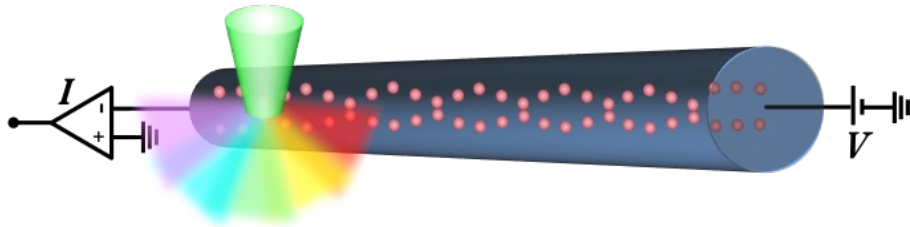


# Engineering thermal transport in nanowires

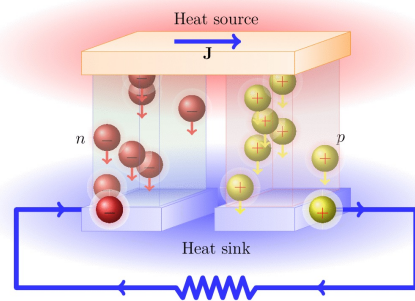
C. Arya, D. de Matteis, Y. Kaur, G. Raciti,  
G. de Vito, B. Abad, A. K. Sivan, M. De  
Luca, M. Y. Swinkels, X. Cartoixà, R.  
Rurali, **I. Zardo**



# Manipulating heat flow at the nanoscale

## THERMOELECTRIC DEVICES

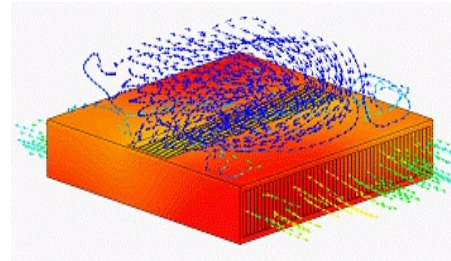
Conversion of DT into electricity through the Seebeck effect



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

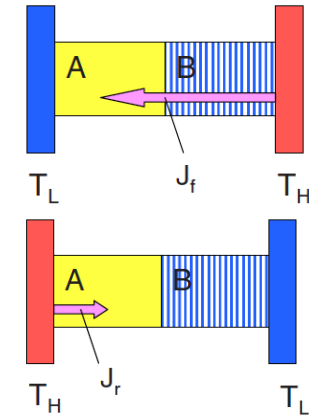
## THERMAL MANAGEMENT

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

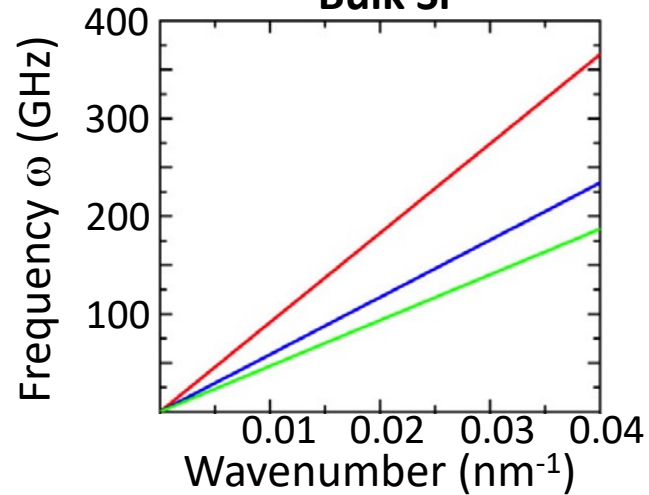
# Outline

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

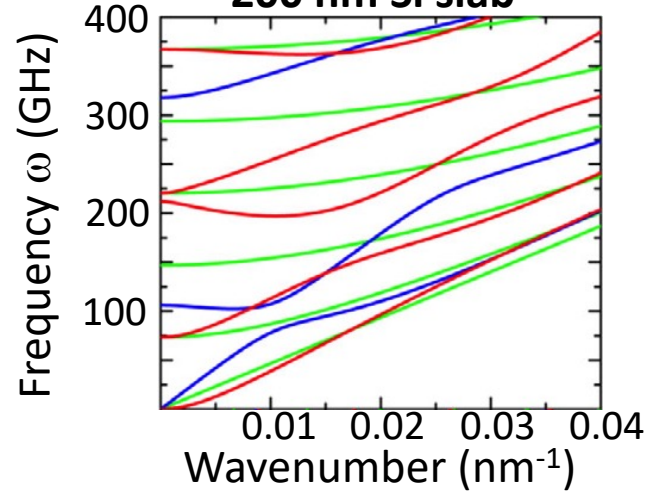
# Phonon engineering

## PHONON DISPERSION

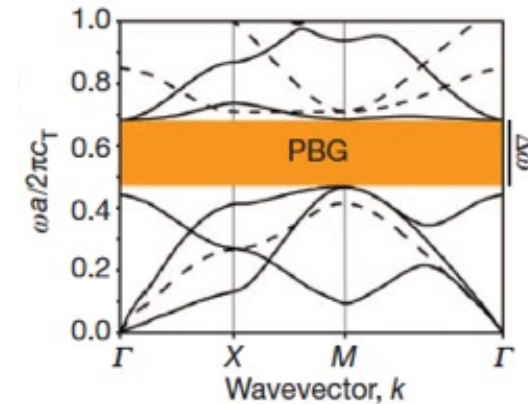
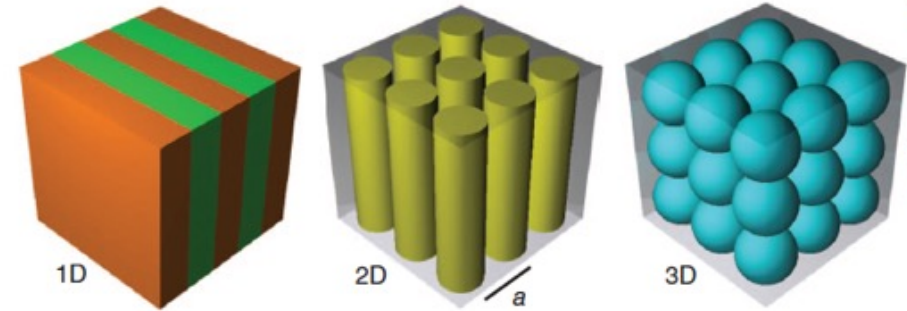
Bulk Si



200 nm Si slab



## PHONONIC BAND GAP

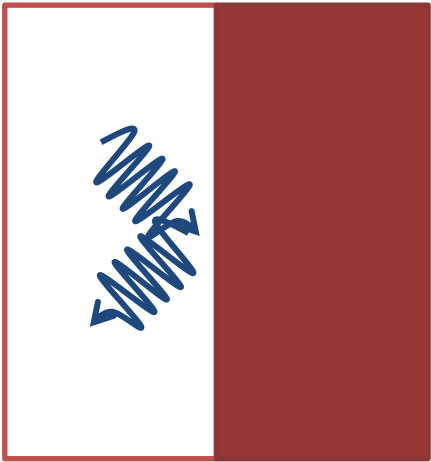


PBGs occur for phonon wavelengths comparable to the structure periodicity  $a$



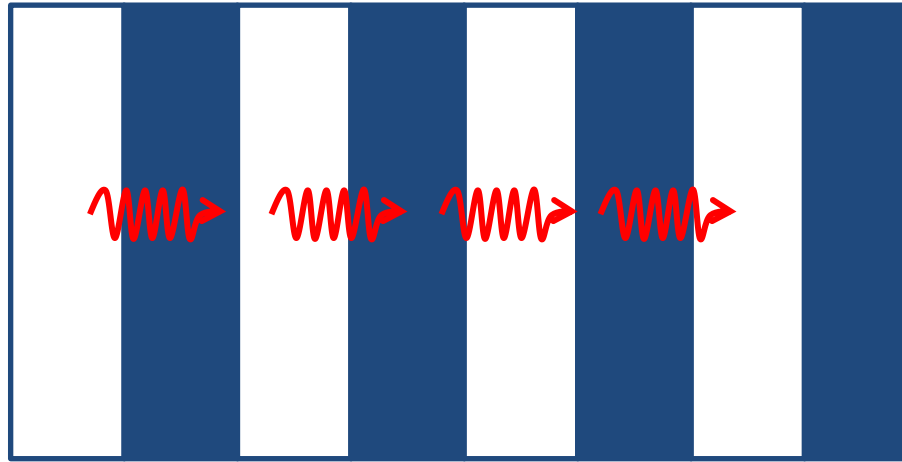
# Phonons in superlattices: particles vs. wave

## Casimir limit



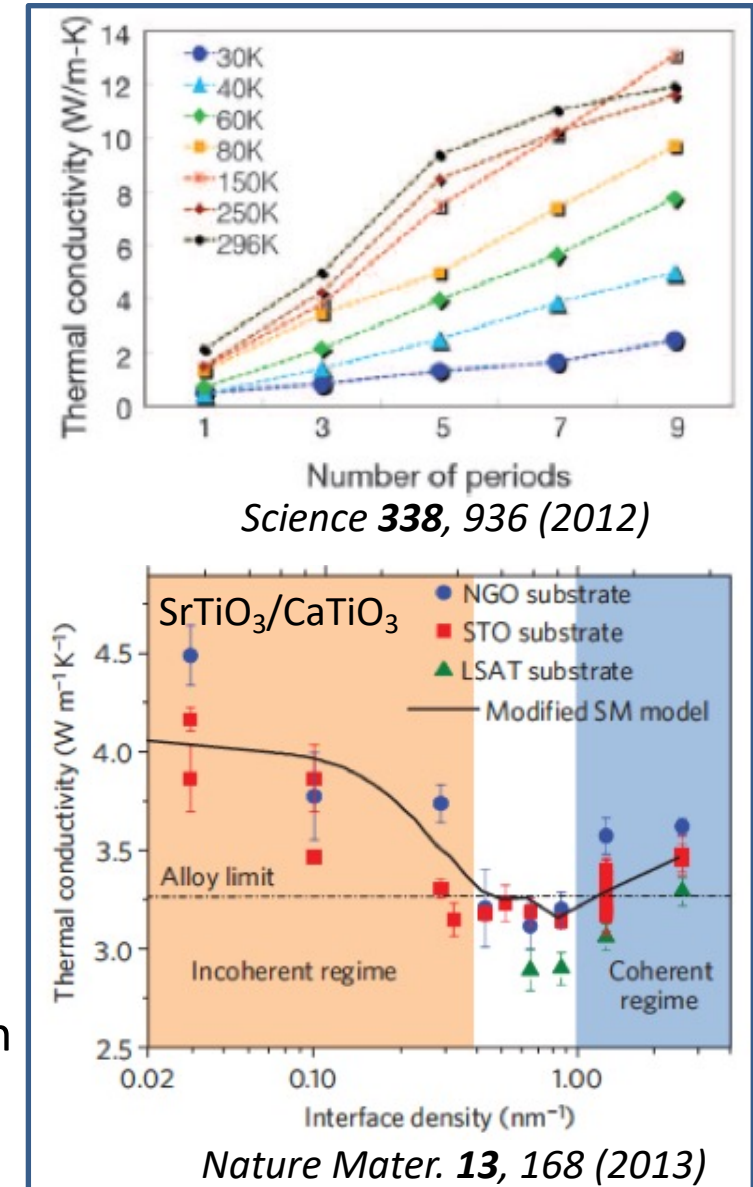
Diffusive scattering  
Lost of phase information

## Coherent phonon regime

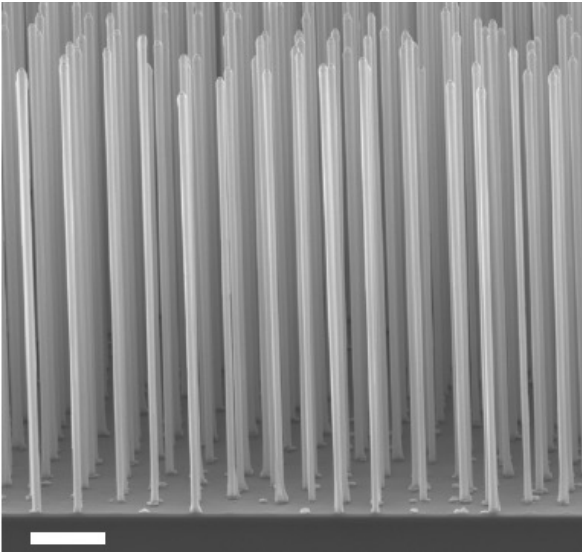


New material with its own phonon dispersion  
arising from phonon interference

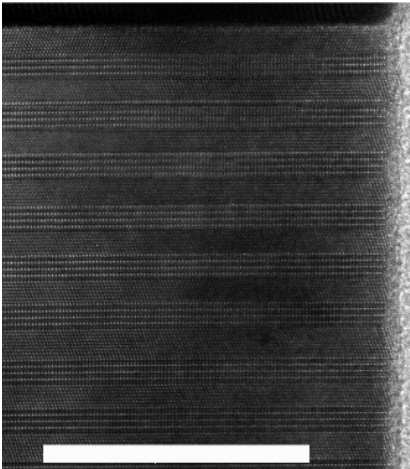
- **Coherent acoustic phonons:** ballistic wavepackets of compressive/tensile stress.
- **Coherent optical phonons:** standing waves of in-phase atomic oscillations, in which the adjacent atoms swing against each other.



