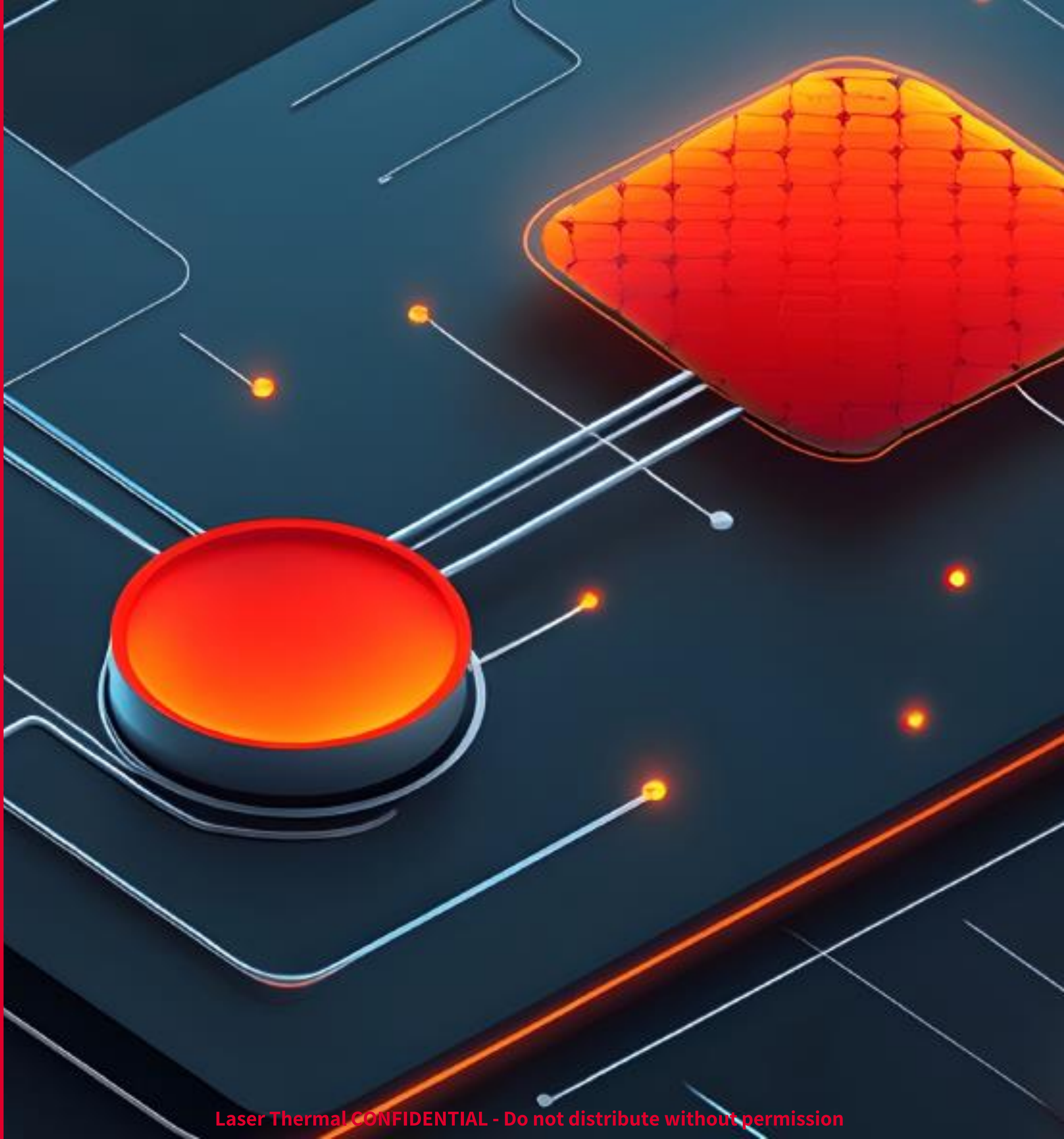
FCMN 2026

Thermoreflectance Characterization of Thermal Materials for BSPDN and Bonded Stacks

Cross-validated AlN film conductivity and bonded-interface transport for advanced integration

John Gaskins, CEO
Laser Thermal

*Temperature shows where.
Measurements tell you why.*



Agenda –Why This is a Metrology Problem

- Why thermal materials matter in advanced architectures
- Why thin-film thermal properties are hard to measure
- How thermoreflectance characterizes these materials
- What we learn from AlN films and bonded oxide examples

Agenda – Practical Problem Statement

- Dimension, complexity, and stacking make thermal management harder
- Materials innovation is needed to manage local temperatures
- Better characterization is needed to evaluate those materials
- Non-destructive in-line thermal metrology remains limited

Review article

Thermal management materials for 3D-stacked integrated circuits

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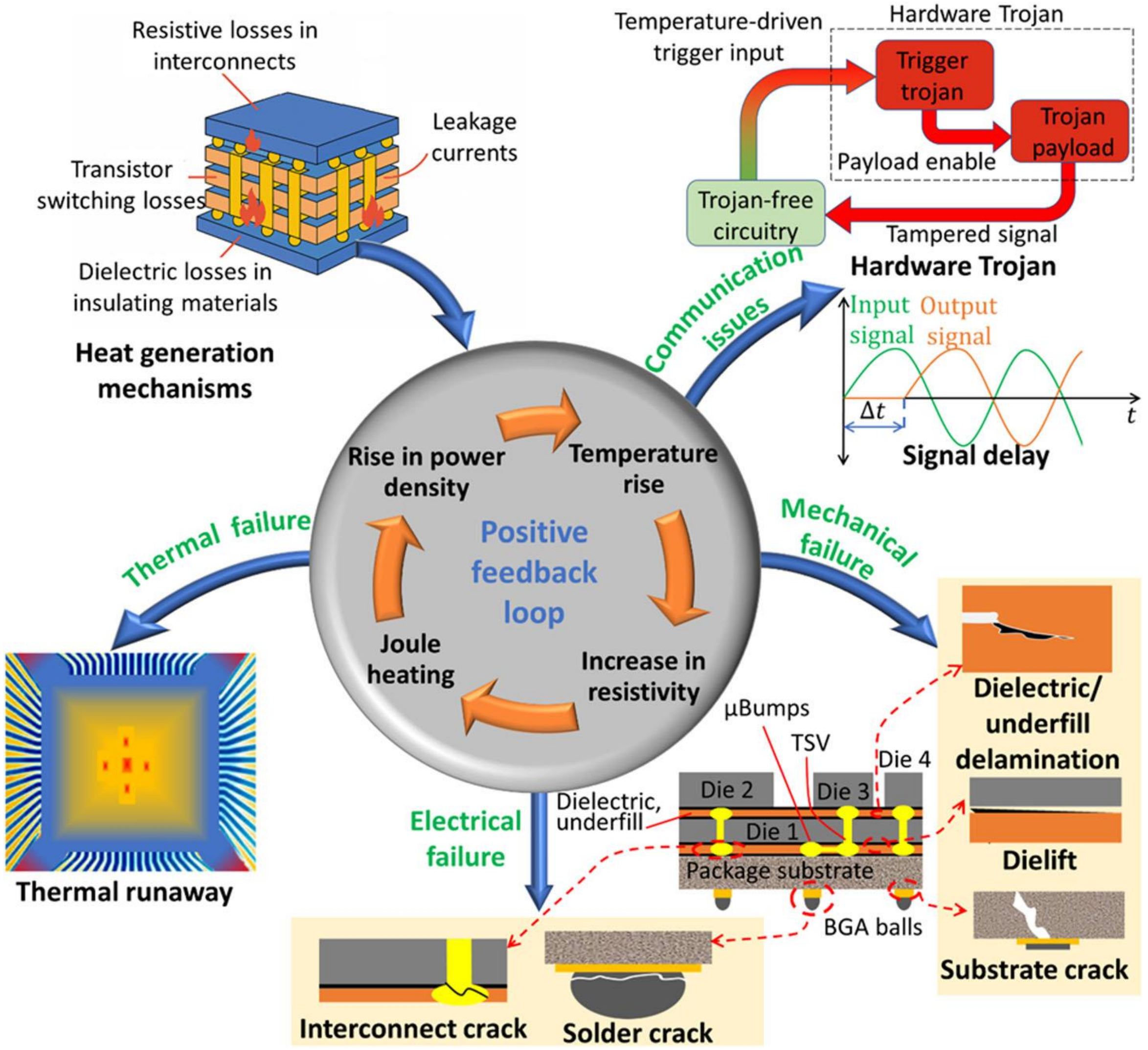
Key points

- The shrinking dimensions, increased structural complexity and 3D stacking of silicon-based semiconductor devices are intensifying challenges in thermal dissipation.
- Breakthroughs are needed to address maximum temperatures near hot spots in 3D-stacked devices, requiring innovation in material growth, processing and integration.
- Advancements are necessary in the characterization of the thermal properties of the materials and in the methods to enhance heat transport across interfaces.
- The development of non-destructive in-line metrologies compatible with semiconductor processing flows is highly desirable for the characterization of thermal management film stacks and the monitoring of thermal dissipation performance within chips.

