Thermoelectricity: From Atoms to Systems

Week 3: Thermoelectric Characterization

Lecture 3.4: Thin Film Thermoelectric Characterization

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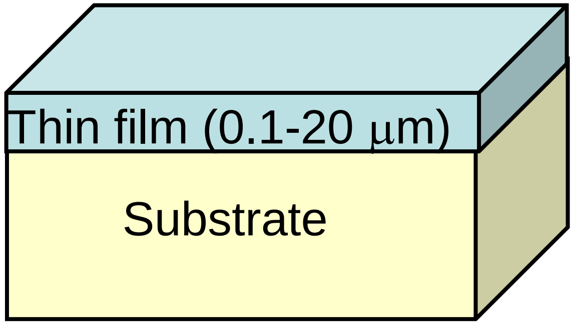
Thin film thermal characterization

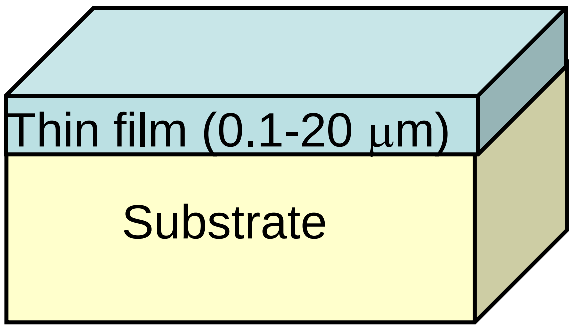


Applications:
- TE material optimization
- Important in electronic and optoelectronic device optimization

Thermal conductivity measurement

- Cross-Plane: (3ω, laser thermoreflectance –next lecture)
- In-Plane: need suspended structures or modeling of heat flow around point/line sources

Thin film electrical characterization



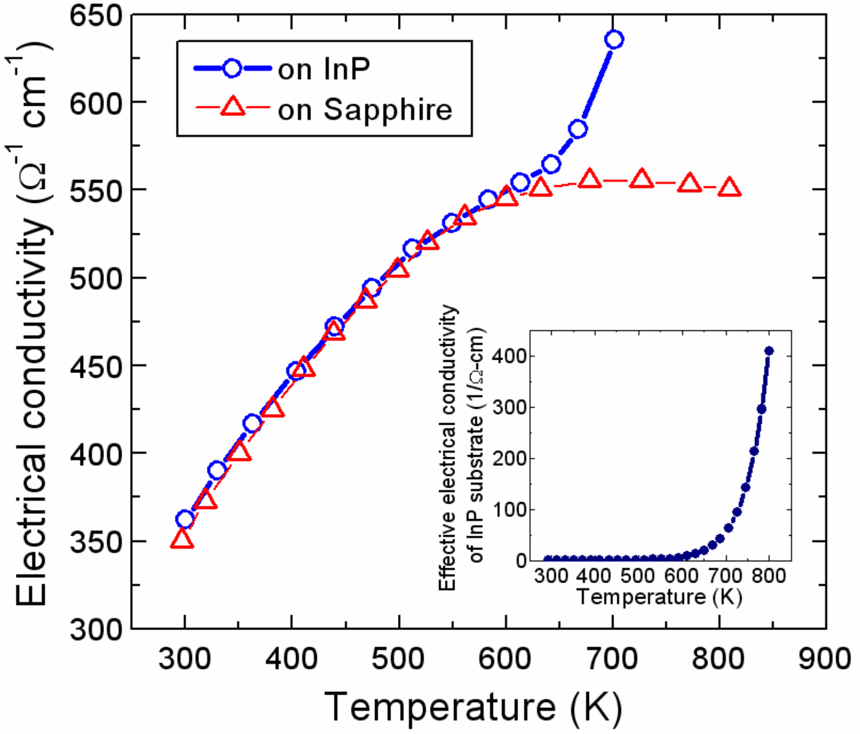
Applications:

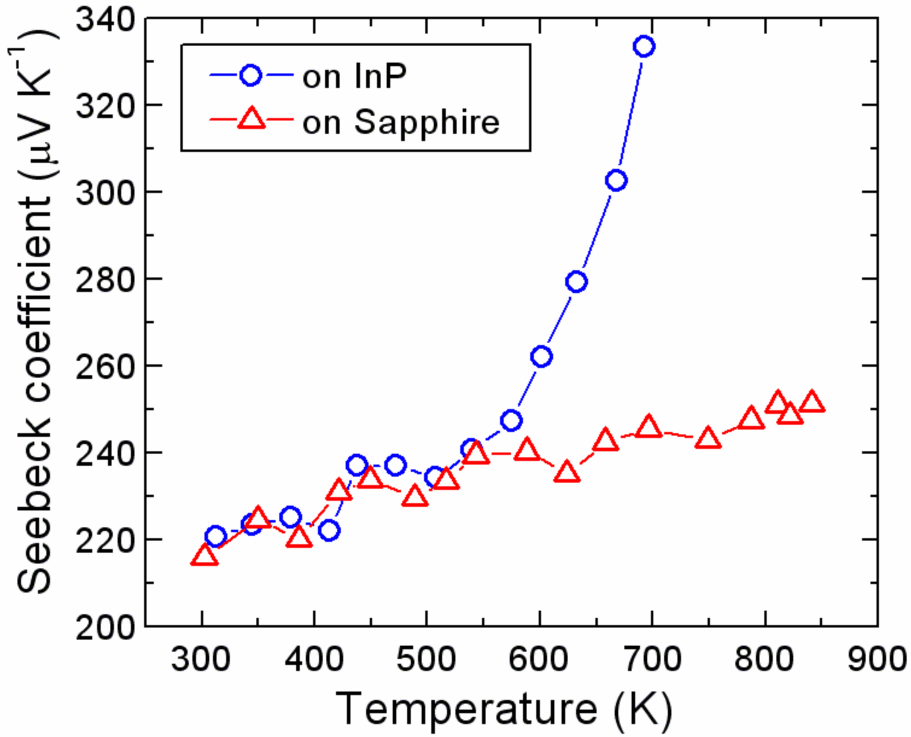
- Micro refrigeration
- TE material optimization

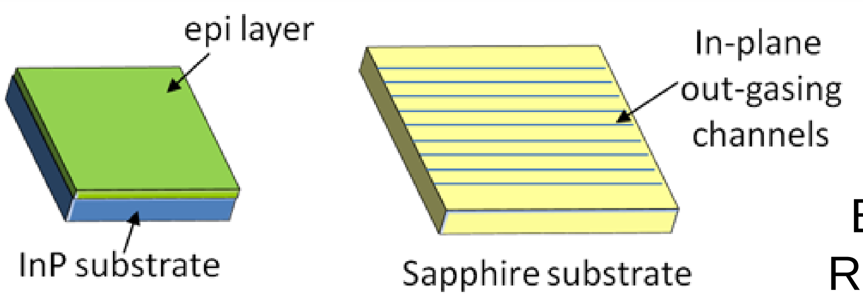
Electrical conductivity and Seebeck measurements

