UVA SCHOOL of ENGINEERING & APPLIED SCIENCE

Bi-directionally tuning the thermal resistance of materials and interfaces with irradiation induced defects

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Students, collaborators and funding

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Thomas Pfeifer

Prof. Khalid Hattar
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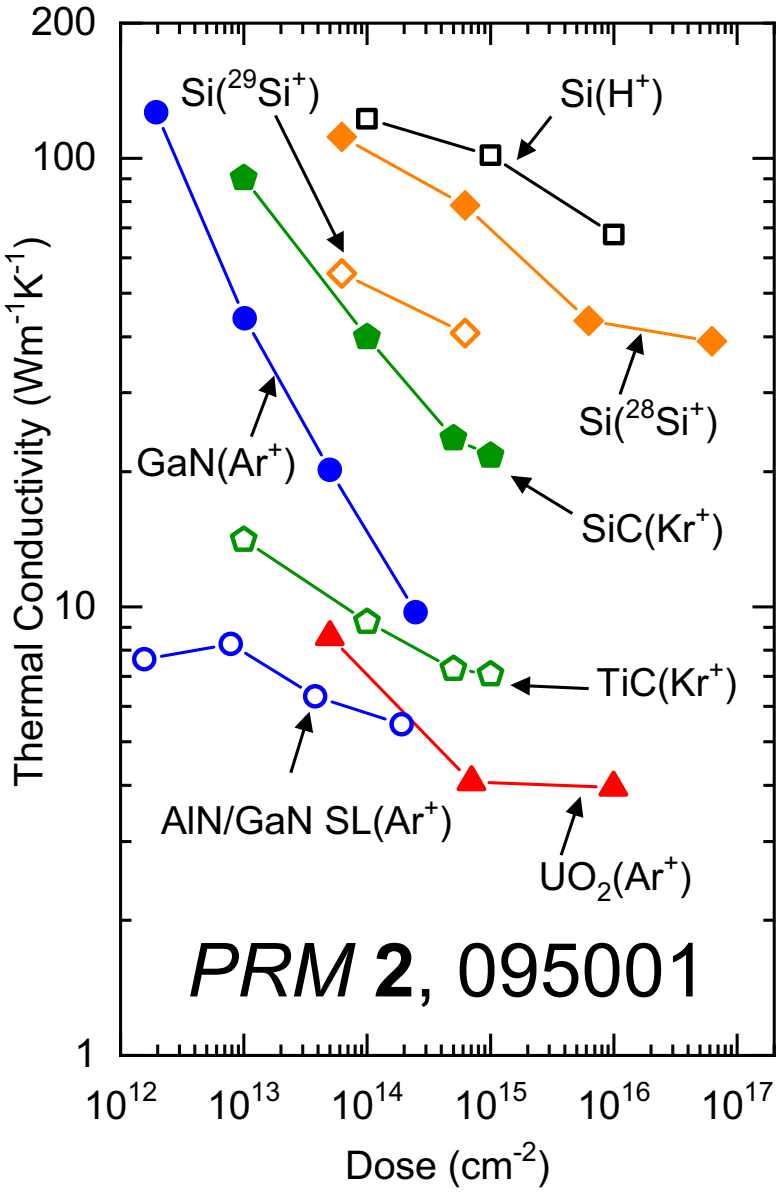
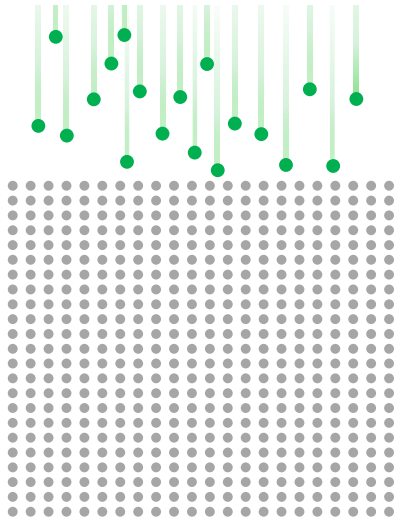
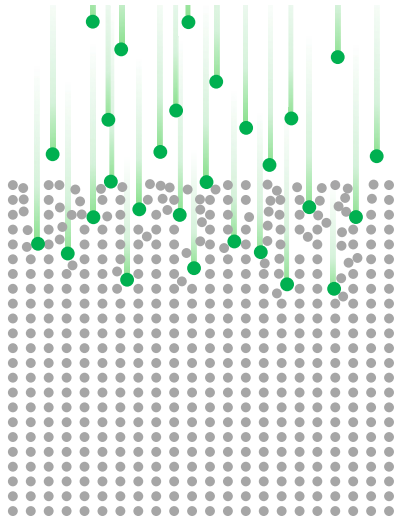
Collaborators

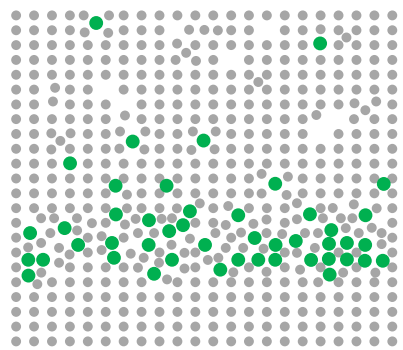
- King (Intel)
- Gaskins (LT)
- Goorsky (UCLA)
- Rost (VT)
- Esfarjani (UVA)
- Braun (LT)
- Olson (LT)
- Lang (UNM)
- Hoglund (ORNL)
- Aller (UMD)
- McGaughey (CMU)
- Doolittle (Ga Tech)
- Giri (URI)

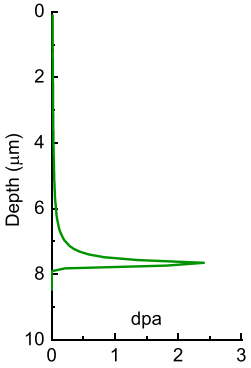
Thermal conductivity of ion irradiated solids

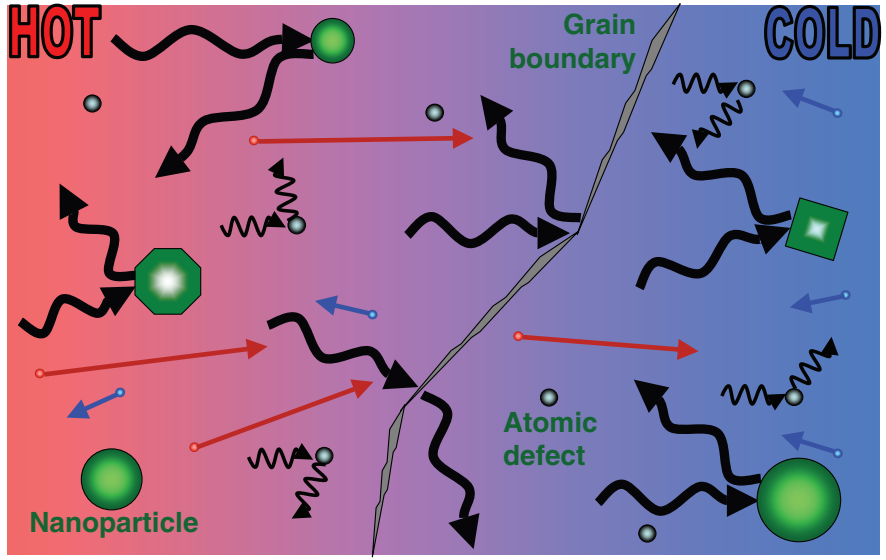












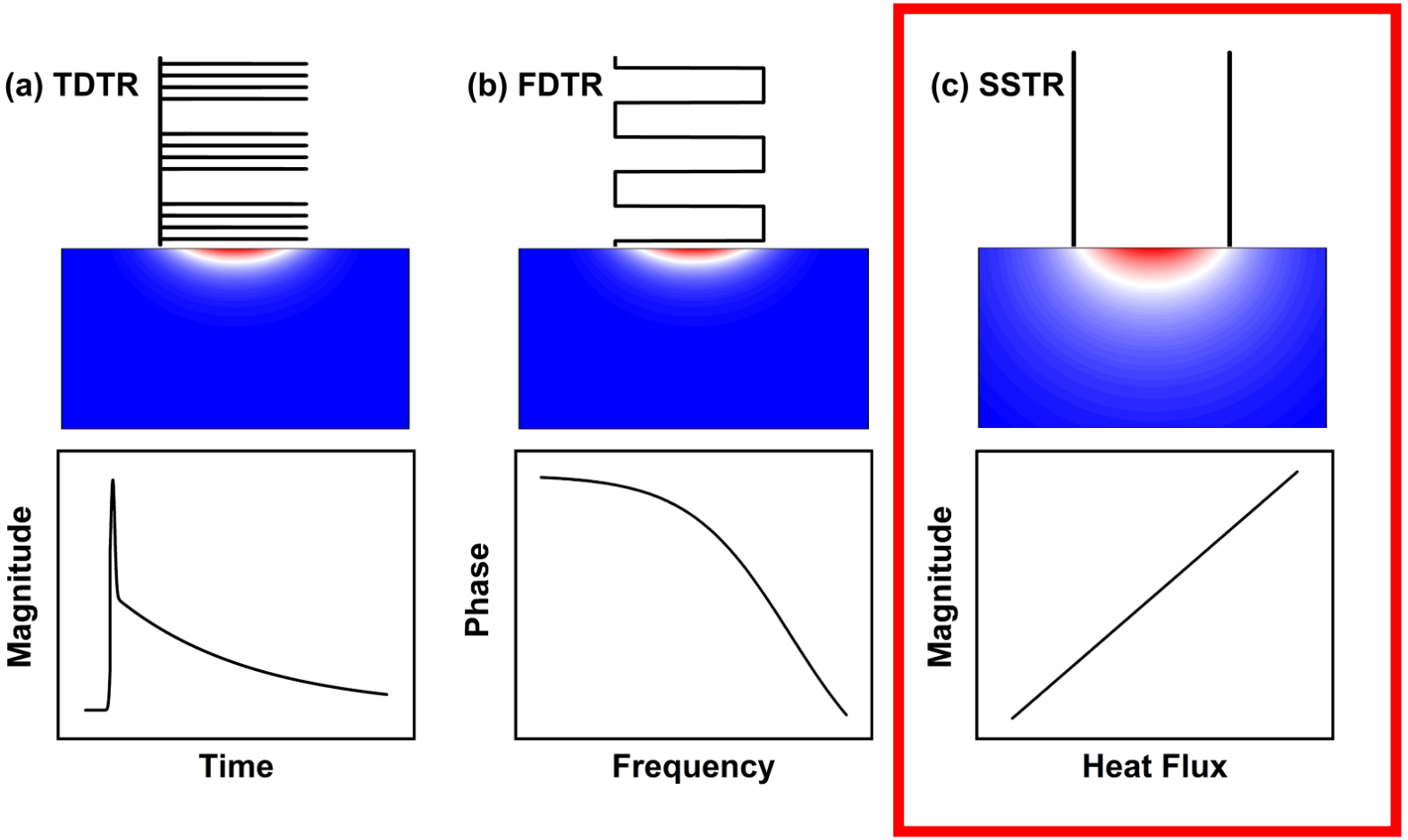
$$\kappa = \frac{1}{3} C v \lambda$$

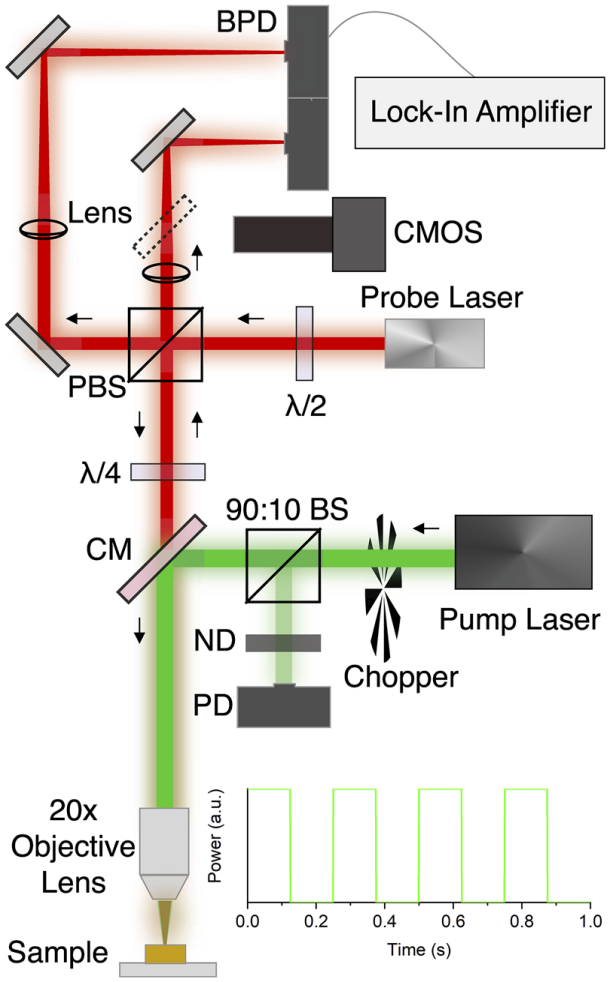
Adv. Mat. **22**, 3970

Outline

- Length scales of thermal conductivity (κ) measurements and pump-probe thermoreflectance (*JAP* **126**, 150901)
- Displacement damage governs thermal conductivity reduction in irradiated solids (*PRB* **104**, 134306)
- Increasing thermal transport in irradiated solids
  - Increasing κ of amorphous carbon (*Nano Lett*. **21**, 3935)
  - Reducing thermal boundary resistance (*PRB* **109**, 165421)
- Sub-surface thermal conductivity depth profiling of irradiated solids
  - N^{3+} implanted diamond (*JAP* **129**, 055307)
  - Kr^{+} irradiated silicon (*JAP* **132**, 075112)
- Ultrahigh temperature thermometry for measuring nuclear materials up to and through their melting points (*PRL* **132**, 146303)

Measuring the “near surface” thermal conductivity of solids

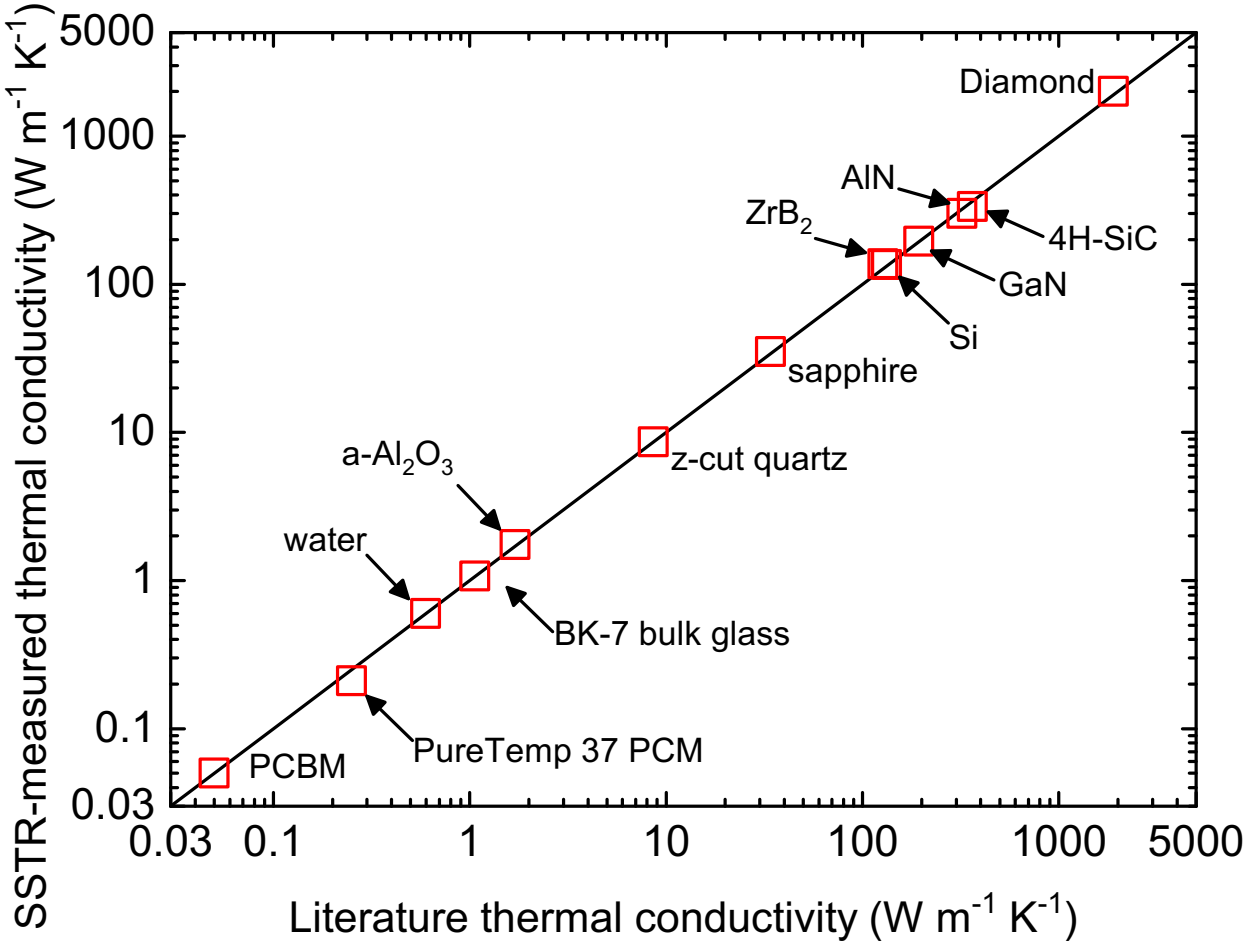


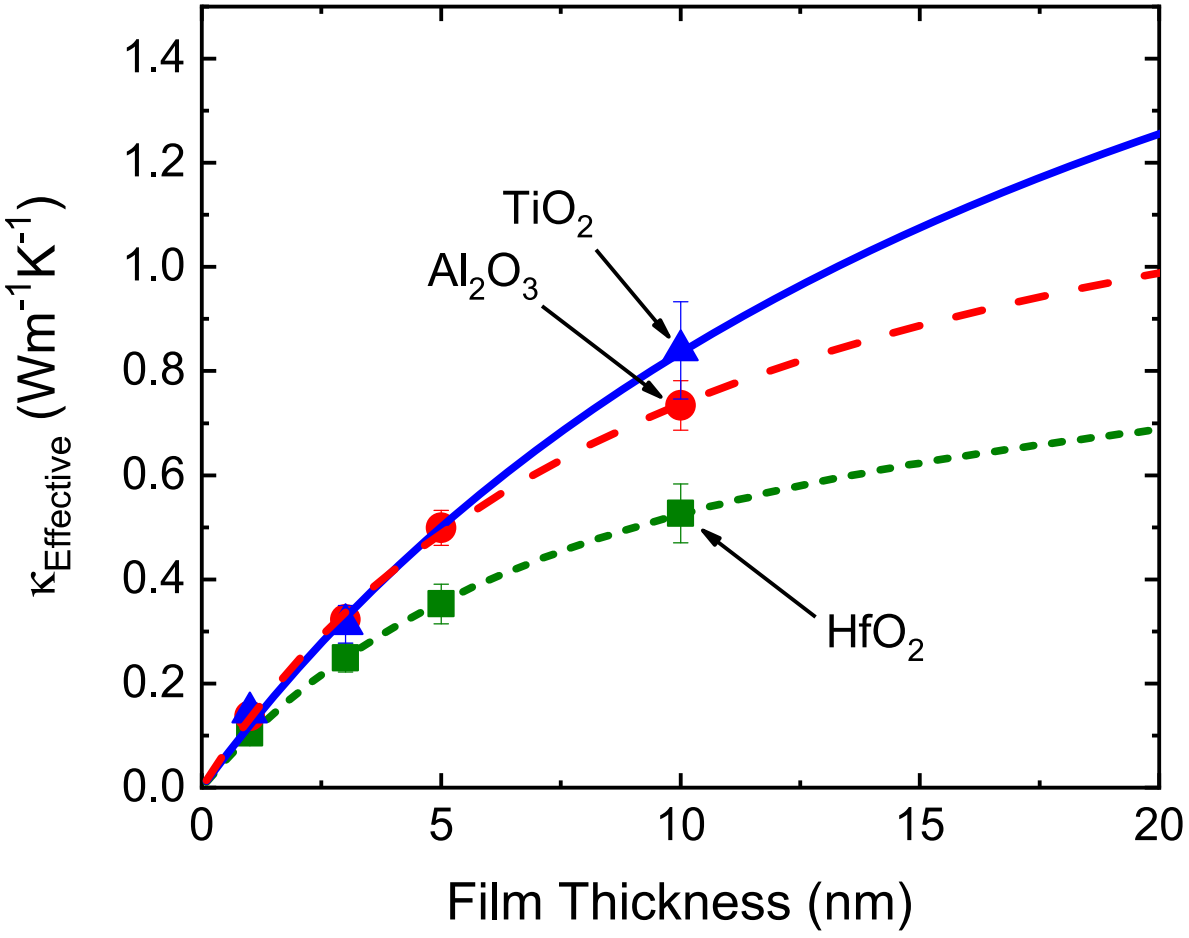


Steady-state thermoreflectance

Rev. Sci. Intr. **90**, 024905 (2019)

