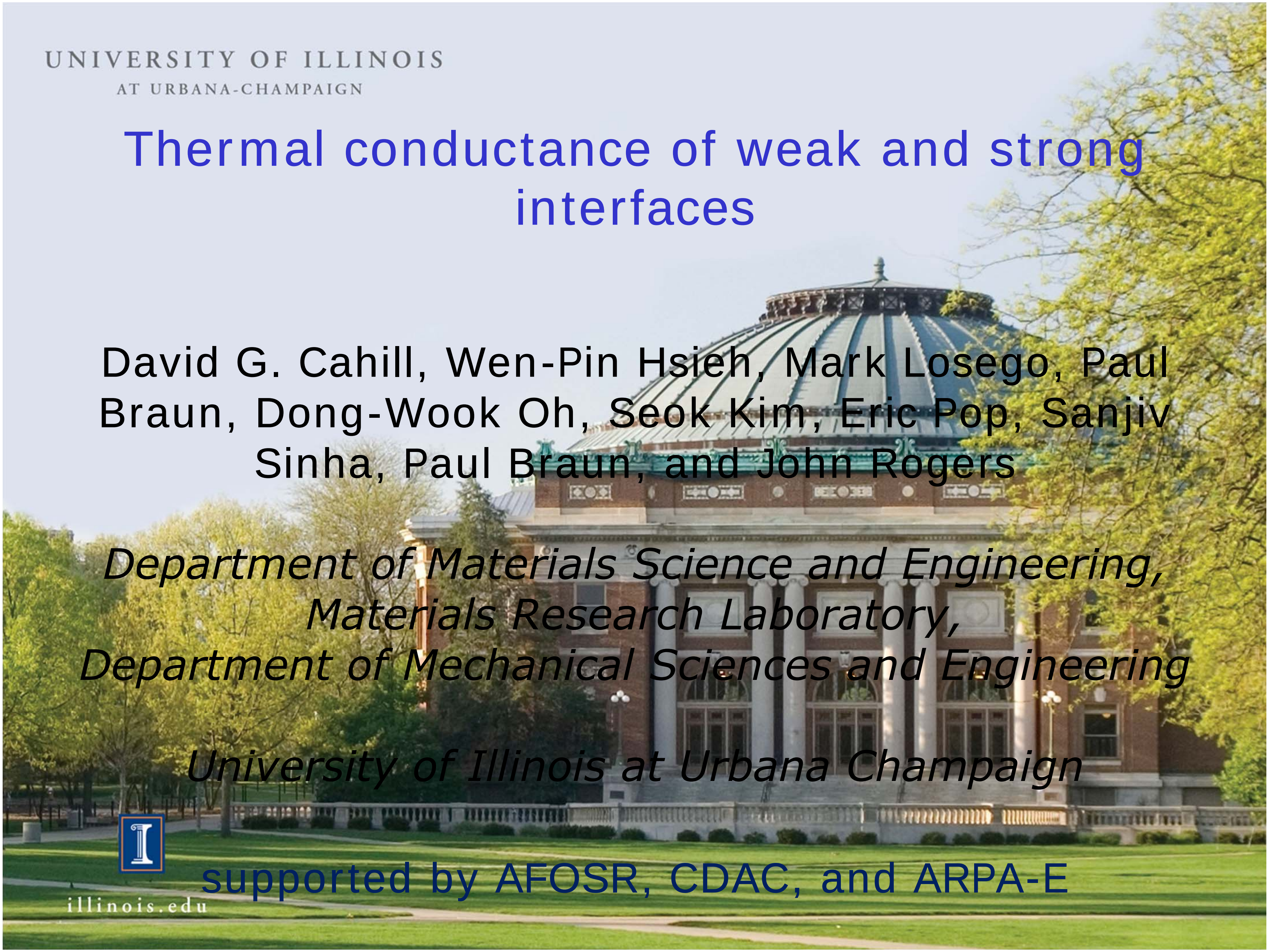

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Thermal conductance of weak and strong interfaces

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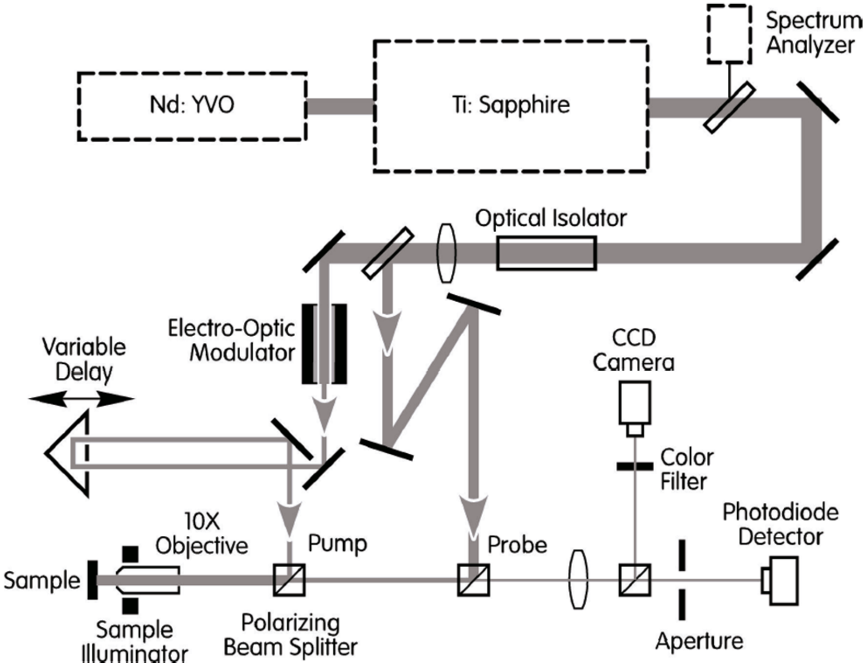
Outline

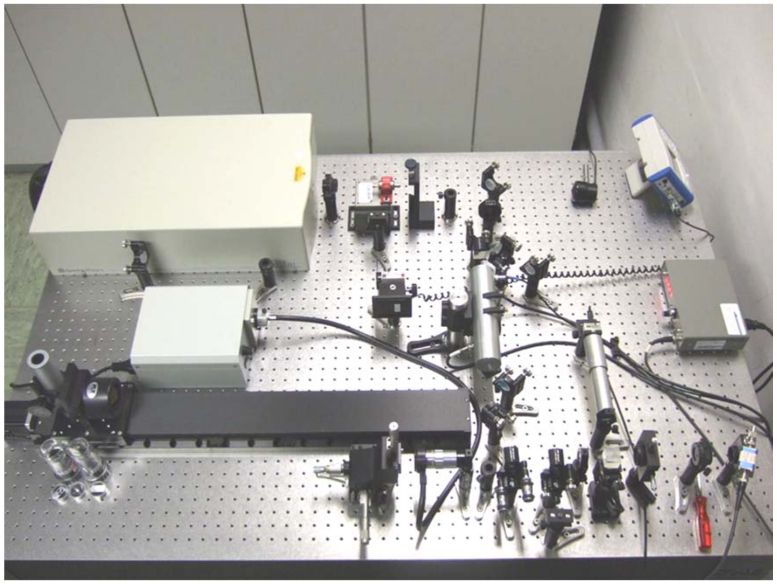
- Modify thermal conductance of interfaces using
  - chemistry: transfer-printing on self-assembled monolayers with controlled chemistry
  - pressure: systematically vary the strength of weak, anharmonic, interfacial bonds
  - morphology: transfer-printing of rough and smooth films on a variety of elastically stiff substrates