Nature Reviews Electrical Engineering **volume 2**, pages598–613 (2025) https://doi.org/10.1038/s44287-025-00196-0

Dimensions, Complexity, and Stacking Make Thermal Problems Worse

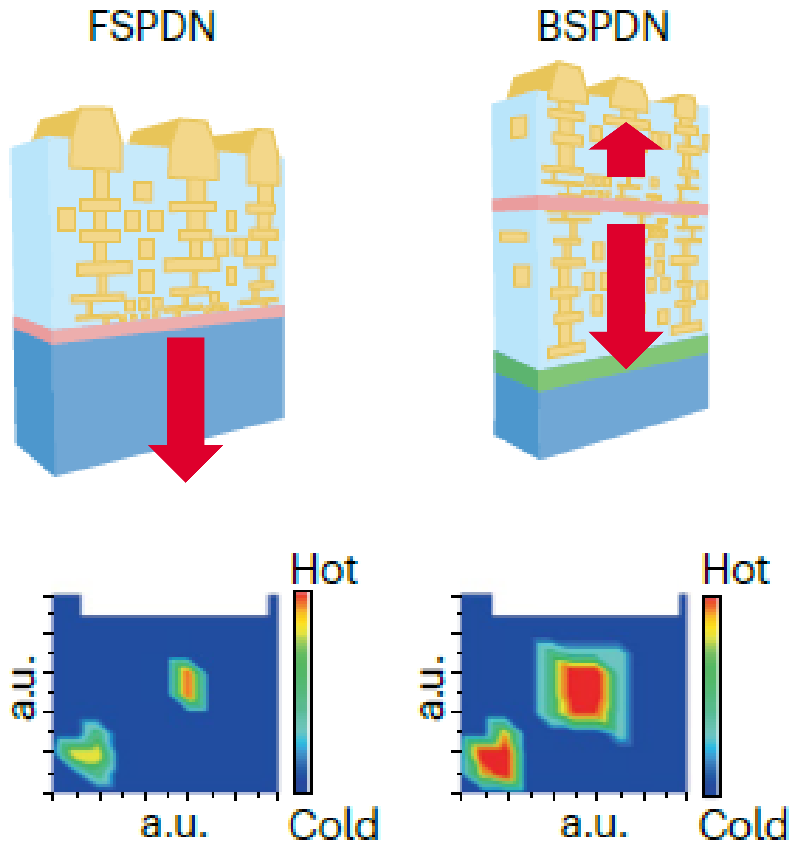
- Higher power density makes more **severe local hot spots**
- 3D integration **constrains heat-removal pathways**
- Materials and interfaces at **multiple length scales** now shape performance



https://doi.org/10.1038/s44172-026-00590-y Communications Engineering (2026)5:28

BSPDN Makes Thermal Materials More Important

- BSPDN improves routing, but increases thermal isolation
- Bonding oxides and BEOL dielectrics become part of the heat dissipation path
- Thermal-management materials must spread heat while preserving electrical isolation

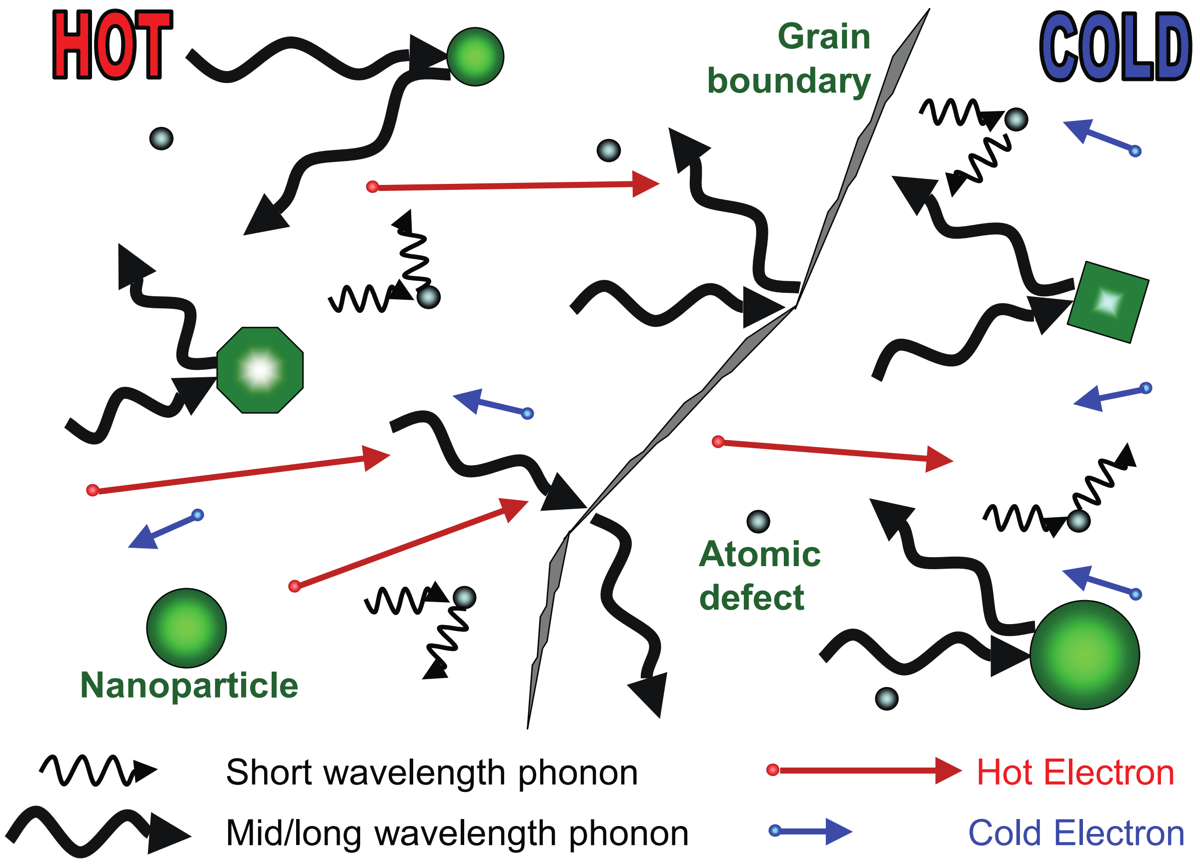


Architecture is making materials in the stack more important to thermal performance.

Nature Reviews Electrical Engineering **volume 2**, pages598–613 (2025) https://doi.org/10.1038/s44287-025-00196-0

Why Thin-Film Thermal Characterization is Essential

- Bulk values do not reliably predict thin-film performance
- Deposition conditions, defects, texture, and thickness can change thermal conductivity
- Interfaces can distort the apparent response of the film
- Candidate materials must be measured in integration-relevant stacks whenever possible



