Nano-Optics

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Chair of excellence, CEA Grenoble in the group of Jean-Michel Gerard

Nano-Optics

- Generation
- Manipulation and applications
- Detection

light a the nanoscale: enables to play with single photons, explore fundamental physics and also to develop new applications making use of quantum physics.

Generating quantum light

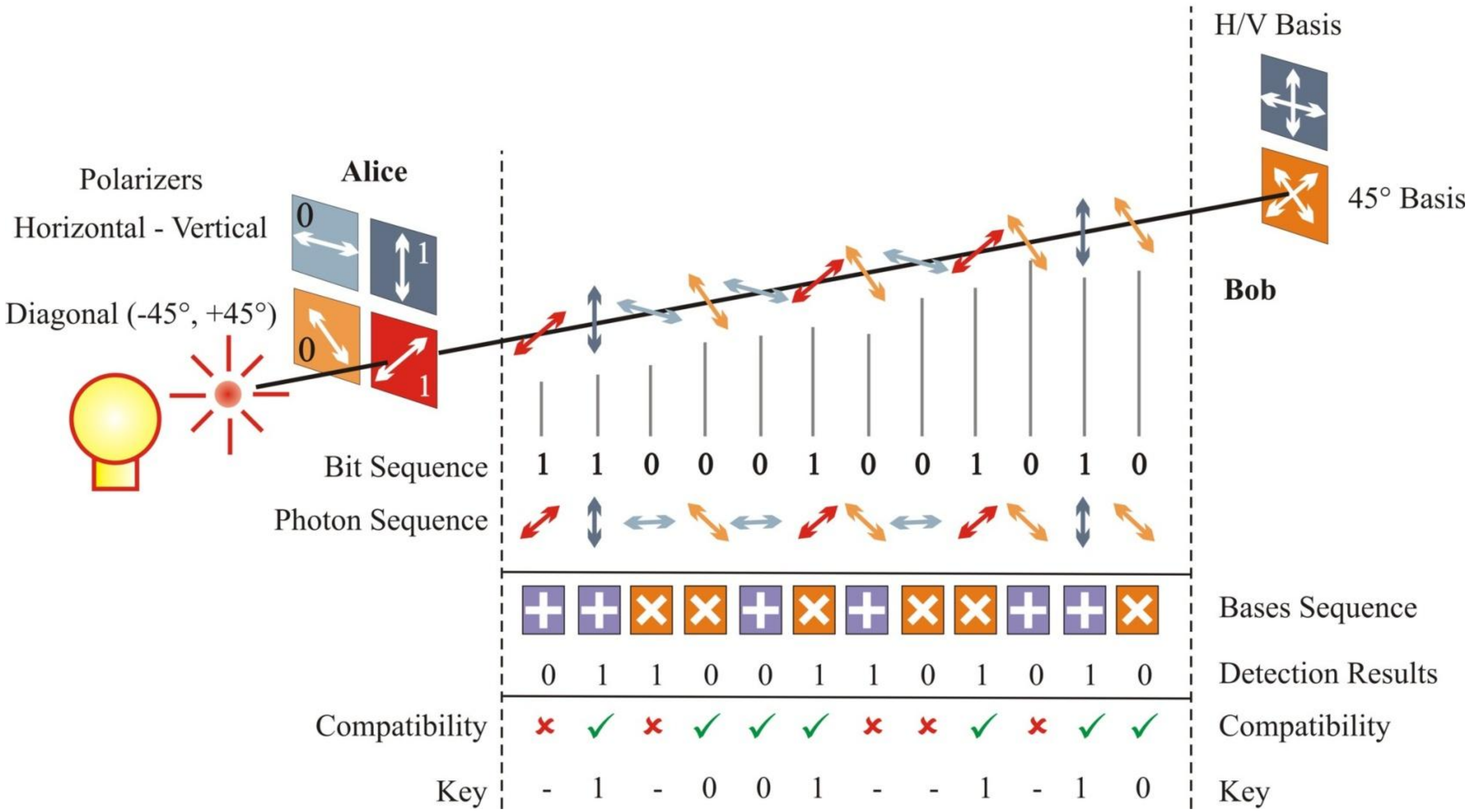
Requires optically active nanostructures:

III-V materials, II-VI, Carbon Nanotubes, Colloidal quantum dots.

Uses of single photons

Quantum cryptography: BB84

Secure communication based on the no cloning theorem.



Quantum physics meets politics: privacy is possible, but do we want it?
Note: quantum hacking...

Quantum dots

Confine charges so that energy level spacing is lager than kT.

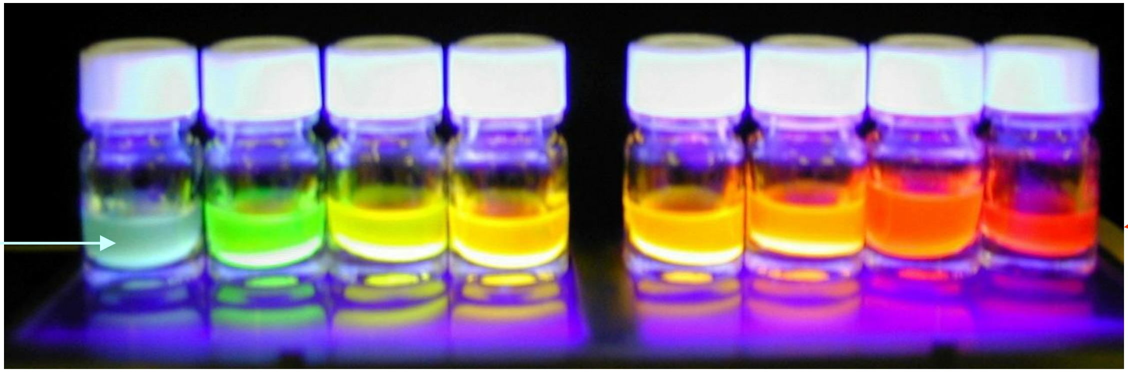
Optically active quantum dots confine electrons and holes, radiative transitions generate photons.

CdSe nanocrystals

P Reiss, J Bleuse
CEA-Grenoble

Fluorescence under UV lamp excitation

R~3nm



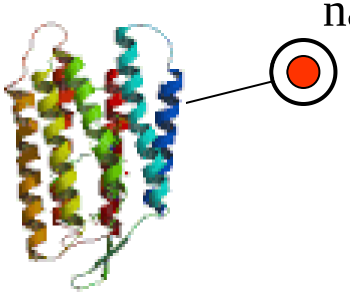
R~5.2 nm

Increasing growth time

Color is set by the quantum dots size.
(quantum confinement)

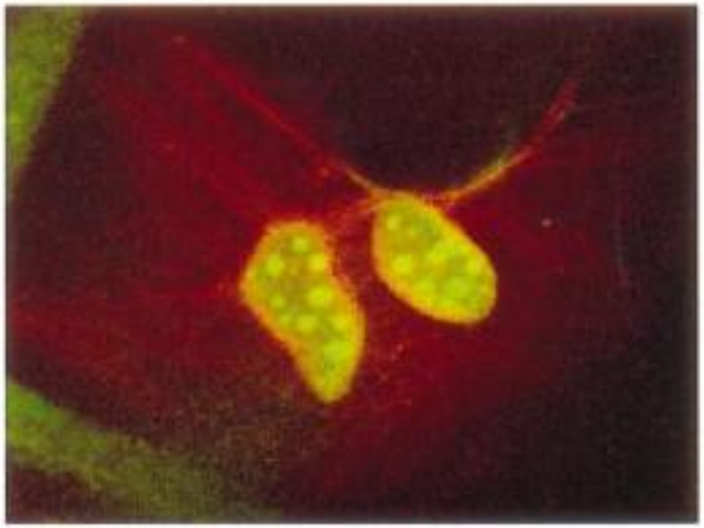
Nanocrystals as biological markers

Biocompatible
nanocrystal



Proteins,
DNA…

50 µm



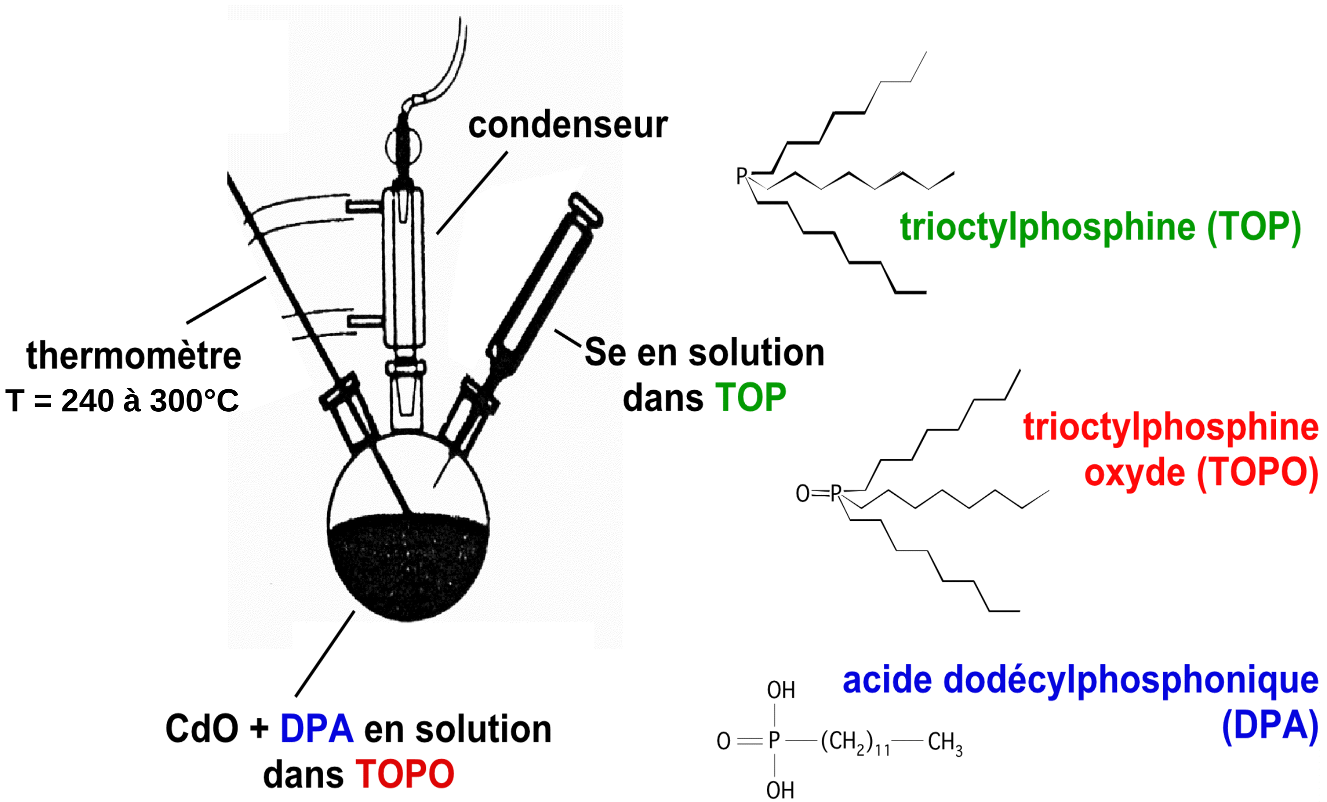
Quantum dots in mice cells

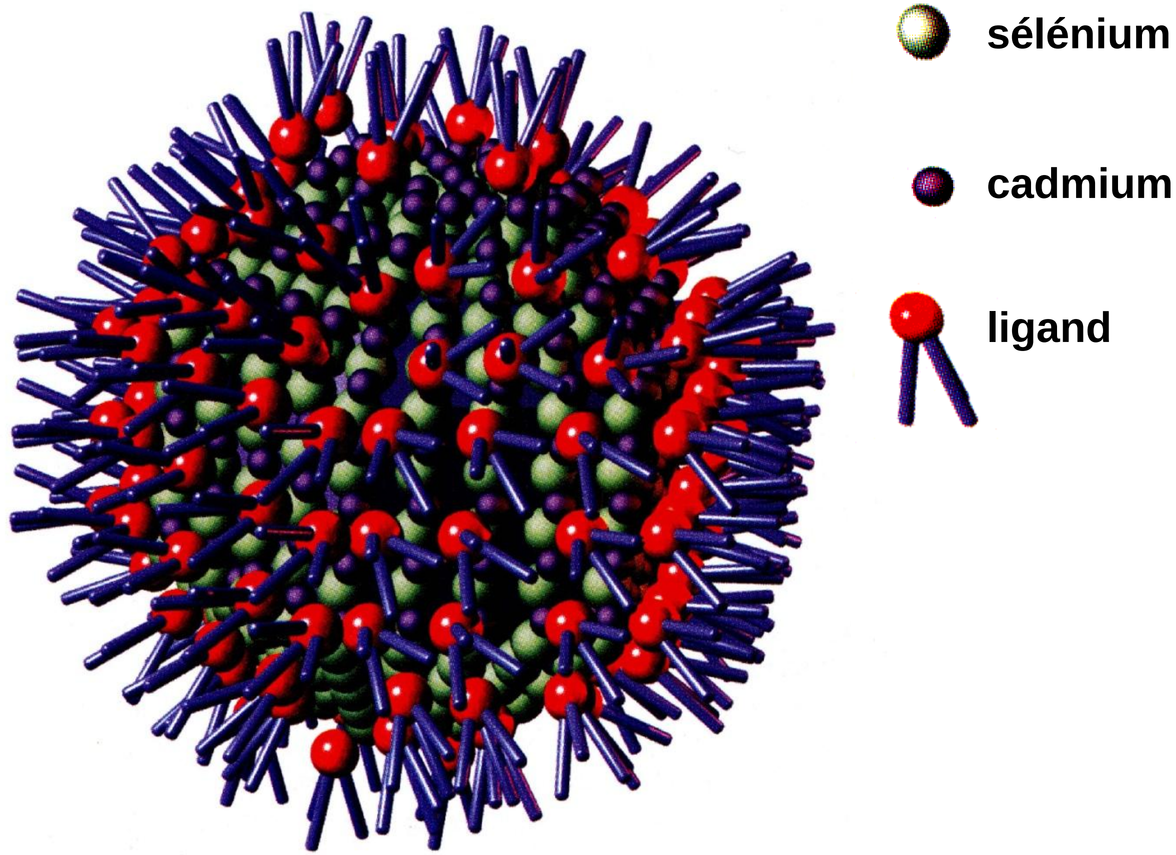
M. Bruchez Jr.et coll, *Science* **281** (1998) 2013

Many advantages over other bio markers

- Stability (bleaching)
- Several quantum dot sizes can be used simultaneously
- Biocompatible

Synthesis of nanocristals (ex: CdSe)



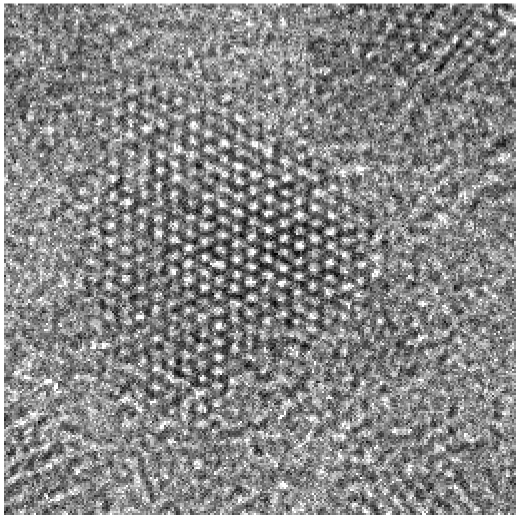


Fast injection => simultaneous germination of the nanocristals

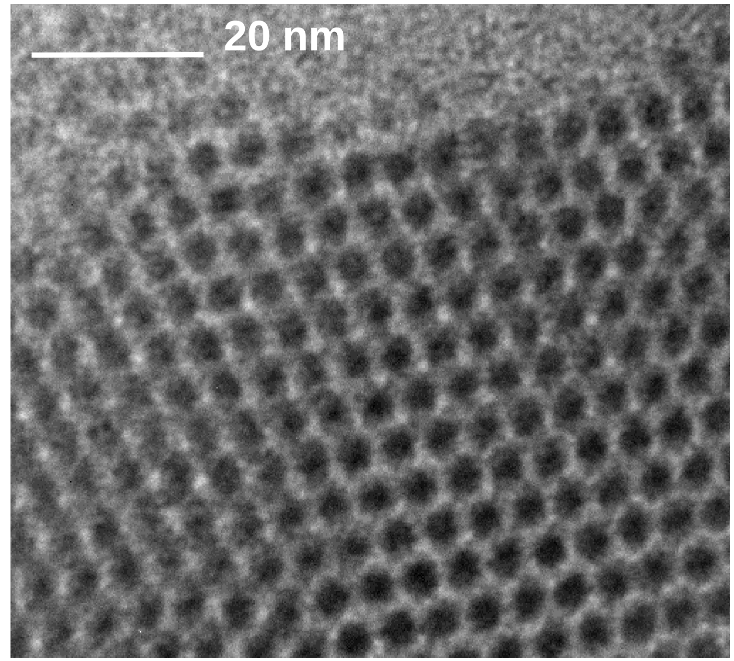
Slow growth, moderated by surface ligands

→ Similar sizes

CdSe Nanocristals, as seen by electron microscopy



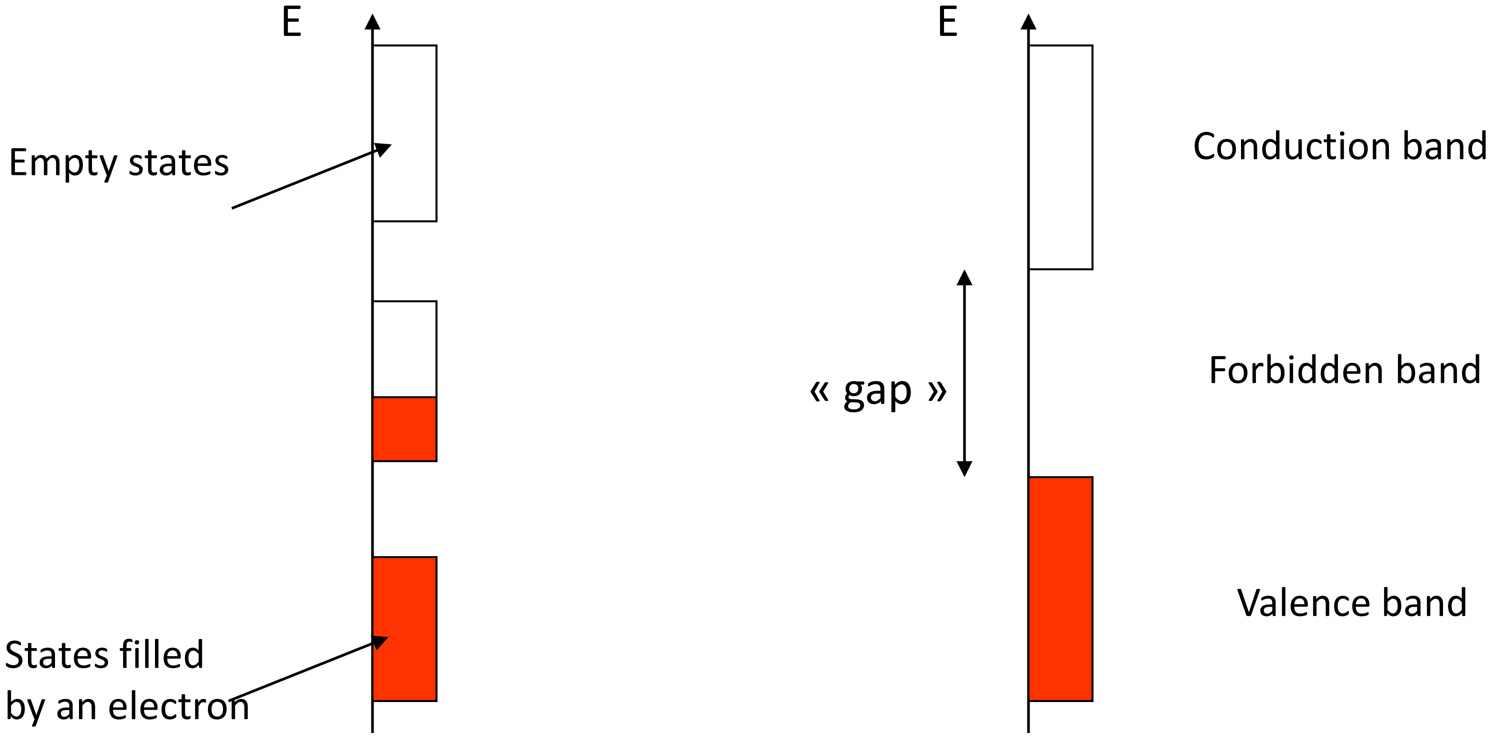
5 nm



ΔR/R ≈ 0,05

What is a semiconductor?

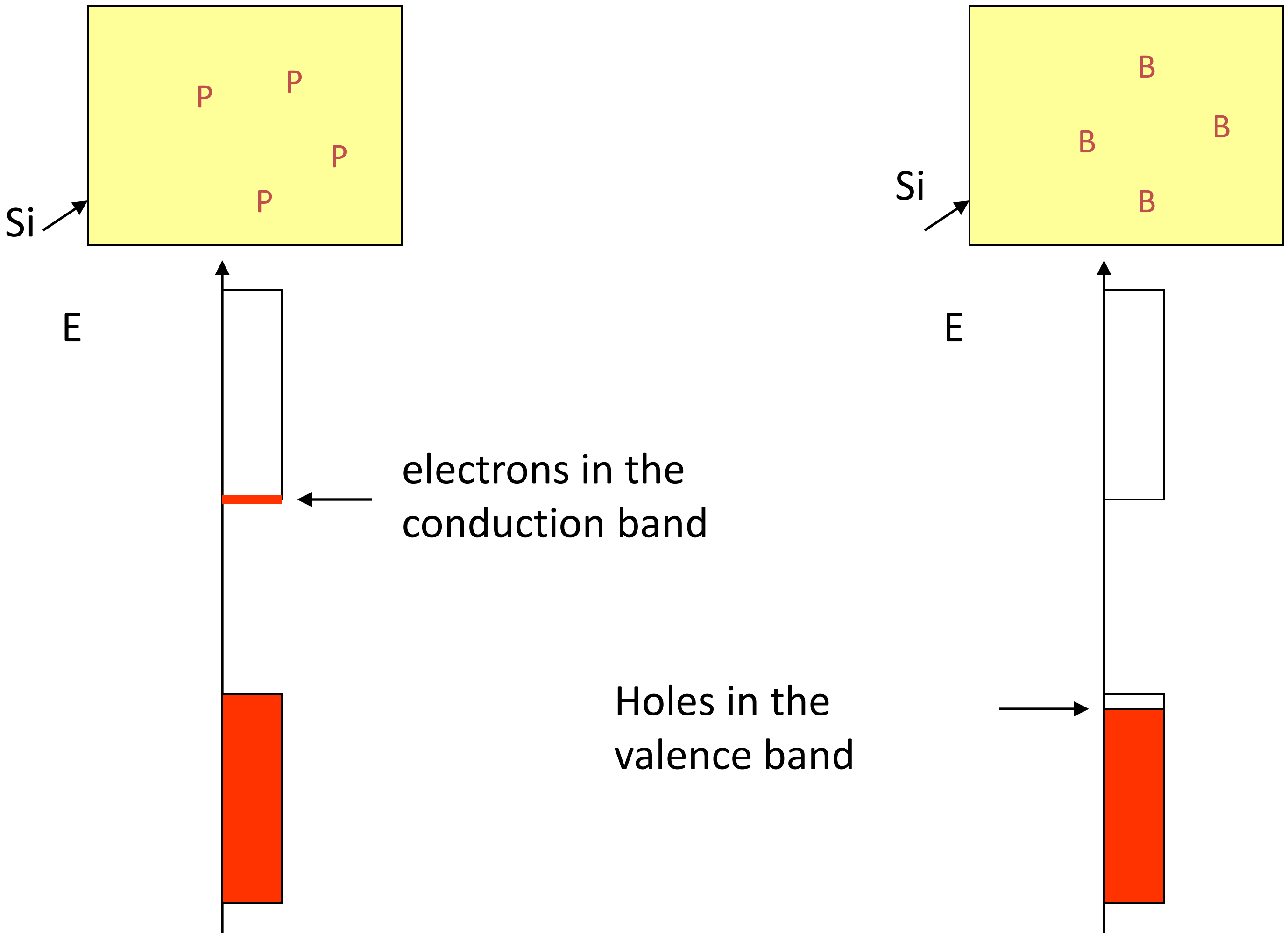
T ~ 0K



Metal

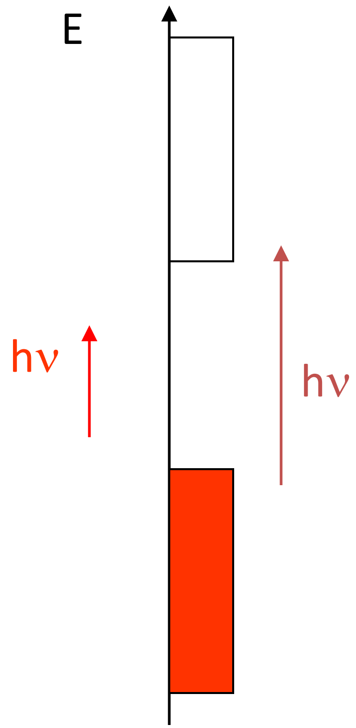
Semiconductor (or insulator)

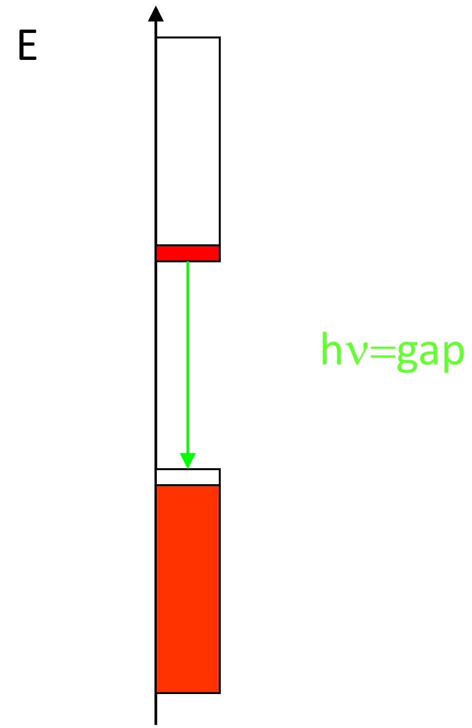
Doping



=> Transistor 1948…

Basic optical properties

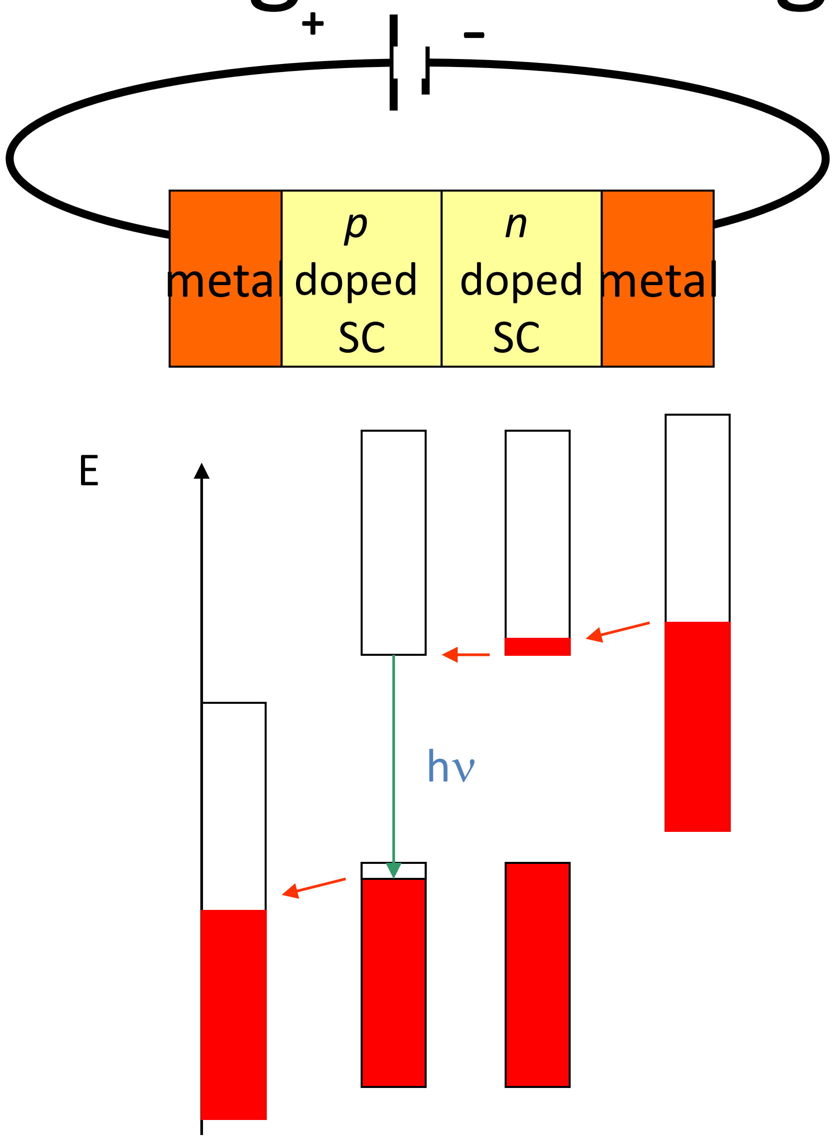




Transparent if $h\nu$ < gap
Absorbant if $h\nu$ > gap

Light emission at the bandgap energy (GaAs, GaN, InP…)

Light emitting diode



Signals, lighting, optical sensors…

Market ~ 5 10^9 $ /an

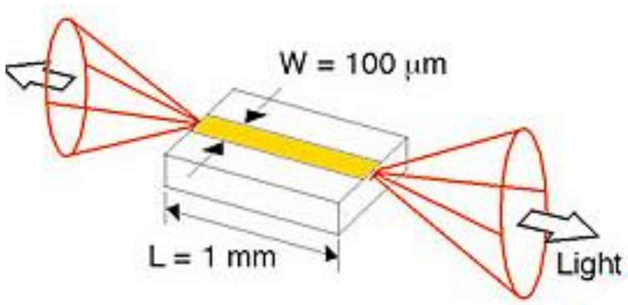
+ 20% /an

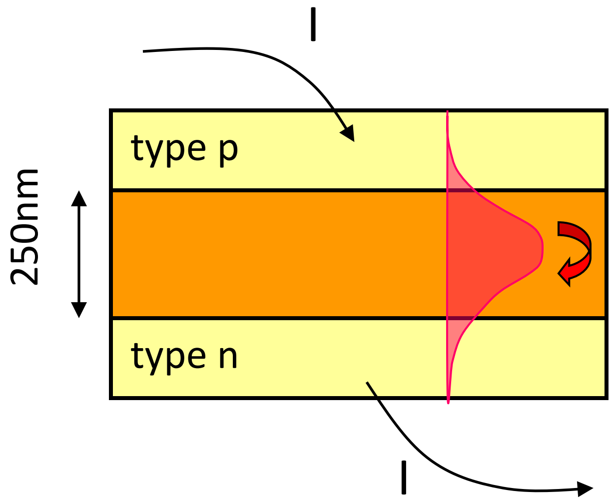
Reversible: can avalanche photodiode for photon detection.

