Sandia National Laboratories

SAND2011-1620P

Manipulating Phonons Using Phononic Crystals:

Reducing the Thermal Conductivity of Silicon

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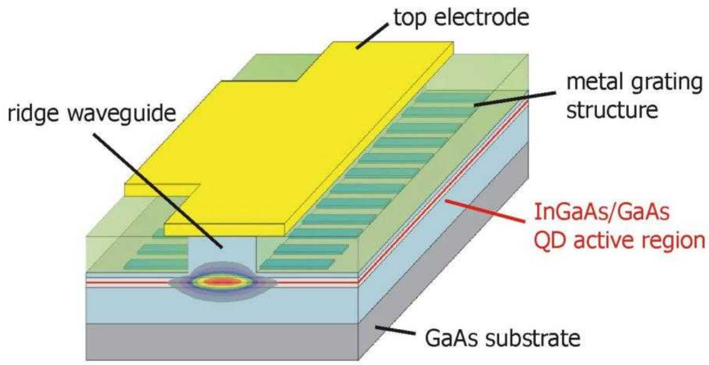
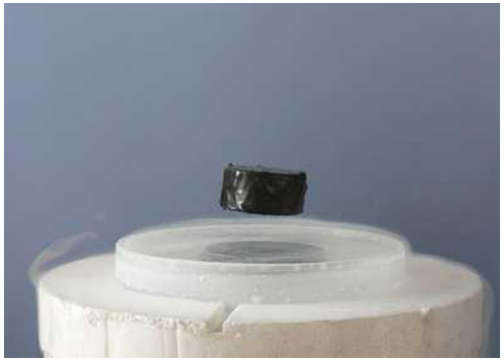
Outline

- **Phononic Crystals**
  - ***Why Phononic Crystals (PnCs)?***
  - ***Bandgaps in PnCs***
  - ***RF Applications of PnCs***
- **Manipulating Thermal Phonons**
  - ***Modifying Thermal Conductivity (κ)***
  - ***Realizing Ultra-Low κ Si***
  - ***High ZT Devices in Silicon using PnCs***

Motivation:
Manipulating the Propagation of Phonons

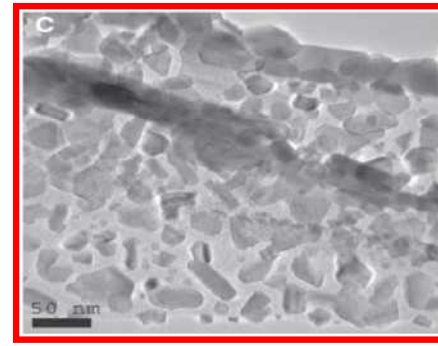
- ***Who Cares? (Why?)***
  - ***Nonradiative relaxation in QW's***
    - ***Cap on SS-laser efficiency***
    - ***Cap on SSL device efficiency***
  - ***Spin wave relaxation***
    - ***Stability of spintronics***
    - ***Quantum computing***
  - ***Superconductivity***
    - ***Binding of Cooper pairs***
    - ***Phonon bottleneck***
    - ***Hi-TC***
  - ***Quantum Friction***
  - ***Indirect Bandgap Semiconductors***
  - ***Electronics***
    - ***ZT figure of merit***
    - ***TE scavenging/TE-cooling***



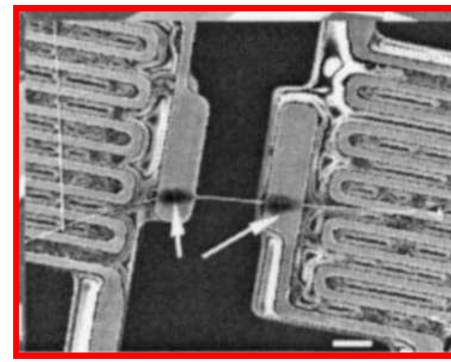


Manipulating the Phonon Population

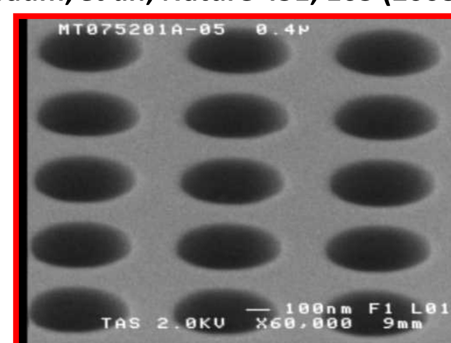
- ***Current Approaches (How?)***
  - ***Surface scattering: roughening the surface to increase phonon scattering***
    - ***Affects only surface propagating modes***
    - ***Acts only on a narrow spectrum $\Delta\lambda$~roughness length scale***
    - ***Non-deterministic***
  - ***Grain boundary/impurity scattering:***
    - ***Highly non-deterministic***
  - ***Nanowires/meshes: waveguide cutoff***
    - ***Acts only on a narrow thermal spectrum $\lambda \leq$ diameter***
    - ***Suppresses low frequency phonons, rather than THz phonons***
- ***What is Needed (PnC Approach)***
  - ***Highly deterministic: "at-will" control***
  - ***Wide spectrum: into the THz regime***
  - ***3D control: bulk, surface, shear, etc.***



Poudel, *et al.*, Science 320, 634 (2008)



Hochbaum, *et al.*, Nature 451, 163 (2008)



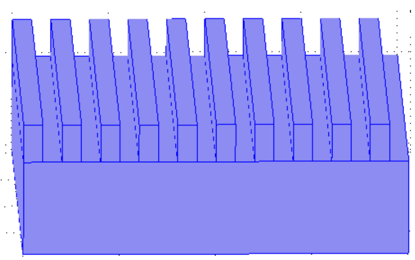
Su, *et al.* , APL 96, 053111 2010

What are Phononic Crystals?

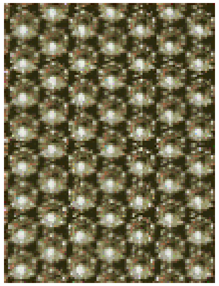
A PnC is a periodic arrangement of elastic materials that can scatter phonons of comparable wavelength

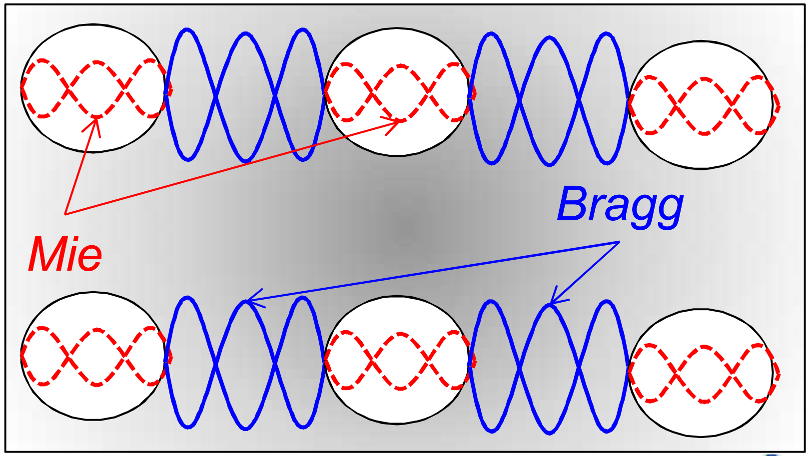
- ***How does it work?***
  - ***Caused by a superposition of Mie and Bragg resonances in the periodic lattice***
  - ***Requires sufficient acoustic impedance contrast***
  - ***Allows for full 3D macro- to micro-scale control of phonon propagation***

1D

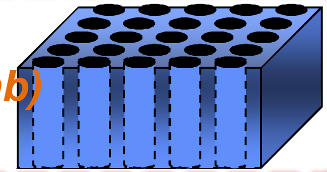


3D



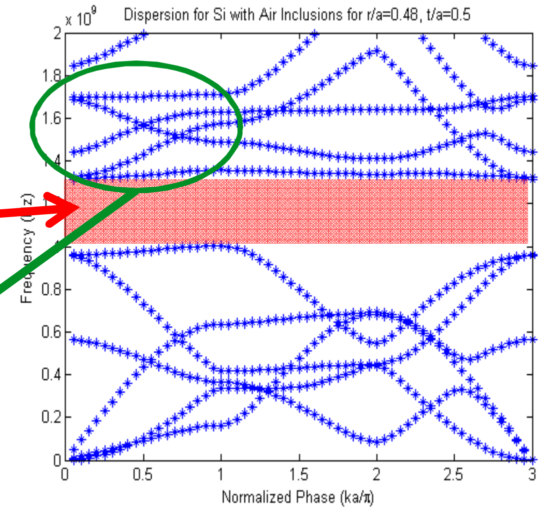


2D (finite slab)



What are Phononic Crystals?

- ***Properties of Phononic Crystals (PnCs)***
  - ***Engineered phononic dispersion***
  - ***Phononic bandgap***
  - ***Anomolous dispersion (flat and negatively-sloped bands)***



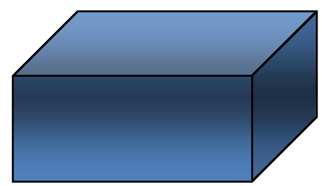
$$n(\omega_{k,s}) = \frac{1}{\exp(\hbar\omega_{k,s}/k_B T) - 1}$$

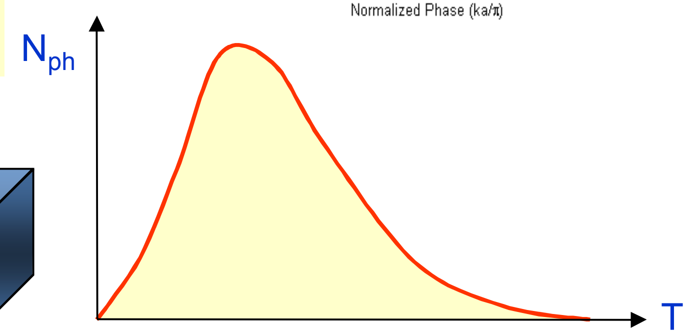
- ***Phononic Density of States (DOS)***

DOS is the number of allowed modes of the material at a given frequency.

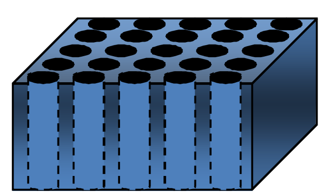
  - ***Redistribution of the bulk DOS possible due to modified phonon dispersion.***
  - ***Bandgap creates a range of frequencies with zero states, enhanced DOS at the higher and lower edges.***

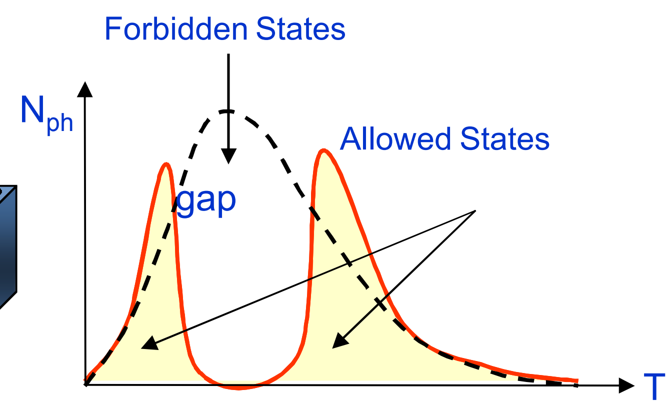
Bulk





PnC



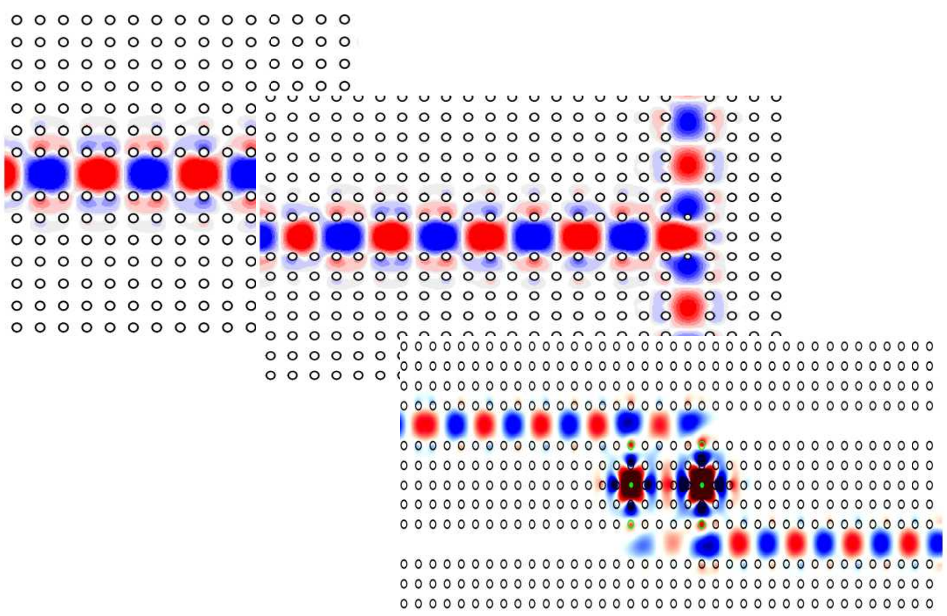


Why Phononic Crystals?

Why are we interested in the PnC—PhC analogy?

- *Wealth of literature on PhCs that can be used as a first iteration for the design and study of PnC applications*

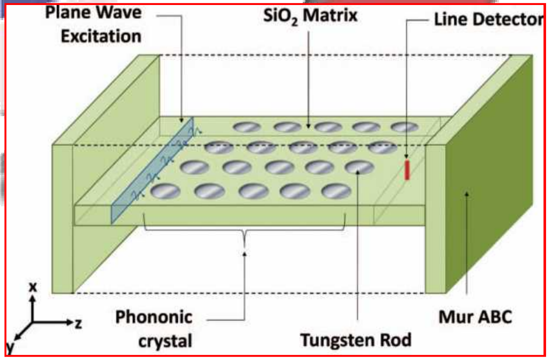
Photonic Crystals (PnC)	Phononic Crystals (PhC)
Refractive index mismatch	*Velocity and density mismatch*
Integration of lasers and photodetectors problematic	*Micromachined integration of piezoelectric or capacitive couplers*
3D required for full control	*2D (+vacuum) required for full control*
Inherently linear	*Inherently non-linear*
2nd order coupled vector equations with 2 polarizations	*2nd order coupled vector equations with 3 polarizations*
Usually isotropic constitutive parameters	*Usually anisotropic constitutive parameters*



What materials should we use?

