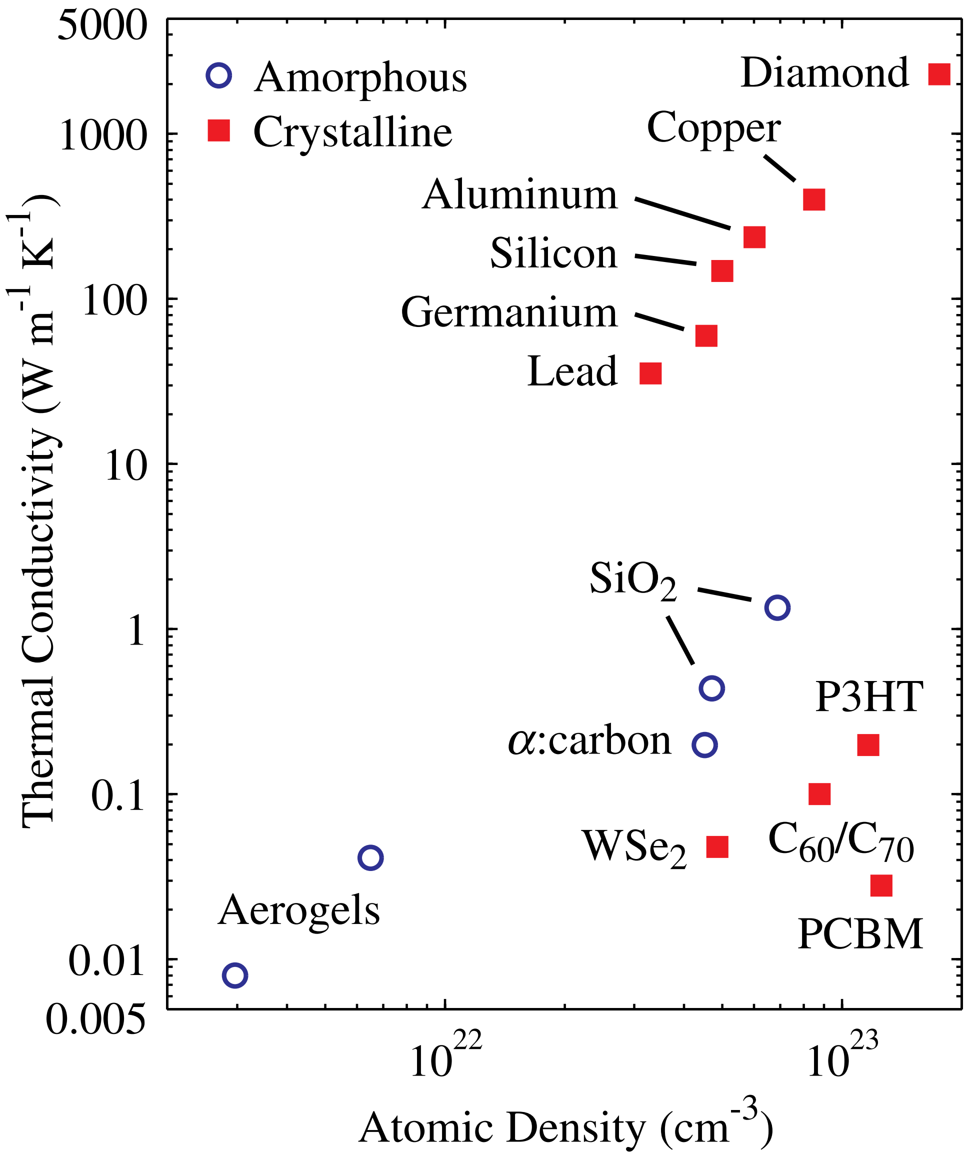
SCHOOL of ENGINEERING & APPLIED SCIENCE
UNIVERSITY of VIRGINIA

Tunable thermal transport and reversible thermal conductivity switching in topologically networked bio-inspired materials

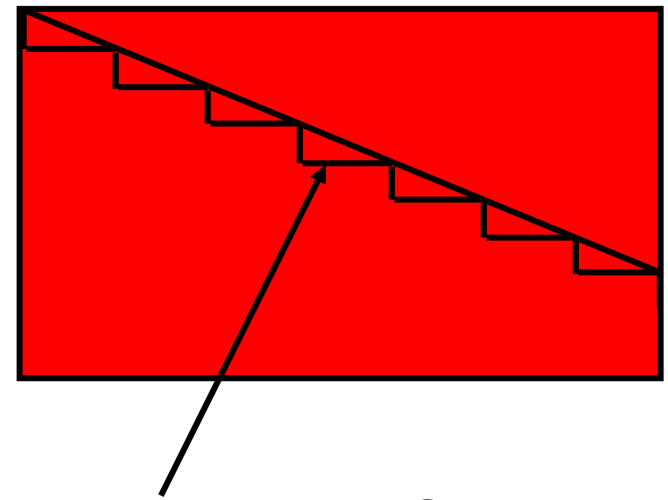
Patrick E. Hopkins
Professor
Dept. Mech. & Aero. Eng.
Dept. Mat. Sci. & Eng.
Dept. Physics
University of Virginia
phopkins@virginia.edu
patrickehopkins.com

Thermal conductivity of materials



PRL **110**, 015902 (2013)

Microscopic Picture



λ = Mean free path

$$\kappa = \frac{1}{3} C v \lambda = \frac{1}{3} C v_g^2 \tau$$

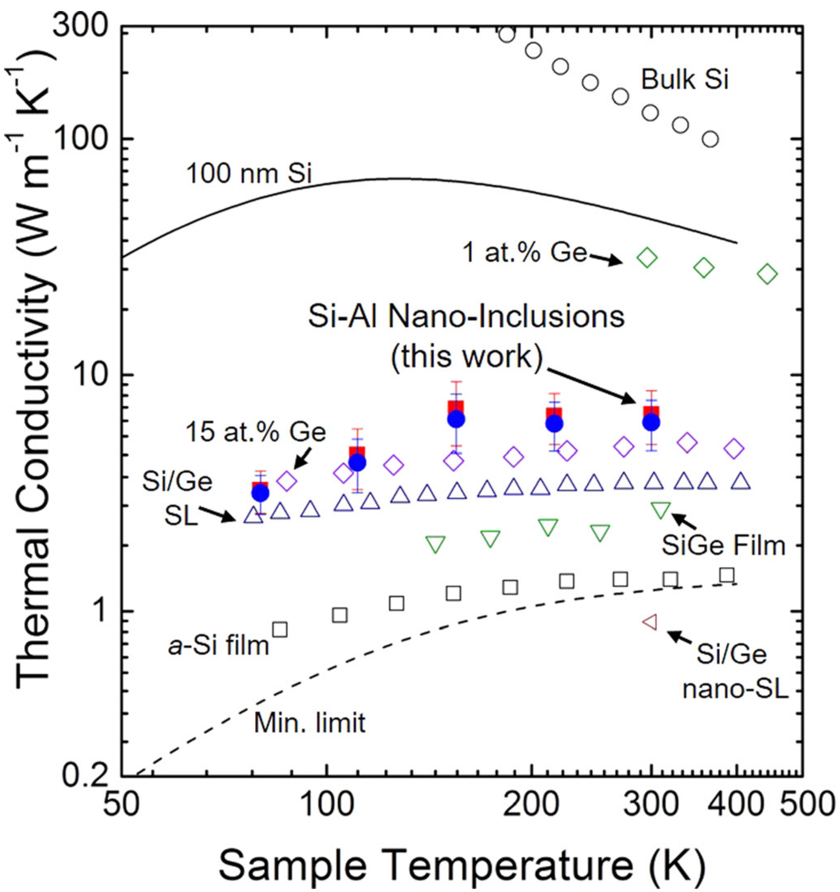
Heat capacity

Velocity

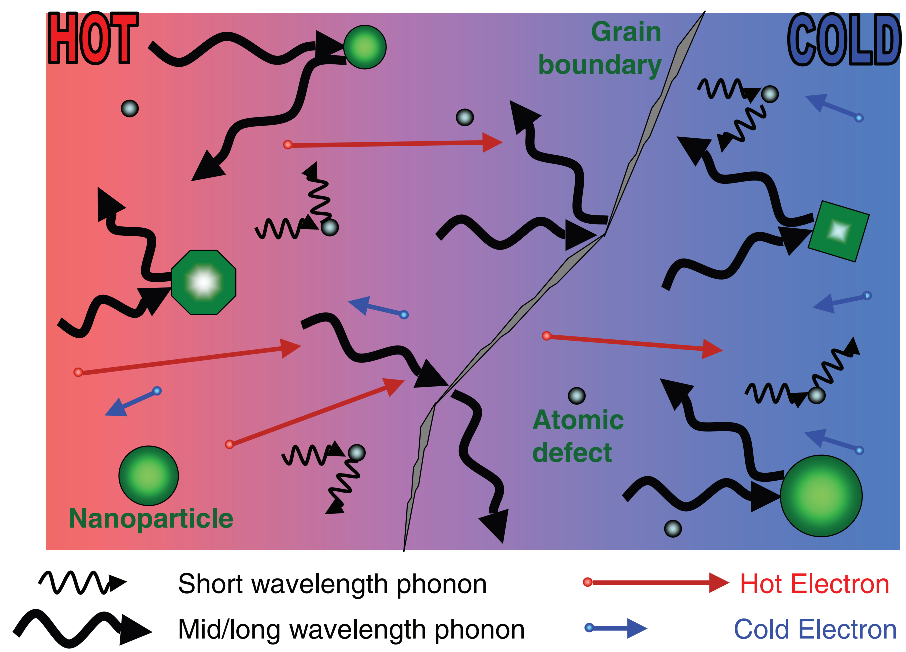
Controlling thermal conductivity - Static

Nanoscale heat transfer

Well controlled and prescribed inclusions, defects, or interfaces to *permanently* change thermal conductivity