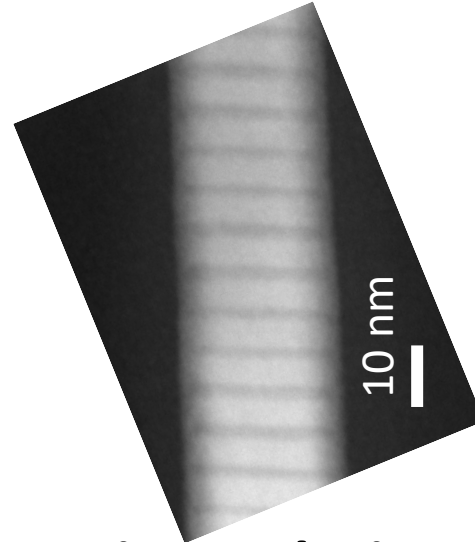
# Phonon engineering in nanowires



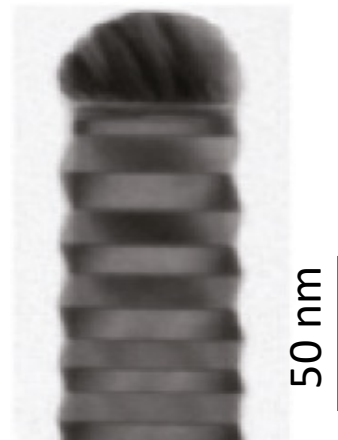
Crystal phase superlattices



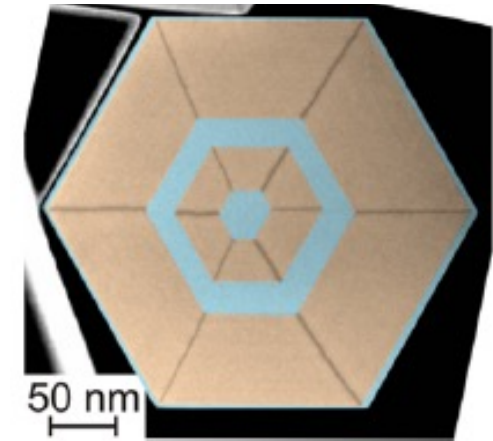
Axial heterostructures



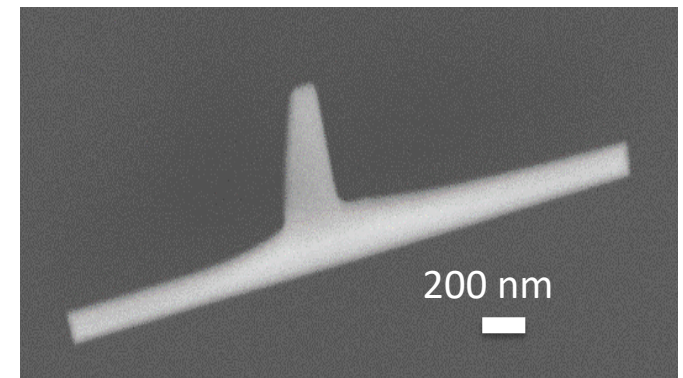
Twin superlattices



Radial heterostructures



Branched junctions



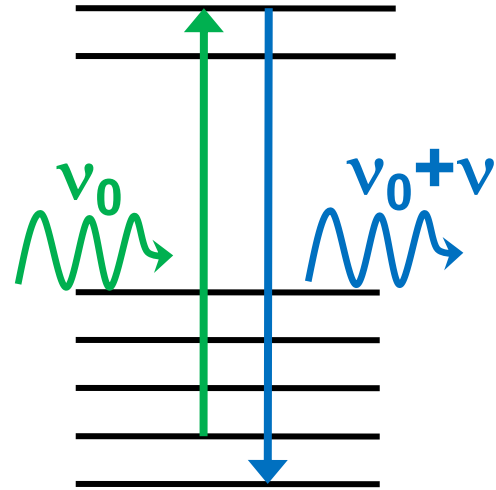
# Outline

- 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

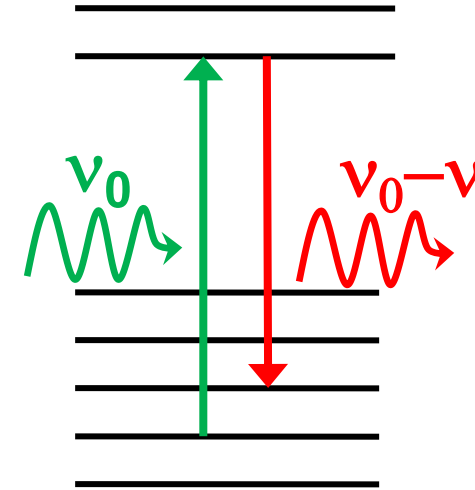


Photon gains energy

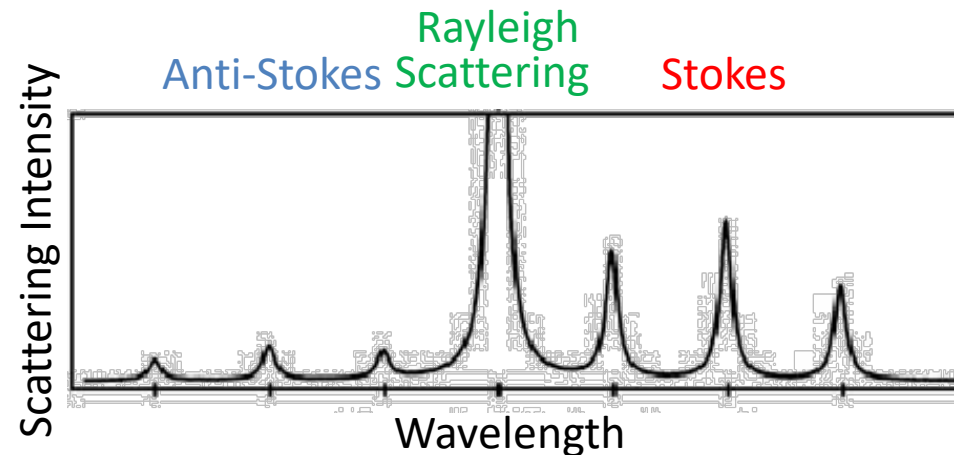
Virtual Energy States

Vibrational Energy States

Stokes Scattering



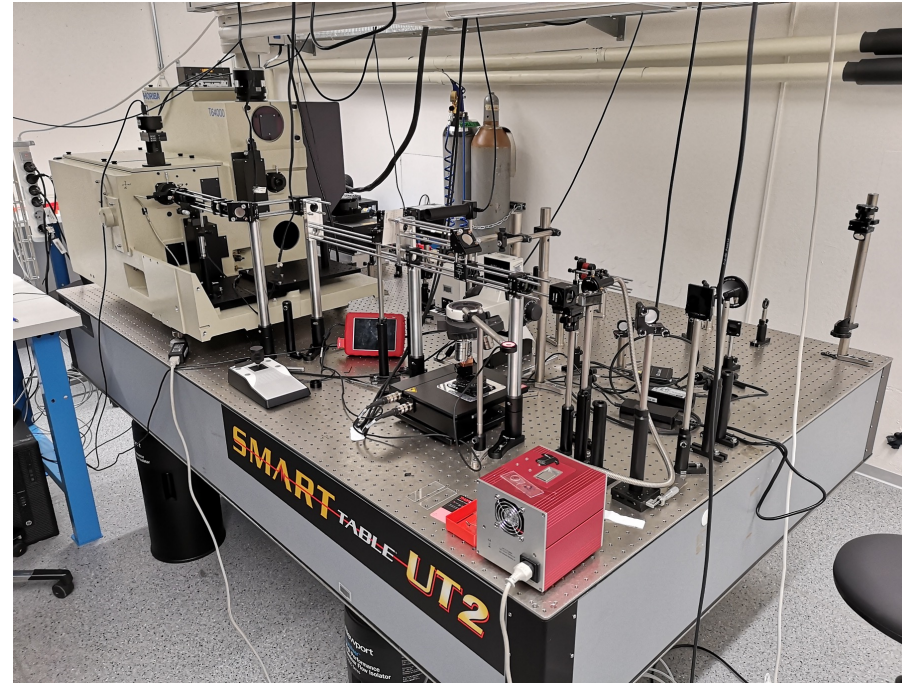
Photon loses energy



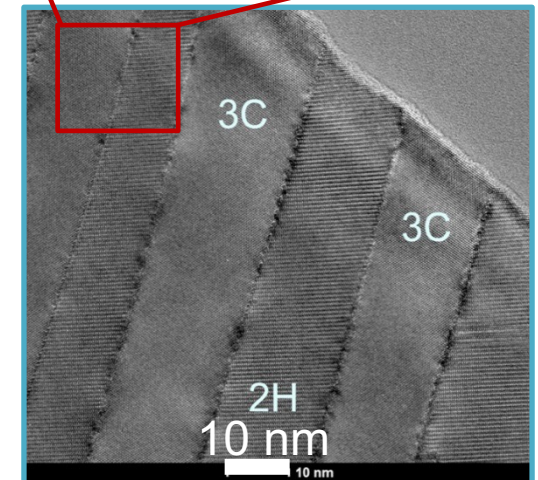
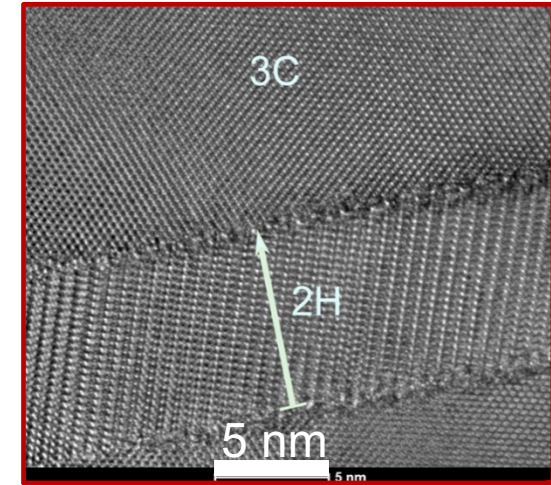


# Investigating phonons by (Resonant) Raman Spectroscopy

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



- Relative orientation of heterostructures

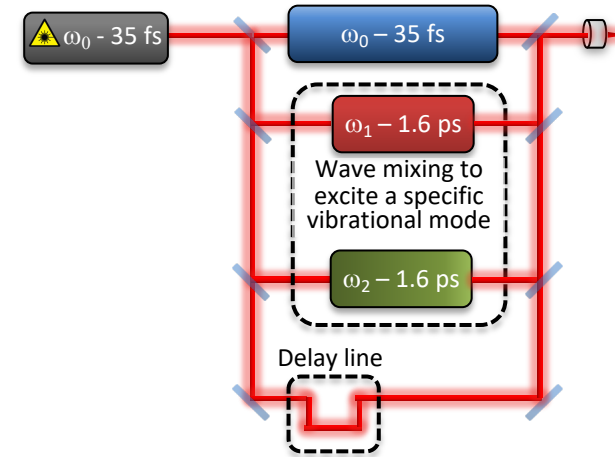


Nano Lett. **18** (11), 7075-7084 (2018)

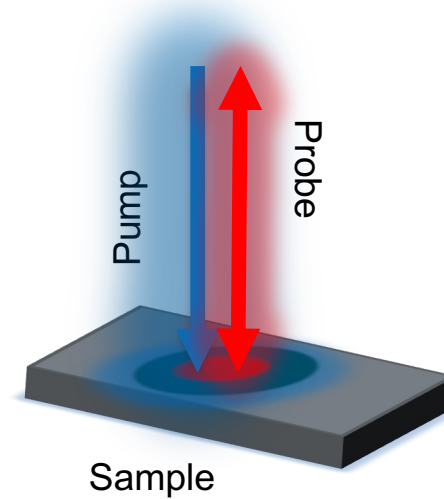
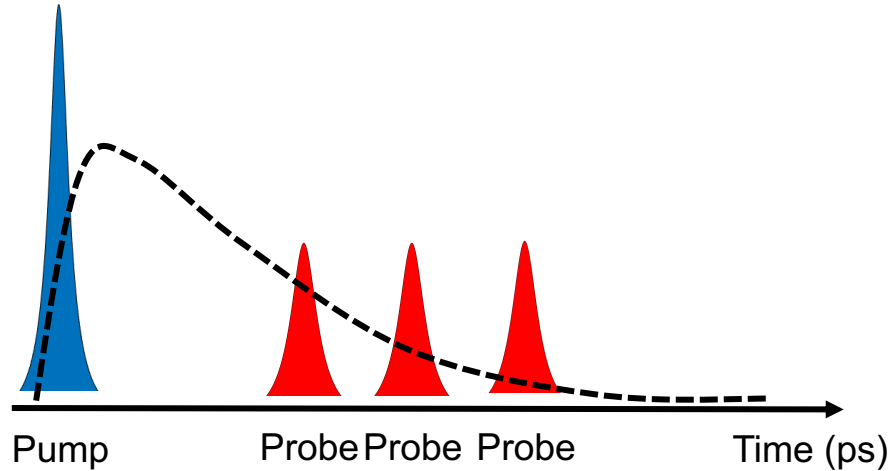


# Investigating phonons by pump-probe spectroscopy

- 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.

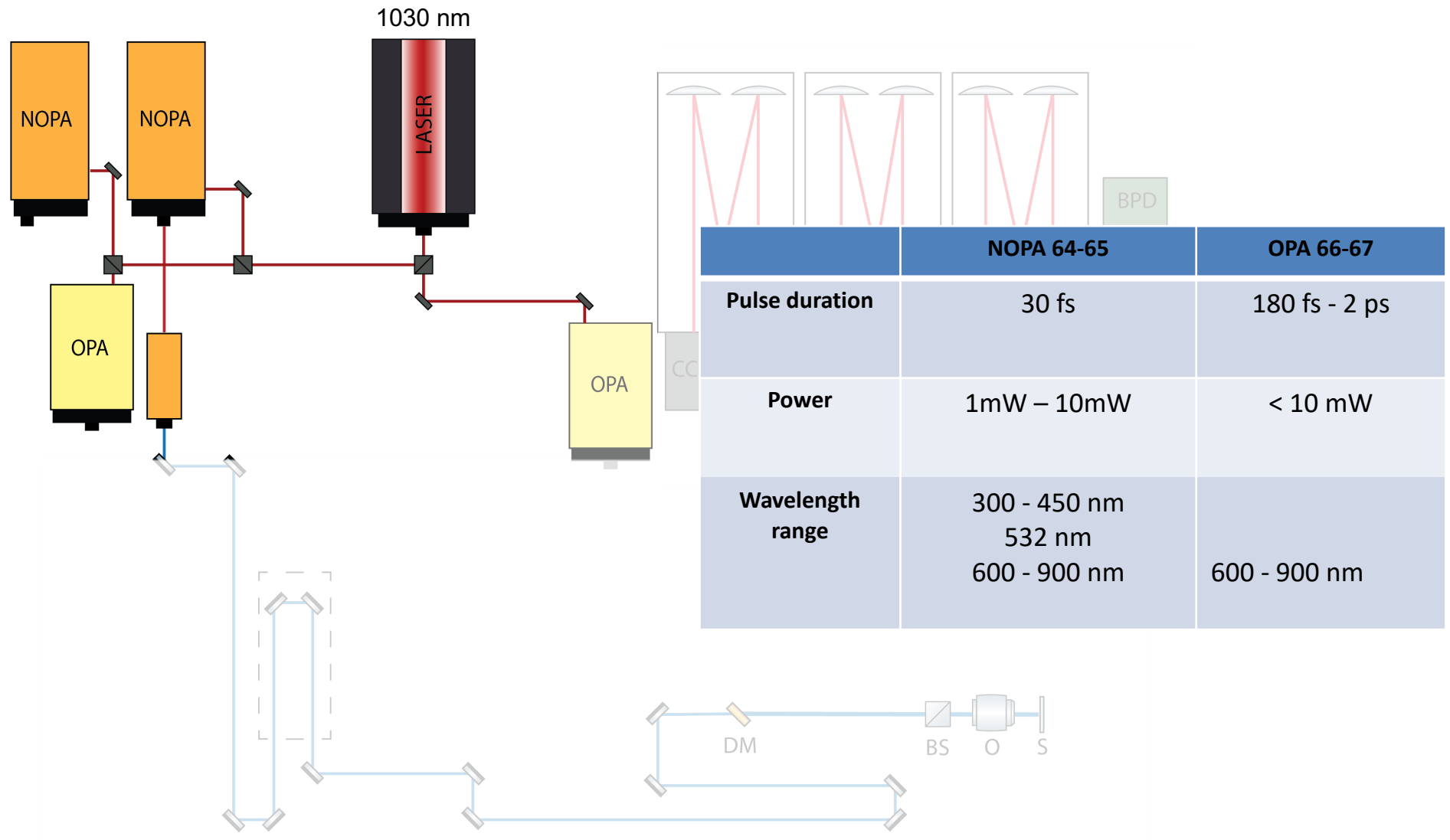
## Transient reflectivity

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

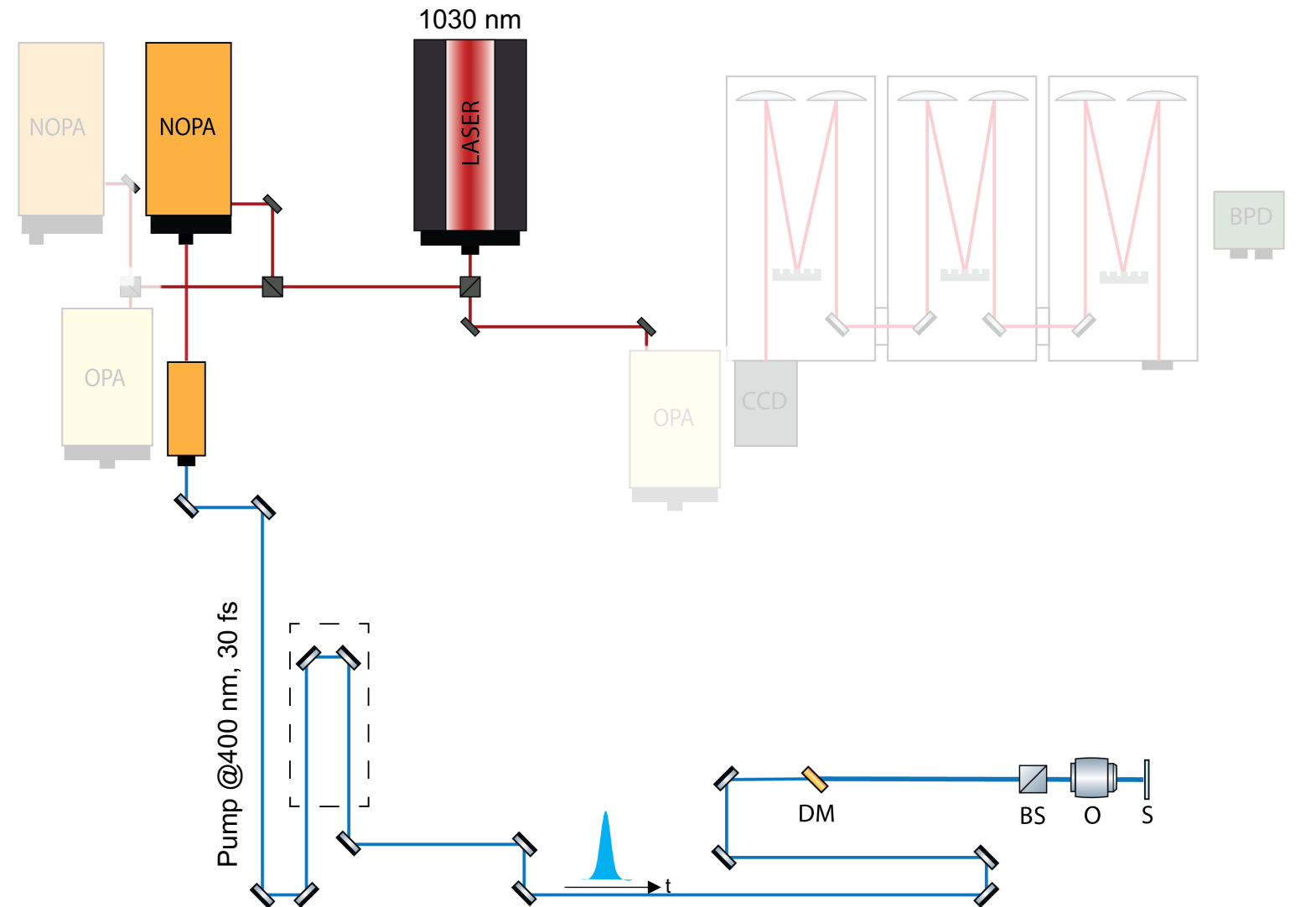
## Time resolved Raman

Well-established probe for incoherent phonon population dynamics in semiconductors