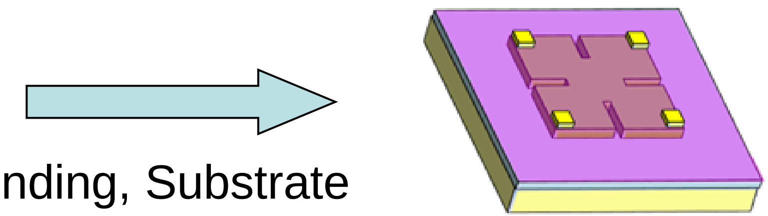
- In-Plane: Need non-conducting substrate (difficult at high temperatures); no charge/electrical conduction at various interfaces. Substrate transfer: consider stress induced changed in electrical properties
- Cross-plane: Requires especially fabricated devices to confine current, low contact resistance → minimum film thickness, extract substrate contributions

Measurements of substrate-removed samples







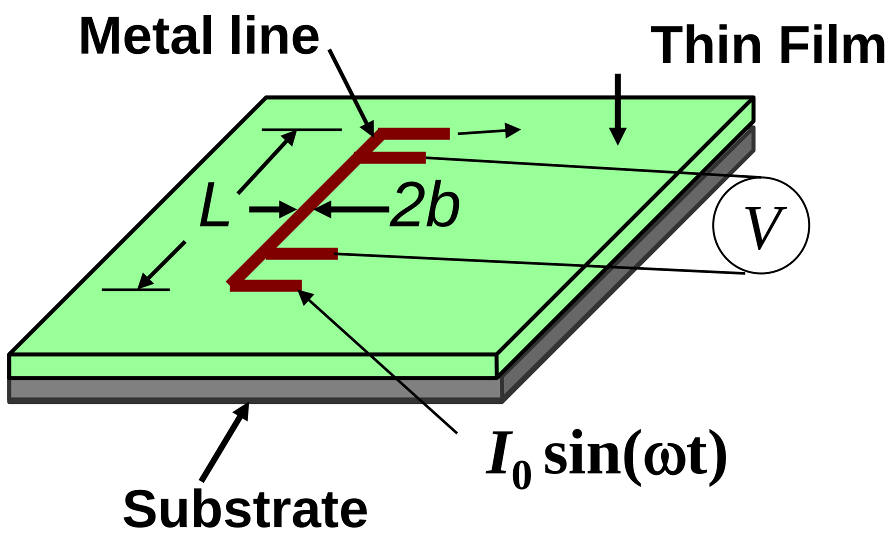


Bonding, Substrate Removal, Processing

J.-H. Bahk *et al.*, *J. Electron. Mater.* 2010.

3ω method for thermal conductivity

3ω method
(Cahill, *Rev. Sci. Instrum*. 61, 802)



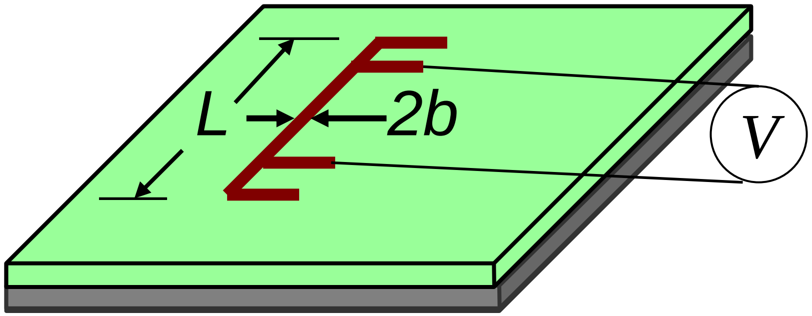
- $I \sim 1\omega$
- $T \sim I^2 \sim 2\omega$
- $R \sim T \sim 2\omega$
- $V \sim IR \sim 3\omega$

$$\Delta T(2\omega) = \frac{P}{L\pi k_s}\left[\frac{1}{2}\ln\left(\frac{D_s}{b^2}\right) + \eta - \frac{1}{2}\ln(2\omega) - \frac{i\pi}{4}\right] + \frac{Pd}{2Lbk_f}$$

See: Annual Review of Heat Transfer, Edited by Gang Chen, 2013

3ω method for thermal conductivity

- Minimum film thickness needed to separate thin film thermal resistance from substrate/interfaces
  - ~0.3-1μm depends on the thermal conductivity of the material
- Need good electrical isolation between heater and thin film (challenge at high temperatures)
  - Electrical parasitics could contribute to the 3ω signal)



