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Reduction of Thermal Conductivity in Silicon via Ion Implantation and Phononic Crystal Patterning

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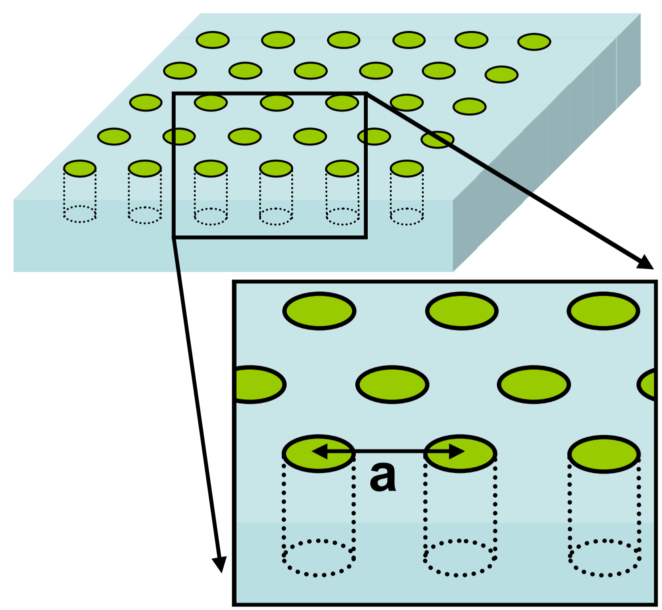
Outline

- Introduction to Phononic Crystals (PnCs)
- Recent thermal conductivity measurements
- Use of Focused Ion Beam (FIB) to fabricate PnCs
- Ion Implantation
- Fabrication of Doped Samples and Phononic Crystals
- Thermal Conductivity Measurement using Time Domain Thermoreflectance (TDTR)
- Results
- Conclusion

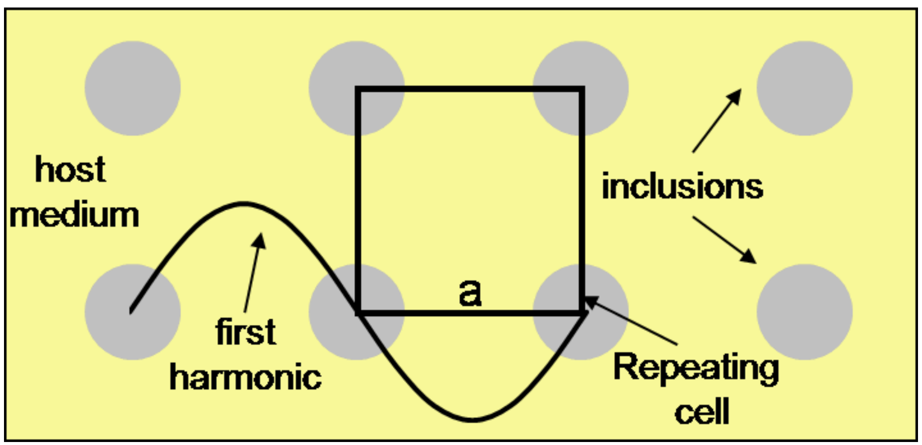
Phononic Crystals (PnC's)

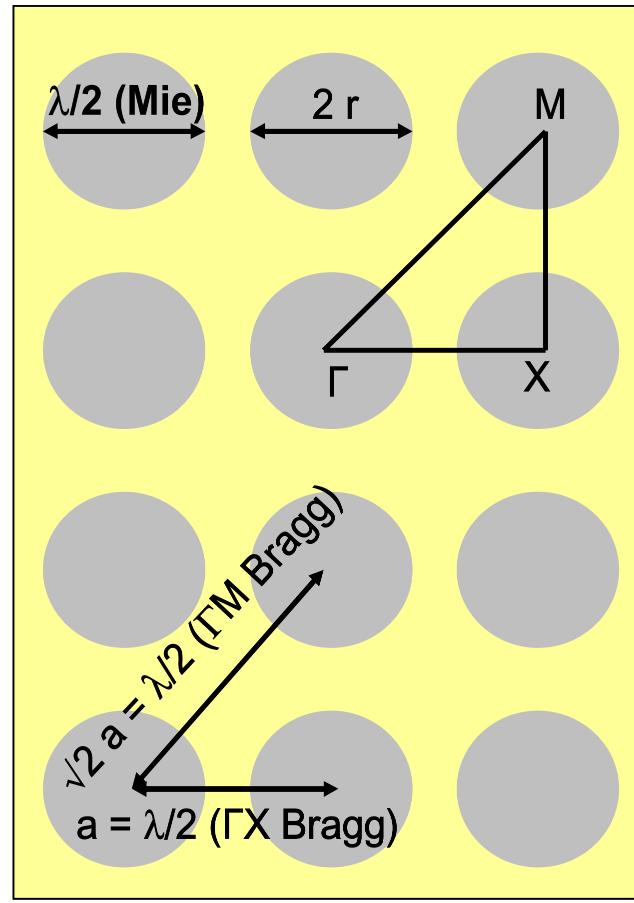
- What are they?
  - Periodic array of scattering inclusions located in a homogeneous host material (1,2, or 3 dimensional)
  - Cause amplitude reduction of a range of wavelengths or frequencies propagating through the crystal
  - Create an acoustic/phononic bandgap
  - Desire bandgap to be wide and "deep"
- Applications
  - Communications
  - Ultrasonic application
  - Non-destructive evaluation (NDE)