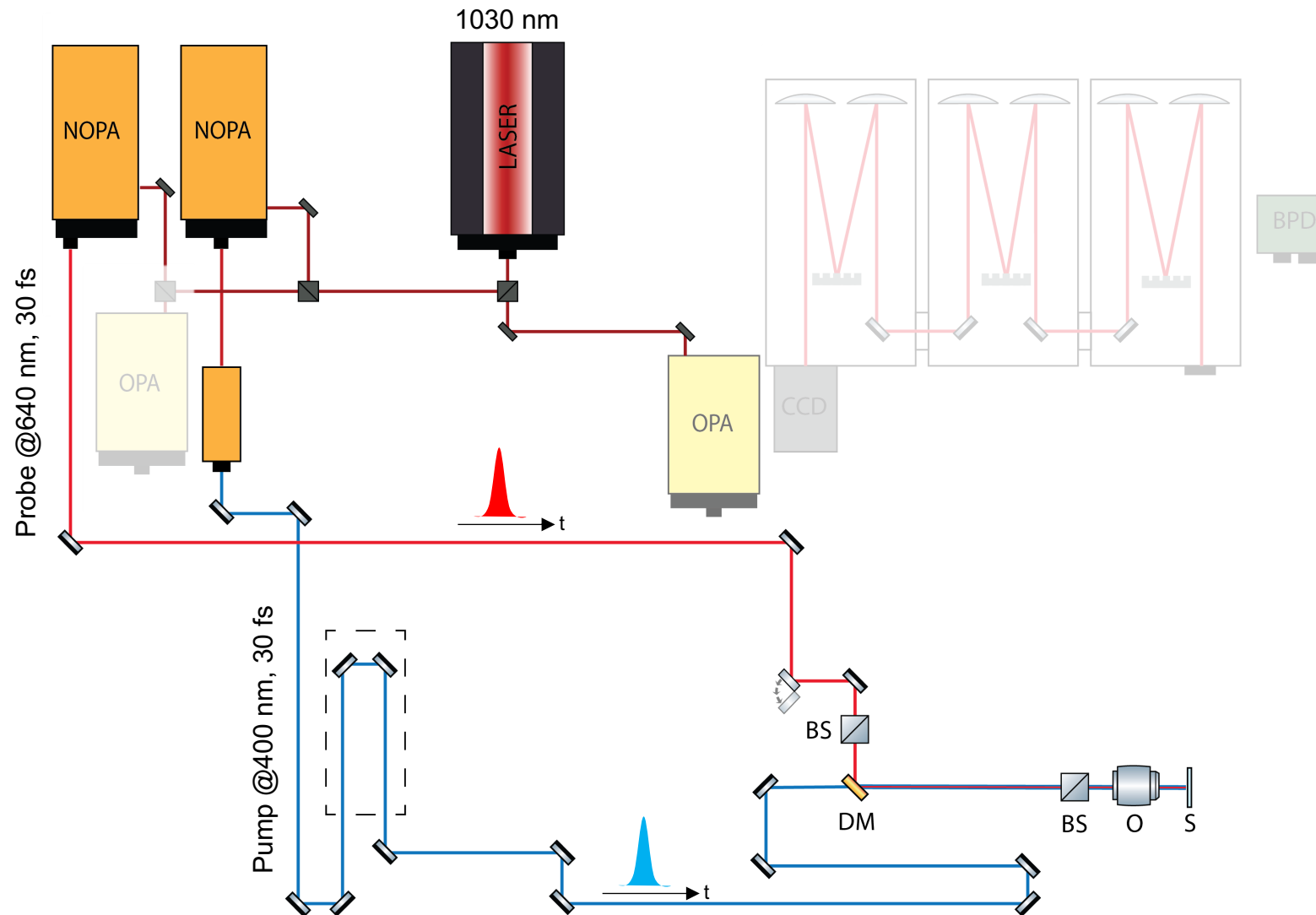
# Experimental setup



# Transient reflectivity experimental scheme

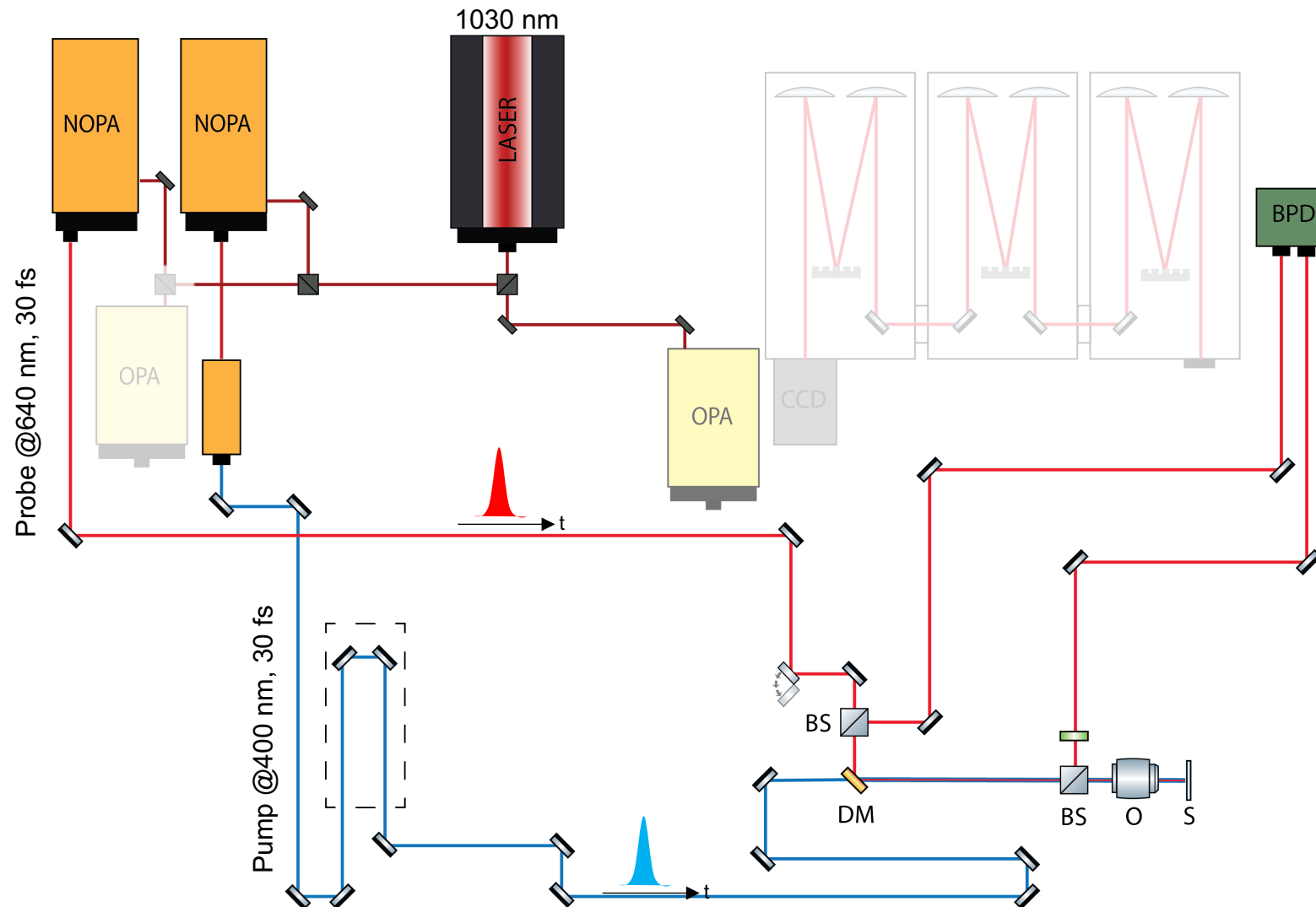


# Transient reflectivity experimental scheme





# Transient reflectivity experimental scheme



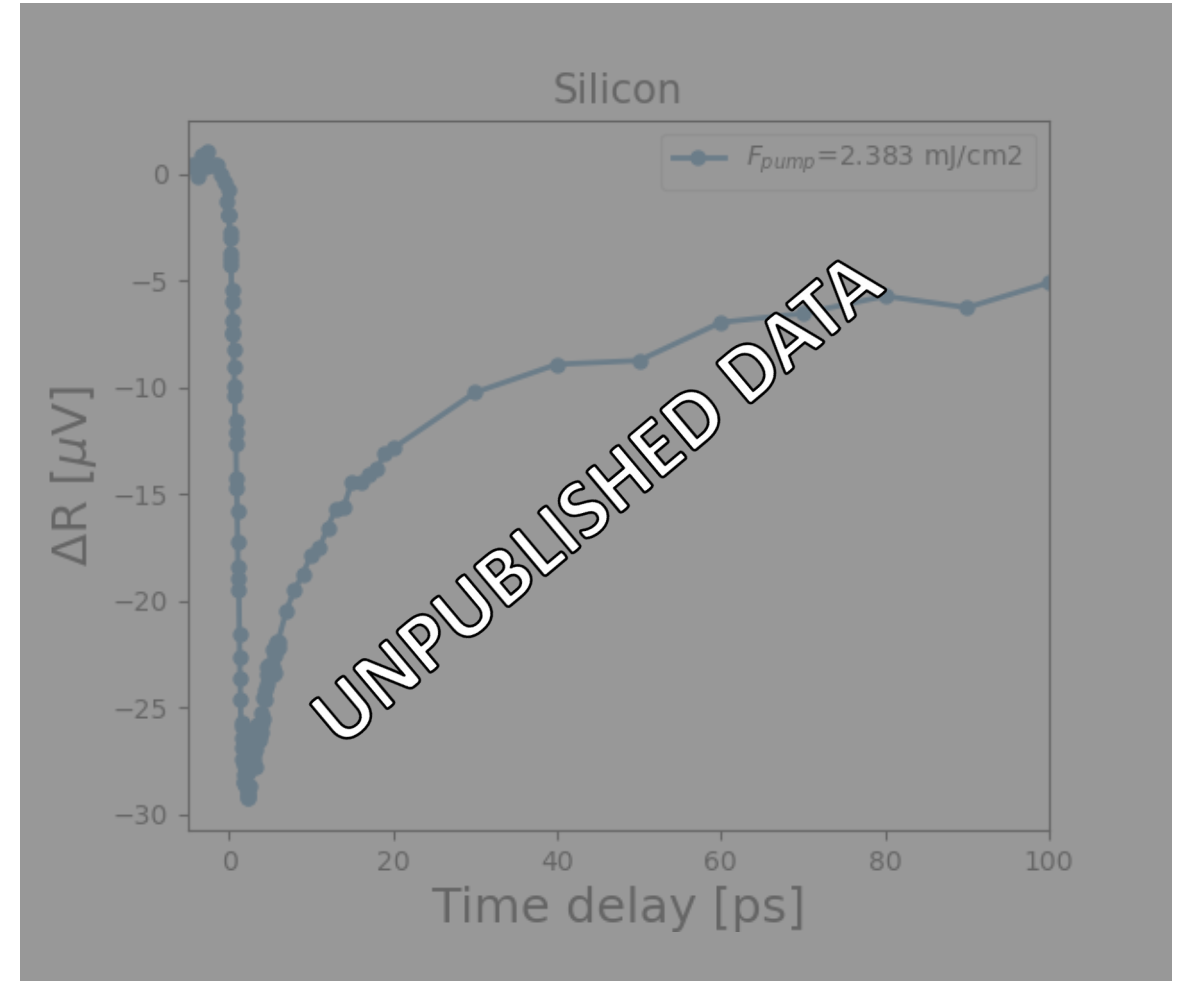
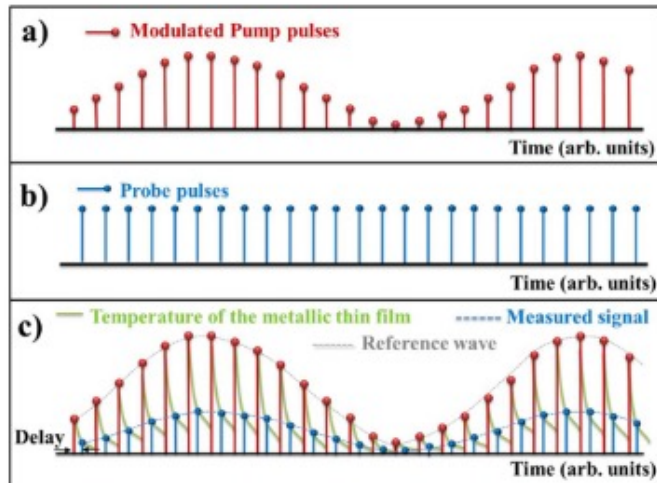
# Transient reflectivity detection scheme



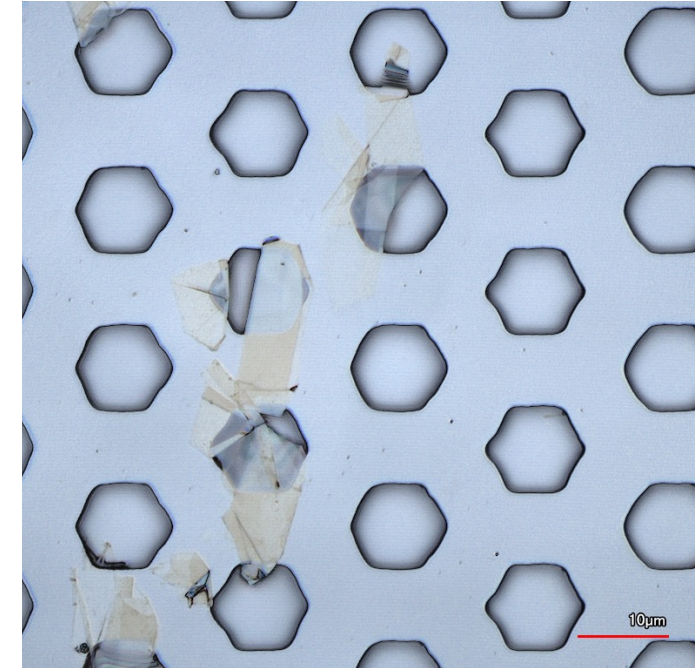
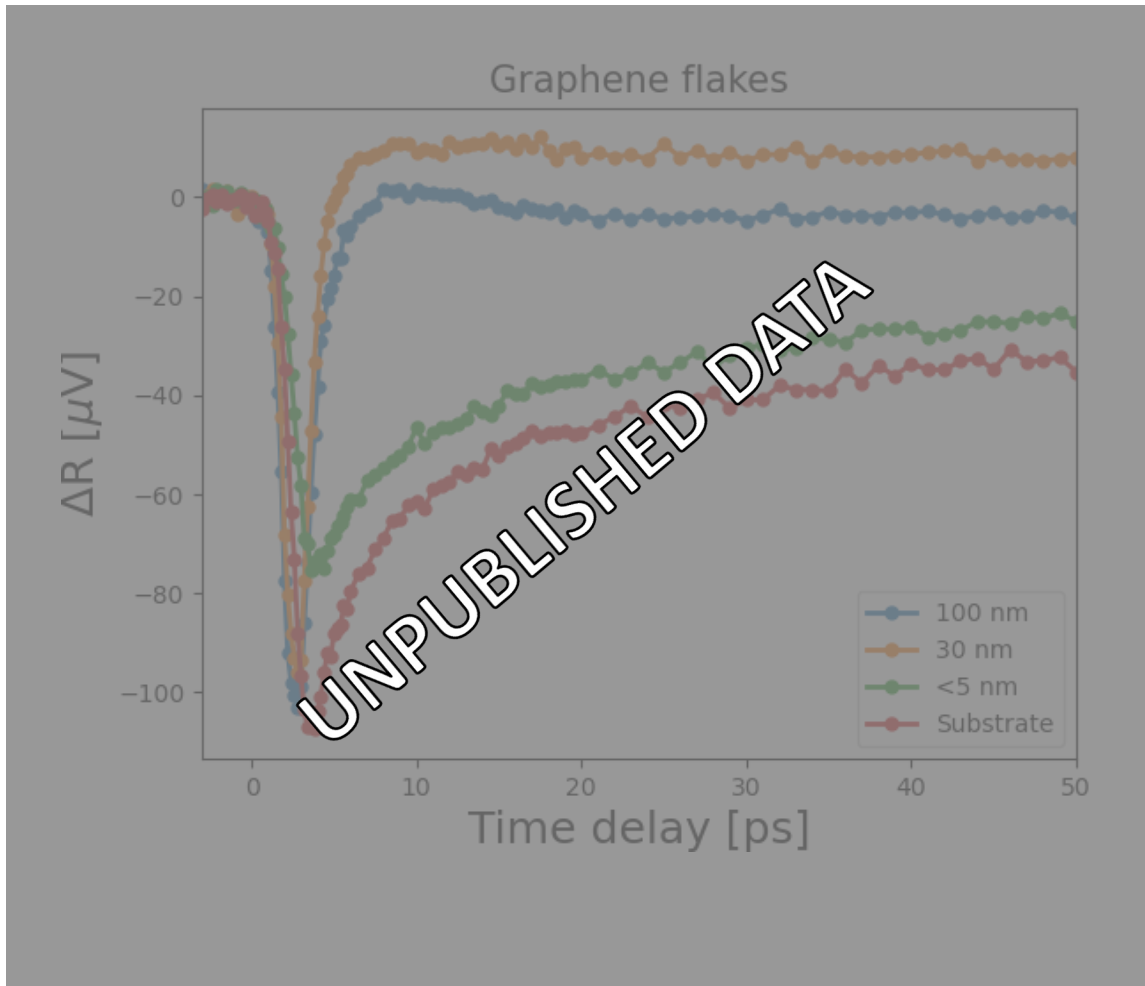
Chopper



Lock in amplifier

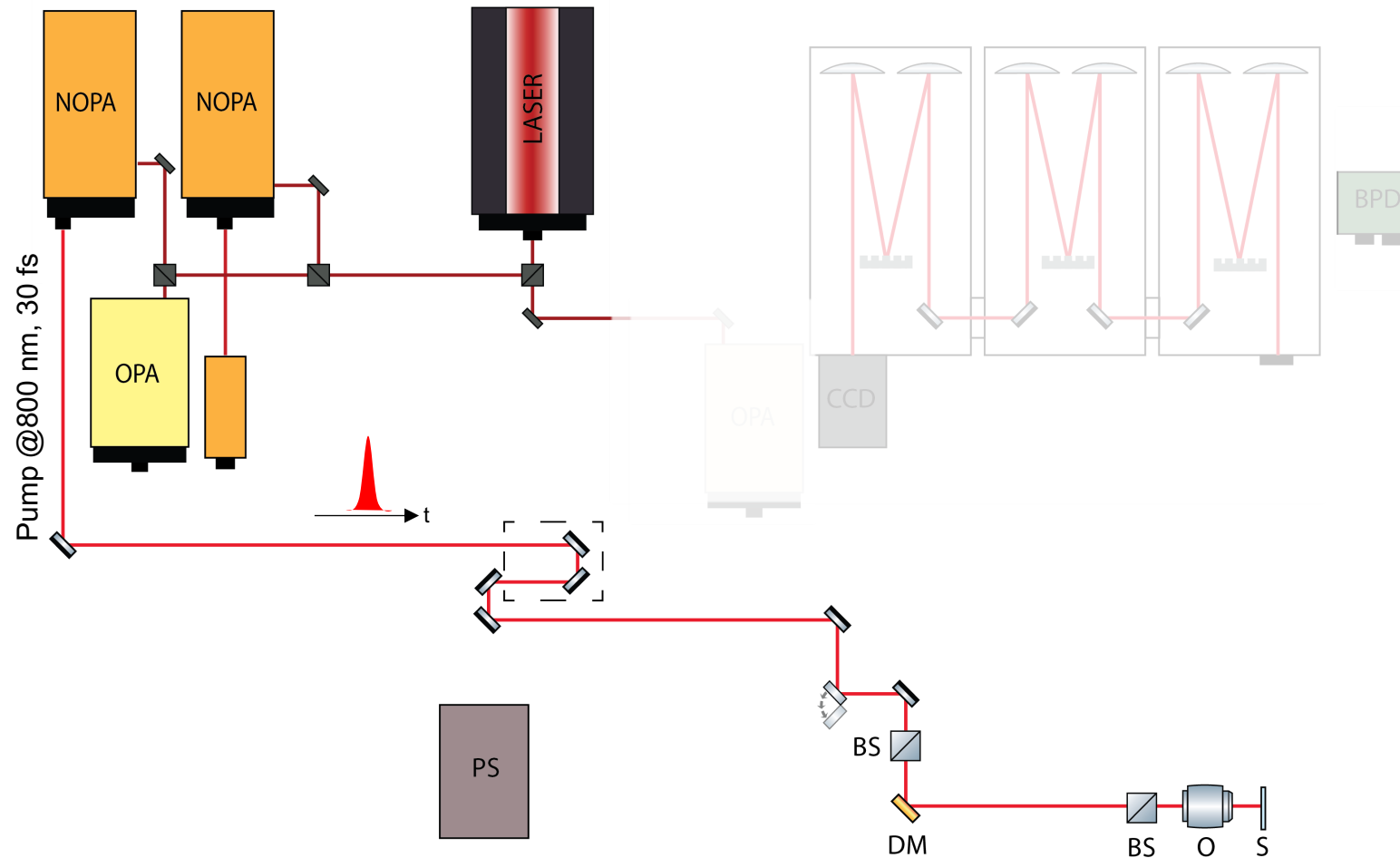


# Transient reflectivity on graphite flakes

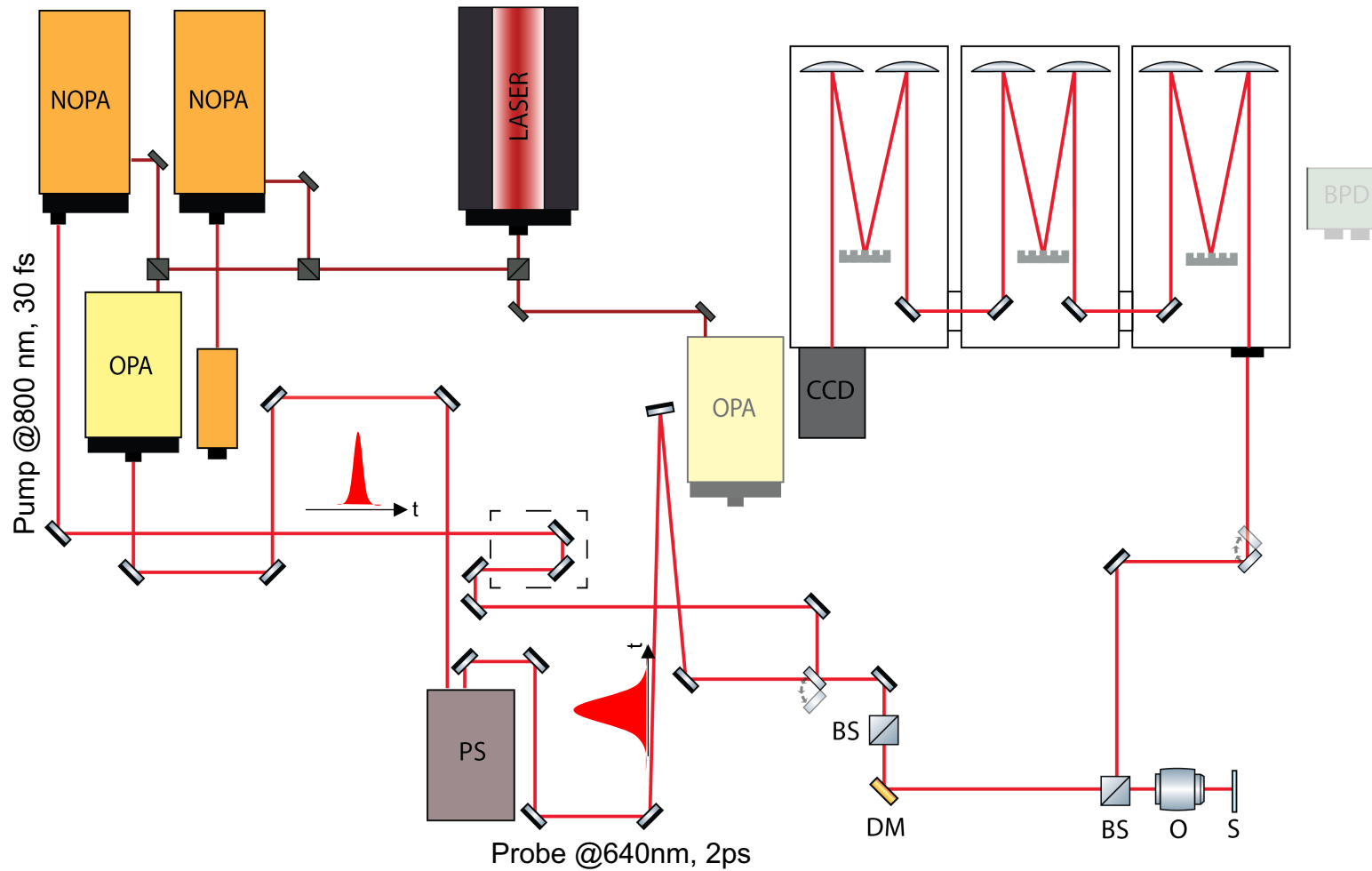


Si trenches, flake transfer with PDMS+PC

# Time-resolved Raman experimental scheme



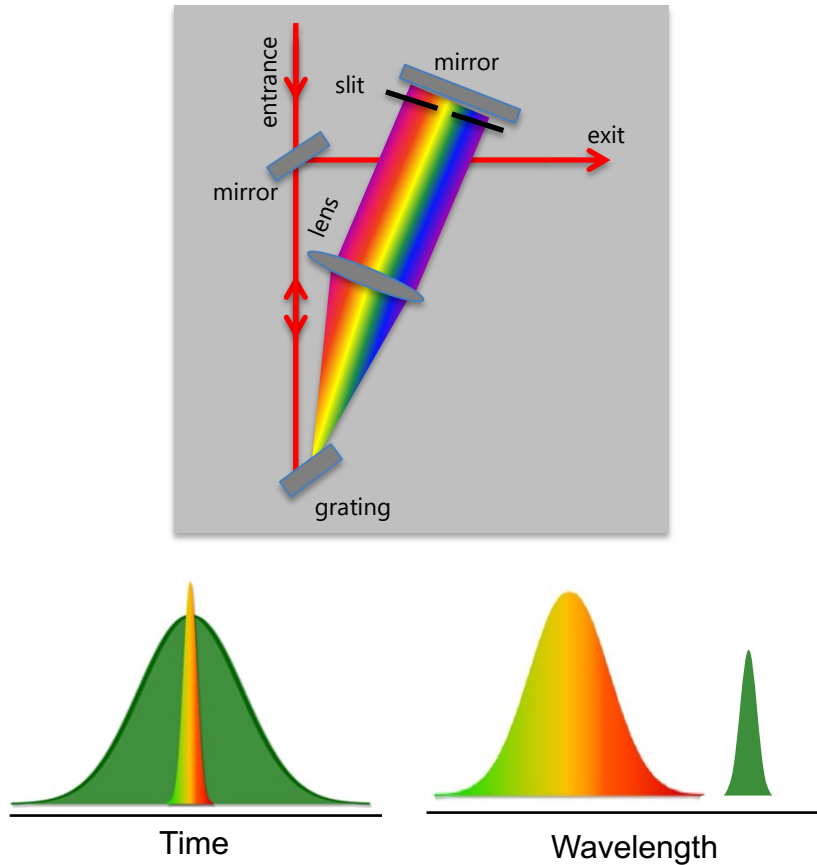
# Time-resolved Raman experimental scheme