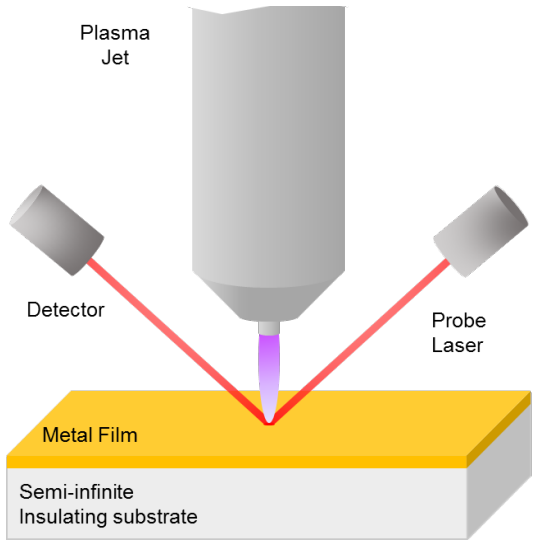
Thermoreflectance: from bulk to thin films and interfaces

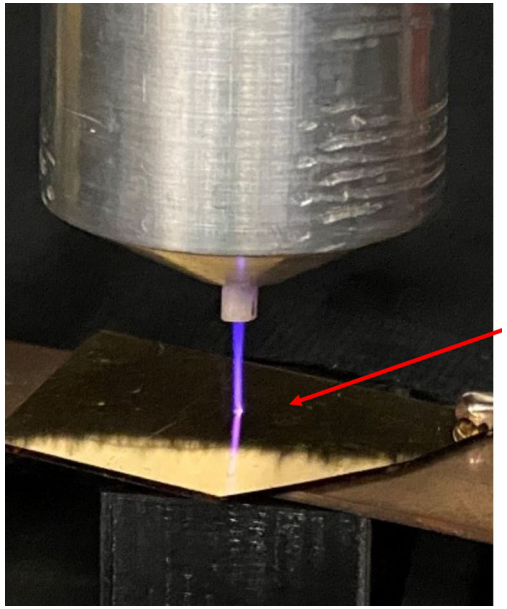


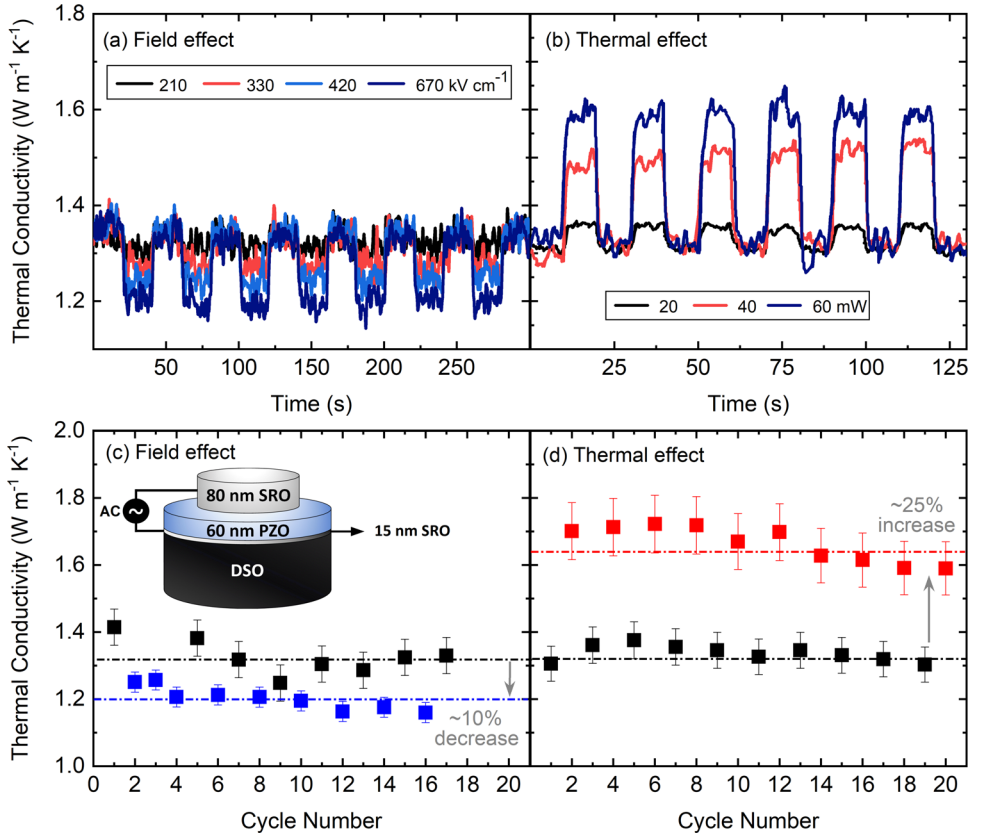


APL Materials **6**, 058302

Thermoreflectance measurements for *in situ* diagnostics







nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-022-30170-5 OPEN

Check for updates

Plasma-induced surface cooling

John A. Tomko[1✉], Michael J. Johnson[2], David R. Boris[3], Tzvetelina B. Petrova[3], Scott G. Walton[3✉] & Patrick E. Hopkins[1,4,5✉]

nature COMMUNICATIONS

ARTICLE

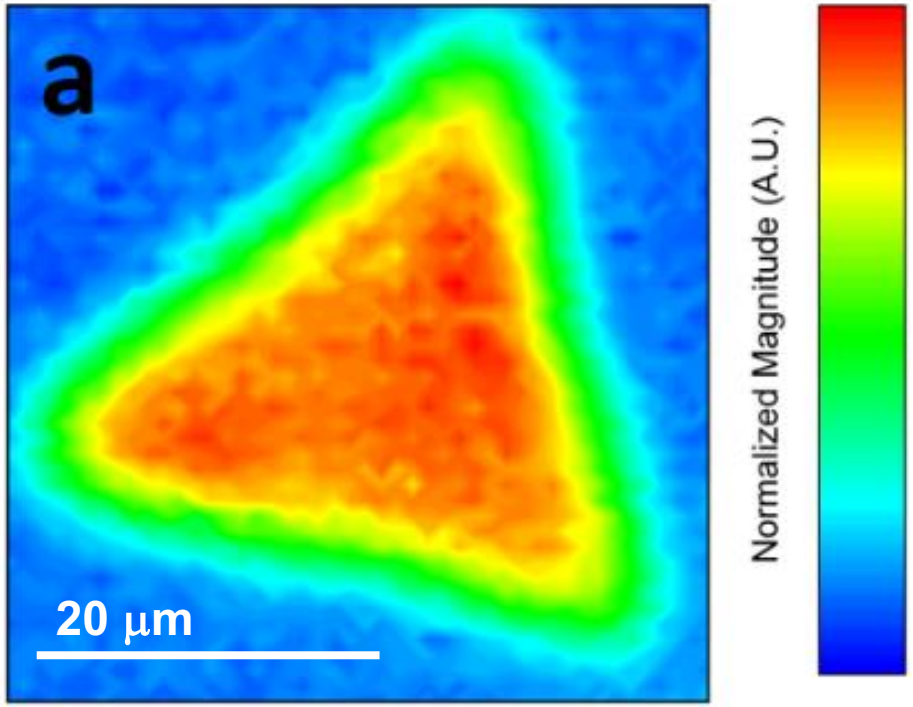
https://doi.org/10.1038/s41467-022-29023-y OPEN

Check for updates

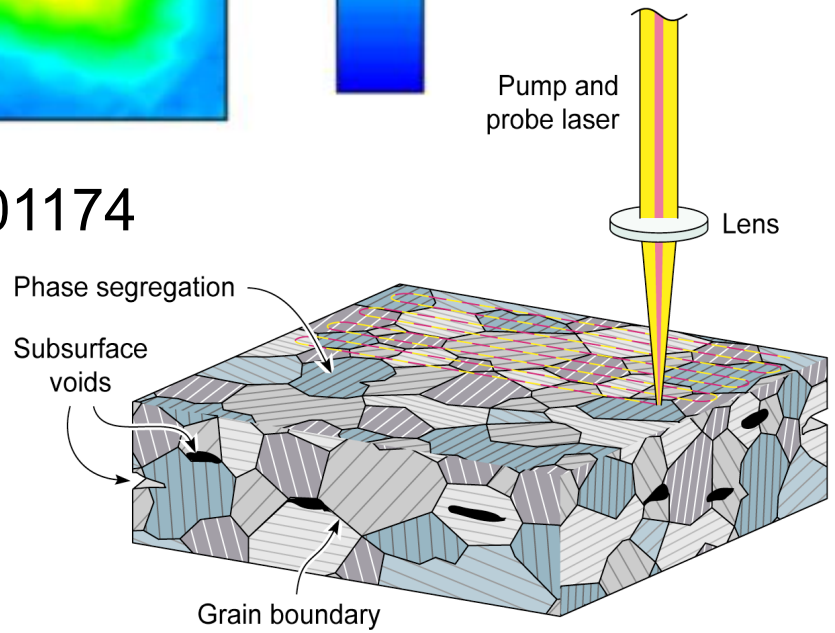
Observation of solid-state bidirectional thermal conductivity switching in antiferroelectric lead zirconate ($PbZrO_3$)

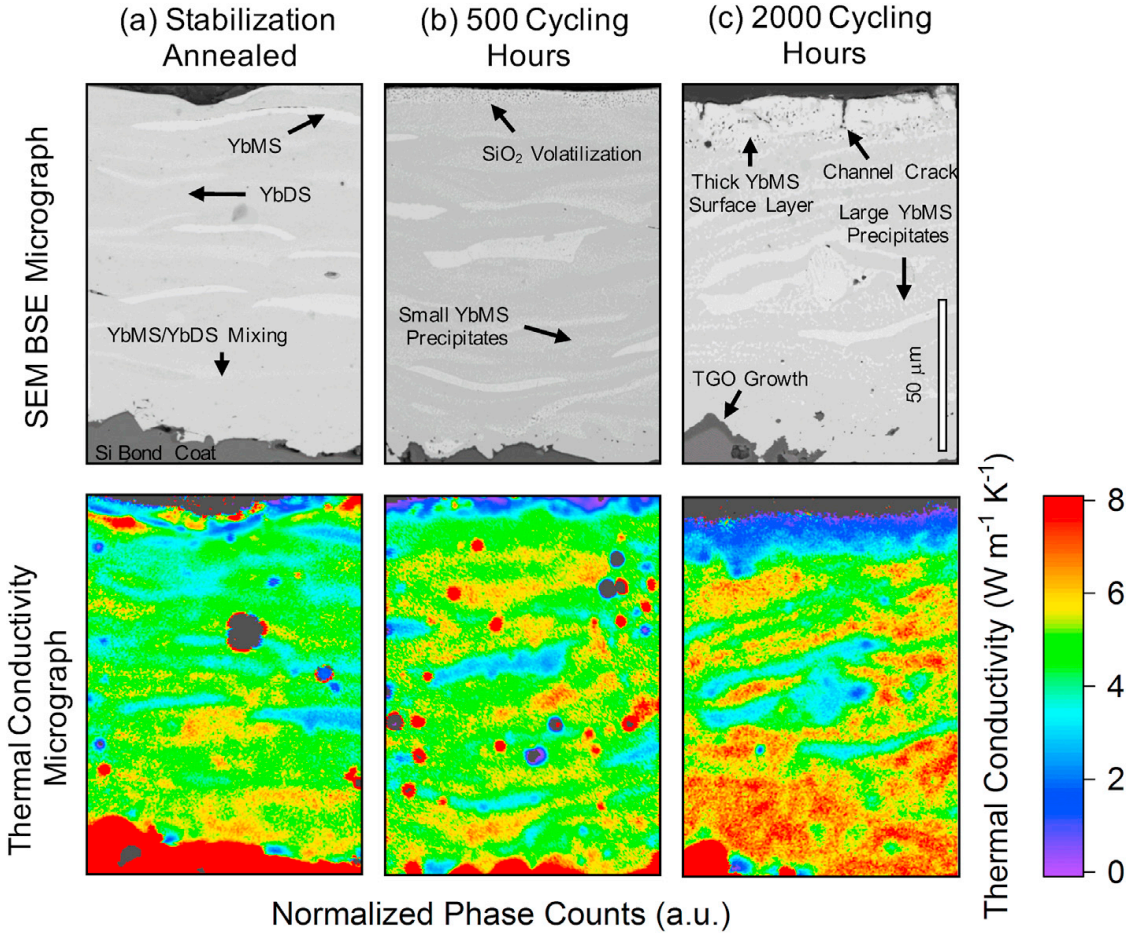
Kiumars Aryana[1], John A. Tomko[1], Ran Gao[2], Eric R. Hoglund[3], Takanori Mimura[3], Sara Makarem[3], Alejandro Salanova[3], Md Shafkat Bin Hoque[1], Thomas W. Pfeifer[1], David H. Olson[1], Jeffrey L. Braun[1], Joyeeta Nag[4], John C. Read[4], James M. Howe[3], Elizabeth J. Opila[1,3], Lane W. Martin[2,5], Jon F. Ihlefeld[3,6✉] & Patrick E. Hopkins[1,3,7✉]

