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Semiconductor nanostructures for acoustic and acoustooptic engineering at terahertz frequencies

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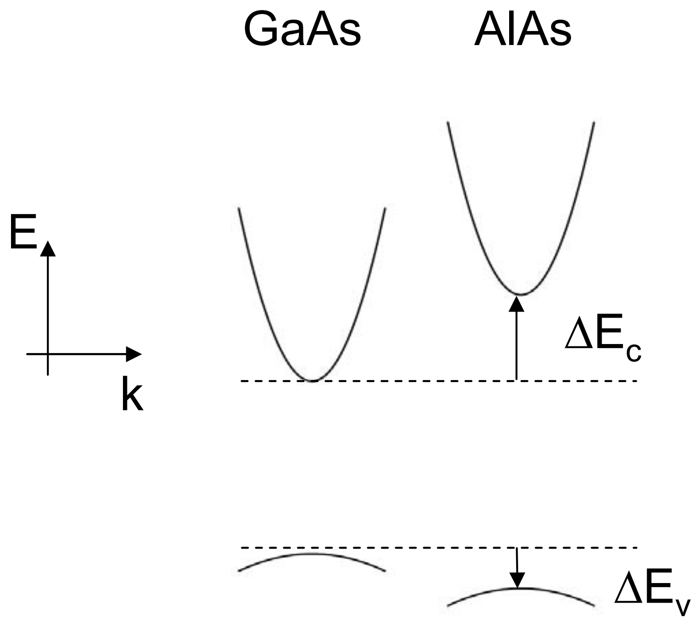
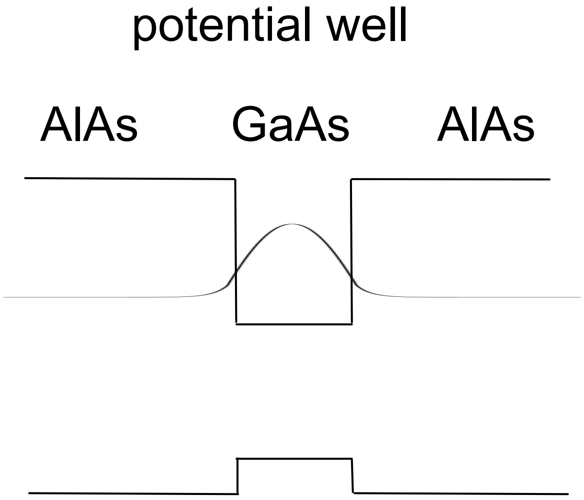
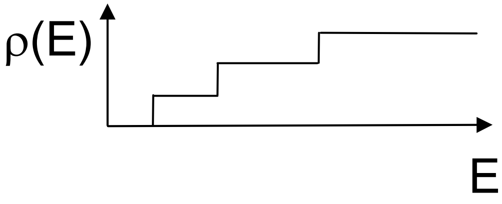
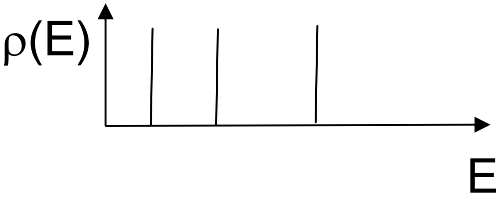
confinement in semiconductors 1) electrons





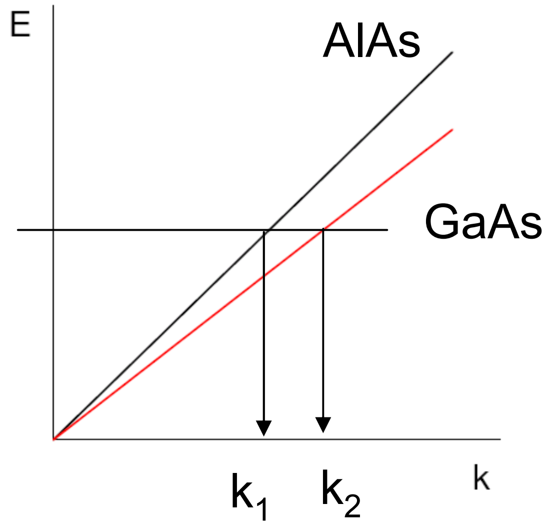




confinement
1D ➔ quantum well (1980)
2D ➔ quantum wire
3D ➔ quantum dot (1990)

➔microelectronic (2DEGFET), optoelectronic (QW laser),
quantum optics (single photon laser)

