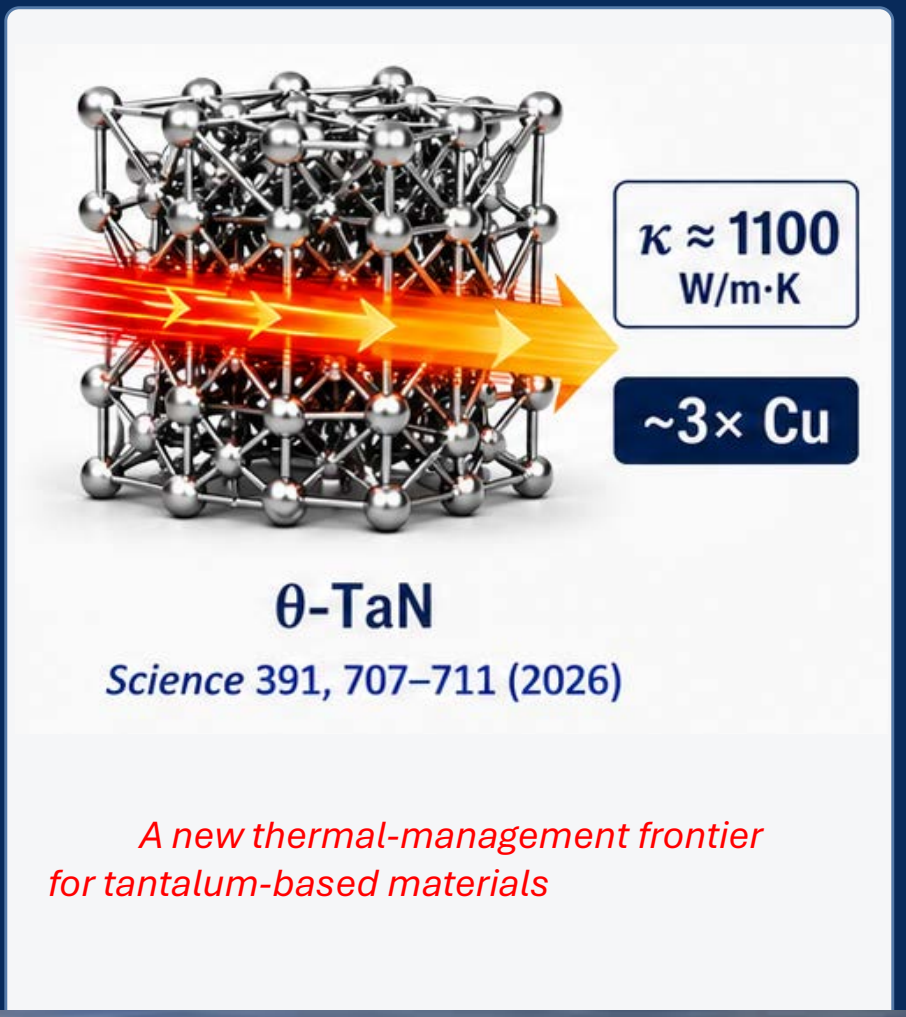
2026 T.I.C. EKEBERG AWARD KEYNOTE

Metallic θ-Phase Tantalum Nitride Has a Thermal Conductivity Triple That of Copper

Yongjie Hu

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University of California, Los Angeles (UCLA)
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T.I.C. 67th General Assembly • September 15, 2026



A new thermal-management frontier for tantalum-based materials

Ĥ-LAB
University of California, Los Angeles



H-Lab Research Platform: Multiscale Thermal Transport from Atoms to Systems

Integrated theory, synthesis, ultrafast metrology, and device integration

Theory & AI Modeling

DFT | Lattice Dynamics | e–p Coupling | BTE / Monte Carlo | MD | Device Modeling | AI Multiscale

prediction | mechanism | validation | feedback | design rules

Atomic | Nanoscale | Mesoscopic | Microscale | System

Å | nm | μm | mm | cm

Experiment & Integration

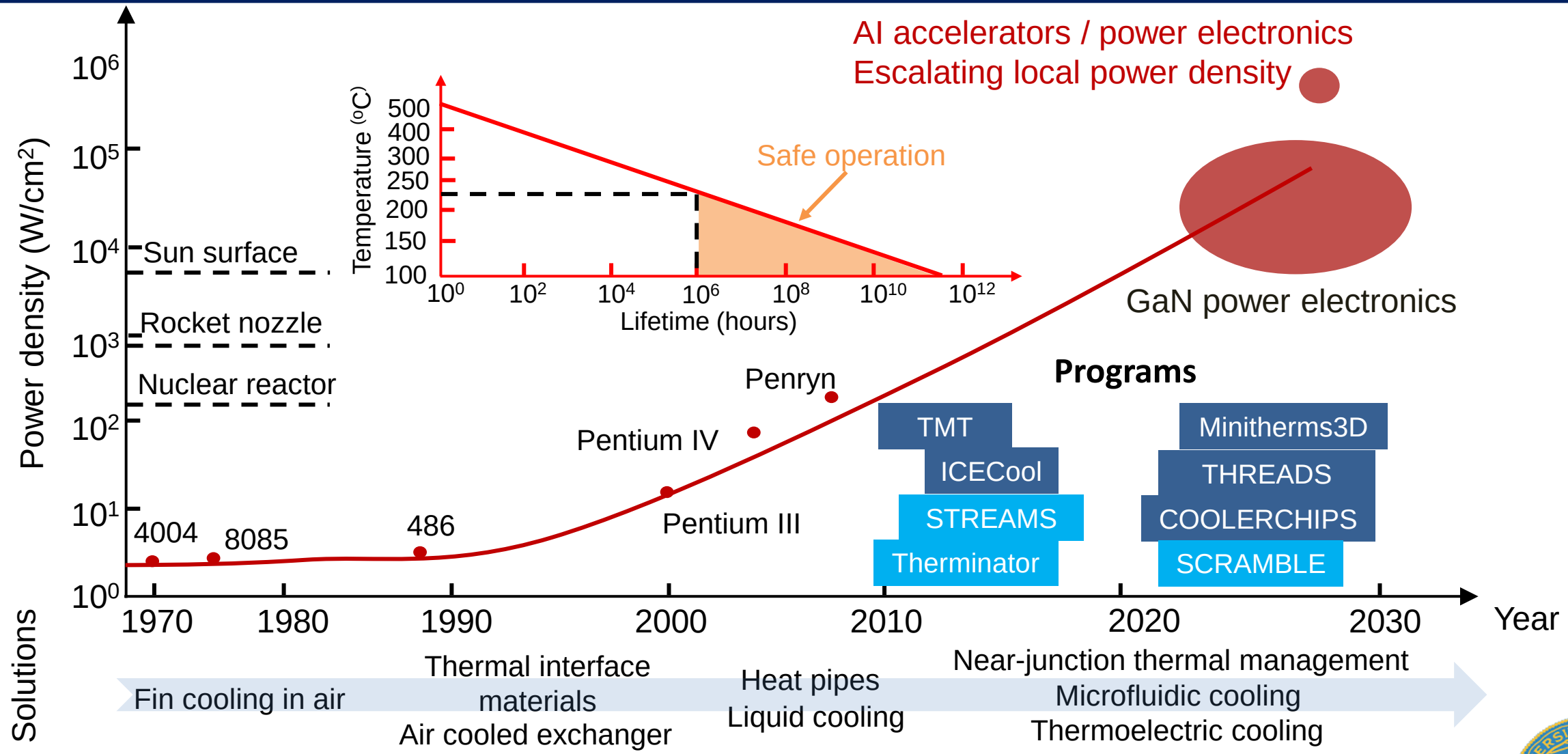
Synthesis | TEM / STM / SPM | TDTR | Raman / Brillouin | Ultrafast Spectroscopy | Fabrication | Device Transport | System Integration

Predict | Learn | Integrate | Make | Measure

Closed-loop discovery and engineering of heat flow across scales

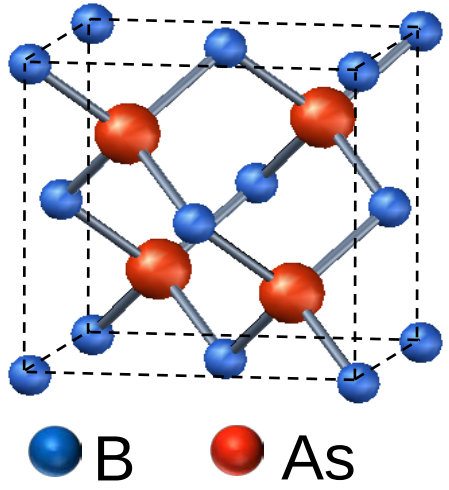
UCLA | H-Lab Thermal Transport

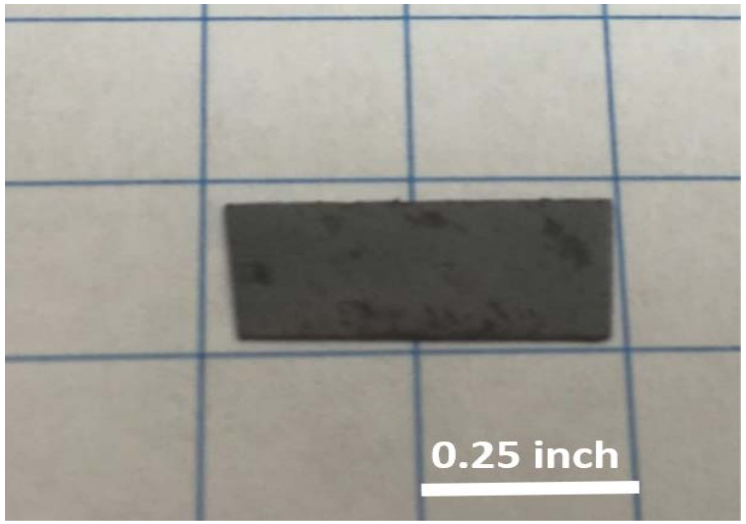
Heat is the Critical Limit in Electronics, AI Hardware, and Energy Systems