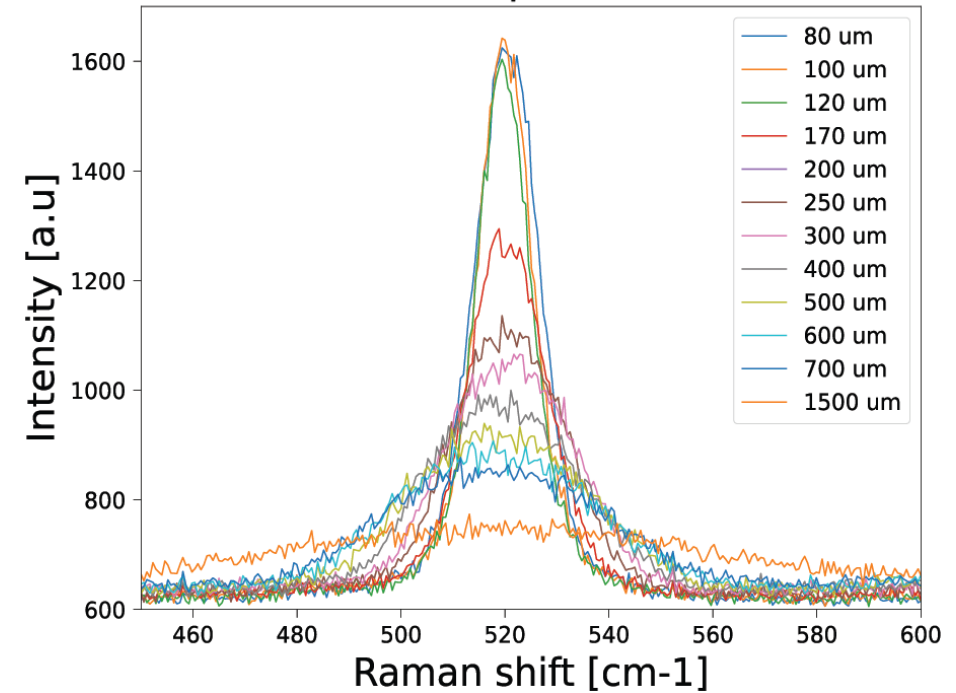
# Increasing the spectral resolution

Pulse shaper

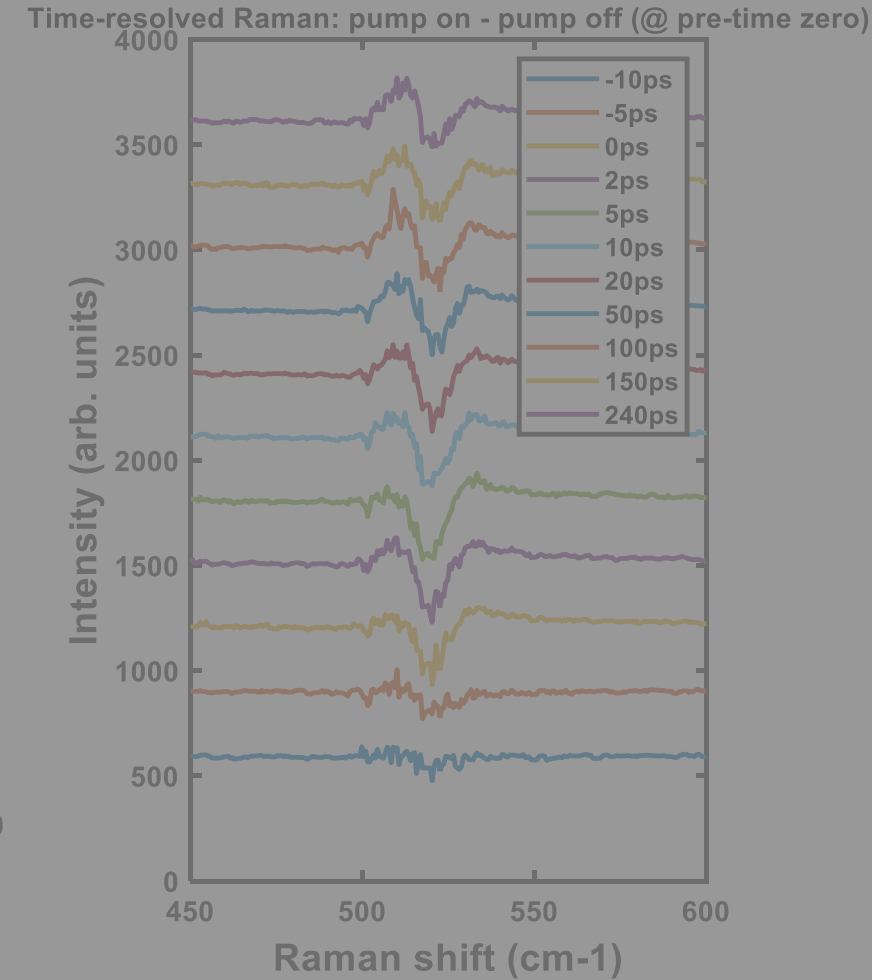
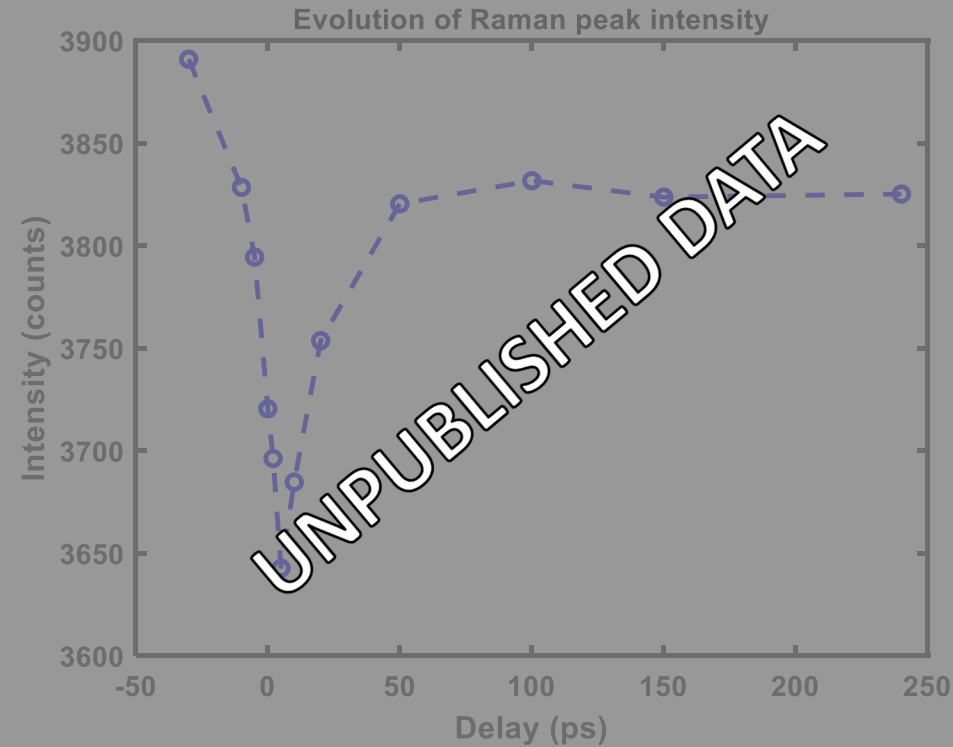
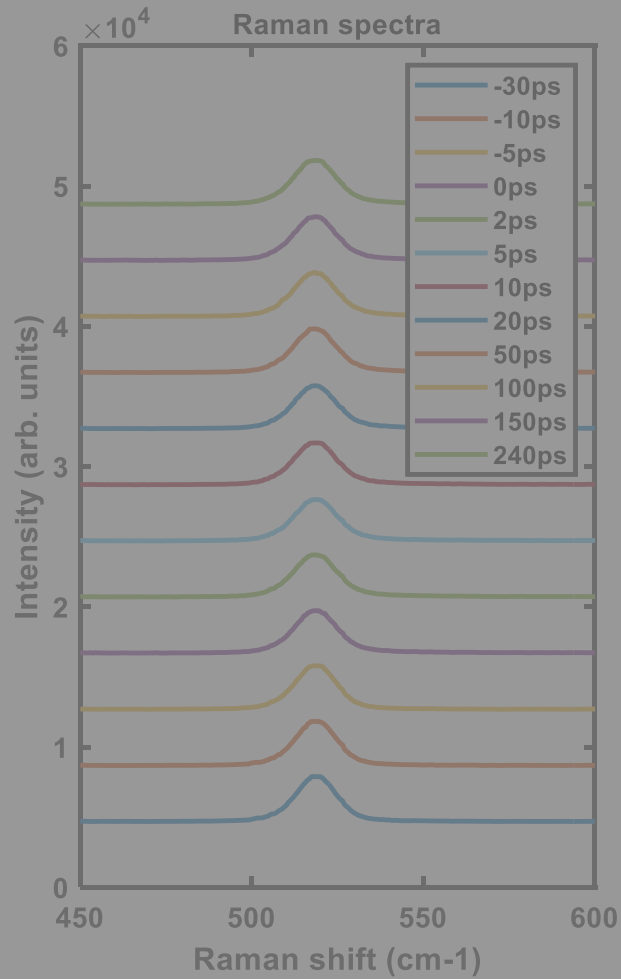


Increasing of the spectral resolution up to 10 cm<sup>-1</sup>

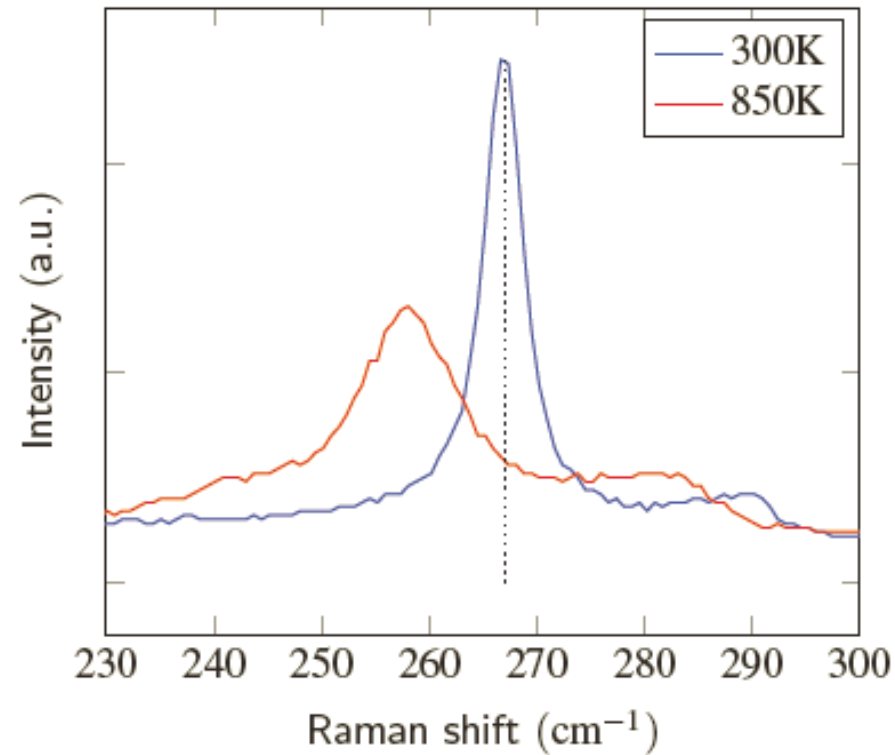
Slit aperture



# Time resolved Raman on Silicon

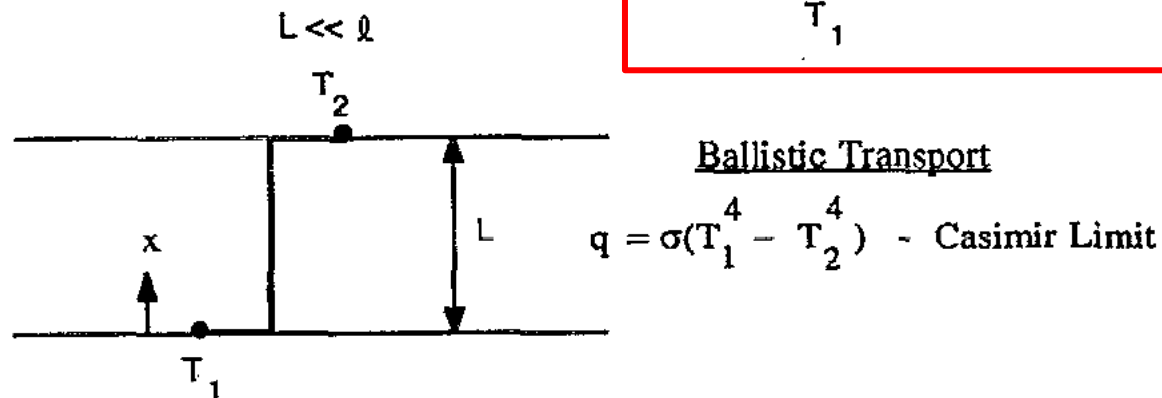
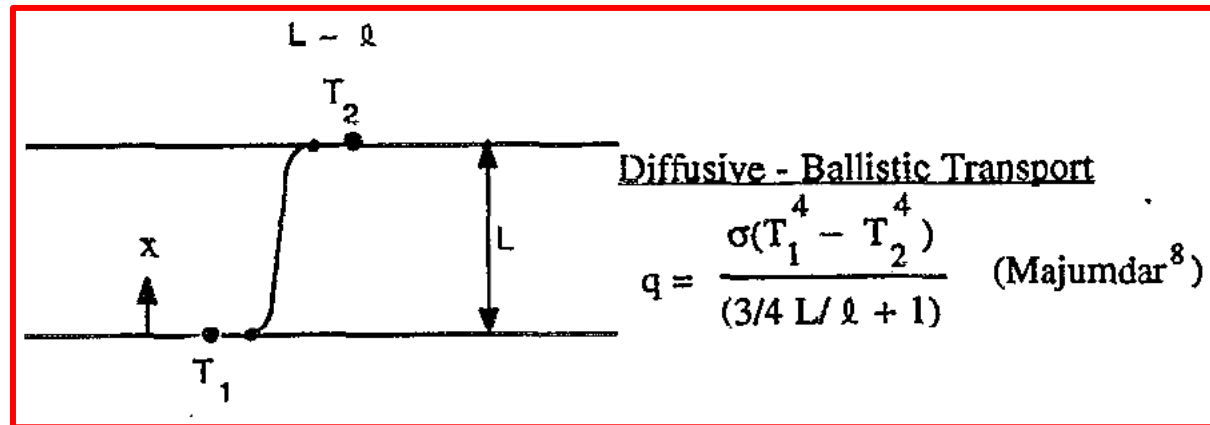
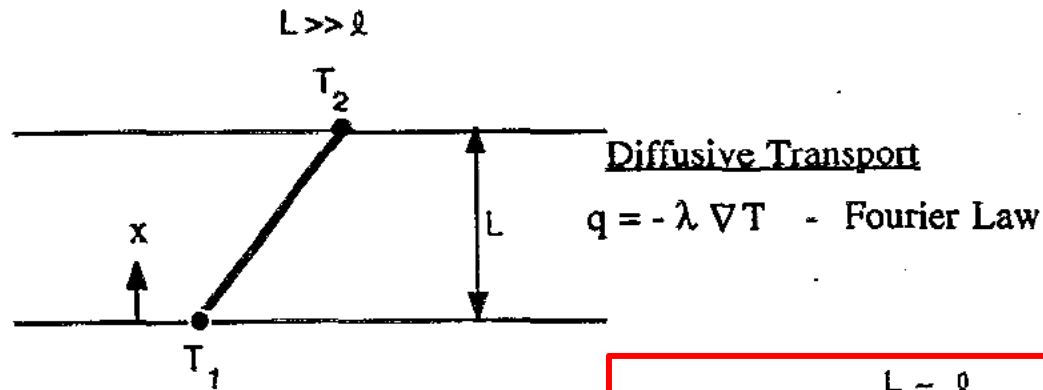


