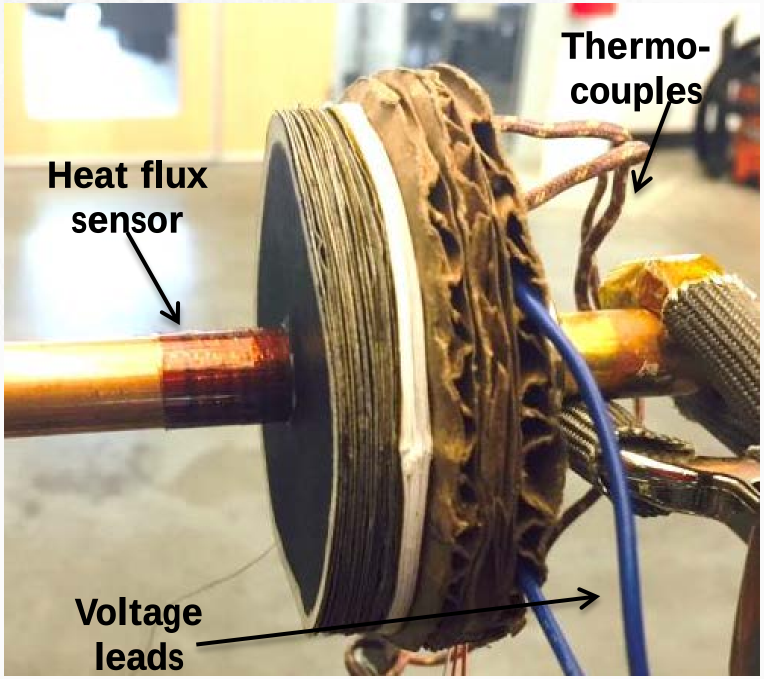
r_{out} = 35 mm

r_{in} = 6.5 mm

t_{sub} = 100 μm

t_{sep} = 25 μm

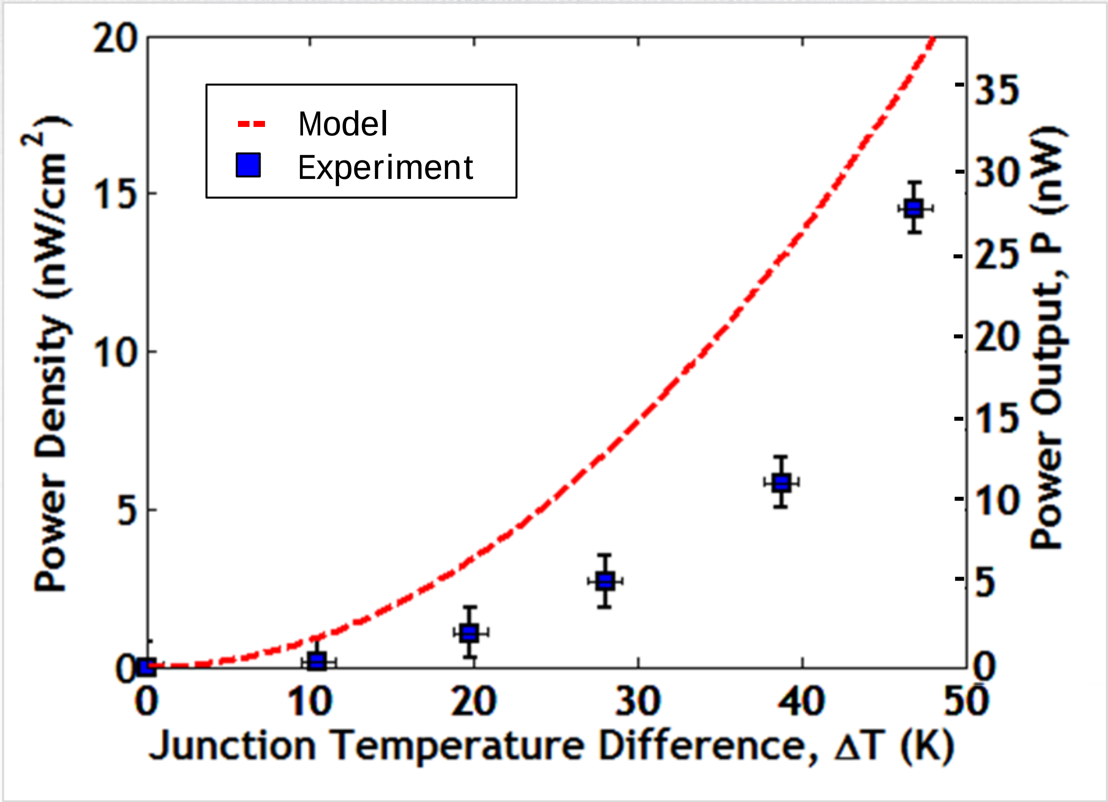




Menon, Meek, Eng, & Yee. J. of Appl. Polymer Sci,, 134, 3, (44060), 2016

Device Performance

15 p-n junctions



Max. power output = 27 nW and power density = 14.5 nW/cm^2

Max. open circuit voltage = 85 mV/K

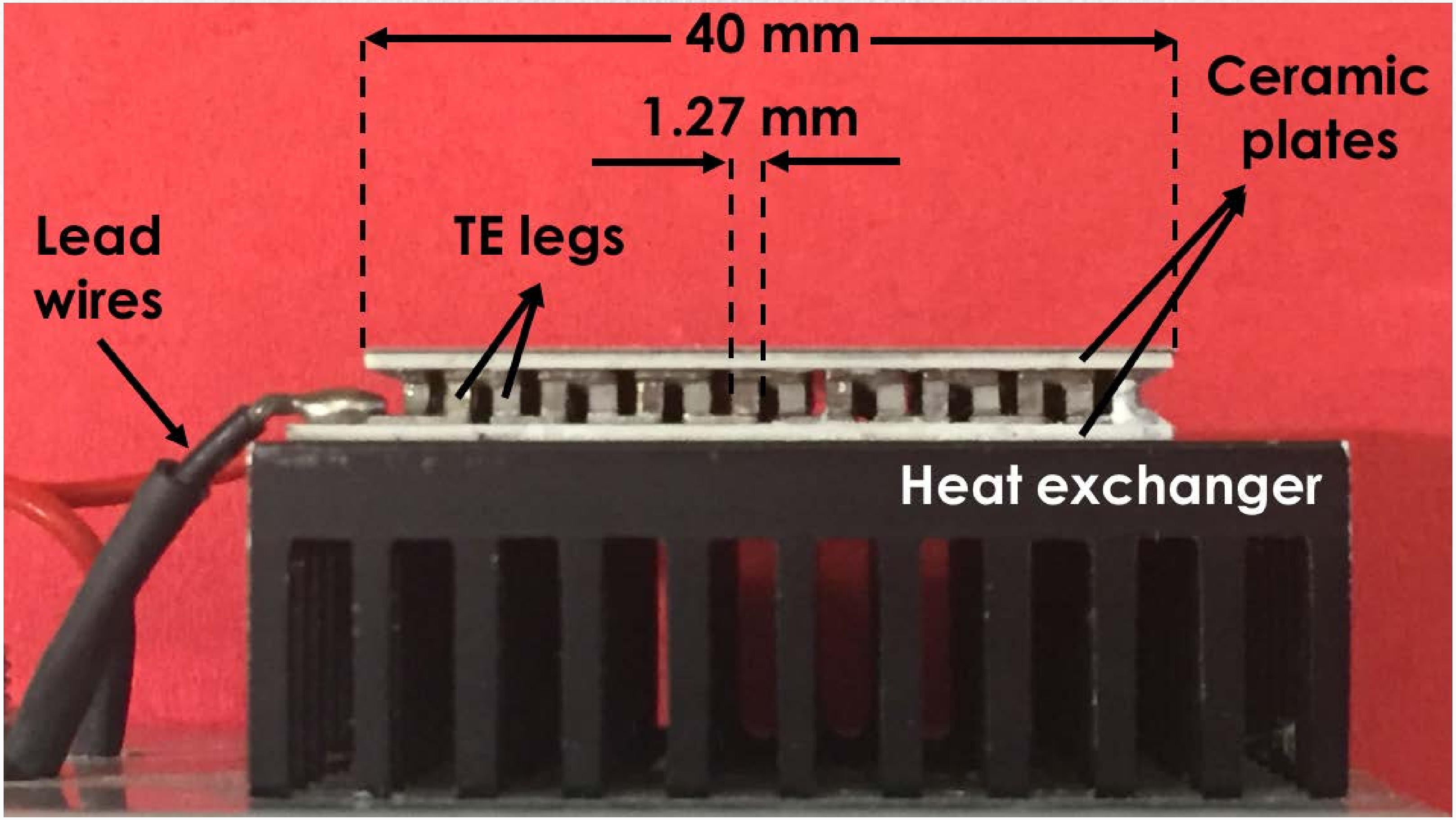
First demonstration of a radial polymer TEG

Menon, Meek, Eng, & Yee. J. of Appl. Polymer Sci,, 134, 3, (44060), 2016

Part V

PRINTED THERMOELECTRICS & TEXTILE-INTEGRATED THERMOELECTRICS

Conventional Inorganic Thermoelectric Module



FF=0.25

Leg Length ~1.5 mm

Gordiz, Menon, & Yee. *Journal of Applied Physics, 122, 124507, 2017*

Comparing Inorganic and Polymer Thermoelectrics

Inorganics **- Bi_2Te_3**

$\sigma \approx$ 1000 S/cm
$S \approx$ 200 μV/K
$k \approx$ 1.2 W/m-K
$S^2\sigma \approx$ 4000 μW/m-K^2
$zT \approx$ 0.8