confinement in semiconductors 2) photons



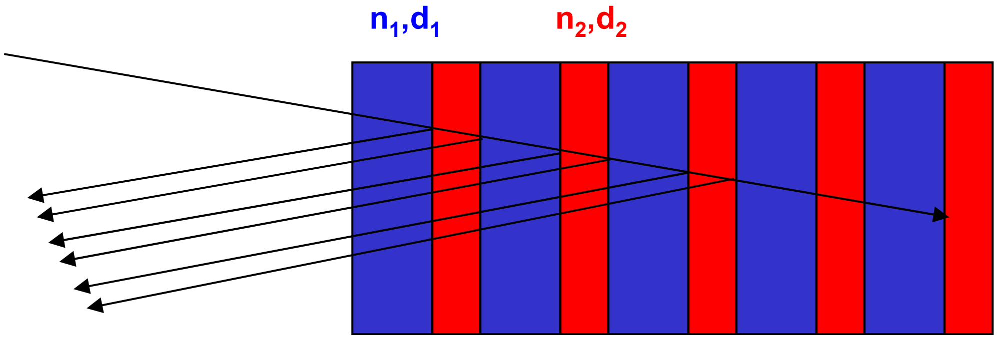
no confinement

$$R = \left| \frac{n-1}{n+1} \right|^2$$

n>>1 ➔ metallic mirror

interface multiplication + phase matching

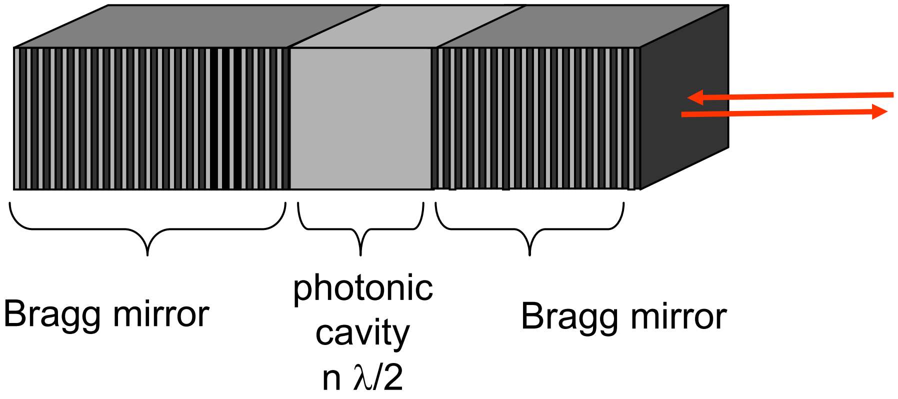
$$R = \left| \sum e^{2ik_i d_i} \frac{n_i - n_{i+1}}{n_i + n_{i+1}} \right|^2$$

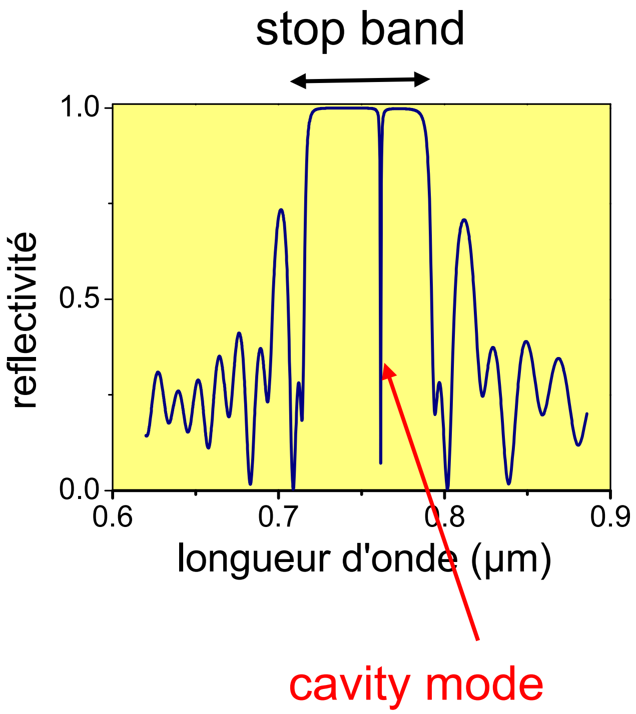


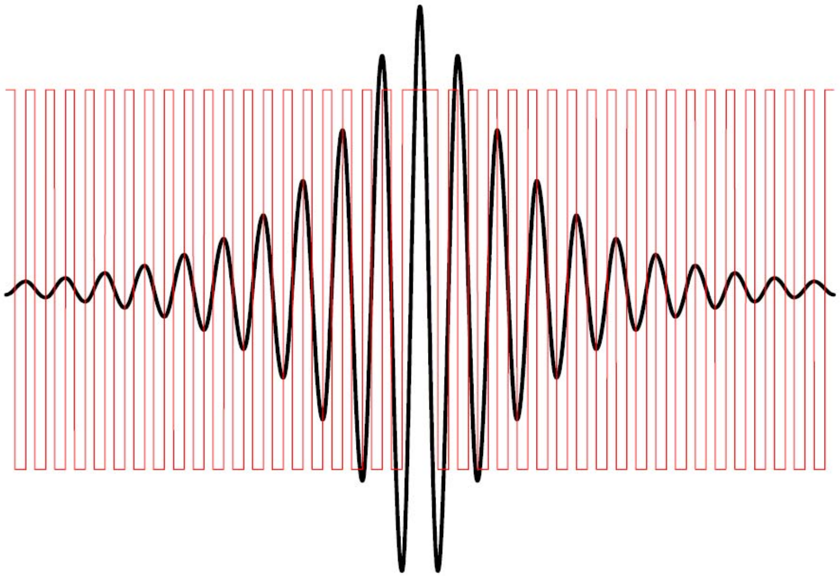
R ➔ 1, « stop band », λ/4 / λ/4

Bragg mirror

photonic microcavity





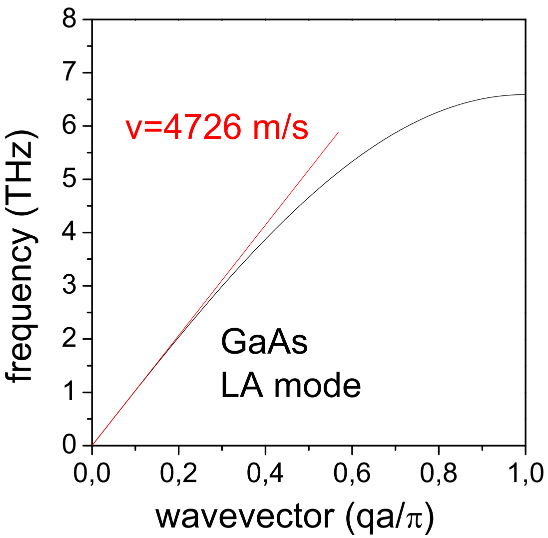


modification of the photon density of states ➔

modification of the light-matter interaction, Purcell effect

confinement in semiconductors 3) acoustic waves

photons ➔ acoustic waves: similar and different!



