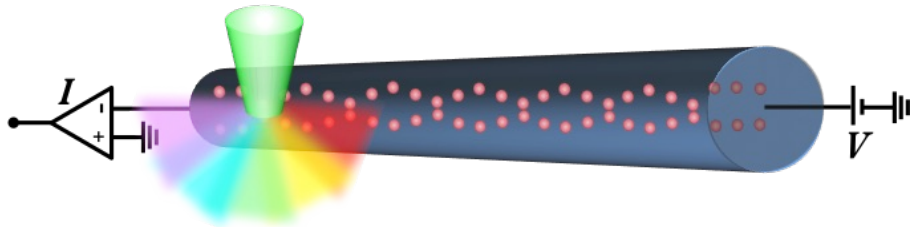


Engineering thermal transport in nanowires

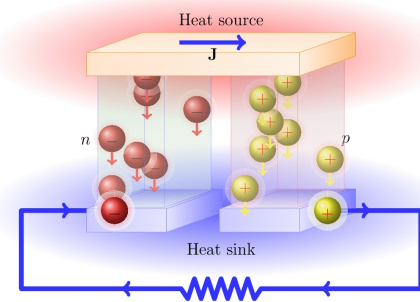
C. Arya, D. de Matteis, Y. Kaur, G. Raciti,
G. de Vito, B. Abad, A. K. Sivan, M. De
Luca, M. Y. Swinkels, X. Cartoixà, R.
Rurali, **I. Zardo**



Manipulating heat flow at the nanoscale

THERMOELECTRIC DEVICES

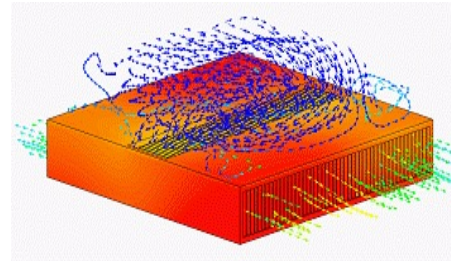
Conversion of ΔT into electricity through the Seebeck effect



$$ZT = S^2 T \frac{\sigma}{\kappa}$$

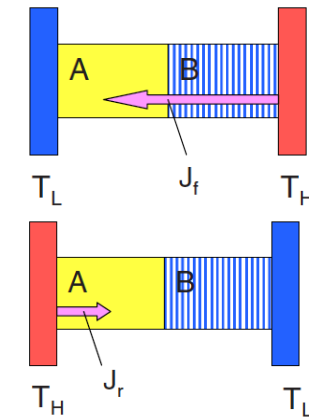
THERMAL MANAGEMENT

Heat dissipation at the nanoscale is becoming a major issue



New generation electron devices must be cooled

PHONONICS



Manipulating heat flow to code and transmit information

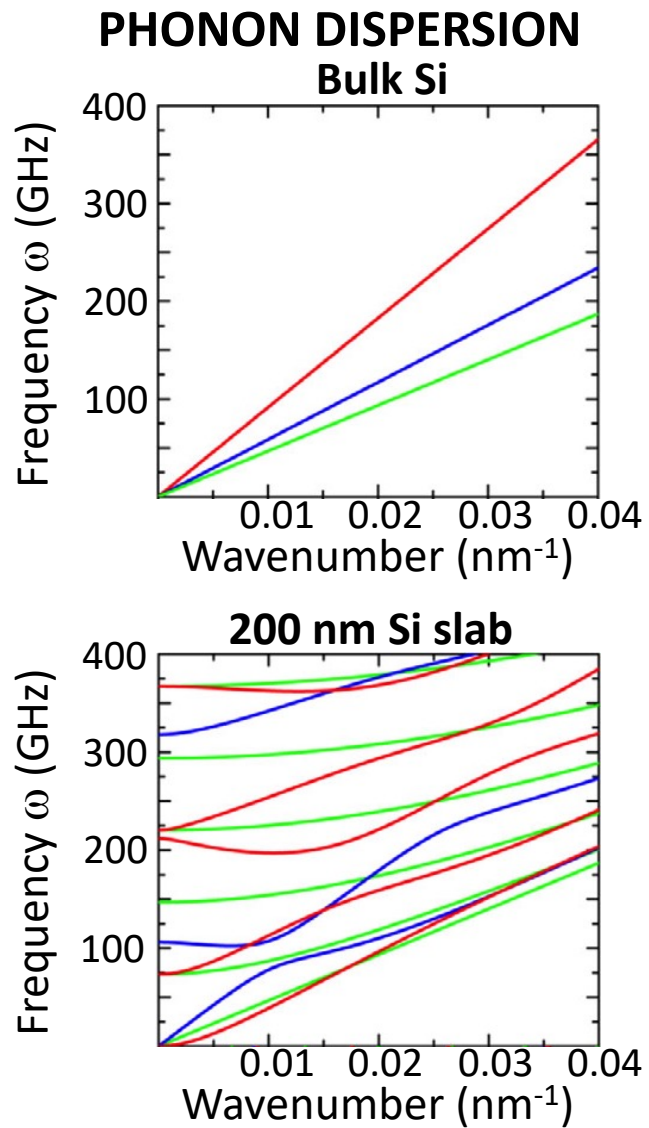
PHONON ENGINEERING

MEASUREMENT METHODS FOR PHONONS AND PHONON TRANSPORT

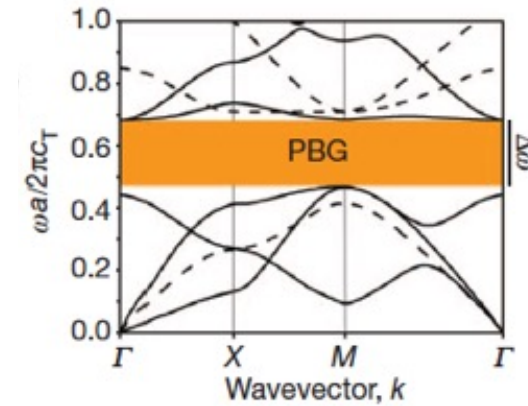
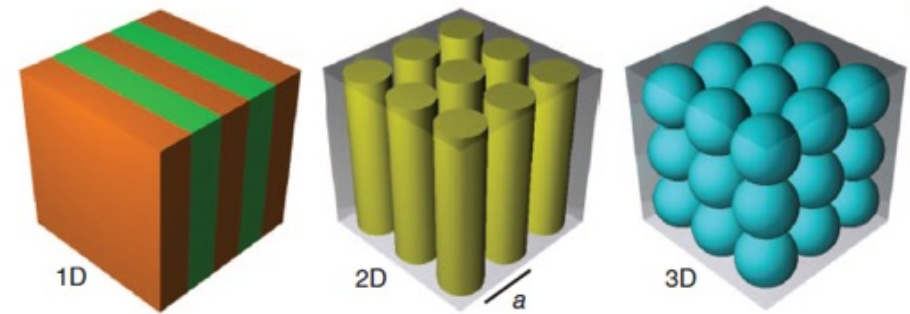
Outline

- The concept of phonon engineering in nanowires
- Experimental techniques
- Phonons and thermal transport in engineered nanowires

Phonon engineering



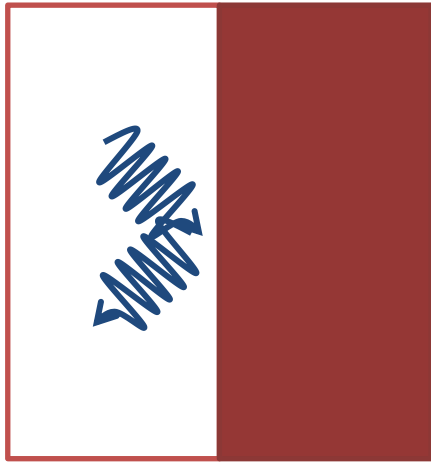
PHONONIC BAND GAP



PBGs occur for phonon wavelengths comparable to the structure periodicity a

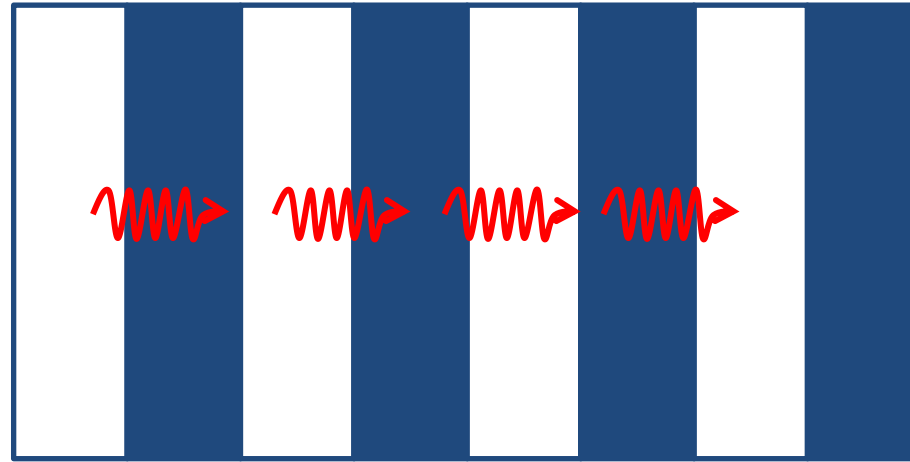
Phonons in superlattices: particles vs. wave

Casimir limit



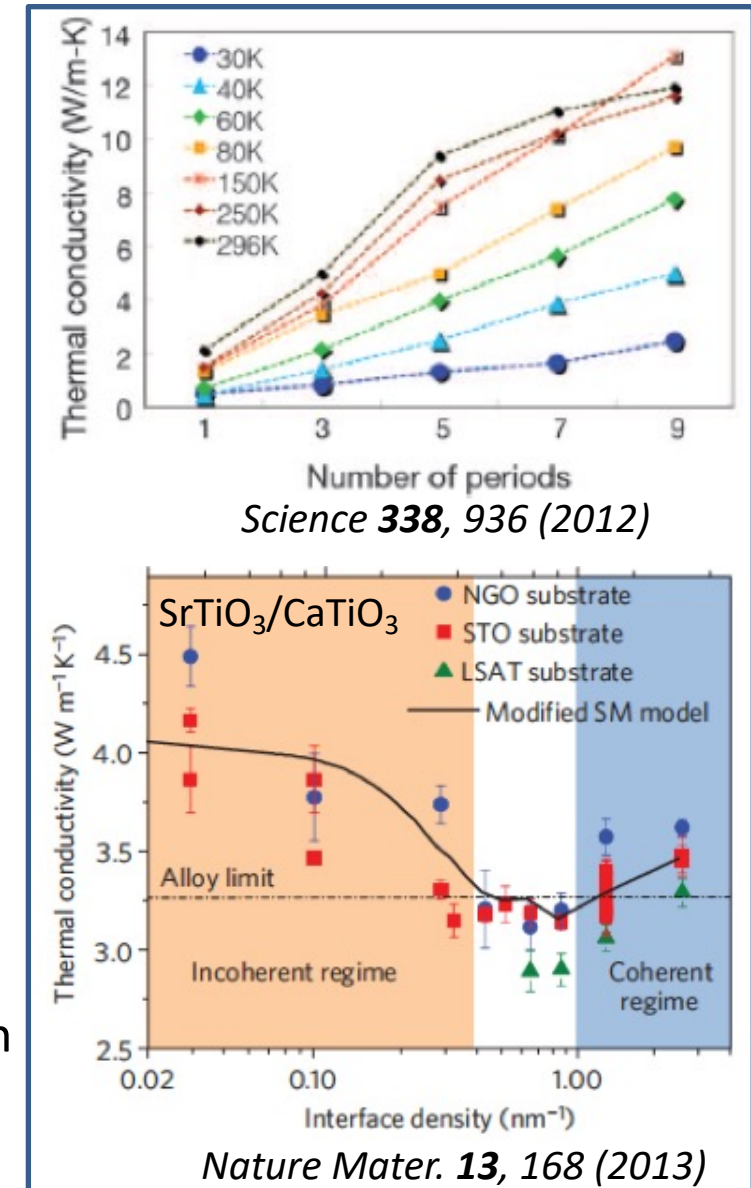
Diffusive scattering
Lost of phase information

Coherent phonon regime

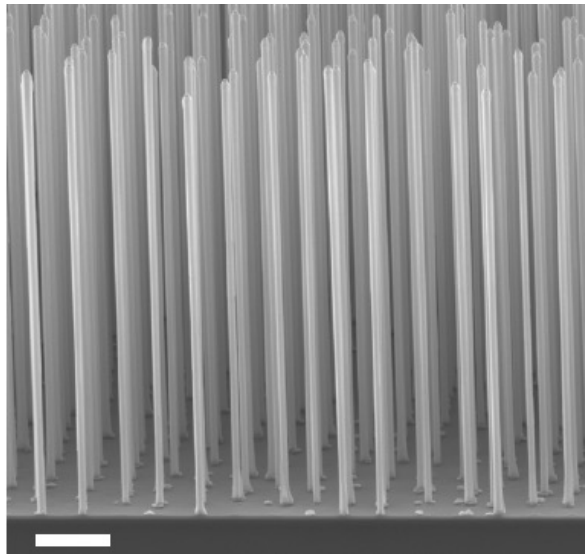


New material with its own phonon dispersion
arising from phonon interference

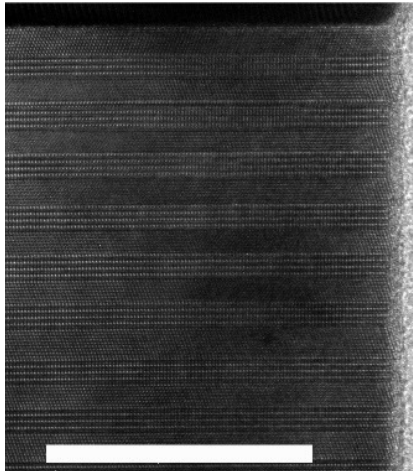
- **Coherent acoustic phonons:** ballistic wavepackets of compressive/tensile stress.
- **Coherent optical phonons:** standing waves of in-phase atomic oscillations, in which the adjacent atoms swing against each other.



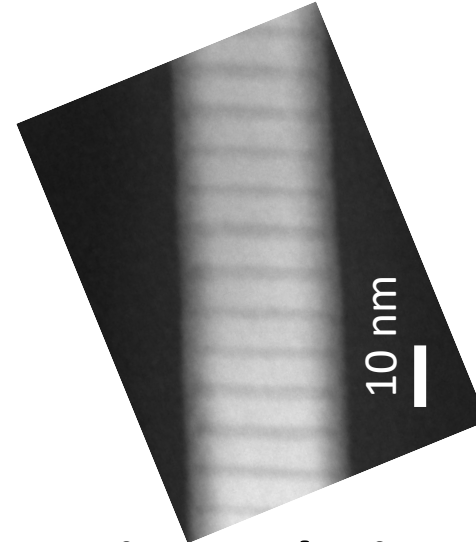
Phonon engineering in nanowires



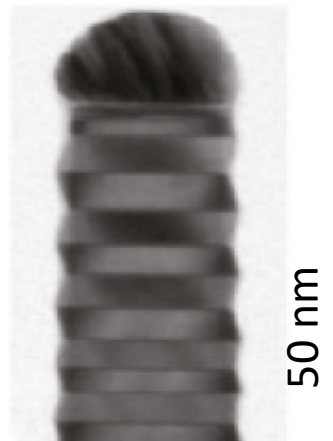
Crystal phase superlattices



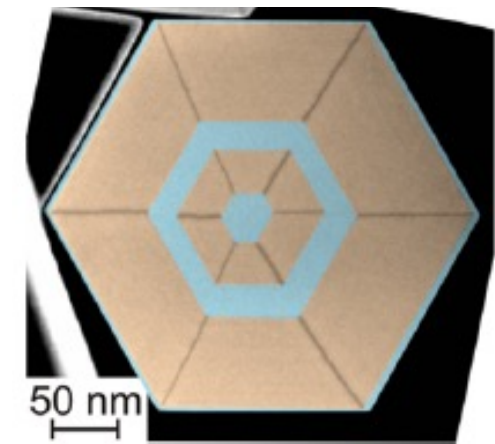
Axial heterostructures



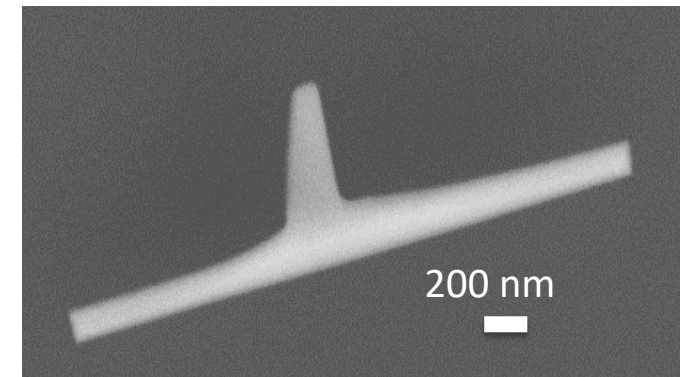
Twin superlattices



Radial heterostructures



Branched junctions



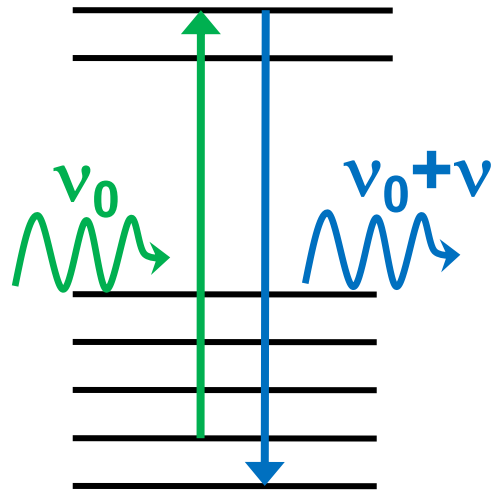
Outline

- The concept of phonon engineering in nanowires
- **Experimental techniques**
- Phonons and thermal transport in engineered nanowires

