Phonon lifetimes in silicon from 50 GHz to 15 THz

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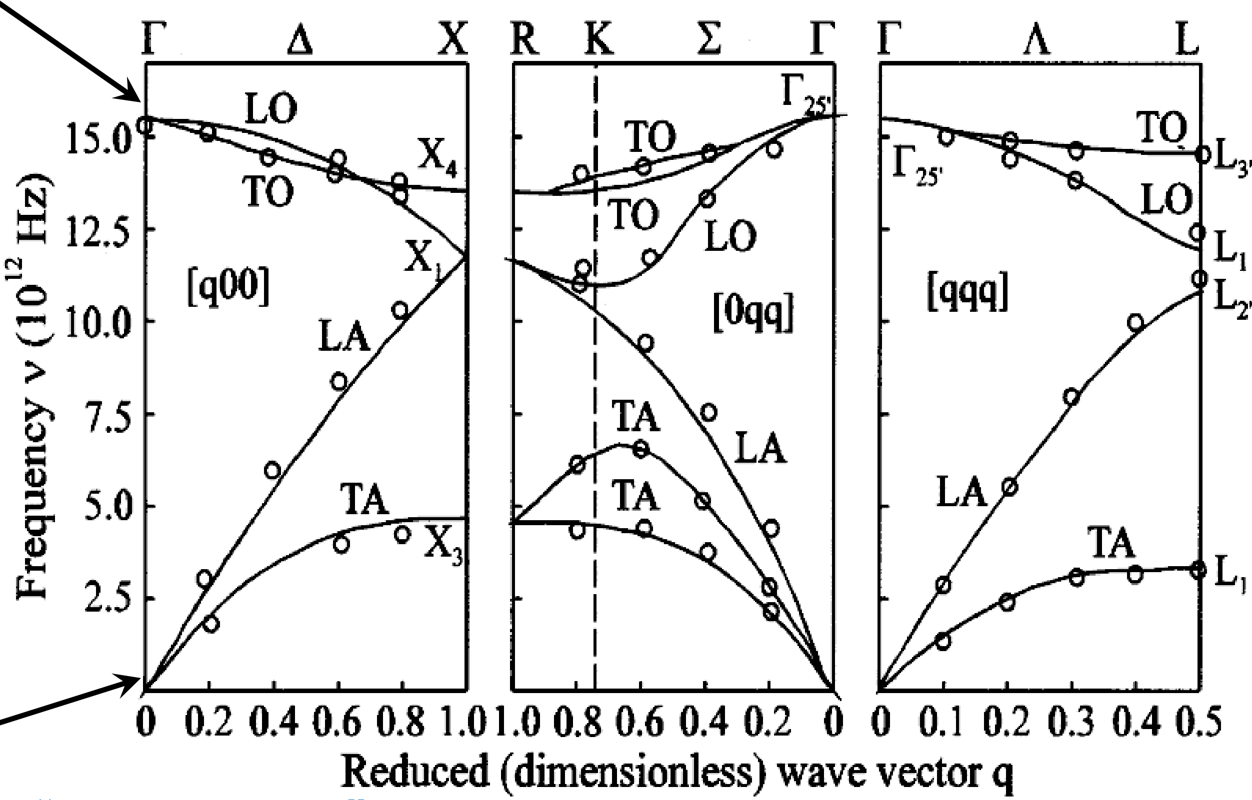
Experimental studies of silicon phonon lifetimes at room temperature

- Attenuation of 50-100 GHz longitudinal acoustic phonons measured by picosecond acoustics.
  - PRB **80**, 174112 (2009).
- Thermal acoustic phonons (1-10 THz) and reduction of thermal conductivity by mass disorder.
  - PRB **71**, 235202 (2005); JAP **104**, 024905 (2008).
- Lifetimes of 15 THz optical phonons by time-resolved incoherent anti-Stokes Raman scattering.
  - APL **90**, 252104 (2007).

Si phonon dispersion

high-field carrier mobility, hot carrier photovoltaics

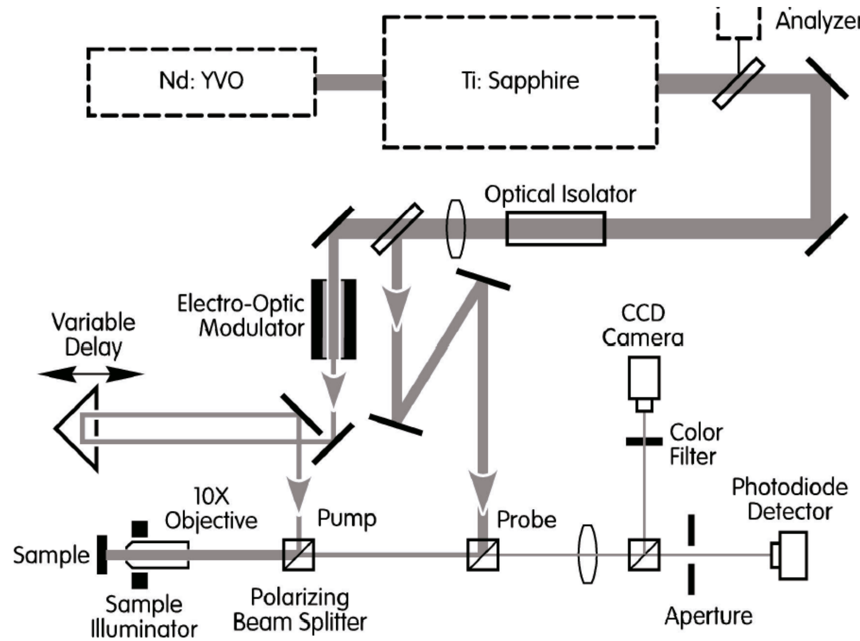
Thermal management, heat conduction

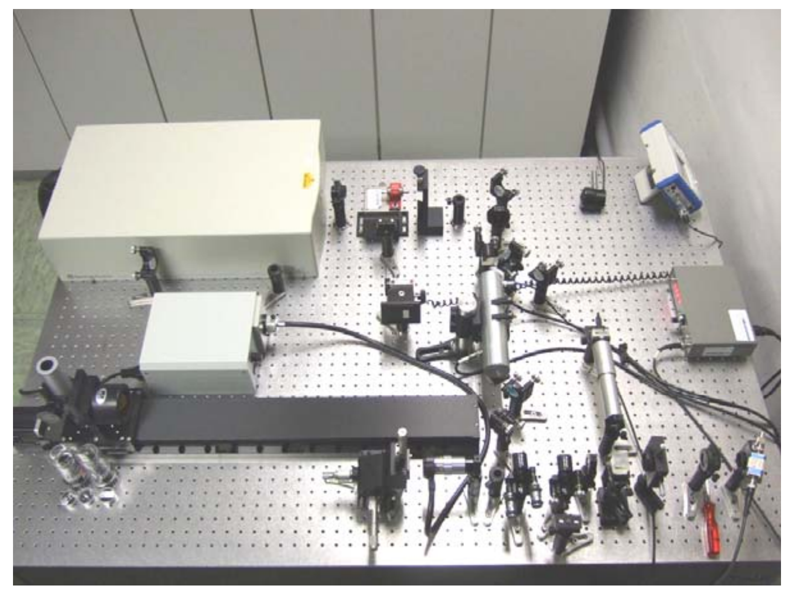


acoustic imaging, “phononics”