Adv. Mat. **22**, 3970

Why Thin-Film Thermal Characterization is Essential

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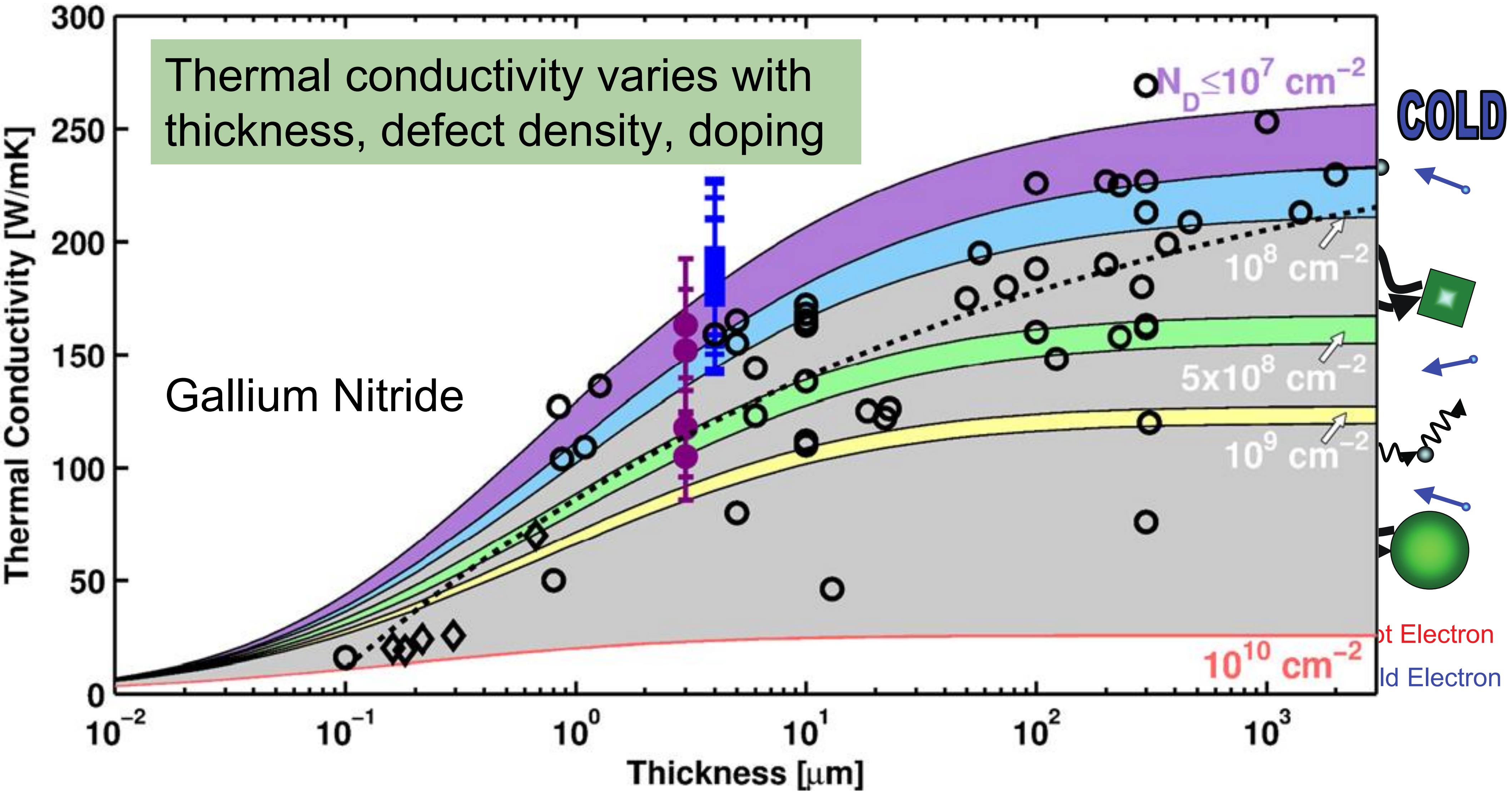
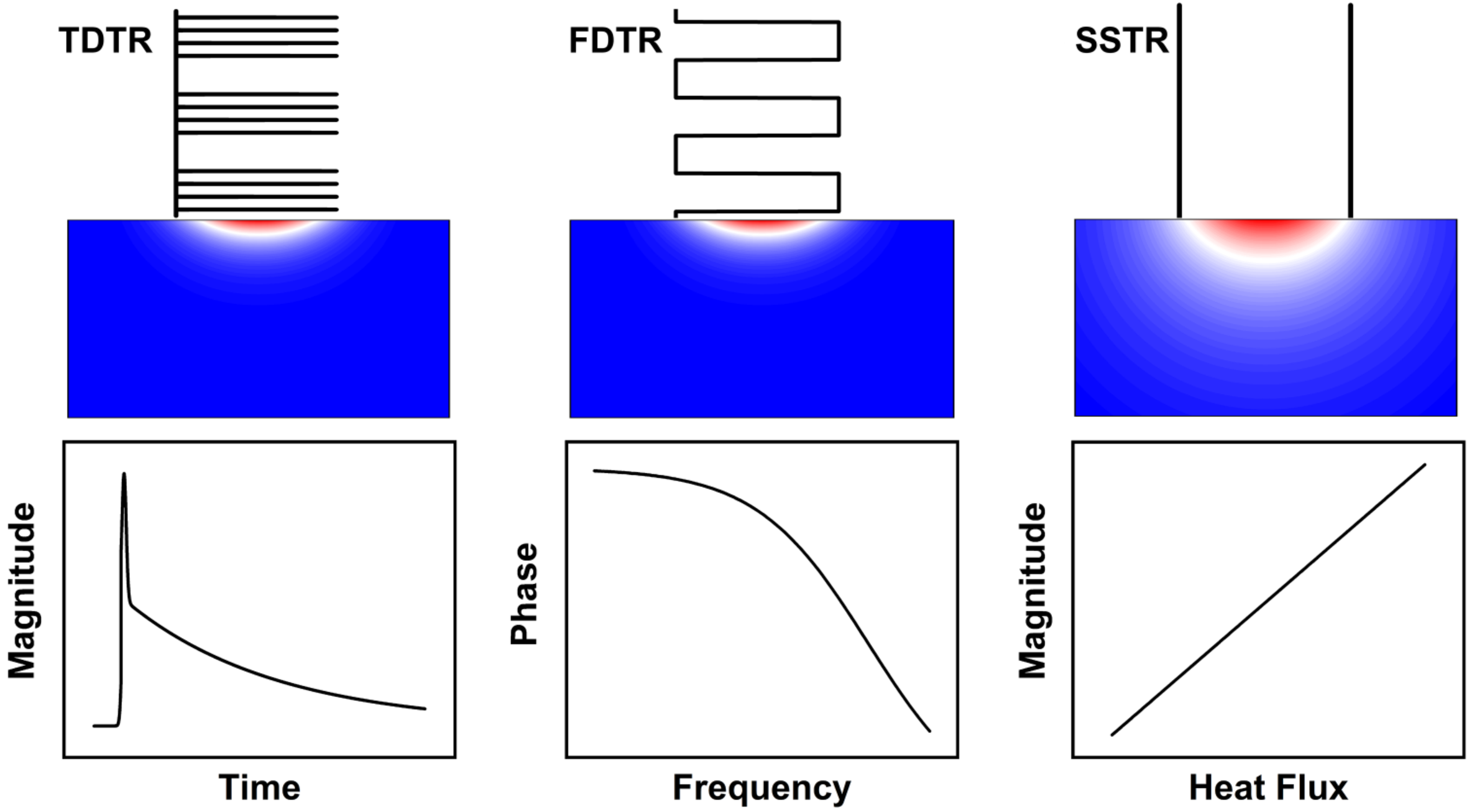
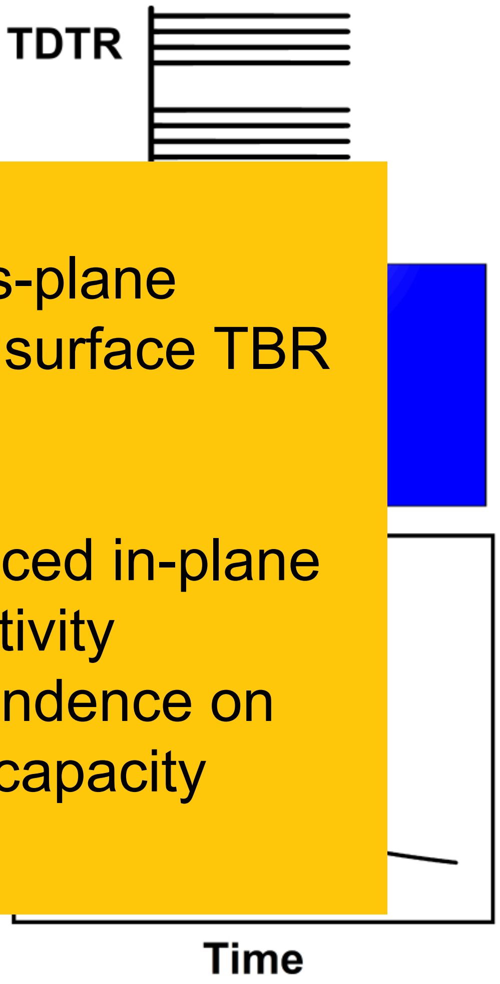


Thermoreflectance: What Each Method Gives You



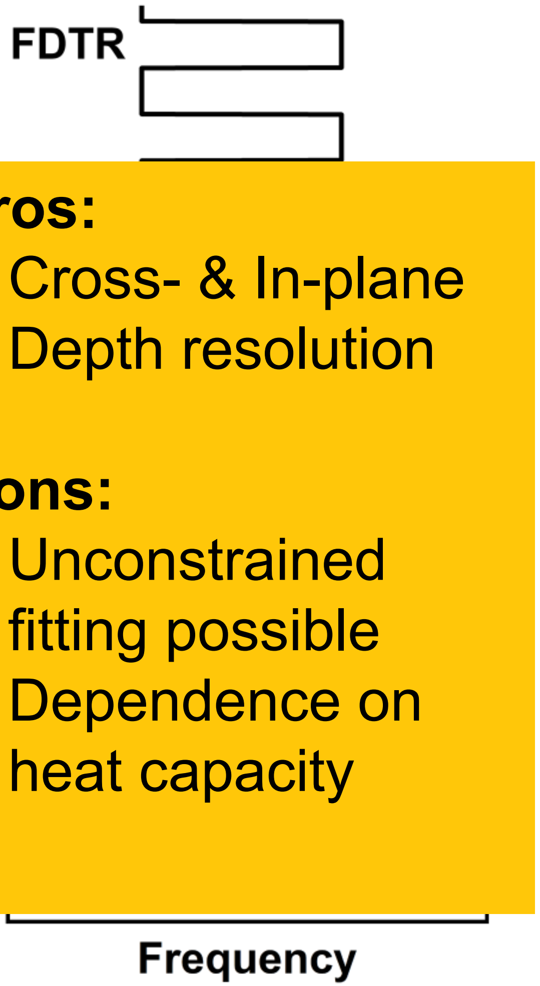
No single method gives you everything!

