Ondas acústicas de superfície como ferramenta para estudo de nanoestruturas

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Outline

Introdução

Espectroscopia ótica de nanoestruturas semicondutoras

Ondas acústicas de superfície (SAW)

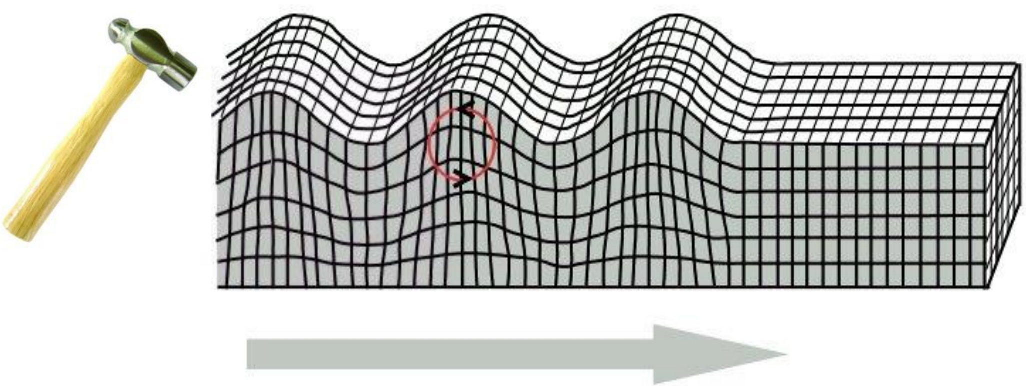
- **Transporte induzido acusticamente**
  - ✓ **Portadores (elétrons e buracos)**
    - ✓ **Spins**
  - ✓ **Injeção de portadores**
    - ✓ **Fonte de fótons únicos bombeada acusticamente**
- **Perspectivas**

Conclusão

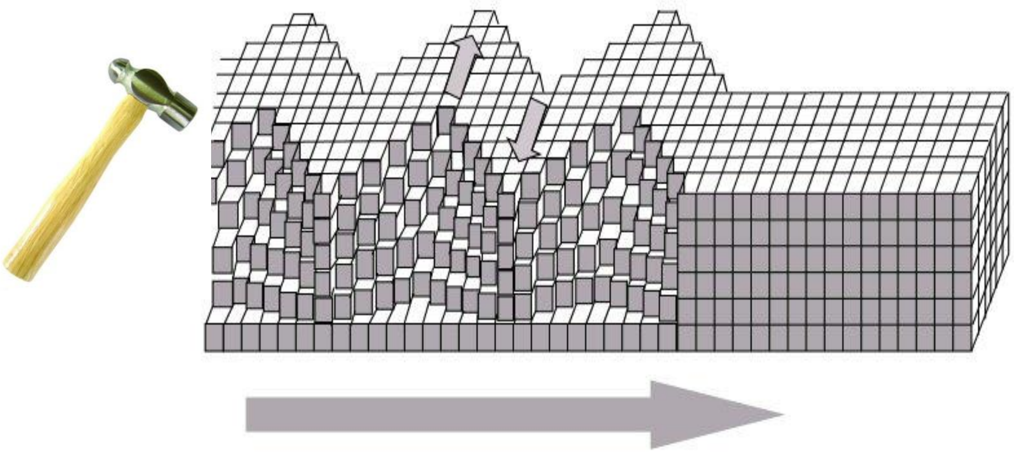
SAW

Elastic wave propagating on the surface of solids

Rayleigh Wave



Love Wave



Applications:

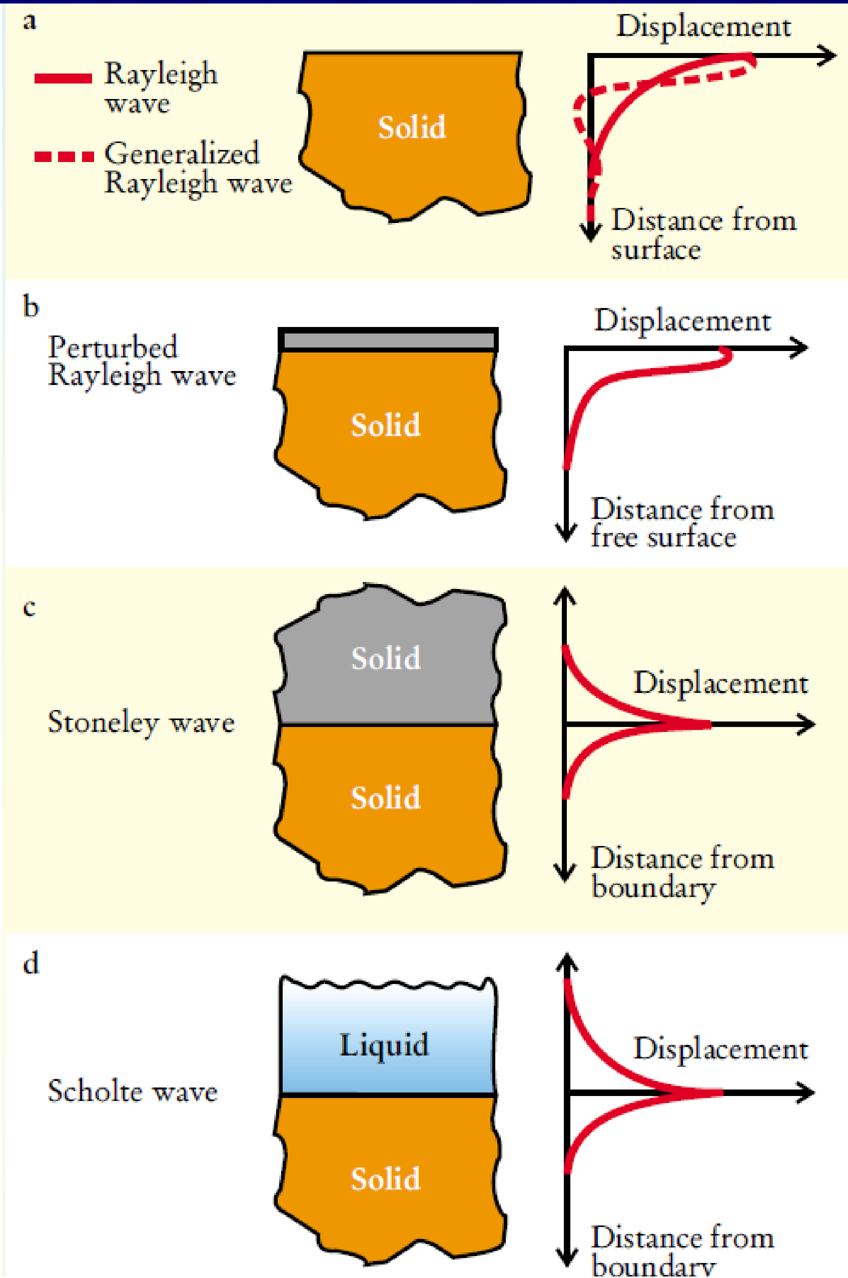
- Mobile, Wireless communication
    - Sensors, filters, resonators….

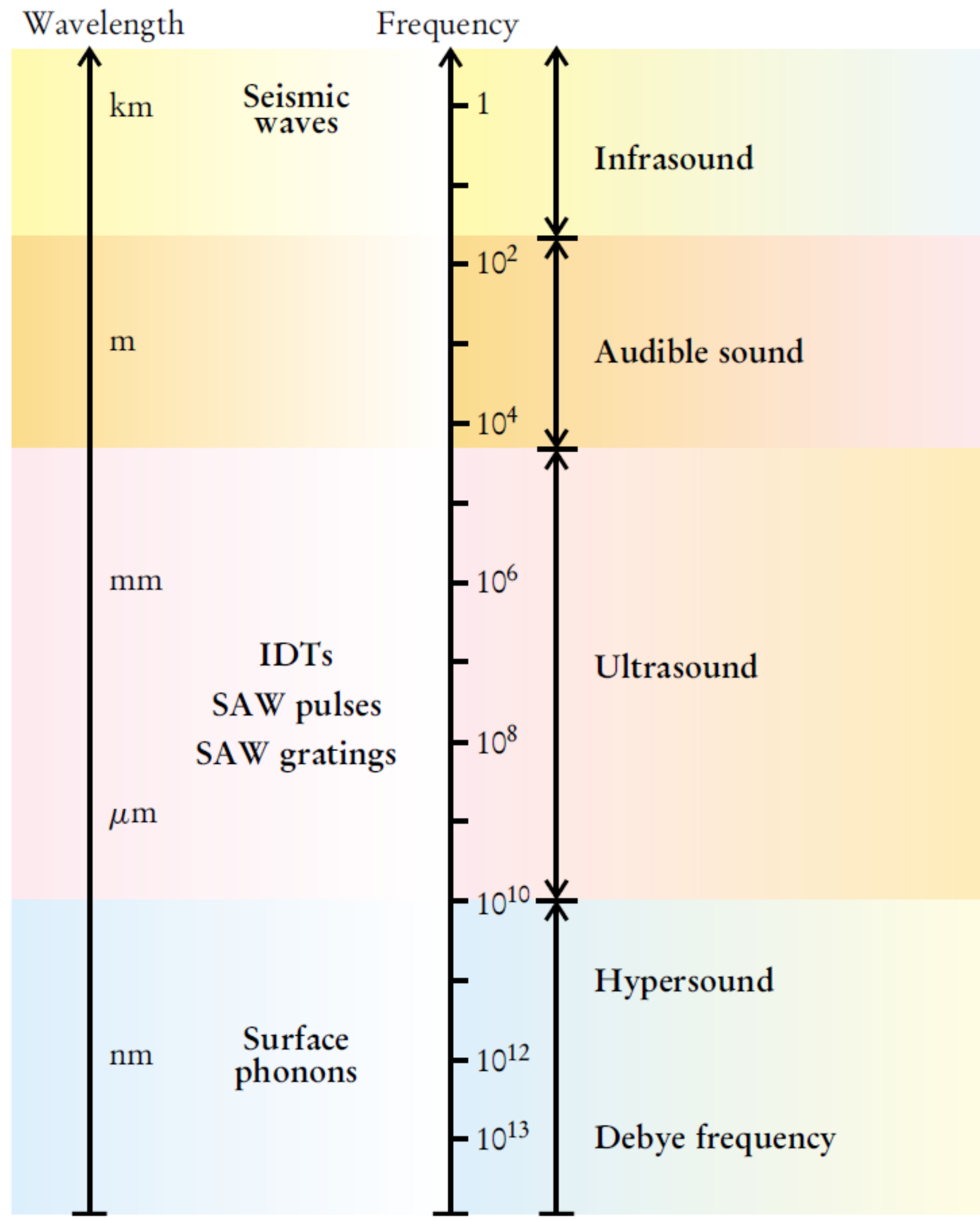
Estimate

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

SAW Touch Screen Technology

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
Ultrasound
IDTs
SAW pulses
SAW gratings
10^8
μm
10^{10}
Hypersound
nm
Surface phonons
10^{12}
10^{13}
Debye frequency

Motivação (a melhor que já vi)

"Chemical and biological-based surface acoustic wave (SAW) sensors will be an important part of fulfilling the Air Force goal of global situational awareness (GSA). "

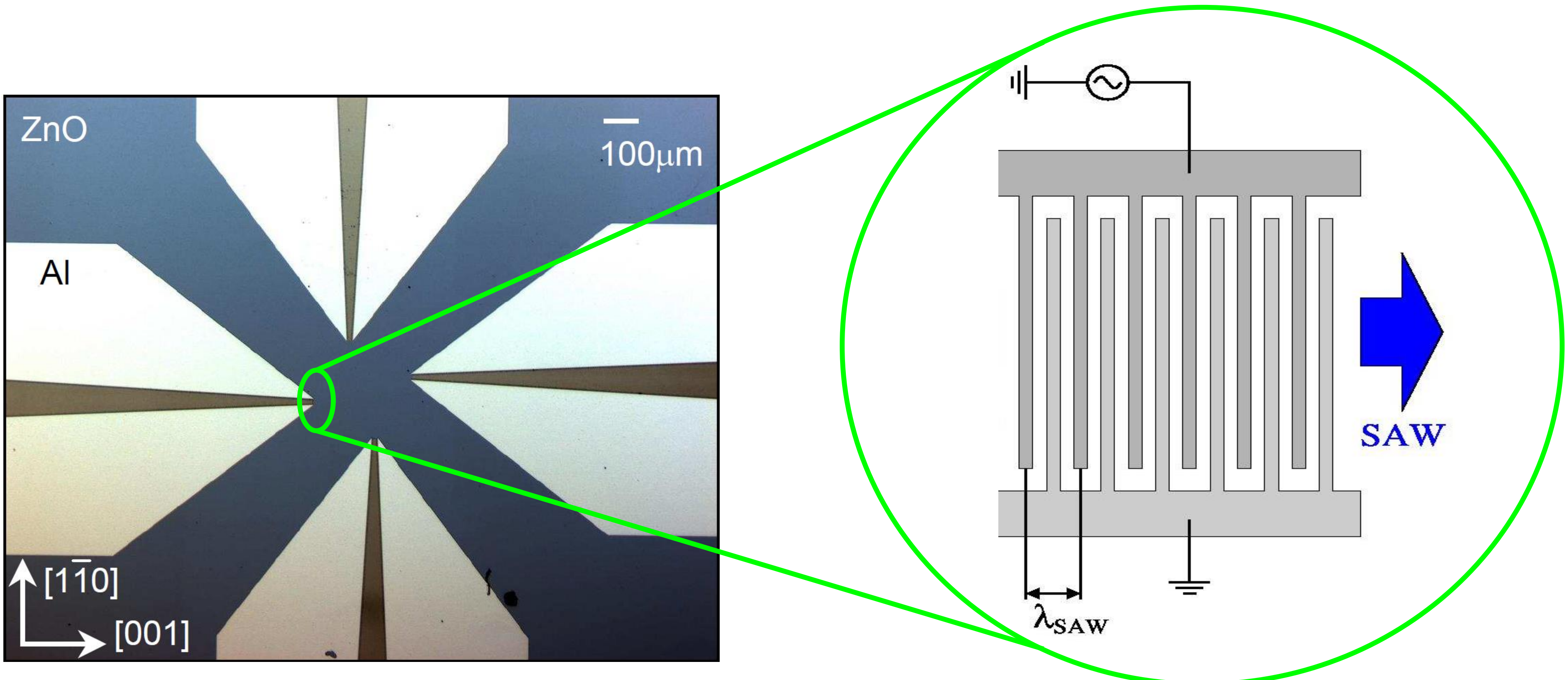
"A part of GSA, the Air Force Research Laboratories Focused Long Term Challenge (FLTC) # 3's stated goal is to have the ability to "**detect, identify, tag, track, and target adversaries, improvised explosive devices (IED), and Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) weapons in congested or concealed environments**" ".