APL **112**, 213103



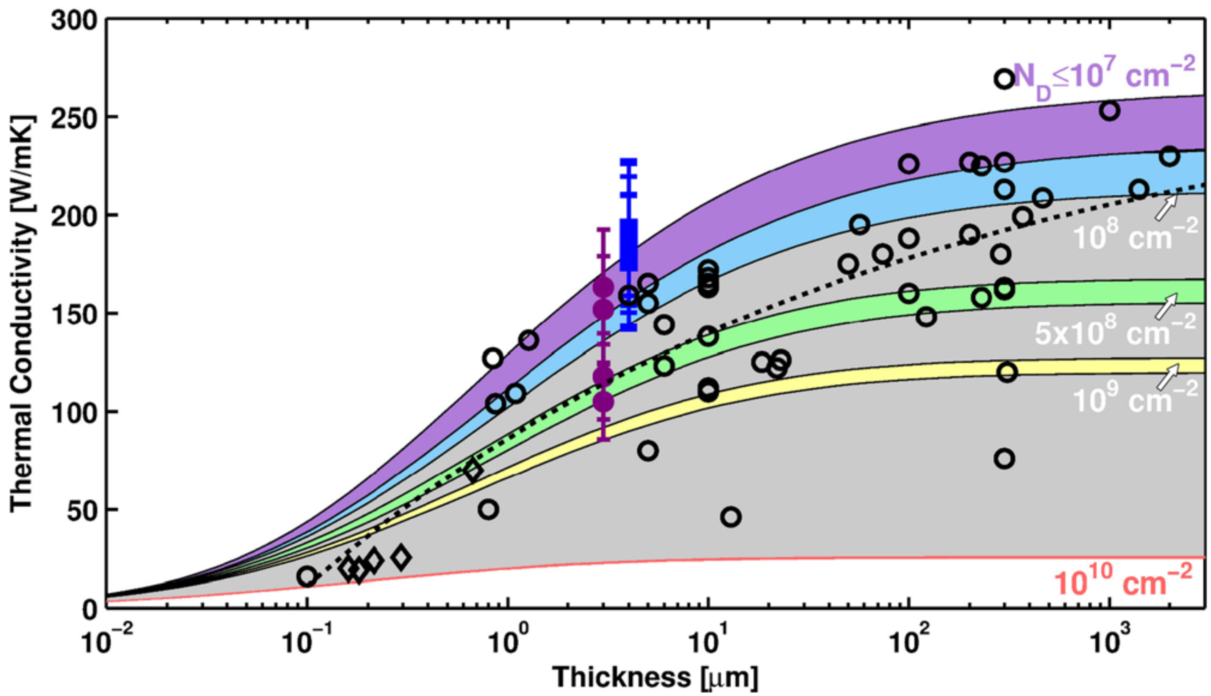
Adv. Mat. **22**, 3970

Controlling thermal conductivity - Static

Nanoscale heat transfer

Well controlled and prescribed inclusions, defects, or interfaces to *permanently* change thermal conductivity

Thermal conductivity of GaN films



JAP **120**, 095104

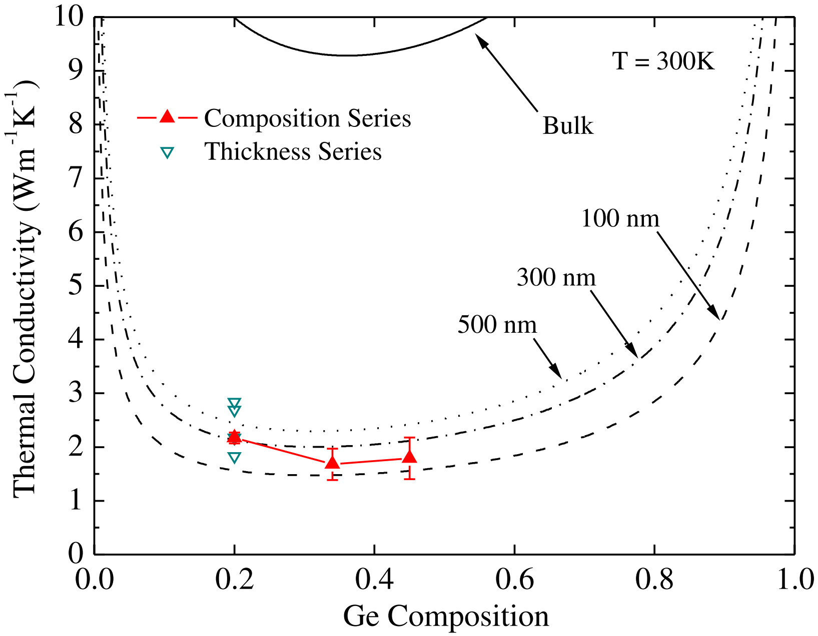
Controlling thermal conductivity - Static

Nanoscale heat transfer

Well controlled and prescribed inclusions, defects, or interfaces to *permanently* change thermal conductivity

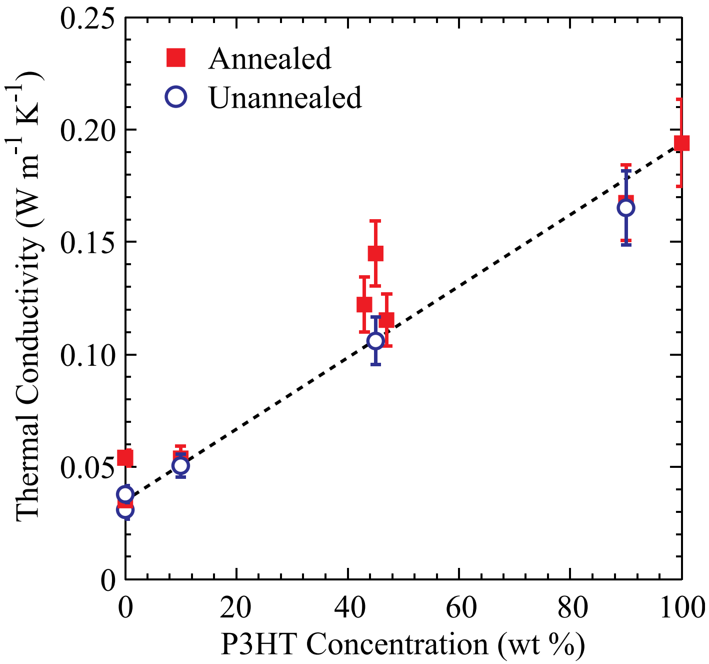
Thermal conductivity of alloy thin films

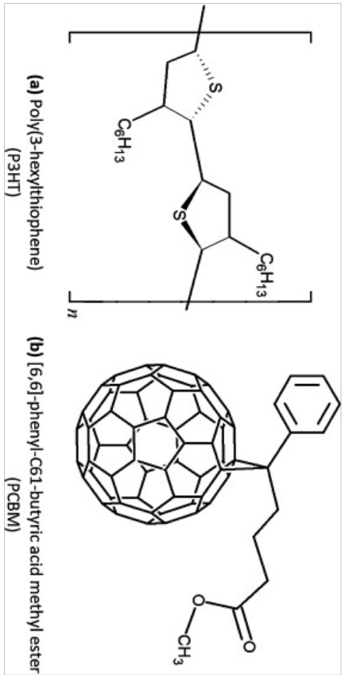
$Si_{1-x}Ge_x$



PRL **109**, 195901

PCBM/P3HT



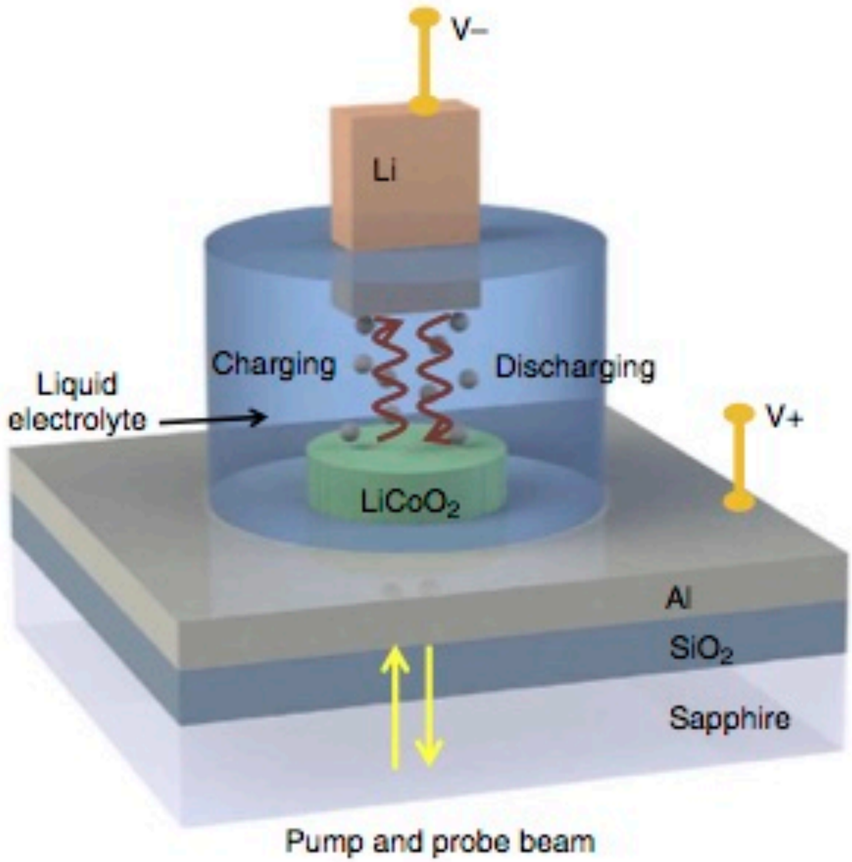


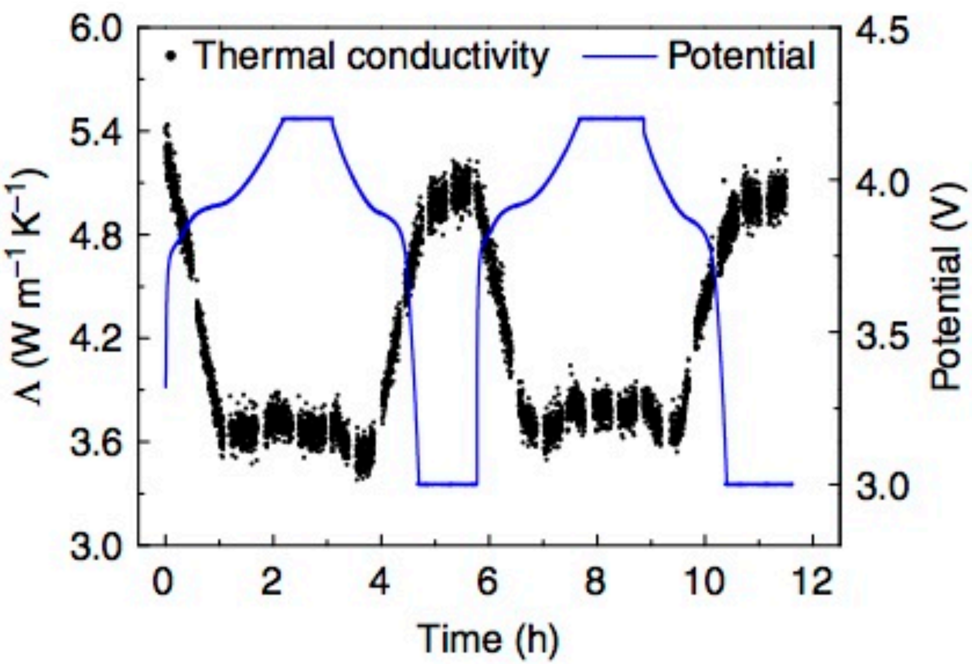
APL **102**, 251912

The thermal conductivity switch

Reversibly switching the thermal conductivity of a material via an external stimulus