Thermoreflectance: What Each Method Gives You



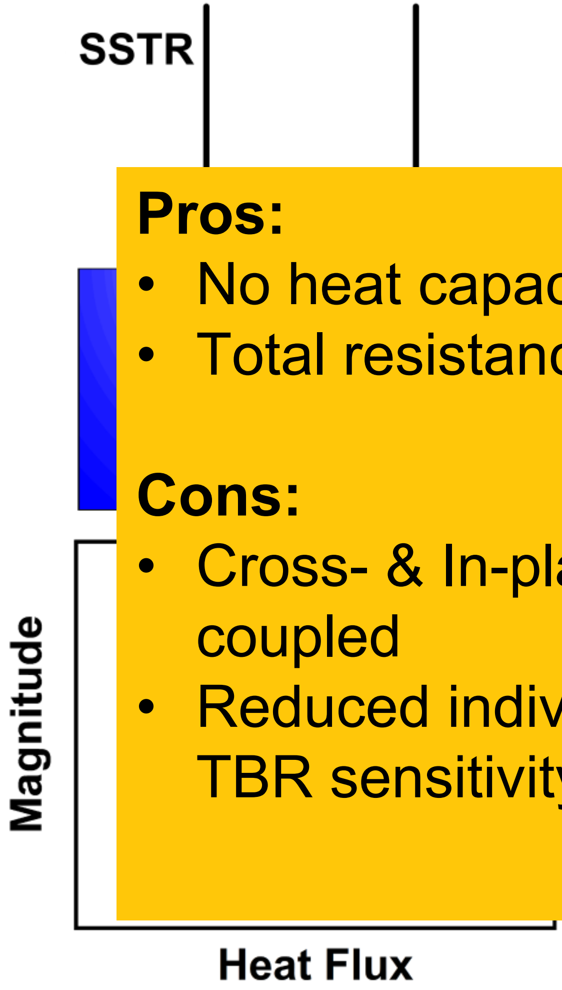
Pros:
- Cross-plane
- Near surface TBR

Cons:
- Reduced in-plane sensitivity
- Dependence on heat capacity



Pros:
- Cross- & In-plane
- Depth resolution

Cons:
- Unconstrained fitting possible
- Dependence on heat capacity



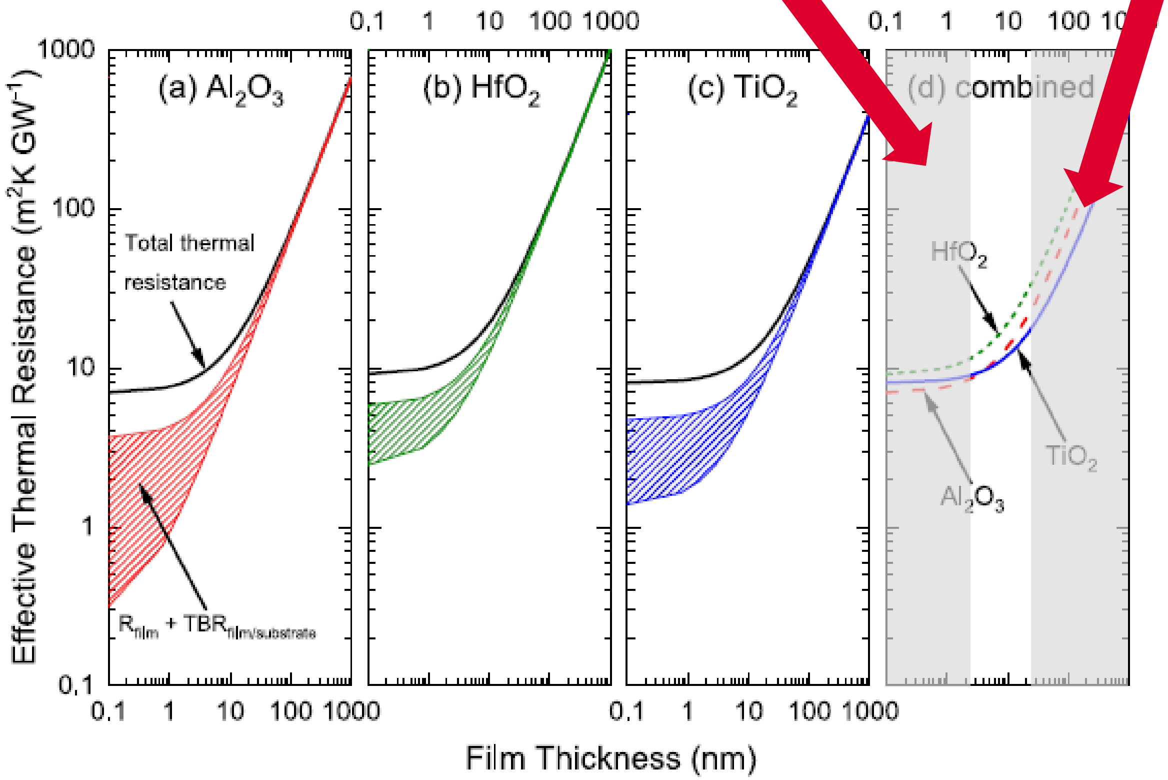
Pros:
- No heat capacity
- Total resistance

Cons:
- Cross- & In-plane coupled
- Reduced individual TBR sensitivity

No single method gives you everything!

What Thermal Properties Can We Separate?

Interface Dominated   Film Dominated



Interface Dominated

- Total signal mainly $R_1 + R_2$
- Common for thinner films or strong boundary effects
- Useful for constraining total resistance

Film Dominated

- Total signal mainly from film resistance
- Enables extraction of thermal conductivity
- With the right stack can emphasize in- vs. cross-plane thermal conductivity

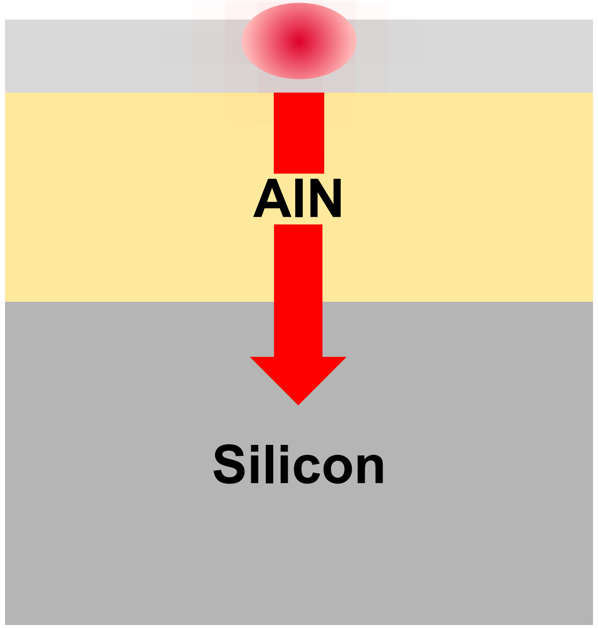
Stack design determines which property can be extracted.

APL Materials 6, 058302 (2018)

We Design the Stack to Isolate Material Properties

Cross-Plane, k⊥

Thick AlN on Si



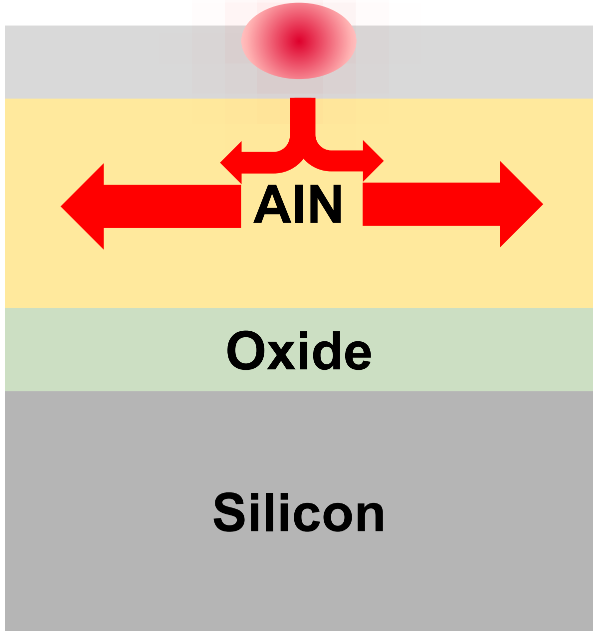
Maximize sensitivity to cross-plane thermal conductivity

- Stack design can be used as a metrology variable
- Instead of relying on one measurement, we utilize multiple measurements
- Increases confidence in results and variety of properties we can measure

Geometry determines sensitivity.