Thin film electrical conductivity measurement

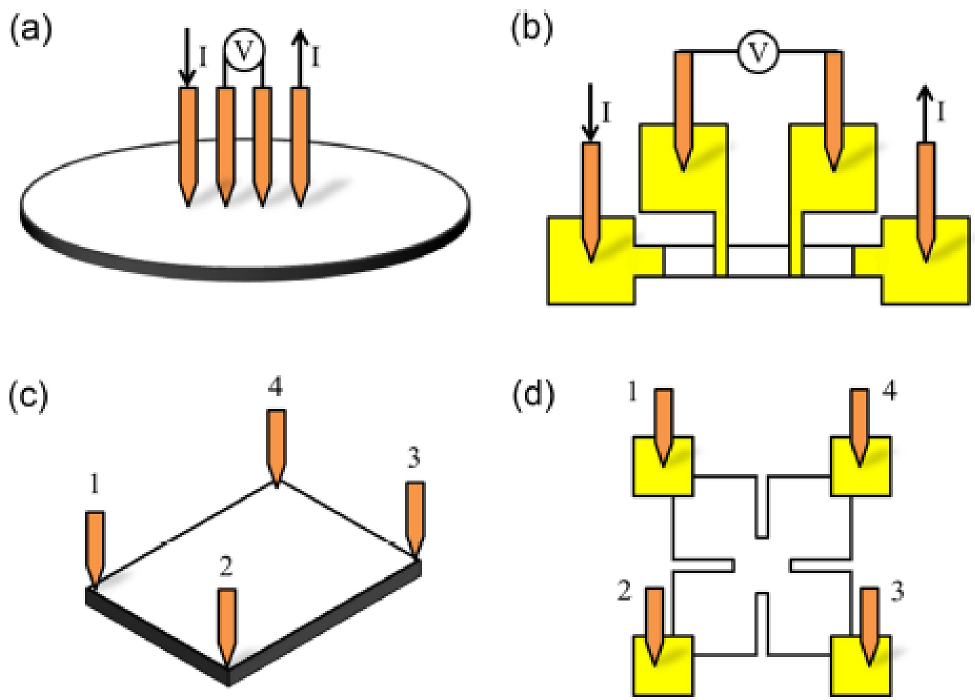
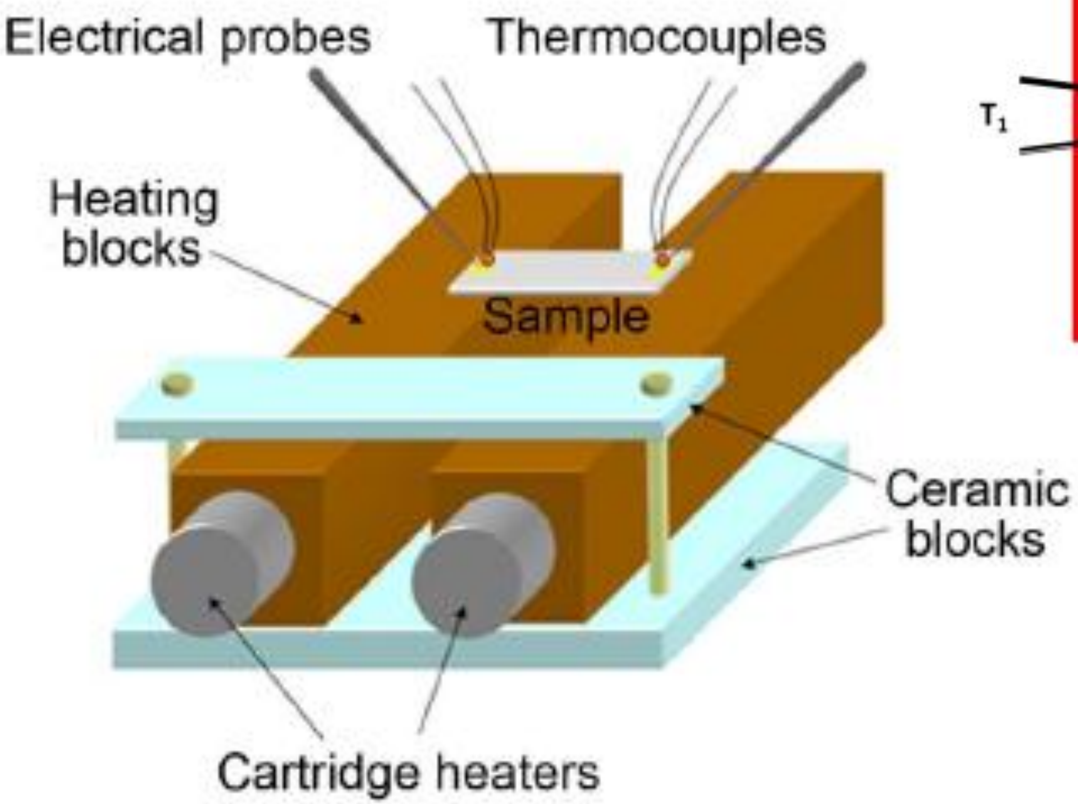
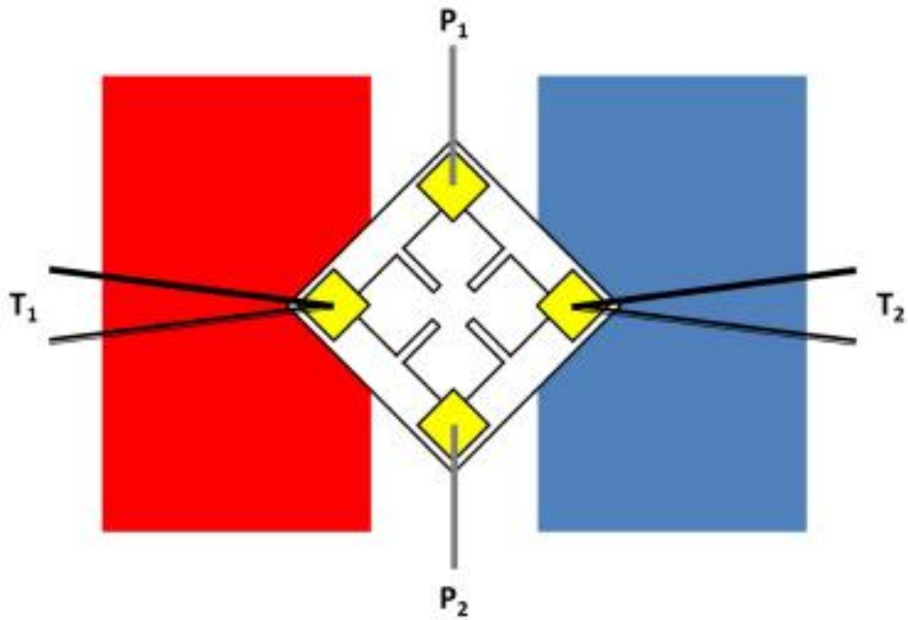


FIG. 1: Various four-probe configurations for electrical conductivity measurement of thin films: (a) a conventional collinear four-point probe for a large sample; (b) a bar-shaped thin film with four probes; (c) a conventional probing geometry for the van der Pauw (vdP) method; (d) a cloverleaf vdP geometry.

J.-H Bahk, T. Favaloro and A. Shakouri, "Thin film thermal characterization techniques," *Annual Review of Heat Transfer, Chapter 3,* 2013

In-plane Seebeck/electrical conductivity





J.-H Bahk, T. Favaloro and A. Shakouri, “Thin film thermal characterization techniques,” *Annual Review of Heat Transfer, Chapter 3,* 2013

Cross-plane Seebeck/electrical conductivity

J.-H Bahk, T. Favaloro and A. Shakouri, *Annual Review of Heat Transfer, Chapter 3,* 2013