Defect diffusion, e.g., “de-litiation” of $LiCoO_2$





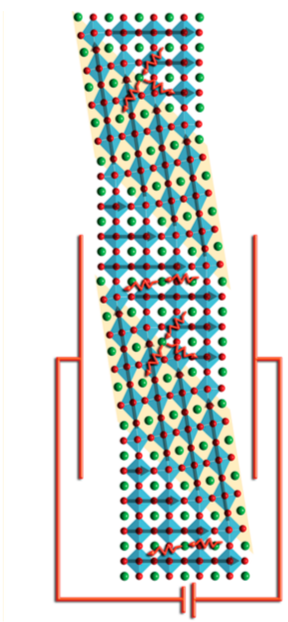
Nat. Comm. **5**, 4035

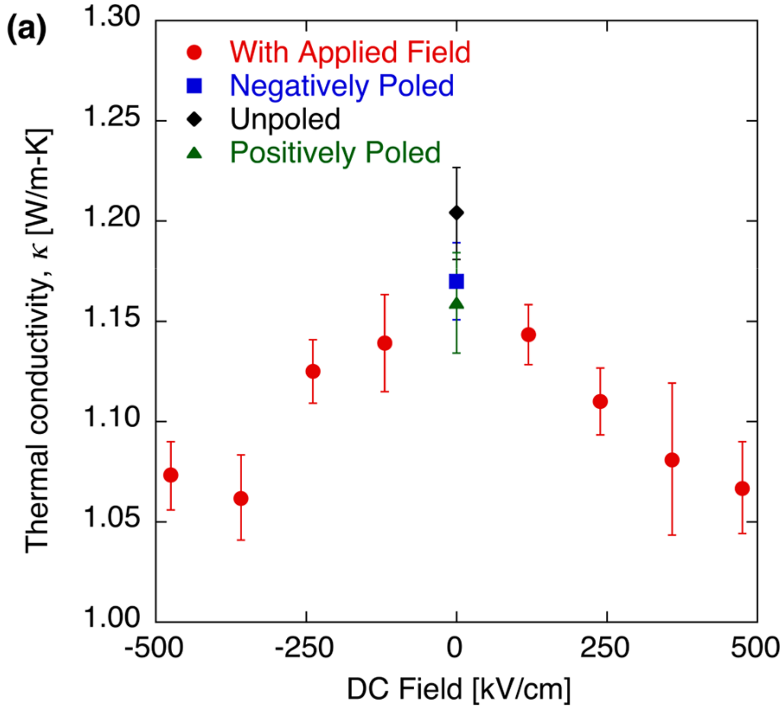
Controlling thermal conductivity - Dynamic

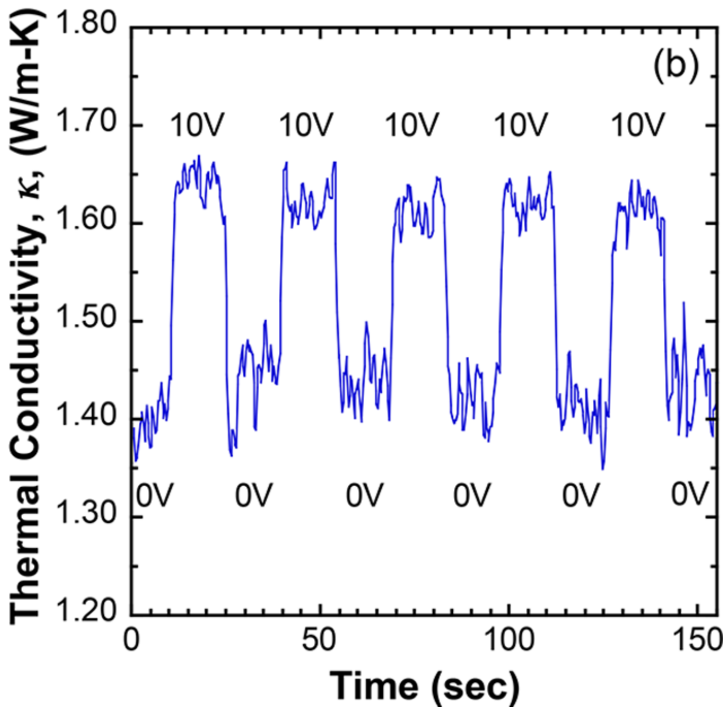
The thermal conductivity switch

Reversibly switching the thermal conductivity of a material via an external stimulus

Field controlled ferroelastic domain mobility in PZT





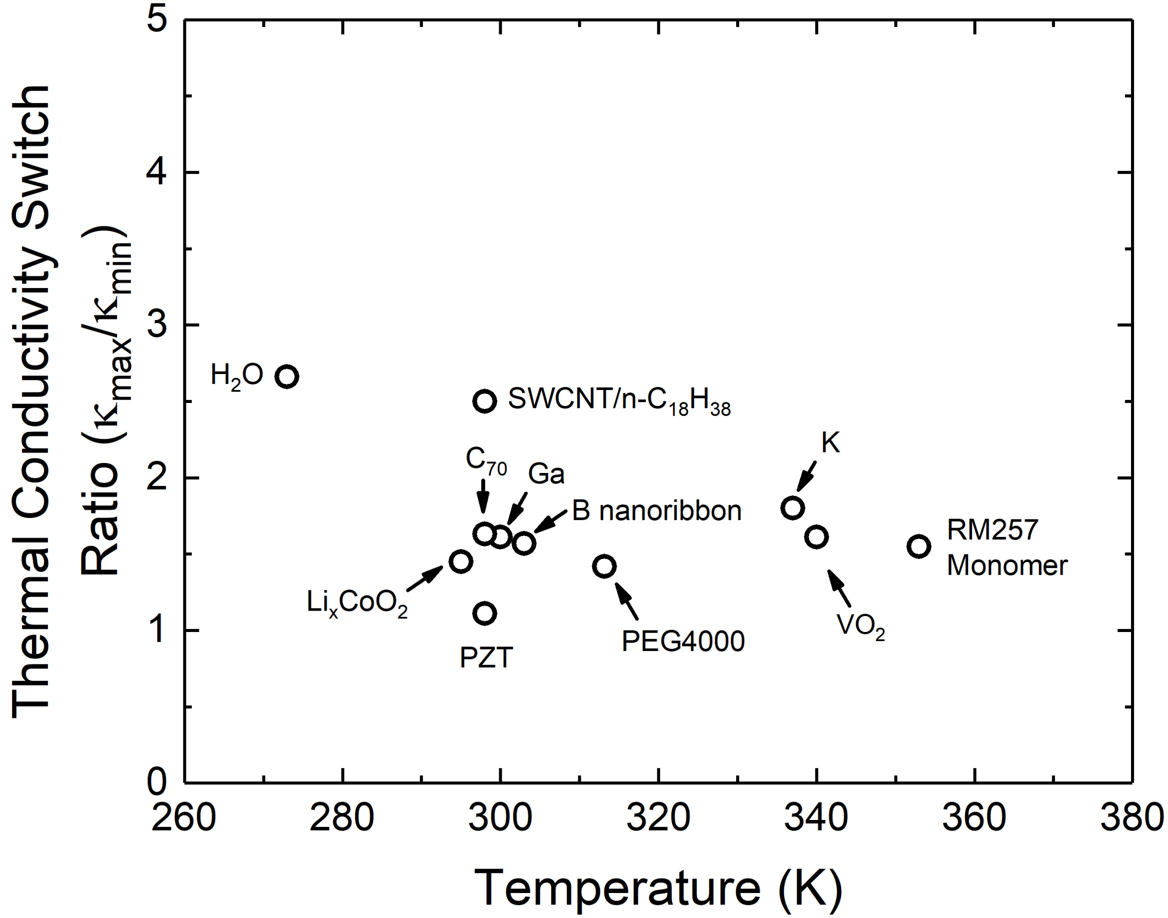


Nano Letters **15**, 1791 (2015) *Appl. Mat. & Int.* **10**, 25493 (2018)