Thermoreflectance measurements for *spatial* diagnostics



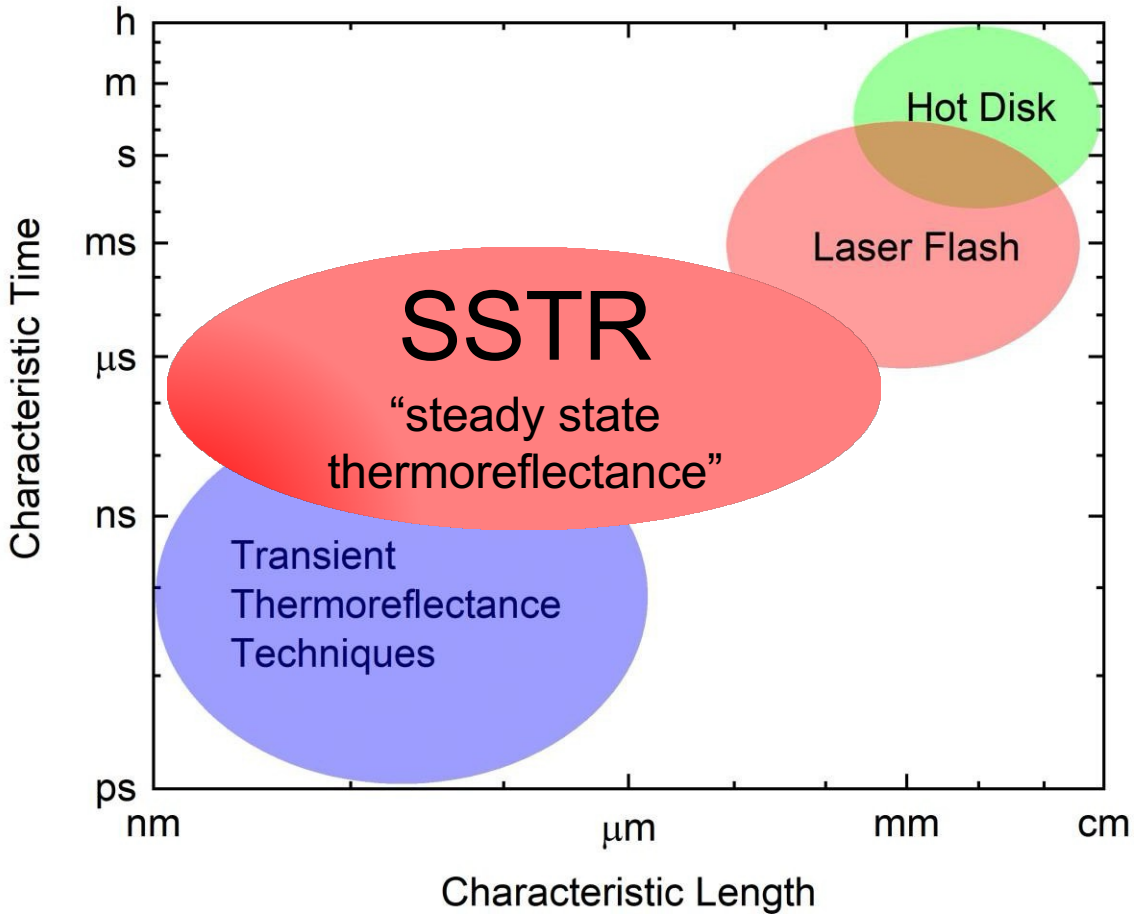
Adv. Sci. **7**, 2001174



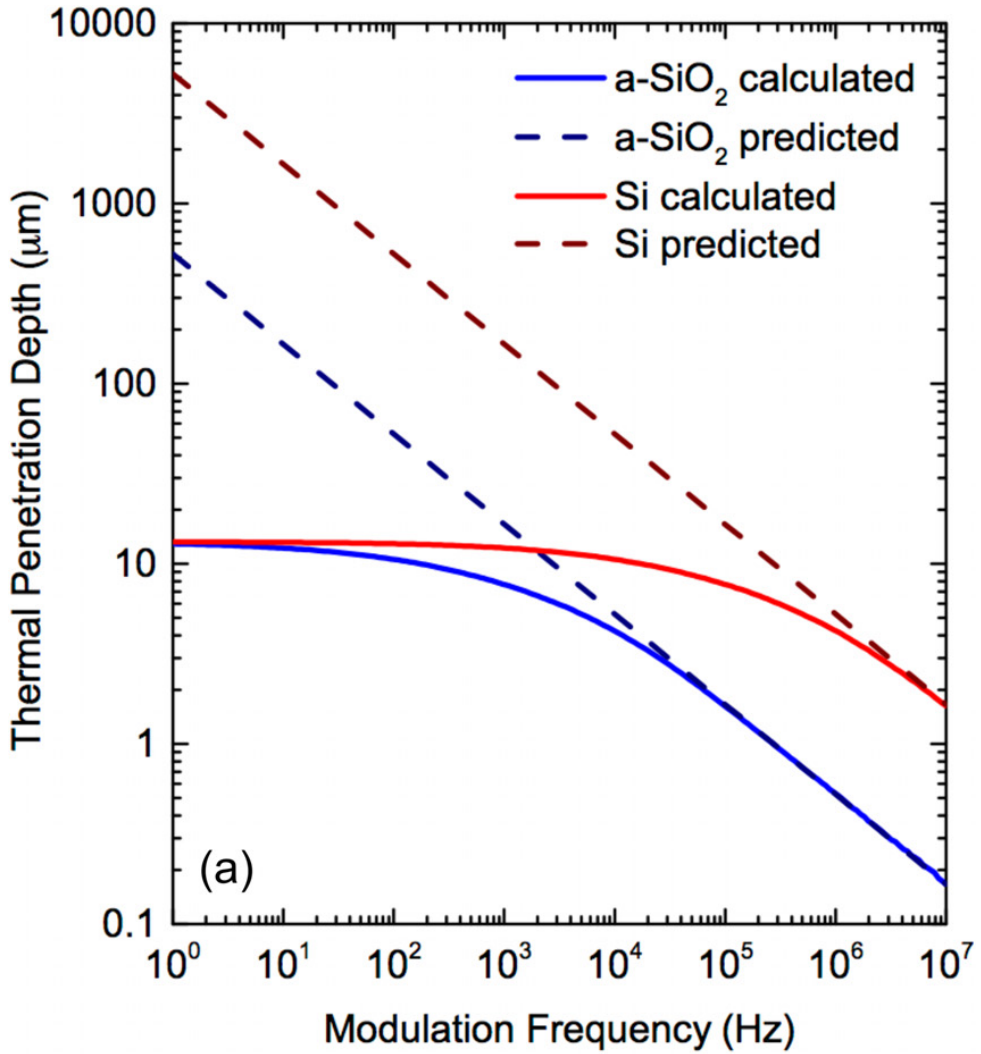


Mat. Today Phys. **17**, 100304

Depth (cross plane) length scales of thermoreflectance



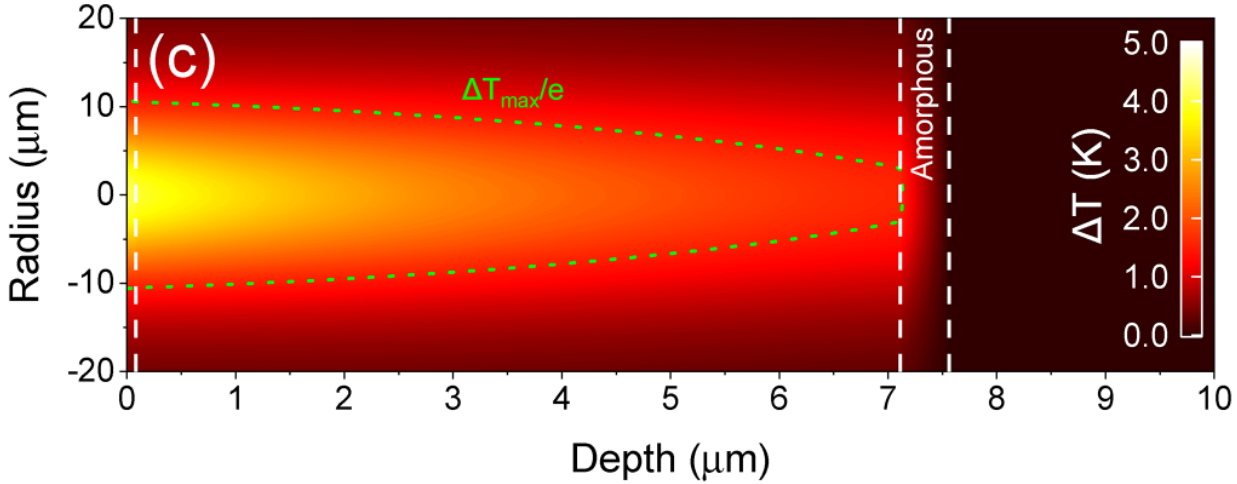
JAP **126**, 150901

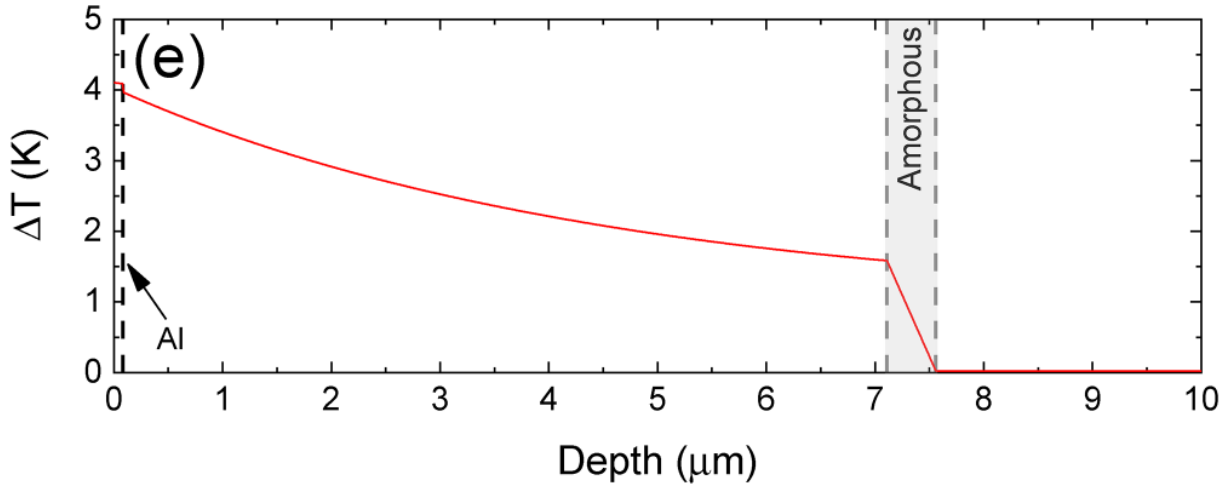


JAP **121**, 175107

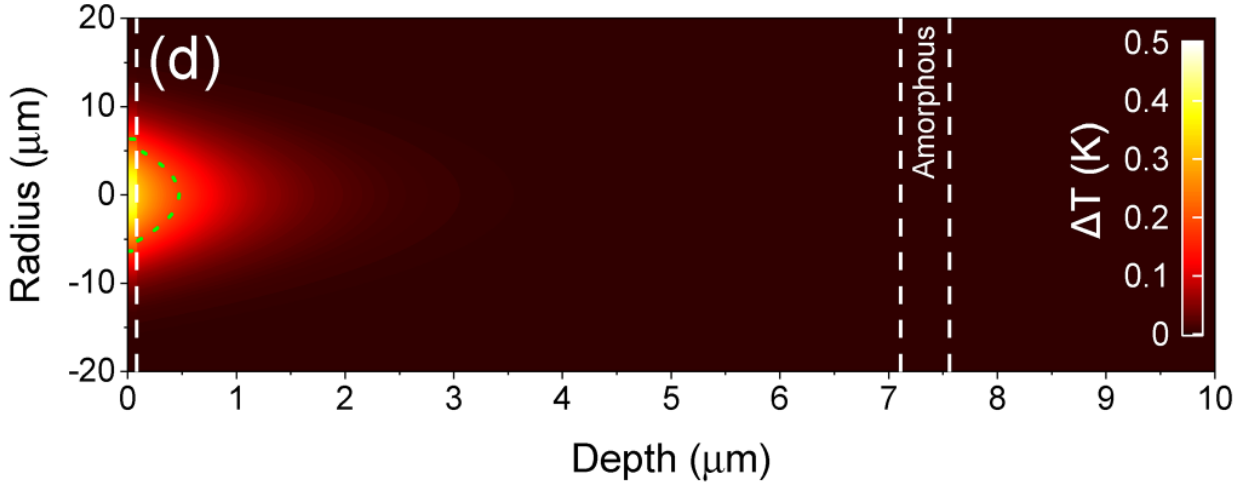
Measurement volumes in TDTR vs. SSTR

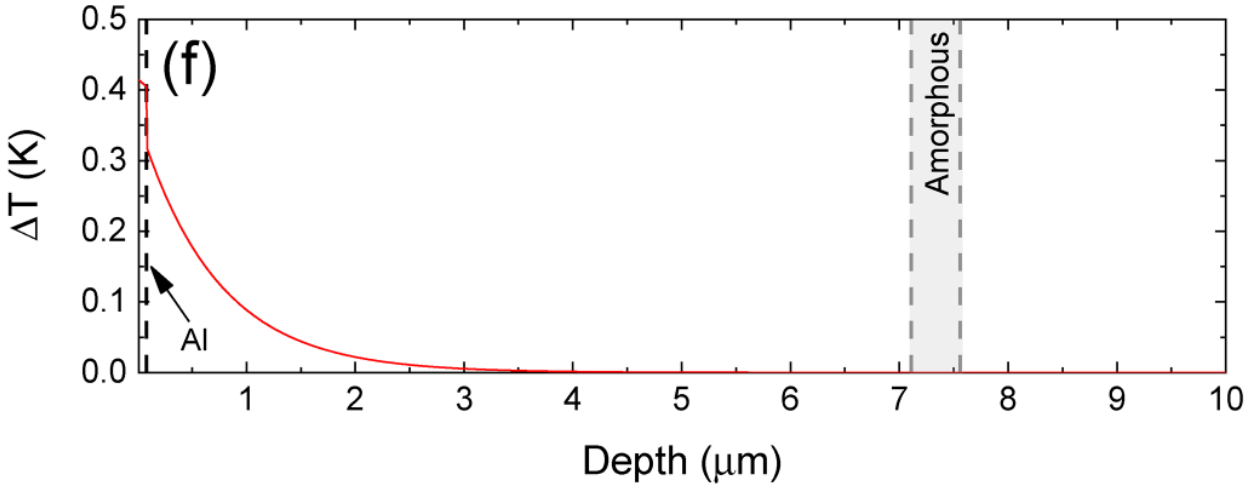
SSTR





TDTR

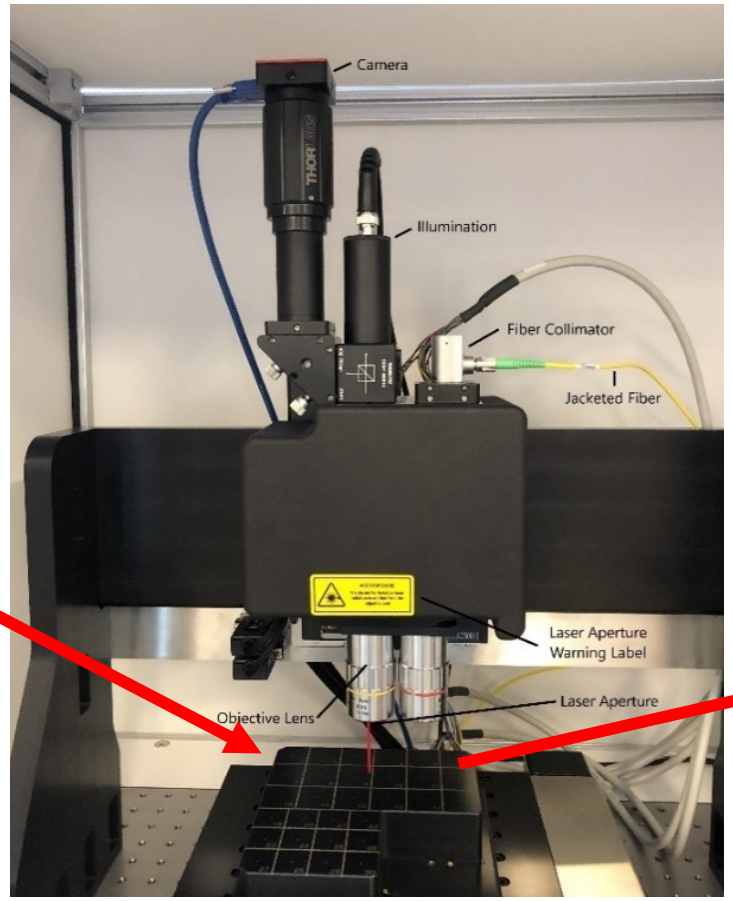




JAP **129**, 055307

Commercializing SSTR: Laser Thermal

Turn-key automated tool enables high throughput, spatially resolved measurements of *k*



Commercial SSTR-F tool from LaserThermal, Inc

COI Statement: Hopkins is a co-founder of LT, Inc.

Outline

- Length scales of thermal conductivity (κ) measurements and pump-probe thermoreflectance (*JAP* **126**, 150901)
- **Displacement damage governs thermal conductivity reduction in irradiated solids (*PRB* 104, 134306)**
- Increasing thermal transport in irradiated solids
  - Increasing κ of amorphous carbon (*Nano Lett*. **21**, 3935)
  - Reducing thermal boundary resistance (*PRB* **109**, 165421)
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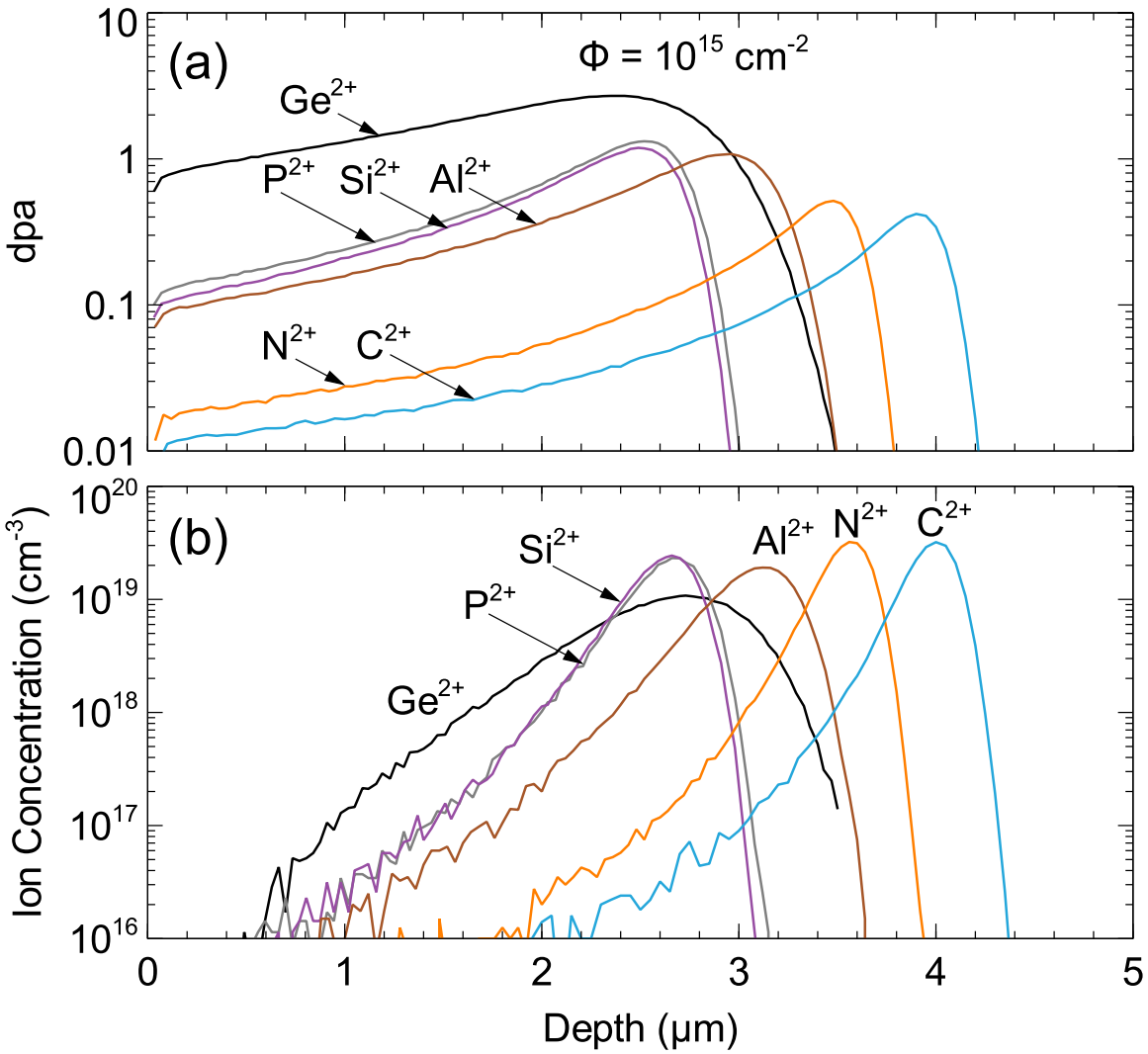
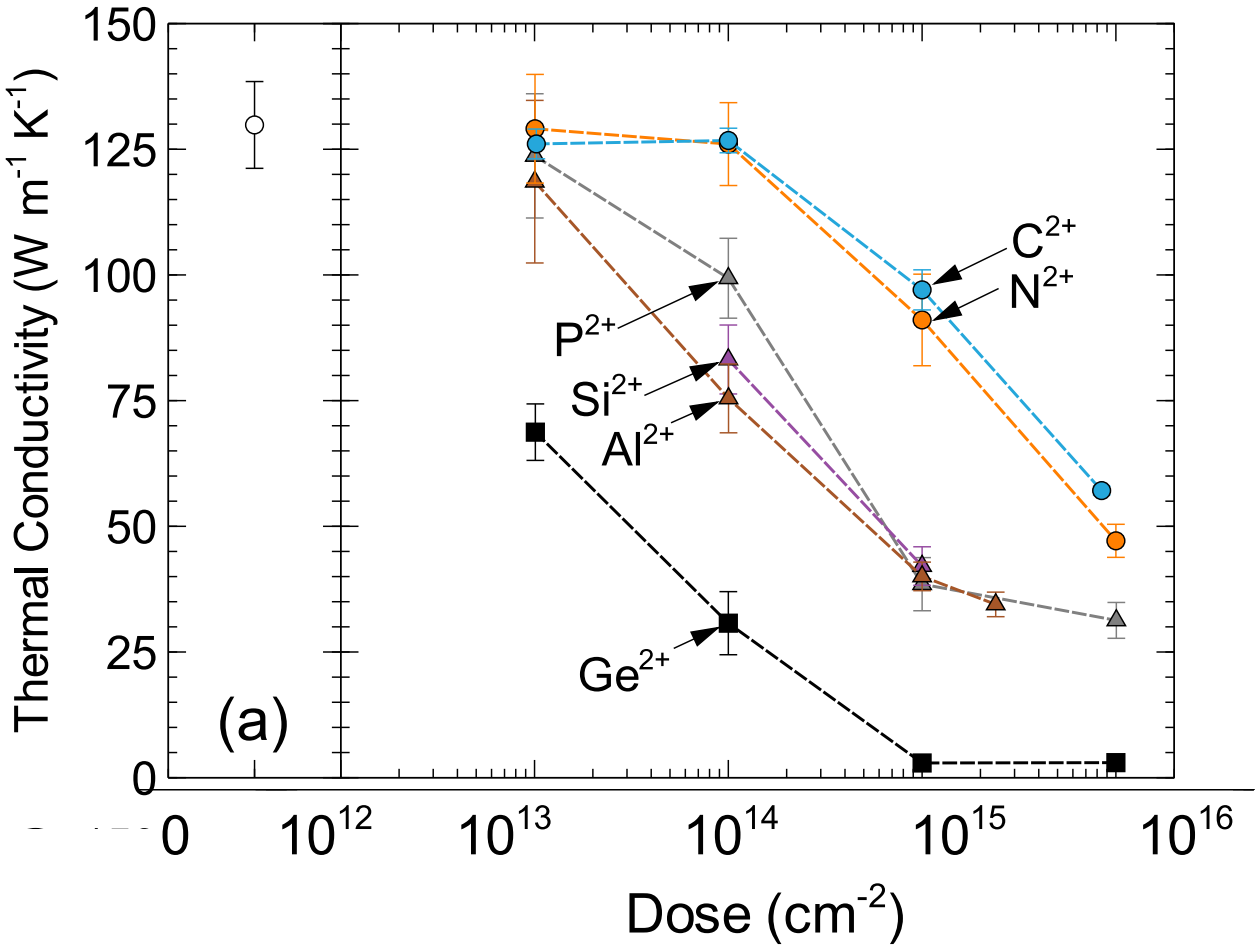
  - Kr^{+} irradiated silicon (*JAP* **132**, 075112)
- Ultrahigh temperature thermometry for measuring nuclear materials up to and through their melting points (*PRL* **132**, 146303)