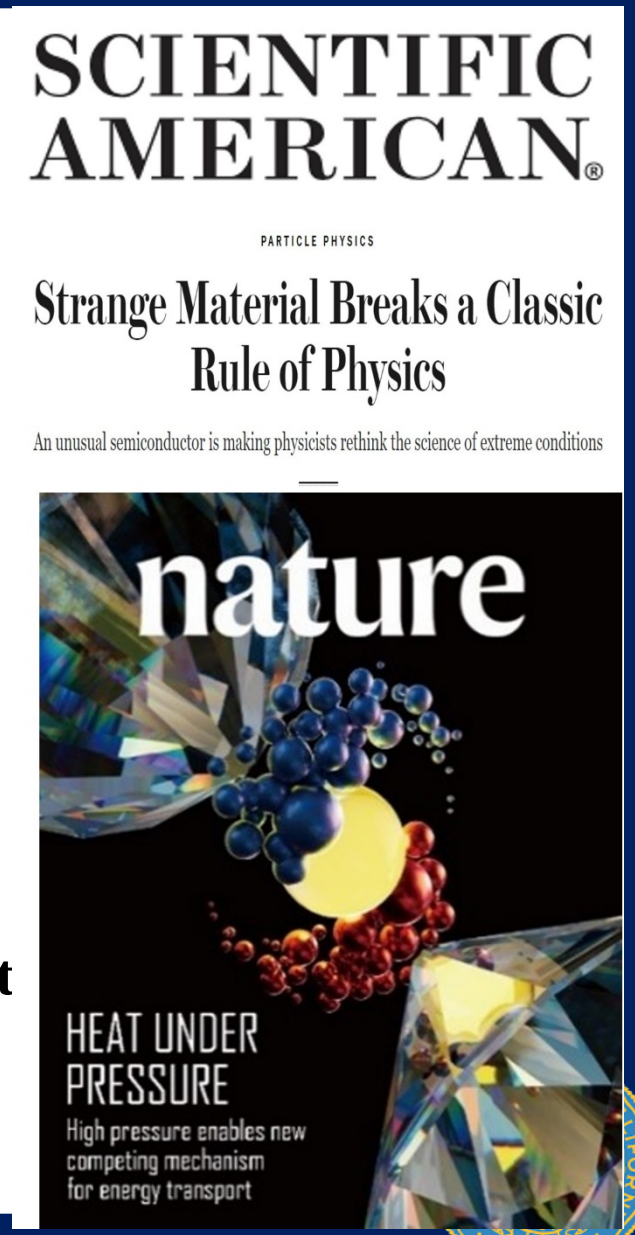


Adapted from M Li and Y Hu et al., "Advancing Thermal Management Technology for Power Semiconductors through Materials and Interface Engineering," *Accounts of Materials Research* 6, 563 (2025).

Breaking the Limits of High Thermal Conductivity (κ) : Our Early Discovery of BAs







- Large acoustic-optical band gap
- Bunching together of the acoustic phonon branches

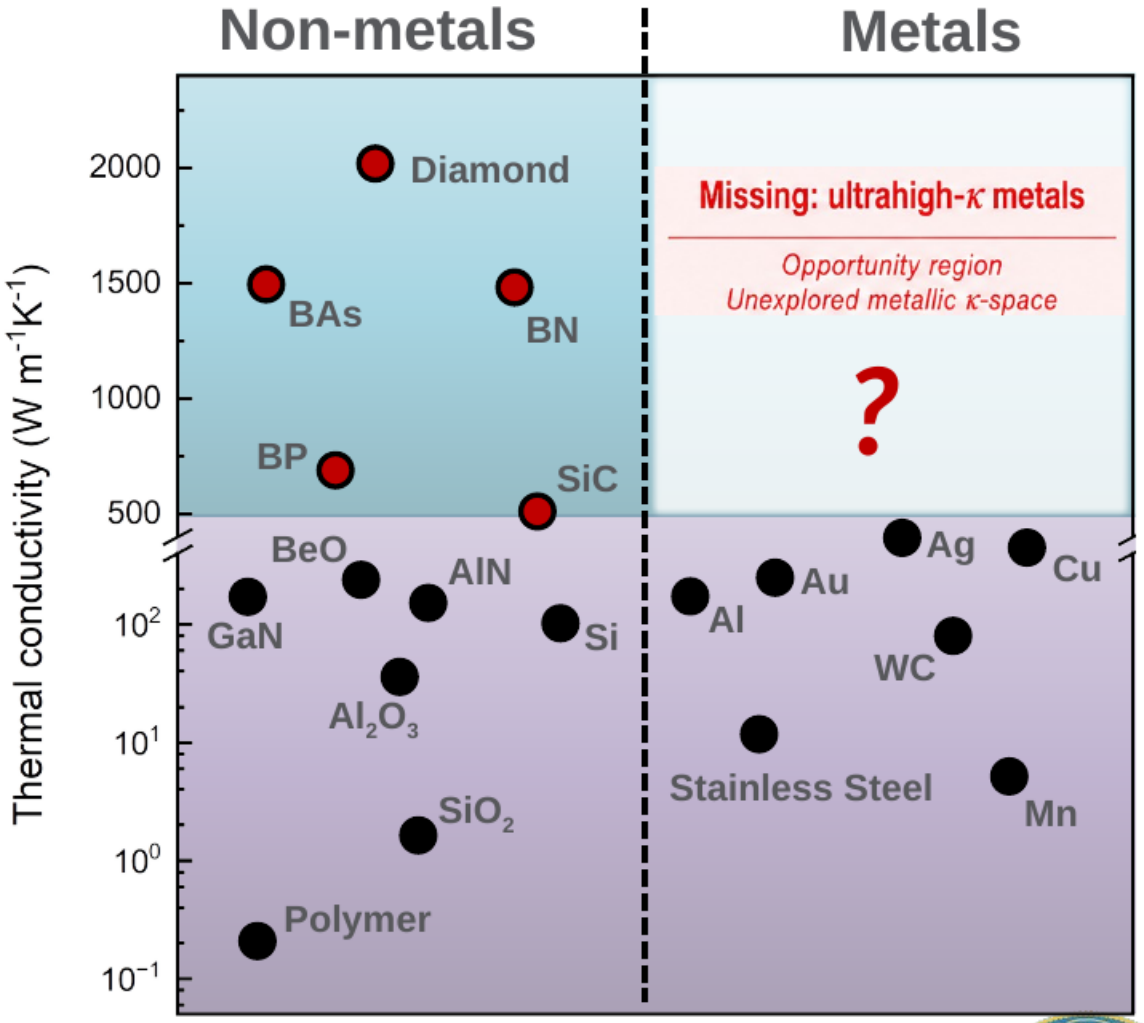
- **Unique phonon band structures**
- **Record-high thermal conductivity** among semiconductors
- **BAs established a materials-to-device pathway for thermal management**

J. Kang M. Li, H. Wu, H. Nguyen, and Y. Hu, *Science* 361, 575 (2018).
S. Li, Z. Qin, H. Wu, M. Li, M. Kunz, A. Alatas, A. Kavner, Y. Hu, *Nature* 612, 459 (2022).

The Missing Materials Class: Ultrahigh-κ Metals



Advancing Thermal Management Technology for Power Semiconductors through Materials and Interface Engineering, *Accounts of Materials Research* 6, 563–576 (2025)

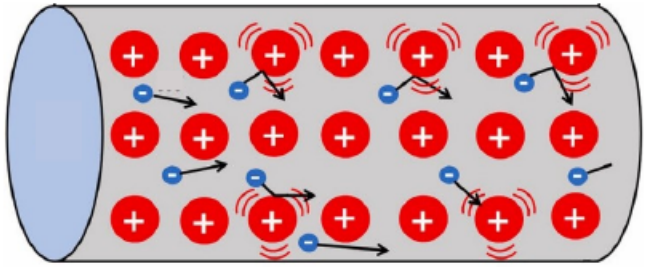


- Cu: **~30%** of the global heat sink materials market
- Al & Power demand beyond-copper cooling capability
- **The ultrahigh- κ metallic materials space has remained largely unexplored**

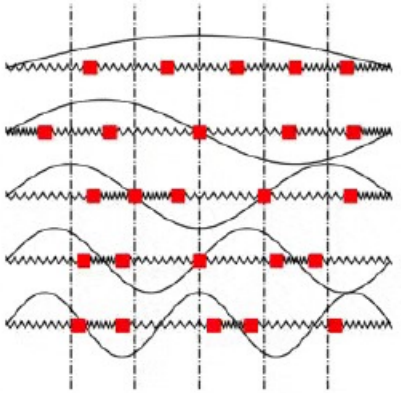
Li et al., *Accounts of Materials Research* 6, 563 (2025).