- ***Ideal photonic materials may not work for phononics!***

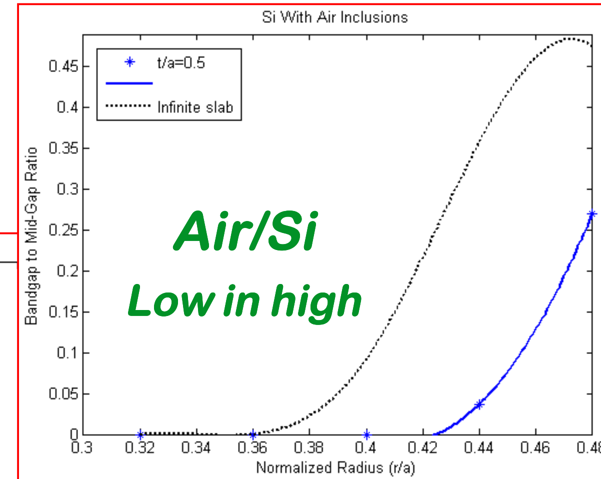
Realizing a Phononic Bandgap



Sqr PnC

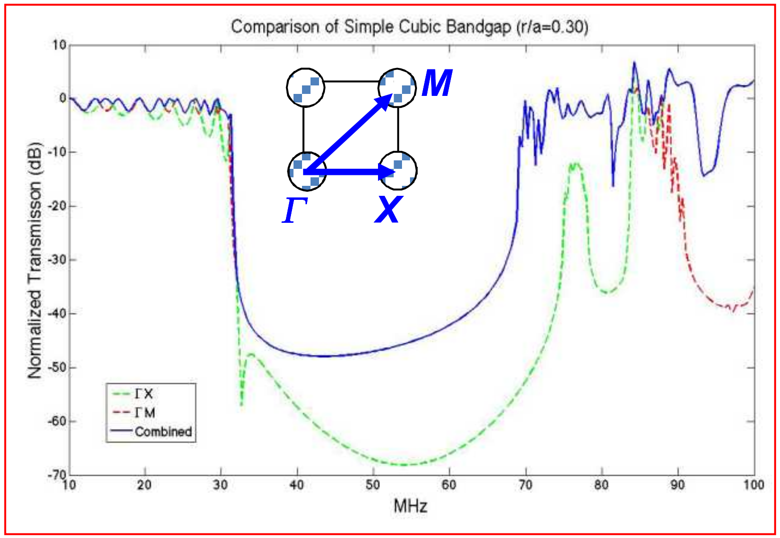
PWE

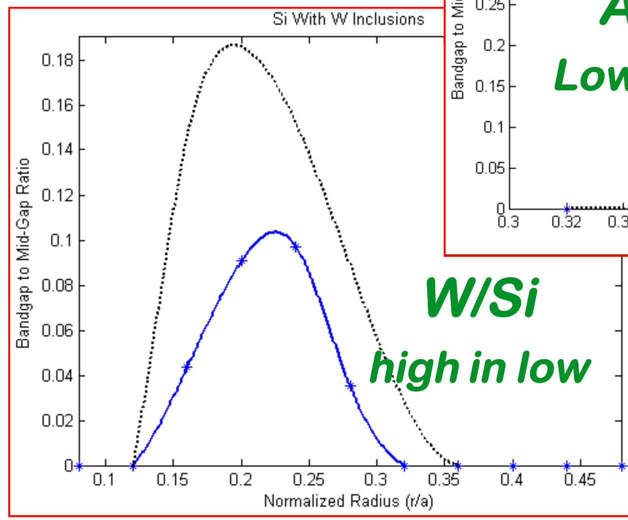
FDTD



Air/Si

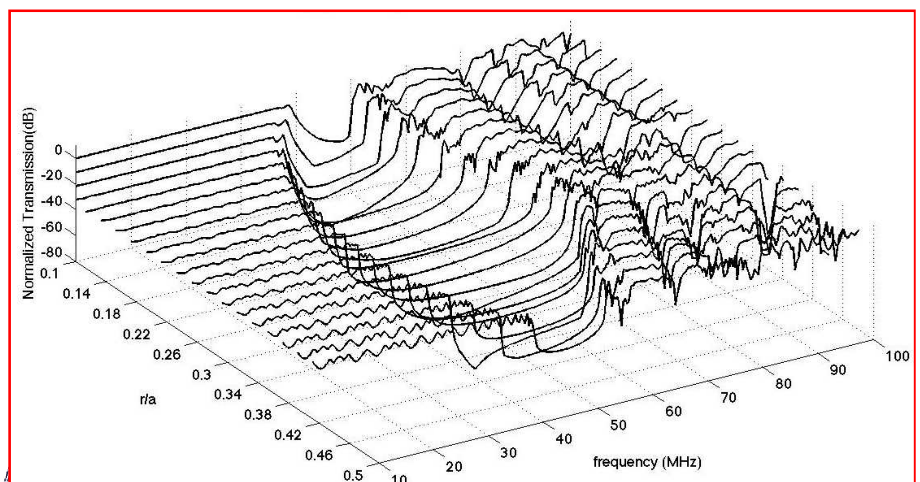
Low in high

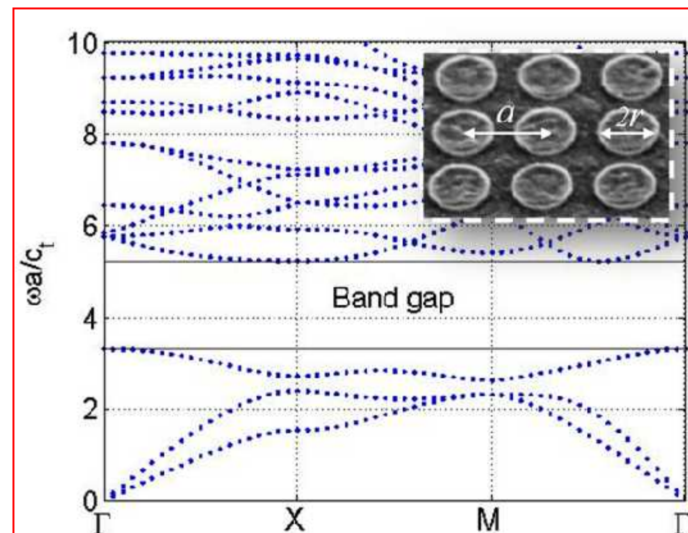




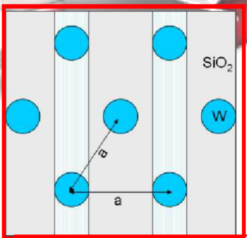
W/Si

high in low



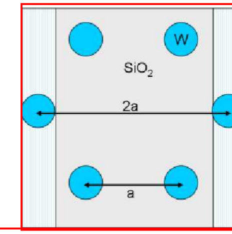


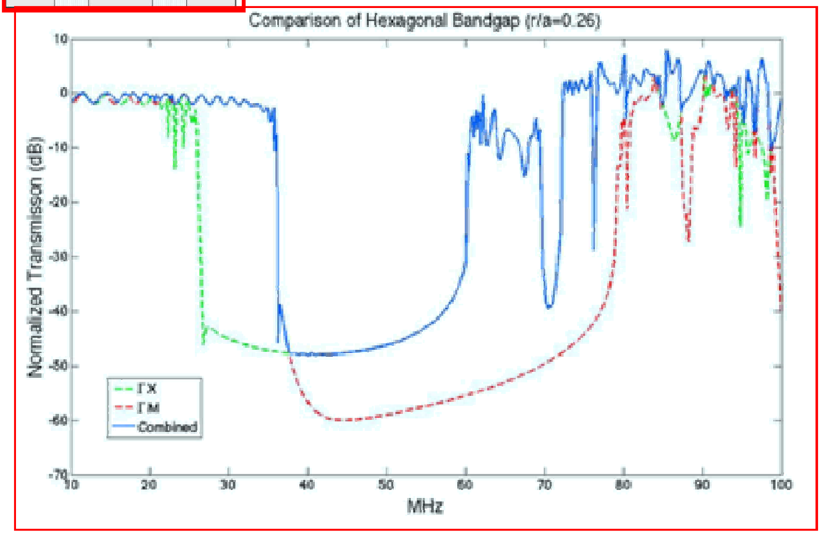
Realizing a Phononic Bandgap



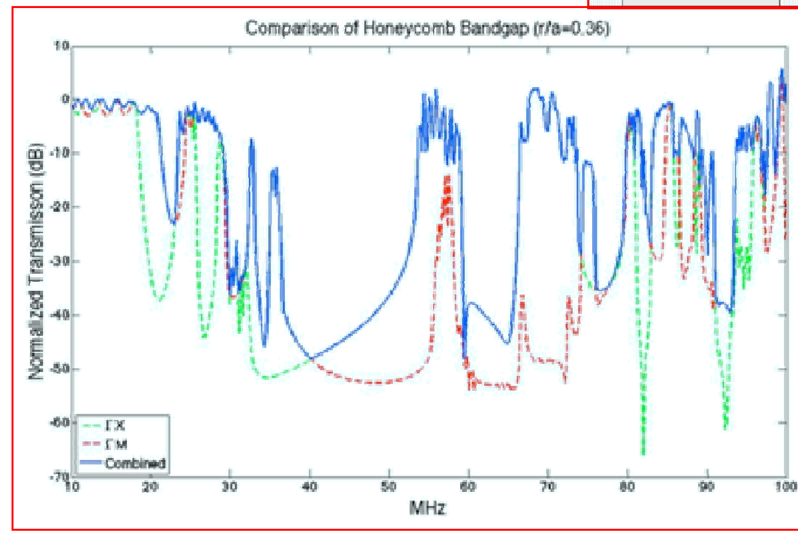
Hex PnC

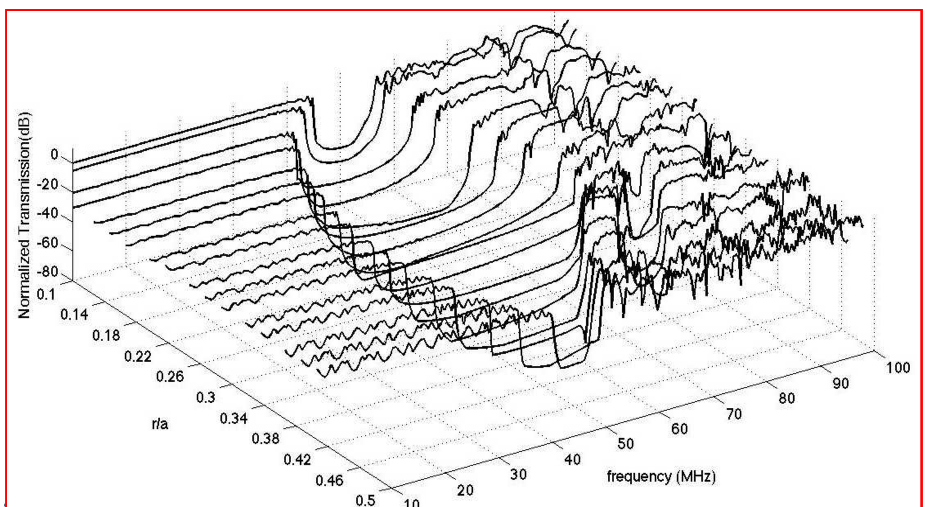
HonC PnC

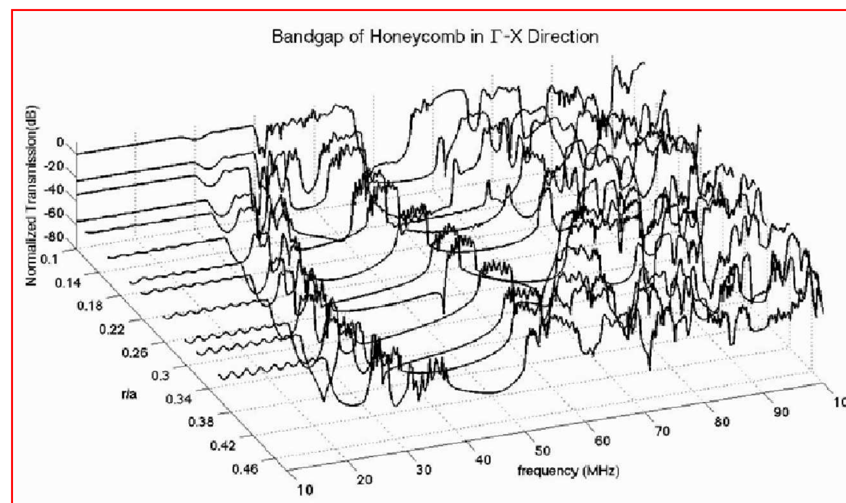




W/Si



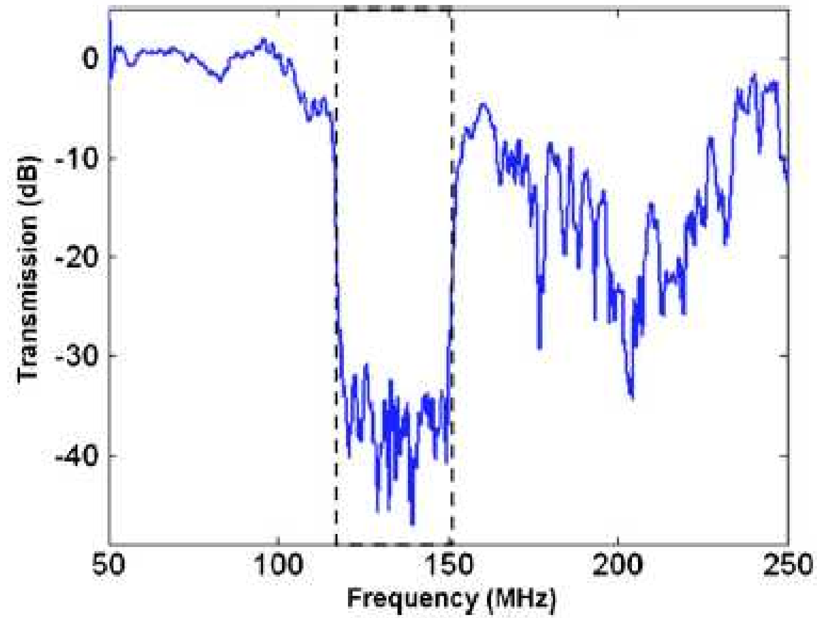




Solid-Air vs. Solid-Solid PnCs

Solid-Air (Si-air) PnC

- ***Hexagonal lattice***
  - ***Lattice constant** a = 15μm*
  - ***Hole radius** r/a = 0.43*
  - ***Slab thickness** t/a = 1*
  - ***Bandgap from** f = 118-150MHz*



APPLIED PHYSICS LETTERS 92, 221905 (2008)

Evidence of large high frequency complete phononic band gaps in silicon phononic crystal plates

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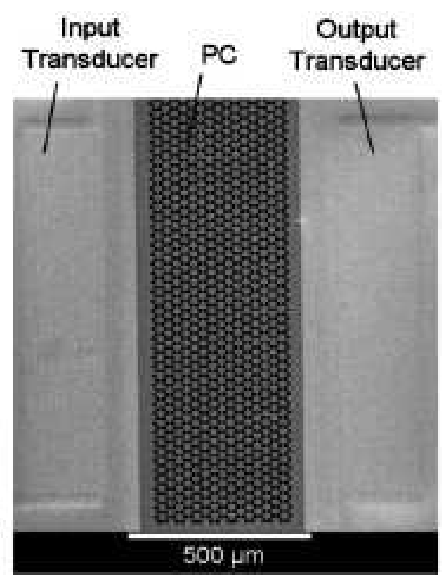
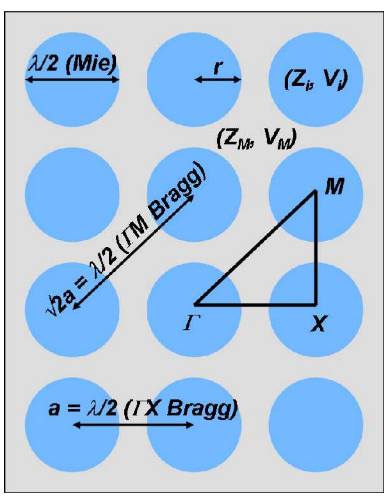


Origin of the Phononic Bandgap

2D PnC can be approximated by a 1D stack of alternating layers

- ***Bandgap formation depends on the ratio of the acoustic impedance Z of these two layers***
  - ***Z_{P2}/Z_{P1} = 2.68 for Si-air as compared to Z_{P1}/Z_{P2} = 3.11 for Si-W***

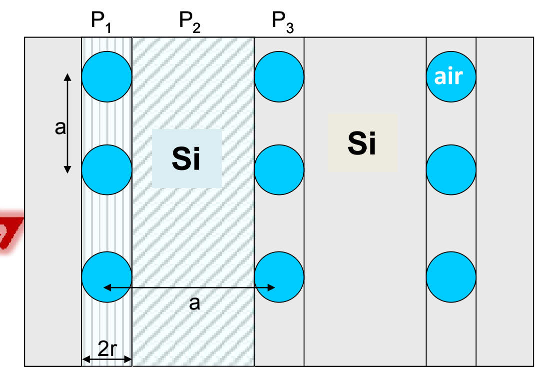


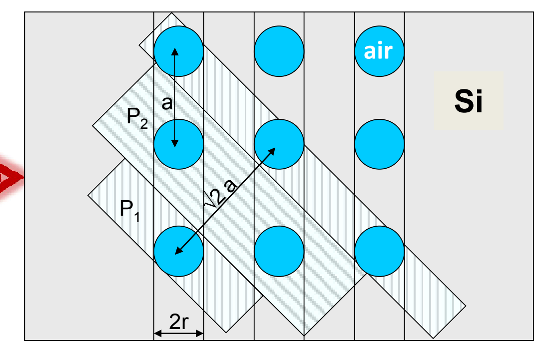
$$f(Bragg)_{\Gamma X} = \frac{V_{avg}}{2a}$$

$$f(Bragg)_{\Gamma M} = \frac{V_{avg}}{(2a)\sqrt{2}}$$

$$f(Mie) = \frac{V_i}{4r} \qquad V = \sqrt{\frac{E}{\rho}}$$

$$V_{avg} = \pi\left(\frac{r}{a}\right)^2 V_i + \left(1 - \pi\left(\frac{r}{a}\right)^2\right) V_M$$



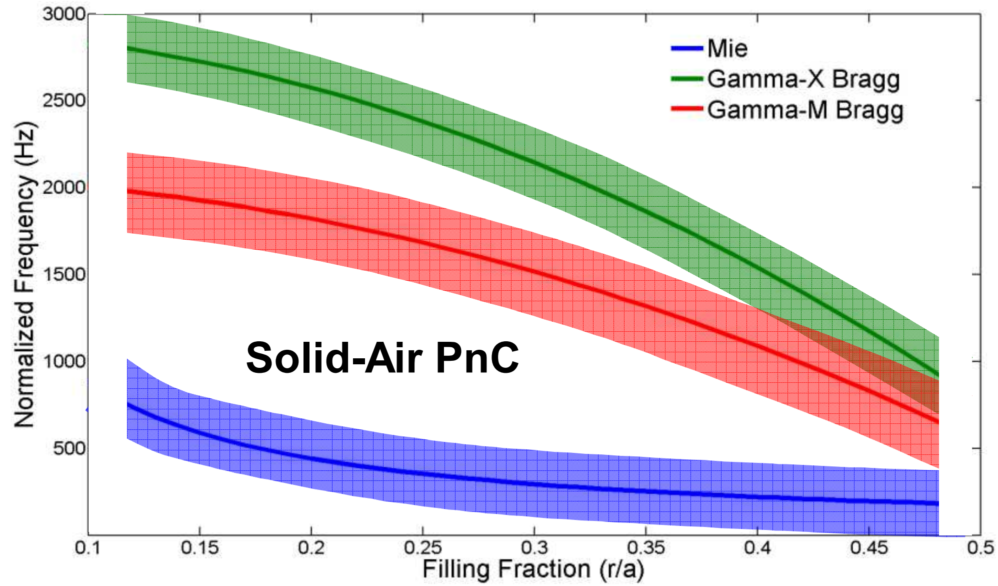


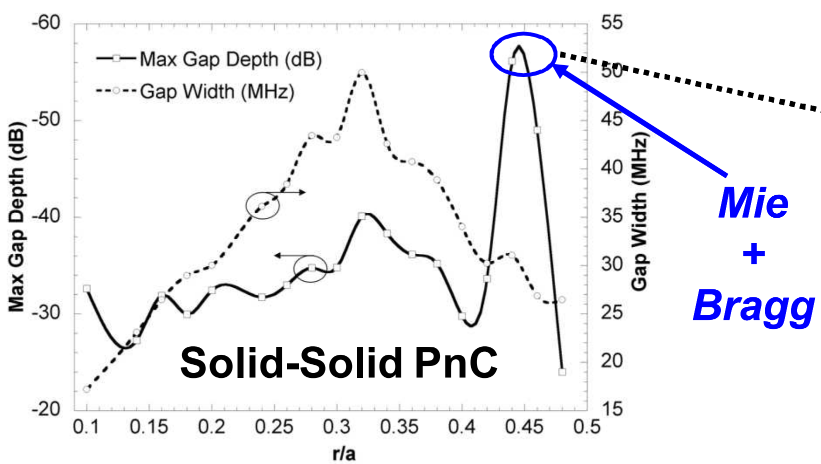
$$Z_{eff\,1} = ff_1 \cdot Z_{air,W} + (1\text{-}ff_1) \cdot Z_{Si},$$