Time domain thermoreflectance (TDTR)since 2003

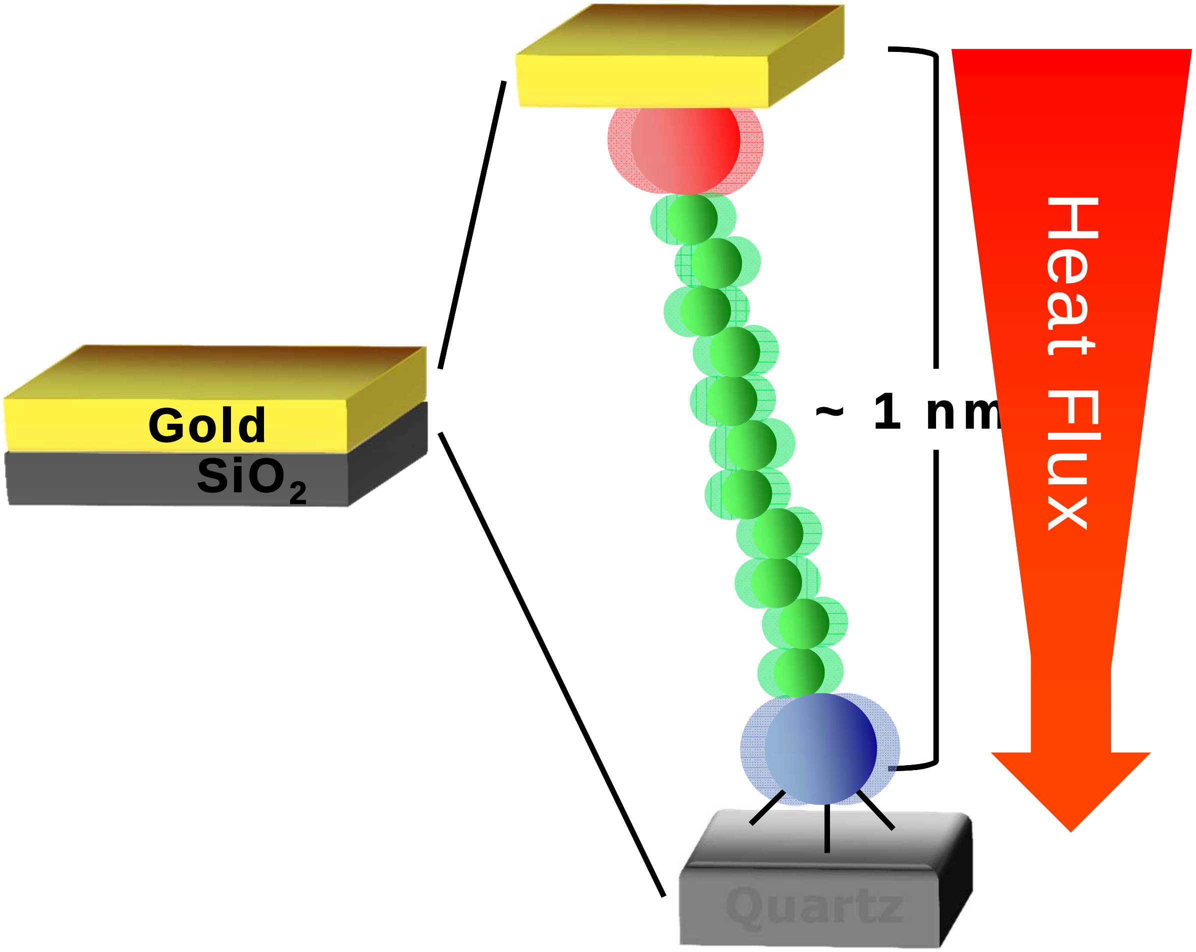
- Improved optical design
- Normalization by out-of-phase signal eliminates artifacts, increases dynamic range and improves sensitivity
- Exact analytical model for Gaussian beams and arbitrary layered geometries
- One-laser/two-color approach tolerates diffuse scattering

Clone built at Fraunhofer Institute for Physical Measurement, Jan. 7-8 2008





Self-assembled monolayers with controlled chemistry



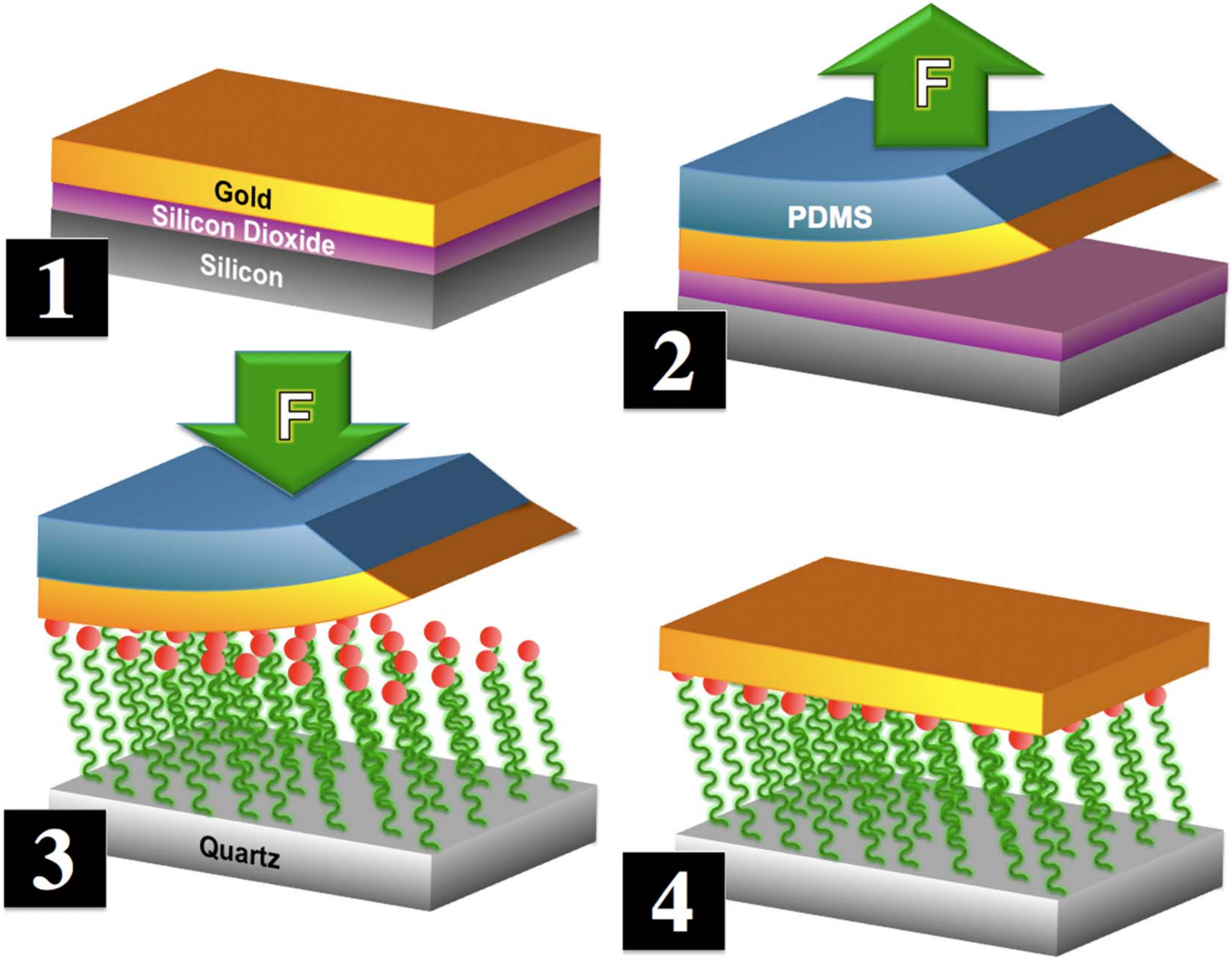
1. Can we modify the thermal conductance of an interface by introducing a molecular layer?