Time domain thermoreflectance and picosecond acoustics

- 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

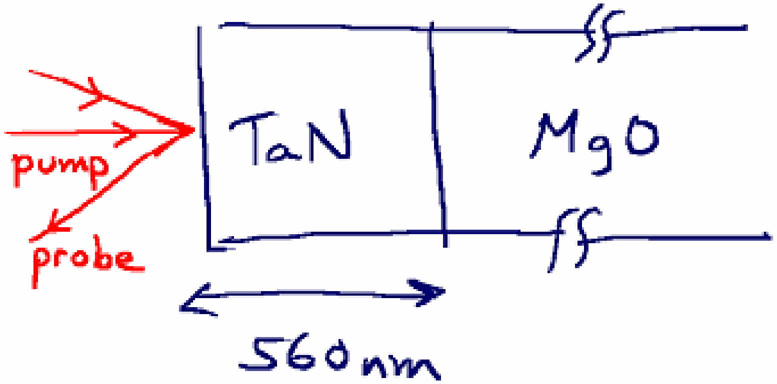


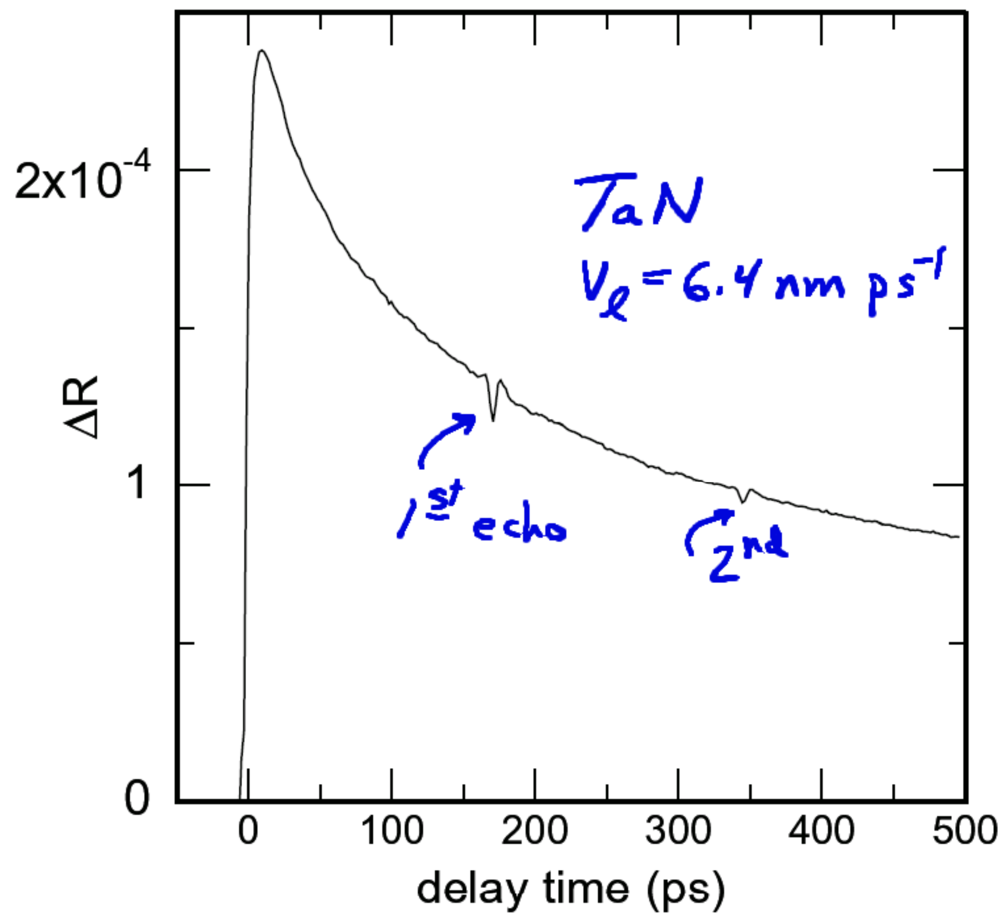


Clone built at Fraunhofer Institute for Physical Measurement, Jan. 7-8 2008

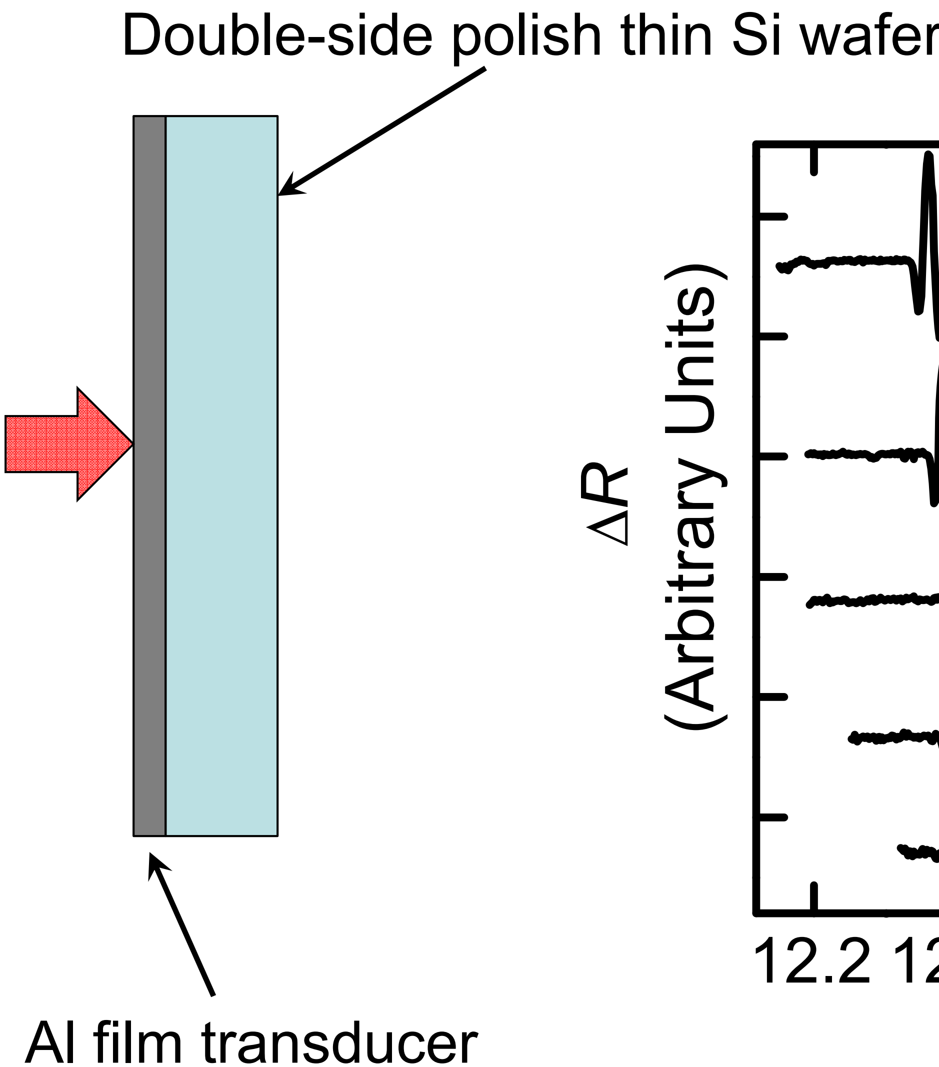
Time domain thermoreflectance and picosecond acoustics