Heat Carriers and Scattering in Solids

Electrons: charge carriers occupying electronic bands



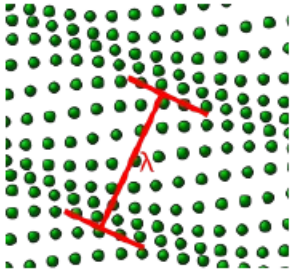
Phonons: quasiparticles describing quantized lattice vibrations



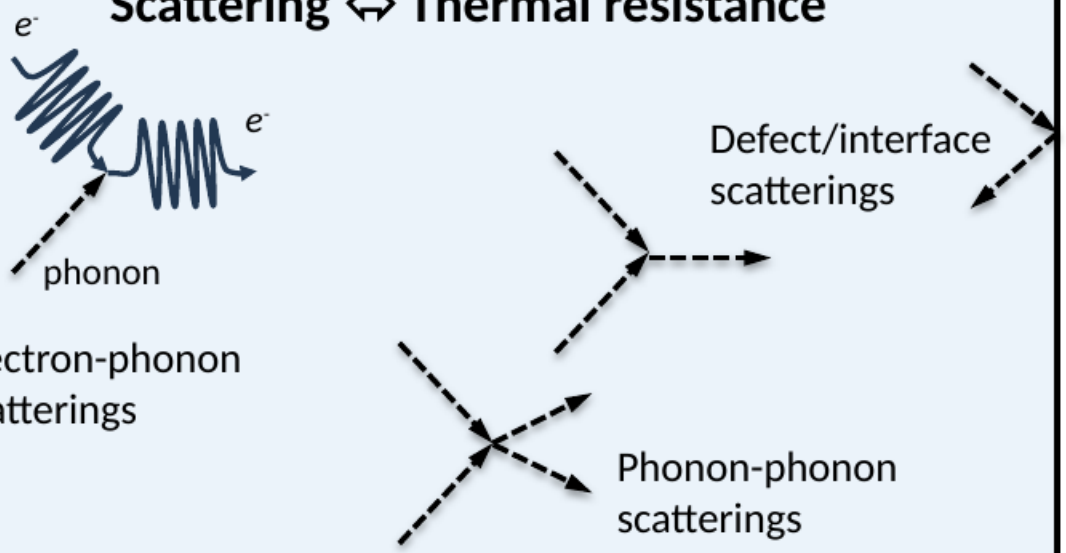
Lattice waves

Quantization by quantum mechanical principles

Phonons



Scattering ⇔ Thermal resistance



In solid materials:

- Heat is mainly carried by electrons and phonons
- Scattering (between carriers, defects, and interfaces) creates thermal resistance
- Key parameter: Scattering lifetime τ

Why Have Ag/Cu Defined the Metallic Ceiling for a Century?

$$\kappa \propto Cv^2\tau$$

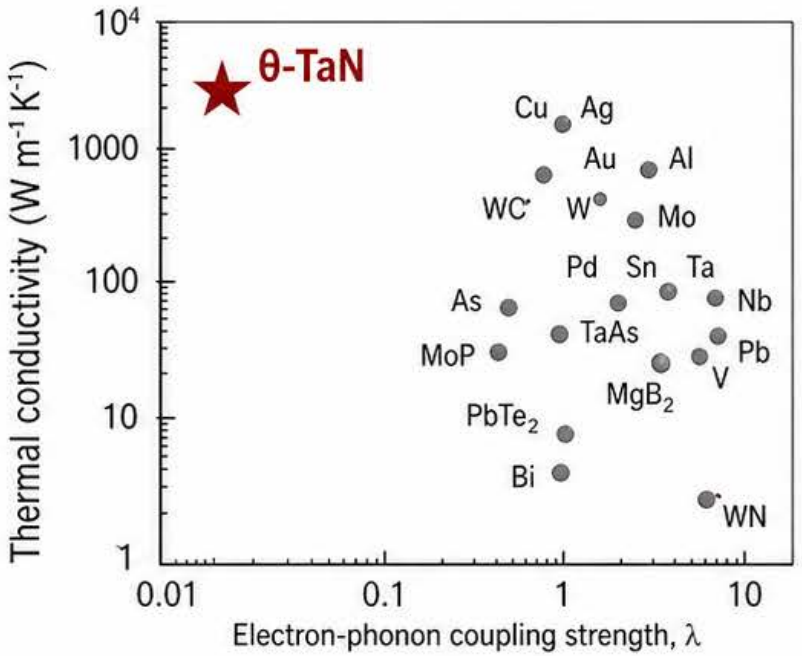
Kinetic theory:
Thermal conductivity determined by scattering process

$$\tau^{-1} = \tau_{p-p}^{-1} + \tau_{e-p}^{-1}$$

Scattering: **phonon-phonon (p-p)**
electron-phonon (e-p)

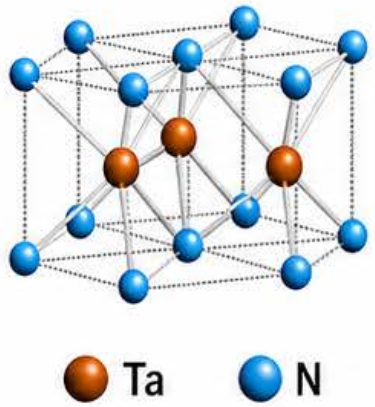
- In nonmetals, heat is carried mainly by phonons: e.g., diamond, BAs, graphene
- Typical metals: high electron density + soft metallic lattice
- Metallic κ is limited by both p-p and e-p scattering
- Silver and copper have defined the metallic κ **ceiling at ~ 400 W/mK** for over a century
- **Beyond-copper metals require unusually weak scattering in both channels**

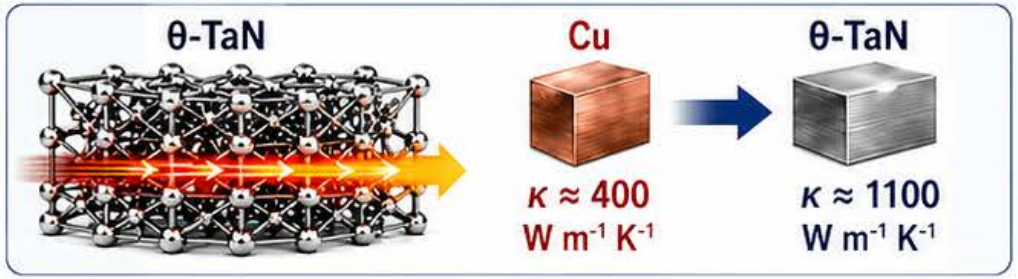
Record-Setting Heat-Conducting Metallic Material Breaks a Century-Old Limit



θ-TaN (red star) surpasses all known metals in thermal conductivity.

θ-TaN crystal structure





κ ≈ 1100 W m⁻¹ K⁻¹

~3× Cu

Scientific Achievement

- Discovered metallic θ-TaN with record-high thermal conductivity.
- Measured $\kappa \approx 1100$ W m^{-1} K^{-1}, nearly three times copper.

Significance and Impact

- Breaks the century-old metallic heat-conduction ceiling set by Cu/Ag.
- Redefines fundamental thermal-transport limits in metals.
- Establishes θ-TaN as a new benchmark for microelectronics, AI hardware, and energy systems.

Research Details

- High-quality single-crystal synthesis and structural characterization.
- Ultrafast and TDTR thermal measurements.
- Transient microscopy, IXS phonon spectroscopy, and first-principles theory reveal ultra-weak scattering.

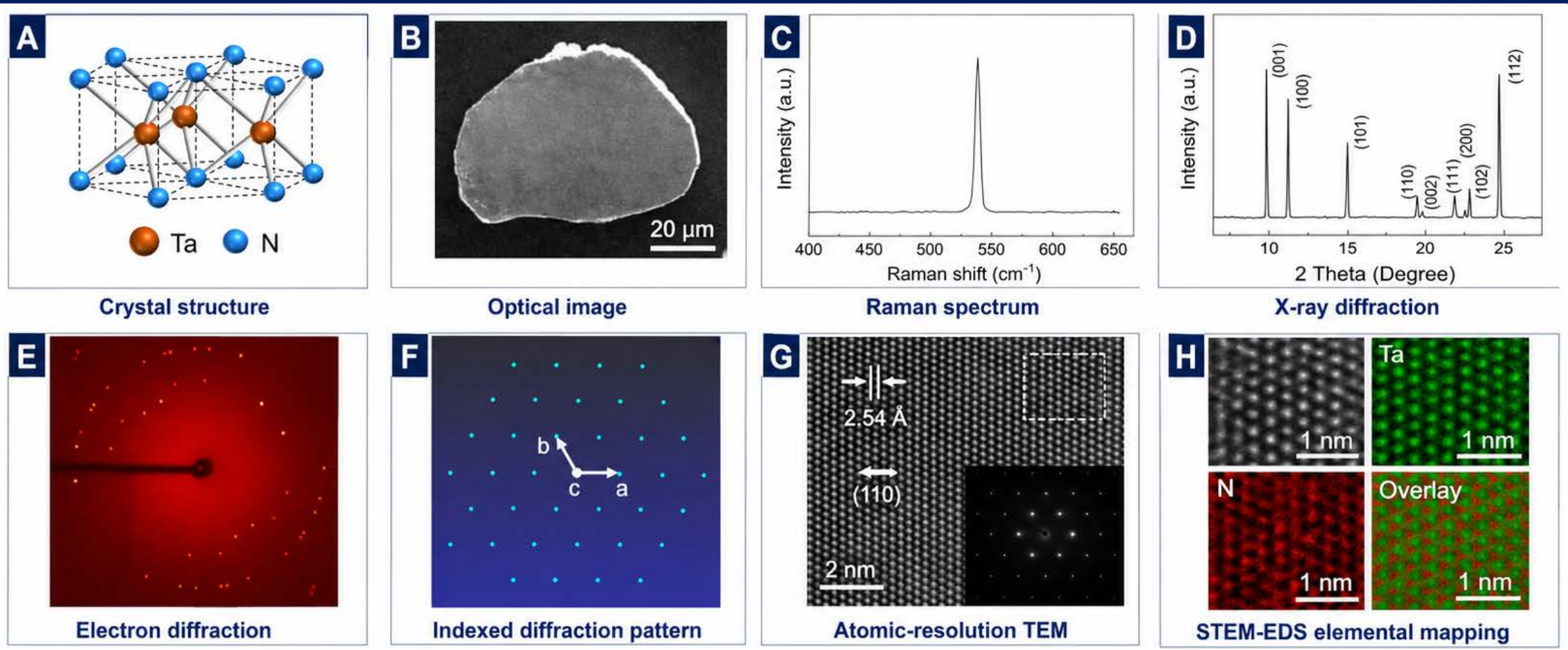
θ-TaN establishes a new benchmark metallic thermal material for microelectronics, AI hardware, and energy-dense systems.