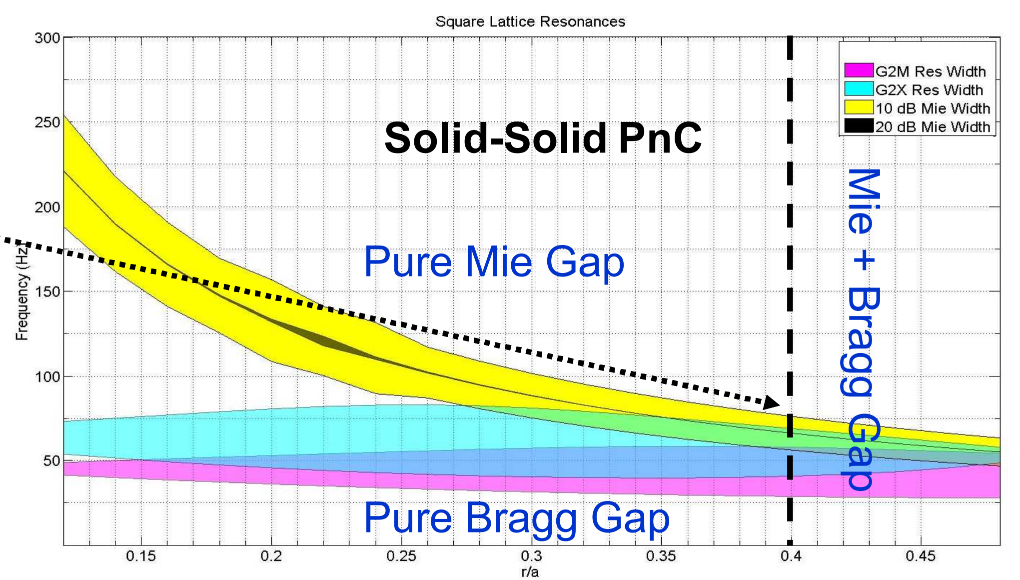
$$where \quad ff_1 = \frac{\pi r}{2a}$$

Origin of the Phononic Bandgap

- *Solid-air PnC only has Bragg resonance overlap*
  - *Large r/a values agree with PWE!*
- *Solid-solid PnC has greater overlap of Bragg, Mie resonances*





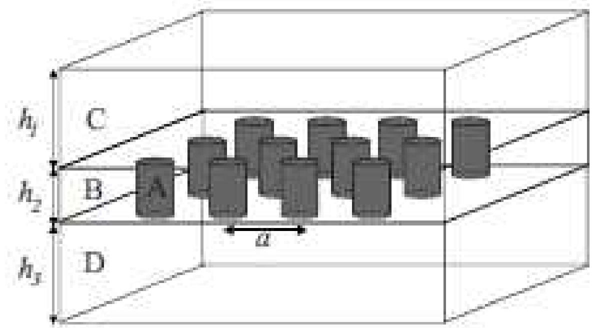


Plane Wave Expansion

- **Plane wave expansion (PWE) solves an eigenvalue problem for the modes of a periodic structure**
  - *FFT algorithm used to calculate structure factors*

$$\rho(\vec{r})\frac{\partial^2 u_i(\vec{r},t)}{\partial t^2} = \sum_{j,k,l}\frac{\partial}{\partial x_j}\left(C_{ijkl}(\vec{r})\frac{\partial u_l(\vec{r},t)}{\partial x_k}\right)$$

- **Densities**
  - *Silicon: 2332 kg/m³*
  - *Air: 10⁻⁴ kg/m³*
  - *Tungsten: 19250 kg/m³*



$$C_{air} = \begin{bmatrix} 10^6 & -10^6 & -10^6 & 0 & 0 & 0 \\ -10^6 & 10^6 & -10^6 & 0 & 0 & 0 \\ -10^6 & -10^6 & 10^6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10^6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 10^6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10^6 \end{bmatrix}$$

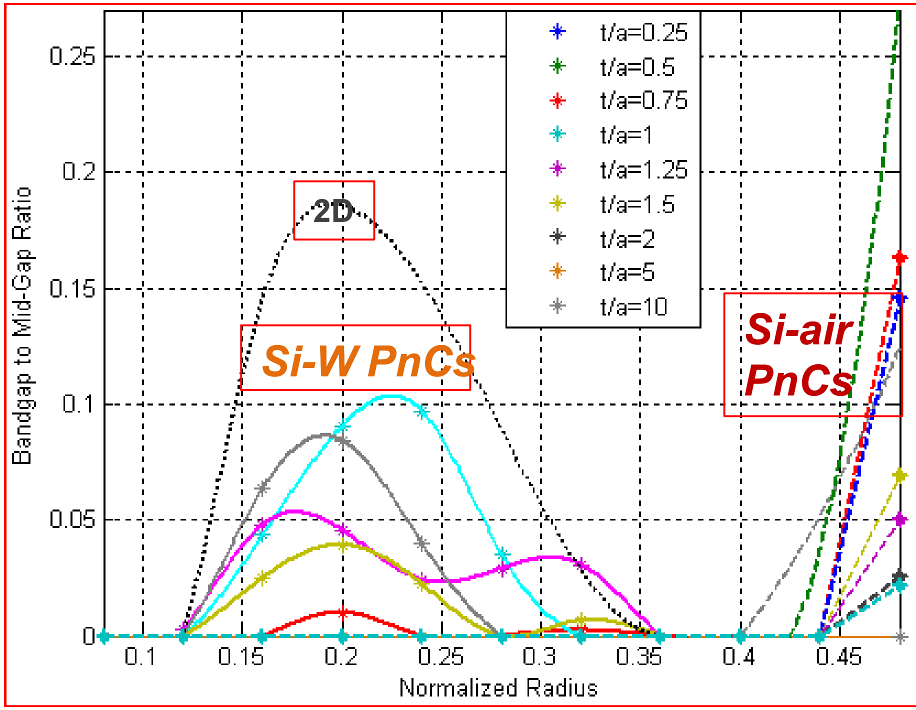
$$C_{Si} = \begin{bmatrix} 16.7\cdot10^{10} & 6.39\cdot10^{10} & 6.39\cdot10^{10} & 0 & 0 & 0 \\ 6.39\cdot10^{10} & 16.7\cdot10^{10} & 6.39\cdot10^{10} & 0 & 0 & 0 \\ 6.39\cdot10^{10} & 6.39\cdot10^{10} & 16.7\cdot10^{10} & 0 & 0 & 0 \\ 0 & 0 & 0 & 7.956\cdot10^{10} & 0 & 0 \\ 0 & 0 & 0 & 0 & 7.956\cdot10^{10} & 0 \\ 0 & 0 & 0 & 0 & 0 & 7.956\cdot10^{10} \end{bmatrix}$$

$$C_W = \begin{bmatrix} 40.9\cdot10^{10} & 17.1\cdot10^{10} & 17.1\cdot10^{10} & 0 & 0 & 0 \\ 17.1\cdot10^{10} & 40.9\cdot10^{10} & 17.1\cdot10^{10} & 0 & 0 & 0 \\ 17.1\cdot10^{10} & 17.1\cdot10^{10} & 40.9\cdot10^{10} & 0 & 0 & 0 \\ 0 & 0 & 0 & 6.74\cdot10^{10} & 0 & 0 \\ 0 & 0 & 0 & 0 & 6.74\cdot10^{10} & 0 \\ 0 & 0 & 0 & 0 & 0 & 6.74\cdot10^{10} \end{bmatrix}$$

Vasseur, *et al.*, *Phys. Rev. B*, **77**, 085415 (2008)

Solid-Air vs. Solid-Solid PnCs

- ***Air- solid PnCs can have large bandgaps, but for a limited range of hole radii***
- ***Solid-solid PnCs have bandgaps for a wider range of inclusion radii***
  - ***Easier fabrication, larger design parameter space***



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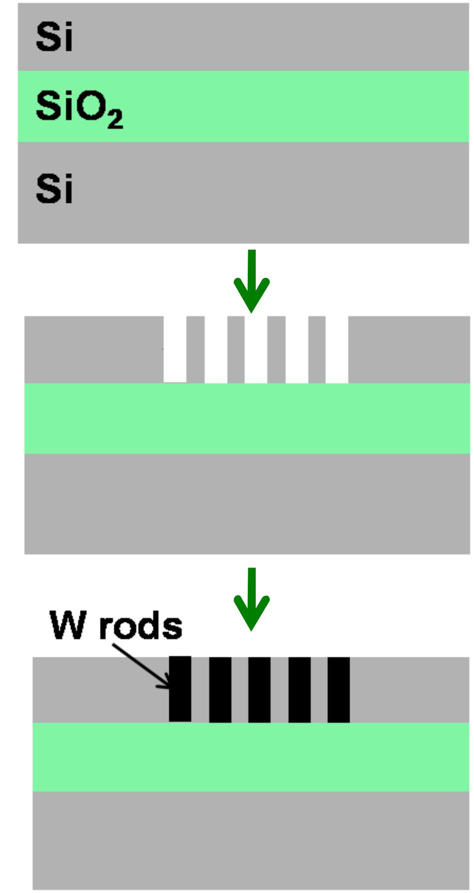
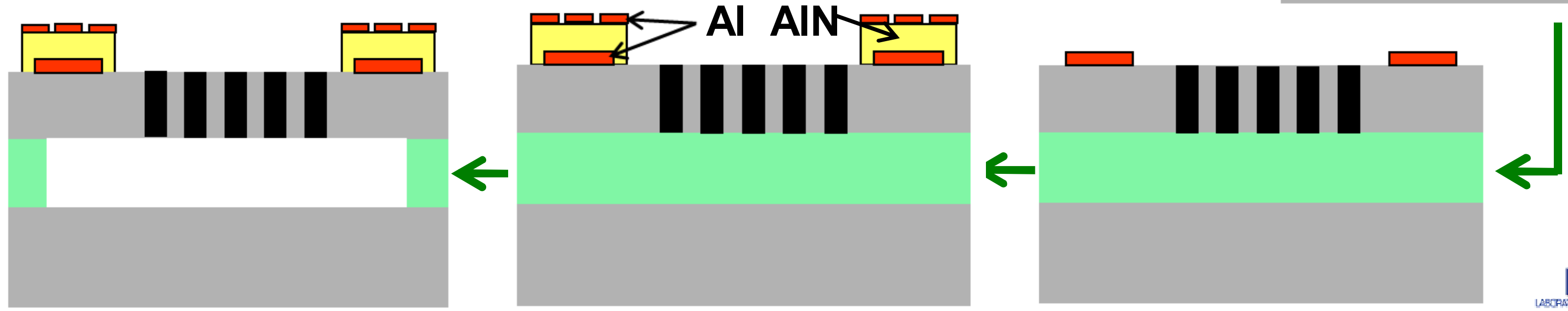
PnC Fabrication

Fabrication of Si-based PnC membranes

- *SOI wafer*

1. *Air holes are patterned and etched*
2. *W is deposited with CVD (solid-solid only)*
3. *Al bottom electrodes are deposited/patterned*
4. *AlN films and Al top electrodes are deposited/patterned*
5. *PnC membrane is released*

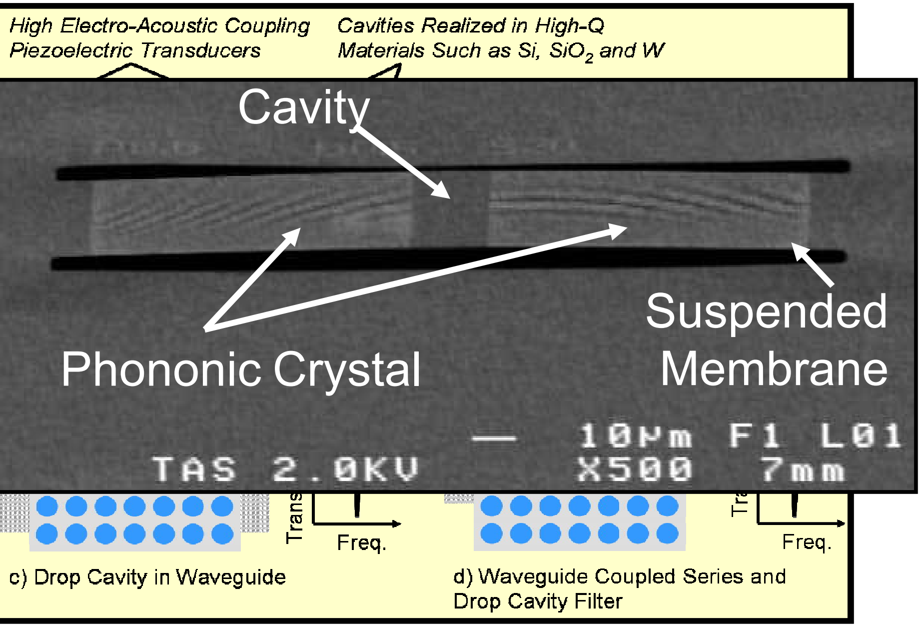


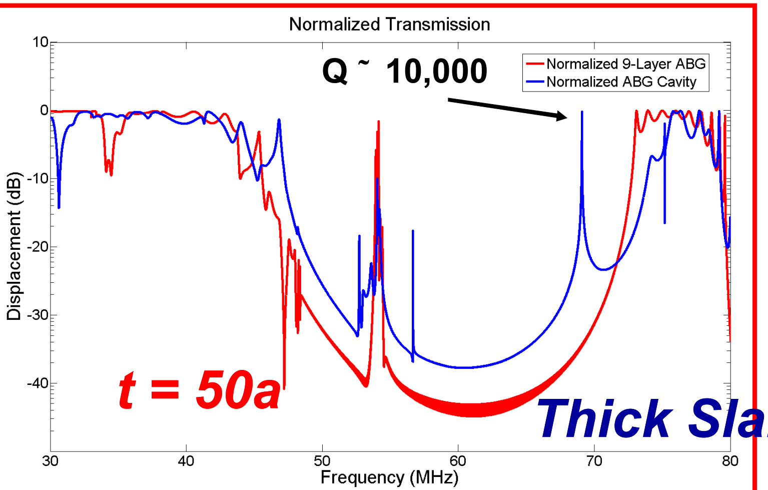


PnC RF Applications

Cellular Phone bands: ~900MHz to ~5GHz

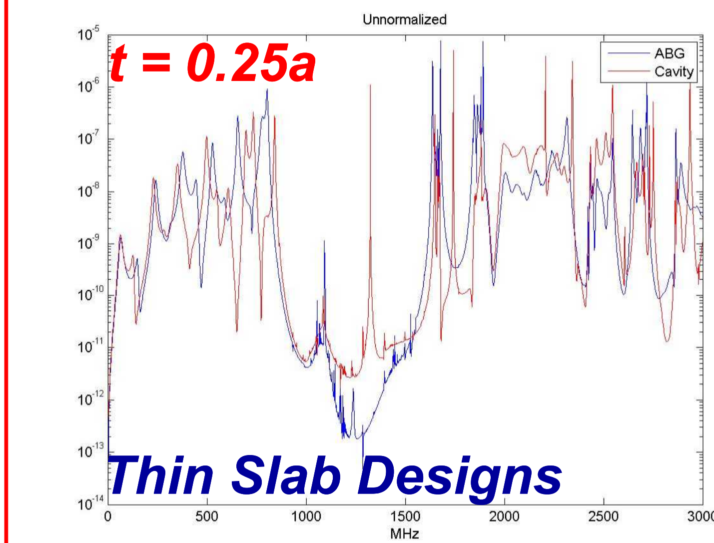
Phononic Logic



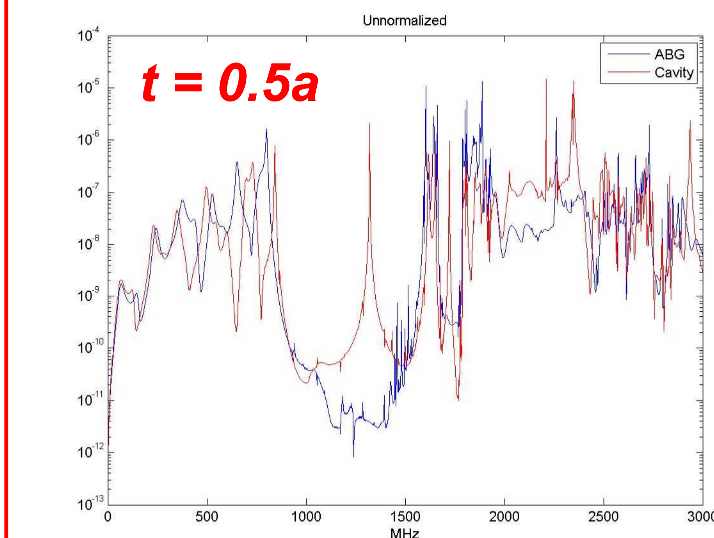


Thick Slab Designs

High Q Cavities



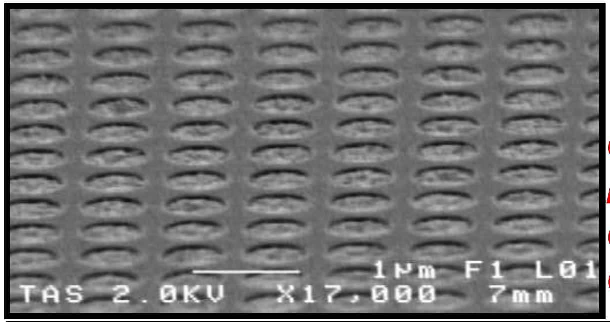
Thin Slab Designs



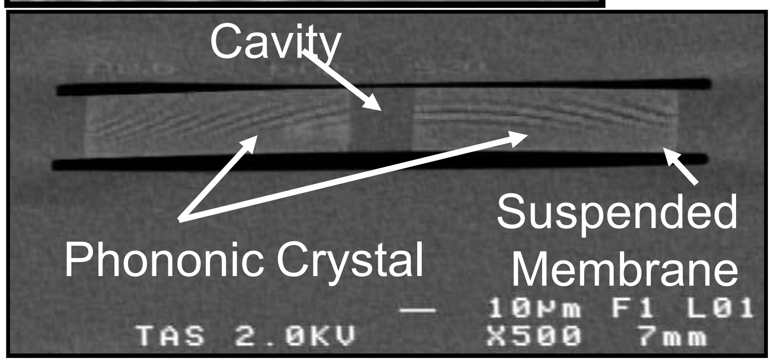
Phonon Signal Processing

Cellular Phone bands: ~900MHz to ~5GHz

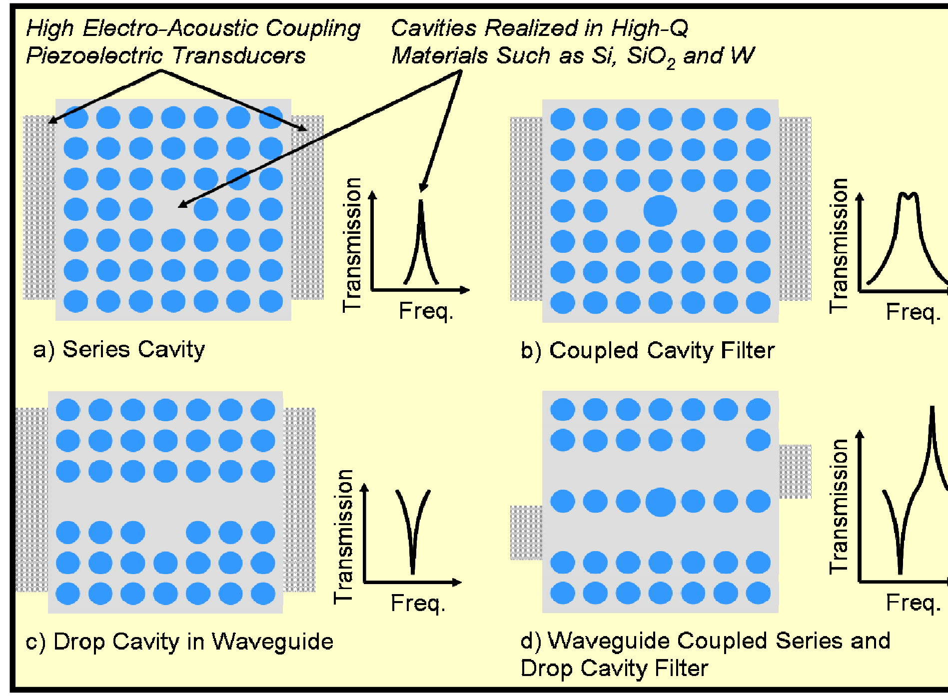
4.25-8.6 GHz PnCs (UHF) 2009



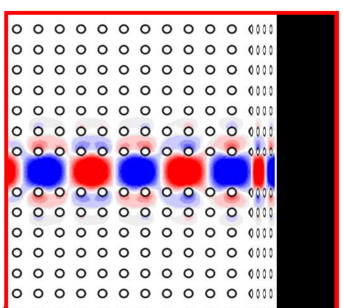
Overtone Cavity Between Two 5.3 GHz Phononic Crystals