2. What parameters matter?

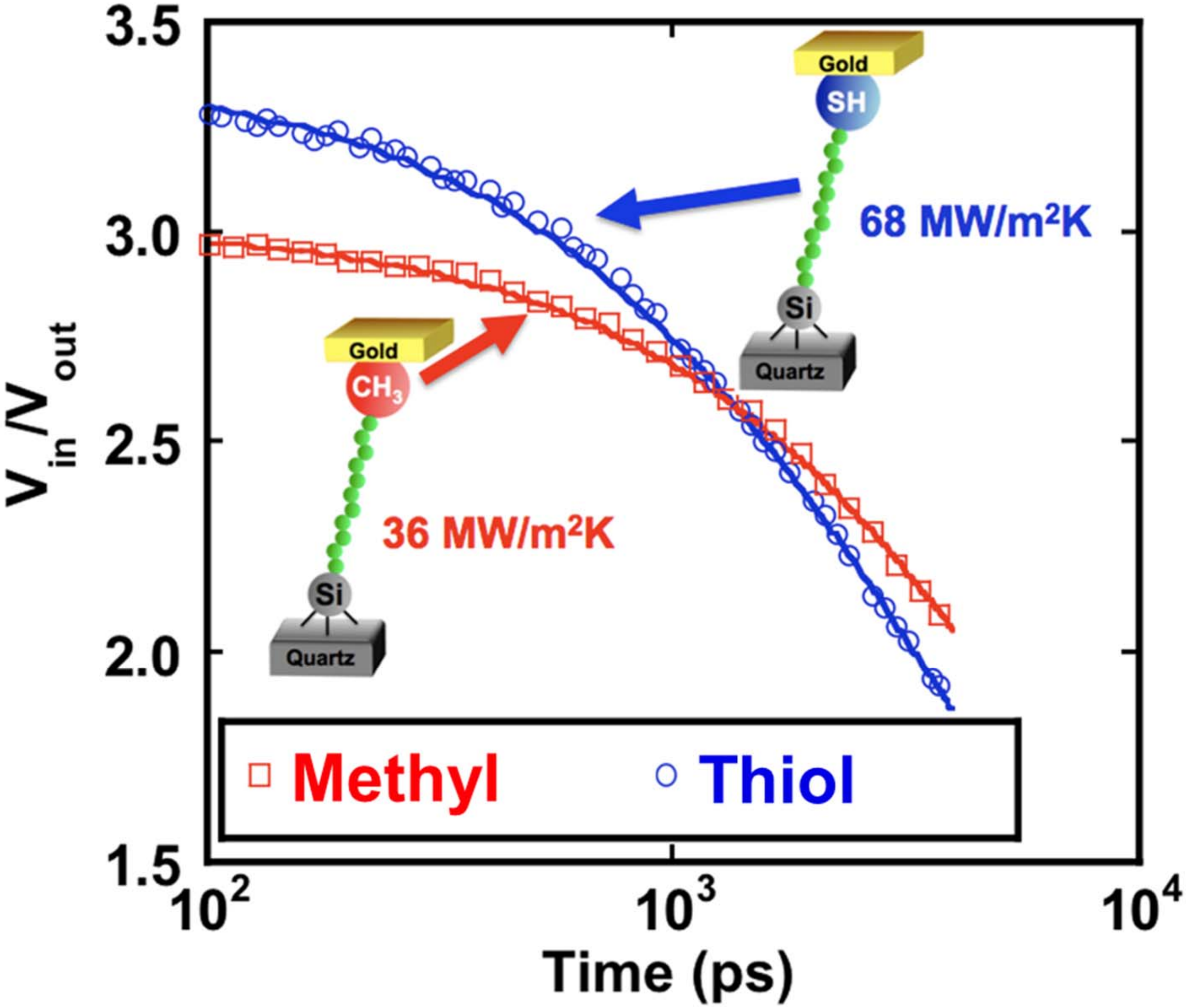
-Bonding?

-Chain Length?