Thermal conductivity reduction in irradiated silicon





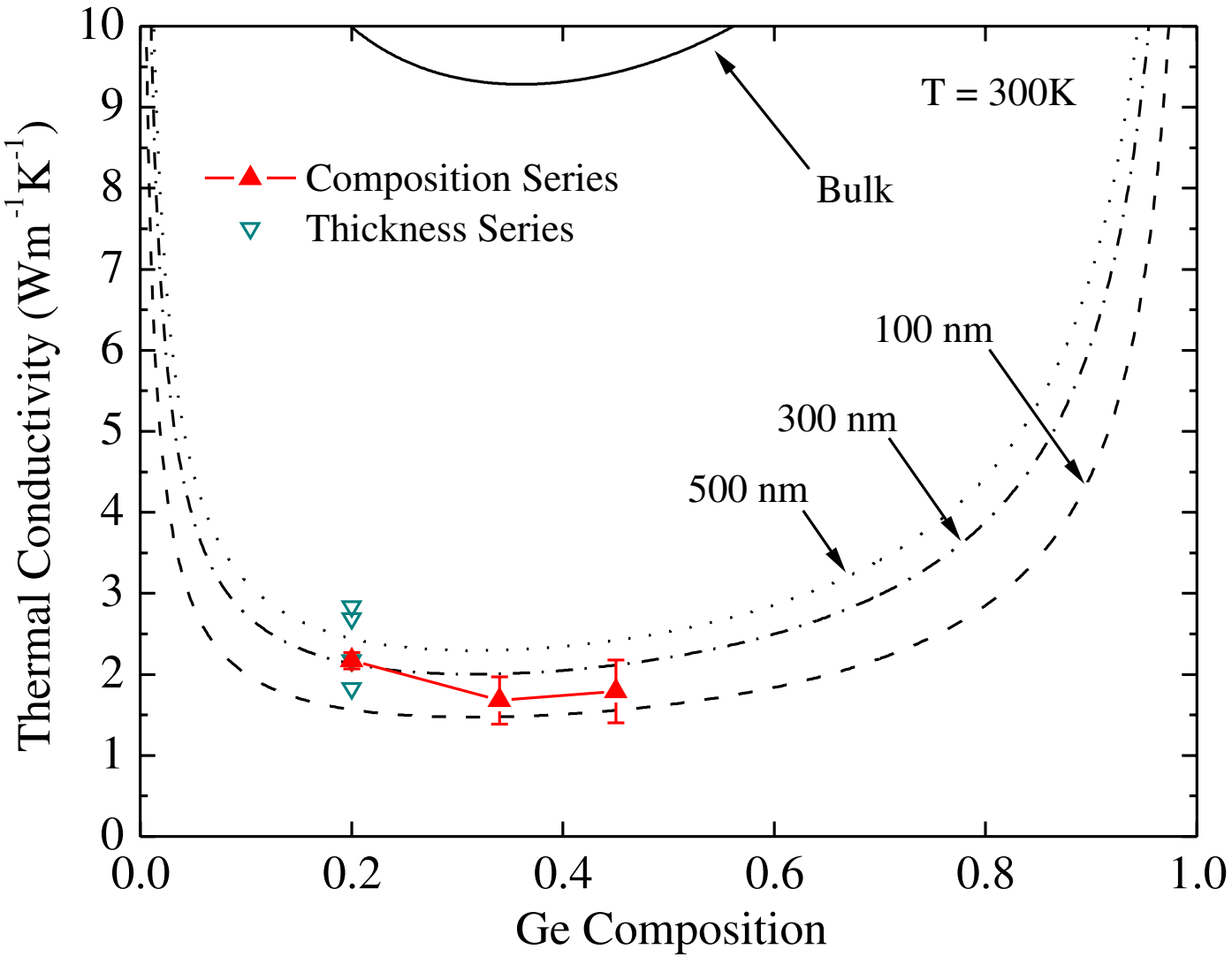
PRB **104,** 134306

Phonon scattering with impurities

$$\kappa = \frac{1}{3} C v \lambda$$

$$\frac{1}{\lambda} = \frac{1}{\lambda_{\text{intrinsic}}} + \frac{1}{\lambda_{\text{defect}}}$$

$$\frac{1}{\lambda_{\text{defect}}} \propto \left(\frac{\Delta M}{M} \right)^2$$



PRL **109,** 195901

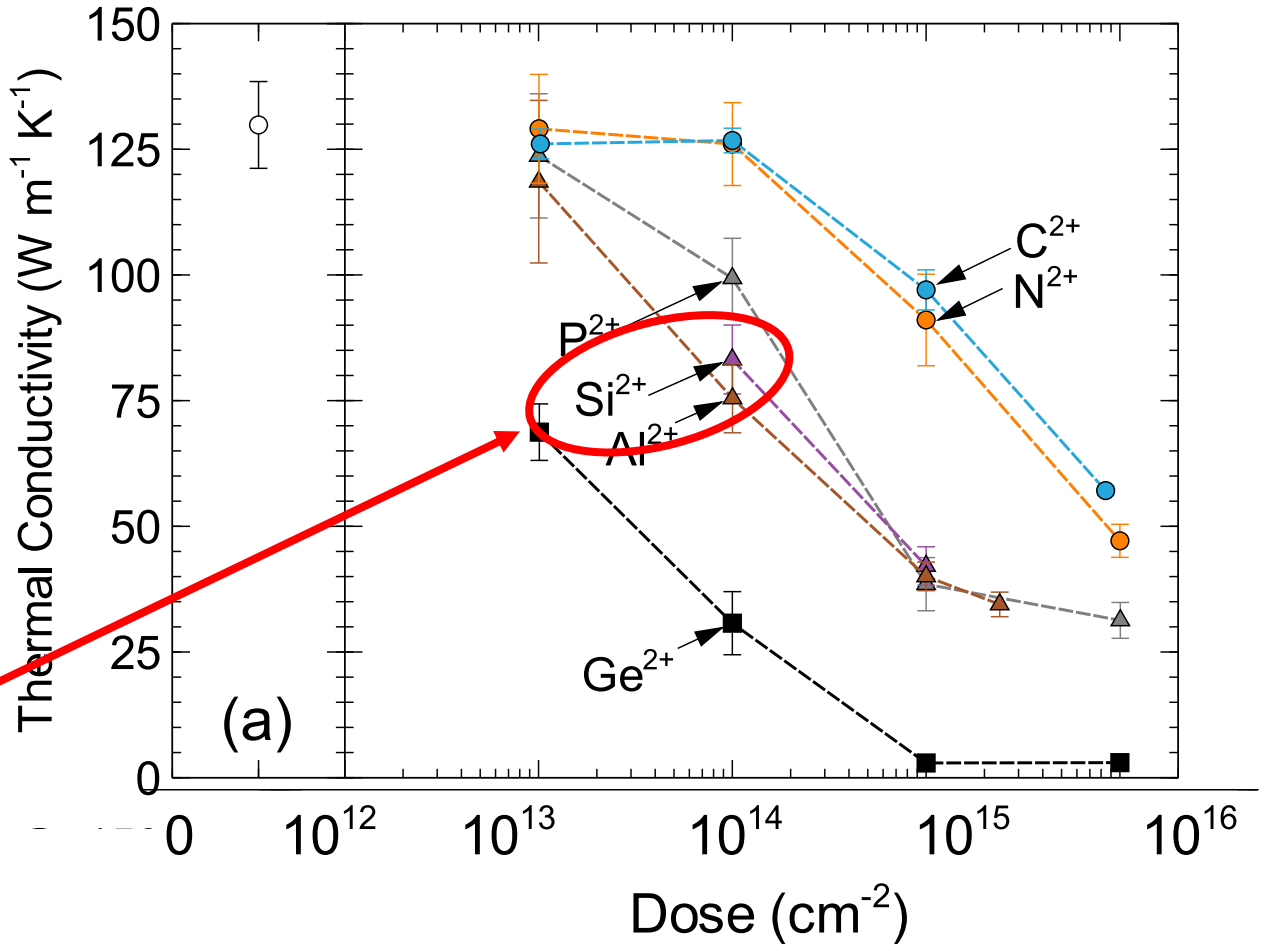
Thermal conductivity reduction in irradiated silicon

$$\kappa = \frac{1}{3} C v \lambda$$

$$\frac{1}{\lambda} = \frac{1}{\lambda_{\text{intrinsic}}} + \frac{1}{\lambda_{\text{defect}}}$$

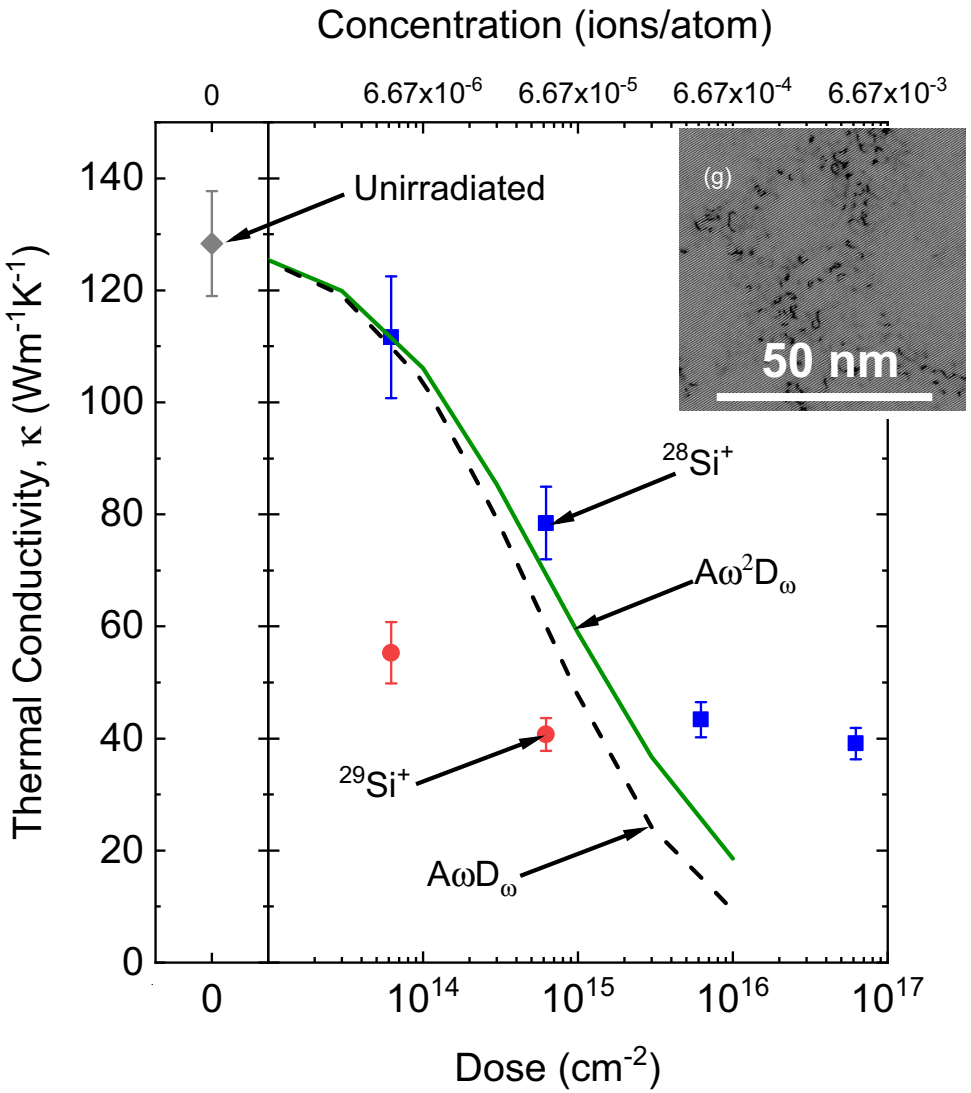
$$\frac{1}{\lambda_{\text{defect}}} \propto \left(\frac{\Delta M}{M} \right)^2$$

ΔM = 0!

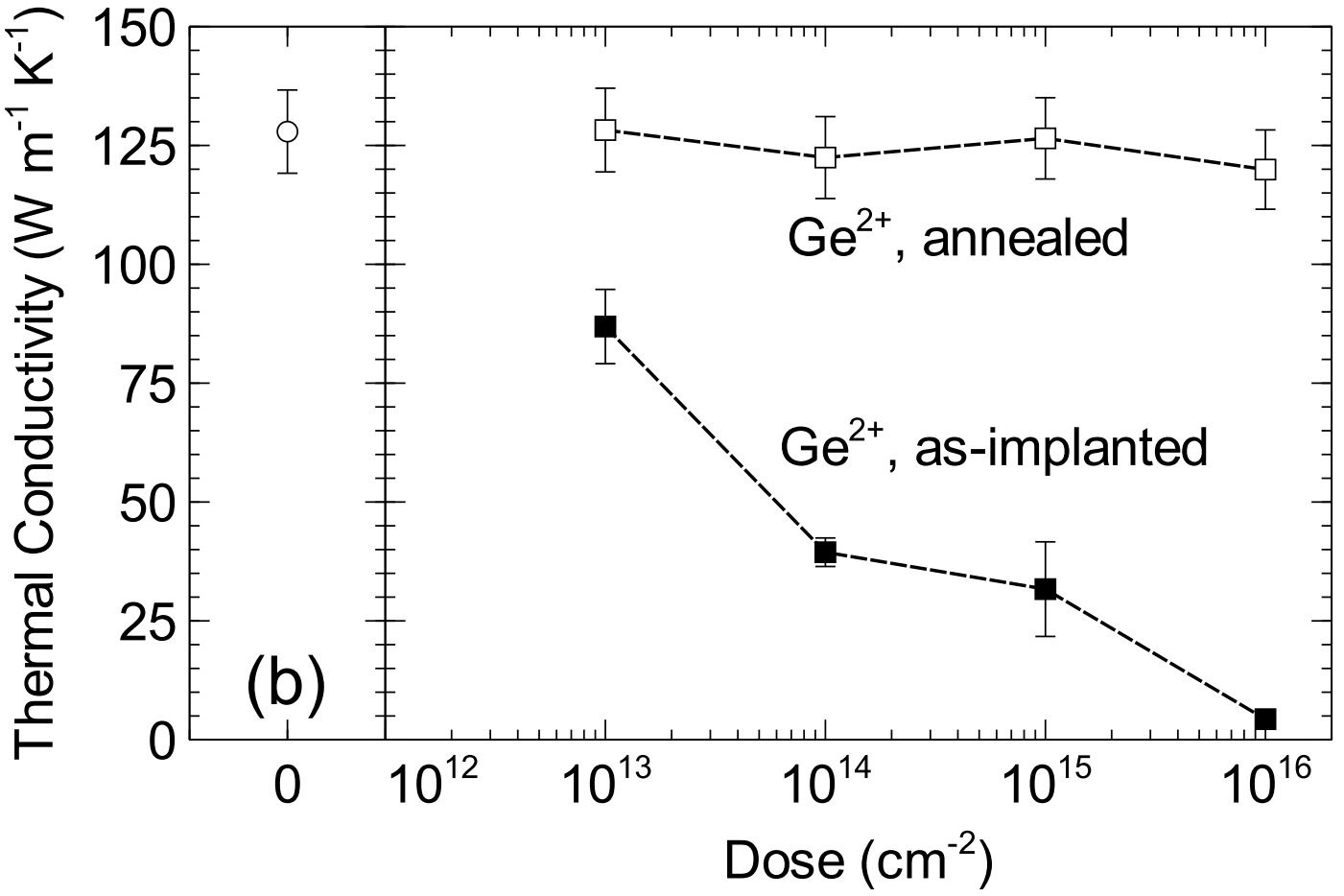


PRB **104,** 134306

It's not the implanted ion, it's the irradiation damage!