elastic approximation, propagation equation:

$$\rho(z)\frac{\partial^2 u}{\partial t^2} = \frac{\partial}{\partial z}\left[c(z)\frac{\partial u}{\partial z}\right]$$

$$\mathbf{v} = \sqrt{\mathbf{c}/\boldsymbol{\rho}}$$

Sound velocity in a solid : 5000 m/s

\+ acoustic frequencies : 0 < ν < a few THz

Acoustic wavelength : 5 nm at 1 THz

- no propagation in vacuum ➔ specular surface = perfect mirror
- finite lifetime (lattice anharmonicity) (strong dependence with T and ν)
- large thermal population of phonons states at room temperature
- refractive index ➔ **acoustic impedance : $Z = \rho v$**

terahertz acoustic waves: why?

1 THz ≈ 5 nm ≈ 4 meV ≈ 33 cm^{-1}

electron transport : carrier mobility at room temperature ⇔ phonons

modify the phonon density of state ?

direct vibrationnal spectroscopy : localization in glasses, quasicrystals, …

design efficient (and compatible!) sources for phonons ?

embedded nanostructures Imaging

push the diffraction limit down to a few nanometers ?

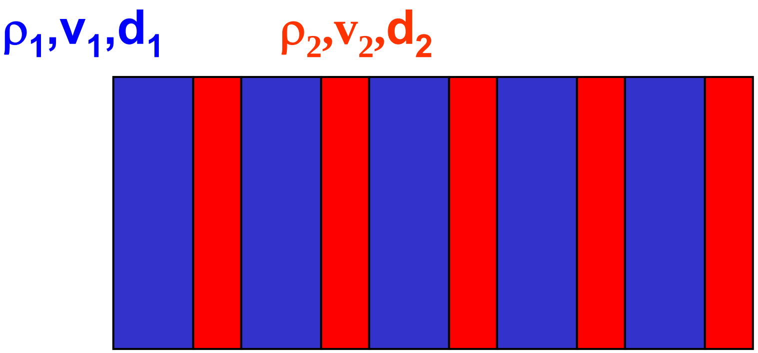
picosecond modulation of optoelectronic properties

design coherent monochromatic wavepackets sources ?

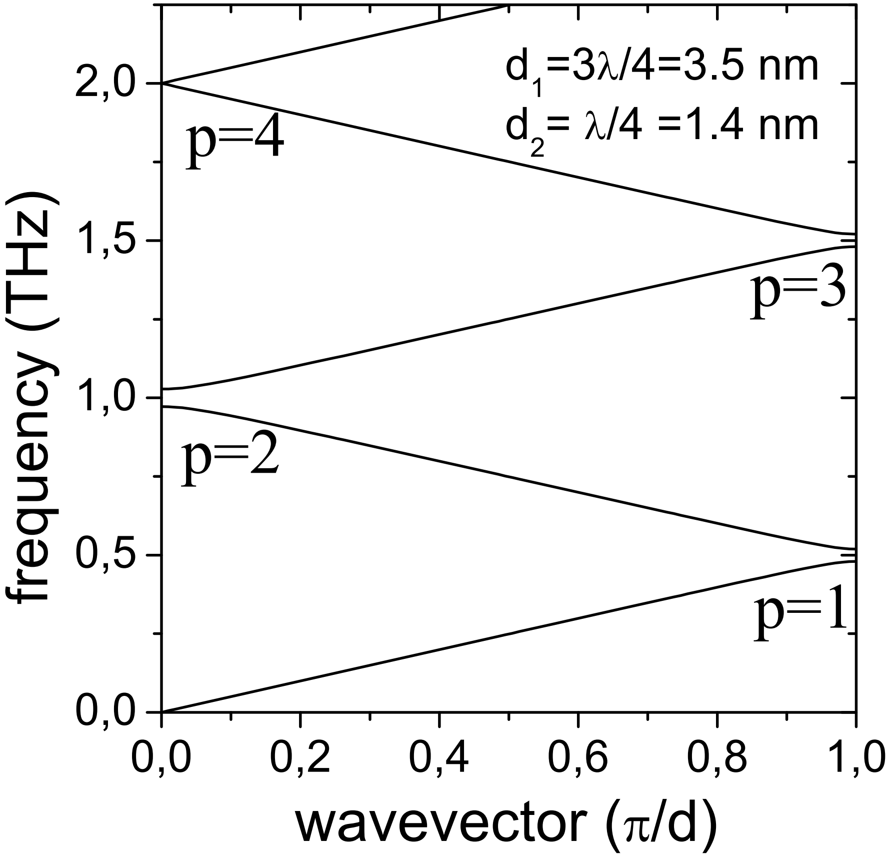
terahertz acoustic waves: how?