Controlling thermal conductivity - Dynamic

The thermal conductivity switch

State of the art around biologically relevant temperatures

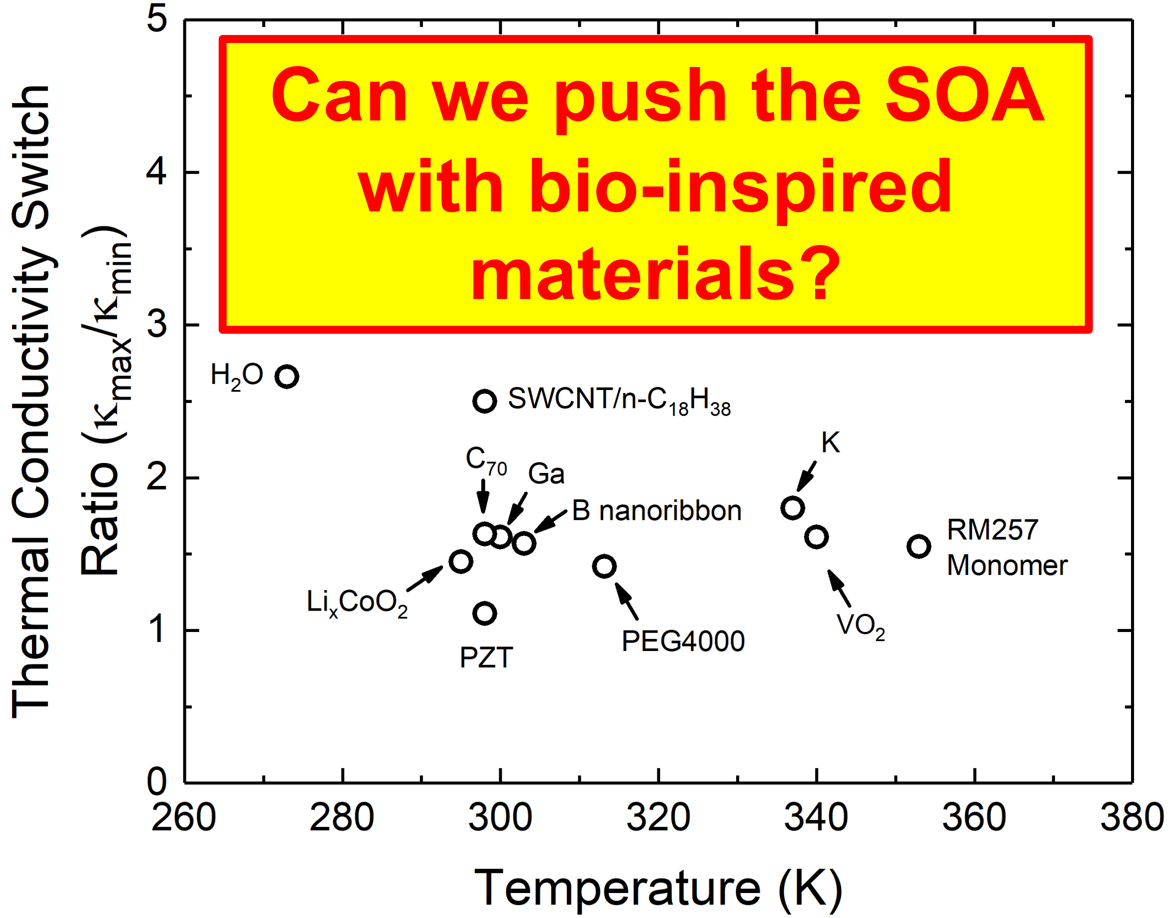


Nature Nanotechnology **13**, 959 (2018)

Controlling thermal conductivity - Dynamic

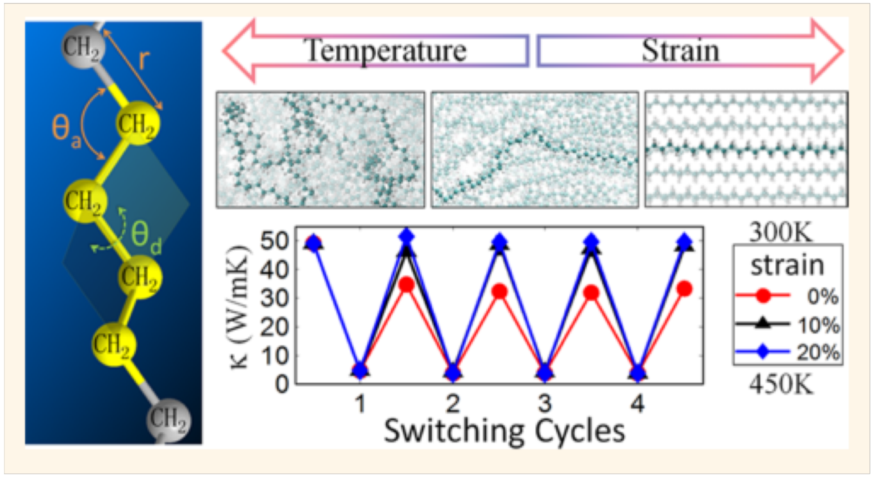
The thermal conductivity switch

State of the art around biologically relevant temperatures



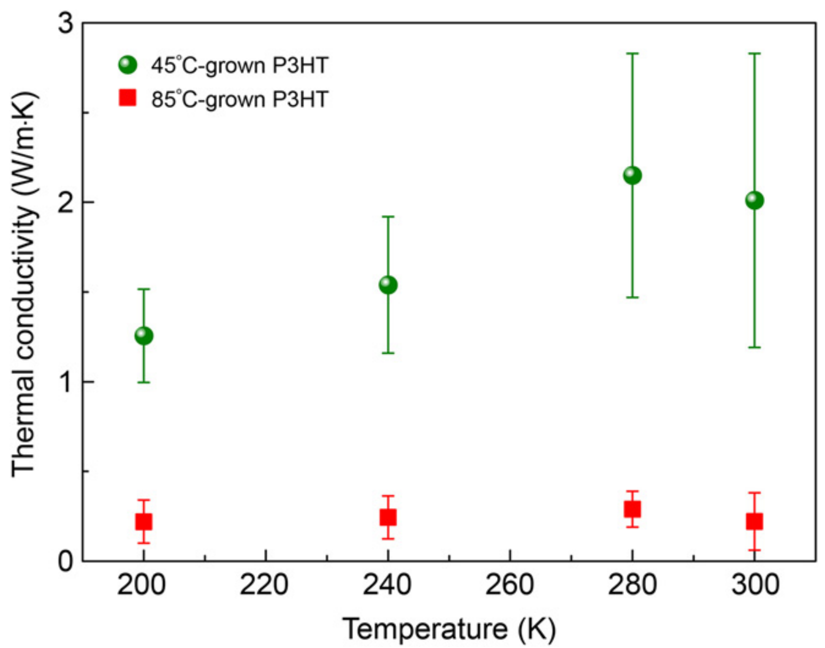
Nature Nanotechnology **13**, 959 (2018)

Heat transfer and thermal conductivity in polymers



ACS Nano **7**, 7592

Polyethylene predicted to vary thermal conductivity by a **factor of 12**

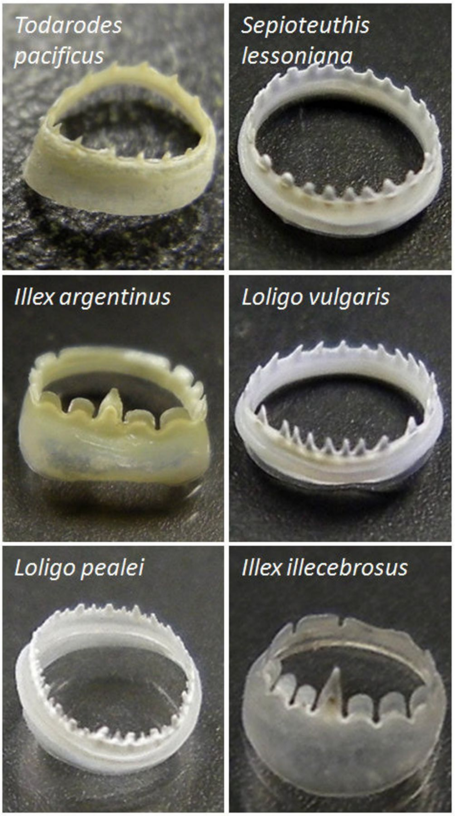


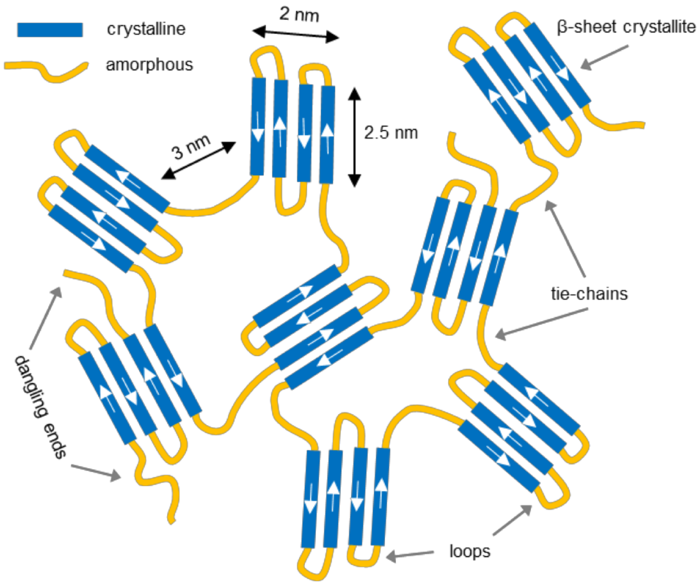
Science Advances ***4***, eaar3031

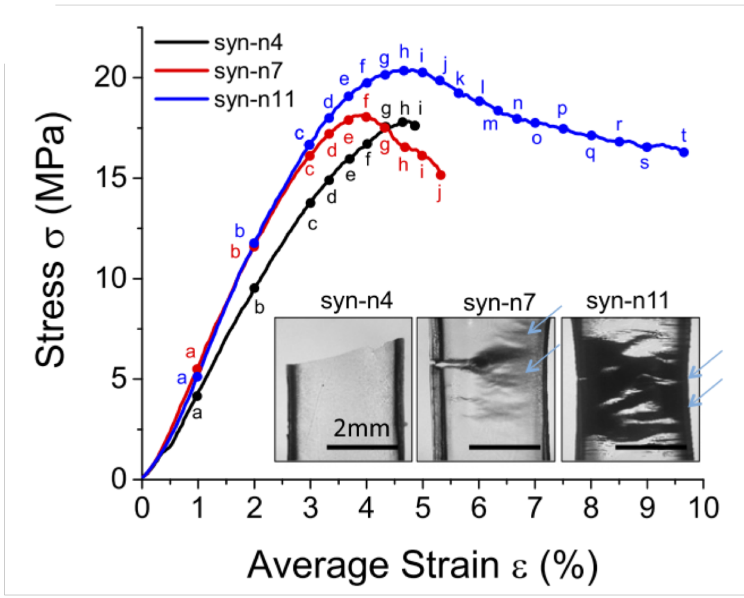
Increased inter- and intramolecular bonding has been shown to **create polymers with ~10x higher κ than conventional polymers**