Li et al., *Science* **391**, 707–711 (2026) **DOI:** 10.1126/science.aeb1142

Work led by Yongjie Hu (UCLA).

UCLA · Argonne NATIONAL LABORATORY · APS · ALS ADVANCED LIGHT SOURCE · TOHOKU UNIVERSITY

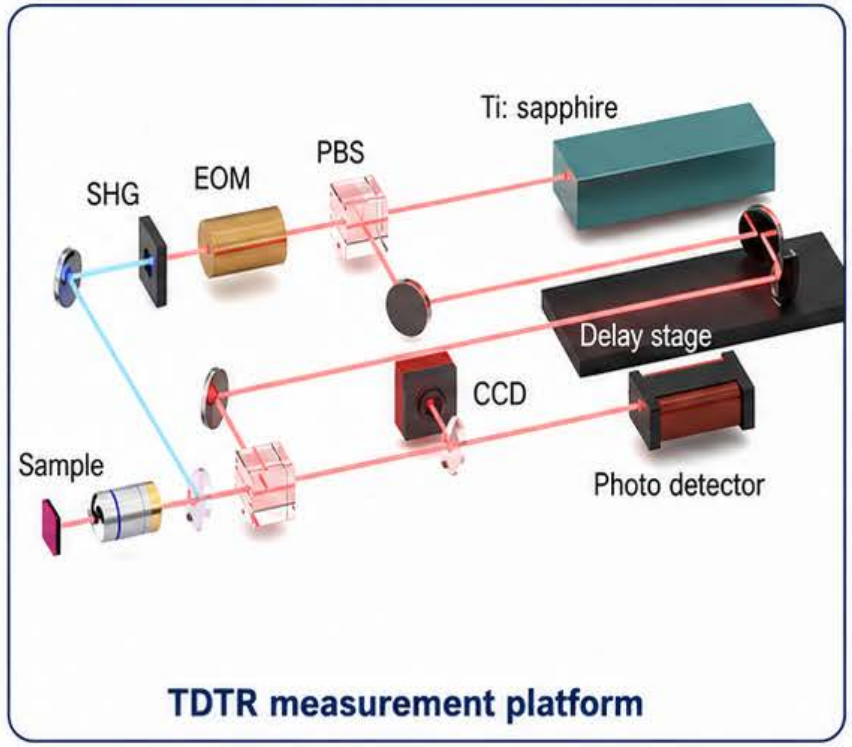
θ-TaN: Crystal Structure and Structural Characterization



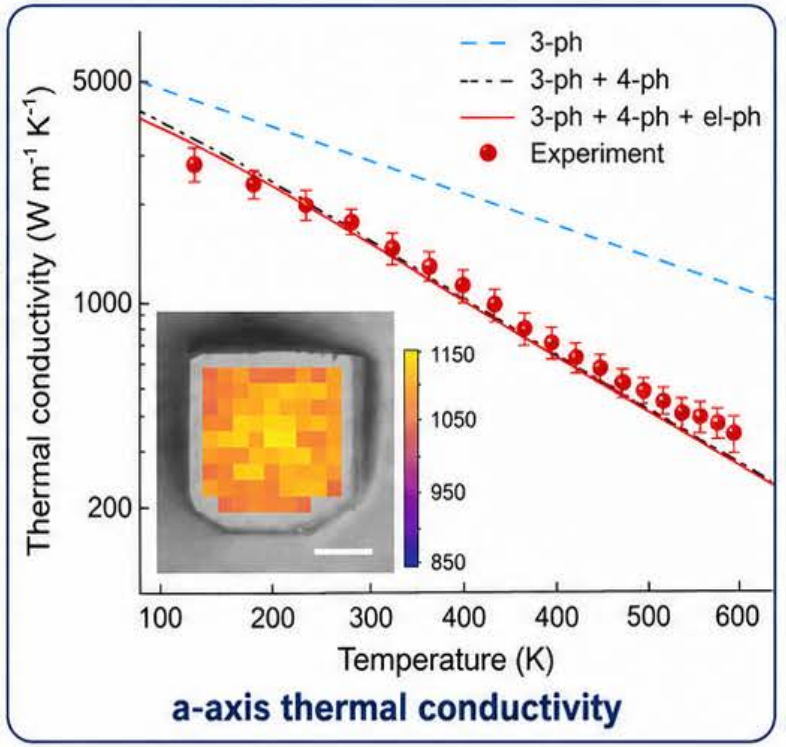
- **High-quality single-crystalline θ-TaN enables reliable intrinsic thermal measurements**

S. Li, C. Su, Z. Qin, A. Alatas, M. Kunz, T. Yamada, S.D. Kelly, M.H. Upton, A. Gironda, J. Zhao, B. Kalkan, W. Yang, T. Aoki, and Y. Hu, ***Science*** 391, 707-711 (2026)

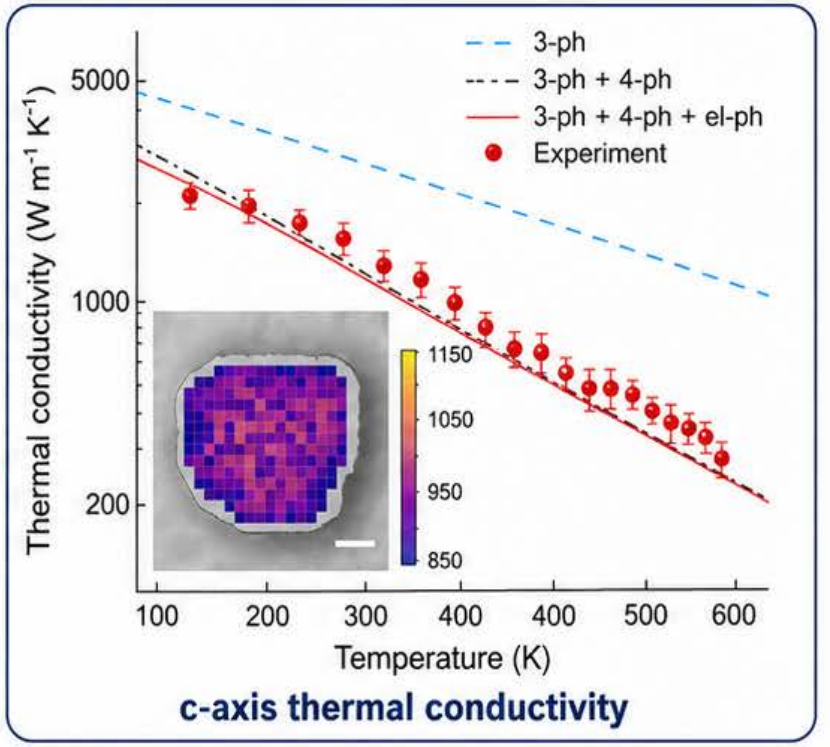
Temperature-Dependent Thermal Conductivity of θ-TaN



TDTR measurement platform



a-axis thermal conductivity



c-axis thermal conductivity

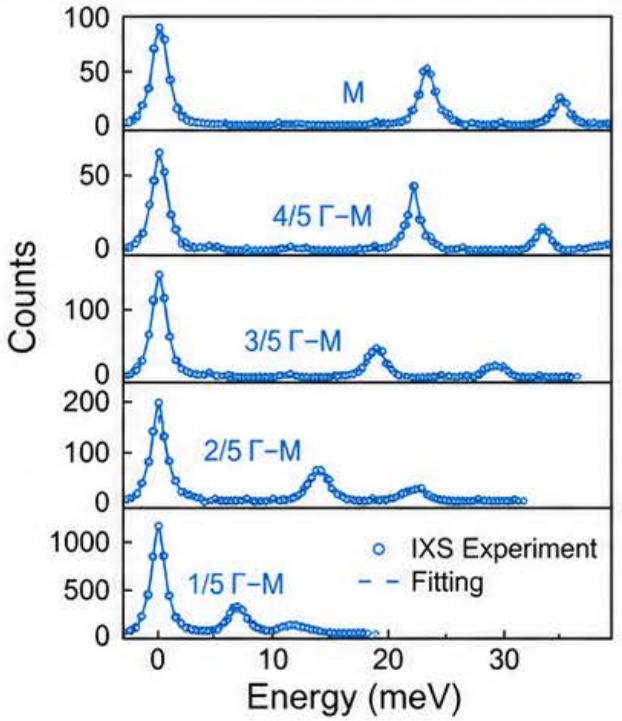
- Record metallic thermal conductivity: κ ~1100 W/mK
- Highlights a promise beyond-copper platform for next-generation thermal management