Phononic Bandgap

- Bandgap creation
  - Bragg Scattering
  - Mie Scattering
- Coherent scattering





Parameters that Affect PnC's

Desired Values for Large Bandgaps

- Velocity of Sound, c
- Density, ρ
- Impedance ($Z=c\rho$)

} → High mismatch between matrix and inclusions

- Lattice constant, *a*

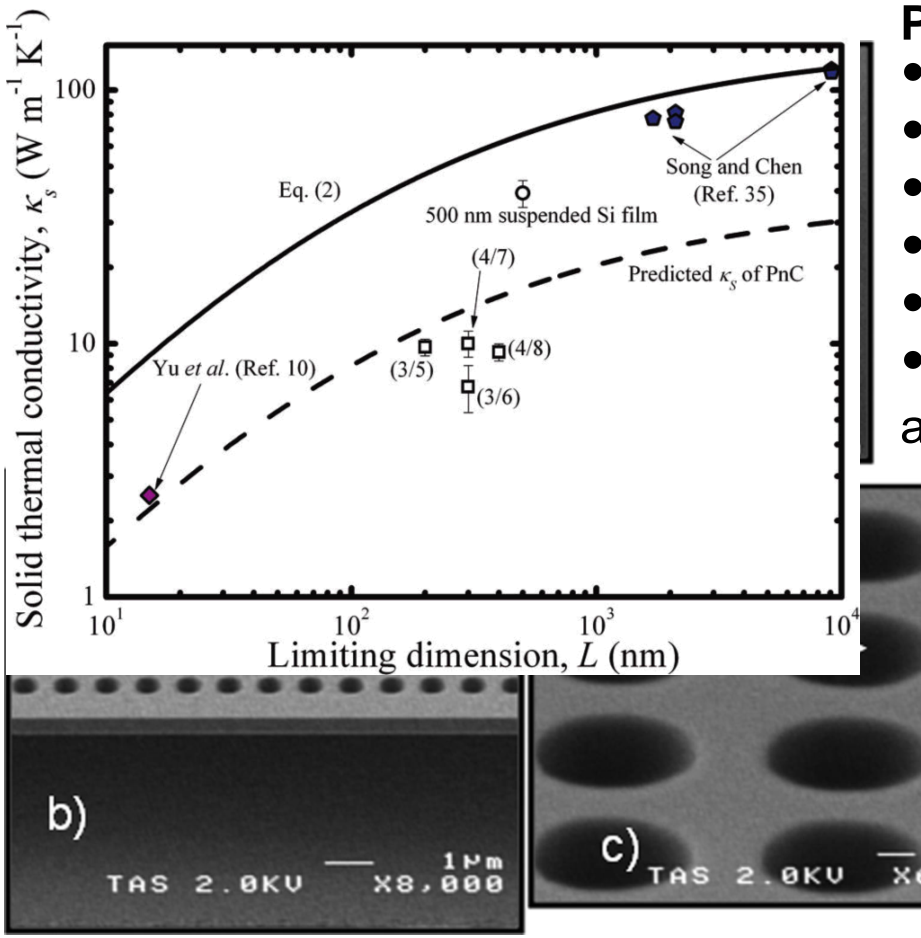
$$f = c_{avg} / 2a$$

} → Frequency control

- Radius of inclusion, *r*
- *r*/*a* Ratio → 0.25-0.32

Reduction of the Thermal Conductivity of Si

Nanoengineered a PnC that significantly reduced thermal conductivity of Si from 148 W m^{-1} K^{-1} to 6.8 W m^{-1} K^{-1}



PnCs fabricated on SOI wafers

- 150 mm diameter
- 500 nm device layer
- 3 µm BOX layer
- (100) n-type
- 37.5 - 62.5 Ω-cm resistivity
- Released using vapor phase hydrofluoric acid