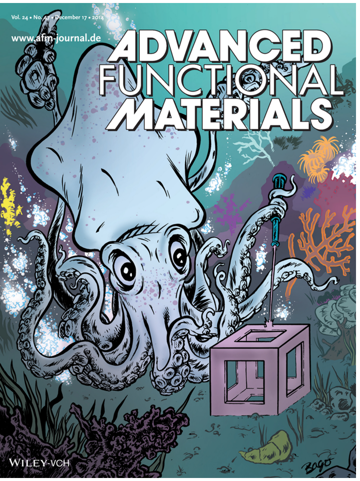
Strain, chain alignment and crystallinity lead to large changes in polymer thermal conductivity (static)

Squid ring teeth proteins – Prof. Melik Demirel (Penn State)



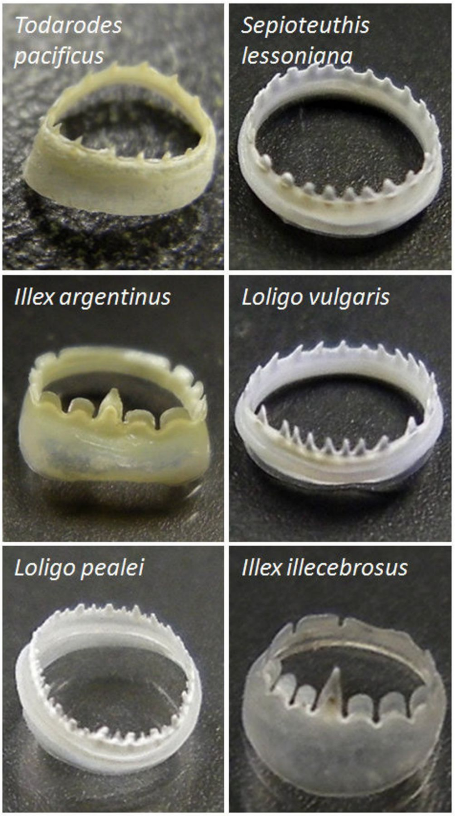


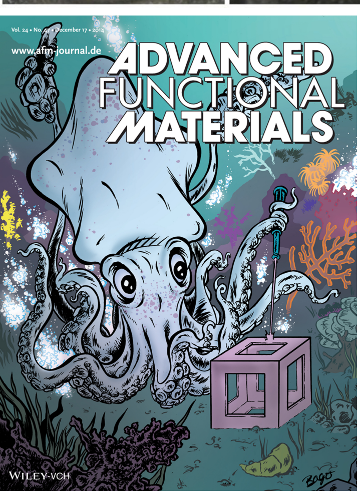


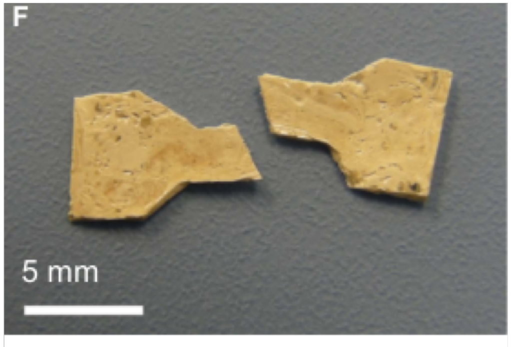


High strength protein due to semi crystalline (beta sheets) hydrogen bonded network

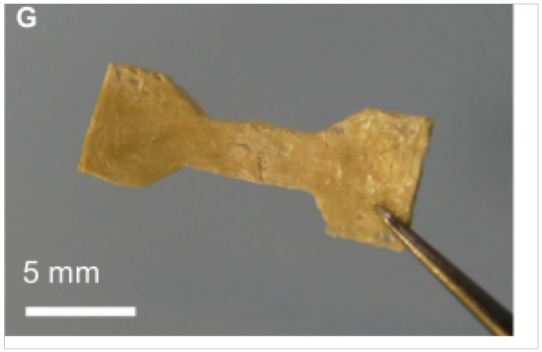
Squid ring teeth proteins – Prof. Melik Demirel (Penn State)





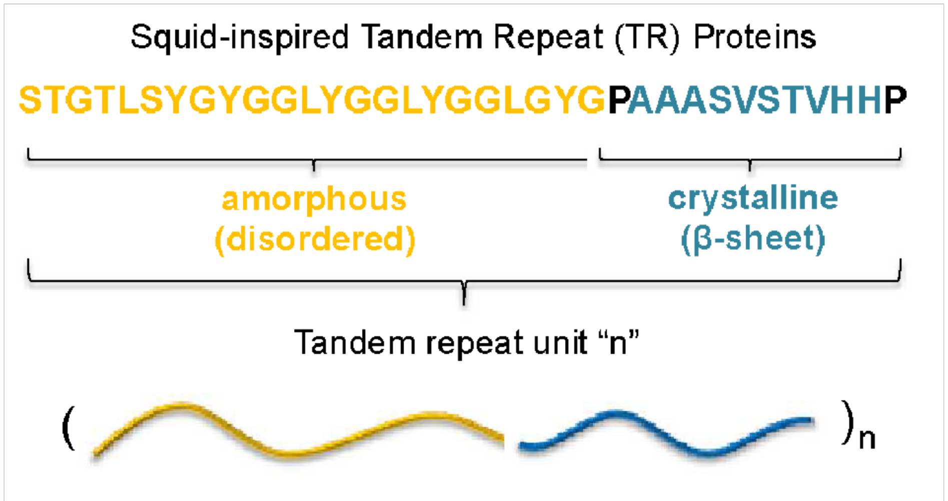


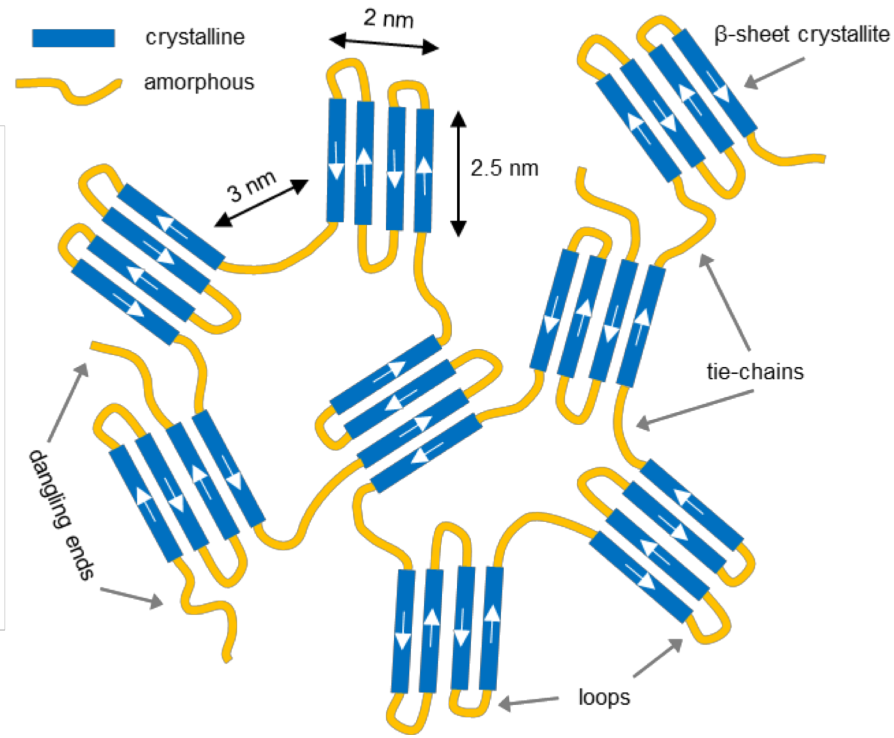
Add water!



Self healing when hydrated
(with a little bit of heat)

Squid ring teeth proteins – Prof. Melik Demirel (Penn State)



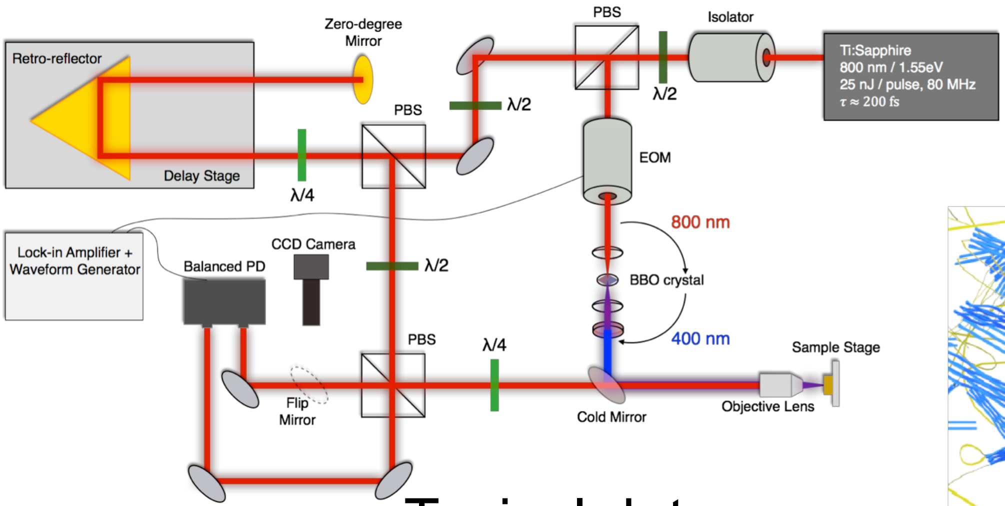


- Can we tune the thermal conductivity buy changing the molecular structure? (static)
- Can we dynamically control the thermal conductivity with hydration? (dynamic thermal conductivity switch)

