Thermal conductance of interfaces

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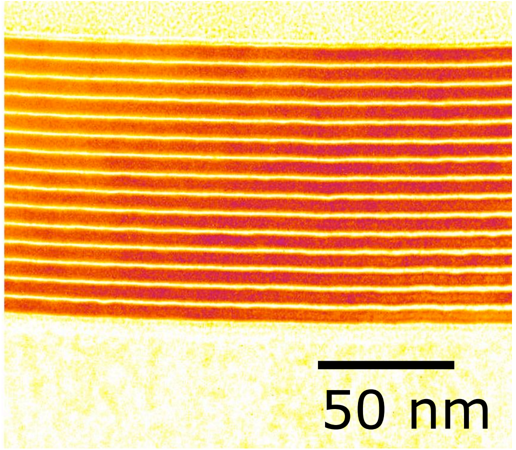
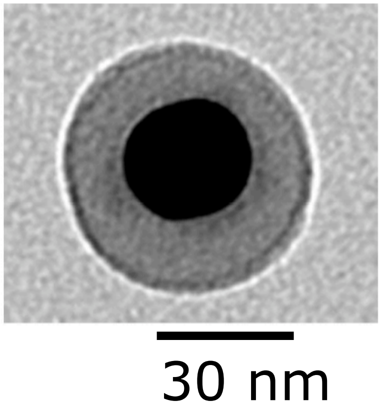
Interfaces are critical at the nanoscale

- Low thermal conductivity in nanostructured materials
  - improved thermoelectric energy conversion
  - improved thermal barriers
- Understanding composites and suspensions
  - high thermal conductivity composites based on single-walled carbon nanotubes
  - nanoparticle-based photo-thermal medical therapies

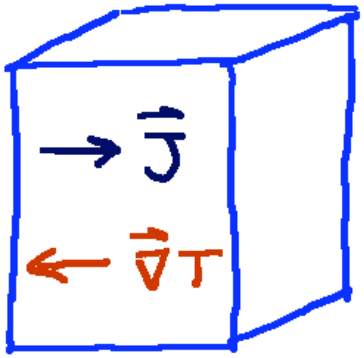




Interface thermal conductance

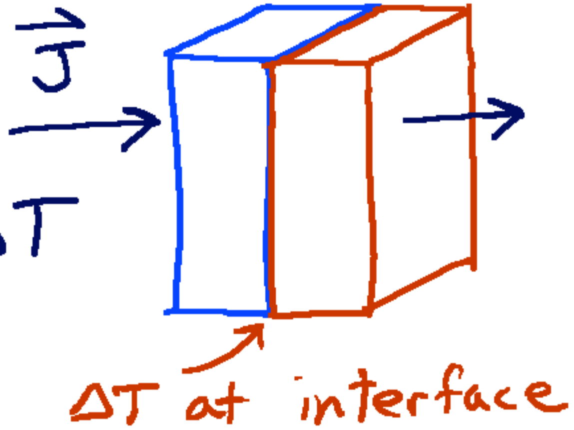
- Thermal conductivity Λ is a property of the continuum

$$\vec{J} = -\Lambda \vec{\nabla} T$$



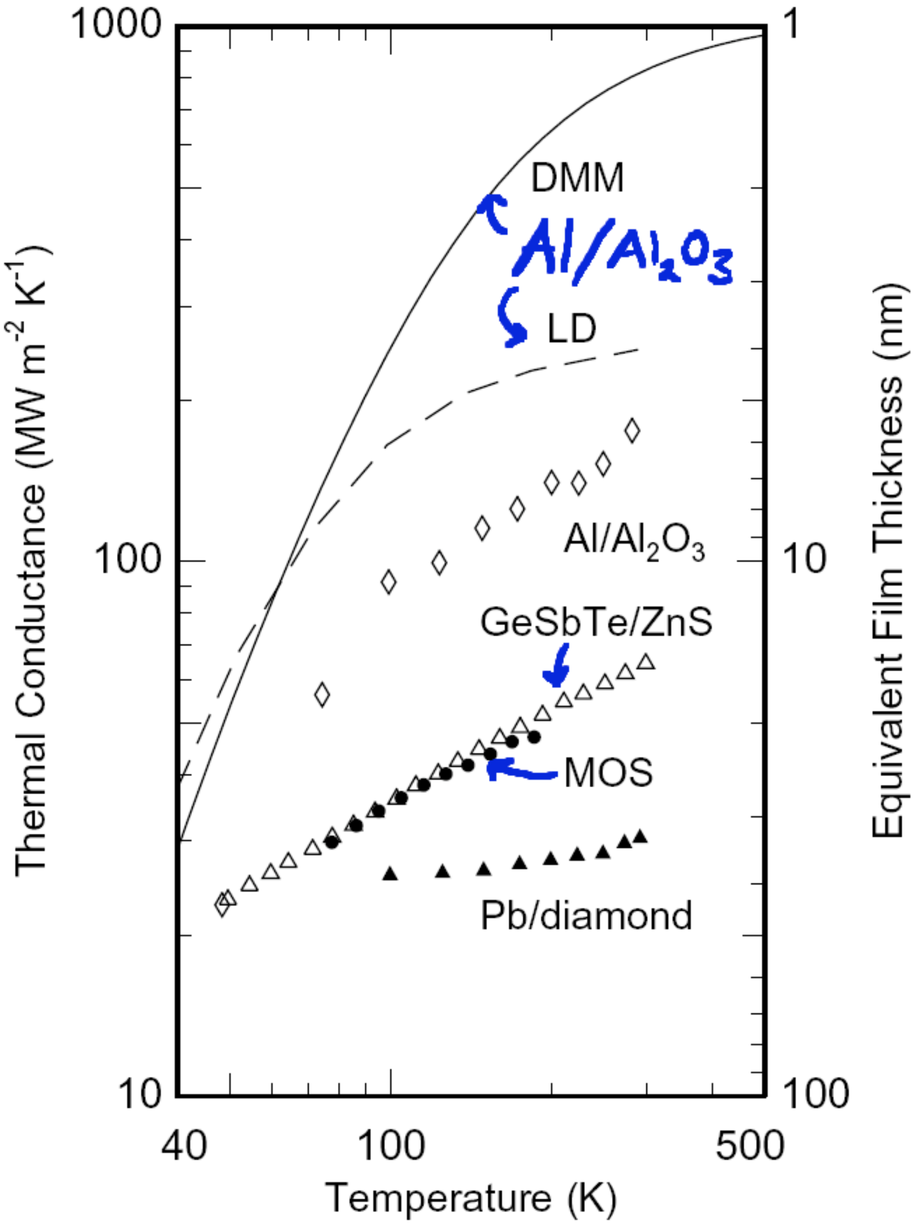
- Thermal conductance (per unit area) *G* is a property of an interface