- multilayers
- optical transduction

acoustic phonon folding in superlattices



$$\cos qd = \cos 2\pi\nu \frac{d}{v} - \frac{\varepsilon^2}{2} \sin 2\pi\nu \frac{d_1}{v_1} \sin 2\pi\nu \frac{d_2}{v_2}$$



acoustic impedance contrast:

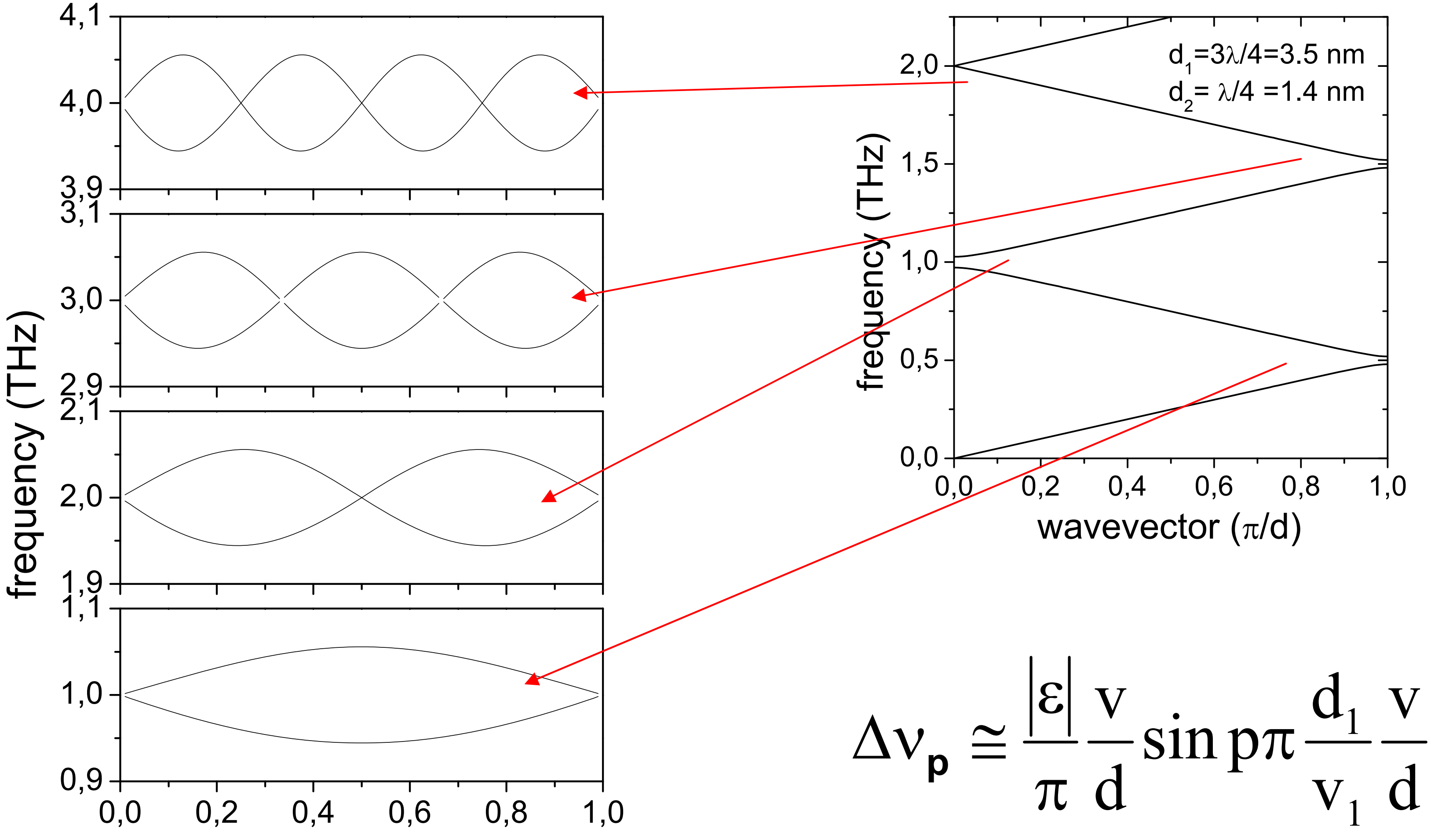
$$\boldsymbol{\varepsilon} = \frac{Z_2 - Z_1}{\sqrt{Z_1 Z_2}} \approx \mathbf{0.18}$$

Average velocity :