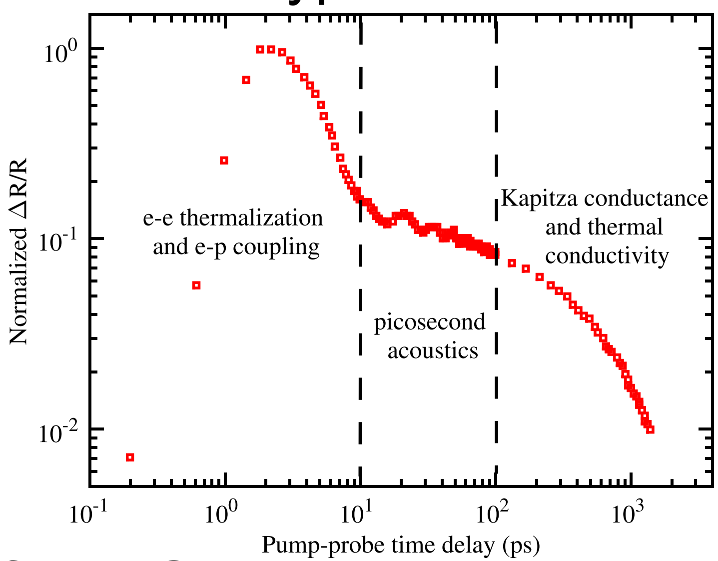
Nature Nanotechnology **13**, 959 (2018)

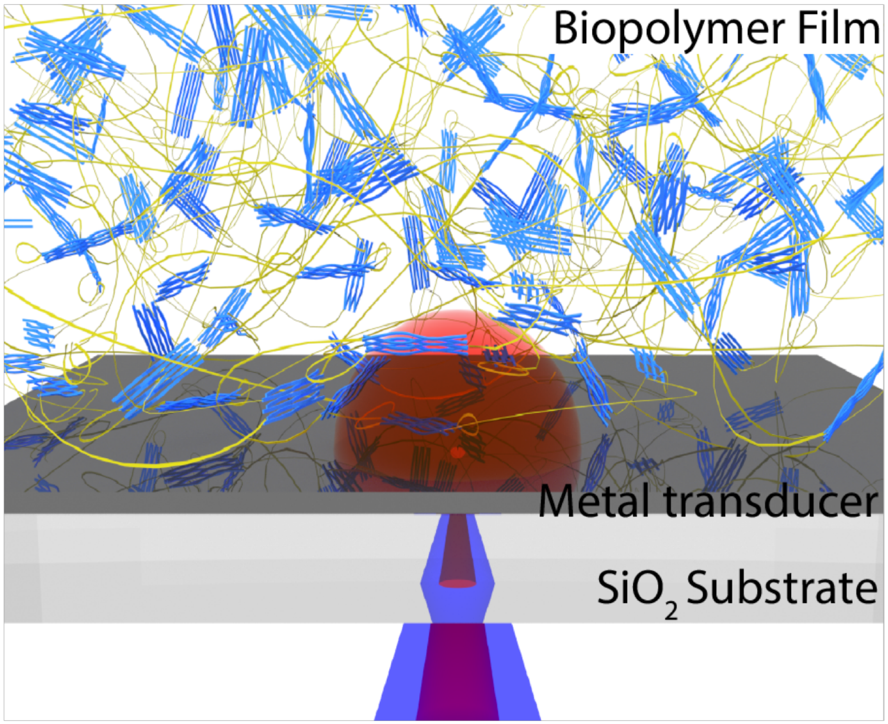
Time domain thermoreflectance (TDTR)

A typical sub-picosecond pump-probe system



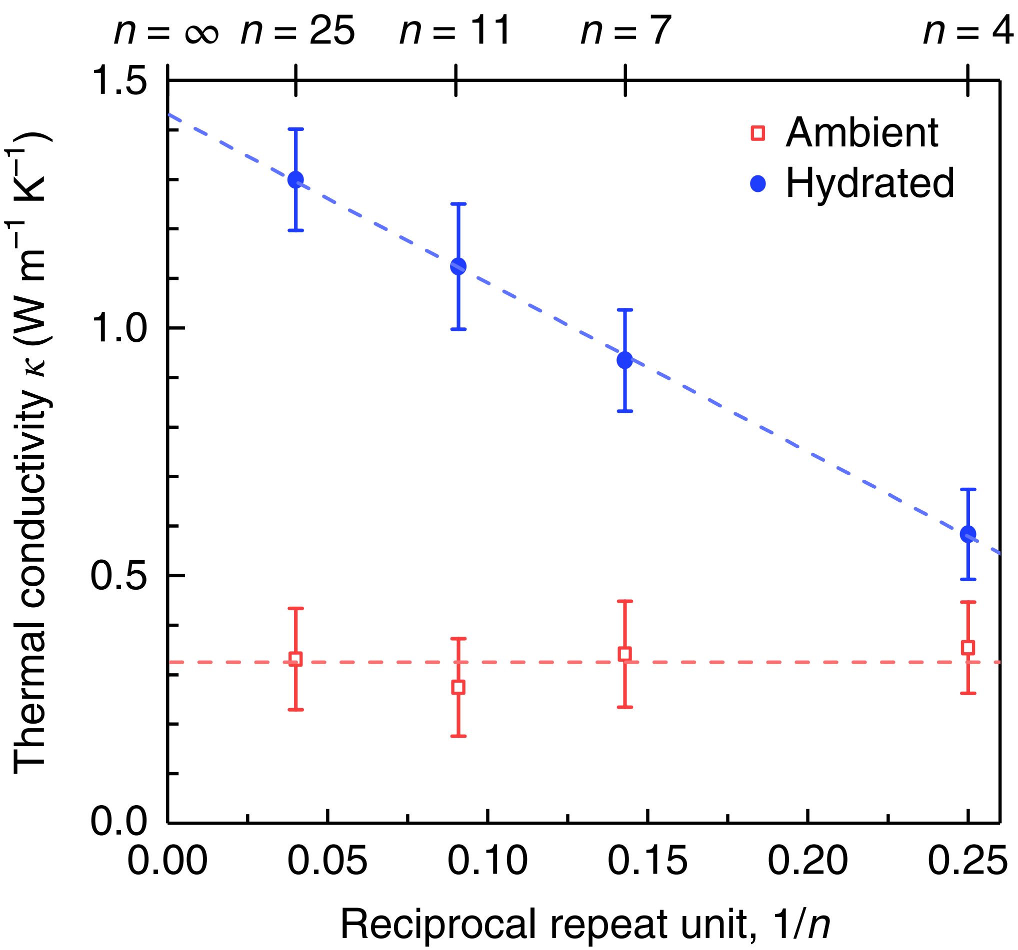
Typical data





Data from: Giri *et al. J. Appl. Phys.* **117**, 105105 (2015)

Results – Programmable thermal conductivity



<u>κ ambient</u>

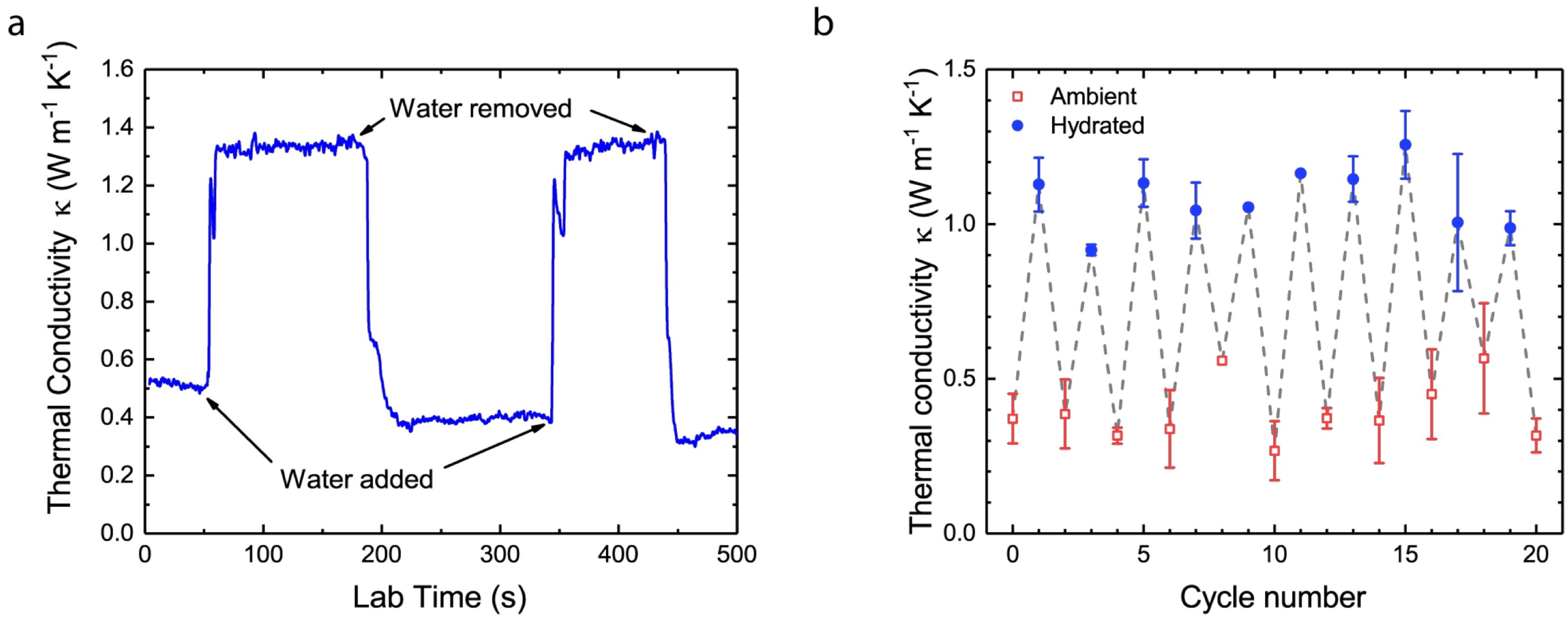
- No dependence on *n*
- Typical κ for polymer/protein
- Disorder dominates