Raman Spectroscopy

Raman effect is a 2-photon scattering process

Anti-Stokes Scattering

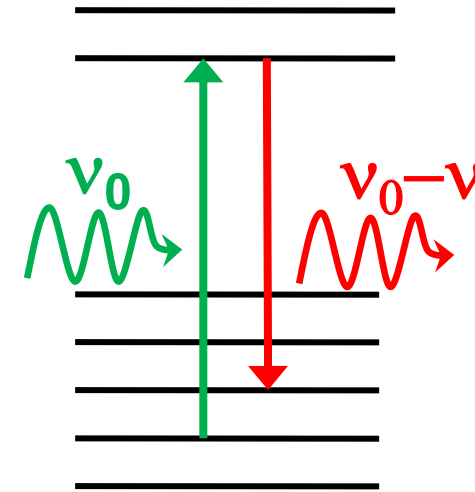


Photon gains energy

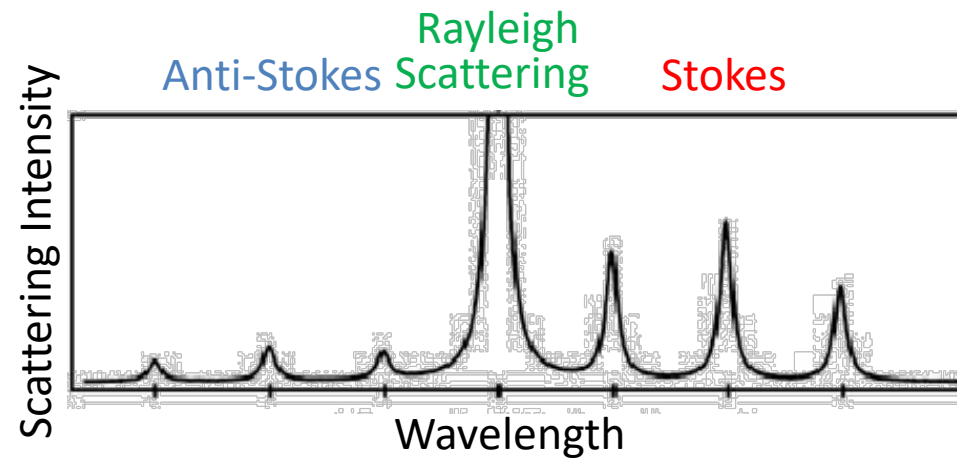
Virtual Energy States

Vibrational Energy States

Stokes Scattering

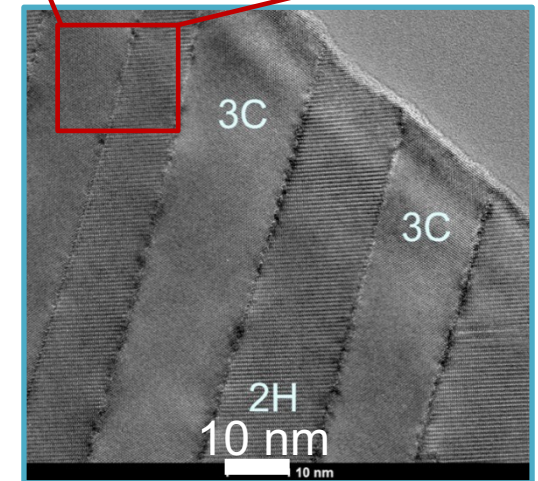
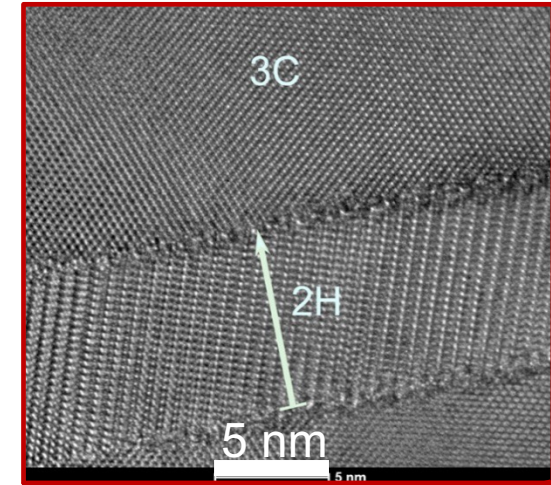
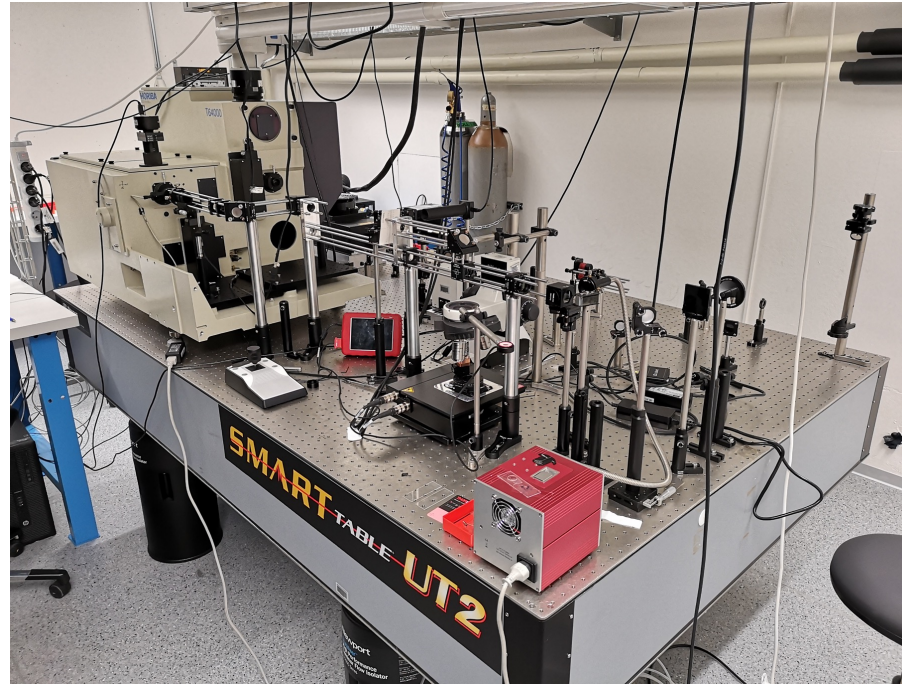


Photon loses energy



Investigating phonons by (Resonant) Raman Spectroscopy

- Lattice dynamics
- Crystal structure
- Composition / Doping
- Strain
- Structural transition
- Electronic states
- Interaction with charges/spins/photons

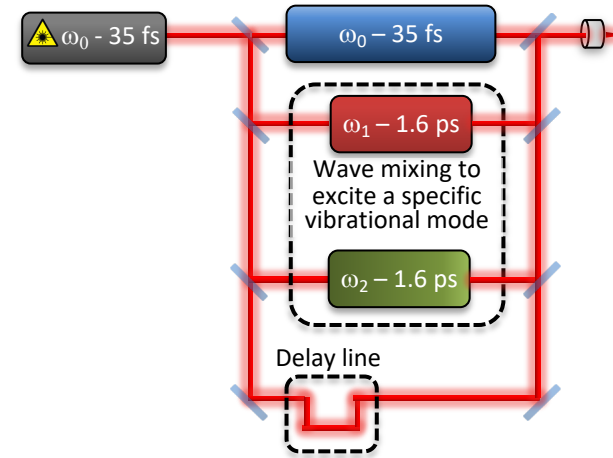


- Relative orientation of heterostructures

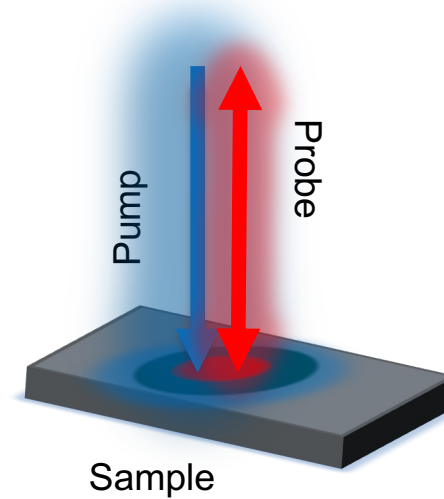
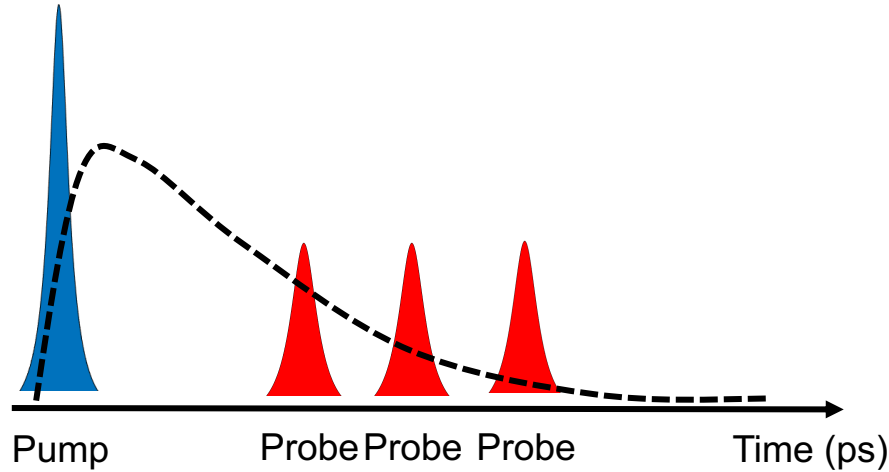
Nano Lett. **18** (11), 7075-7084 (2018)

Investigating phonons by pump-probe spectroscopy

- Phonons lifetime
- Absolute phonon mode population
- Temporal evolution of the phonon mode population



Phonon dynamics



- The pump brings the system out of equilibrium;
- A second less intense pulse, the probe, measures the effect of the pump excitation;
- A mechanical delay line allows to monitor the time evolution of the system over a sub-picosecond timescale.

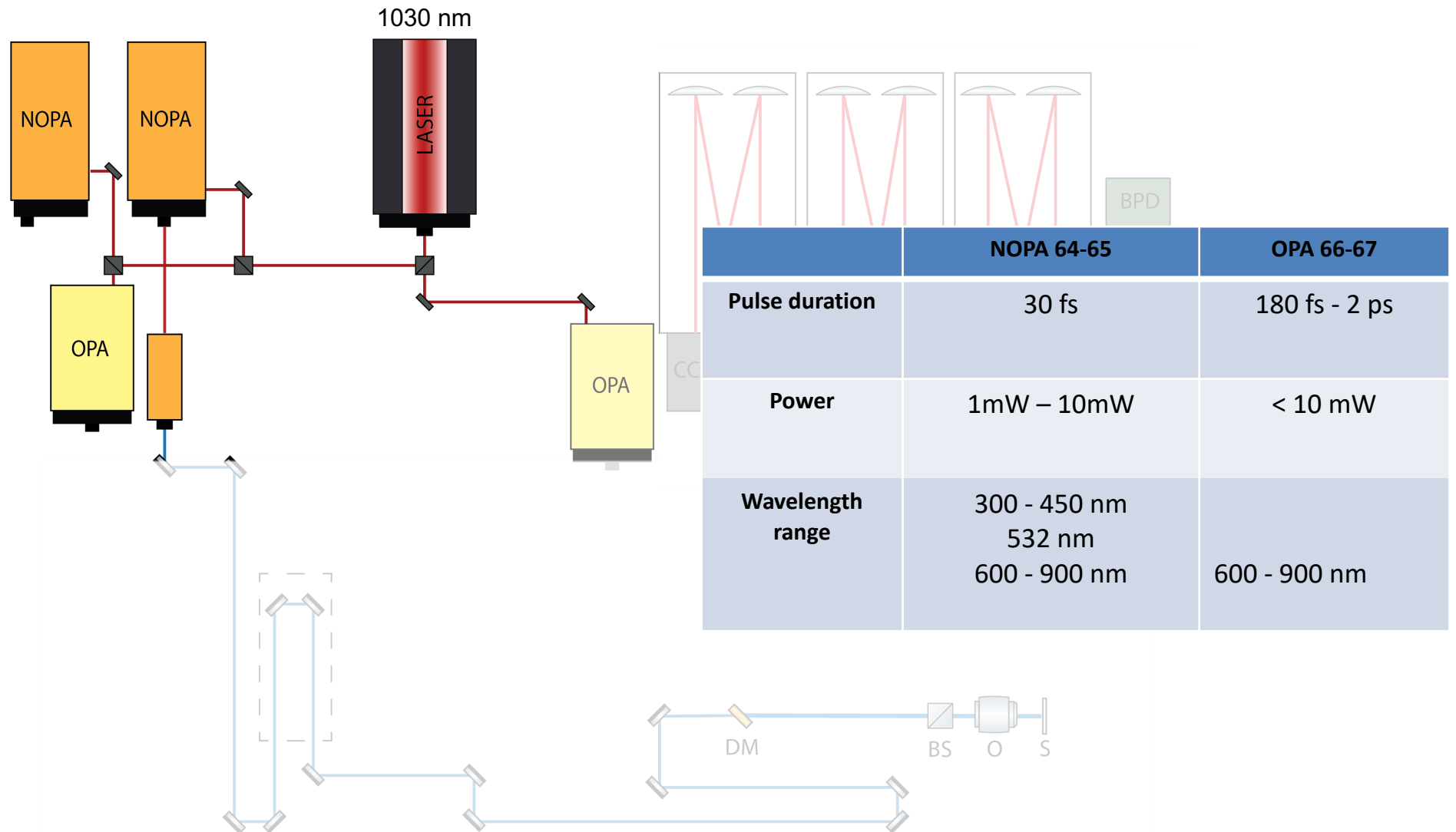
Transient reflectivity

Looking at the change in reflectivity from the sample we have access to e-ph and ph-ph coupling information

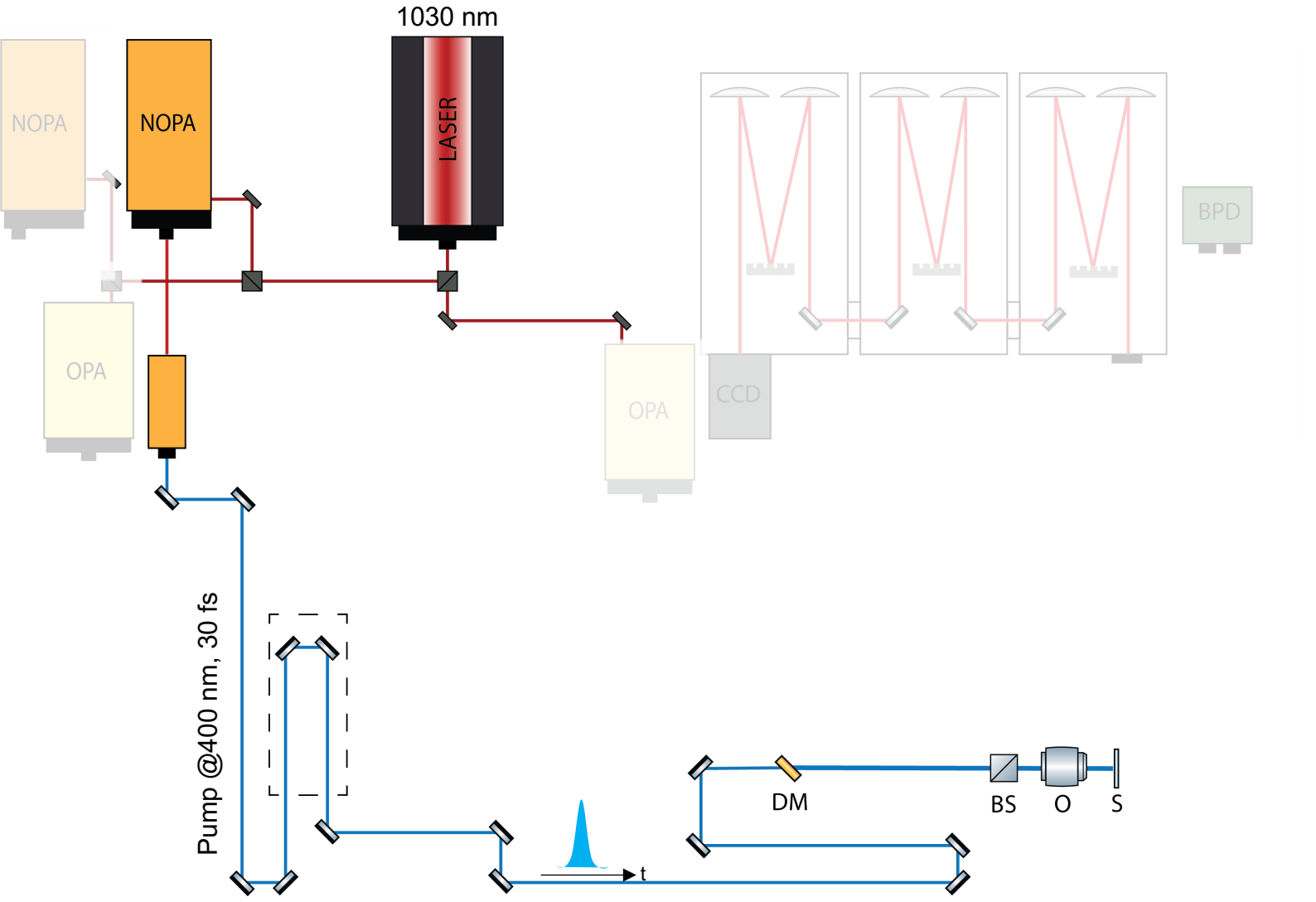
Time resolved Raman

Well-established probe for incoherent phonon population dynamics in semiconductors