$$\frac{d}{v} = \frac{d_1}{v_1} + \frac{d_2}{v_2}$$

$$\nu_p = \frac{p}{2}\frac{v}{d}$$

acoustic gaps

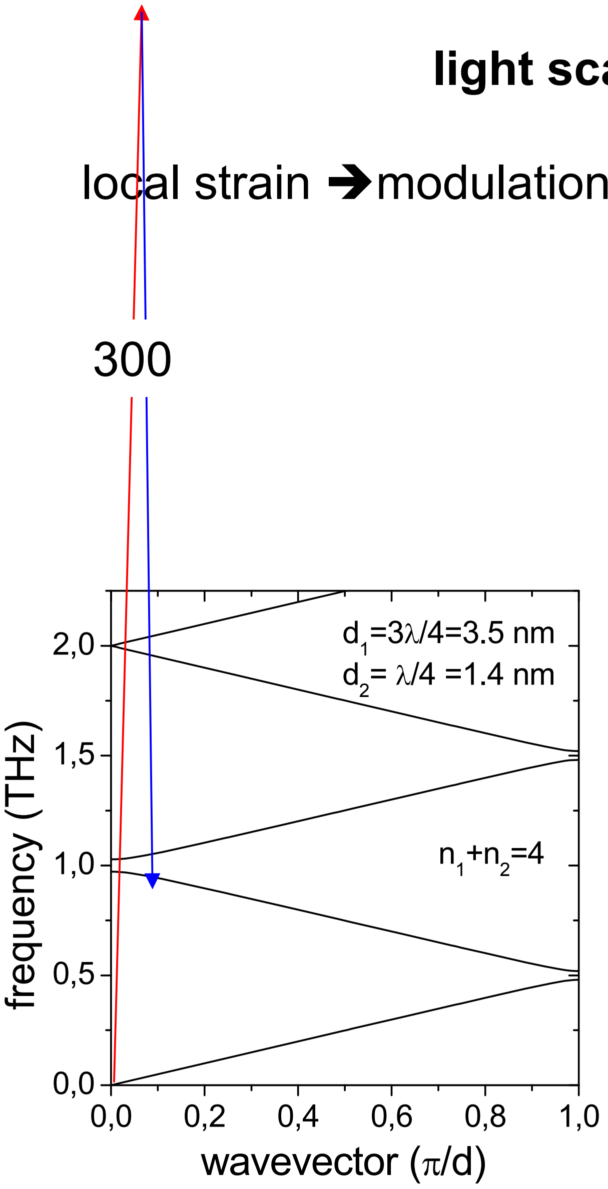


$$\Delta\nu_{\mathbf{p}} \cong \frac{|\varepsilon|}{\pi}\frac{v}{d}\sin p\pi\frac{d_1}{v_1}\frac{v}{d}$$

$$\frac{d_1}{v_1}\frac{v}{d}$$

light scattering by (folded) acoustic waves

local strain ➔modulation of the optical response at the acoustic frequencies



➔ photoelastic model

$$I \propto \left| \vec{e}_s \bullet \Pi \frac{d\vec{u}}{dz} \vec{E}_L \right|^2$$

three modulations:

photoelastic, acoustic (and optical)

$$I = |A|^2 \propto I_L \left| \int \overbrace{p(z) \frac{du}{dz}} \; e^{-i \underbrace{(k_i - k_s)} z} dz \right|^2$$

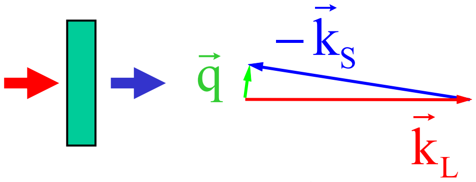
➔probe at a given wavevector q

near zone center

Raman spectroscopy

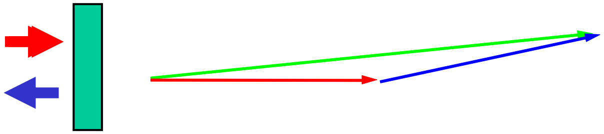
➔phonon population at thermal equilibrium