Transfer printing of Au film to SAM-coated quartz

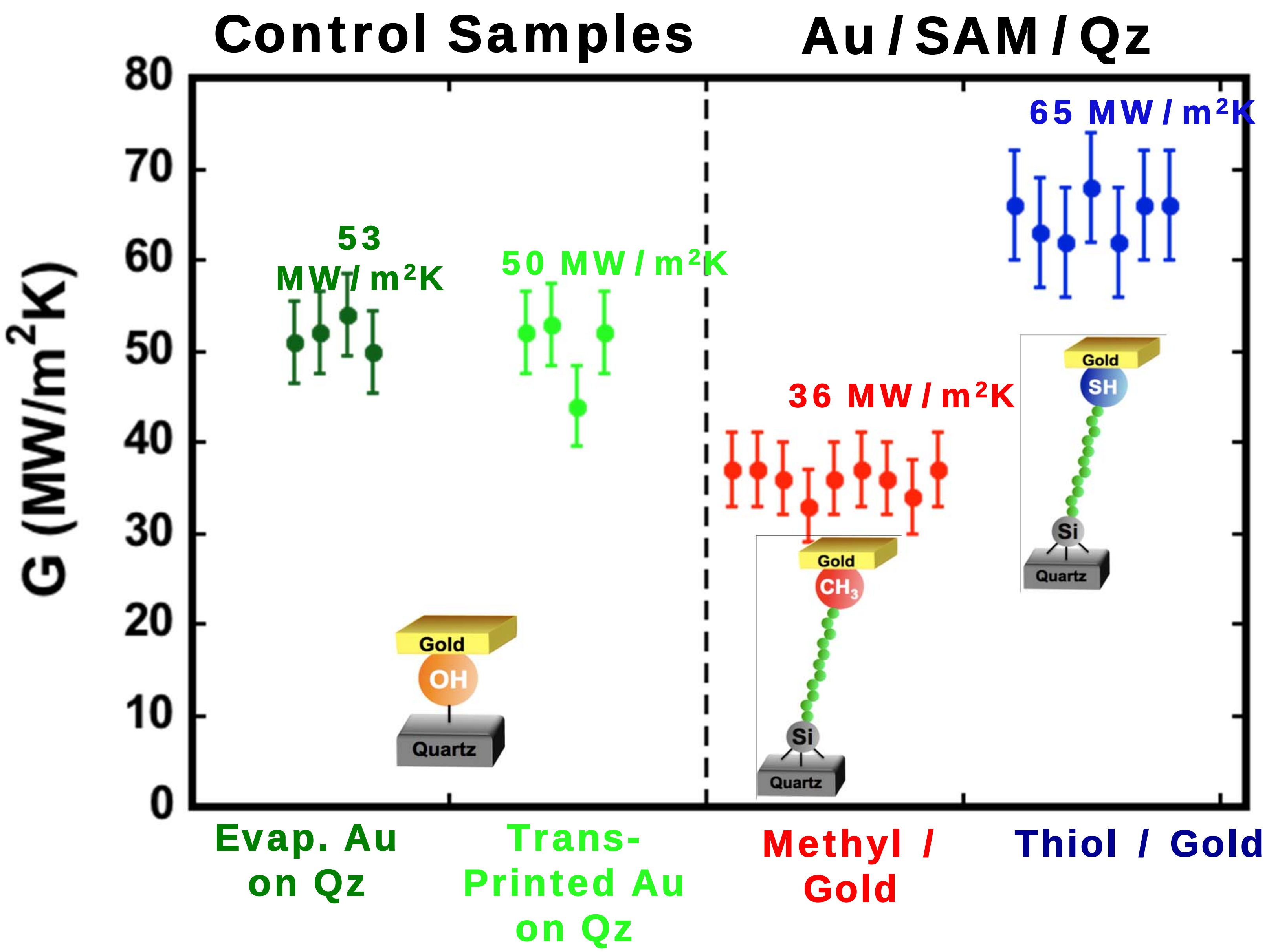


TDTR data for Au/SAM/quartz interfaces



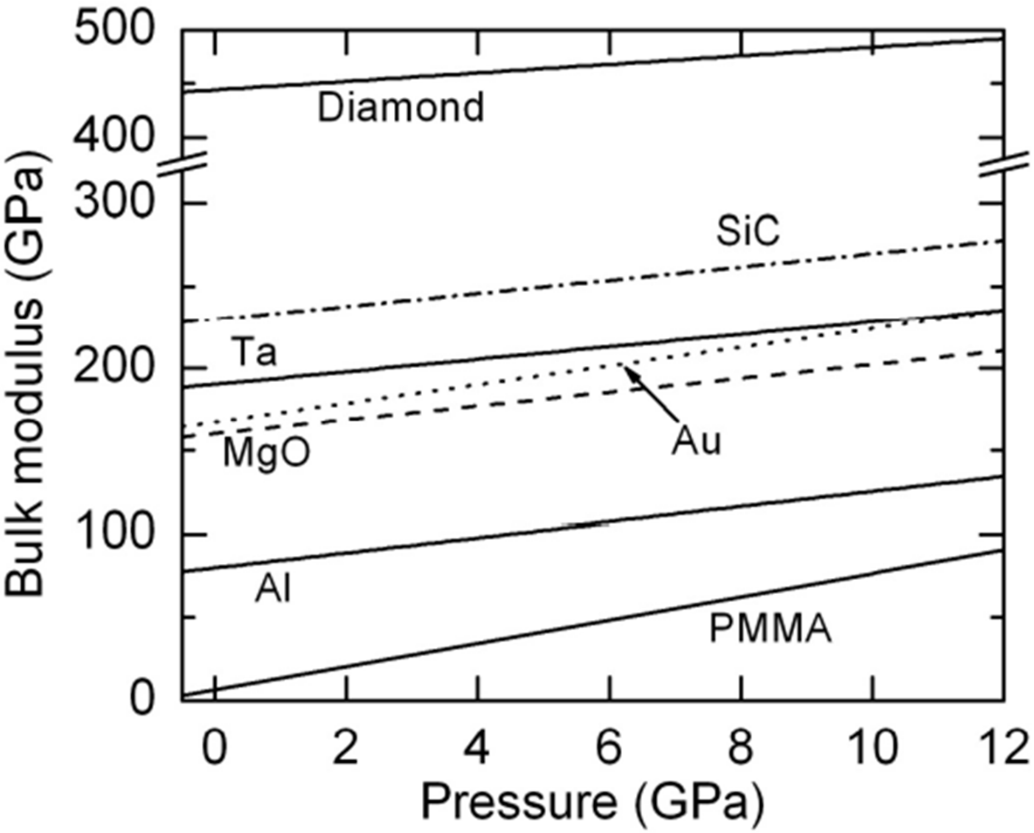
Observe faster temperature decay for the stronger bonded Au/thiol interface

Interfacial bonding controls conductance G



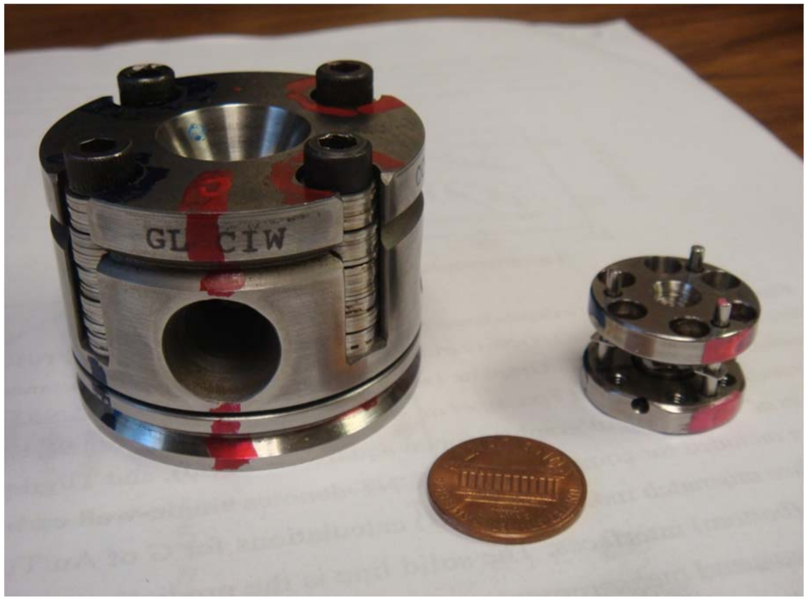
What can pressure dependence tell us about thermal transport at interfaces?

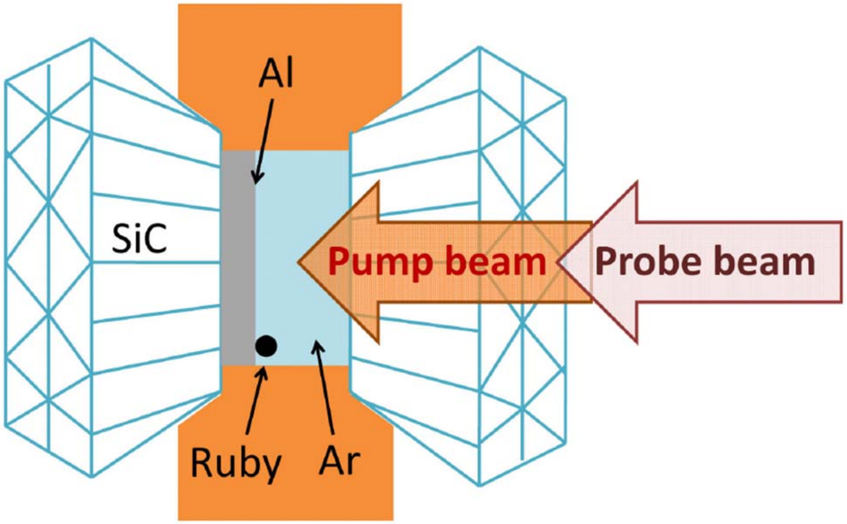
- Elastic constants and phonon spectra of typical materials do not change much between 0 <P <10 GPa.
- But weak interface bonds are expected to be highly anharmonic (more like PMMA than diamond)