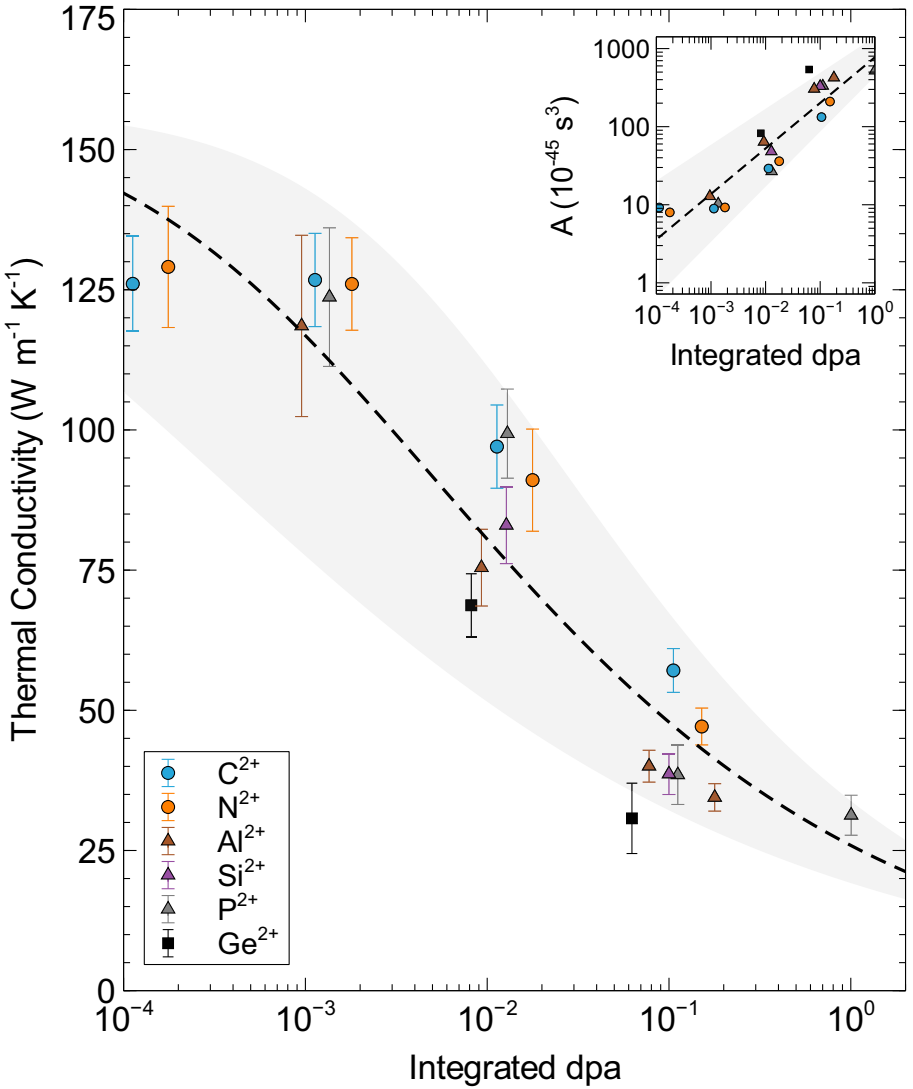


PRM **2,** 095001



PRB **104,** 134306

DPA predictor for κ reduction in irradiated solids



PRB **104,** 134306

Outline

- Length scales of thermal conductivity (κ) measurements and pump-probe thermoreflectance (*JAP* **126**, 150901)
- Displacement damage governs thermal conductivity reduction in irradiated solids (*PRB* 104, 134306)
- **Increasing thermal transport in irradiated solids**
  - **Increasing κ of amorphous carbon (*Nano Lett.* 21, 3935)**
  - **Reducing thermal boundary resistance (*PRB* 109, 165421)**
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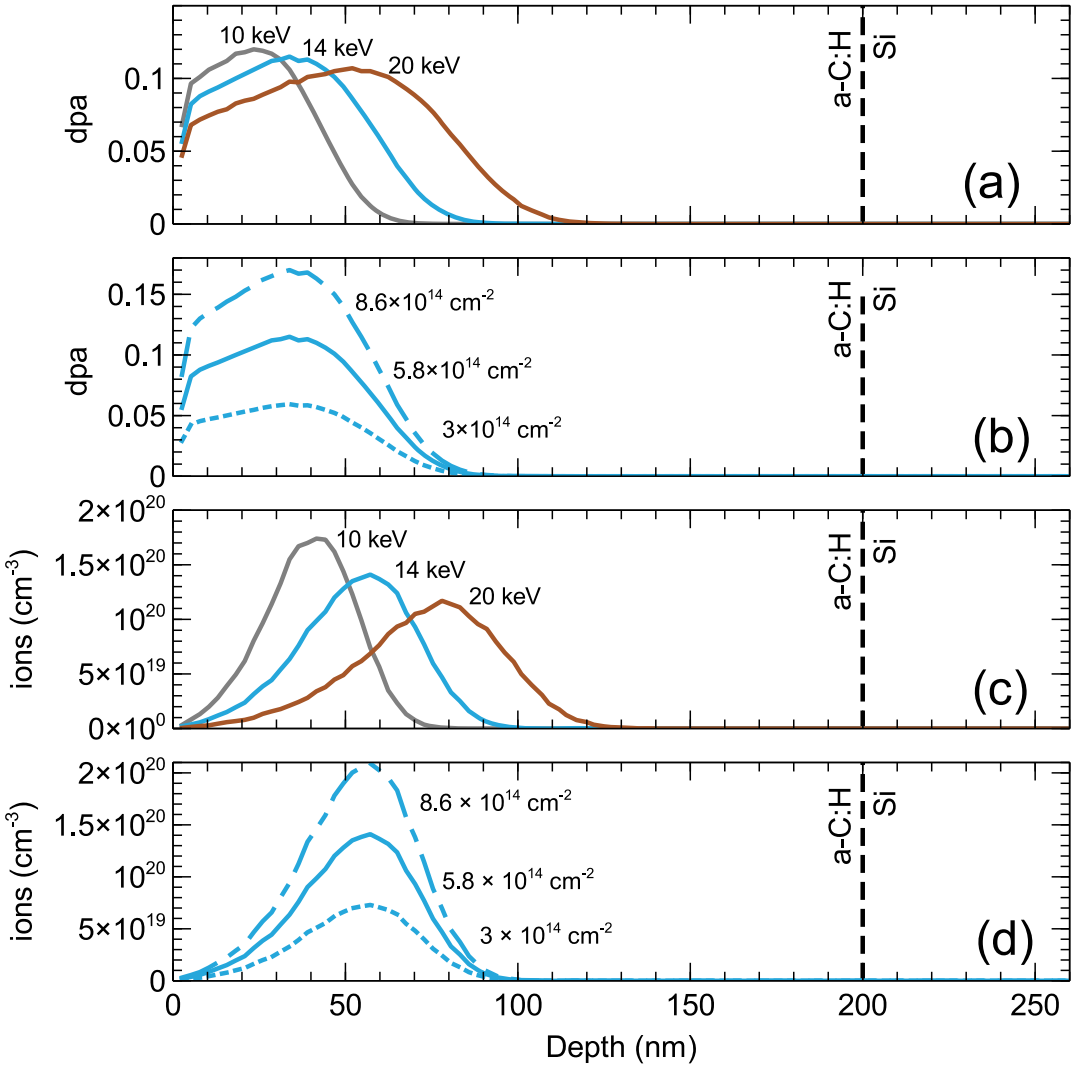
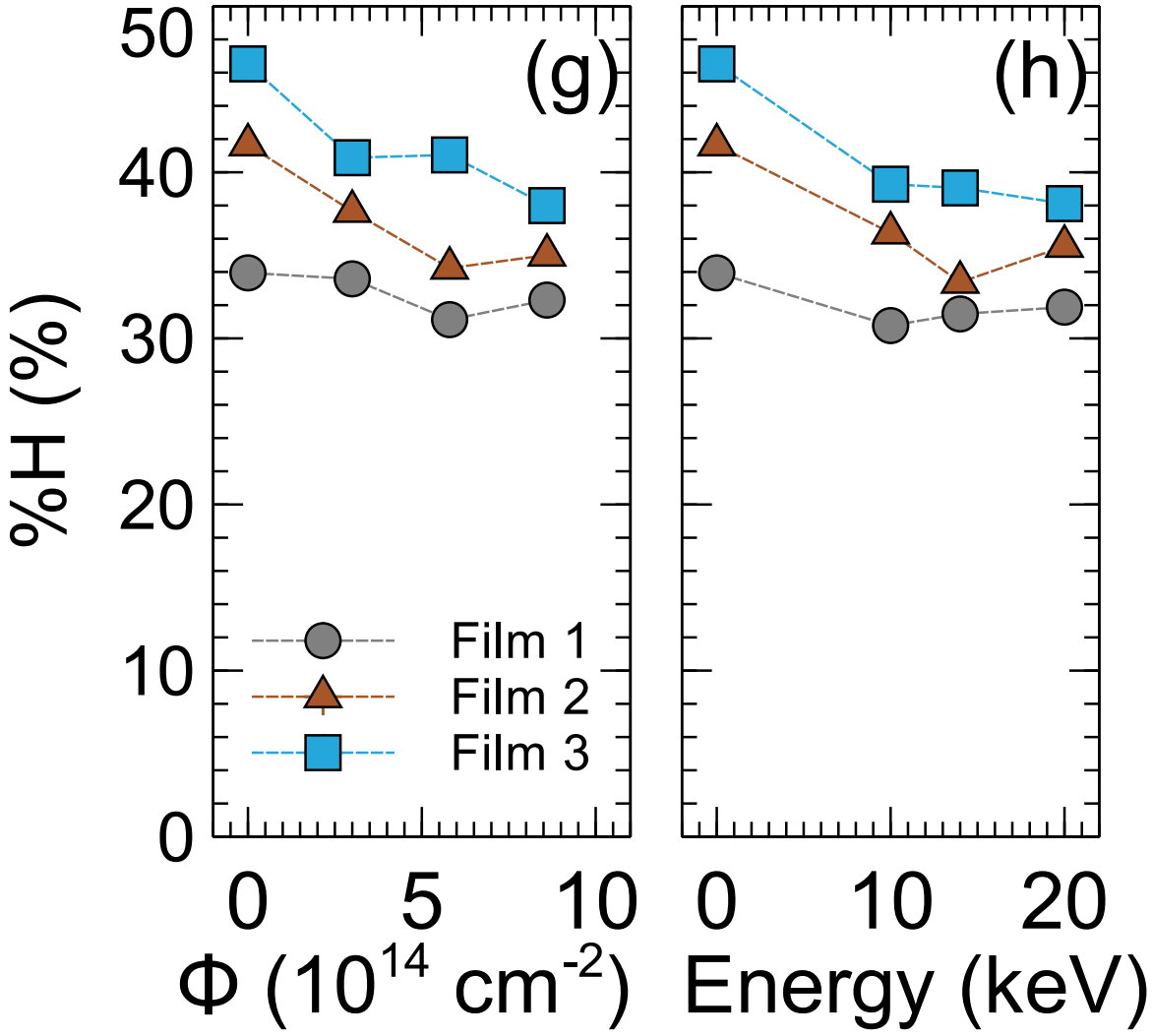
  - N^{3+} implanted diamond (*JAP* **129**, 055307)
  - Kr^{+} irradiated silicon (*JAP* **132**, 075112)
- Ultrahigh temperature thermometry for measuring nuclear materials up to and through their melting points (*PRL* **132**, 146303)

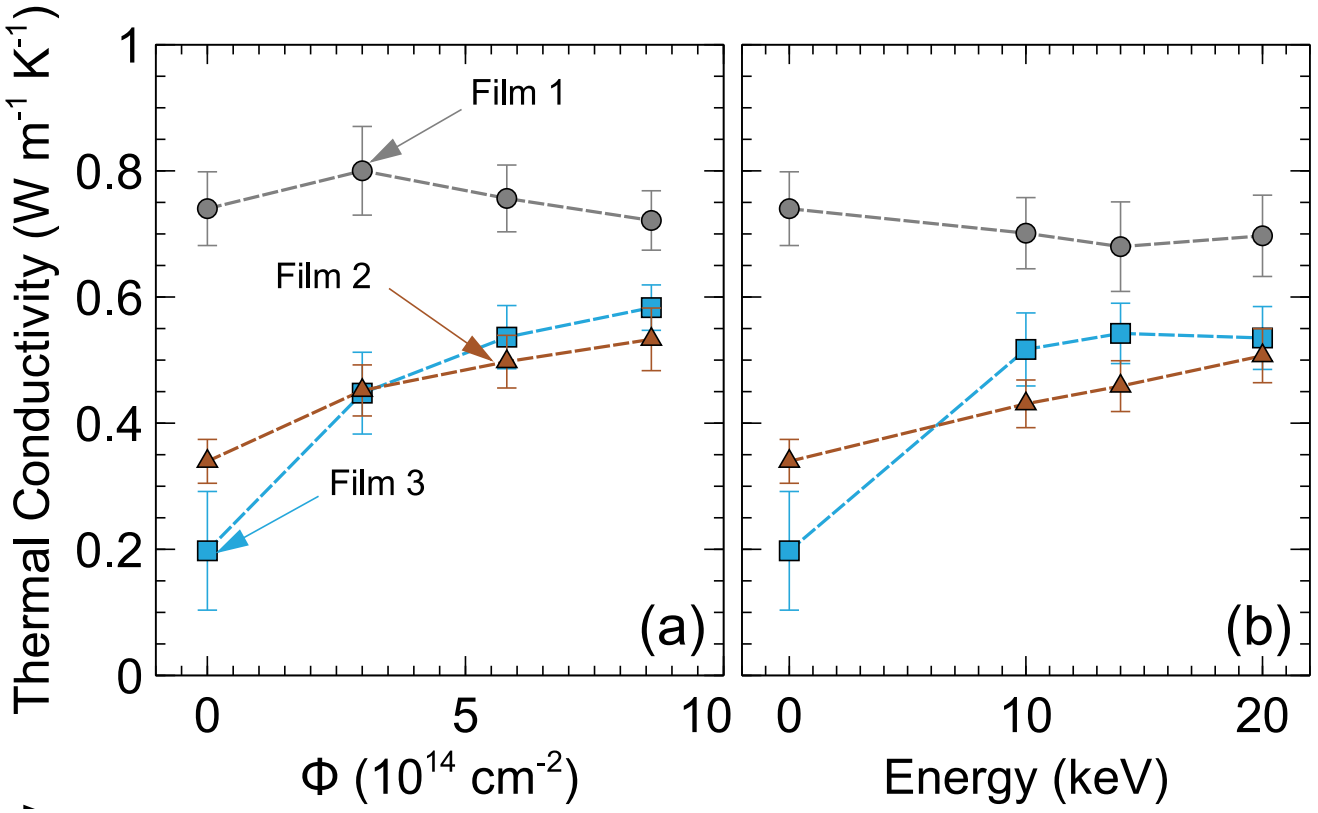
Ion irradiation reduces hydrogen in amorphous carbon

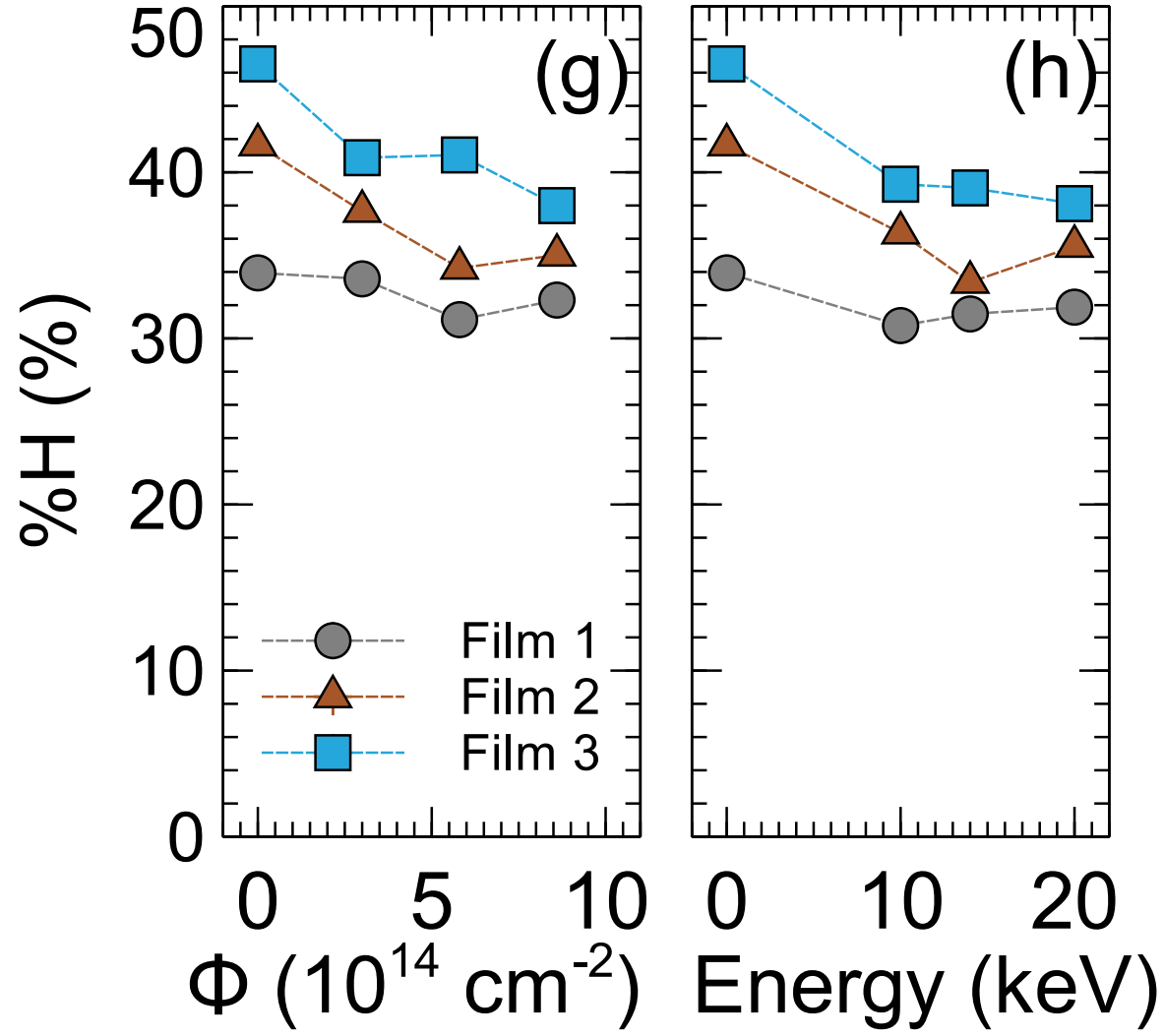




Nano Letters **21,** 3935

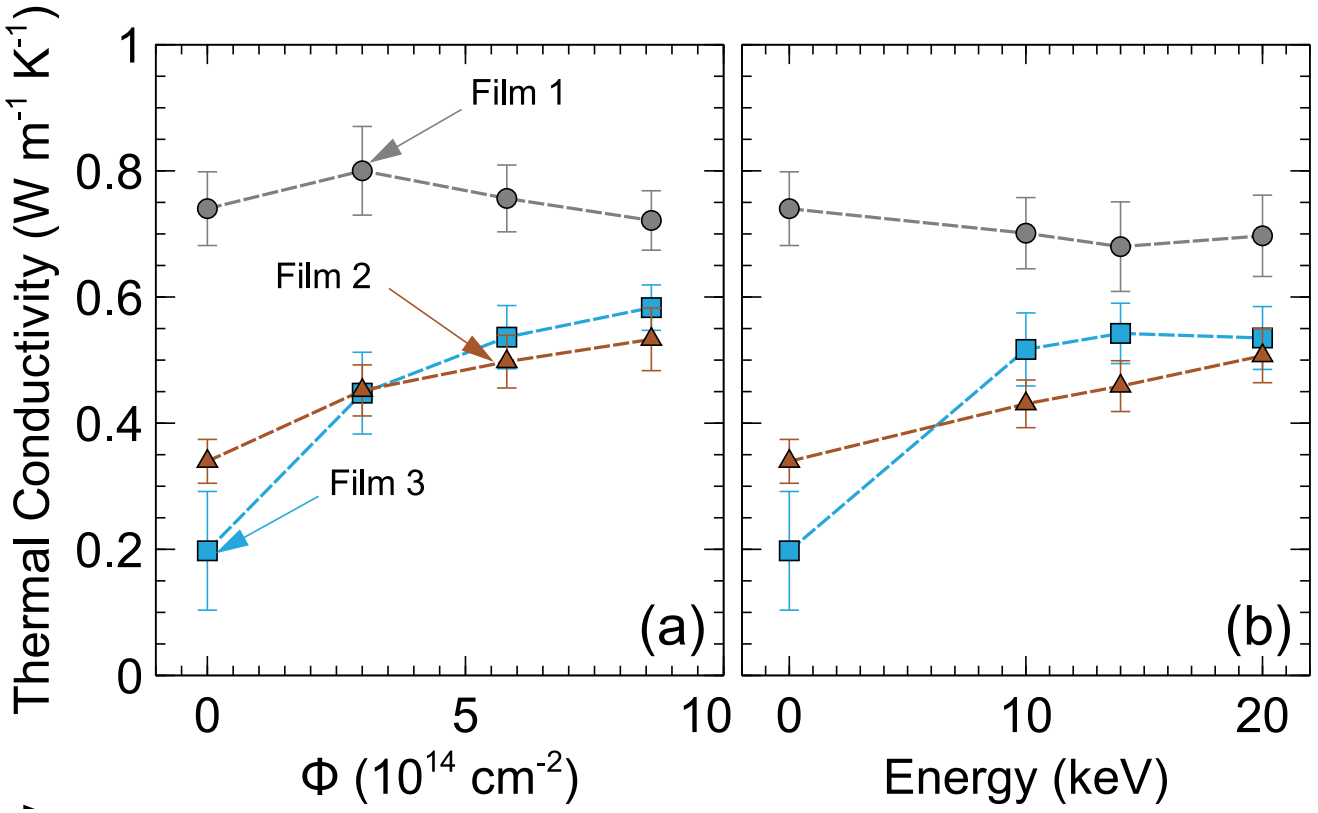
Ion irradiation to increase κ of amorphous carbon