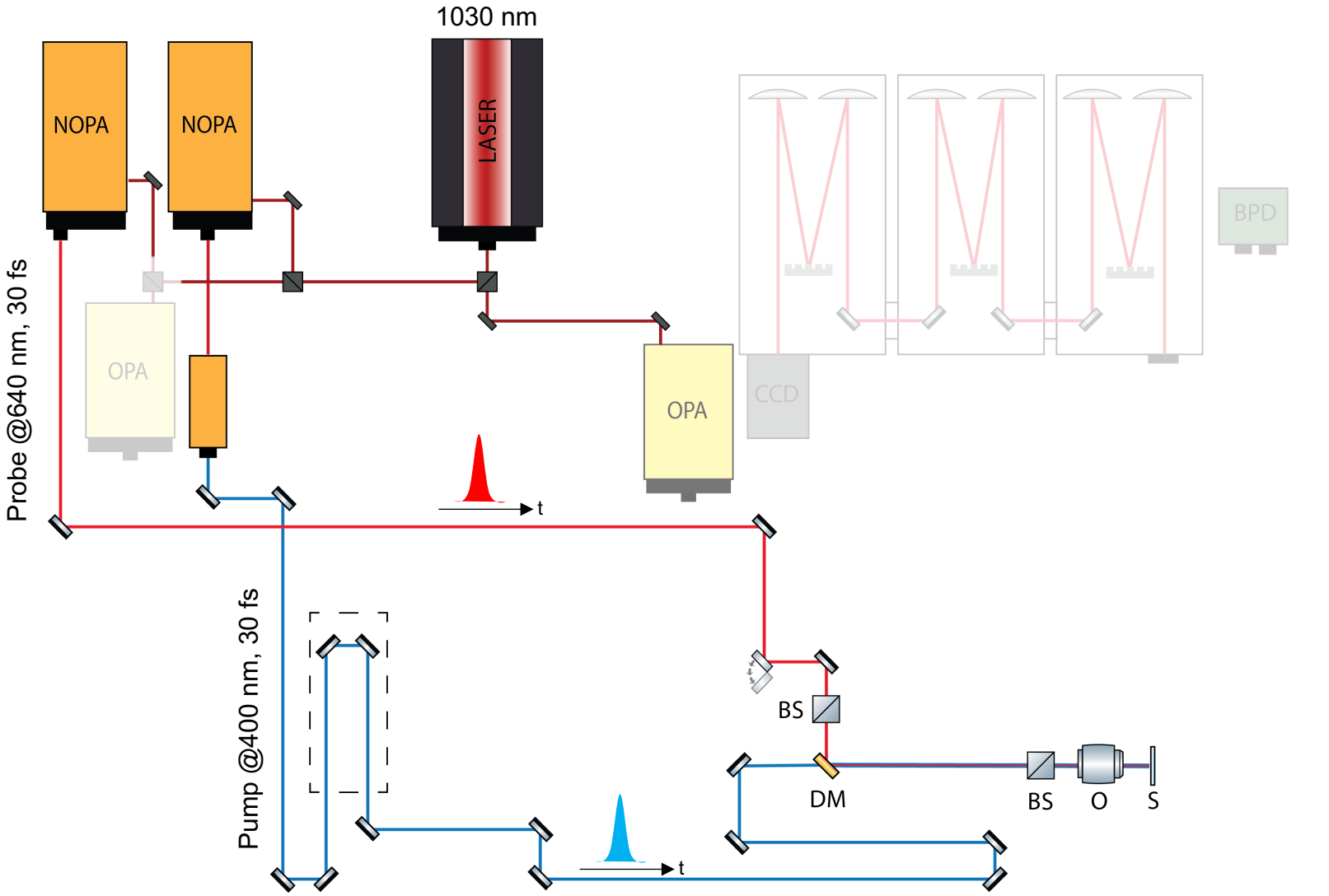
Experimental setup



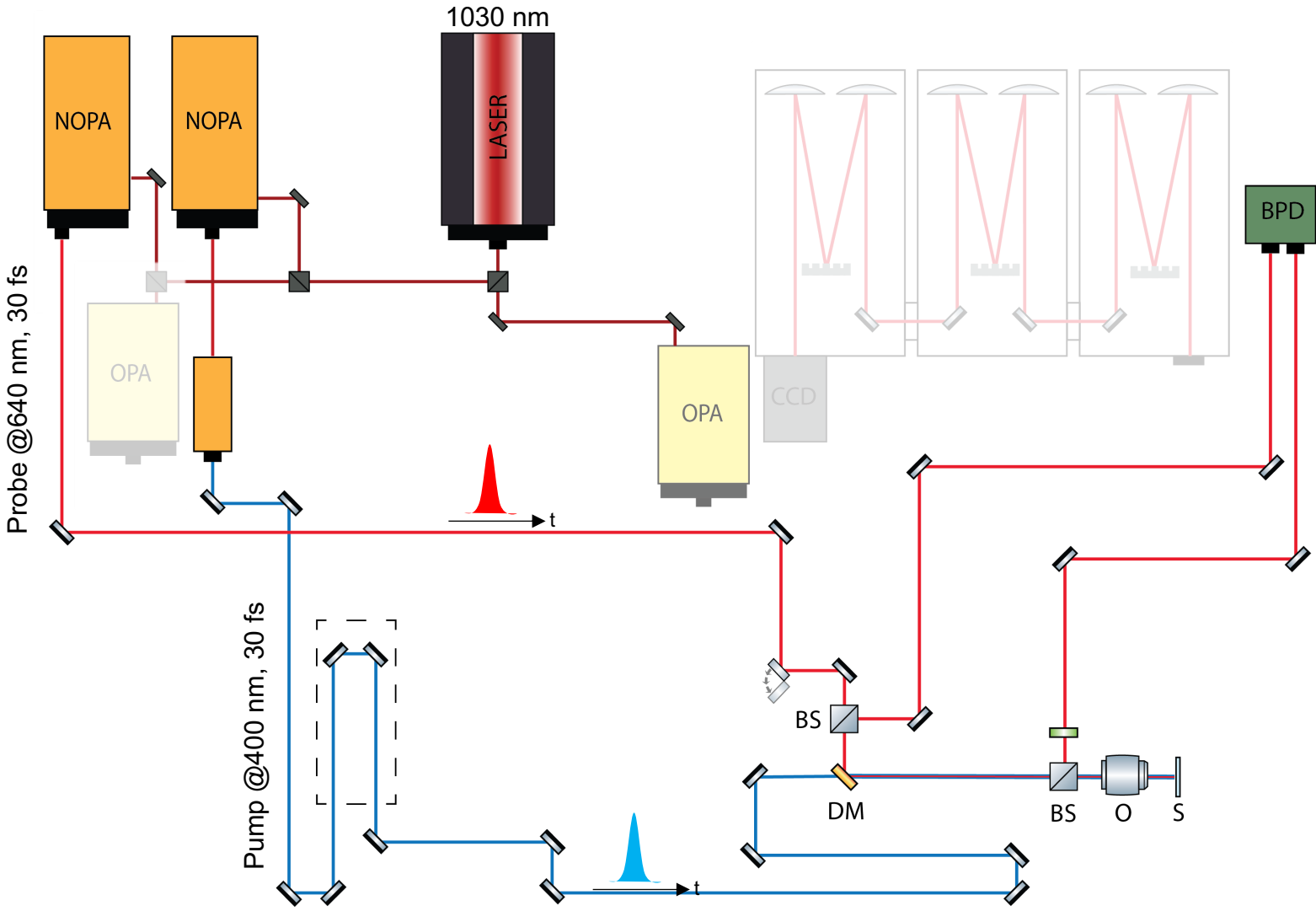
Transient reflectivity experimental scheme



Transient reflectivity experimental scheme



Transient reflectivity experimental scheme



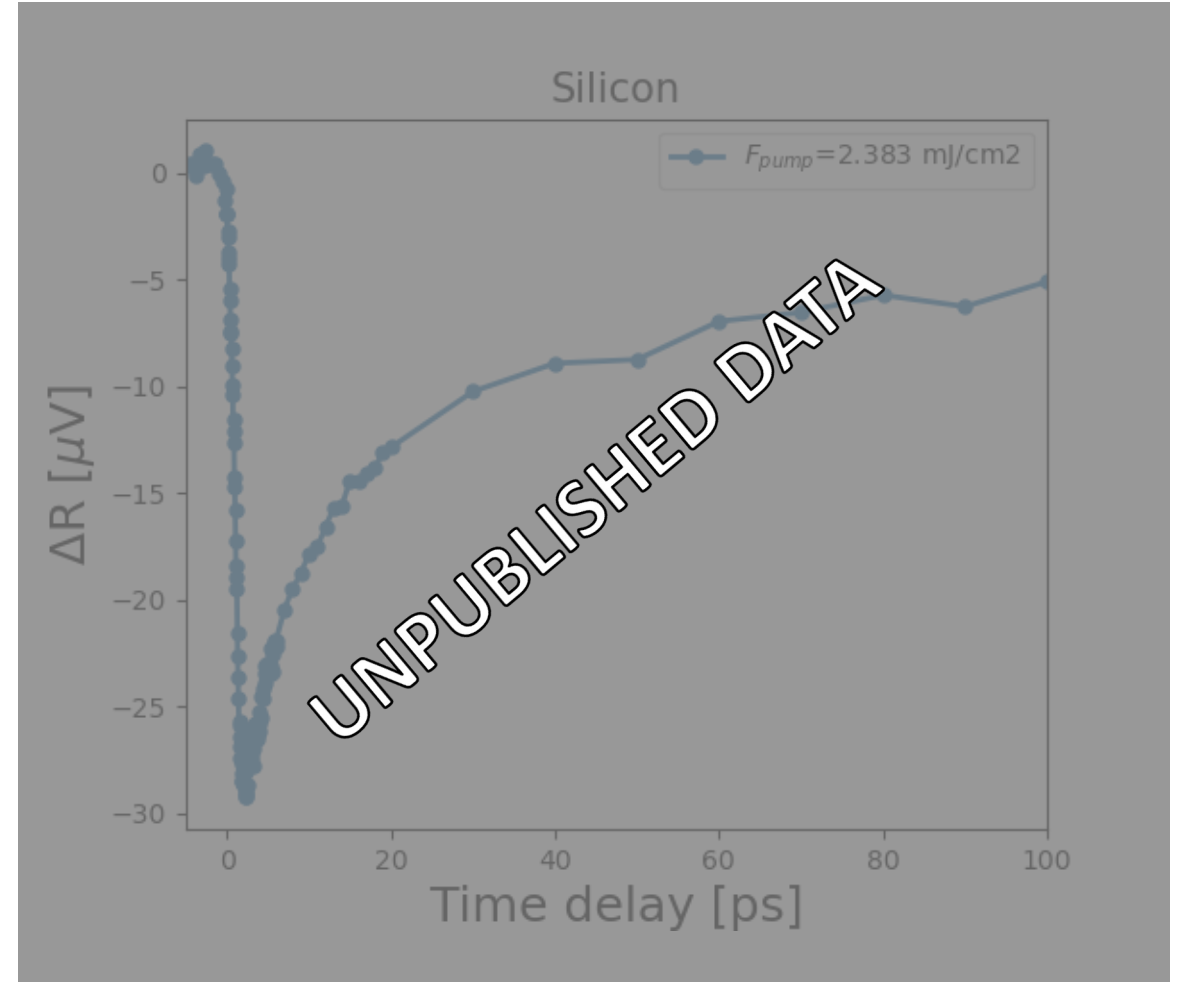
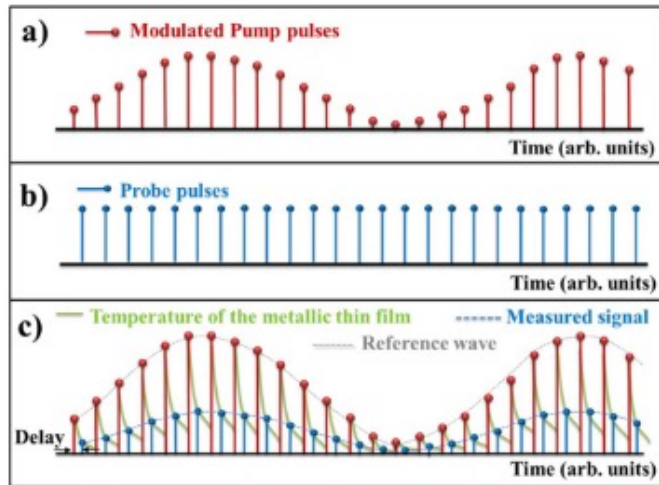
Transient reflectivity detection scheme



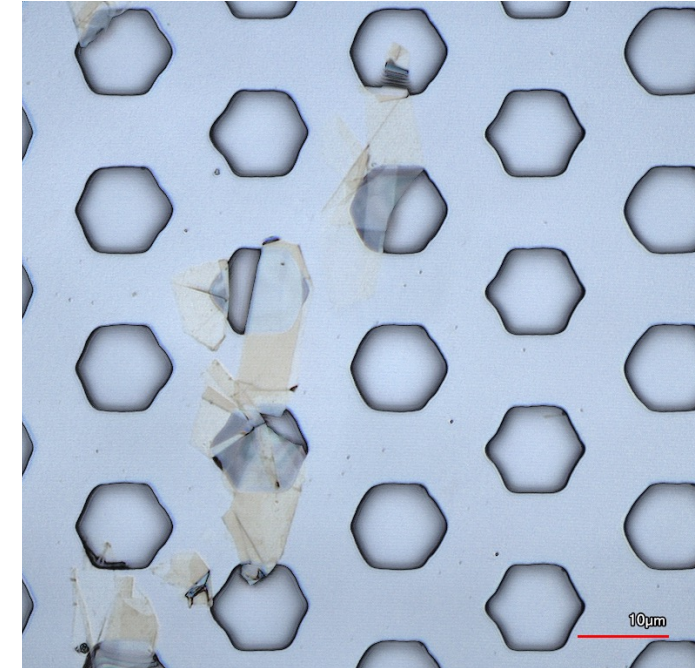
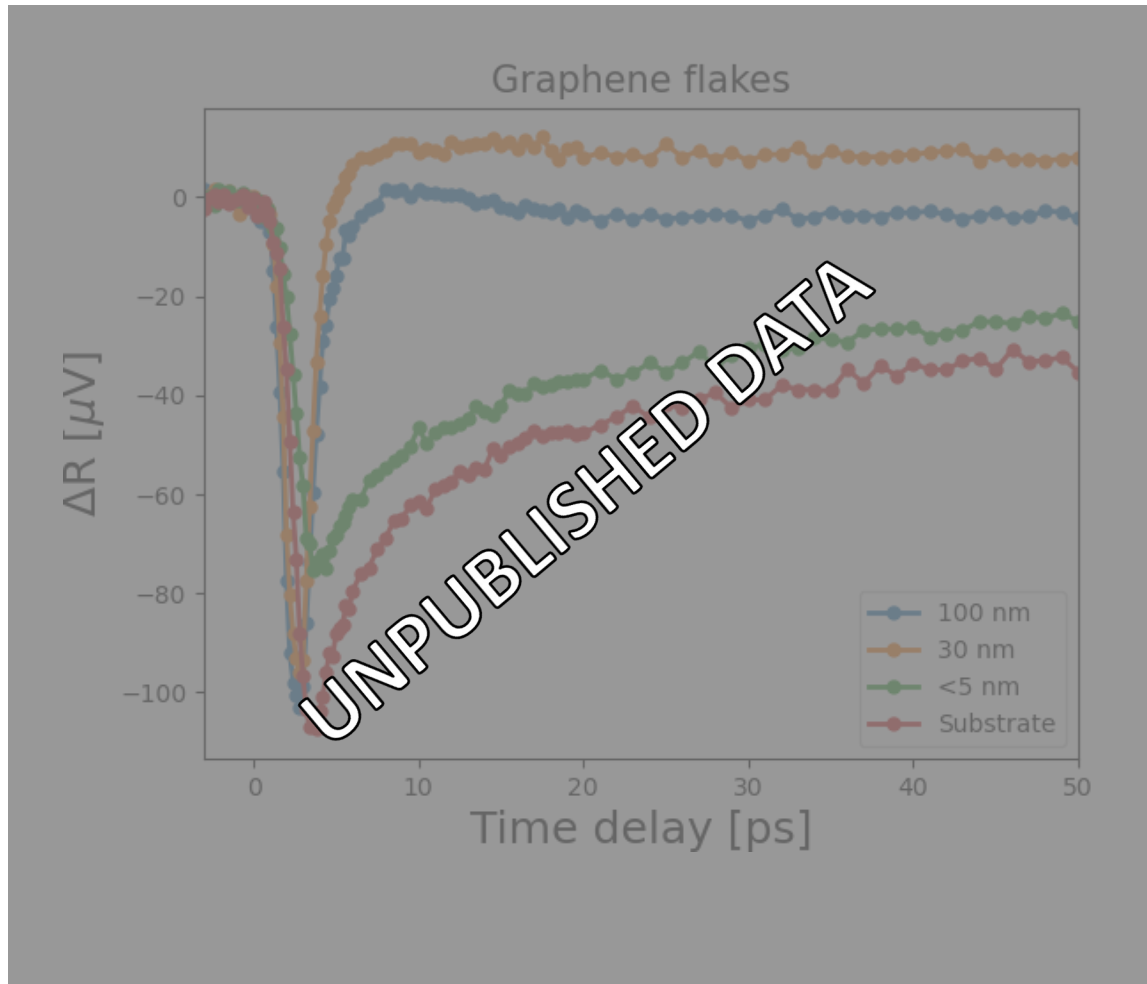
Chopper



Lock in amplifier

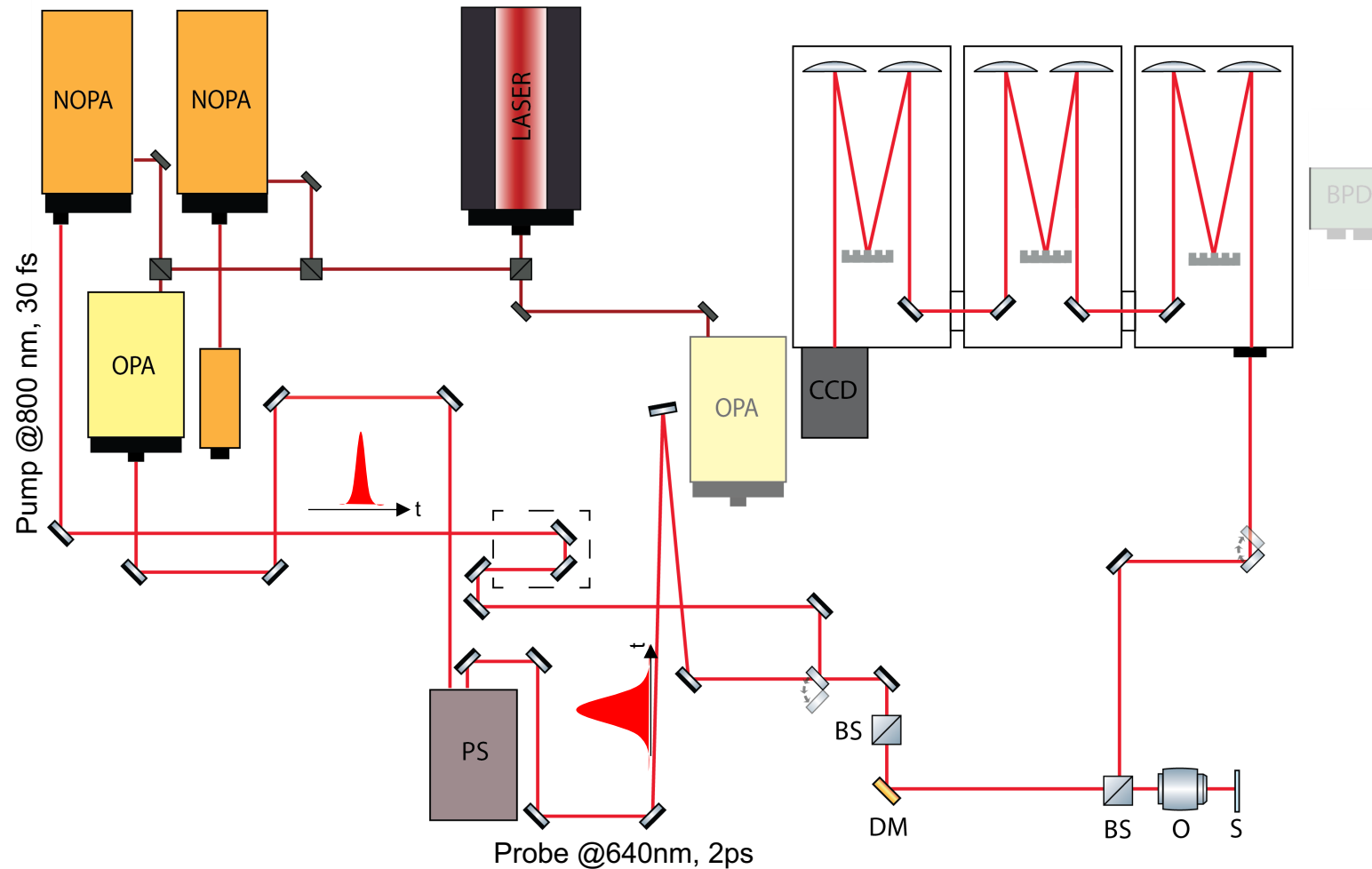


Transient reflectivity on graphite flakes



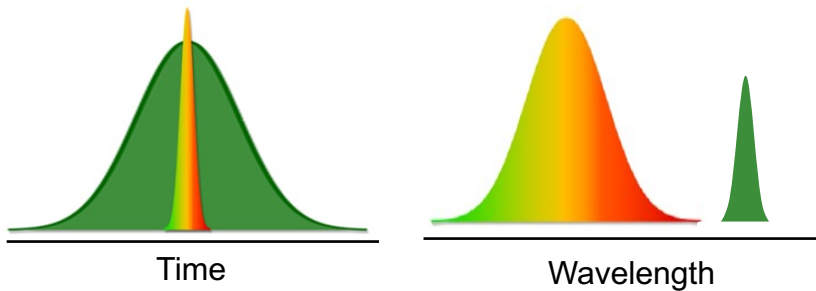
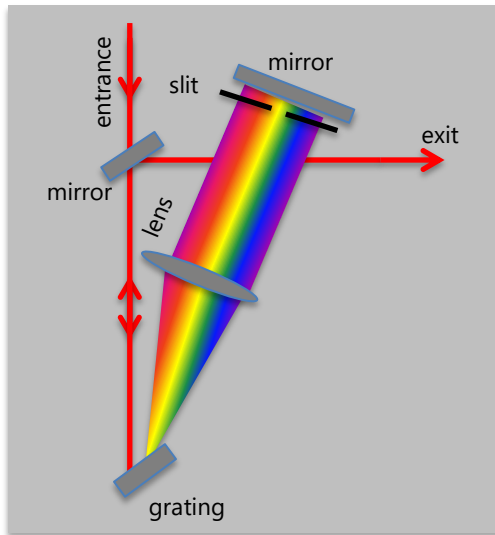
Si trenches, flake transfer with PDMS+PC