In-Plane, k∥

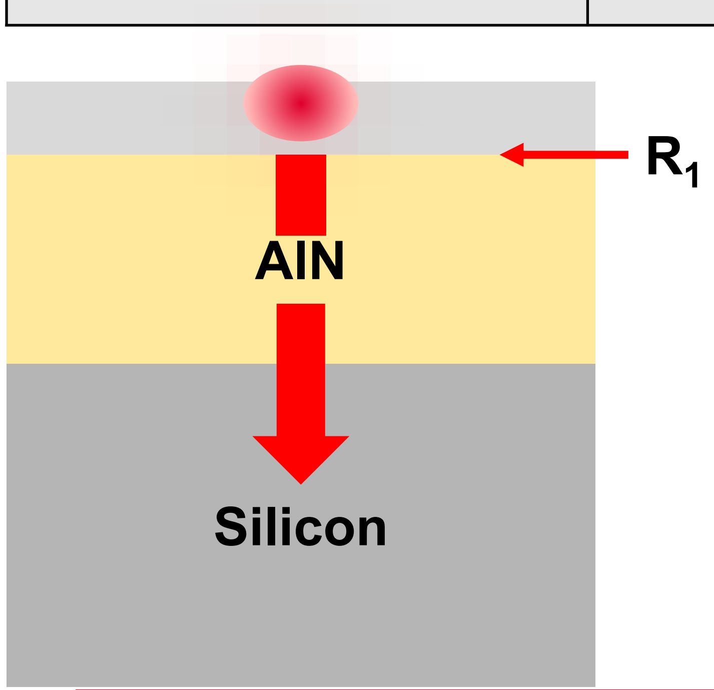
Thick AlN on Oxide/Si



Oxide thermally “shorts” heat, forcing in-plane sensitivity

TDTR Measures R_1 and Bounds k⊥

R_1, m^2 K GW^{-1}	k⊥ TC, W m^{-1} K^{-1}	Uncertainty, W m^{-1} K^{-1}	k‖ Assumption, W m^{-1} K^{-1}
4.8	131.7	15.3	30
4.7	127.8	14.5	60
4.6	124.5	13.9	90



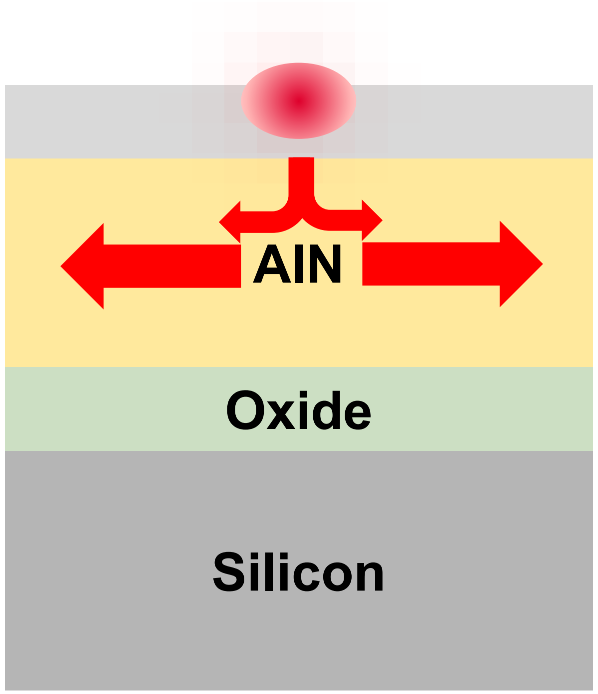
- Strongly sensitive to near-surface thermal resistance
- k⊥ weakly dependent on assumed k‖
- Response remains coupled to R_2 and heat capacity
- TDTR alone cannot decouple all parameters

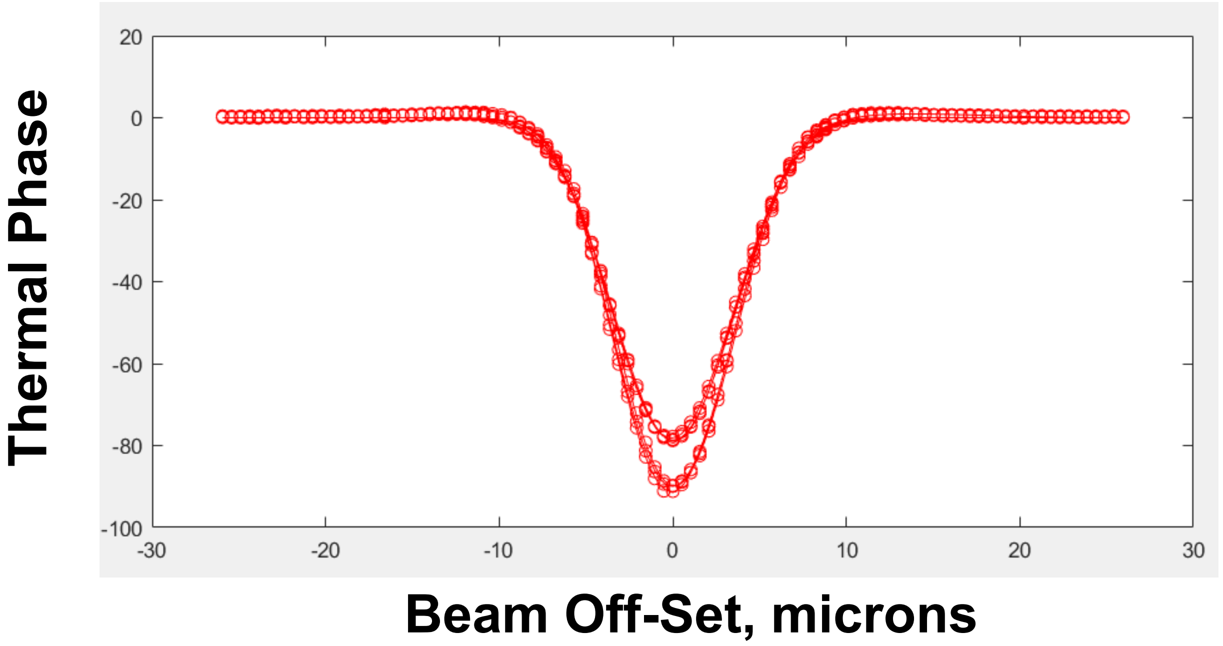
TDTR provides a reliable constraint on R_1 and a bounded estimate of k⊥

SSTR Isolates k∥

$k_\parallel = 61.1 \pm 5.4\ W\ m^{-1}\ K^{-1}$

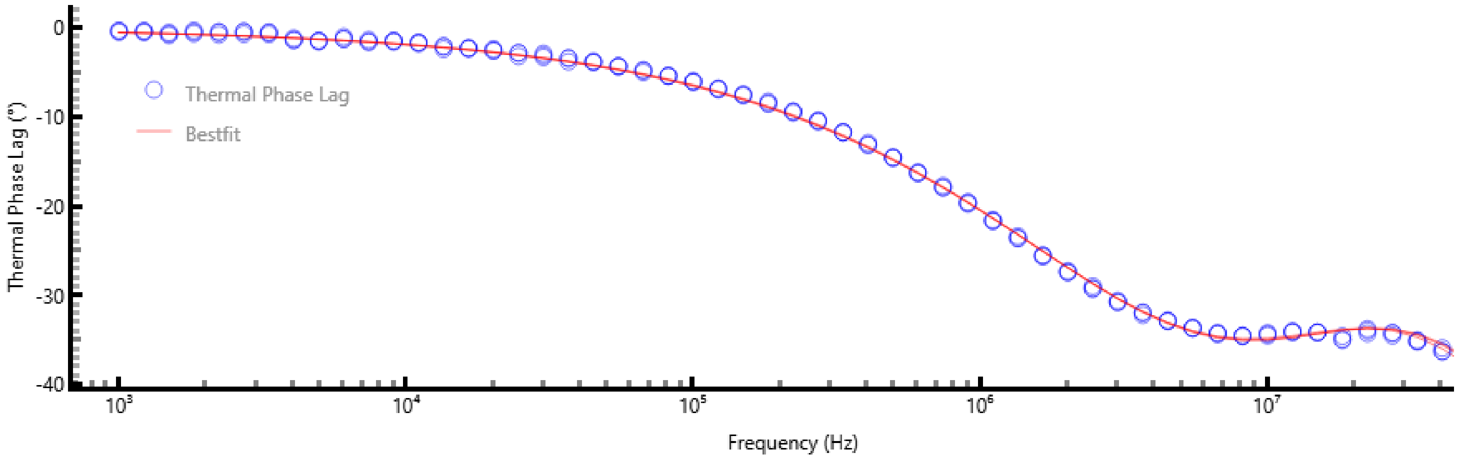
$k_\parallel = 60.5 \pm 9.2\ W\ m^{-1}\ K^{-1}$

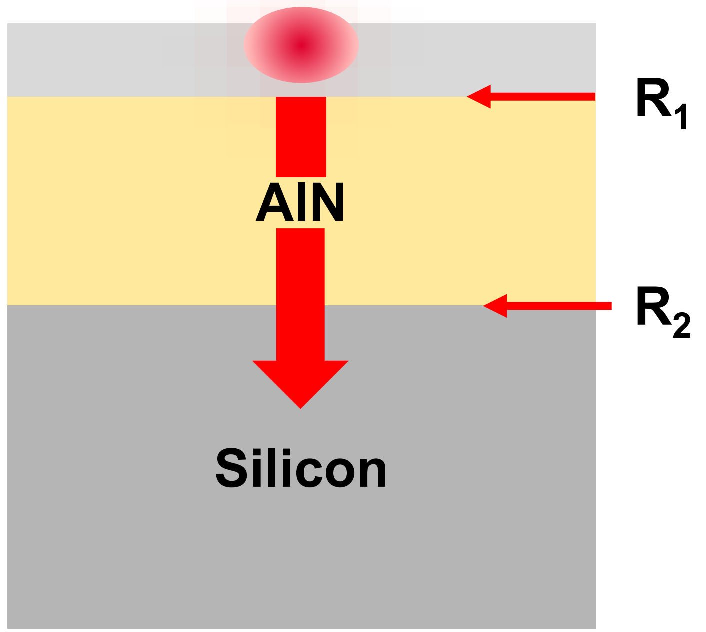




SSTR and Beam Off-Set measurements yield same result.