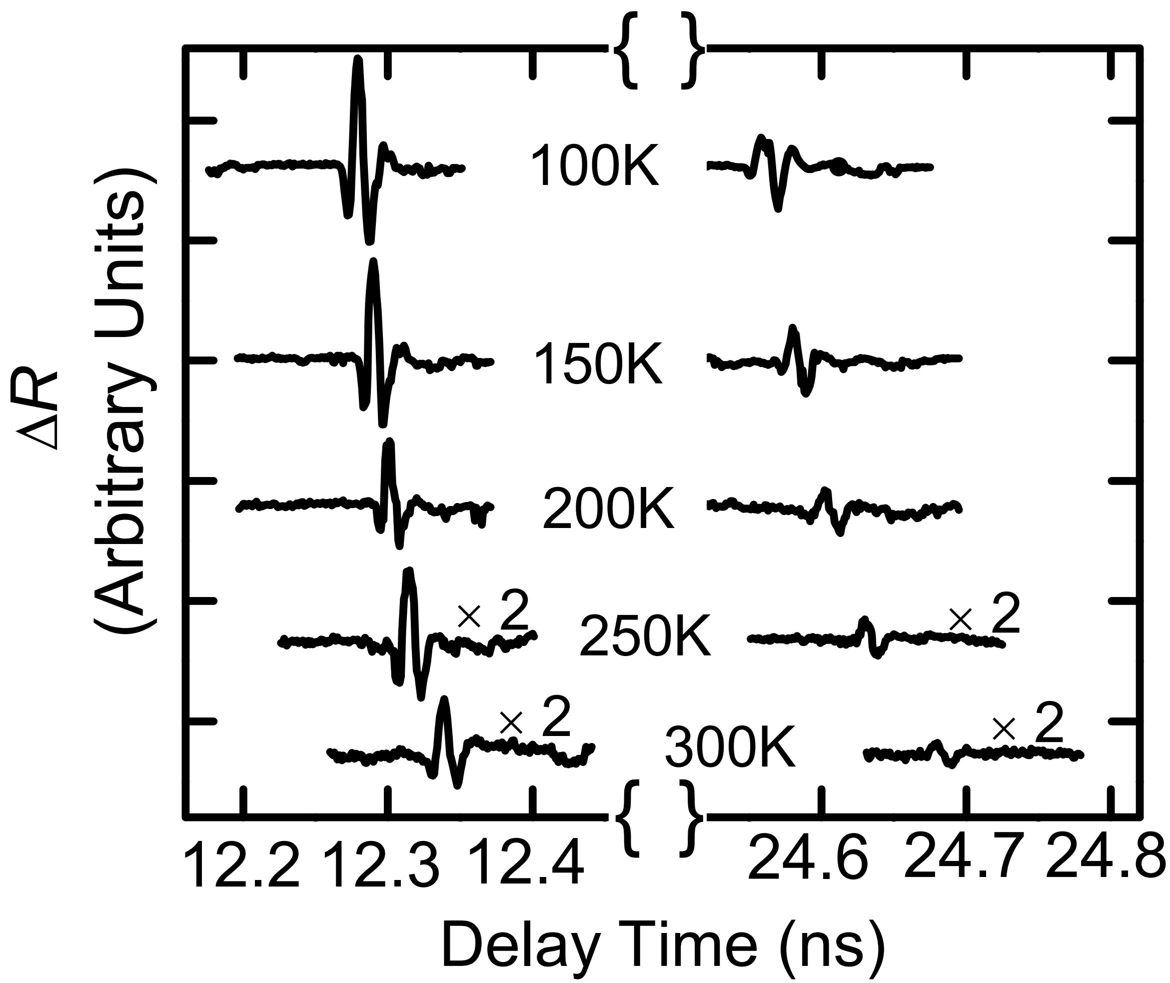
- Optical constants and reflectivity depend on strain and temperature
- Strain echoes give acoustic properties or film thickness
- Thermoreflectance gives thermal properties





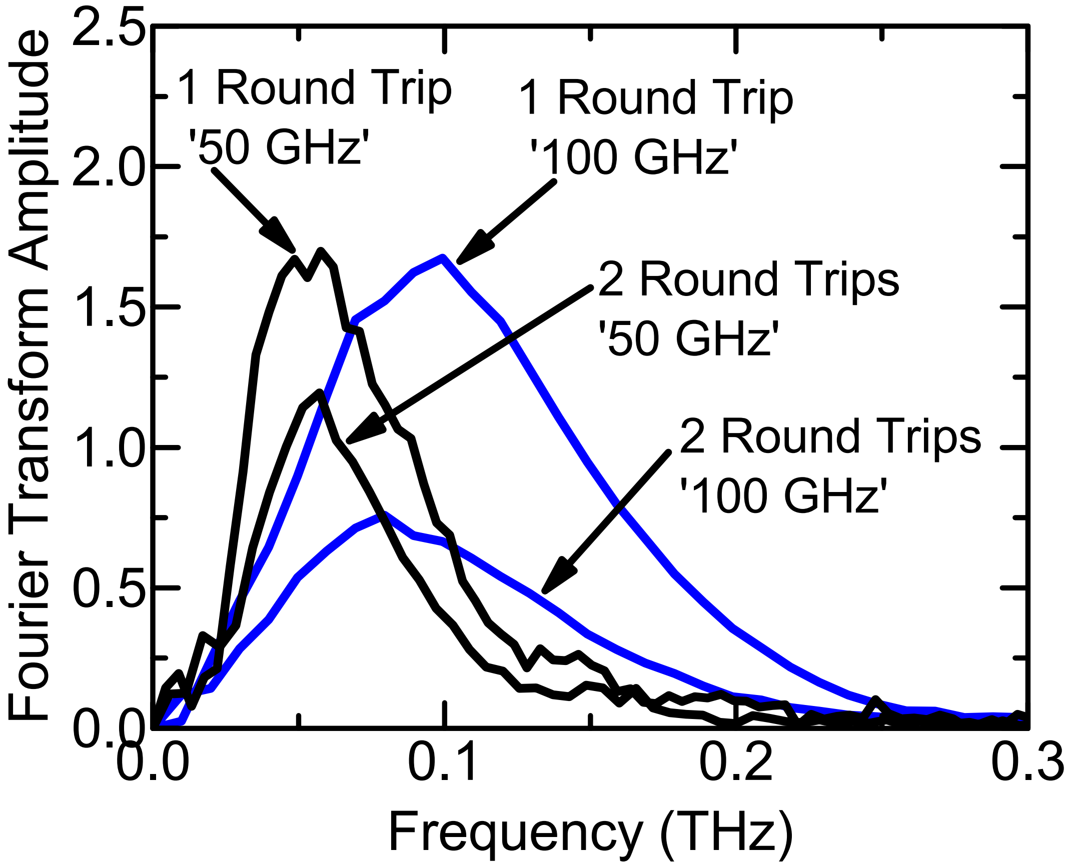
One and two round trips in 50 μm Si wafer