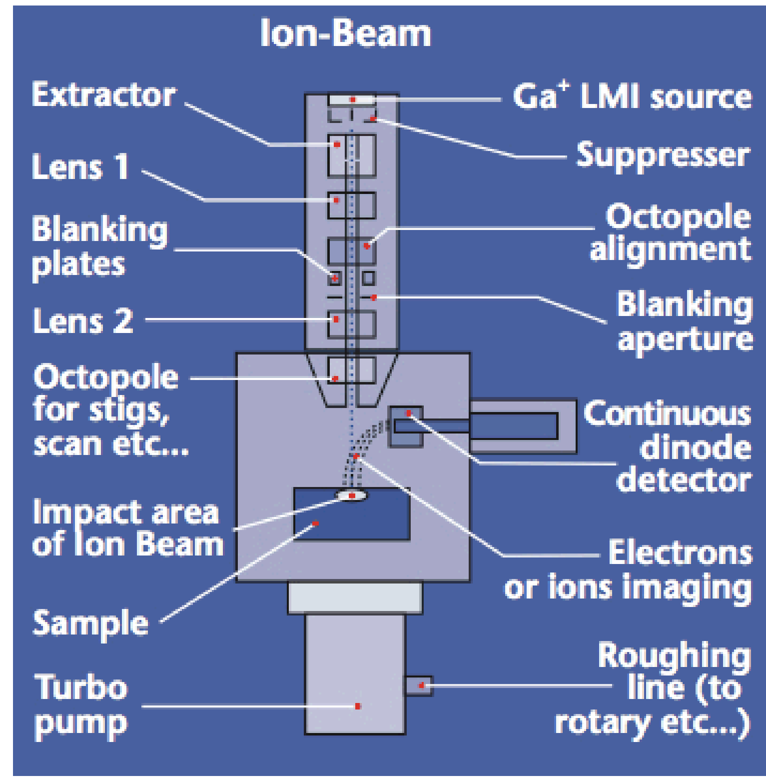
PnC Dimensions

- Air holes with of diameter, d = 300-400 nm
- Center-to-center hole spacings, a, of 500, 600, 700 and 800 nm
- Membrane area is 60 µm wide and 200 µm long

Hopkins et al., Nano Letters (2011)

NanoFIBrication of PnCs

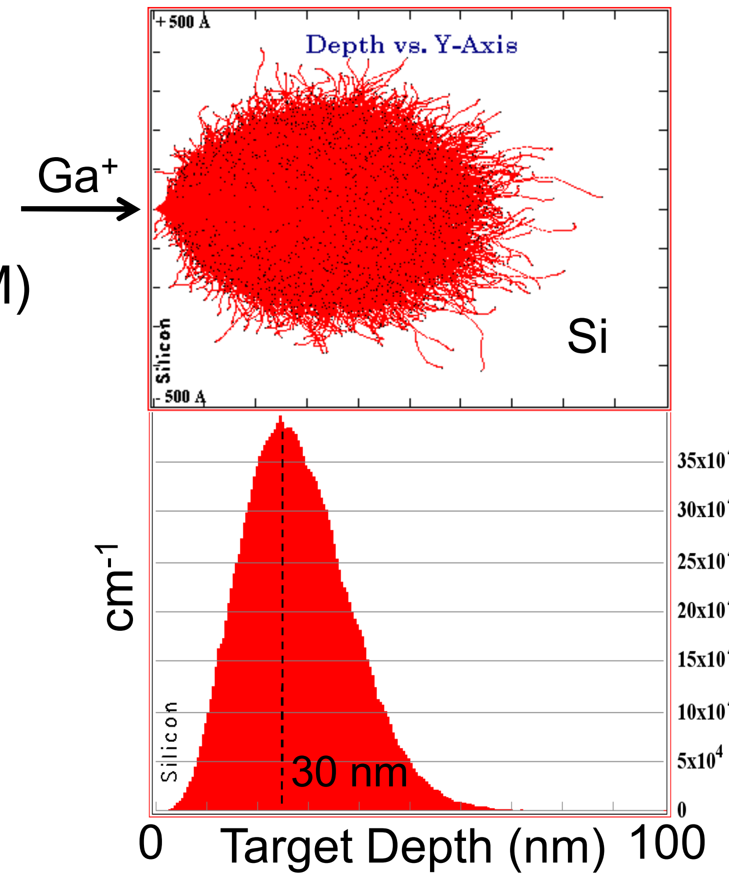
- Need a way to fabricate devices with nm dimensions
  - Focused Ion Beam (FIB)
  - Beam diameter of 7 nm FWHM
- NanoFIBrication
  - Using a FIB to fabricate on the nanometer scale
- Liquid metal ion source for Ga^+ ions
- Gaussian beam of Ga^+ ions
- Sputters material
- Can also be used to add material in specified locations
- FIB instrument used in this work:
  - Dual Beam Quanta 3D FEG



Courtesy of FEI Corp.