How to generate SAWs

Photolithography

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

Poço Quântico



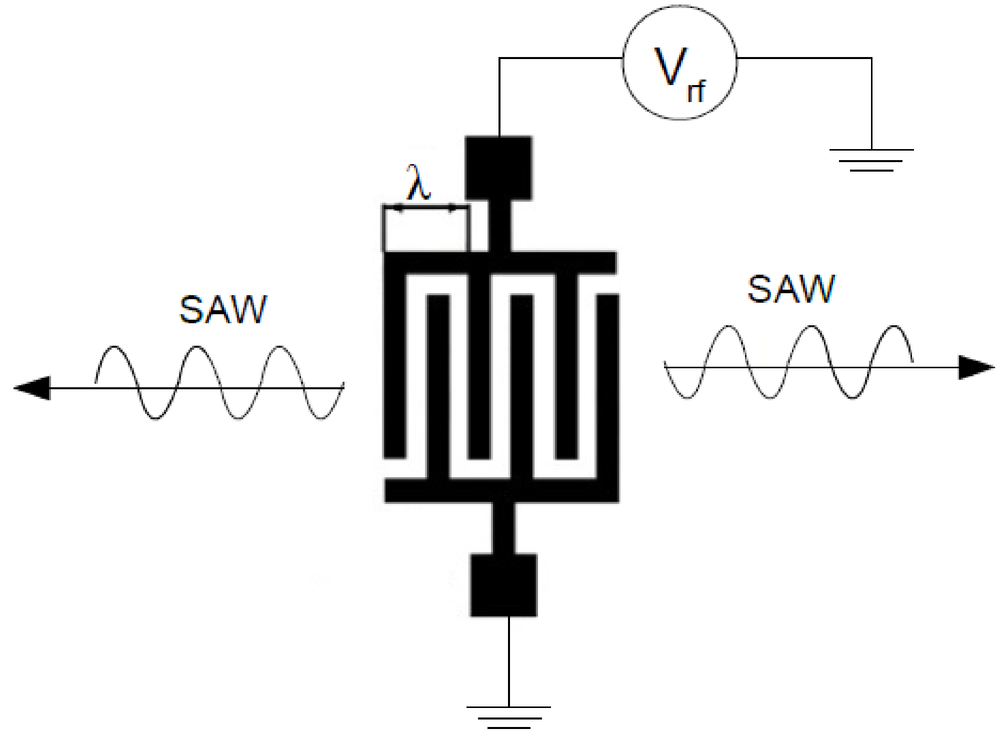
How to generate SAWs

Piezoelectric substrate

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

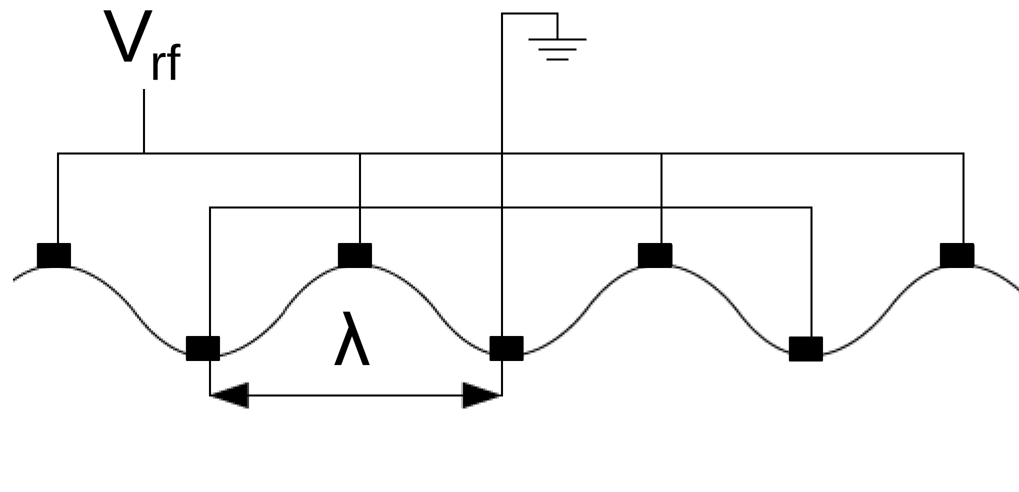
rf-signal

- Efeito piezoelétrico inverso
- Feixe de SAW é lançado



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

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

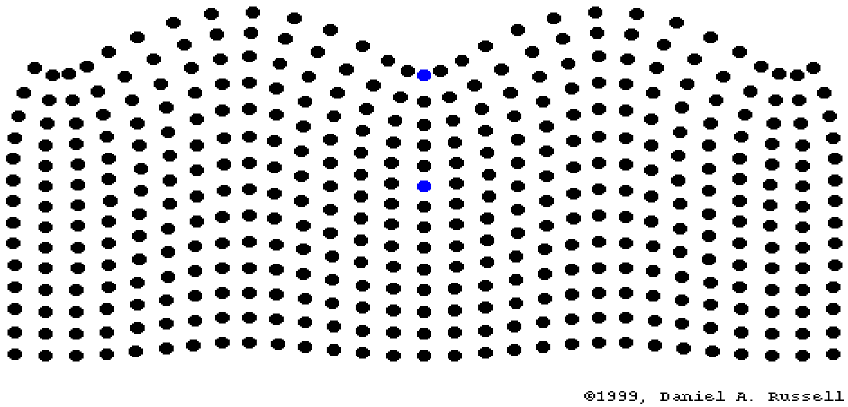


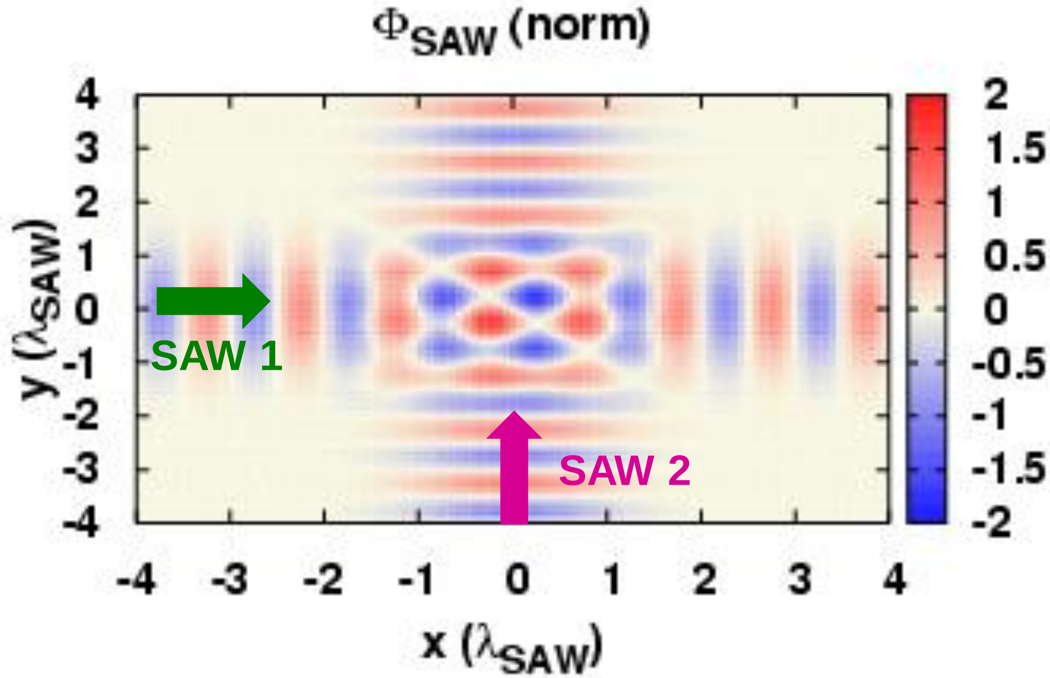
In GaAs $\rightarrow$ $v_{SAW} \approx 3000\, m/s$

$f_{SAW} \approx MHz - GHz$

Acoustic modulation

Rayleigh SAW





Acoustic Modulation

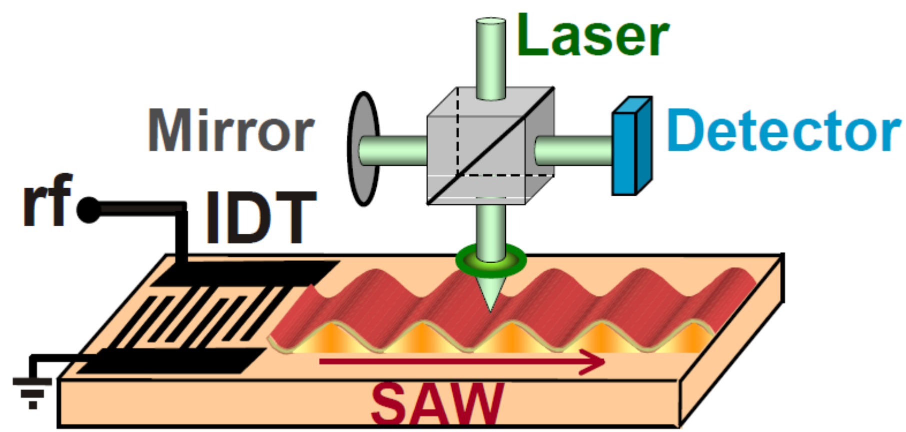
✓ Local non-destructive tool for application of piezoelectric and strain fields

On the surface

✓ Waveguides, quantum wires

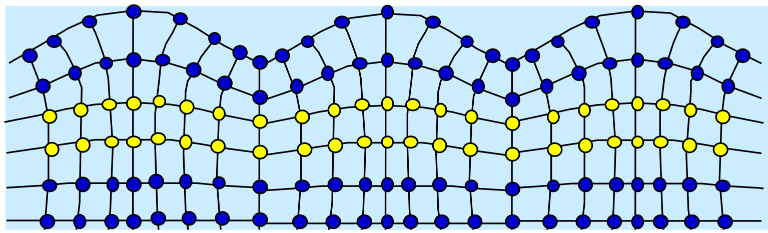
Few nanometers bellow the surface

✓ Quantum wells, quatum dots



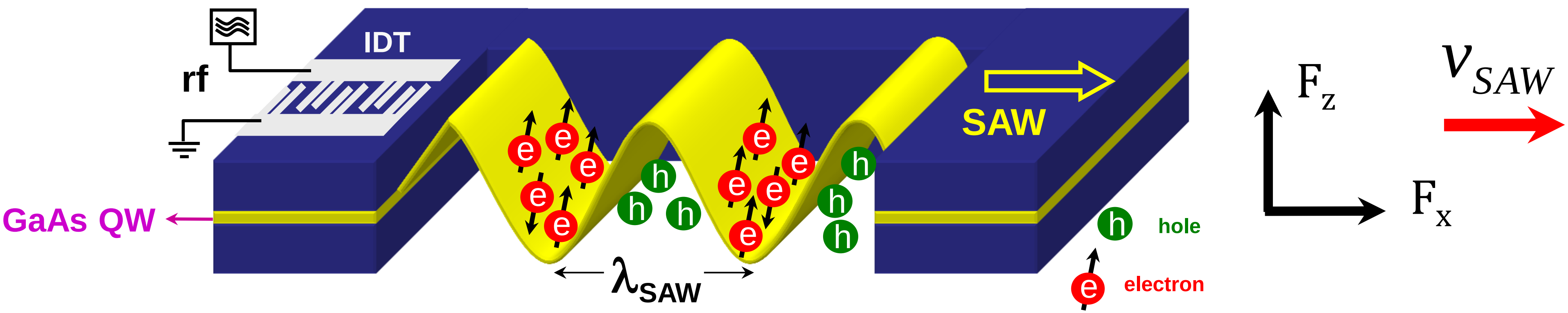
Acoustically induced transport

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

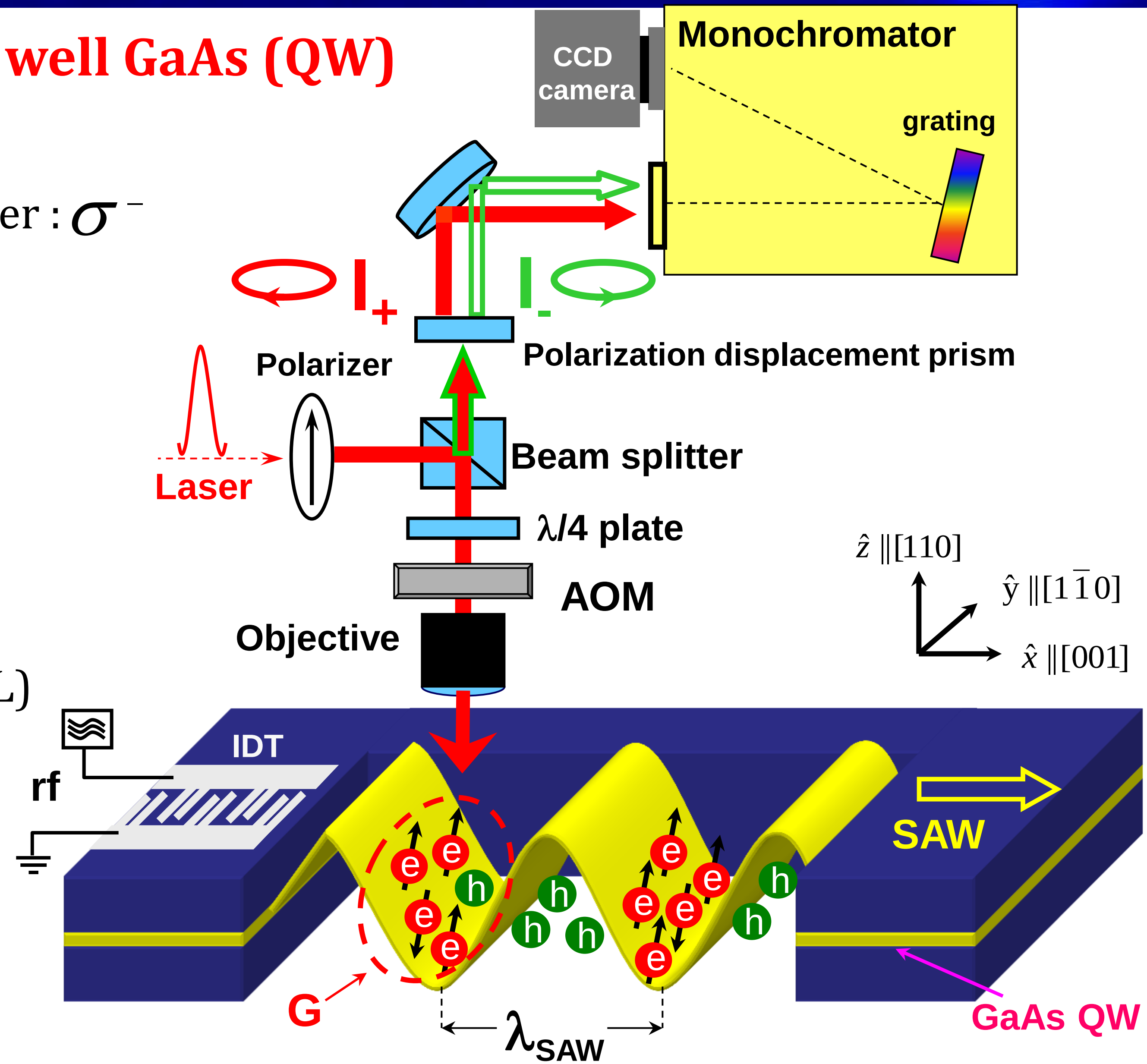
- SAW piezoelectric field (ϕ_{SAW})