Laser diode

LASER

« light amplification by stimulated emission of radiation »

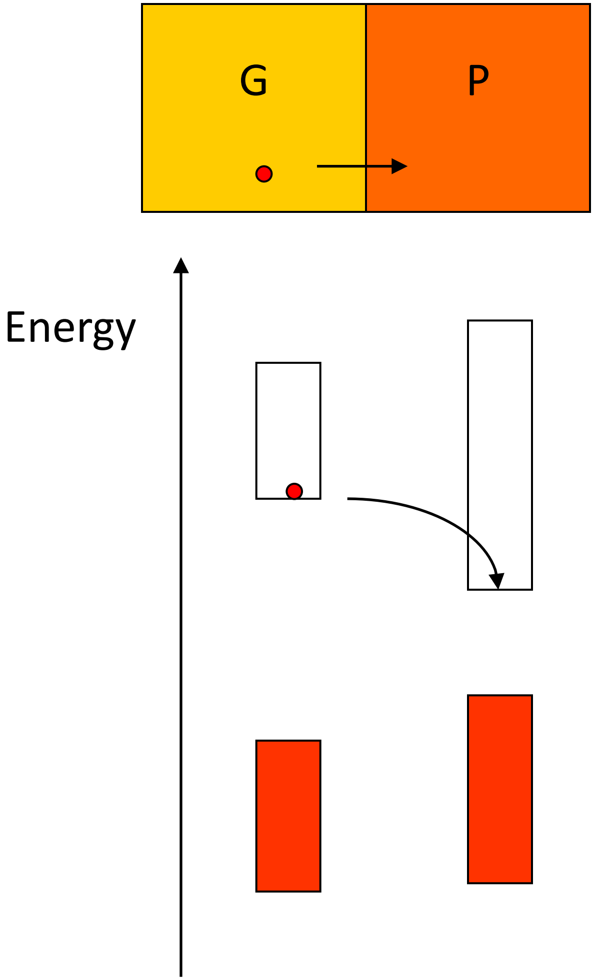


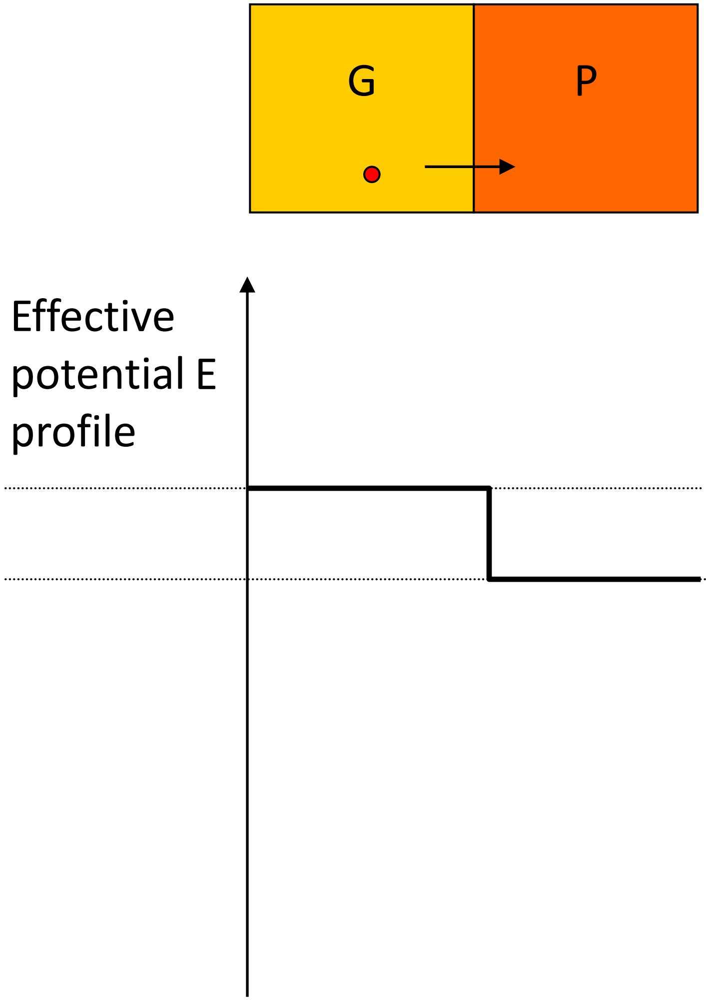


Waveguiding+ mirrors for partial recycling of emitted light

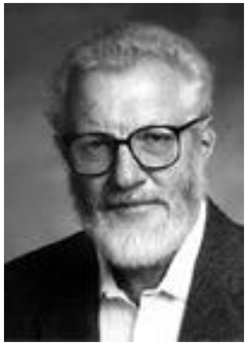
Appl: Telecoms, optical data storage …

Semiconductor heterostructures (~1970)





Semiconductor heterostructures

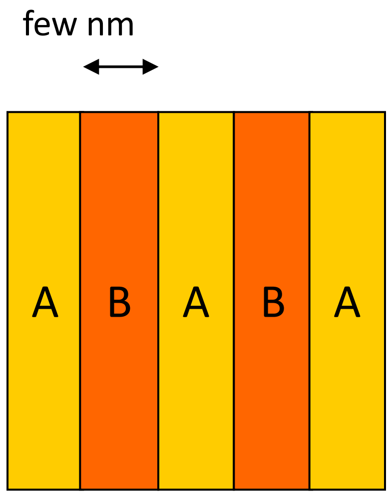


Herbert Kroemer, Nobel 2000

Zhorès Alferov, Nobel 2000

« for the invention of heterostructures enabling the fabrication of high-speed optical and electronic devices »

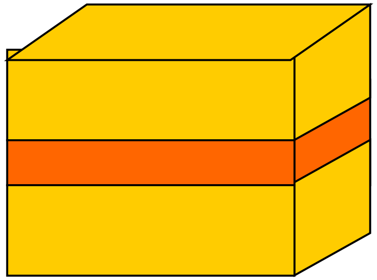
Quantum heterostructures



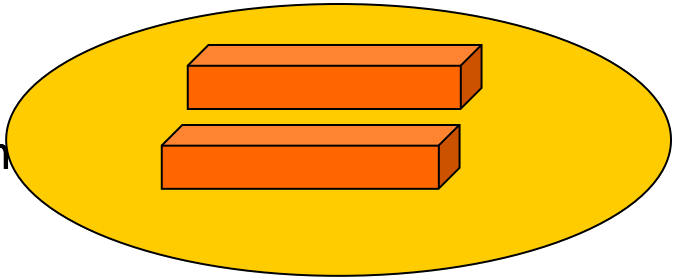
superlattice

Leo Esaki, Nobel 1973

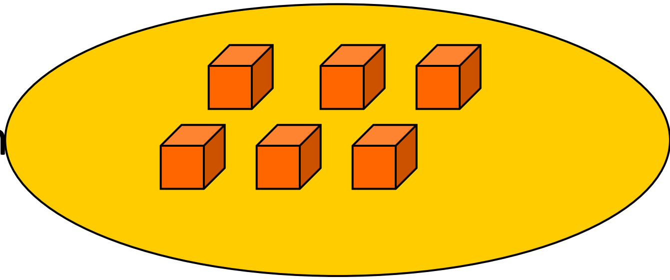
quantum well



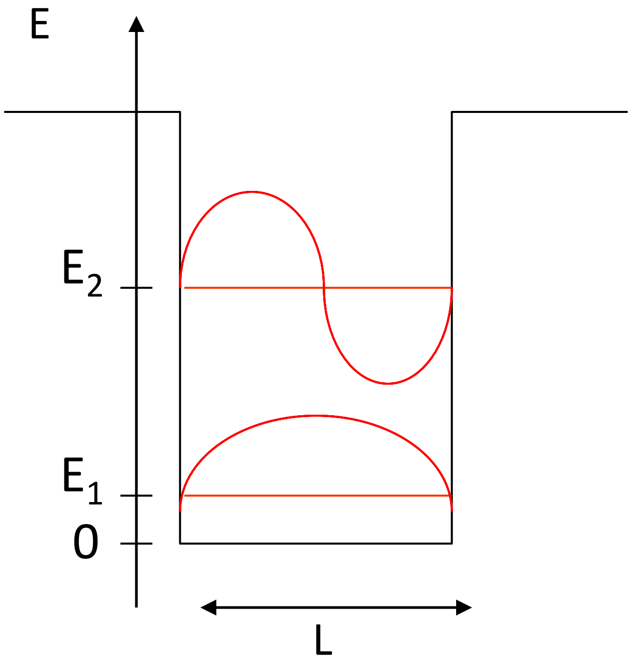
quantum wires



quantum dots



Quantification of electronic states in a 1D quantum well



Single degree of freedom (z) :

ψ (z) ~ sin (k_z z)

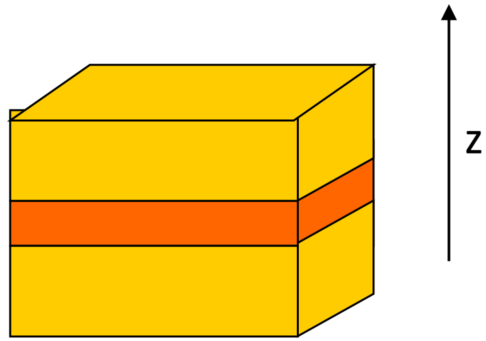
$k_z = n \pi / L$

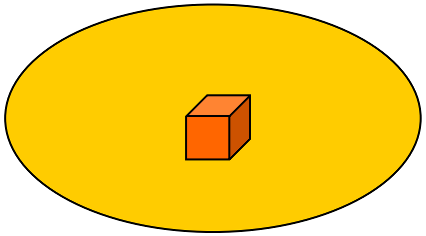
and

$$E_n = \frac{\hbar^2 n^2 \pi^2}{2mL^2}$$

Discrete energy level
Minimum energy, due to spatial confinement
Non classical probability density

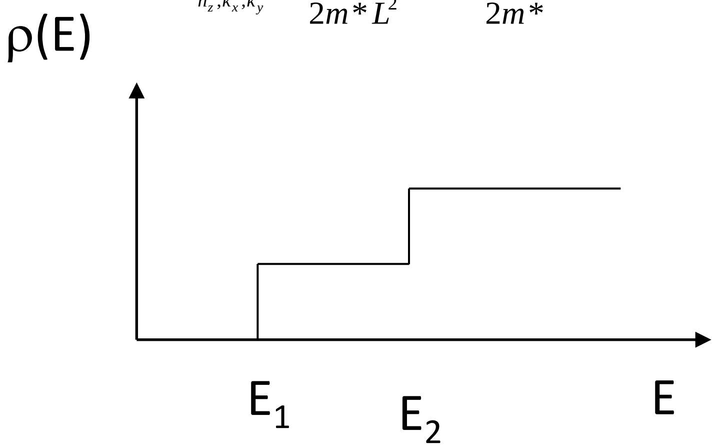
Density of electronic states for a QW and a QD

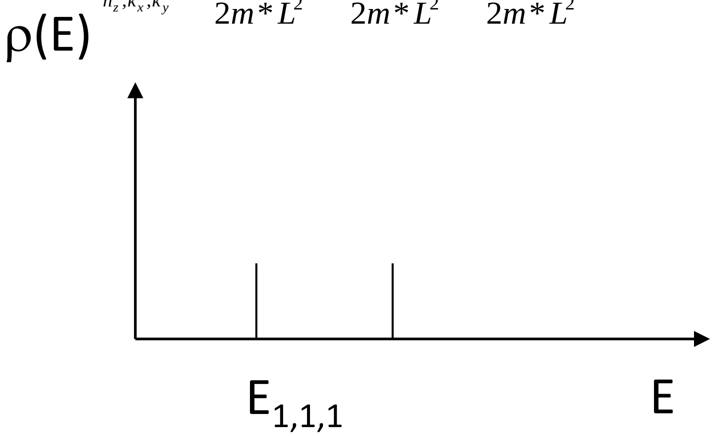




$$E_{n_z,k_x,k_y} = \frac{\hbar^2 n_z{}^2 \pi^2}{2m^* L^2} + \frac{\hbar^2 (k_x{}^2 + k_y{}^2)}{2m^*}$$

$$E_{n_z,k_x,k_y} = \frac{\hbar^2 n_x{}^2 \pi^2}{2m^* L^2} + \frac{\hbar^2 n_y{}^2 \pi^2}{2m^* L^2} + \frac{\hbar^2 n_z{}^2 \pi^2}{2m^* L^2}$$

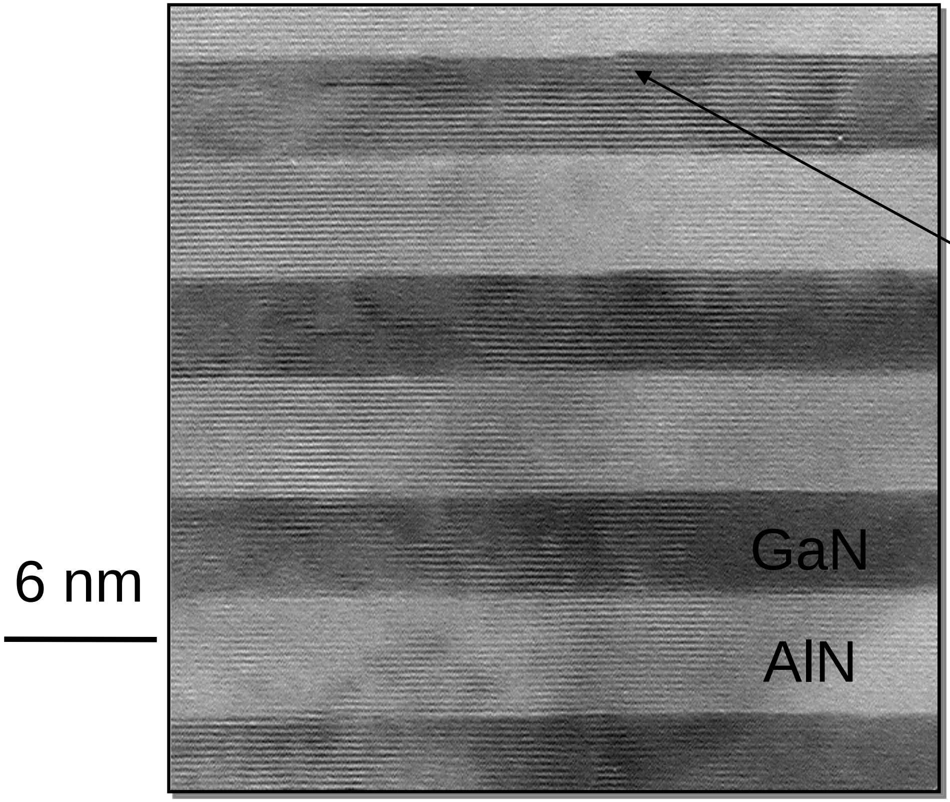




E_2-E_1>kT at 300K => Typical size < 15nm

Cross-section view of a QW

High resolution electron microscopy



Defect
= single molecular step
of GaN

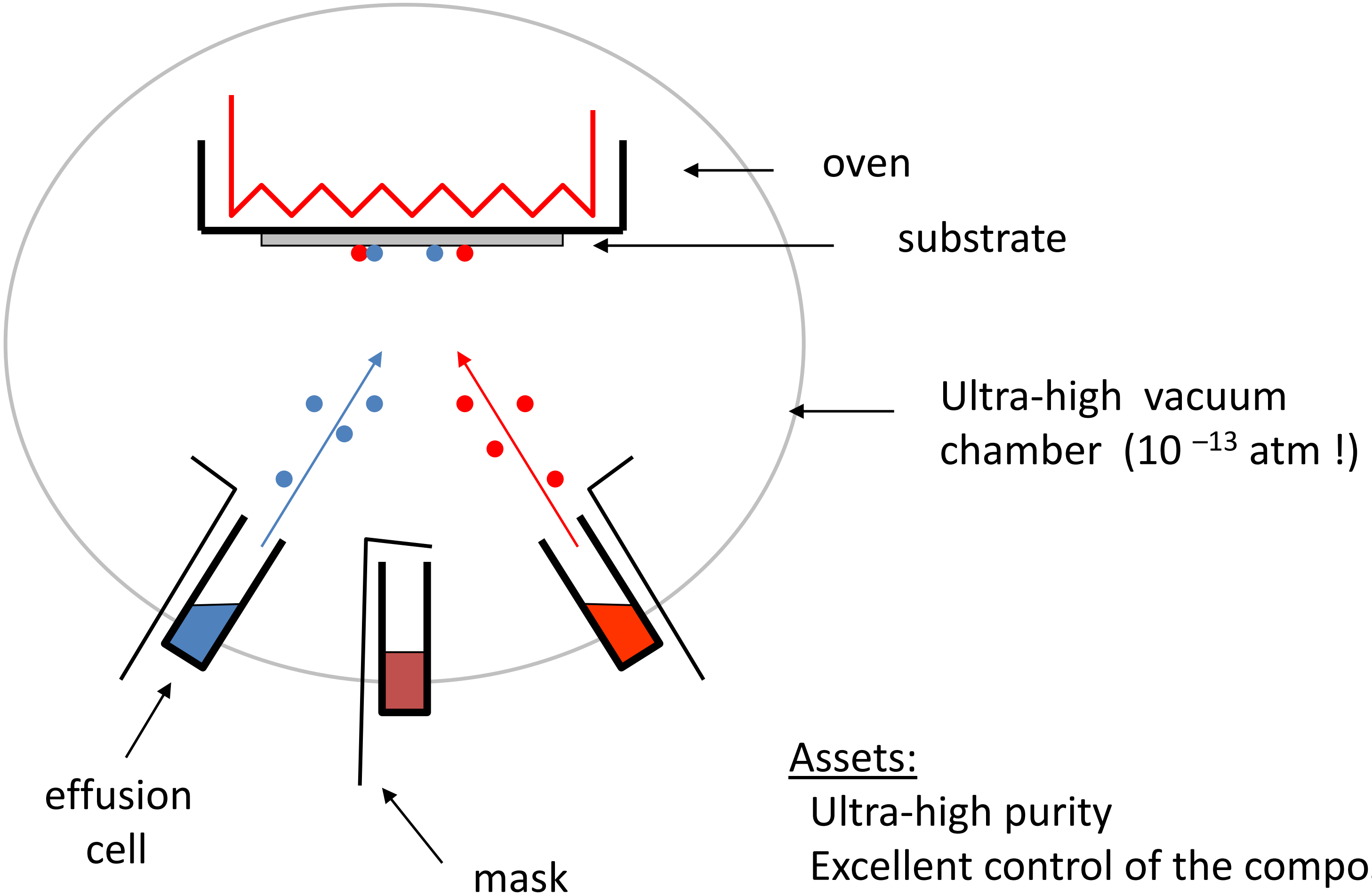
Abrupt variation of the composition

Flat interfaces

at the atomic scale !

Molecular beam epitaxy (~1975)

epitaxy : deposition of a solid layer on a cristalline substrate, keeping the same cristalline order

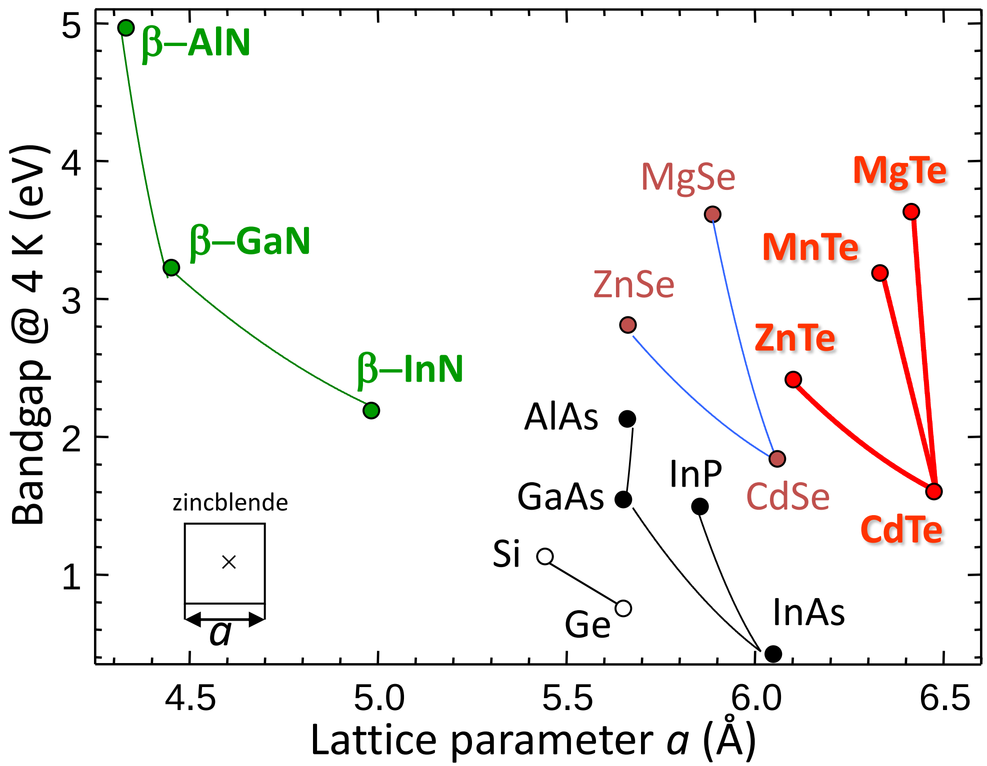


Assets:

Ultra-high purity

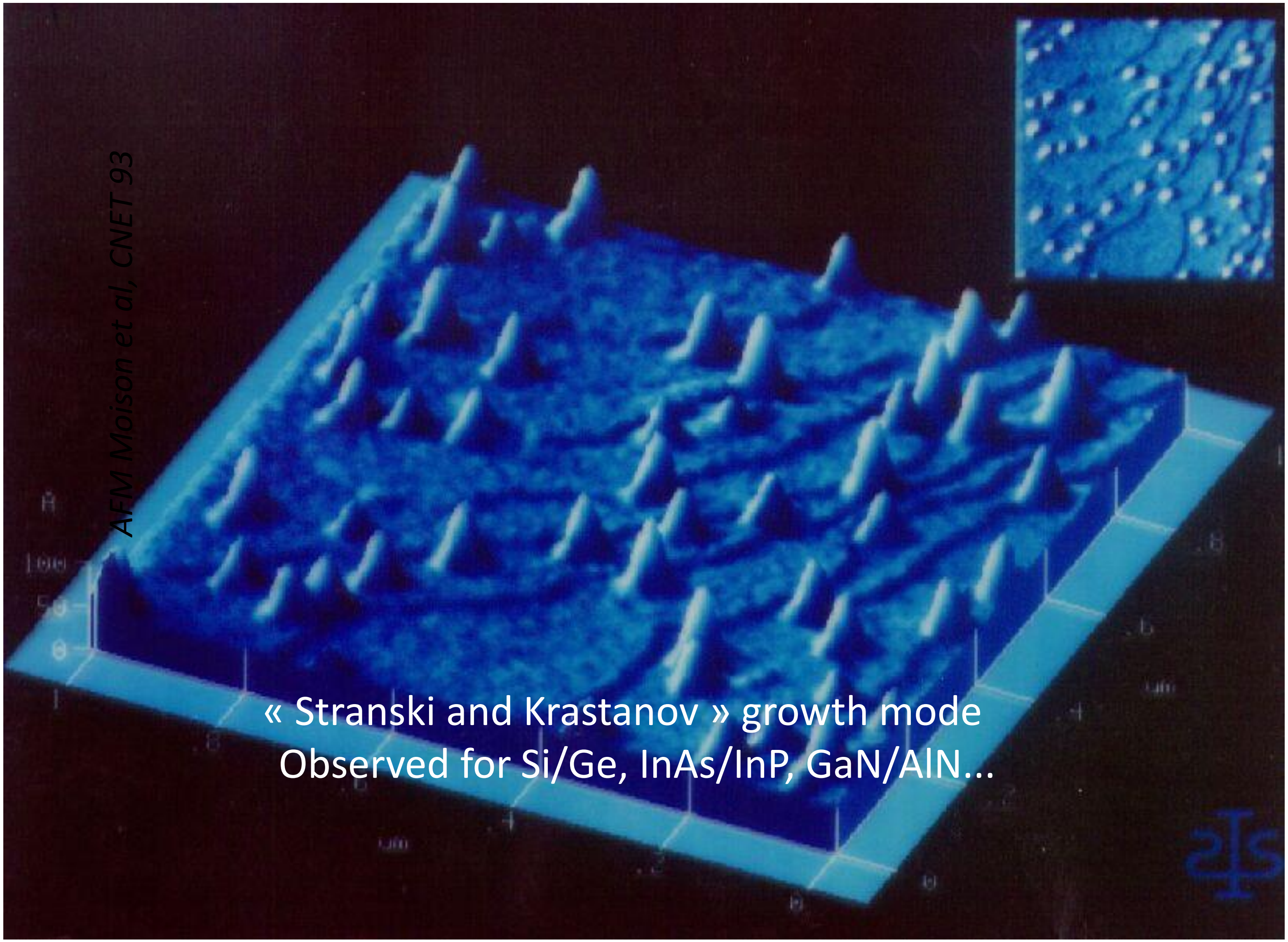
Excellent control of the composition and thickness

Commonly used optically active materials



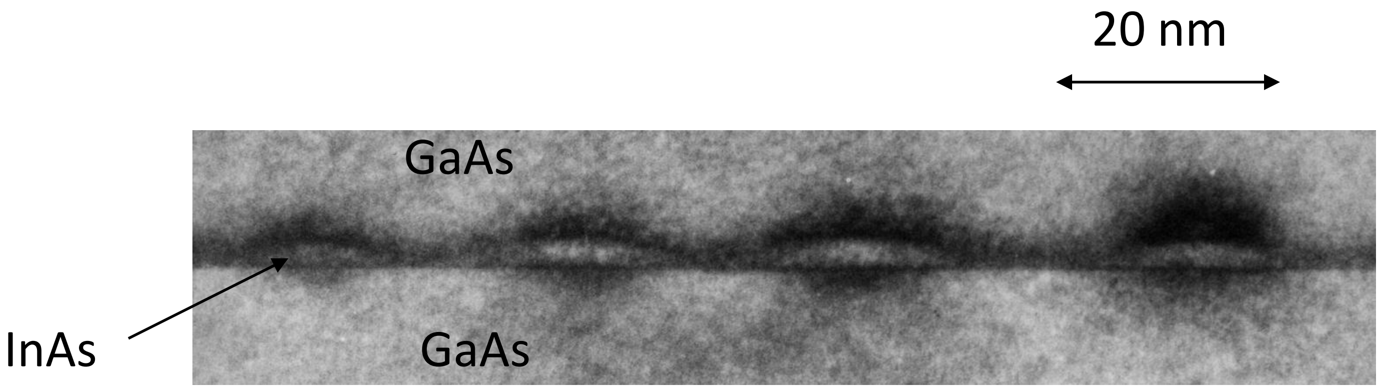
QD self-assembling by molecular beam epitaxy (1)

0.6 nm thick layer of InAs on GaAs, as seen by atomic force microscopy



Self-assembling of QDs in molecular beam epitaxy (2)

First demonstration: L Goldstein et al, France Telecom/CNET, Appl. Phys. Lett 1985



Transmission electron microscopy   A. Ponchet CNRS (95)

View in cross-section of a layer of InAs QDs,
buried in GaAs

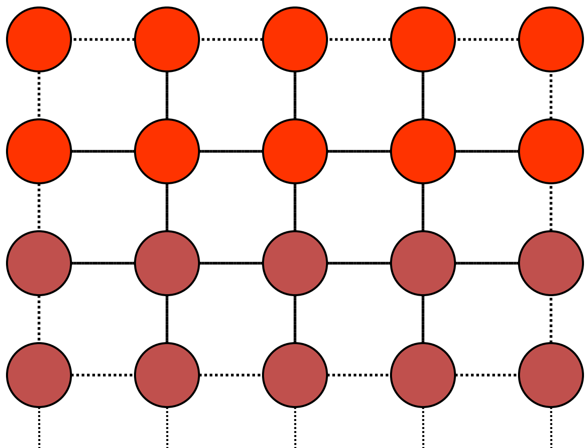
Epitaxial growth modes

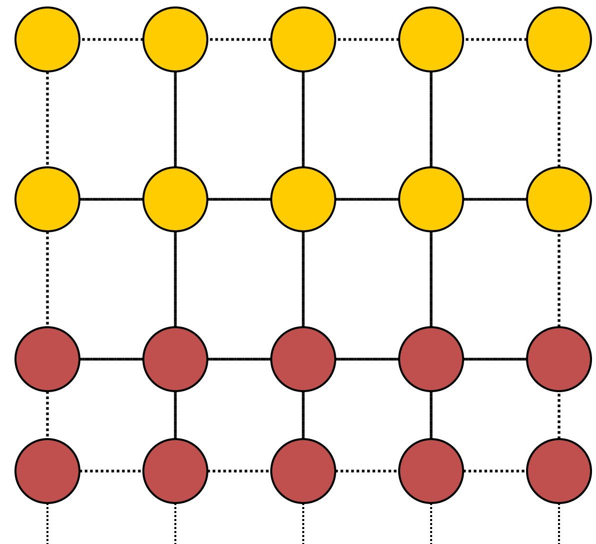
Same inter-atomic distance

Different interatomic distances

Epilayer

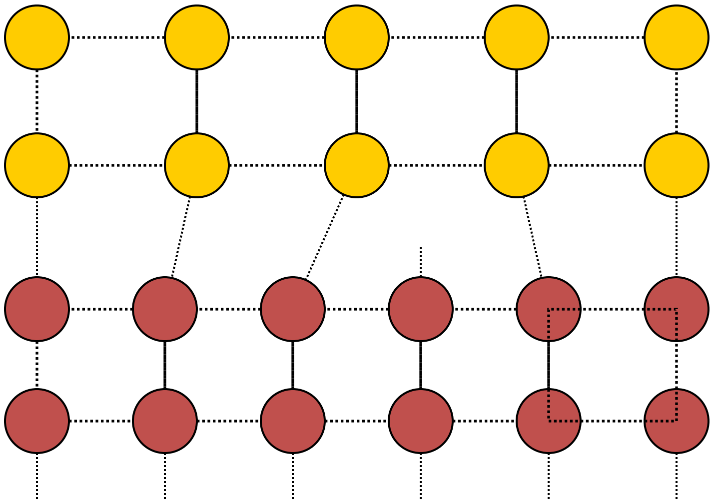
Substrate





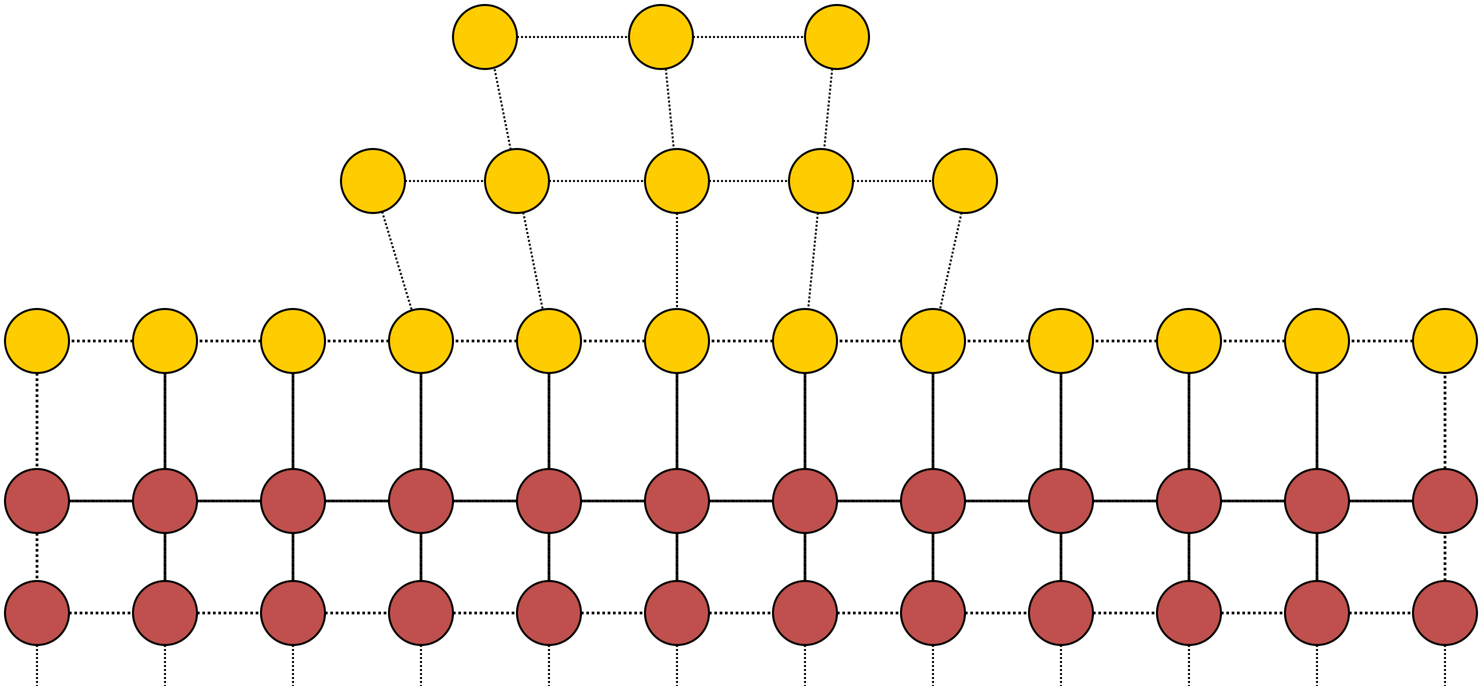
Strained epilayer
=> (elastic) energy cost