Nano Letters **21,** 3935

Ion irradiation to increase κ of amorphous carbon



Driving out hydrogen leads to:

- Increased density
- Increased stiffness
- Increased carbon connectivity/covalent bonding

APPLIED PHYSICS LETTERS **109**, 191905 (2016)

Breaking network connectivity leads to ultralow thermal conductivities in fully dense amorphous solids

Jeffrey L. Braun,[1] Sean W. King,[2] Ashutosh Giri,[1] John T. Gaskins,[1] Masanori Sato,[3] Takemasa Fujiseki,[3] Hiroyuki Fujiwara,[3] and Patrick E. Hopkins[1,a)]

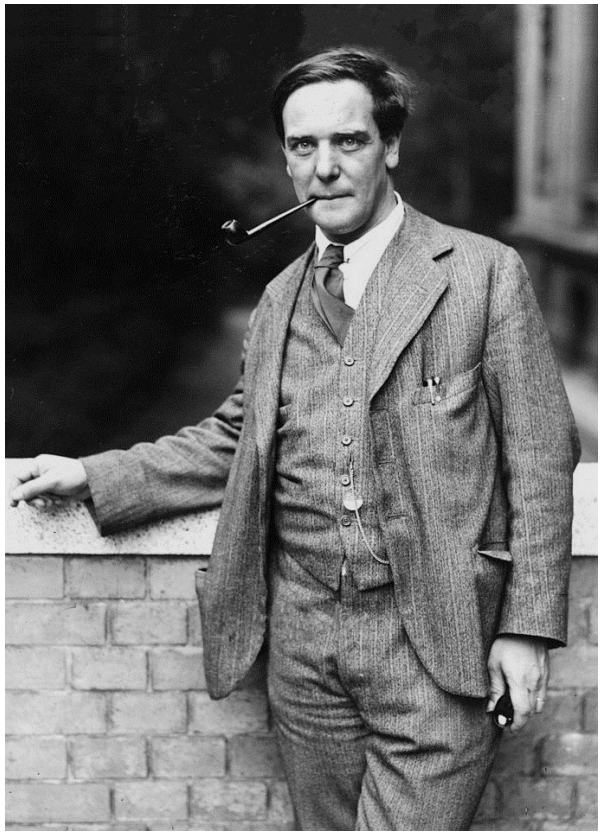
PHYSICAL REVIEW MATERIALS **5**, 035604 (2021)

Hydrogen effects on the thermal conductivity of delocalized vibrational modes in amorphous silicon nitride (*a*-SiN $_x$:H)

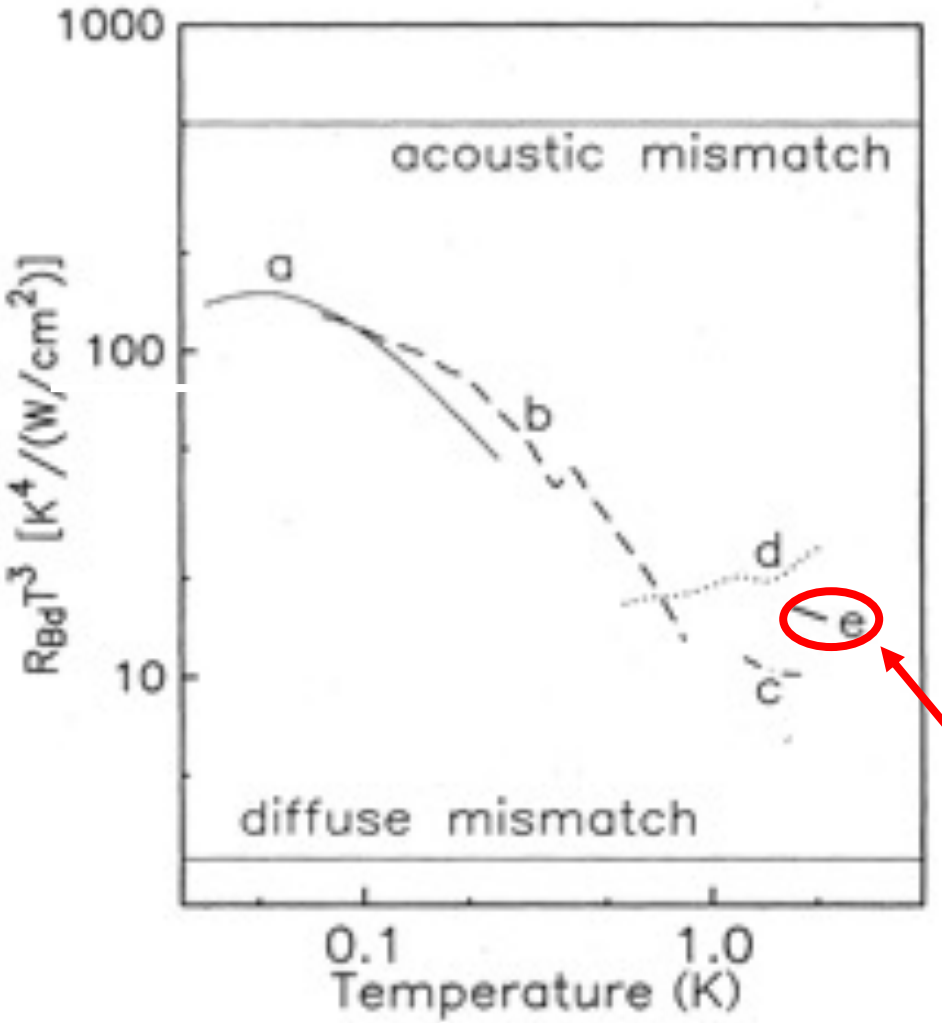
Jeffrey L. Braun,[1] Sean W. King,[2,*] Eric R. Hoglund,[3] Mehrdad Abbasi Gharacheh,[4] Ethan A. Scott,[1] Ashutosh Giri,[1,5] John A. Tomko,[3] John T. Gaskins,[1] Ahmad Al-kukhun,[2] Gyanendra Bhattarai,[6] Michelle M. Paquette,[6] Georges Chollon,[7] Benjamin Willey,[8] G. Andrew Antonelli,[8] David W. Gidley,[9] Jinwoo Hwang,[4] James M. Howe,[3] and Patrick E. Hopkins[1,3,10,†]

Nano Letters **21**, 3935

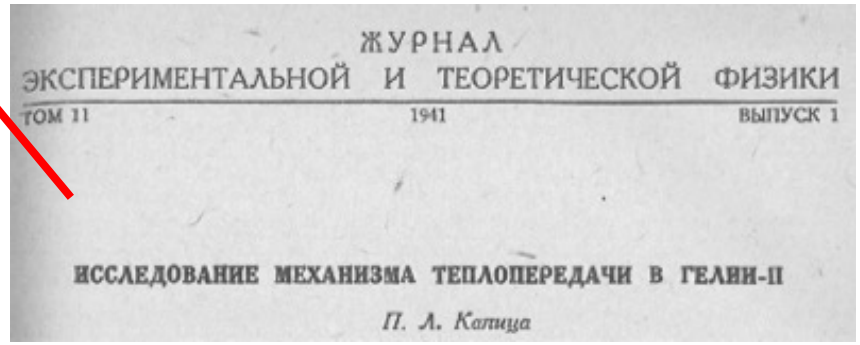
Thermal boundary resistance



Pyotr Kapitsa



Plot from Fig. 1 in Swartz and Pohl, "Thermal boundary resistance," *Rev. Mod. Phys.* **61**, 605 (1989)

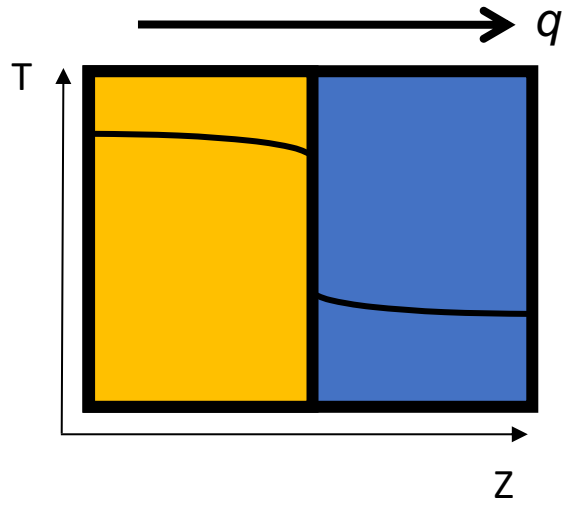

ЖУРНАЛ
ЭКСПЕРИМЕНТАЛЬНОЙ И ТЕОРЕТИЧЕСКОЙ ФИЗИКИ
ТОМ 11 1941 ВЫПУСК 1

ИССЛЕДОВАНИЕ МЕХАНИЗМА ТЕПЛОПЕРЕДАЧИ В ГЕЛИИ-II

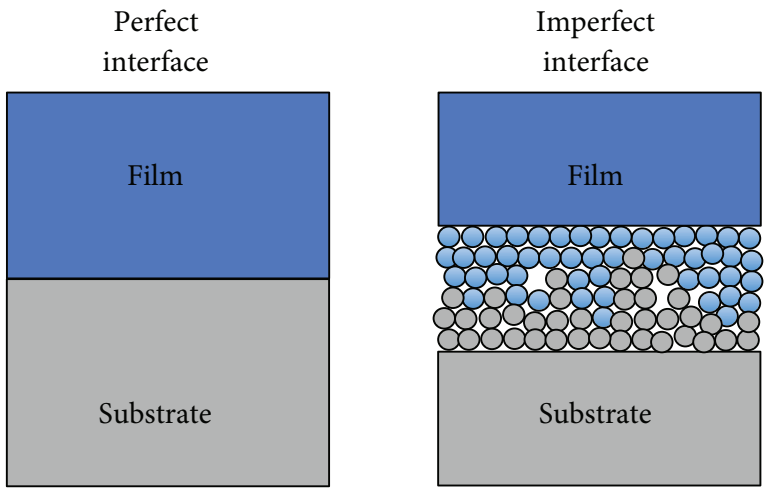
П. Л. Капица

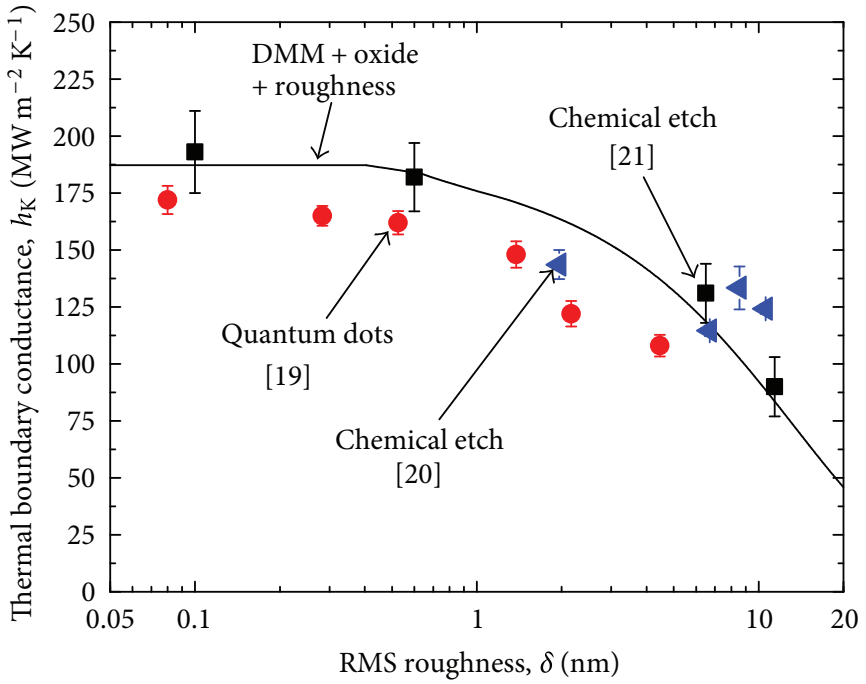
P. L. Kapitza. The study of heat transfer in helium II. Zhurnal eksperimentalnoi i teoreticheskoi fiziki, 11:1–31, 1941.

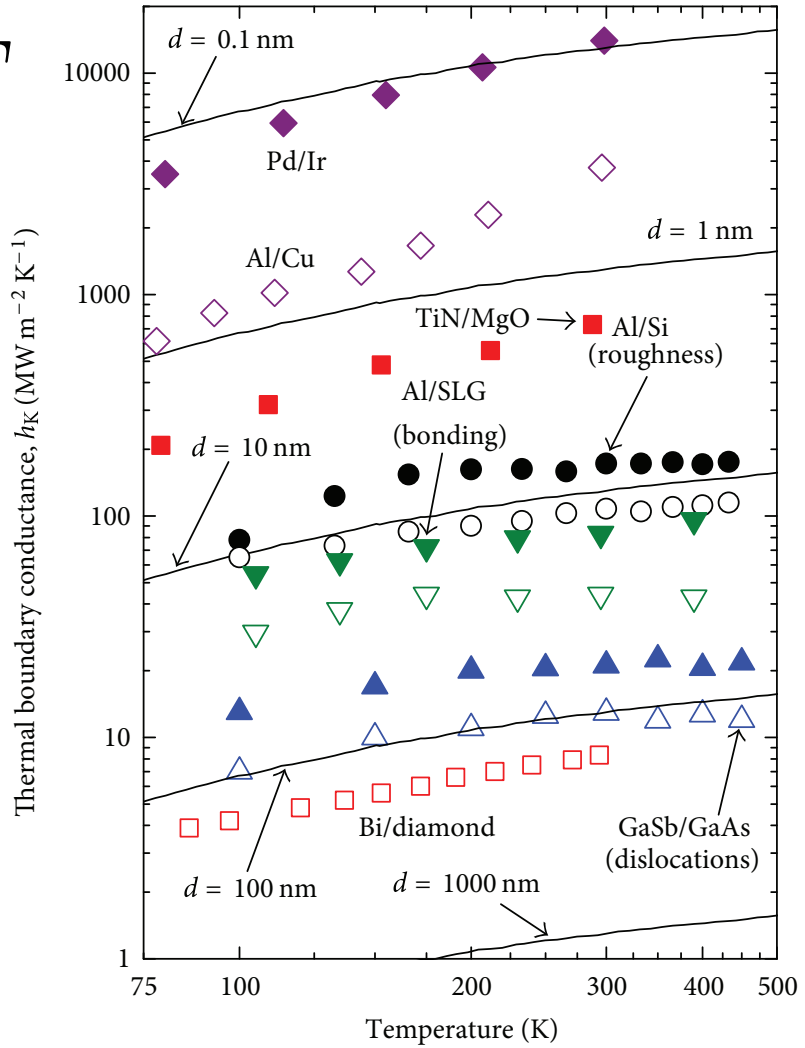
Thermal boundary resistance: increased with defects