Detection

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

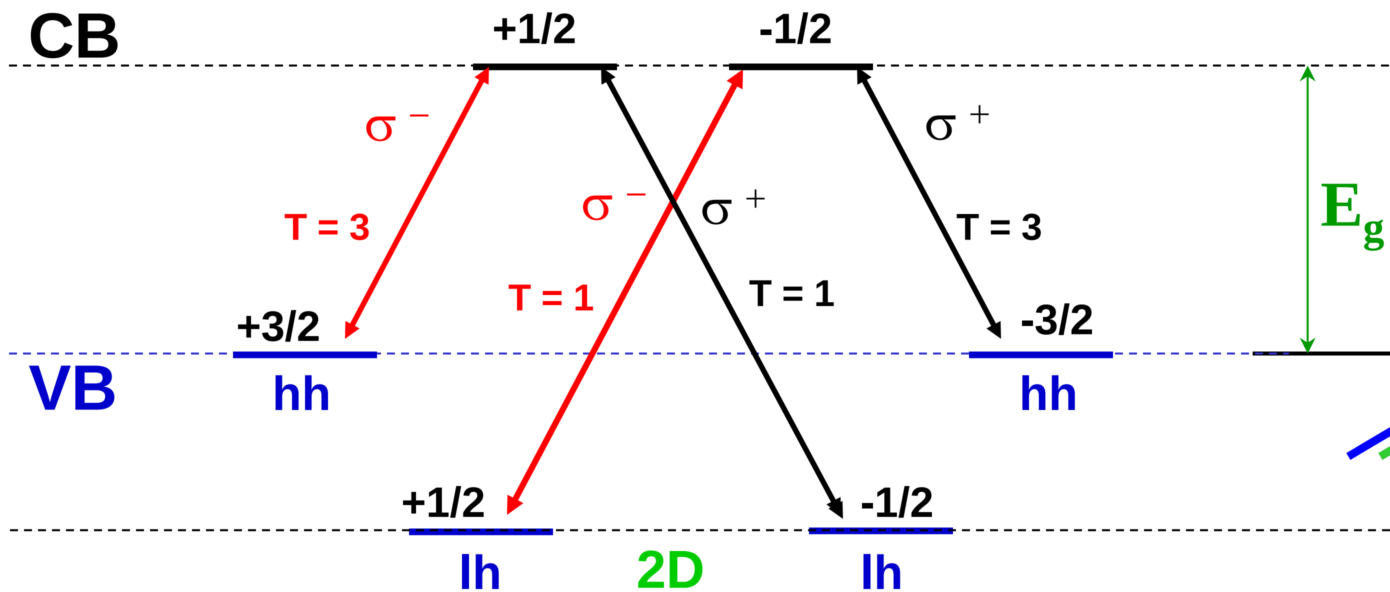
Spin polarization degree

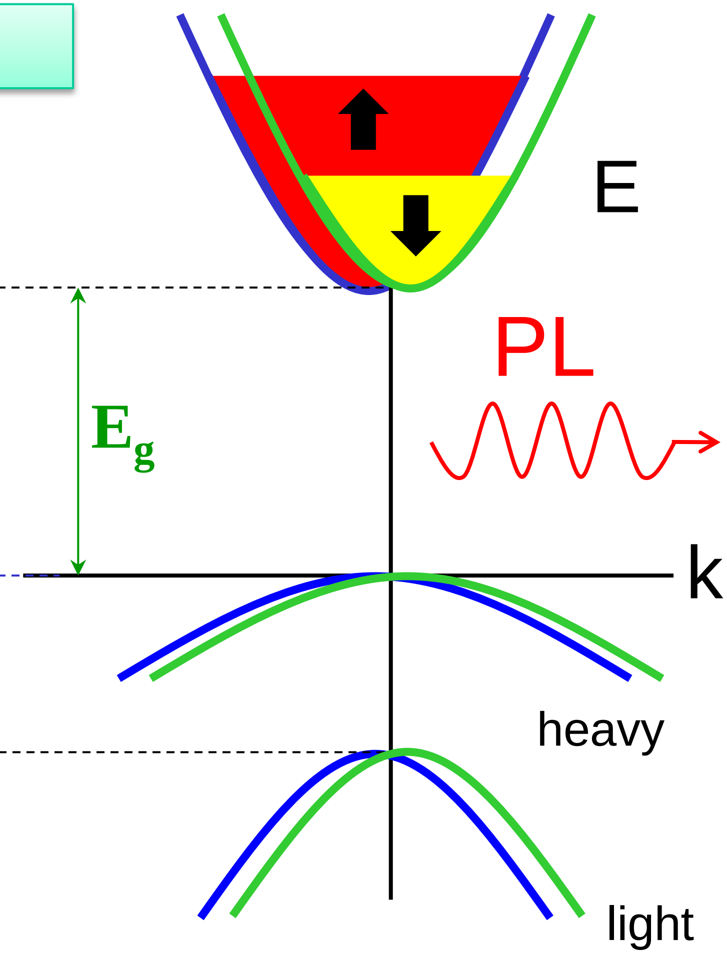
$$\rho_z = \frac{I_+ - I_-}{I_+ + I_-}$$



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

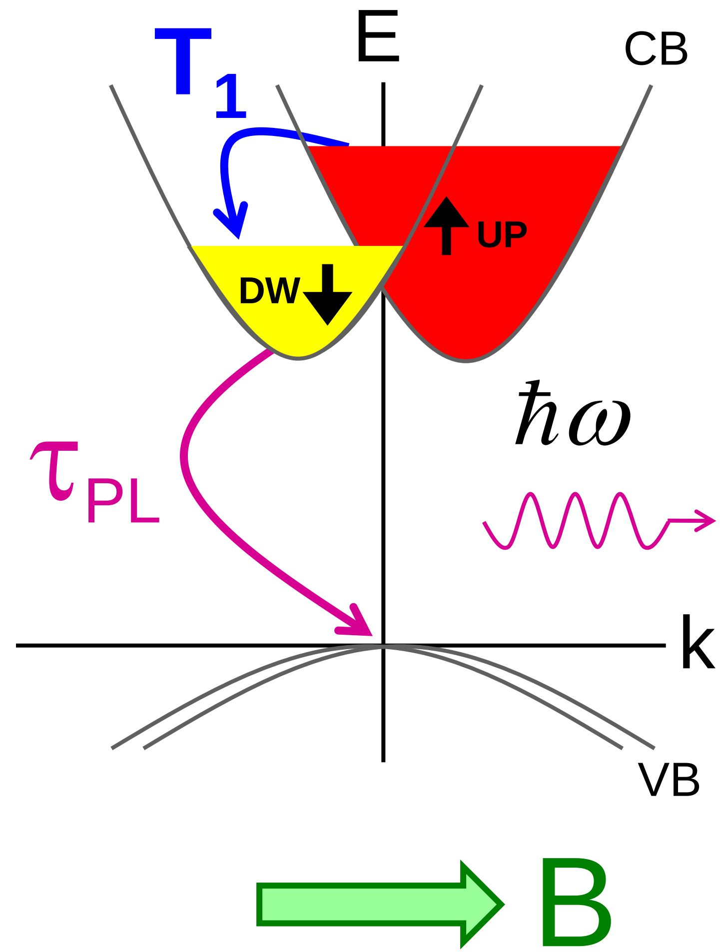
- ✓ Carrier lifetime → τ_{PL}
- ✓ Spin relaxation time → T_1

If there is a transverse magnetic field

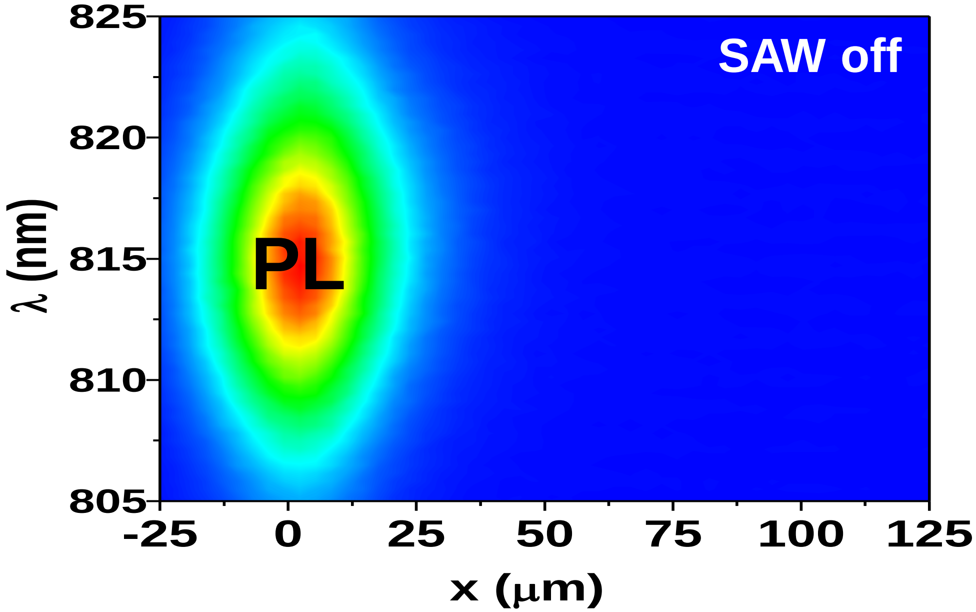
- ✓ Spin decoherence time → $T_2 > T_2^*$

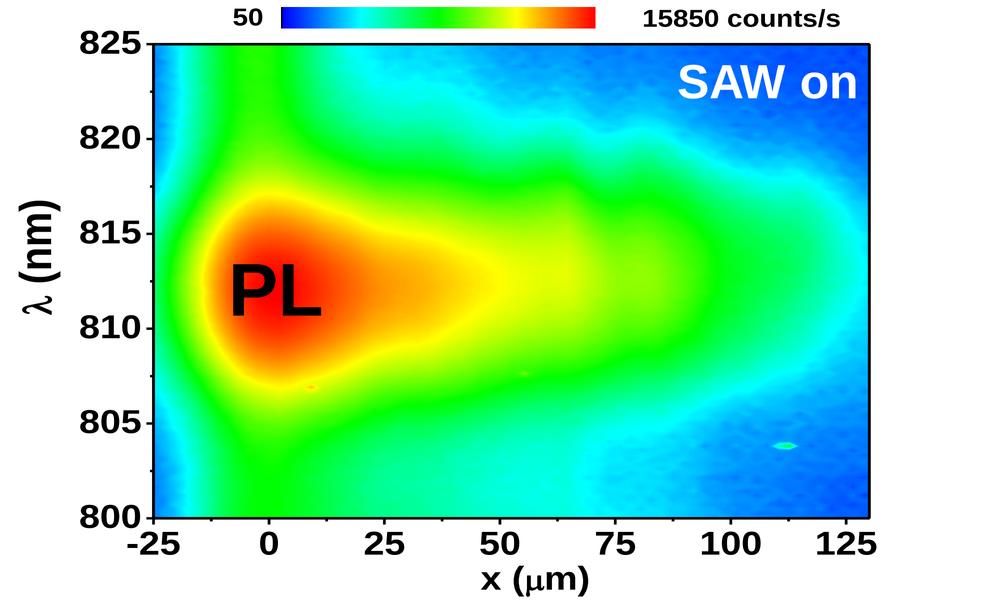
Spin lifetime

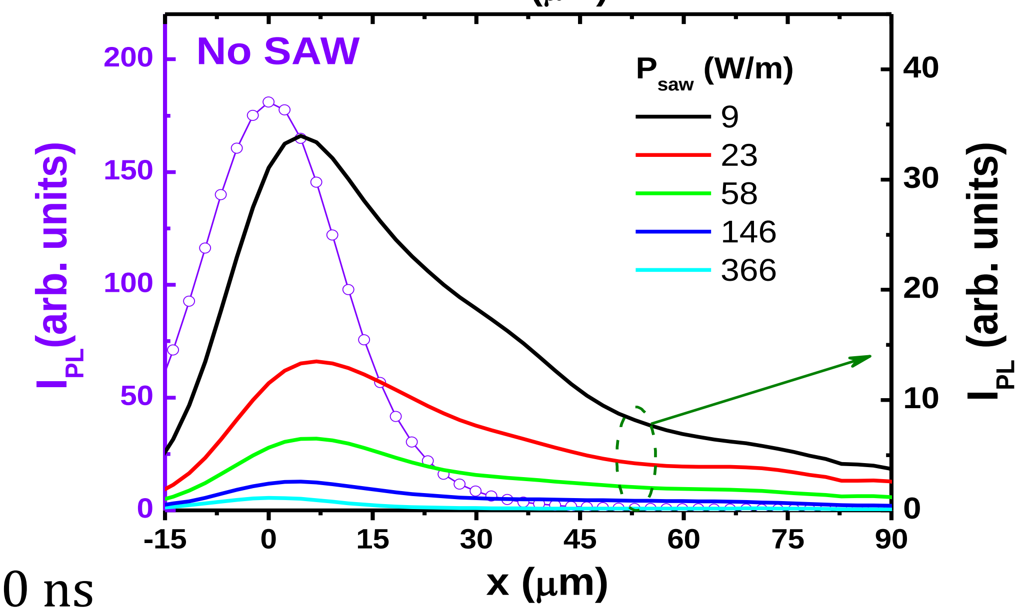
$$\frac{1}{\tau_s} = \frac{1}{T_1} + \frac{1}{T_2^*}$$



