Espectroscopia ótica e a aplicação de ondas acústicas de superfície

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Outline

Introdução

- Espectroscopia ótica de nanoestruturas semicondutoras
- Resultados
- Ondas acústicas de superfície (SAW)
  - Transporte induzido acusticamente
    - ✓ Portadores (elétrons e buracos)
    - ✓ Spins
    - ✓ Injeção de portadores
    - ✓ Fonte de fótons únicos bombeada acusticamente
  - Perspectivas

Conclusão

Going smaller...

Miniaturization of structures

Transition from micro to nano

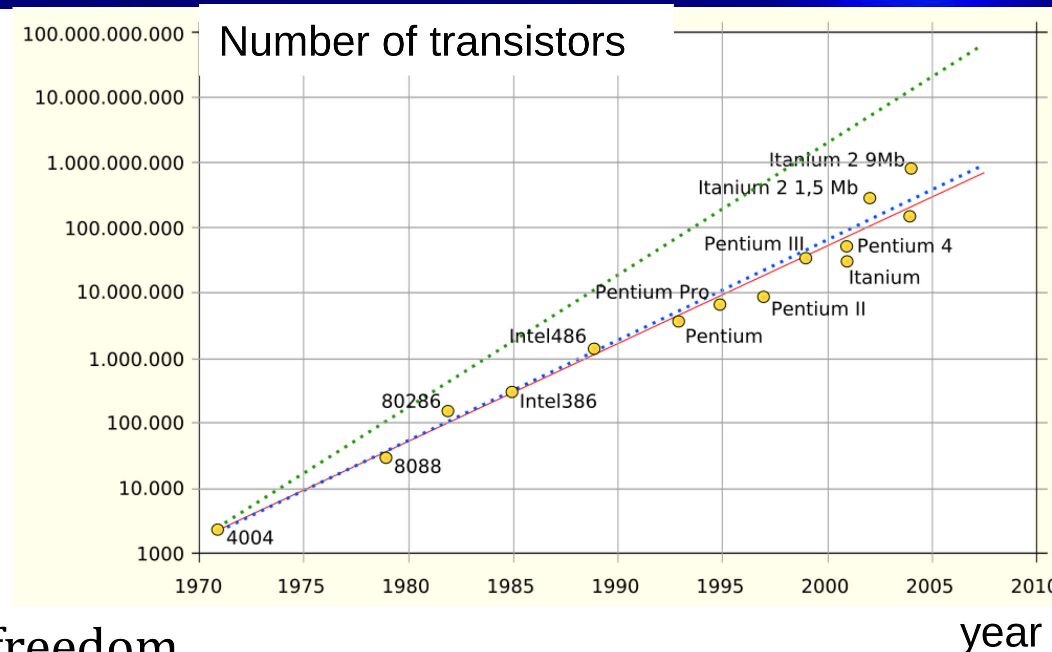
✓ 1nm = 10^{-9} m

✓ Size of an atom ~ 0.1 nm = Å

✓ Few number of atoms

✓ Nano „world“ ~ Quantum „world“

- ✓ Manipulation of quantum degrees of freedom
  - ✓ Spin – spintronics
  - ✓ Photon – (nano)photonics
  - ✓ Phonon – phononics … and so on and so forth



Physical properties depend strongly

✓ Particle number

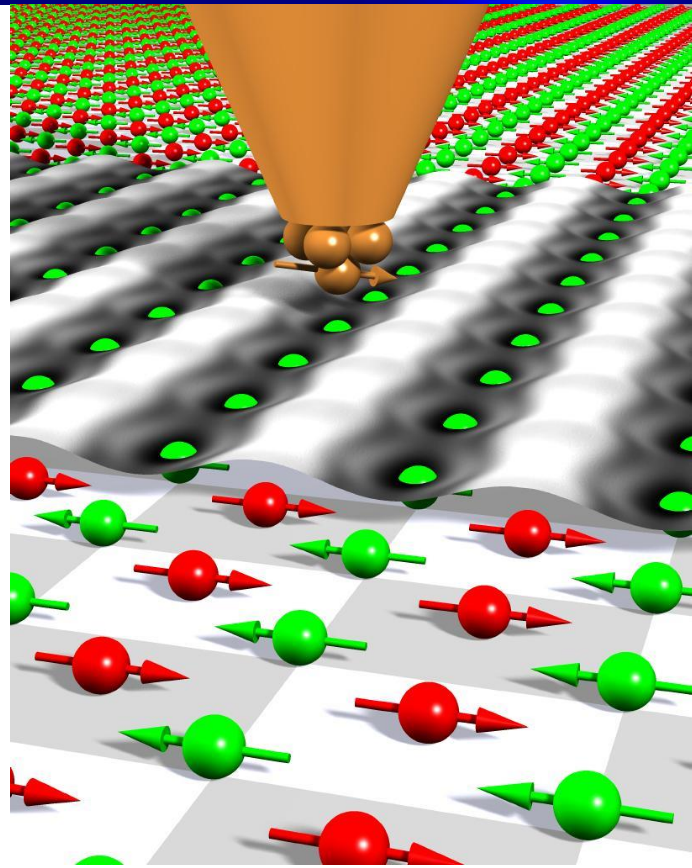
✓ Dimensionality (3D, 2D, 1D, 0D)

⇨ **New funcionalities in comparison to „classical“ devices**

Going more powerful...

For probing nanoscale structures

- ✓ Detection/manipulation have to be modified
  - ✓ Become smaller
  - ✓ More precise
    - ✓ Space, energy, time selectivity

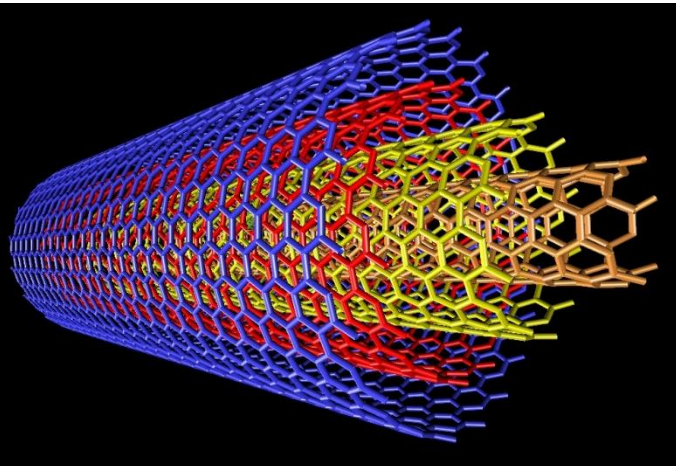


New experimental techniques

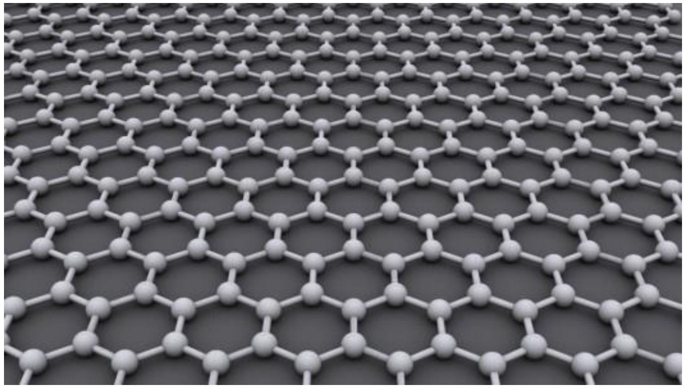
- ✓ Sensitive to
  - ✓ Number of particles
  - ✓ Specific interactions
  - → Quantum information processing

The systems

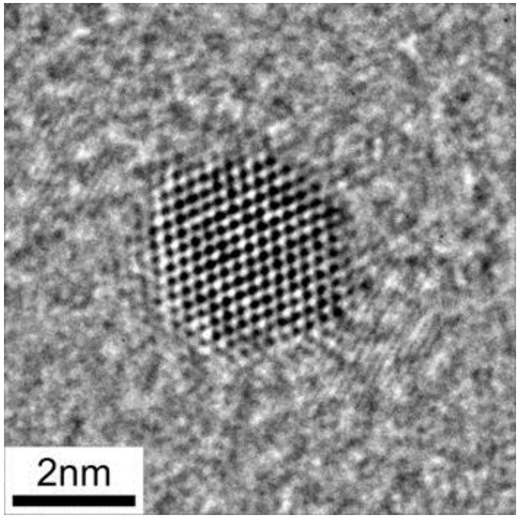
Carbon nanotubes



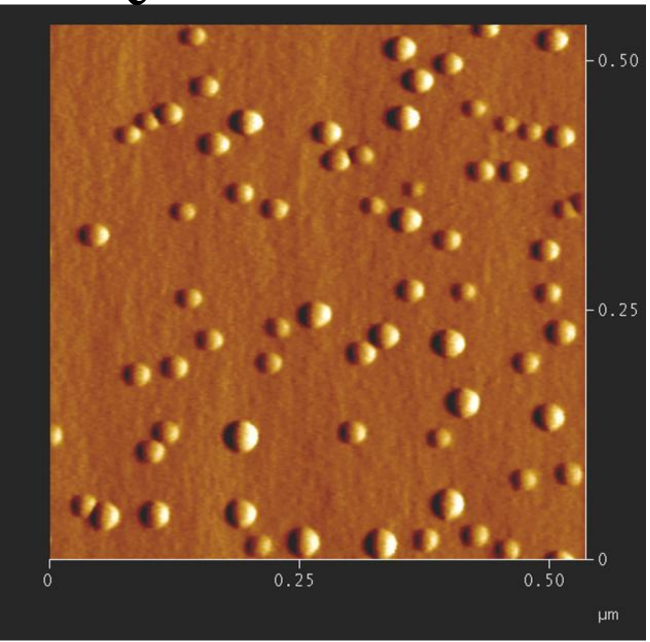
Graphene



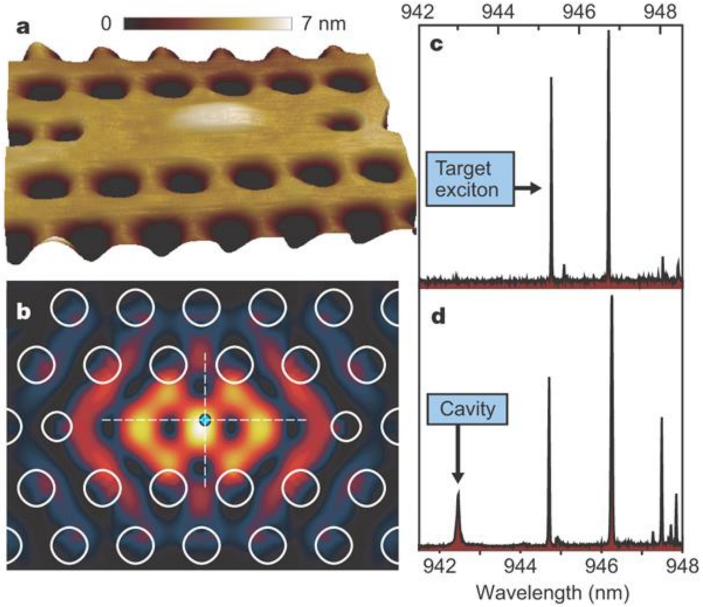
Magnetic nanoparticles



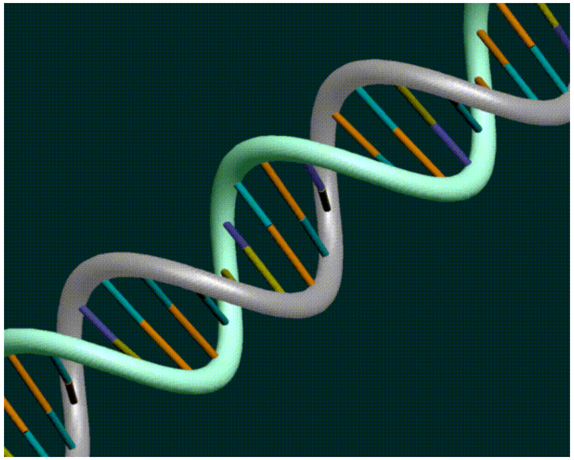
Quantum dots



Photonic crystals



DNA



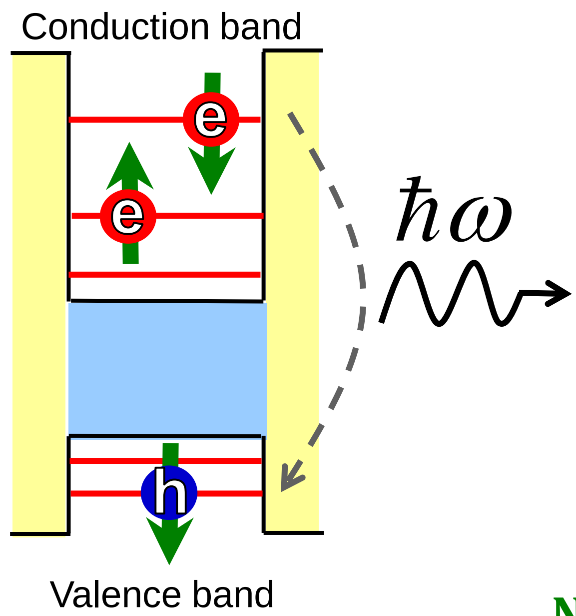
In this talk

Semiconductor nanostructures

Confinement

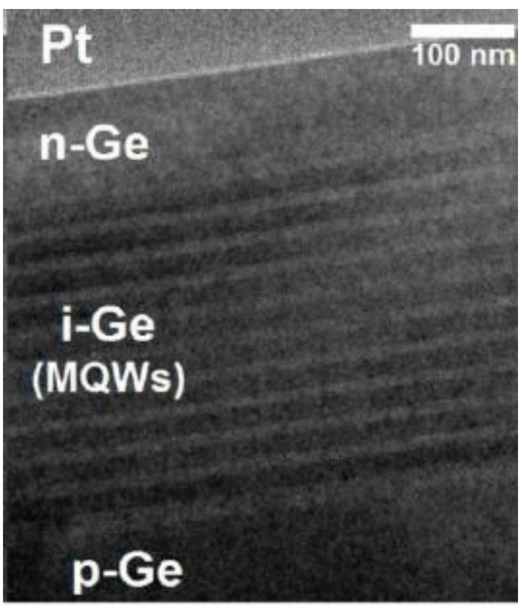
<u>Energy quantization</u>

- Quantum wells → (2D)
- Nanowires → (1D)
- Quantum dots → (0D)

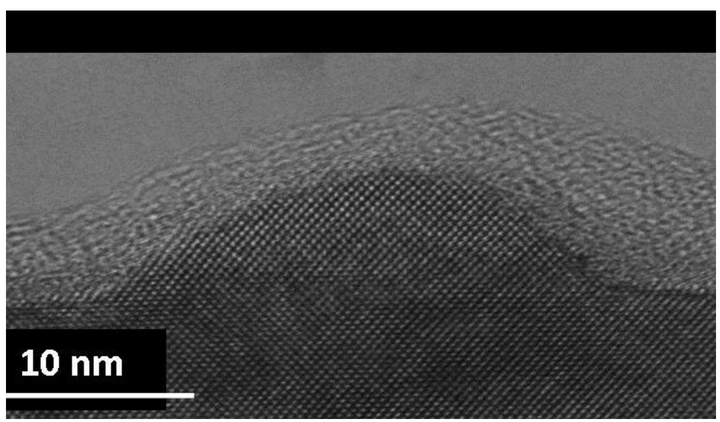


Light emission
↓
Information about quantum states

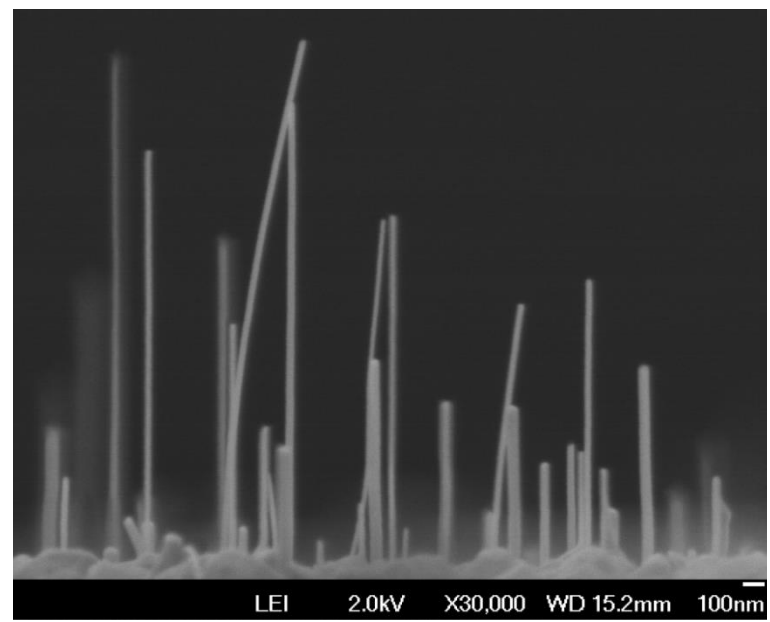
Quantum well (QW)



Quantum dot (QD)



Nanowire (NW)



Espectroscopia Ótica

How do we probe the nanostructure energy states?

⇩

Optical spectroscopy techniques

Excitação ótica (laser) ➔ **Sistema de interesse** (amostra) ➔ **Detecção ótica** (intensidade, energia, polarização, tempo, espaço,...)

⇩

Técnicas mais usadas em nosso laboratório

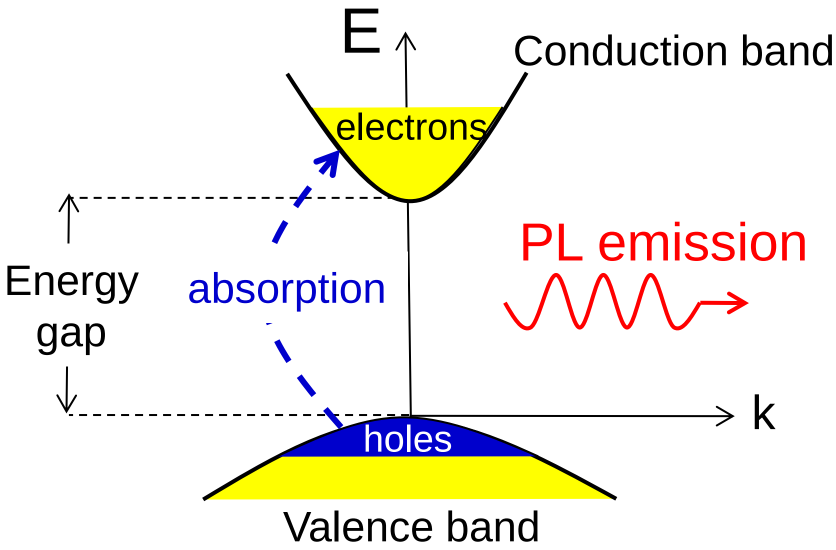
Fotoluminescência

- ✓ Excitação ótica inter ou intra-banda
- ✓ Detecção da recombinação de portadores
- ✓ Informação sobre os níveis de energia
- ✓ Dinâmica de portadores

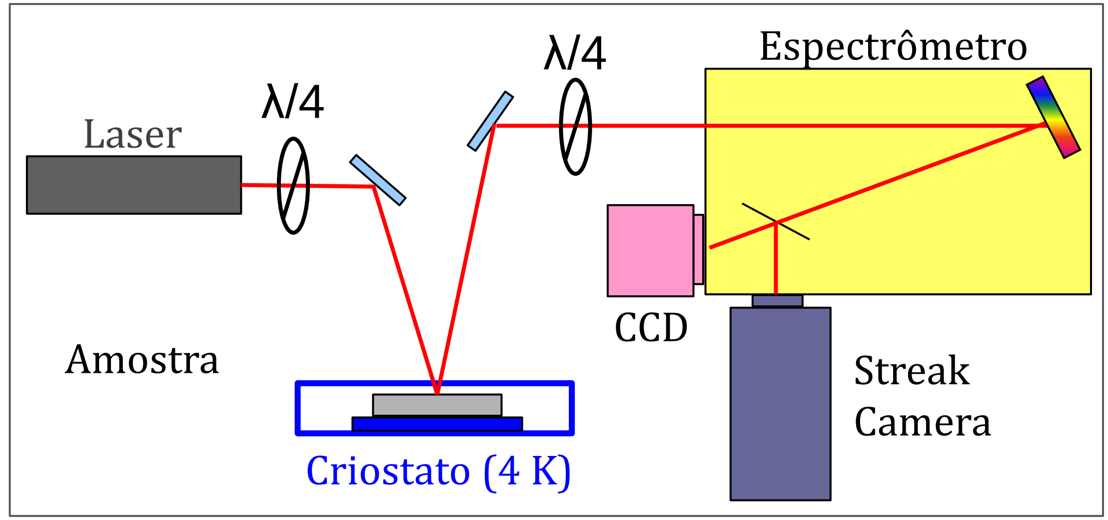
Espalhamento Raman

- ✓ Stoke e anti-Stoke shift
- ✓ Modos de vibração da rede
- ✓ Dispersão de fônons
- ✓ Interação com fônons

Fotoluminescência PL



Simplificadamente



Semiconductor nanostructures

✓Laser excitation → Light absorption

✓ Electrons excited to the conduction band

✓ Electron-hole recombination

  ✓ Light emission→Photoluminescence (PL)

  ✓ Mapping of the energy states

Espectrômetro

- Resolução em energia

Camera CCD

- Intensidade da emissão e resolução espacial

Streak Camera

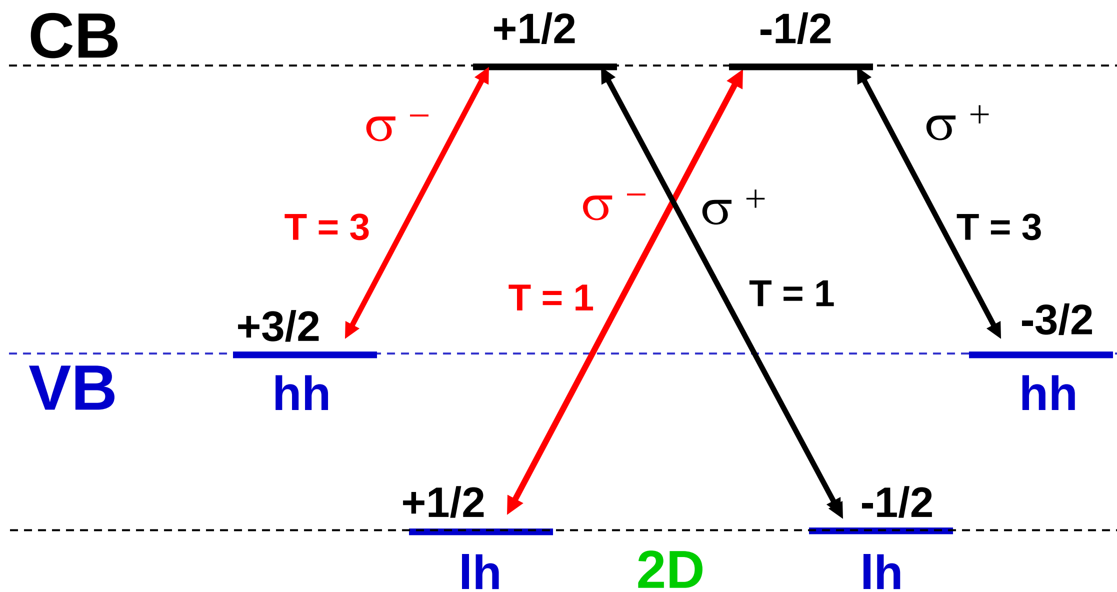
- Resolução temporal (~2ps)

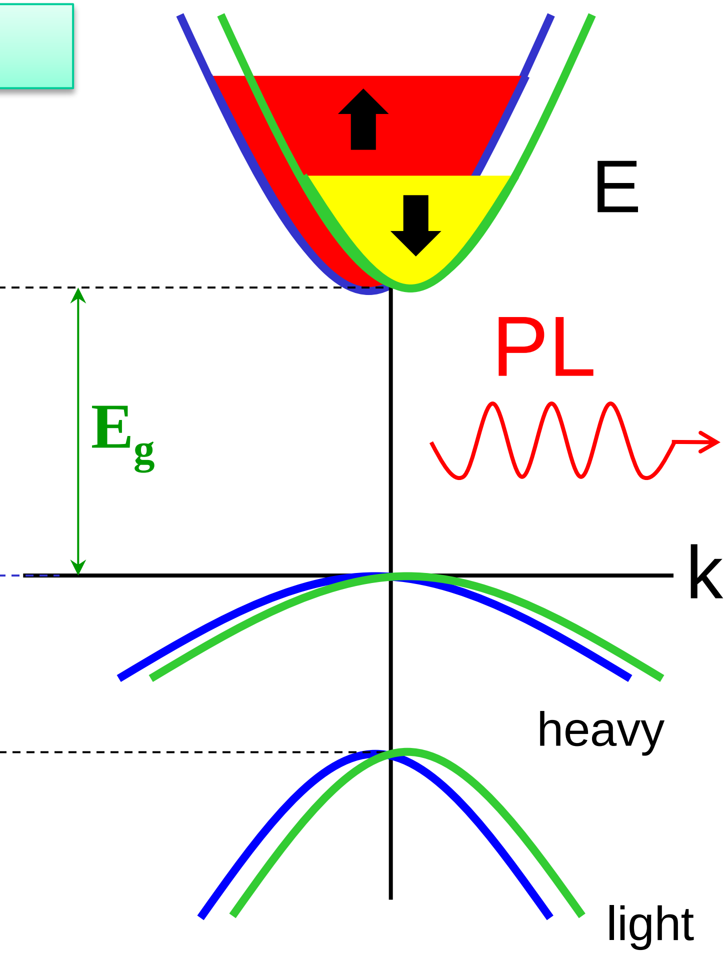
Ótica de polarização

- Elicidade da luz (dinâmica de spins)

Optical orientation

How do we know what is the electron spin?