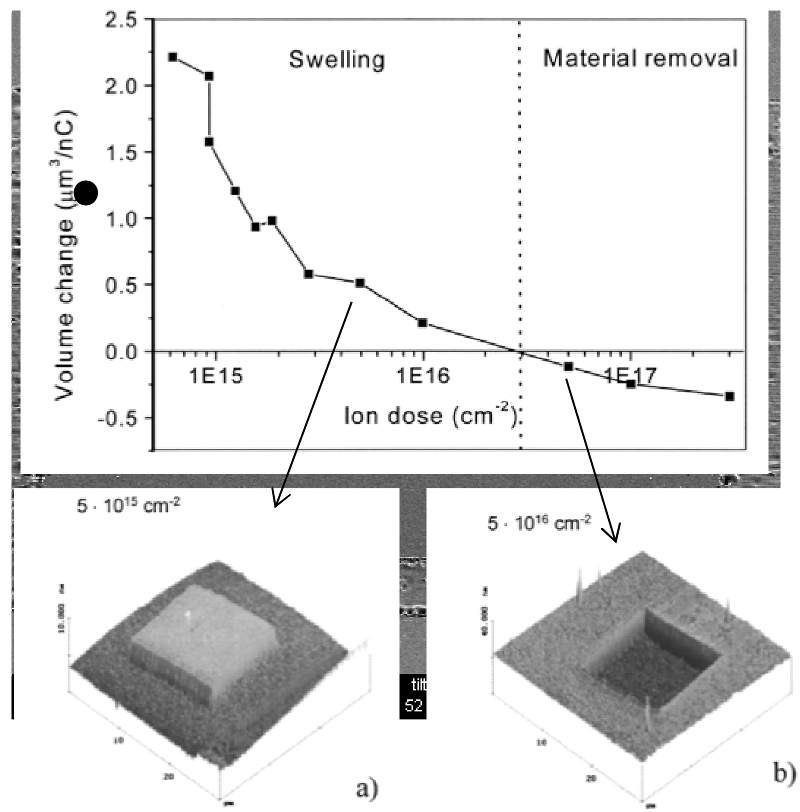
Ion Implantation

- Ga^+ ions penetrate into a material's surface
- Model implantation using simulation called TRansport of Ions in Matter (TRIM)
  - Quantum mechanical treatment of ion-atom collisions
  - Monte Carlo simulation
  - 100k ions
- Implanted Ga^+ ions disrupt atomic structure of material
- Dopants affect a material's properties
- Want to distinguish between affect of PnC and Ga dopant on thermal conductivity



Fabrication of Ga Doped Samples

- Raster beam with specific current and dwell time per pixel (pitch)
- Determine dose based on beam current, dwell time, and surface area
- No protective layer
- Swelling occurs



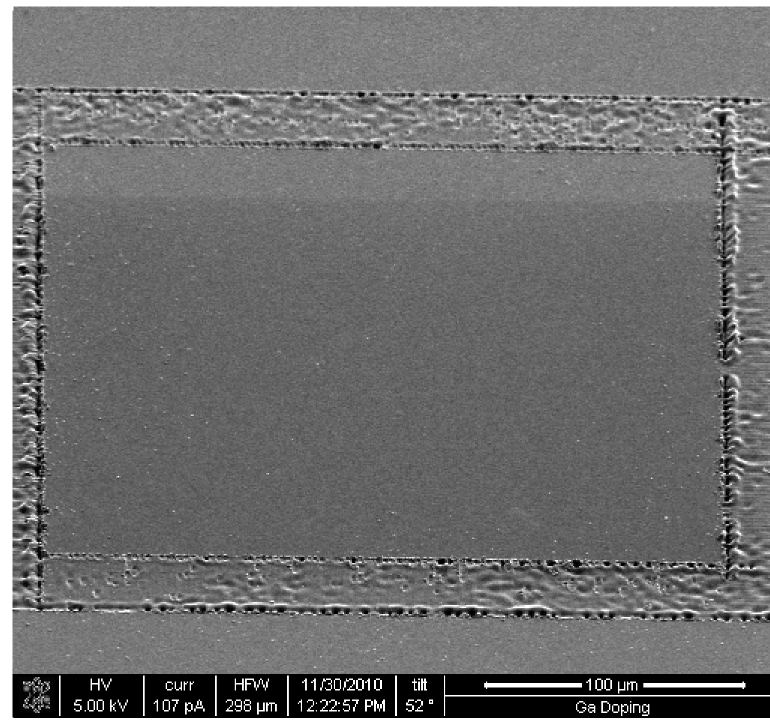
Lehrer et al., J Vac Sci and Tech B. (2001)

Ga Doped Si

- Doped Si with Ga^+ ions from FIB
  - 9 Dopant levels ions/cm^2

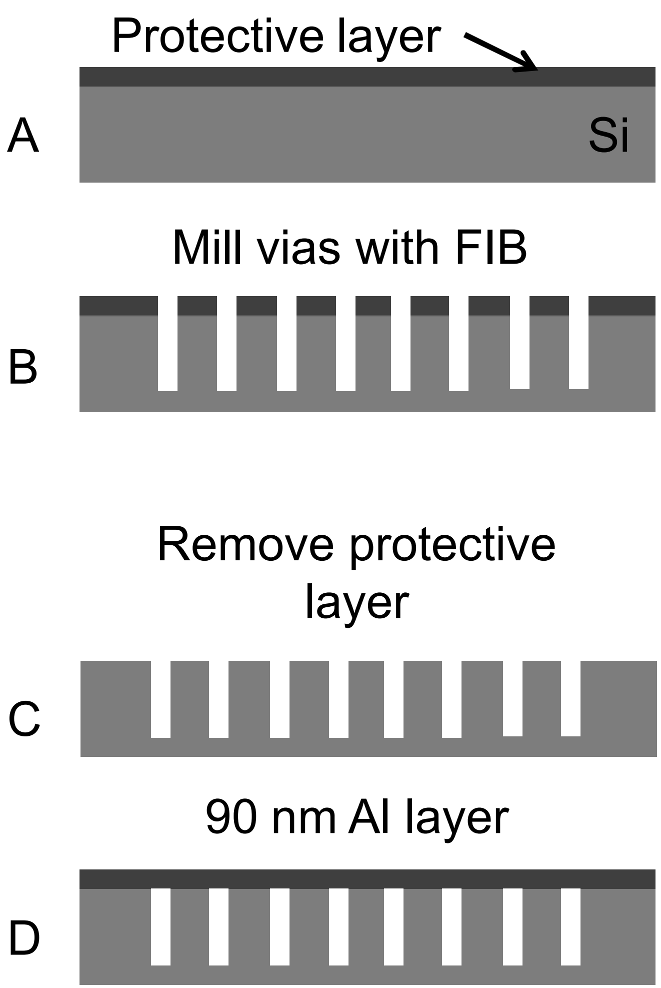
Dwell Time	10 µs	40 µs	100 µs
Current	Dose (ions cm^{-2})		
1.5 pA	1 1.1e14	2 4.5e14	3 1.1e15
10 pA	4 7.5e14	5 3.0e15	6 7.3e15
30 pA	7 2.3e15	8 9.0e15	9 2.2e16