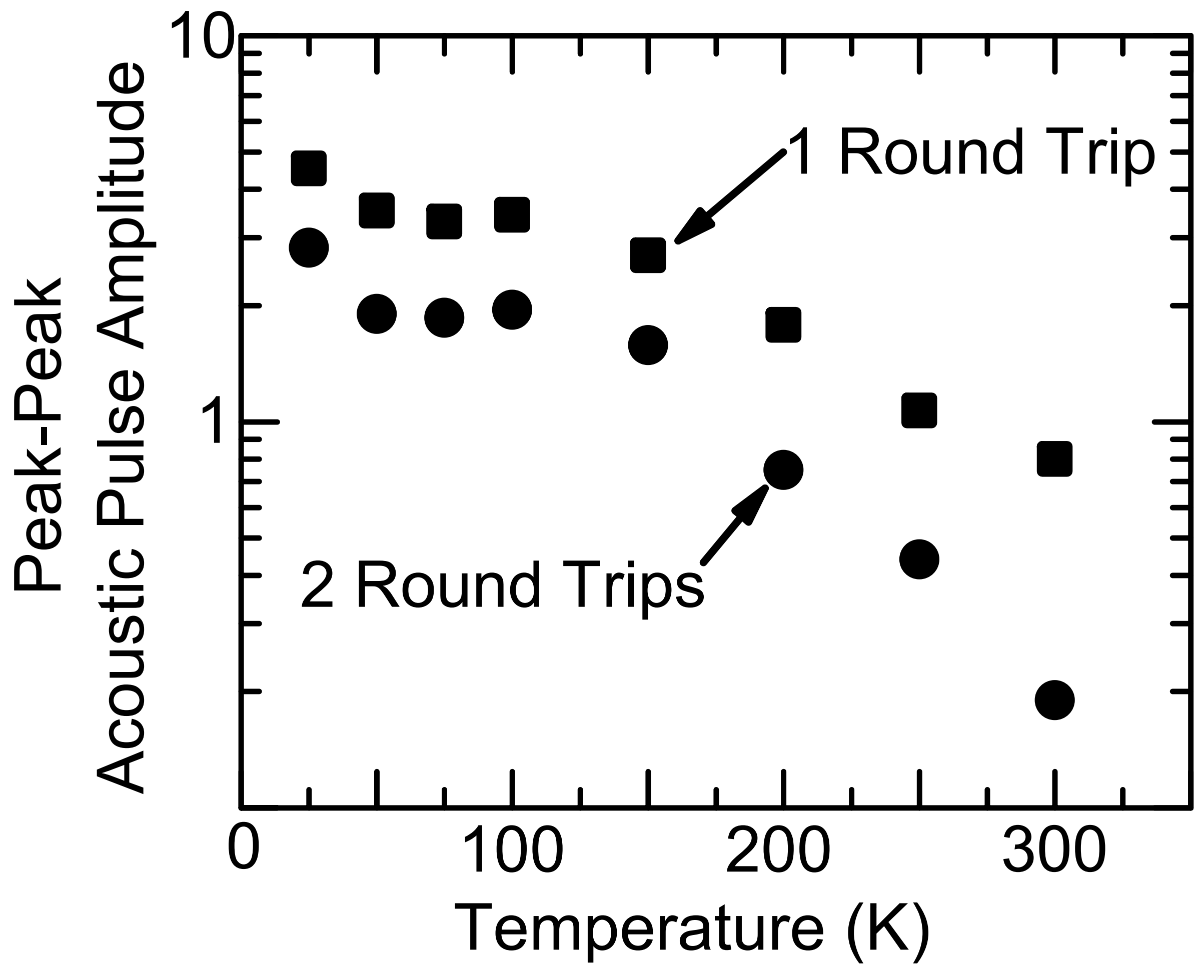


Broadband acoustic pulses

- Fourier transforms of echoes from 10 nm (100 GHz) and 20 nm (50 GHz) Al films

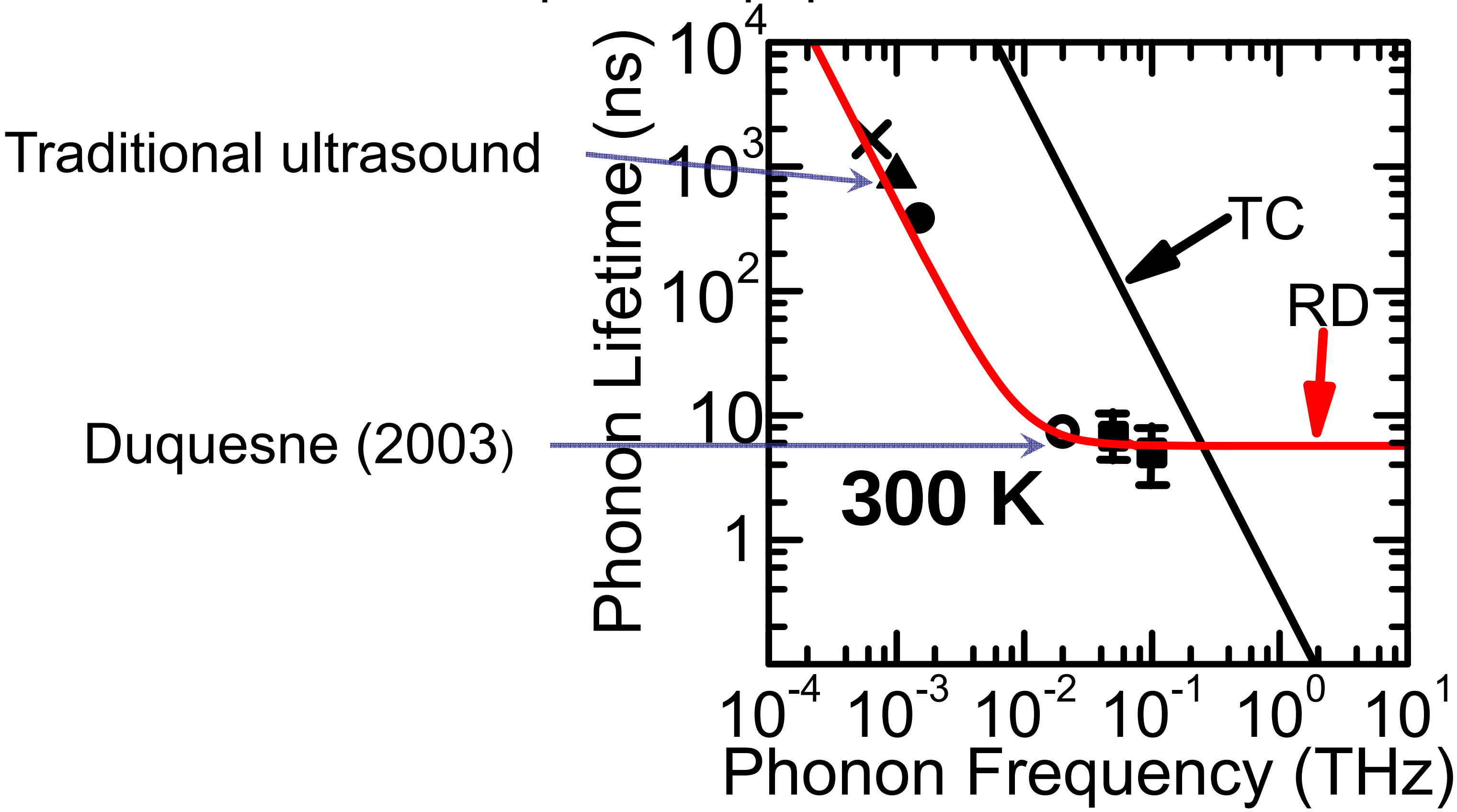


Analyze temperature dependence to eliminate surface effects



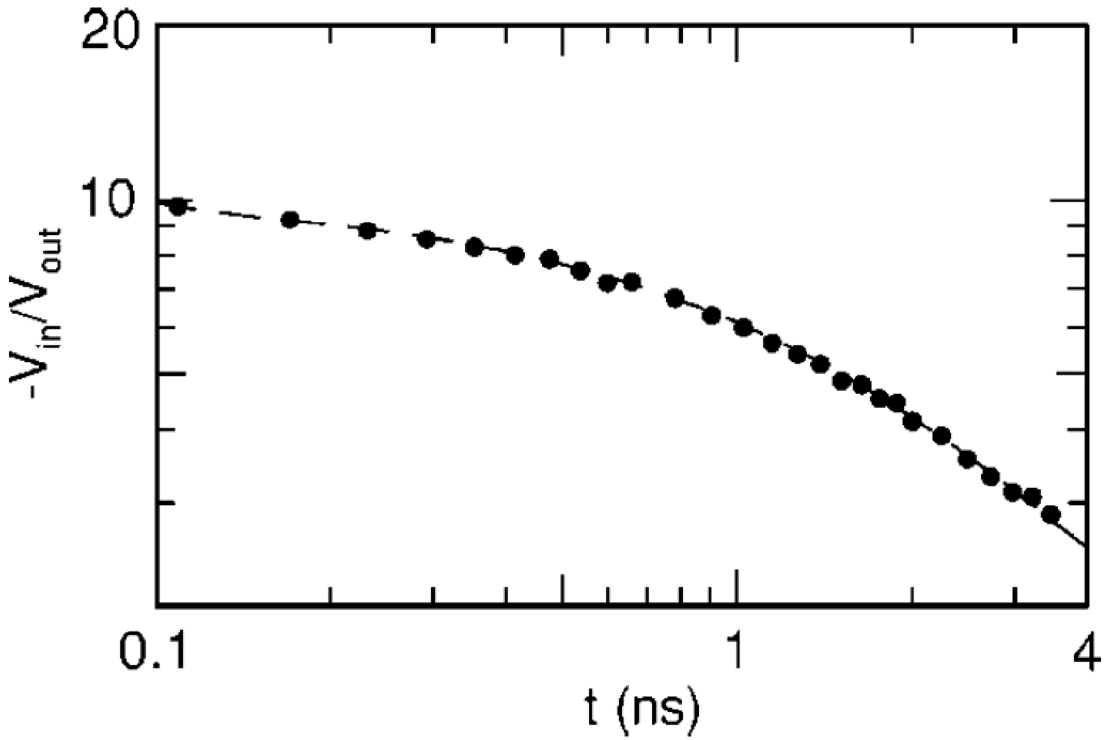
f<100 GHz phonons decay by Akhieser mechanism

- TC=prediction from thermal conductivity measurements, based on three-phonon scattering and truncated Debye model