Time-resolved Raman experimental scheme



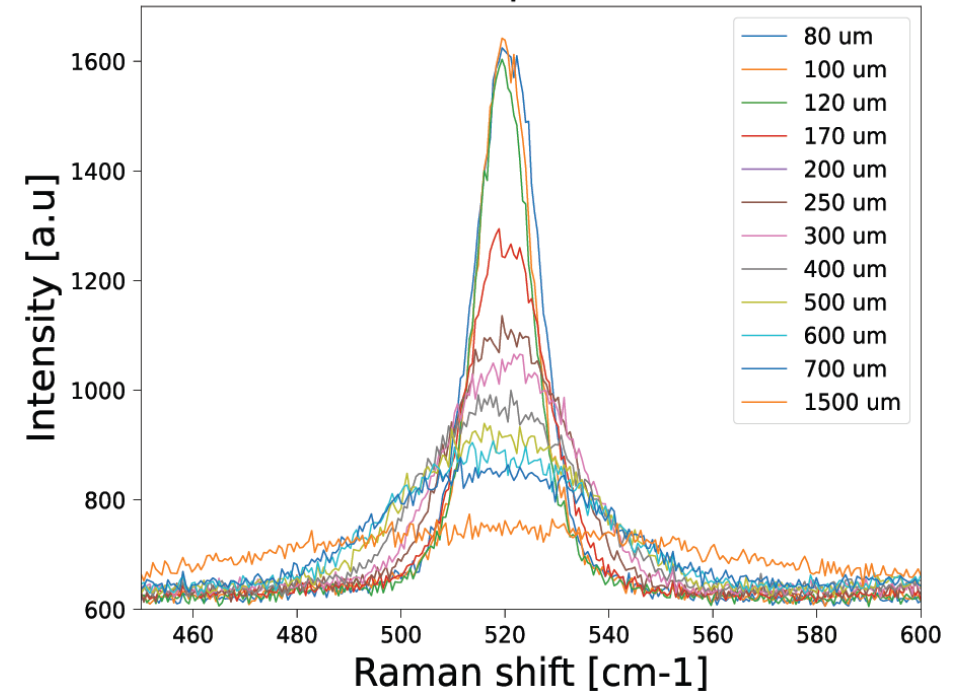
Increasing the spectral resolution

Pulse shaper

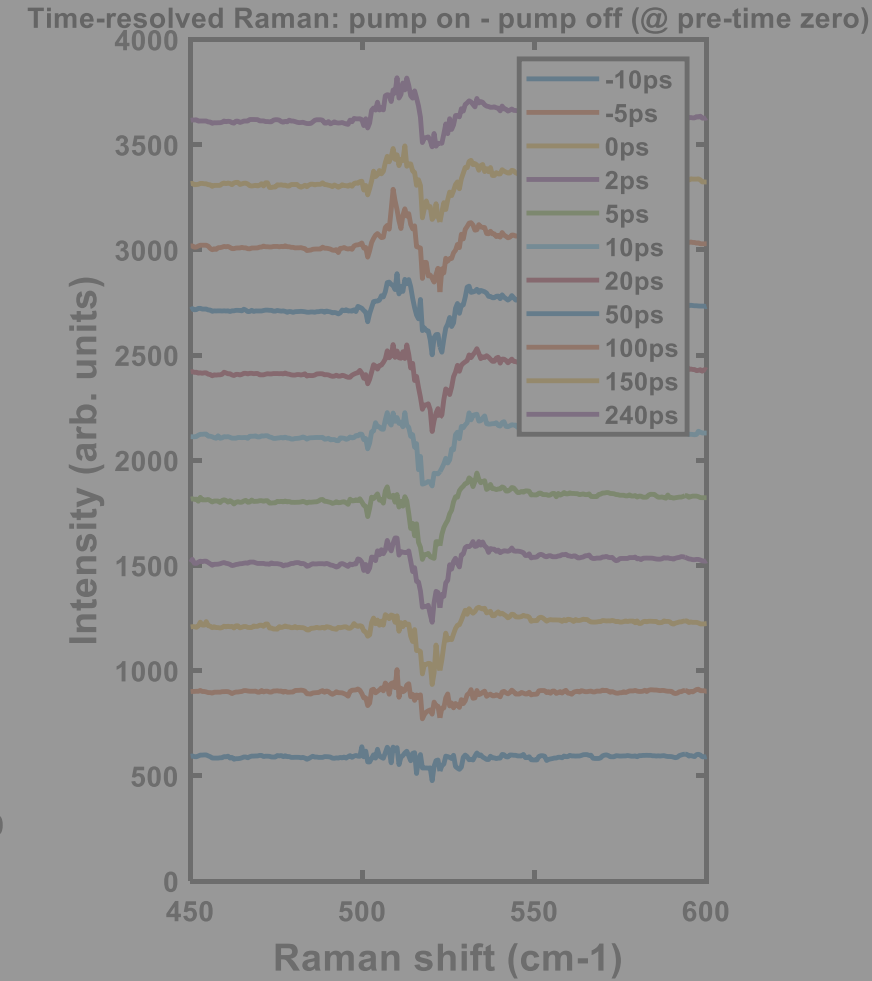
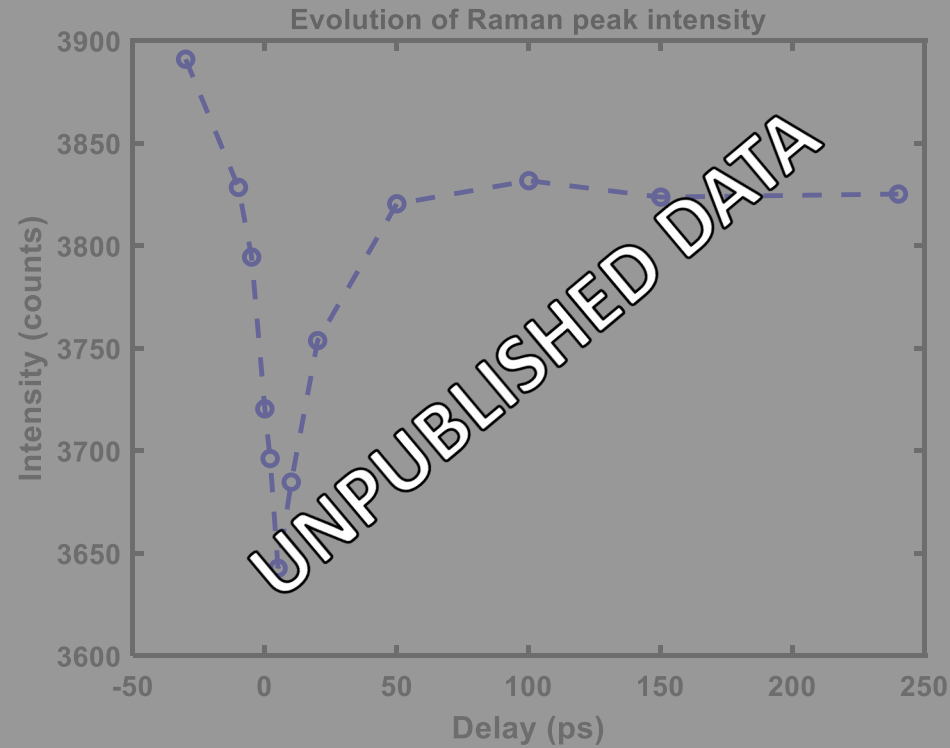
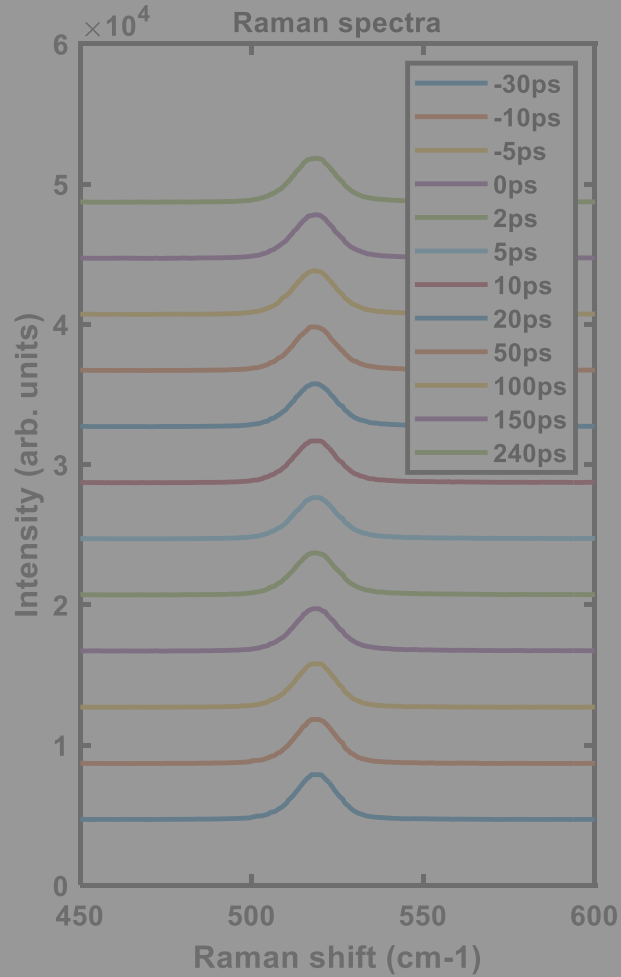


Increasing of the spectral resolution up to 10 cm⁻¹

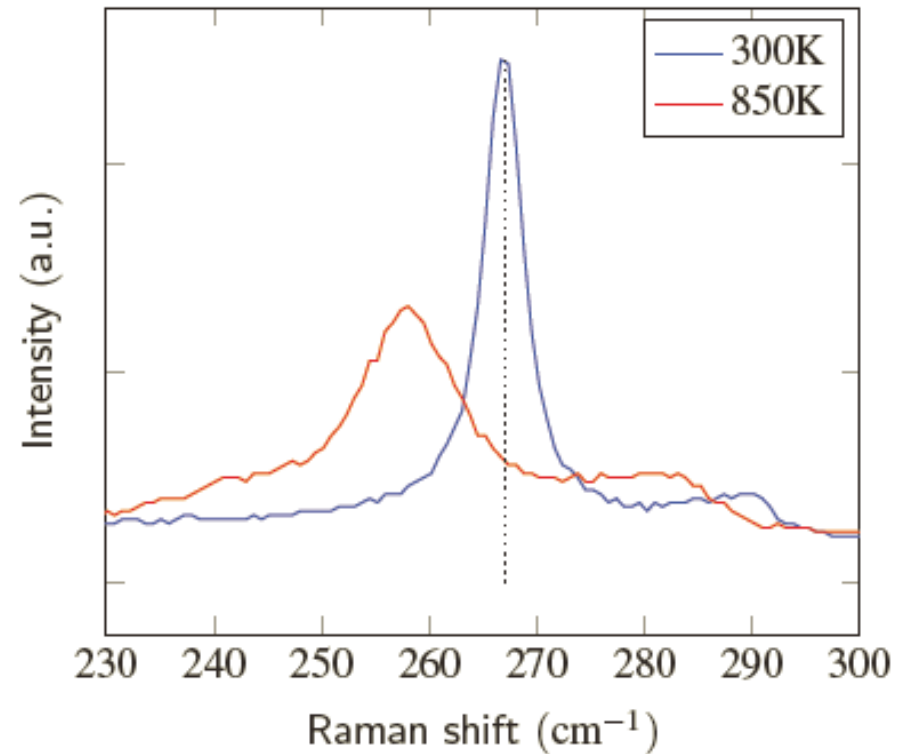
Slit aperture



Time resolved Raman on Silicon



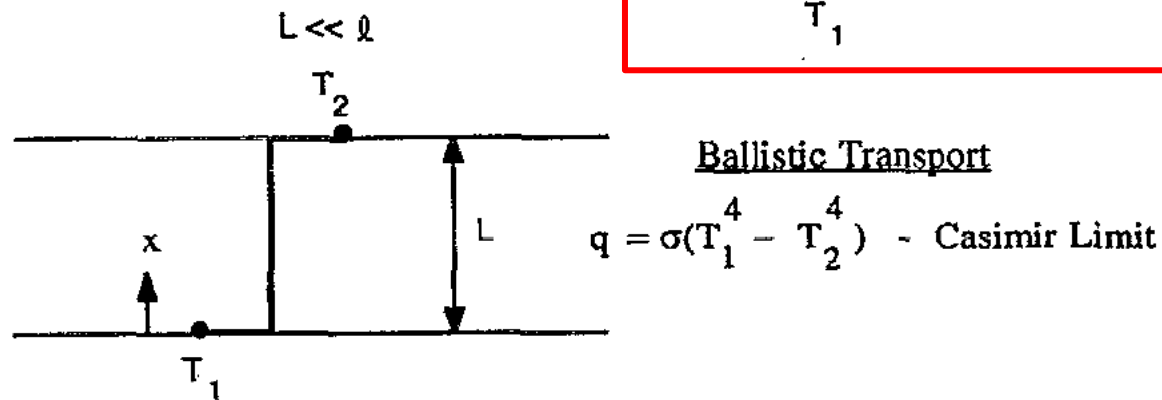
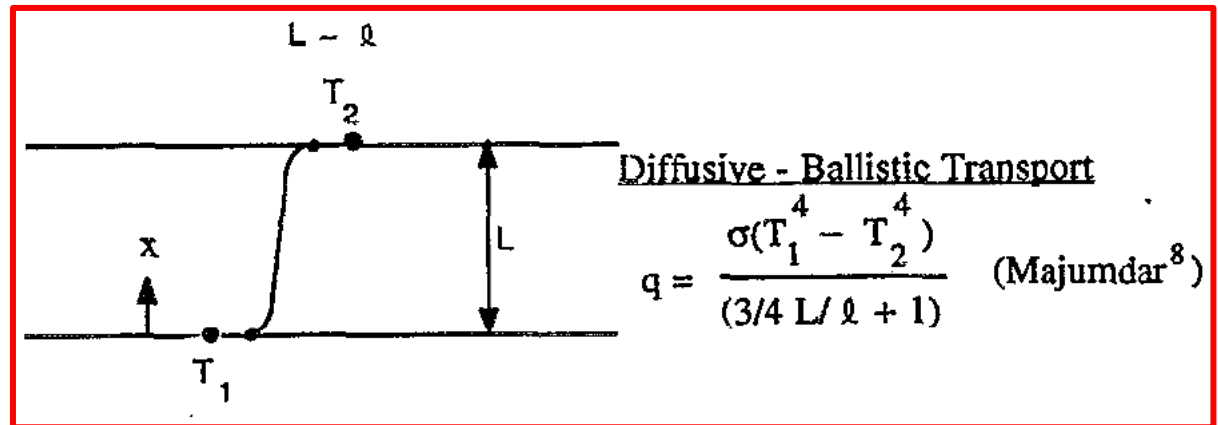
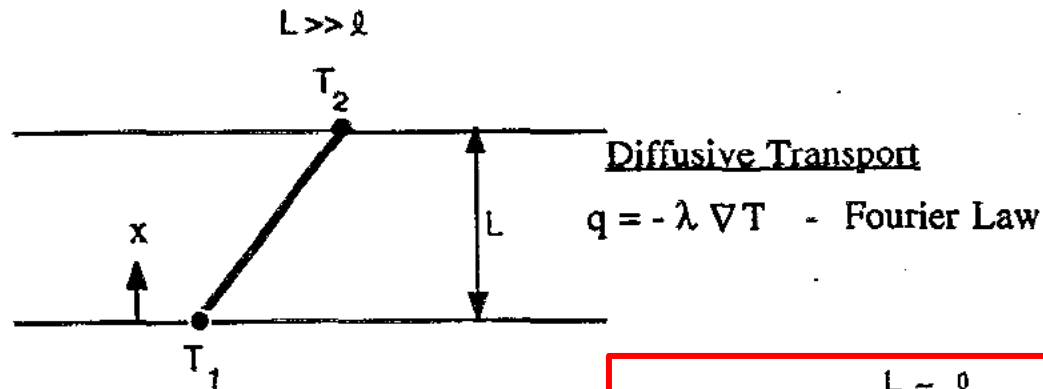
Raman thermometry



$$\Omega(T) = \omega_0 + \Delta(T) \quad \text{with} \quad \Delta(T) = A \left(1 + \frac{2}{e^x - 1} \right) + B \left(1 + \frac{3}{e^y - 1} + \frac{3}{(e^y - 1)^2} \right)$$