Carrier transport







Continuous PL detection

Carrier transport

✓ SAW off

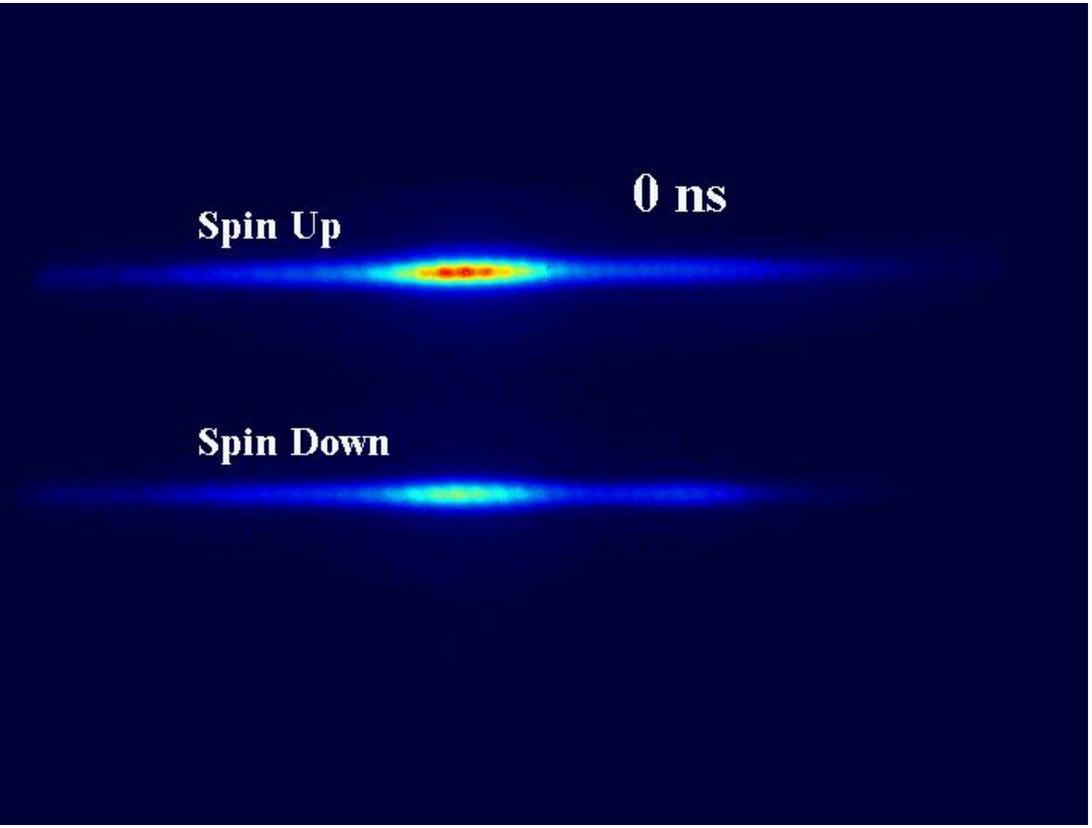
✓ Carrier diffusion → $\tau_{PL} \sim 1$ ns

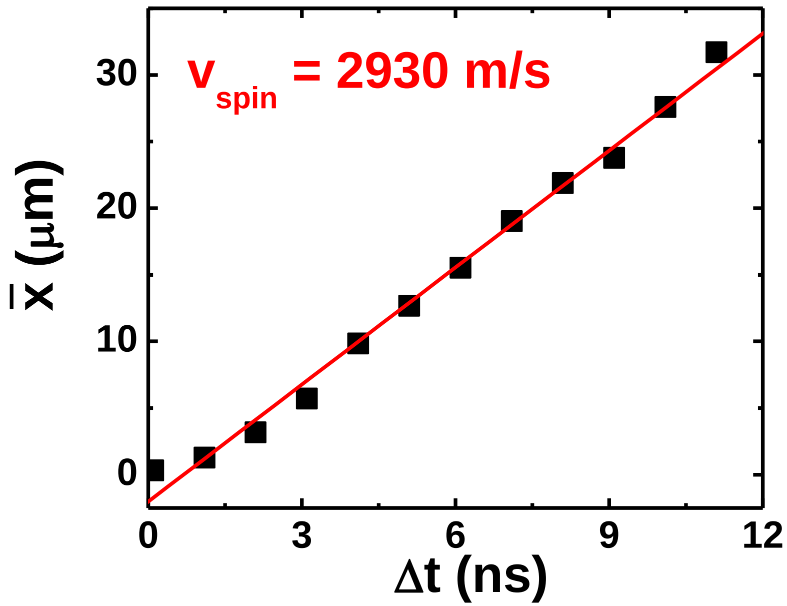
✓ SAW on

✓ PL quenching ~ 90 times for high acoustic powers

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

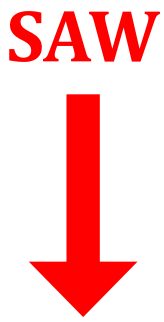
Time-resolved detection

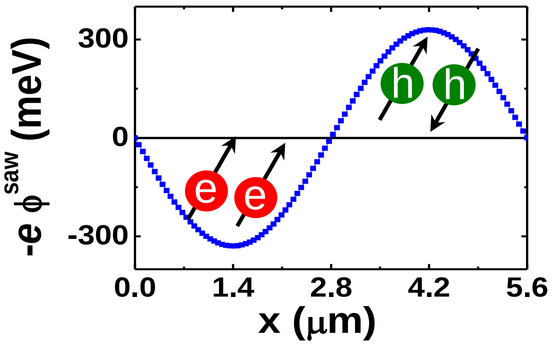




Coherent carrier transport

- ✓ Well-defined carrier packets
- ✓ $v_{spin} = v_{SAW}$

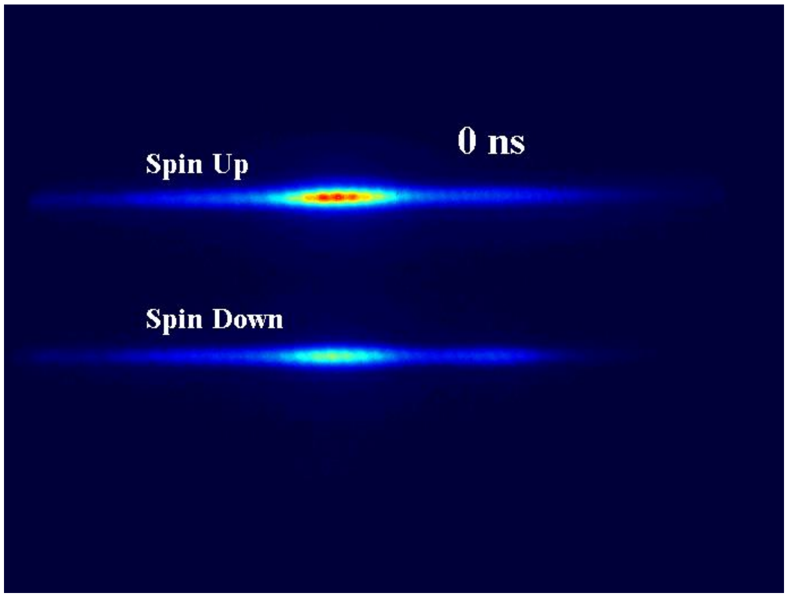




Spin transport (110) QWs

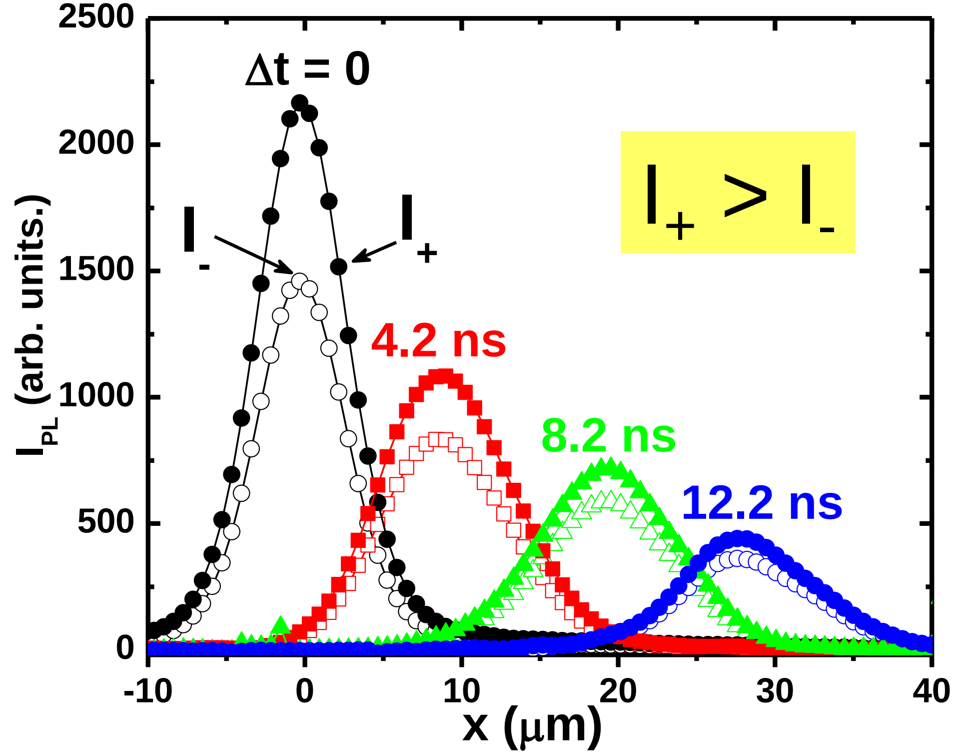
Time-resolved PL detection

- Electron-heavy hole transition



x || [001]

SAW

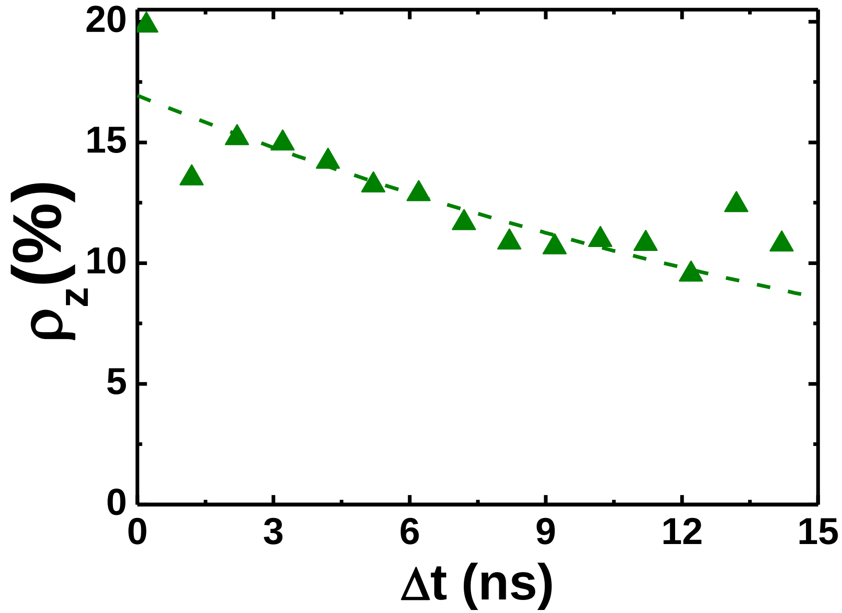


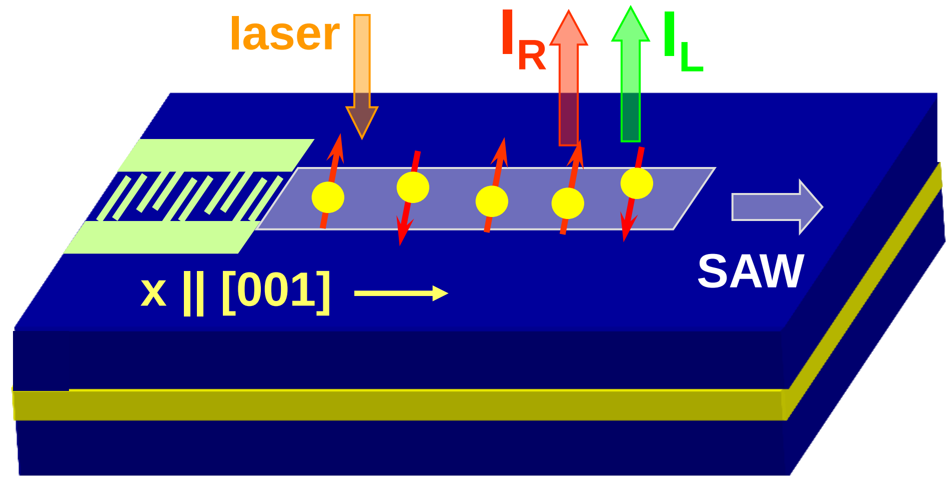
$I_R \propto n_\uparrow$ and $I_L \propto n_\downarrow$