Angular momentum conservation

- Absorbed light has well-defined angular momentum σ^-
- N (s = ½) > N (s = - ½) in the CB
  - ✓ **PL is polarized**

$$\rho_z = \frac{I_+ - I_-}{I_+ + I_-}$$

Time scales

After relaxation to the bottom of CB

Electron dynamics

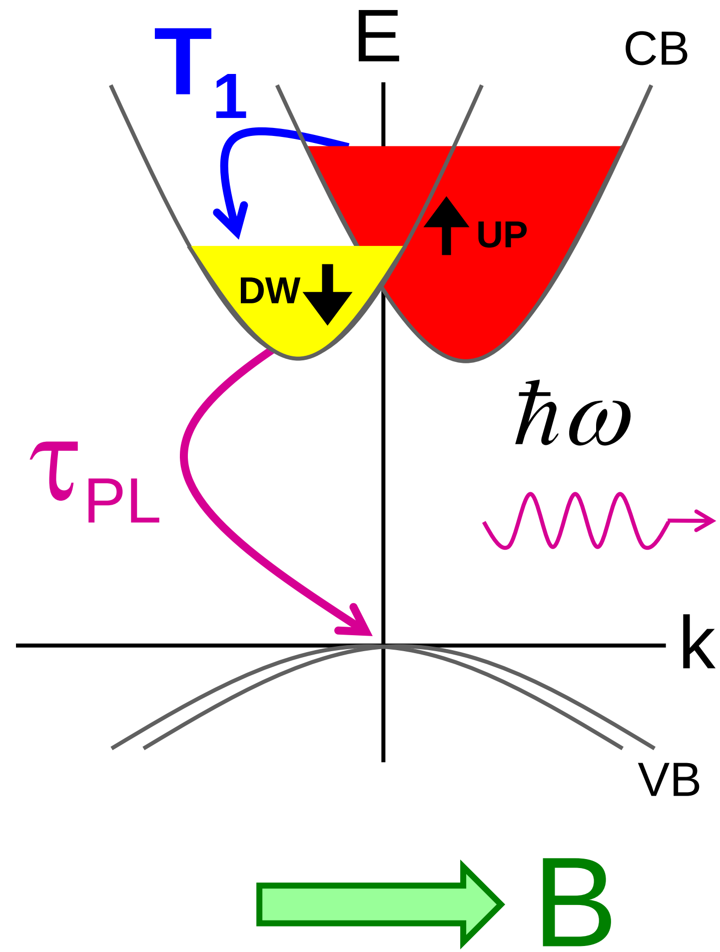
- ✓ Carrier lifetime → τ_{PL}
- ✓ Spin relaxation time → T_1

If there is a transverse magnetic field

- ✓ Spin decoherence time → $T_2 > T_2^*$

Spin lifetime

$$\frac{1}{\tau_s} = \frac{1}{T_1} + \frac{1}{T_2^*}$$



Challenges

Munhoz et. al., PRB 51, 4247 (1995)

Under equilibrium conditions

✓ Free carriers and spins average to zero (unlike Ferromagnetic metals!)

Out of equilibrium → ρ_c , $\rho_s \neq 0$

Strong interaction with the enviroment

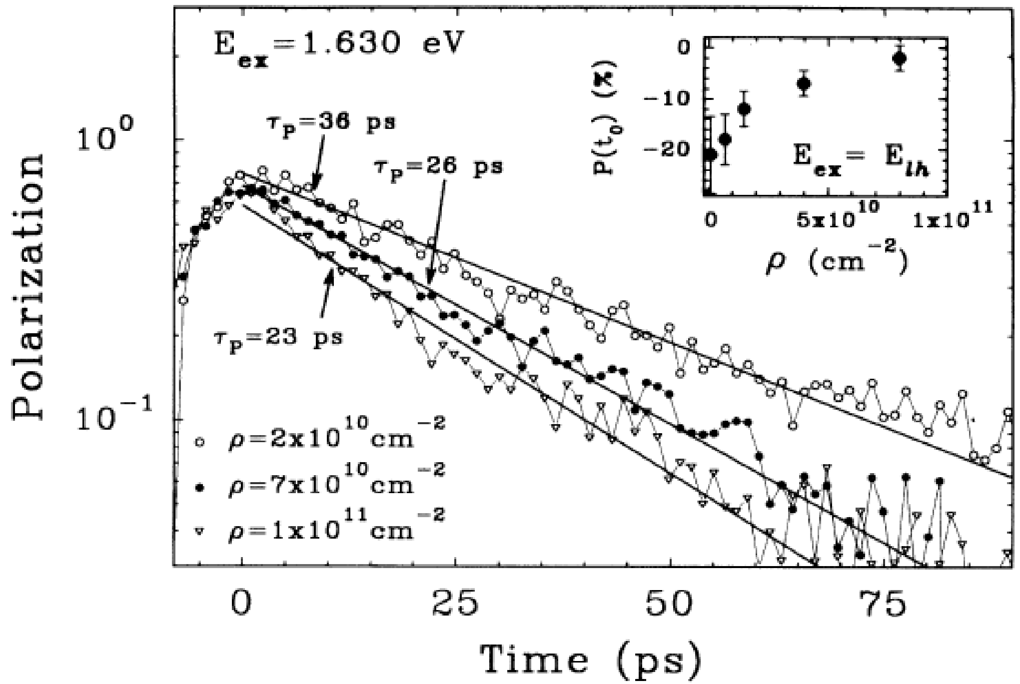
✓ Other atoms (crystal lattice)

✓ Impurities

✓ Temperature (phonons)

⇩

Relaxation



For semiconductor QWs

$$\tau_{PL} \rightarrow 1 \text{ ns}$$

$$T_1 \leq \tau_{PL}$$

$$T_2 \leq T_1$$

But it depends on the system!

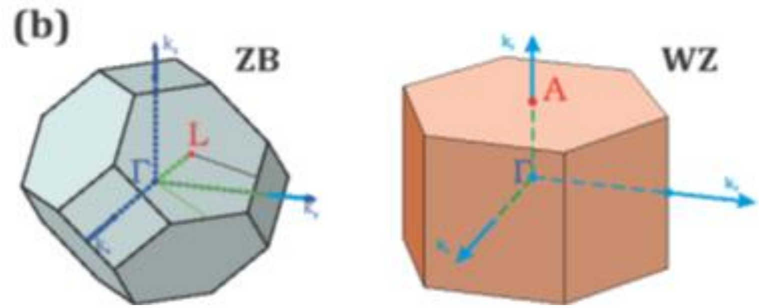
Information process

- Understand carrier/spin dynamics
  - Enhance lifetimes
  - Manipulate particle number/charge/spin
  - Tune energy states
  - Increase temperature ???

Alguns sistemas investigados no Grupo de Propriedades Óticas (GPO)

Nanofios semicondutores

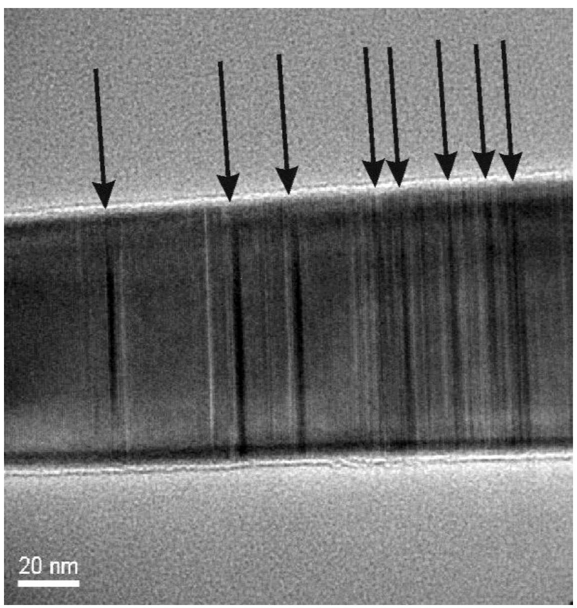
- ✓ Novo tipo de estrutura
- ✓ Novas propriedades estruturais e cristalinas
- ✓ Possíveis aplicações (emissores de luz, sistemas fotovoltaicos)

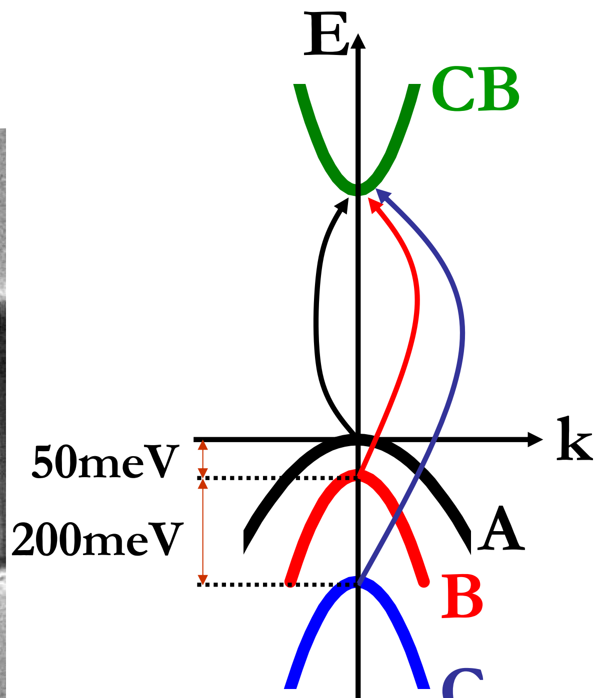


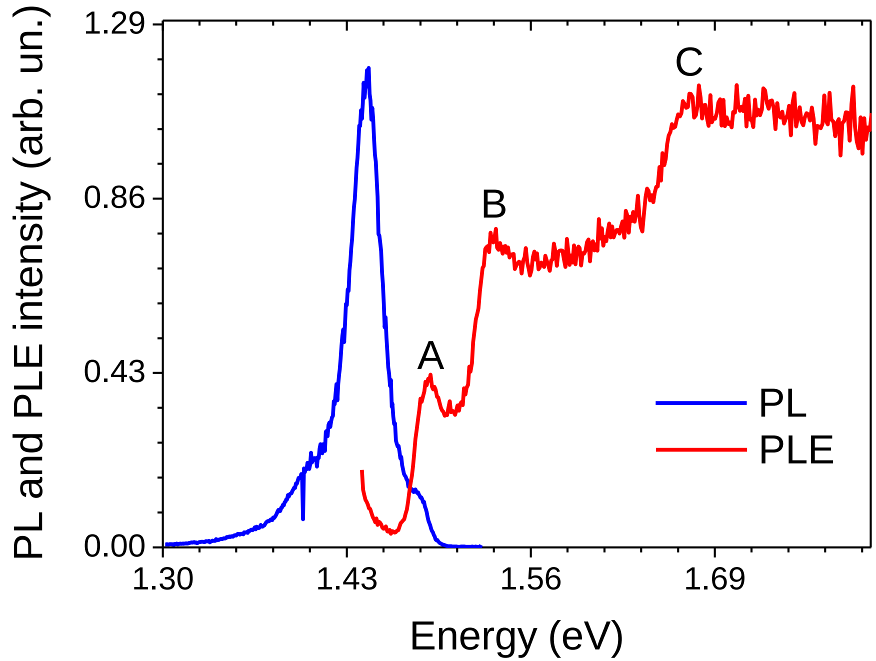
Nanofios de InP (colaboração Profa. M. A. Cotta)

- ✓ Estrutura cristalina → **Wurtzita**

TEM Nanofio de InP





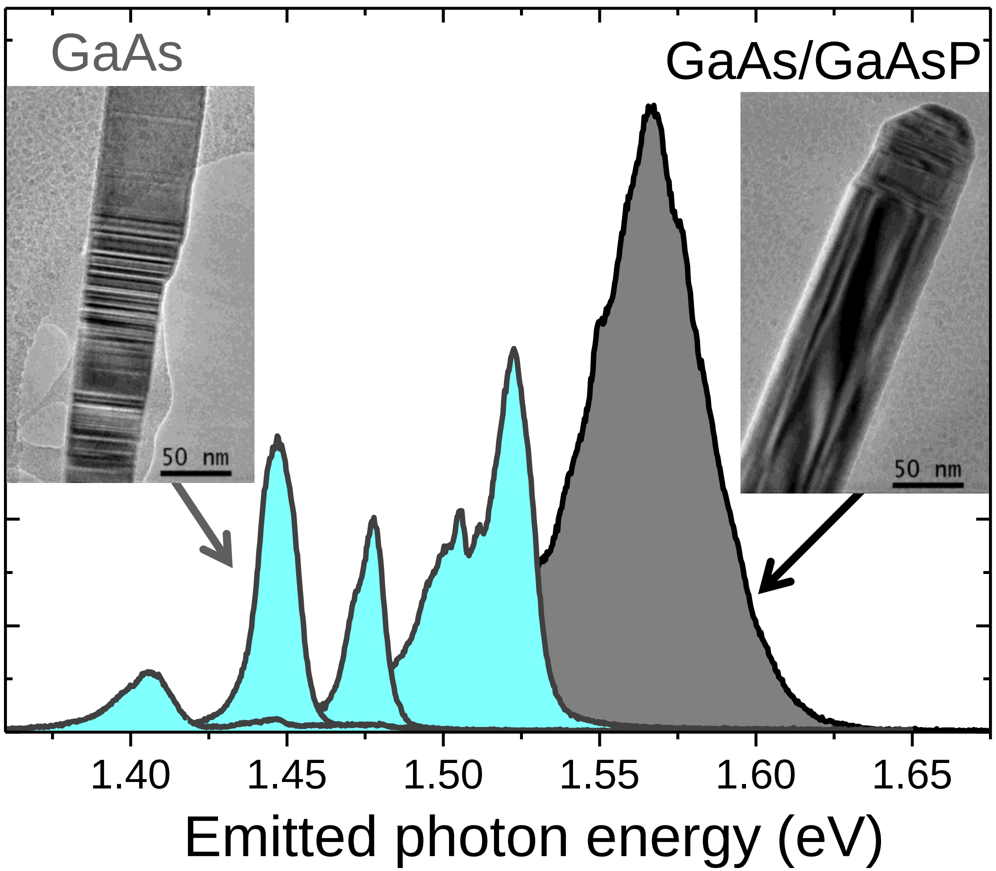


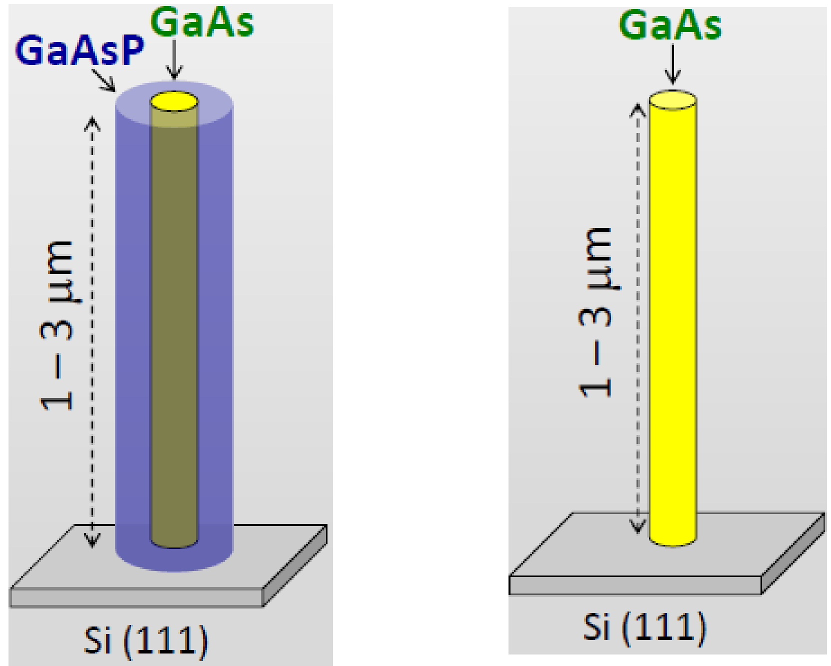
E. A. Gadret *et. al*, *Phys. Rev. B*, **82**, 125327 (2010)

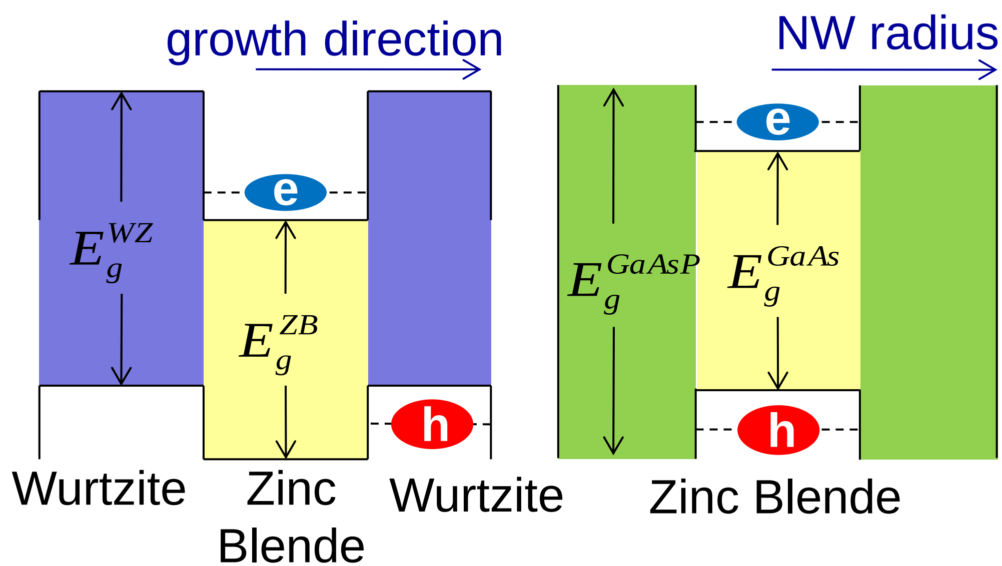
Nanofios semicondutores

Nanofios de GaAs/AlGaAs

- ✓ Core/shell
- ✓ Alta emissão e baixo nível de defeitos de superfície





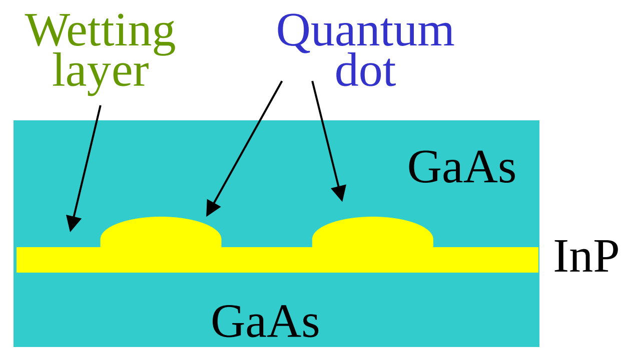


Couto Jr. *et. al*, *Nano Lett.*, **12**, 5269 (2012)