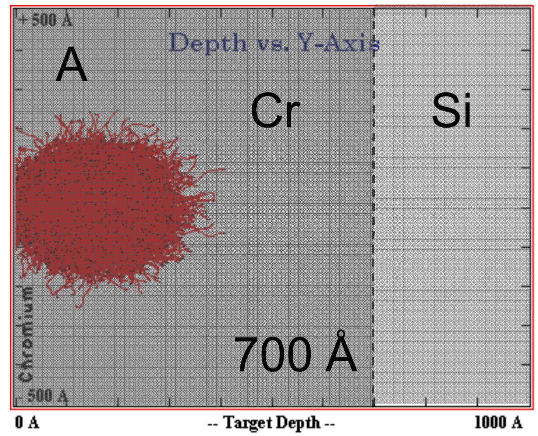
Before After

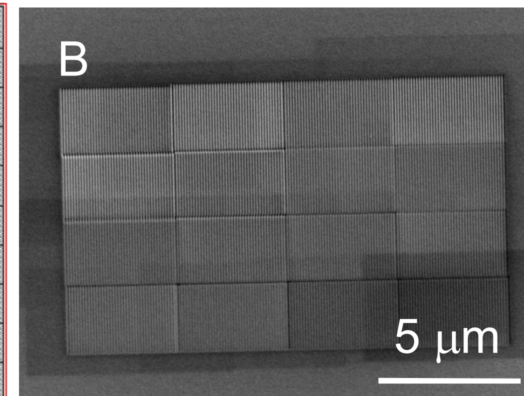


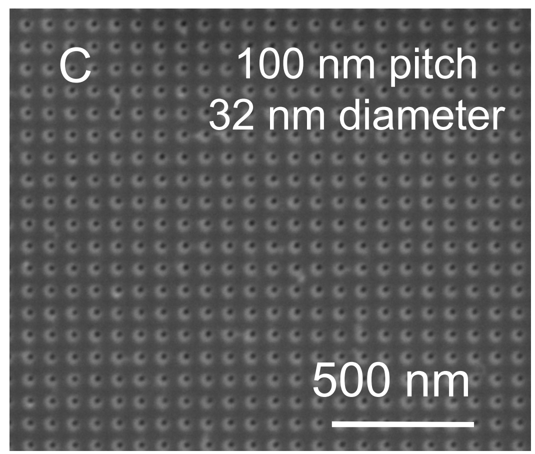
Square 9

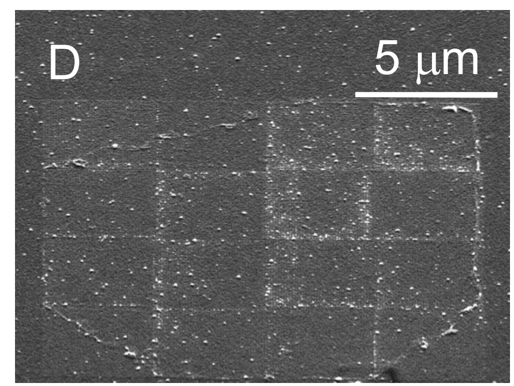