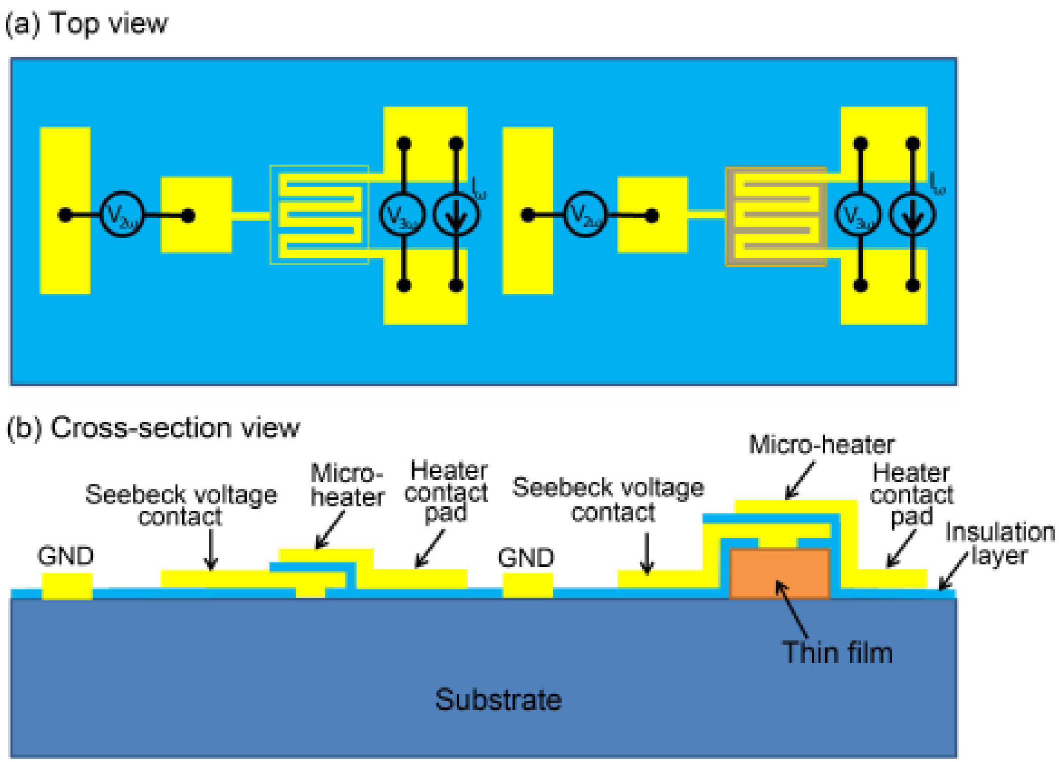
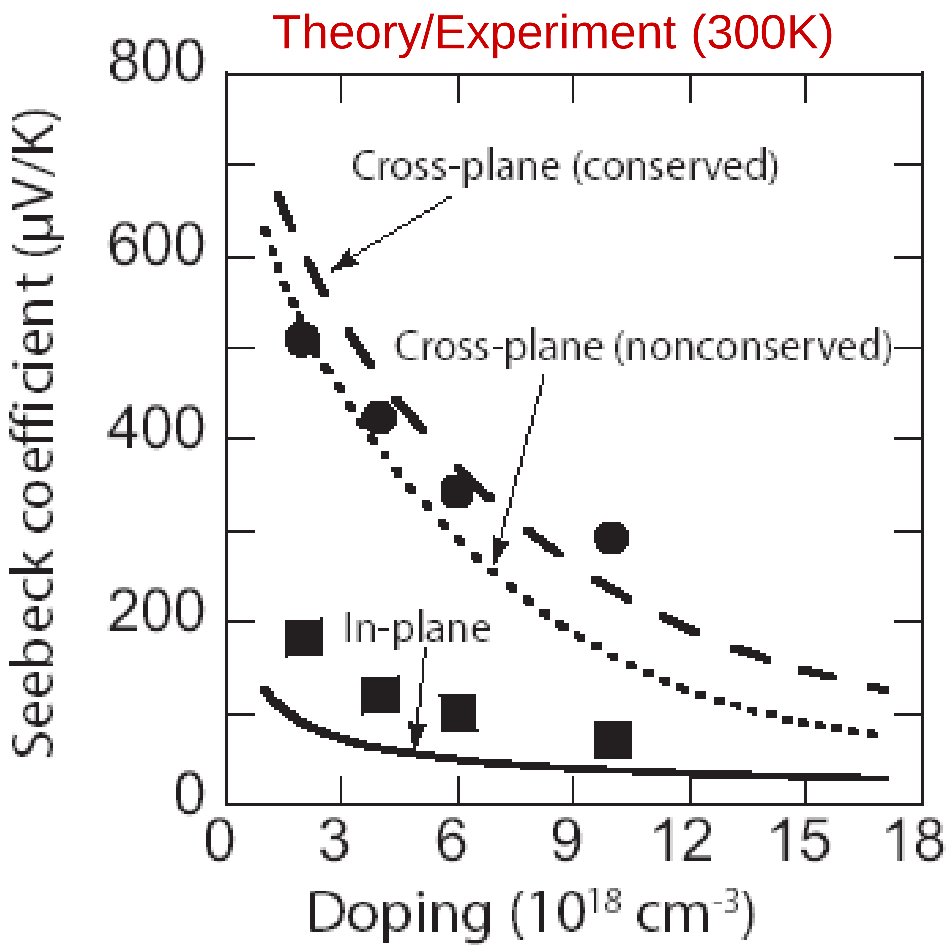
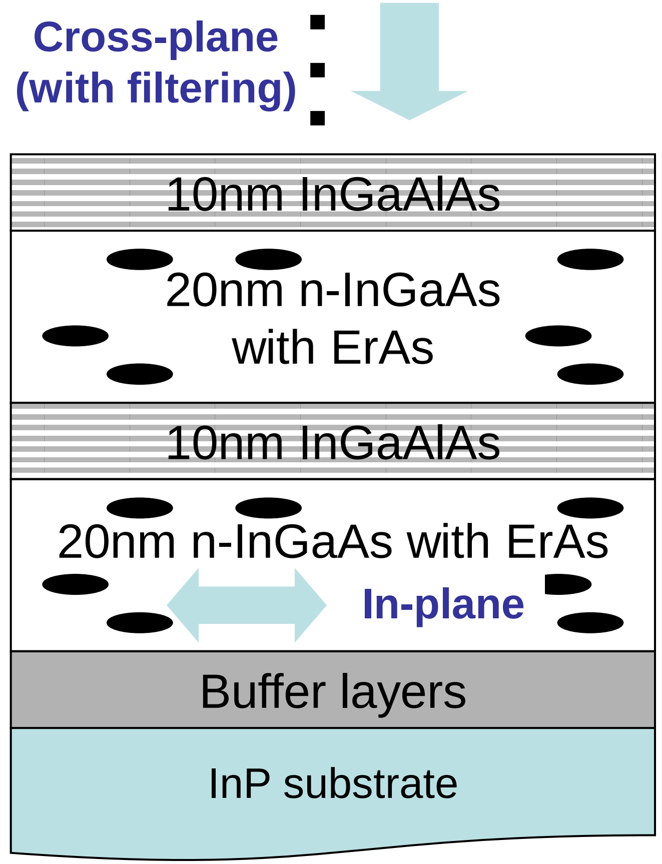


FIG. 8: Schematics, (a) top view and (b) cross-sectional view, of a sample fabricated for cross-plane Seebeck coefficient measurements. Two devices, one with, and one without a thin film mesa, are fabricated (not to scale). Both DC and AC (3ω) measurements are possible. For an AC measurement, a sinusoidal current with 1ω frequency is fed into the microheater, and the 3ω component voltage is measured across the heater line to obtain the temperature difference across the device. Seebeck voltage of 2ω component is measured separately between the voltage pad and the ground contact.

Cross-plane and in-plane Seebeck in thick barrier superlattices InGaAs:ErAs/InGaAlAs

- Enhance energy filtering by inserting InGaAlAs barriers inside ErAs:InGaAs can enhance cross-plane Seebeck by a factor of 3





Zide et al, PRB 74, 205335, 2006

Transient Harman Technique

- Total voltage:

$$V_T = V_R + V_S = IR + S\Delta T$$

- Cooling power:

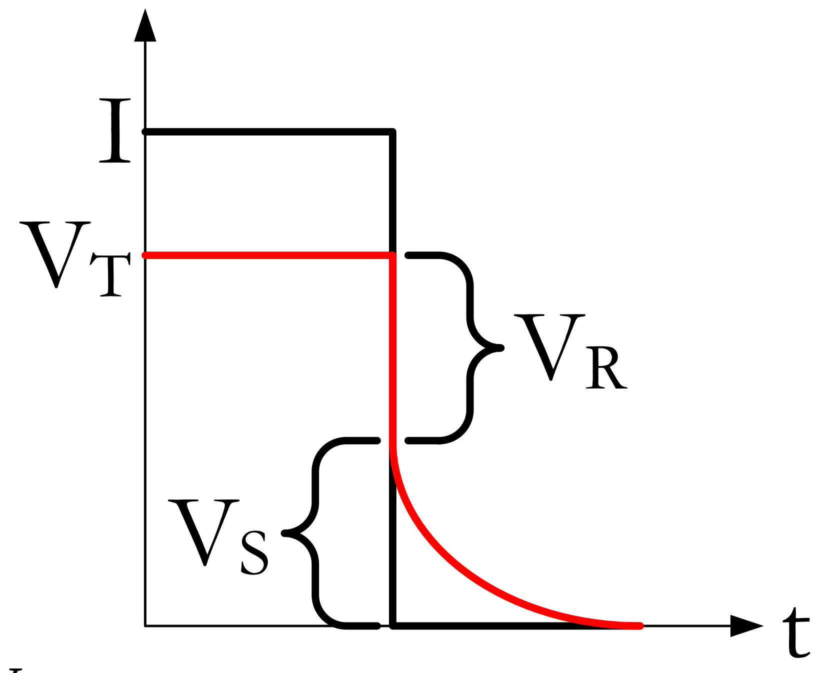
$$Q = STI - \frac{1}{2} I^2 R - \kappa \Delta T$$

- Seebeck voltage:

$$V_S = S\Delta T = S\left(\frac{STI}{\kappa} - \frac{I^2 R}{2\kappa}\right) = V_{SP} - V_{SJ}$$

- **Figure-of-merit**:

$$ZT = \frac{V_{SP}}{V_R} = \frac{S^2 TI}{\kappa}\frac{1}{IR} = \frac{S^2 \sigma T}{\kappa}$$



Harman, T. C. Journal of Applied Physics 29 (1958): 1373-1374.

Transient Harman Technique

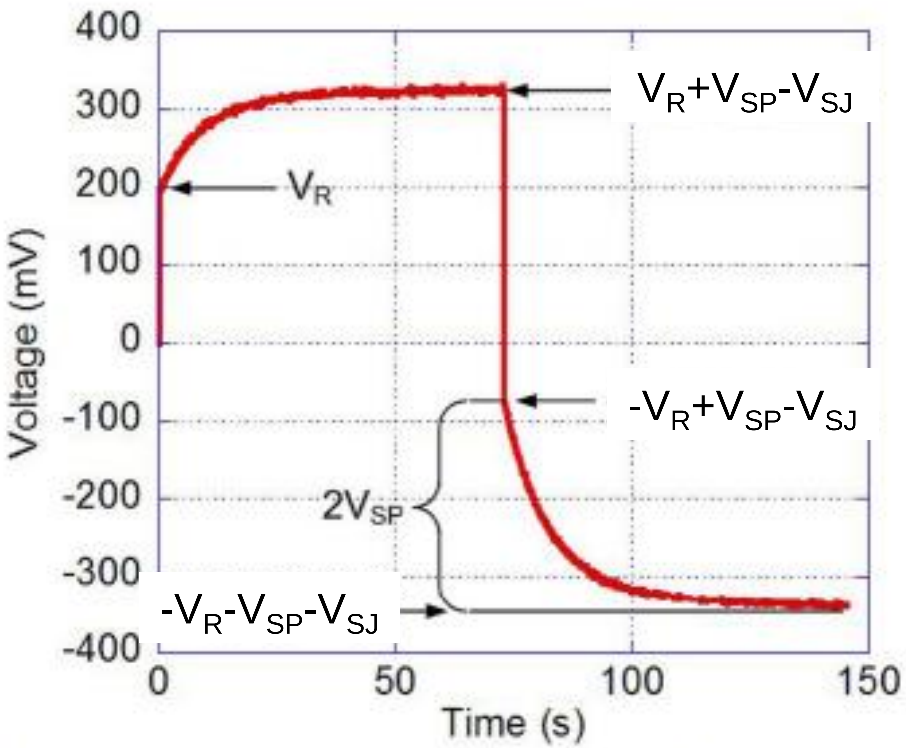
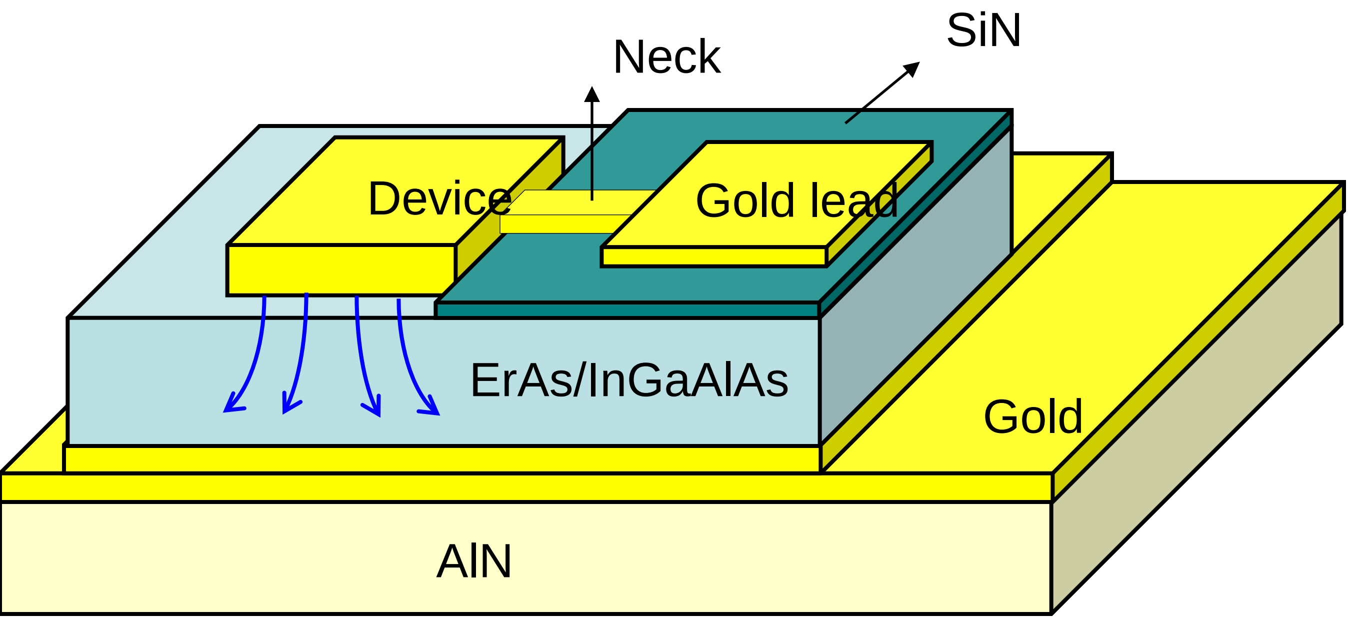
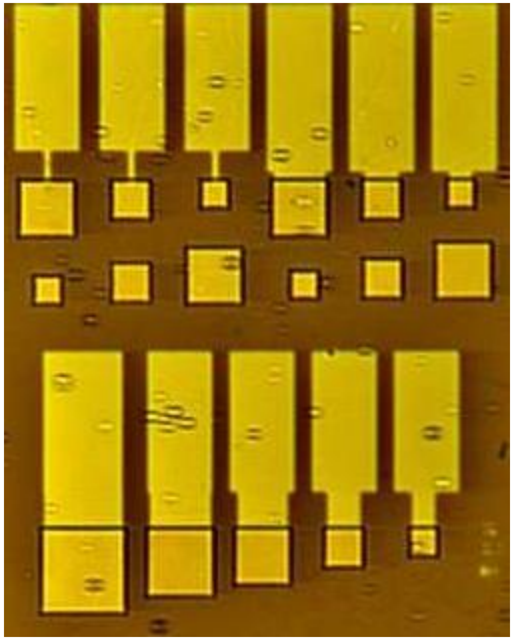


FIG. 12: Example of a transient voltage response of a bulk thermoelectric device, where current is turned on at $t = 0$, and reversed at $t = 70$ s. The slower response of a bulk sample due to its greater thickness is chosen to clearly illustrate the signal decay.