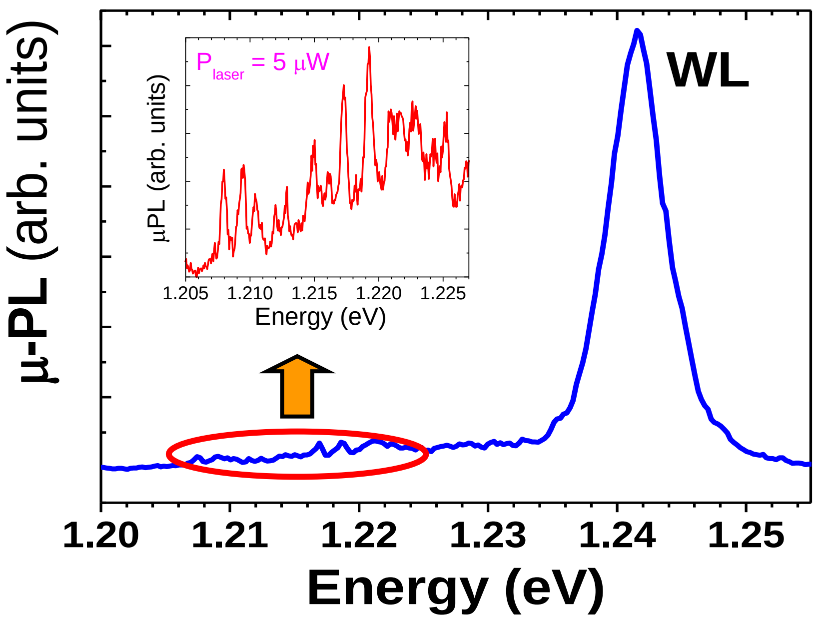
Pontos quânticos

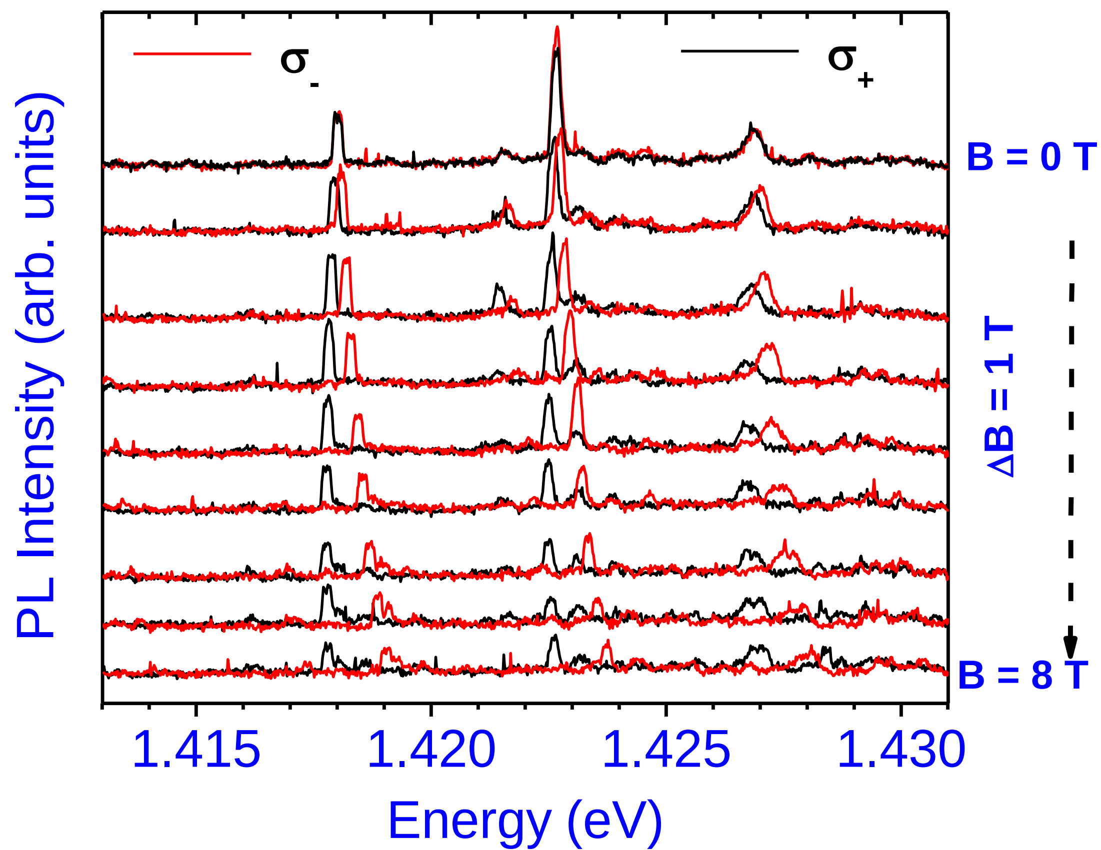
InP/GaAs

- ✓ Estudo de pontos quânticos individuais
- ✓ Medidas μ-PL com campo magnéticos DC
- ✓ Alinhamento tipo II
- ✓ Estudo da interação elétron-burado



$$E_{\pm} = E_0 \pm \frac{1}{2} g_x \mu_B B + \alpha_d B^2$$

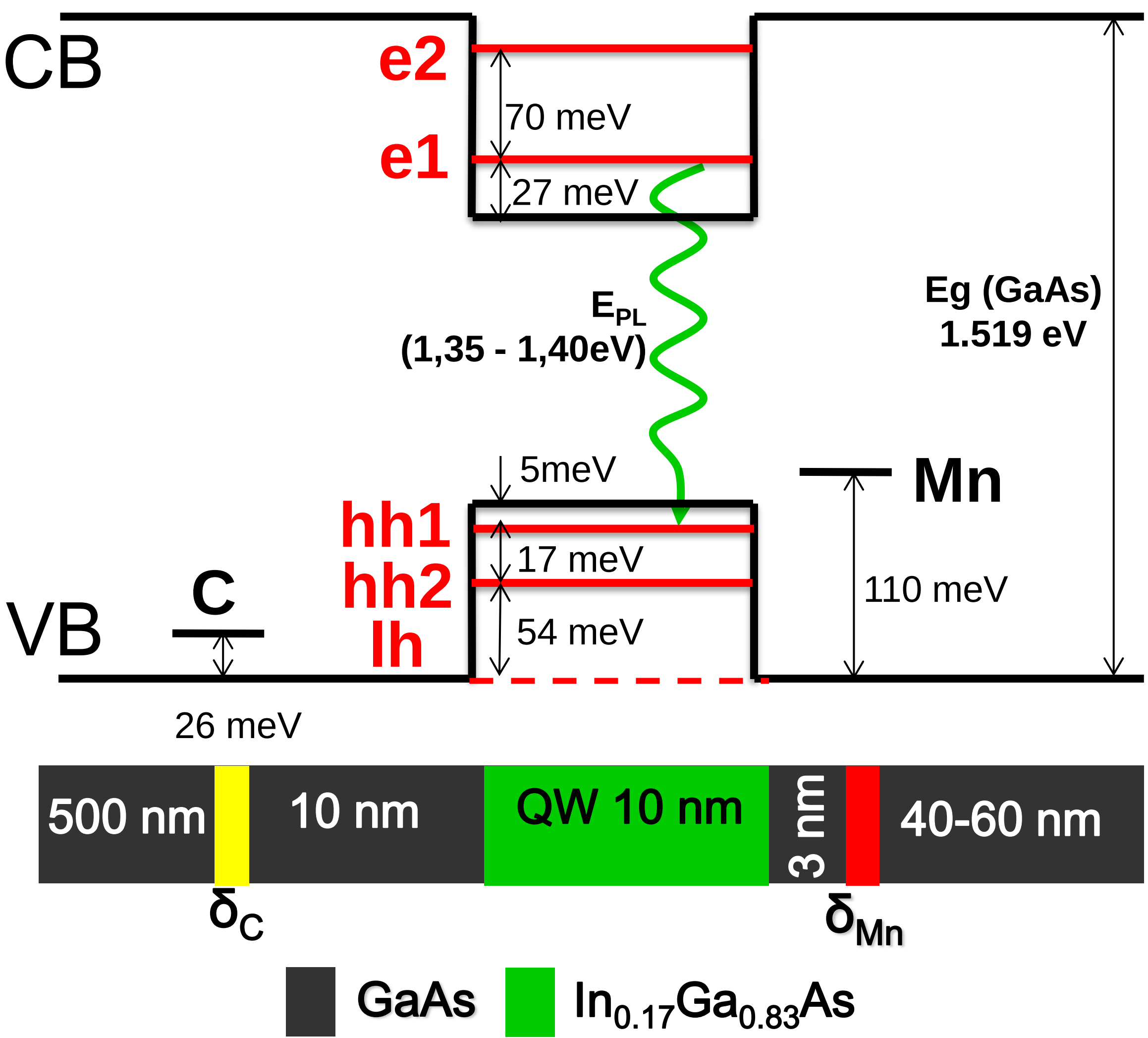


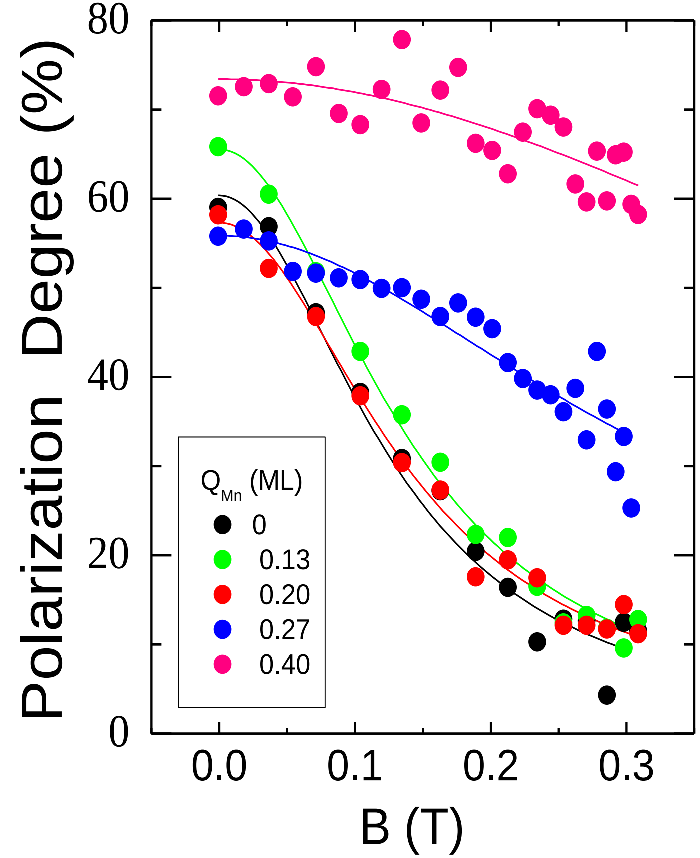


de Godoy *et. al*, *PRB*, **73**, 033309 (2006)

Semicondutores magnéticos

- ✓ Implantação de Mn em GaAs
- ✓ Interação com poço quântico de InGaAs
  - ✓ Diminuição no tempo de vida de spins





Gazoto *et. al*, *APL*, **98**, 251901 (2011)

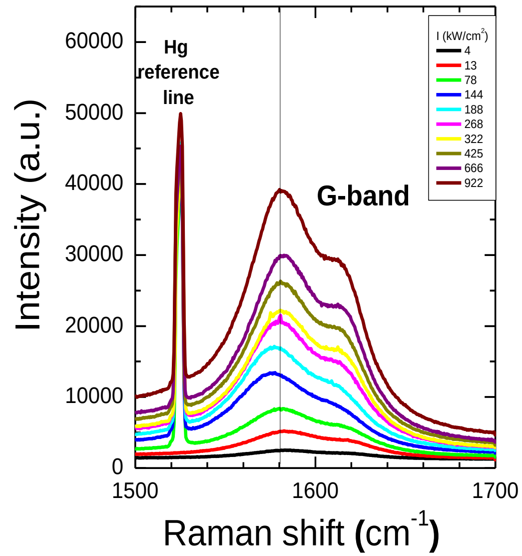
Nanotubos de carbono

Espalhamento Raman

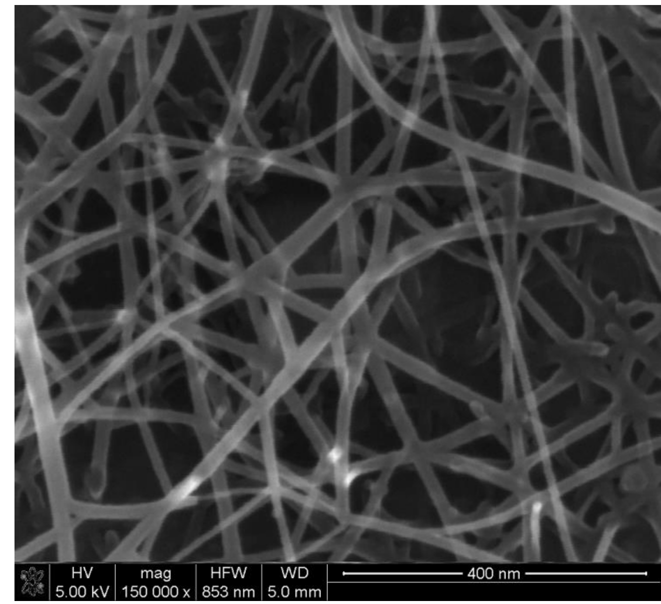
Nanotubos

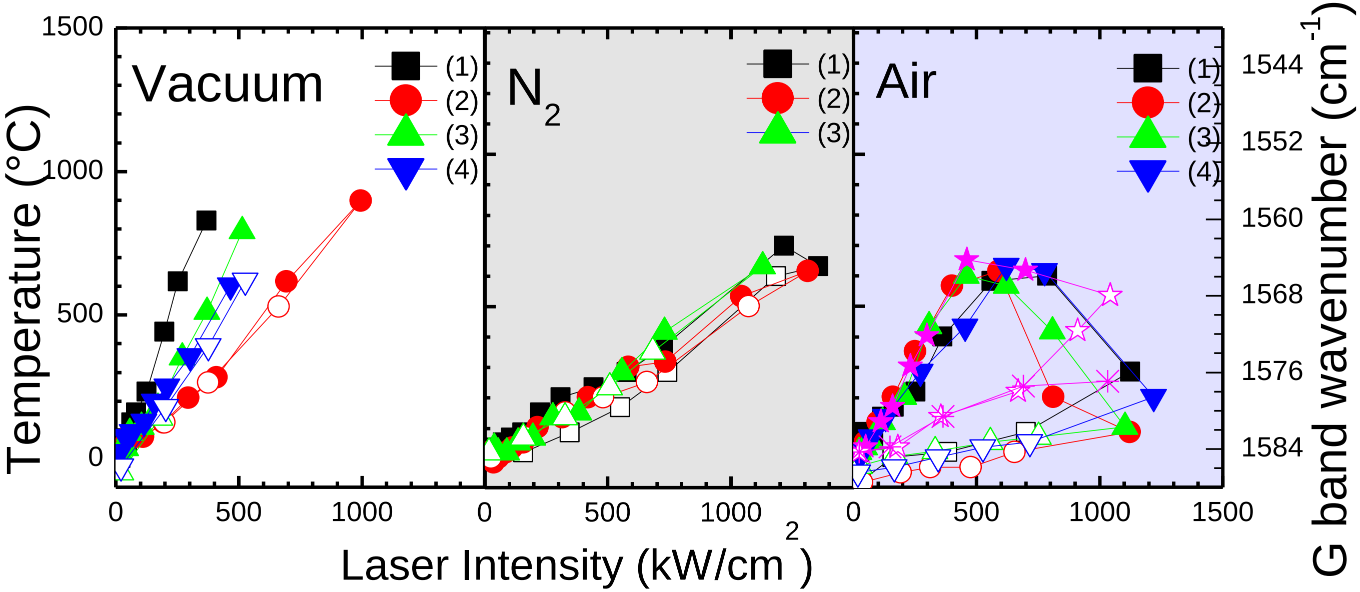
- ✓ Single Wall
- ✓ Multi Wall (MWCNTs)

- Estudo das propriedades térmicas sob diferentes atmosferas



MWCNTs



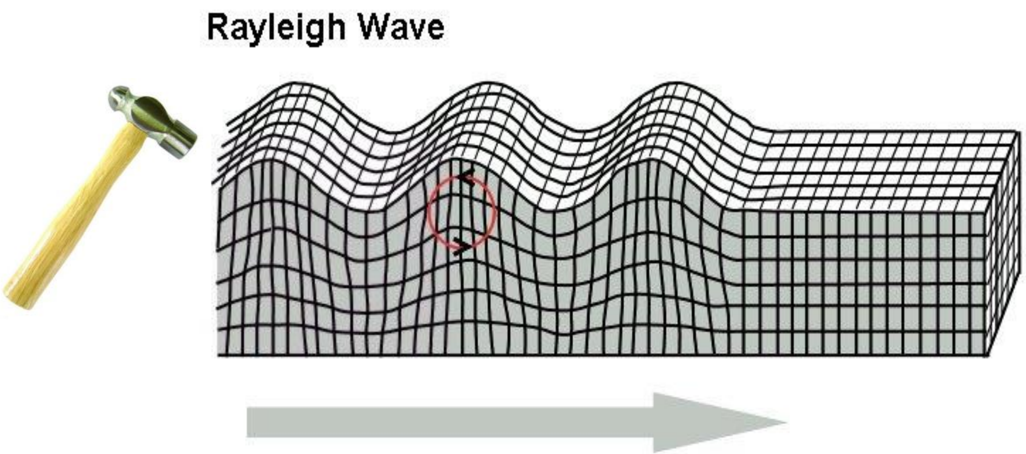


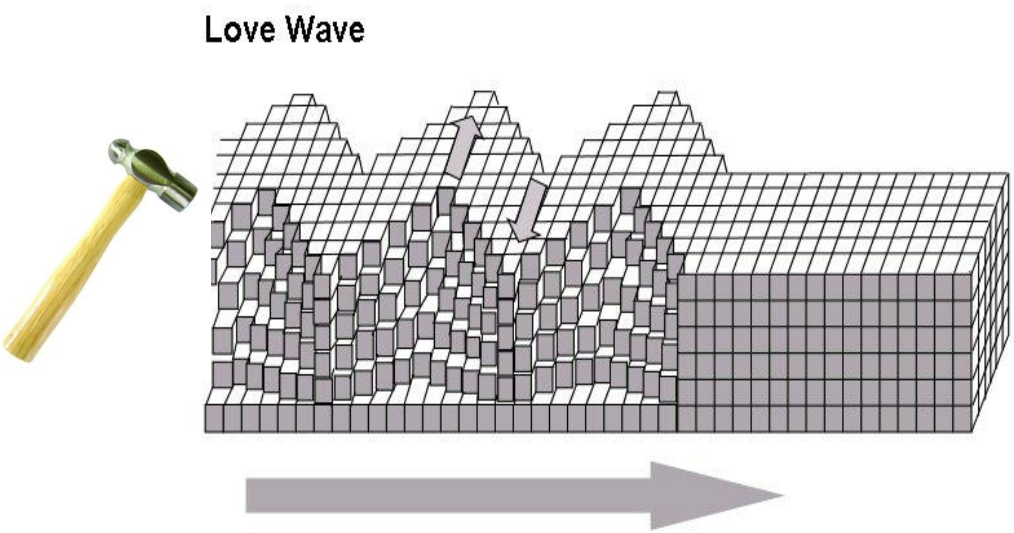
de Zevallos-Marquez *et. al*, *JAP*, **108**, **083501** (2010)

Ondas acústicas de superfície (SAWs)

SAW

Elastic wave propagating on the surface of solids





Applications:

- Mobile, Wireless communication
  - Sensors, filters, resonators….