S. Li, C. Su, Z. Qin, A. Alatas, M. Kunz, T. Yamada, S.D. Kelly, M.H. Upton, A. Gironda, J. Zhao, B. Kalkan, W. Yang, T. Aoki, and Y. Hu, ***Science*** 391, 707-711 (2026)

IXS Phonon Band Structure Reveals Ultra-Weak Phonon-Phonon Scattering in θ-TaN

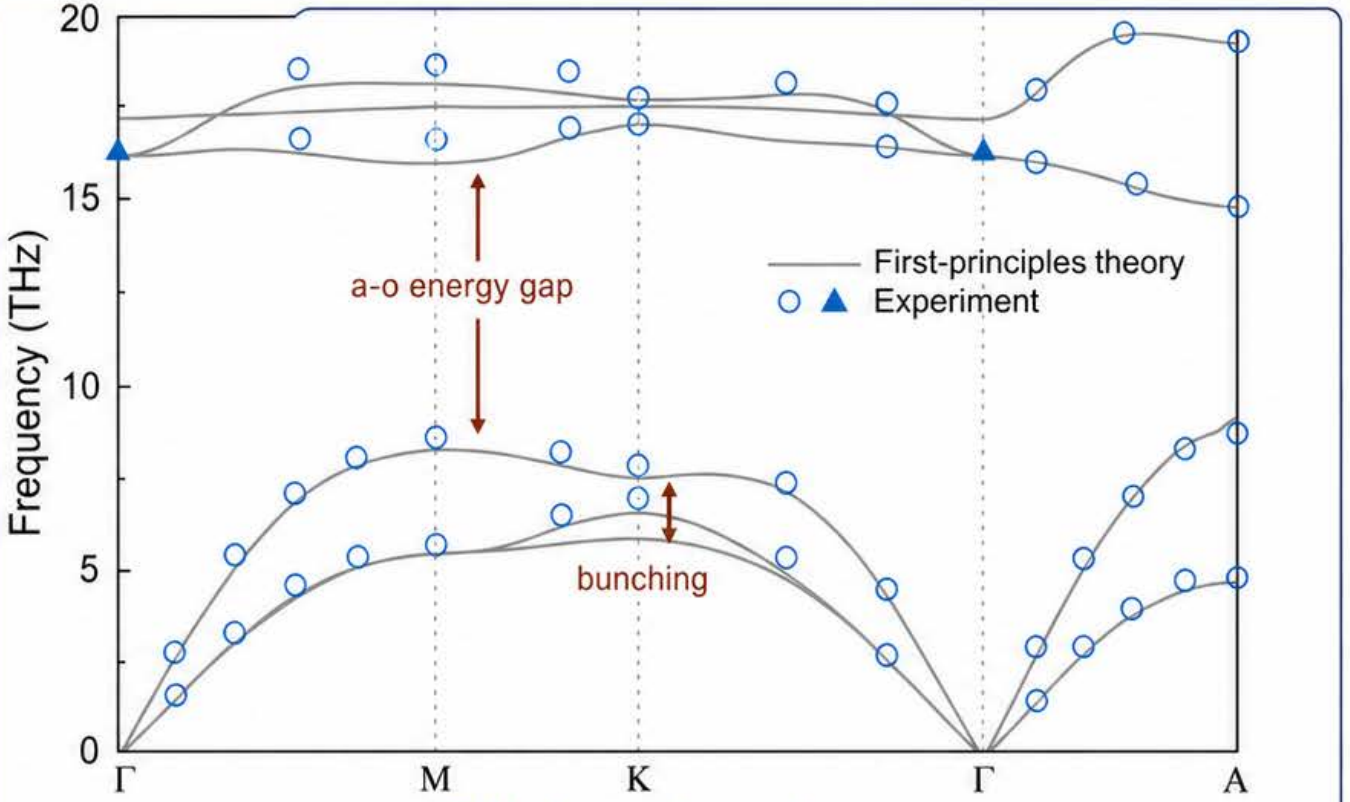
$$\tau^{-1} = \tau_{p-p}^{-1} + \tau_{e-p}^{-1}$$





IXS measurement

Momentum-resolved inelastic x-ray scattering



TaN phonon dispersion

Experiment agrees with first-principles theory

- **IXS measurements validate** the calculated phonon band structure.
- **Large band gap and acoustic bunching** suppress phonon-phonon scattering.

Key consequence: ultra-weak phonon-phonon scattering

Transient Reflection Microscopy Reveals Slow Hot-Electron Relaxation in θ-TaN

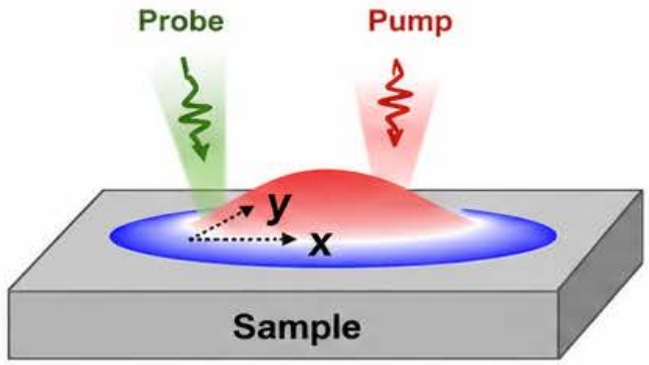
Direct evidence of weak electron–phonon coupling

$$\tau^{-1} = \tau_{p-p}^{-1} + \boxed{\tau_{e-p}^{-1}}$$

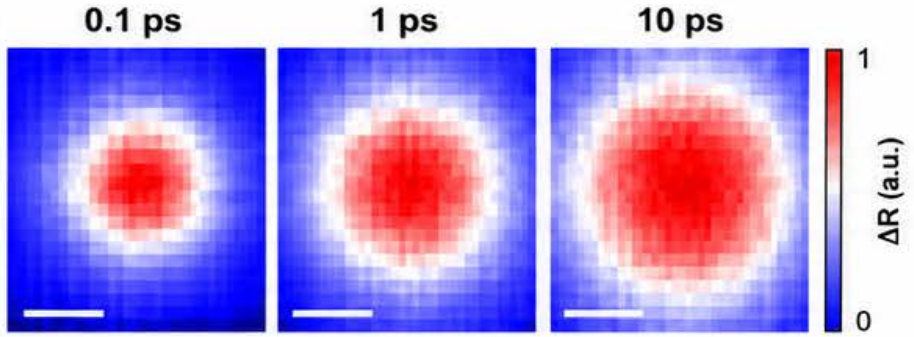
electron–phonon term

1. Transient reflection microscopy

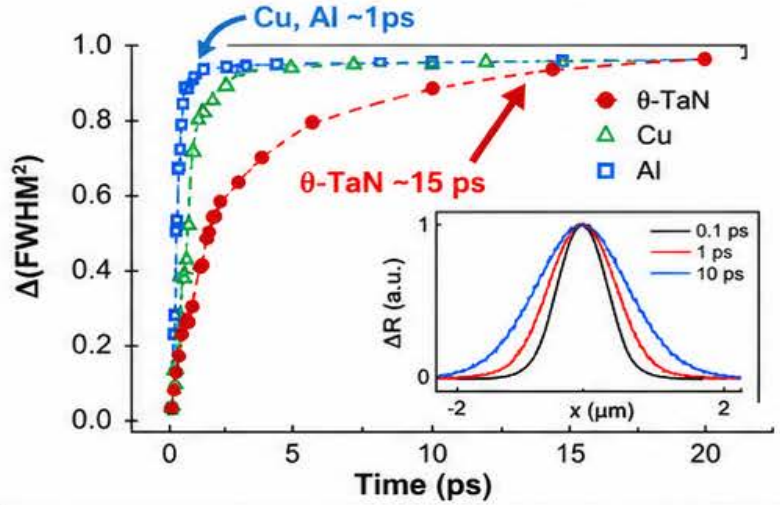
Pump–probe mapping of hot-electron dynamics



2. Spatial mapping of hot-electron diffusion



3. Electron relaxation time



- θ-TaN: ~ 10x slower thermalization than Cu and Al
- indicates weak electron-phonon interaction in θ-TaN
- Slow hot-electron decay provides direct evidence for weak electron-phonon coupling

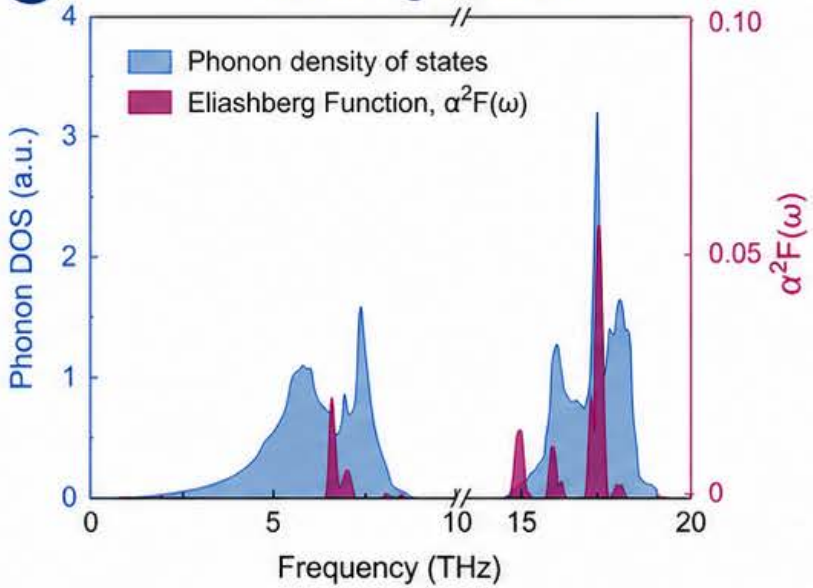
S. Li, C. Su, Z. Qin, A. Alatas, M. Kunz, T. Yamada, S.D. Kelly, M.H. Upton, A. Gironda, J. Zhao, B. Kalkan, W. Yang, T. Aoki, and Y. Hu, ***Science*** 391, 707-711 (2026)