$$J = G \Delta T$$



Interface thermal conductance (2001)

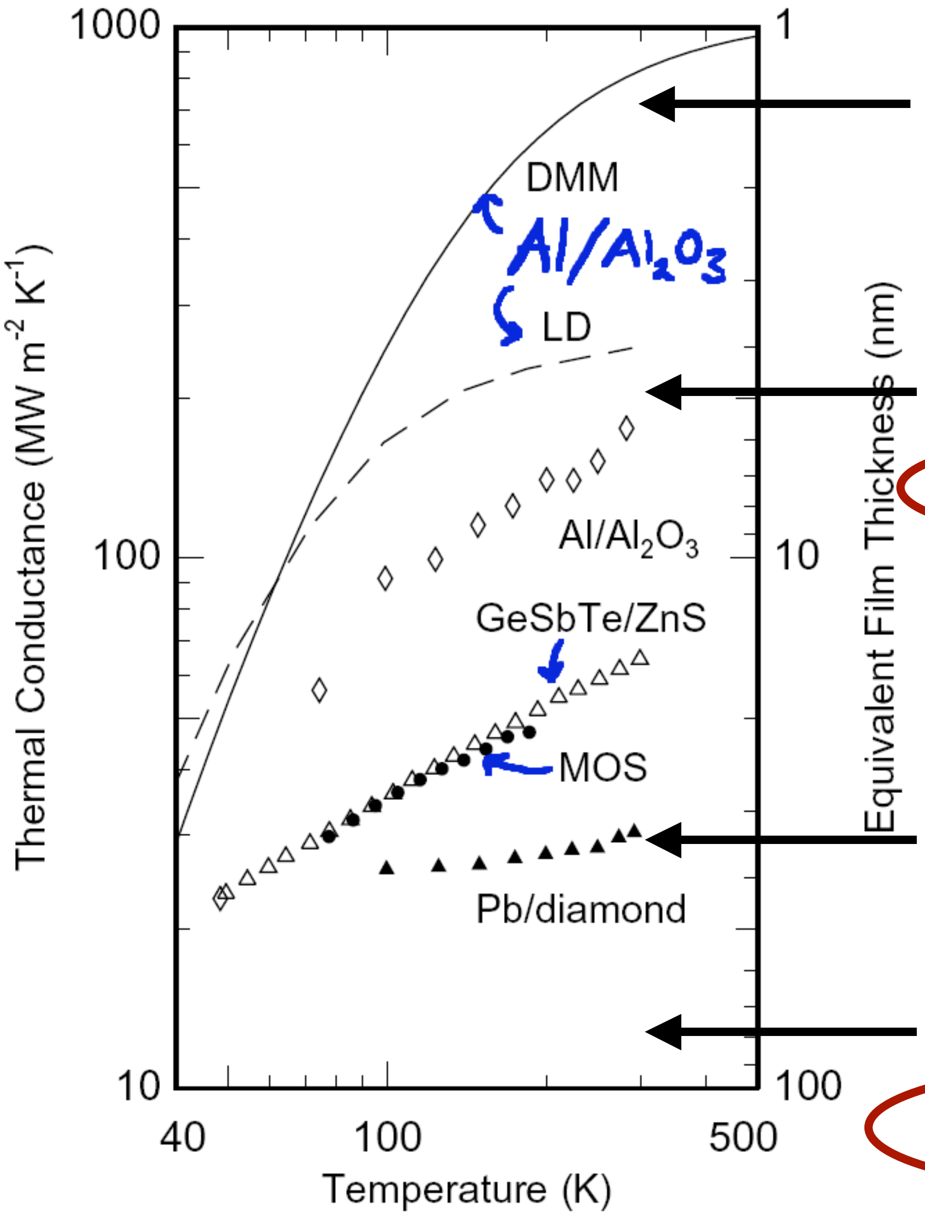
- Observations (2001) span a very limited range
  - Al/sapphire → Pb/diamond
  - no data for hard/soft
- lattice dynamics (LD) theory by Stoner and Maris (1993)
- Diffuse mismatch (DMM) theory by Swartz and Pohl (1987)



Acoustic and diffuse mismatch theory

- Acoustic mismatch (AMM)
  - perfect interface: average transmission coefficient $<t>$ given by differences in acoustic impedance, $Z=\rho v$
  - lattice dynamics (LD) incorporates microscopics
- Diffuse mismatch (DMM)
  - disordered interface: $<t>$ given by differences in densities of vibrational states
- Predicted large range of G not observed (2001)
- For similar materials, scattering decreases G
- For dissimilar materials, scattering increases G