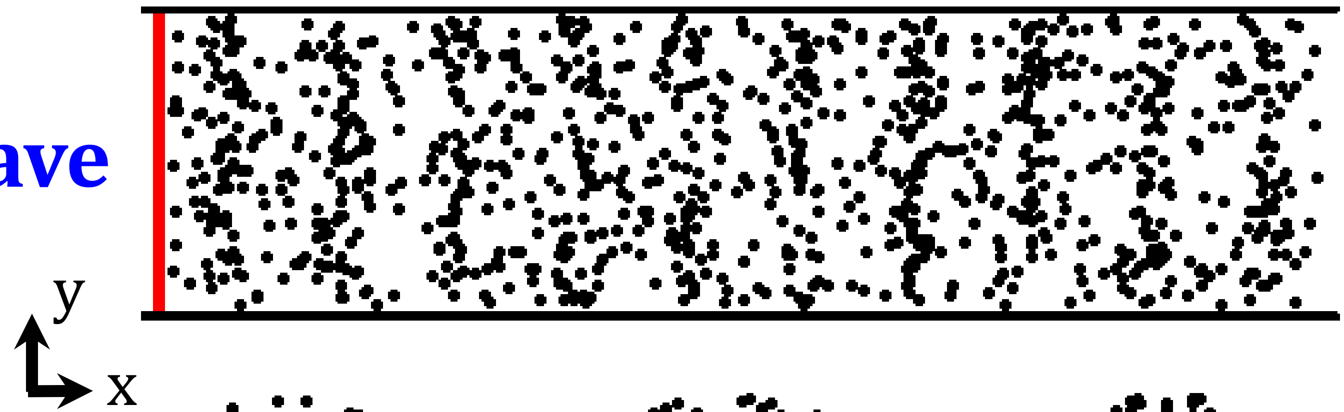
<u>Estimate</u>

- 3 million SAW devices are manufactured **every day!!!**

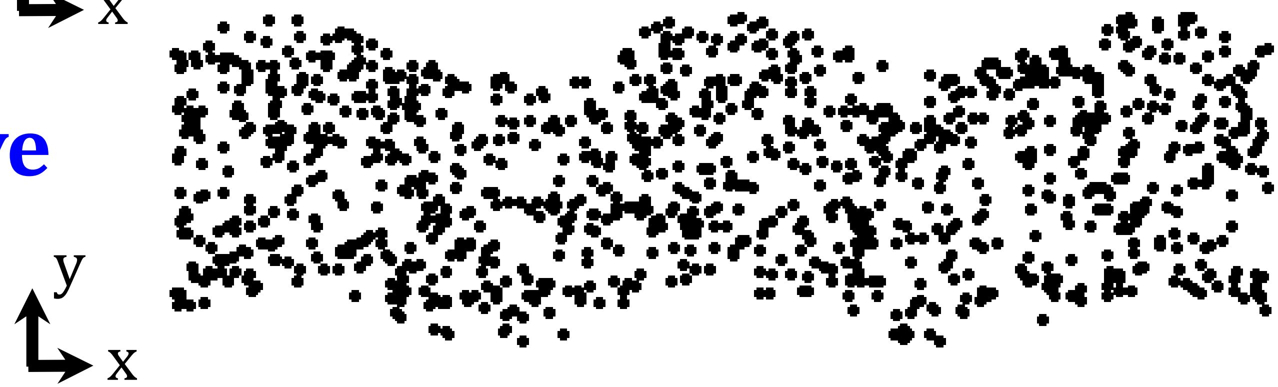
SAW Touch Screen Technology

SAW modes

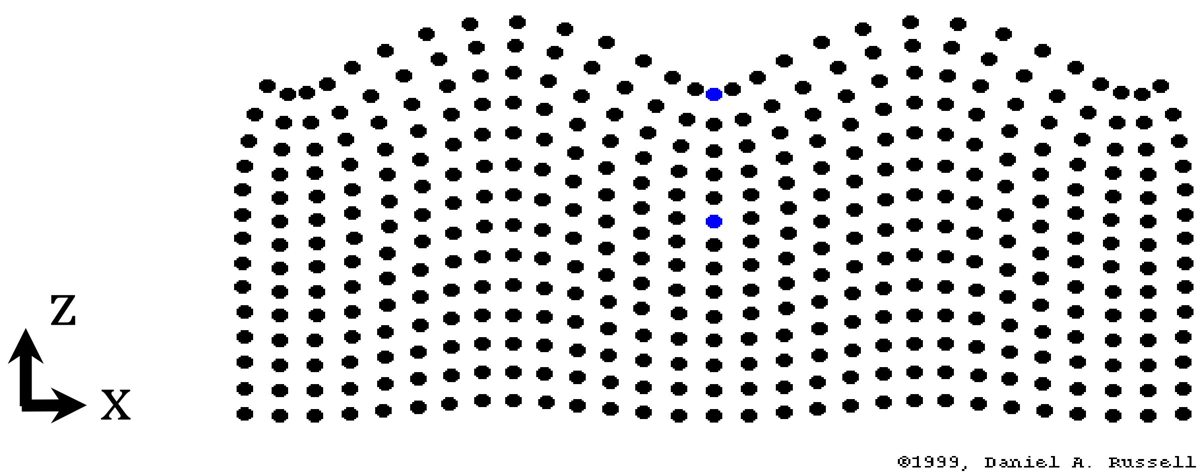
Longitudinal wave



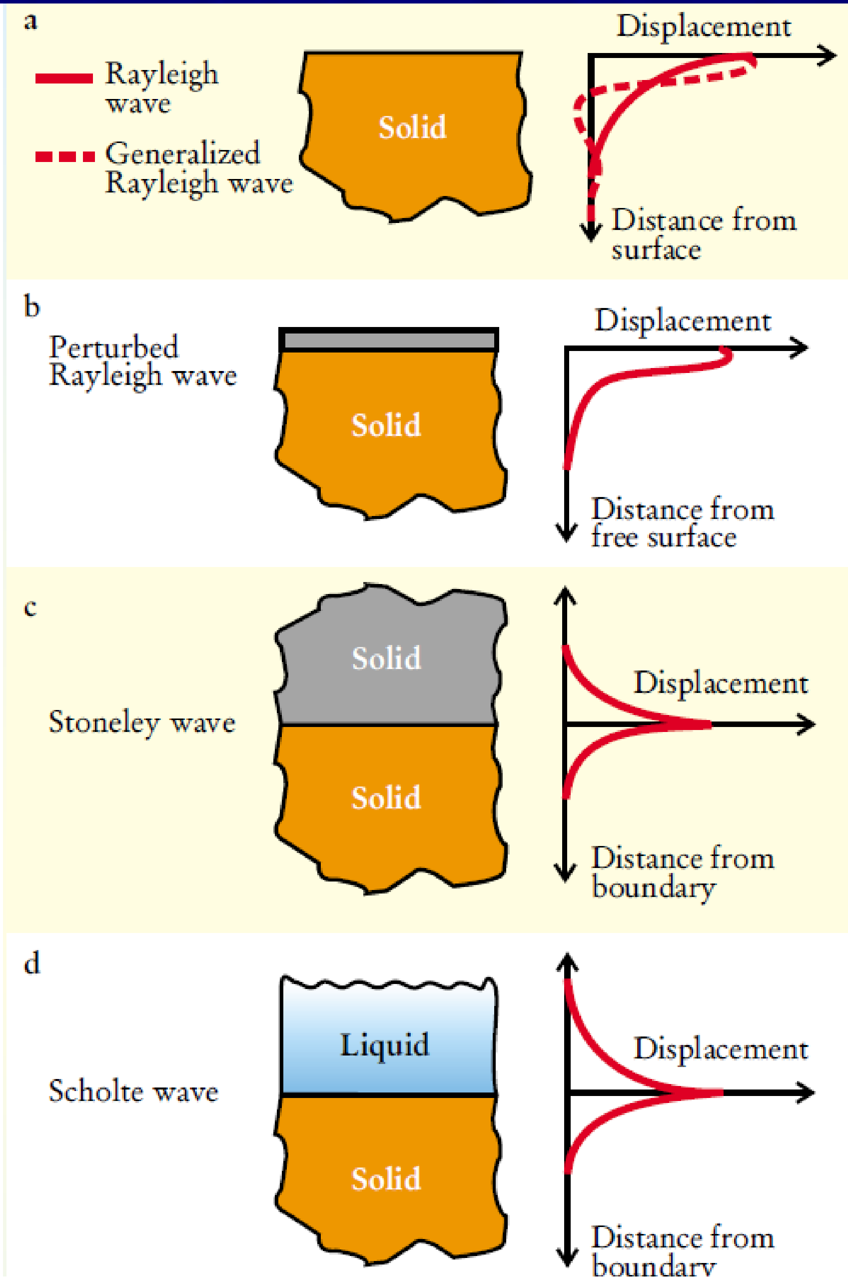
Transverse wave



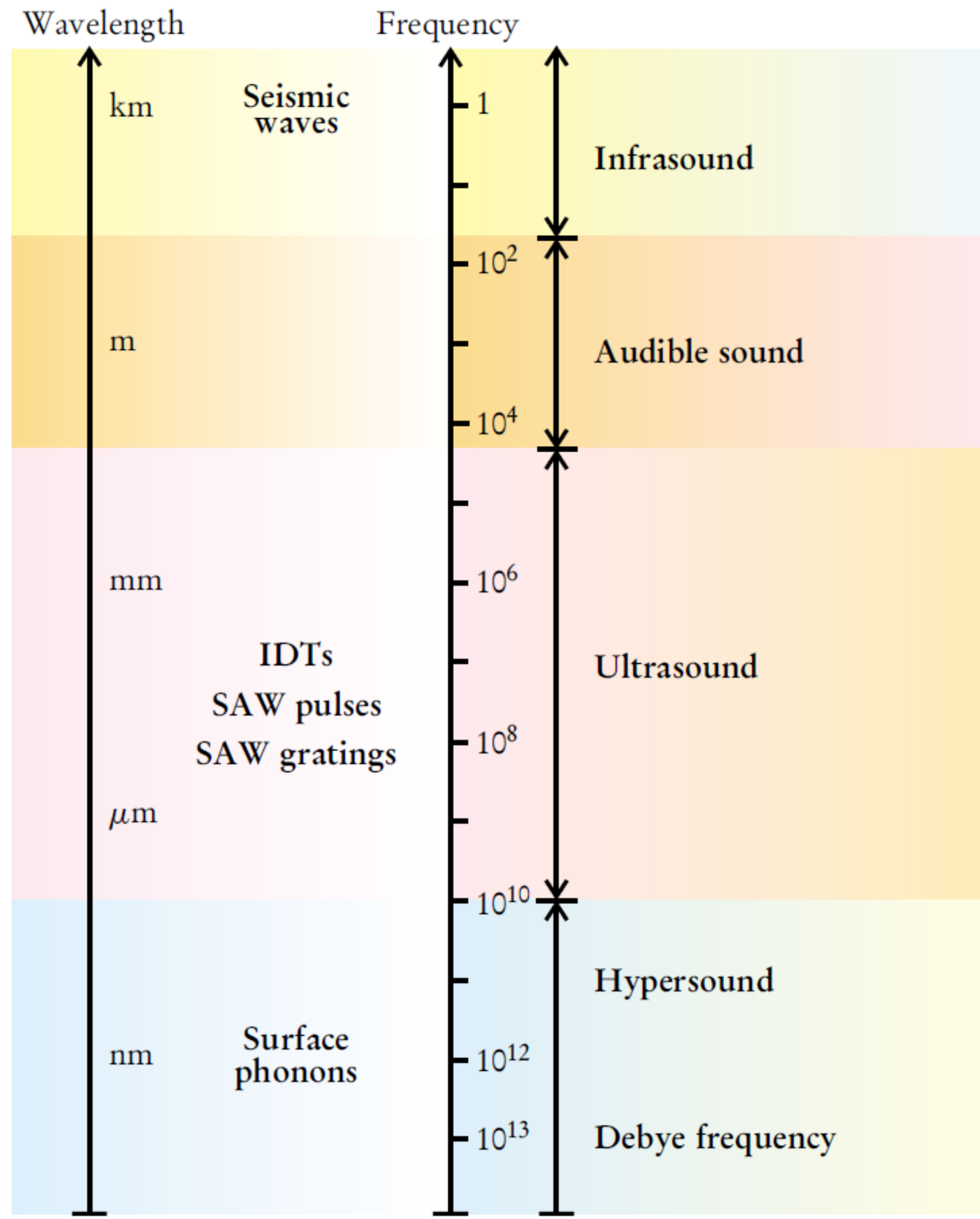
Raleigh wave



SAW



a
Rayleigh wave
Generalized Rayleigh wave
Solid
Displacement
Distance from surface
b
Perturbed Rayleigh wave
Solid
Displacement
Distance from free surface
c
Stoneley wave
Solid
Solid
Displacement
Distance from boundary
d
Scholte wave
Liquid
Solid
Displacement
Distance from boundary

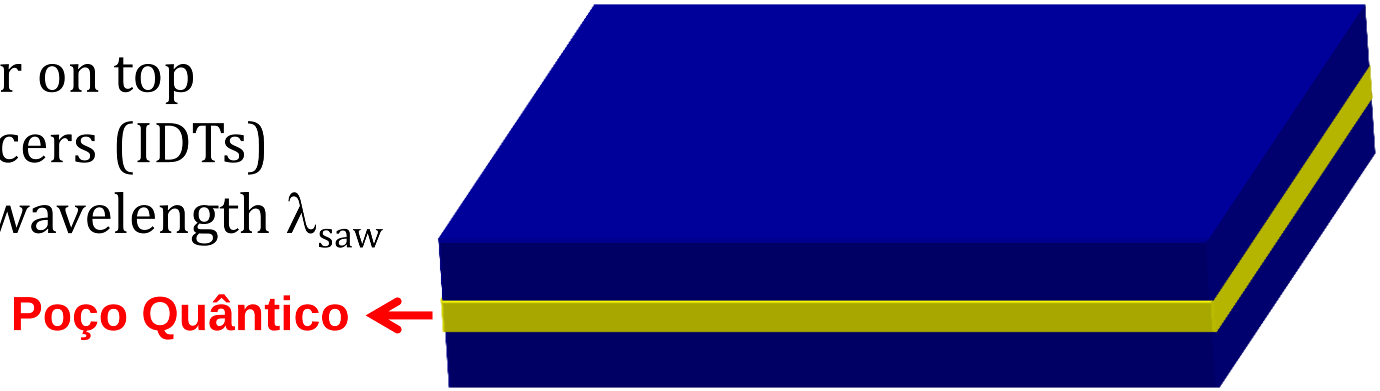


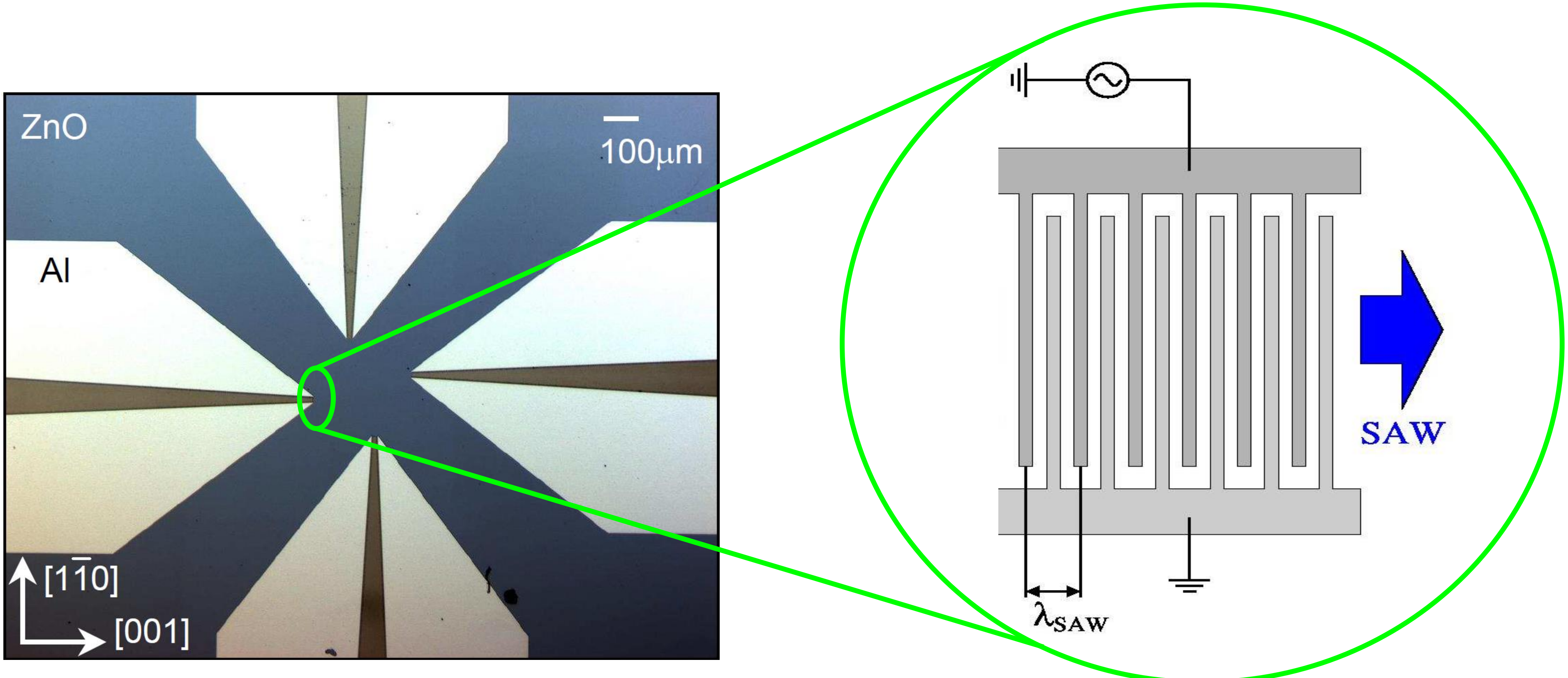
Wavelength
Frequency
km
Seismic waves
1
Infrasound
m
10^2
Audible sound
10^4
mm
10^6
IDTs
SAW pulses
SAW gratings
Ultrasound
μm
10^8
10^10
Hypersound
nm
Surface phonons
10^12
10^13
Debye frequency

How to generate SAWs

Photolithography

- Thin metal (Al) layer on top
- Interdigital transducers (IDTs)
- Defines the acoustic wavelength λ_{saw}





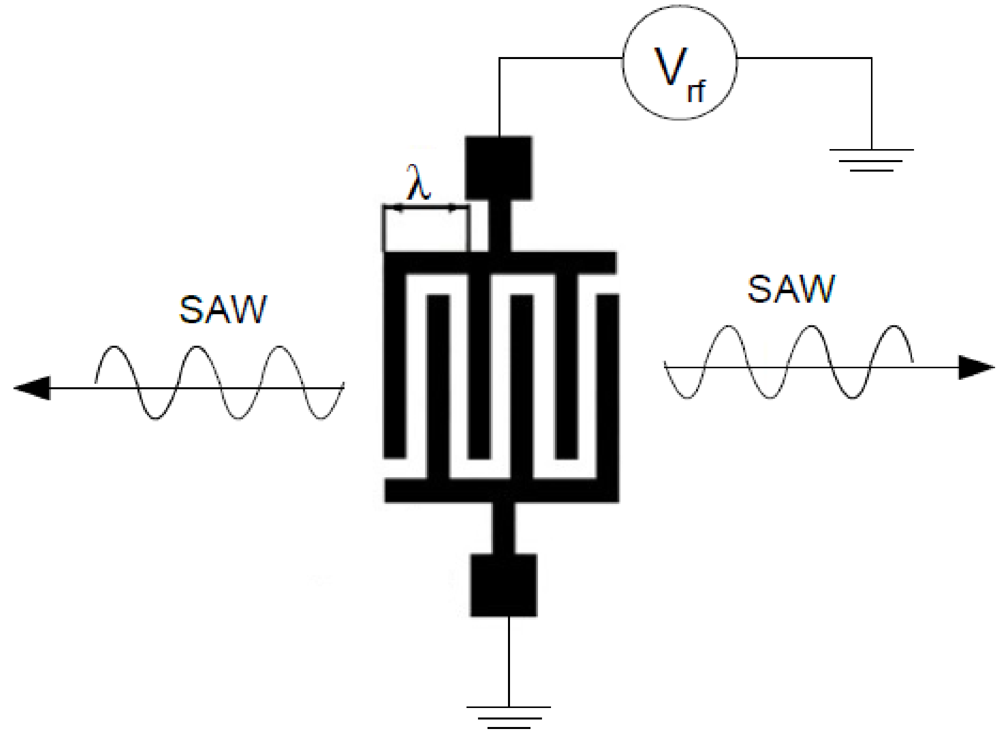
How to generate SAWs

Piezoelectric substrate

- $LiNbO_3$, ZnO
- GaAs (in our case)

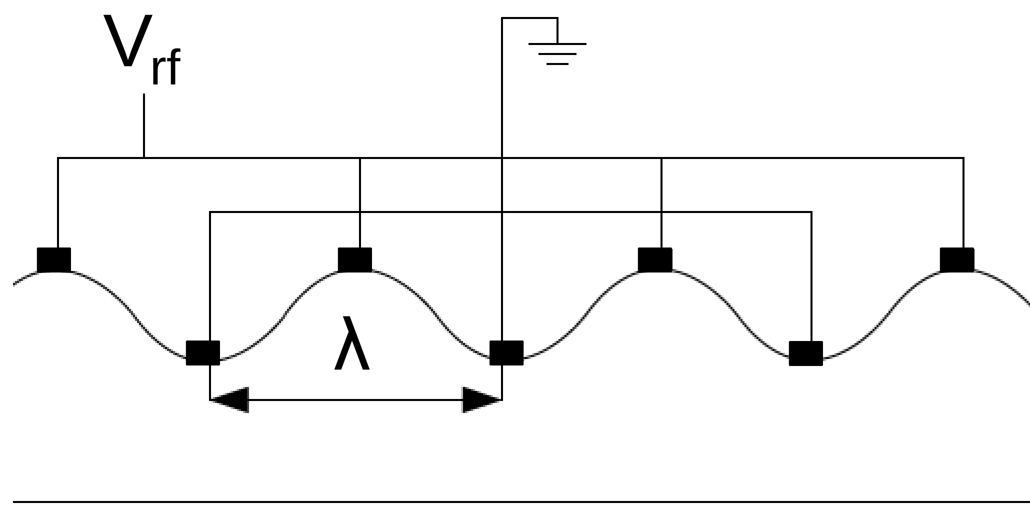
rf-signal

- Efeito piezoelétrico inverso
- Feixe de SAW é lançado



Linear dispersion: ➡ $\omega_{SAW} \times k_{SAW}$

Well-defined velocity $f_{SAW} = \dfrac{v_{SAW}}{\lambda_{SAW}}$



In GaAs $\rightarrow \begin{array}{l} v_{SAW} \approx 3000\, m/s \\ f_{SAW} \approx MHz - GHz \end{array}$

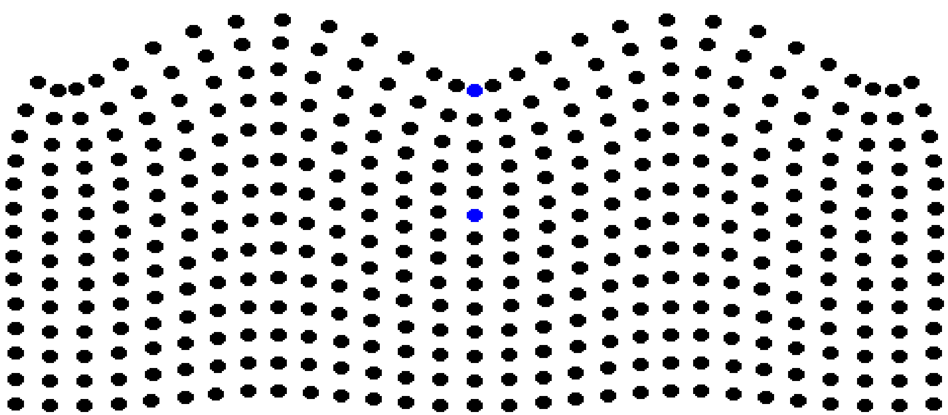
Porque SAWs?

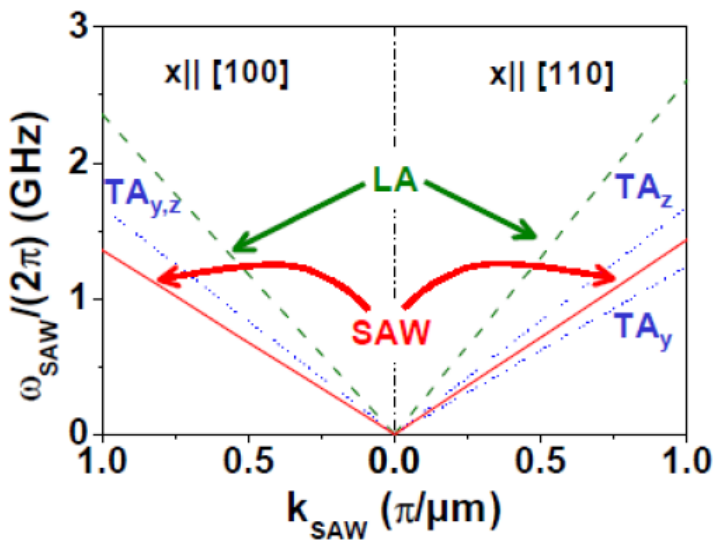
Em ciência de materiais (tipo bulk ou nano)

Novo material → Caracterização (ótica, estrutural, elétrica....)
→ Campos externos (elétricos, magnéticos, tensão)
→ Aplicações (dispositivos)
→ Indústria

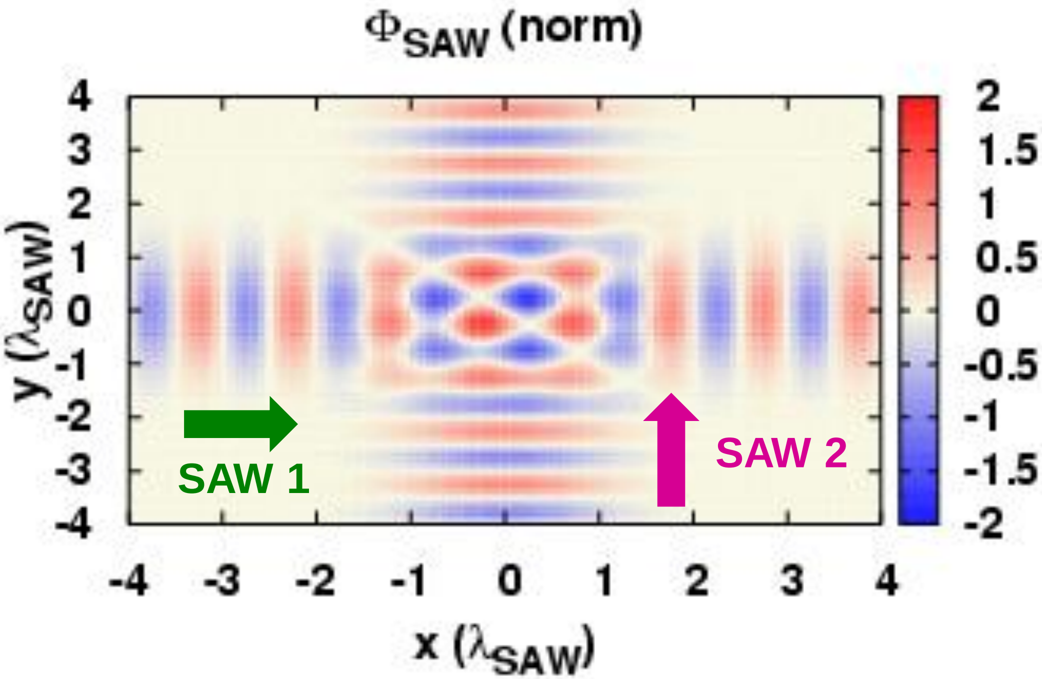
Para nanossistemas

- Método eficaz, local e não destrutivo de aplicação de campos externos
  - SAWs
    - Campo piezoelétrico e de tensão
    - Frequência e velocidade de propagação bem definidas