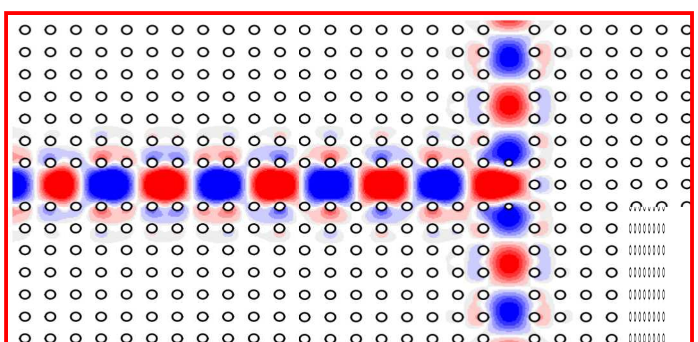


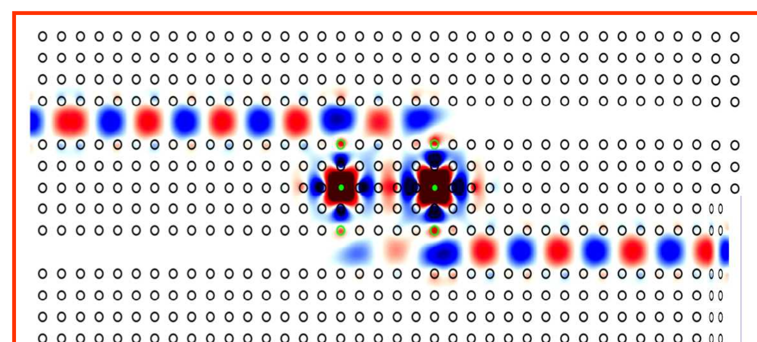
Phononic Logic



Phonon Guides







Advantages of PnC Circuitry

❖ ***Benefits of the Phononic Domain:***

- ***Integration of multiple components on one chip with little or no losses at a size that is 10^4-times smaller than current optical or micro-strip technology.***
- ***Allows for distributed circuit techniques that are commonly used in microwave circuit design to be applied to lower frequency systems (such as cell phones and WLAN) using acoustic rather than EM waves.***

- **Speed of Light = $3x10^8$ m/s**
- **Speed of Sound in SiO_2 = $5.8x10^3$ m/s**
- **Optical Delay Line of 1 μs = 300 m**
- **ABG Delay Line of 1 μs = 5.8 mm**
- ***ABG delay line is 52,000 times smaller than an optical one!***

⇒

Miniature

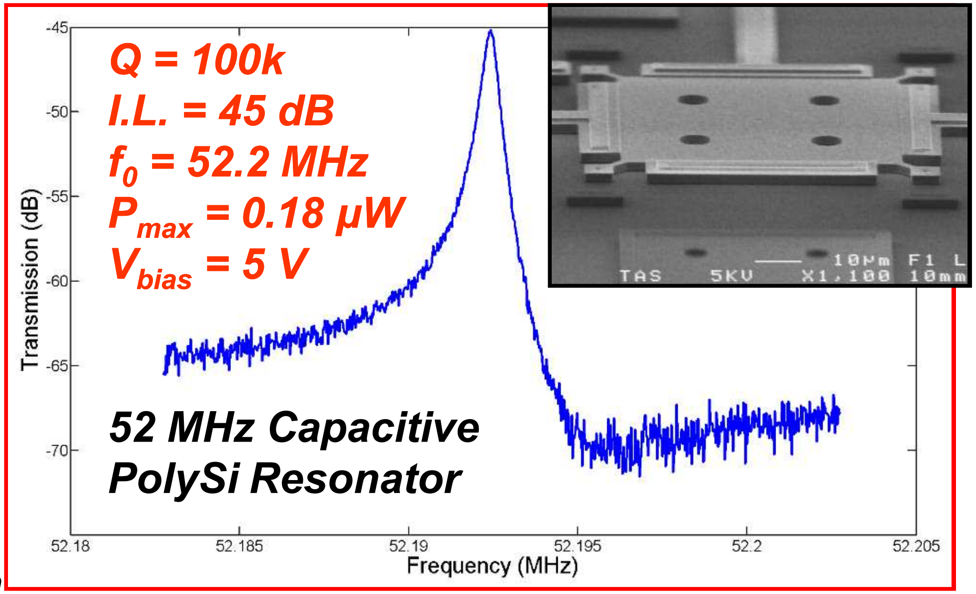
- ***Filters***
- ***Delay Lines***
- ***Phase Shifters***
- ***Acoustic Signal Processing***
- ***Power Combiners/Dividers***

RF Applications:

MEMS Resonator fQ Product/Insertion Loss Trade Off

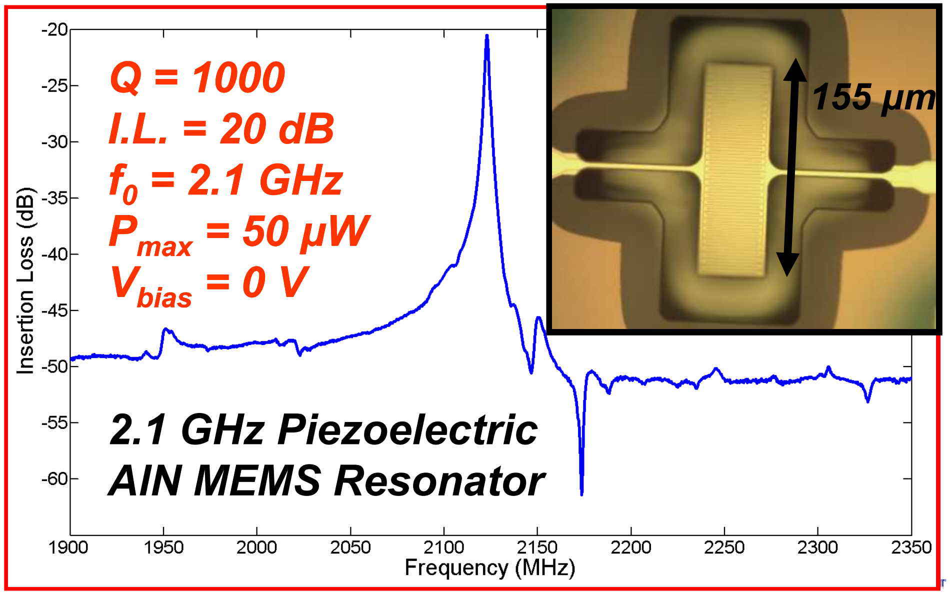
Capacitive MEMS Resonators

- High fQ product for acoustics ($2x10^{13}$), but …
- Weak electro-acoustic transduction leads to high impedance/insertion loss
  - **Higher noise, can't match to antennas or off-chip components**
  - **Arraying and high-K dielectric transduction lead to unmanageable parasitic capacitance**
- Force ≈ V^2 (Low Power Handling)
  - **Unsuitable for transmit filters, limits oscillator phase noise and sensor resolution**



Piezoelectric MEMS Resonators

- Low impedance (< 50)/ Insertion Loss
  - **Strong electro-acoustic transduction**
  - **Easily matched to antenna, off-chip circuits**
- Force ≈ V (High Power Handling), but …
- Q limited to a few thousand
  - **Material damping in metal electrodes and piezoelectric films, creep, aging**



Want Highly Efficient Piezoelectric Transduction + High-Q Materials

RF Applications:

Ultra High Q MEMS PnC Resonators

$$Q_{Total} \approx \left[\frac{\frac{1}{Q_{SiC}} + \frac{t_{AlN}}{t_{SiC} Q_{AlN}}}{1 + \frac{t_{AlN}}{t_{SiC}}} \right]^{-1}$$

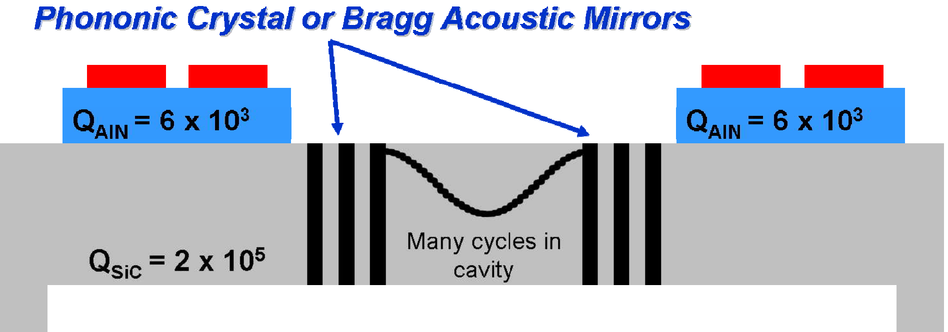
$$Q = 2\pi \frac{E_{Stored}}{\frac{E_{Lost}}{Cycle}}$$

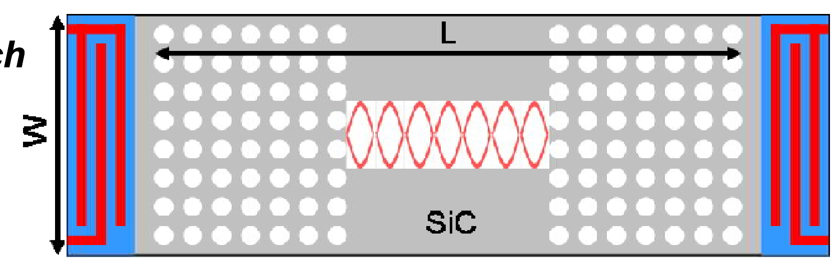
Lithographically Defined Overtone Resonators

- ***SiC has highest phonon-phonon limited fQ***
- ***Thin film SiC can be deposited, patterned and micromachined using Si IC compatible processes***
- ***Lithographically definable frequencies and bandwidths (scalable to multi-frequency, multi-bandwidth frequency banks)***
- ***Low impedance, high dynamic range AlN couplers***
- ***High stop-band rejection***

Phononic Crystal Advantages

- ***≈ 100x smaller size, more scalable to arrays***
- ***Lithographically controlled frequency and bandwidth***
- ***Si IC processing/packaging compatible***
- ***Low Impedance, High dynamic range, High isolation***
- ***Co-fabrication with traditional lateral resonator approach***





Top Down View of a High-Q PhonC Resonator

PnC Fabrication Roadmap

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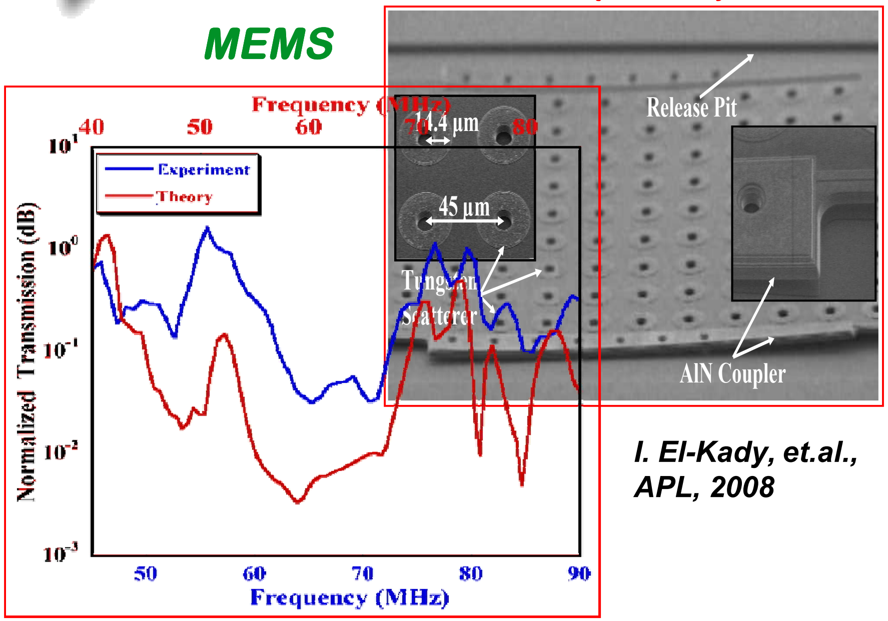
1st MHz MEMS PnC (VHF) 2008

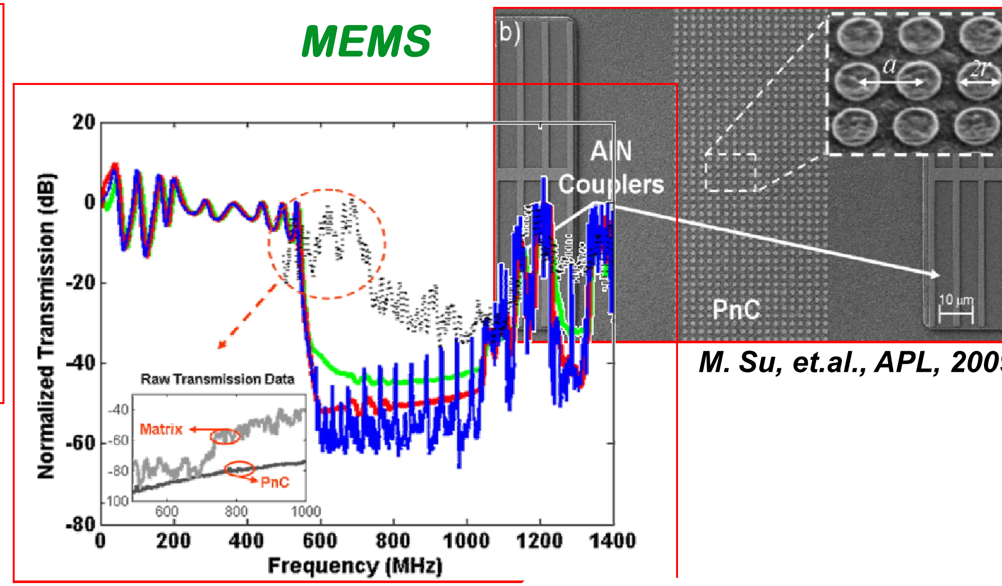
MEMS



I. El-Kady, et.al., APL, 2008

1st GHz MEMS PnCs (UHF) 2009

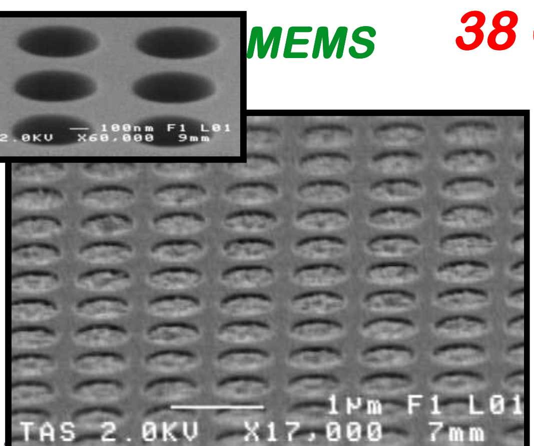
MEMS



M. Su, et.al., APL, 2009

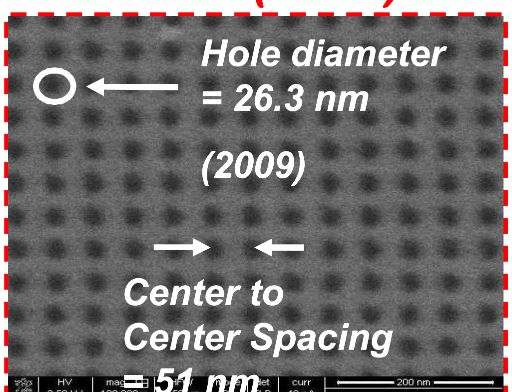
10 GHz PnCs (UHF) 2009

MEMS

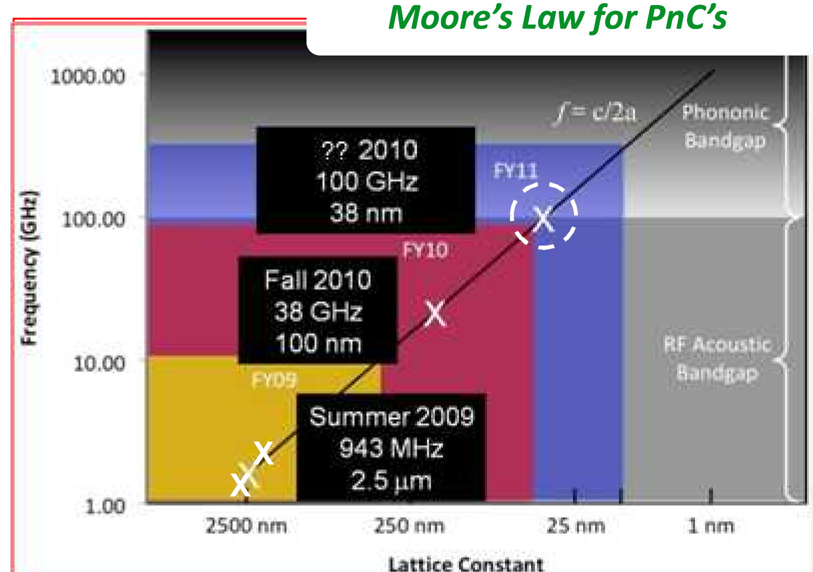


FIB

38 GHz PnCs (UHF) 2010



Moore's Law for PnC's



Outline

- Phononic Crystals
  - Why Phononic Crystals (PnCs)?
  - Bandgaps in PnCs
  - RF Applications of PnCs
- Manipulating Thermal Phonons
  - Modifying Thermal Conductivity (κ)
  - Realizing Ultra-Low κ Si
  - High ZT Devices in Silicon using PnCs