Costs
Material: $125/kg
Manufacturing: $165/m^2

2-3x more couples

HX considerations

$$\eta \le \frac{ZT}{4}\frac{\Delta T}{T_H}$$

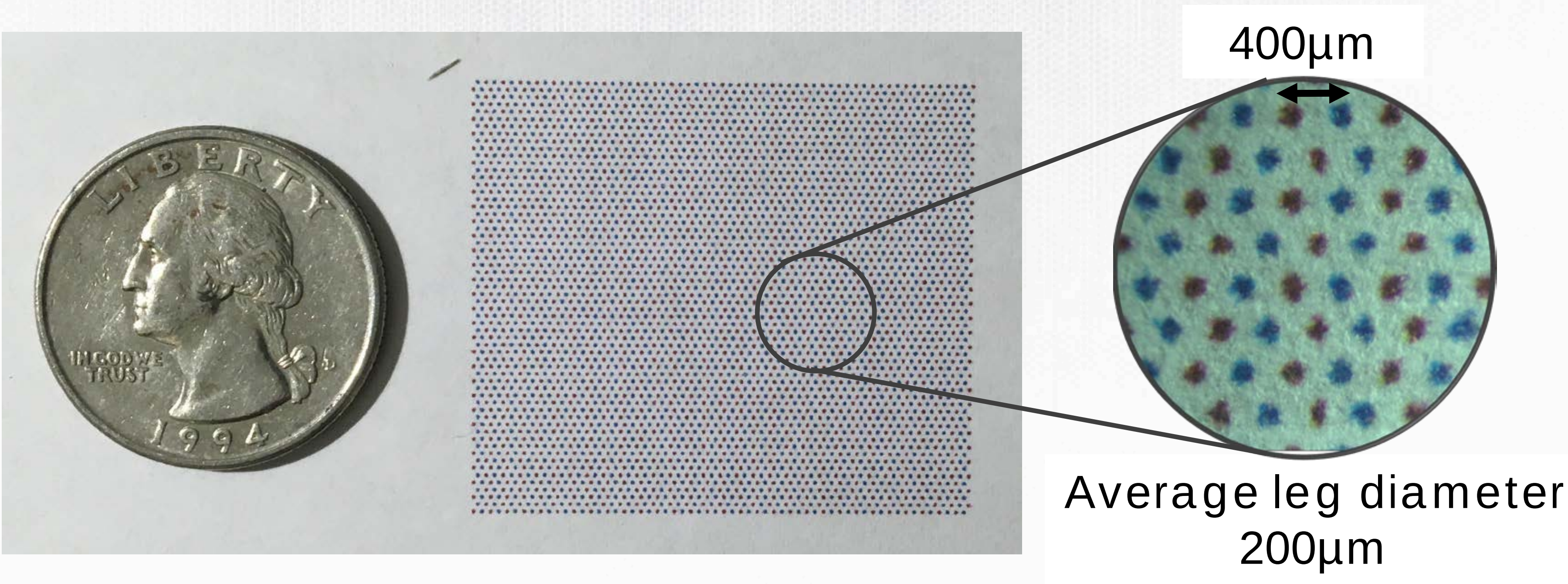
Low Cost Manufacturing

Polymers **- PEDOT:PSS**

$\sigma \approx$ 900 S/cm
$S \approx$ 75 μV/K
$k \approx$ 0.25 W/m-K
$S^2\sigma \approx$ 500 μW/m-K^2
$zT \approx$ 0.4