Relaxation of the elastic energy (1)



two-dimensional growth mode
plastic relaxation (dislocations)

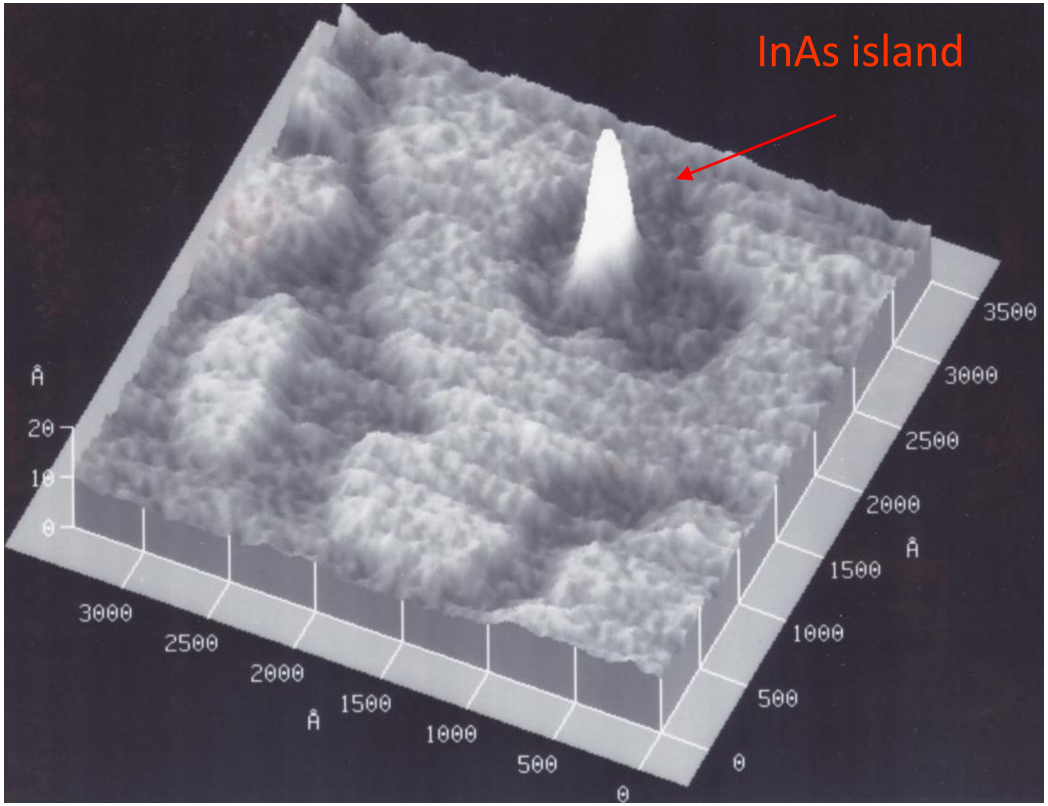
Relaxation of the elastic energy (2)



Elastic relaxation through island nucleation

Study of the nucleation and growth of InAs QDs

AFM JM Moison, CNET 1995



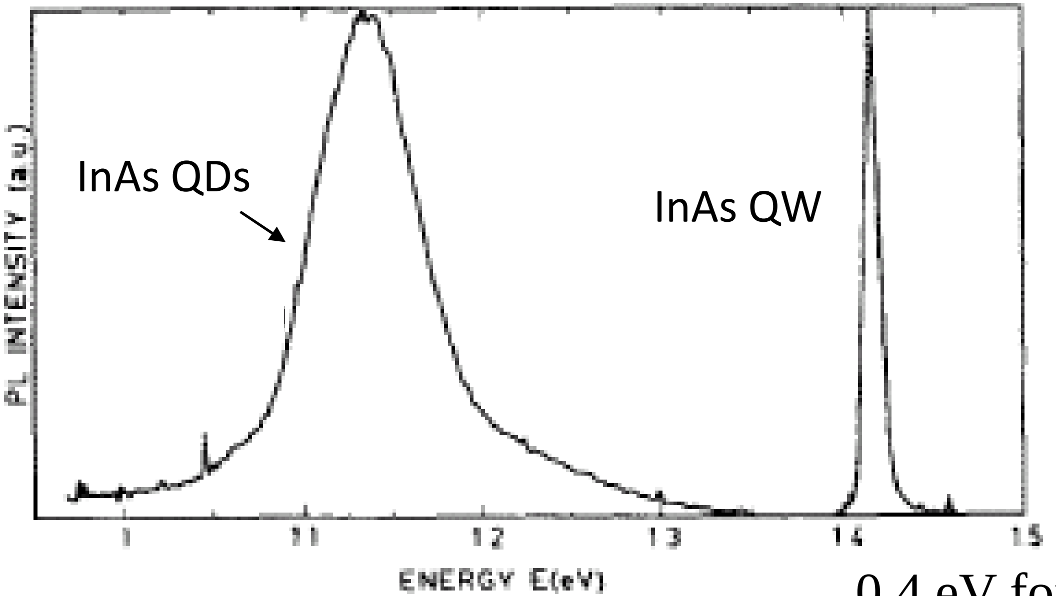
Buildup duration ~ 10s

⇒ Their size can be adjusted by playing with growth parameters

⇒ Reproducible fabrication process

J.M.G, J. Crystal Growth, 150, 351 (1995)

Optical properties of quantum dots (1)



First emission spectrum of InAs/GaAs QDs (*Goldstein et al*, *APL* 1985)

1) Bandgap

0.4 eV for bulk InAs

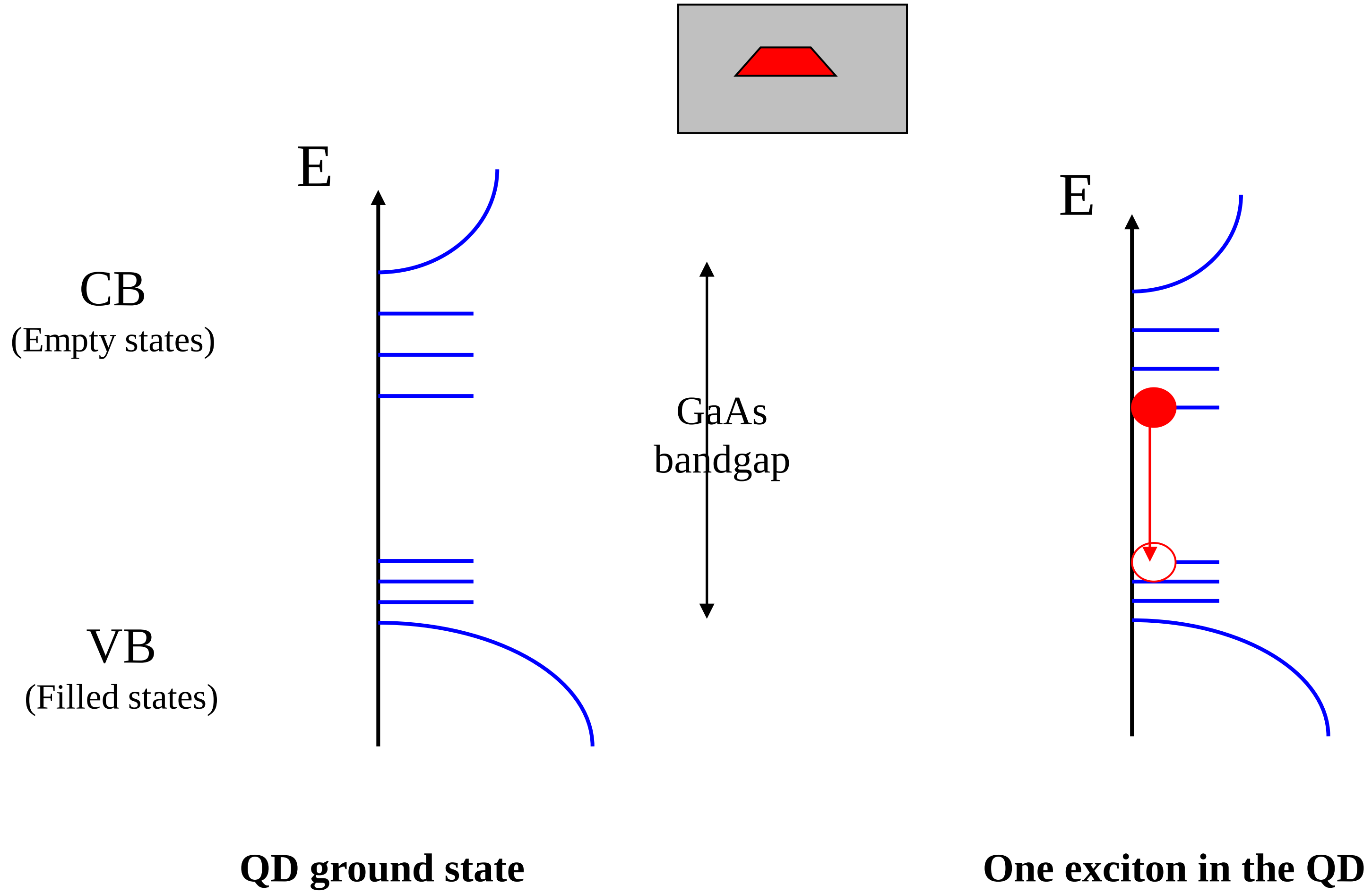
1.15 eV for InAs QDs (in this exp.)

⟶ Giant quantum confinement effect !

2) Large spectral width

⟶ Is it due to size fluctuations ?

Schematic density of states

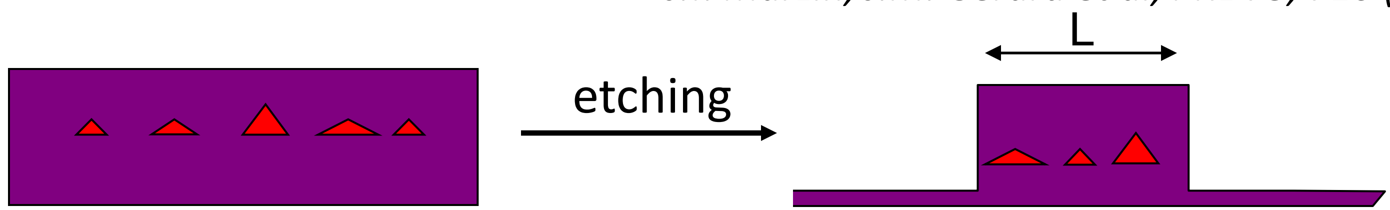


N.B. : each QD is different !

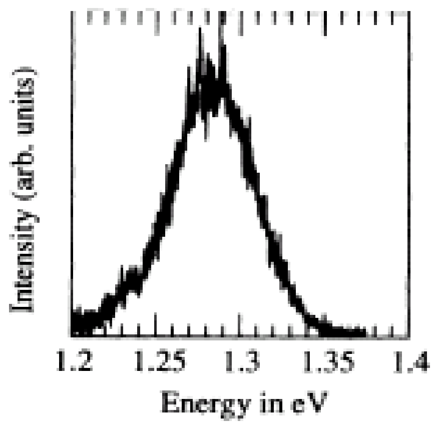
For many applications, the QD should be identical/indistinguishable: need for new schemes.

Fluorescence of a single QD

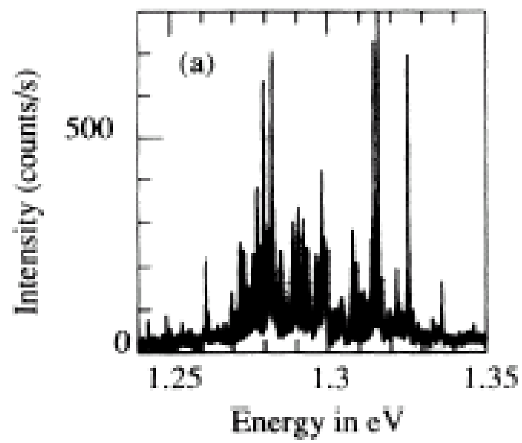
J.Y. Marzin, J.M. Gérard et al, PRL 73, 716 (1994)



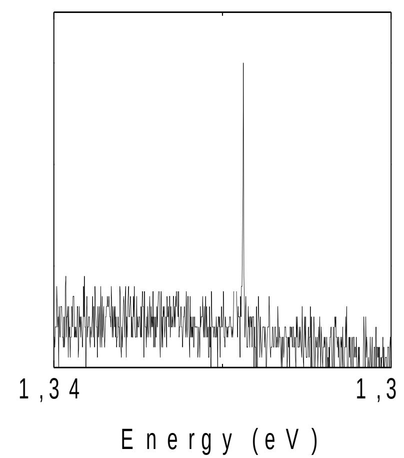
L=5µm : 10000 QDs



L=0.5 µm : 100 QDs

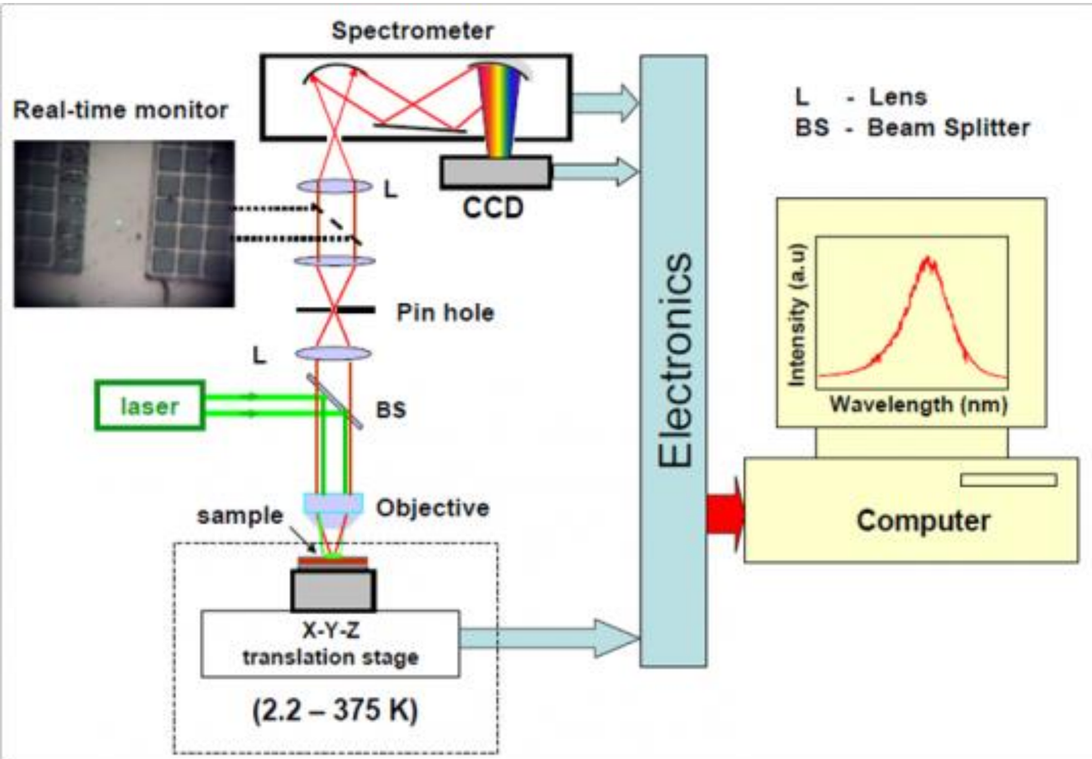


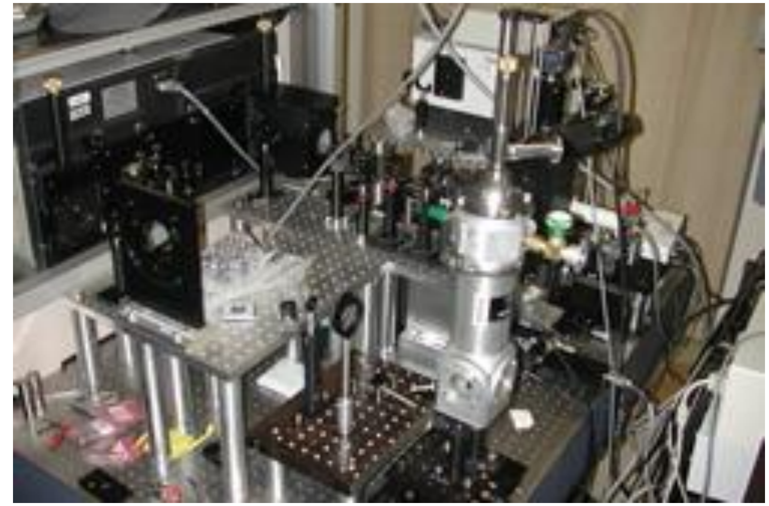
L~50 nm : 1 QD



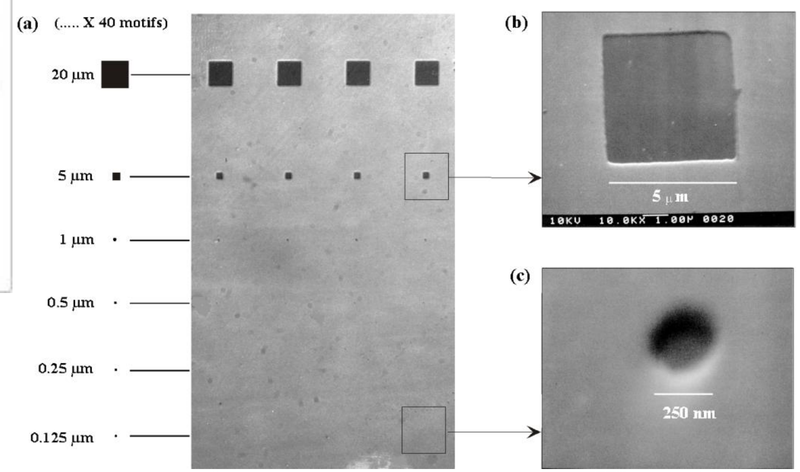
Single QD => Narrow emission line (at T=8 K)

Micro-photoluminescence setup



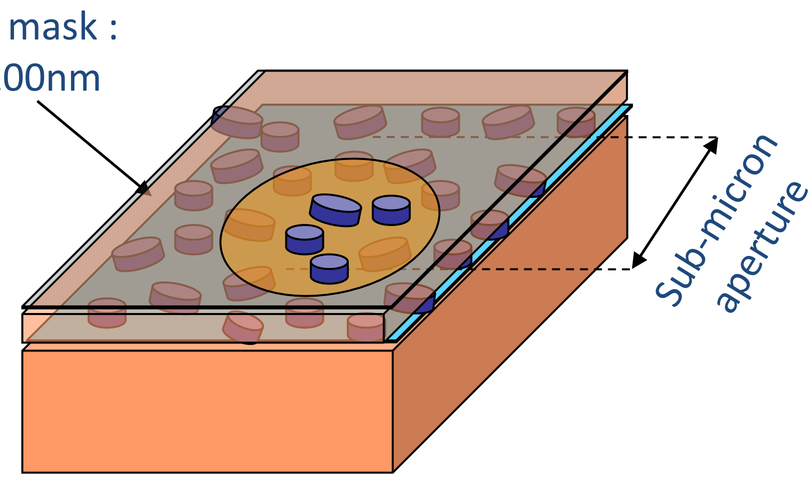


selection of one (or few) QDs using a sub-μm hole in a mask.

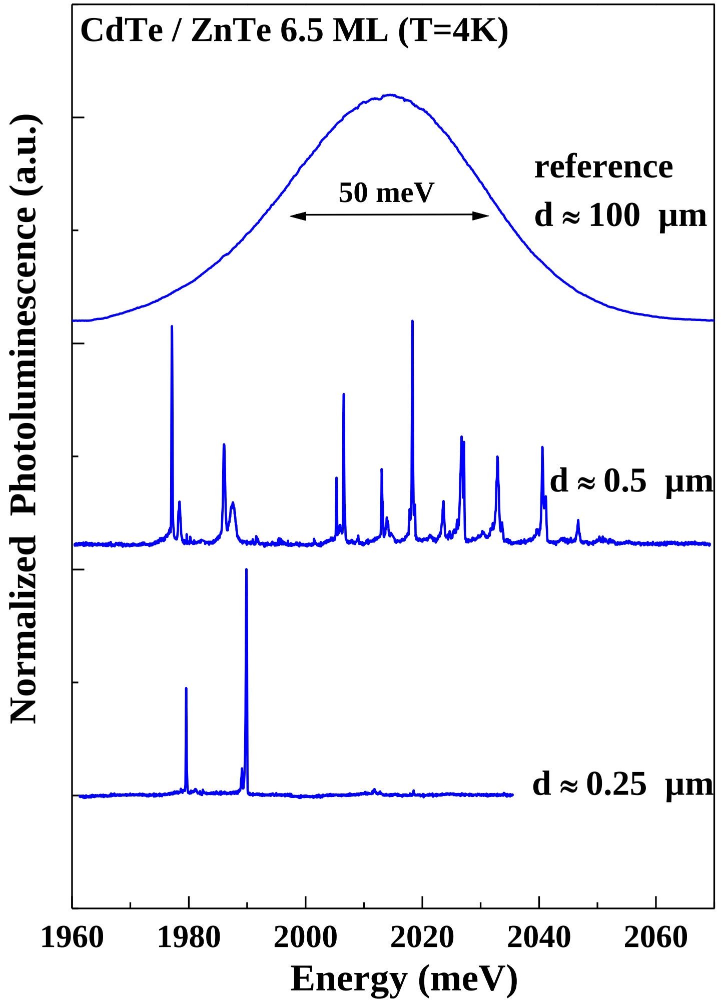


Measurements at cryogenic temperatures with high spatial resolution: vibration and collection efficiencies are challenging. Current rise of cryo-free systems.

Micro-Photoluminescence on CdTe QD (K. Kheng et al)



QD size ~ 2-20 nm, density~10^{10}cm^{-2}



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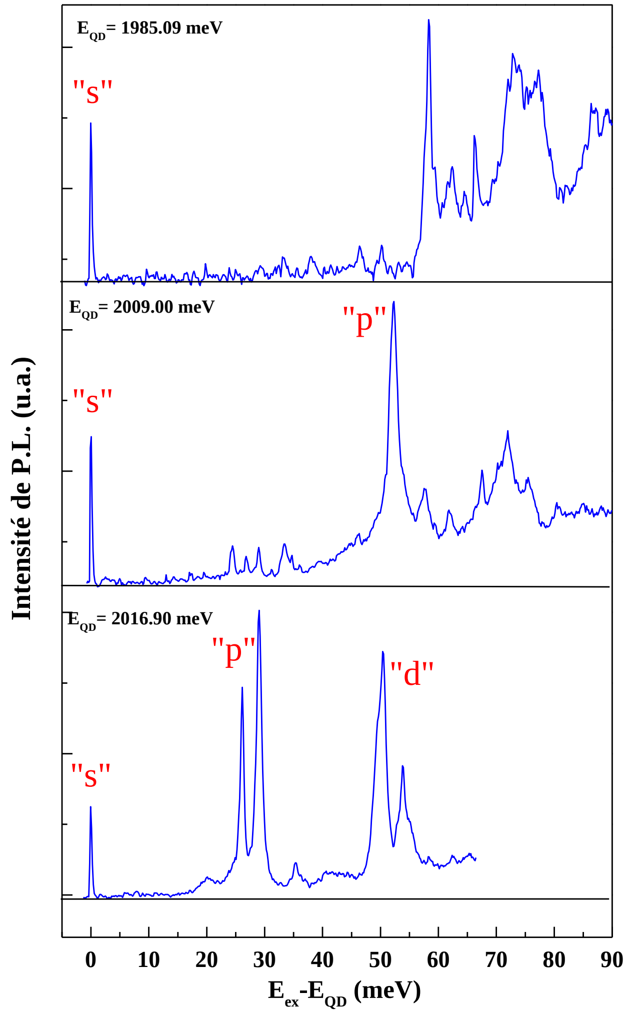
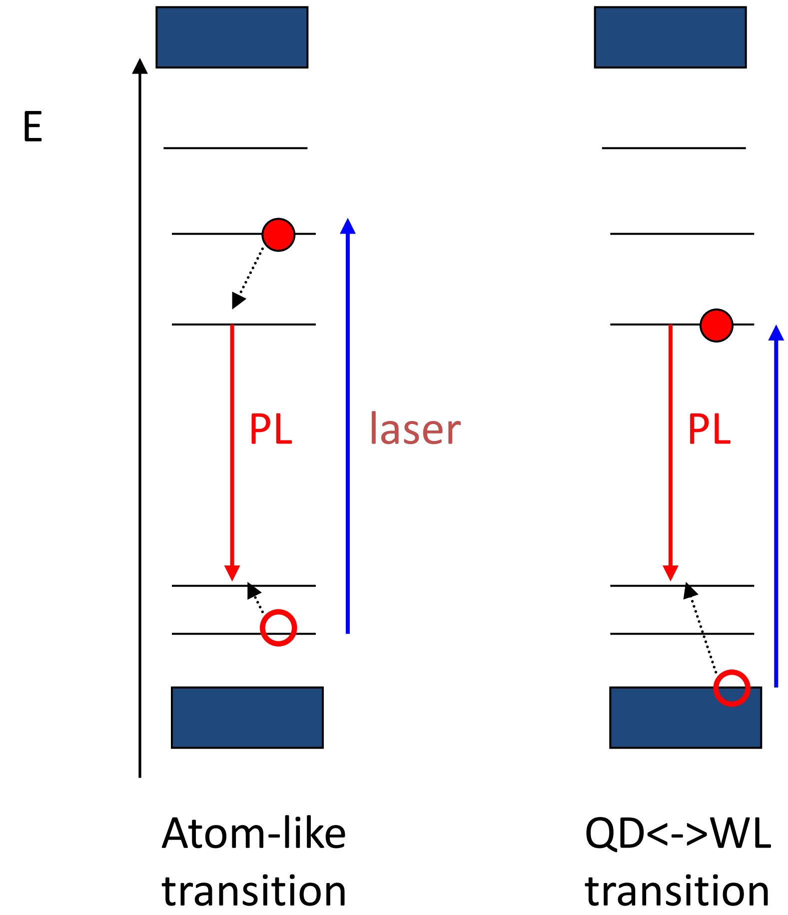
Photoluminescence excitation (PLE) on a single CdTe QD (Besombes et al)

In PLE, we tune the excitation energy (laser wavelength) and measure the emission intensity.





Vasanelli et al, PRL 2003

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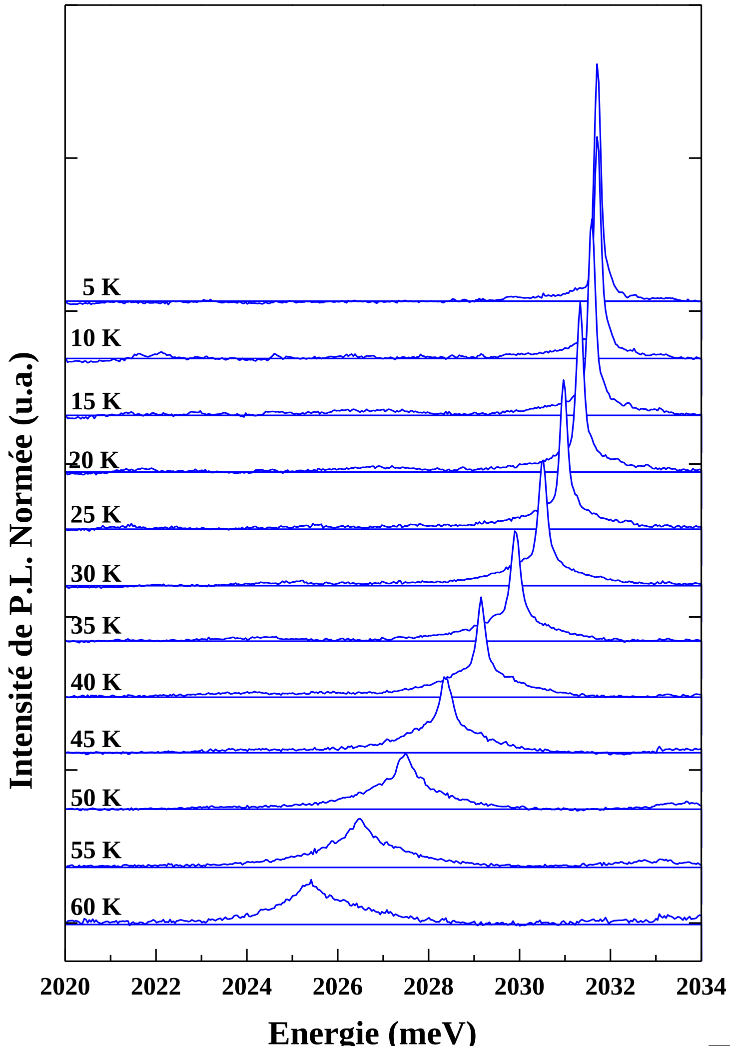
µPL study of a single CdTe quantum dot: T dependence

L. Besombes et al, PRB 63, 155307 (2001)



Localized exciton

=> coupling to acoustic phonons

=> Phonon sidebands

Redistribution of the oscillator strength between the zero phonon line and the phonon sidebands well understood within the Huang-Rhys formalism.

Also observed for GaAs/AlAs QDs *E Peter, PRB 69, 41307 (2004)*

and for InAs/GaAs QDs *I. Favero et al, PRB 68, 233301 (2004)*

The parabolic dependence of the bandgap on temperature is observed.