FDTR Separates k⊥, R_1, and R_2





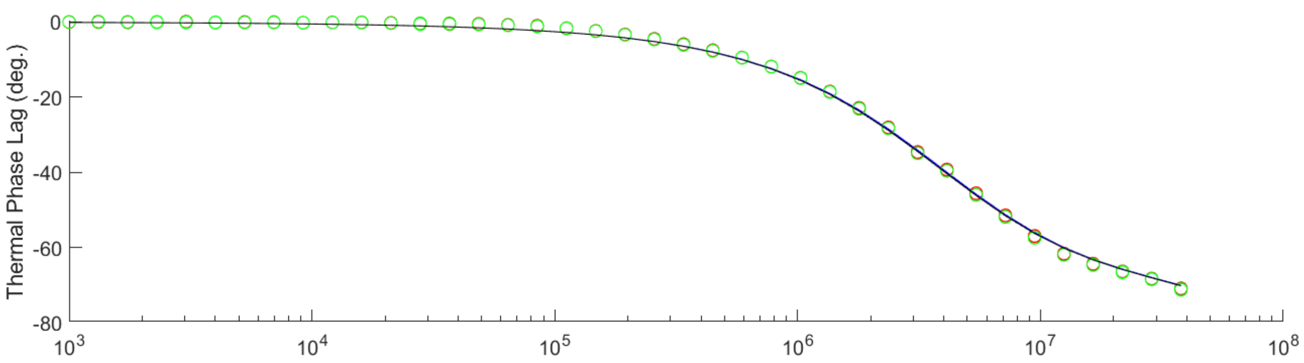
- In-plane from SSTR/Beam Off-set used
- Sensitivity to cross-plane, R_1, and R_2 at different frequency regimes
- Matches TDTR values for R_1 and k⊥ within uncertainty bounds