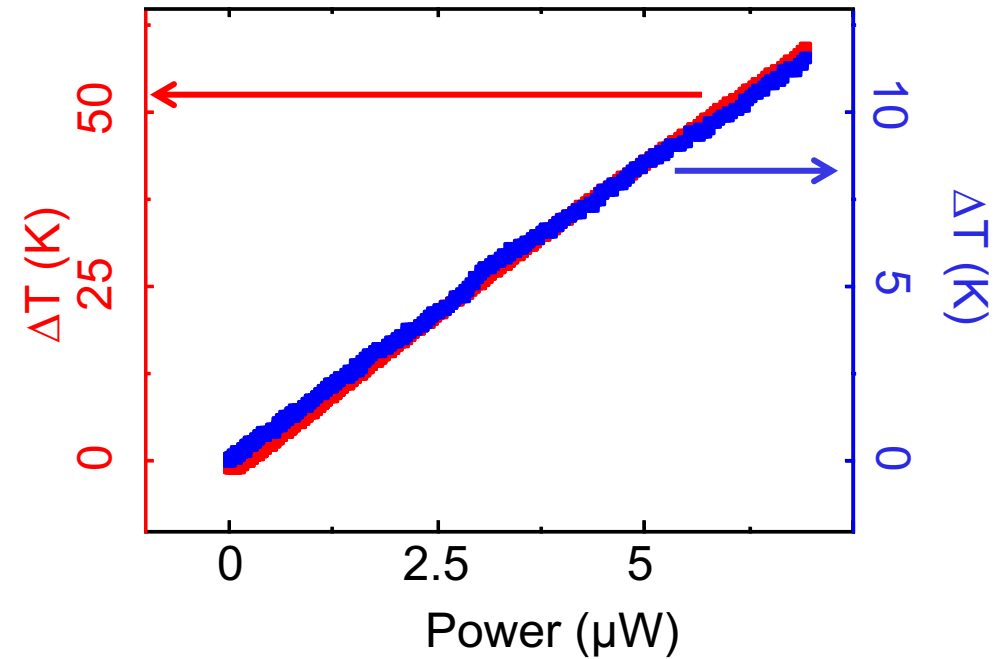
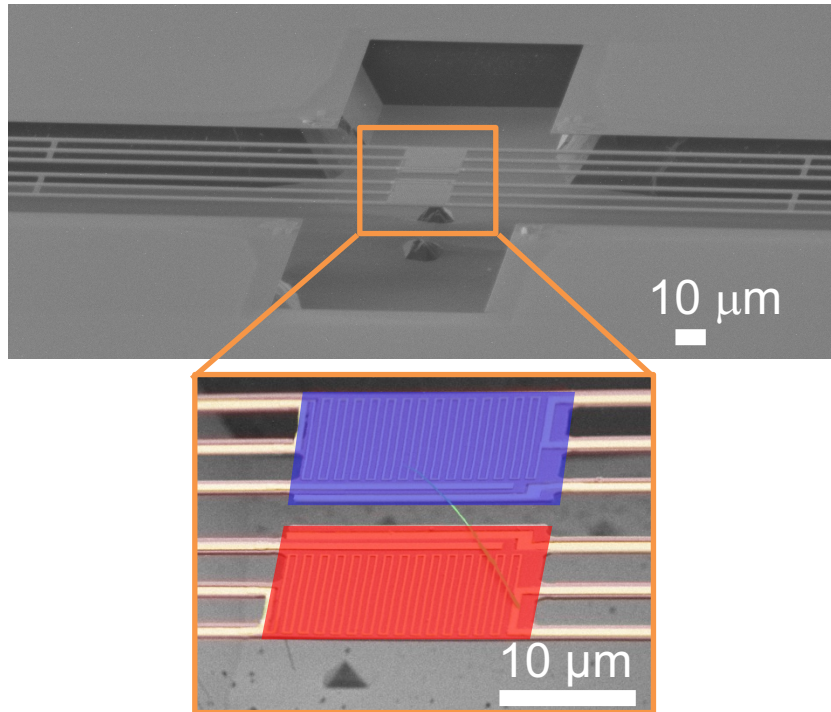
$$\Gamma(T) = C \left(1 + \frac{2}{e^x - 1} \right) + D \left(1 + \frac{3}{e^y - 1} + \frac{3}{(e^y - 1)^2} \right)$$

Thermometry of heat transport channels



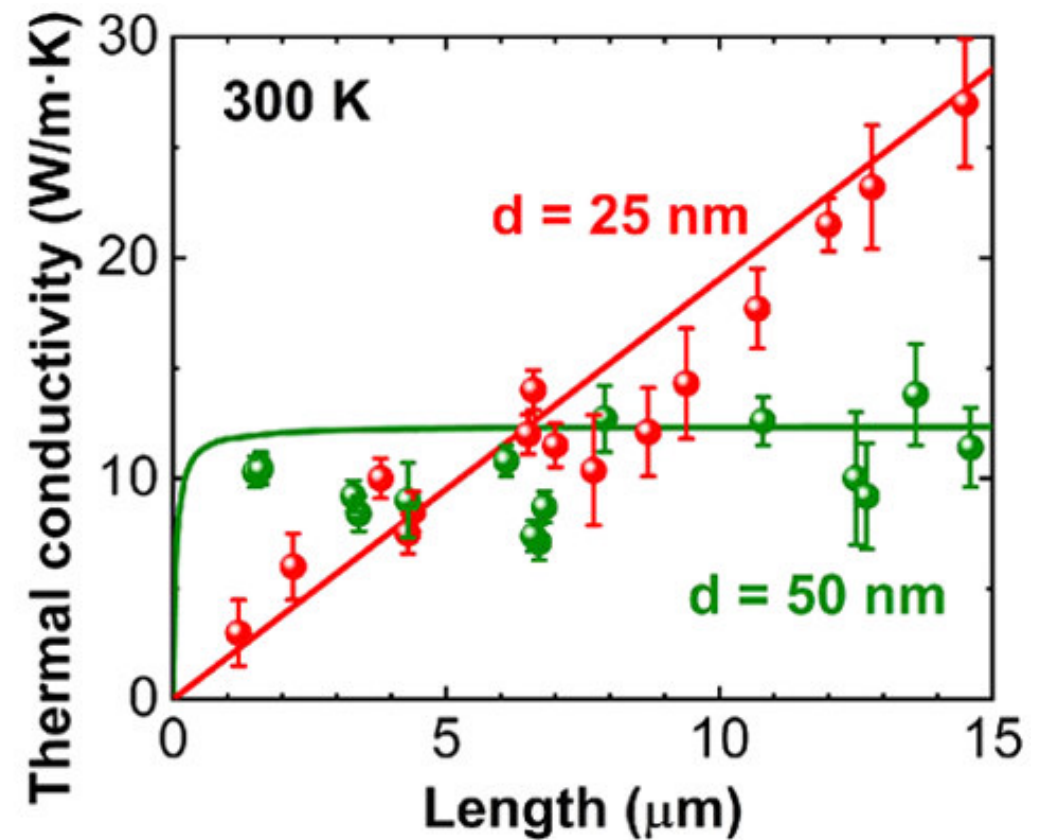
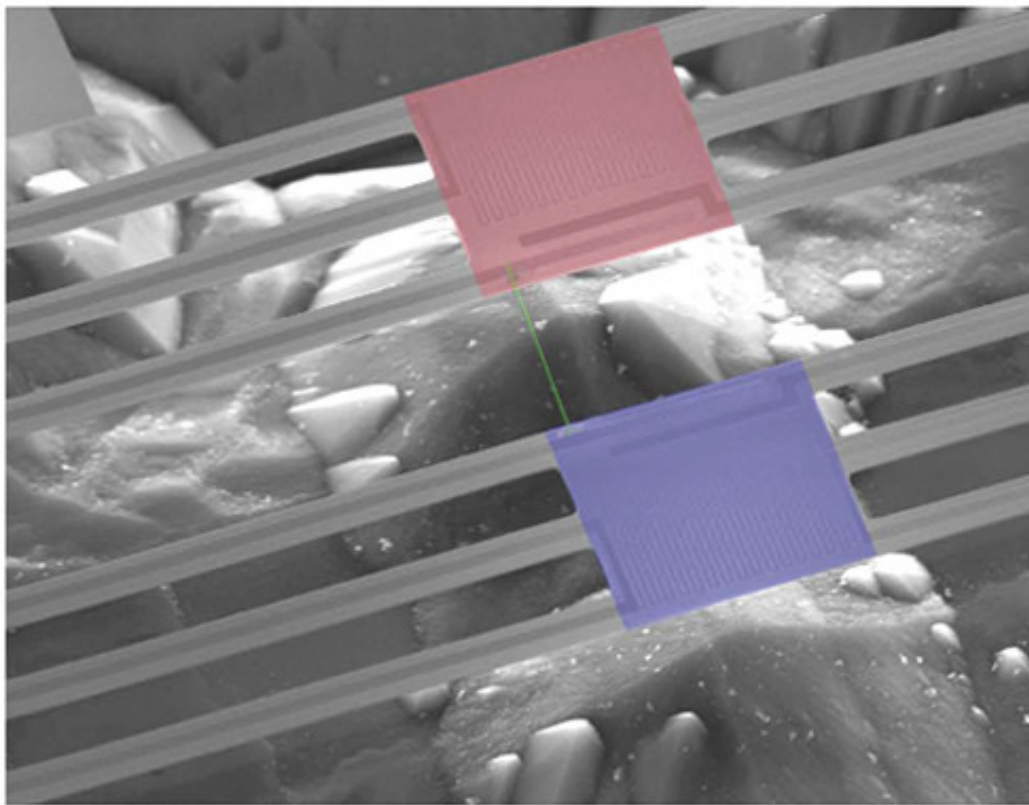
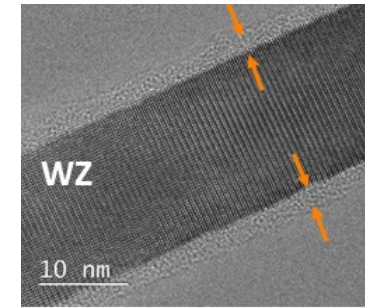
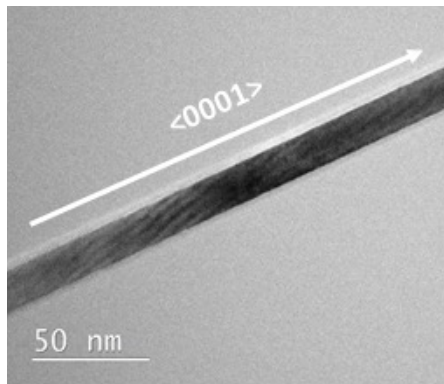
J. Appl. Phys. **74** (1), 31-39 (1993)

Thermal conductivity measurements



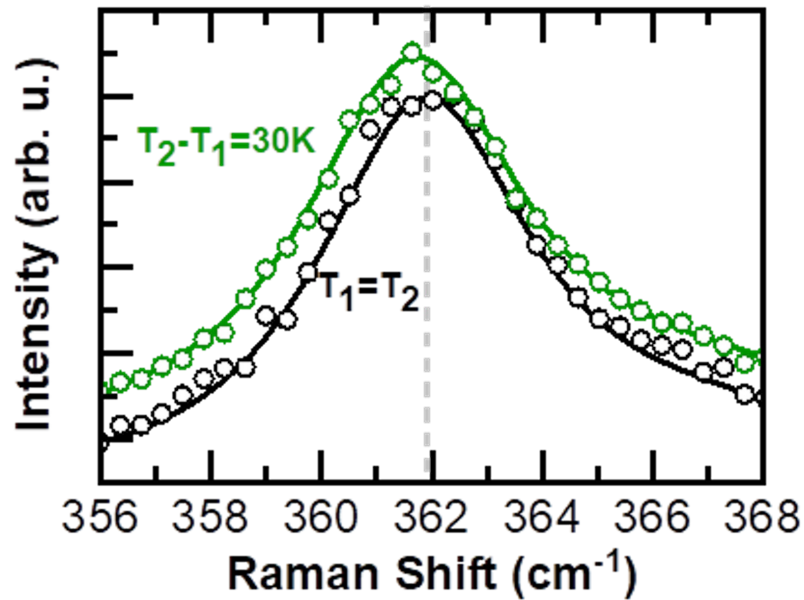
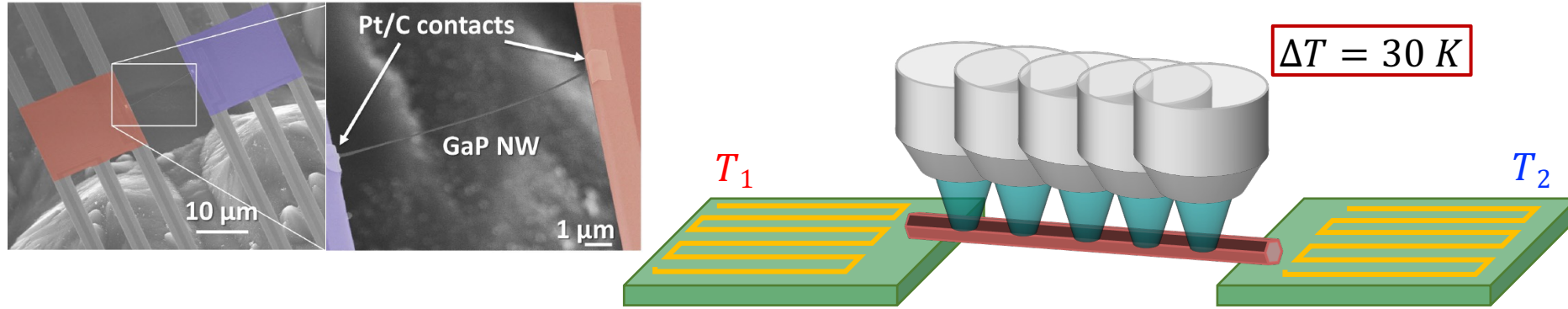
Nanotechnology **26**, 385401 (2015)

Ballistic heat transport in wurtzite GaP nanowires



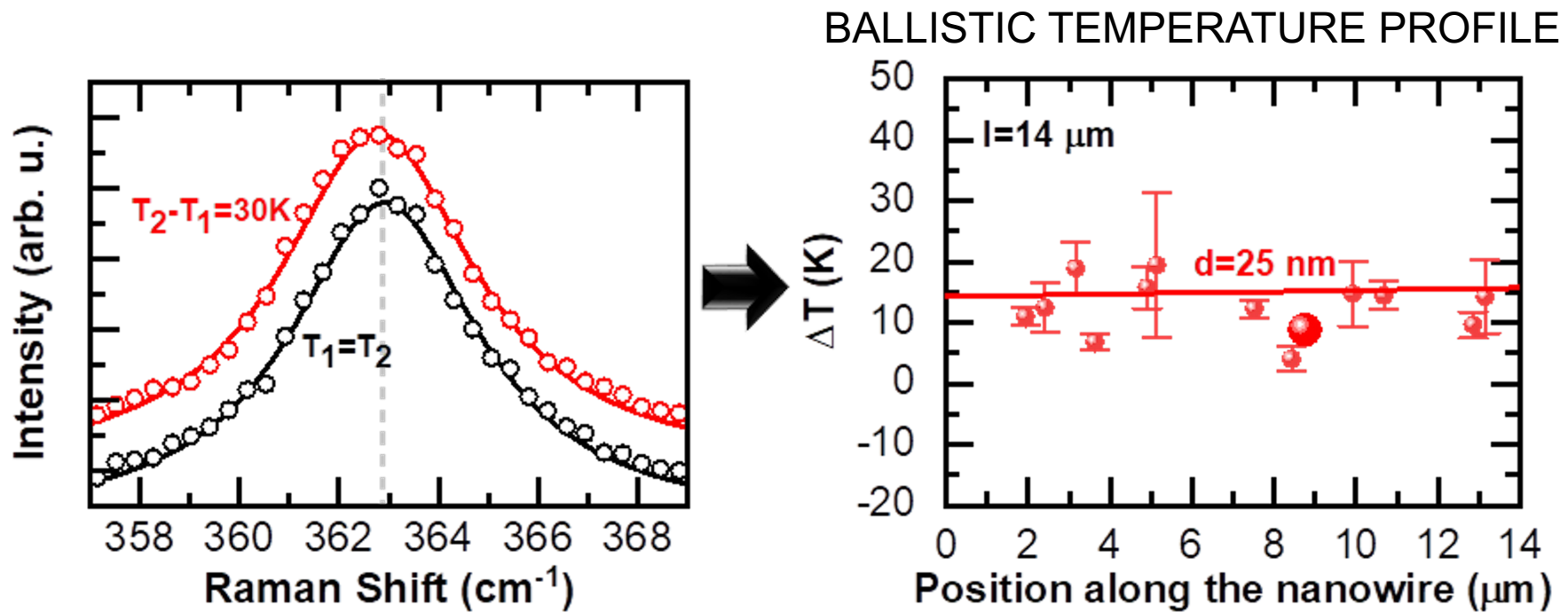
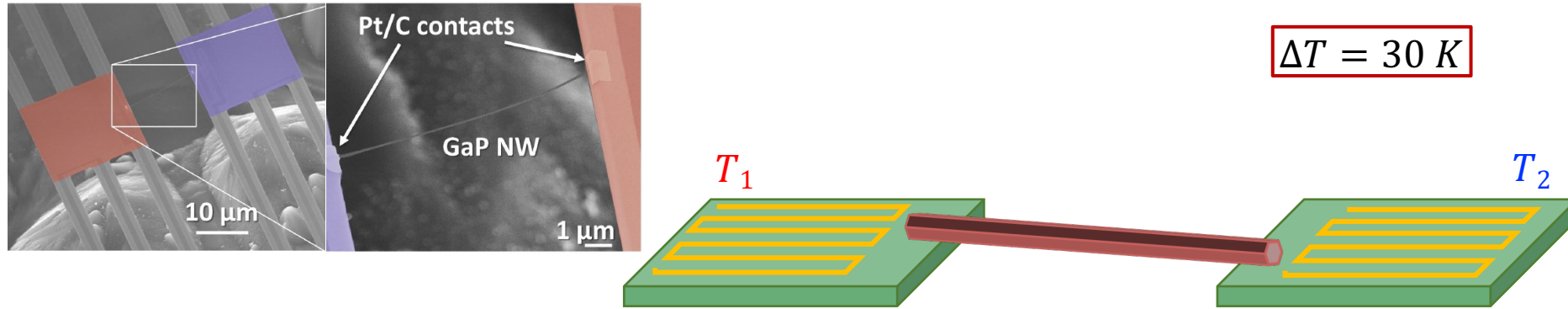
Nano Lett. **20**, 2703 (2020)