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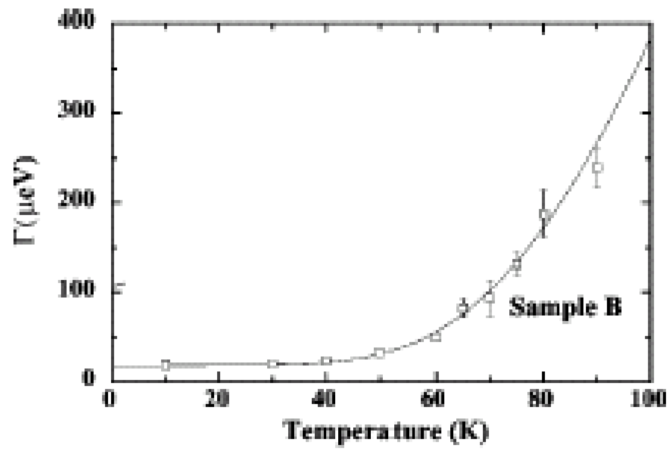
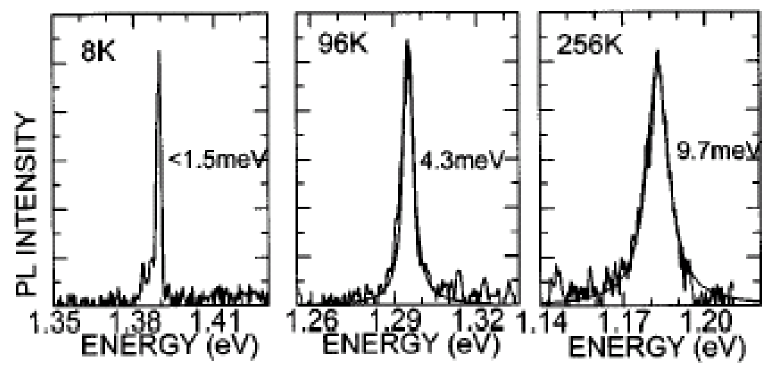
T-induced broadening of the X line

µPL C. Kammerer et al,
PRB 66, 41306 (2002)



SNOM K. Matsuda et al,
PRB 63, 121304 (2001)



$$\Gamma(T) = \Gamma(0) + aT + b\,e^{-\hbar\omega_{LO}/kT}$$

QW : 2.5 µeV/K

QD : 0.05 µeV/K

OD =>Quenching of dephasing processes due to acoustic phonons at low T

Strong broadening at 300K !!

Fluctuations of the electrostatic environment

Electron traps close to the QD

⇩

Fluctuating local electric field

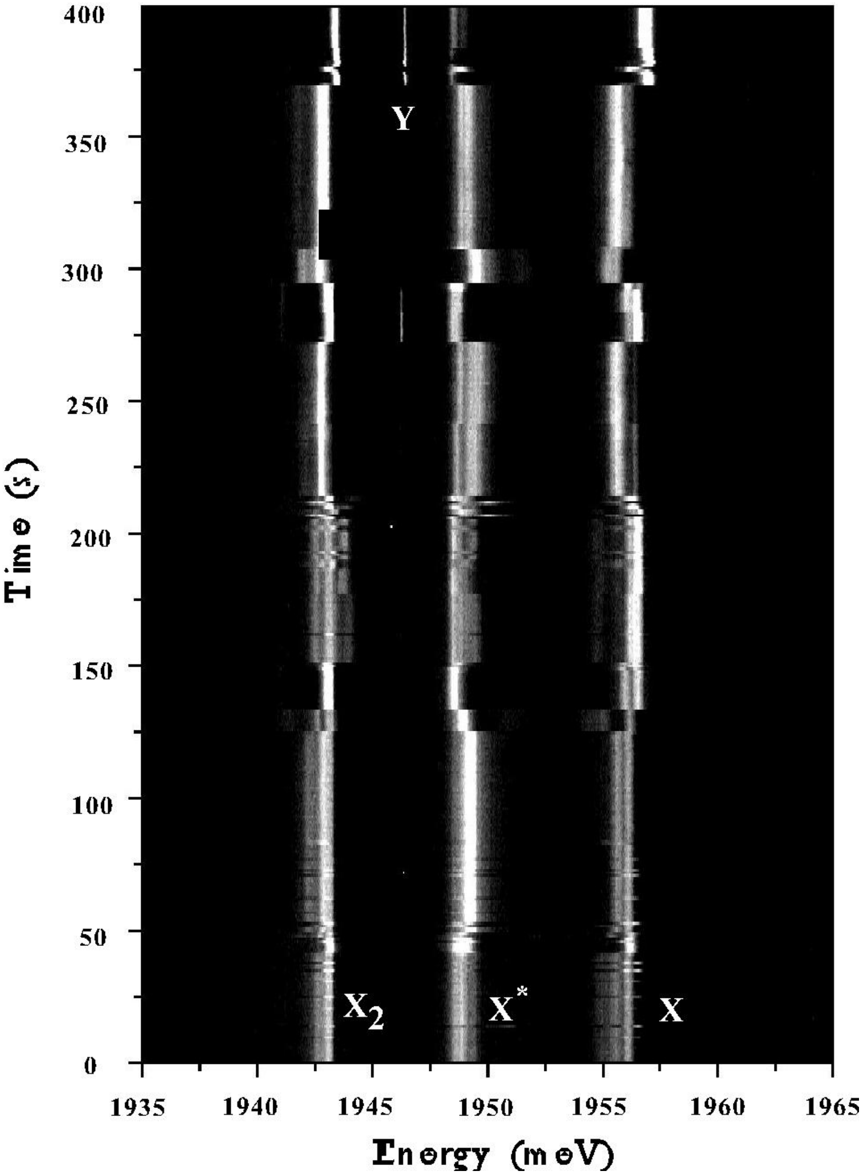
⇩

Random Stark effect on QD transitions

Synchroneous fluctuations of three lines

⇕

Exciton, biexciton and charged exciton lines from the same QD



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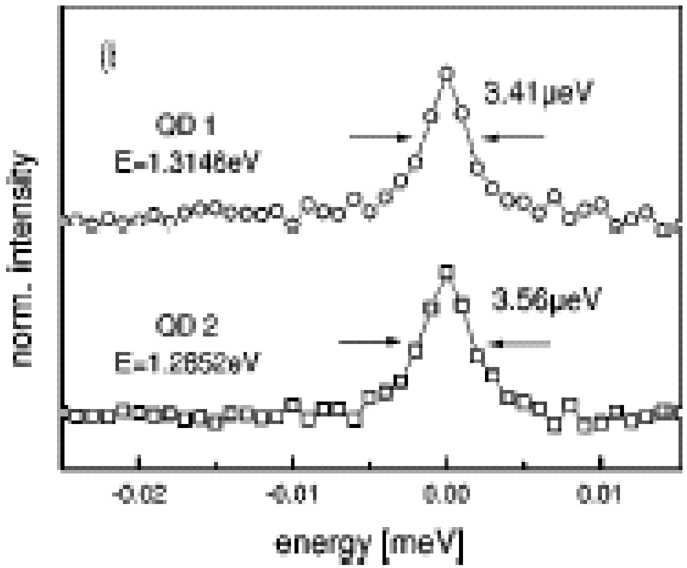
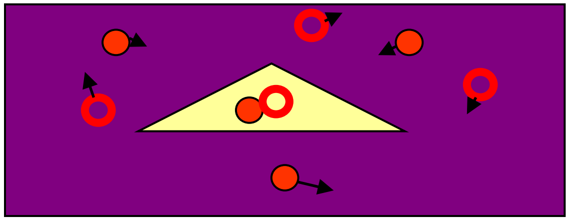
Decoherence (2) : Coulomb effects

Photoluminescence from a single InAs/GaAs QD (T=2K)

M. Bayer et al, PRB 65, 41308 (2002)





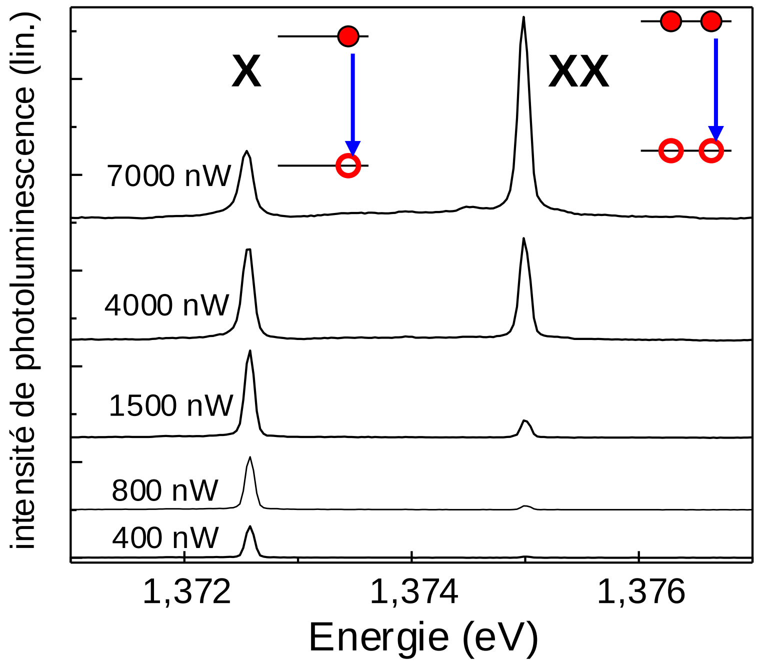
linewidth > radiative lifetime limit (~0.6 µeV)

⇒ Fast fluctuations of the electrostatic environment (T_2 <2 T_1)

See e.g. *C. Kammerer et al, Phys Rev B 66, 41306 (2002)*

A. Berthelot et al, Nature Physics (2006)

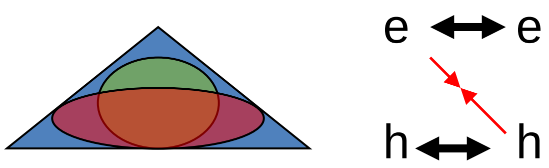
Bi-exciton in a single InAs QD



QD spectra dominated by level filling and Coulomb effects

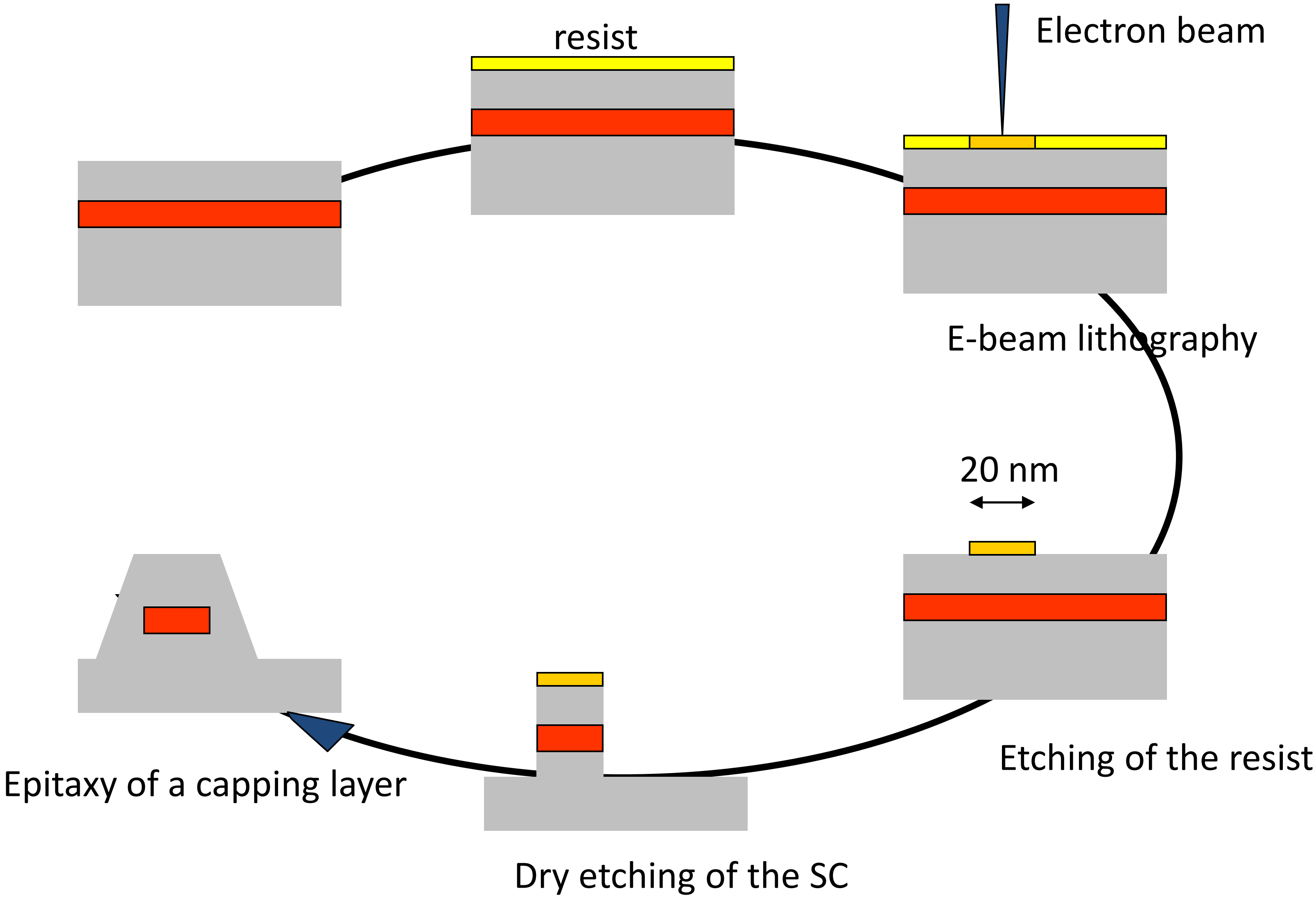
No Auger effect!

Unlike QWs, the X-XX splitting can be positive or negative for QDs



depending on the overlap of the e and h wavefunctions

The sculptor approach…

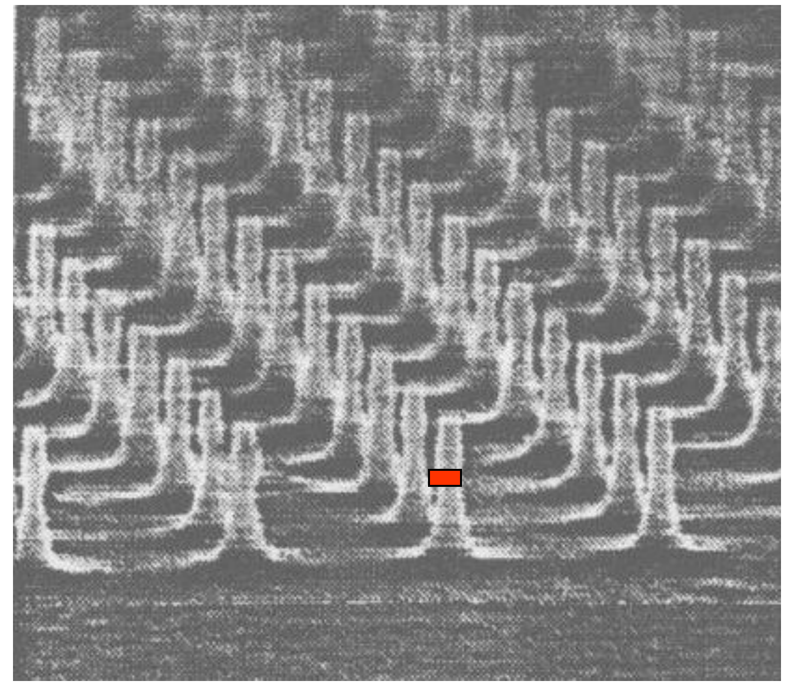


Etched quantum wires and dots

Quantum wire (width 20 nm)

A Izraël, CNET 1991

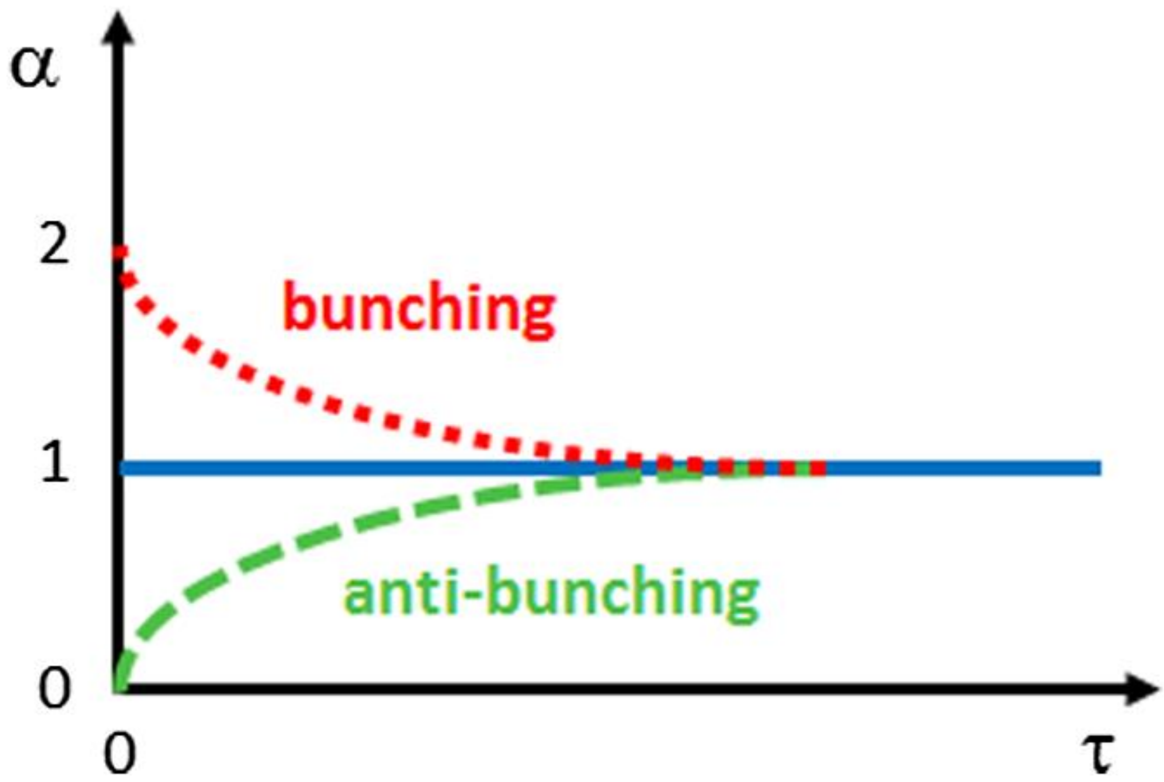
Quantum dots (size 25 nm)



Problems :
. Size fluctuations : +/- 3 nm
. Lithography of the QDs one by one !

Photon statistics

Antibunched, bunched, Poissonian



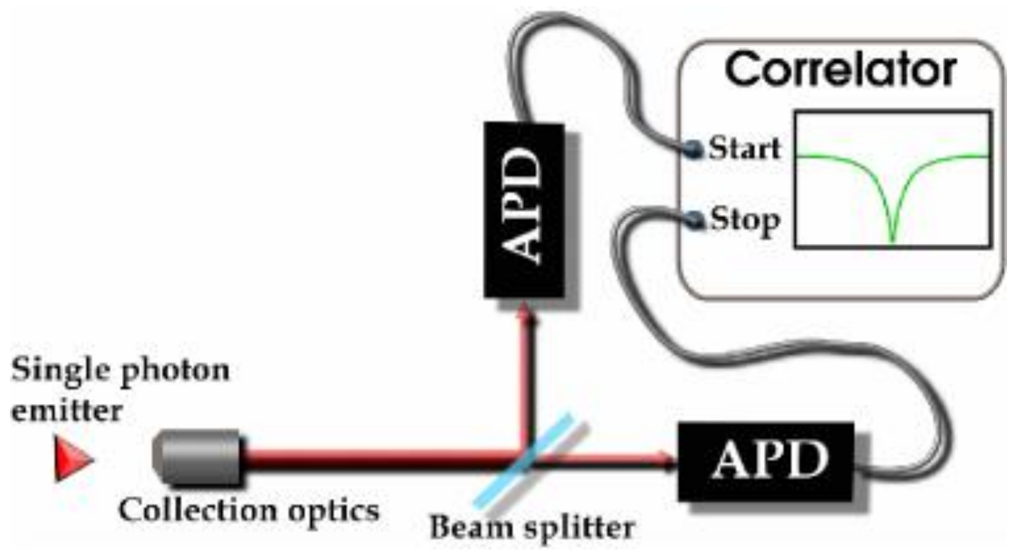
Antibunching

A stream of single photons where two or more photons are never emitted simultaneously = clean light.

Not easy, photons are Bosons.

We get antibunching by relying on Coulomb interactions in a quantum dot.

The Hanbury-Brown Twiss interferometer



What is a single photon source ?

Source able to emit single photons pulses on demand

Non-classical state of light

Applications : quantum cryptography
metrology (energy standard)
quantum computing (?)

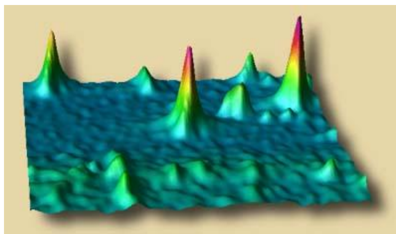
For most applications, the single photons must be prepared in the same quantum state !!

Single mode spontaneous emission wanted !!

Solid-state « artificial atoms » as single photon emitters

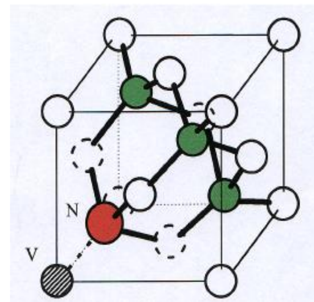
at 300 K !

Molecule



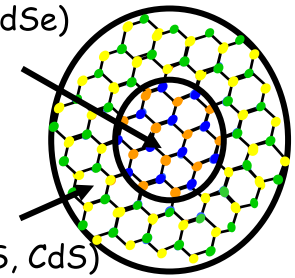
Lounis and Moerner, Nature 407, 491 (2000)

F center



Kurtsiefer et al, PRL 85, 290, 00

Nanocristal



Michler et al, Nature 406, 968, 00

T<300K, but

No bleaching

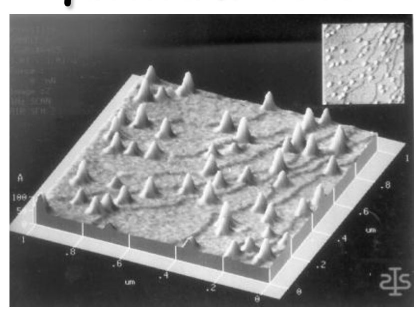
No blinking

Fast (1 ns)

Easy electrical pumping

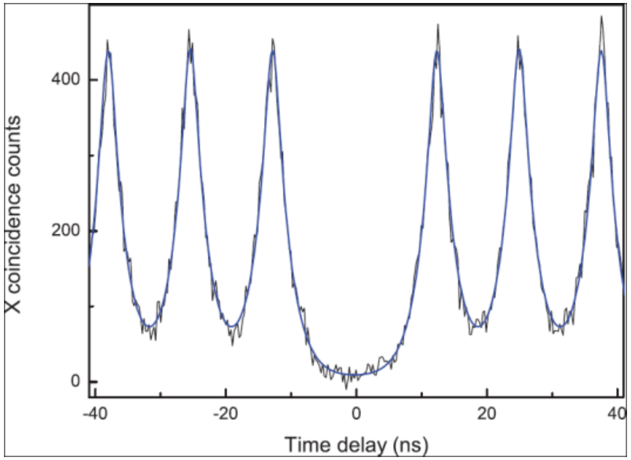
λ in telecom windows possible

Self-assembled quantum dots

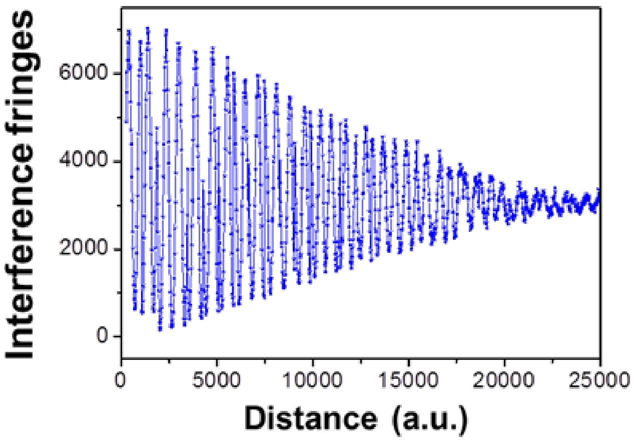


Ideal quantum emitter?

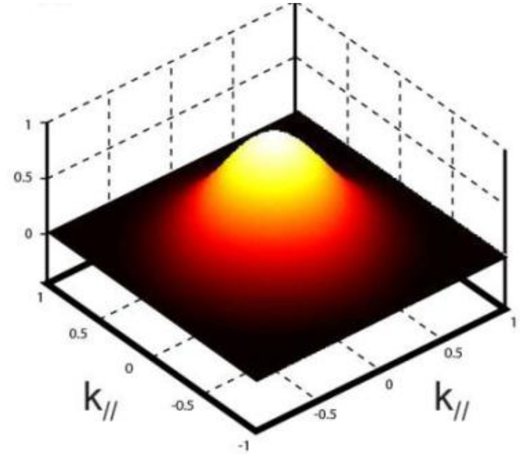
Bright, pure, on demand



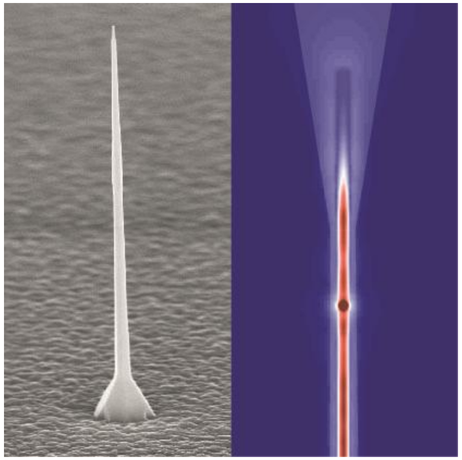
Coherent: Fourier limited



Gaussian emission profile



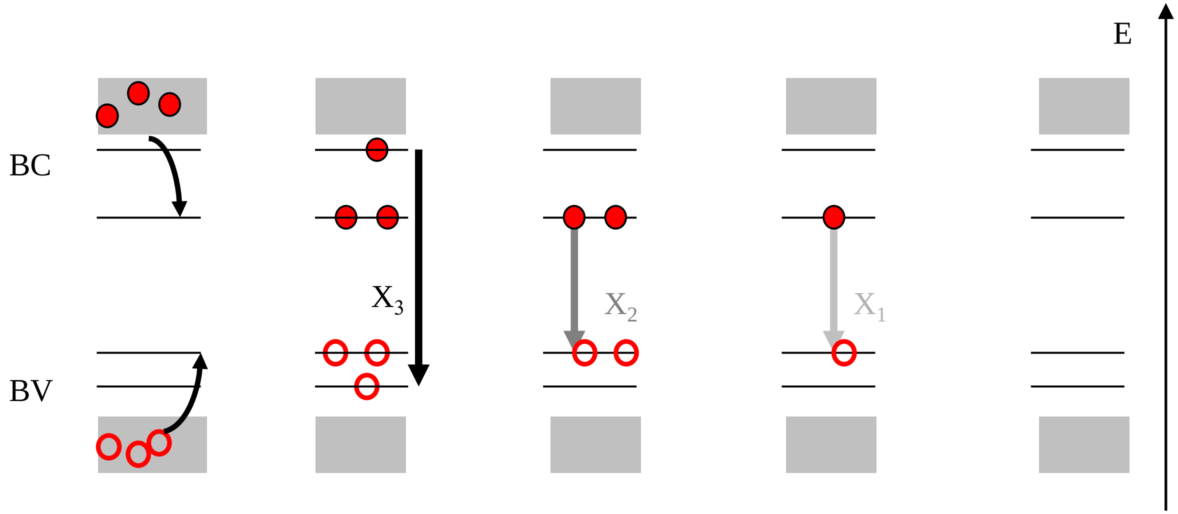
Entanglement generation

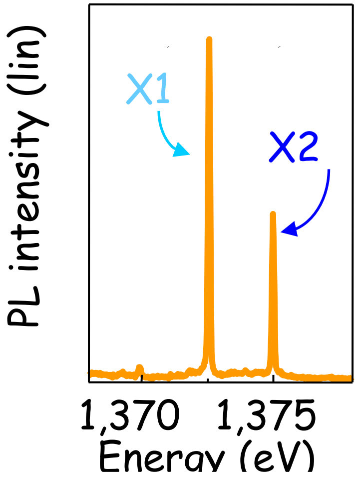


And: compact, scalable, power efficient, indistinguishable.

Single photon generation protocol

Proposal: J.M. Gérard et B. Gayral,
J. Lightwave Technol. 17, 2089 (1999)



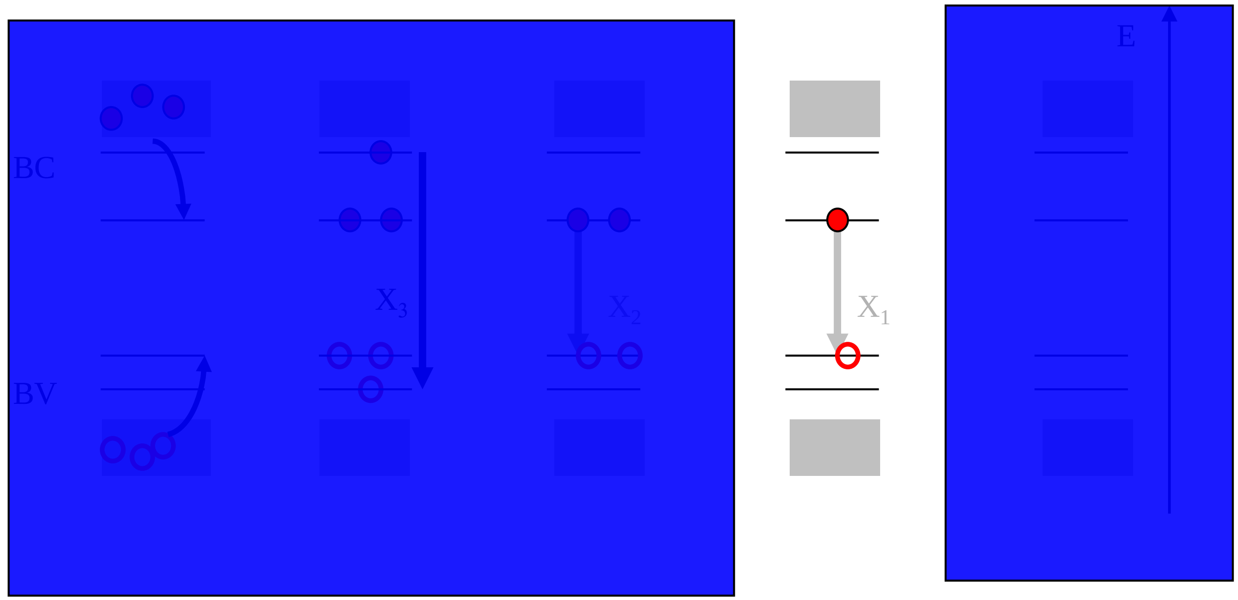


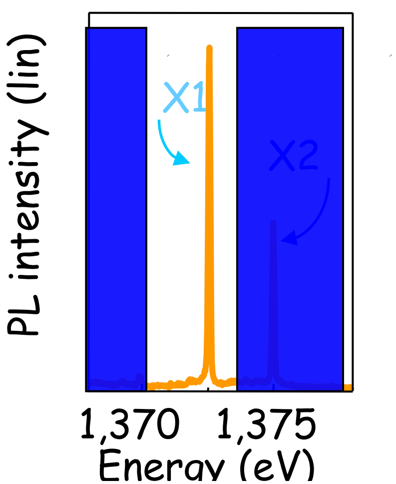
Radiative cascade from a QD

Successive photons emitted at different frequencies
due to Coulomb interaction!