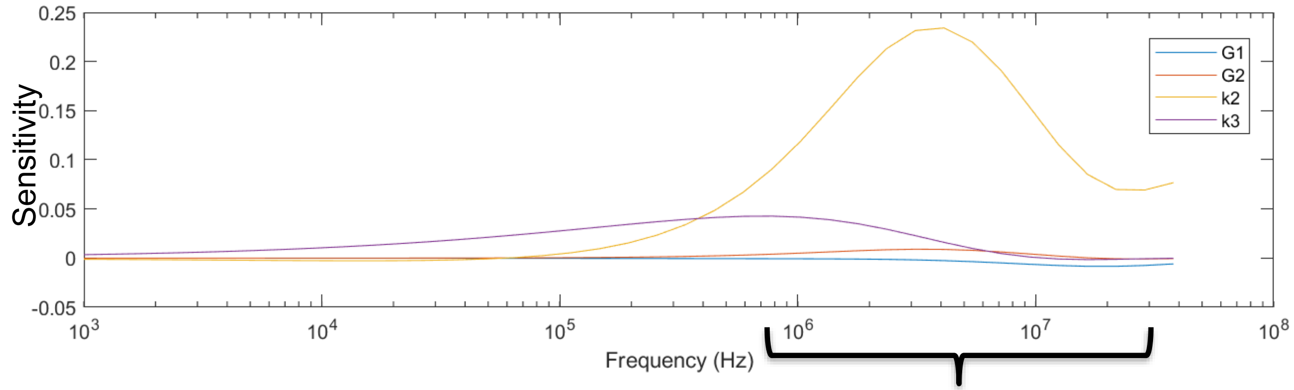
k⊥ = 119.1 +/- 4.3 W m^{-1} K^{-1}

R_1 = 4.8 +/- .2 m^2 K GW^{-1}

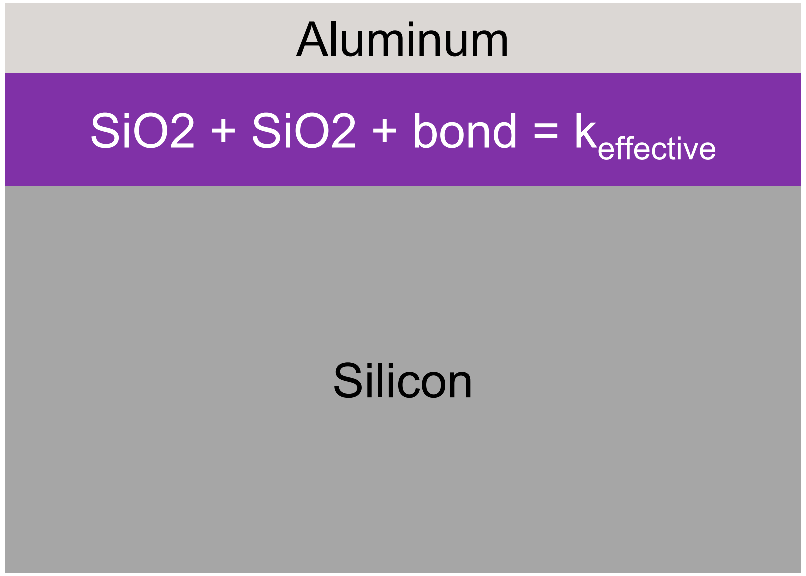
R_2 = 7.5 +/- .5 m^2 K GW^{-1}

Extension Beyond AlN – Bonded Interfaces



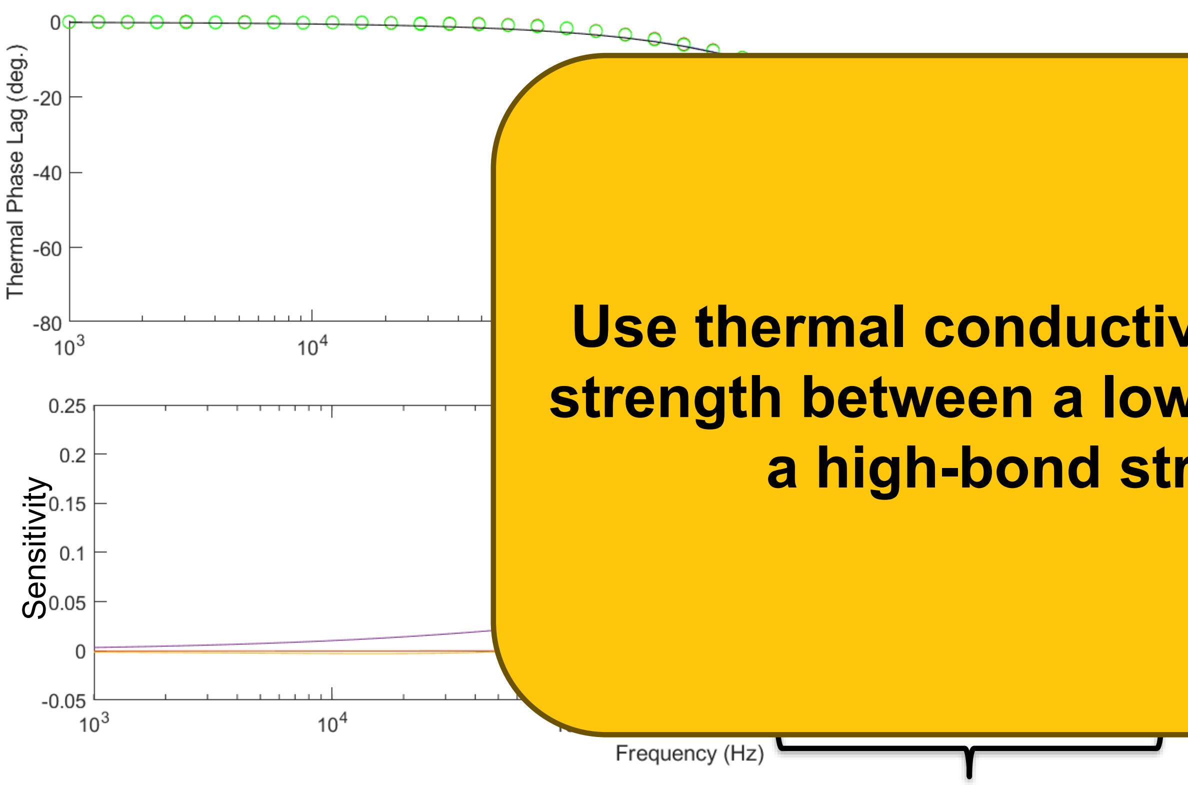


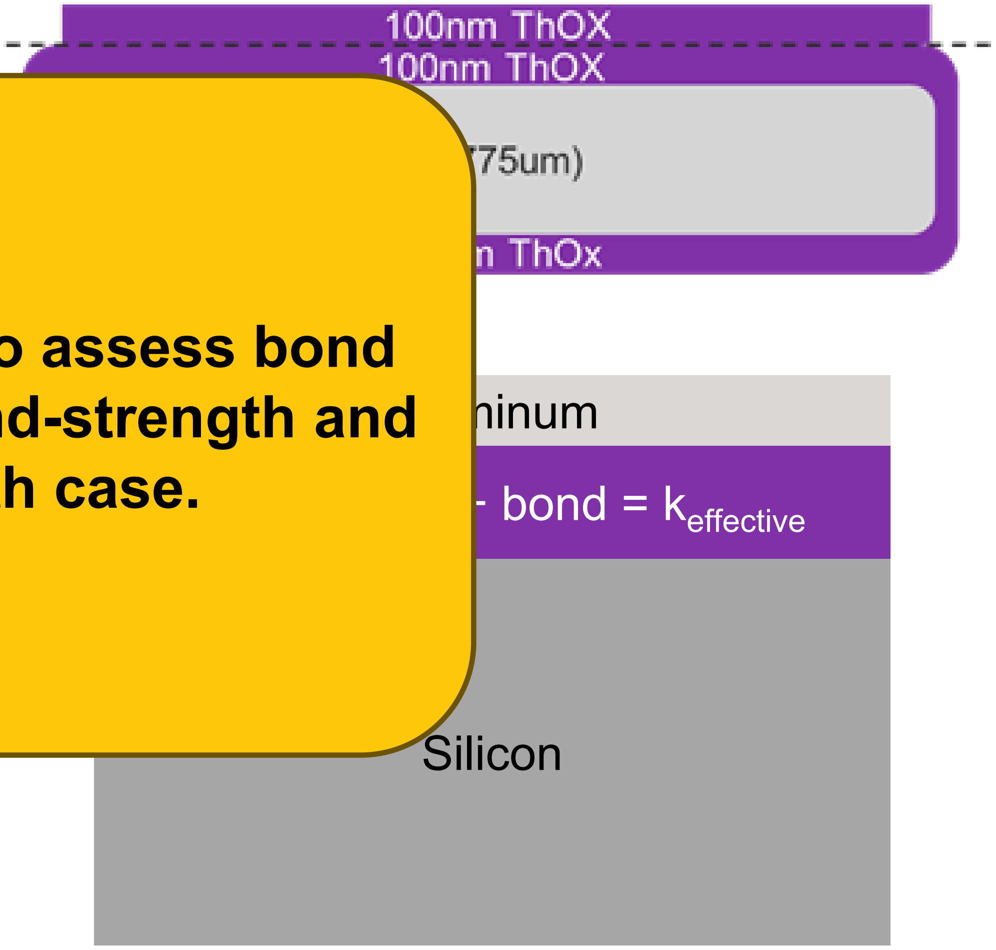
Maximum sensitivity to k⊥ (oxide+oxide)



Acknowledgment: Andrew Tuchman, Ilseok Son

Extension Beyond AlN – Bonded Interfaces



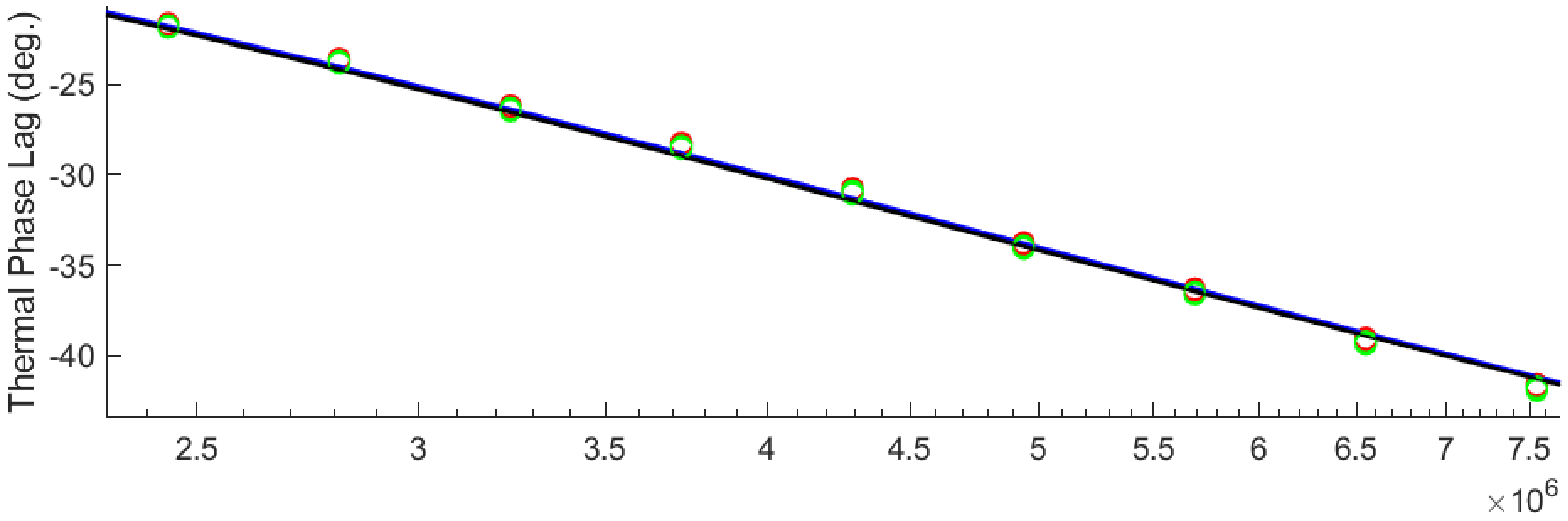


Use thermal conductivity to assess bond strength between a low bond-strength and a high-bond strength case.

Maximum sensitivity to k⊥ (oxide+oxide)

Acknowledgment: Andrew Tuchman, Ilseok Son

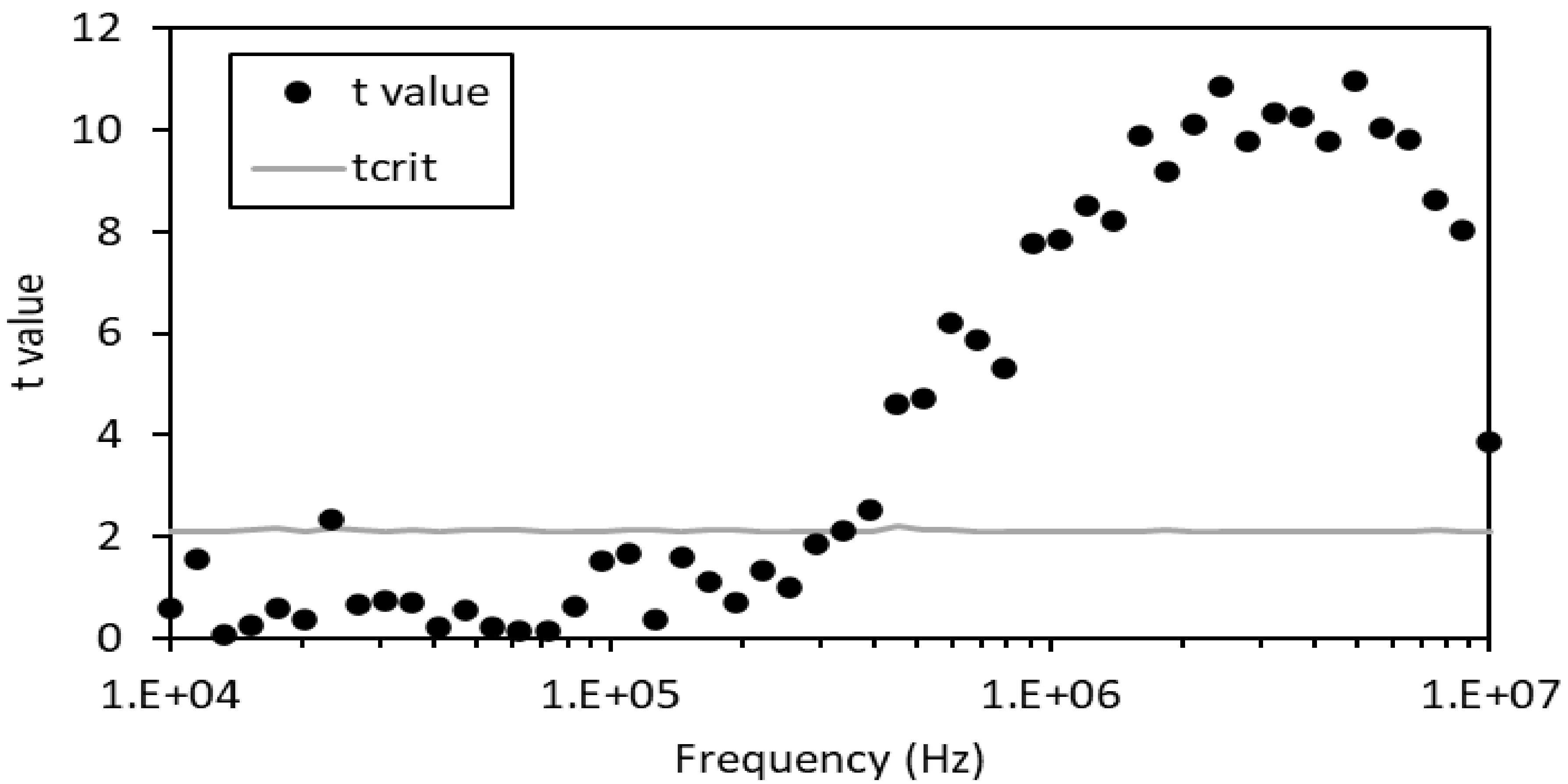
Extension Beyond AlN – Bonded Interfaces



In areas of highest sensitivity, signals differ by ~ 0.6%.