$$q = h_K \Delta T = \frac{1}{R_K} \Delta T$$

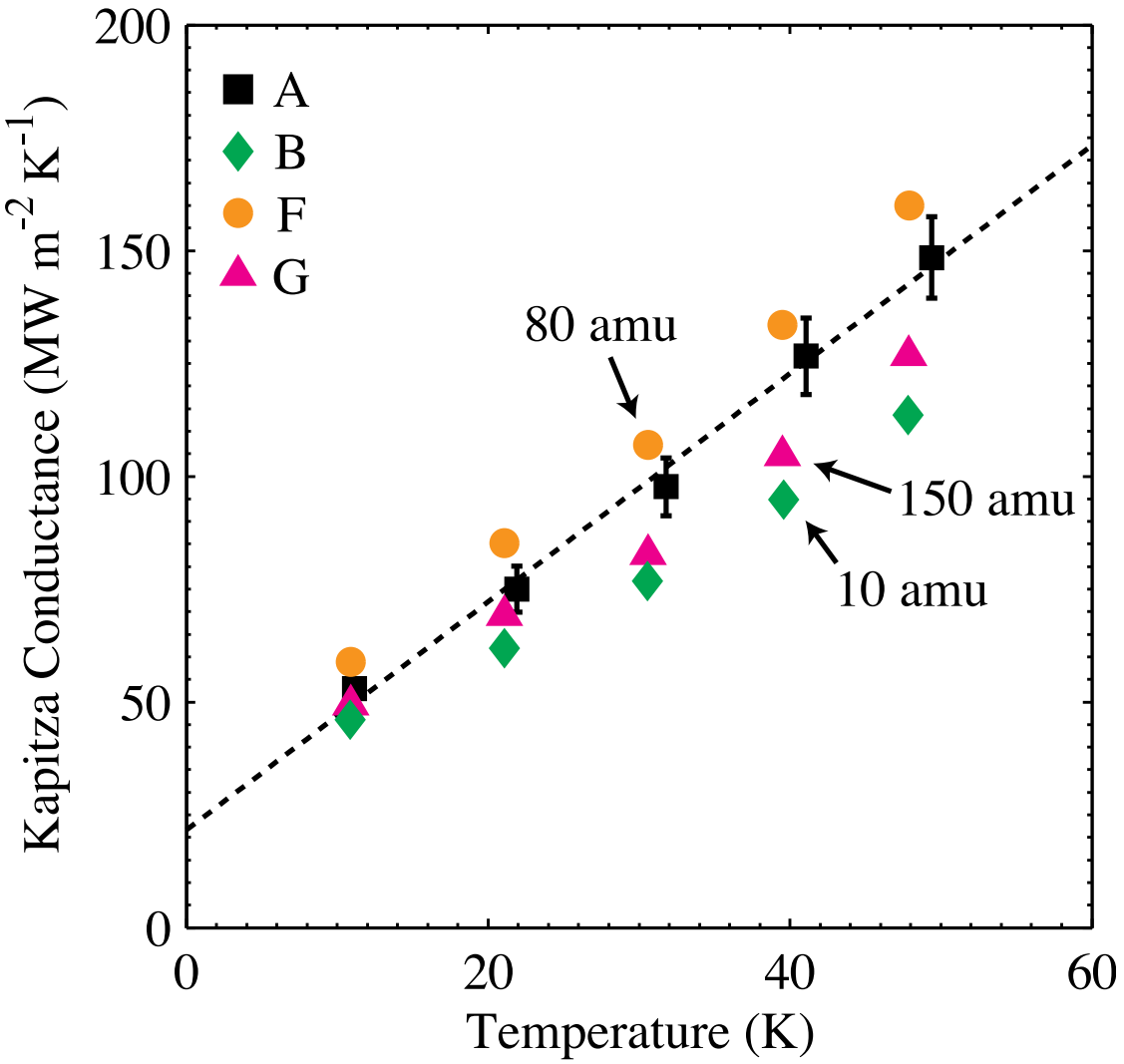


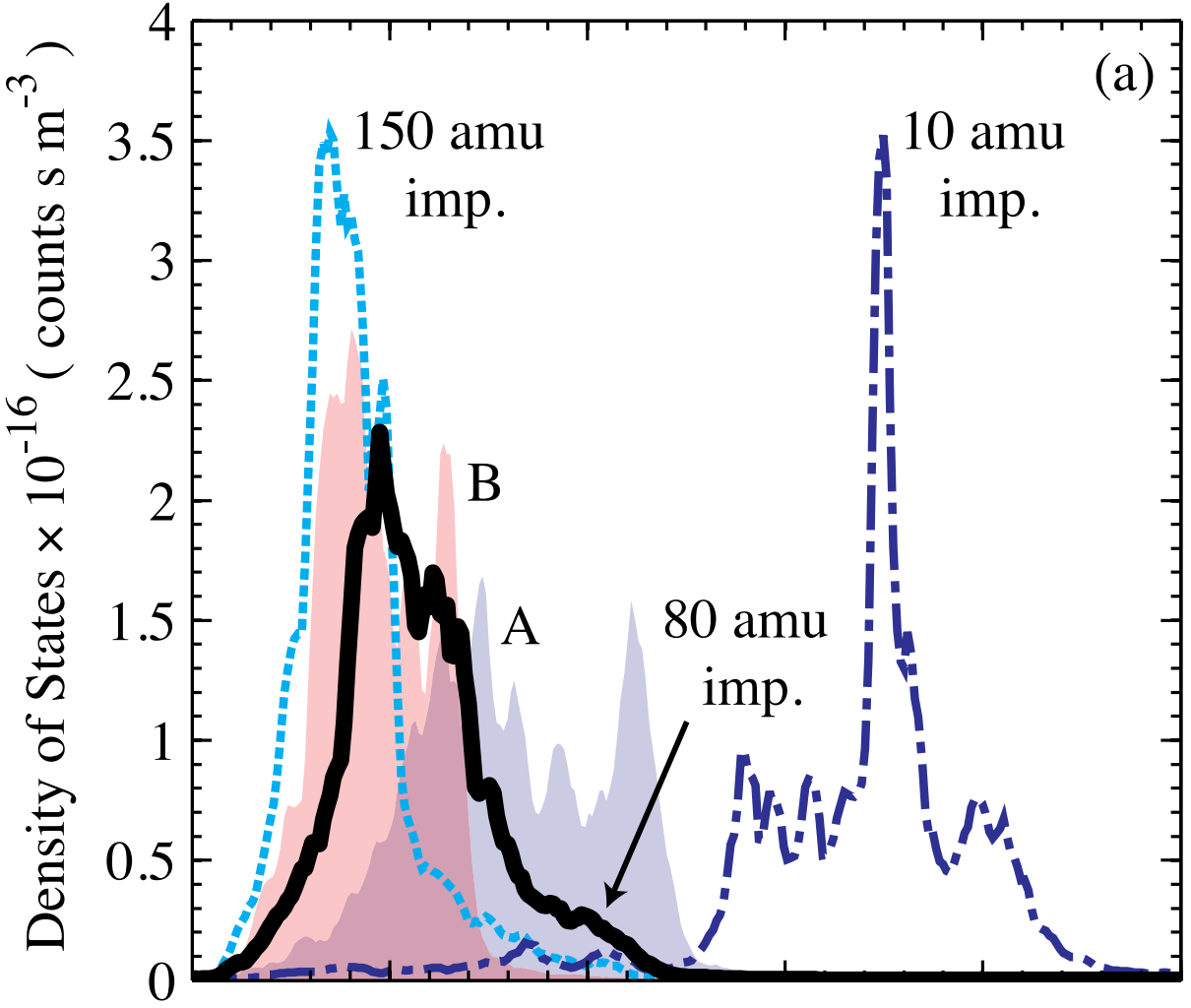




Hopkins *ISRN Mech. Eng.* **2013** 682586 (2013)

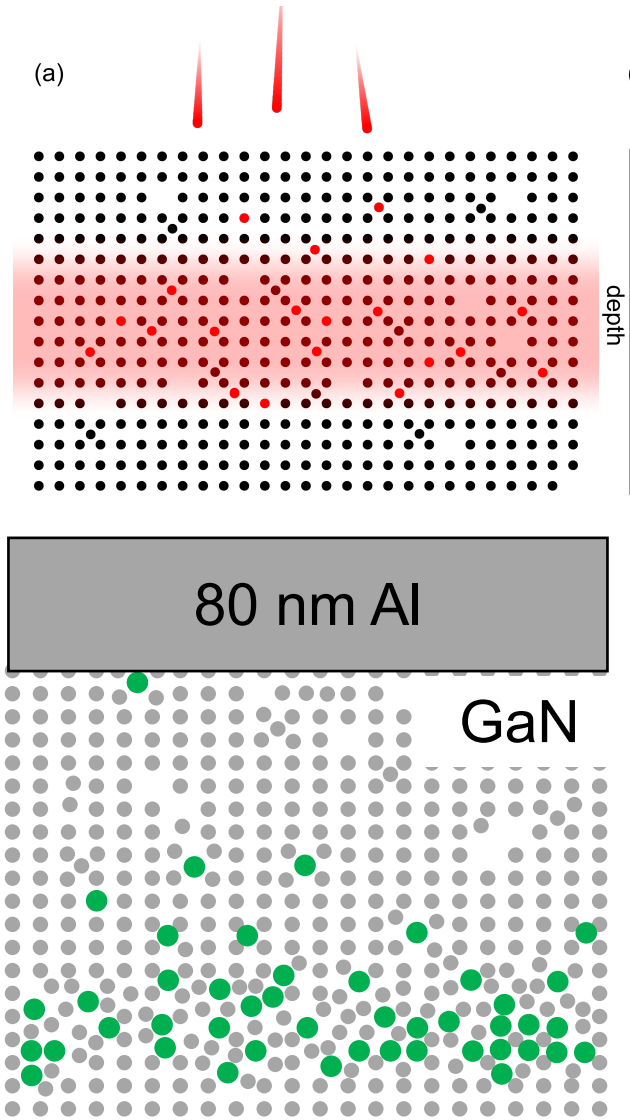
Decreasing TBR with defects



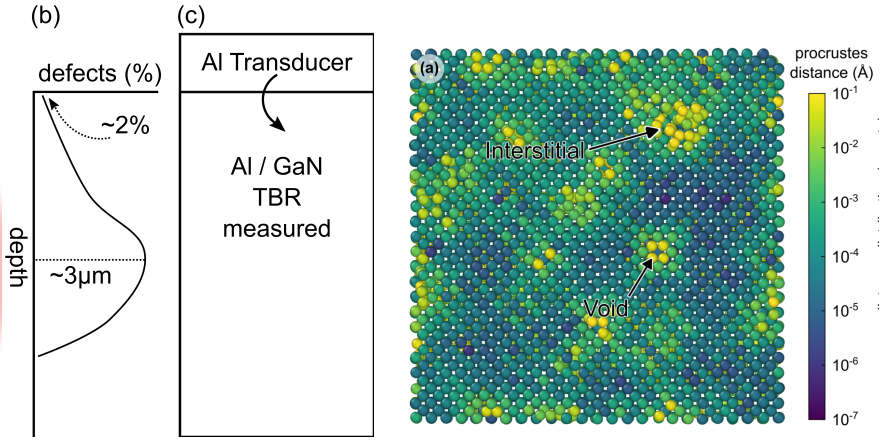


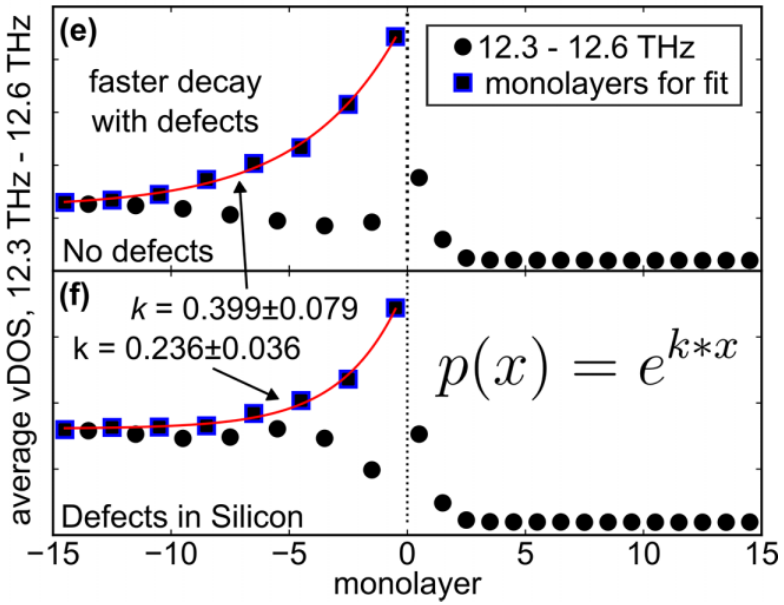
JAP **112** 073519

Irradiation-induced defects reduce TBR at Al/GaN interfaces

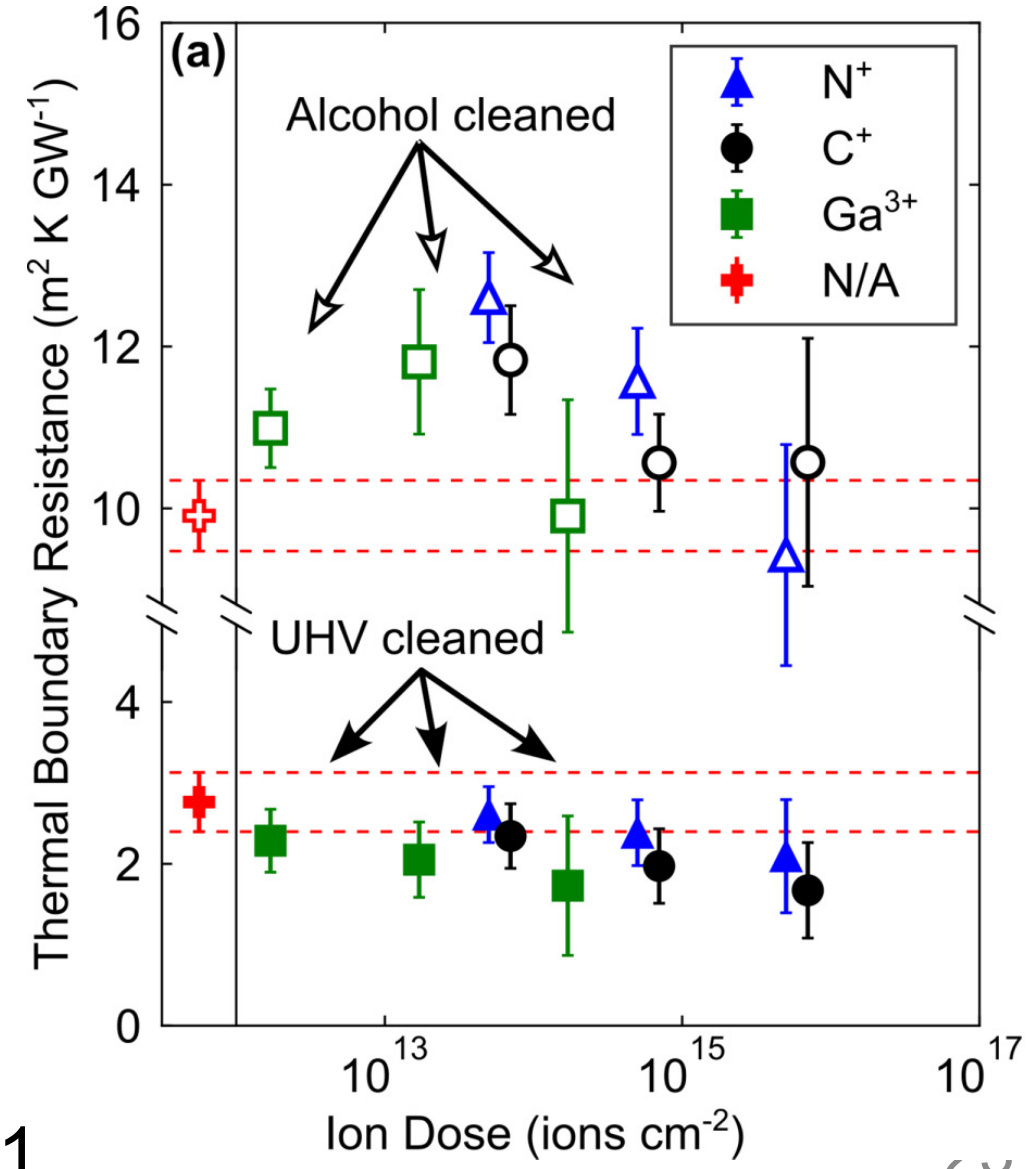


400 keV He+ implants:
end of range dep





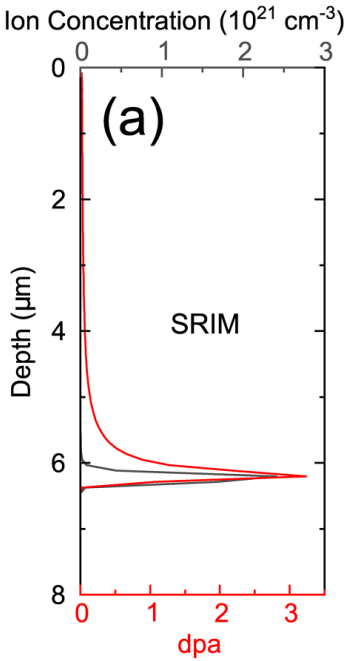
PRB **109** 165421

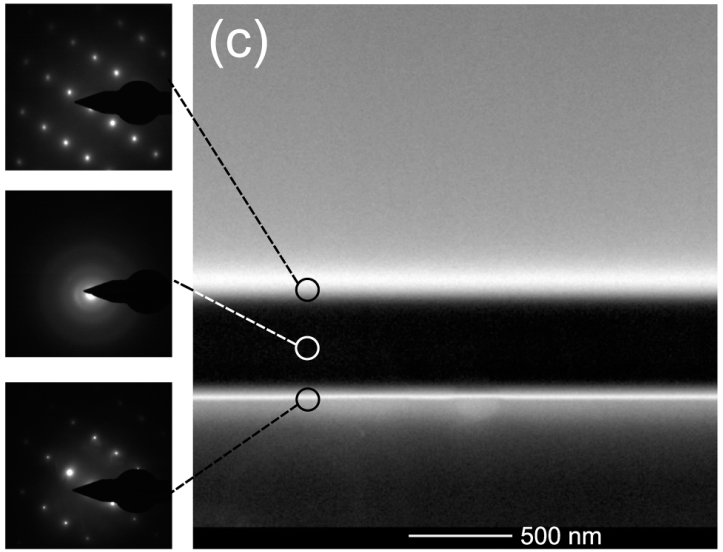


Outline

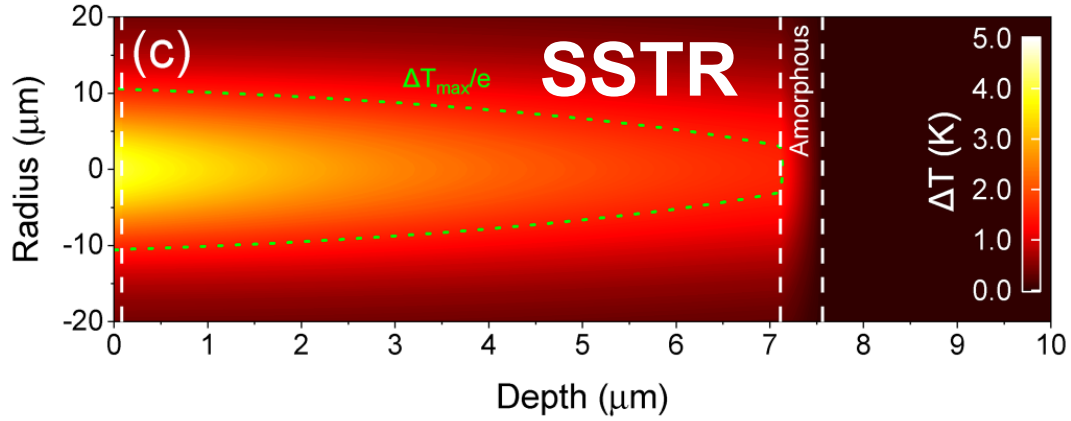
- Length scales of thermal conductivity (κ) measurements and pump-probe thermoreflectance (*JAP* **126**, 150901)
- Displacement damage governs thermal conductivity reduction in irradiated solids (*PRB* 104, 134306)
- Increasing thermal transport in irradiated solids
  - Increasing κ of amorphous carbon (*Nano Lett*. 21, 3935)
  - Reducing thermal boundary resistance (*PRB* 109, 165421)
- **Sub-surface thermal conductivity depth profiling of irradiated solids**
  - **N^{3+} implanted diamond (*JAP* 129, 055307)**
  - **Kr^{+} irradiated silicon (*JAP* 132, 075112)**
- Ultrahigh temperature thermometry for measuring nuclear materials up to and through their melting points (*PRL* **132**, 146303)

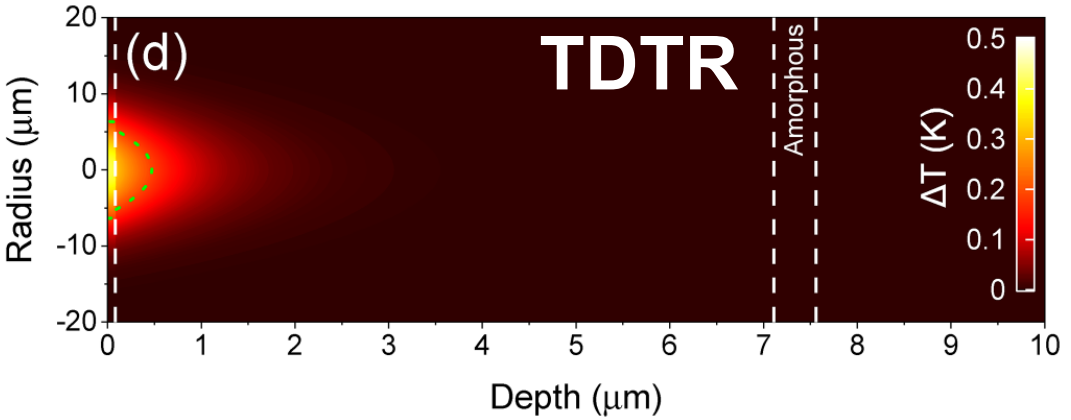
Sub-surface thermal resistances induced from ion damage