Costs
Material: $0.34/kg
Manufacturing: $4.76/m^2

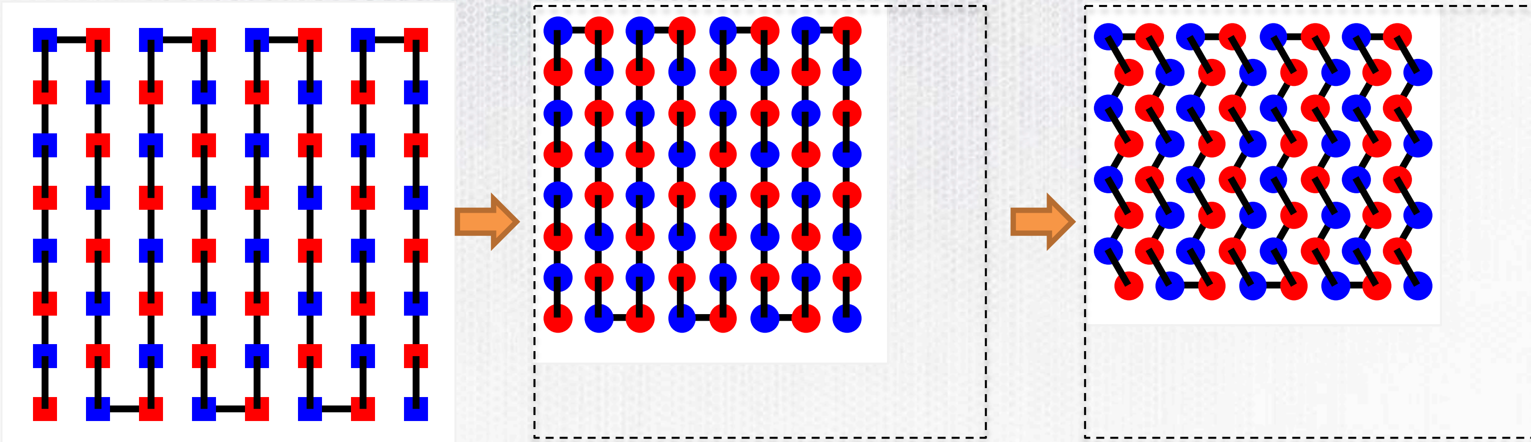
Printed Thermoelectrics

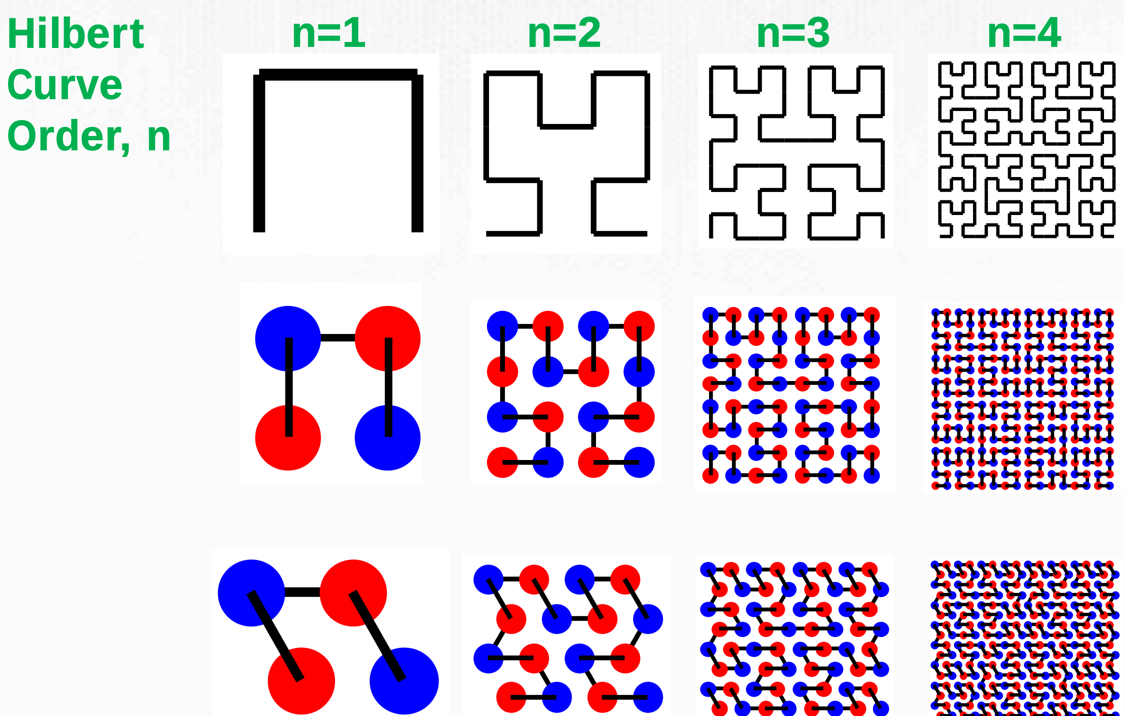


FF=0.90
Leg Length 0.160 mm

Gordiz, Menon, & Yee. *Journal of Applied Physics, 122, 124507, 2017*

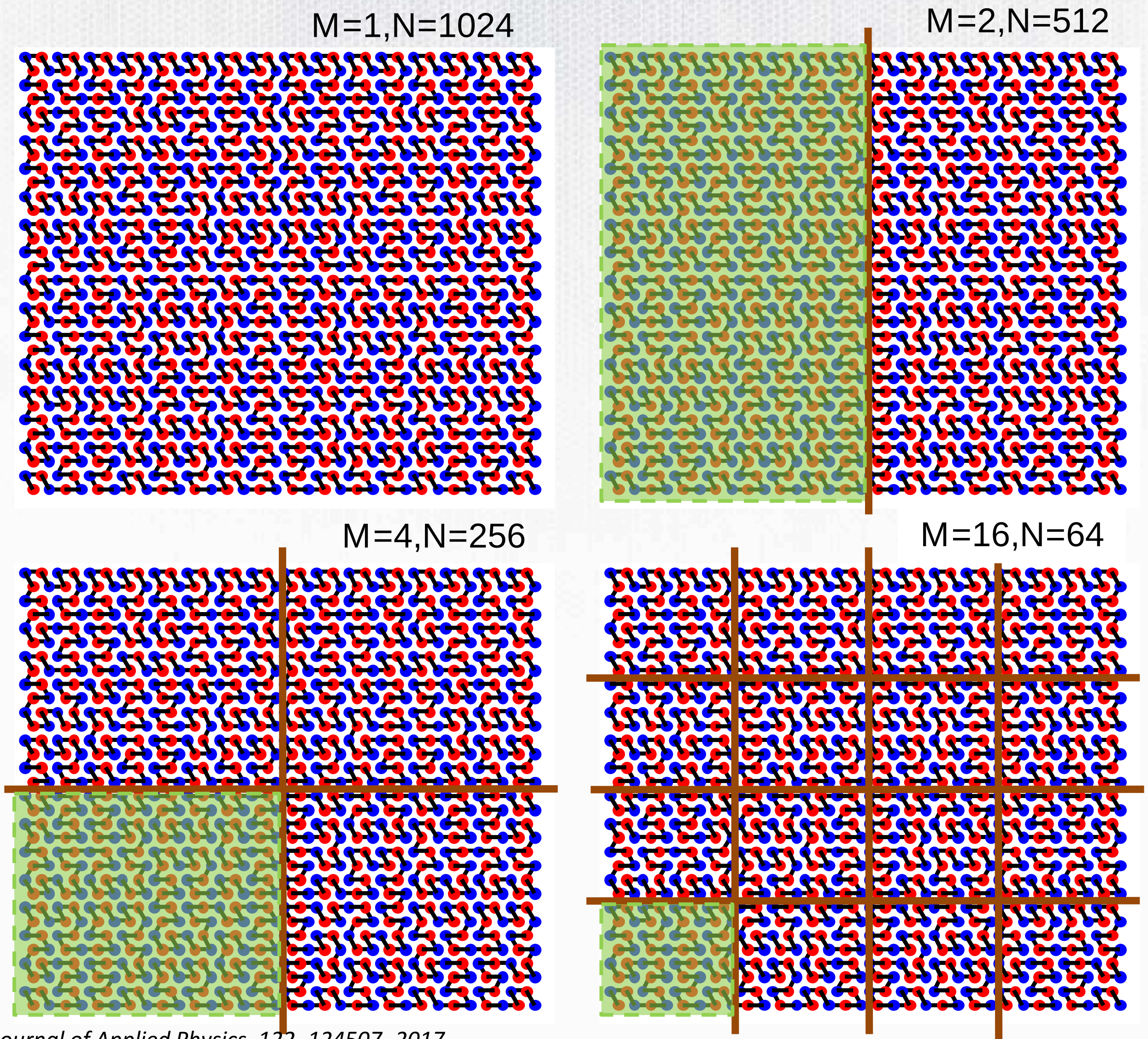
Interconnect Patterns