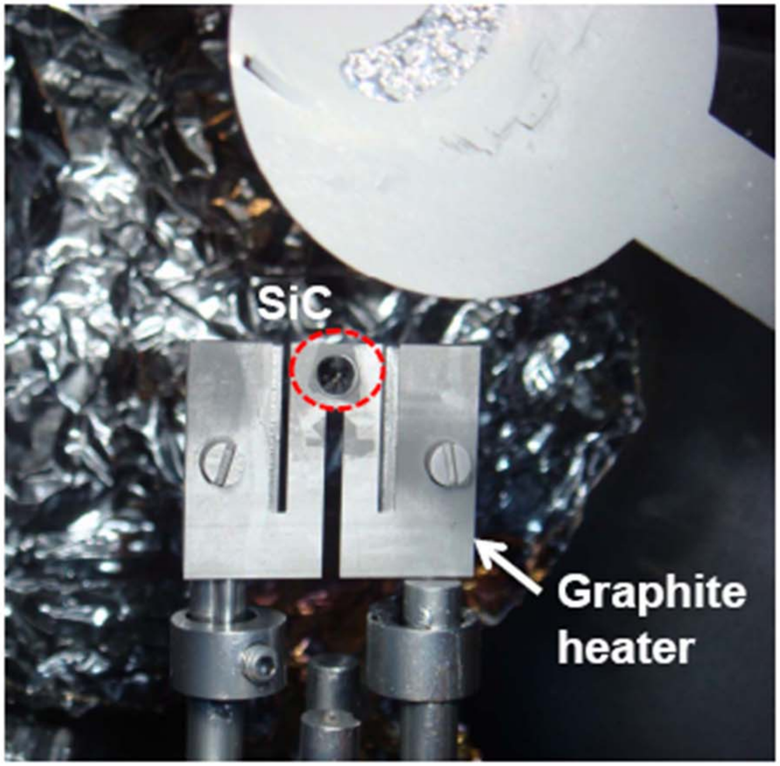
TDTR is all optical method: adaptable to "extreme" environments such as high pressure

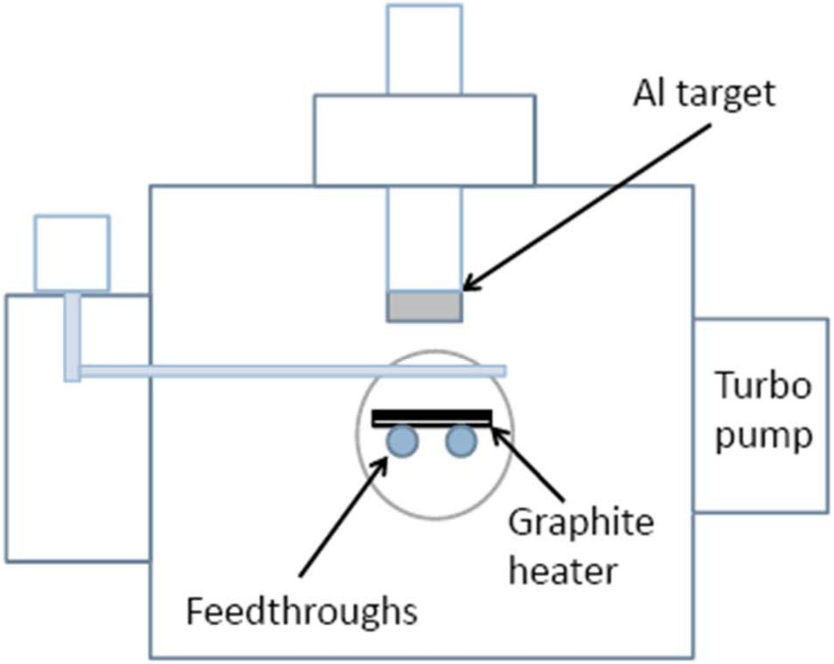
Diamond anvil cell





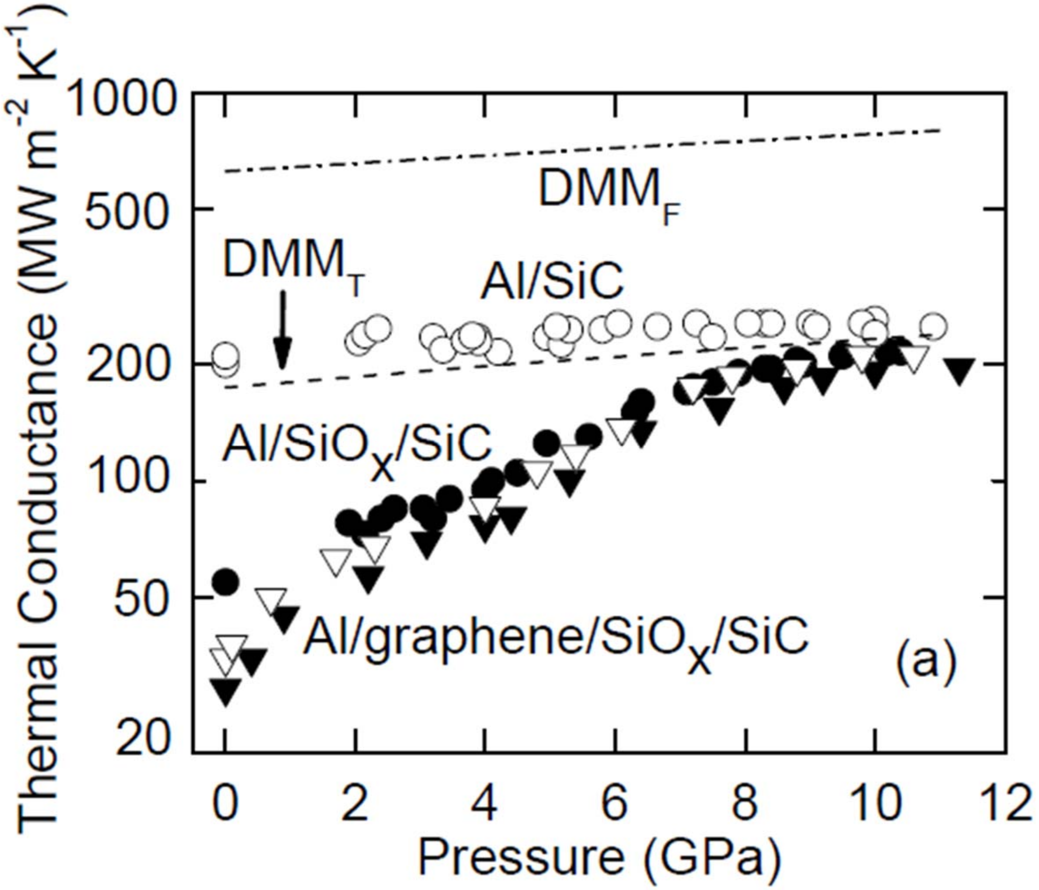
Clean SiC anvil at high temperatures and deposit Al film *in-situ* by sputtering