Single photon generation protocol

Proposal: J.M. Gérard et B. Gayral,
J. Lightwave Technol. 17, 2089 (1999)





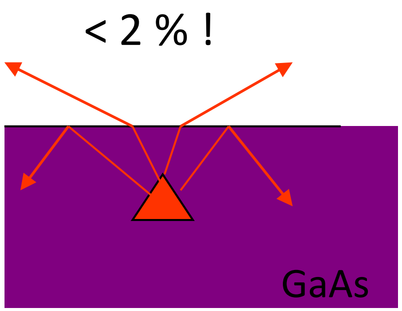
Radiative cascade from a QD

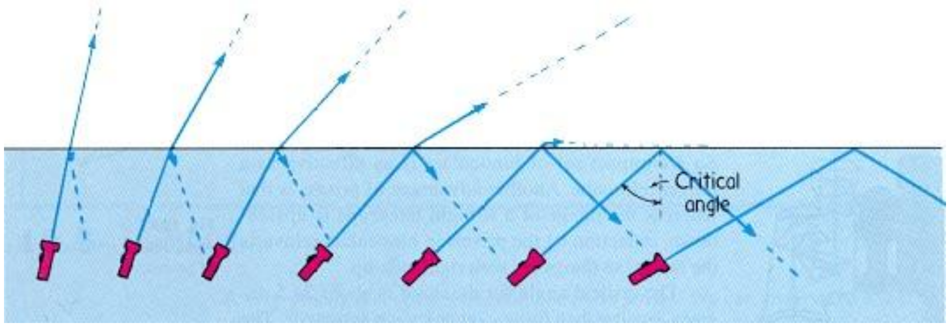
Preparation of a single photon by spectral filtering !

A single QD, NV center, molecule… can emit single photons on demand

but

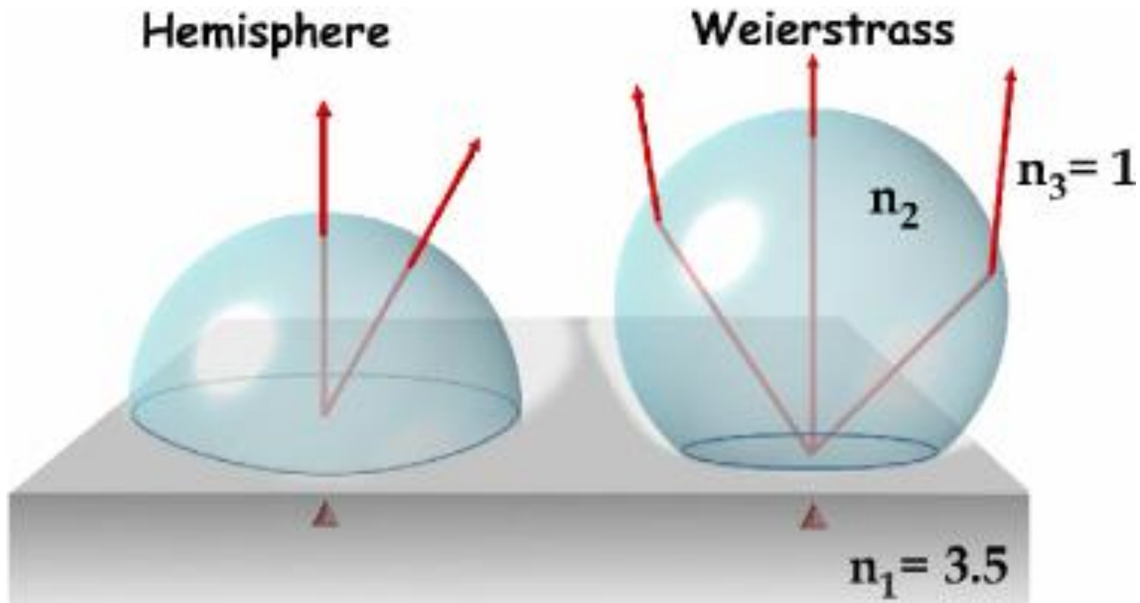
extracing the light emission from tehe sample is a critical step.





Because semiconductors have large refractive indexes, total internal reflections occurs for small angles (~ 17 degrees for GaAs), implying very weak extraction, of the order of a few %.

Solid immersion lenses



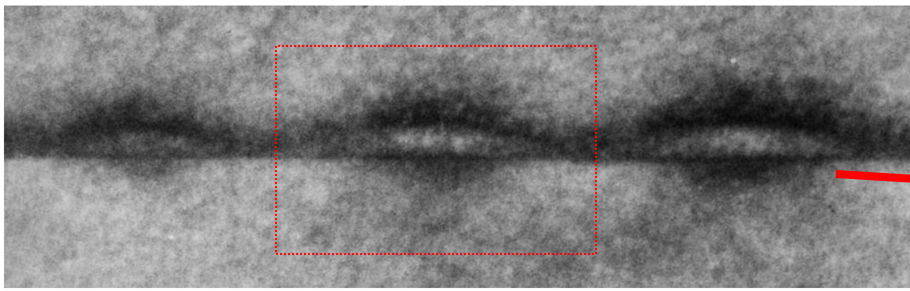
With a solid immersion lens, the total internal reflection problem can be solved. Provided the lens has the same refractive index than the substrate.

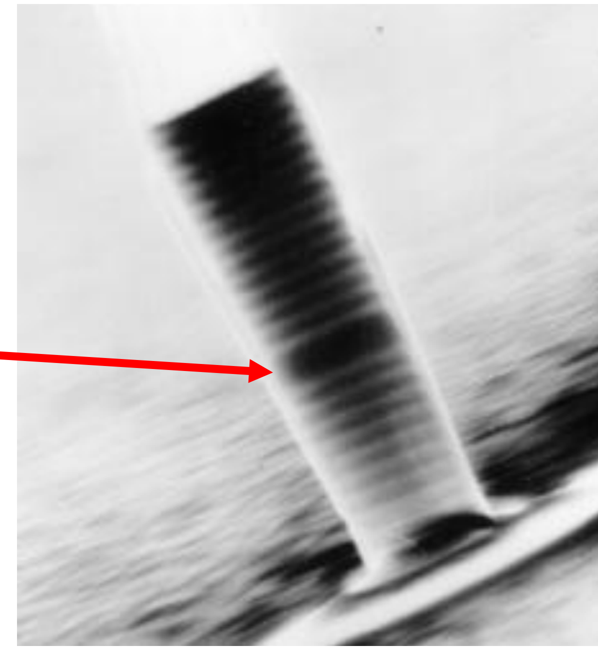
2001 : The first single-mode single-photon source (CNRS/LPN)

GaAs/AlAs micropillar

Isolated InAs QD as « artificial atom »

20 nm





=> Single-photon emission

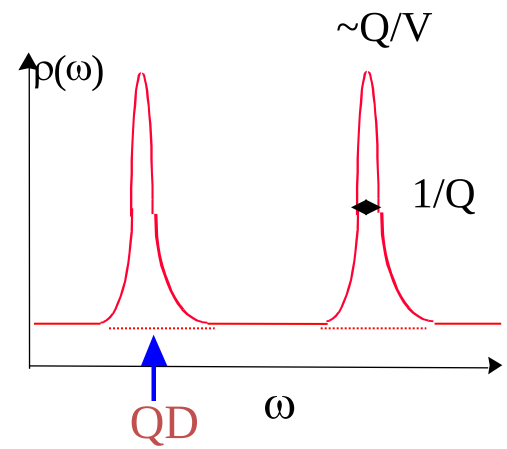
Purcell effect

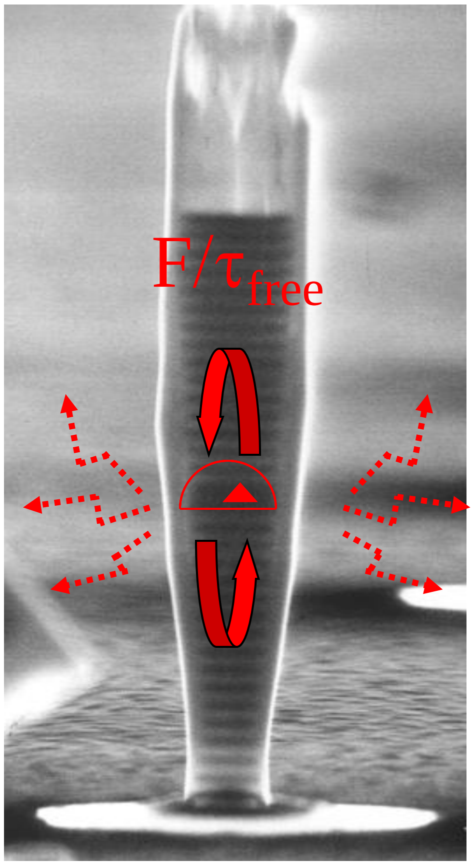
⇒ Efficient collection
+
single-mode behavior

With a microcavity, the emission profile is modified and so is the lifetime: The Purcell effect.

« Nearly » single-mode spontaneous emission

Purcell effect
=
<u>selective</u> enhancement of
SE into the resonant mode





γ/τ_{free}

(γ~1)

$$\beta = \frac{F}{F+\gamma} \approx 1$$

J.M. Gérard et al
PRL 81, 1110 (1998)

The Purcell effect ensures a « nearly » single-mode behavior of the QD-SPS !

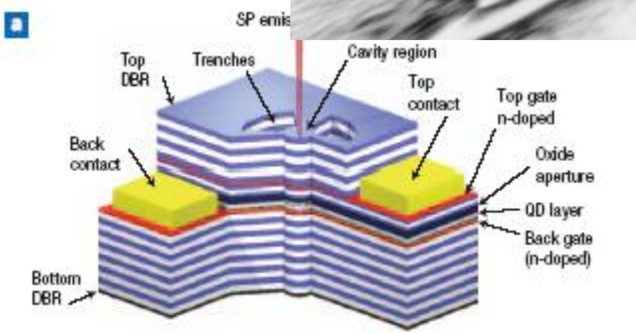
QD-SPS efficiency : the state of the art

Optically pumped :

~40 % for a QD in a micropillar

E.Moreau et al, Physica E13, 418 (2002)

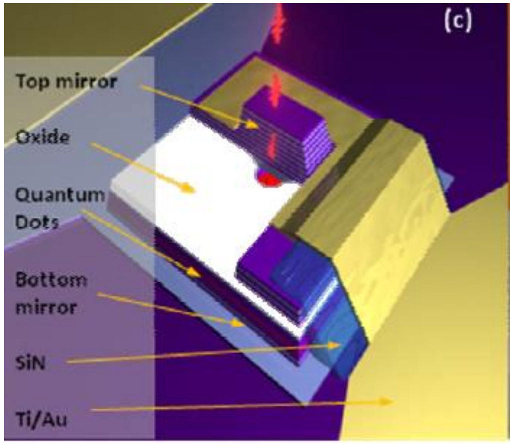
M Pelton et al, PRL. 89, 23 3602 (2002)



38 % in an oxide-apertured planar cavity

S Strauf et al, Nat. Phot. 1, 704 (2007)

Electrically pumped:



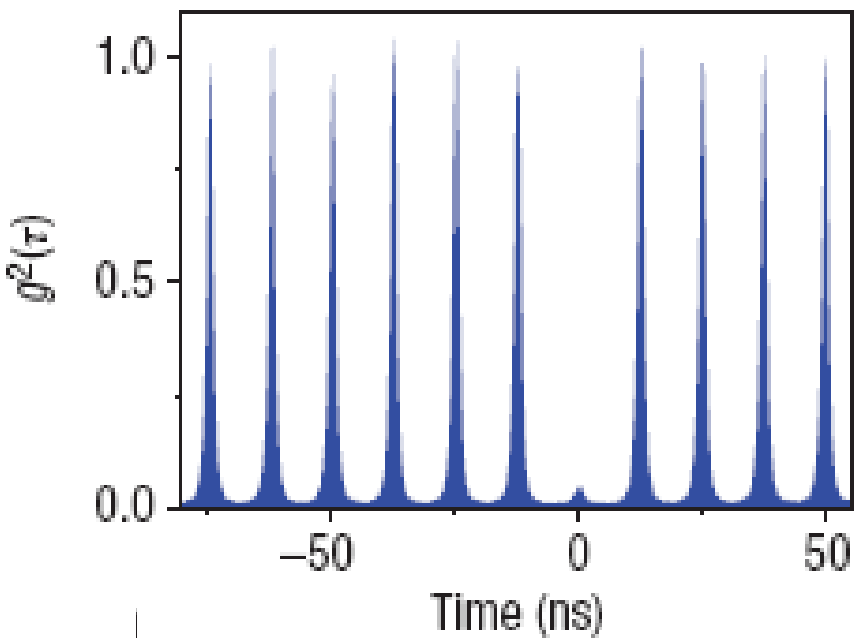
14 % in a VCSEL like structure

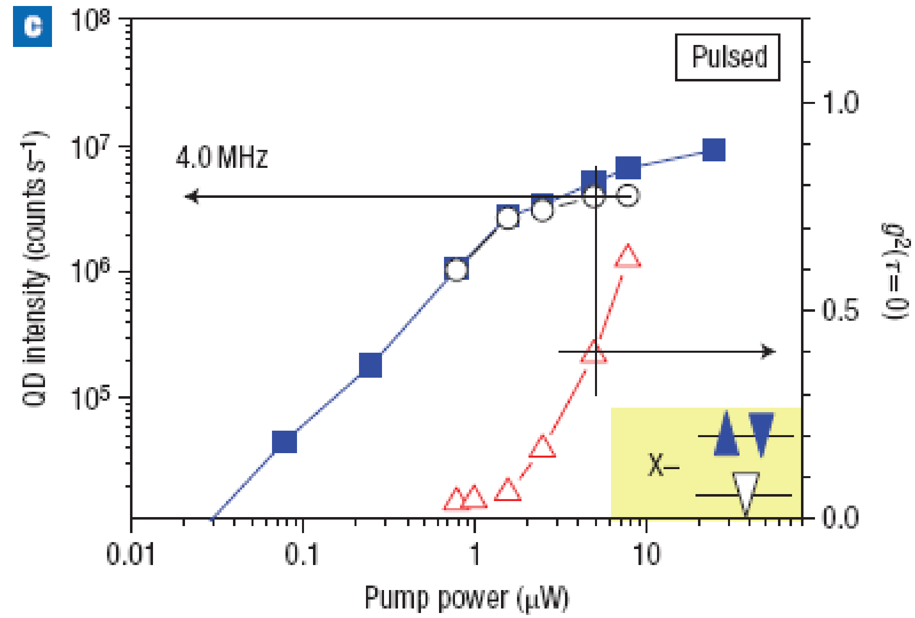
DJP Ellis et al, New J Phys 2008

34% for a QD in a micropillar

T Heindel et al, APL 96, 11107 (2010)

The $g^{(2)}(0)$ issue for QD-microcavity SPS





From S. Strauf et al, Nat Phot 1, 704 (2007)

See also Pelton et al PRL 2002, Heindel et al, APL 2010

Low $g^{(2)}(0)$ only observed for weak pumping levels

$g^{(2)}(0)>0.5$ at QD saturation level !

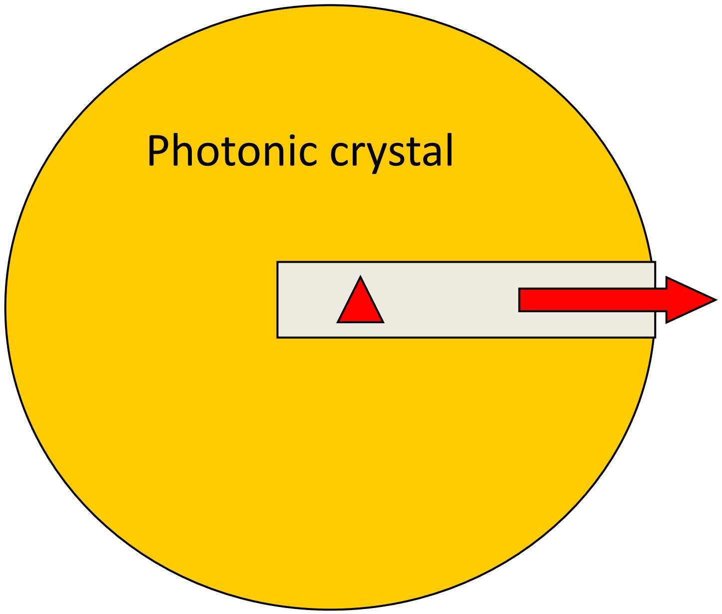
A novel strategy toward high efficiency single-mode SPS :

Let's get rid of high Q cavities !

~~Selective enhancement of SE in one mode~~ → Inhibition of SE in useless modes

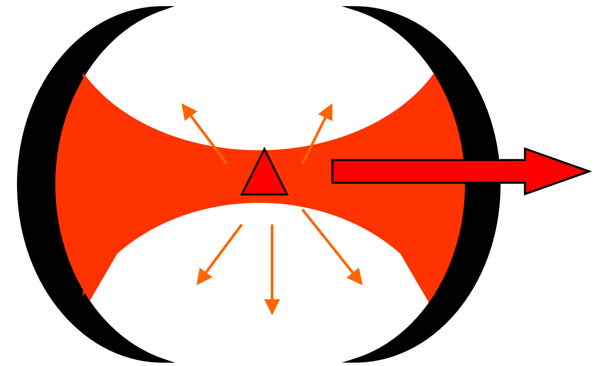
QD in a photonic wire

Two avenues toward single-mode SpE



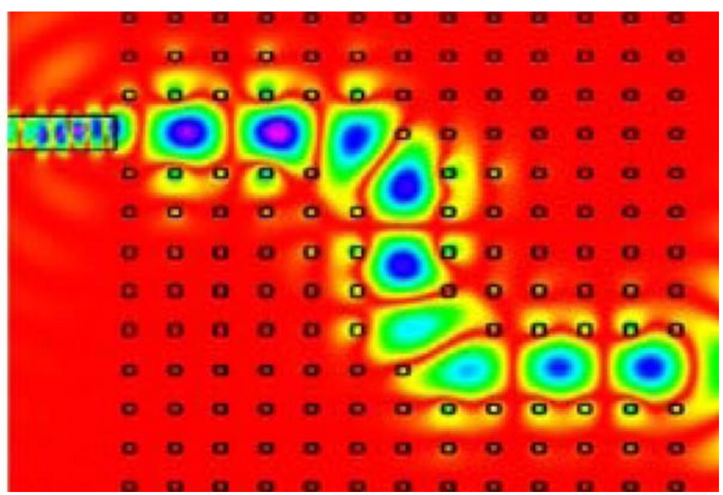
Inhibition of SpE into all useless modes

(e.g. E. Yablonovitch 1993)



Selective enhancement of SpE into a single resonant cavity mode (Purcell effect)

(e.g. JM Gérard et al, PRL 1998)



« Because of its promised utility in controlling the spontaneous emission of light in quantum optics, the pursuit of a photonic bandgap has been a major motivation for studying photonic band structures »

E. Yablonovitch,
J. Opt. Soc. Am. B10, 283 (1993)

Single-Mode Light-Emitting Diode

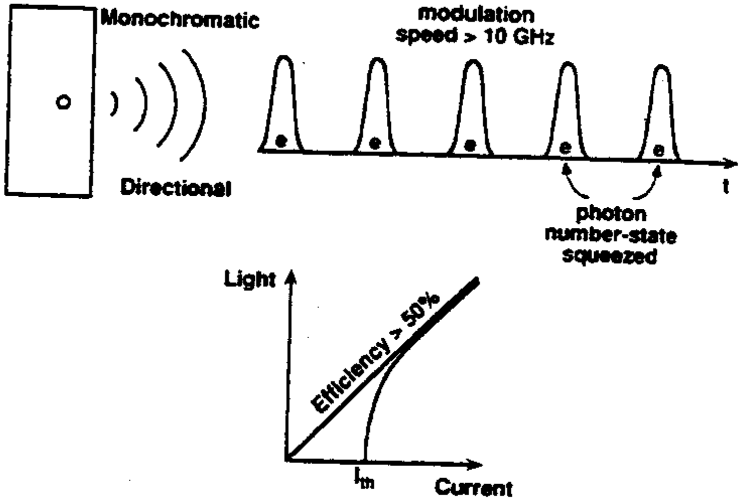


Fig. 24. Properties of the SM-LED, whose cavity is represented by the small circle inside the rectangular photonic crystal at left. The words Monochromatic and Directional represent the temporal and spatial coherence of the SM-LED output, as is explained in the text. The modulation speed can be >10 GHz, and the differential quantum efficiency can be >50%, which is competitive with that of laser diodes. But there is no threshold current for the SM-LED, as indicated by the curves for light output versus the input current at the bottom. The regular stream of photoelectrons, e's, is meant to represent photon-number-state squeezing, which can be produced by the SM-LED if the spontaneous-emission factor β of the cavity is high enough.

Photonic wires : a novel template for solid-state CQED

Basics of photonic wires

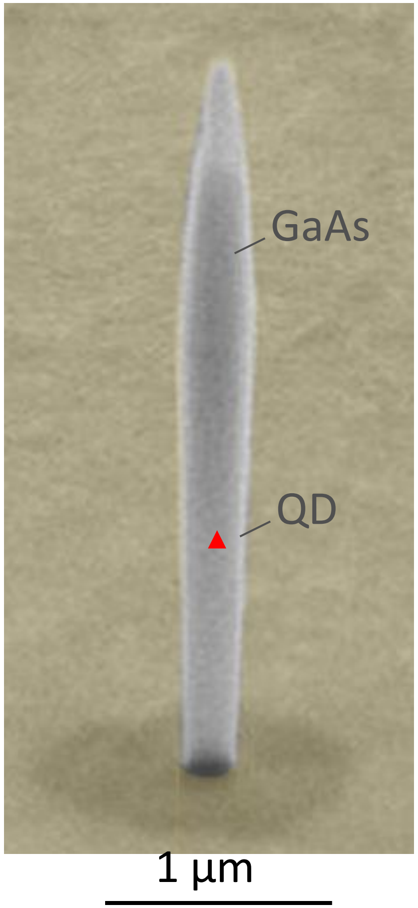
Controlling QD SpE with photonic wires

A first practical application :

an « ultrabright » QD single photon source

Perspectives

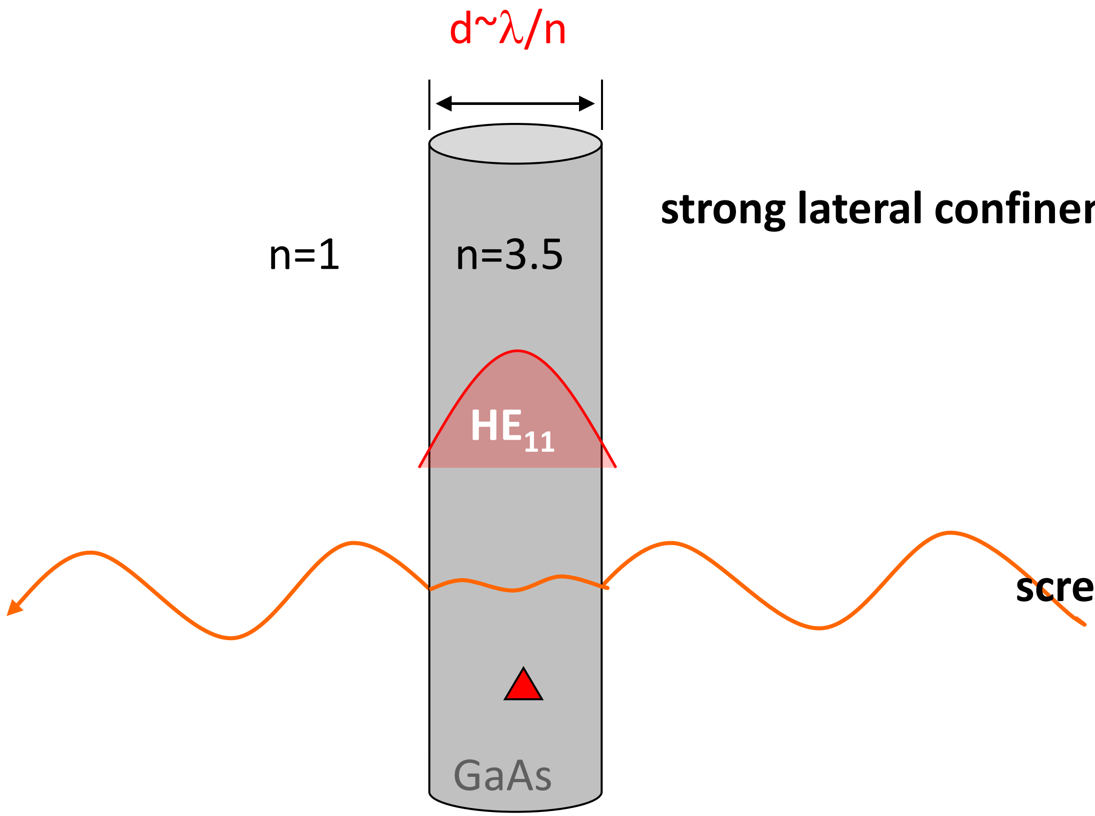
novel opportunities opened by PWs



What is a photonic wire?

First introduced by S.T. Ho et al, see PRL 1995

Single mode optical waveguide with a high refractive index

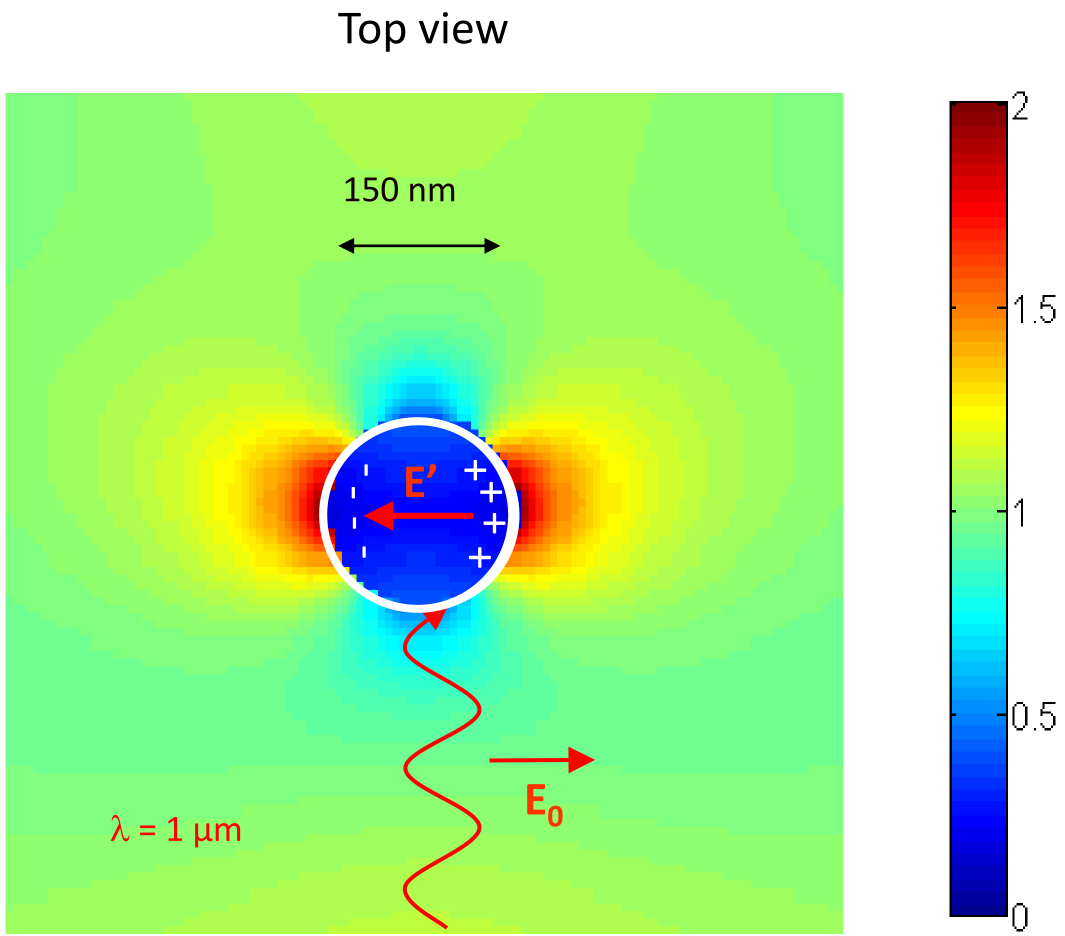


strong lateral confinement of the guided mode

screening of the radiative modes

=> Highly preferential coupling of QD SpE into the guided mode !

Dielectric screening : simulation



d<<λ

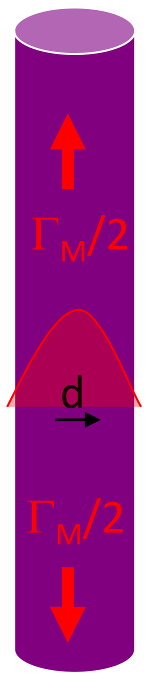
$$\frac{|\vec{E}_{tot}|}{|\vec{E}_o|} = \frac{2}{n^2+1}$$

Strong screening of the incident field
when the polarisation is ⊥to the wire axis

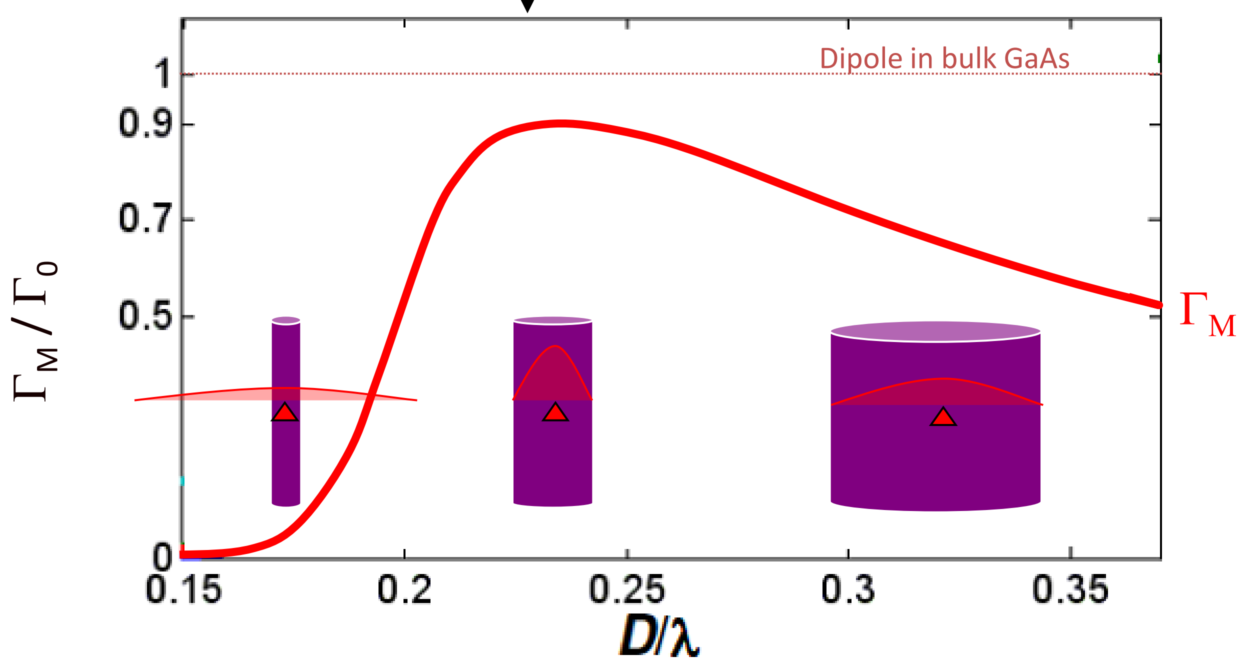
Coupling to the fundamental guided mode

$$\Gamma_m = 2 \times \frac{3}{8\pi} \frac{(\lambda/n)^2}{S_{\text{eff}}} \frac{n_g}{n}.$$

λ_e = 1 µm
emitter on axis
in-plane dipole

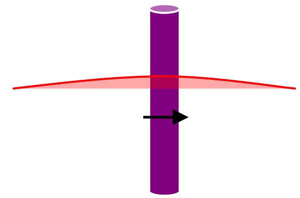


optimum confinement
of the guided mode

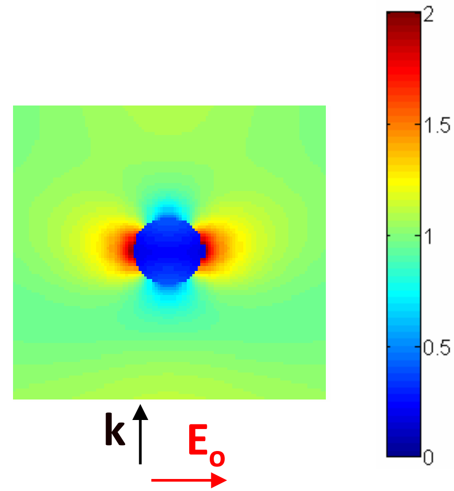


I. Friedler et al., Opt. Express **17**, 2095 (2009).

SE inhibition in ultrathin dielectric wires (d/λ < 0.15)



1) Deconfined guided mode



2) Screening of non-guided modes (in plane polar.)

$$\frac{\gamma}{\gamma_0} = \frac{1}{n}\left(\frac{2}{n^2+1}\right)^2$$ ~ 1/150 !!