Theory Reveals Ultraweak Electron–Phonon Coupling in θ-TaN

Phonon bottleneck and suppressed hot-carrier energy relaxation

$$\tau^{-1} = \tau_{p-p}^{-1} + \tau_{\boldsymbol{e}-p}^{-1}$$

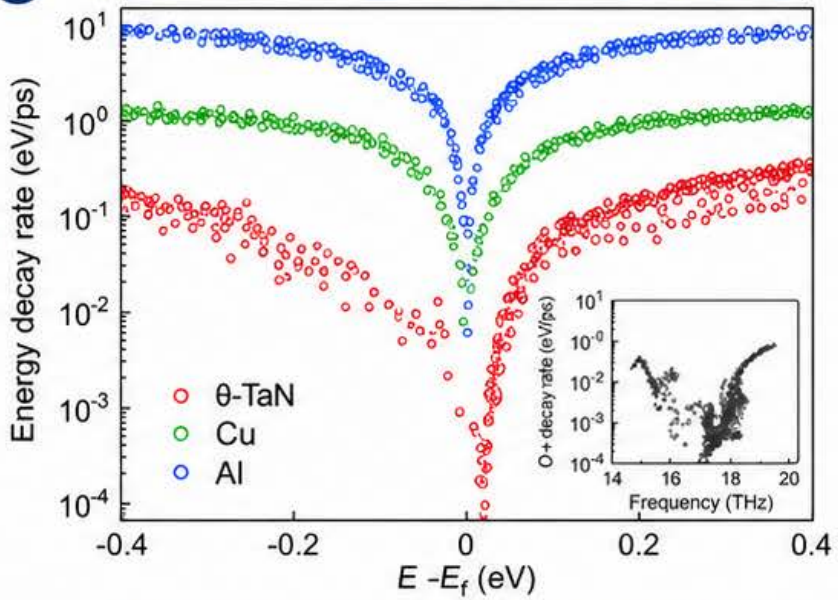
1 Eliashberg function



Eliashberg function

Weak spectral overlap limits electron–phonon energy transfer

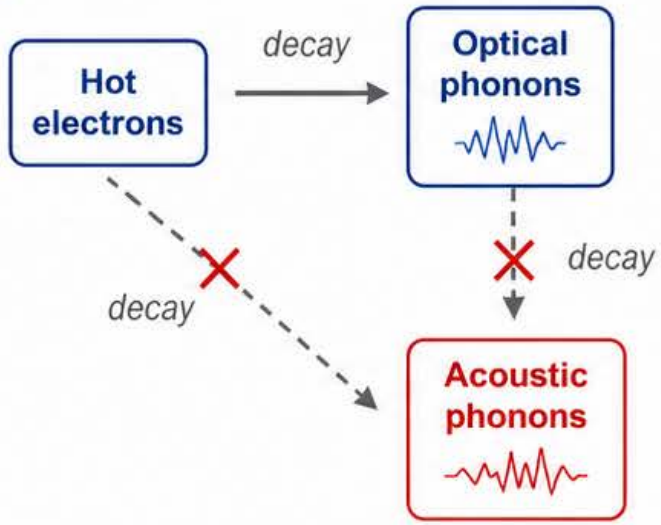
2 Hot-carrier energy decay via e–p coupling



Hot-carrier energy decay via e–p coupling

θ-TaN shows strongly suppressed energy relaxation compared with Cu and Al

3 Phonon bottleneck picture



Phonon bottleneck picture

Hot-electron relaxation is slowed by weak electron–phonon coupling

- **Hot electrons experience a pronounced phonon bottle neck**
- **Exceptionally weak electron-phonon coupling suppressed hot-carrier cooling**

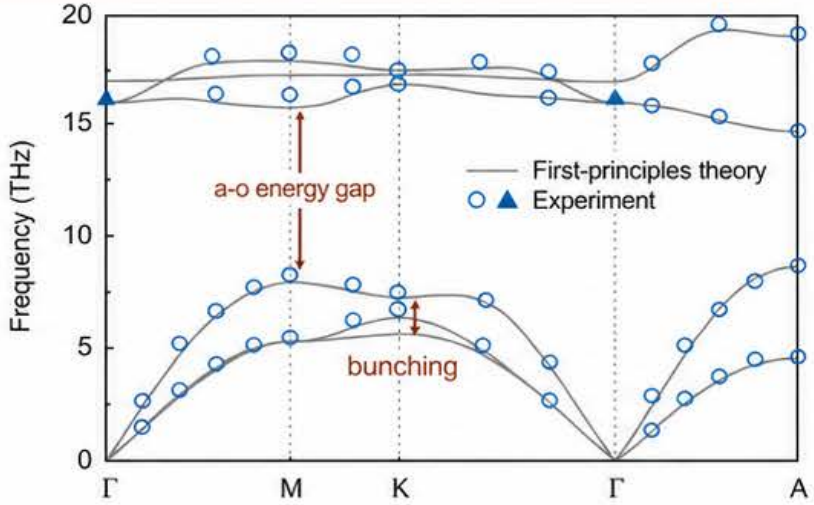
S. Li, C. Su, Z. Qin, A. Alatas, M. Kunz, T. Yamada, S.D. Kelly, M.H. Upton, A. Gironda, J. Zhao, B. Kalkan, W. Yang, T. Aoki, and Y. Hu, ***Science*** 391, 707-711 (2026)

θ-TaN Combines Ultra-weak Phonon-Phonon and Electron-Phonon Scattering

A rare combination that enables beyond-copper metallic thermal conductivity

$$\tau^{-1} = \tau_{p-p}^{-1} + \tau_{e-p}^{-1}$$

Ultra-weak phonon–phonon scattering



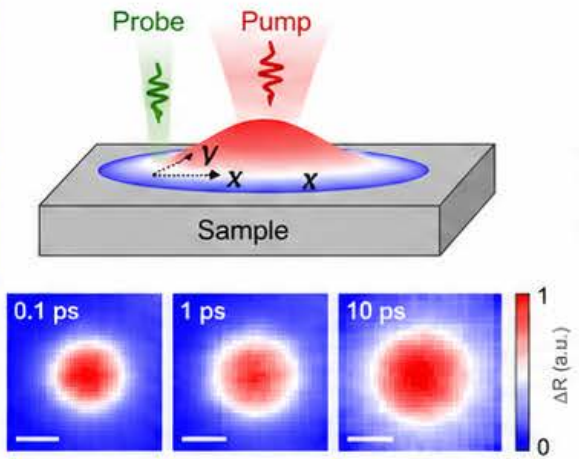
IXS phonon dispersion

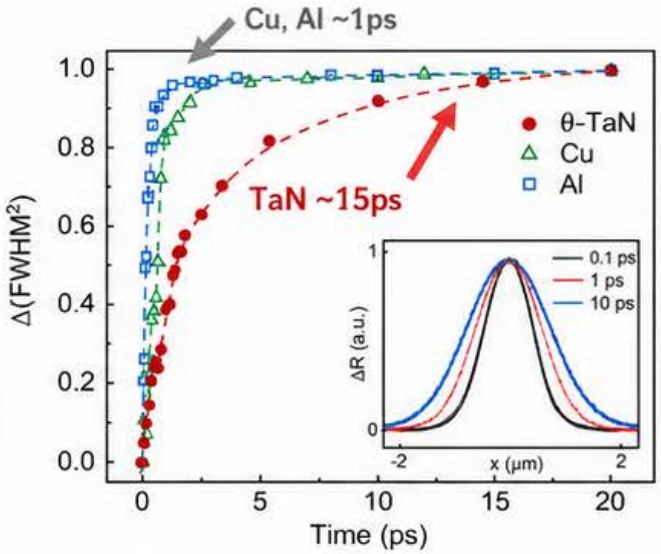
Large phonon band gap and acoustic bunching suppress p–p scattering

Validated by IXS + first-principles theory

Ultra-weak electron–phonon scattering

Transient reflection microscopy





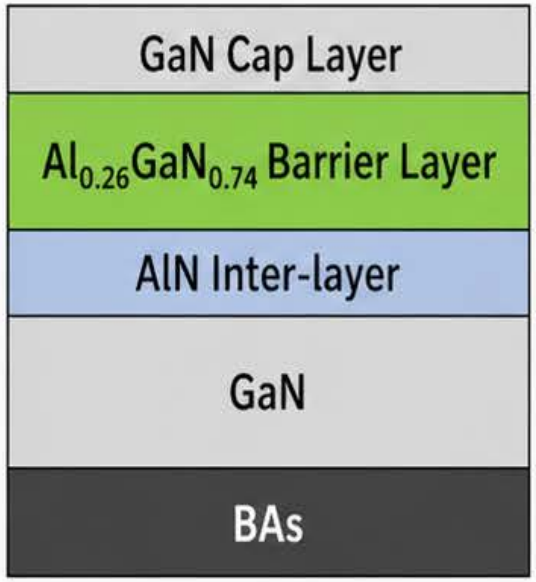
Slow hot-electron relaxation reveals weak e–p coupling