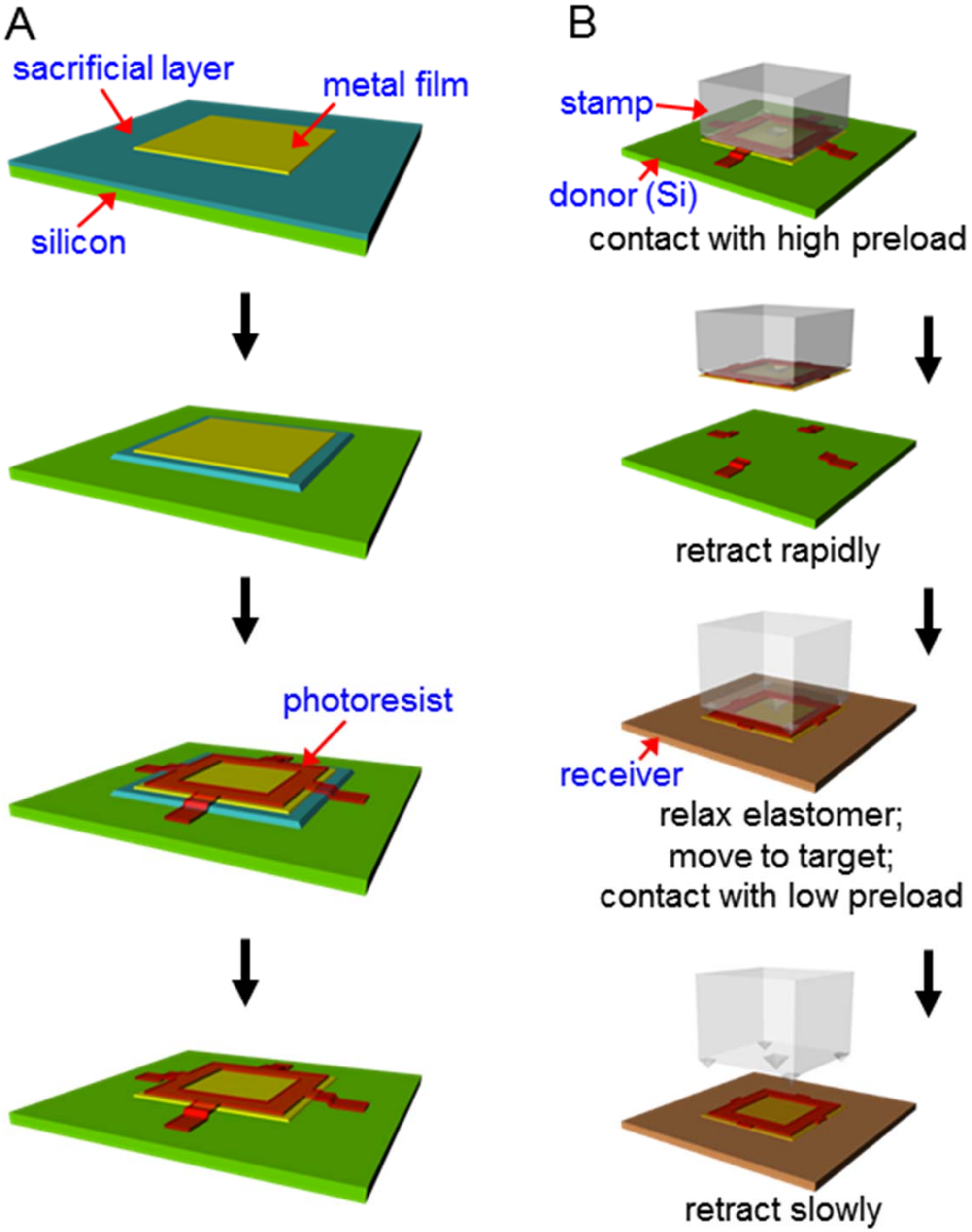


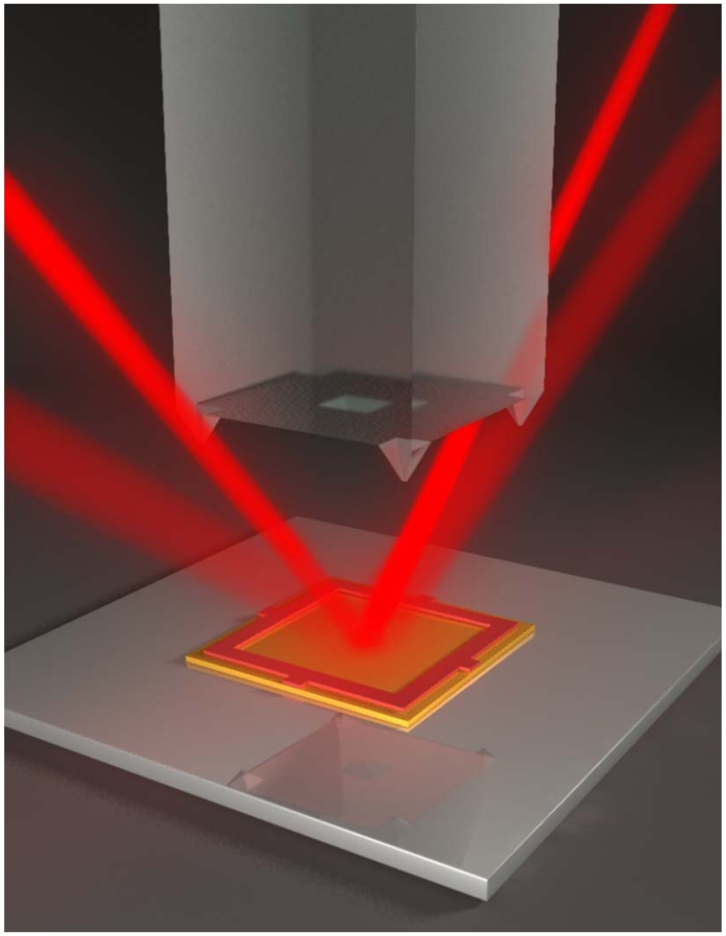
Compare clean interface with a layer of CVD graphene inserted at the interface

- Clean interface has the weak pressure dependence expected from diffuse-mismatch (DMM) calculations.
- Insert graphene: low conductance and strong pressure dependence.
- At P>8 GPa, “weak” interface becomes “strong” and conductance is high.