Raman thermometry of heat transport channels



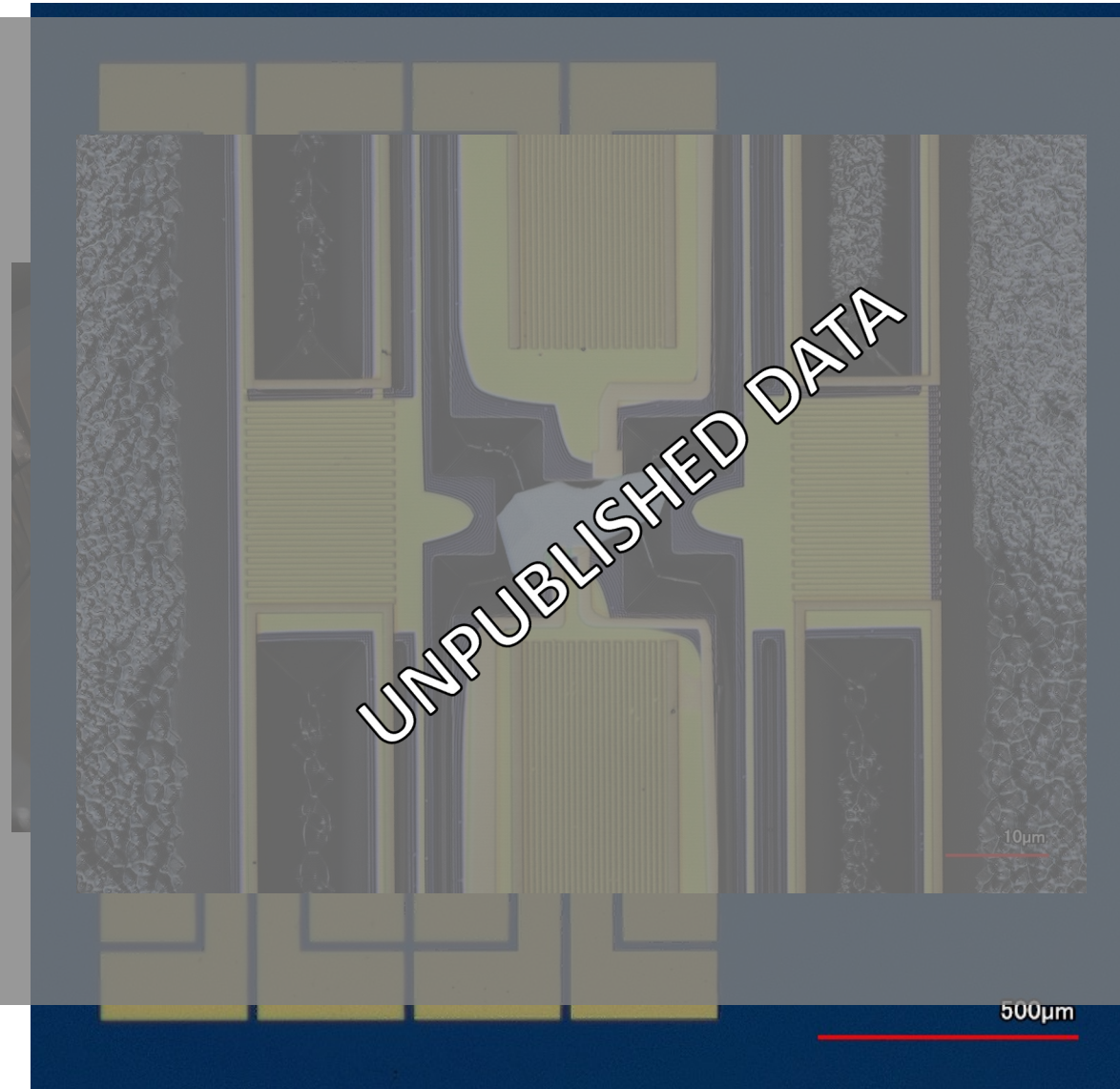
Nano Lett. **20**, 2703 (2020)

Raman thermometry of heat transport channels



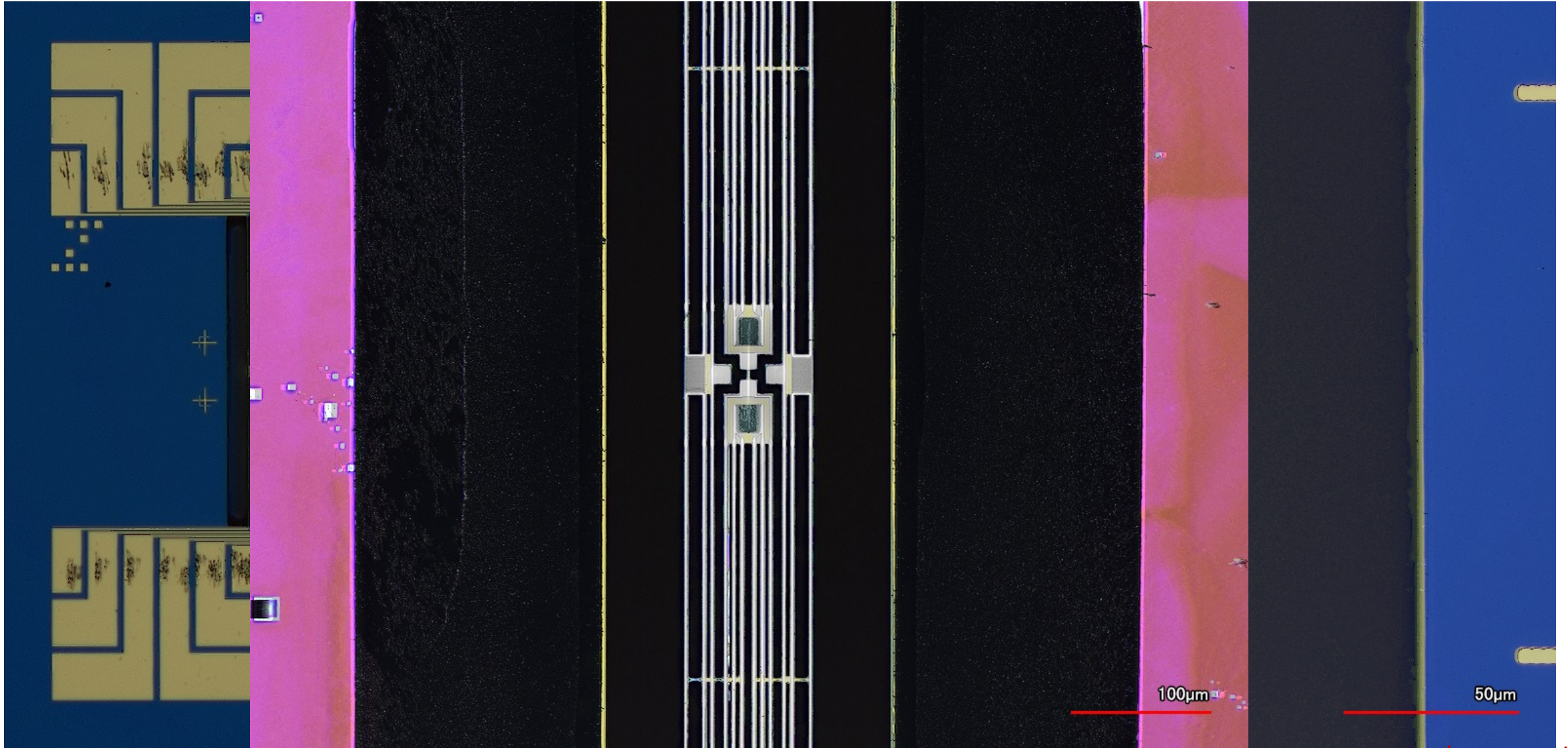
Nano Lett. **20**, 2703 (2020)

4-point thermal measurements



In preparation

Fabricated device

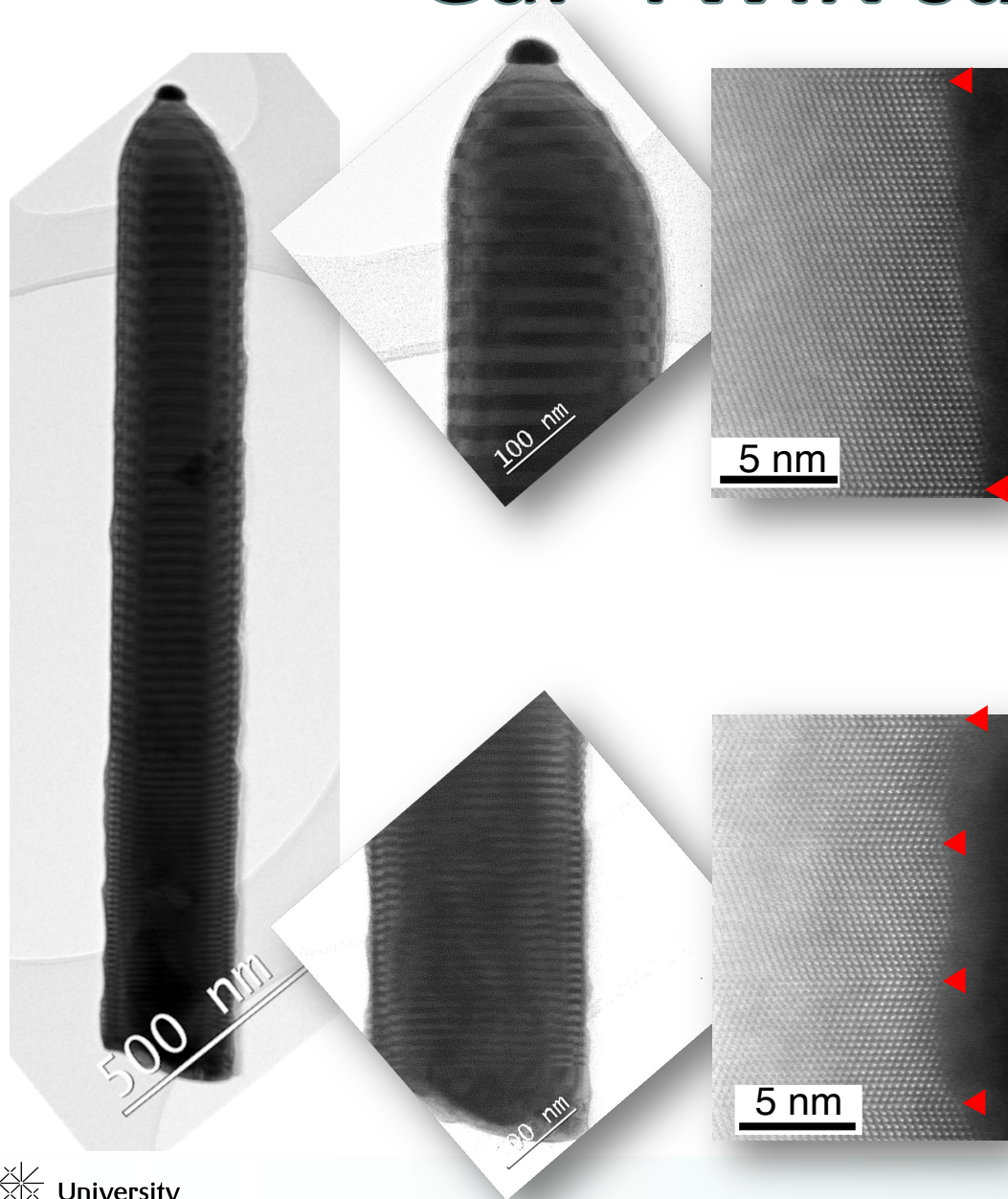


In preparation

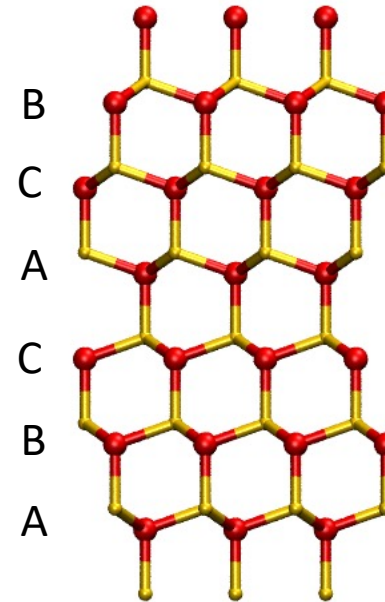
Outline

- The concept of phonon engineering in nanowires
- Experimental techniques
- Phonons and thermal transport in engineered nanowires

GaP TWIN superlattice nanowires

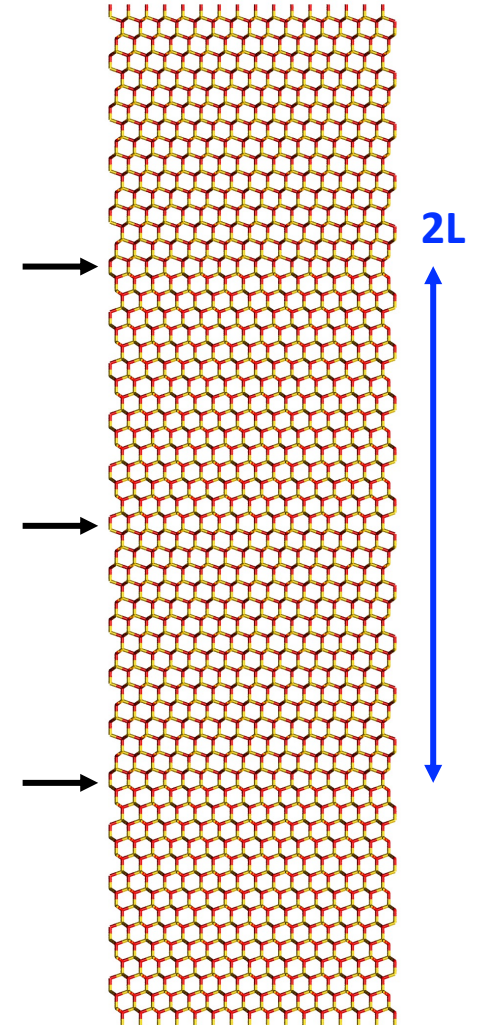


TWIN PLANE

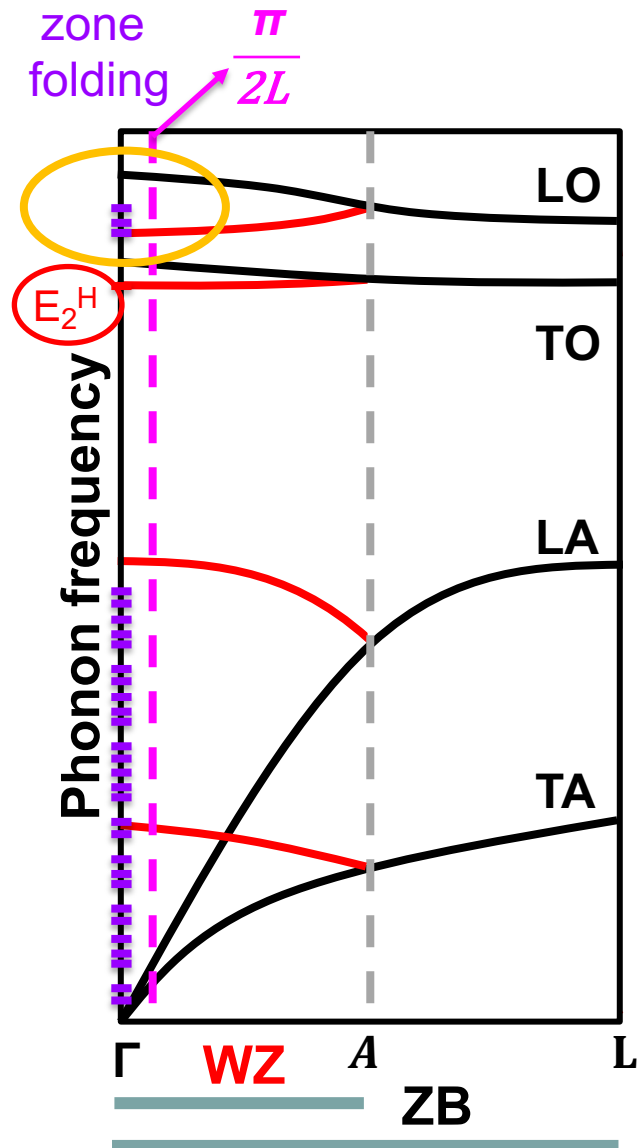


The twin boundary acts as a mirror plane:
the stacking goes from
ABCABC... to CBACBA