- RD=relaxational decay (Akhieser mechanism): strain wave distorts thermal phonon population with relaxation time $\tau = 17$ ps

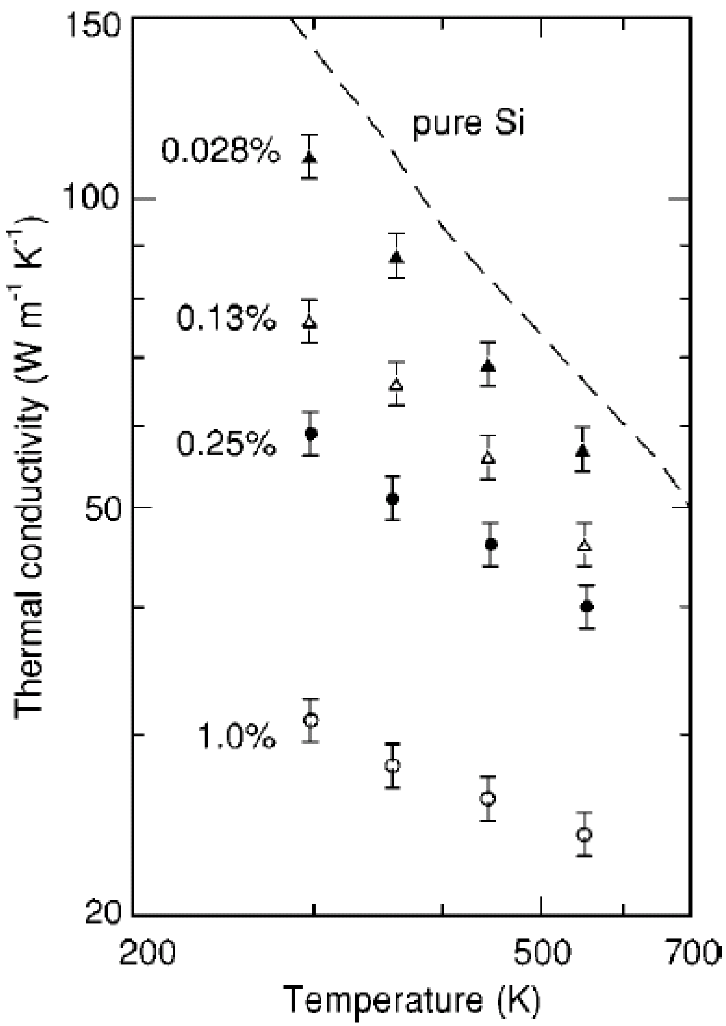


TDTR enables measurements of epitaxial layers of high thermal conductivity

- Time-domain thermoreflectance (TDTR) data and model fit for isotopically pure ^{28}Si
  - Two free parameters: thermal conductivity: Λ=164 W/m-K; interface conductance G=185 W/m^2-K