forward scattering



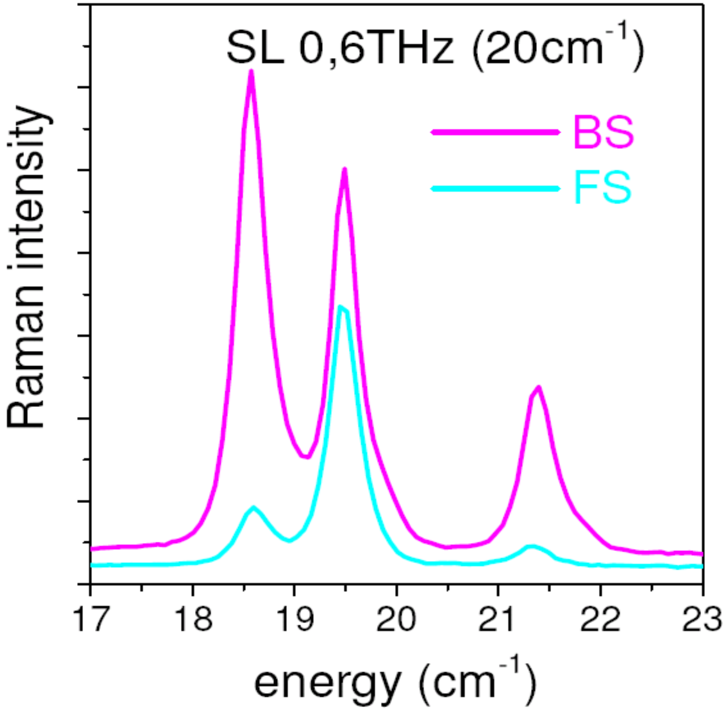
FS $\vec{\mathbf{q}} \approx 0$

backscattering



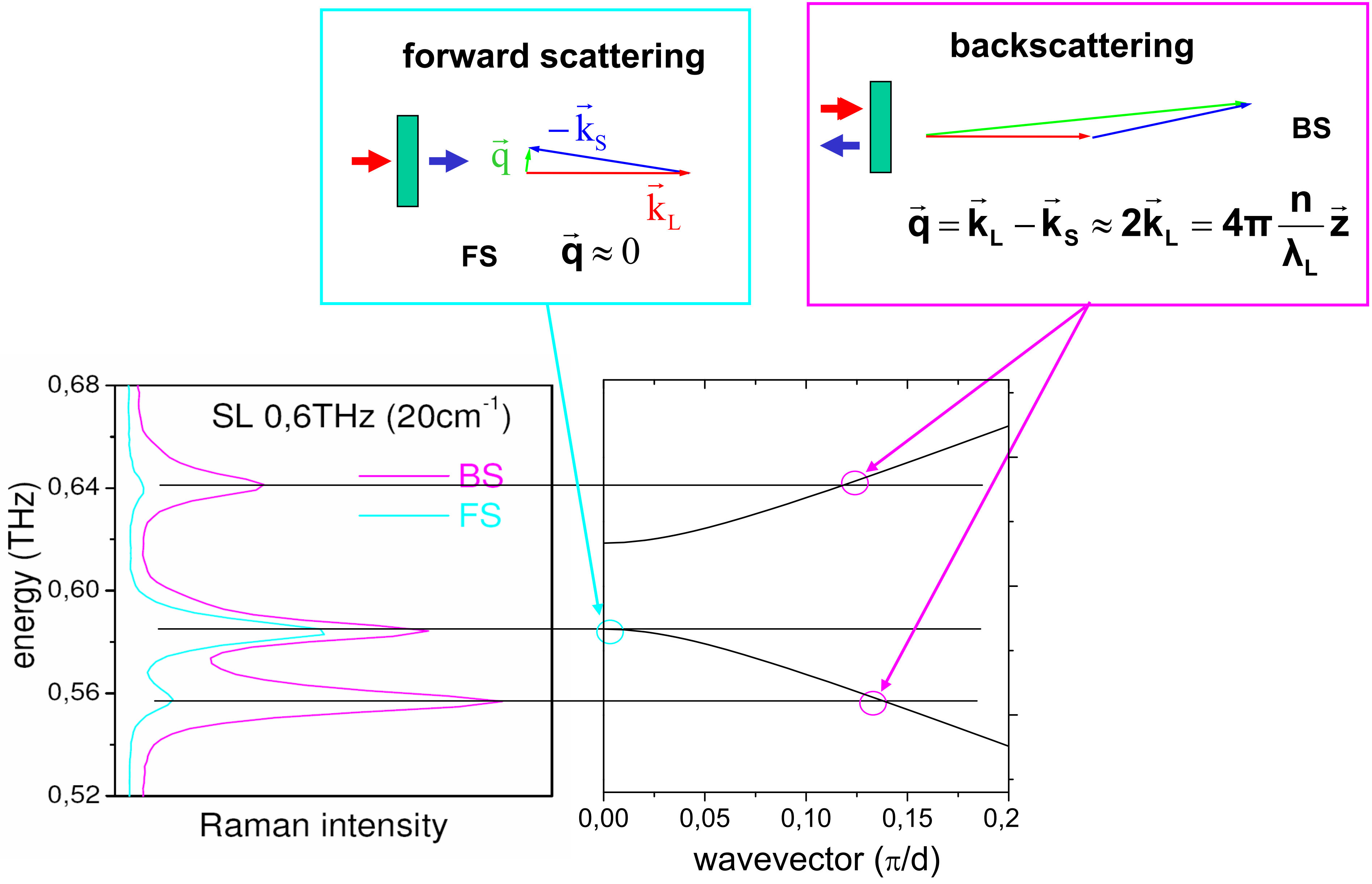
BS

$$\vec{\mathbf{q}} = \vec{\mathbf{k}}_L - \vec{\mathbf{k}}_S \approx 2\vec{\mathbf{k}}_L = 4\pi \frac{\mathbf{n}}{\boldsymbol{\lambda}_L} \vec{\mathbf{z}}$$



Raman spectroscopy

➔phonon population at thermal equilibrium



forward scattering

FS $\vec{q} \approx 0$

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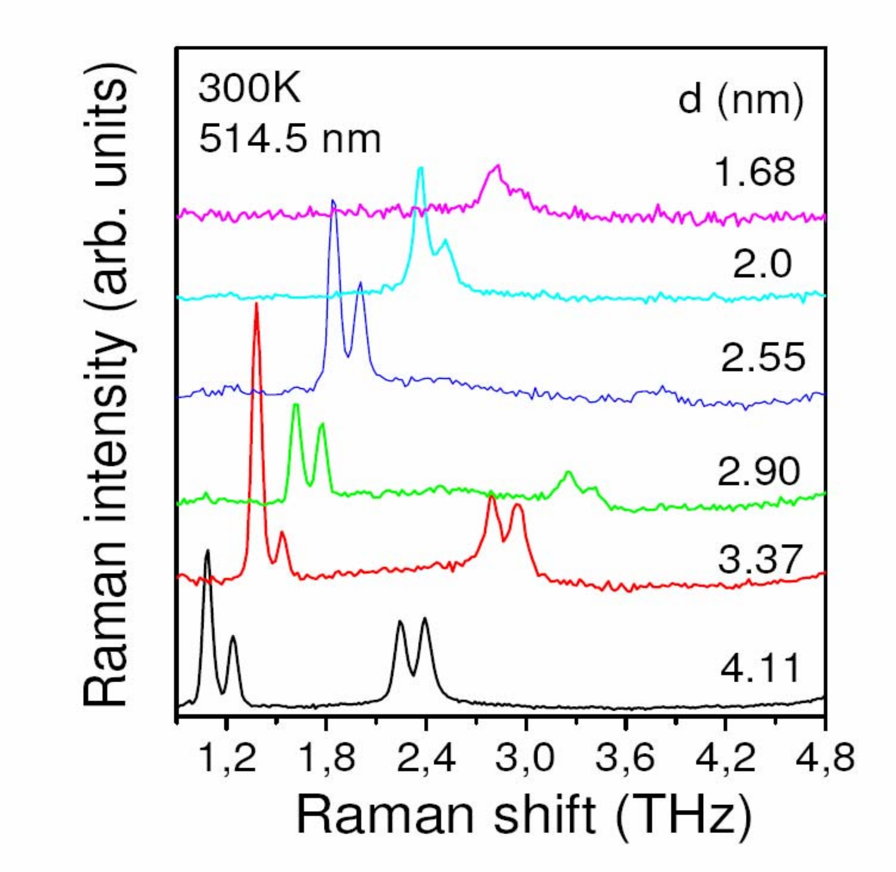
Raman spectroscopy