TWIN SL

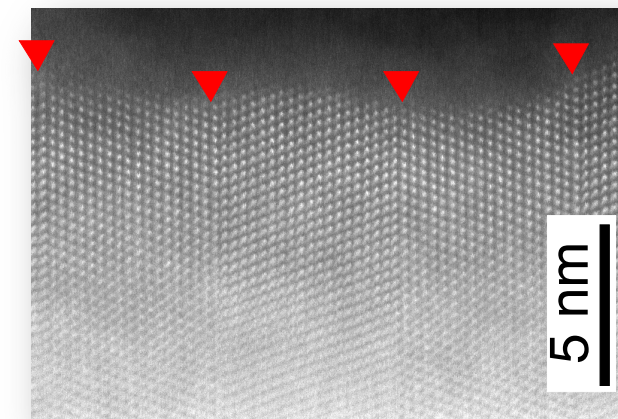


Phonons in GaP



THEORY

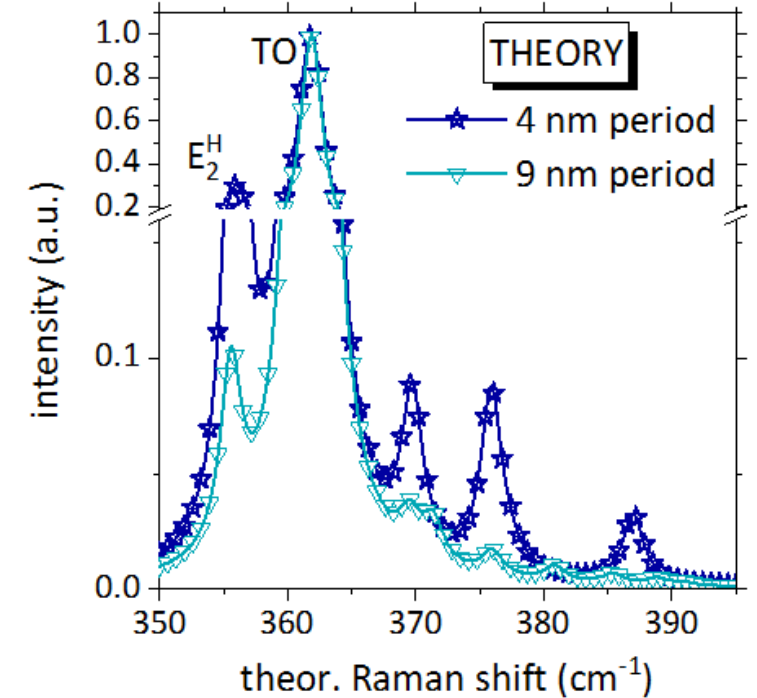
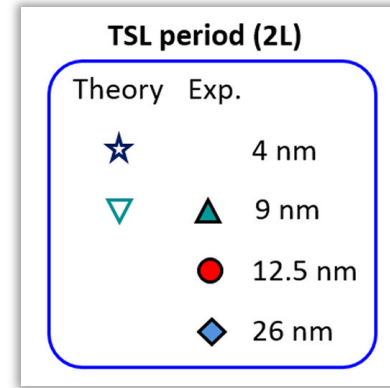
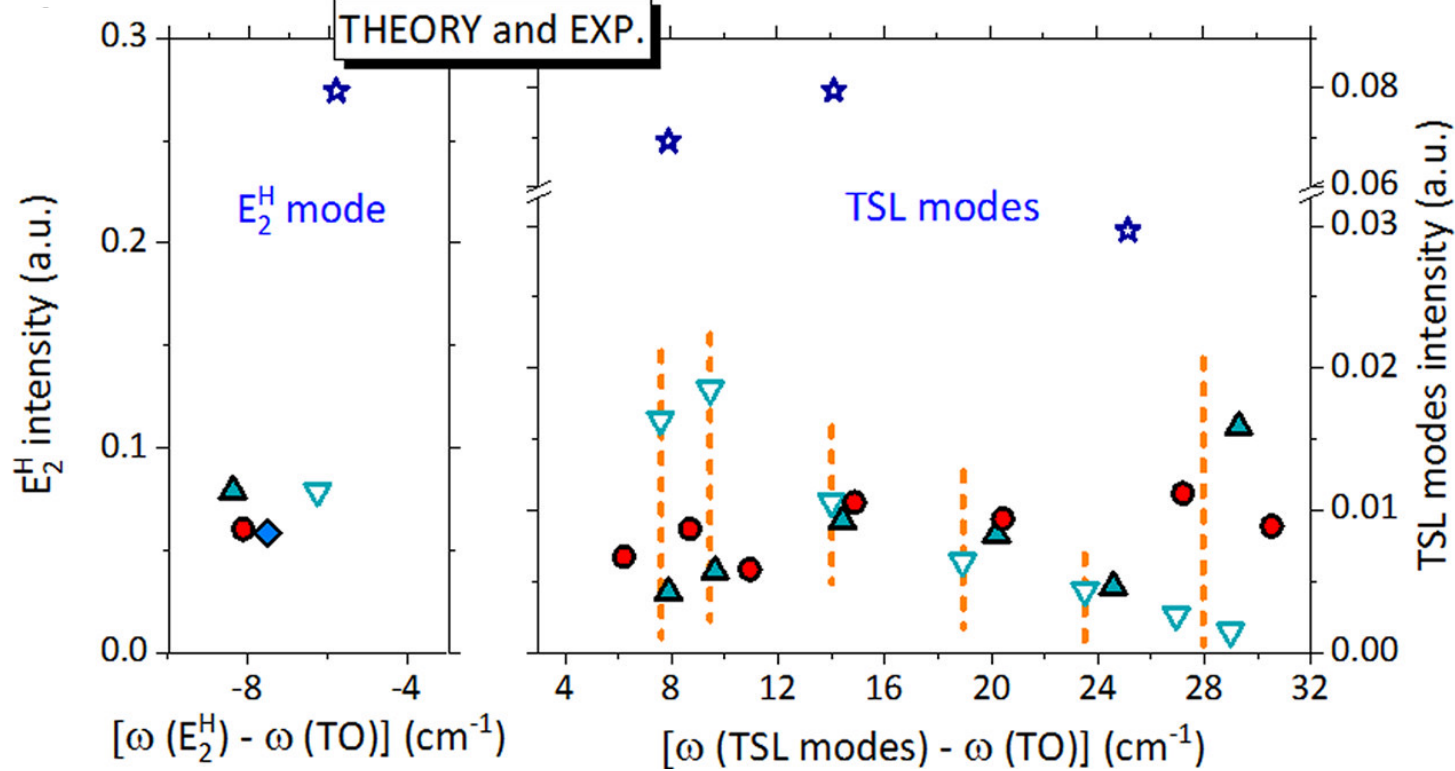
EXPERIMENT



Nano Lett. **19**, 4702 (2019)

Phonon engineering in GaP twin SL nanowires

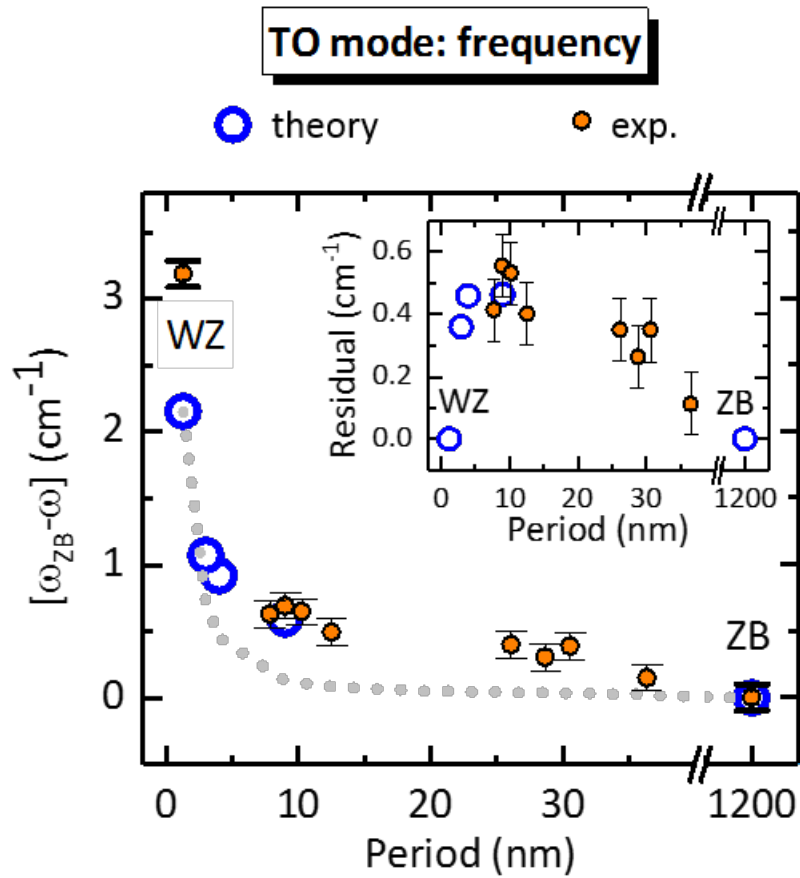
TUNABILITY



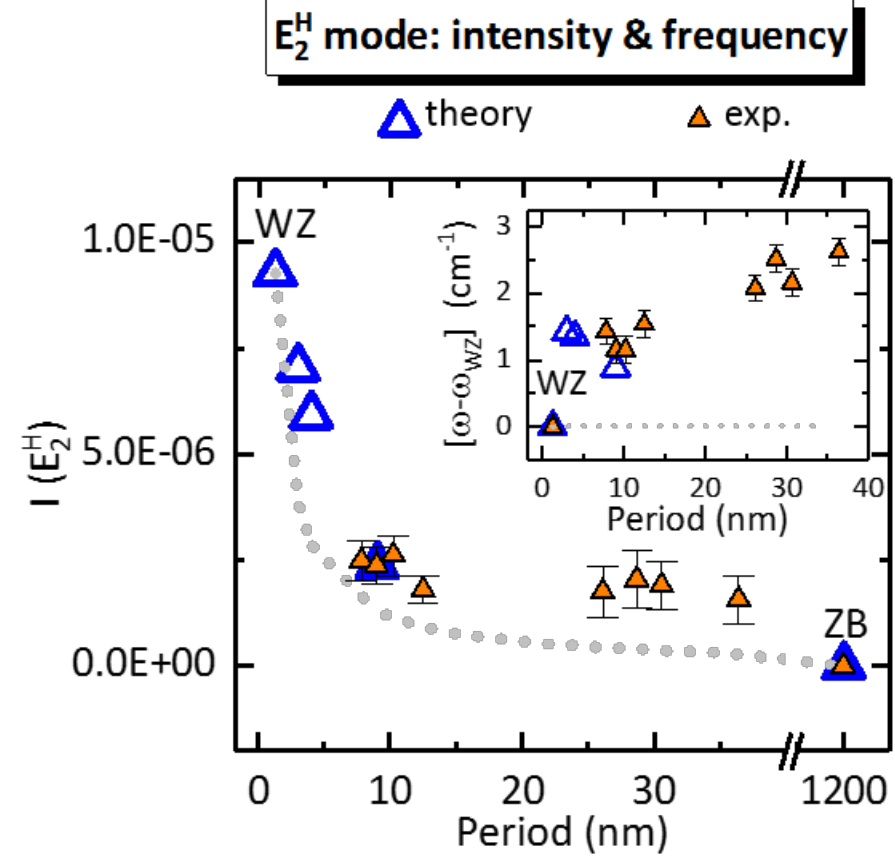
Nano Lett. **19**, 4702 (2019)

Phonon engineering in GaP twin SL nanowires

Expected long coherence

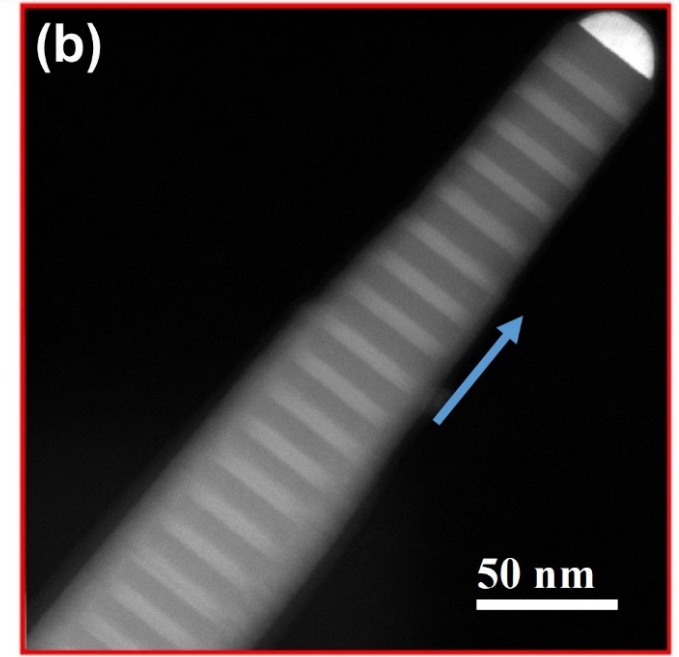
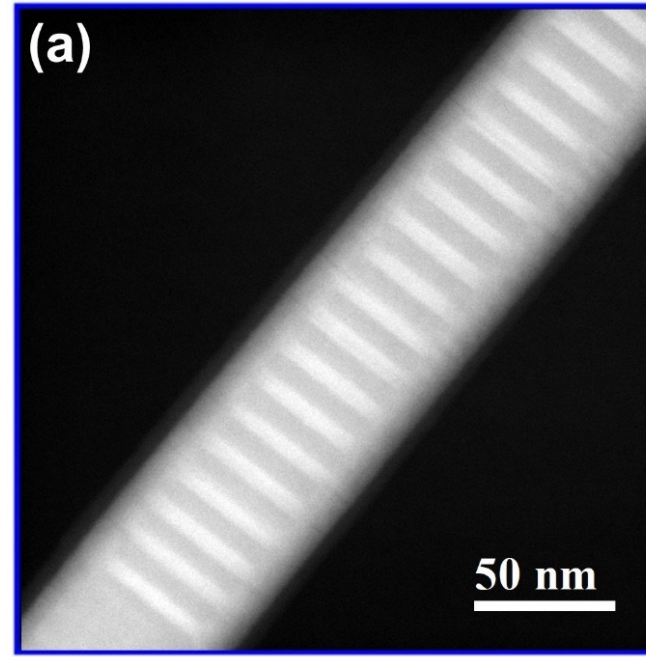
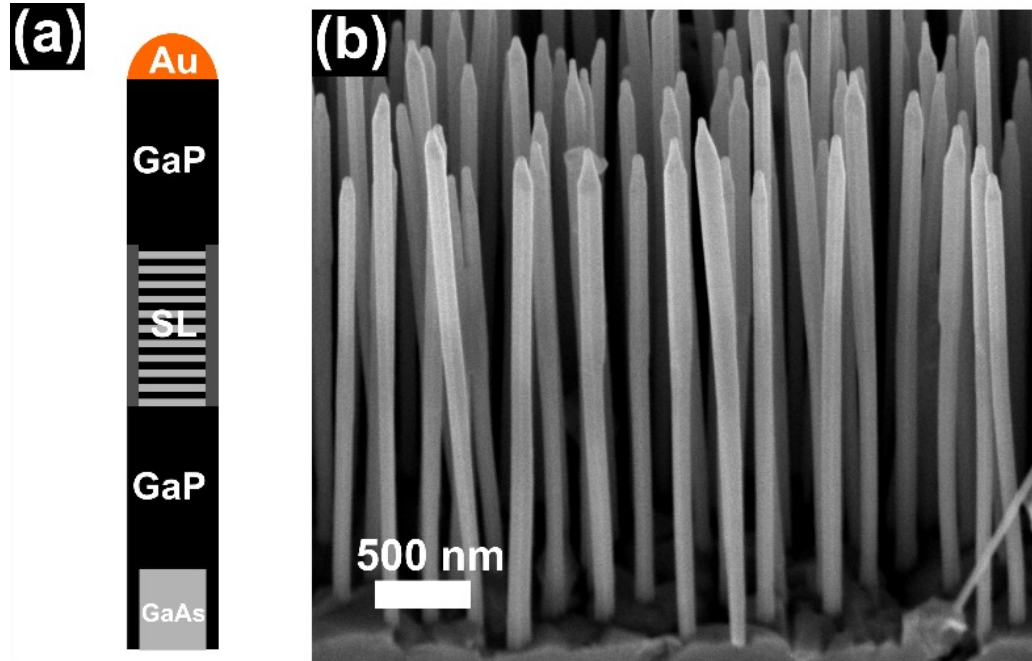


New metamaterial



Nano Lett. **19**, 4702 (2019)