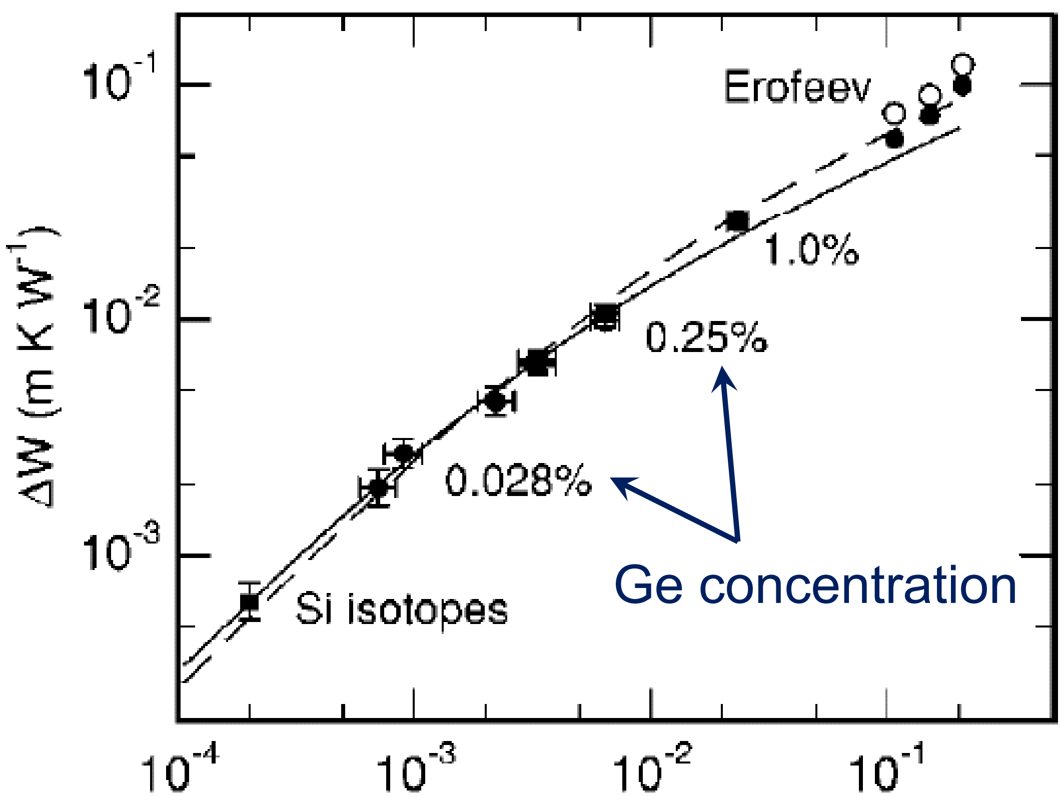


Dilute SiGe alloys grown by gas-source molecular beam epitaxy



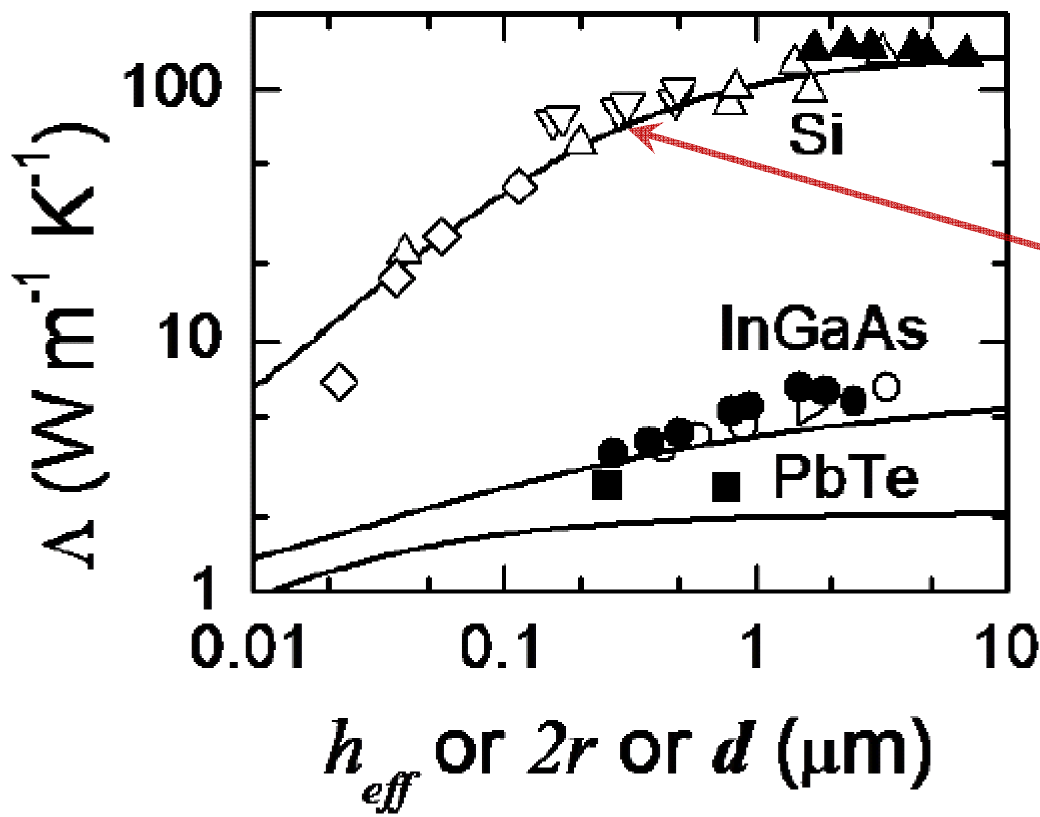
Change in thermal resistance

$$\Delta W = \Lambda^{-1} - \Lambda_{28}^{-1}$$



$$\Gamma_1 = \sum_i c_i \left(\frac{m_i - \overline{m}}{\overline{m}} \right)^2$$

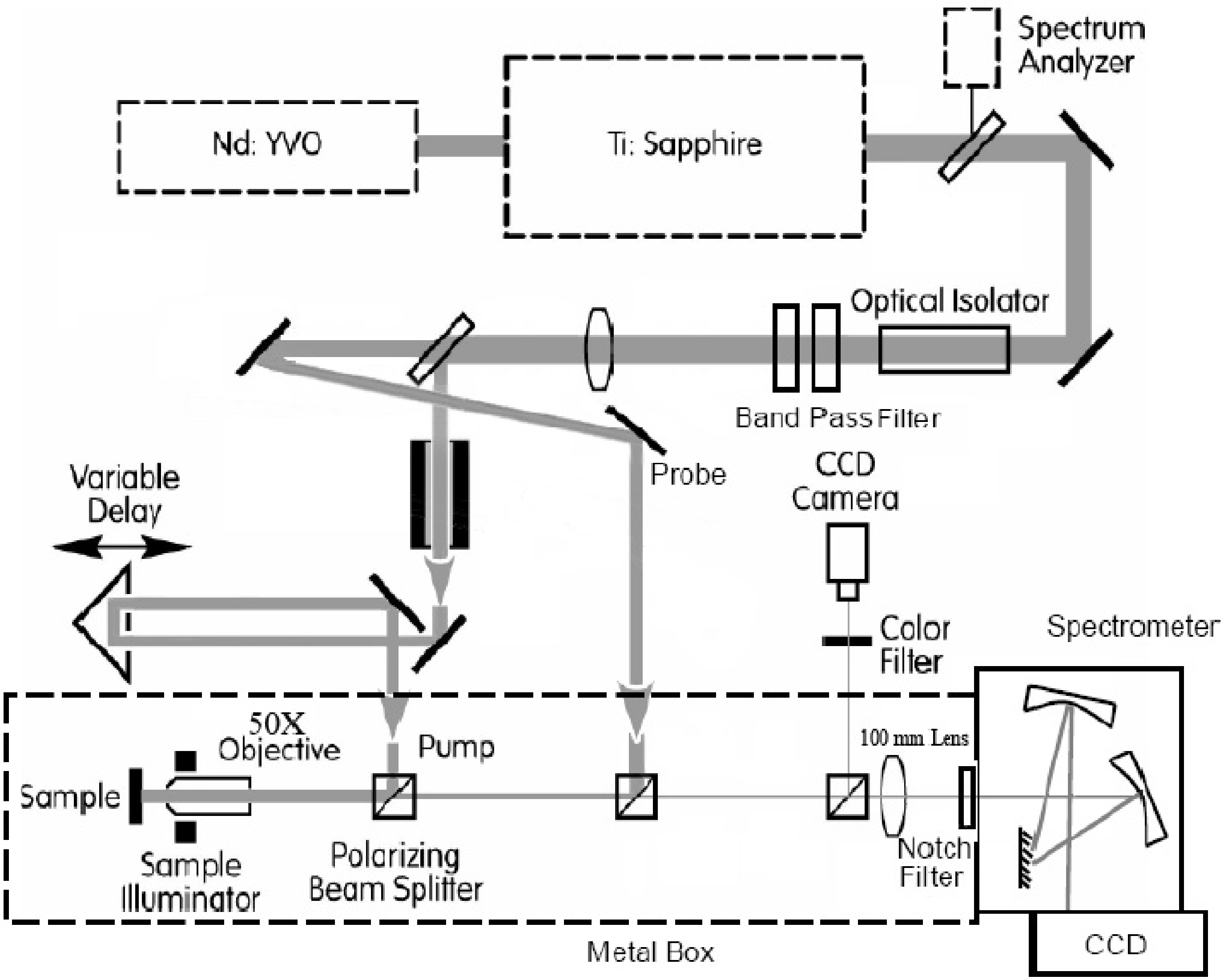
Same truncated Debye-Callaway model predicts boundary scattering