θ–TaN ≈ 15 ps vs Cu, Al ≈ 1 ps

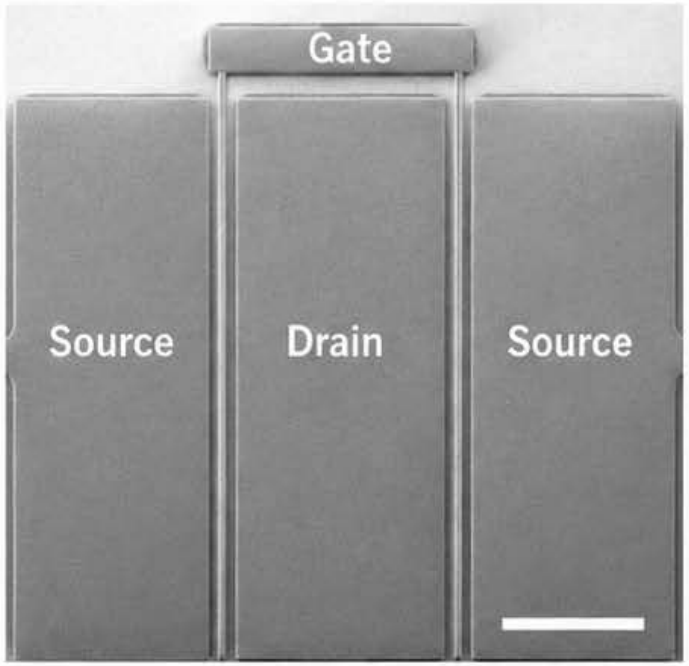
- θ-TaN suppresses both p-p and e-p scattering
- This rare combination is needed for record metallic thermal conductivity
- The dual suppression helps explain ~ 1100 W/mK, nearly 3x Cu

Application Example 1: Integration with GaN Electronics

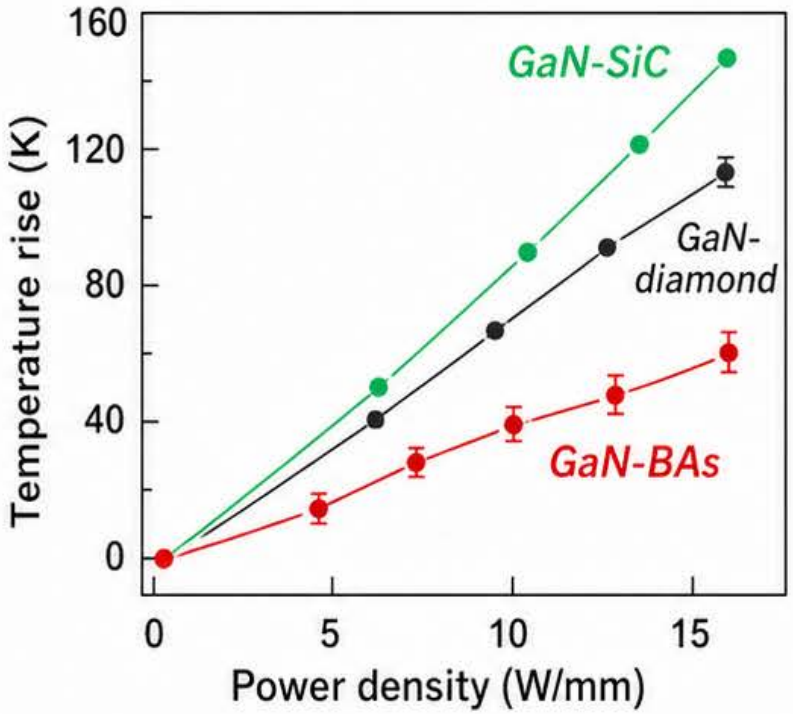
HEMT stack on BAs



Operating GaN HEMT



Temperature rise vs. power density

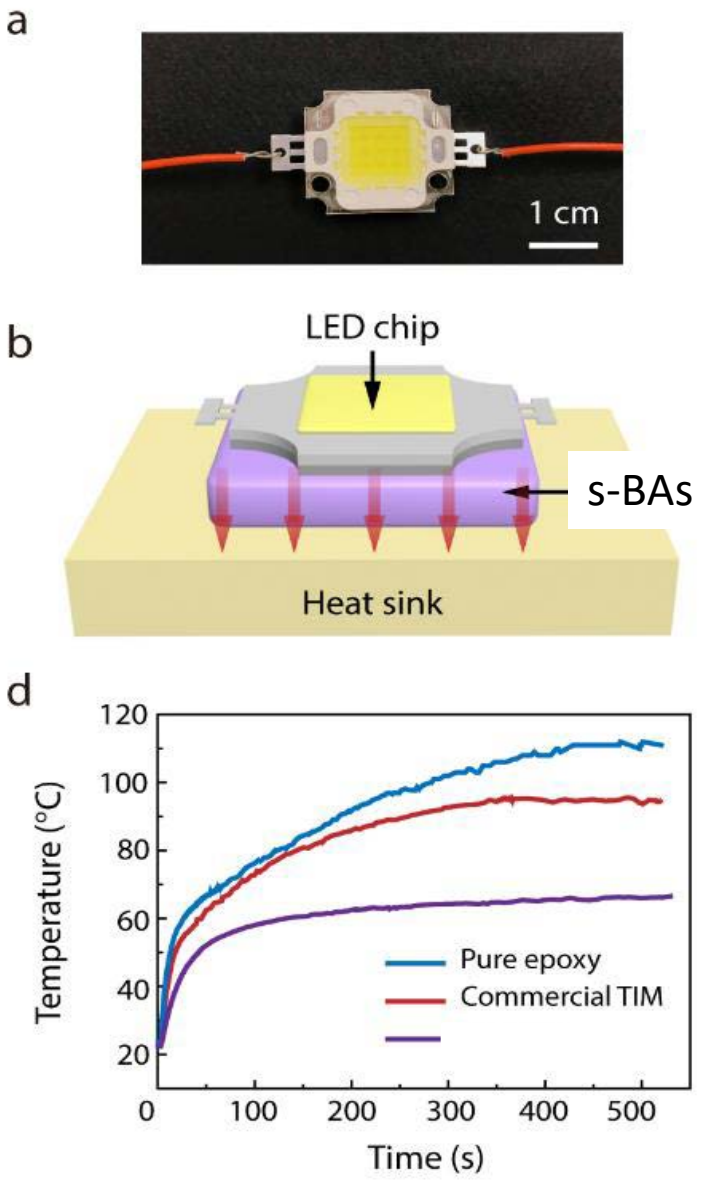


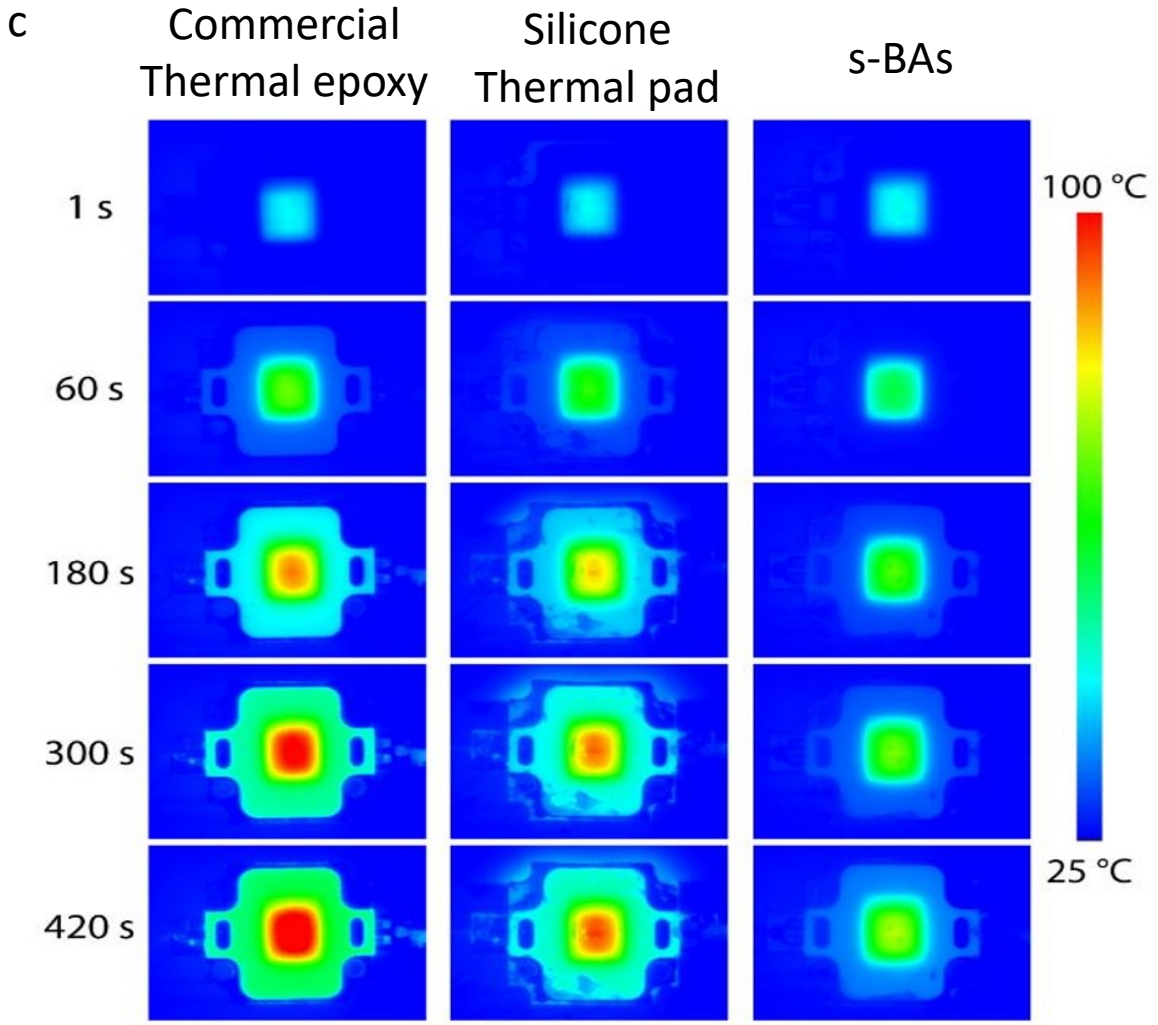
- *In situ* thermal measurements on operating GaN HEMTs
- GaN-BAs exhibits the **lowest temperature rise** across the measured power range
- Demonstrates record-high cooling performance for power electronics

➢ Device integration delivers superior hotspot cooling in operating GaN power devices.