# Raman thermometry



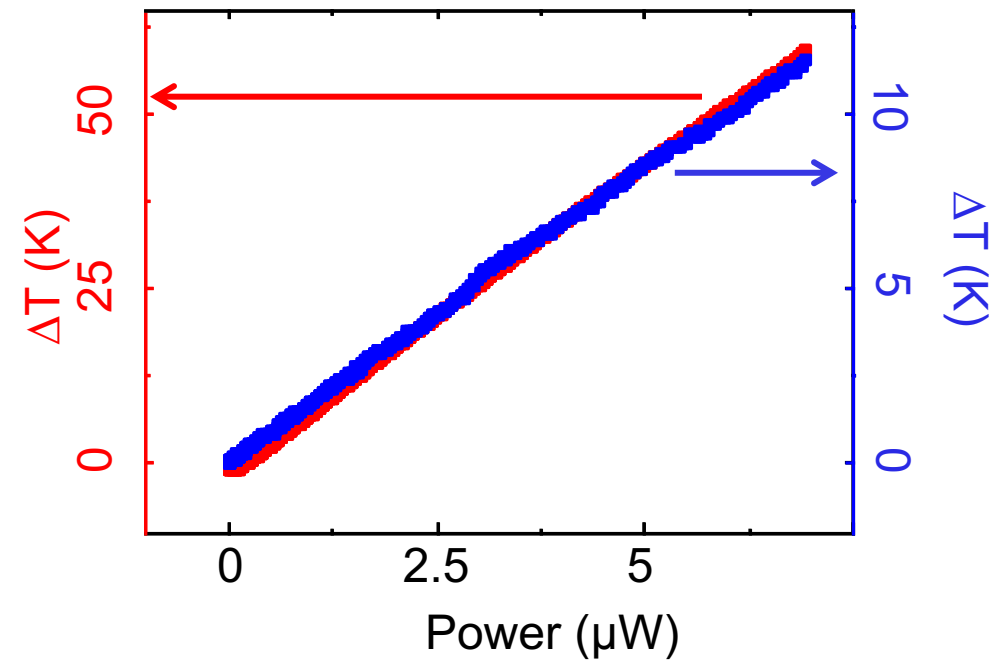
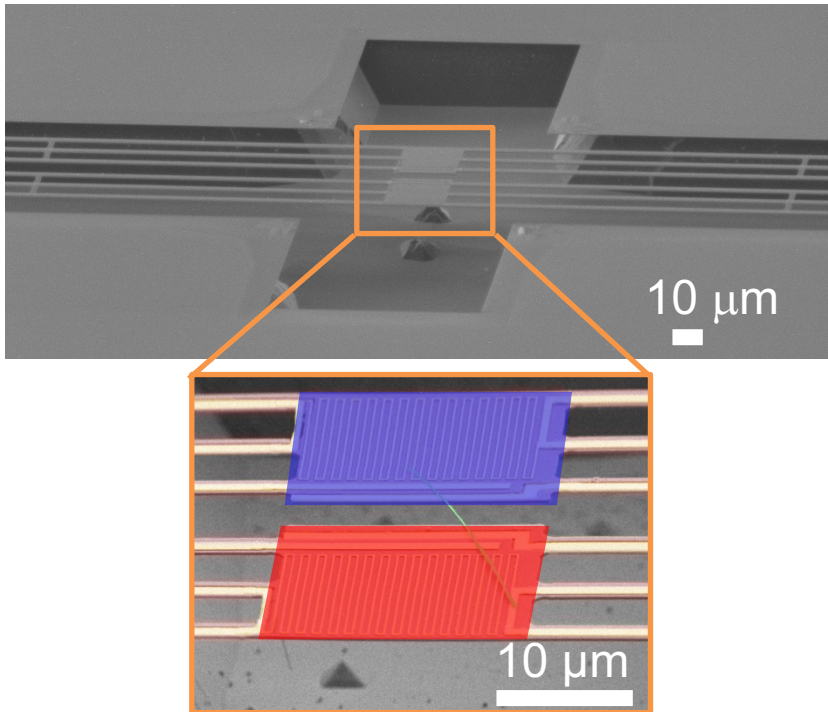
$$\Omega(T) = \omega_0 + \Delta(T) \quad \text{with} \quad \Delta(T) = A \left( 1 + \frac{2}{e^x - 1} \right) + B \left( 1 + \frac{3}{e^y - 1} + \frac{3}{(e^y - 1)^2} \right)$$
$$\Gamma(T) = C \left( 1 + \frac{2}{e^x - 1} \right) + D \left( 1 + \frac{3}{e^y - 1} + \frac{3}{(e^y - 1)^2} \right)$$

# Thermometry of heat transport channels



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

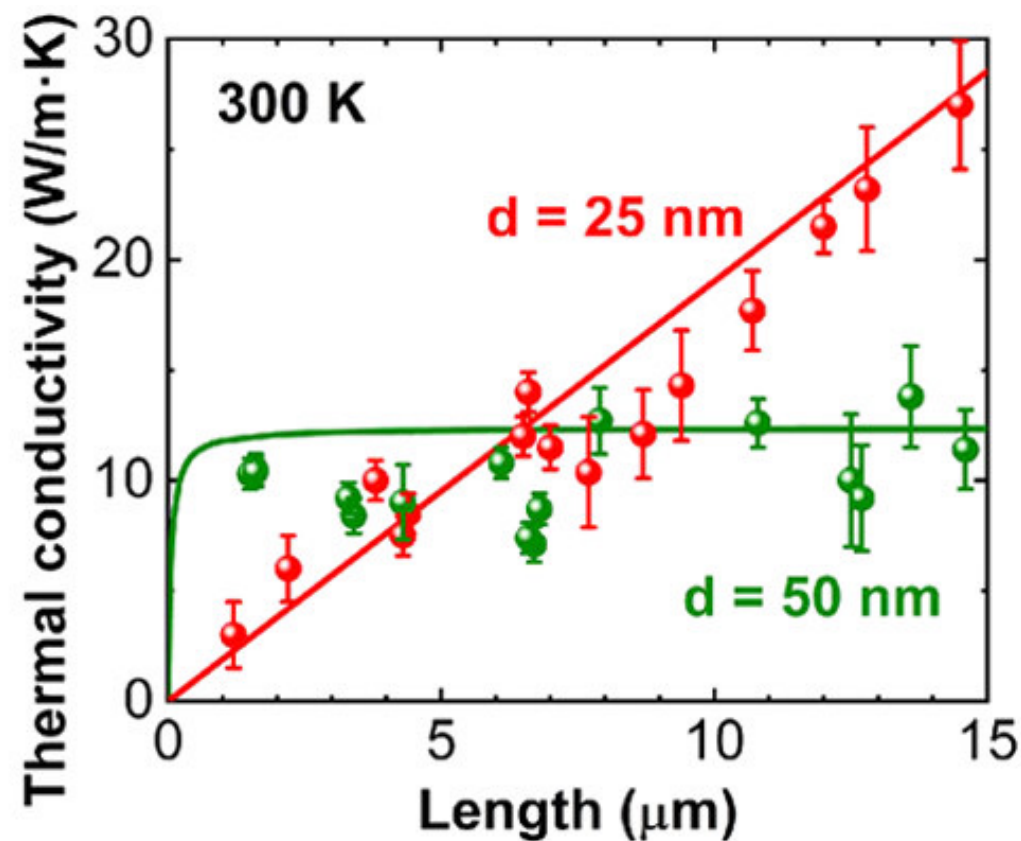
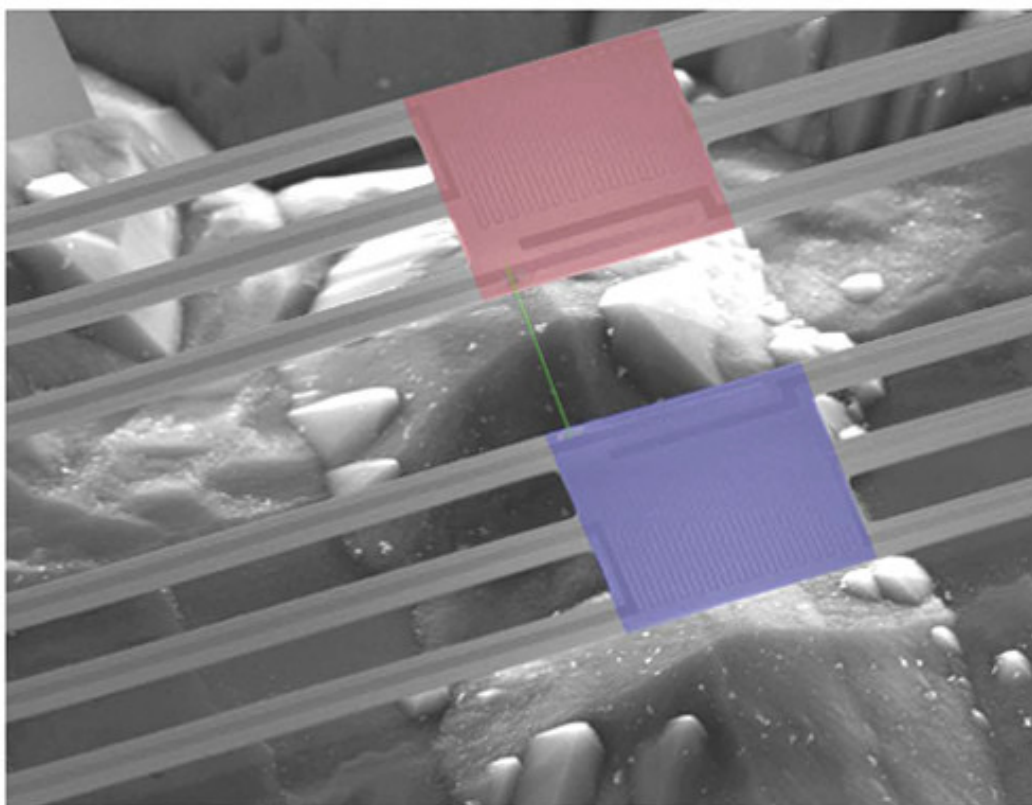
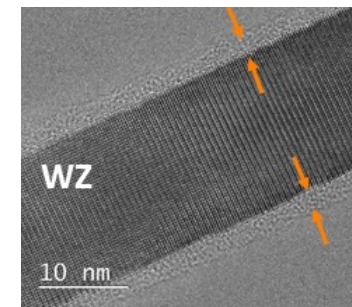
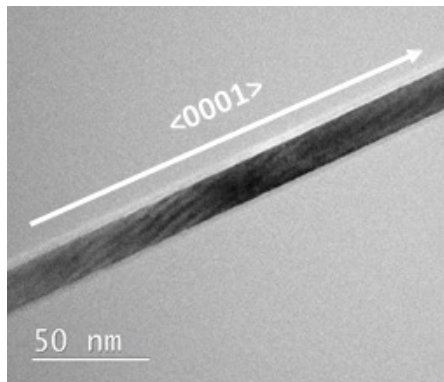
# Thermal conductivity measurements



Nanotechnology **26**, 385401 (2015)

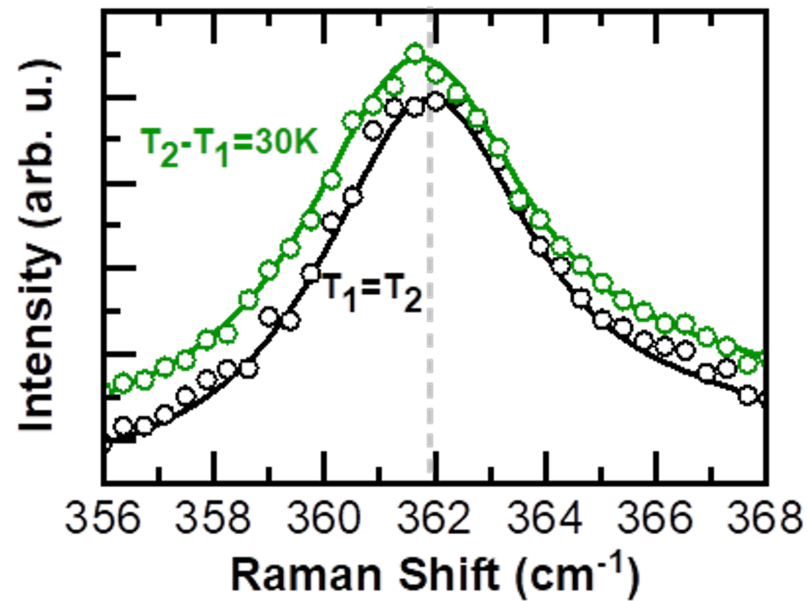
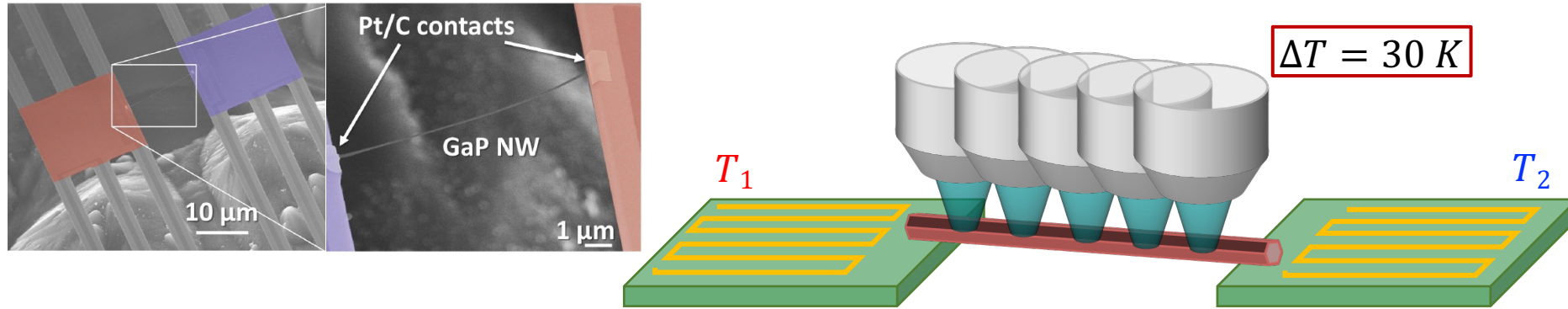


# Ballistic heat transport in wurtzite GaP nanowires



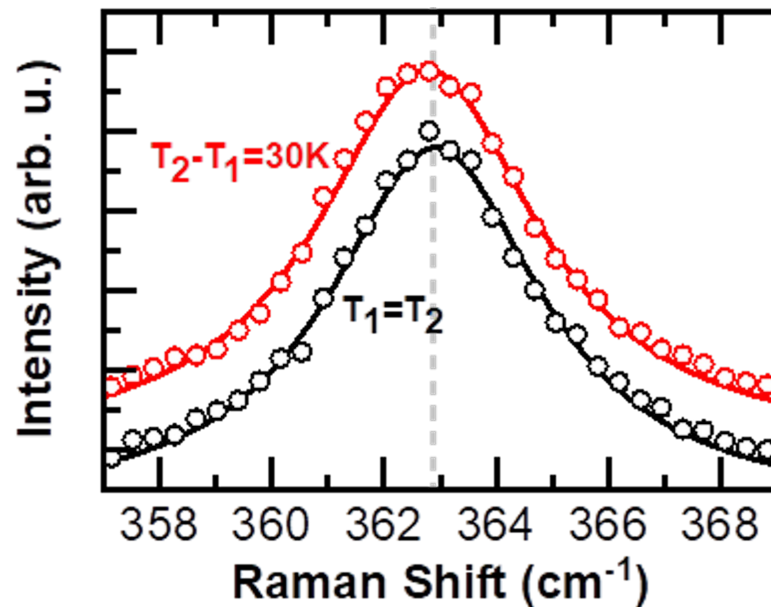
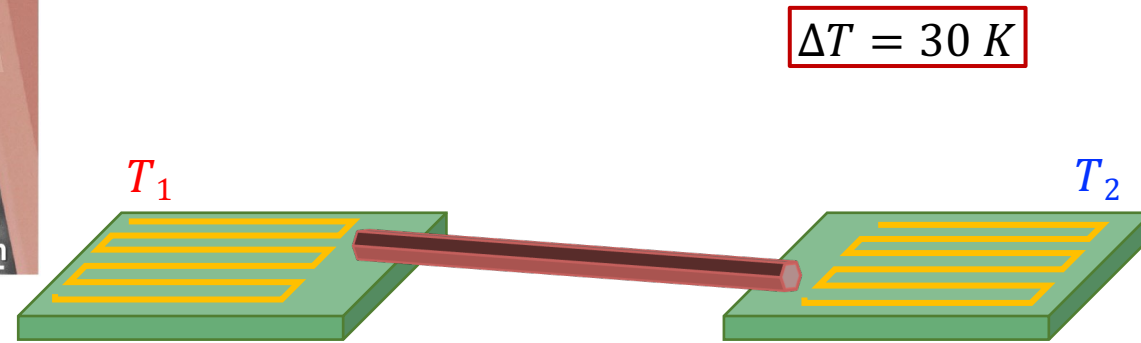
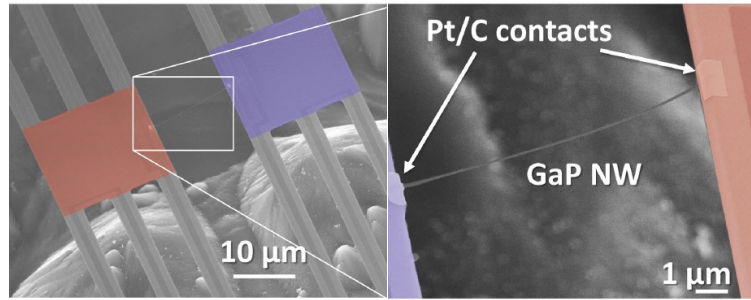
Nano Lett. **20**, 2703 (2020)

# Raman thermometry of heat transport channels

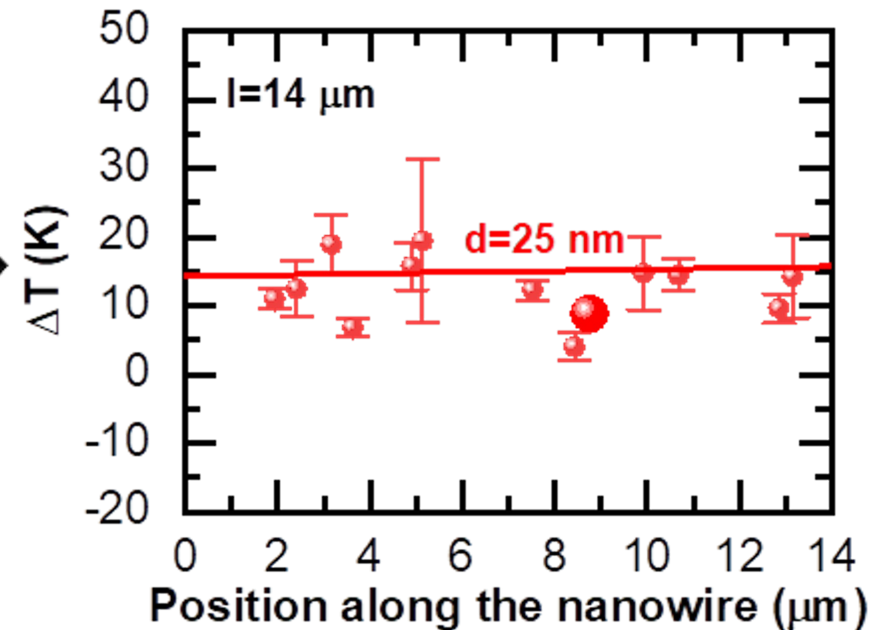


Nano Lett. **20**, 2703 (2020)