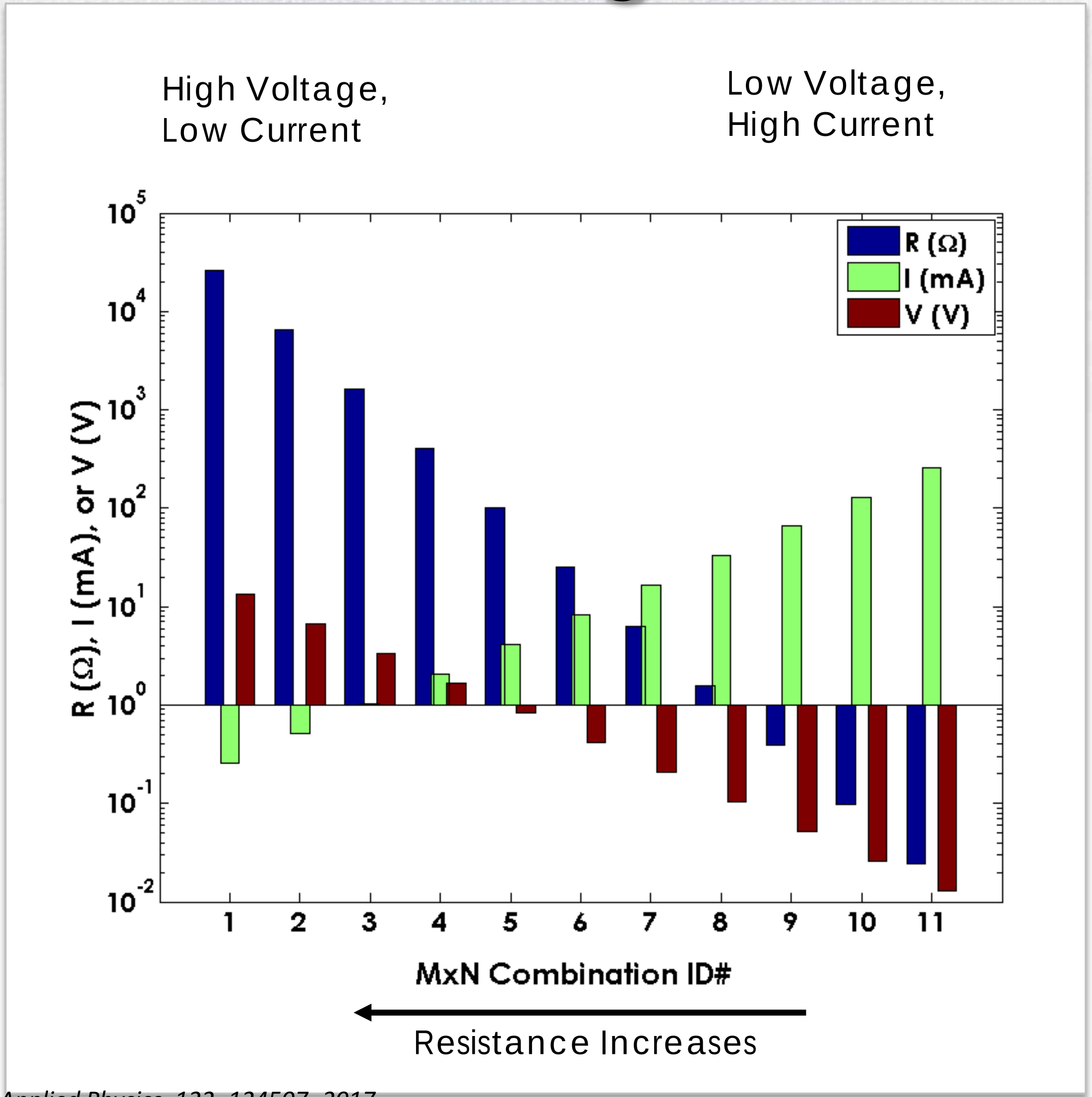
Gordiz, Menon, & Yee. *Journal of Applied Physics, 122, 124507, 2017*

Sub-Module Localization



Gordiz, Menon, & Yee. *Journal of Applied Physics, 122, 124507, 2017*

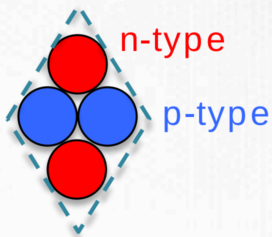
Impedance tuning avoids power conditioning circuits