2004: Factor of 60 range at room temperature



TiN/MgO

W/Al_2O_3

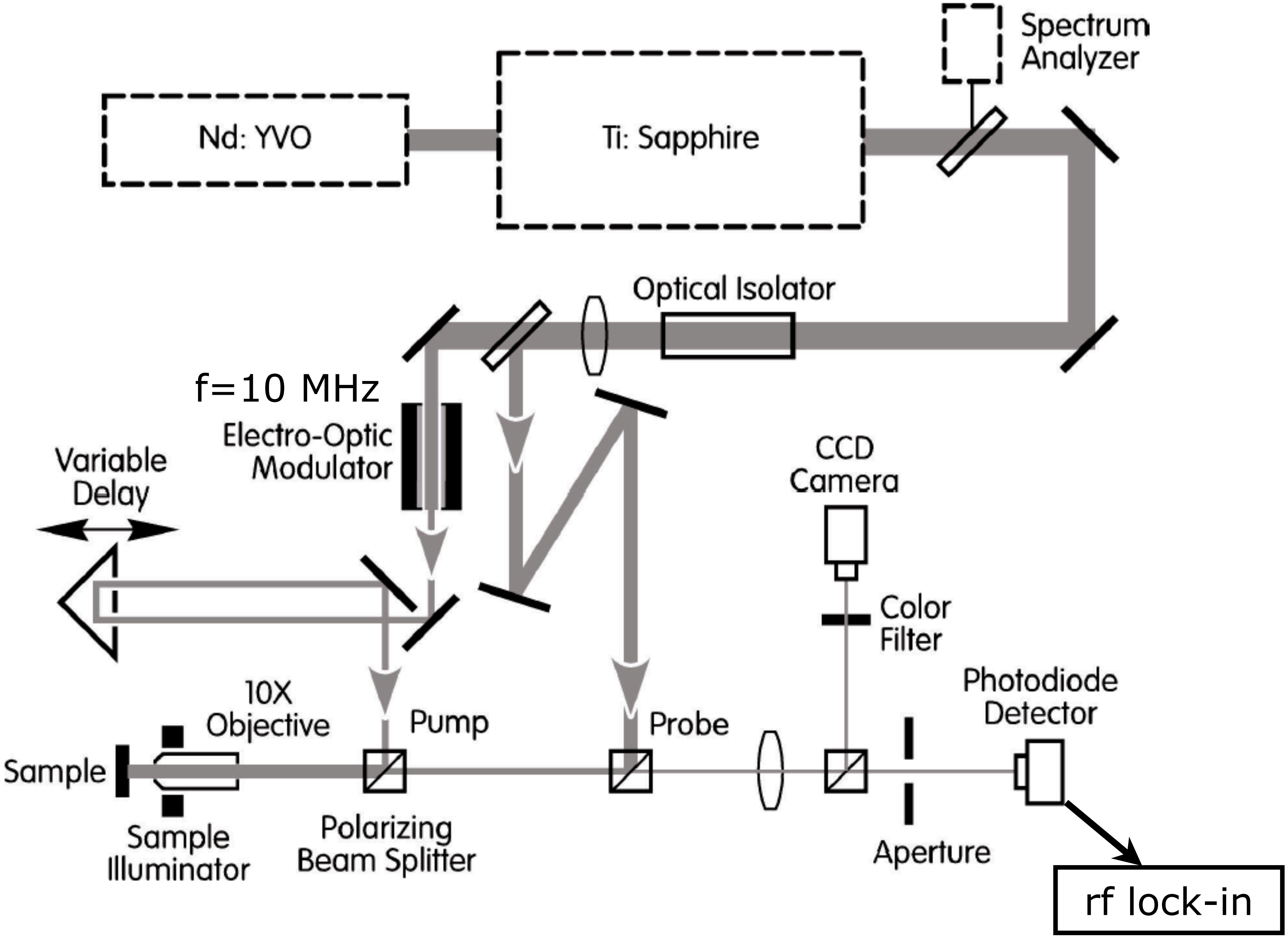
Au/water

PMMA/Al_2O_3

nanotube/alkane

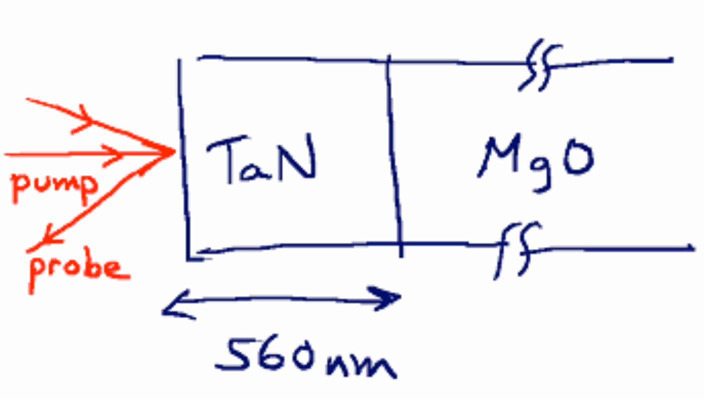