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

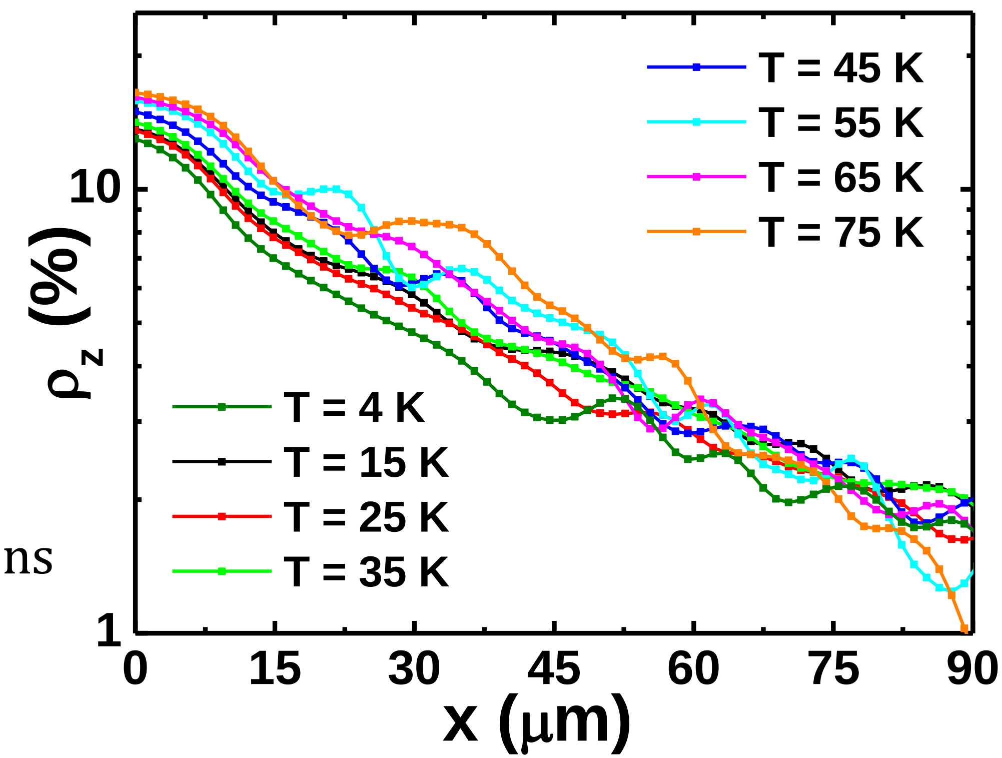
Temperature

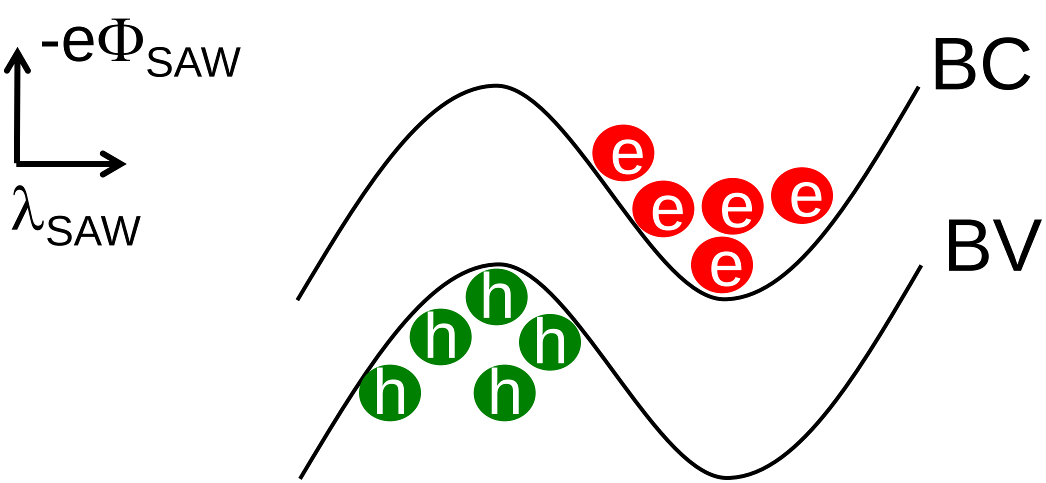
✓ Spin decay is independent of T up to 75 K

✓ SAW piezoelectric field avoids electron-hole recombination

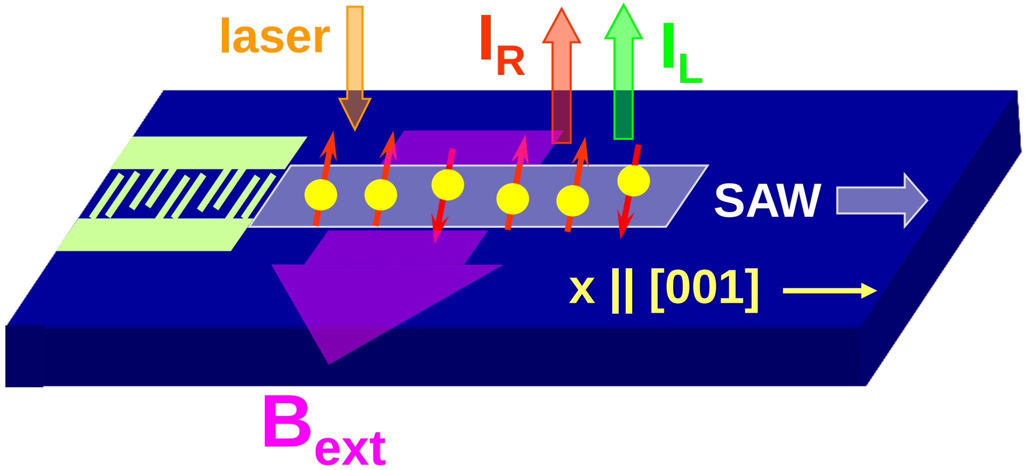
✓Spin transport at liquid nitrogen temperature

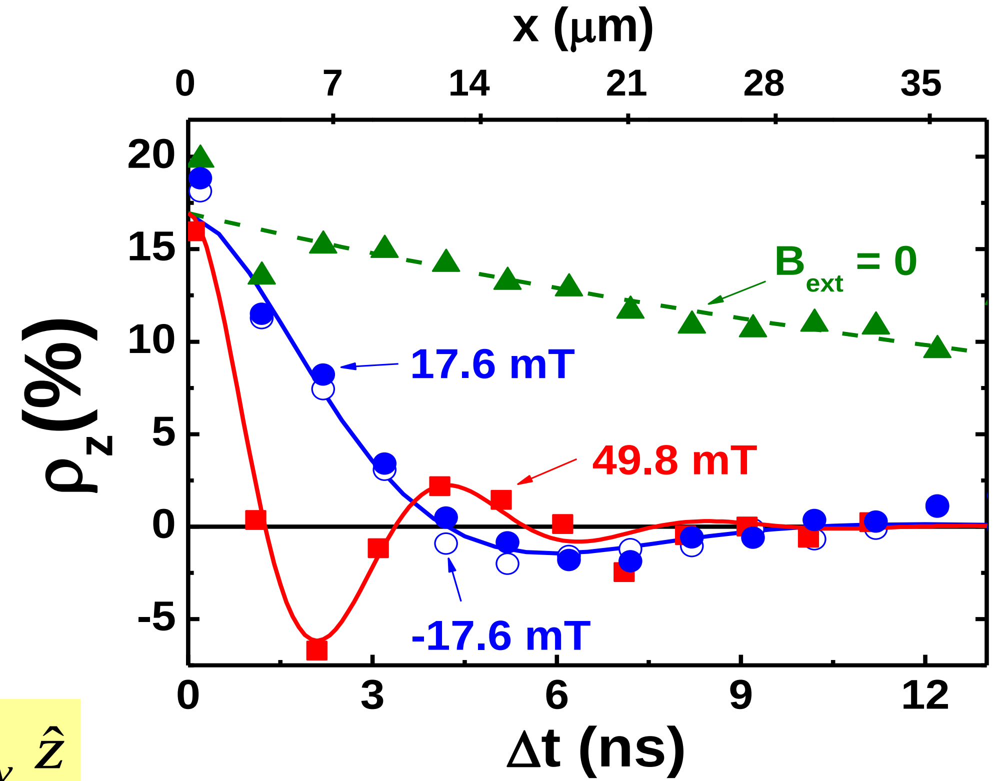
✓ Interesting for future applications





Spin manipulation

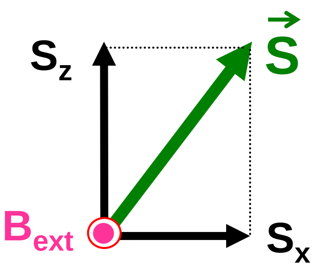




- Spin precession around B_{ext}
  - Precession is damped
    - Spin dephasing

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

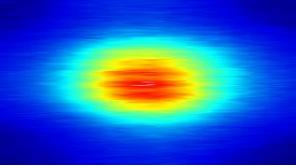
B_{int} || z fluctuates



- High in-plane relaxation rates appear

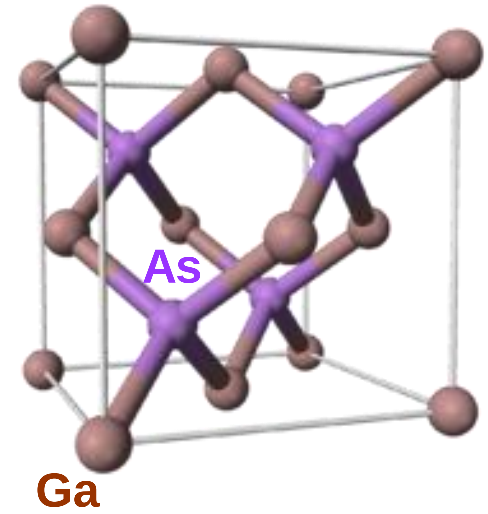
Effective spin dephasing time: $T_2^* = 2.3\ ns$

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

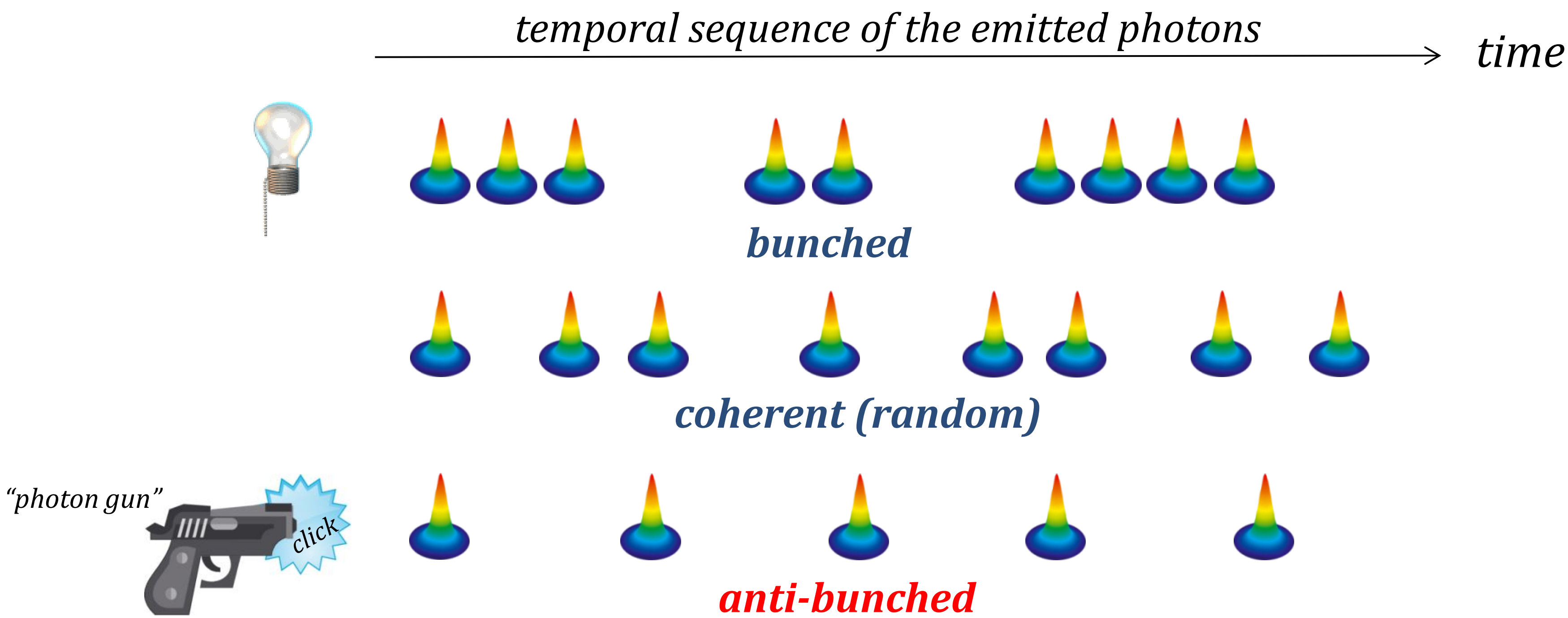
- ✓ SAW confinement potential screens electron spins → T_1 ~ 22 ns

* 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)

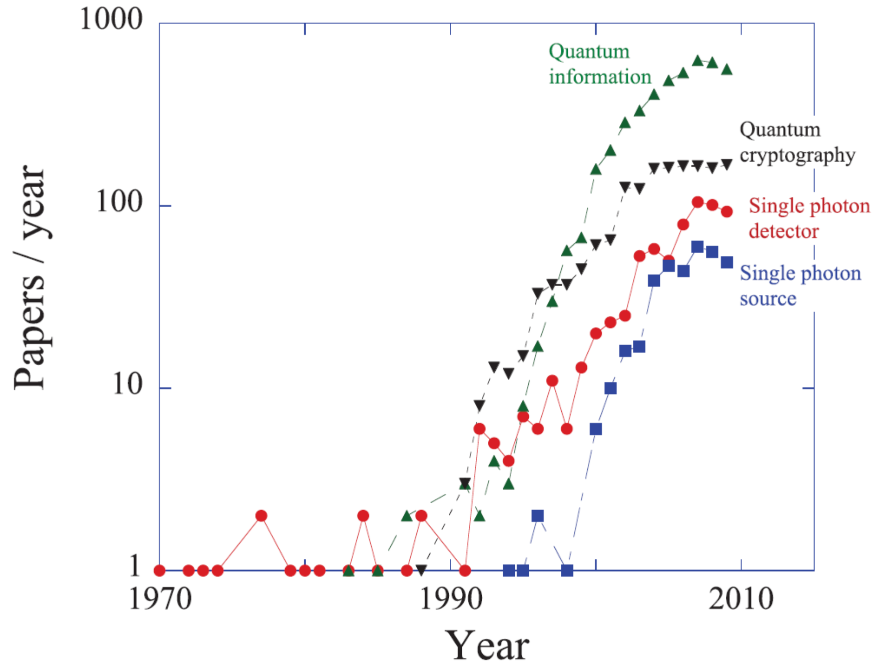
SPS applications

Why do we need SPSs? ** B. Lounis and M. Orrit, "Single-photon sources", Rep. Prog. Phys.* ***68****, 1129 (2005)*

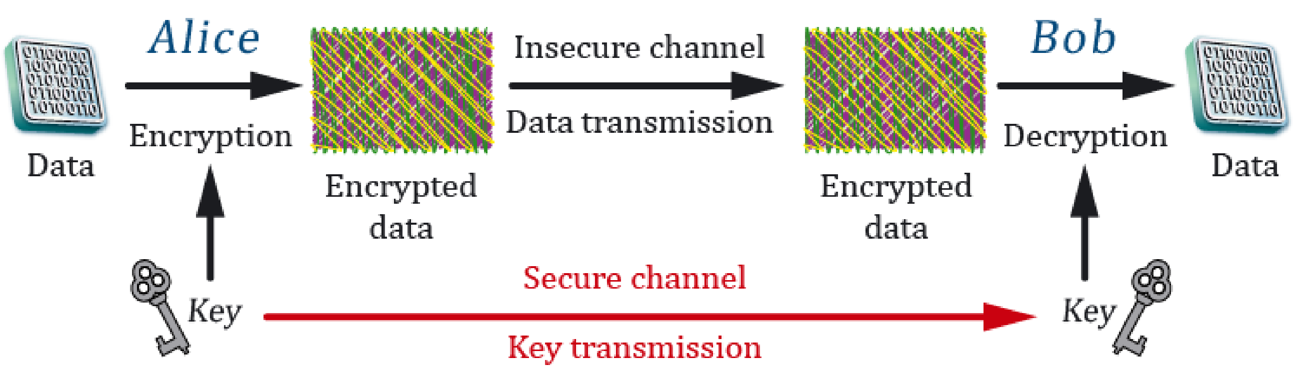
- fundamental tests of quantum mechanics