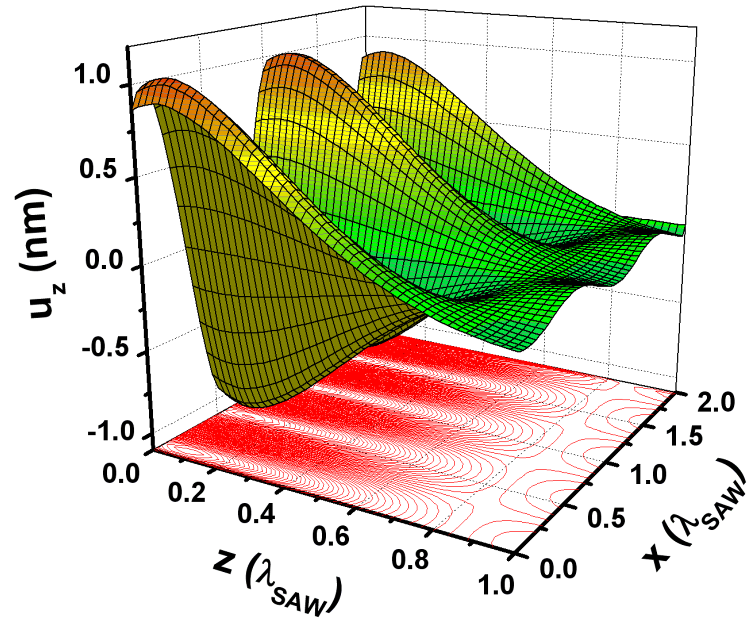




Acoustic modulation



Particle displacement (wave amplitude) decays exponentially bellow the surface



Acoustic Modulation

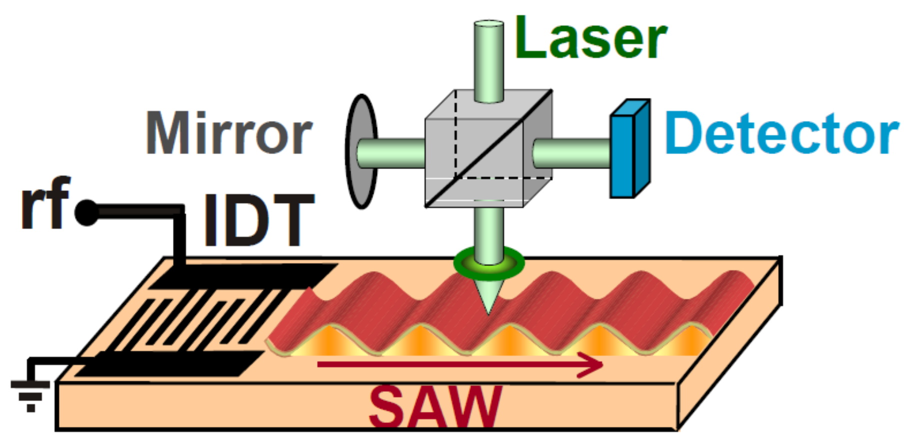
SAWs in Solid-state systems

On the surface

Waveguides, quantum wires

Few nanometers bellow the surface

Quantum wells, quatum dots

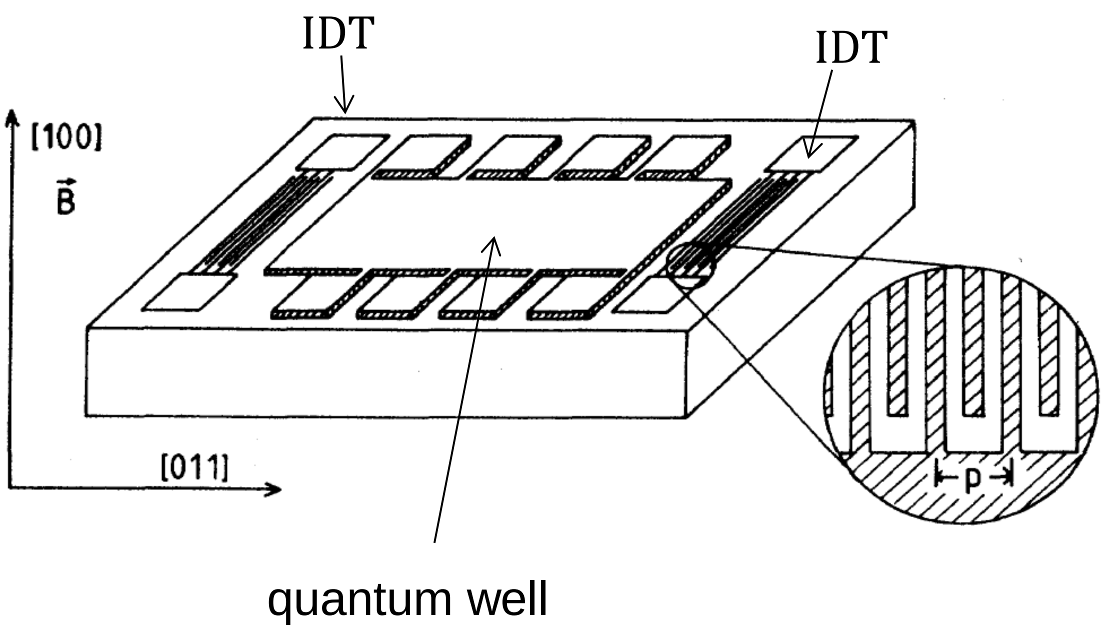


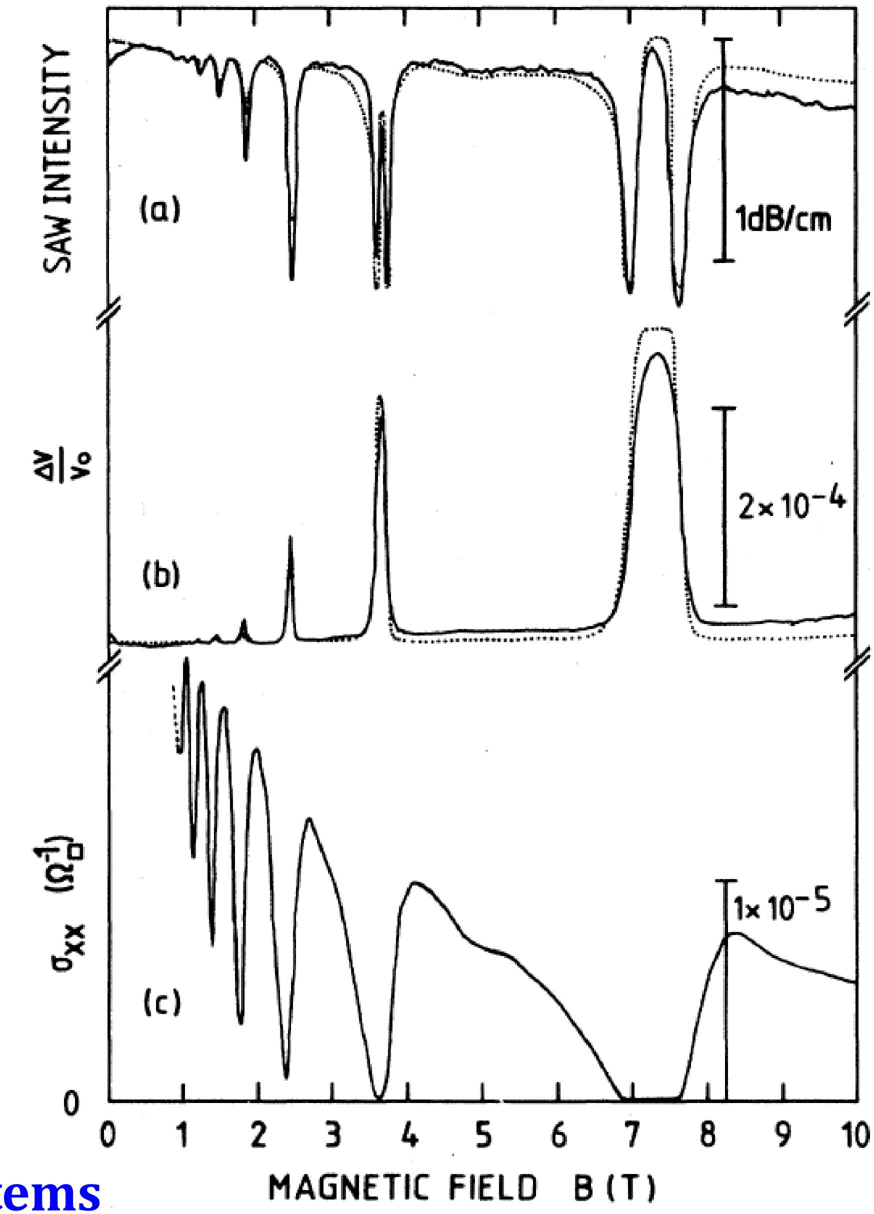
First experiments

2D electron gases under high magnetic fields

✓Alternative tool to study the Quantum Hall effect

Wixforth, Phys. Rev. Lett. 40, 7874 (1989)





Untill the end of the 90's this was the major application of SAWs in the studies solid state systems

Other solid state systems

Control of elementary excitations

Carriers

✓Rocke *et. al Phys. Rev. Lett.*, 78, 4099

✓M. M.de Lima *et. al. Appl. Phys. Lett*. **84**, 2569

Spins

✓T. Sogawa *et. al. Phys. Rev. Lett*. **87**, 276601

✓J. A. Stotz *et. al. Nature Mat*. **4**, 585

✓O. D. D. Couto Jr. *et. al. Phys. Rev. Lett*. **98**, 036603

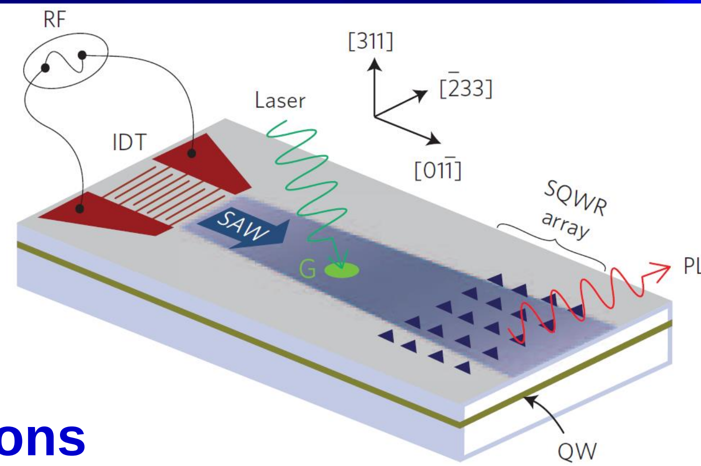
Excitons

✓J. Rudolph *et. al. Phys. Rev. Lett*. **99**, 047602

Bose-Einstein Condensates

✓M. M. de Lima et. al. *Phys. Rev. Lett*. **97**, 045501

✓E. Cerda-Méndez et. al. *Phys. Rev. Lett*. **105** 116402



Photons

Mach-Zehnder interferometer

✓M. M. de Lima *et. al. Appl. Phys. Lett*. **89**, 121104

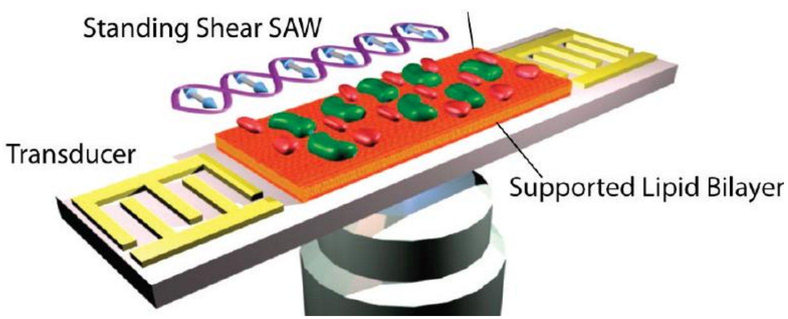
Single photon sources

✓O. D. D. Couto Jr. *et. al. Nature Photon*. **3**, 645

✓A. Hernandez-Minguez *et. al. Nanolett*. **12**, 252

Photonic crystal nanocavities modulation

✓D. A. Fuhrmann et. al. *Nature Photon*. **5**, 605



⇨

Biological systems (new trends)

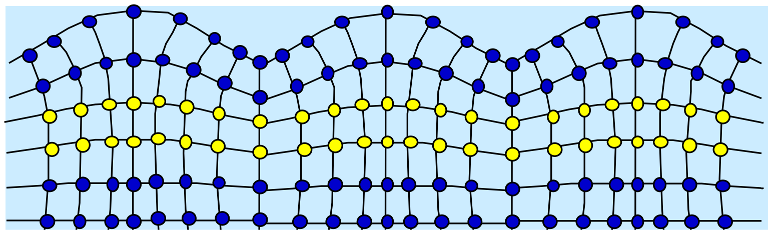
DNA dynamics

M. Hennig *et. al*. *Langmuir* **27**, 14721

J. Neumann et. al. *Nano Lett*. **10**,2903

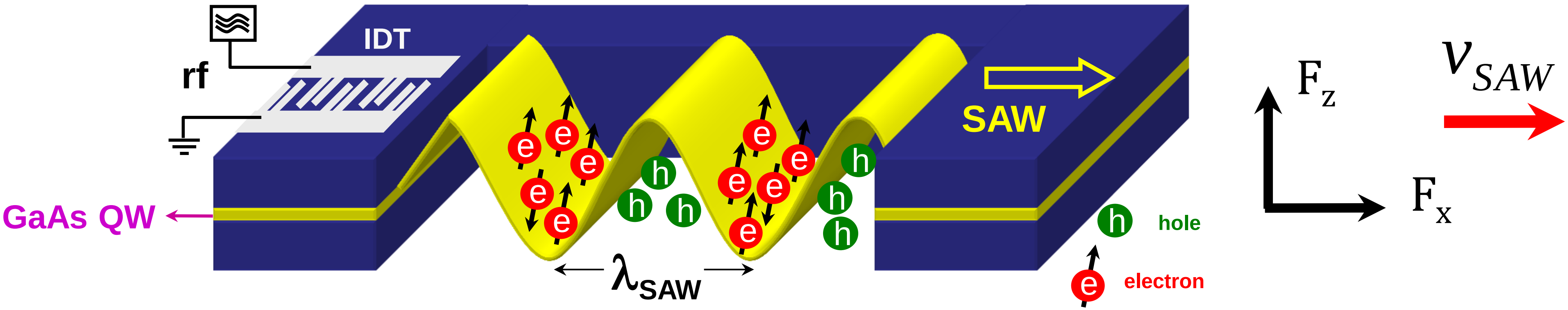
Acoustically induced transport

Strain field (S)



Piezoelectric field (E)

- F_x drags carriers along SAW propagation
- F_z modulates confinement potential
  - Electrons and holes confined in the minima of moving potential
    - Longer carrier lifetimes (τ_{PL})



An electron is created at time t_0, is it possible to know where it will be at $t>t_0$?

Carriers are transported by the SAW with a well-defined velocity $m^* v_{SAW} = \hbar \langle k \rangle$

If $t < \tau_s$: information about the spin state of the particle!!!

Experiments

Semiconductor quantum well GaAs (QW)

Generation (excitation)

- Circularly polarized pulsed laser : σ^-
  - Spins polarized along z

Transport

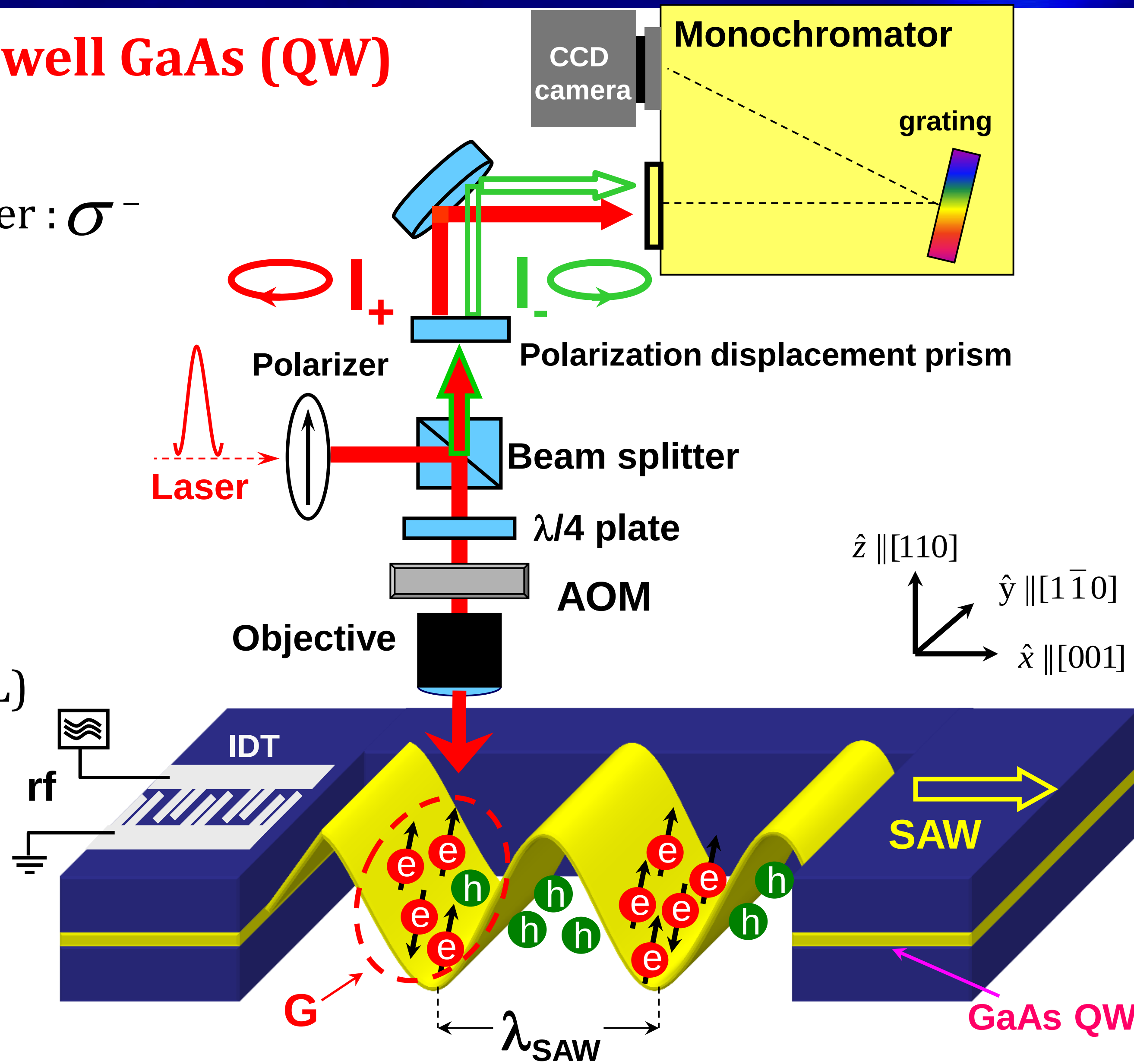
- SAW piezoelectric field (ϕ_{SAW})

Detection

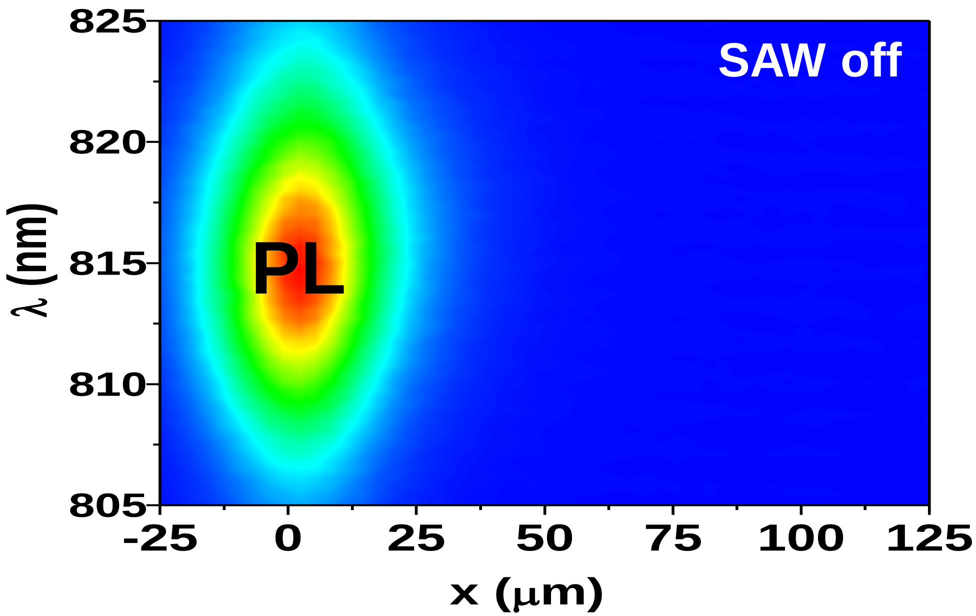
- Time, space, and polarization resolved photoluminescence (PL)

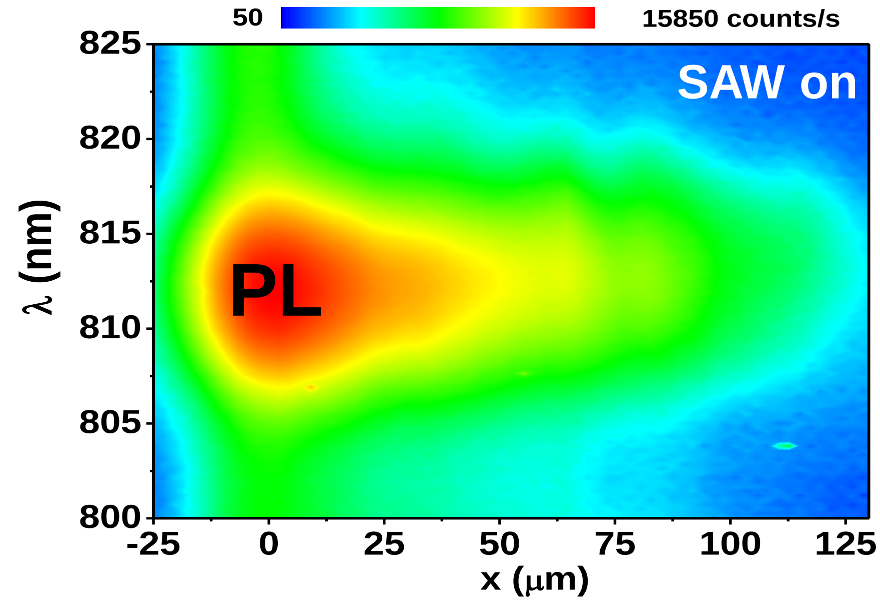
Spin polarization degree

$$\rho_z = \frac{I_+ - I_-}{I_+ + I_-}$$



Carrier transport





Continuous PL detection

Carrier transport

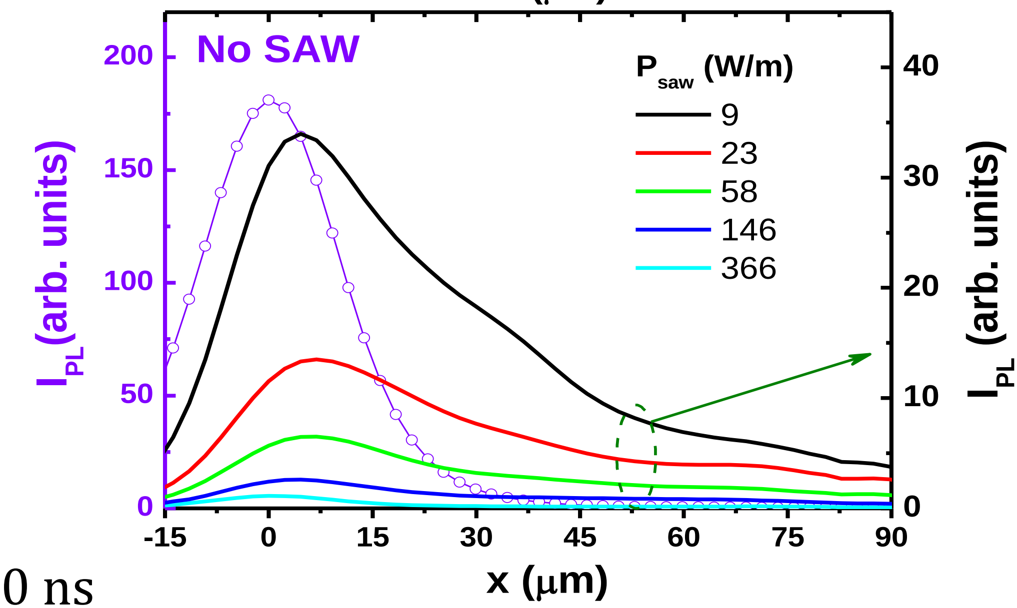
✓ SAW off

✓ Carrier diffusion → $\tau_{PL} \sim 1$ ns

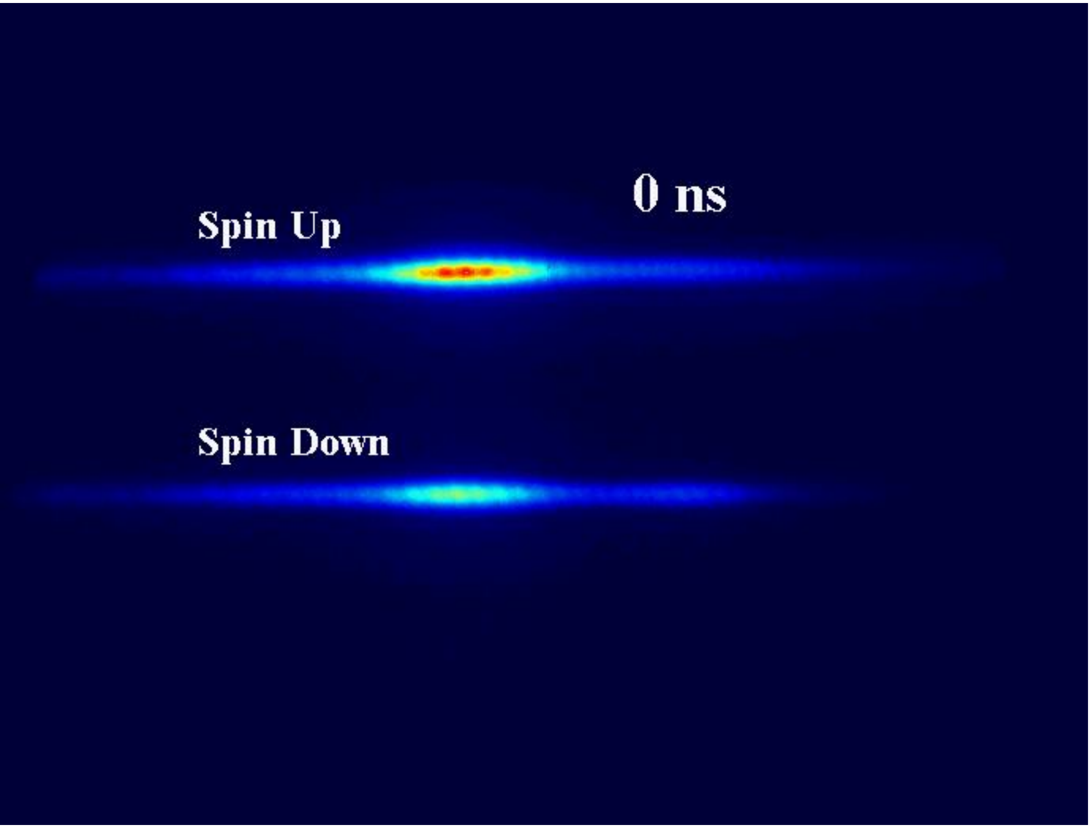
✓ SAW on

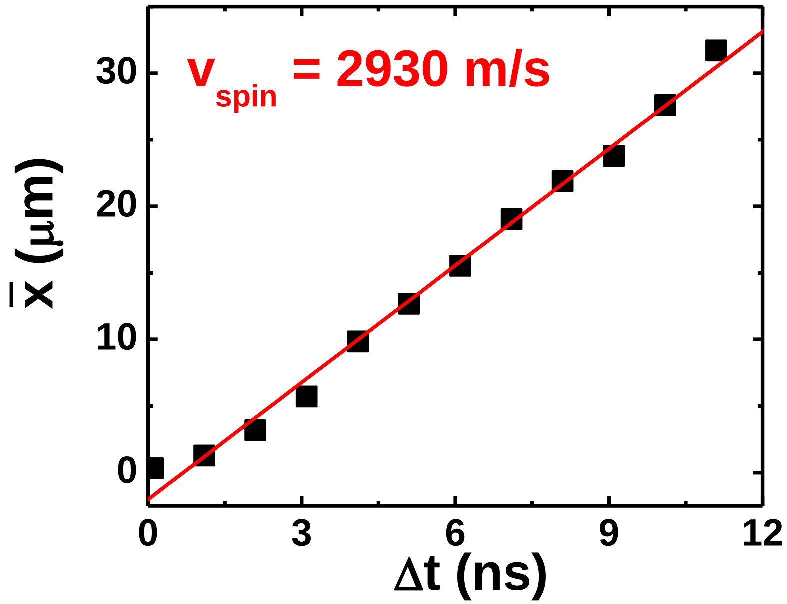
✓ PL quenching ~ 90 times for high acoustic powers