Bi/H/diamond

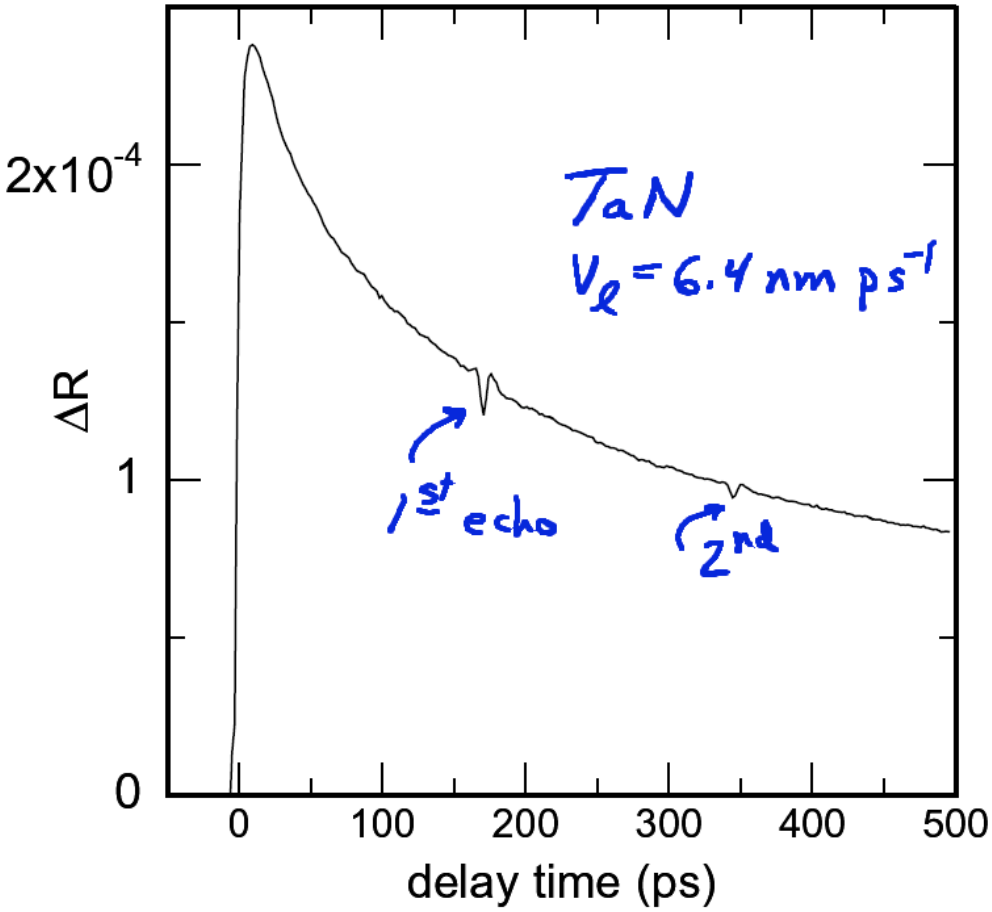
Modulated pump-probe apparatus



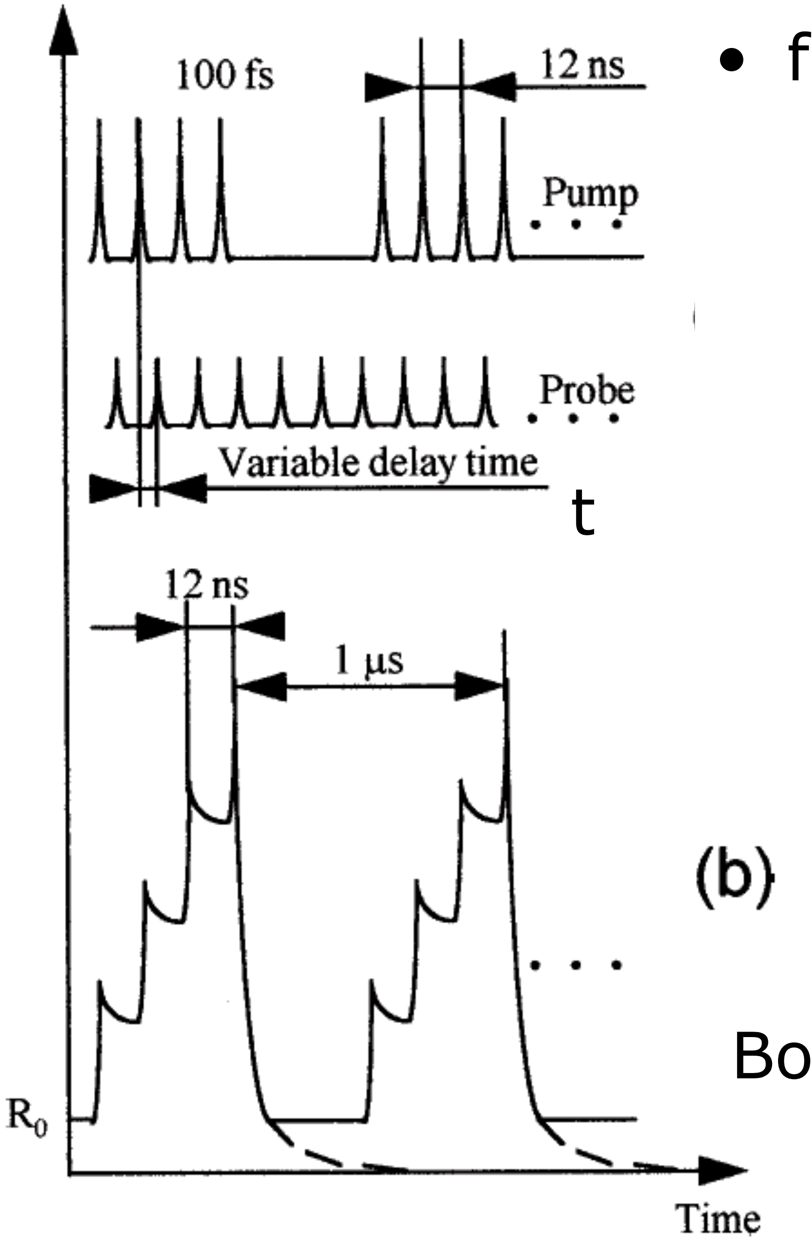
psec acoustics and time-domain thermoreflectance