Katsenelenbaum 1949 !

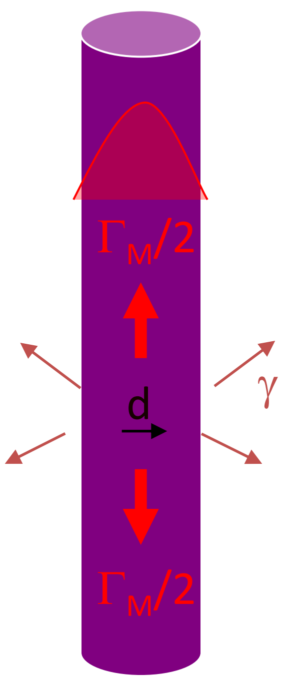
Ducloy et al, PRA 2004

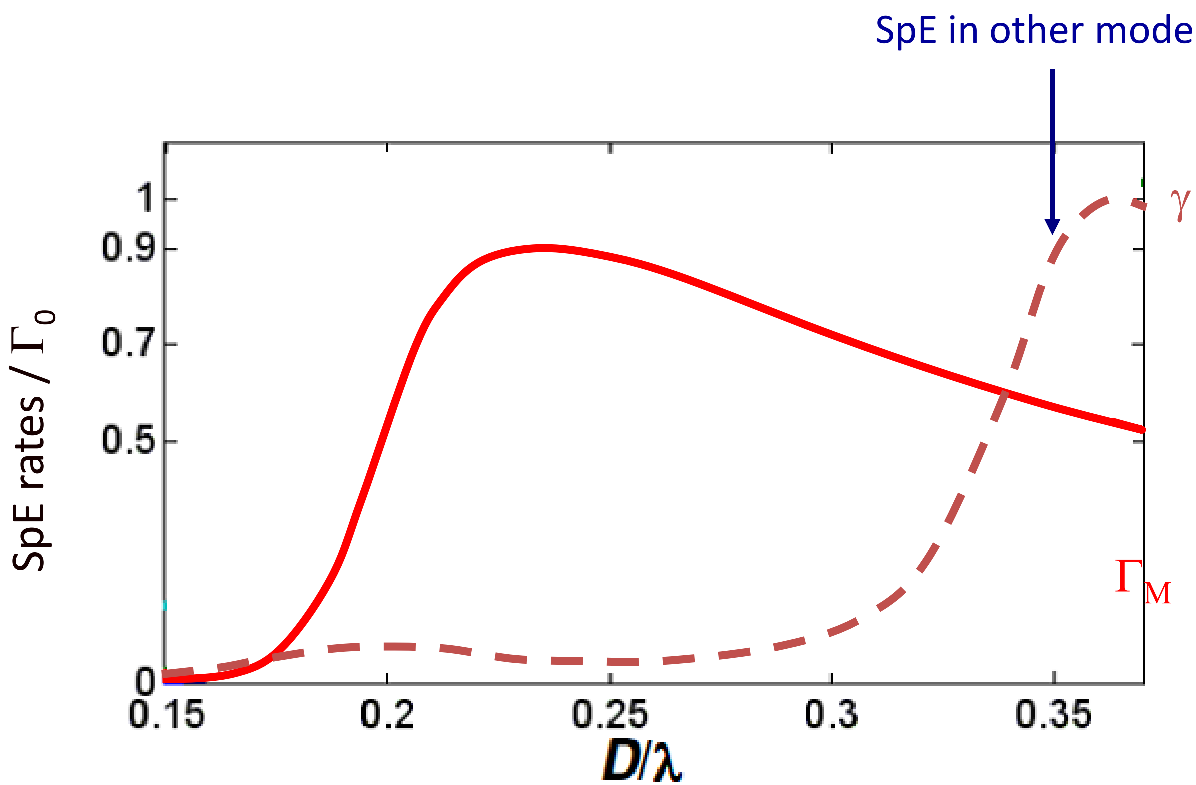
Maslov et al, JAP 2006

SpE control in an infinite photonic wire (1)

I. Friedler et al., Opt. Express **17**, 2095 (2009).

λ_e~1µm
emitter on axis
in-plane dipole



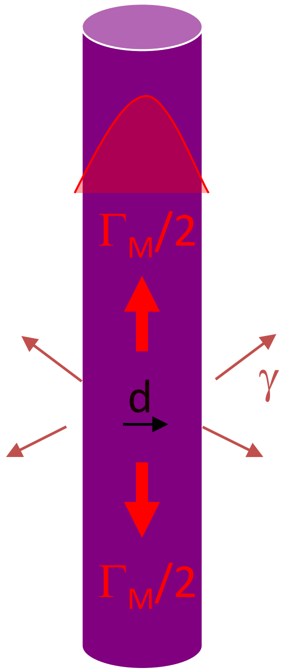


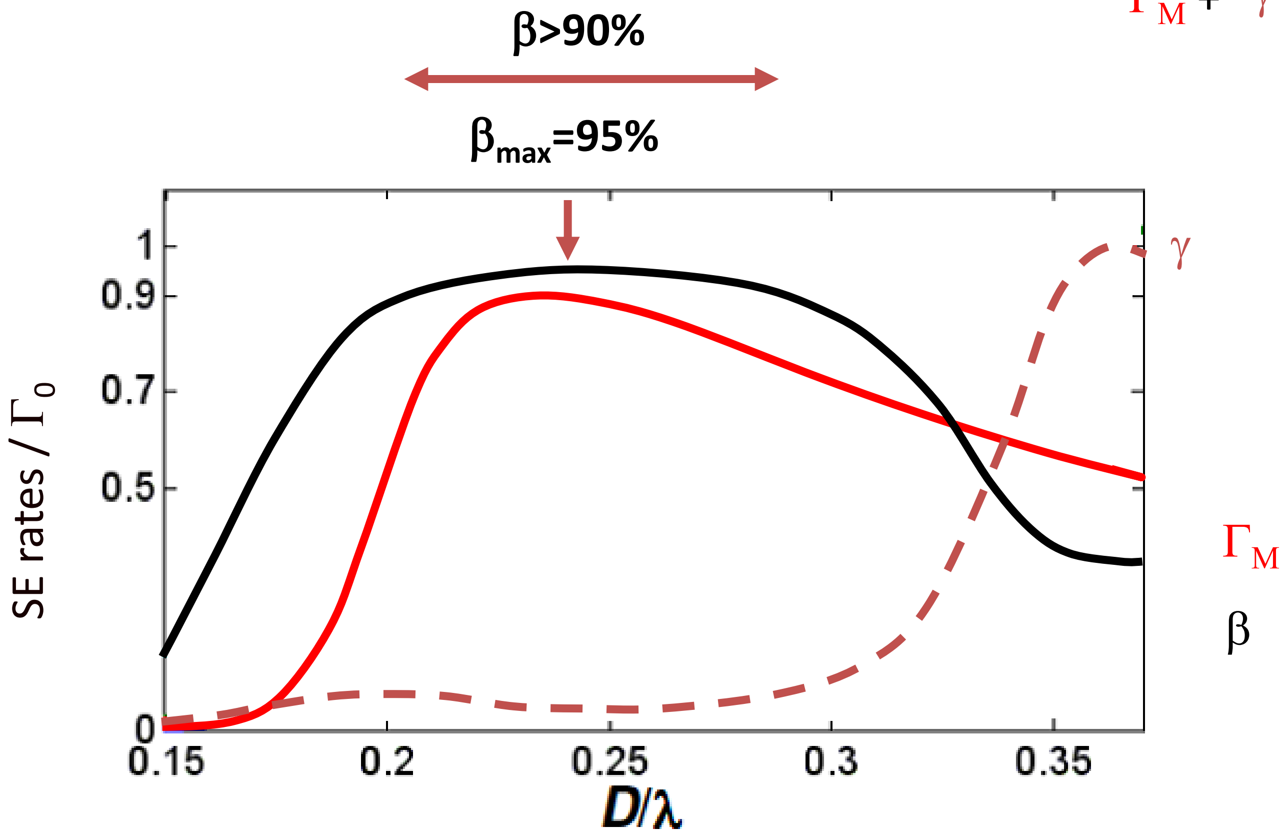
Strong SpE inhibition for small diameter PWs ($d/\lambda < 0.17$)

SpE in the guided mode predominant for $0.2<d/\lambda<0.3$

SpE control in an infinite photonic wire (2)

$$\beta = \frac{\Gamma_M}{\Gamma_M + \gamma}$$

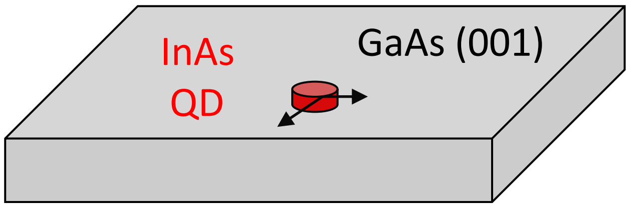




Efficient and broadband SE control

Small diameter (0.2 < d/λ < 0.28), close to the single mode cut-off

InAs QDs as test emitters in photonic wires

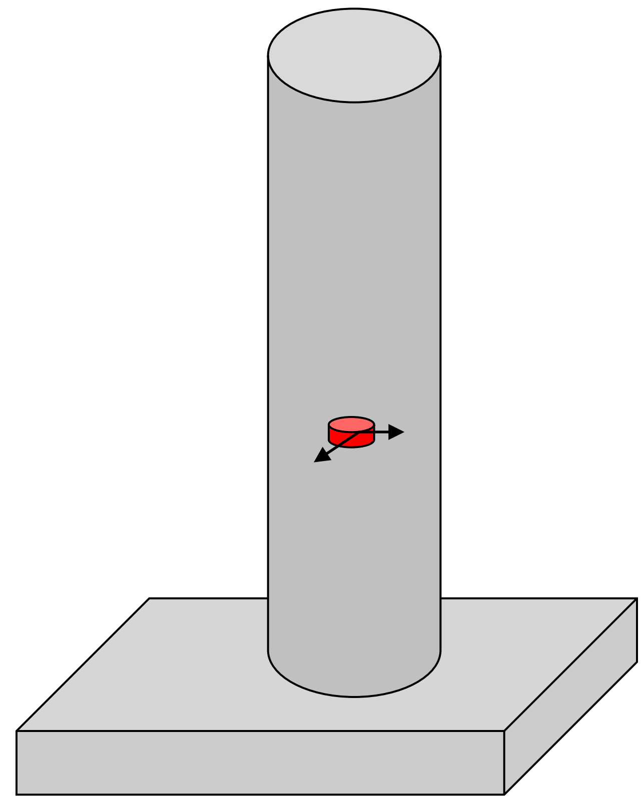


Low energy excitonic complexes have

in plane optical dipoles

Bright X, X-, X+ : x or y polarized dipole

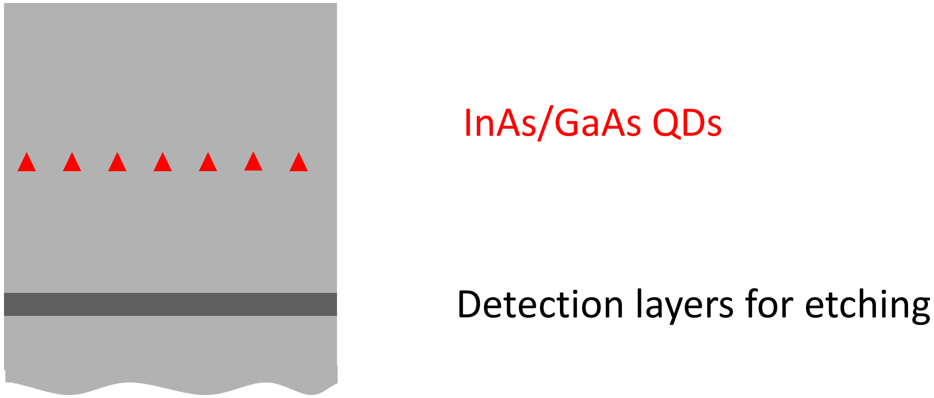
XX : x and y polarized dipoles



=> InAs QDs in vertical PWs

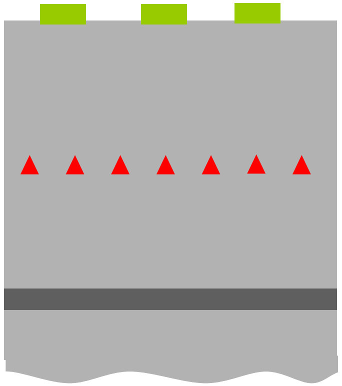
Overview of the fabrication process

1. MBE Growth

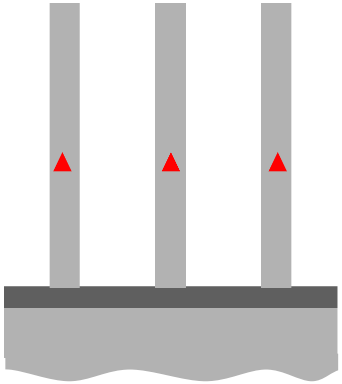


2. **Etching mask definition :**

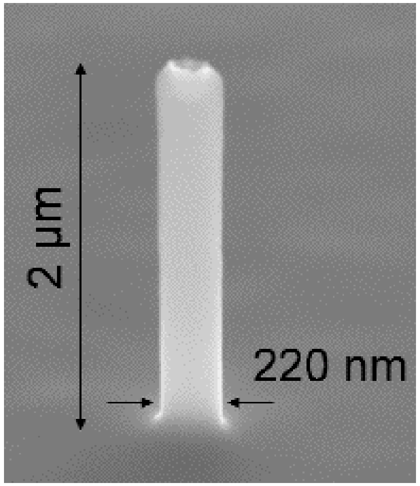
E-beam lithography, Deposition of Ni, lift-off

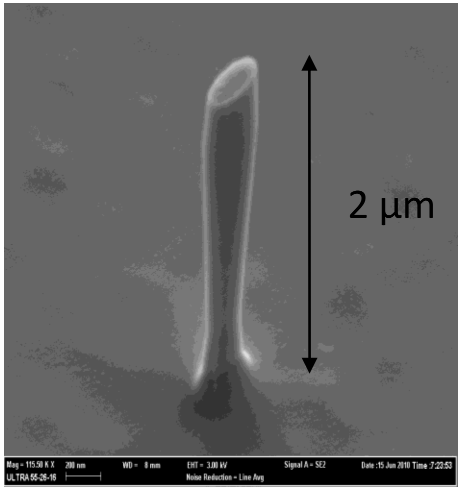


3. **Dry-Etching**

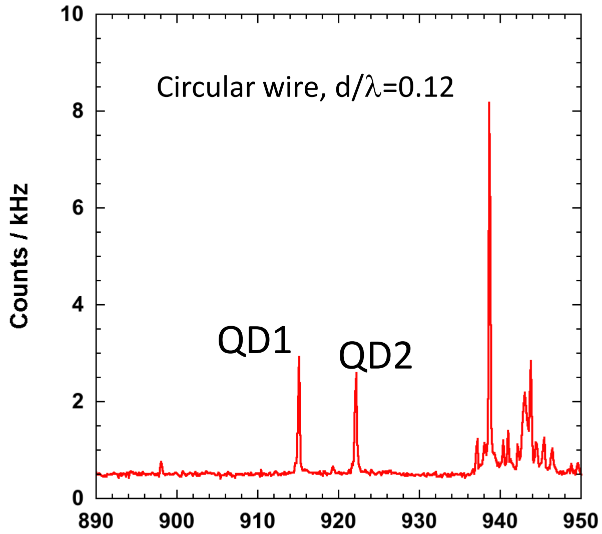


Etched GaAs Photonic Nanowires



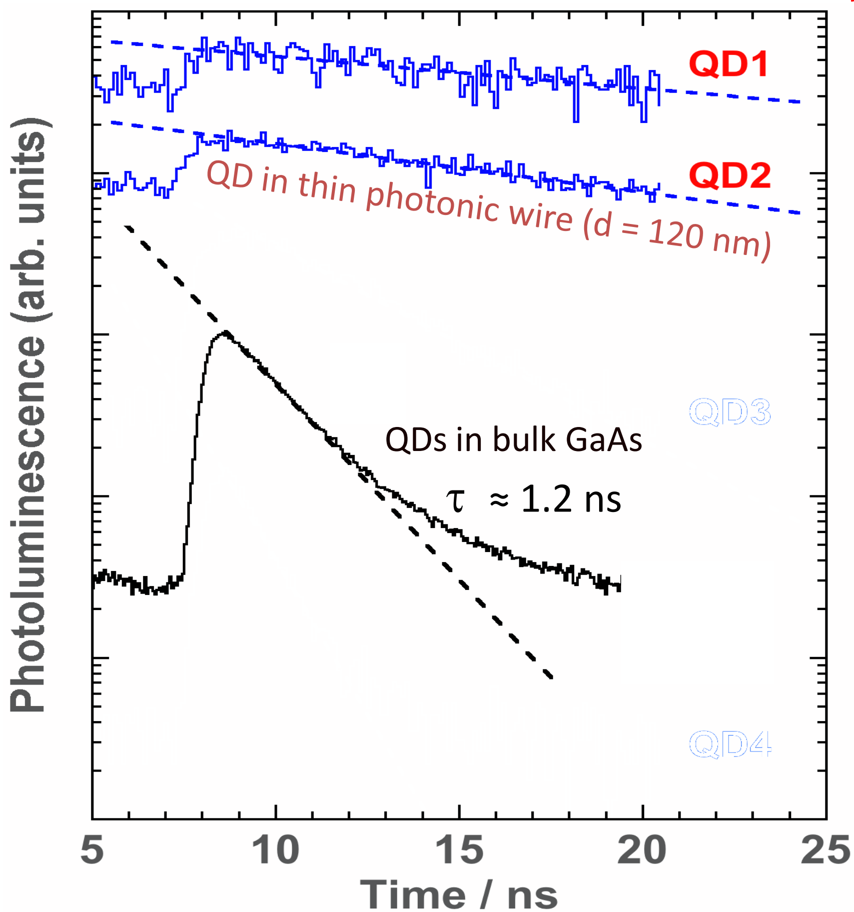


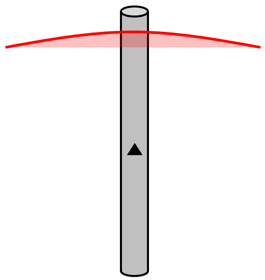
Typical microPL spectrum for few QDs in a photonic wire

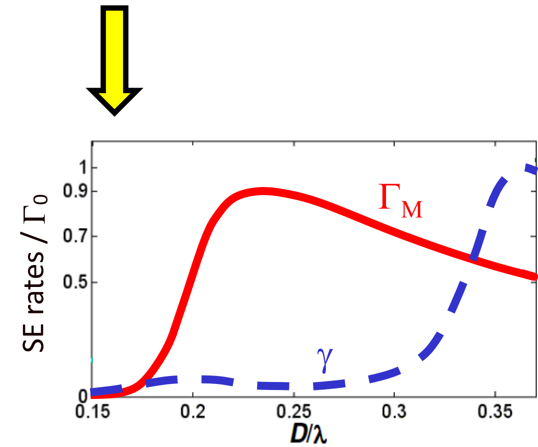


QD properties ?

Time resolved PL for QDs in ultrathin (d<λ/n) PWs







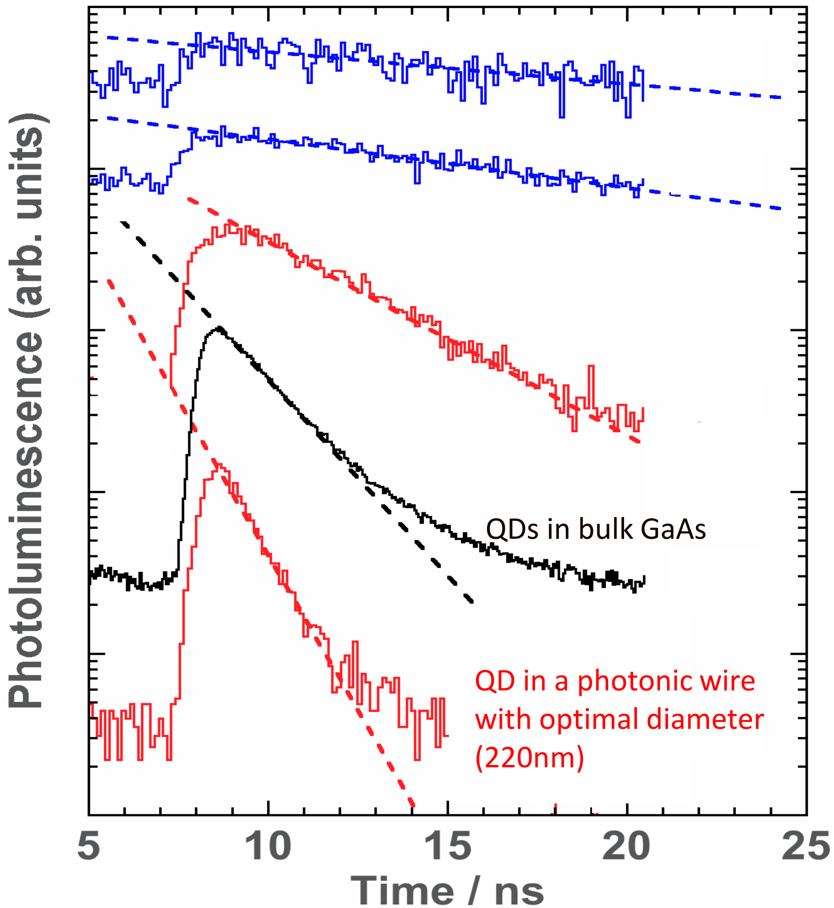
τ ≈ 23 ns for QD1

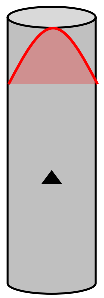
Strong Inhibition (~1/20) of QD SpE !

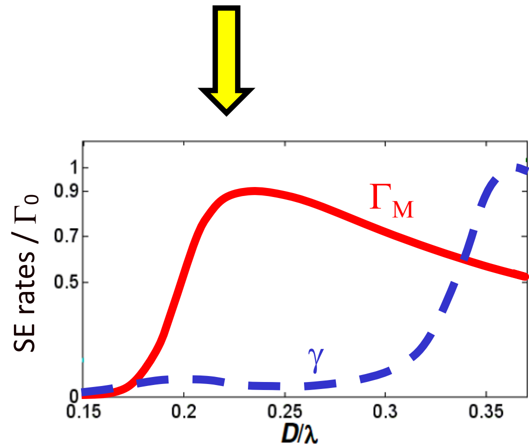
First observation of this effect, predicted in 1949 !

J. Bleuse et al, Phys. Rev. Lett. 106, 103601 (2011)

Time resolved PL for QDs in PWs





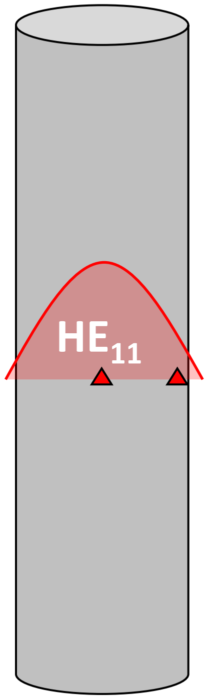


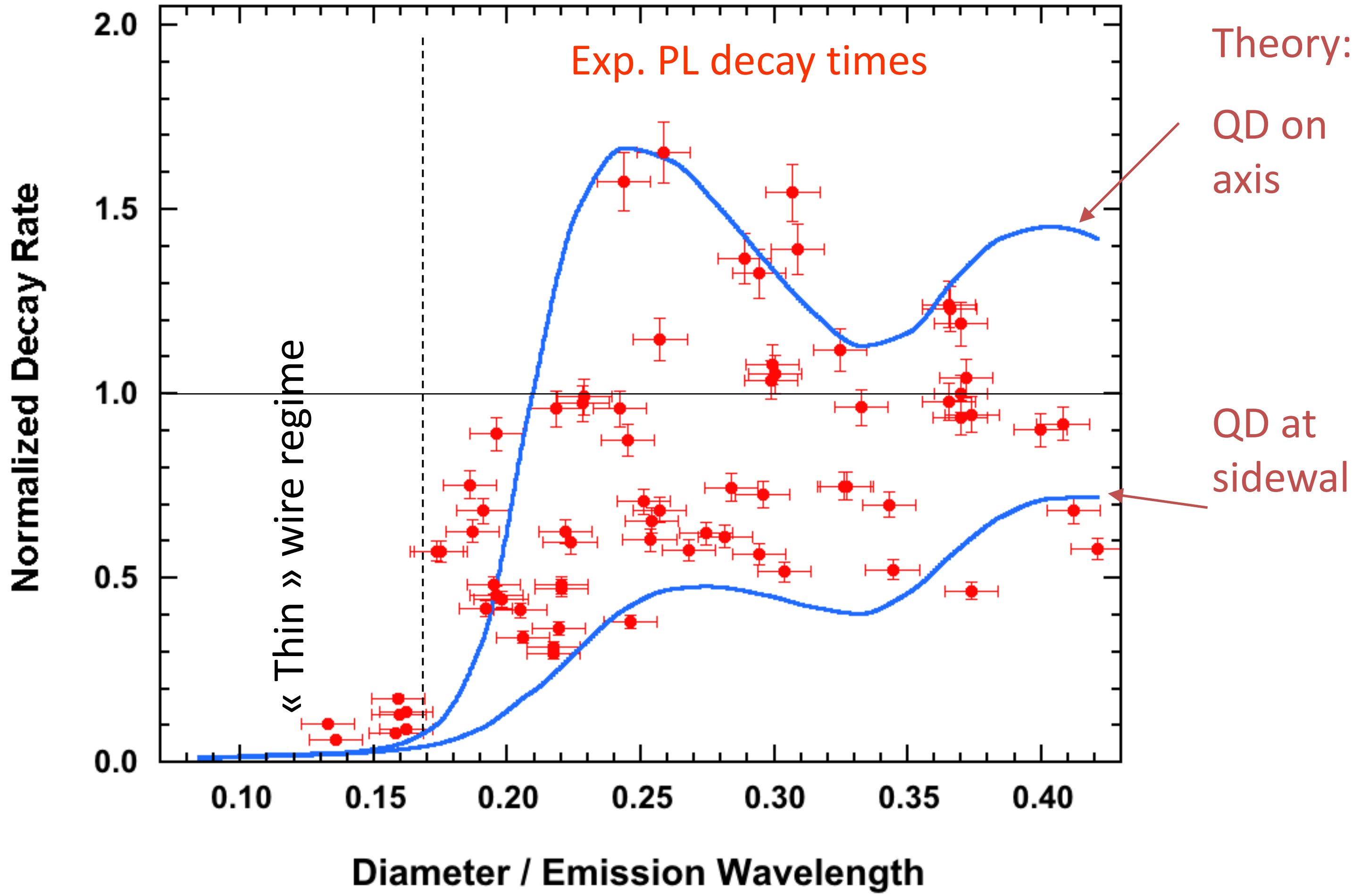
$\Gamma_m >> \gamma$

QD spontaneous emission
is funnelled into the guided mode

J. Bleuse et al, Phys. Rev. Lett. 106, 103601 (2011)

QD spontaneous emission rate in photonic wires



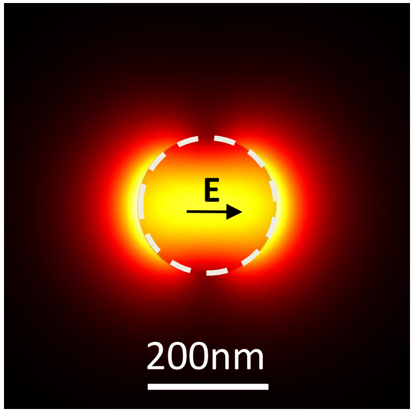


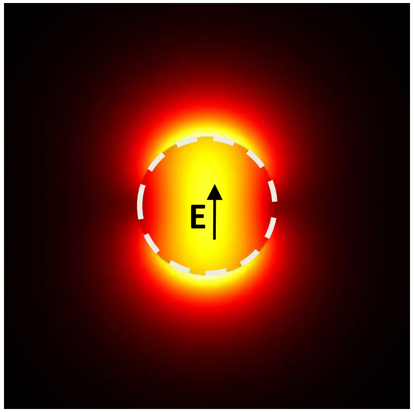
Strong SpE inhibition for all QDs in the « thin wire » regime

Dispersion of QD SpE rates due to random QD position in larger wires

Good agreement between exp. and theory

Cylindrical photonic wires have two polarization-degenerate guided modes



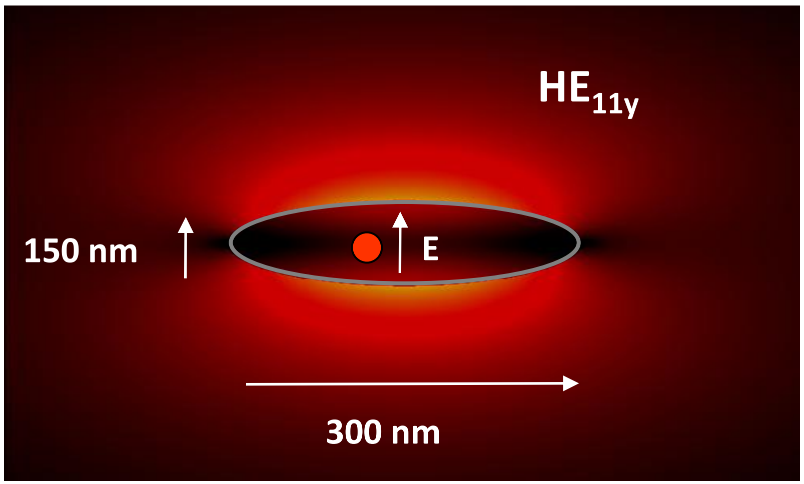


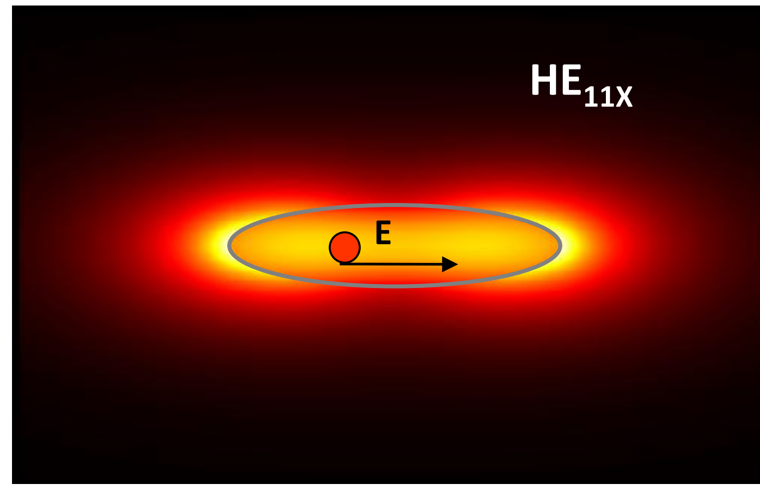
Standard semiconductor nanostructures (QWs, QDs) have both x and y in-plane dipoles

=> Coupling to both guided modes ($\beta \sim 0.5$)

How to get true single mode SpE?