# Raman thermometry of heat transport channels

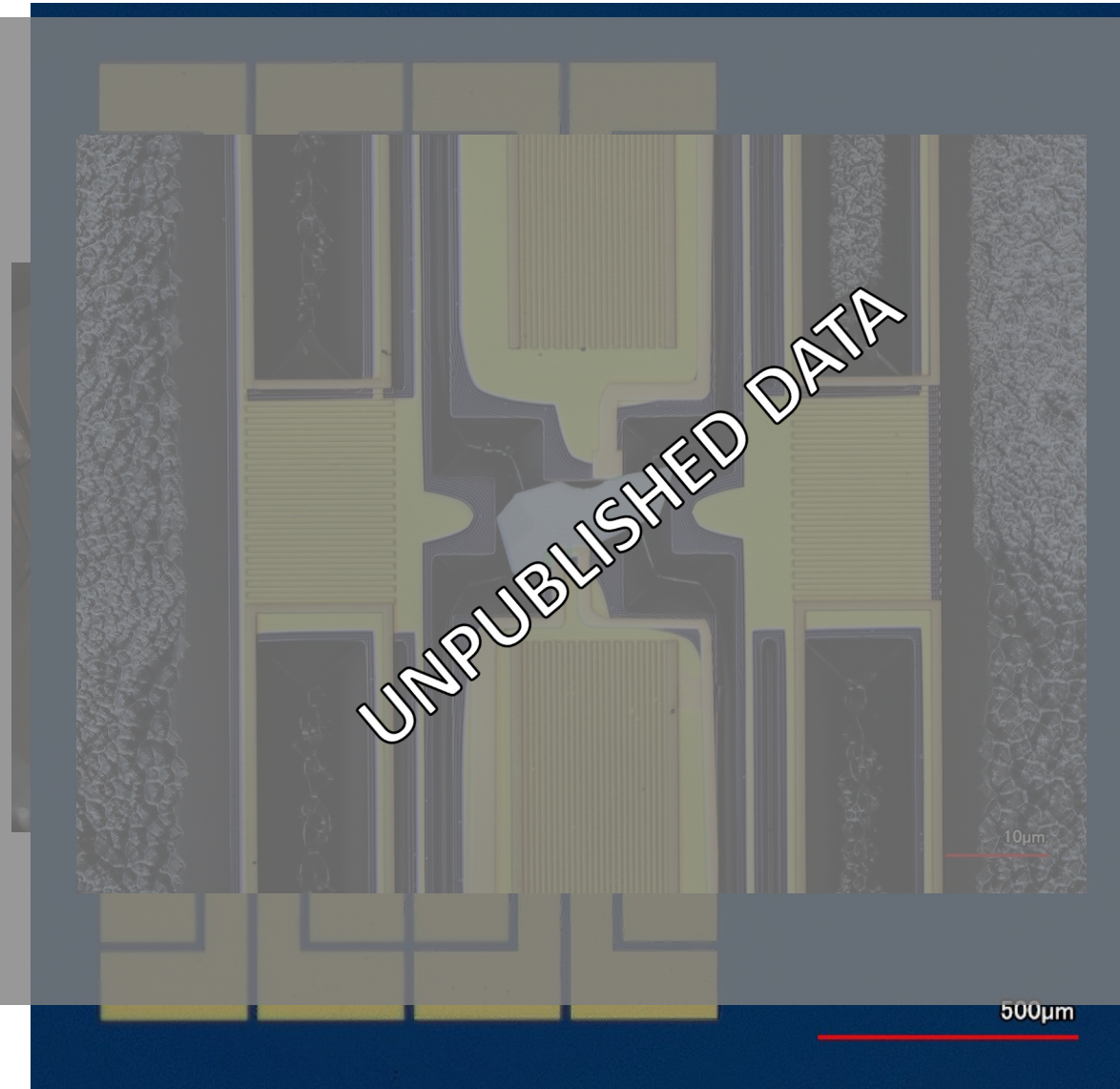


BALLISTIC TEMPERATURE PROFILE



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

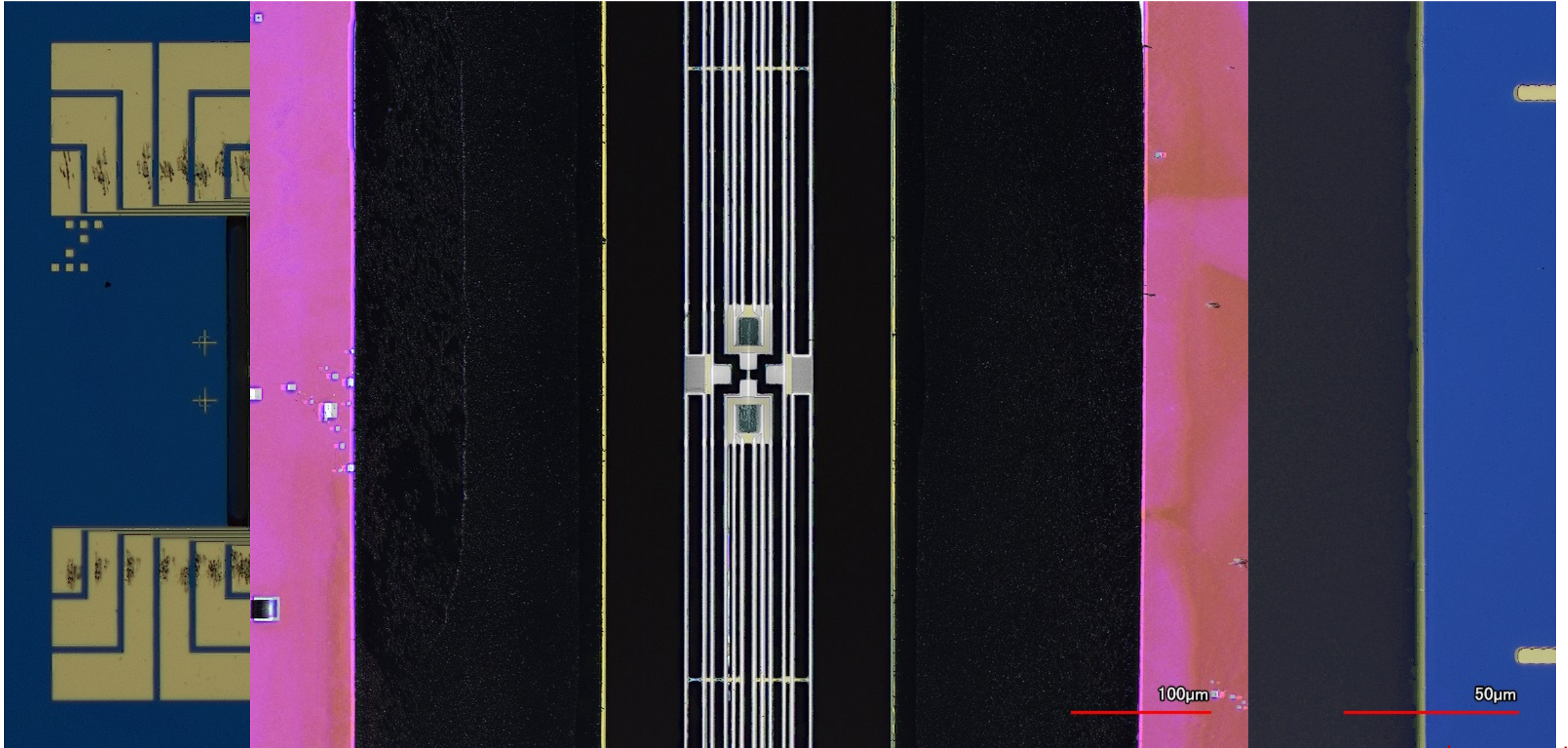
# 4-point thermal measurements



In preparation



# Fabricated device



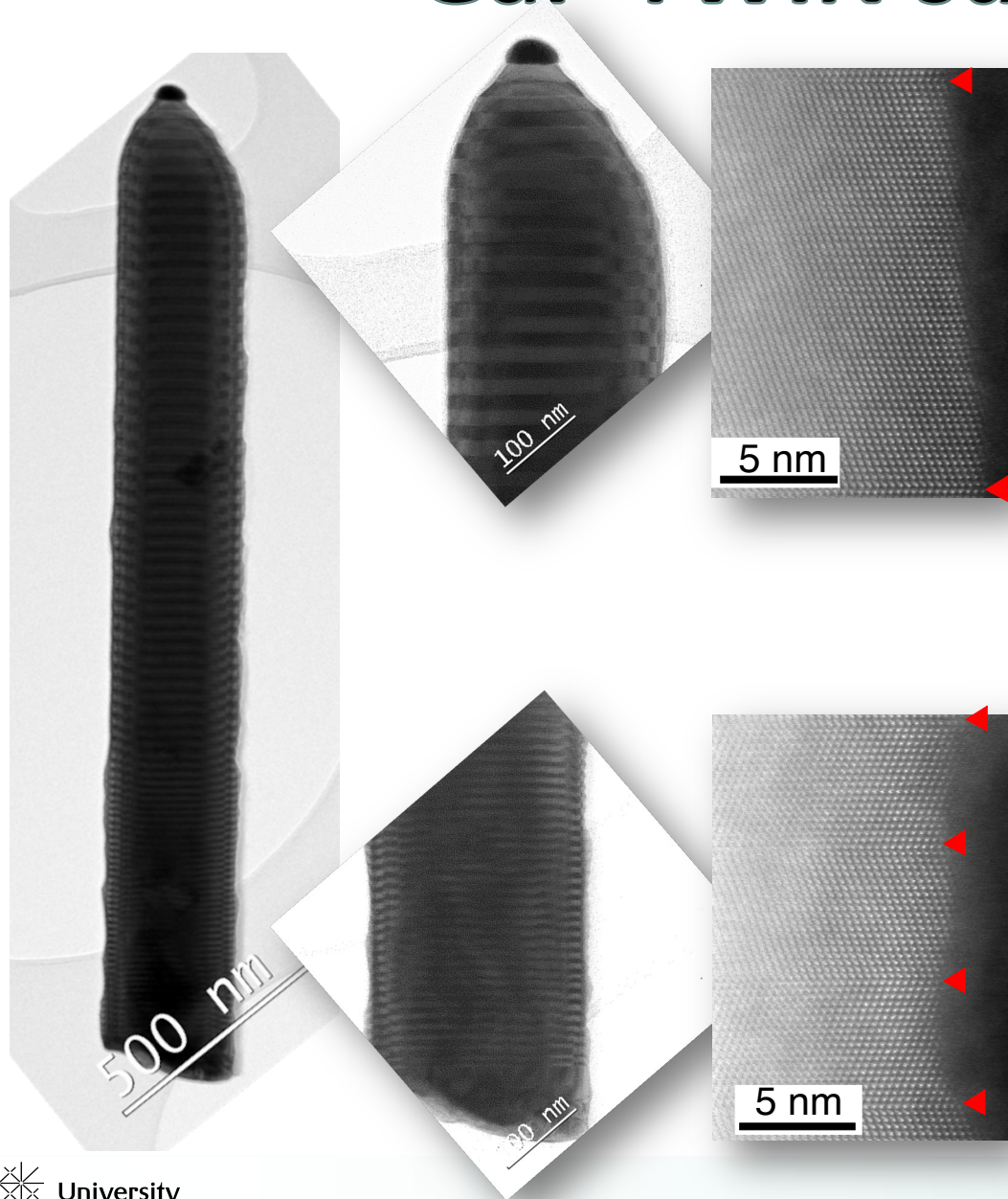
In preparation



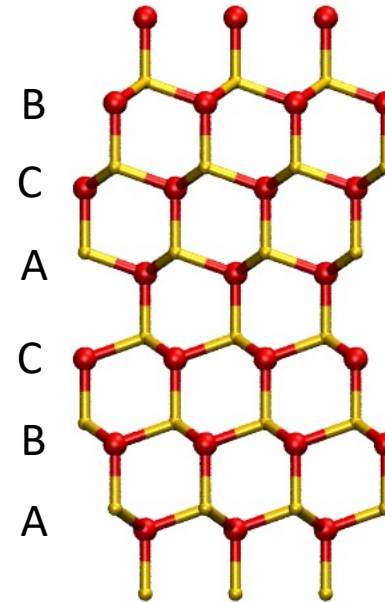
# Outline

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

# GaP TWIN superlattice nanowires

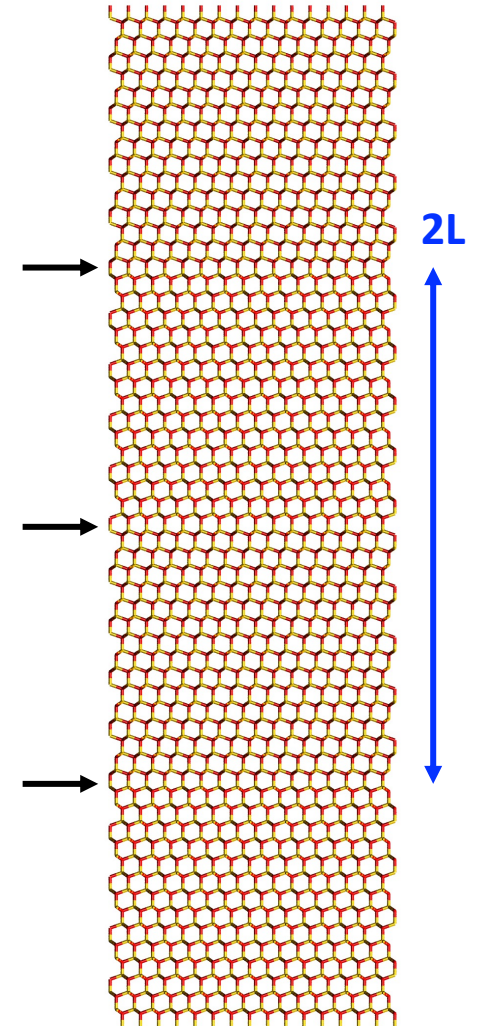


TWIN PLANE

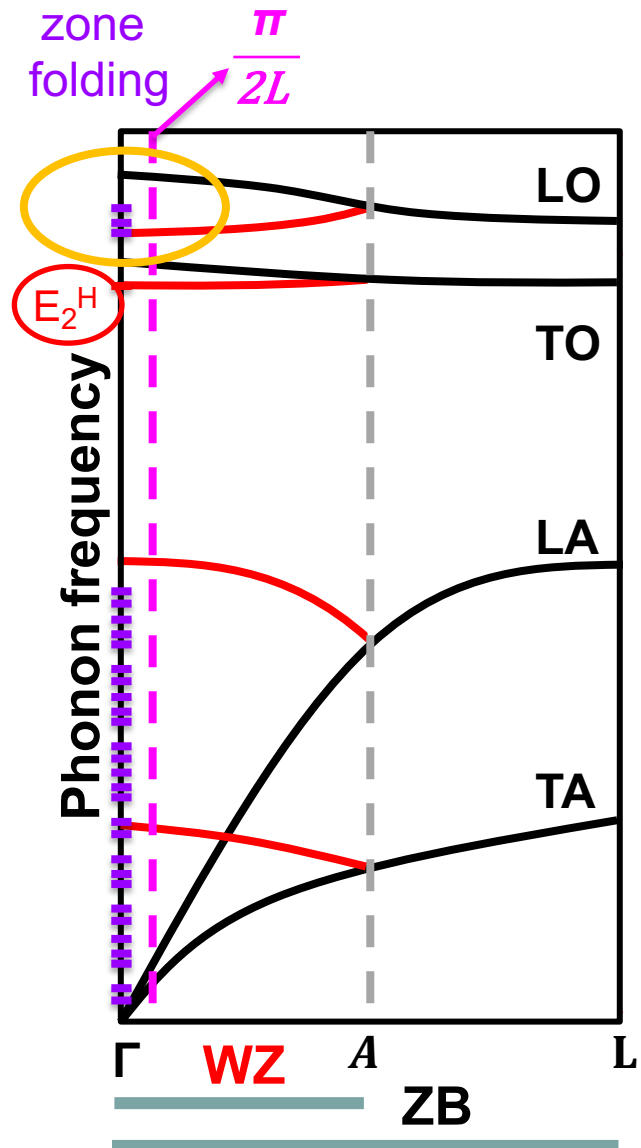


The twin boundary acts as a mirror plane:  
the stacking goes from  
ABCABC... to CBACBA

TWIN SL

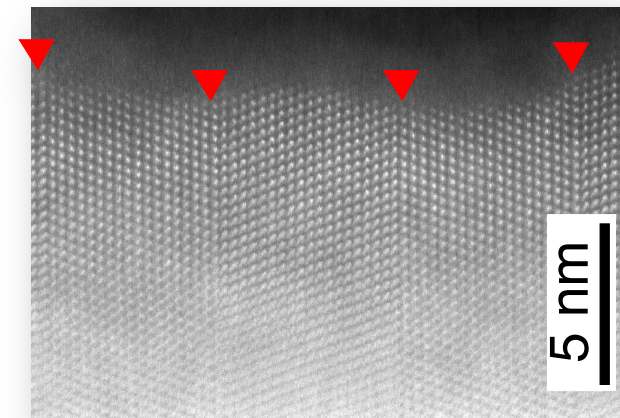


# Phonons in GaP



THEORY

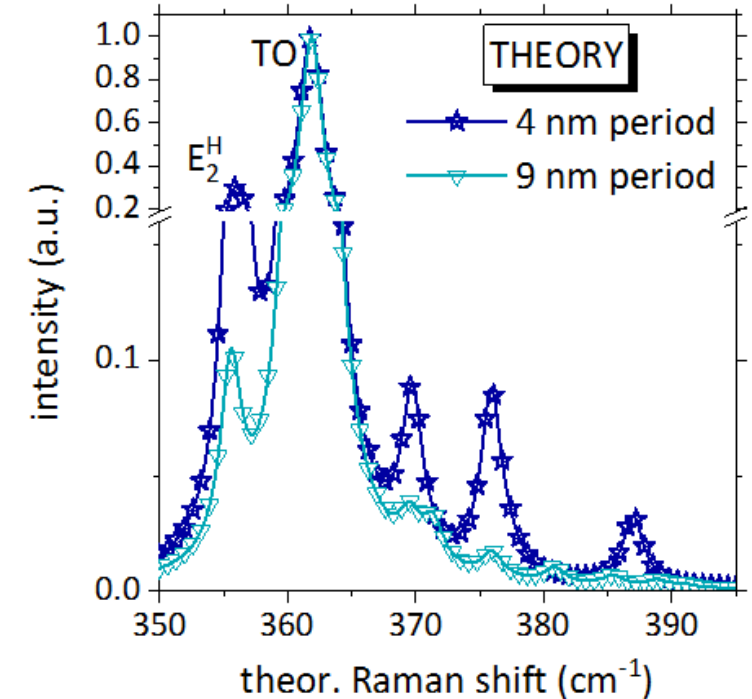
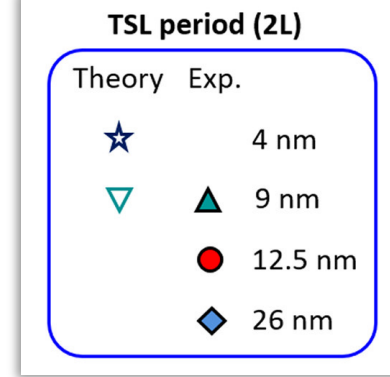
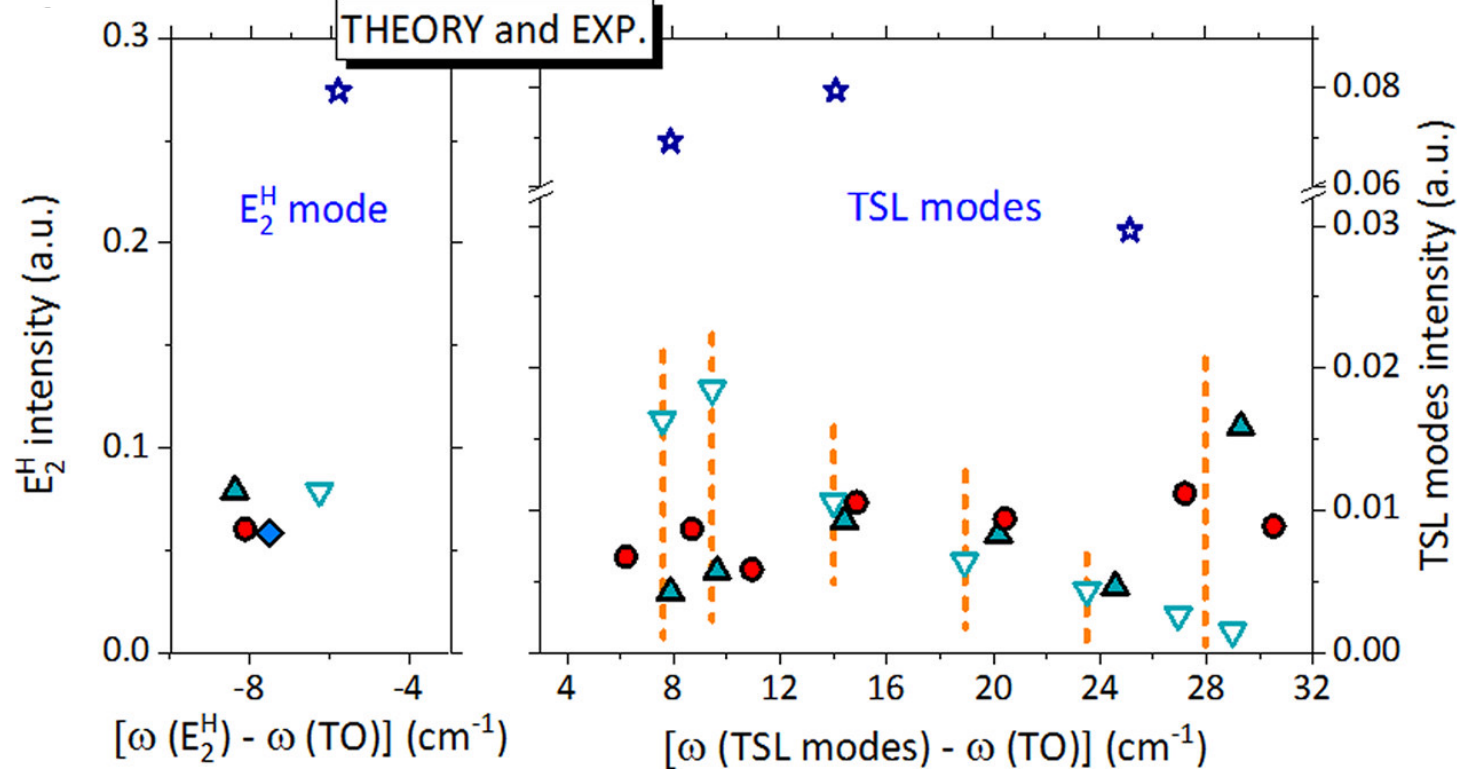
EXPERIMENT