- Optical constants and reflectivity depend on strain and temperature
- Strain echoes give acoustic properties or film thickness
- Thermoreflectance gives thermal properties





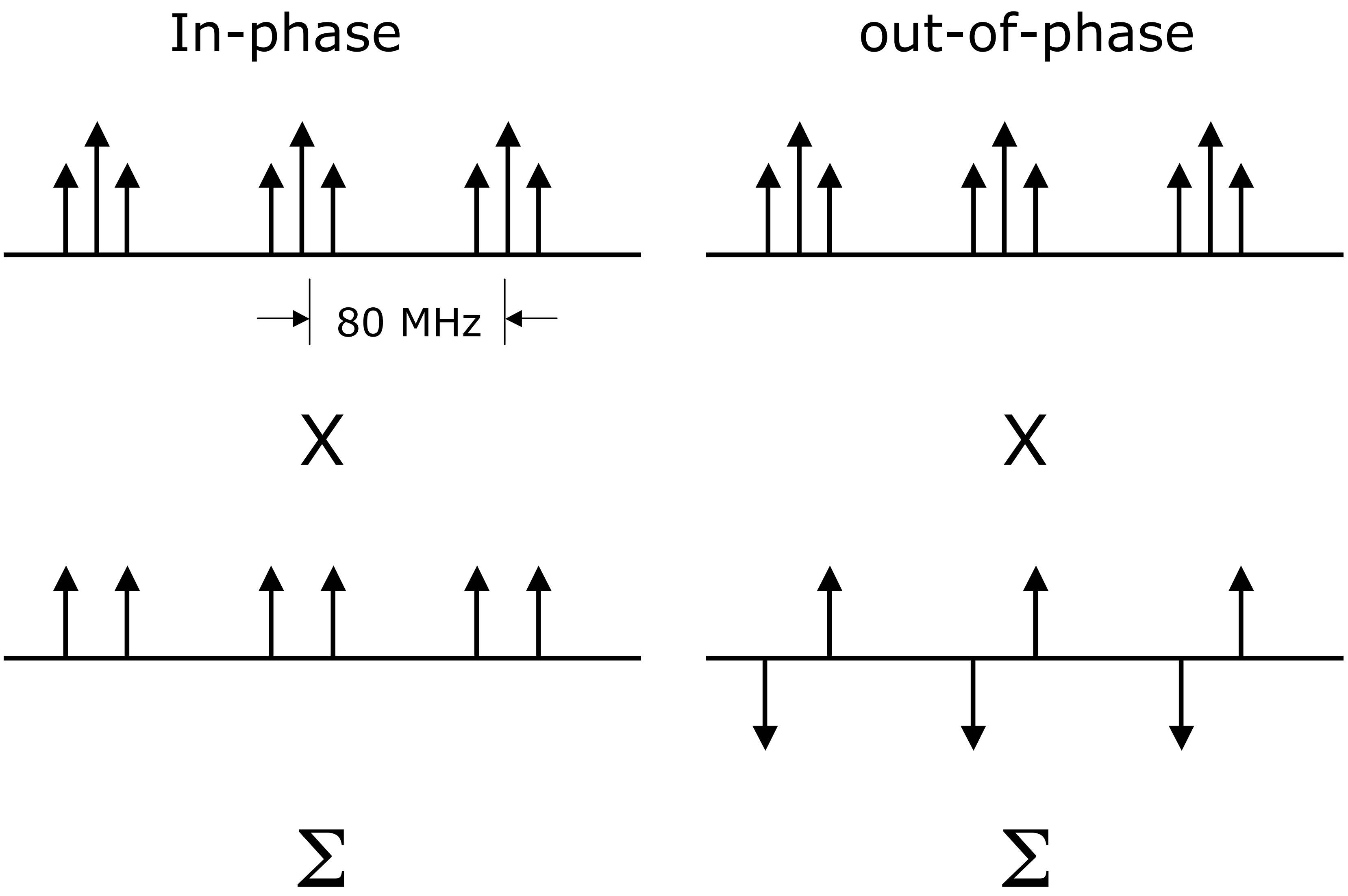
Modulated pump-probe



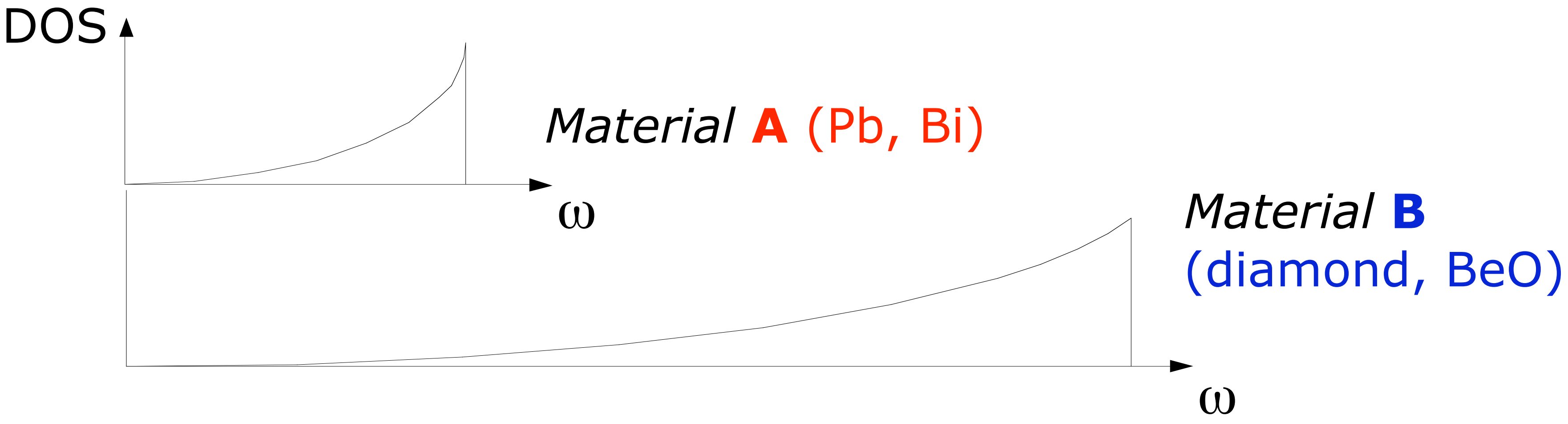
- four times scales:
  - pulse duration, 0.3 ps
  - pulse spacing, 12.5 ns
  - modulation period, 100 ns
  - time-delay, t