J.-H Bahk, T. Favaloro and A. Shakouri, *Annual Review of Heat Transfer, Chapter 3,* 2013

Simultaneous S, σ, κ, ZT measurements





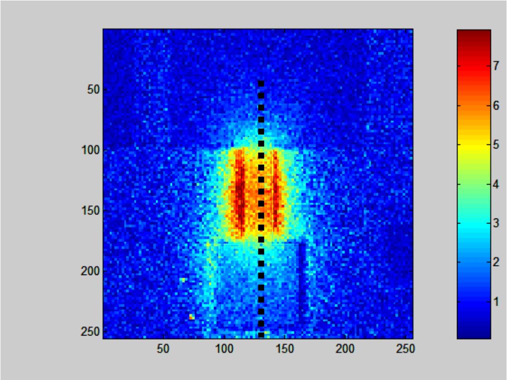
Courtesy:
Gehong Zeng
UCSB

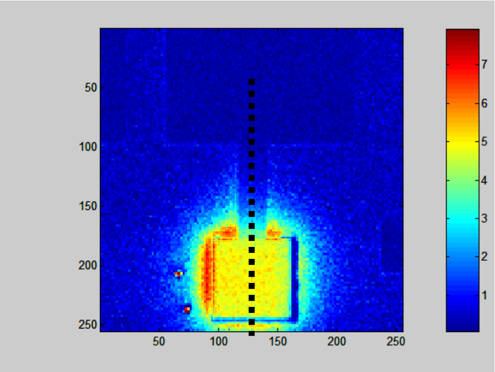
Key issues:

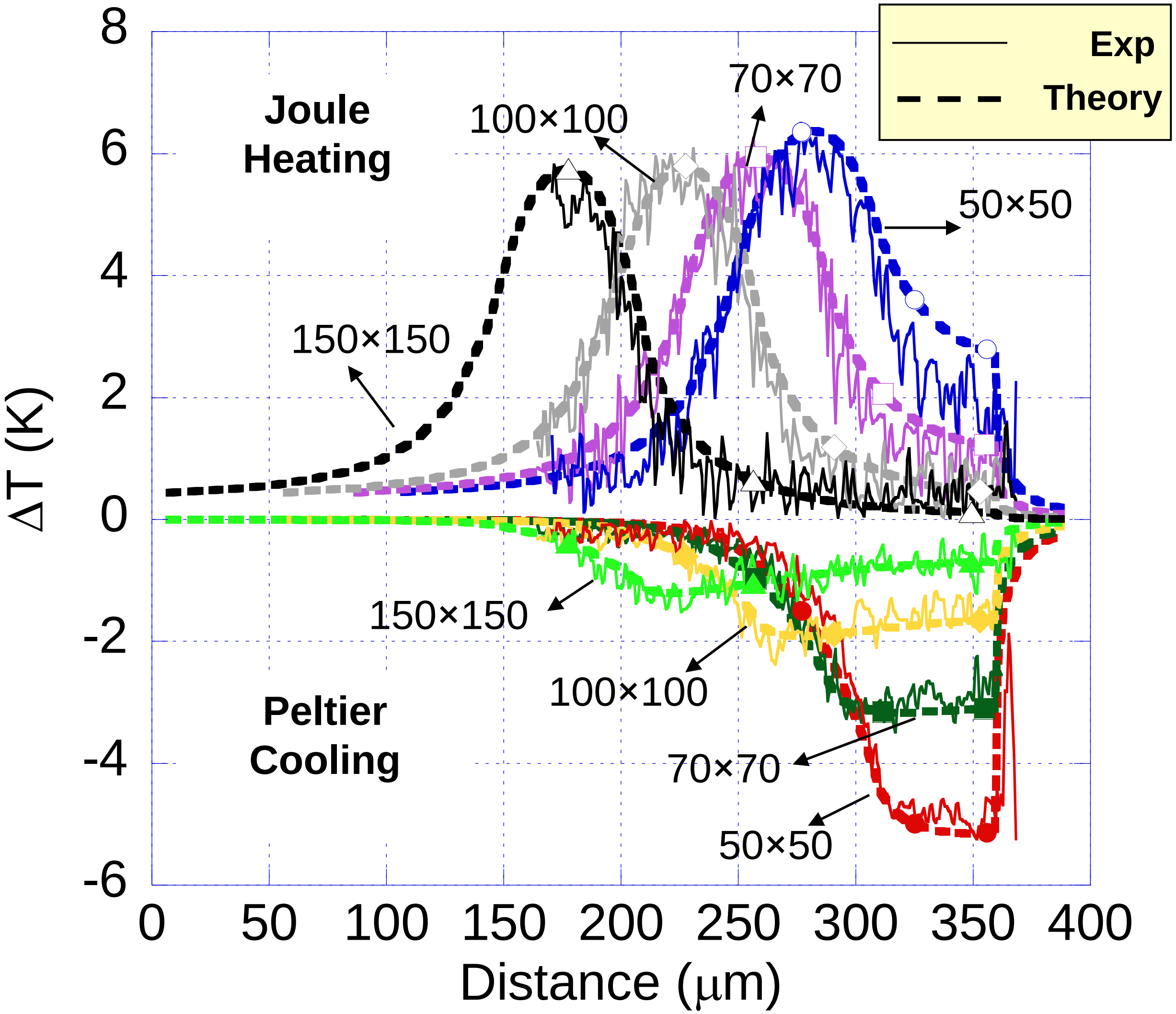
- Current injection uniformity (aspect ratio)
- Heat load from probes or leads
- Transient response in 0.1-10 μsec