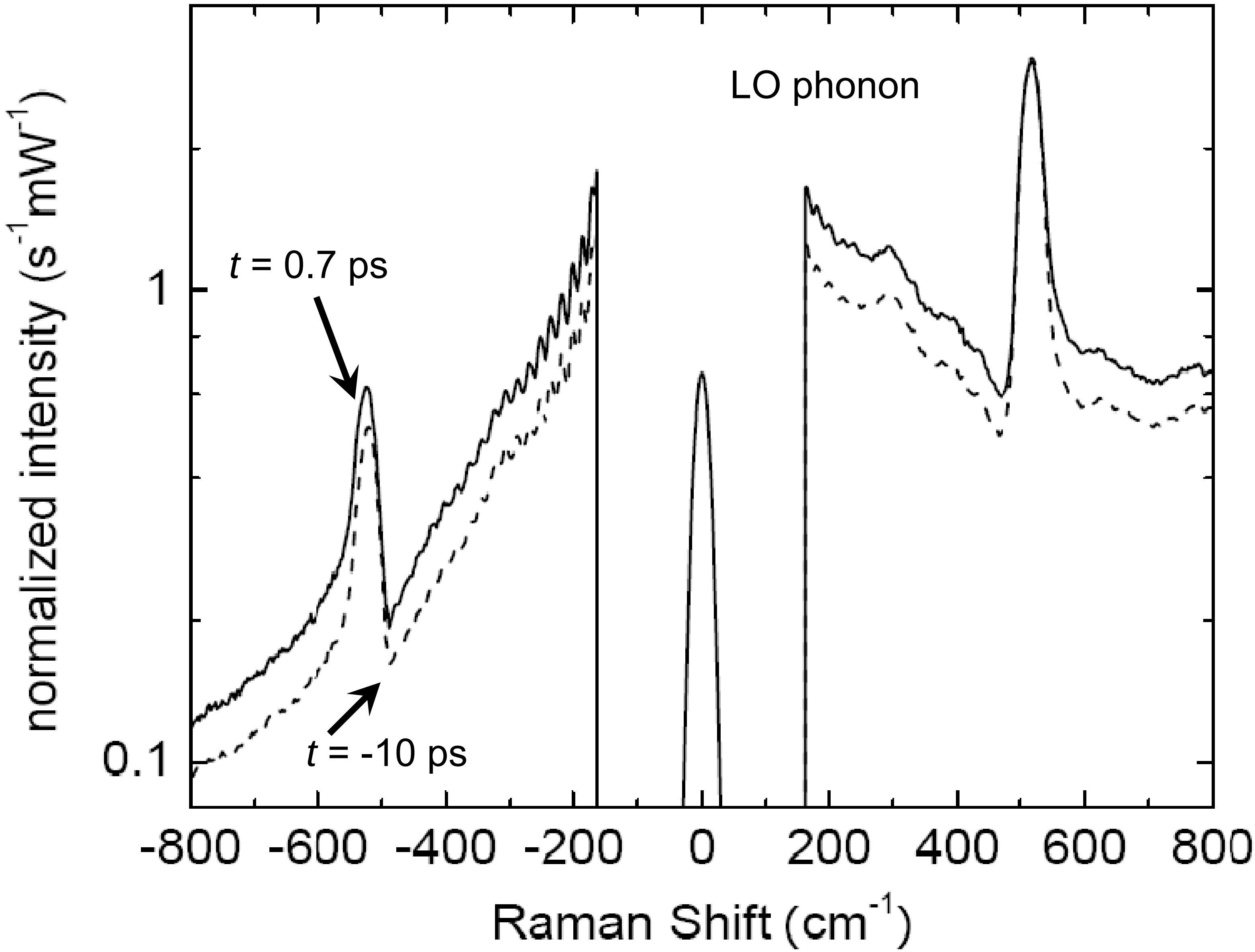
×2 reduction at ≈300 nm

Si thin films: Ju & Goodson; Asheghi *et al;* Liu & Asheghi
Si nanowires: Li *et al.*, APL, 2003
InGaAs thin films: Koh & Cahill, PRB, 2007
PbTe: Koh *et al.*, in preparation