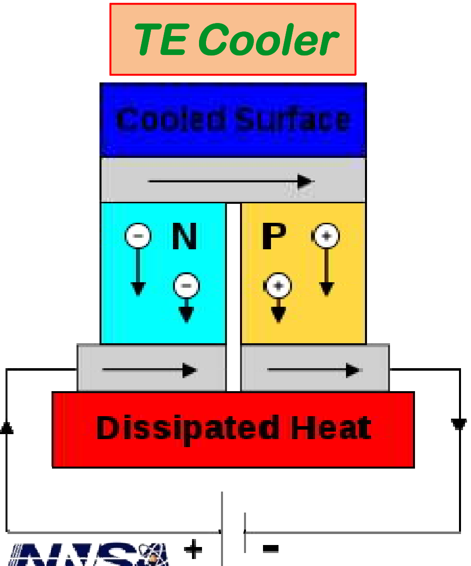
Motivation:
Manipulating Thermal Phonons

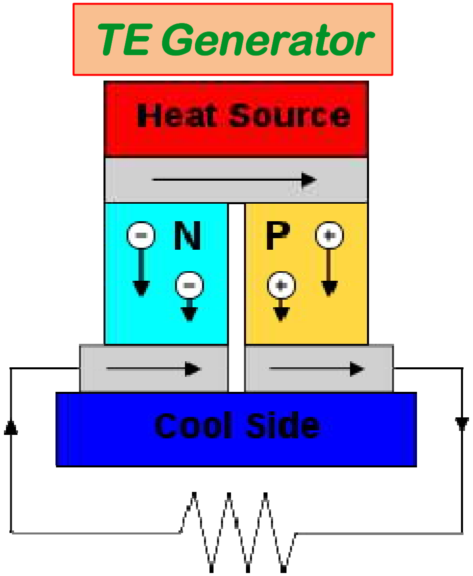
TE Peltier Effect:

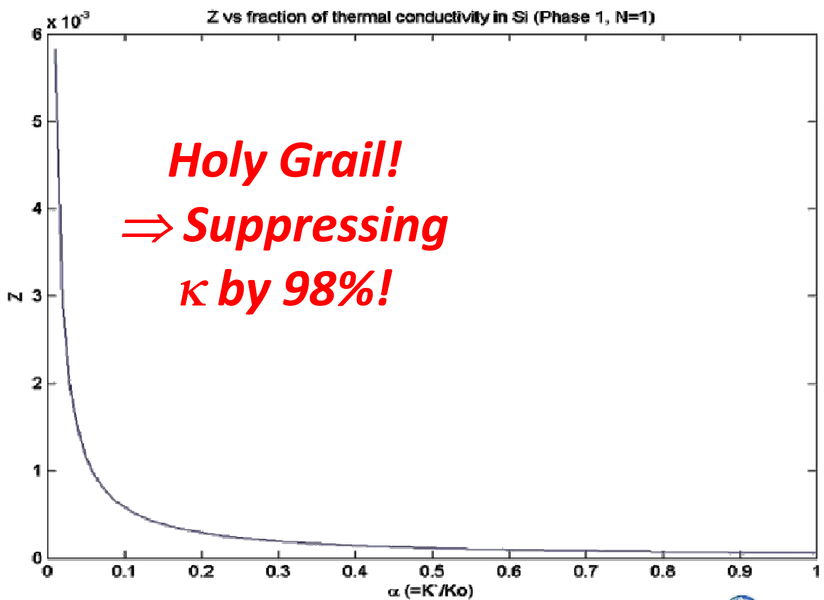
- **Cooler:** Apply DC voltage ➔ heat moves from cold-side to hot-side
- **Generator:** Heat gradient ➔ current flow
- **Efficiency:** Quantified by the dimensionless quantity ZT
- **S:** Seebeck coefficient ($\Delta V/\Delta T$)
- **σ:** Electrical conductivity
- **K:** Thermal conductivity ($= K_e + K_{ph}$)

Thermoelectric Figure of Merit

$$ZT = \frac{S^2 \sigma T}{\kappa}$$







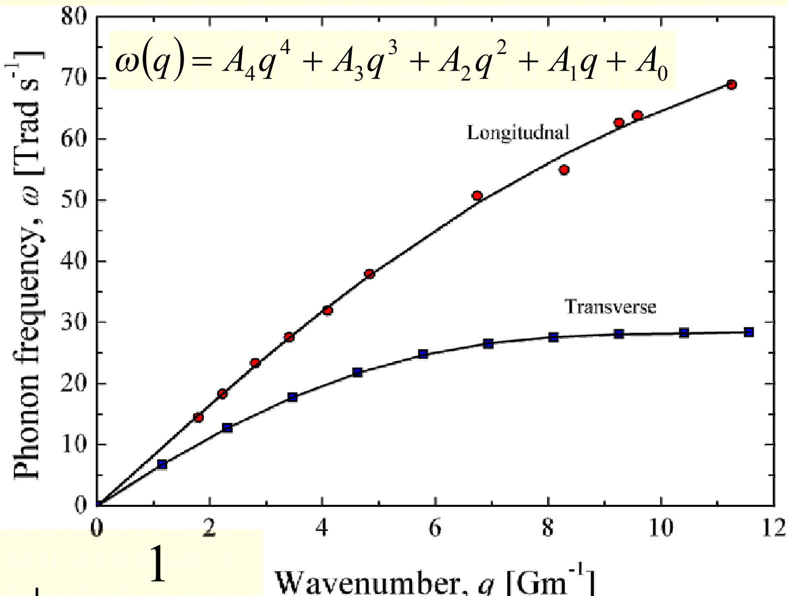
Manipulating the Thermal Conductivity of Silicon

- **The thermal conductivity is given by**

$$\kappa = \frac{1}{6\pi}\sum_j \int_q \frac{\hbar^2\omega_j^2(q)}{k_B T^2} \frac{\exp\left[\frac{\hbar\omega(q)}{k_B T}\right]}{\left(\exp\left[\frac{\hbar\omega(q)}{k_B T}\right]-1\right)^2} \upsilon_j^2(q)\tau_j(q) q^2 dq$$

$\omega(q)$ is the phonon dispersion.
$\upsilon(q) = \partial\omega(q)/\partial q$ is the phonon group velocity,
$\tau(q)$ is the scattering time of the phonons,
q is the wavevector, and the thermal conductivity,
$j = 1, 2, 3$ (1 longitudinal, and 2 transverse).

- **We use measured Si dispersion data and fit the data to a 4th degree polynomial for an analytical expression of the phonon dispersion**



- **In bulk Si, phonon scattering is dominated by Umklapp scattering, impurity scattering, and boundary scattering.**

$$\frac{1}{\tau_{Umklapp,j}} = BT\omega_j^2(q)\exp\left[\frac{C}{T}\right]$$

$$\frac{1}{\tau_{impurity,j}} = D\omega_j^4(q)$$

$$\frac{1}{\tau_{boundary,j}} = \frac{\upsilon_j(q)}{E}$$

- **Mattheissen's Rule:**

$$\frac{1}{\tau_j(q)} = \frac{1}{\tau_{Umklapp,j}} + \frac{1}{\tau_{impurity,j}} + \frac{1}{\tau_{boundary,j}}$$

- **where B, C, D, and E are constants determined by fitting κ to experimental data.**

Manipulating the Thermal Conductivity of Silicon

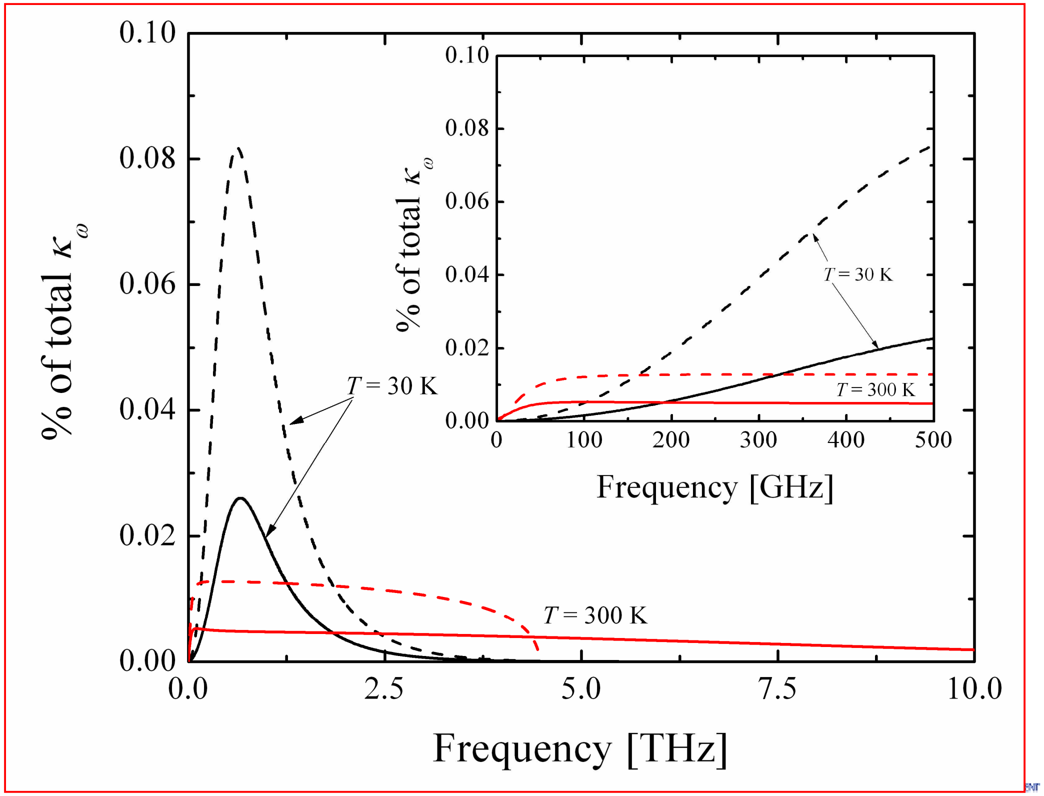
Sandia National Laboratories

- The fractional contribution to κ is given by:

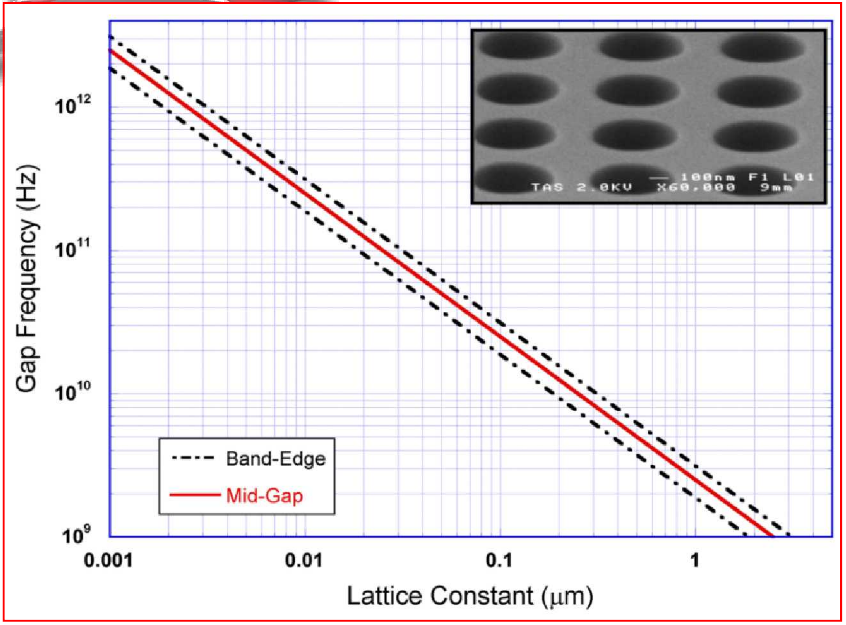
$$\frac{\kappa_{\omega,j}}{\sum_j \sum_\omega \kappa_{\omega,j}}$$

- Fraction of the total spectral thermal conductivity for **30K** and 300K. Longitudinal (solid lines) and transverse (dashed lines) contributions.
- (inset) Spectral phonon contribution on the range of 0 to 500 GHz.
- The major contribution to κ is from **10GHz-4THz** phonons

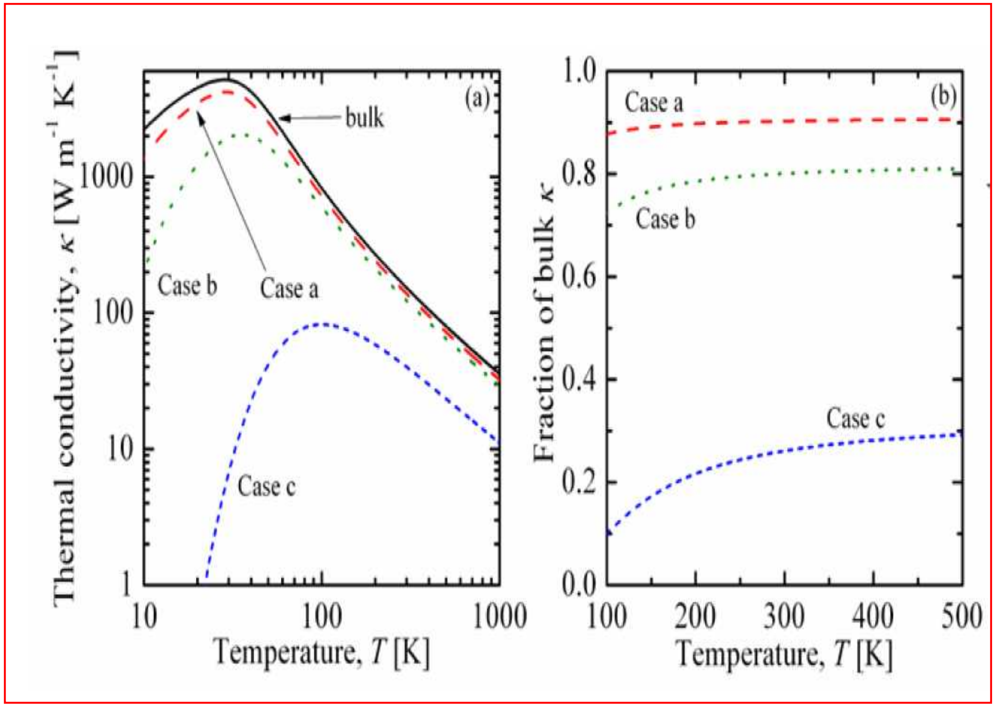
- Transverse spectral thermal conductivity is multiplied by 2 since we assume degenerate transverse branches.