R. Singh, Z. Bian et al. Appl. Phys. Lett. 2009 May; 94: 212508

Finite Element Analysis of Temperature Profile







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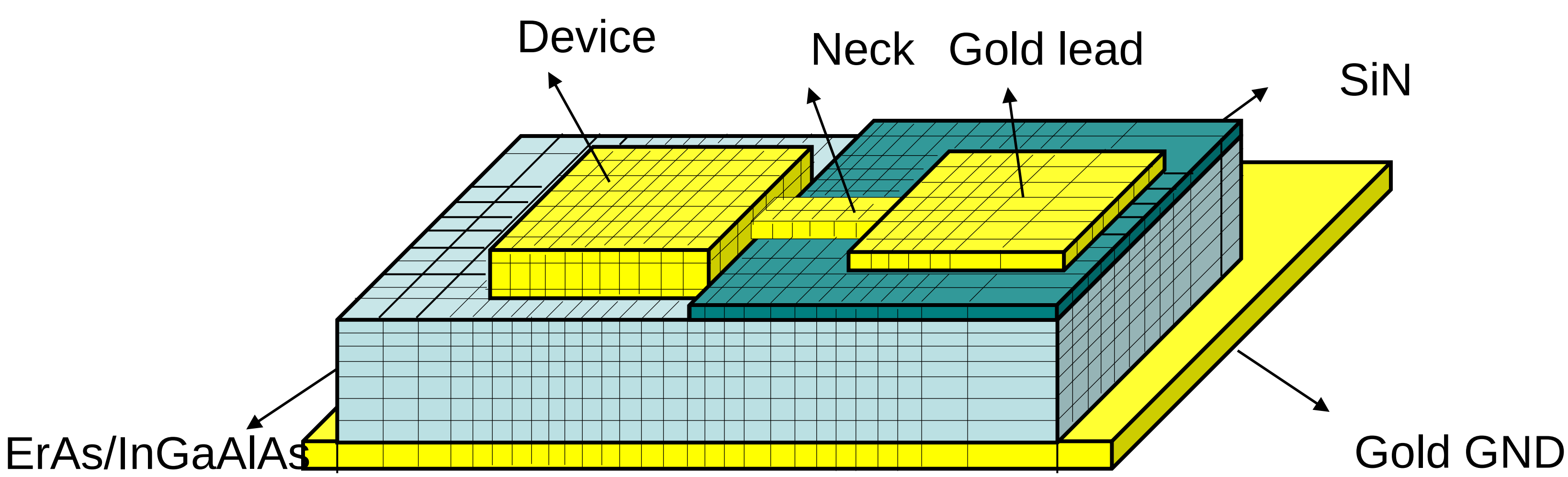
Self-consistent finite element thermoelectric transport

Heat capacity, conduction, Joule, Peltier

$$C\frac{\partial T}{\partial t} = \nabla(\kappa \nabla T) + J^2/\sigma - JT\nabla S$$

$$F = J/\sigma + S\nabla T$$

Electrical field, Ohmic, Seebeck

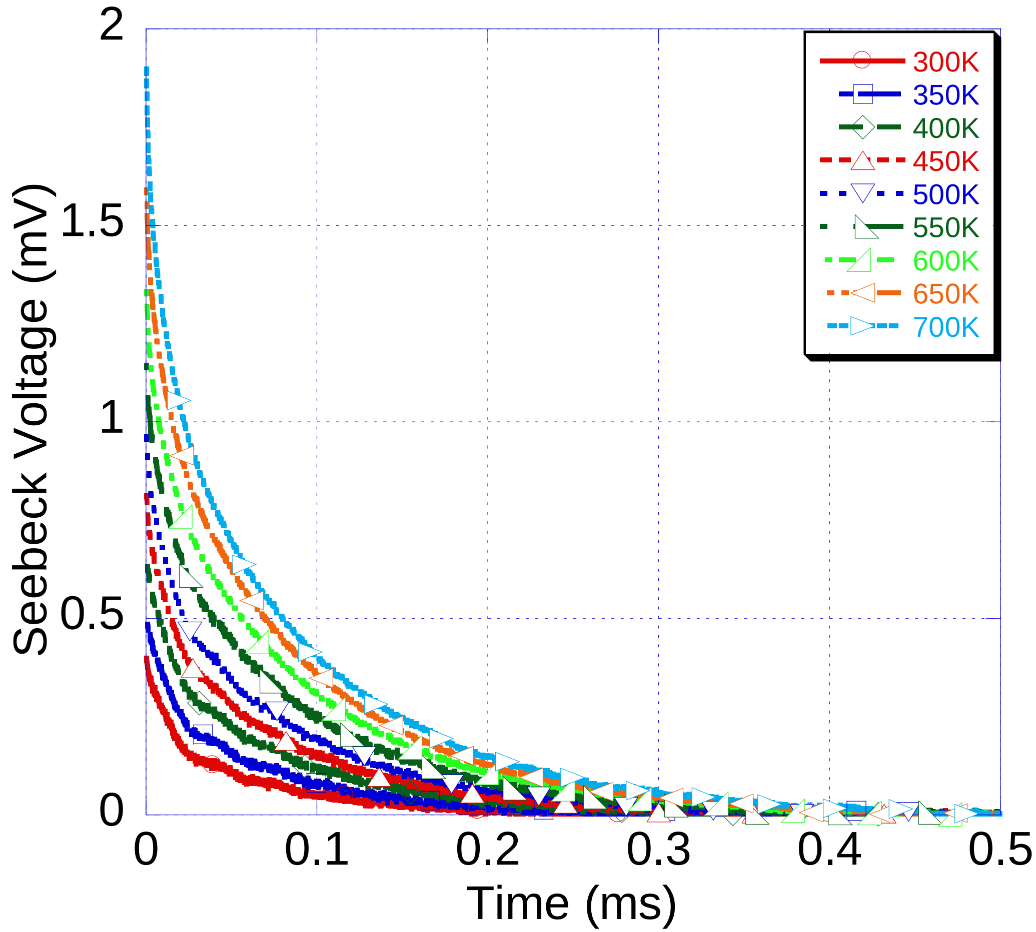


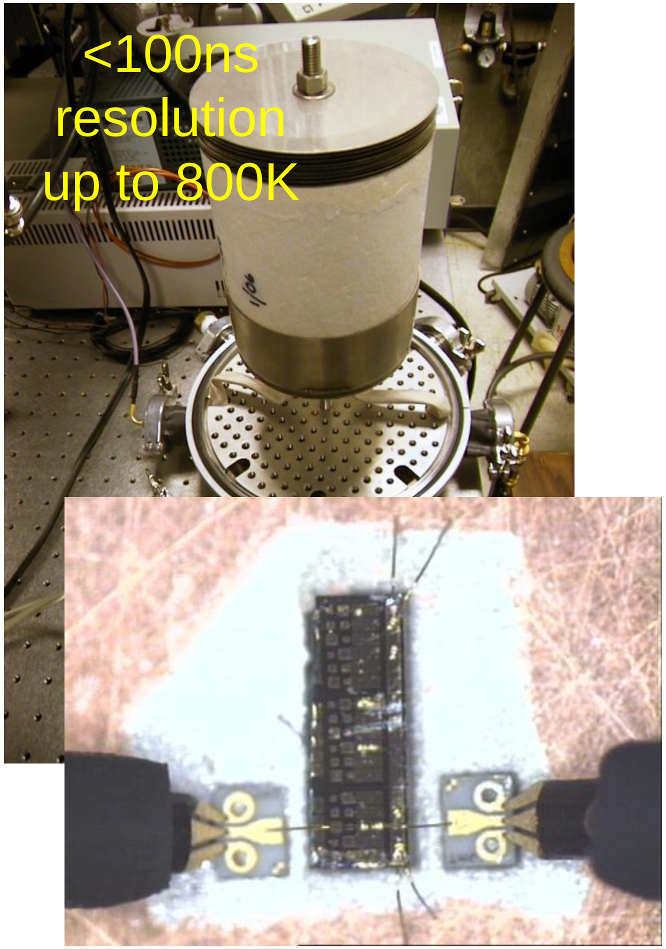
R. Singh, Z. Bian et al. Appl. Phys. Lett. 2009 May; 94: 212508