✓ Efficient carrier transport → $\tau_{PL} > 50$ ns



Time-resolved detection

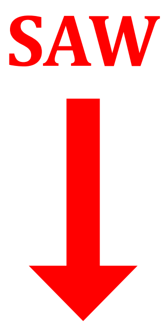


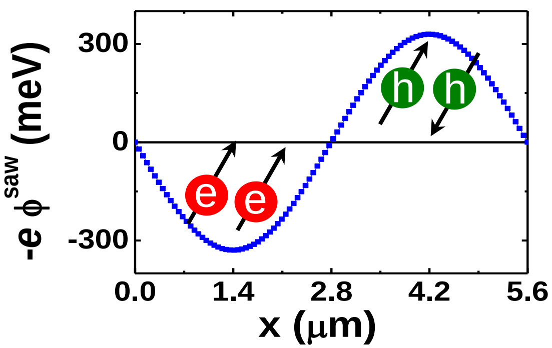


Coherent carrier transport

✓ Well-defined carrier packets

✓ $v_{spin} = v_{SAW}$

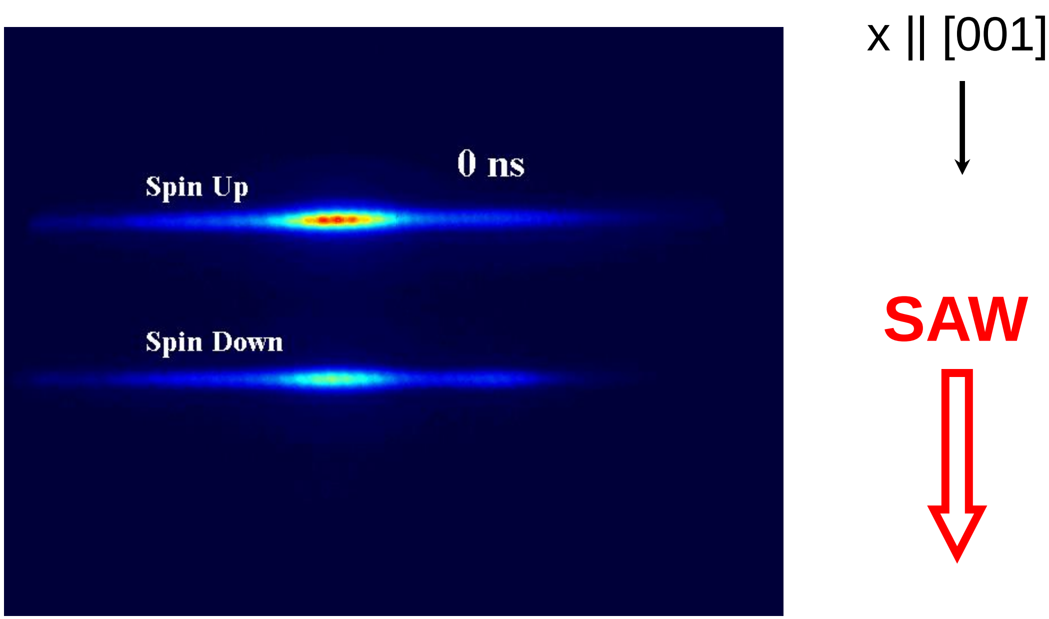


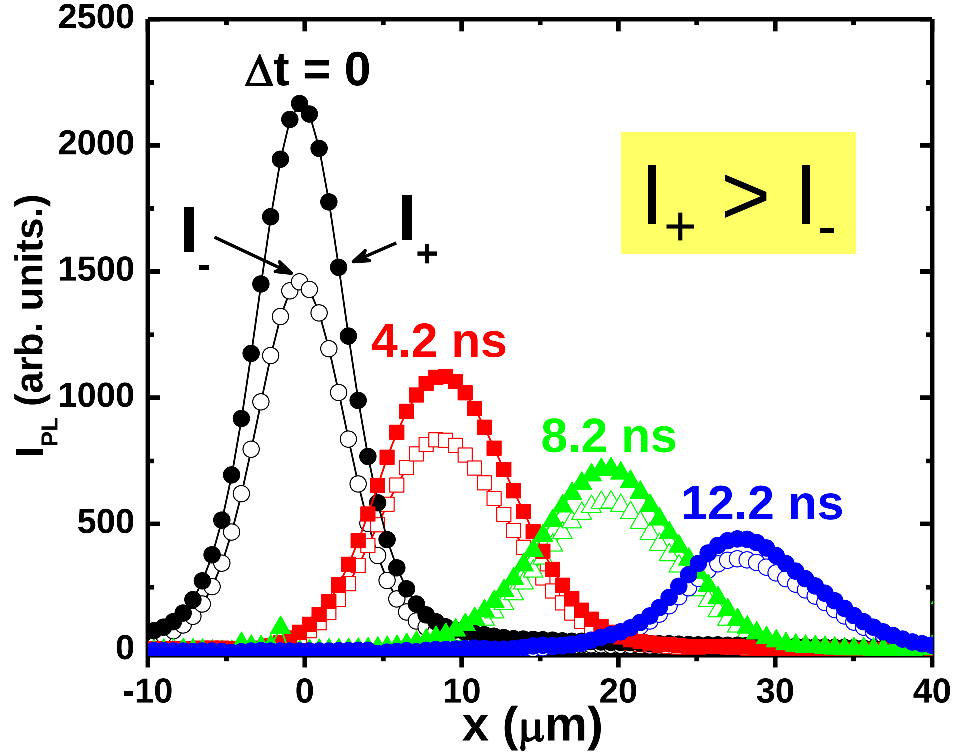


Spin transport (110) QWs

Time-resolved PL detection

- Electron-heavy hole transition



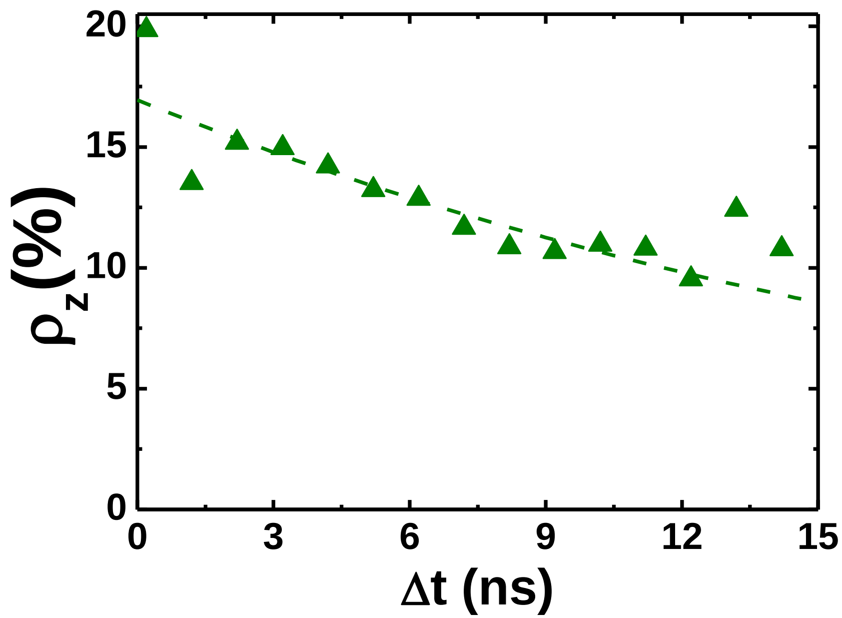


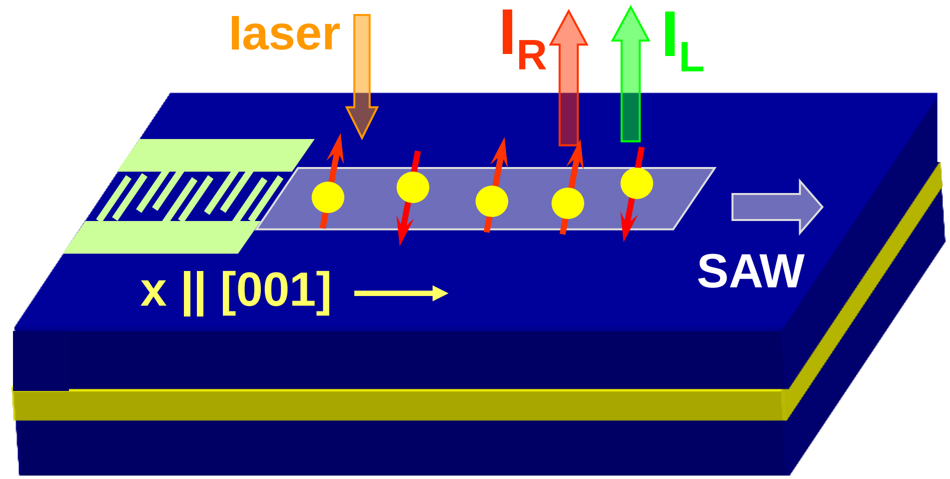
$I_R \propto n_\uparrow$ and $I_L \propto n_\downarrow$

Spin polarization degree: $\rho_z = \dfrac{I_R - I_L}{I_R + I_L}$

Spin relaxation

Transport along [001] direction





- ✓ Exponential decay
  - ✓ Spin lifetime : $T_1 = (22 \pm 2)\,ns$
  - ✓ Spin transport length: $L_s = T_1 v_{SAW} = (63 \pm 5)\,\mu m$

Longest spin lifetime and transport distance for this type of quantum well!!!!

Suppression of relaxation for z-oriented spins

O. D. D. Couto Jr. et al, *Phys. Rev. Lett.* **98**, 036603

Increasing temperature

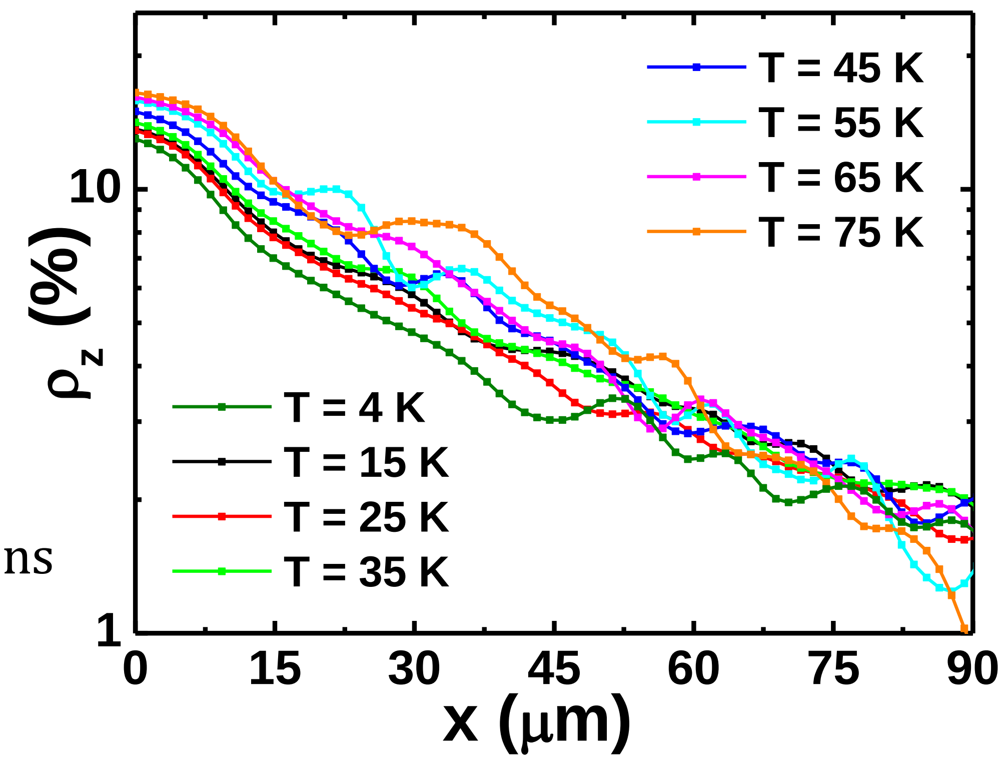
Temperature

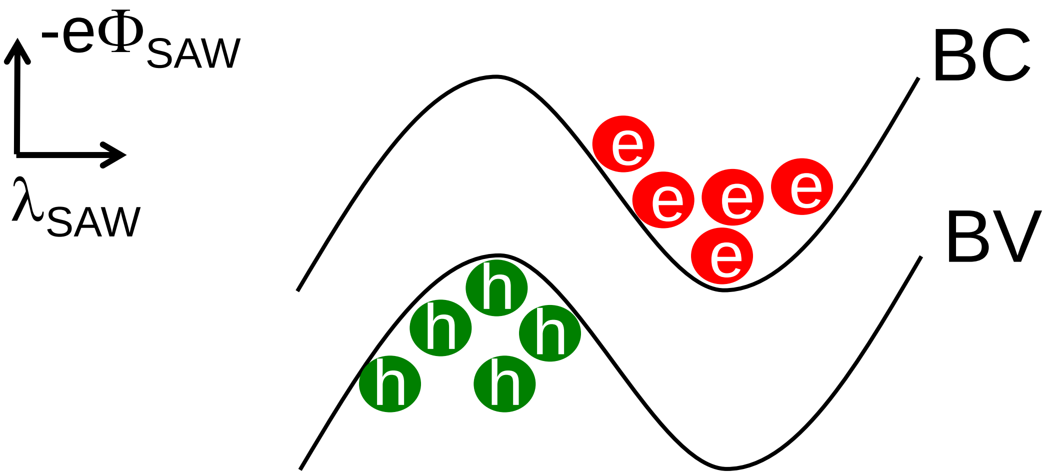
✓ Spin decay is independent of T up to 75 K

✓ SAW piezoelectric field avoids electron-hole recombination

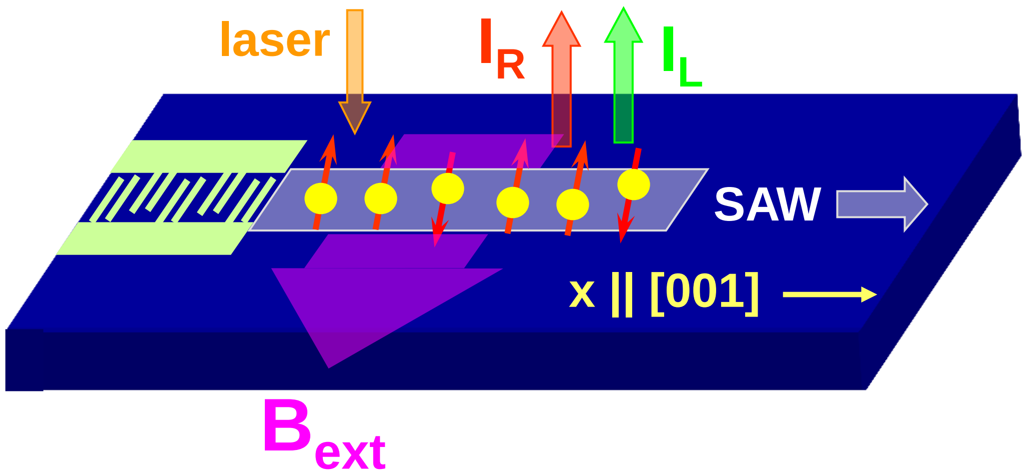
✓Spin transport at liquid nitrogen temperature

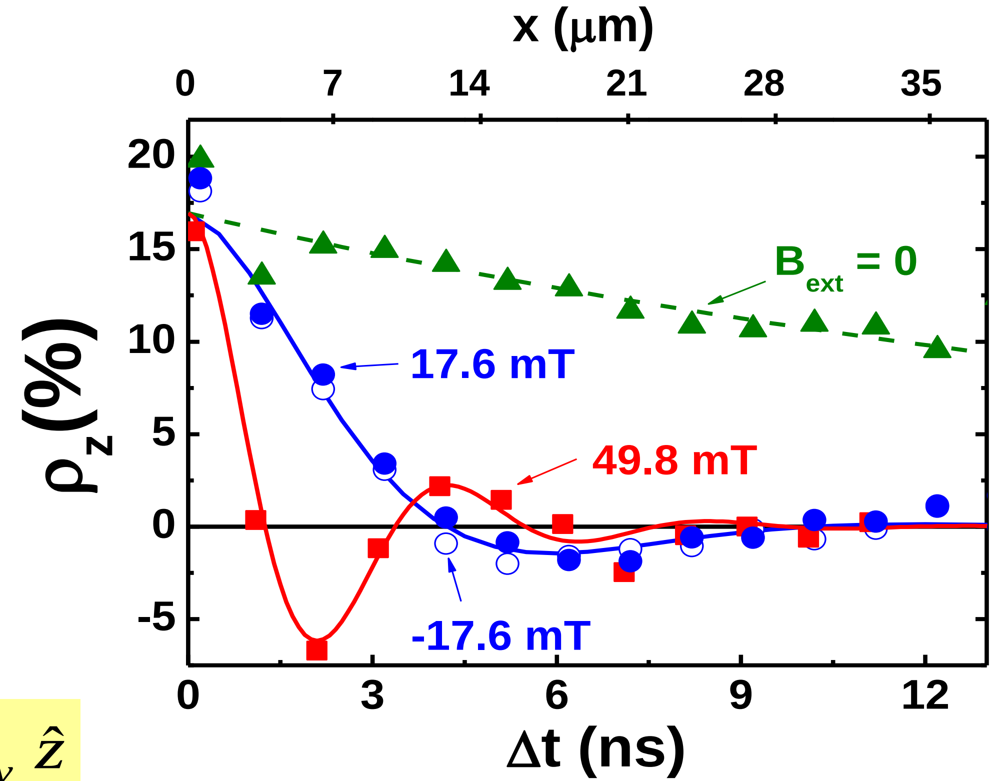
✓ Interesting for future applications





Spin manipulation

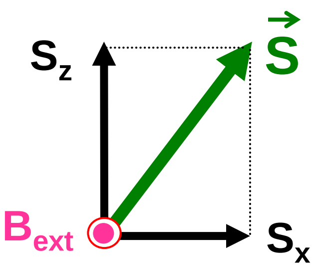




- Spin precession around B_{ext}
  - Precession is damped
    - Spin dephasing

$$\vec{B}_{BIA}(k) \propto k_y \hat{z}$$

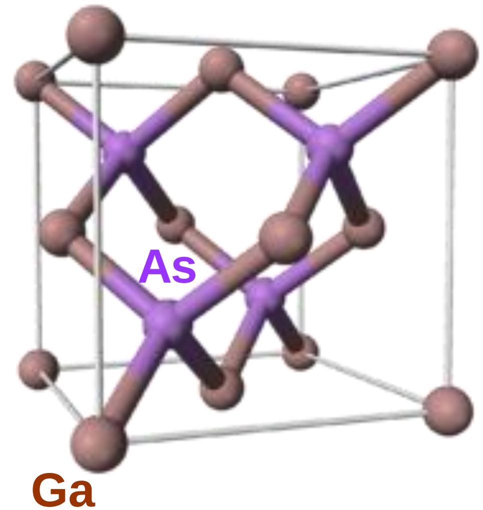
B_{int} || z fluctuates



- High in-plane relaxation rates appear

Effective spin dephasing time: $T_2^* = 2.3\ ns$

Spin relaxation dynamics



Spin-orbit Coupling

- ✓ Bulk inversion asymmetry
  - ✓ Binary semiconductors: GaAs
  - ✓ Electrons move in the crystal lattice
    - ✓ “Feel” the crystal potential

Effective magnetic field felt by the electron $B_{BIA}(k)$

$$H_{BIA}(k) = \hbar\,\Omega_{BIA}(k)\cdot\frac{\sigma}{2} = g_e\,\mu_B\,B_{BIA}(k)$$

$$mv = \hbar k$$

- **Ensemble of 10^3 – 10^4 spins**
- **k momentum dependence**
- **Fast average spin relaxation → T_1 ~ 100 - 300 ps**

(110) quantum wells*

✓ Structural simmetry enhances the spin lifetimes → T_1 ~ 1-2ns

Acoustic transport

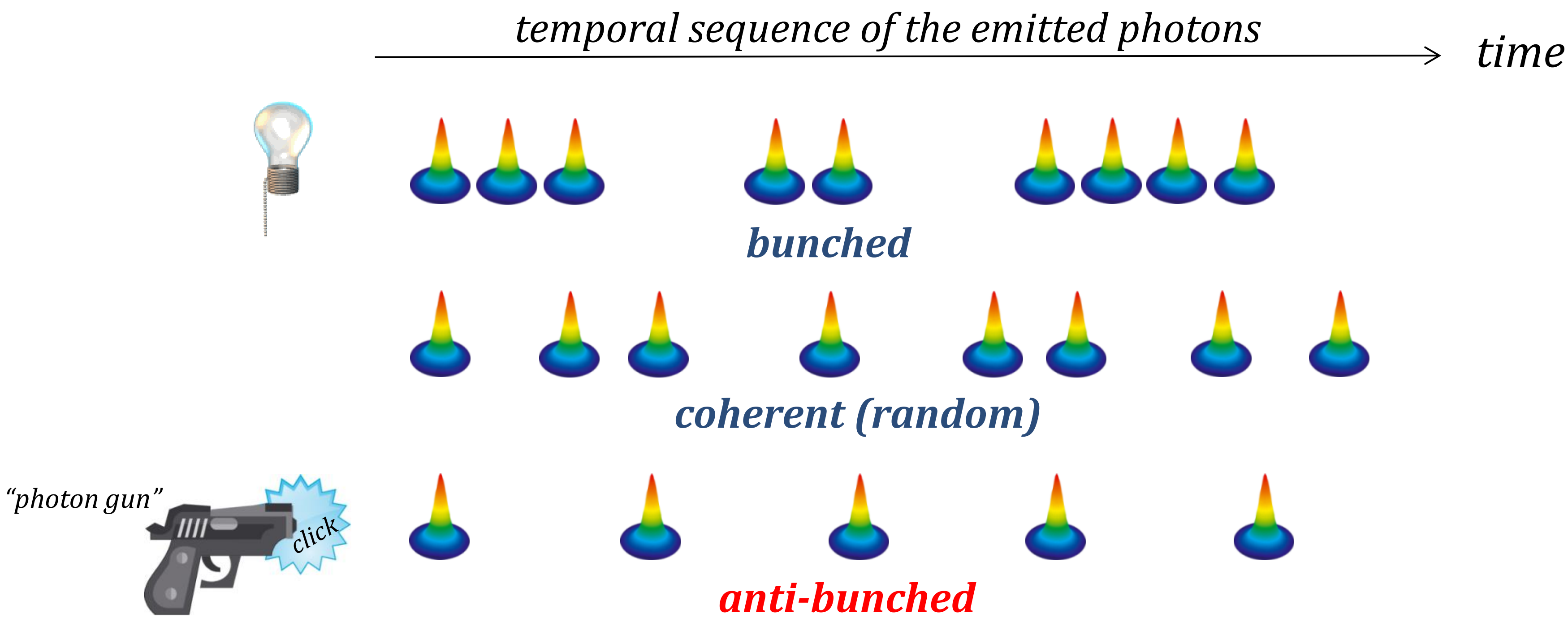
✓ SAW confinement potential screens electron spins → T_1 ~ 22 ns