PnC Fabrication with FIB



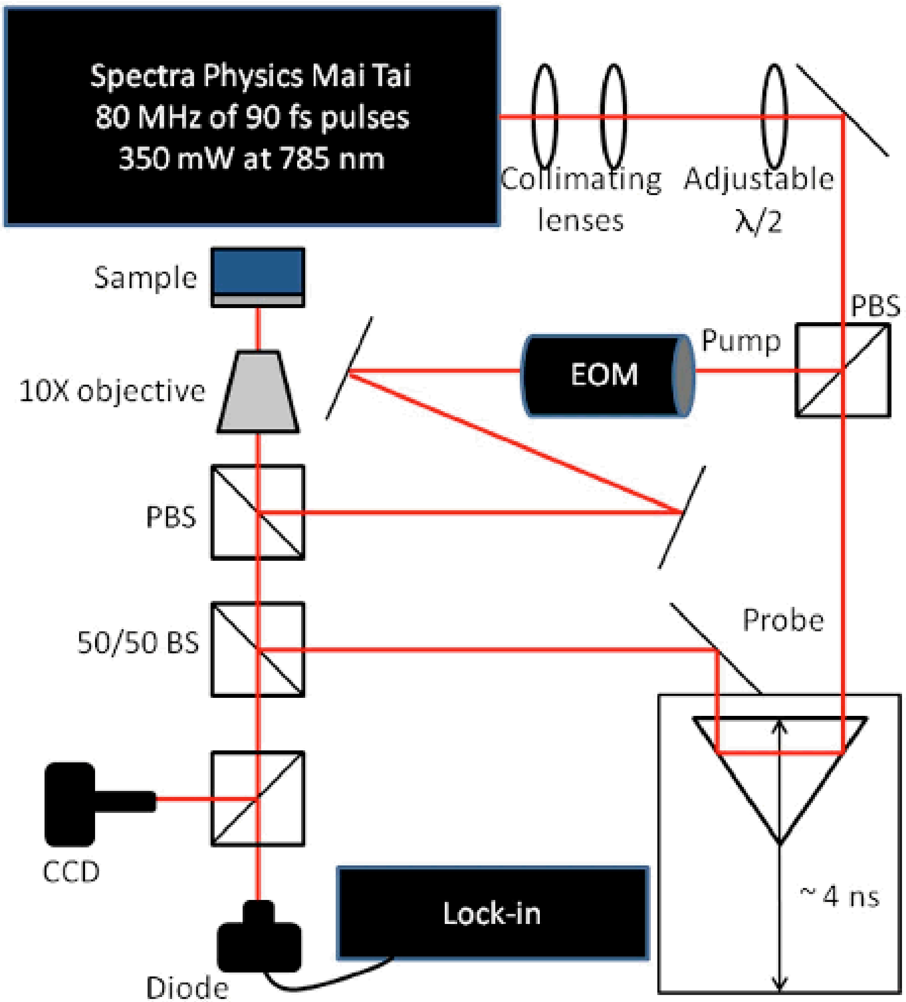








TDTR Measurements of the Thermal Conductivity of Si

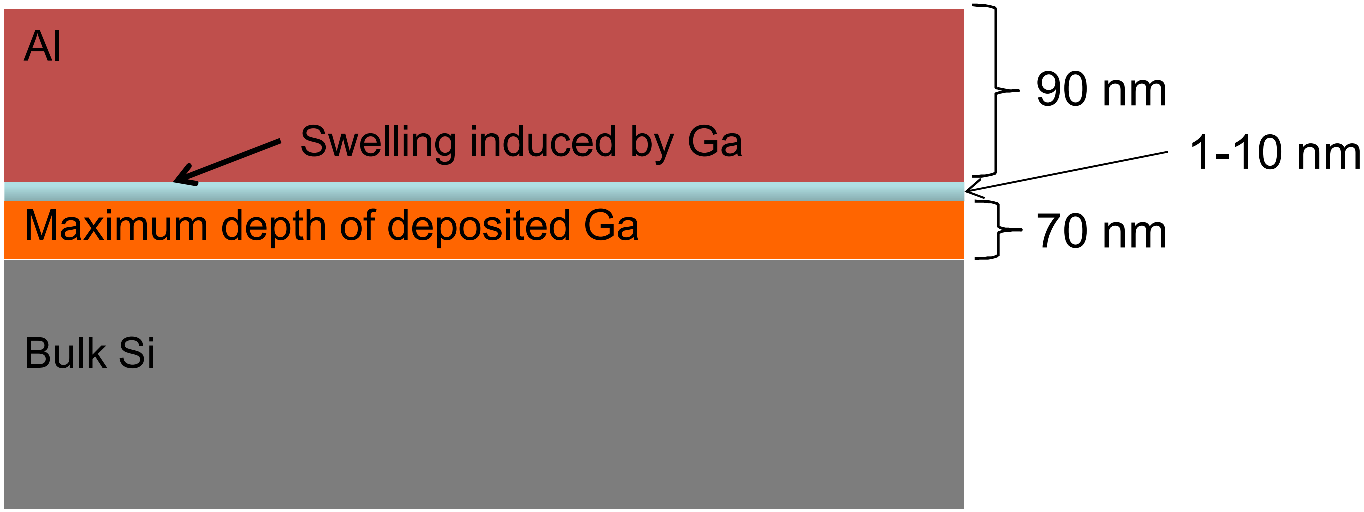


Hopkins et al., Nano Letters (2011)