Elliptical photonic wires for true single mode SpE

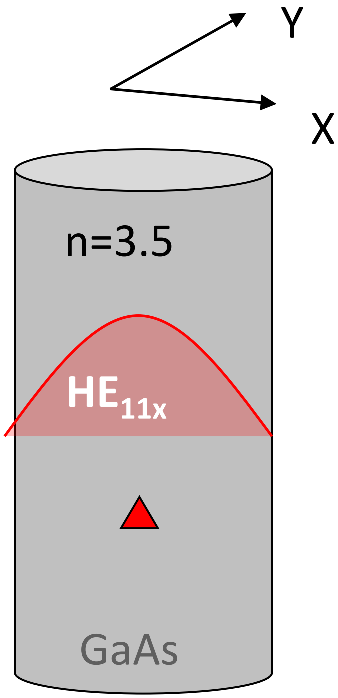




- Selective deconfinement of one guided mode
- β~1 and linearly polarized SpE

M. Munsch et al, Phys. Rev. Lett 02/2012

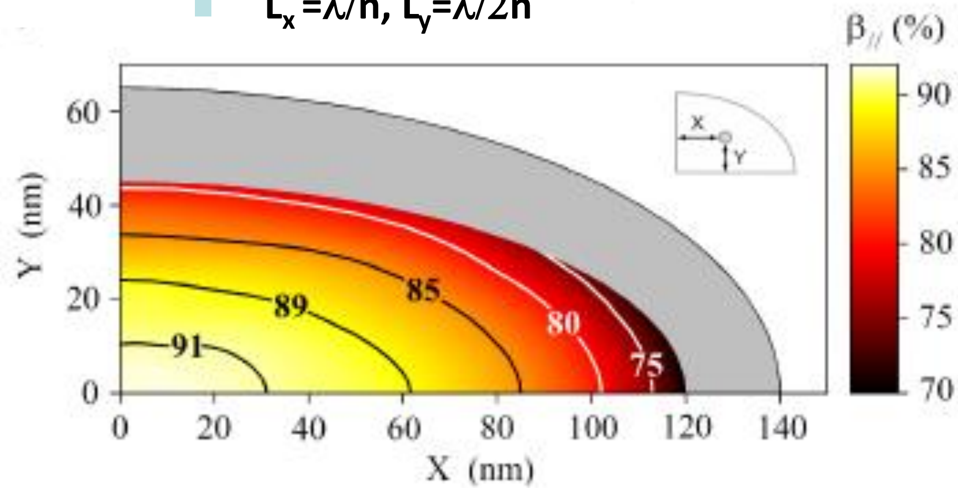
Fraction β_X of SpE emitted in the x-polarized mode



Isotropic, planar dipole

$$\beta_X = \frac{\Gamma_M(X)}{\Gamma_M(X) + \Gamma_M(Y) + \gamma_{leaky}}$$

- $L_x = \lambda/n$, $L_y = \lambda/2n$

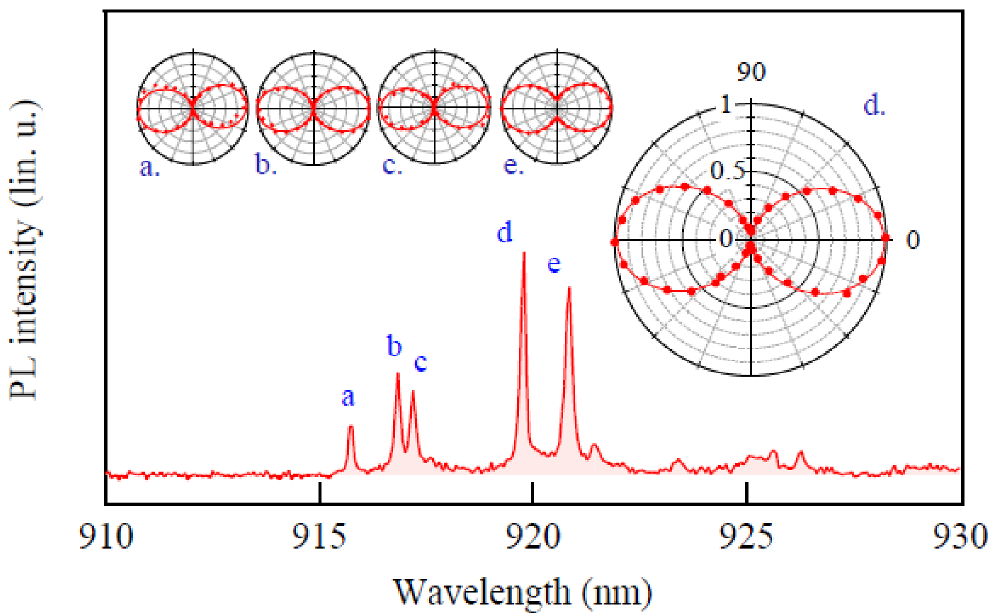


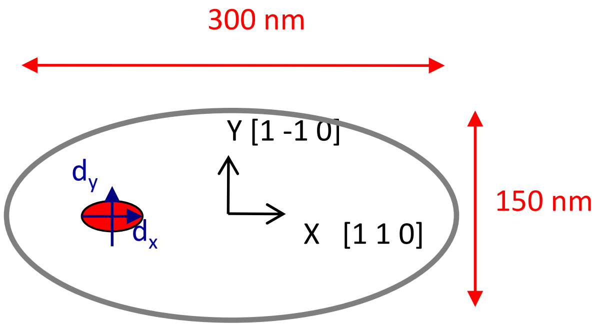
- **$\beta_X > 0.9$**
- **Wide choice of (R_x/λ, R_y/λ)**
- **Broadband operation**

QD position vs axis is not critical

Polarization-control in elliptical PWs

Rem: InAs QDs in bulk GaAs display a weak linear polarisation (0-20%)





-**Strong polarization** ratio for all QDs: $0.75 < PR < 0.95$

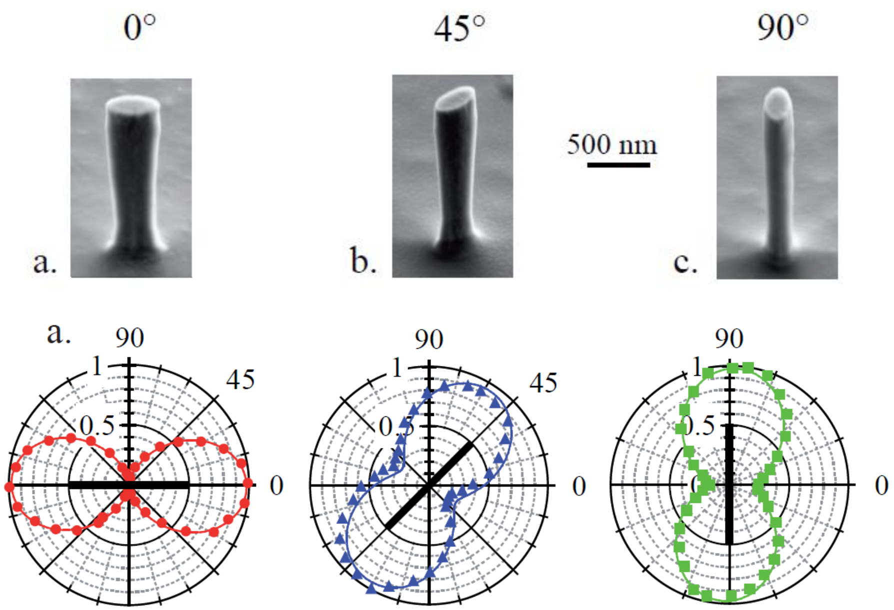
$$PR = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

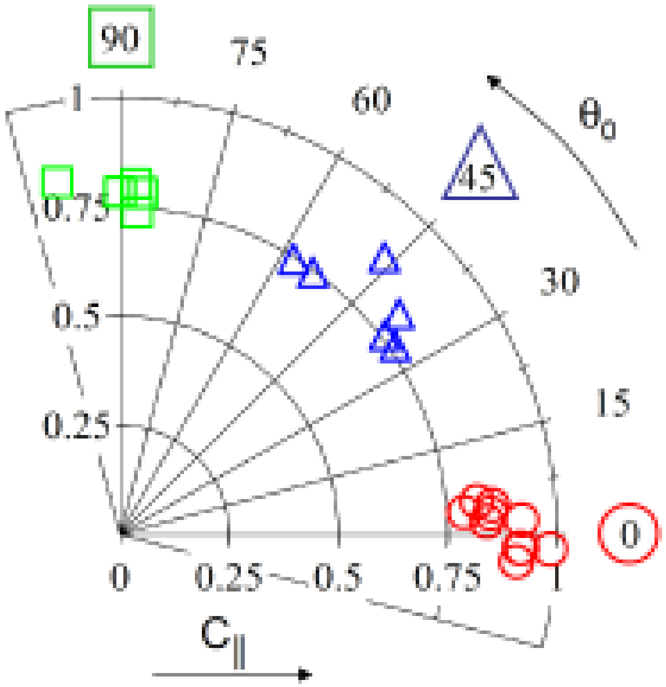
-Polarization angle corresponds to the **wire major axis**

- **Broadband effect**: effect measured on a bandwidth larger than 5 nm

QD polarisation control by PWs (2)

M. Munsch et al, Phys. Rev. Lett 02/2012





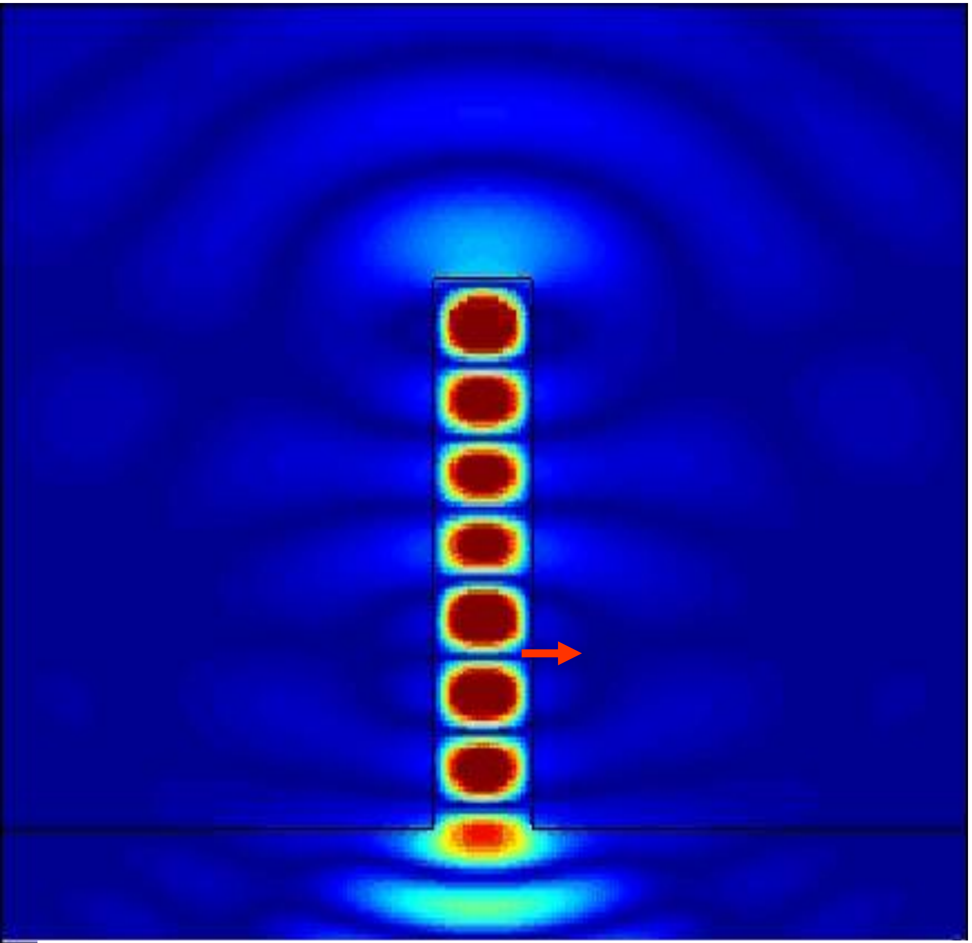
The linear polarization angle is determined by the photonic structure

Application of photonic nanowires

to

QD single photon sources

Courtesy A.L. Henneghien, CEA/LETI/DOPT



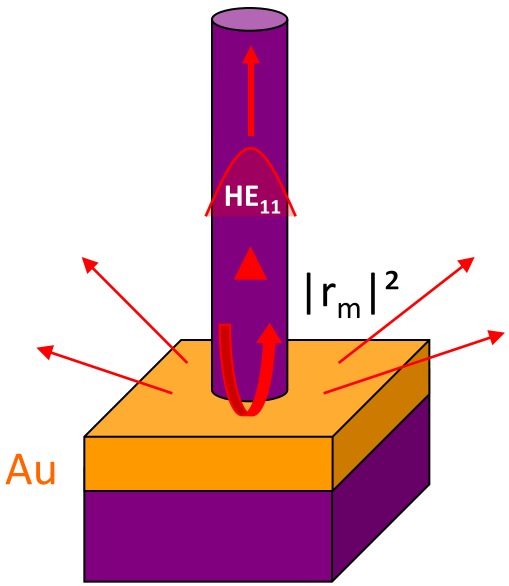
Collection efficiency limited by :

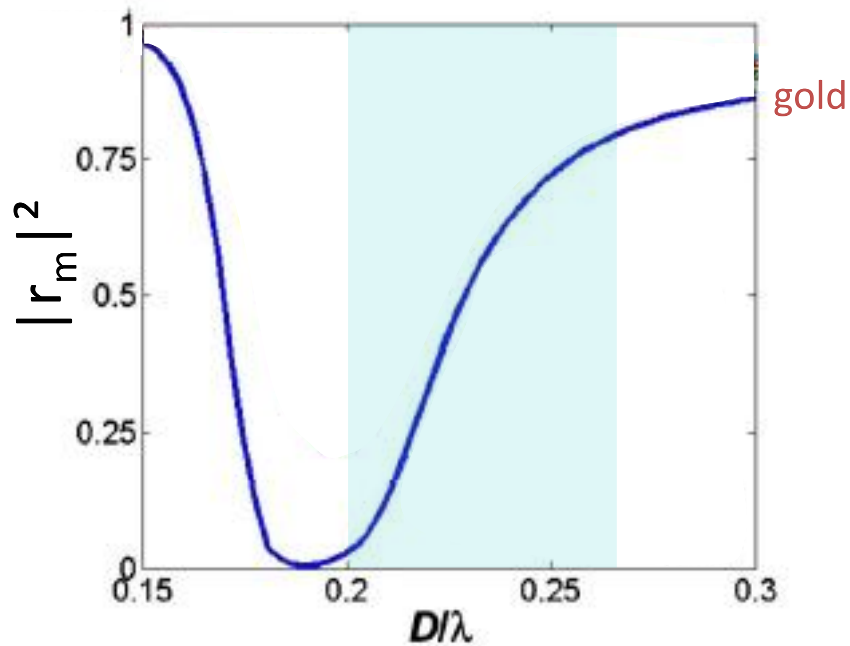
Divergence of the output beam (vs NA)
=> shape engineering

Photon escape toward the substrate
=> integrated mirror

Bottom mirror (1)

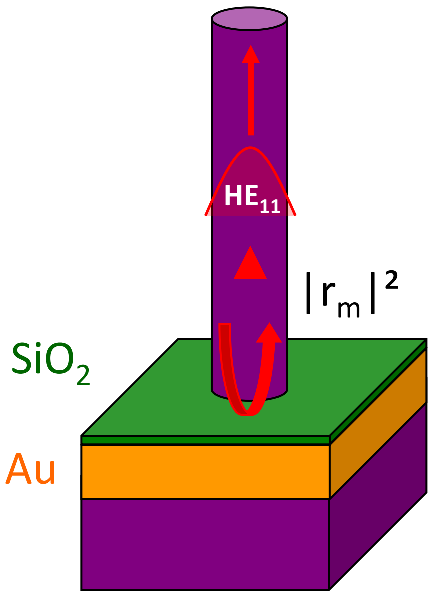
DBRs cannot be used as mirrors for PWs => metallic mirror

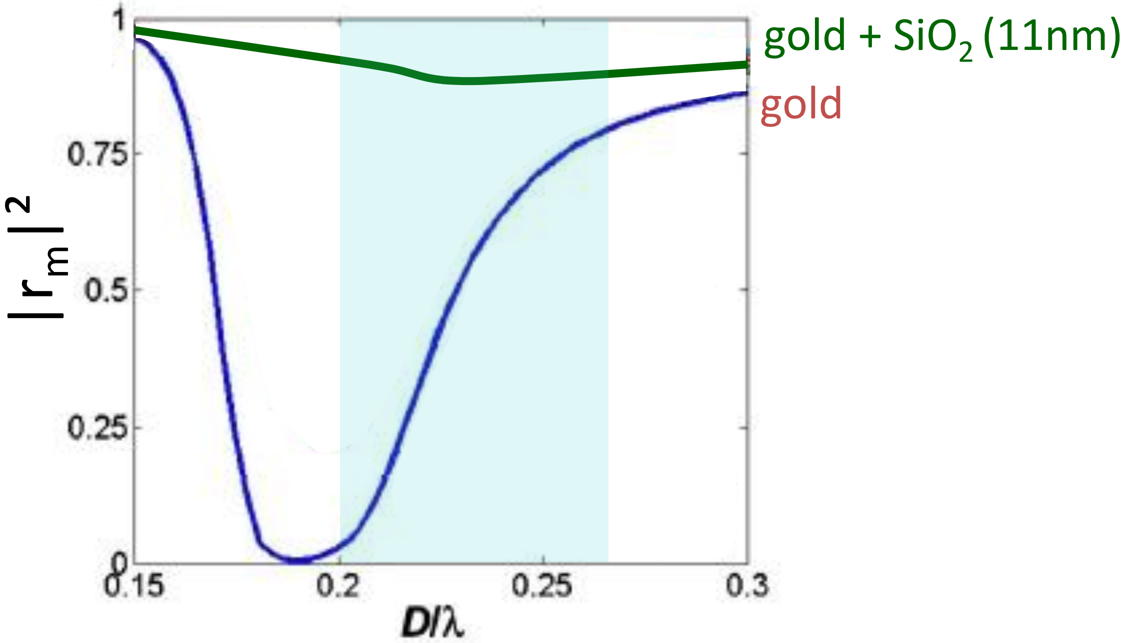




I. Friedler et al., Opt. Lett. **33**, 2635 (2009)

Bottom mirror (2) : Hybrid gold+dielectric planar mirror

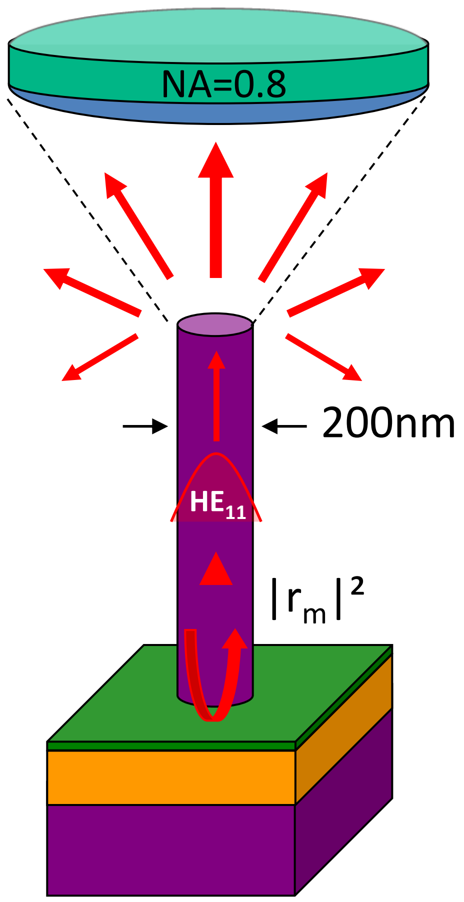




High modal reflectivity ($|r_m|^2 > 90\%$),
for all the diameters of interest

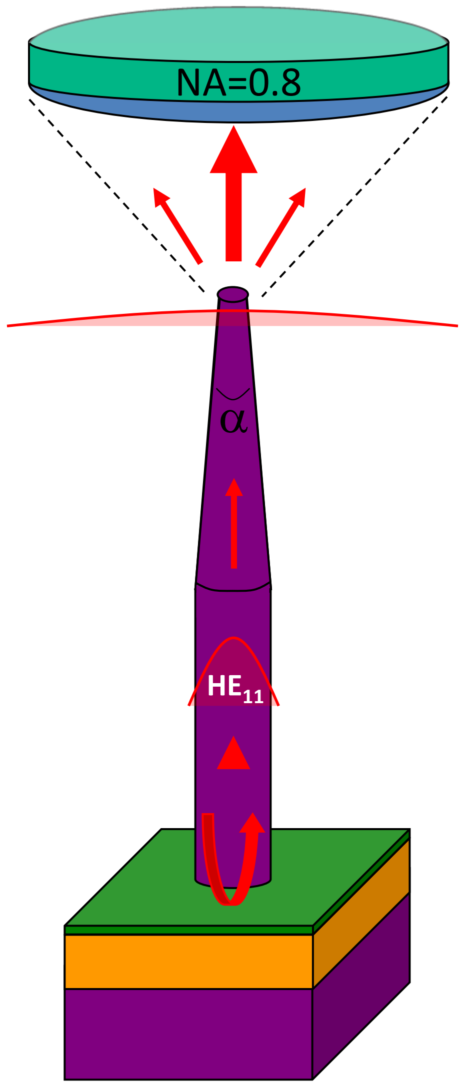
I. Friedler et al., Opt. Lett. **33**, 2635 (2008)

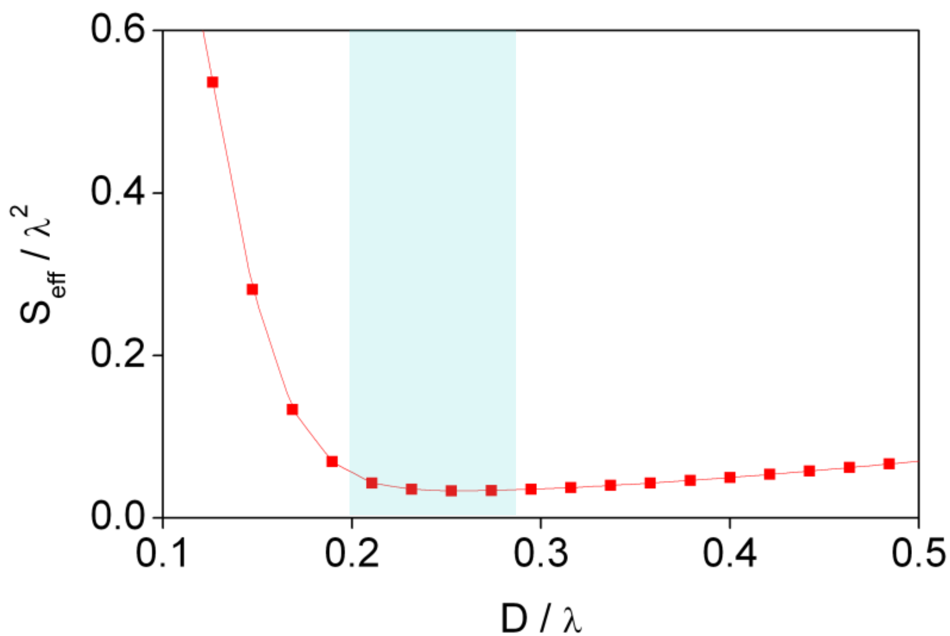
Control of the far field radiation pattern



Huge far-field divergence (Maslov et al, Opt Lett 2004)

Control of the far field radiation pattern : taper





adiabatic expansion of the guided mode

➡ reduced the far-field divergence

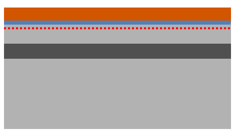
α=5°, 90% of light into a first lens with NA = 0.8

N. Gregersen et al., Opt. Lett. **33**, 1693 (2008)

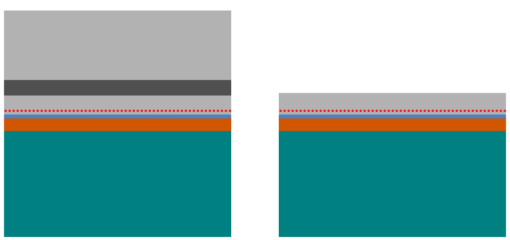
Sample fabrication

■ molecular beam epitaxy

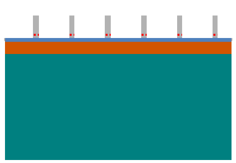
■ mirror deposition (Au + SiO_2)

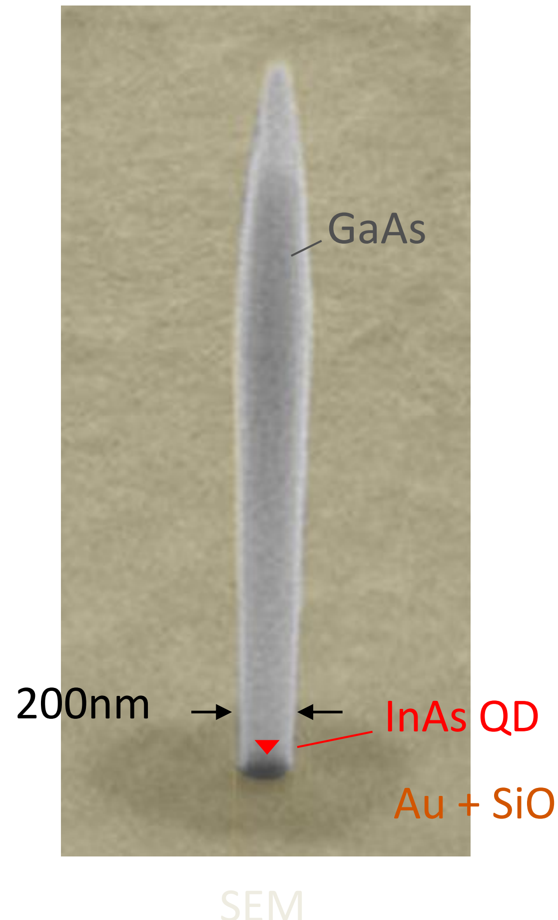


■ flip-chip, removal of the growth substrate



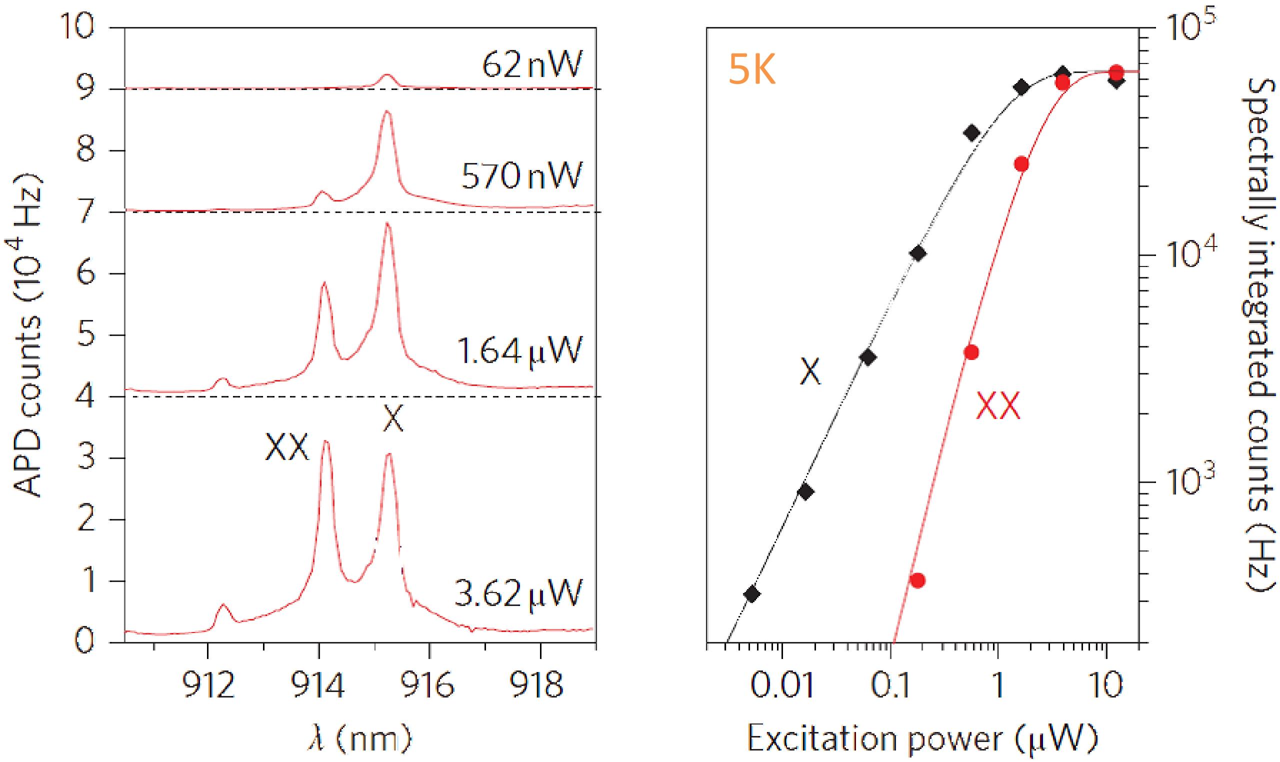
■ top-down definition of the wires:
e-beam lithography and dry etching (RIE)



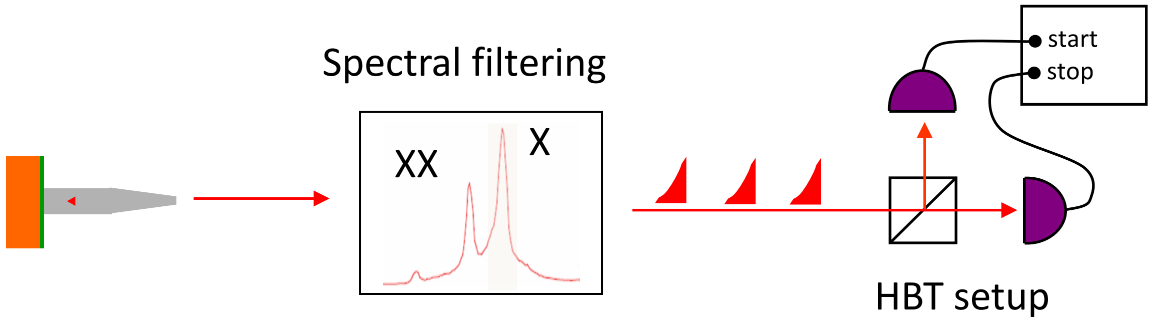


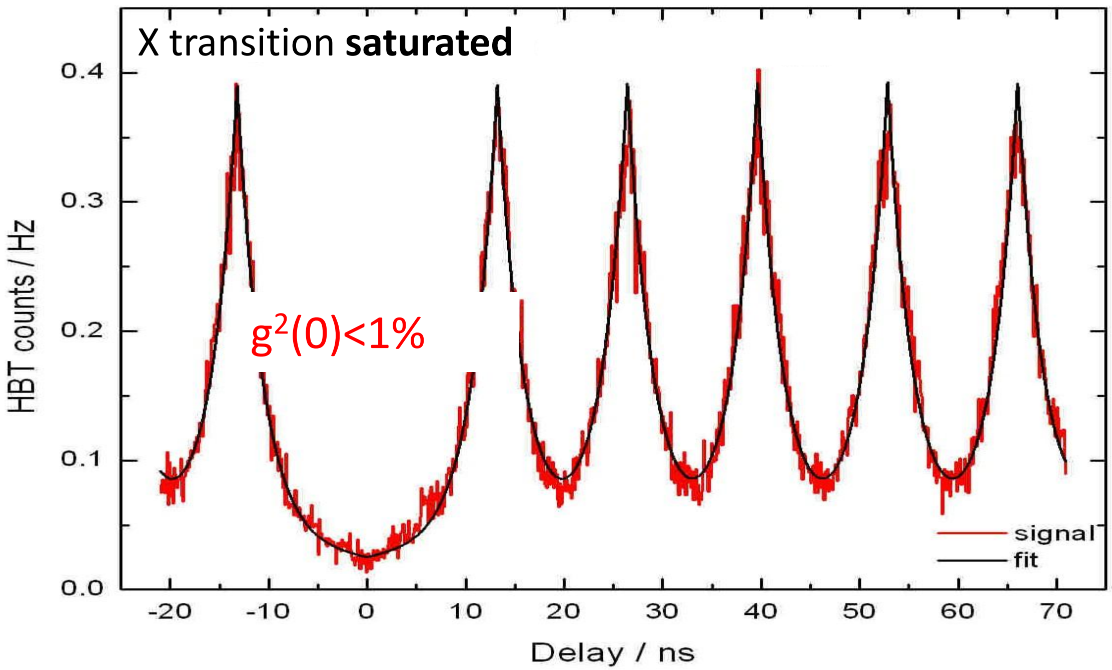
Optical characterization by µPL

Micro-photoluminescence setup
QD pumping: optical, pulsed, non-resonant (820nm)