Acknowledgment: Andrew Tuchman, Ilseok Son

Extension Beyond AlN – Bonded Interfaces

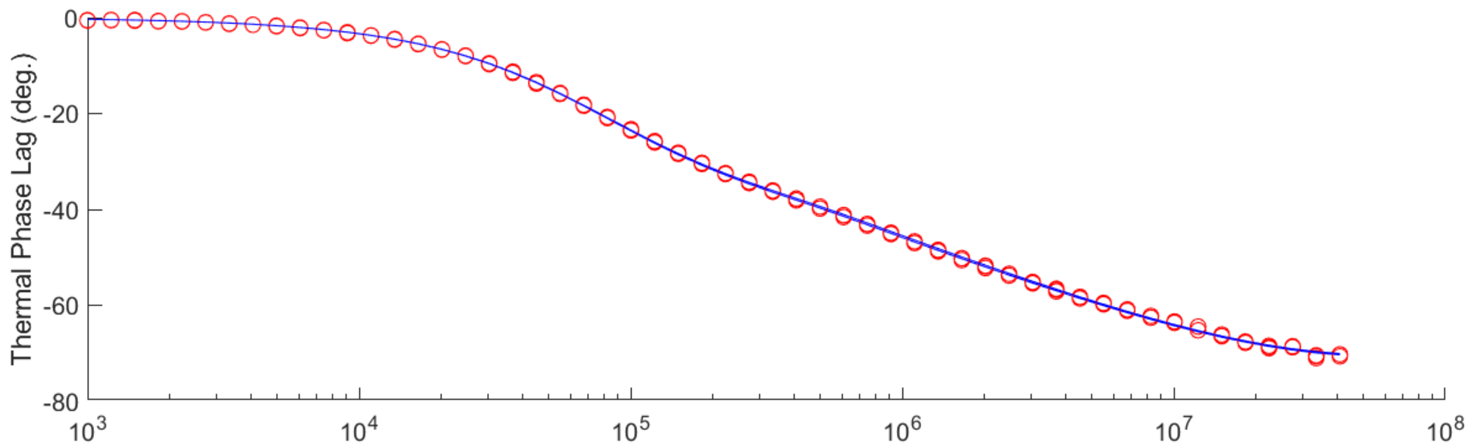


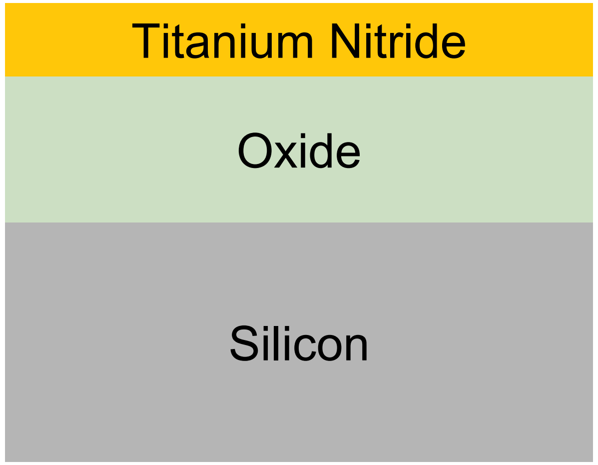
And are statistically significantly different.

Acknowledgment: Andrew Tuchman, Ilseok Son

Extension Beyond Aluminum as a Transducer

- **Direct measurement of TiN in-plane thermal conductivity.**

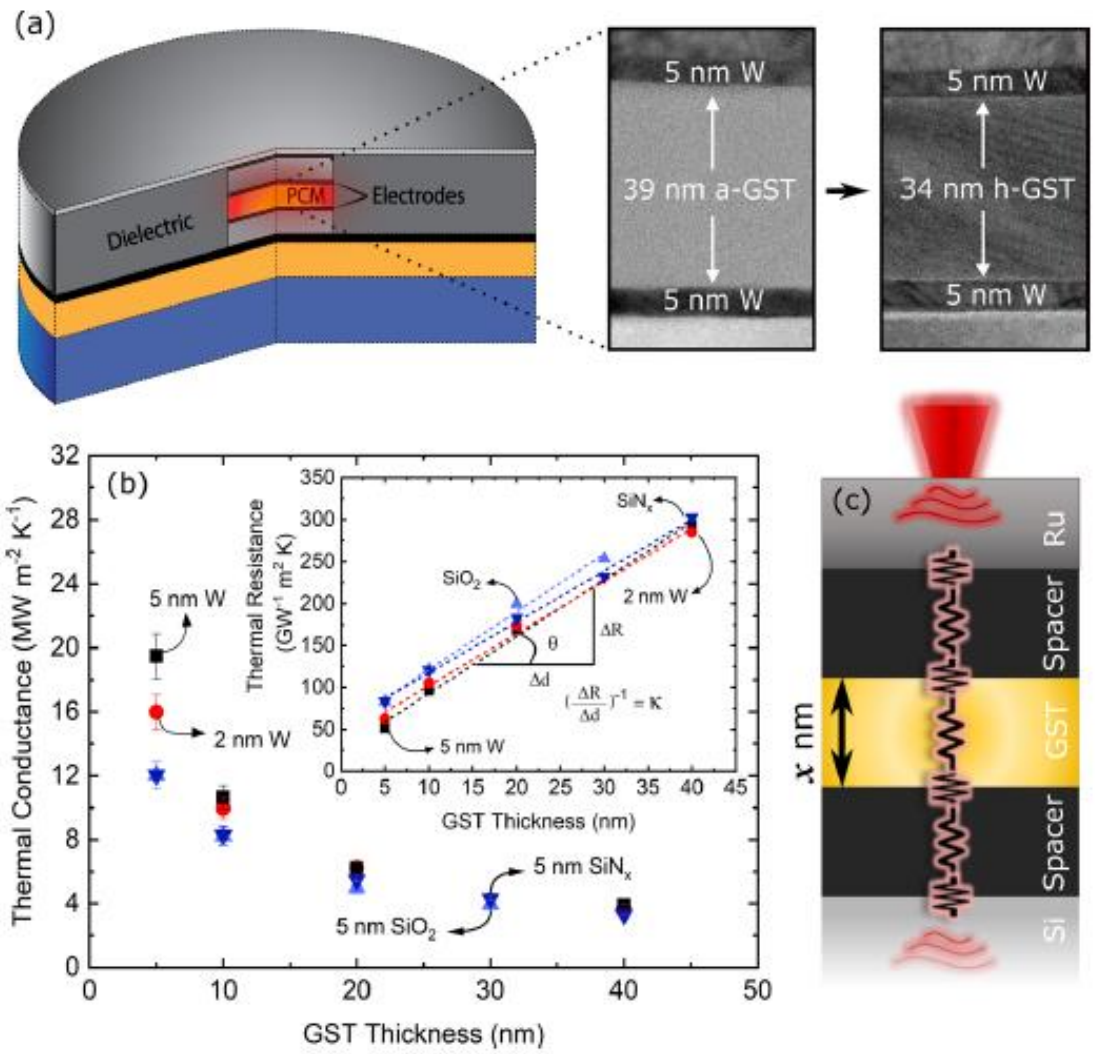




Resistivity (μΩ·cm)	k‖ electrical ($Wm^{-1}K^{-1}$)	k‖ ($Wm^{-1}K^{-1}$)
184	3.9	11

Extension Beyond Aluminum as a Transducer

- Ruthenium as a transducer
- Investigating spacer/thickness effects on thermal resistance
- Temperature dependent measurements through, and back from, phase change transitions



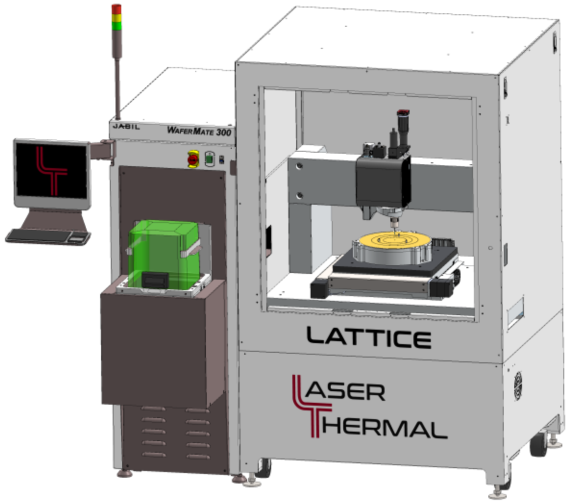
Nature Communications | (2021) 12:774 | https://doi.org/10.1038/s41467-020-20661-8 |

Toward Manufacturing Relevant Thermal Metrology

Available Now → First Prototype Q3 2026 Available Q1 2027 → In Development Prototype Q1 2027

FASTR 150
150 mm XY Travel
Coupon Batch Testing
R&D and FA uses
Room Temperature – 400 °C

FASTR 300
300 mm XY Travel
Manual Wafer Loading
Process Property Correlation
Wafer Scale Thermal Testing



FASTR 300 EFEM (LATTICE)
300 mm XY Travel
Automated Wafer Loading/Handling
Higher Throughput
Wafer Scale Thermal Testing

Key Takeaways

- Advanced architectures increase the importance of thermal materials
- Thin-film properties need to be measured, not assumed
- Combinations of thermoreflectance techniques and stack design offer practical paths forward
- Thermal metrology is needed and will become increasingly important