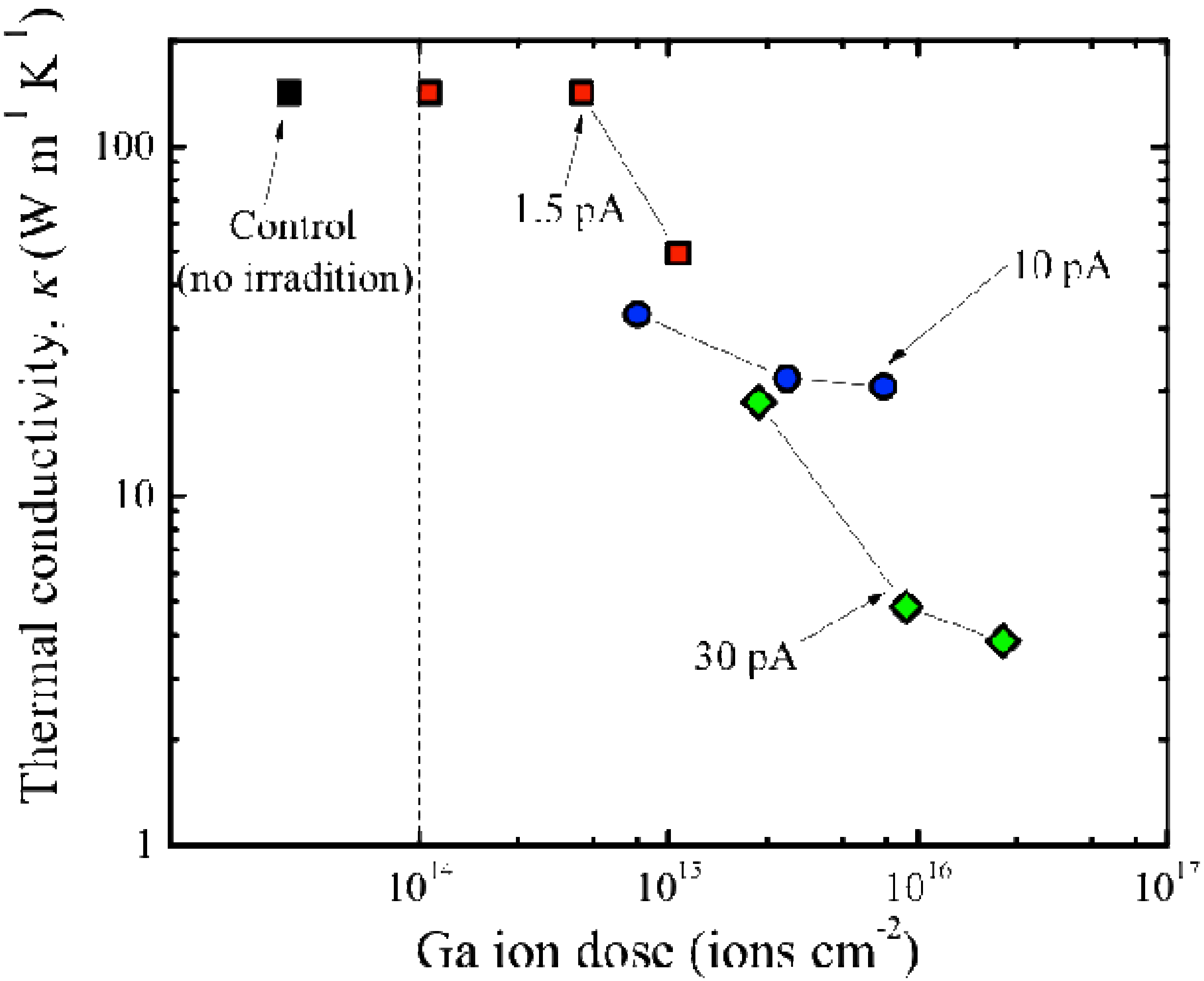
- Thermoreflectance signal directly proportional to temperature change
- $$C\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2}$$
- Given temperature change with time, we fit the heat equation to the data yielding κ