* Ohno et. al., Phys. Rev. Lett. 83, 4196 (1999)

Carrier injection in coupled nanostructures

Single photon sources

What is a single photon source (SPS)



→ low probability of emitting two or more photons at the same time

SPS → source able to emit ***single photons*** pulses ***on demand***…

✓ regular stream of photons delivered one at a time

✓ high emitting probability (ideally, with certainty)

SPS applications

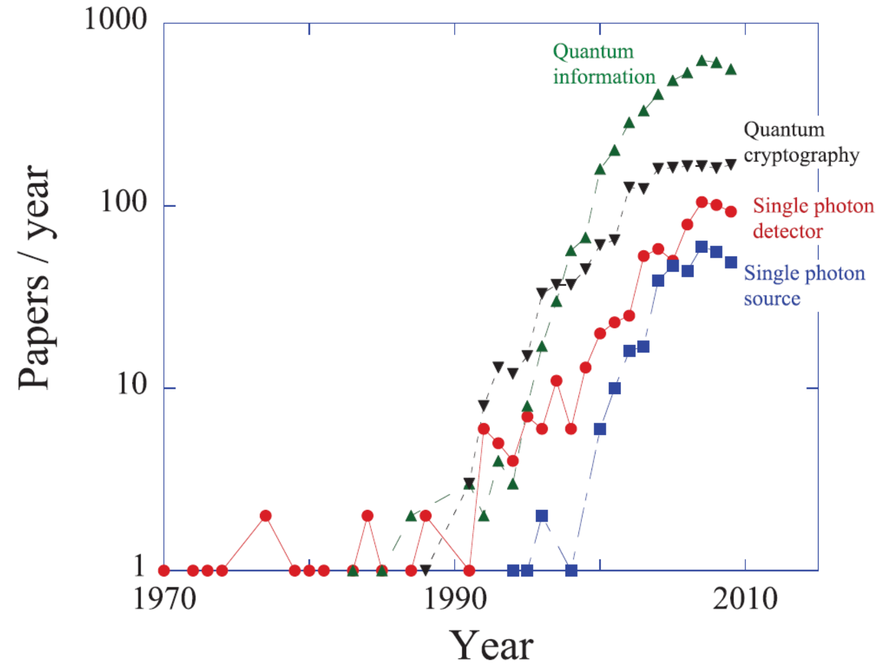
Why do we need SPSs?

** B. Lounis and M. Orrit, "Single-photon sources", Rep. Prog. Phys.* ***68****, 1129 (2005)*

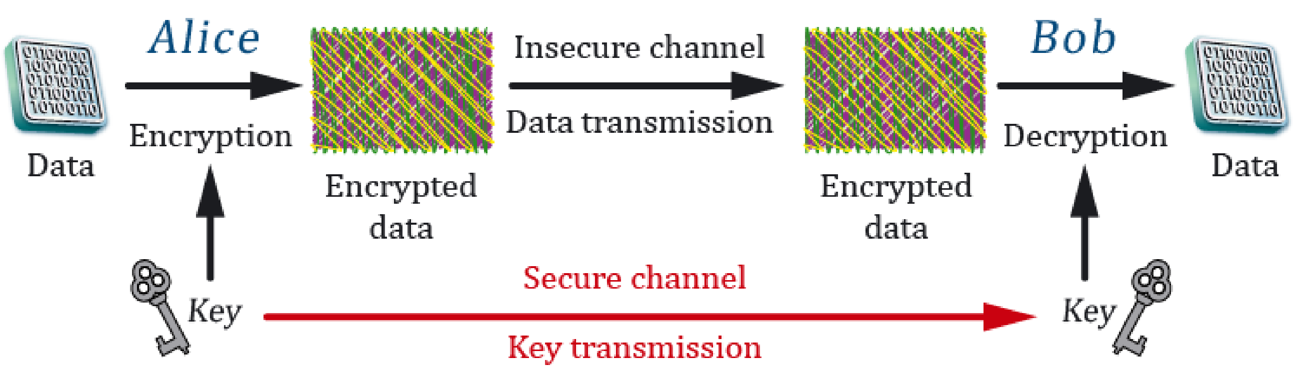
- fundamental tests of quantum mechanics
- quantum information processing
  - ✓ quantum computation
  - ✓ quantum cryptography

    → secure quantum key distribution

  by single photon pulses



Eisanan et. al. Rev. Sci. Inst. 82 071101

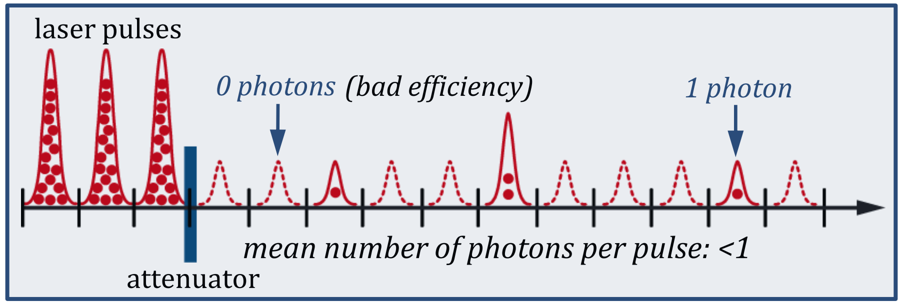


How to make a SPS

→ elimination of multiple photon events: *single photon source*

✷ <u>*early and macroscopic*</u>

✓faint laser source

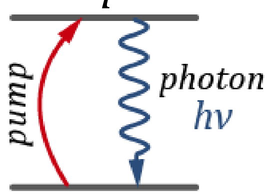


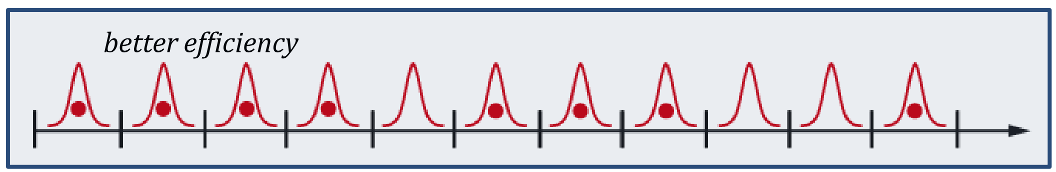
→ non-deterministic (Poisson) statistics:
random generation of single photons

H.J. Kimble et al., PRL **39, 691 (1977)*
D.F. Walls Nature **280, 451 (1979)*

✷ <u>*microscopic*</u>

✓single quantum emitters
two-level quantum systems





→ deterministic (sub-Poissonian) statistics

(e.g. atoms, organic molecules, defect centers, semiconductor nanocrystals & heterostructures)

SPS emission frequency → f_{pump}

B. Lounis and M. Orrit,, Rep. Prog. Phys. **68, 1129 (2005)*

SAW + SPS

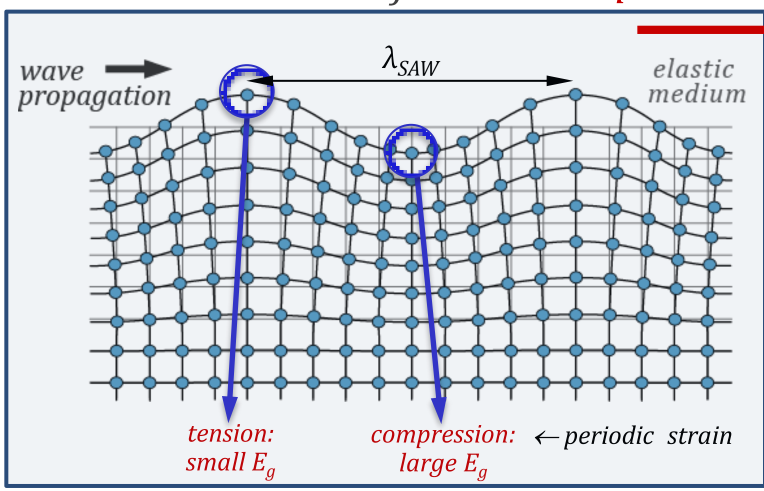
$\rightarrow$ alternative way to generate semiconductor-based SPSs

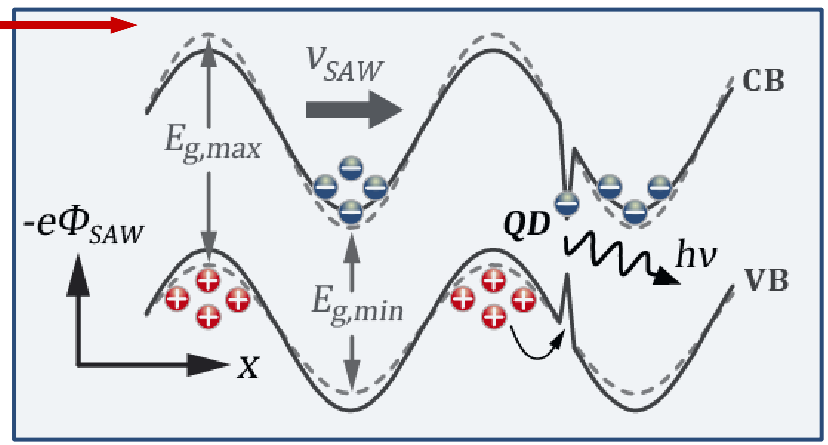
SAW $\rightarrow$ surface elastic vibrations (acoustic phonons)

✓SAW frequency: f_{SAW} $\rightarrow$*100's of MHz to a few GHz* $\rightarrow$ **high-repetition rate SPS**

Modulation mechanisms

strain field *piezoelectric materials* *piezoelectric field*





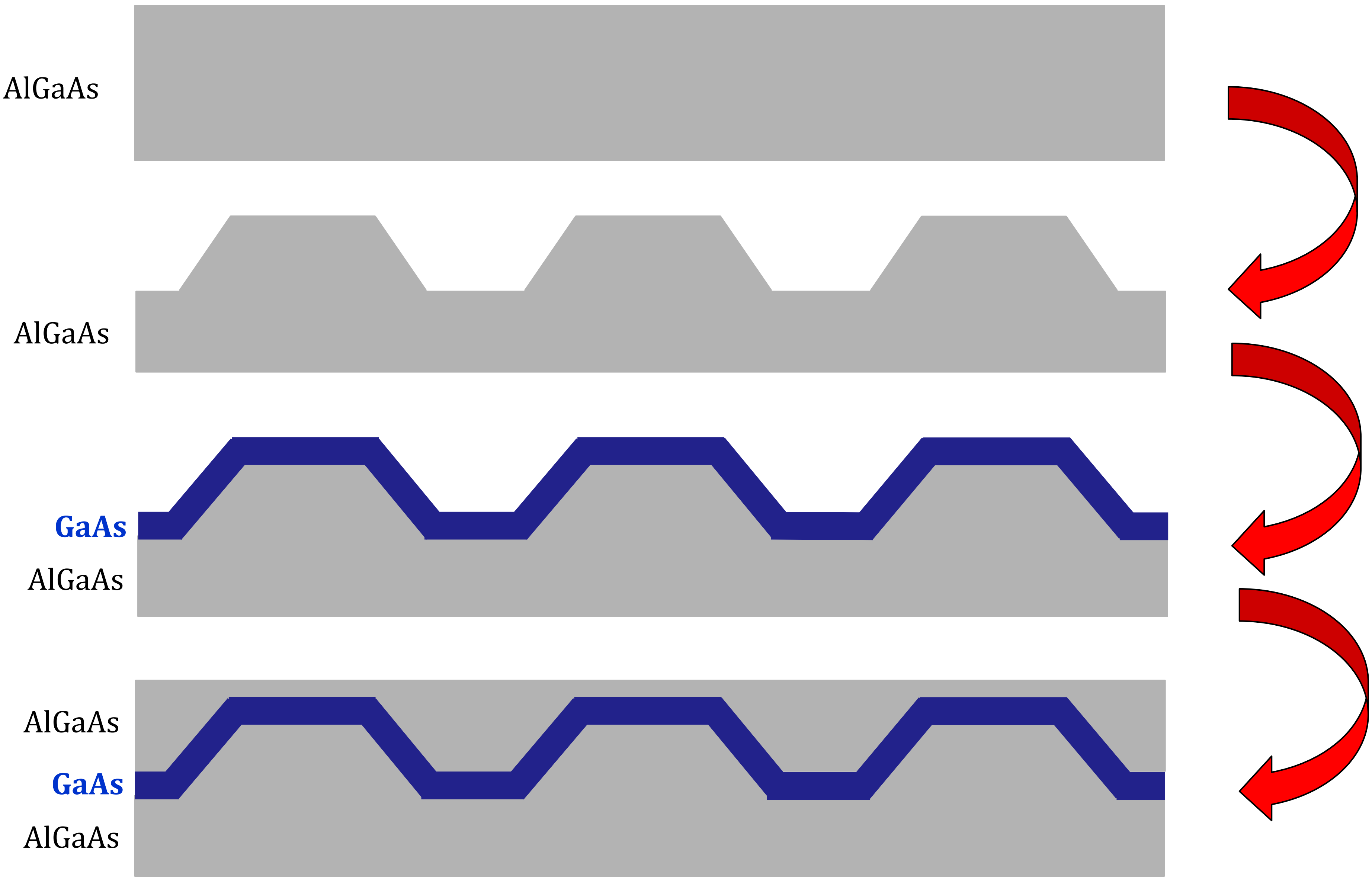
type-II potential modulation

$\rightarrow$ spatial separation of electrons and holes

✓***controllable transport*** of carriers (unipolar or ambipolar)

Como obter o sistema de 2 níveis?

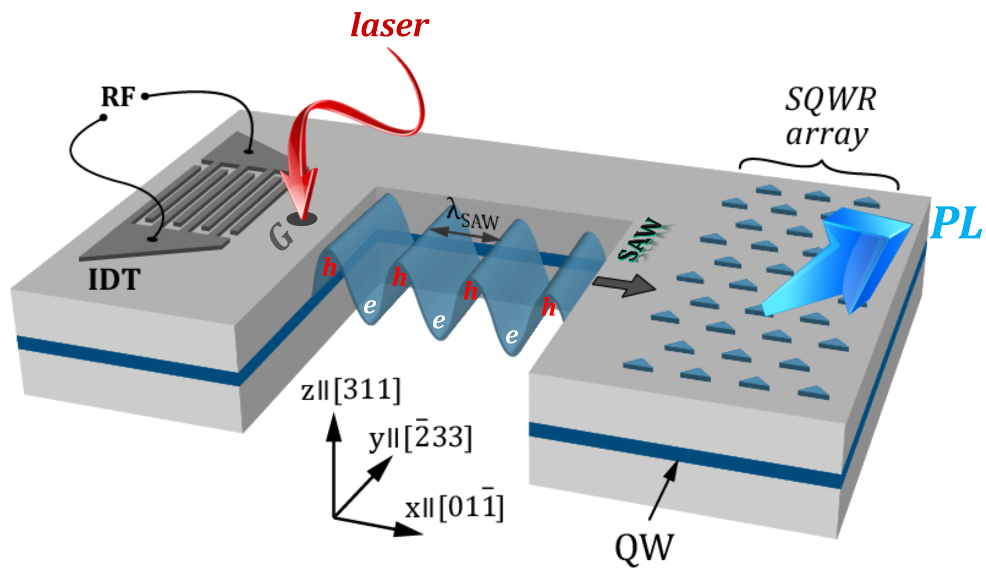
Etching process



Our approach

SPS on GaAs (311)A

- acoustic transport on (311)A GaAs QWs
  - ✓ formation of short quantum wires (SQWRs) containing shallow dots
  - ✓ SQWRs embedded in the QW: carrier transport QW → SQWR



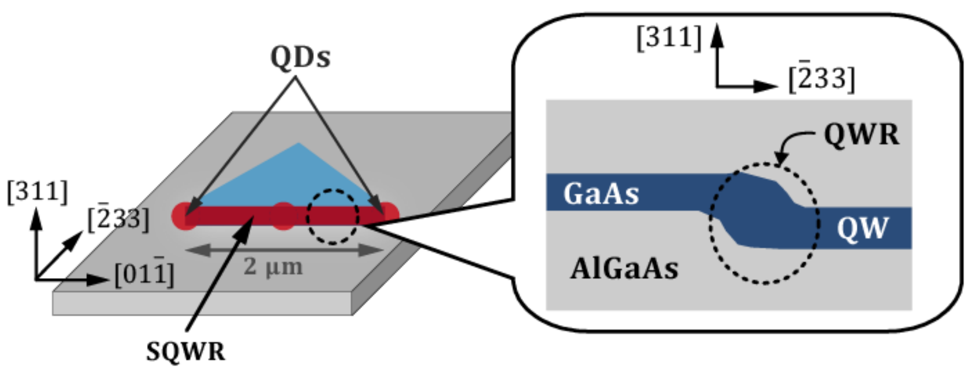
SQWR fabrication

- side-wall (311)A GaAs quantum wires
  - ✓ MBE overgrowth on substrates patterned with shallow mesa
    - ✓ **SQWR:** material accumulation at [01-1] mesa edges

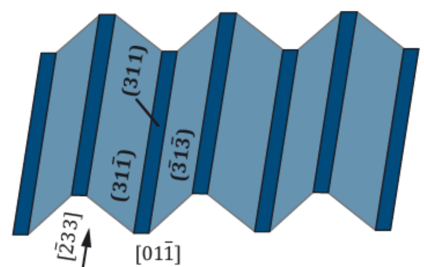
SAW generation

✓SAW wavelength: $\boldsymbol{\lambda_{SAW}= 4\ \mu m}$

✓SAW frequency: $\boldsymbol{f_{SAW}=750\ MHz}$



*R. Nötzel et al., Appl. Phys. Lett. **68**, 1132 (1996)*

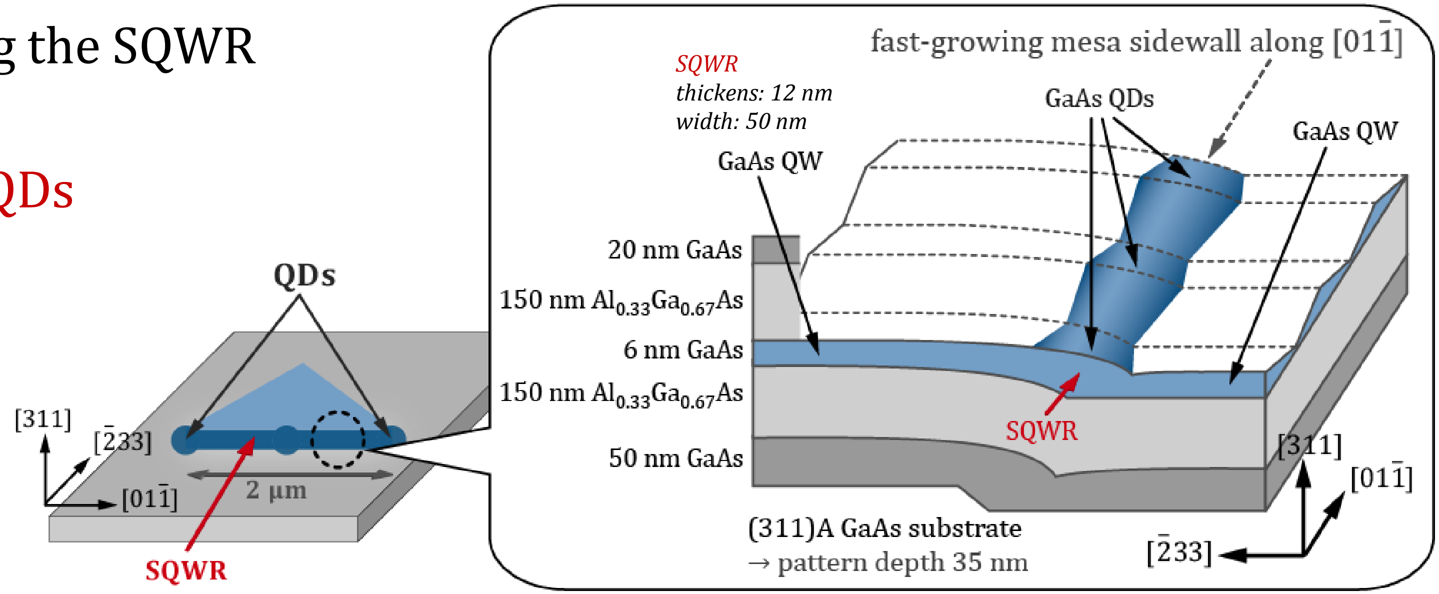


Short Quantum Wires (SQWRs)

Potential fluctuations along the SQWR

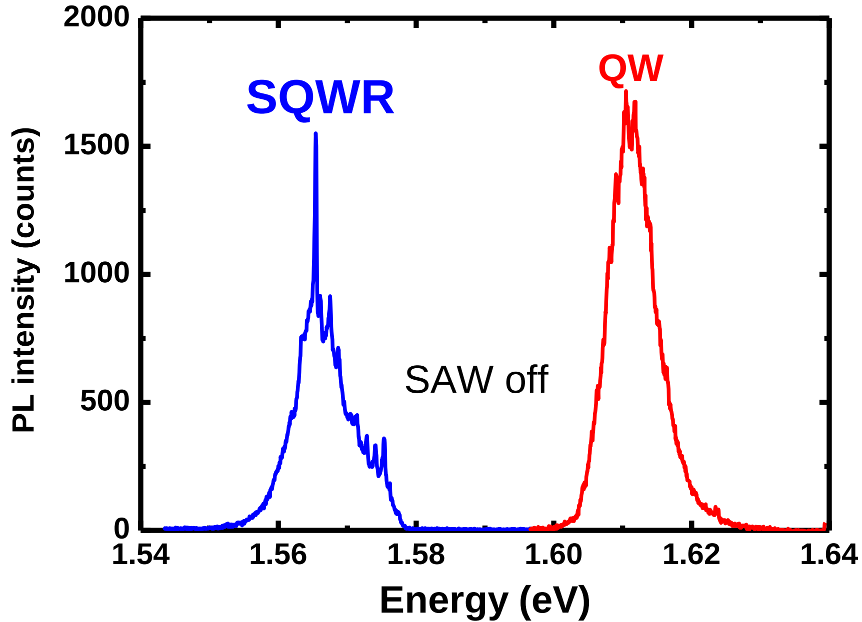
- ✓ Step-bunching
- → linear array of QDs