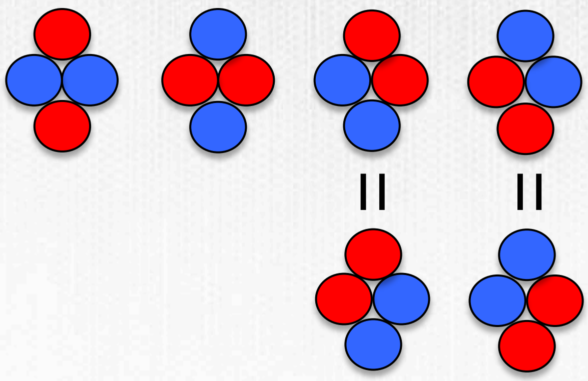
Gordiz, Menon, & Yee. *Journal of Applied Physics, 122, 124507, 2017*

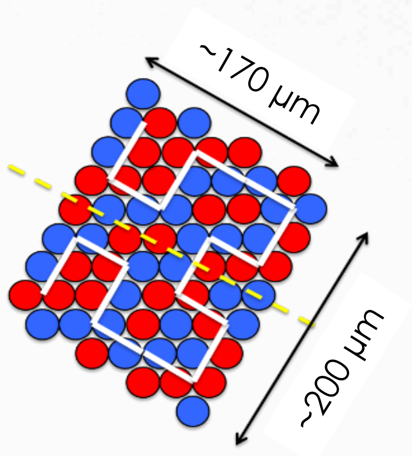
Printing into any shape requires a change of basis from two-legs to four-legs