Bonello et al. (1998)

Signals measured in a modulated pump-probe experiment



Interfaces between highly dissimilar materials



- high temperature limit of the radiation limit

$$G = \frac{\pi}{3}\frac{k_b \nu_{\max}^3}{v_D^2}$$

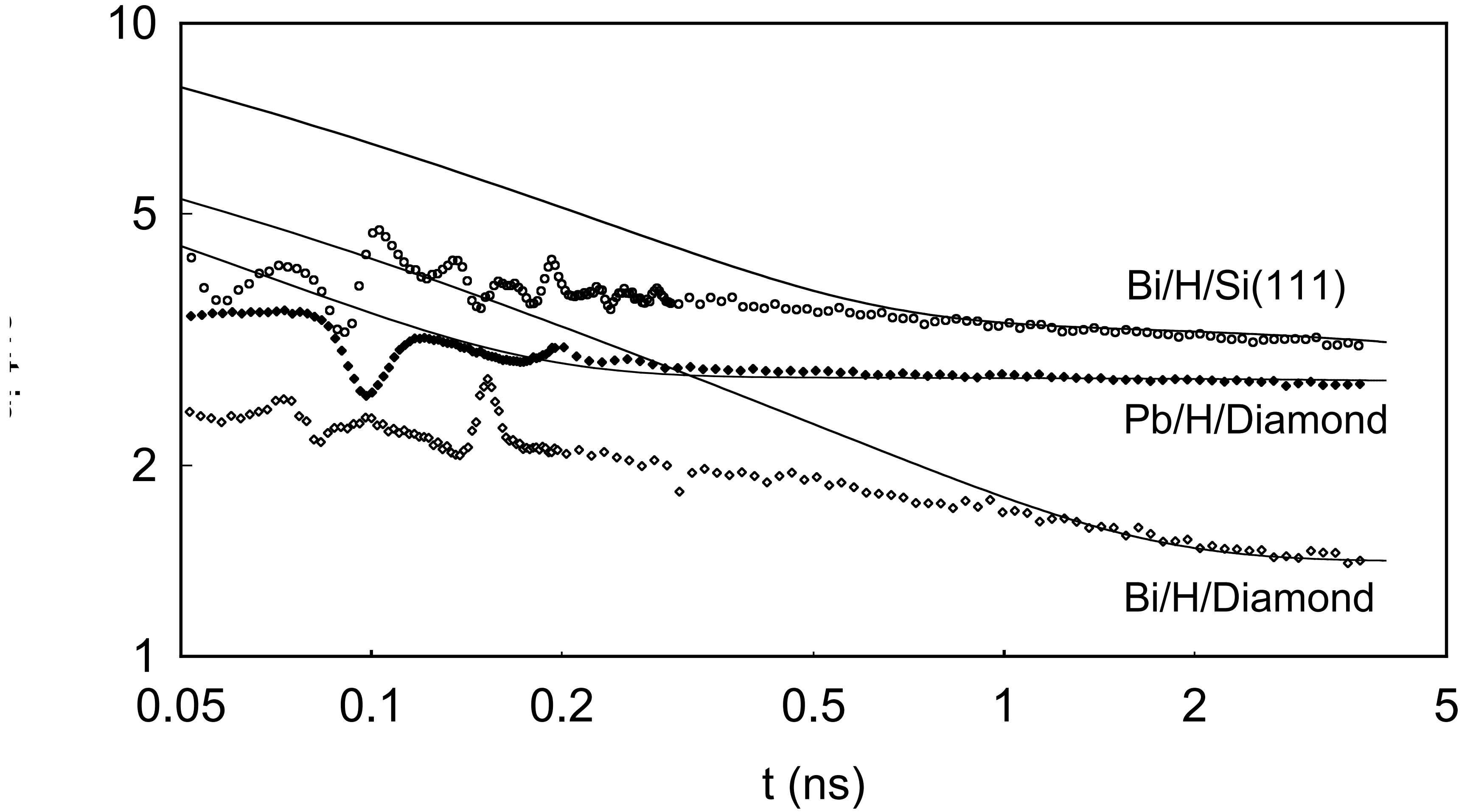
$\nu_{\max}$: vibrational cutoff frequency of material A

($\nu_{\max} = 1.8$ THz for Bi, 2.23 THz for Pb)