- quantum information processing
  - ✓ quantum computation
  - ✓ quantum cryptography
    → secure quantum key distribution

  by single photon pulses



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

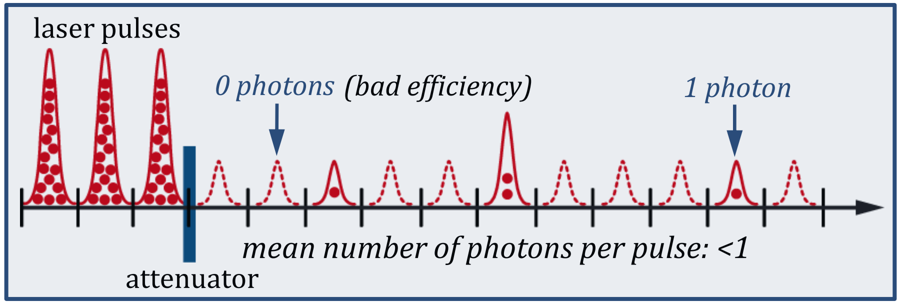


How to make a SPS

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

⁕ *early and macroscopic*

✓faint laser source

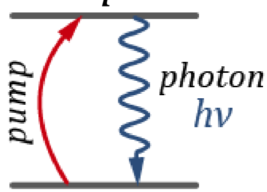


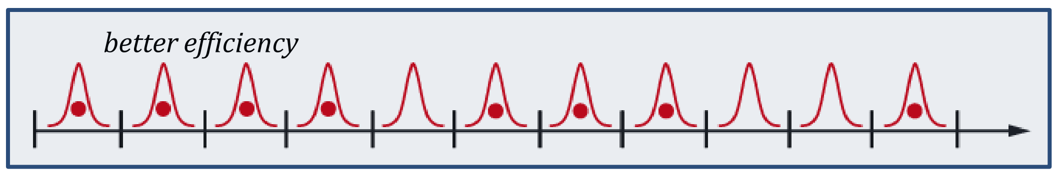
H.J. Kimble et al., PRL **39, 691 (1977)*
D.F. Walls Nature **280, 451 (1979)*

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

⁕ *microscopic*

✓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

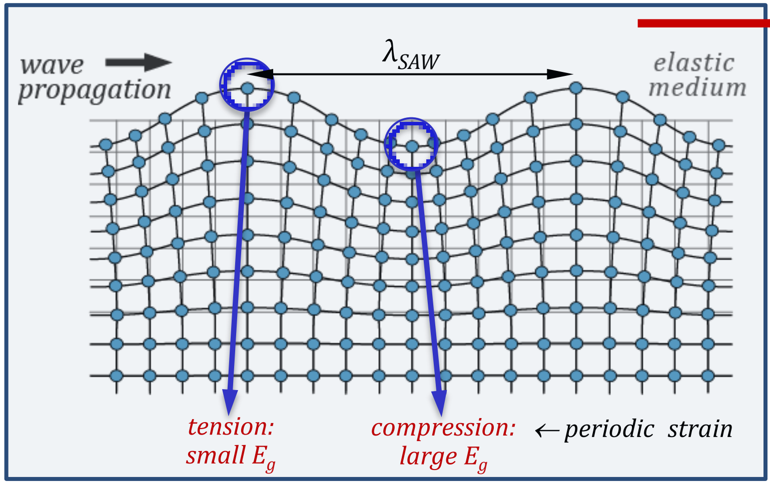
→ alternative way to generate semiconductor-based SPSs

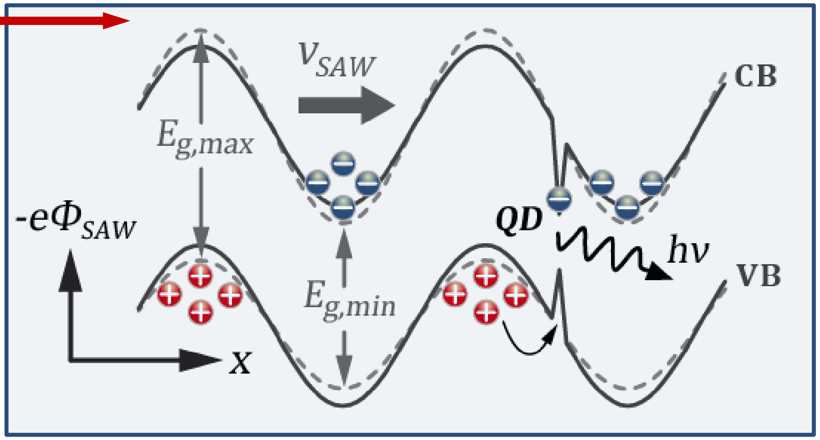
SAW → surface elastic vibrations (acoustic phonons)

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

Modulation mechanisms

strain field *piezoelectric materials* *piezoelectric field*





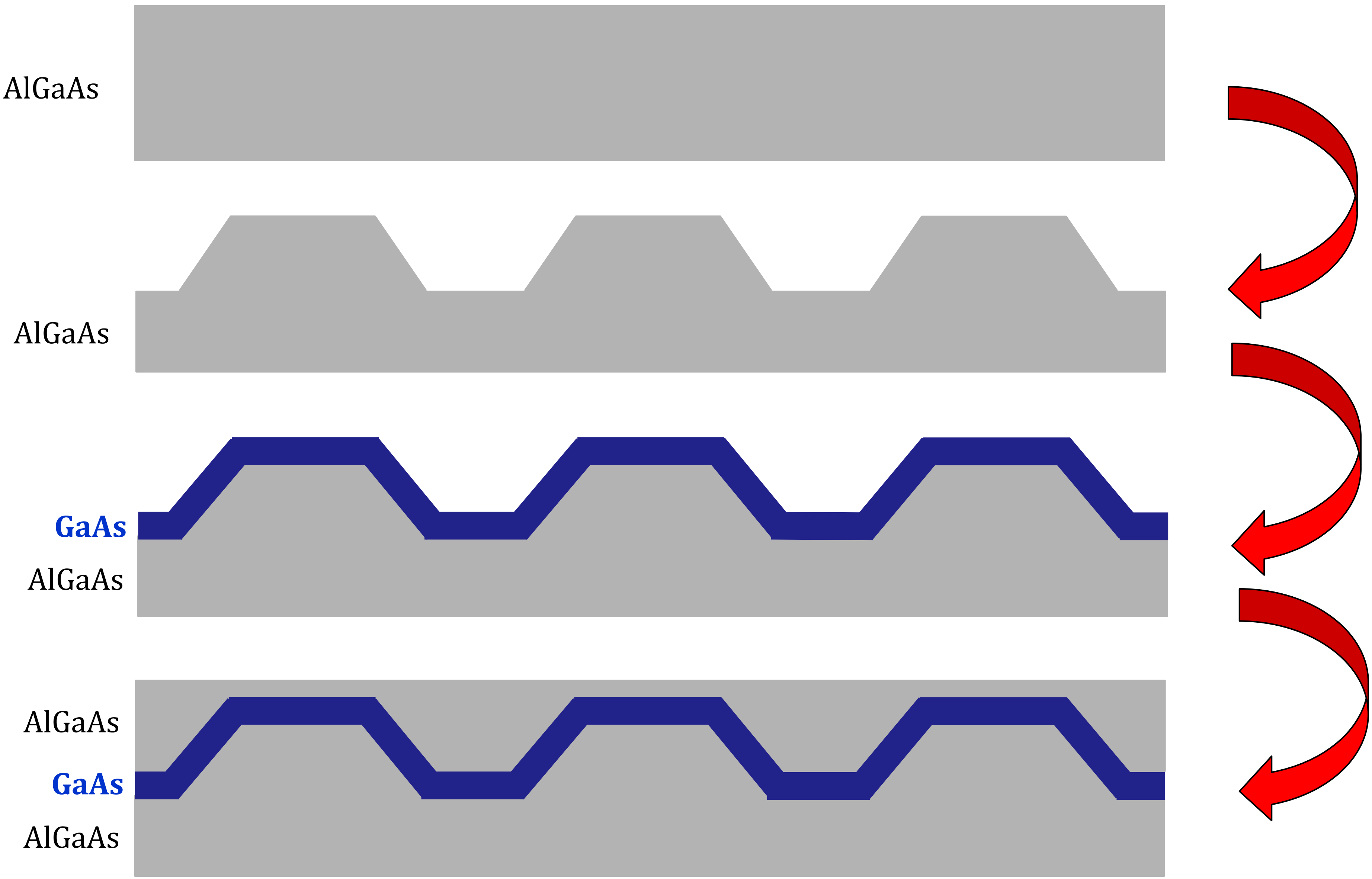
type-II potential modulation

→ spatial separation of electrons and holes

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

Como obter o sistema de 2 níveis?

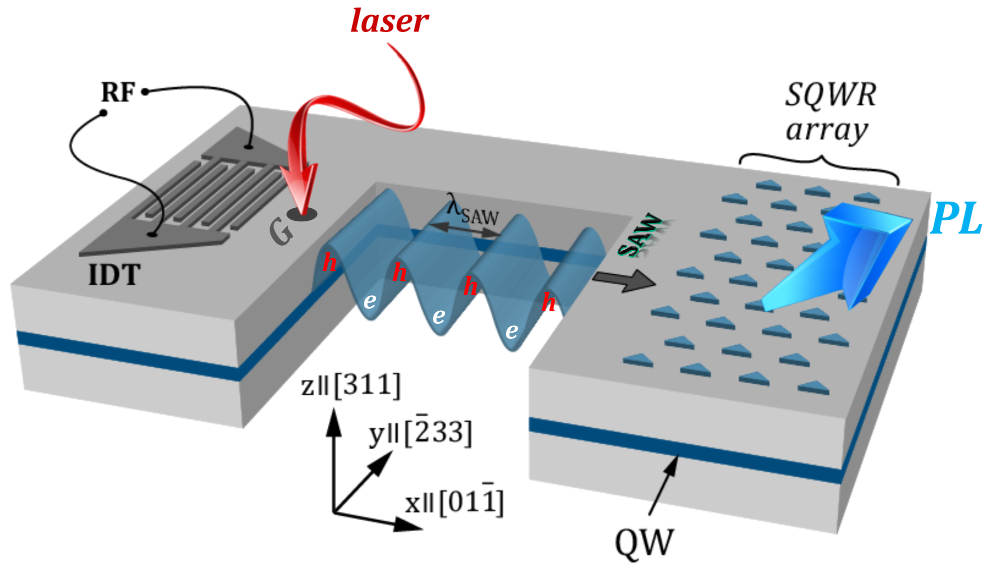
Etching process



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



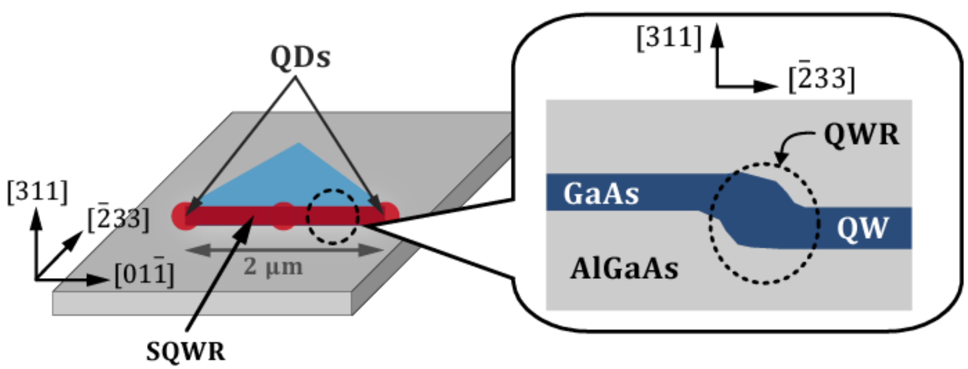
SQWR fabrication

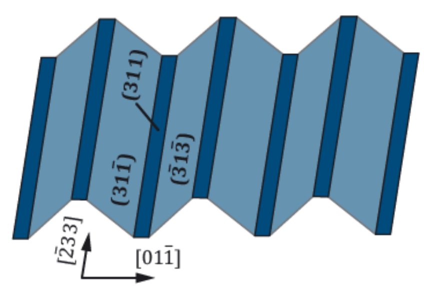
- side-wall (311)A GaAs quantum wires
  - ✓ MBE overgrowth on substrates patterned with shallow mesa
    - ✓ **SQWR:** material accumulation at [01-1] mesa edges

SAW generation

✓SAW wavelength: λ_{SAW}= 4 μm

✓SAW frequency: f_{SAW}=750 MHz





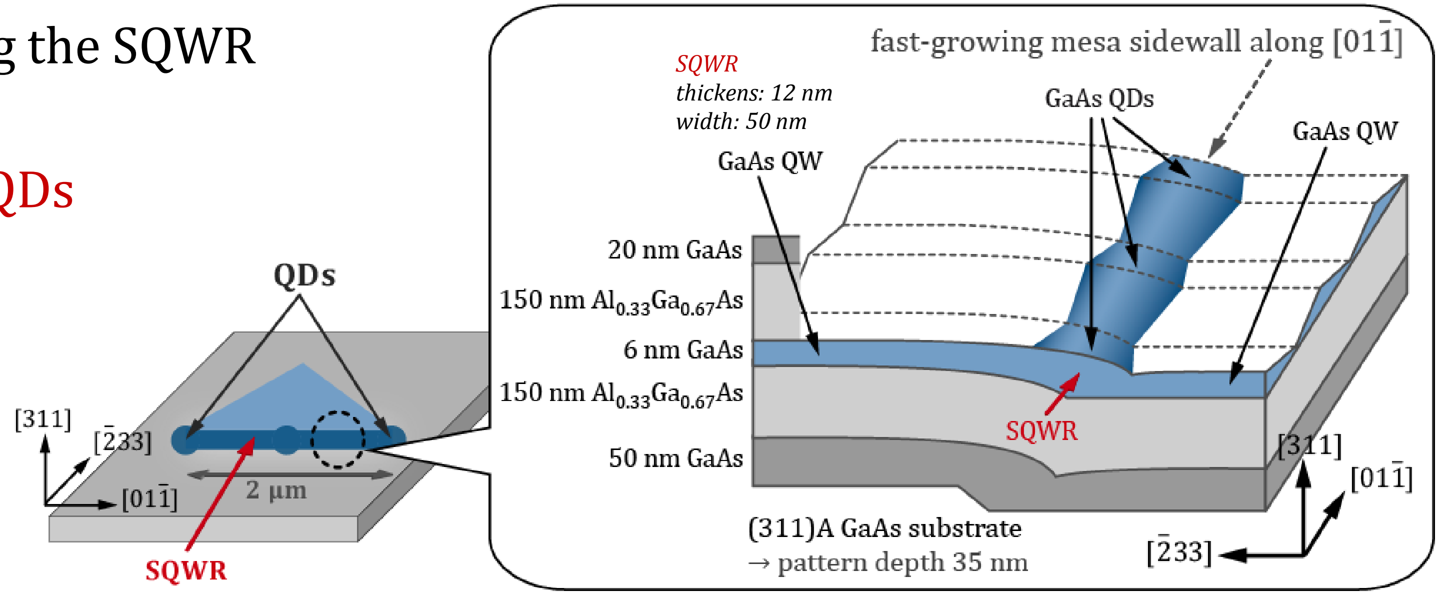
*R. Nötzel et al., Appl. Phys. Lett. **68**, 1132 (1996)