Cell



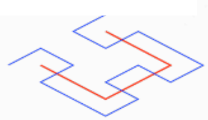
4 types of cells

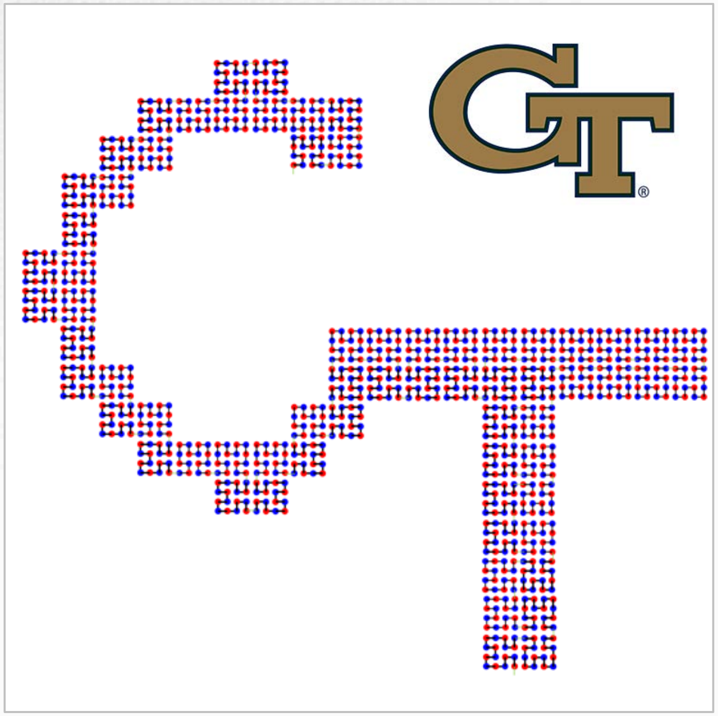




n=2
[Total # legs]=64

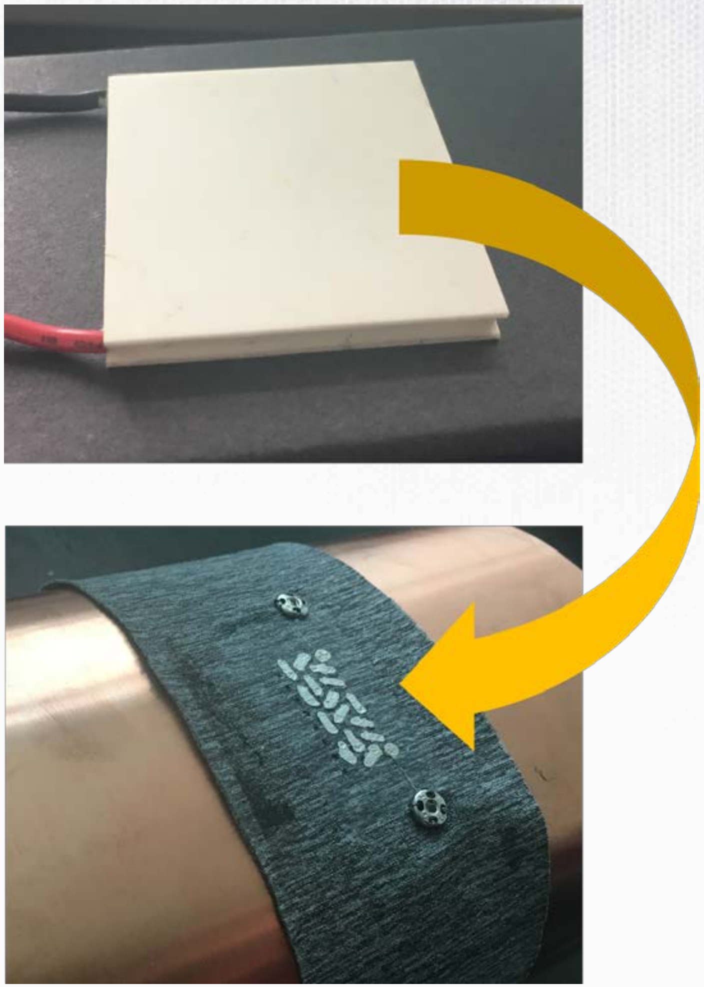
4 x 4

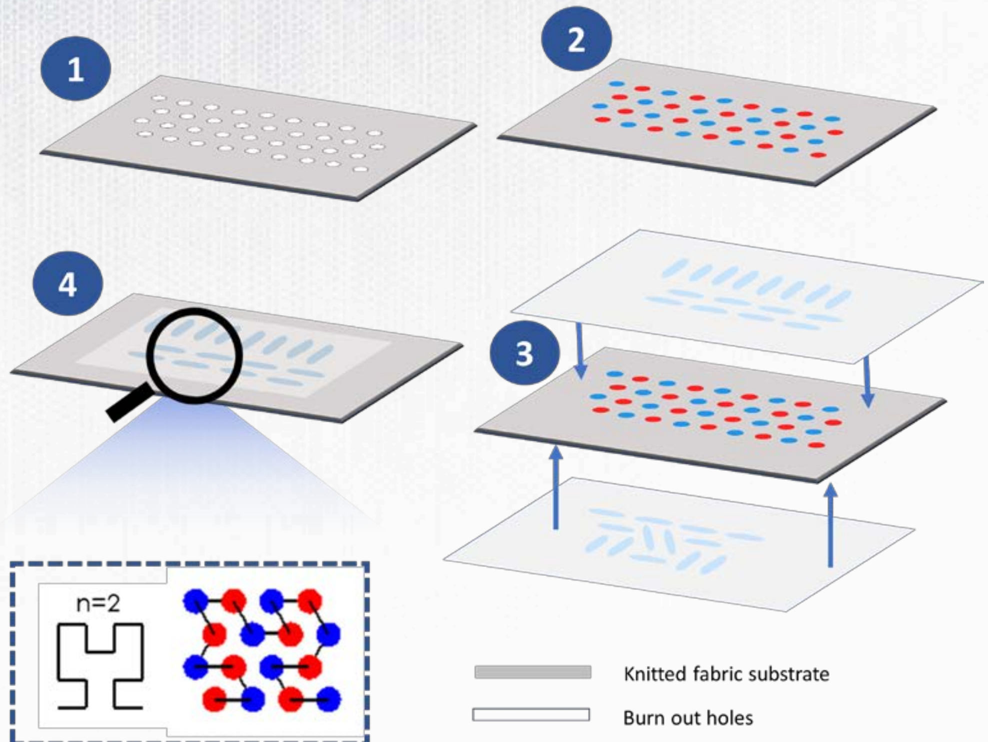




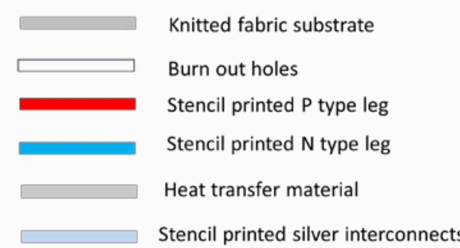
Gordiz, Menon, & Yee. *Journal of Applied Physics, 122, 124507, 2017*