<u>κ hydrated</u>

- Linear dependent on 1/n
- Up to 4X increase in κ compared to ambient

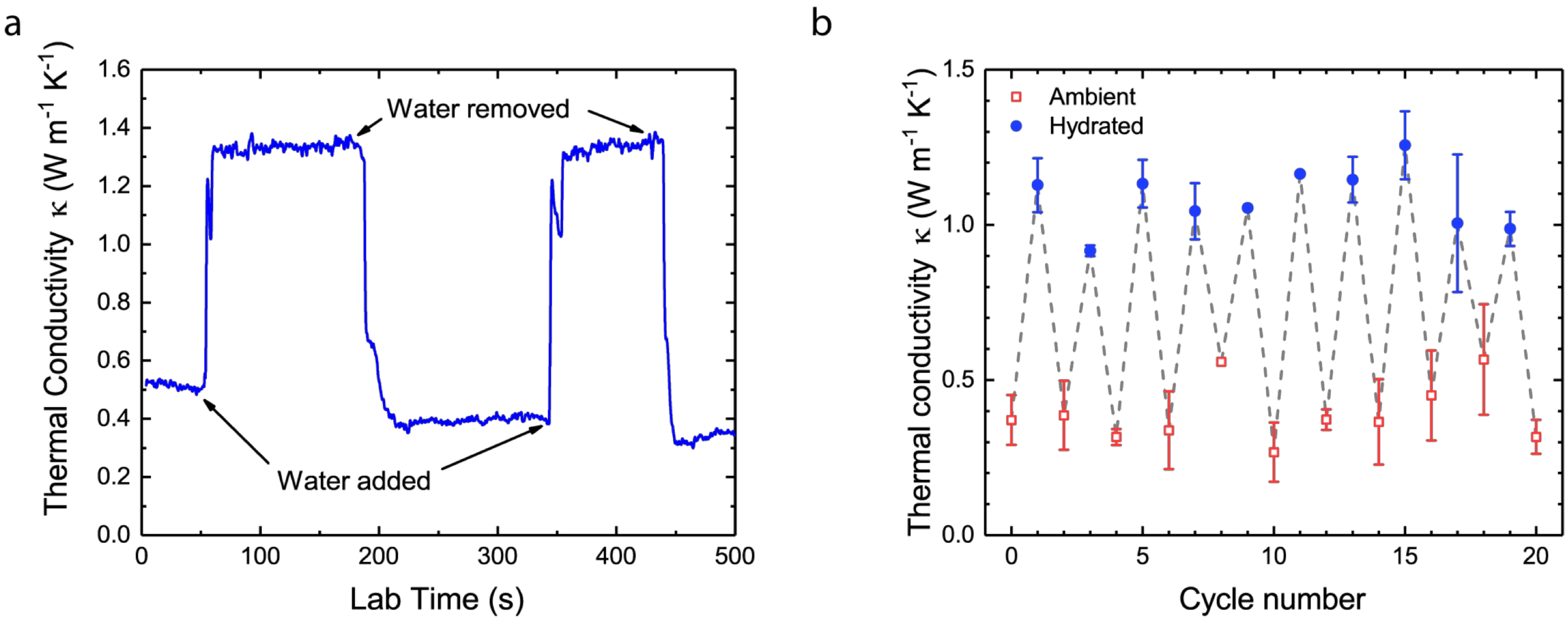
Nature Nanotechnology **13**, 959 (2018)

Results – Switchable thermal conductivity



Nature Nanotechnology **13**, 959 (2018)

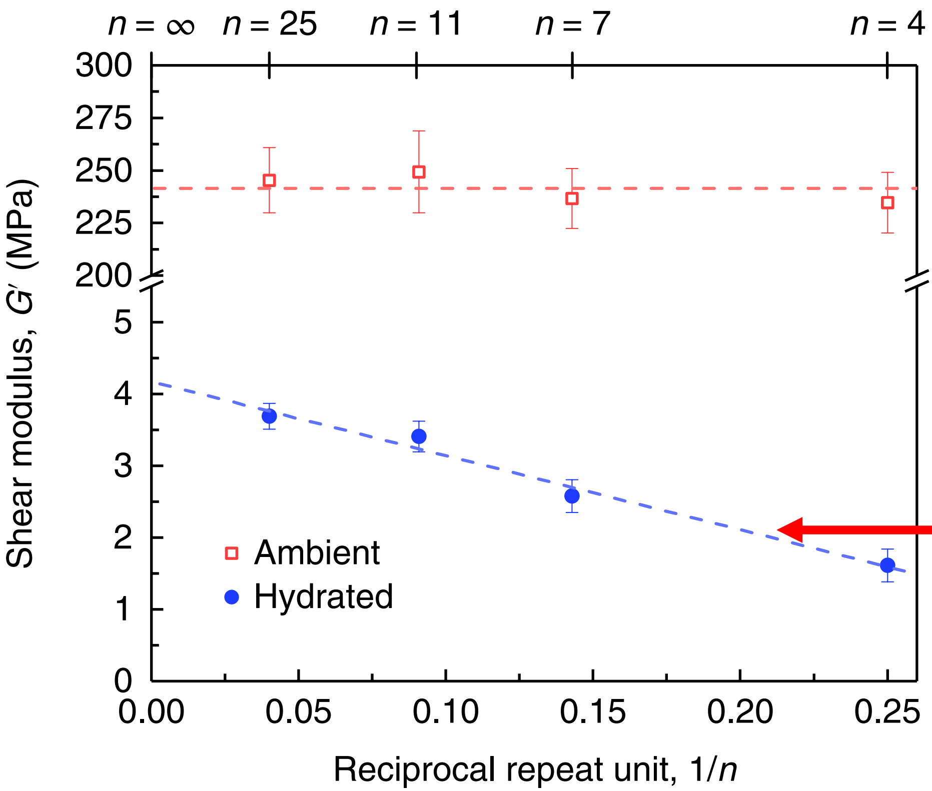
Results – Switchable thermal conductivity



But why???

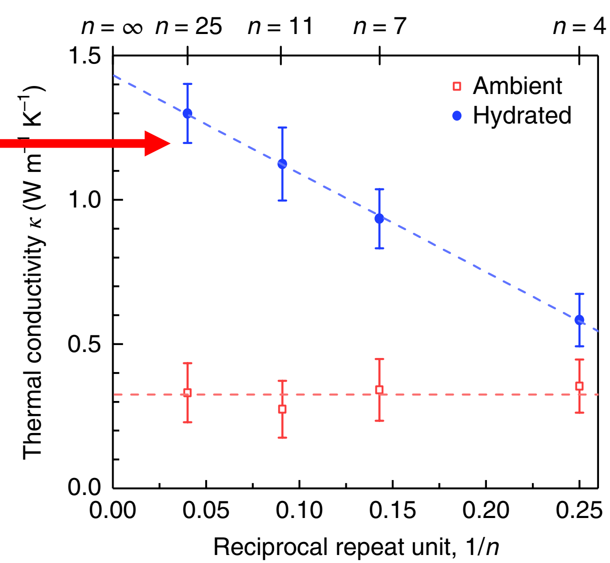
Nature Nanotechnology **13**, 959 (2018)

Results – Rheology



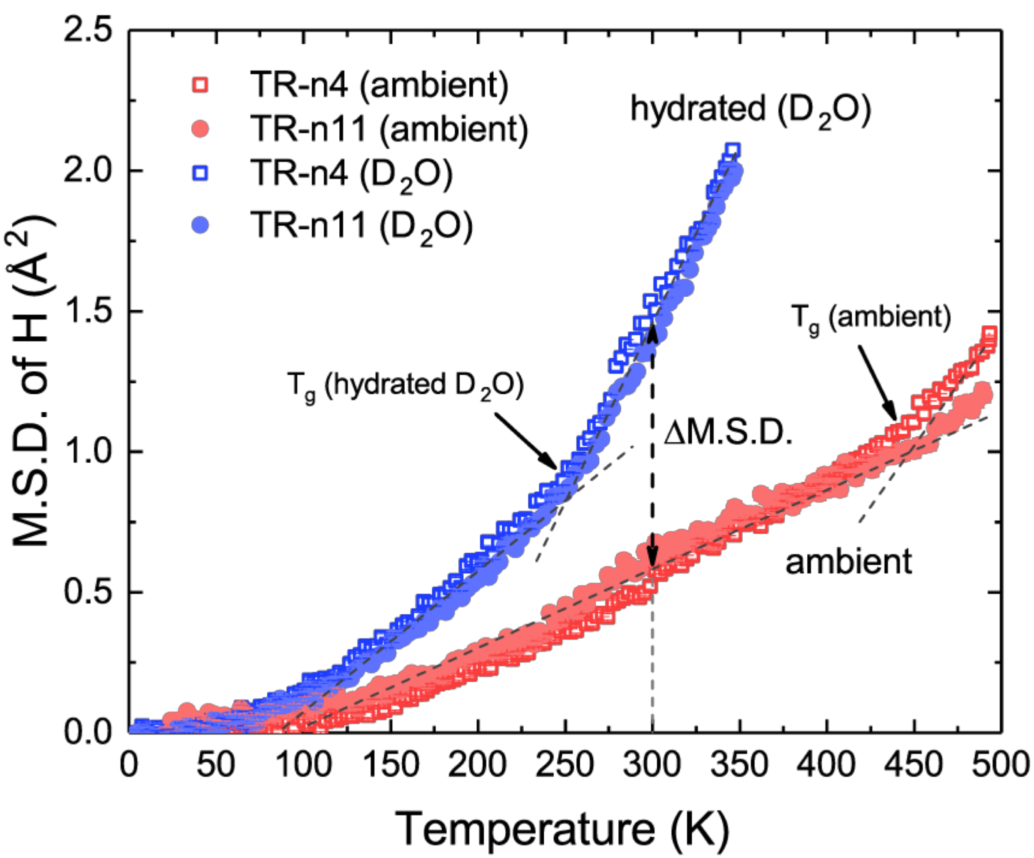
<u>$\kappa \sim G'$</u>

- Diamond = Strong bonds = high κ
- Polymers = weak bonds = low κ
- κ trends with $G'(1/n)$
- **Why does κ increase with hydration?**