Short Quantum Wires (SQWRs)

Potential fluctuations along the SQWR

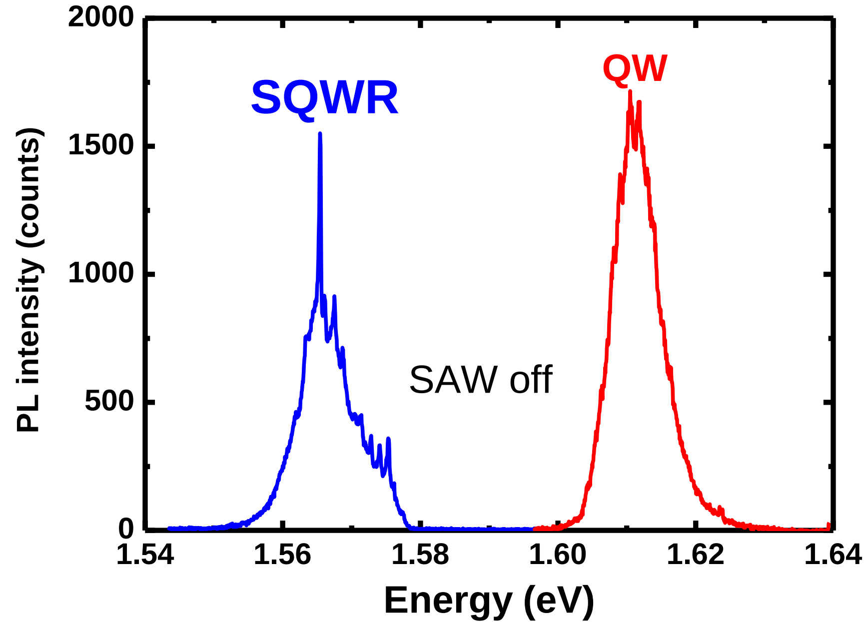
- ✓ Step-bunching
- → linear array of QDs

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



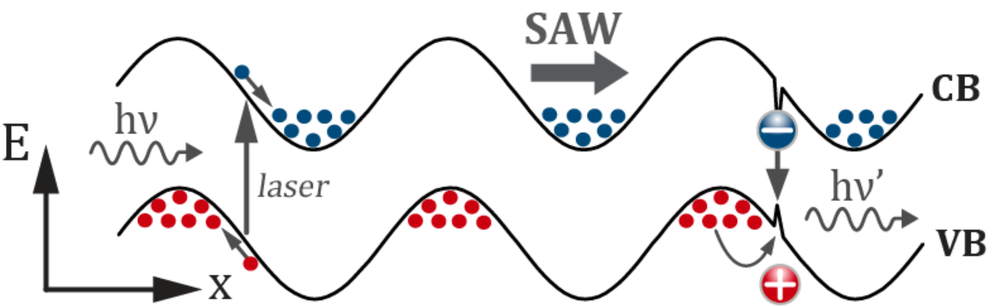
Spectral response from SQWRs

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



Carrier injection

λ_{SAW}= 4 μm
f_{SAW}=750 MHz

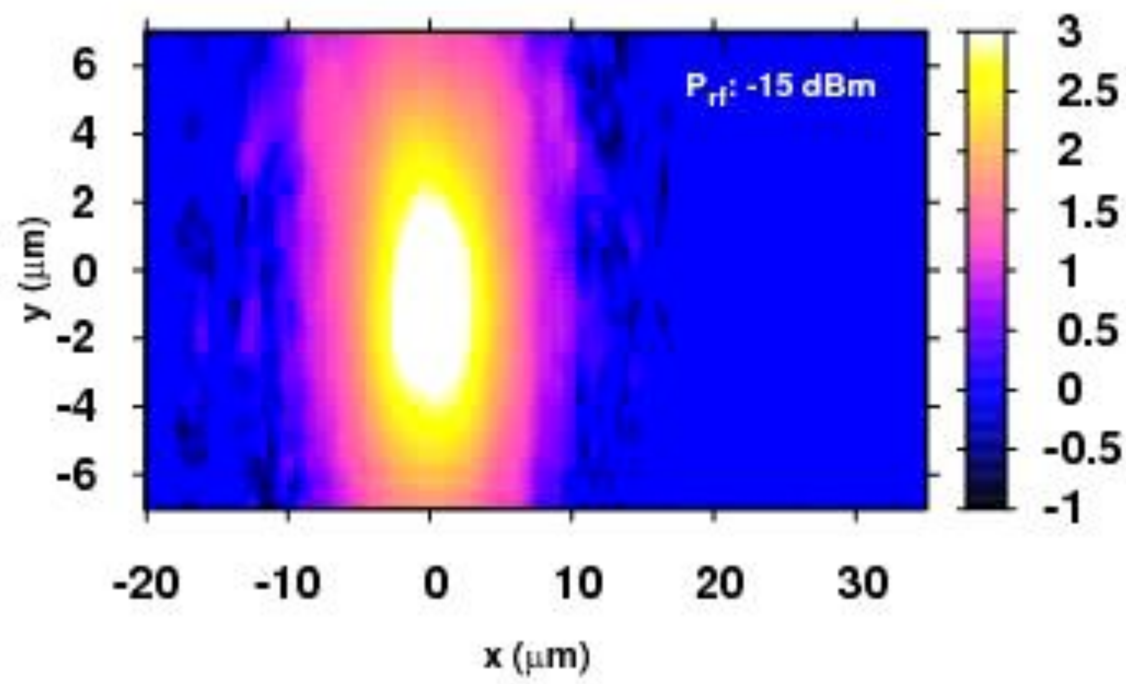


✓***coupling*** of different electronic systems: carrier transport QW → SQWR

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

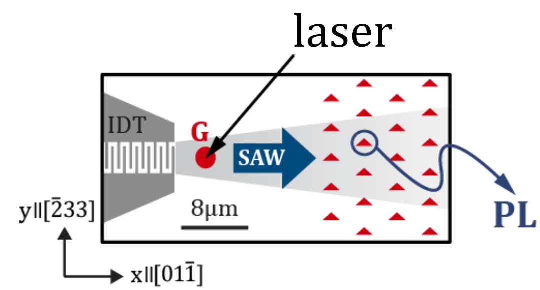
Carrier transport and injection

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



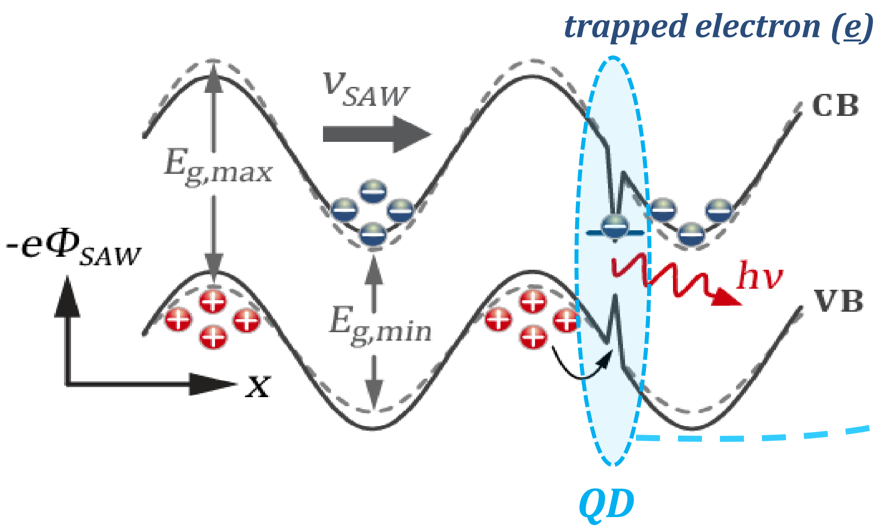
PL from a single SQWR

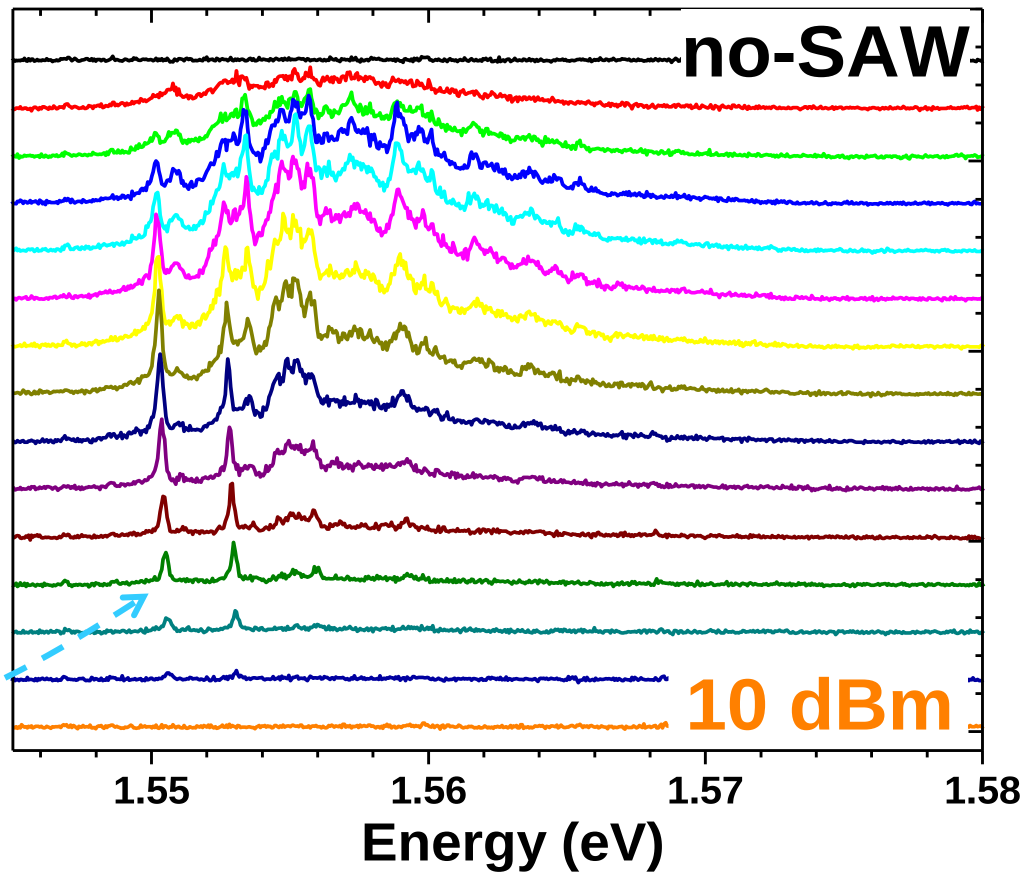
- ***low acoustic powers***
  - ✓large density of trapped electrons
- ***high acoustic powers***
  - ✓low density of trapped electrons
    - → fewer recombination events