Transient S, σ, κ, ZT measurements (Harman Technique)

R. Singh and A. Shakouri, Rev. Sci. Instrum. 2009; 80: 025101

Acknowledge:
ONR DURIP
(Dr. Mihal Gross)

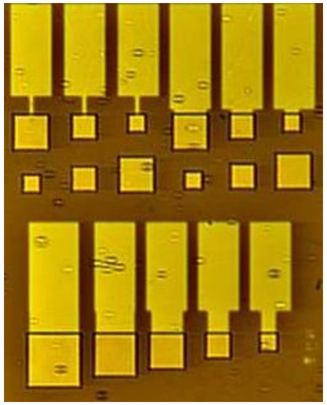




Extraction of Thin-film ZT

Single element microrefrigerator used to extract all thermoelectric properties of 20μm films in cross-plane direction

	S(μV/K)	σ(/Ωcm)	K (W/mK)
In-plane data	-224	348	N/A
Cross-plane	-233	347	3 (3ω), 5
Finite Element	-220	330	5



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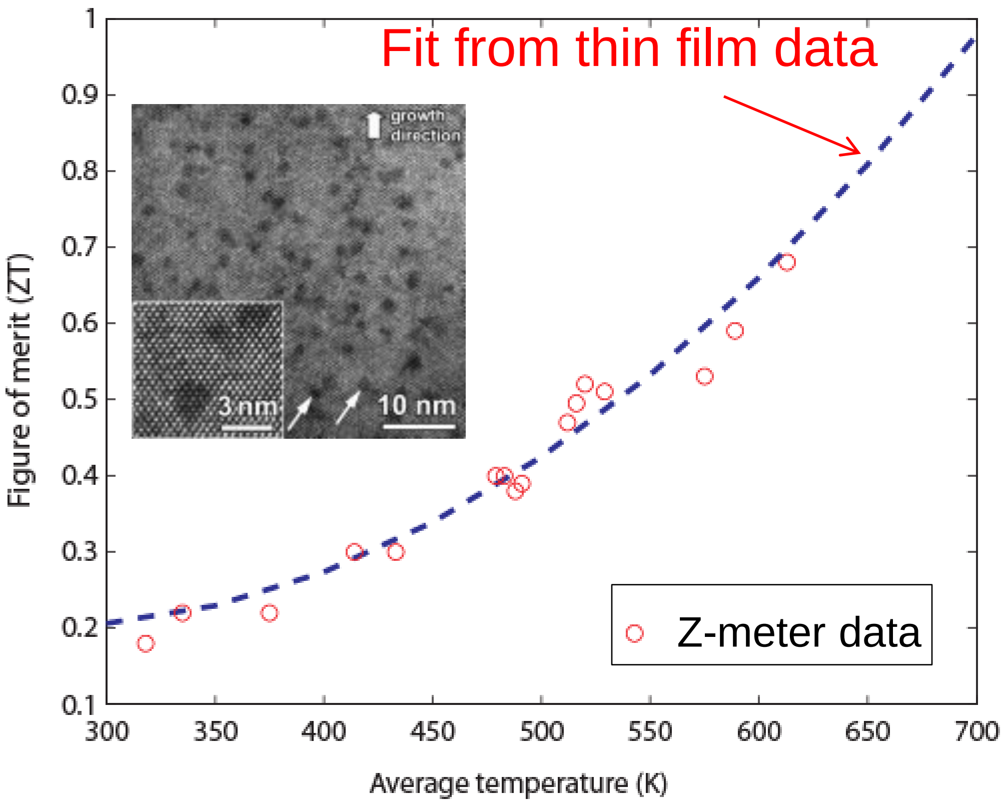
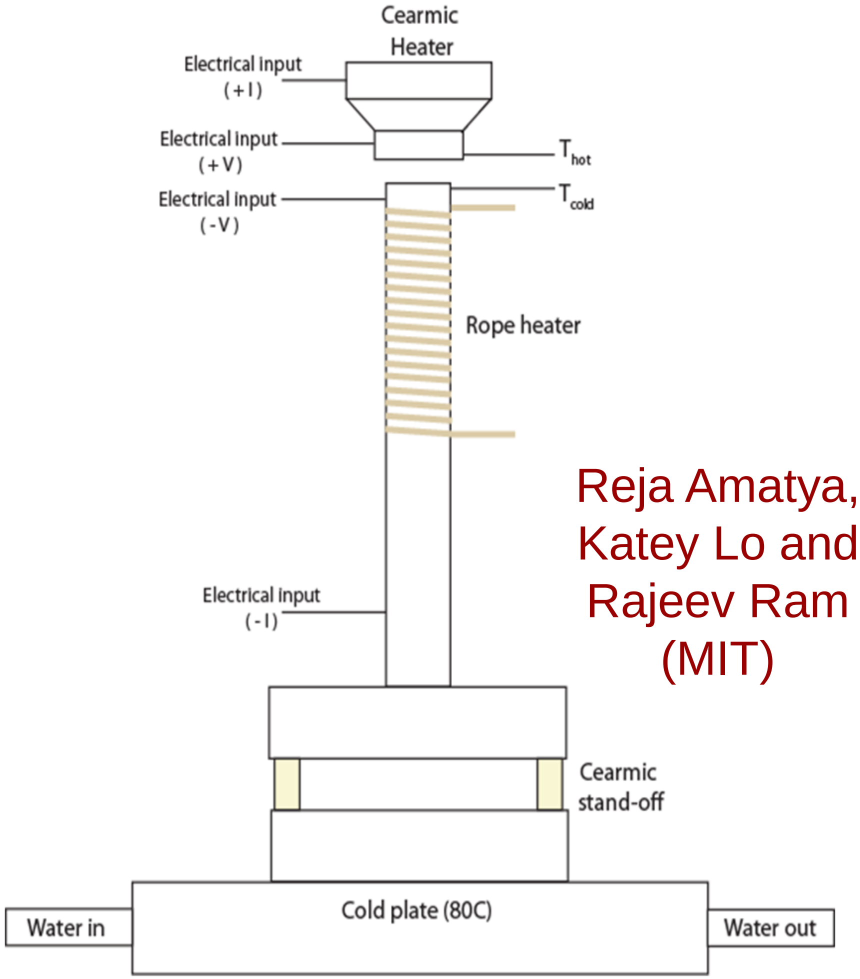
Z-meter measurement: n- ErAs: InGaAlAs

- Measured parameters: Seebeck coefficient, thermal conductivity and electrical conductivity + output power and efficiency
- 50um thick material





Reja Amatya, Katey Lo and Rajeev Ram (MIT)

Lecture 3.4: Summary

- Thin film thermal characterization (3ω)
- Thin film electrical and Seebeck characterization (in-plane, cross-plane)
- Microrefrigerator/Transient Harman for ZT characterization
- Z-meter