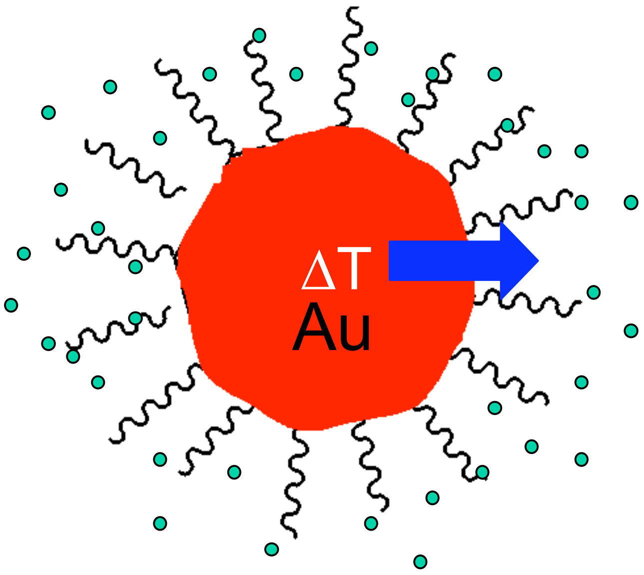
v_D : Debye velocity of material B

R. J. Stoner and H. J. Maris, *Phys.Rev.B* **48**, 22, 16373 (1993)

Thermoreflectance data for Bi and Pb interfaces

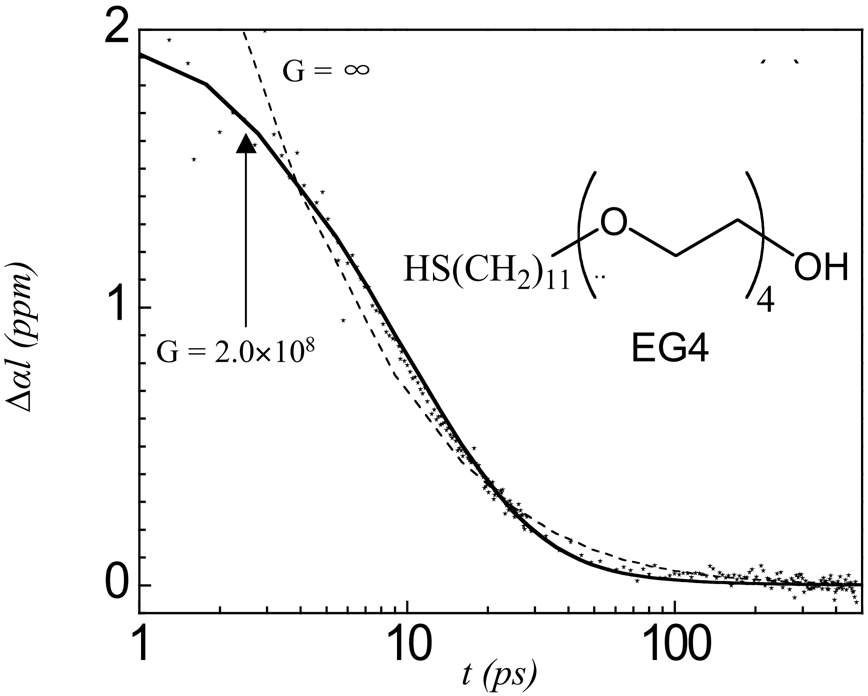


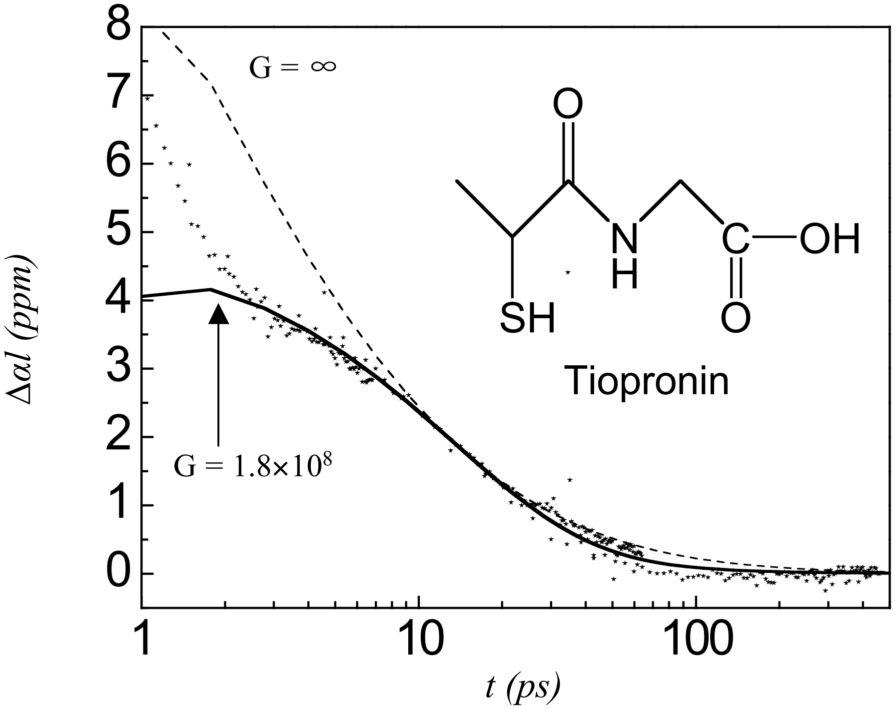
Solid-liquid interfaces: cooling of nanoparticles