Manipulating the κ of Silicon

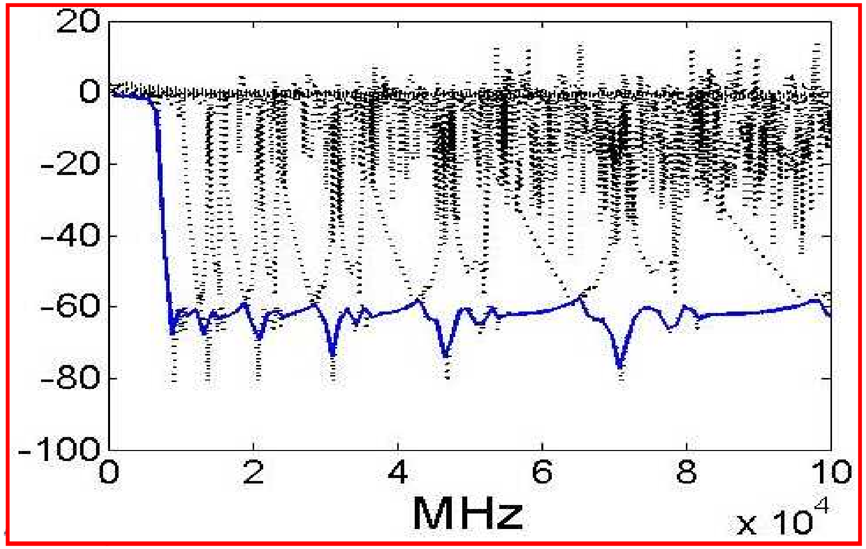


- **Modified spectral thermal conductivity**



- **Cascaded PnC gaps 10GHz-to-1THz:**

Normalized Trans (dB) (Chirped Lattice)



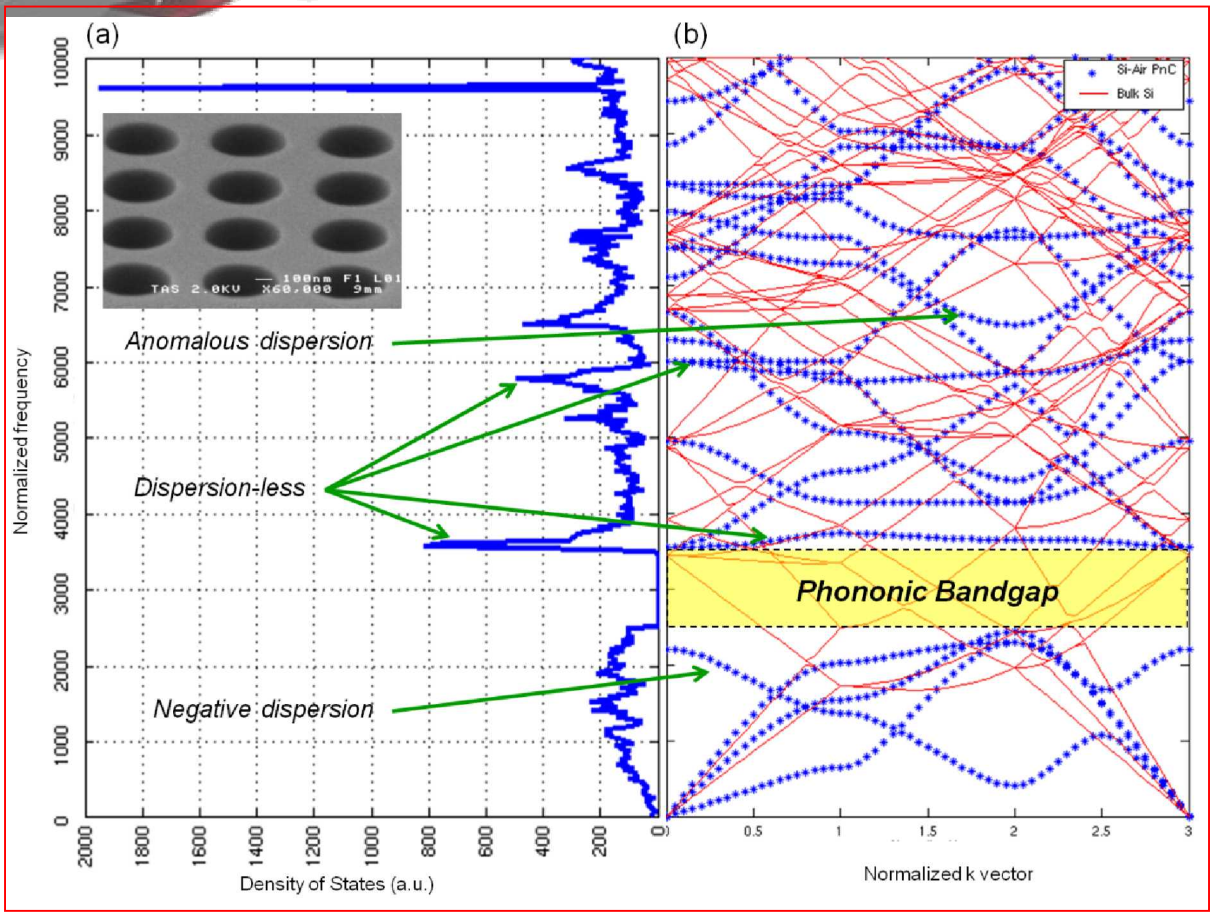
Thermal conductivity of Si assuming unmodified bulk dispersion with:

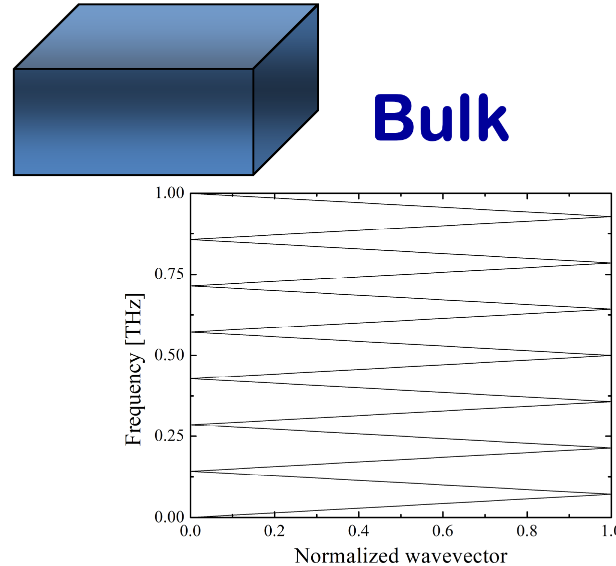
- ***Case a: Suppression of 10GHz-to-0.5THz Phonons***
- ***Case b: Suppression of 10GHz-to-1THz Phonons***
- ***Case c: Suppression of 10GHz-to-4THz Phonons***

1- Hopkins, Rakich, Olsson III, El-Kady, and Phinney, "Origin of the reduction in phonon thermal conductivity of microporous solids," Applied Physics Letters 95, 161902 (2009).

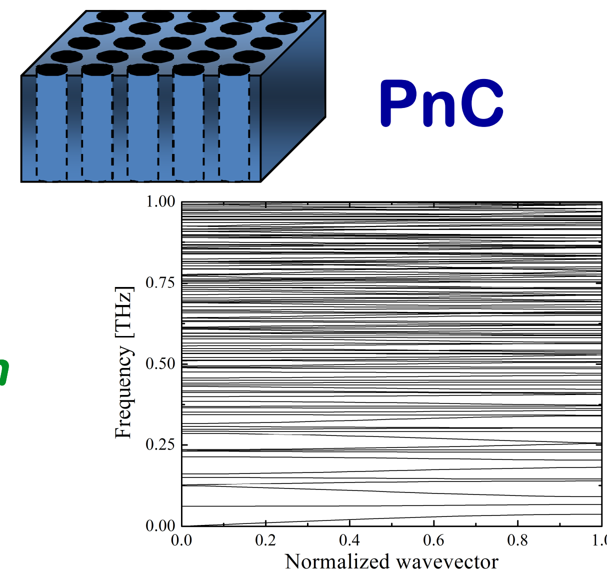
2- Hopkins, Phinney, Rakich, Olsson III, El-Kady, "Phonon considerations in the reduction of thermal conductivity in phononic crystals," currently under review JAPA.

Harmonic and Anharmonic Effects





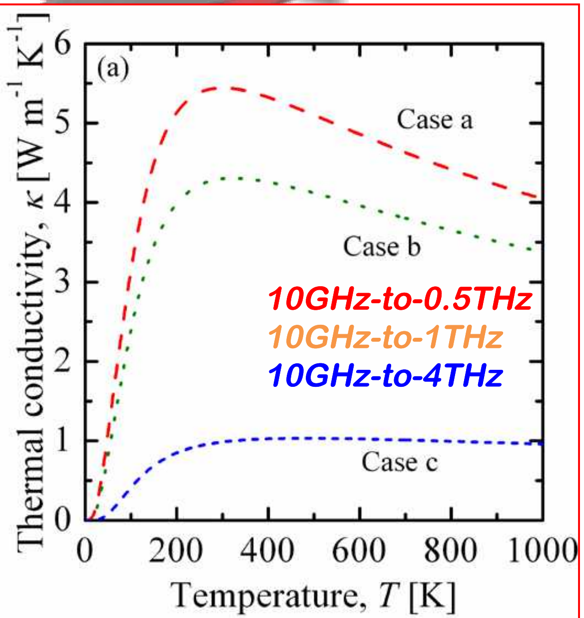
Bulk

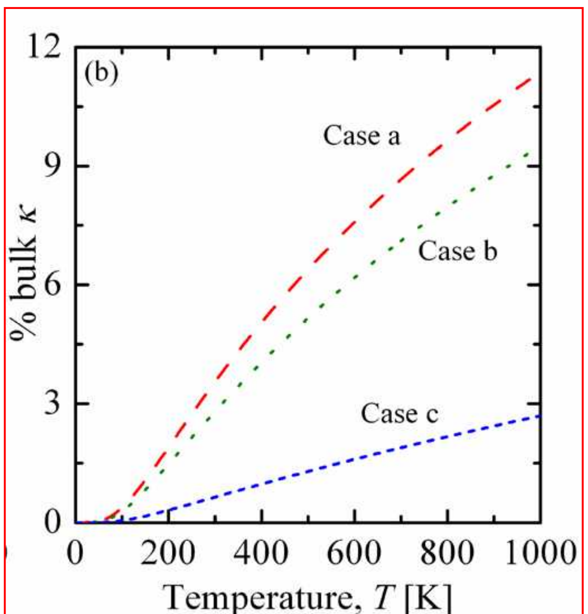


PnC

- ***Harmonic (coherent) Reflections* → *Bandgap creation***
- ***Anharmonic Effects* → *Anomalous dispersion***
- ***Flat Bands* → *Reduced group velocity***
- ***Negative Bands* → *Backward propagation (backscattering)***

Si κ with Modified PnC Dispersion

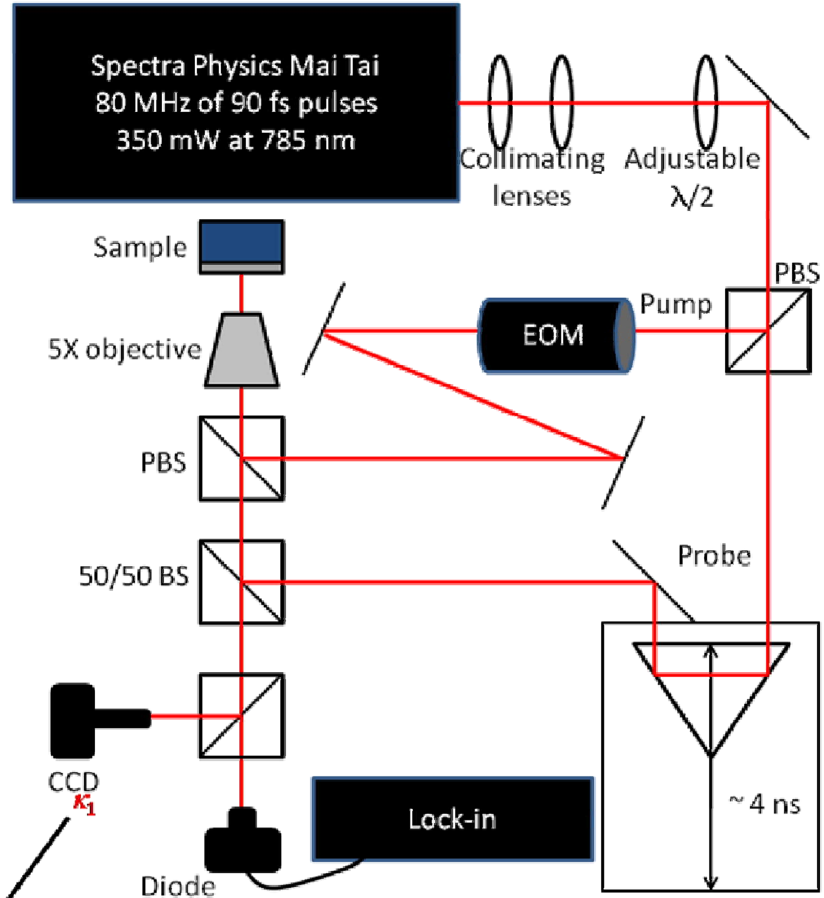


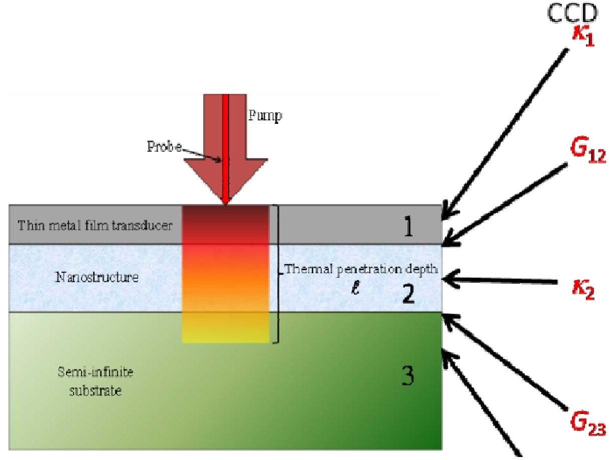


Thermoreflectance signal directly proportional to temperature change

$$C\frac{\partial T}{\partial x} = -\kappa\frac{\partial^2 T}{\partial x^2}$$

Given temperature change with time, we fit the heat equation to the data to determine k





➔Deposit Al on top surface and measure GHz lattice!

P. Hopkins, R. H. Olsson-III, L. Phinney and I. El-Kady, App. Phys. A (2010)

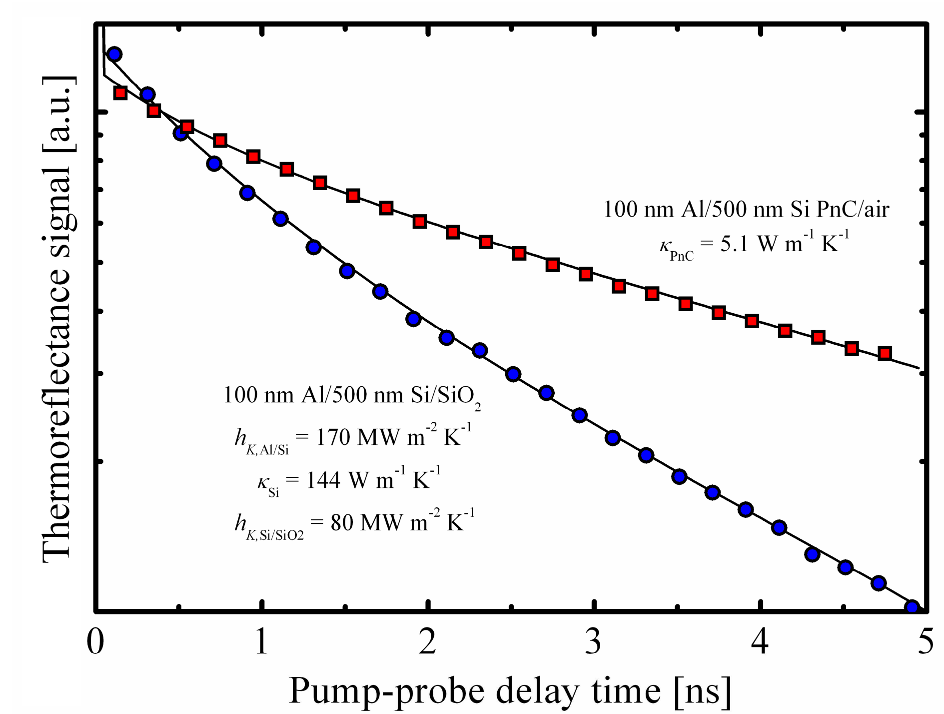
Measured κ of Silicon PnC

$$\kappa_{\omega,j} = \frac{1}{6\pi}\frac{\hbar^2\omega_j^2(q)}{k_B T^2}\frac{\exp\left[\frac{\hbar\omega(q)}{k_B T}\right]}{\left(\exp\left[\frac{\hbar\omega(q)}{k_B T}\right]-1\right)^2}\upsilon_j(q)\tau_j(q)q^2$$

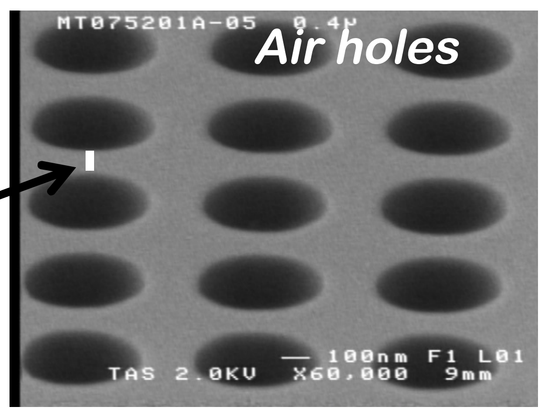
$$\frac{1}{\tau_j(q)} = \frac{1}{\tau_{Umklapp,j}} + \frac{1}{\tau_{impurity,j}} + \frac{1}{\tau_{boundary,j}}$$

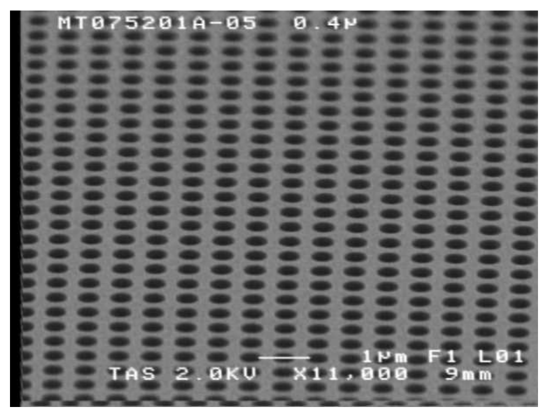
$$\frac{1}{\tau_{Boundary,j}} = \frac{\partial\omega_j(q)}{\partial q}\frac{1}{L}$$

Thermal conductivity measurements on a 500nm-thick suspended PnC structure



Limiting dimension, L (min. feature size)

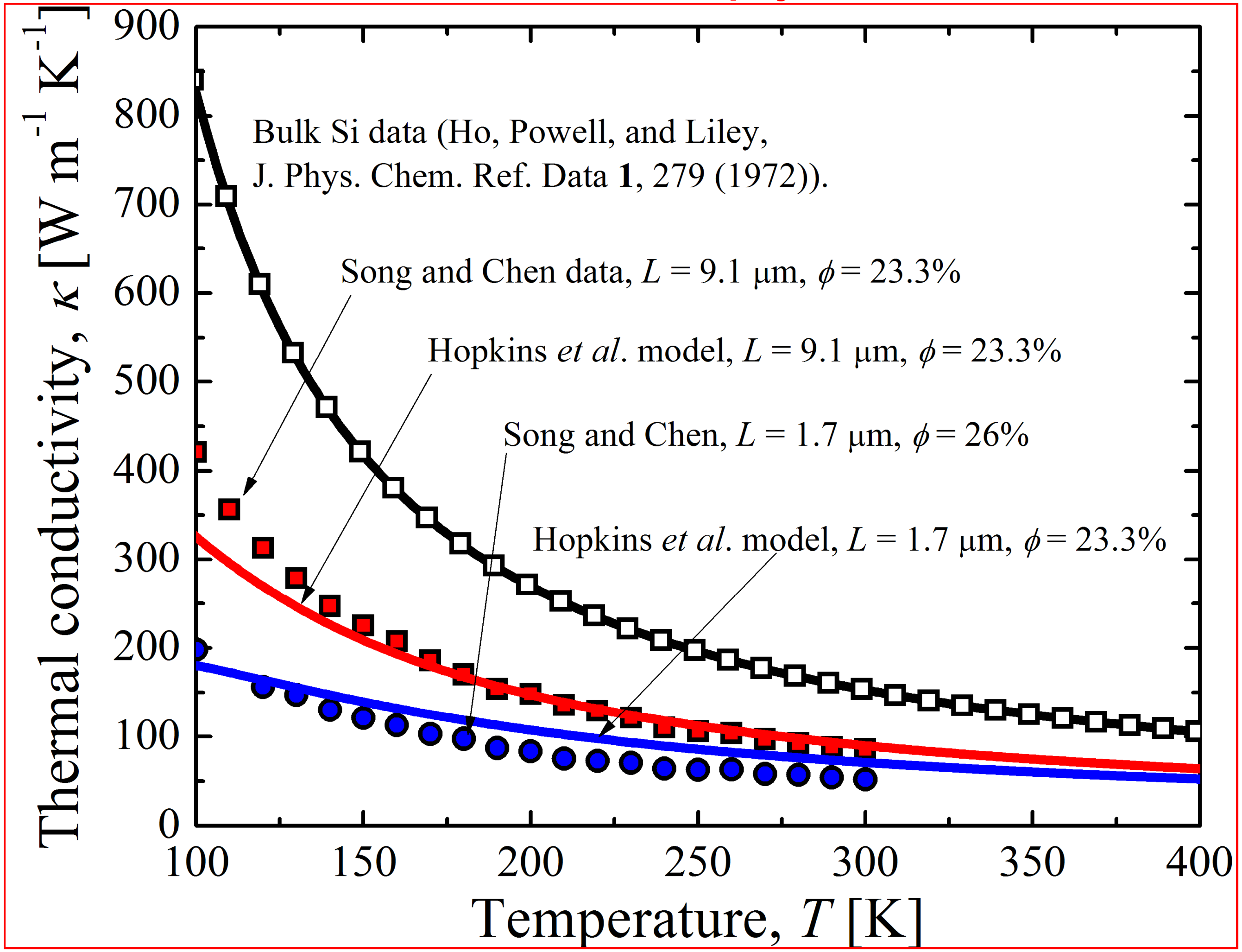




$$\frac{\kappa_{PnC}}{\kappa_{bulk}} = 0.035$$

Understanding the Effect of Porosity:

Did we simply remove too much material?