sharp lines for high P_{SAW}

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

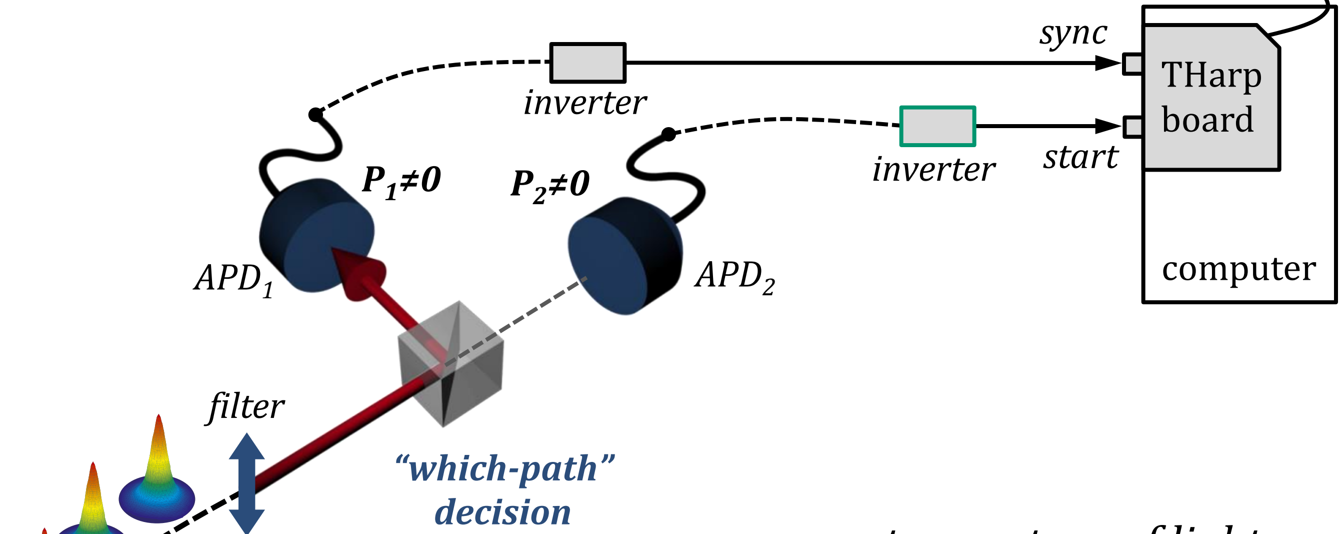


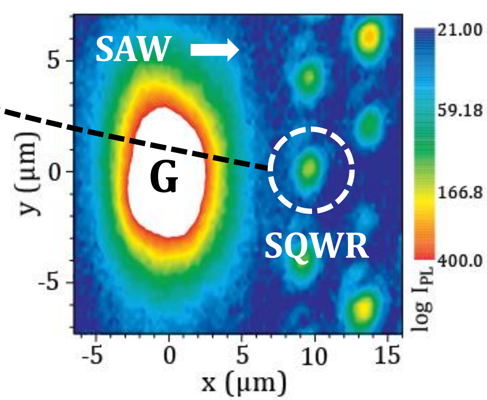


Photon correlation

Hanbury-Brown and Twiss setup

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

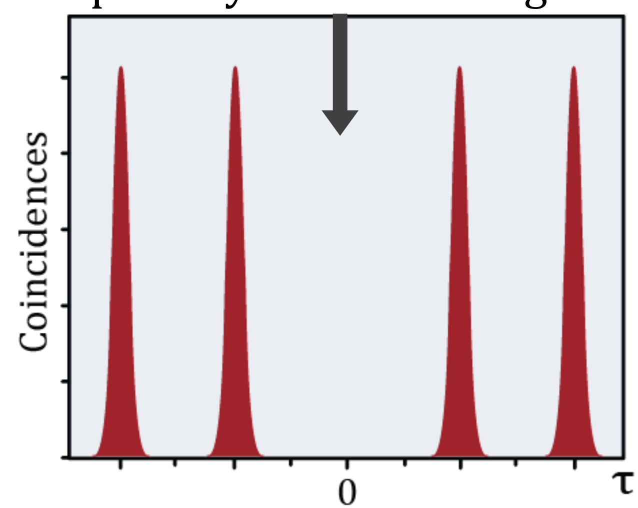




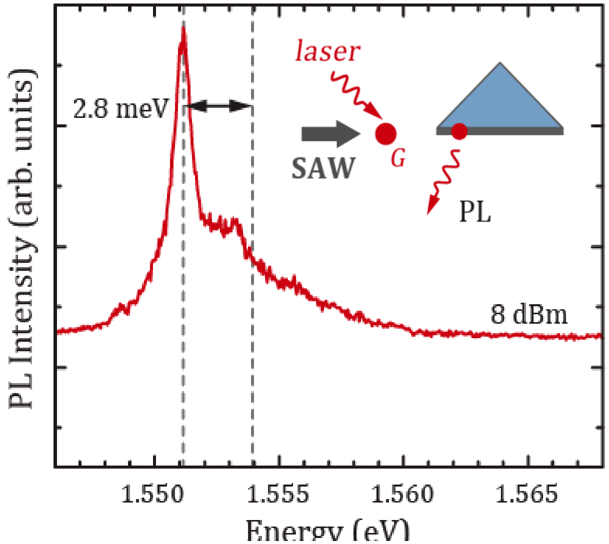
quantum nature of light

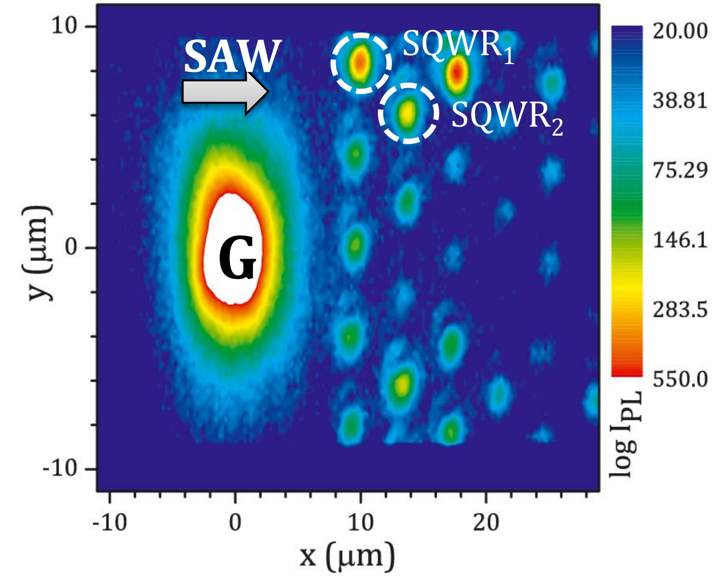
✓ *joint photo-detection probability:* ***P = 0*** *at $\tau=0$*

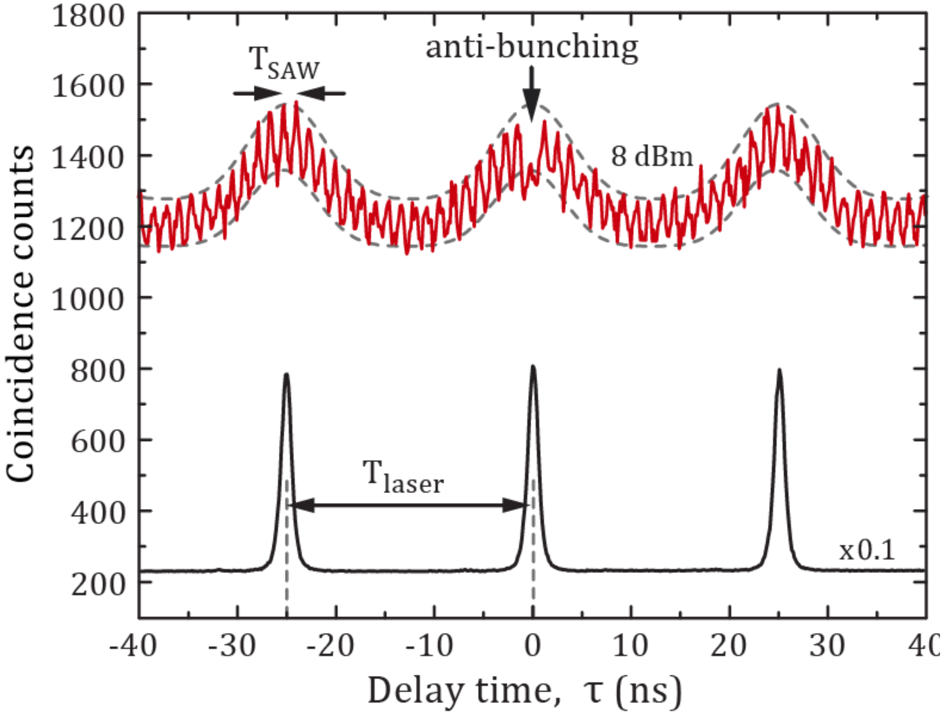
suppression of zero-delay peak by anti-bunching



Anti-buching

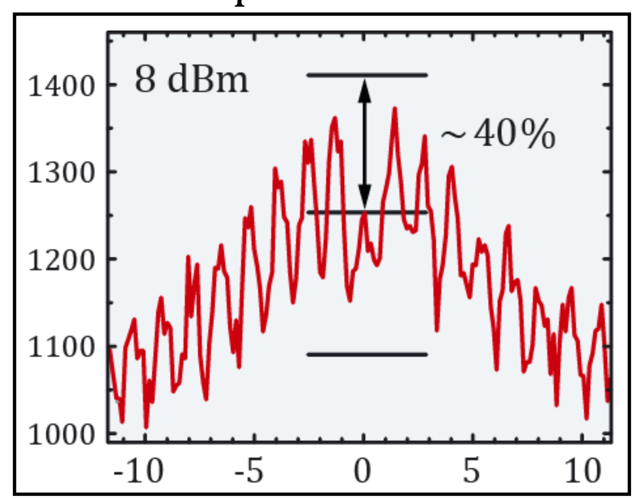




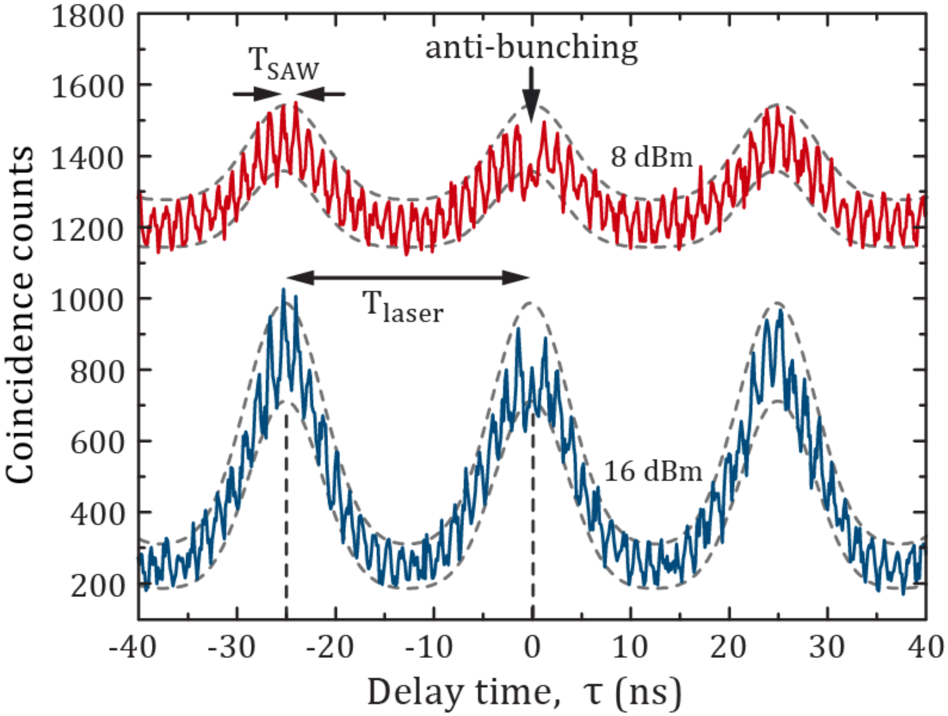


Reduced amplitude at *τ=0*

→lower probability for simultaneous emission of two photons



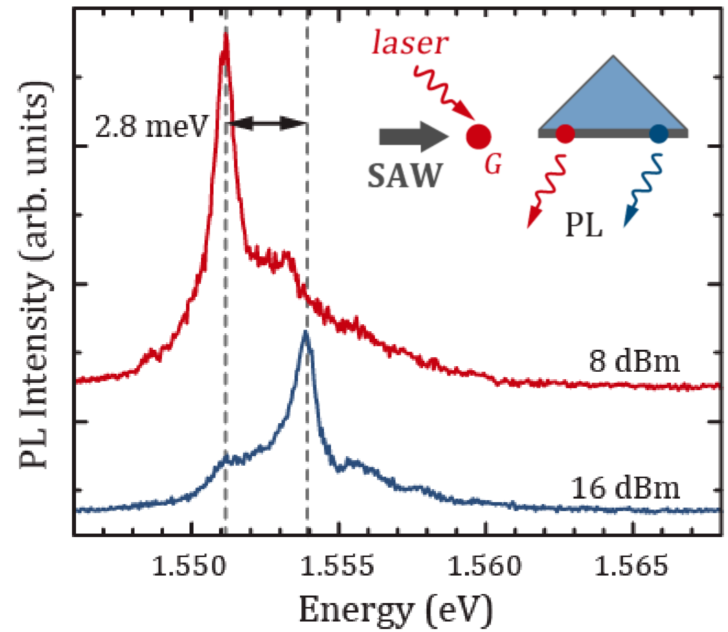
Anti-buching



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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UNICAMP

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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

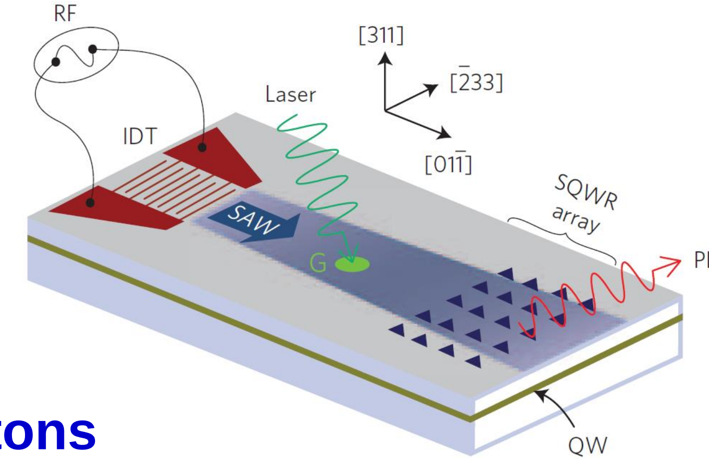
✓J. A. Stotz *et. al. Nature Mat*. **4**, 585

✓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



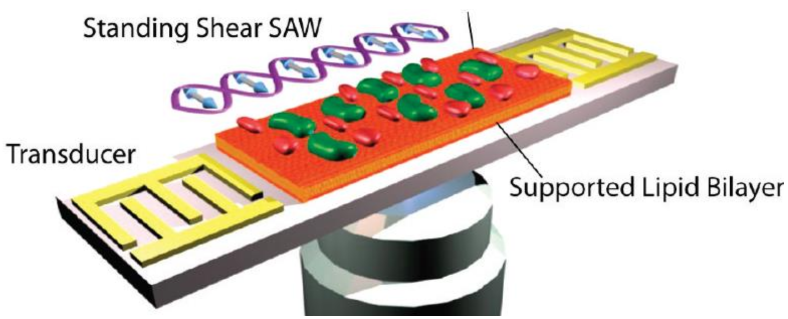
Photons

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

Time-resolved PL

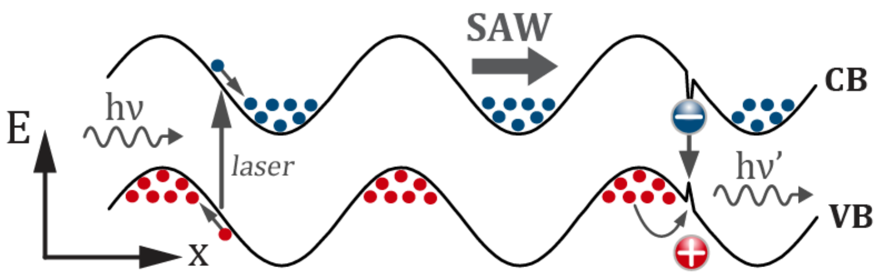
For a single SQWR

- Oscillations with SAW periodicity

$\rightarrow T_{SAW} = 1/f_{SAW} = 1.33\ ns$

Compatible with $\boldsymbol{h} \rightarrow \underline{\boldsymbol{e}}$ recombination

✓Carriers transported in packets



- Amplitude and decay time limited by experimental time resolution

$\rightarrow \delta t = 0.40\ ns$

✓short and well-defined recombination times