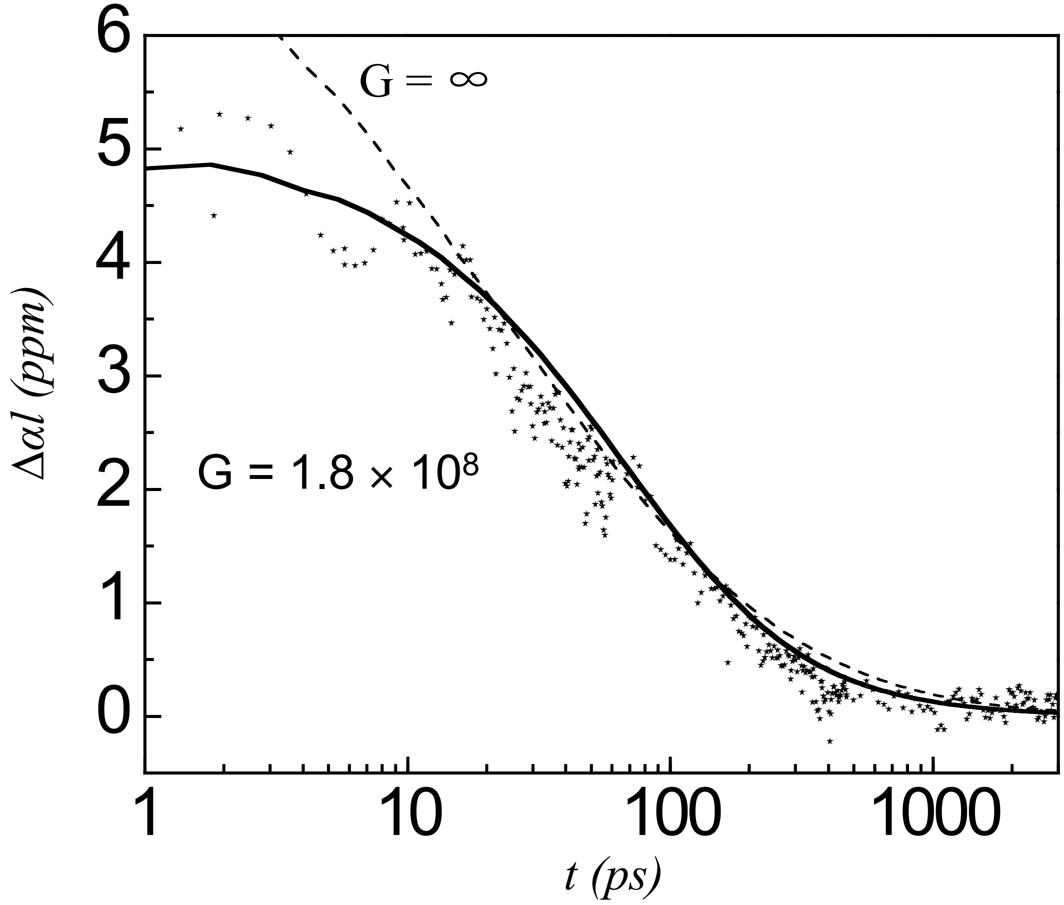
- pump beam heats the nanoparticle
- probe beam measures the decay of the temperature of the nanoparticle through time-resolved changes in optical absorption
- Need to look out for optical Kerr effect at short times

4 nm diameter Au:Pd nanoparticles in water





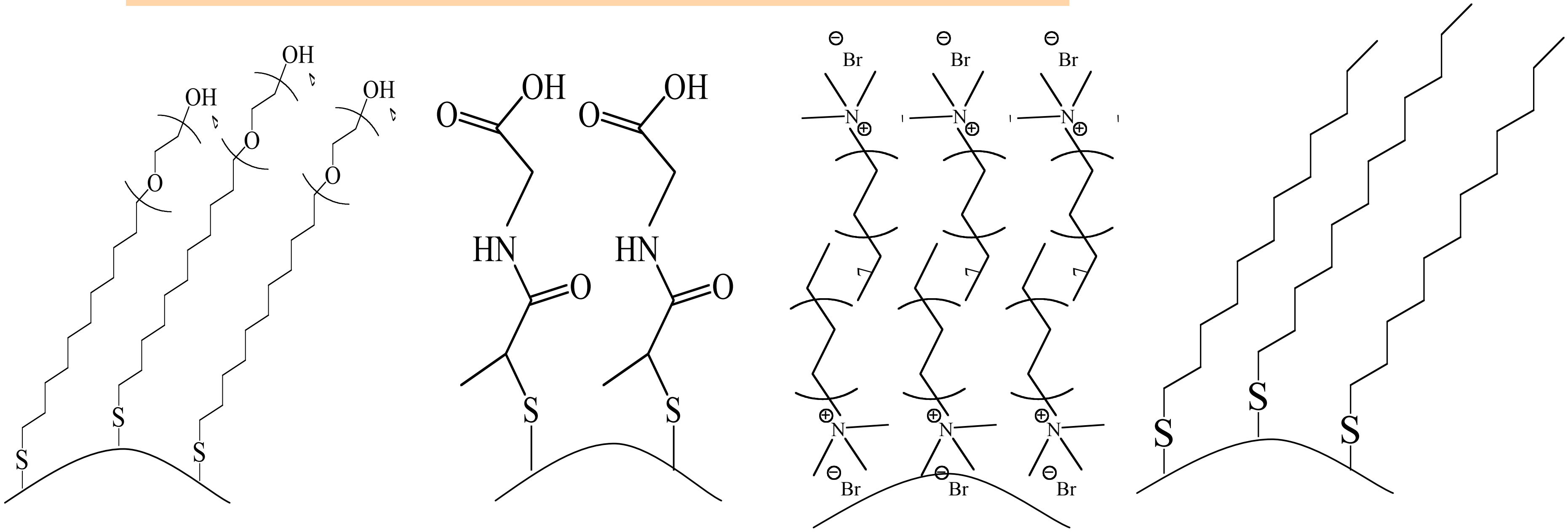
22 nm diameter Au:Pd nanoparticles in water



Nanoparticle summary

In water

In Toluene



G ~ 200 MW m^{-2} K^{-1}

G ~ 15 MW m^{-2} K^{-1}

Conclusions

- Much to learn about transport of heat across interfaces.
- Pb/diamond, Bi/diamond interfaces show a temperature dependent conductance far above the radiation limit. What is the correct description of this inelastic channel?
- Conductance of nanoparticle/surfactant/water interfaces is essentially independent of the surfactant layer. Difficult to understand why this should be the case.