J. Kang and Y. Hu et al., *Nature Electronics 4, 416 (2021).*

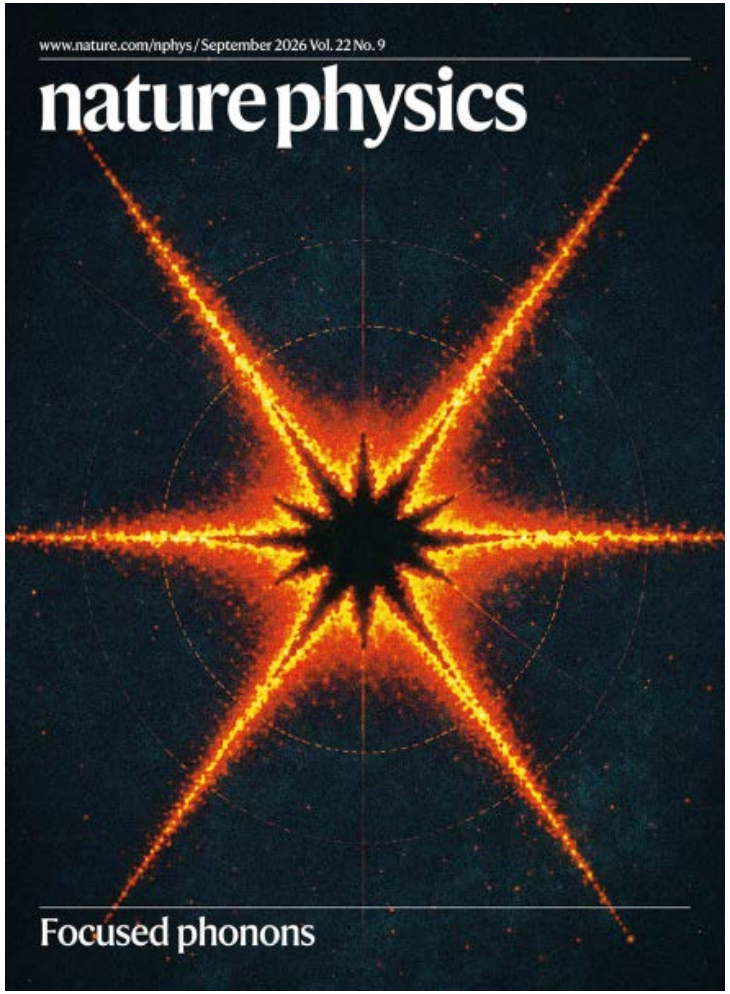
Example 2: High-κ Thermal Interfaces





Y. Cui, Z. Qin, H. Wu, M. Li, and Y. Hu, *Nature Communications* 12, 1-7 (2021).

Example 3: Quantum Heat Waves at Room Temperature Beyond Diffusion



September 2026 Issue, Cover Highlight

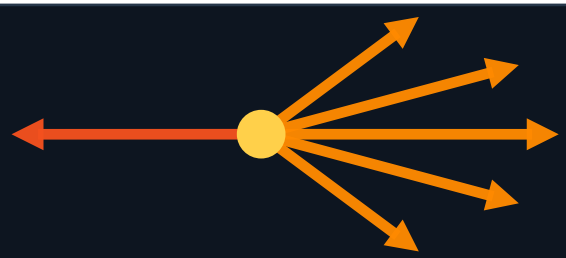
Room-temperature phonon focusing reveals wave-governed thermal transport beyond conventional diffusion

Conventional thermal management



Heat spreads diffusively
(Fourier picture)

Phonon waves



Heat can be guided along
nanoscale confined pathways

High κ + long phonon lifetimes can do more than move heat faster

Quantum mechanical nature opens a wave-governed transport regime with opportunities for directional heat routing, focusing, redistribution, and new device operating principles.

M. Li, H. Wu, Z. Qin, C. Su, H. Nguyen, and Y. Hu,
"Phonon focusing at room temperature,"
Nature Physics **22**, 1416–1421 (2026).

From High Thermal Conductivity to New Technologies

What our research suggests for the future technologies

1 Better device cooling

Intrinsic high κ can directly reduce hotspot temperature and improve performance and reliability in operating electronics.

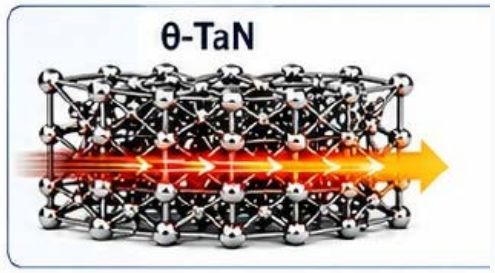
2 Practical thermal materials

High-κ physics can be translated into interfaces, composites, heat spreaders, and other manufacturable formats.

3 New operating principles

Long-lived phonons can enable wave-governed heat flow — routing, focusing, and redistribution beyond classical diffusion.

θ-TaN



A new ultrahigh-κ metallic platform

$\kappa \approx 1100\ W\ m^{-1}\ K^{-1}$

Future opportunity

AI hardware

Power electronics

Thermal interposers / heat spreaders

Extreme-environment electronics

New device concepts

Discovery → processing → integration → devices

0 → 1: the scientific possibility is established. 1 → N: processing, integration and scale-up require the broader tantalum community.

The Magic of Tantalum: From Ekeberg's Discovery to a New Frontier



1802

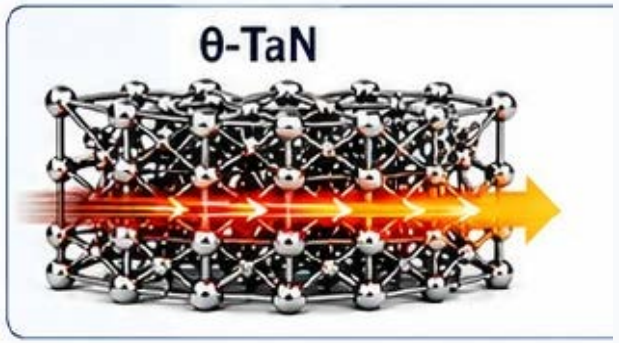
Anders Gustaf Ekeberg discovers tantalum

More than two centuries of tantalum science & technology

capacitors • superalloys • semiconductor contacts
• aerospace • energy • superconductivity • nuclear systems

two centuries of continual discovery

2026



An unexpected property of a tantalum compound

Metallic θ-TaN conducts heat at ~1100 W m^{-1} K^{-1} — nearly 3× Cu.

new possibility
Metallic κ far beyond Cu/Ag

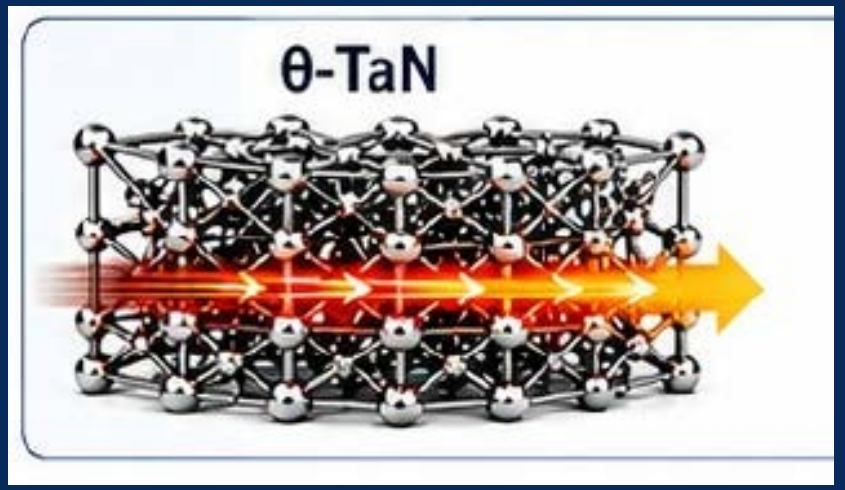
new physics
Dual suppression of p–p and e–p scattering

new opportunity
Translate extreme transport into technology

Thank You

I am deeply grateful to T.I.C. and the Ekeberg Award Committee for this recognition.

My sincere thanks to my students, collaborators, and funding partners whose efforts made this discovery possible.



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Science 391, 707–711 (2026)

$\kappa \approx 1100\ \mathrm{W\,m^{-1}\,K^{-1}}$ • ~3× Cu

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Thank you very much for your attention.