well defined folded modes
large acousto-optic coupling

above 2 THz

line width?
< spectral resolution

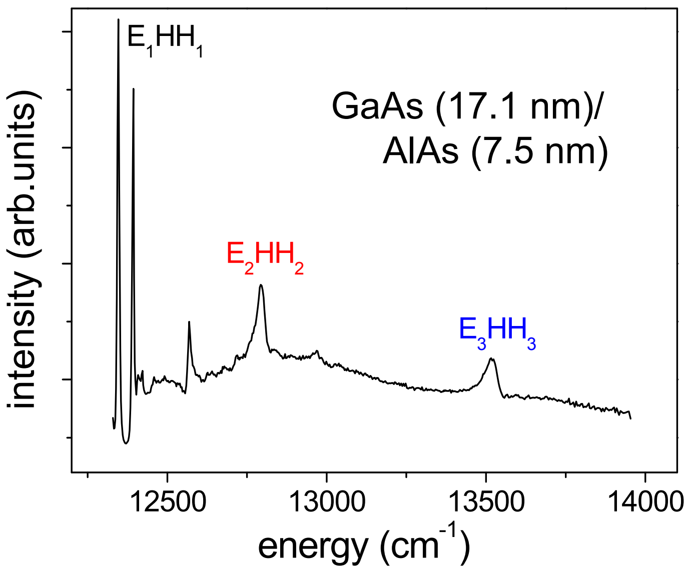
➔

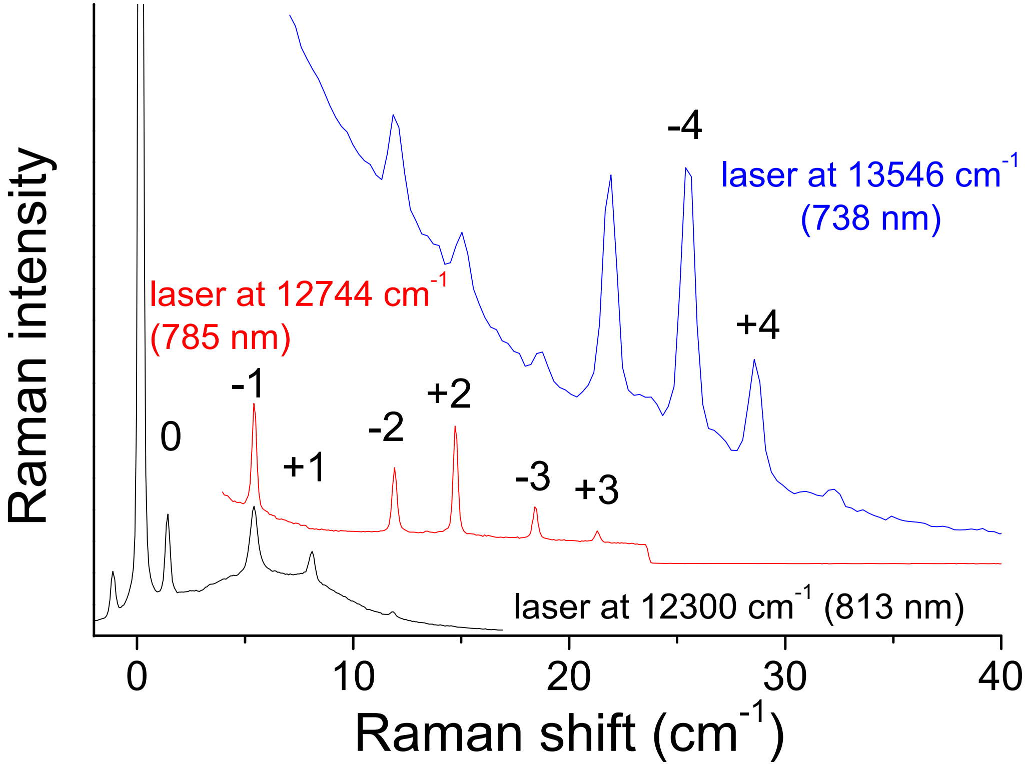
high resolution experiments

selective coupling to well defined vibrations: beyond the « photoelastic model »

$$\mathbf{I} = |\mathbf{A}|^2 \propto \mathbf{I}_L \left| \int \mathbf{p(z)} \frac{\mathbf{du}}{\mathbf{dz}} \; \mathbf{e}^{-i\,(k_i - k_s)\,z} \mathbf{dz} \right|^2$$