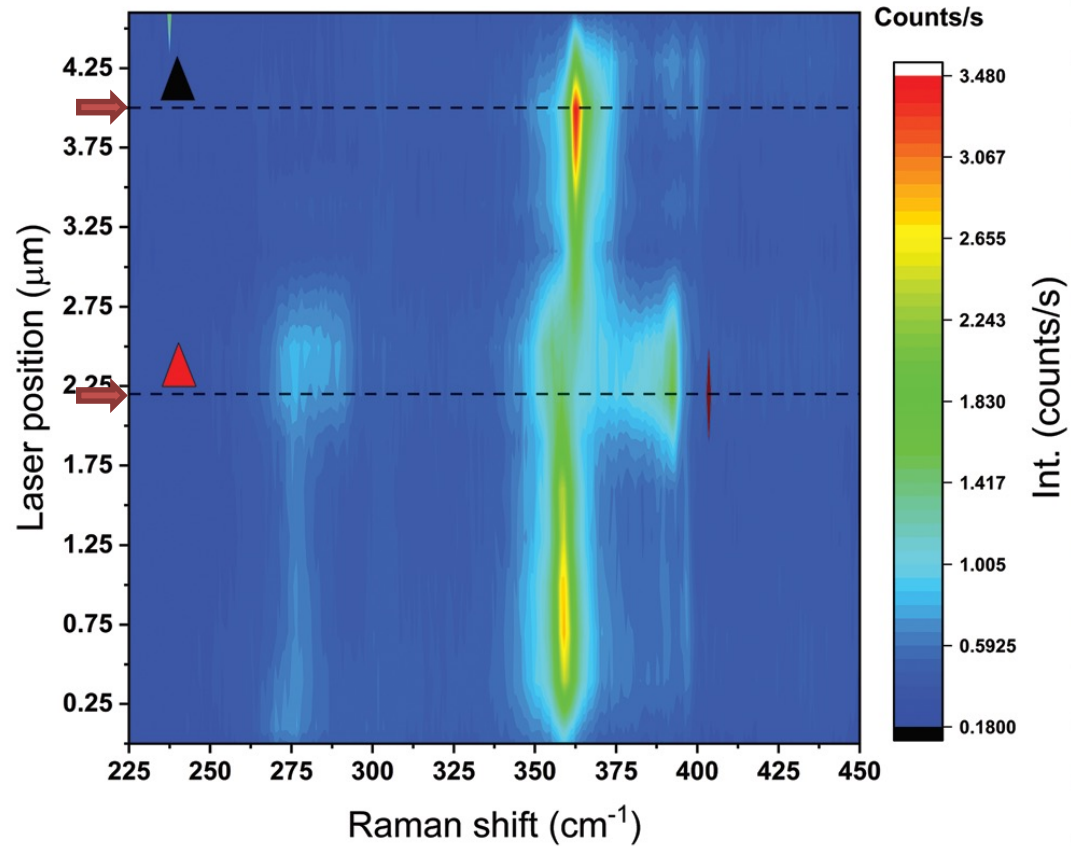
GaAs-GaP superlattice nanowires



CNR-NEST
Lucia Sorba
Valentina Zannier
Omer Arif

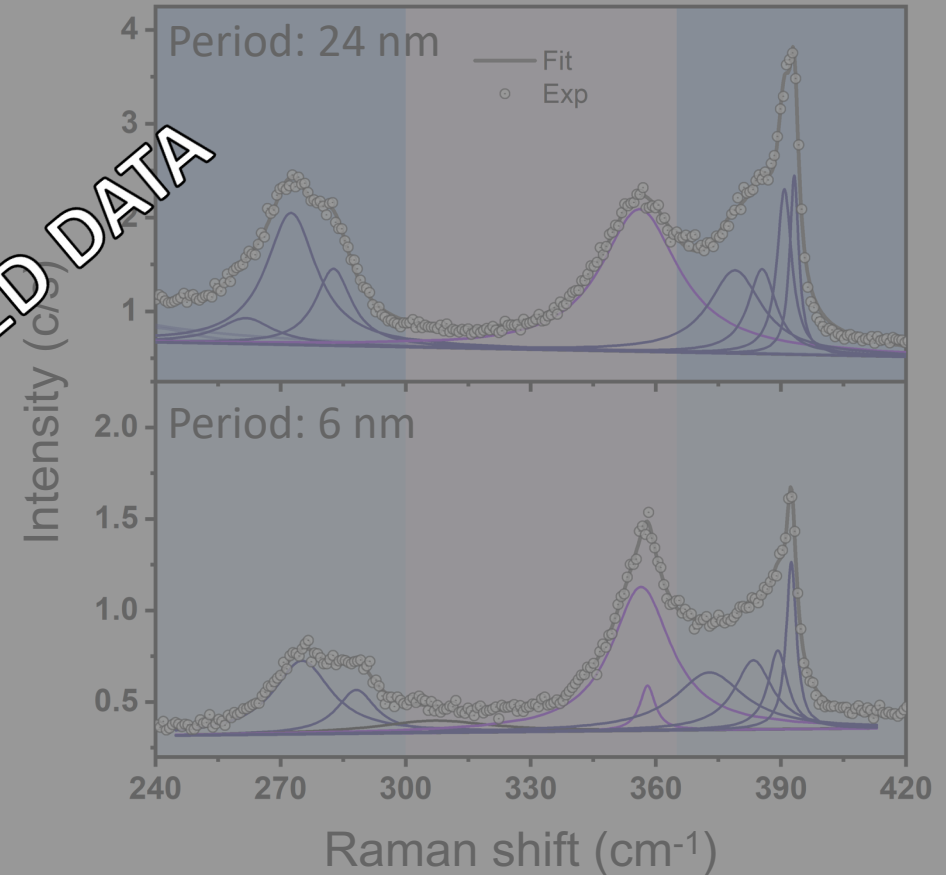
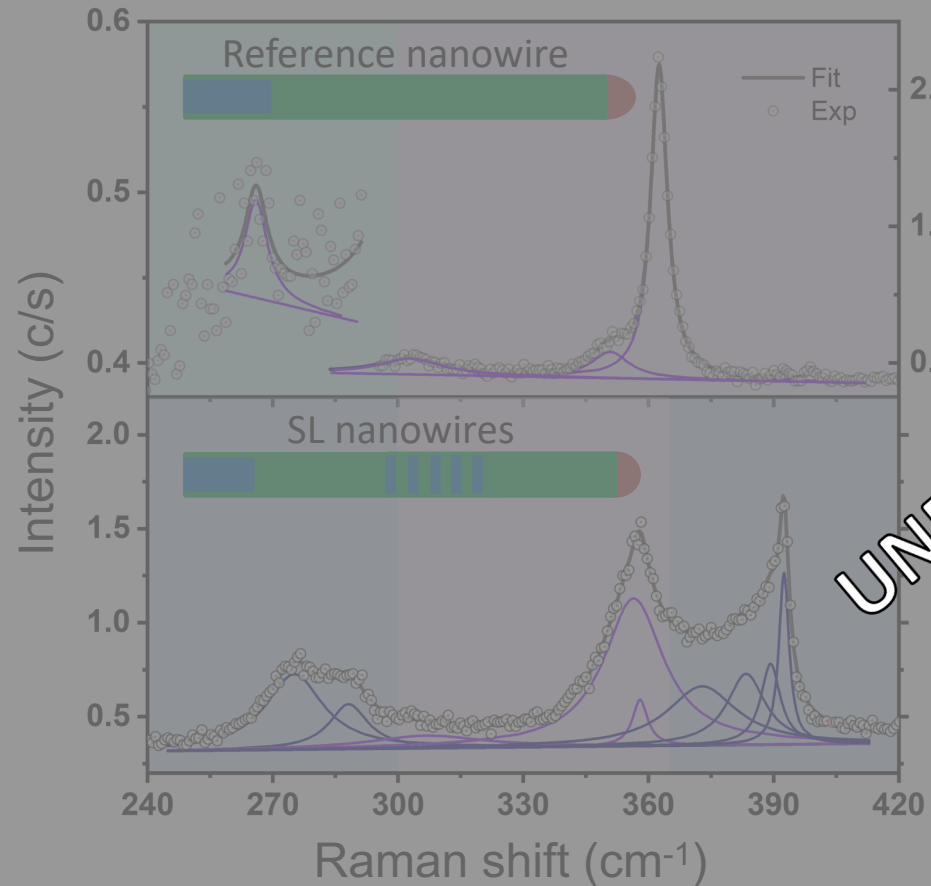
Accepted in Nanoscale 2022

GaAs-GaP SL nanowires



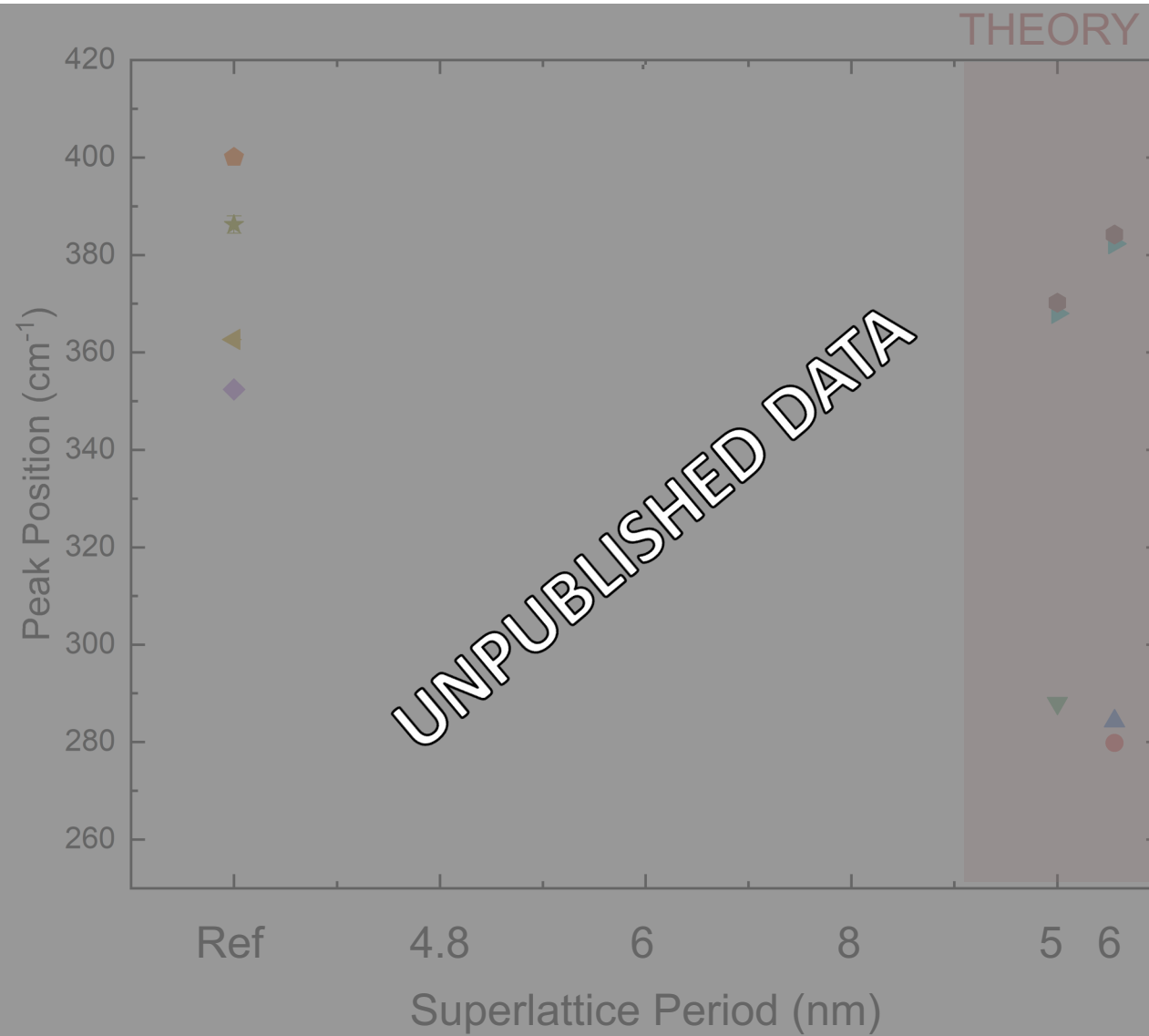
Accepted in Nanoscale (2022)

Phonon modes



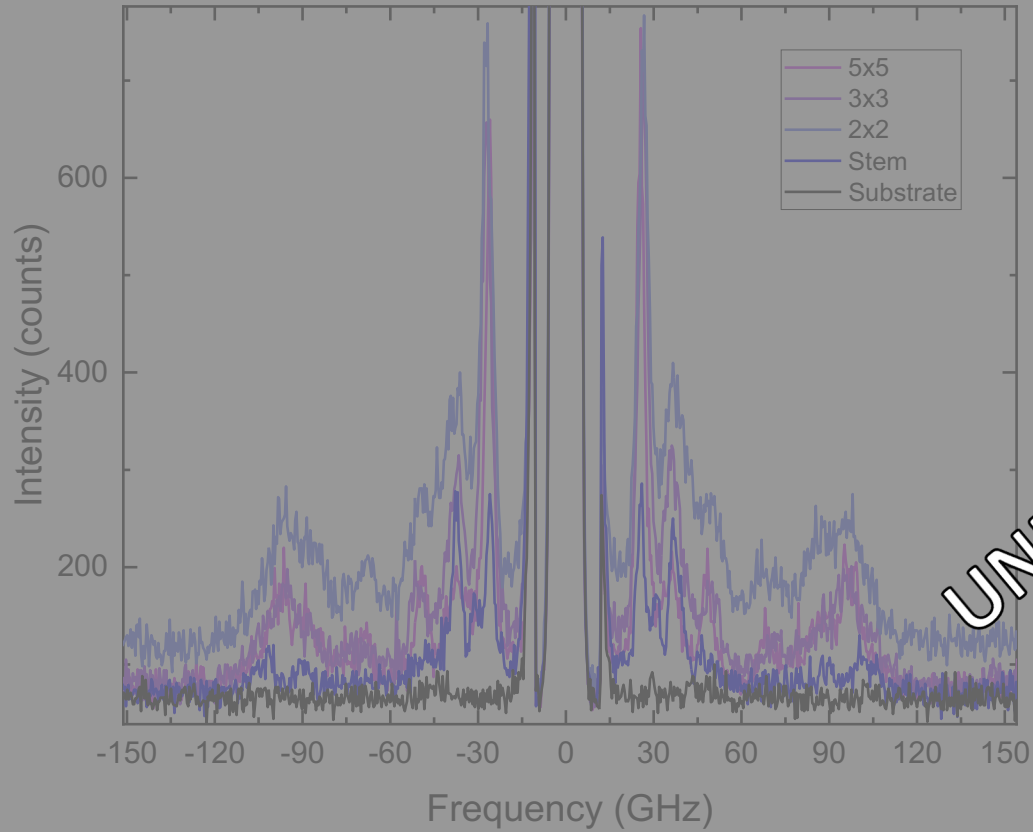
Unpublished data

Tuning of phonon modes

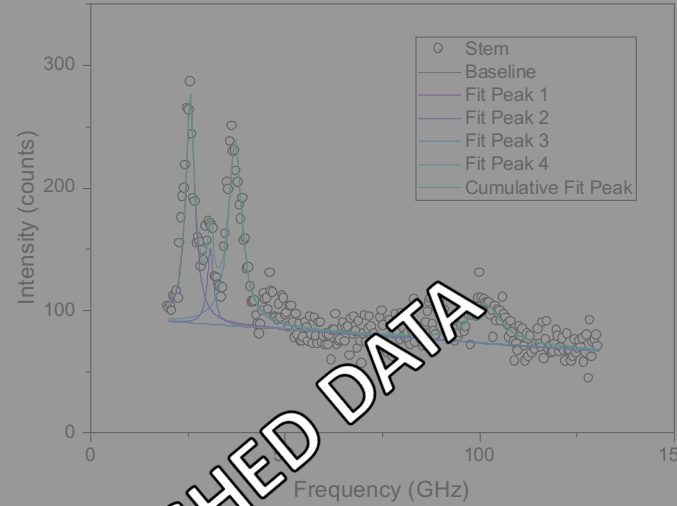


Low frequency phonons

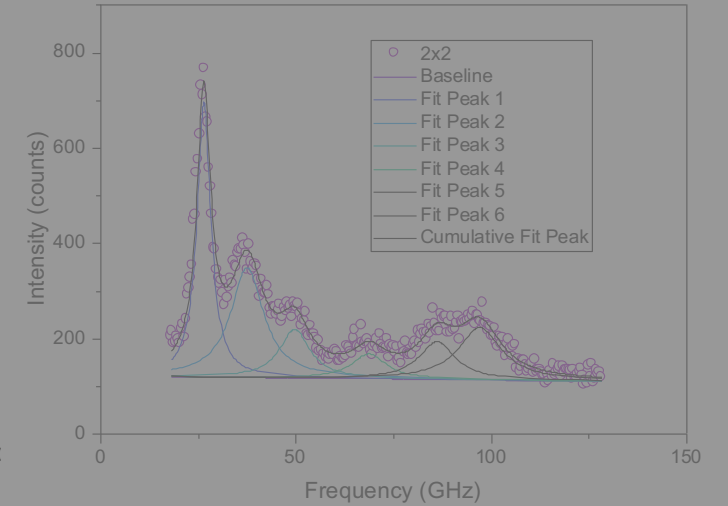
BRILLOUIN SPECTRA



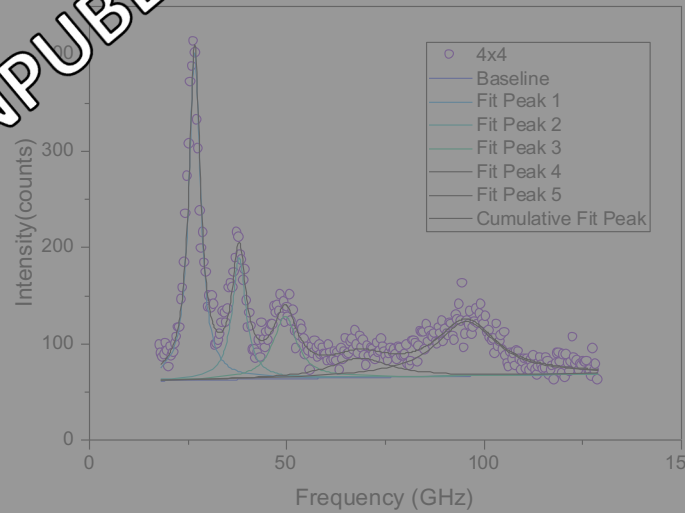
Reference NO SL



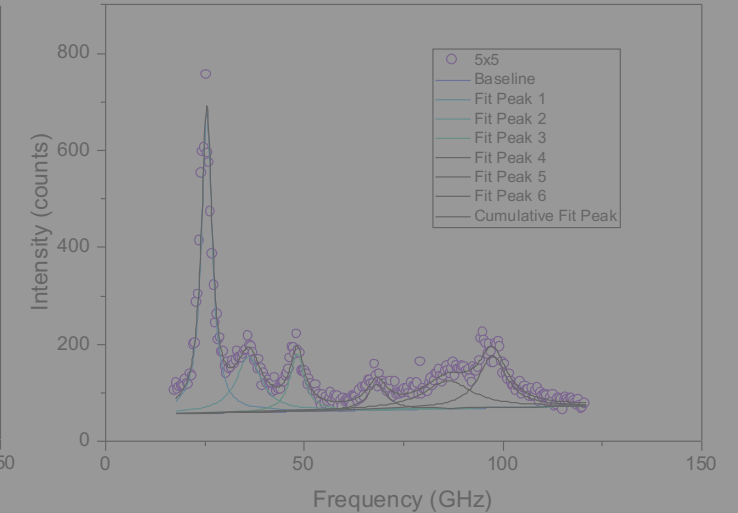
4.8 nm SL



6.0 nm SL

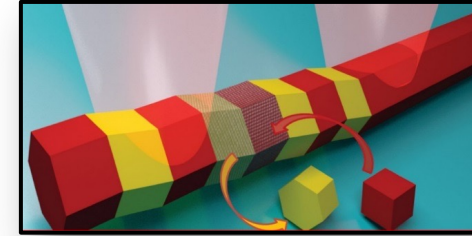


10 nm SL

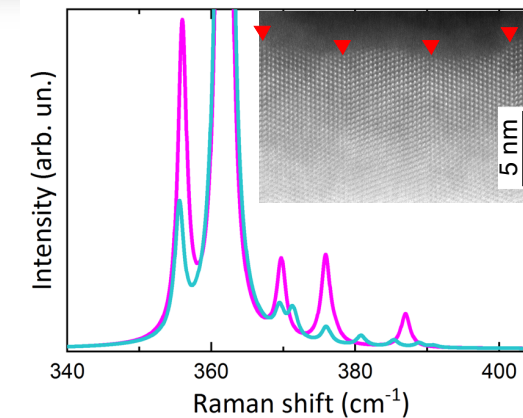


Take home message

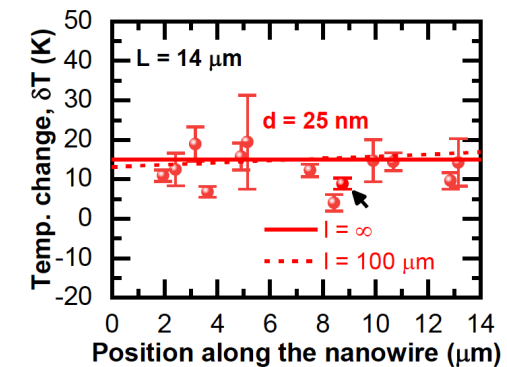
- Probing of phononic properties at the nanoscale



- Phonon engineering for tailoring phononic properties



- Probing phonon transport with Raman thermometry



FORMER GROUP MEMBERS

Dr. Marta De Luca (now tenure track Ass. Prof. in Italy)

Dr. Milo Swinkels

Dr. Claudia Fasolato (now researcher in Italy)

Dr. Gerard Gadea Diez (now clean room manager)

Medina Umar (now lecturer in Nigeria)

Alessio Campo (Now in Rolic)

Lucas Gubser (Now in IWB)

Miguel Carballido (now PhD in Zumbühl's group)

Kamiar Davallou

Giulia Di Iorio (now PhD in Italy)

Matteo Camponovo

Robert Hersberger (now high school teacher)

Nanophononics Group

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Aswathi K. Sivan (PostDoc)

Rahul Swami (Postdoc)

Saeko Tachikawa (Postdoc)

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Nadine Gächter (PhD)

Giulio de Vito (PhD)

Grazia Raciti (PhD)

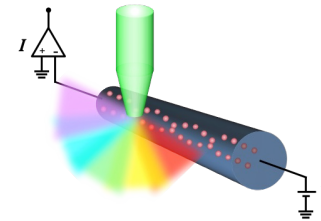
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Thank you for your attention