Cross Section of Sample

- TDTR takes into account all 3 layers

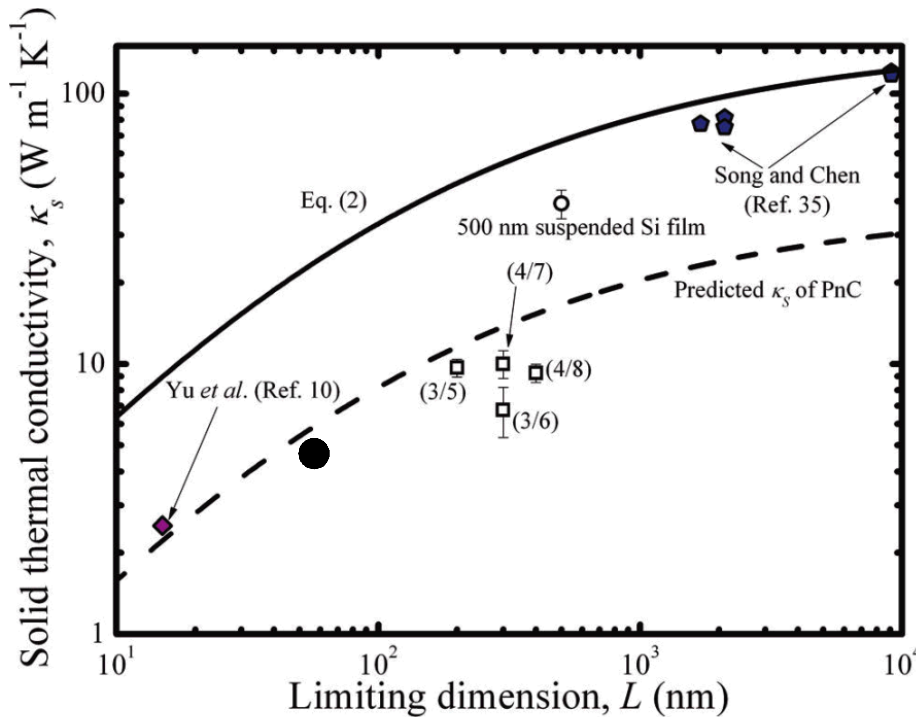


Ga Doped Si Results



NanoFIBricated Phononic Crystal Results

- κ_s=4.13 ± 1.2 W/mK
- 70 nm limiting dimension
- 100 nm lattice constant and 32 nm air hole diameter
- 100 nm via depth



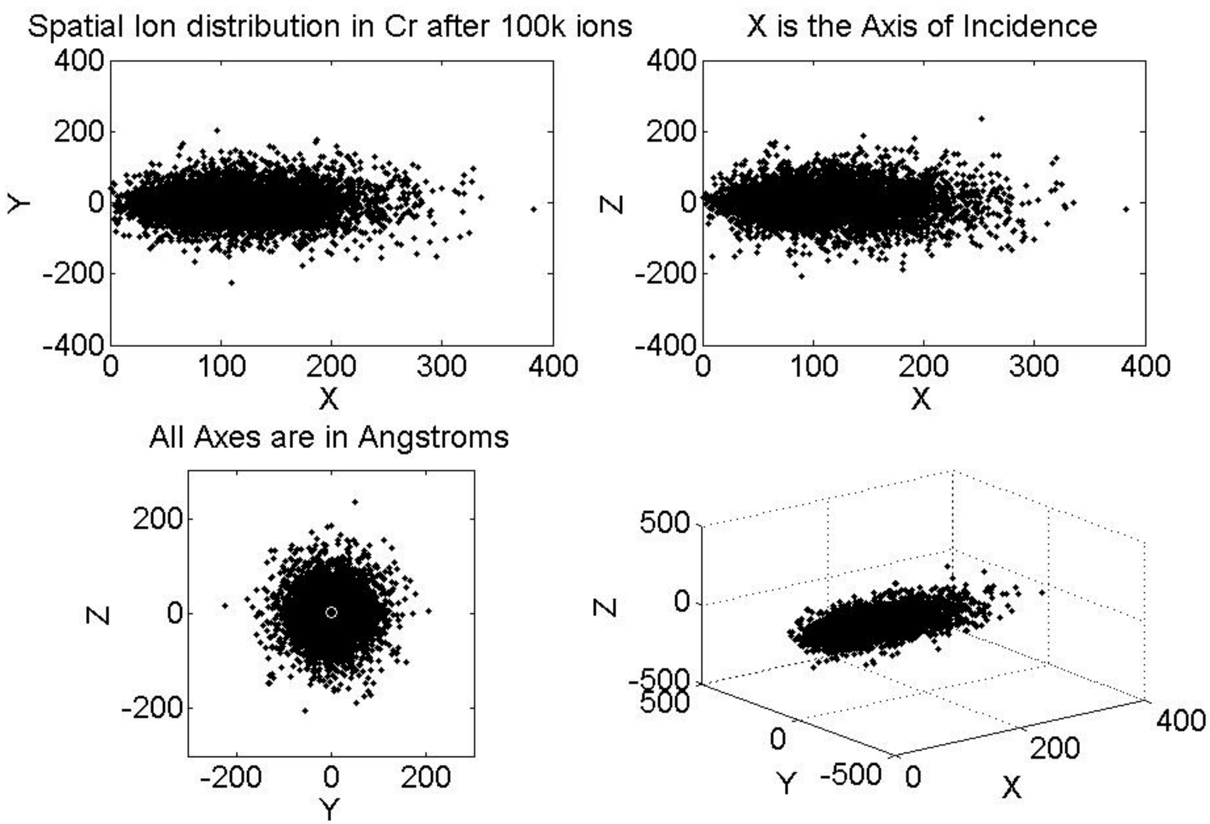
Hopkins et al., Nano Letters (2011)

Conclusion

- Measured effect of Ga doping on thermal conductivity
  - Increasing Ga^{+} ion dose lowers thermal conductivity
- Developed method to minimize unnecessary Ga doping during nanoFIBrication
  - Ga^{+} ions implant into protective layer rather than sample
- Measured thermal conductivity of 4.13 W/mK for Si/Air PnC using TDTR

Questions?

Protective Layer



Fabrication Steps for PnC

- Start with bare Si
- Use laser to define 300 x 300 μm areas
- Coat Si with 70 nm of Cr
  - Used to protect Si from Ga ions
- Mill 16 x 16 μm PnC with 100 nm pitch
- Remove Cr using
  - 6 min Piranha etch
- Coat Si with 90 nm of Al