Textile-Integrated Devices

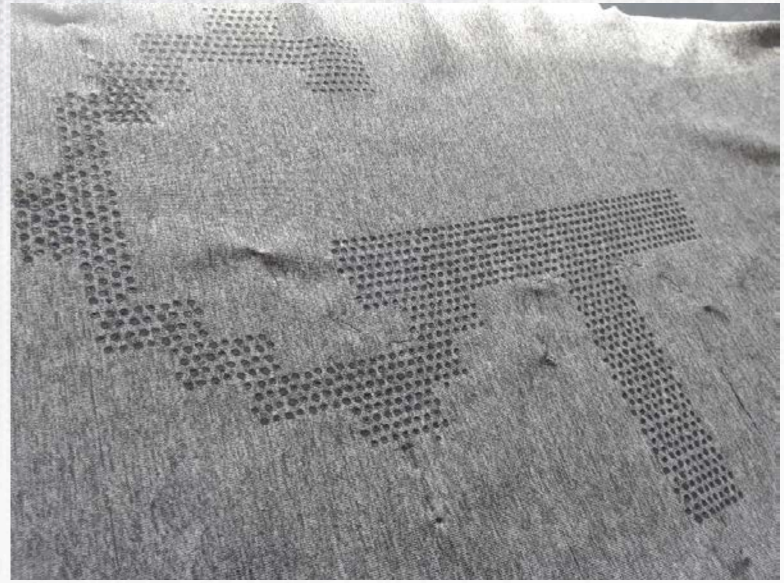


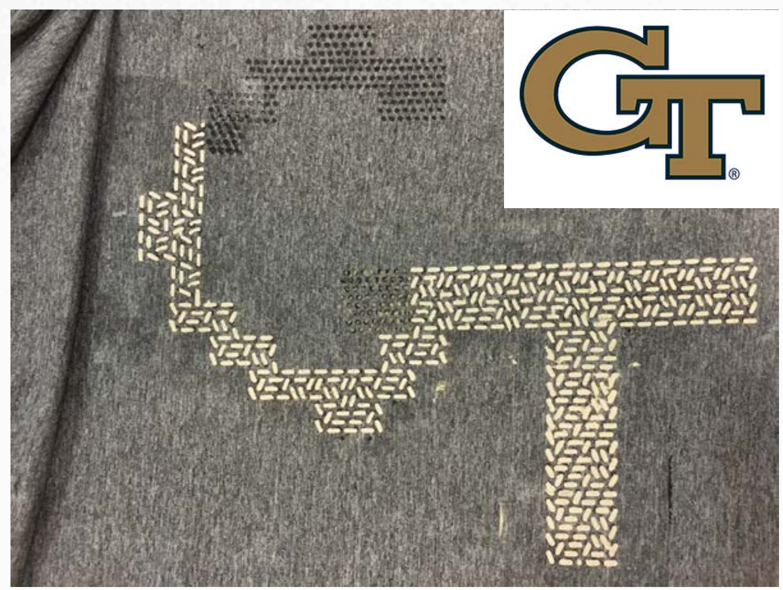


TE legs arranged in hexagonal closed-packed layout and connected by the Hilbert curve thus increasing the Fill Factor (FF=0.36)



Design Concepts: Textile-Integrated TE





To Be Continued...

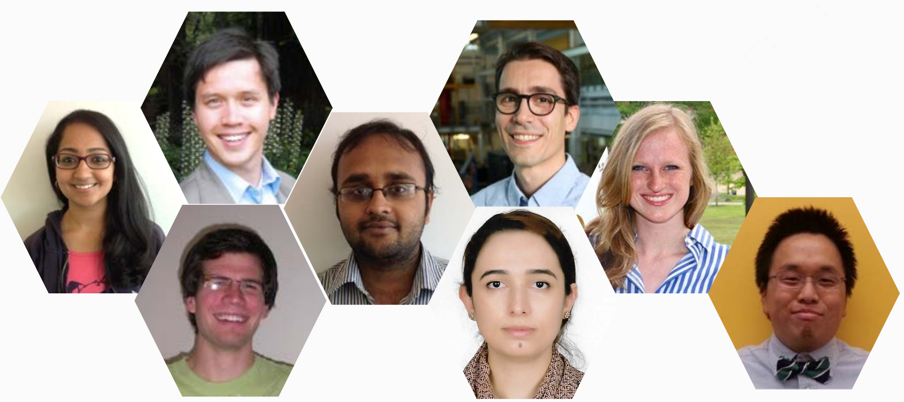
Georgia Institute of Technology

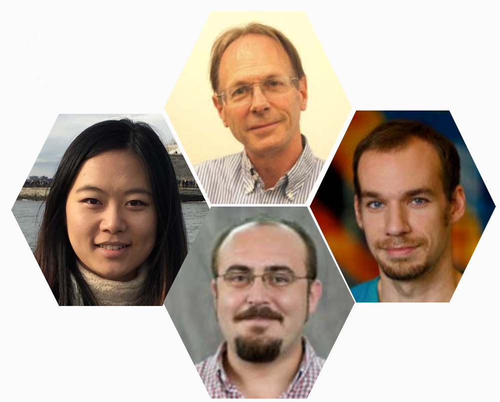
ORGANIC THERMOELECTRICS

Prof. Shannon Yee
Akanksha Menon – PhD Candidate
Rylan Wolfe – PhD Candidate
Sampath Kommandur – PhD Candidate
Dr. Kiarash Gordiz – Colorado School of Mines
Dr. Hend Elmoghunni – Qatar STP
Arnold Eng – PNNL
Olivia Meek – Landis & Gyr

Prof. John Reynolds
Dr. Bing Xu
Dr. Urdal Uzunlar
Dr. James Ponder – Imperial College

Prof. Seth Marder
Dr. Desari “Reddy” Raghunath





STEEL & Collaborators

Graduate Students
- Akanksha Menon
- Sampath Kommandur
- David Rodin
- Alex Limia
- Jong Ha
- Rylan Wolfe
- Aravindh Rajan
- Patrick Creamer
- Shawn Gregory

Research Scientists/Postdocs
- Dr. Andrey Gunawan
- Dr. Hend Elmoughni

Undergraduate Researchers
- Shikai Jin
- Andres Menedez
- Sebastien Fernandez
- Jade Marcus
- Kartavya Argawal
- Tim Monroe
- Colten Spivey

STEEL Alumni
- Olivia Meek-Landis+Gyr
- Steven Bohlemann-UTC
- John Kearns-GT
- Jason Hirschey-GT
- Arnold Eng-PNNL
- Jefferson Dixon-Stanford
- Nachiket Naik-CalTech
- Venkatesh Chinnakonda-Tesla
- Dr. Kiarash Gordiz-CSM
- Dr. Seid (Bez) Sadat-Google
- Dr. Thomas Boucher-GT

Lawrence Livermore National Laboratory
- Dr. Jim Trebes

Oak Ridge National Laboratory
- Dr. Peter Bonnesen
- Dr. Kunlun Hong

Stanford University
- Prof. Arun Majumdar's Group
- Prof. Steven Chu's Group

Purdue University
- Prof. Bryan Boudouris' Group

Ceramatec Inc
- Shekar Balagopal

GT Collaborators
- Prof. Andrei Fedorov's Group
- Prof. Seung Woo Lee's Group
- Prof. Seth Marder's Group
- Prof. John Reynolds' Group
- Prof. Peter Hesketh's Group
- Prof. Ajeet Rohatgi's Group
- Prof. Baratunde Cola's Group
- Prof. Sam Graham's Group
- Prof. Mark Losego's Group
- Prof. Asegun Henry's Group

Sponsors:

Building Tech. Off.