Porosity accounted for by "Eucken" model

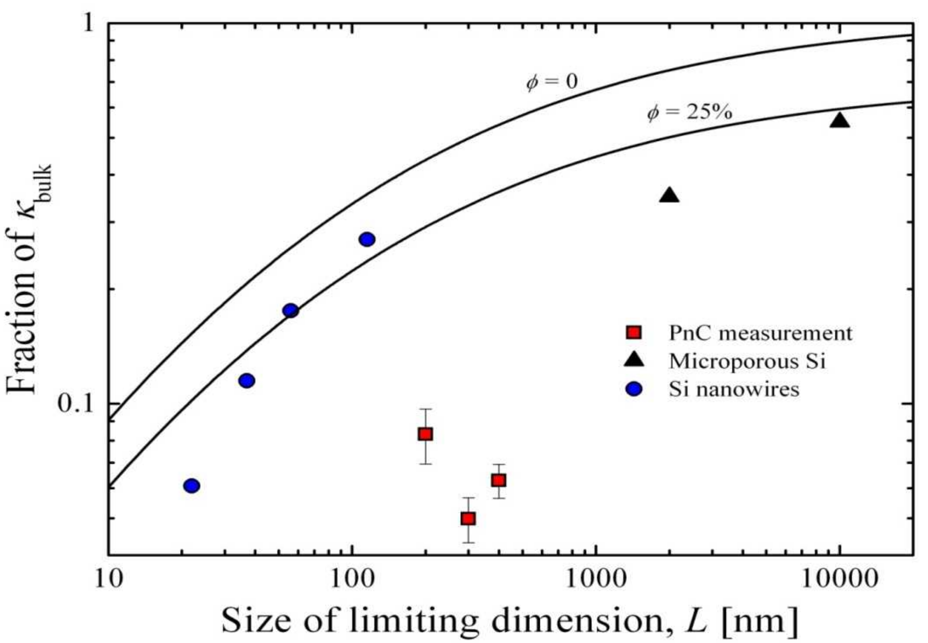
$$\frac{\kappa_{porous}}{\kappa_{solid}} = \frac{1-\phi}{1+\frac{\phi}{2}}$$

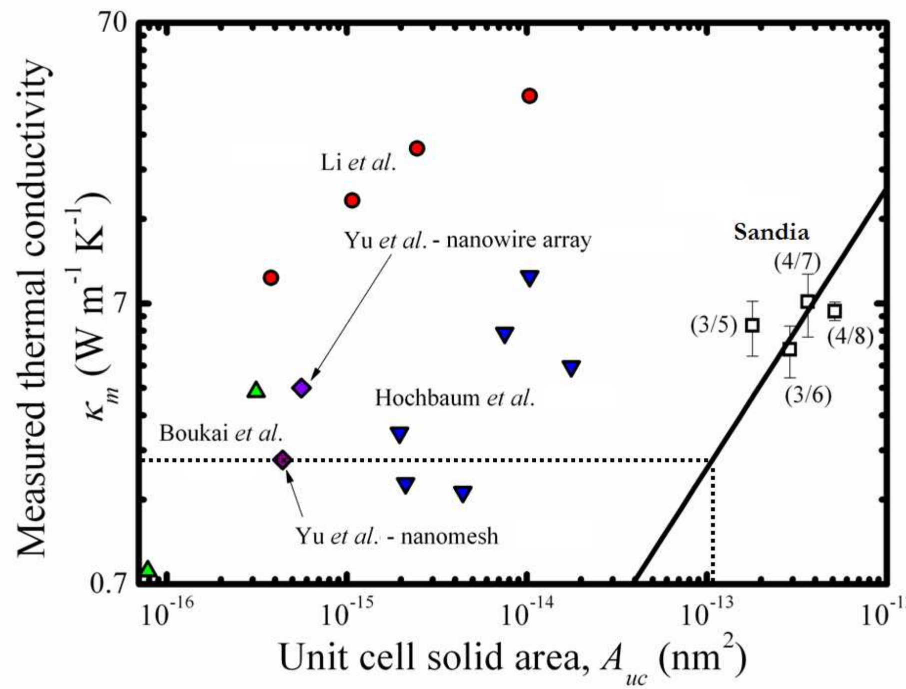
Eucken, Forschung auf dem Gebiete des Ingenieurwesens Ausgabe B(Band 3): 3/4 VDI Forschungsheft 353 (1932).

Hopkins, Rakich, Olsson, El-Kady, and Phinney, APL 95, 161902 (2009)

An Order of Magnitude Lower κ

(as compared to that predicted by the porosity argument)





Nanowires: φ= 0
Microporous Si: φ ~ 25%
PnC: φ < 20%

$$\Rightarrow \frac{1}{\left(\frac{\kappa_{PnC}}{\kappa_{bulk}}\right)} = 500 \;\; !$$

PnC outperforms nanowires @ 2 orders of magnitude larger limiting dimension (L)!

Since the mean free path of electrons is an order of magnitude lower than that of phonons, ➔ Based solely on phonon thermal conductivity reduction, predicted room Temp. ZT enhancement in Si by a factor of 500!

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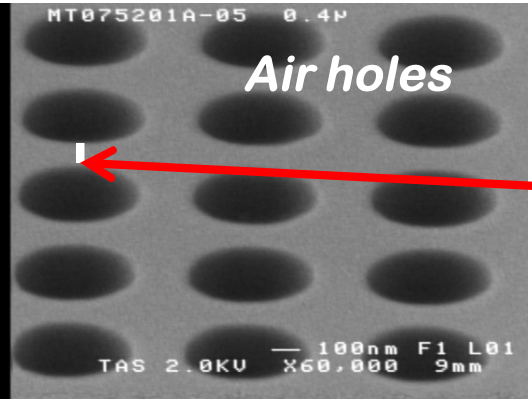
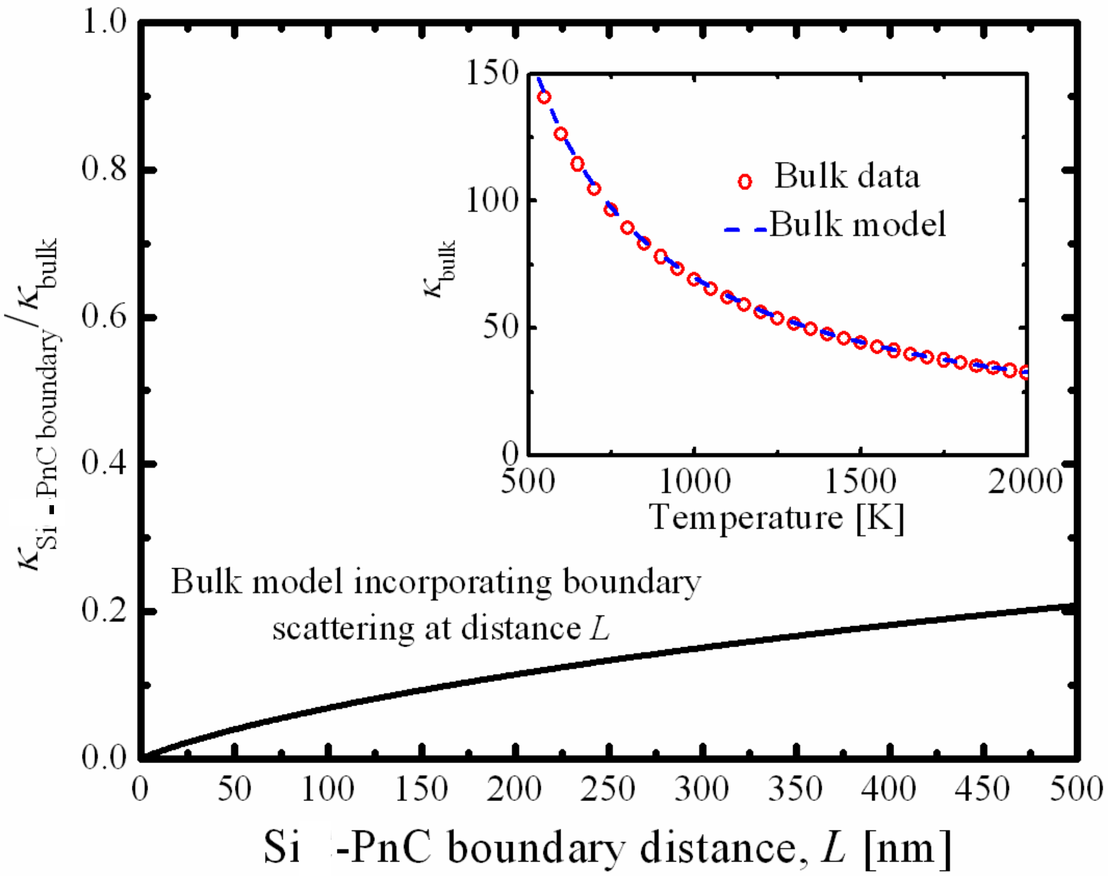
How Can Micron-Size Holes Affect nm Wavelets Such as Phonons?



L, limiting dimension (min. feature size)



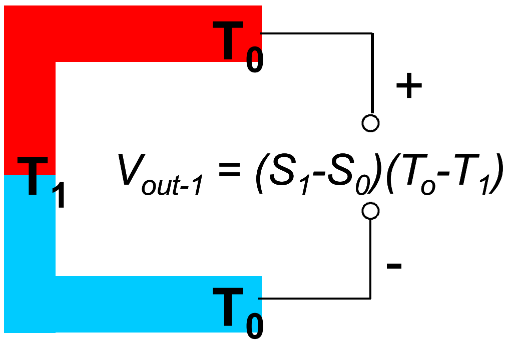
Ratio of the thermal conductivity of Si-PnC to that of bulk as a function of the minimum feature size, *L*, of the Si-PnC. Inset shows the accuracy with which the model predicts bulk behavior. Red is actual experimental data, and the dashed blue line is the result of model.

P. Hopkins, C. M. Reinke, M. F. Su, Z. Leseman , R.H. Olsson-III, L. Phinney and I. El-Kady, Nano Letters, vol. 11, pp. 107-12, 2010

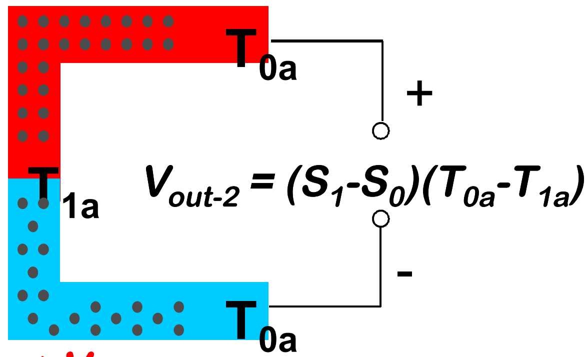
High-ZT PnC TE Device

- ***Thermal Energy Scavenging/TE Cooling***

Generic Thermocouple:



PhonC Thermocouple:

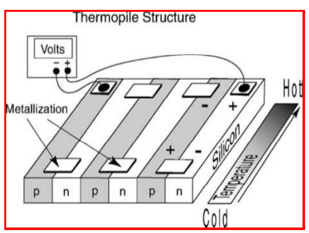


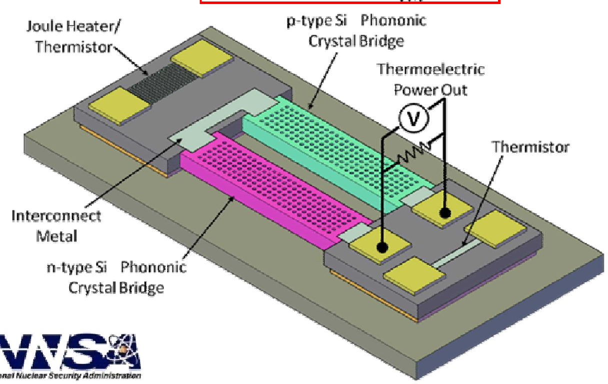
$T_{0a}-T_{1a} > T_0-T_1 \Rightarrow V_{out-2} > V_{out-1}$

Phononic bandgap allows for simultaneous low thermopile series resistance (low losses) and high thermal isolation (high ΔT and ΔV)

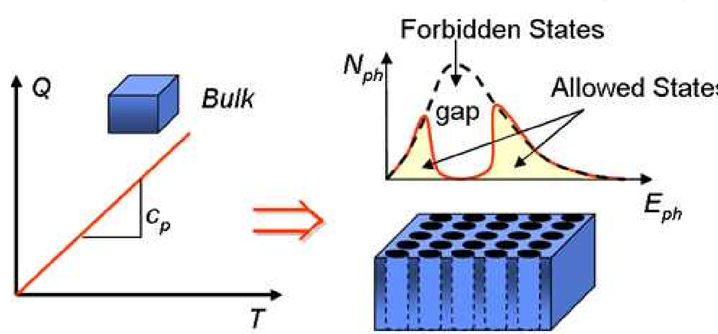
Seebeck coefficients of metals relative to platinum

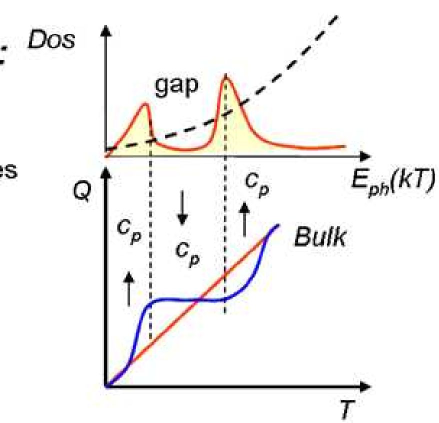
Material	Seebeck coefficient (μV/°C)
Antimony	+48.9
Chromel	+29.8
Tungsten	+11.2
Gold	+7.4
Copper	+7.6
Silver	+7.4
Aluminum	+4.2
p-Silicon, $\rho = 0.0035\ \Omega$cm	+450
p-Germanium, $\rho = 0.00083\ \Omega$ cm	+420
Platinum	0.00
Calcium	−5.1
Alumel	−10.85
Cobalt	−13.3
Nickel	−14.5
Constantan	−37.25
Bismuth	−73.4
n-Silicon, $\rho = 0.0035\ \Omega$cm	−450
n-Germanium, $\rho = 0.69\ \Omega$ cm	−548