Assemble interfaces by transfer-printing

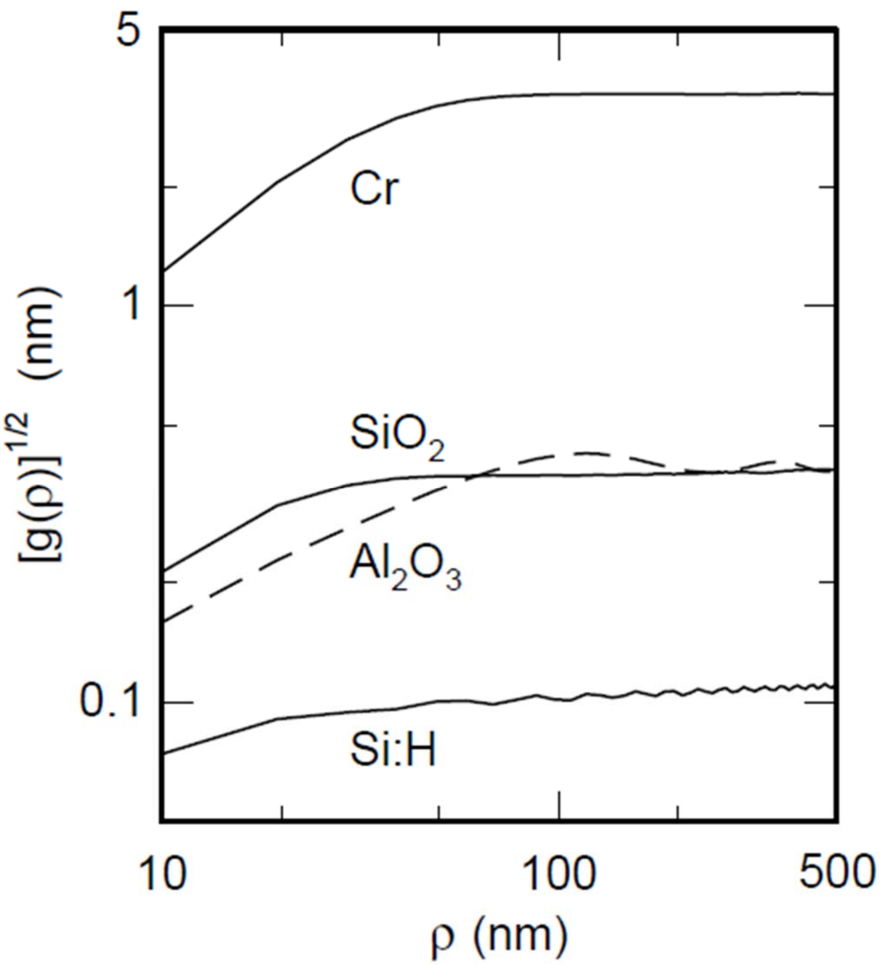




Use height-difference correlation function to characterize roughness

$$g(\rho) = \langle (h_i - h_j)^2 \rangle$$

- h_i, h_j are surface heights at locations i,j; ρ is the distance between i,j.
- Assume that roughness of the sacrificial layers (Cr for Au(Pd) and SiO_2 for Au) is approximately the same as the roughness of the metal film "ink".
- SiO_2, sapphire (Al_2O_3) and hydrogen terminated Si (Si:H) substrates.



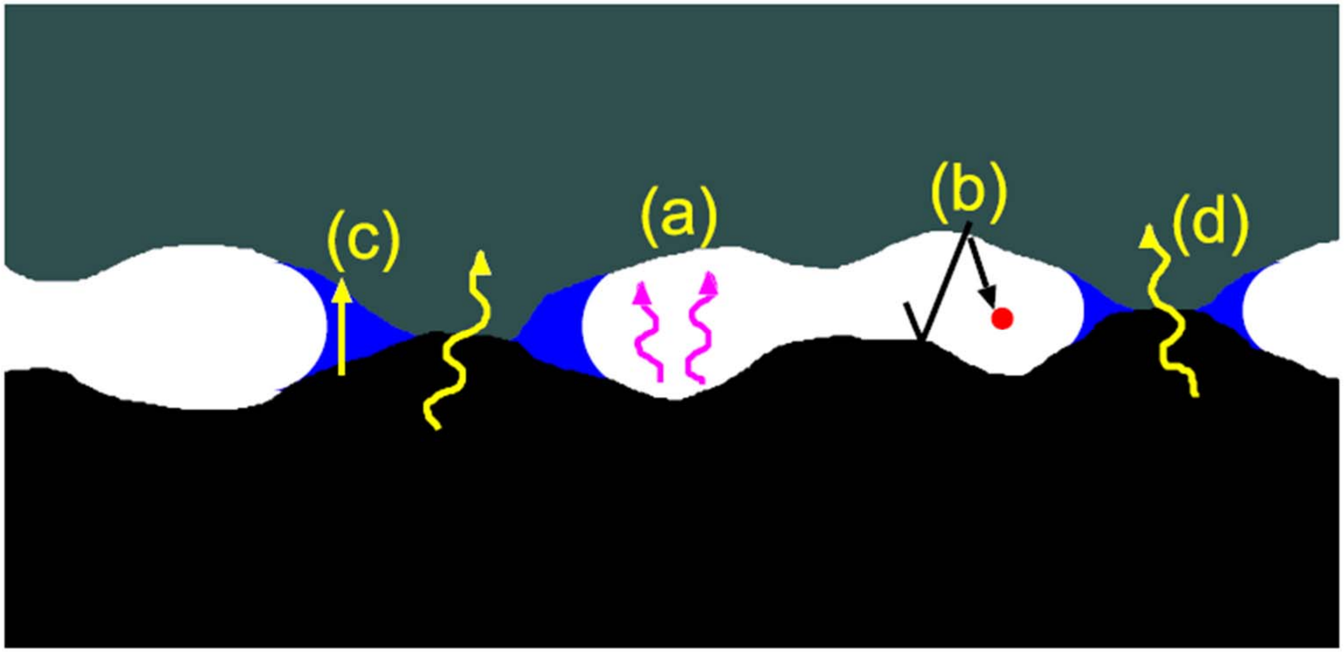
Possible mechanisms for heat transfer at an interface between two elastically stiff solids (Persson 2010)