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

# Phonon engineering in GaP twin SL nanowires

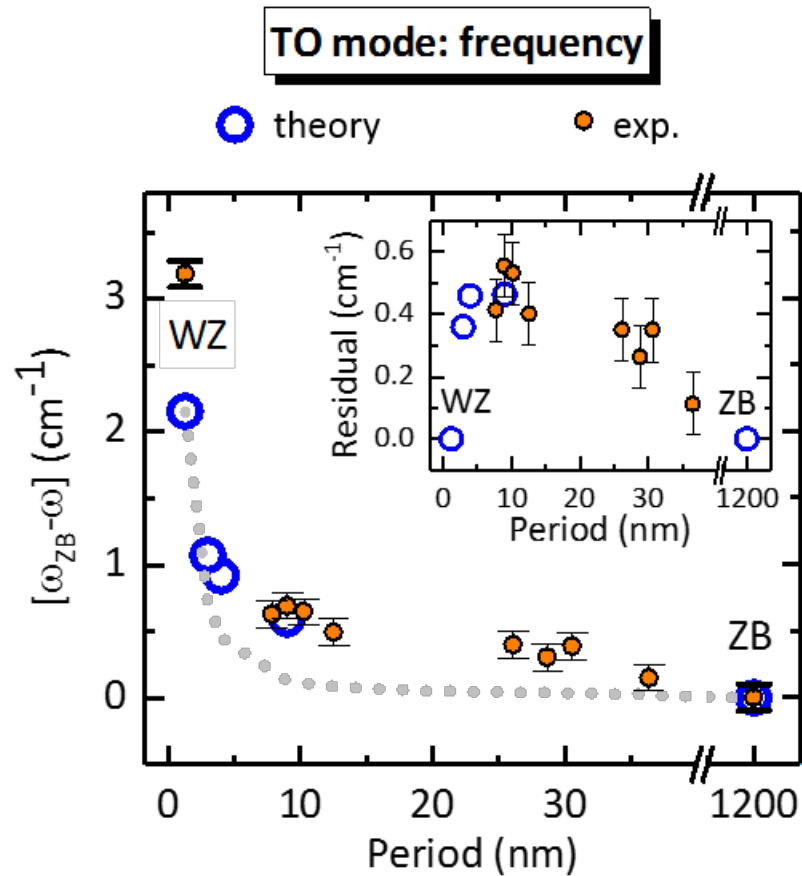
## TUNABILITY



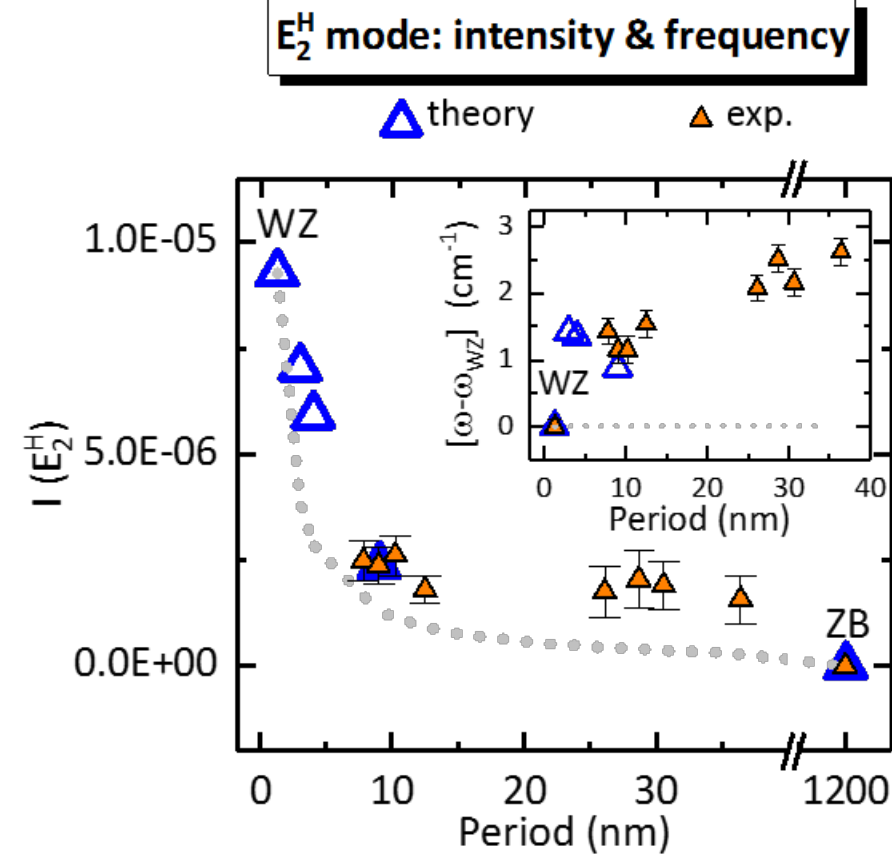
Nano Lett. **19**, 4702 (2019)

# Phonon engineering in GaP twin SL nanowires

## Expected long coherence



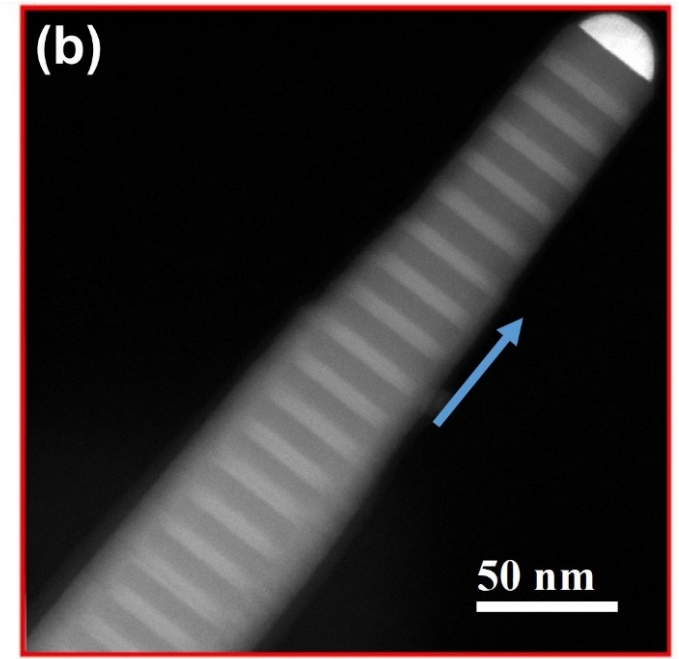
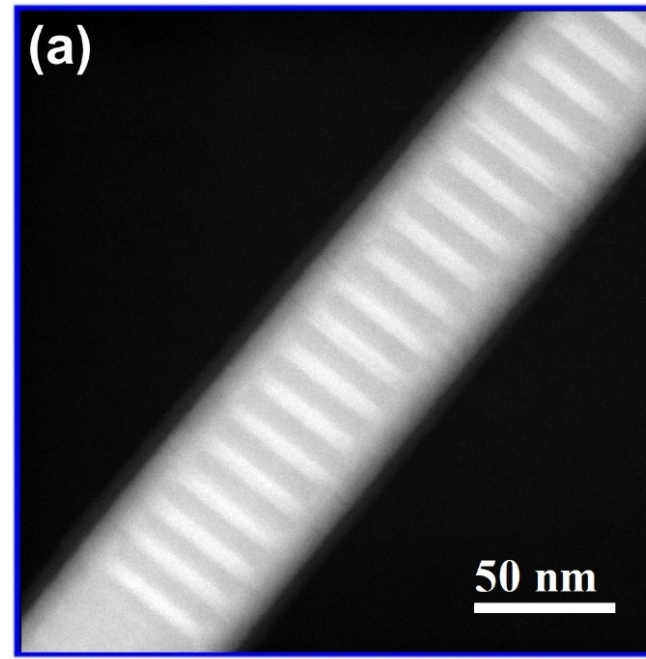
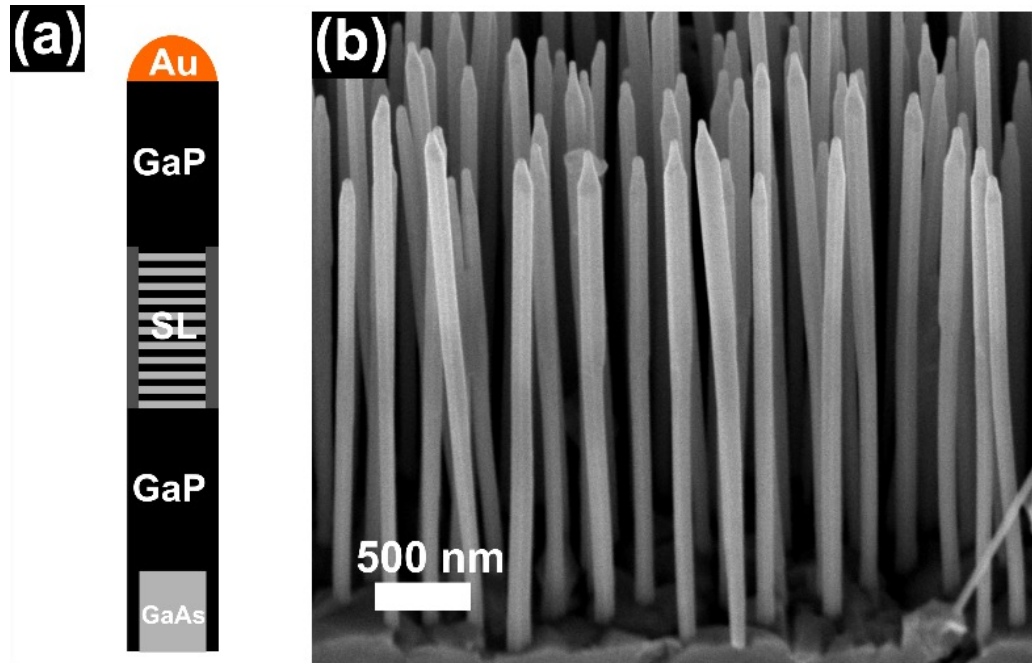
## New metamaterial



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



# GaAs-GaP superlattice nanowires



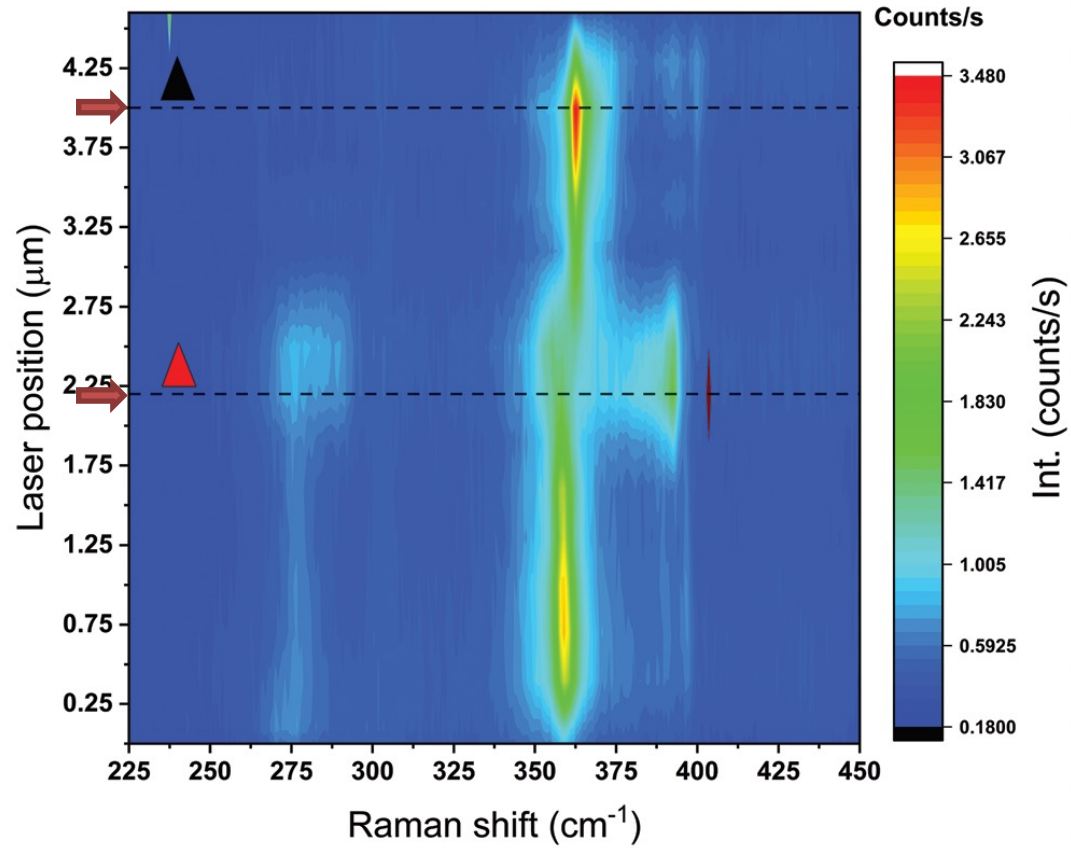
**CNR-NEST**

Lucia Sorba  
Valentina Zannier  
Omer Arif

Accepted in Nanoscale 2022

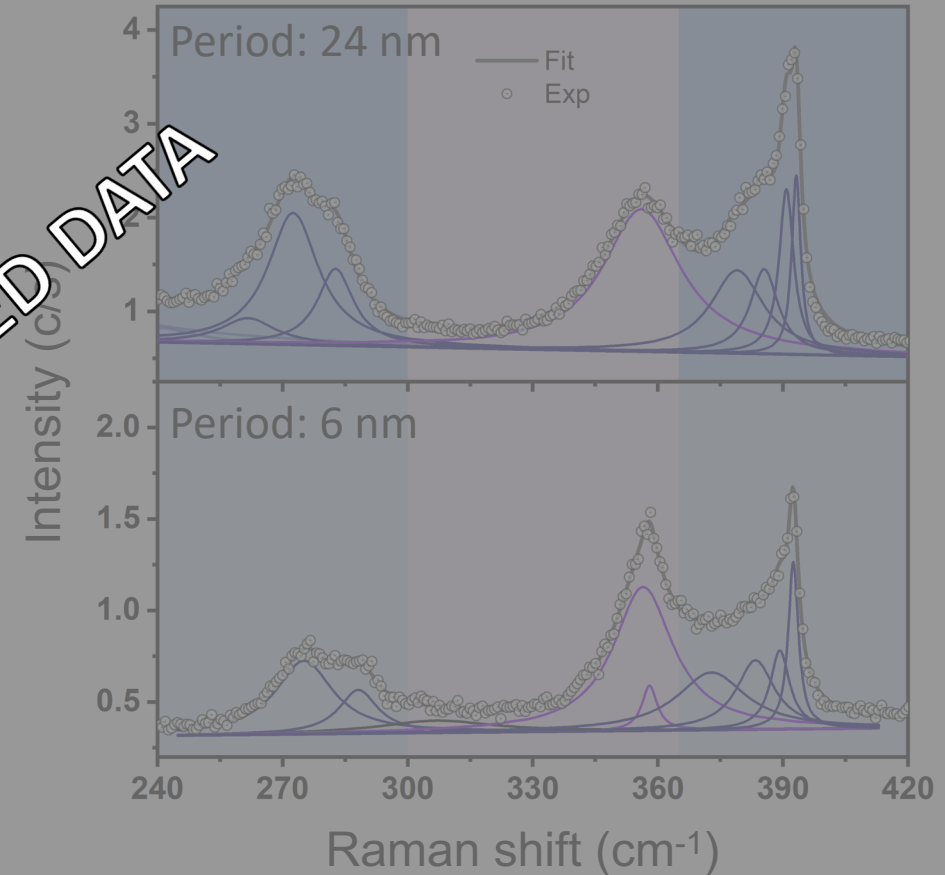
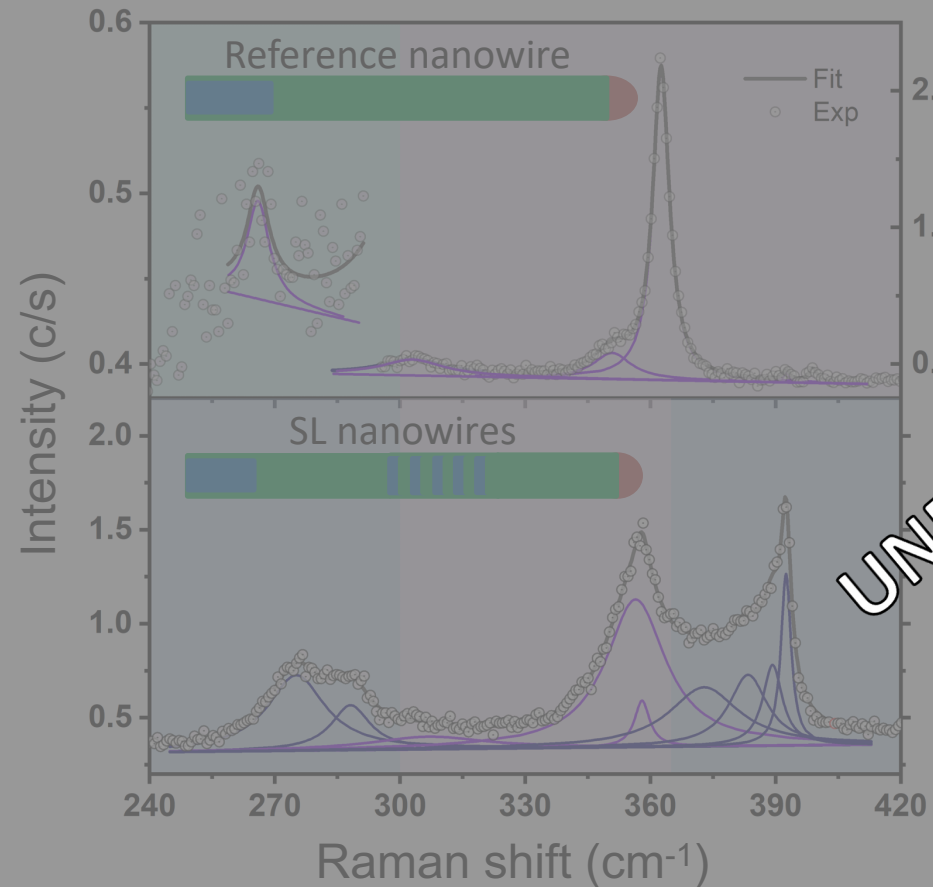