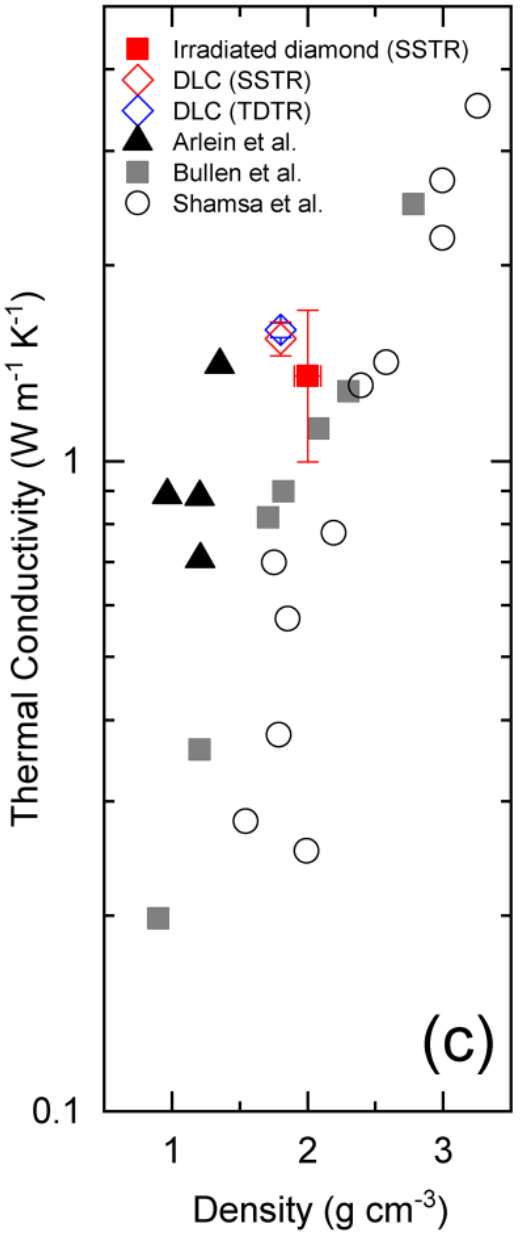


N^{3+} implanted diamond

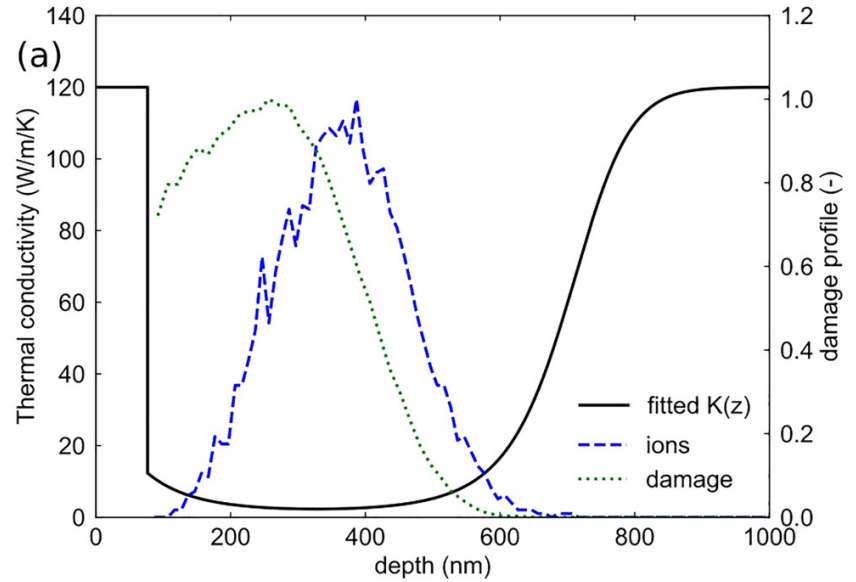




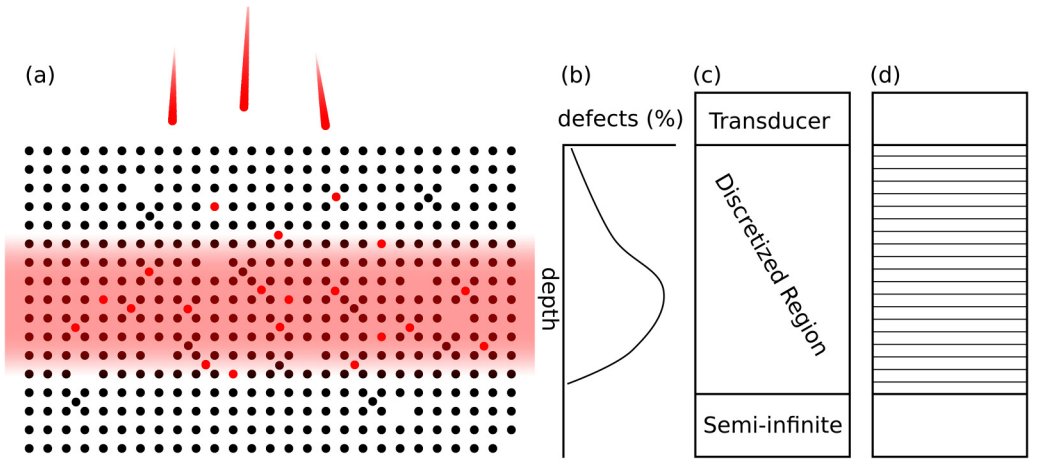
JAP **129** 055307

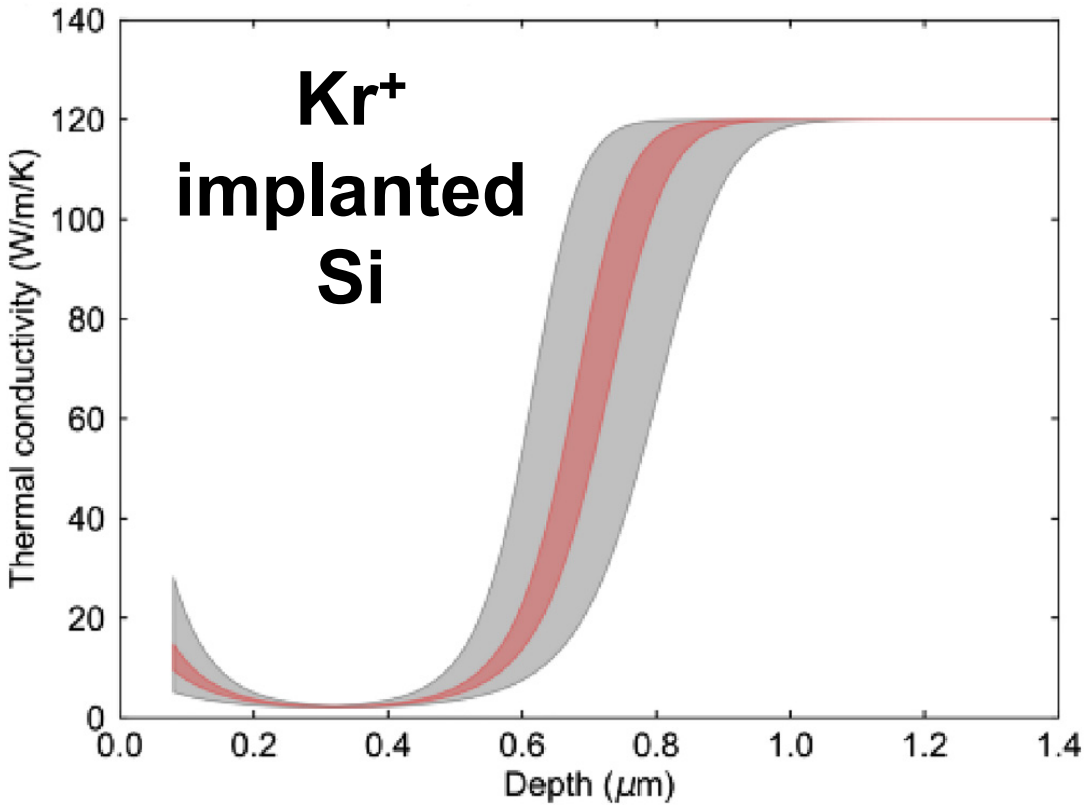


Depth profiling thermal conductivity of ion irradiated solids



JAP **132** 075112





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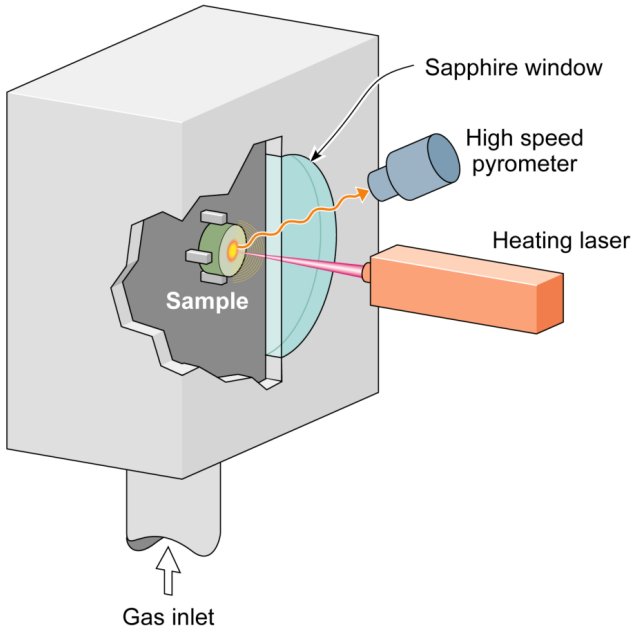
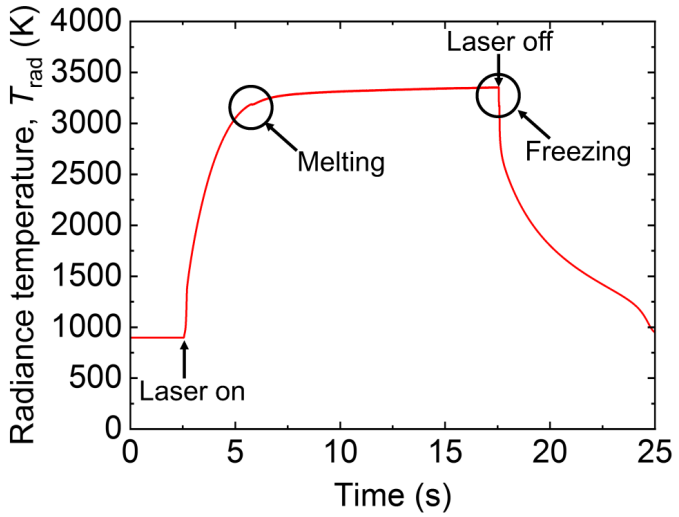
Measurement of thermal properties at ultrahigh temperatures

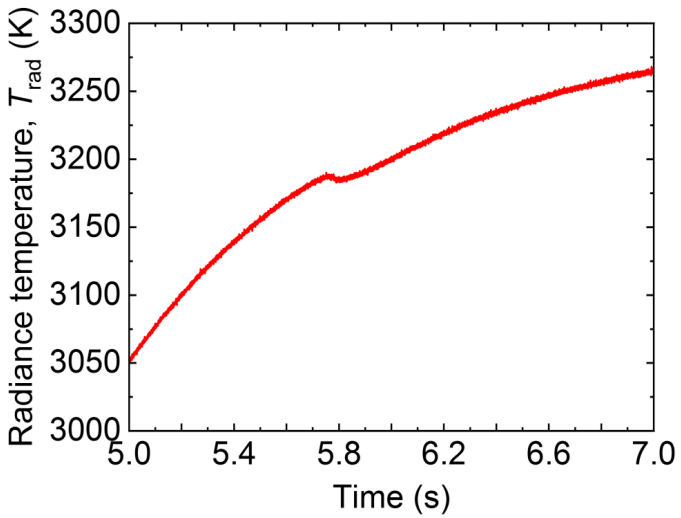
(a)



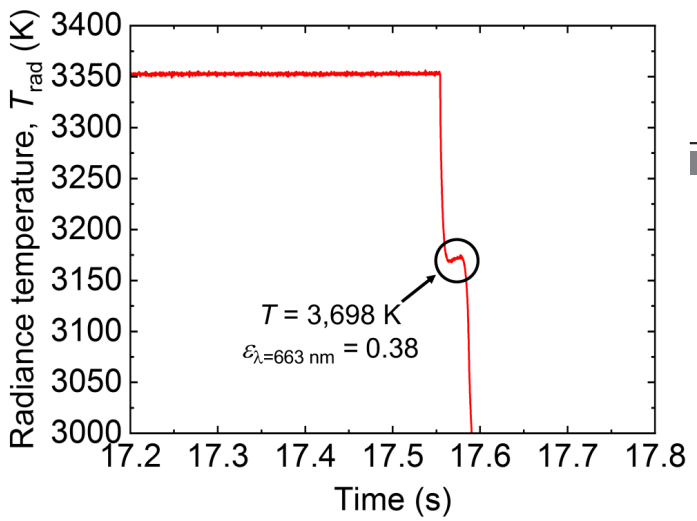
(b)



(c)



(d)



Joint Research Centre

JRC

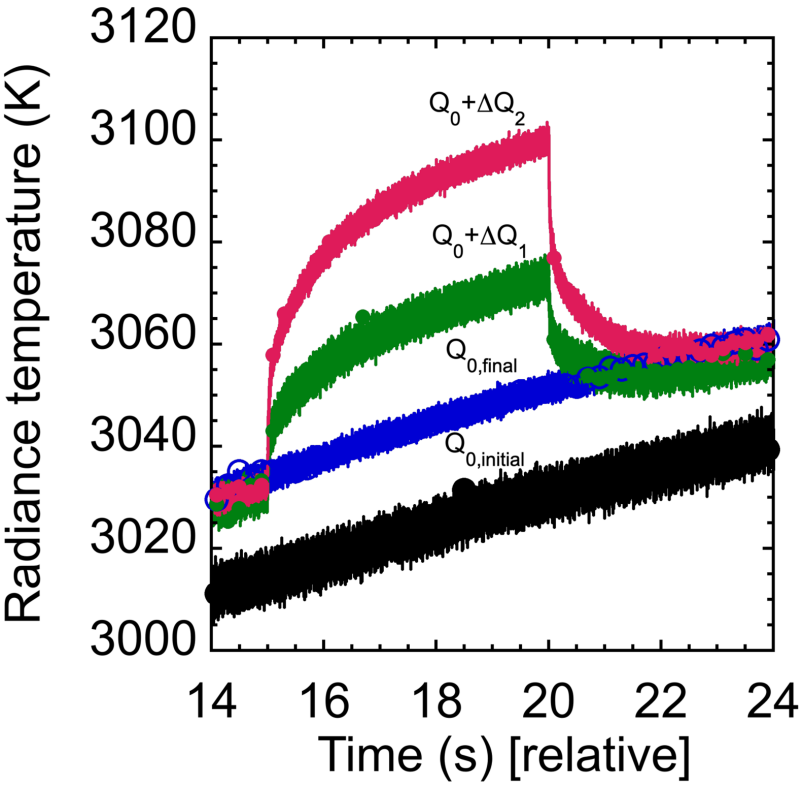
PHYSICAL REVIEW LETTERS **132,** 146303 (2024)

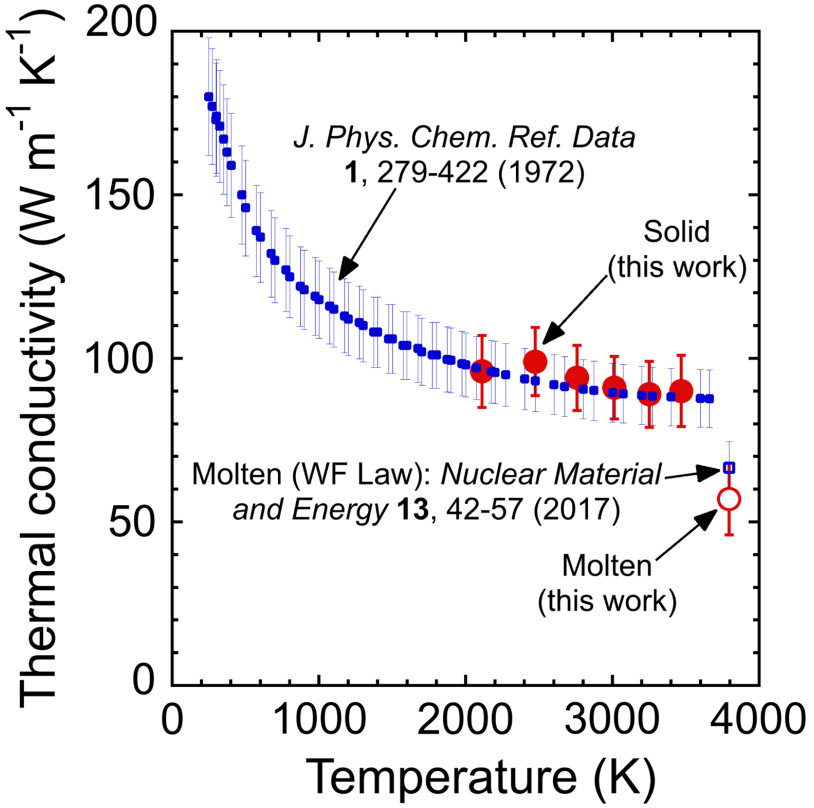
Editors' Suggestion | Featured in Physics

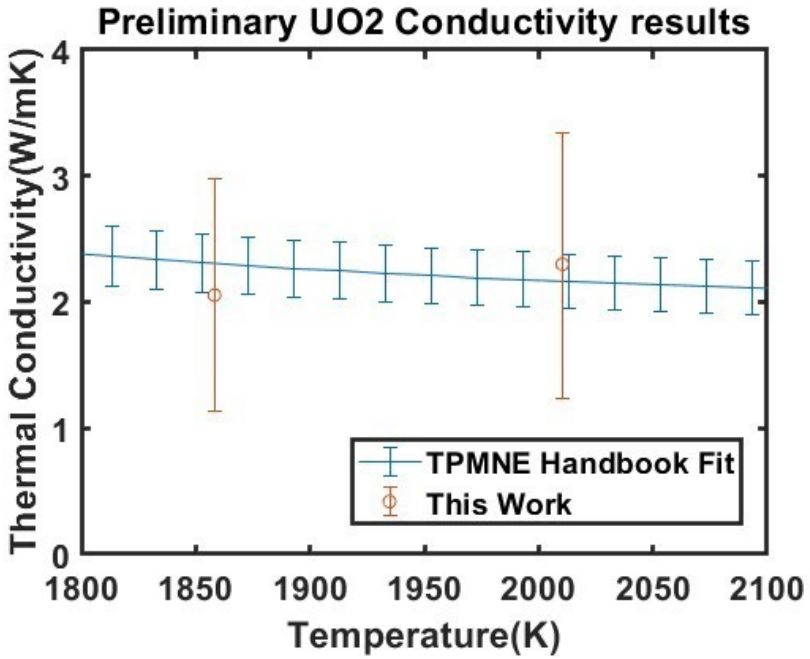
Validation of the Wiedemann-Franz Law in Solid and Molten Tungsten above 2000 K through Thermal Conductivity Measurements via Steady-State Temperature Differential Radiometry

Milena Milich,[1,*] Hunter B. Schonfeld,[1,*] Konstantinos Boboridis,[2] Davide Robba,[2] Luka Vlahovic,[2] Rudy J. M. Konings,[2,†] Jeffrey L. Braun,[3] John T. Gaskins,[3] Niraj Bhatt,[4] Ashutosh Giri,[4] and Patrick E. Hopkins[1,2,5,6,‡]

Measurement of thermal properties at ultrahigh temperatures







PRL **132** 146303

Thanks!

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Prof. Khalid Hattar
(U. Tennessee)

Collaborators

- King (Intel)
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- Giri (URI)