(a) near-field electromagnetic radiation

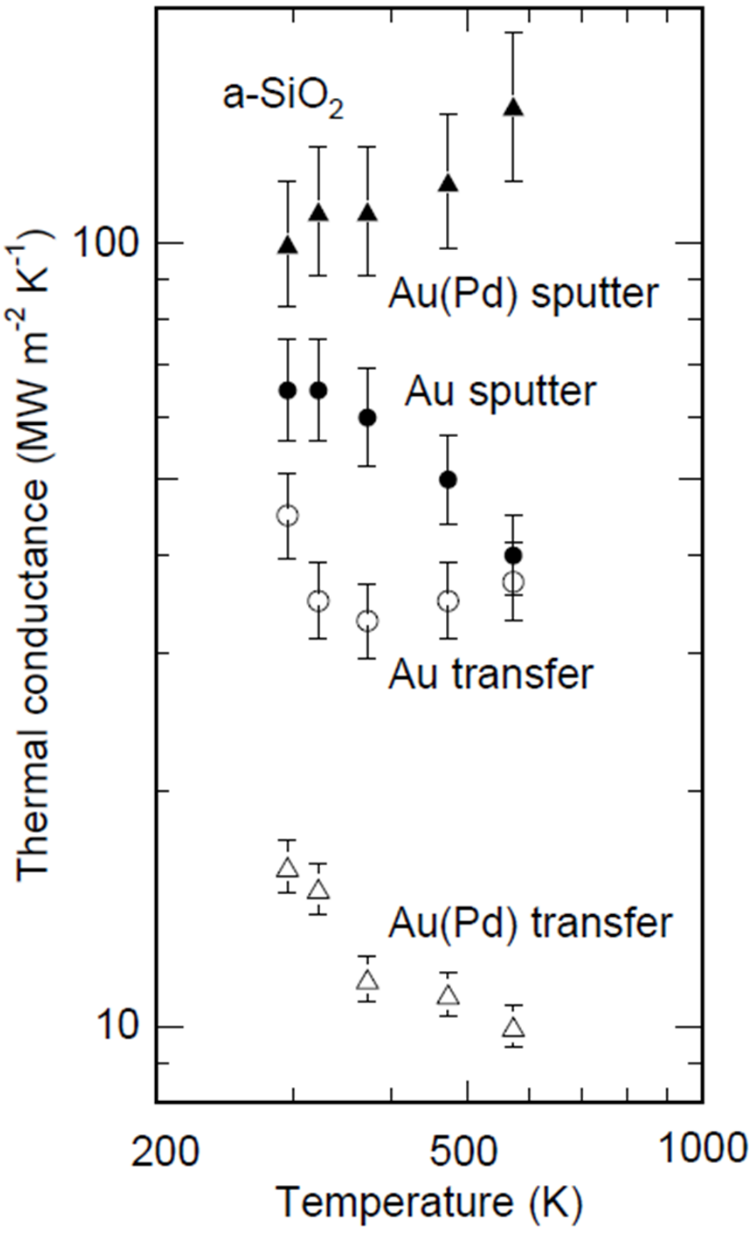
(b) gas conduction

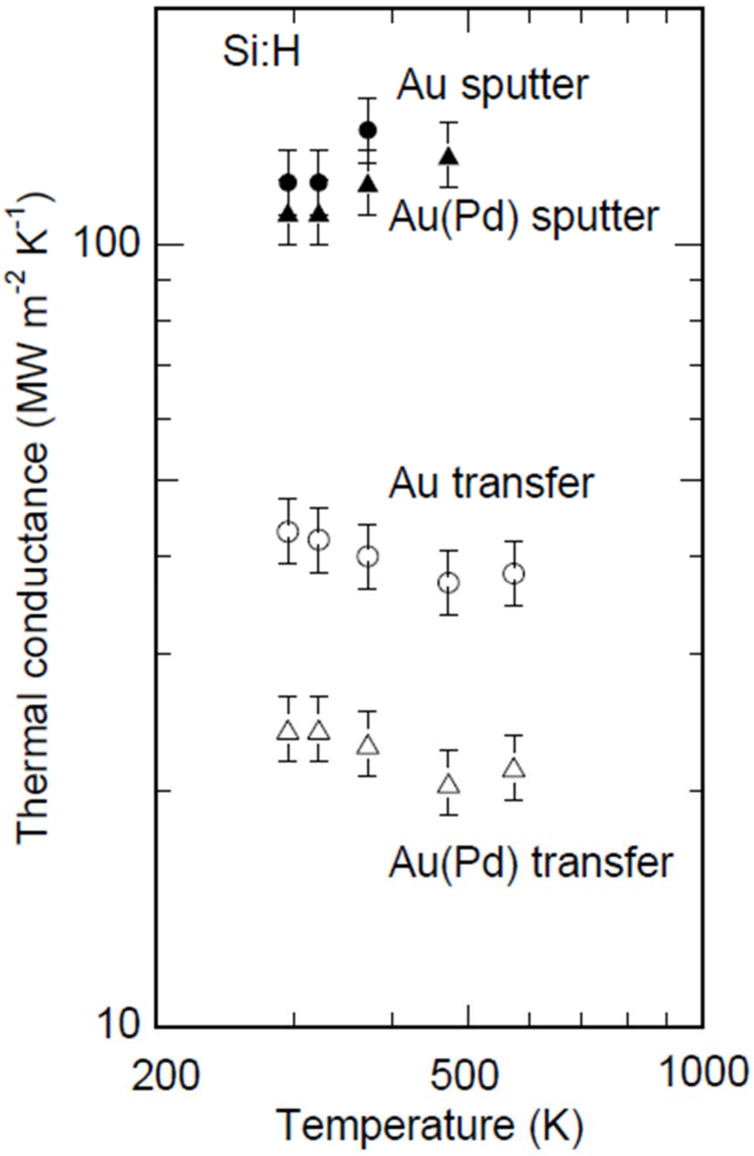
(c) conduction through H_2O liquid bridges

(d) conduction across true area of contact

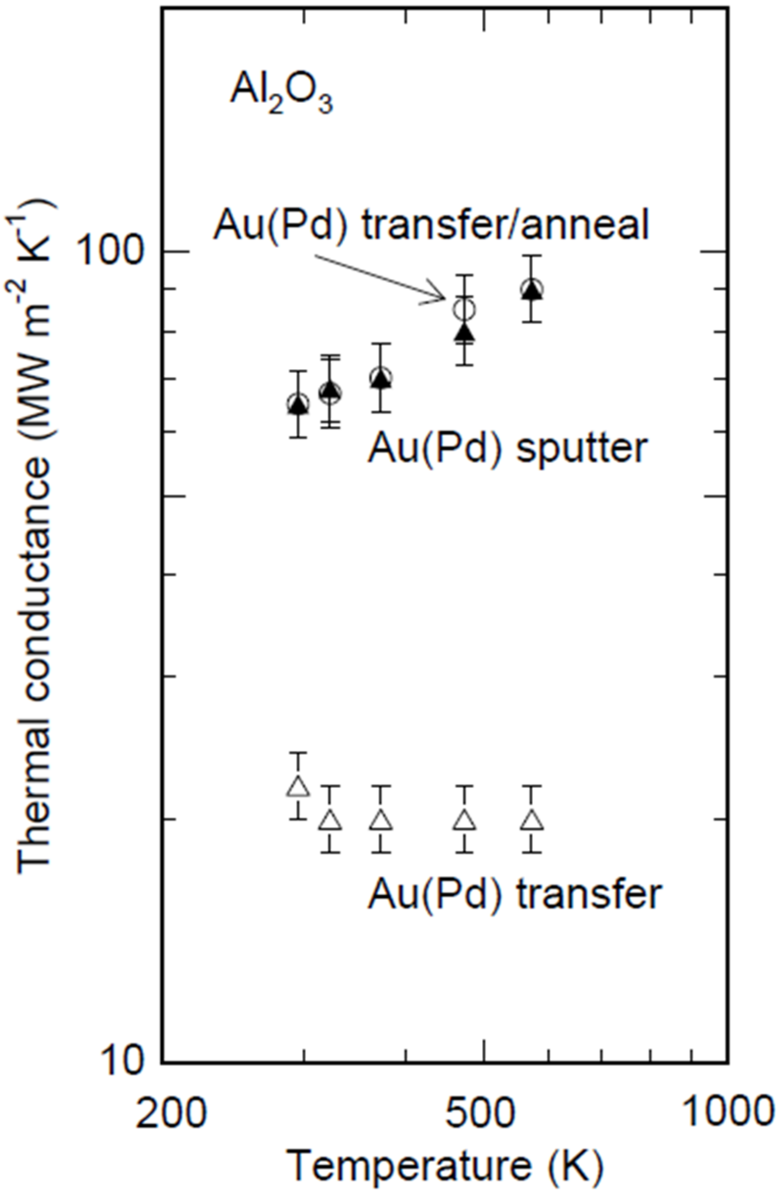


Compare interfaces formed by transfer-printing and sputter deposition





Compare interfaces formed by transfer-printing, sputter deposition, and transfer-print+anneal



Data provide insight and constraints on mechanisms

(a) Near-field electromagnetic radiation is not significant.

Si has no infrared active vibrational modes at long wavelengths. Temperature dependence for transfer-printed interfaces is weak: near-field radiation not an important factor

(b) Gas conduction is not significant.

Small on the scale of our observations

$$G \approx \Lambda\alpha / \lambda \approx 0.1\ \mathrm{MW\ m^{-2}\ K^{-1}}$$

(c) Conductance through H_2O liquid bridges is observable

G initially drops with increasing temperature as capillary bridges are removed but conductance remains high

(d) Conductance through true area of contact.

Relatively large G is caused by relatively large (A/A_0)

Overall conclusions

- Much to learn about the thermal conductance of interfaces but we now have powerful tools (experiment and computation).
- Changing chemistry of SAM/Au interface confirms that weak bonding suppresses thermal conductance.
- Measurements at high pressure (10 GPa) allow us to vary the strength of weak, anharmonic interface bonds and observe changes in thermal conductance.
- Transfer printed interfaces have a surprisingly large conductance: >10% of the value of interfaces formed by sputter deposition.
  - Explained by relatively large area of true contact formed by capillary forces (?)
  - Not an issue for thermal management except in the case of extremely high heat fluxes, > 10 kW cm^{-2}