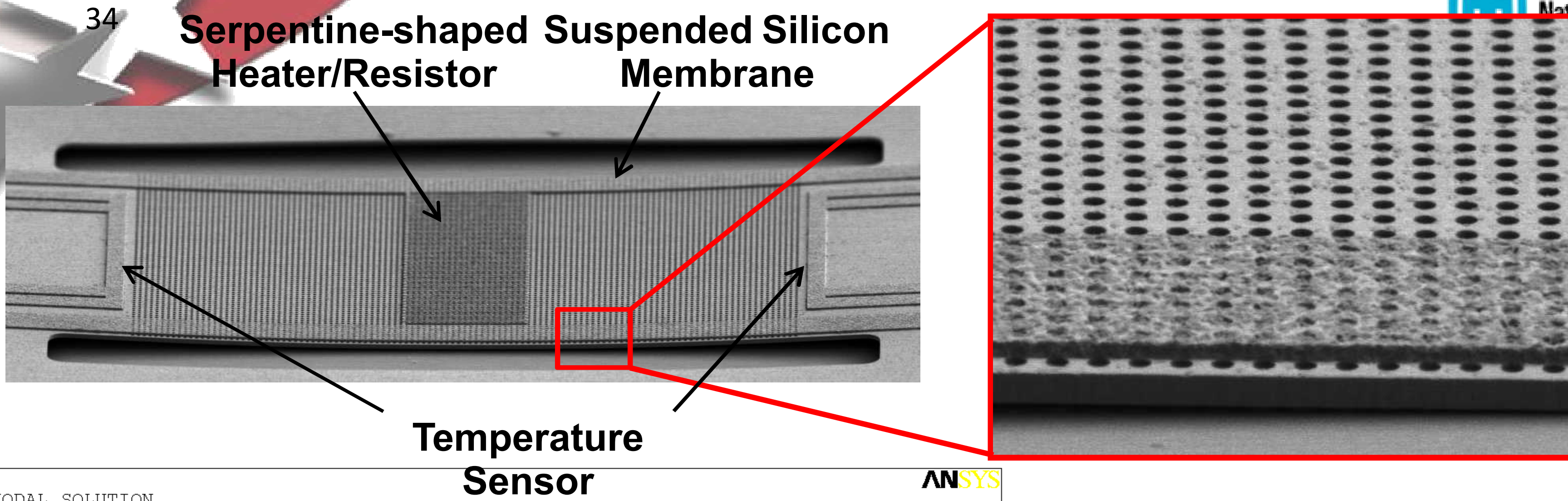


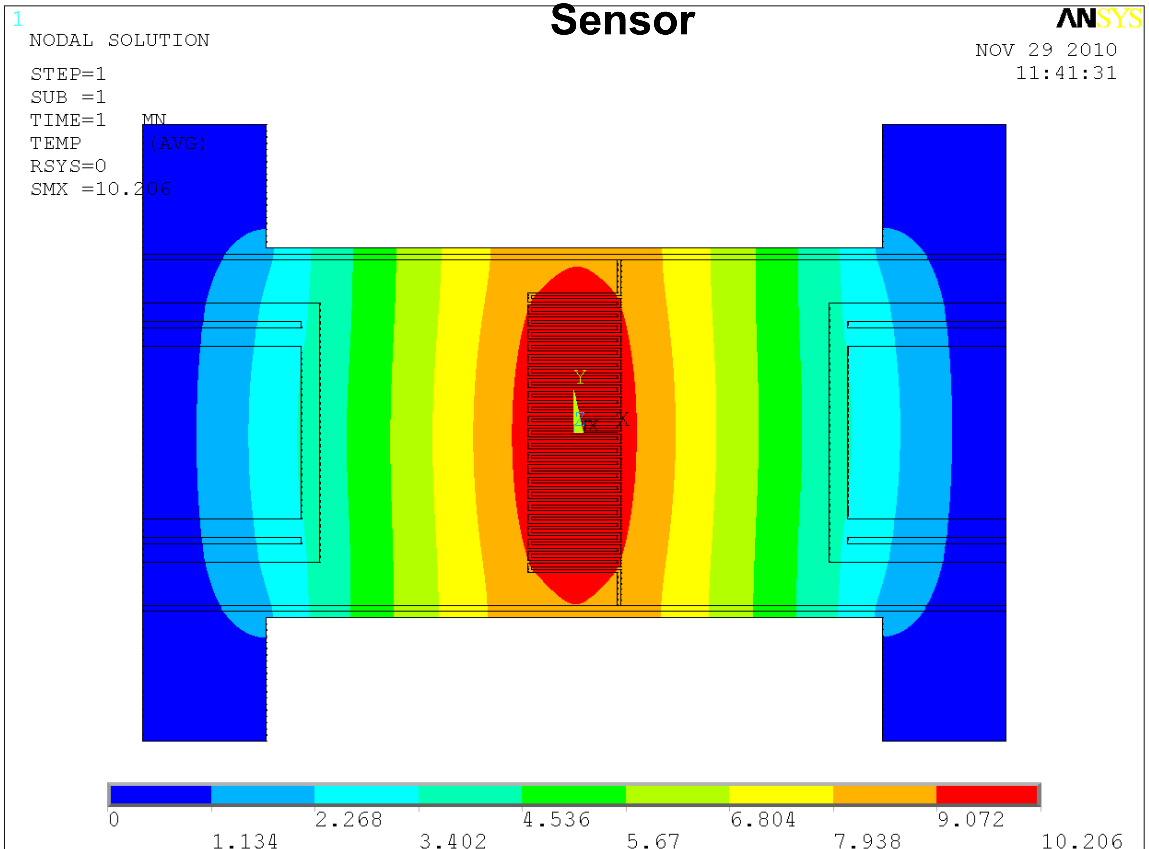


- ***Modification of the Global Heat Capacity:***



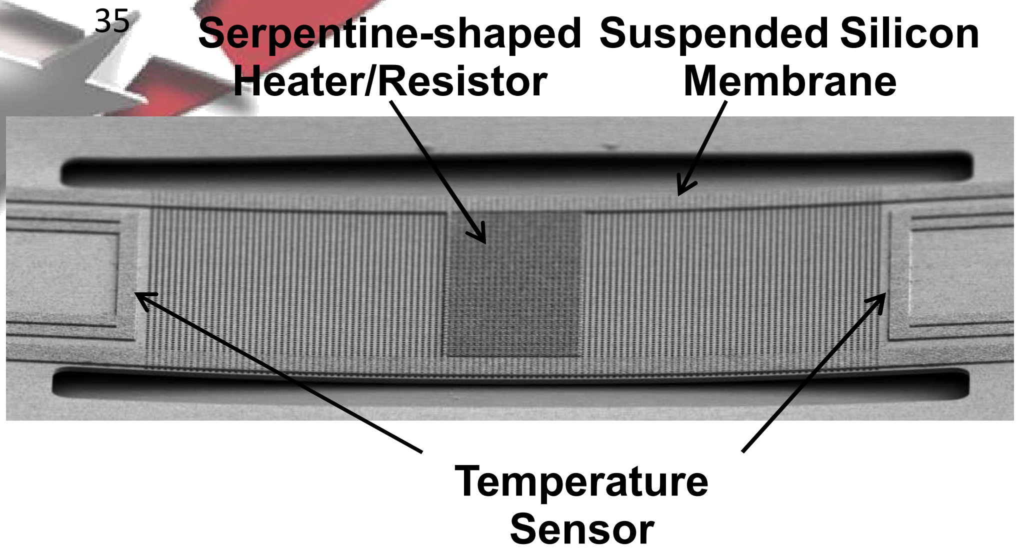


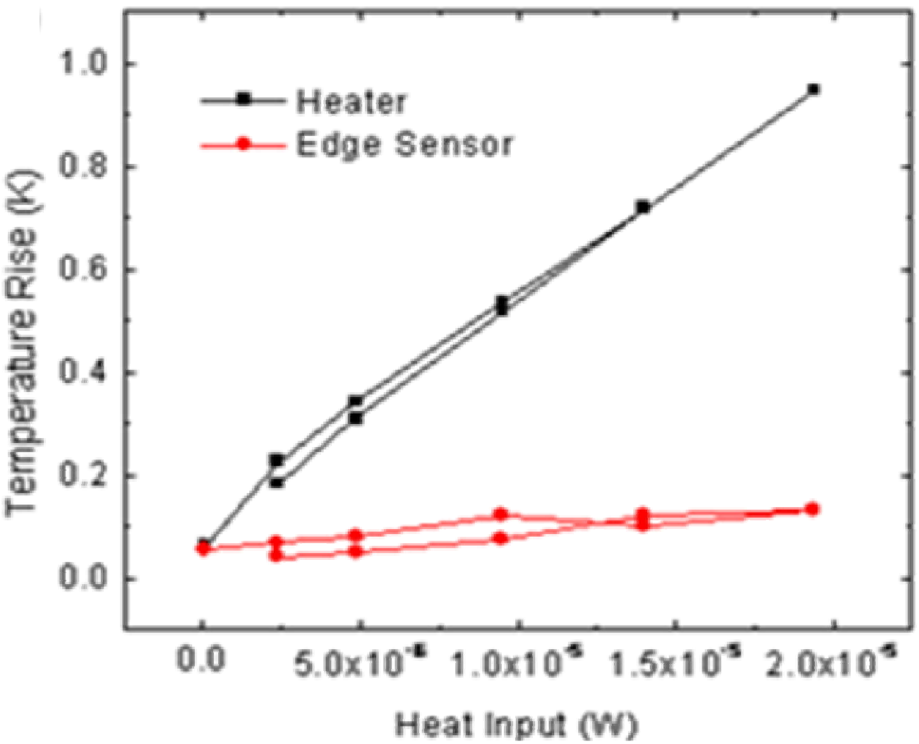




In-Plane PnC Structure Thermal Conductivity Measurement Testbench

Measurement of PnC Thermal Conductivity



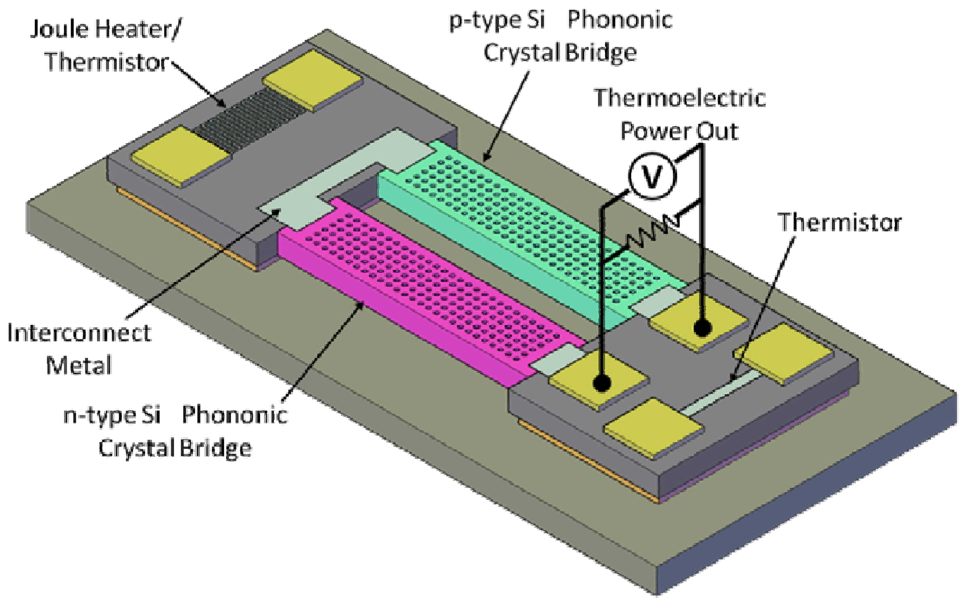


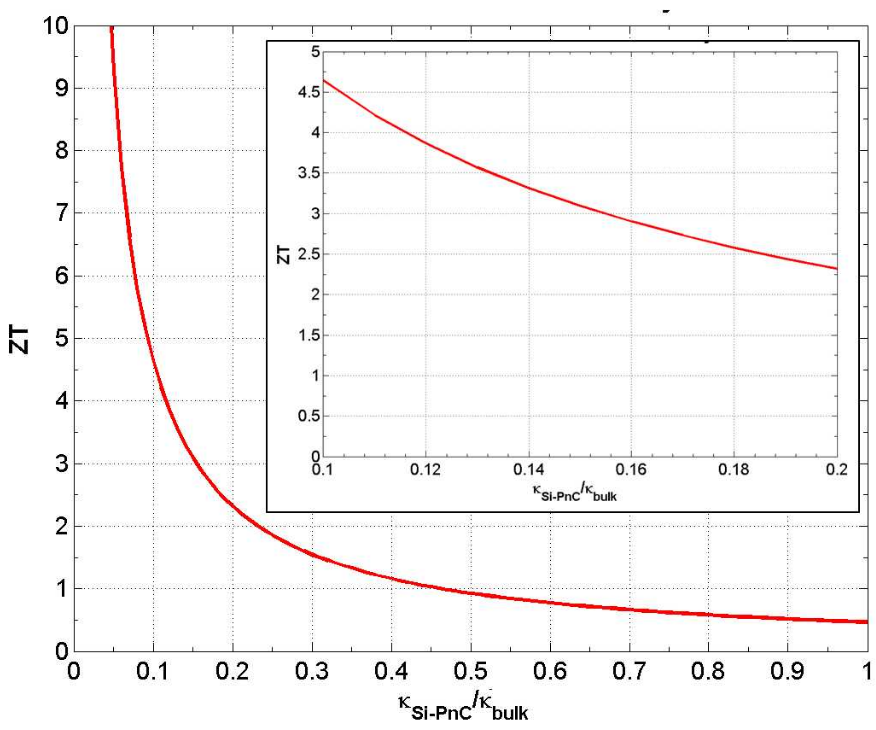
- ***Heater** indicates heat pumped into the membrane*
- ***Edge Sensor** measures heat that has propagated through the sample*
- ***In-plane thermal conductivity** of the PnC calculated from its thermal resistance*

High-ZT PnC Devices in Silicon

Performance Summary:

- *ZT > 2* **predicted for a** *80% reduction* **in bulk thermal conductivity**
- *ZT > 4* **predicted for a** *90% reduction* **in bulk thermal conductivity!**





Future Applications

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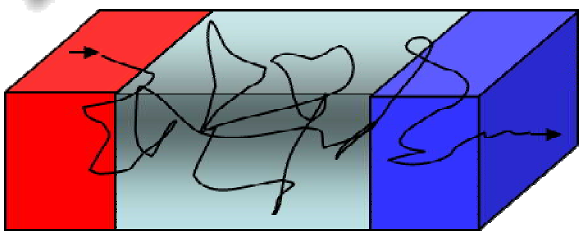
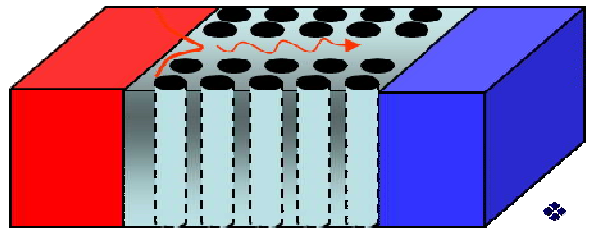
- ***Rapid Cooling?***



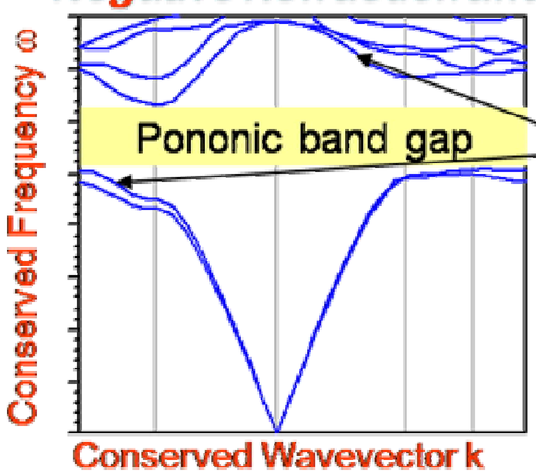
Hot Side → Cold Side



Hot Side → Cold Side

- ***Conventional:***
  - **Random Phonon Scattering**
  - **Overall Drift velocity v_d**
- ***EBG Solution :***
  - **Directive Phonon Guides**
  - **Guide Group velocity v_g**
- ***Concerns:***
  - **Can we engineer the bands so that:**
    1. $V_g > V_d$?
    2. *Match guide impedance*

- ***Negative Refraction and Acoustic Focusing:***



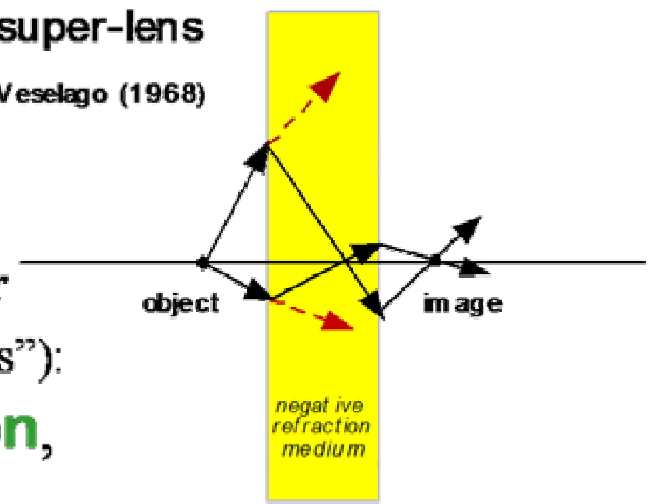
Negative Sloping Bands ⇒ *Negative Refraction*

negative group-velocity or negative curvature (“eff. mass”):

Negative refraction, Super-Lensing

super-lens

Veselago (1968)

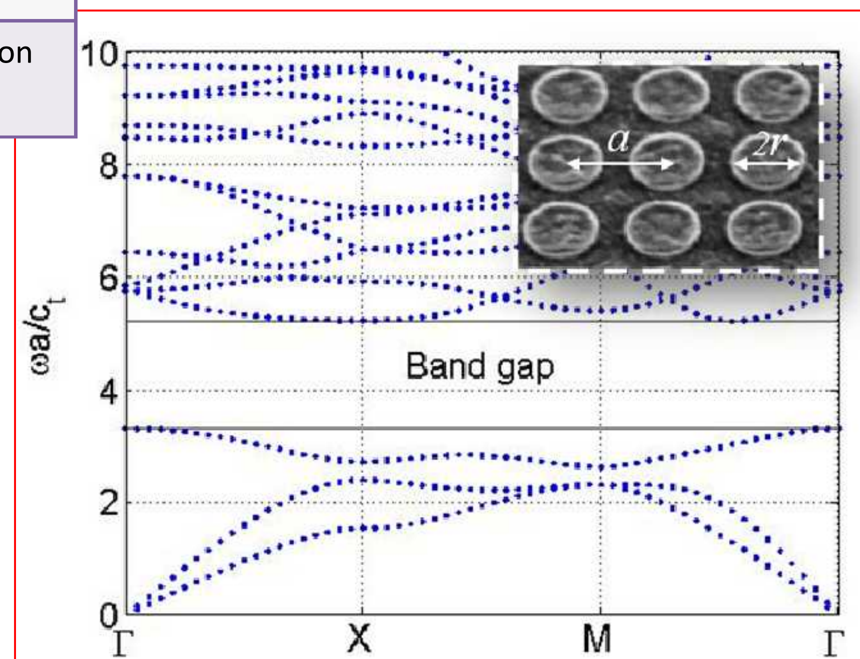


Conclusions

- **Manipulation of phonons using phononic crystals**
  - UHF (38 GHz) operation
  - Air-solid vs. solid-solid PnCs
  - Roadmap to smaller features/higher frequencies
- **Reducing thermal conductivity via phonon manipulation**
  - Theoretically possible to push the ZT of Si to >2
  - Enables ultra-efficient TE coolers/generators

What's Next?
Temperature Dialing of Coherent vs. Incoherent PnC Effects

PnC Parameters				Fab Approach
ν	r	a	T	
10GHz	0.25µm	0.5µm	0.5K	Standard Lithography
100GHz	25nm	50nm	5K	Focused Ion Beam
~1 THz	5nm	10nm	25K	Focused Ion Beam



Broader Impact to Heat Capacity…

- *Modification of the Global Heat Capacity:*