# GaAs-GaP SL nanowires



Accepted in Nanoscale (2022)

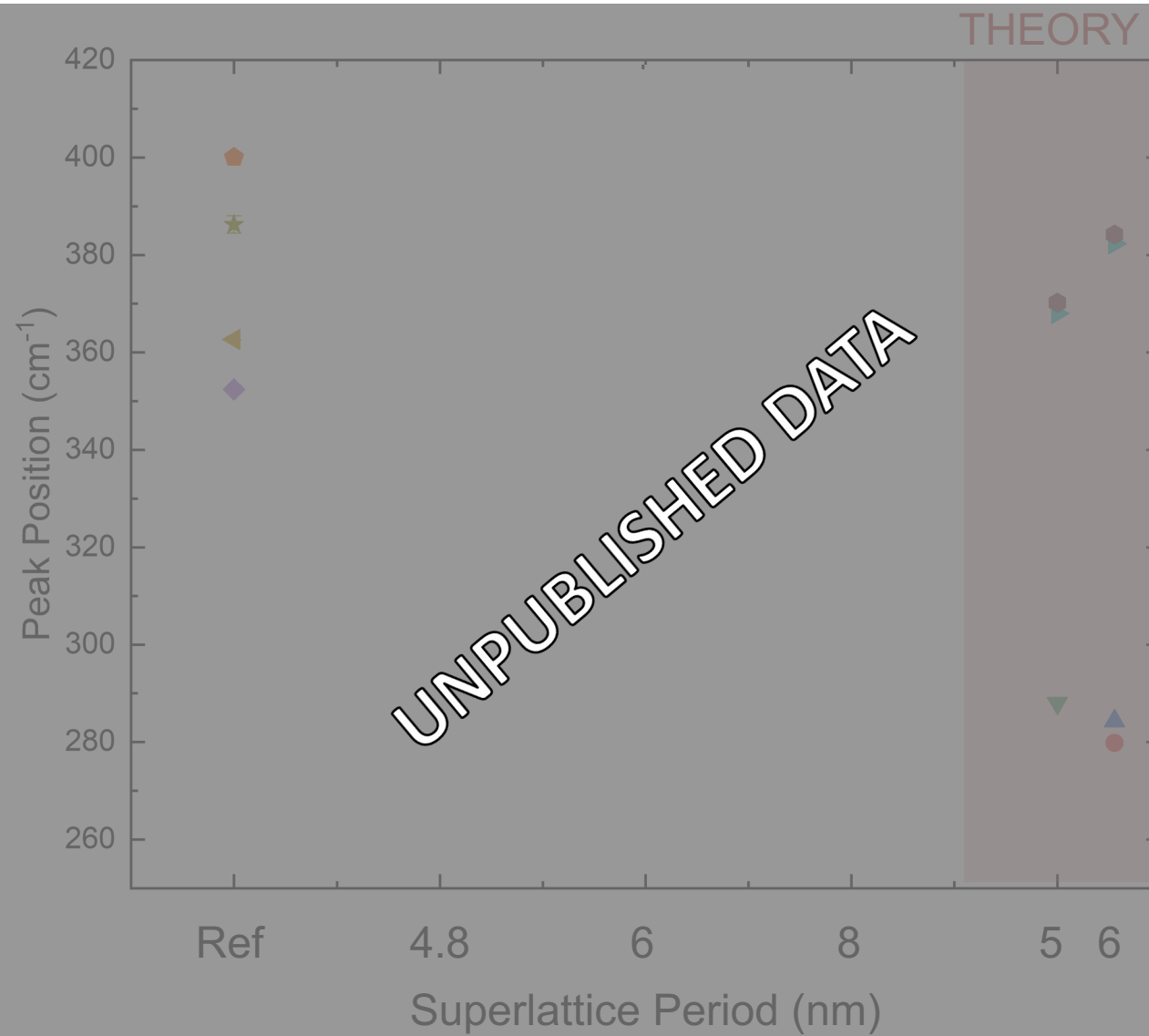
# Phonon modes



UNPUBLISHED DATA

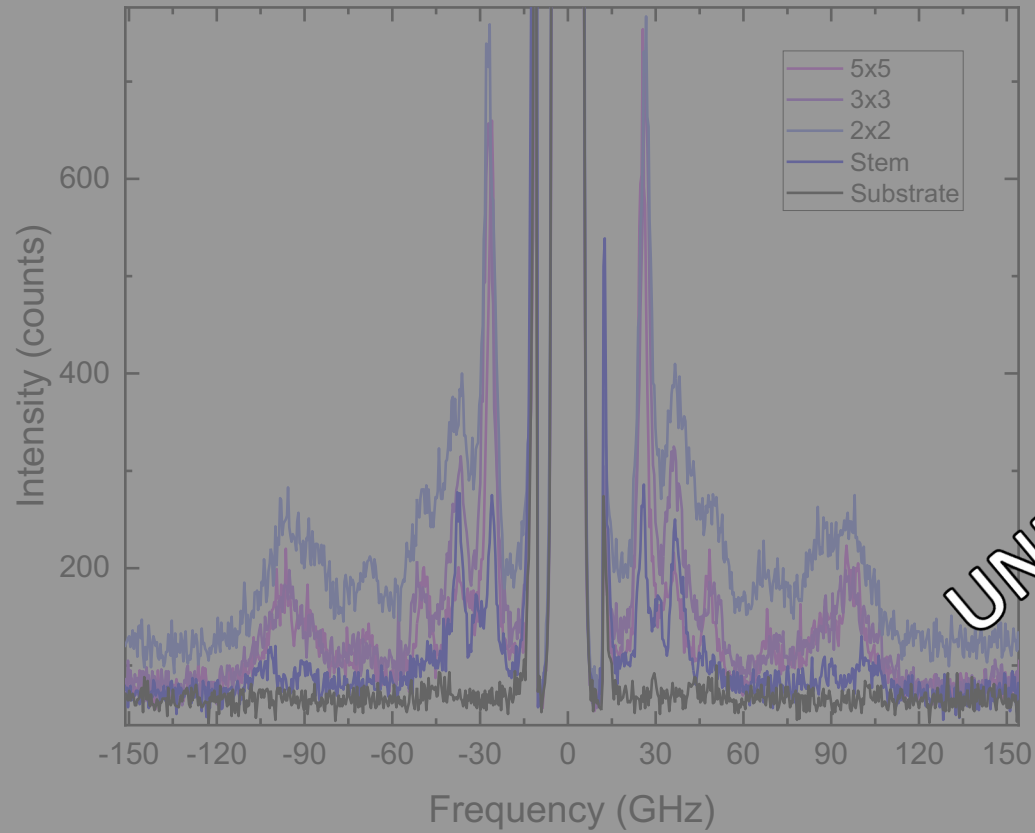
Unpublished data

# Tuning of phonon modes

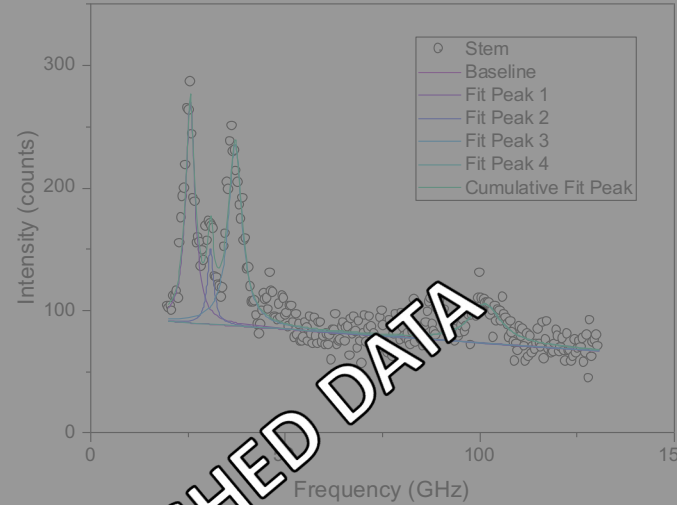


# Low frequency phonons

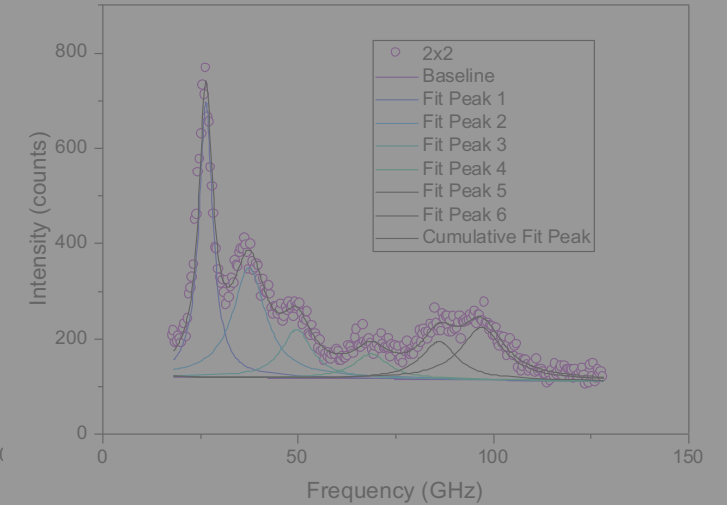
## BRILLOUIN SPECTRA



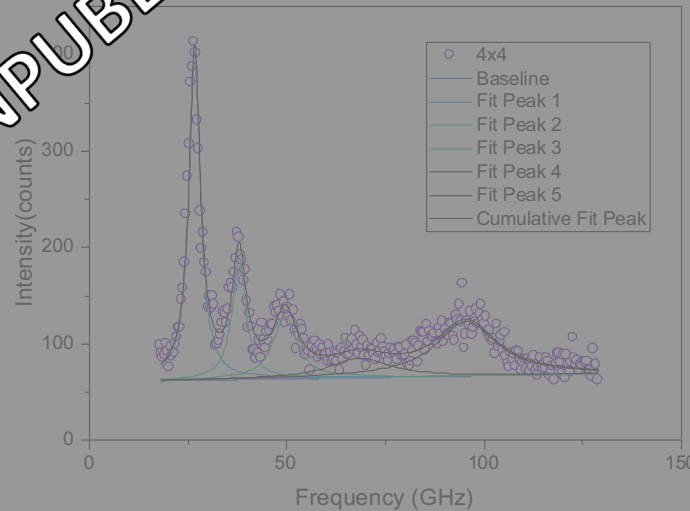
## Reference NO SL



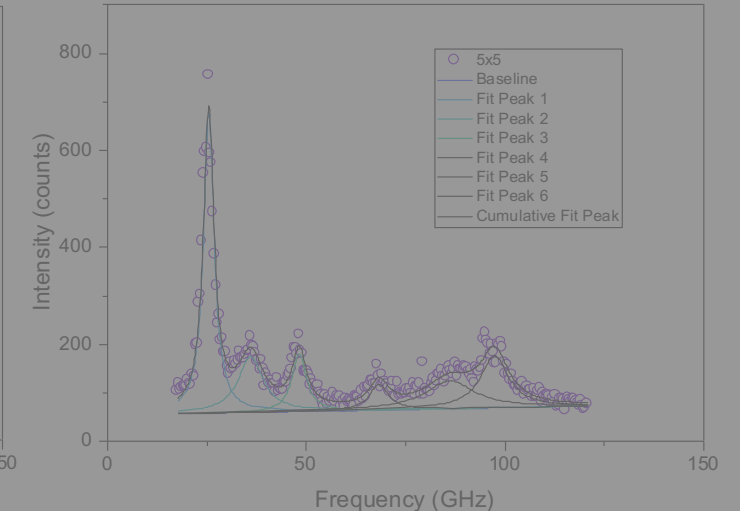
## 4.8 nm SL



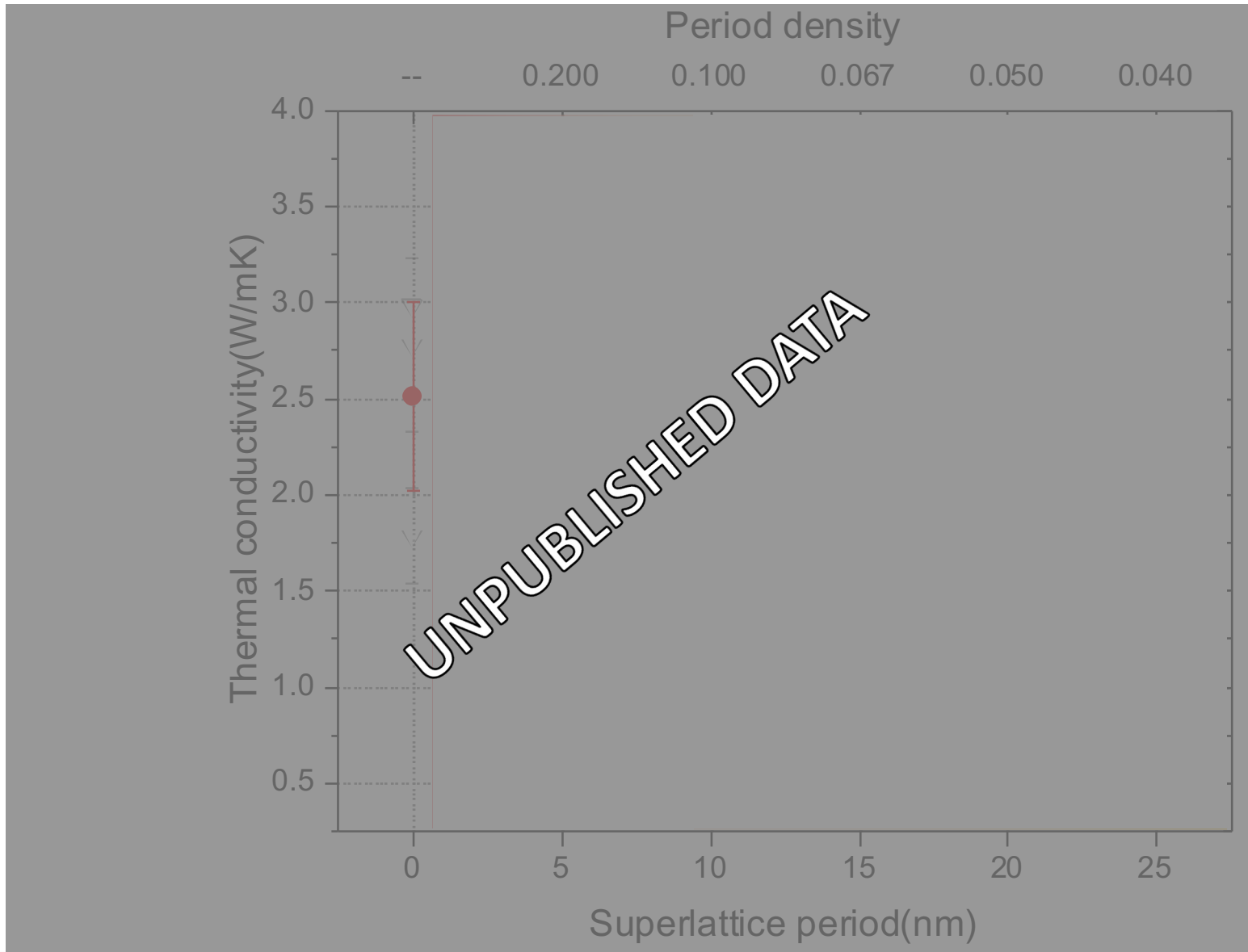
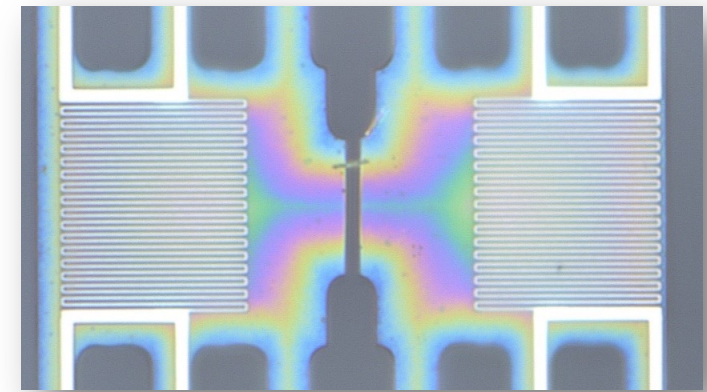
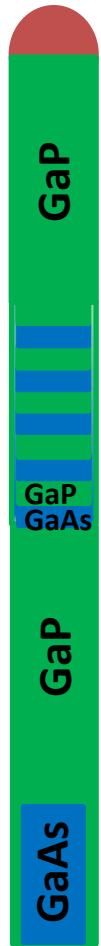
## 6.0 nm SL



## 10 nm SL



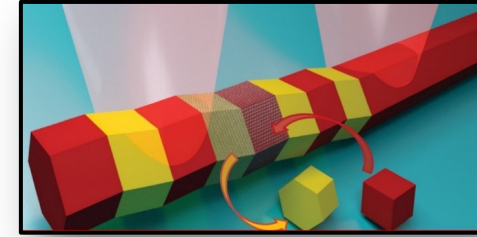
# Thermal conductivity



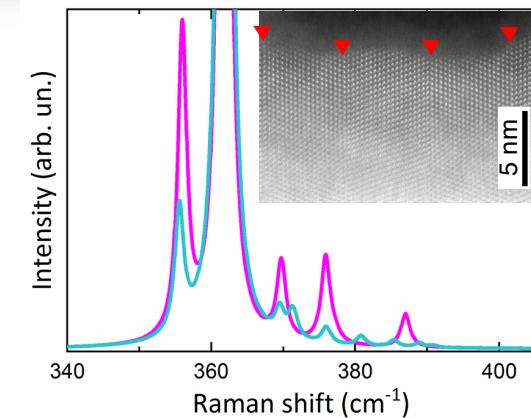
Unpublished data

# Take home message

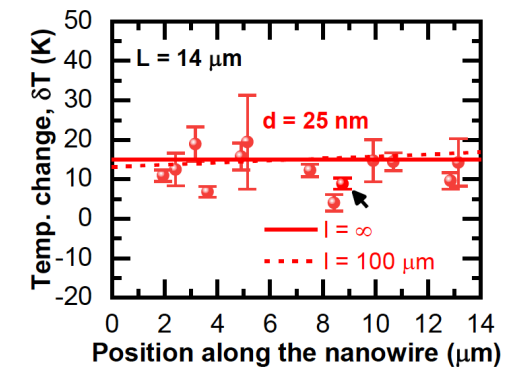
- Probing of phononic properties at the nanoscale



- 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)

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Saeko Tachikawa (Postdoc)

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**Yashpreet Kaur** (PhD)

Nadine Gächter (PhD)

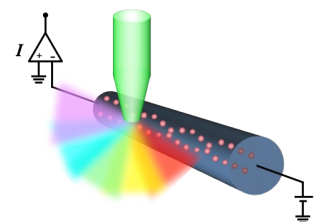
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Martino Poggio  
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# Thank you for your attention