*Intonti et al., Phys. Rev. B **63**, 75313 (2001)*



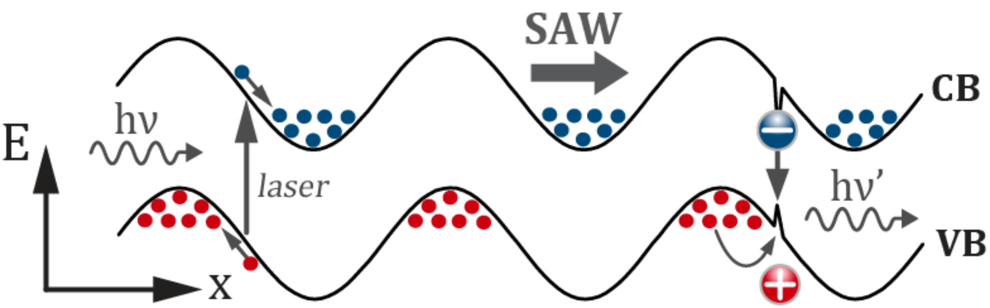
Spectral response from SQWRs

- ✓ Energy separation from the QW
- ✓ Sharp line are QD like states



Carrier injection

λ_{SAW}= 4 μm
f_{SAW}=750 MHz

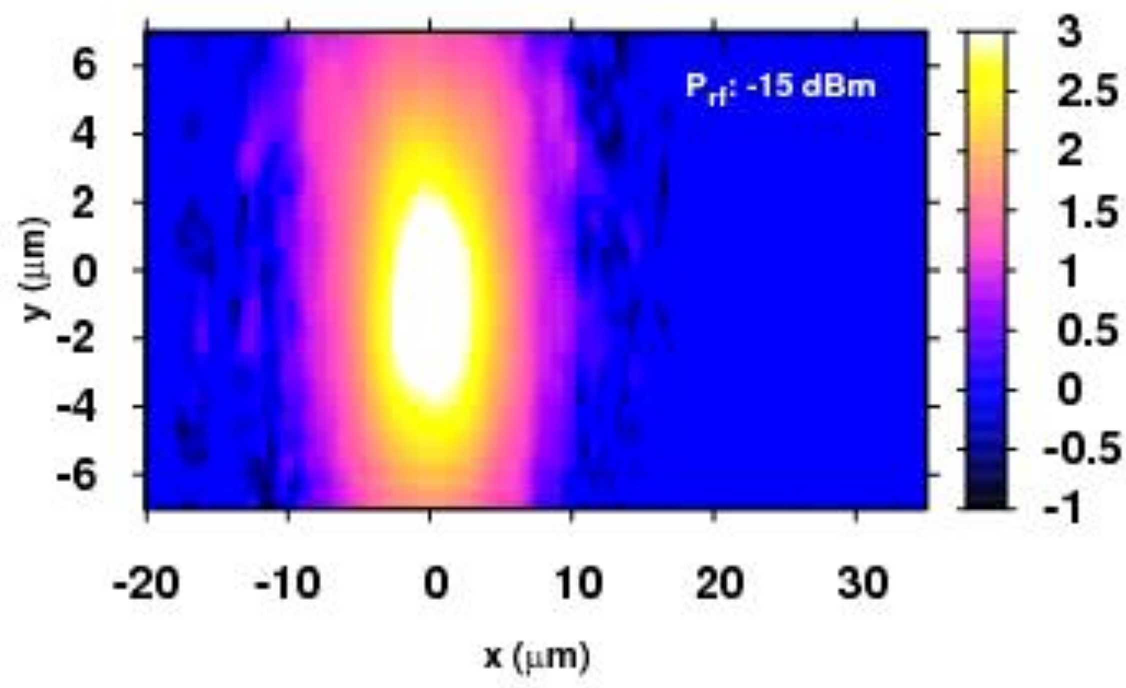


✓***coupling*** of different electronic systems:
carrier transport QW → SQWR

✓recombination dynamics
→ selection of a single QD within a SQWR

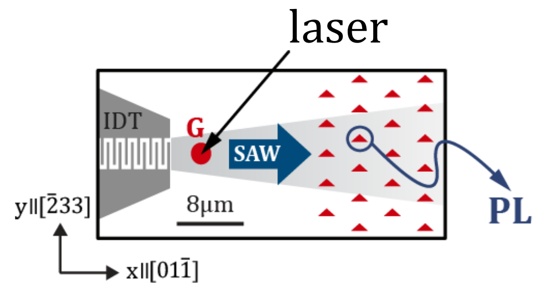
Carrier transport and injection

- Optical excitation in the QW
- ~ 20 µm from the SQWRs
- PL detection



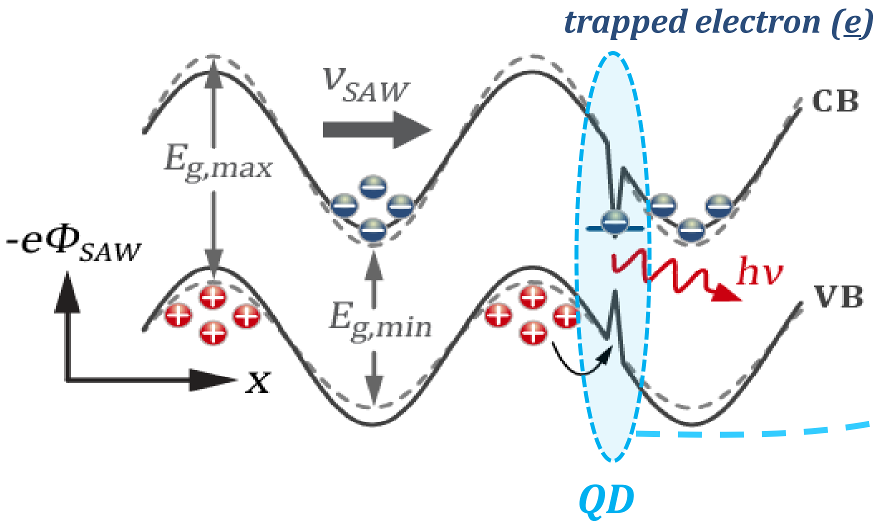
PL from a single SQWR

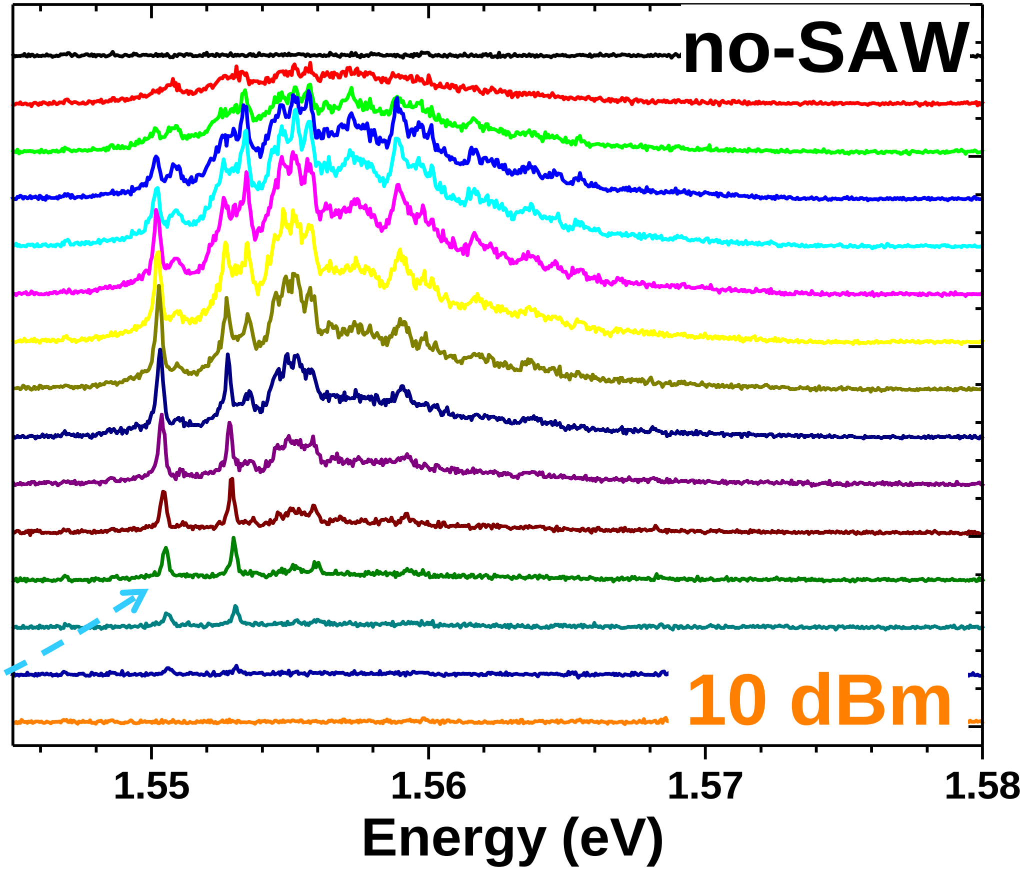
- ***low acoustic powers***
  - ✓large density of trapped electrons
- ***high acoustic powers***
  - ✓low density of trapped electrons
    - → fewer recombination events



sharp lines for high P_{SAW}

- localized states (QDs) within the SQWRs
  - ✓SAW amplitude → selection of single line

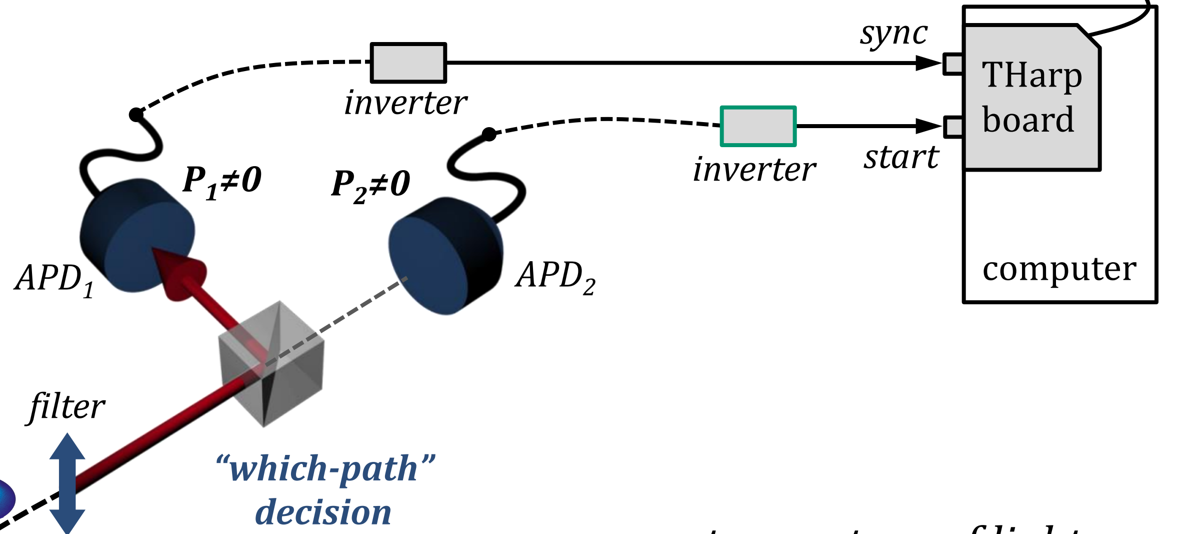


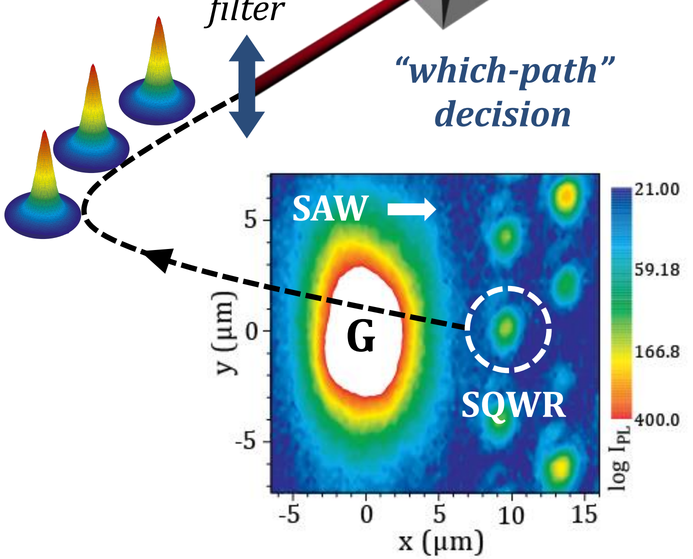


Photon correlation

Hanbury-Brown and Twiss setup

time interval between the successive photon-detection events at two detectors (APD)

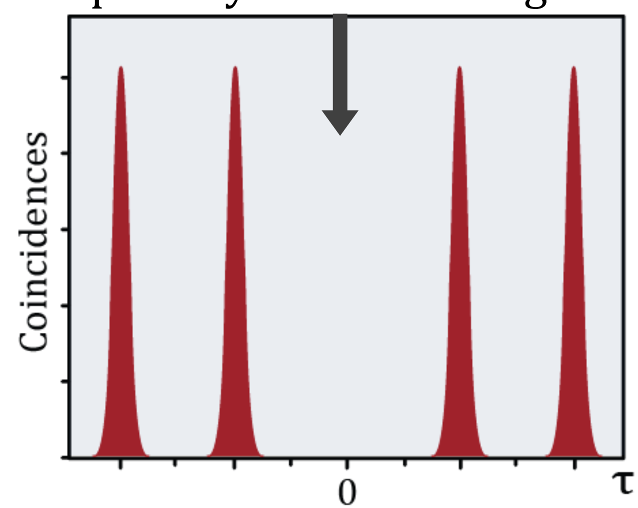




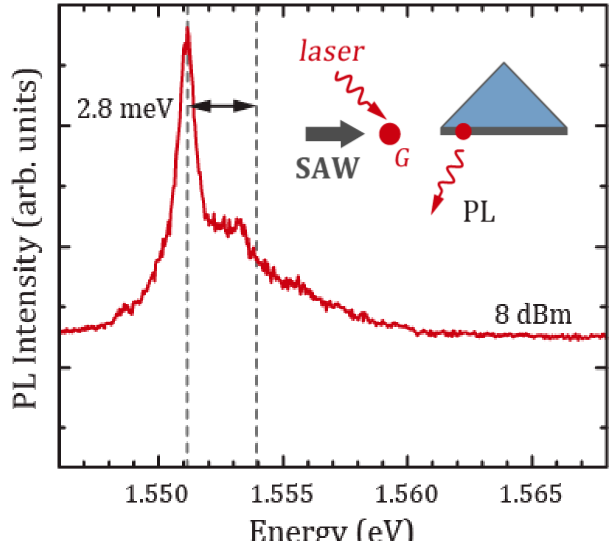
quantum nature of light

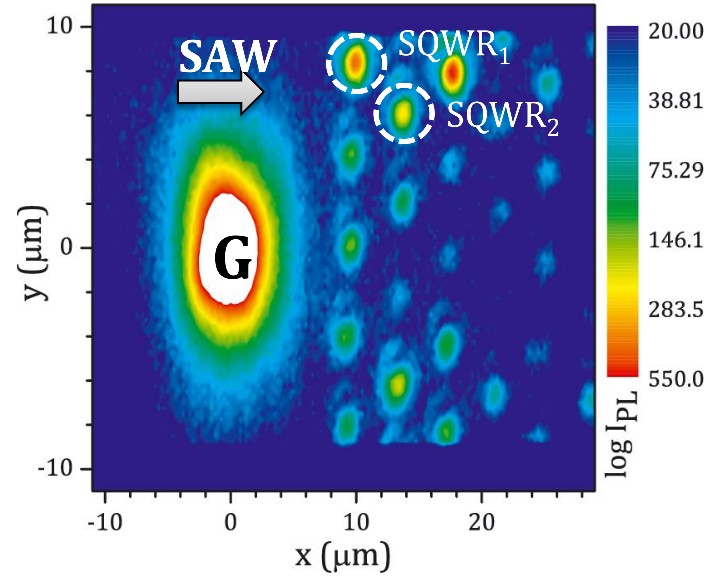
✓*joint photo-detection probability:* ***P = 0*** *at τ=0*

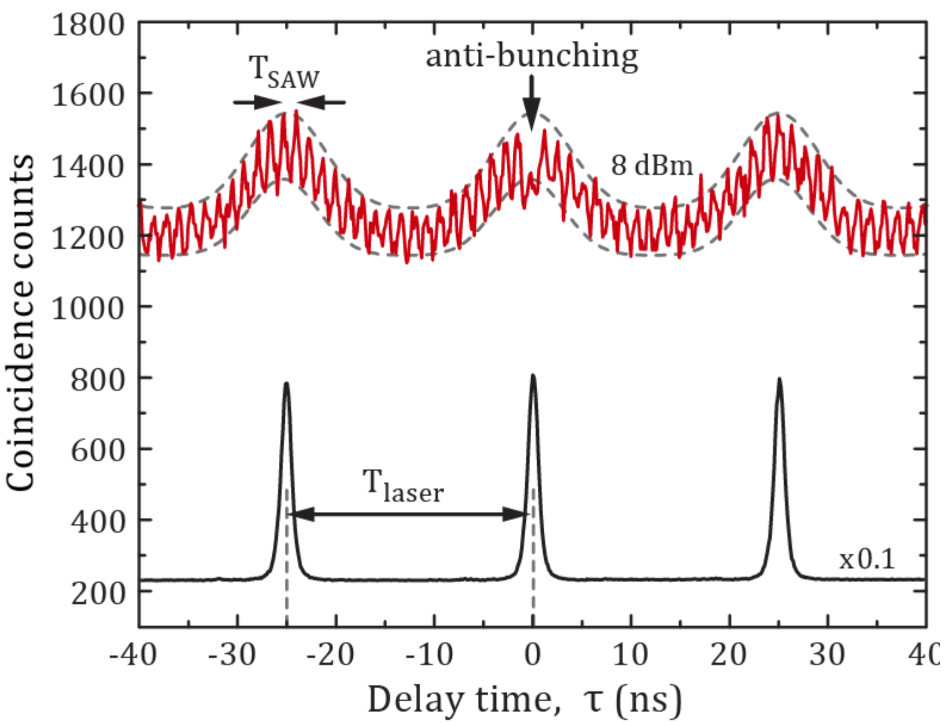
suppression of zero-delay peak by anti-bunching



Anti-buching

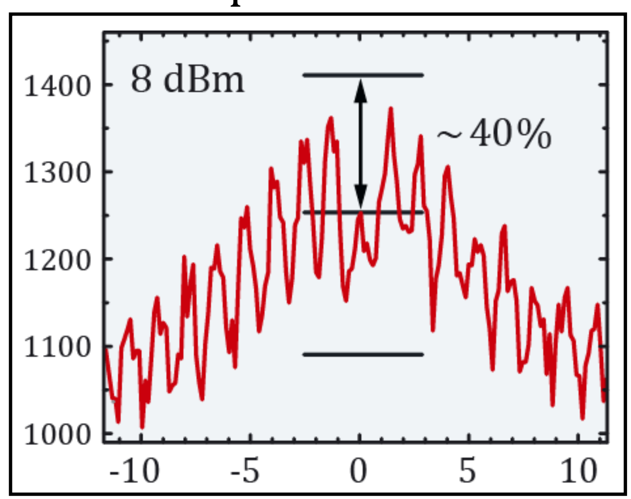




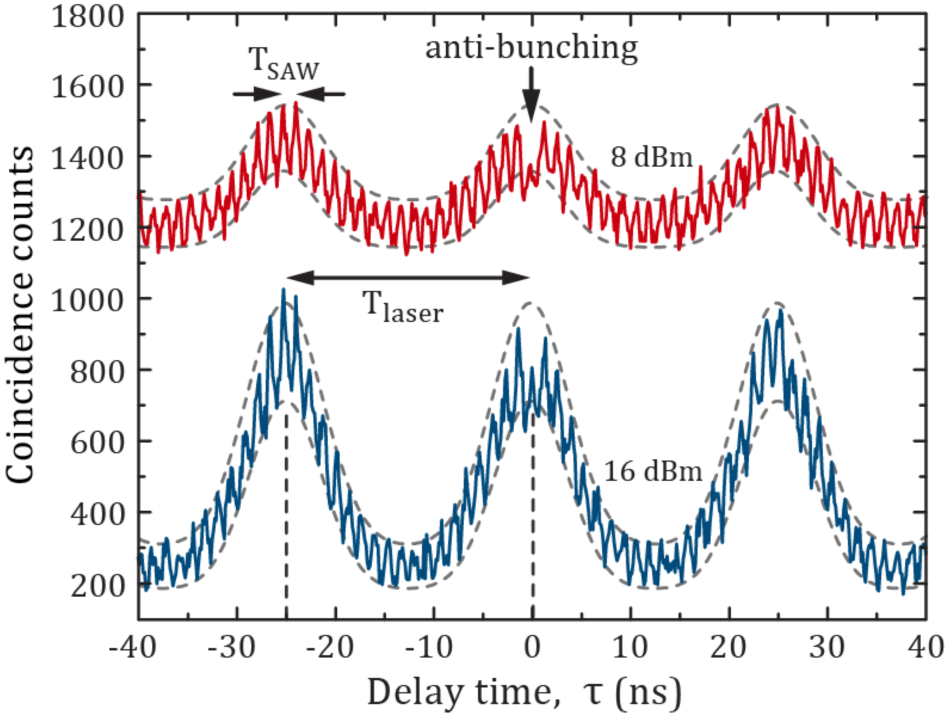


Reduced amplitude at *τ=0*

→lower probability for simultaneous emission of two photons



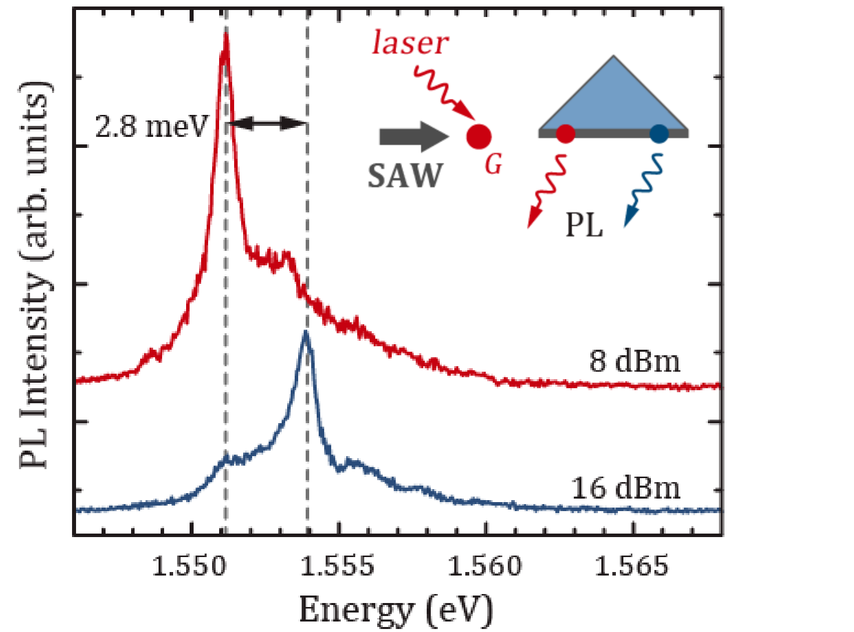
Anti-buching



Emission energy

✓Recombination depends on SAW power

→ selection of emission centre by controlling P_{rf}



- **SAW based SPS**
- Carrier injection from a QW into individual states of SQWRs
    - ~10 times faster (750 MHz) than optically pumped SPSs
- Adjustable emission energy

Nature Photonics ***3***, *645-648*

Outlook

Surface Acoustic Waves (SAWs)

- ✓ Powerful tool coupled to optical spectroscopy
- ✓ Modulation due to strain and piezoelectric fields
- ✓ Manipulation and transport of excitations in nanostructures
  - ✓ Carrier transport/injection
  - ✓ Spin transport
  - ✓ Single photon generation

- Basic research
- Applications

Acknowlegments

Optical modulation of semiconductor nanostructures

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