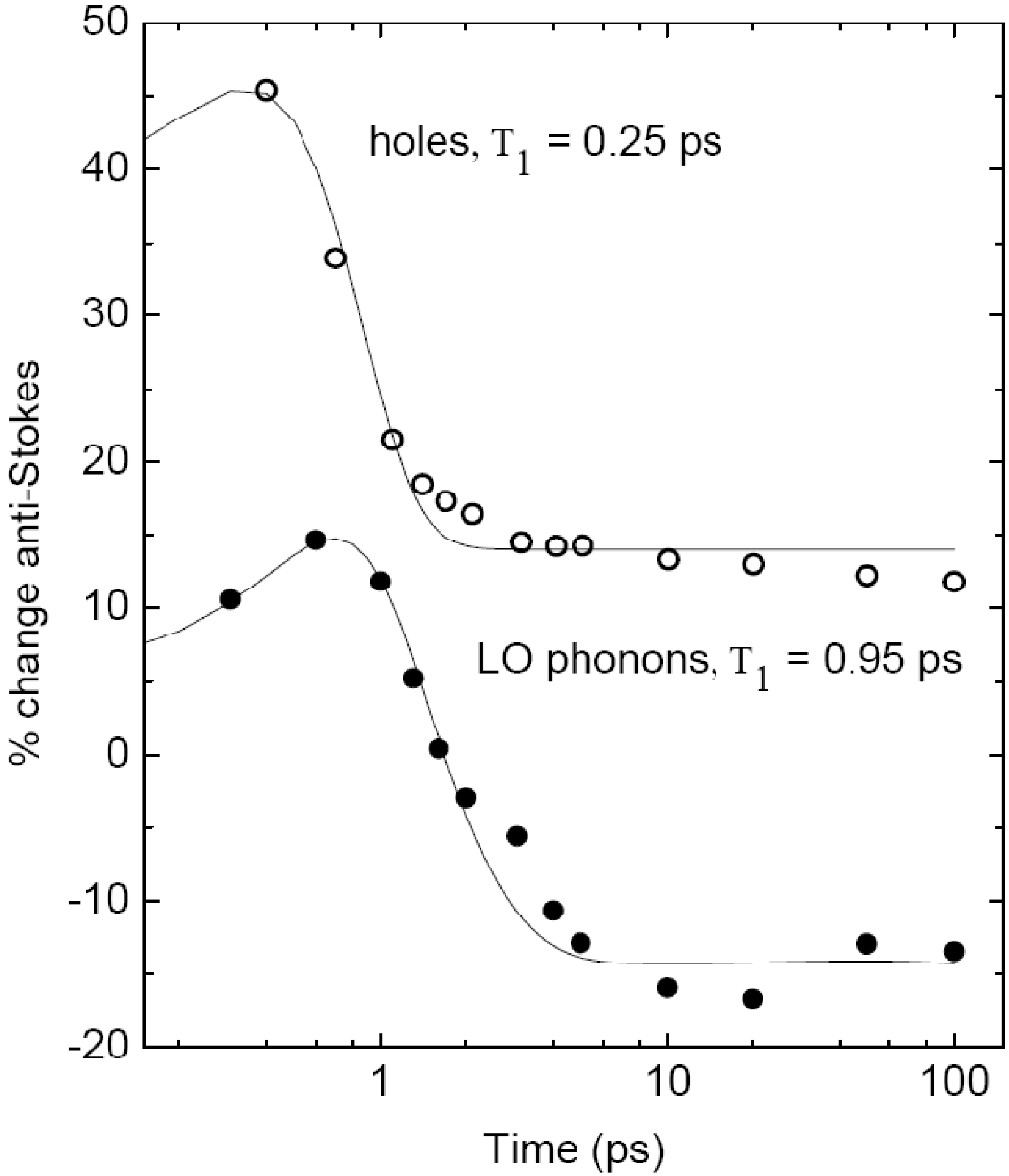
Pump-probe Raman spectrometer



Time-resolved Raman spectra

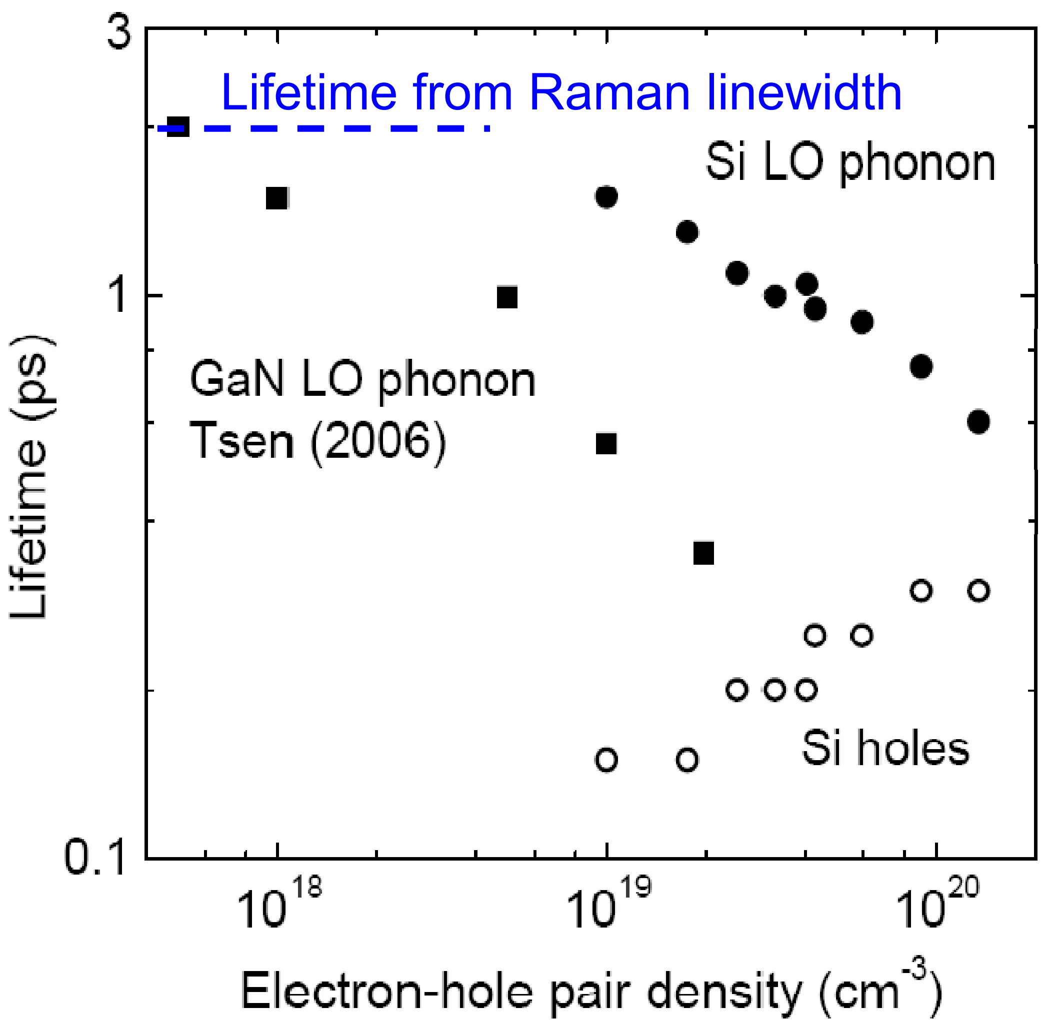


Time-resolved anti-Stokes intensities



- Integral of intensity in range 600-650 anti-Stokes wavenumbers gives electronic scattering by interband hole excitations.
- Integral (after background subtraction) of 490-550 cm^{-1} gives intensity of LO phonon scattering
- Pump power: 86 mW

Lifetime depends on photoexcited carrier density



- At low excitation, lifetime approaches prediction from Raman linewidth: pure-dephasing is not important.
- Lifetime of zone center phonons decreases at higher excitation. Spectral diffusion? Enhanced coupling to acoustic modes?

Summary

- Lifetime of 100 GHz longitudinal phonons is ~5 nsec; fit to Akhieser mechansims gives thermal phonon lifetime of ~20 ps assuming $\langle \gamma^2 \rangle - \langle \gamma \rangle^2 = 1$
- Model fits to thermal conductivity of isotopically pure Si and dilute SiGe alloys is consistent with dominant mean-free-path for heat carrying phonons of 300 nm. Lifetime ~30 ps.
- Lifetime of zone-center optical phonon is 2 ps but depends on carrier (hole) density.