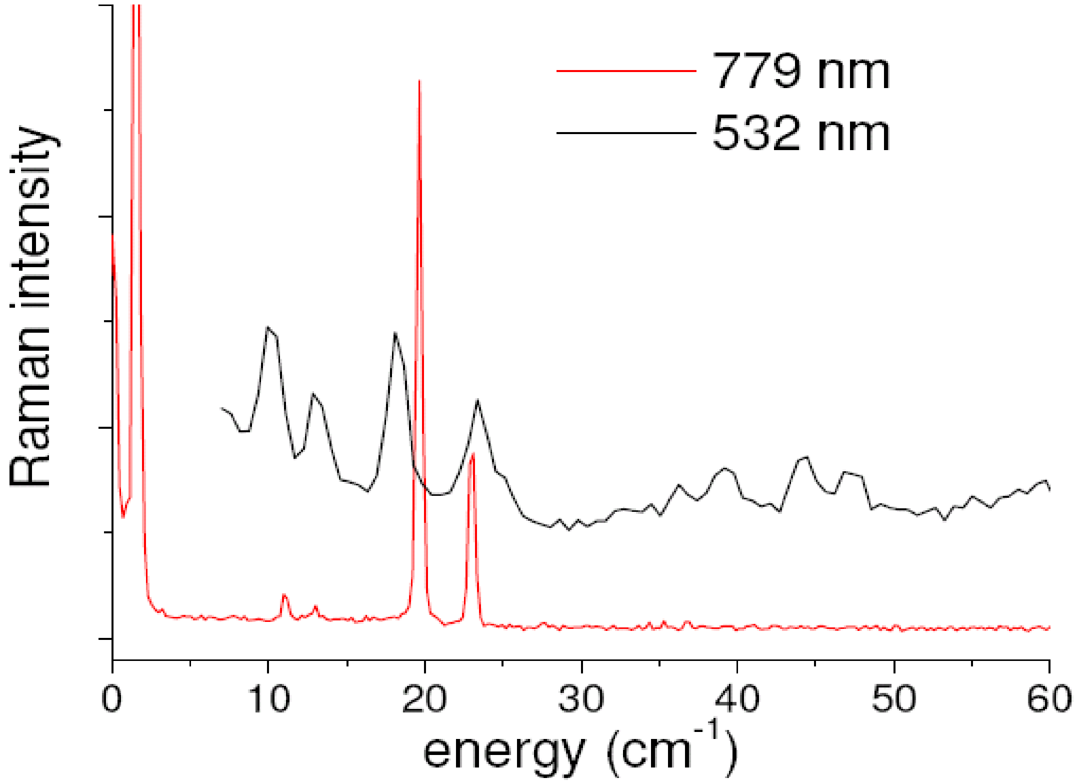
p_1 and p_2 in GaAs and AlAs





acoustooptic ingeneering with electronic resonances selective coupling to well defined vibrations

(311(orientation: compressive wave (LA) + shear waves (TA)



selective resonances ?

a few perspectives

vibrationnal spectroscopy

- **acoustic attenuation at 1 THz in GaAs:**
  mechanisms? temperature dependence?

- **other solids**

compatibility with periodic transducers?

- **direct detection of phonons emission in nanostructures**

coherence? phonon amplification, stimulated emission, SASER?

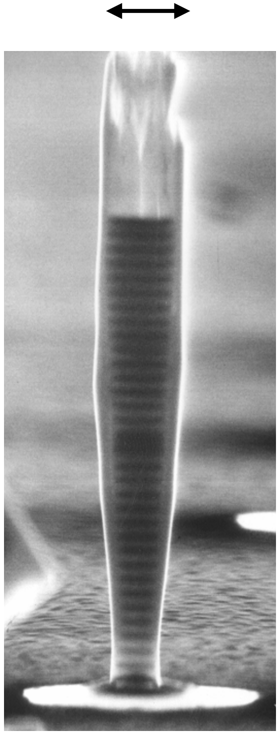
picosecond modulation in nanostructures (excitons) by coherent acoustic pulses

modification of phonon density of state ➔ «acoustic Purcell effect »
3D confinement : 10 nm! phononic crystals?
periodically modulated nanowires ?

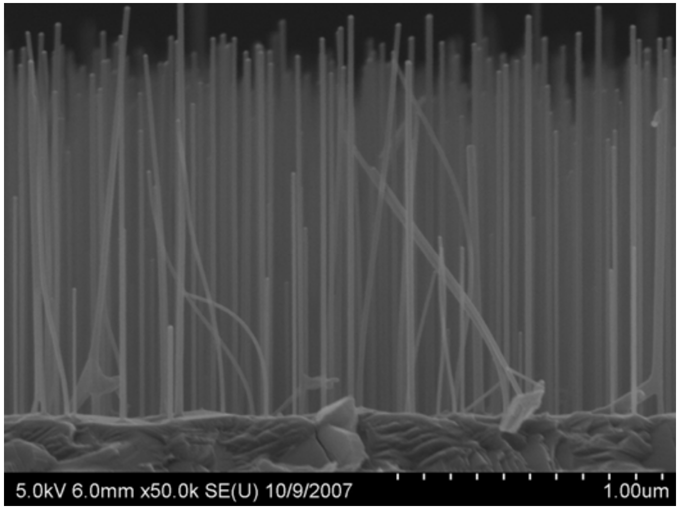
towards 3-dimensionnal confinement of phonons
➔ strong modification of phonon density

microcavity
+ etching of micropillars

1 µm



Selective growth of nanowires:
InAs
$L_{moy} = 1.5$ µm
$\varnothing_{moy} = 15$ nm



+ acoustic modulation along the wires???