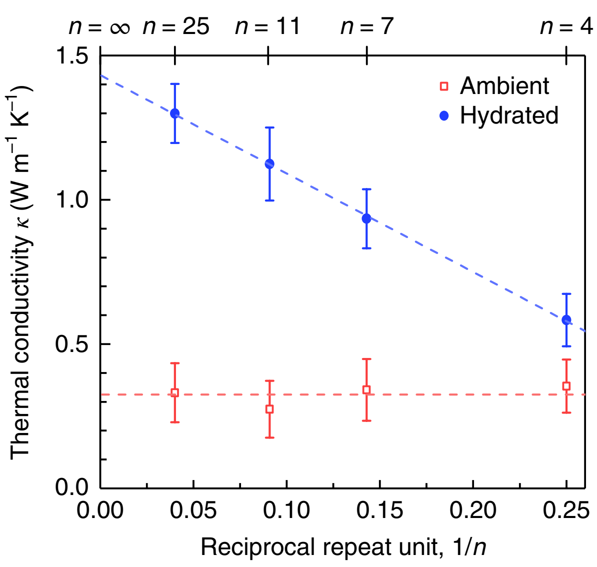
Nature Nanotechnology **13**, 959 (2018)

Results – Neutron scattering (NIST)



$\underline{\kappa \sim \text{MSD}}$

- QENS in ambient and hydrated environments
- Hydration increases mean square displacement of hydrogen atoms in network



Nature Nanotechnology **13**, 959 (2018)

Mechanisms of thermal conductivity switching

Thermal conductivity of crystalline/ordered solids

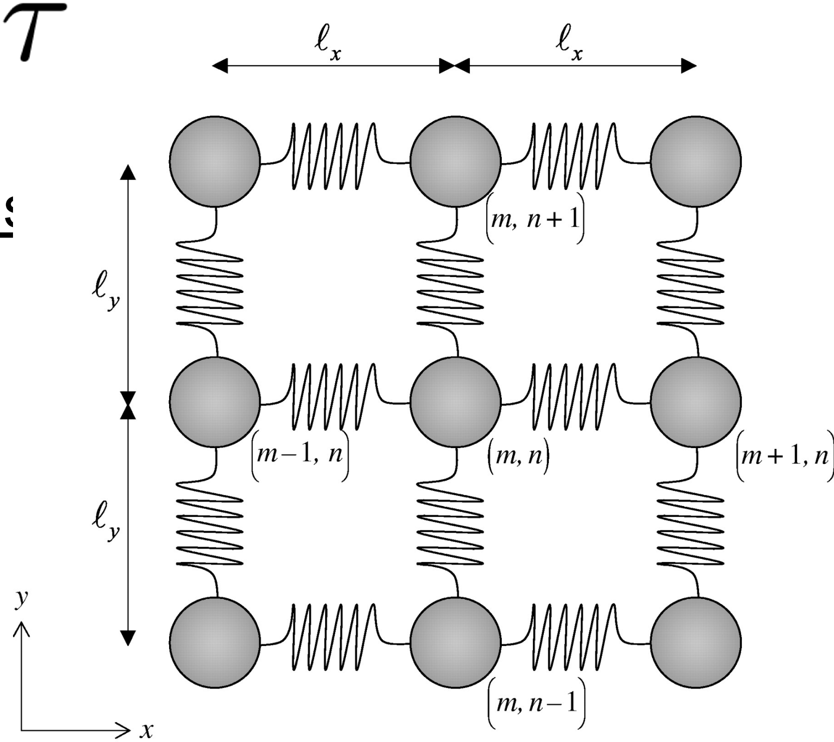
$$\kappa = \frac{1}{3} C v \lambda = \frac{1}{3} C v_g^2 \tau$$

Thermal conductivity of disordered solids

$$\kappa_{\text{Diffuson}} \propto \sum C_\omega D_\omega$$

$$D_\omega = \text{Mode Diffusivity}$$

$$D_\omega \propto \text{MSD} \times G'^2$$



Nature Nanotechnology **13**, 959 (2018)

Mechanisms of thermal conductivity switching

Competing effects

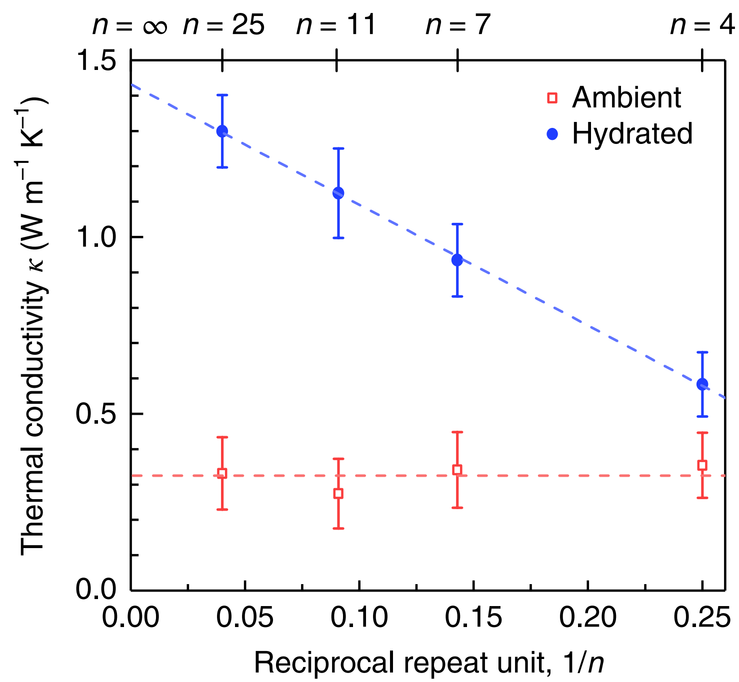
- **Increase in κ due to increase in MSD**
- **Decrease in κ (trend in 1/*n*) due to decrease in *G*'**

Thermal conductivity of disordered solids

$$\kappa_{\text{Diffuson}} \propto \sum C_\omega D_\omega$$

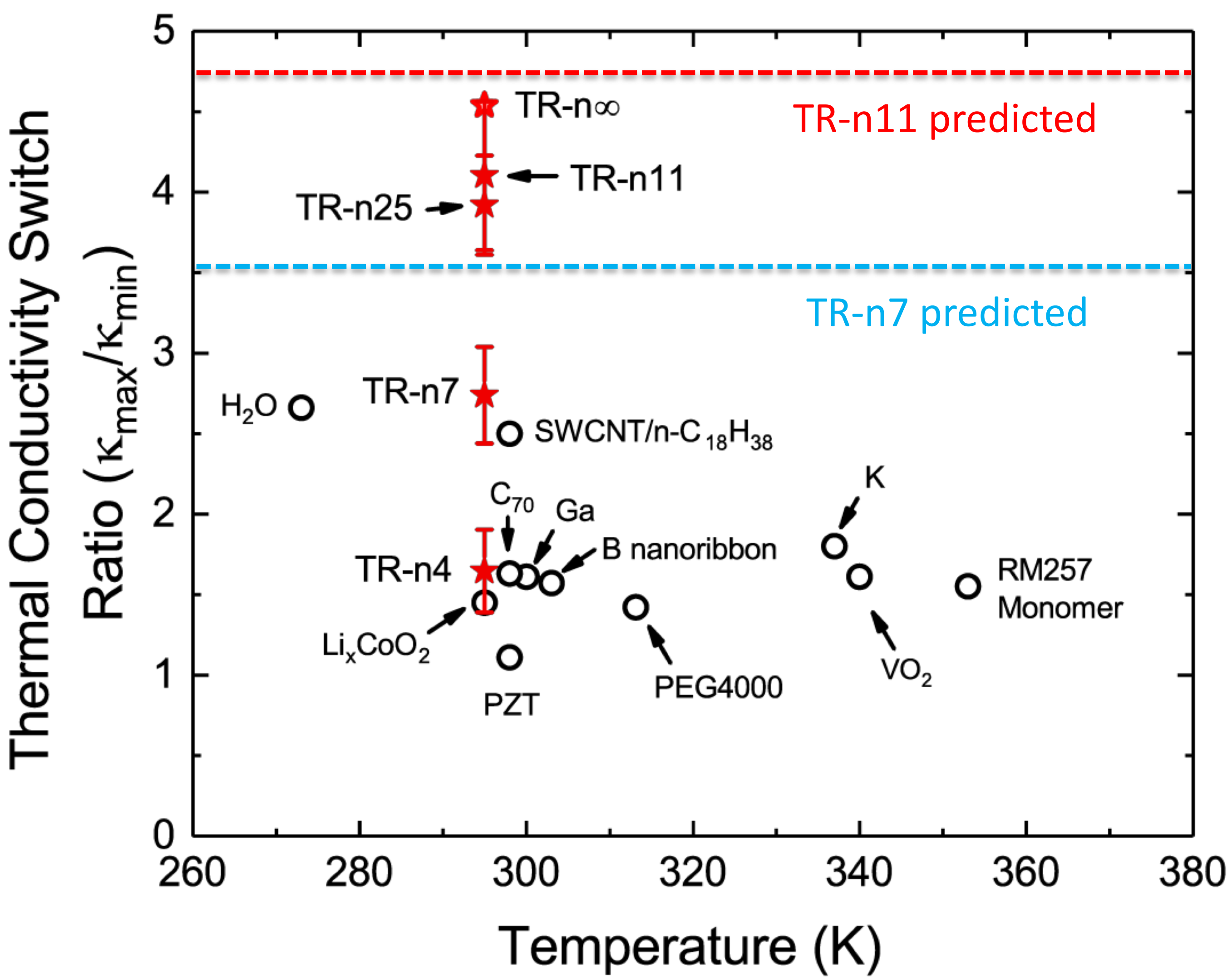
$$D_\omega = \text{Mode Diffusivity}$$

$$D_\omega \propto \text{MSD} \times G'^2$$



Nature Nanotechnology **13**, 959 (2018)

Redefining the SOA of κ switches with SRT



Nature Nanotechnology **13**, 959 (2018)

Summary

nature nanotechnology

ARTICLES

https://doi.org/10.1038/s41565-018-0227-7

Tunable thermal transport and reversible thermal conductivity switching in topologically networked bio-inspired materials

John A. Tomko[1,10], Abdon Pena-Francesch[2,3,10], Huihun Jung[2,3], Madhusudan Tyagi[4,5], Benjamin D. Allen[6,7], Melik C. Demirel[2,3,7]* and Patrick E. Hopkins[1,8,9]*

NATURE NANOTECHNOLOGY | VOL 13 | OCTOBER 2018 | 959–964 |