A pure single-photon emission



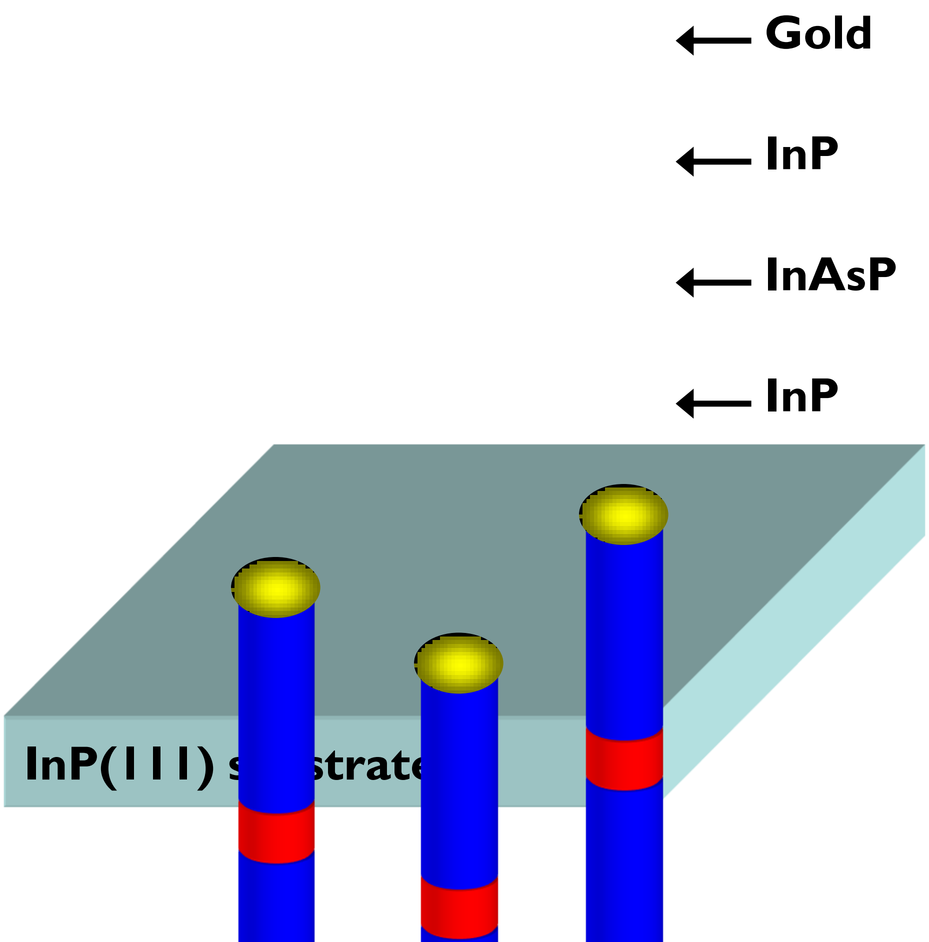


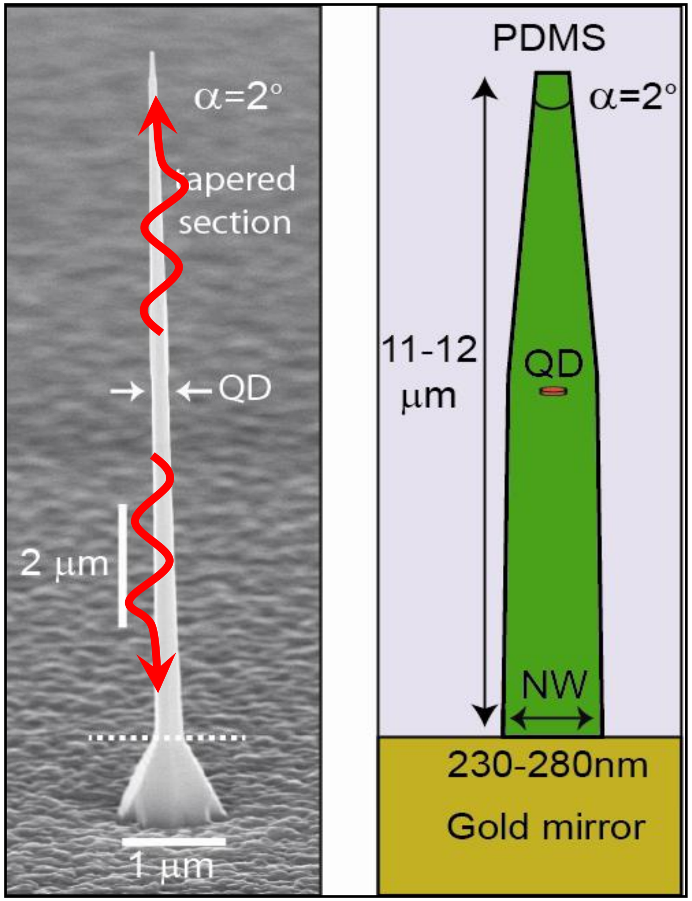
Key difference vs microcavity SPS !

No $g^{(2)}$ spoiling due to cavity-feeding

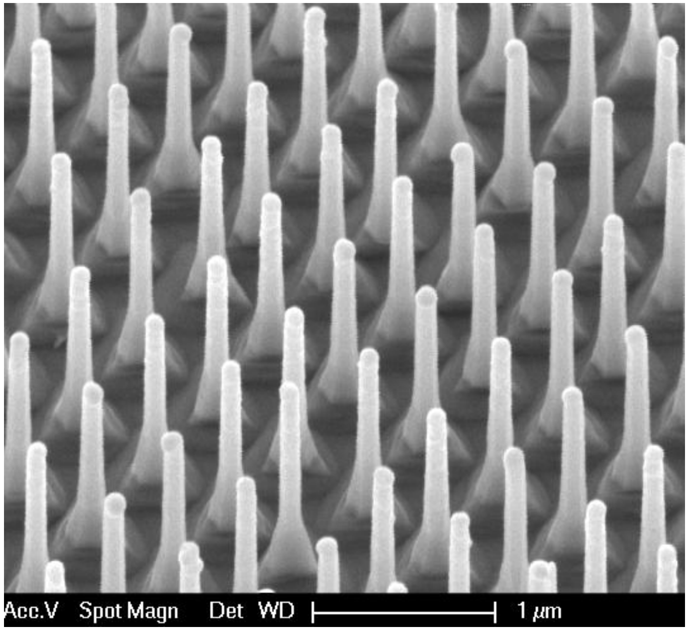
No repumping (fast capture of excess carriers by surfaces)

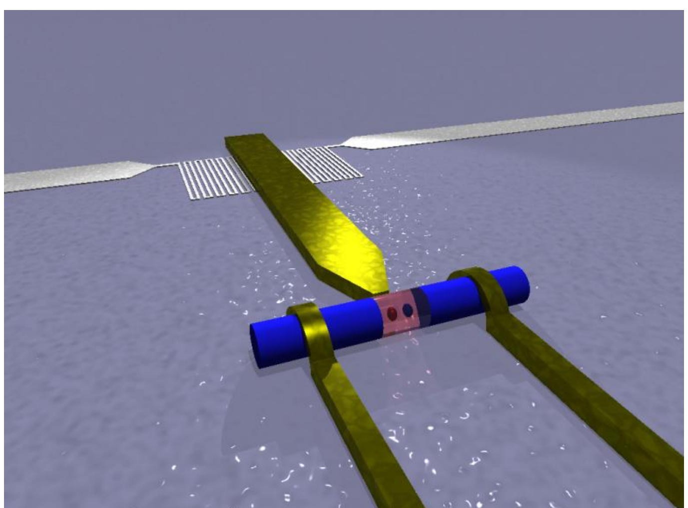
Nanowire growth





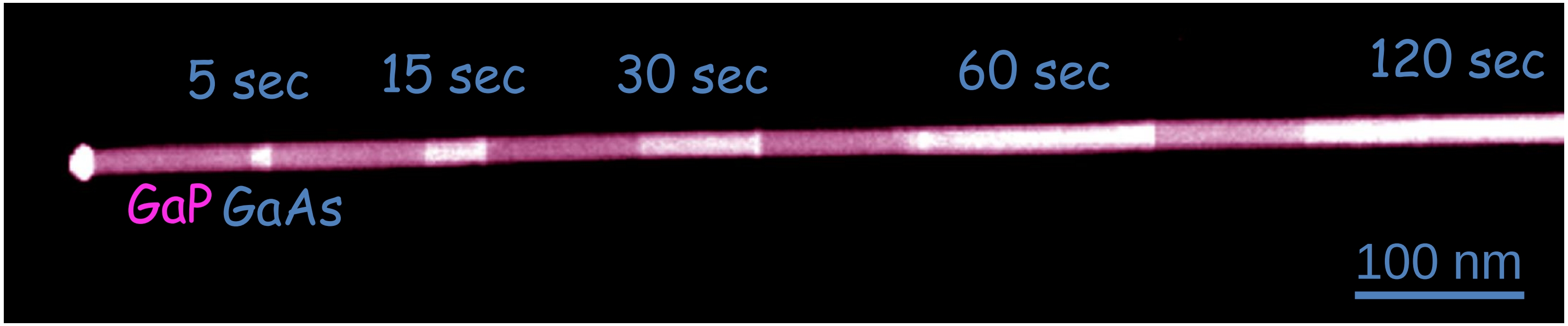
Why nanowires?





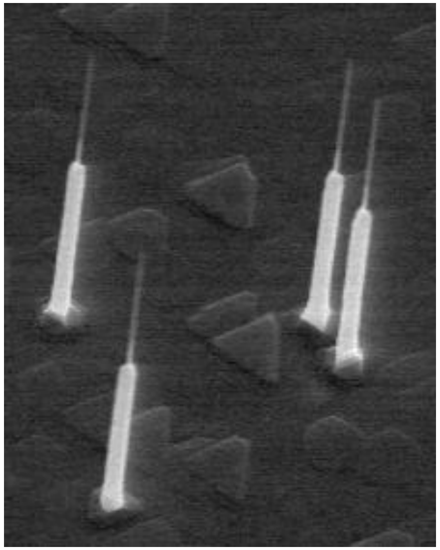
- Control of dot size, position and nanowire doping
- Not embedded in high refractive index material →efficient source of single photon and entangled photon pairs
- All of injected current flows through quantum dot
- Superconducting nanowires are excellent single photon detectors
- Powerful platform for integrated quantum optics

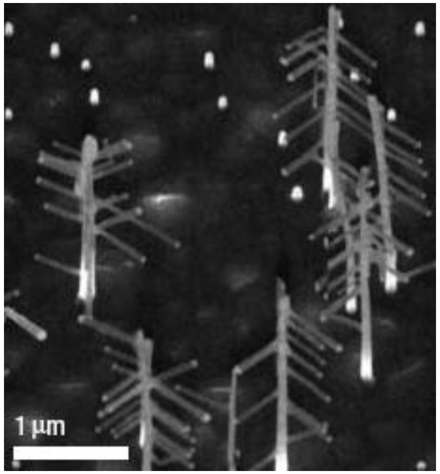
Quantum dot heterostructures in nanowires



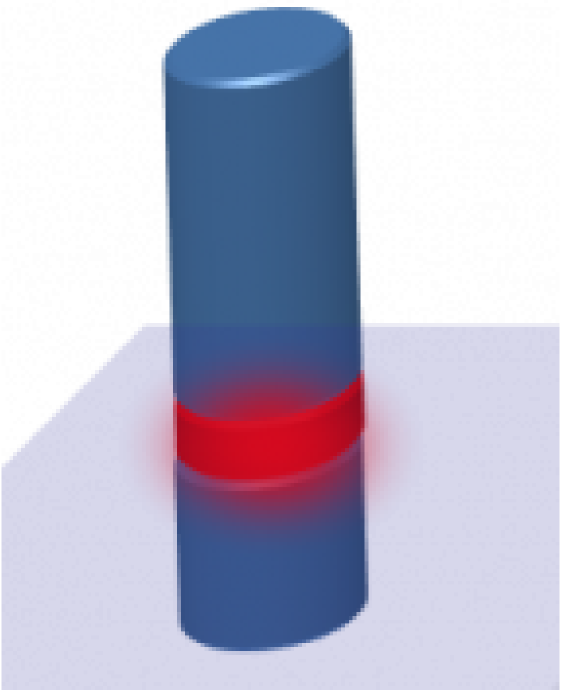
- Diameter, length, position, composition and doping are controlled

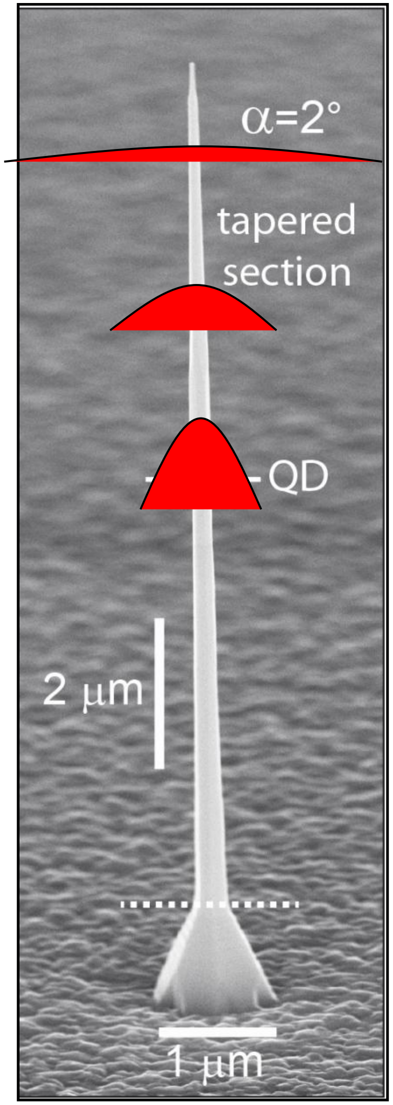
- More advanced geometries can be fabricated, such as core-shell structures and branches.

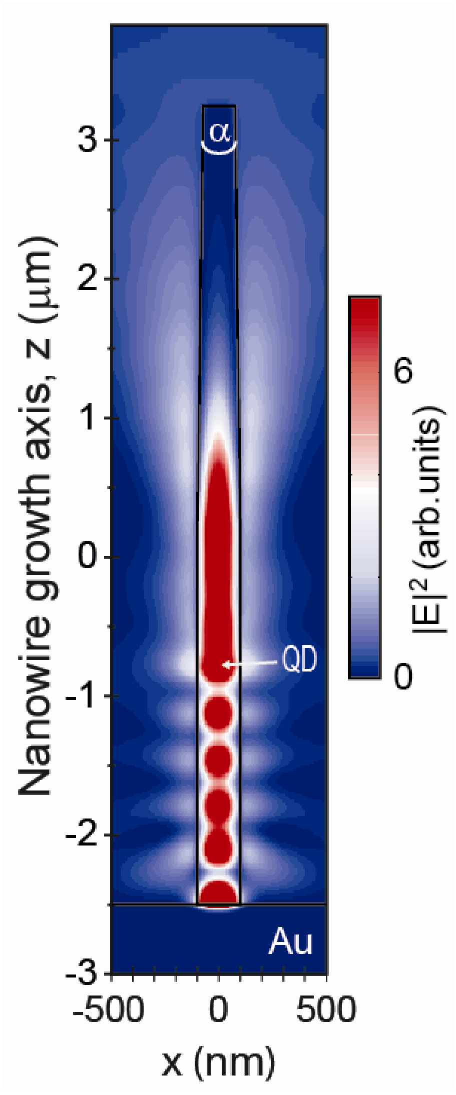




Single quantum dot in a nanowire waveguide

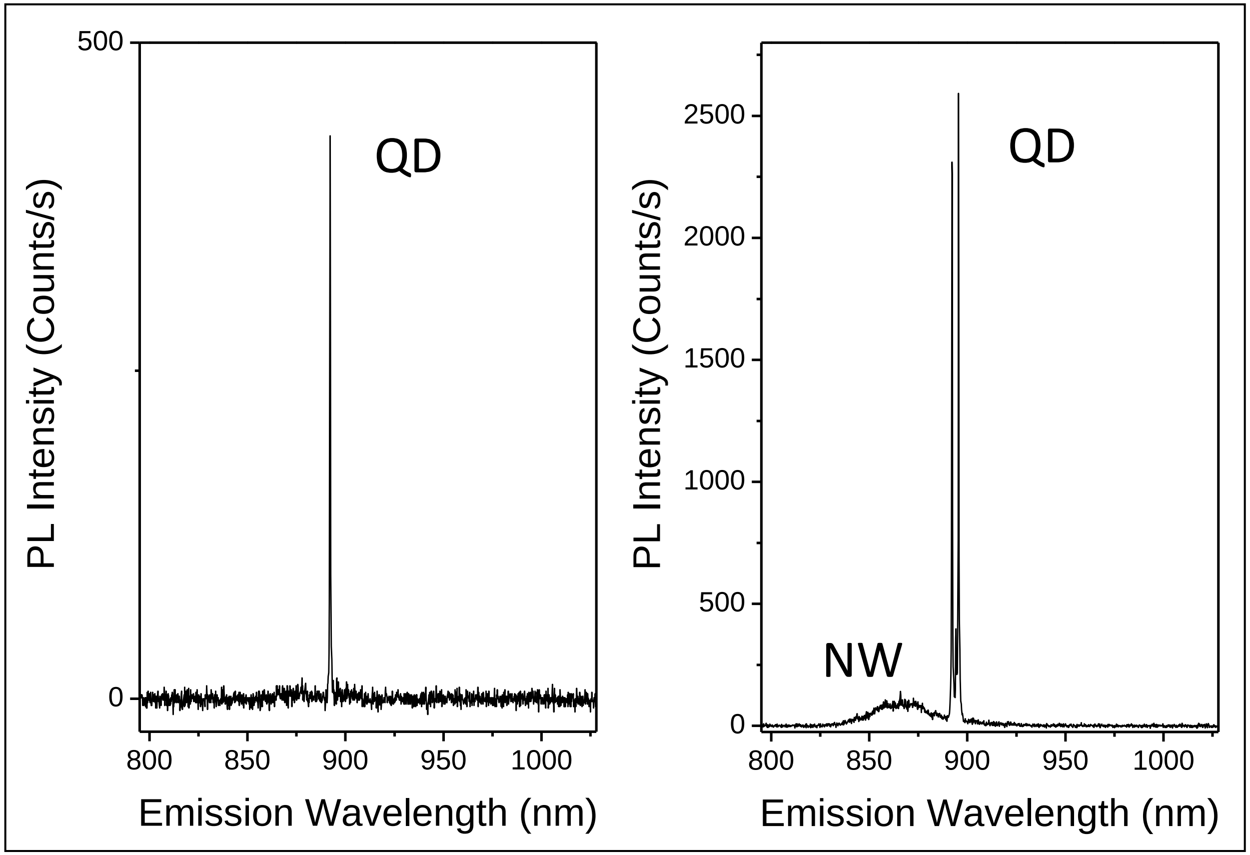


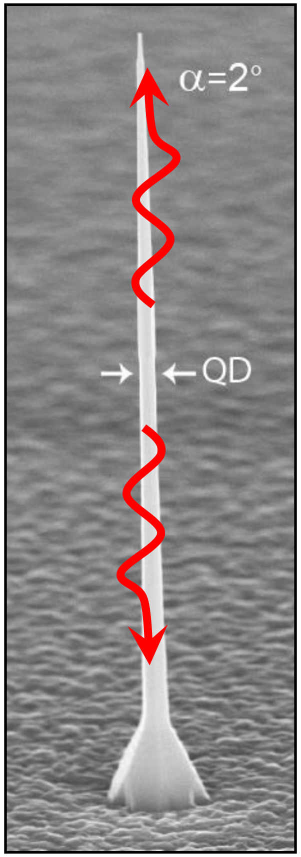




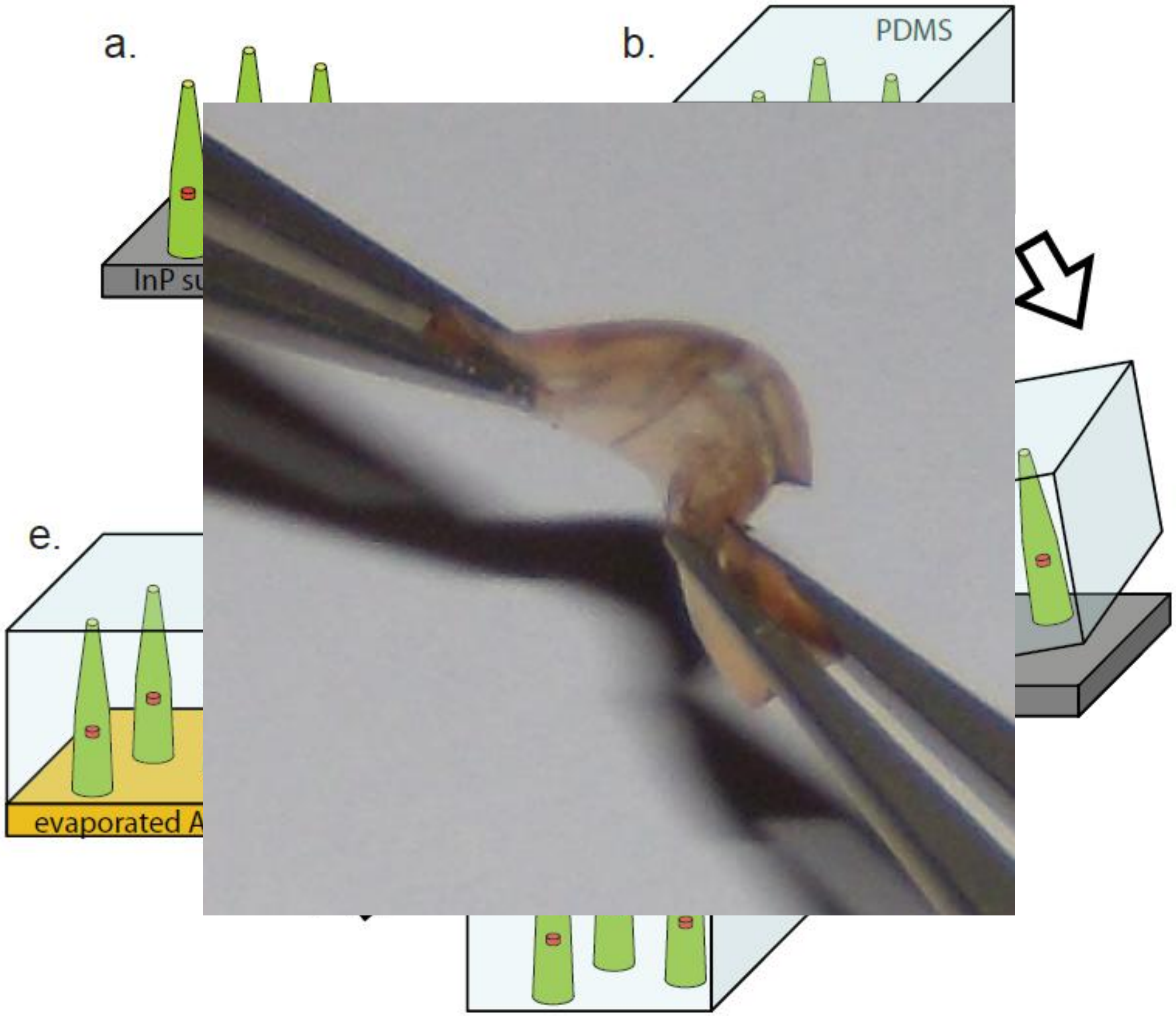
Advantages of 'bottom-up growth'

- Each nanowire contains <u>only a single</u> quantum dot, positioned <u>on-axis</u> of the nanowire





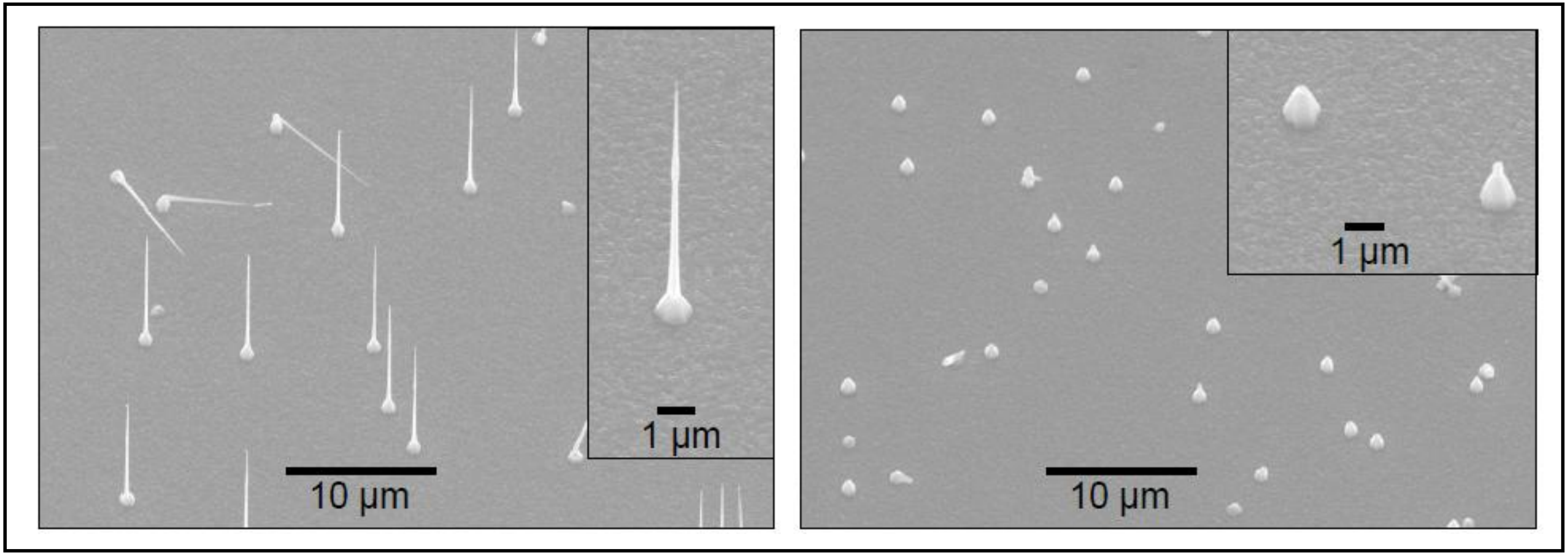
Integrated bottom gold mirror



Transfer into PDMS polymer film

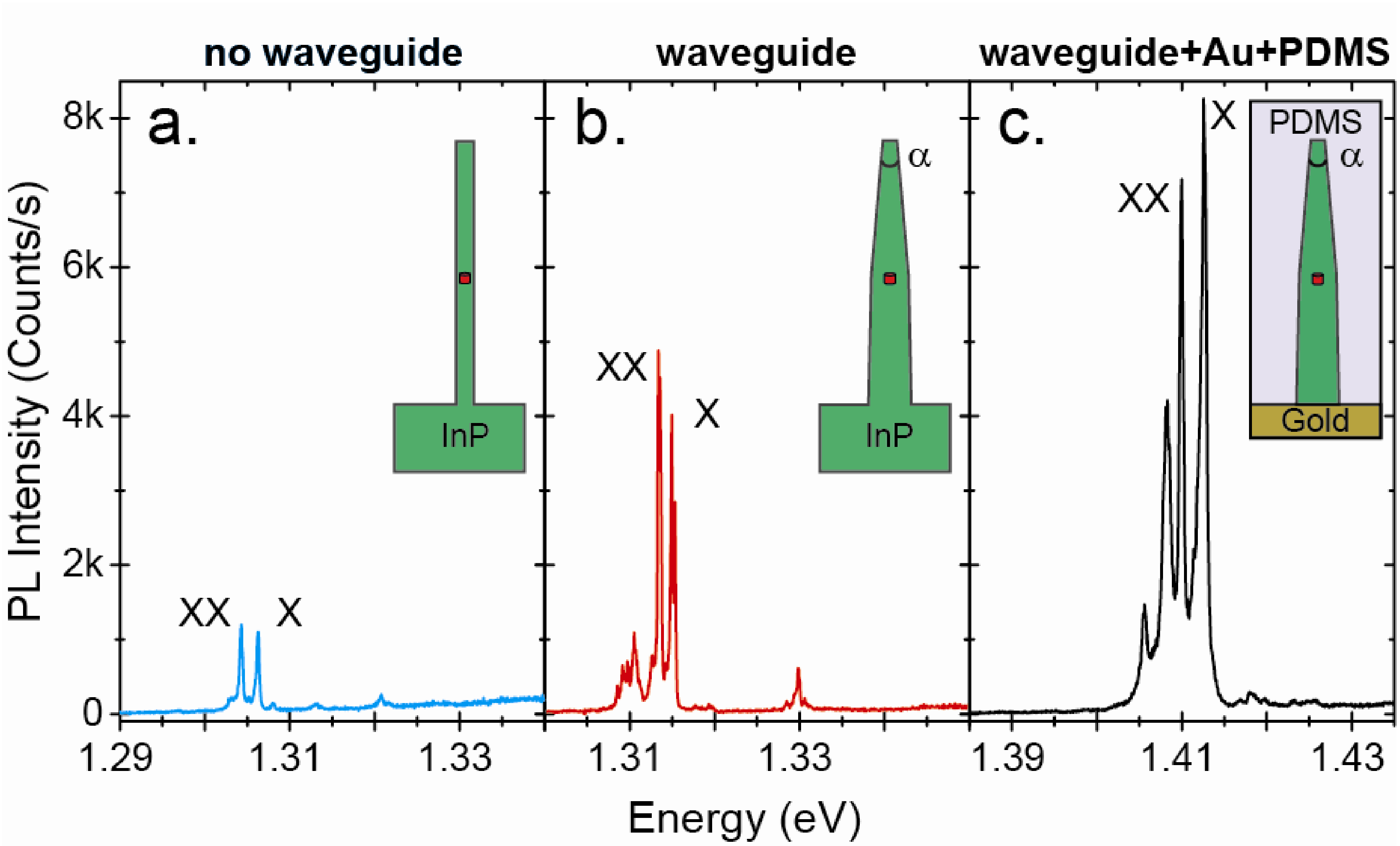
as-grown sample

substrate after transfer

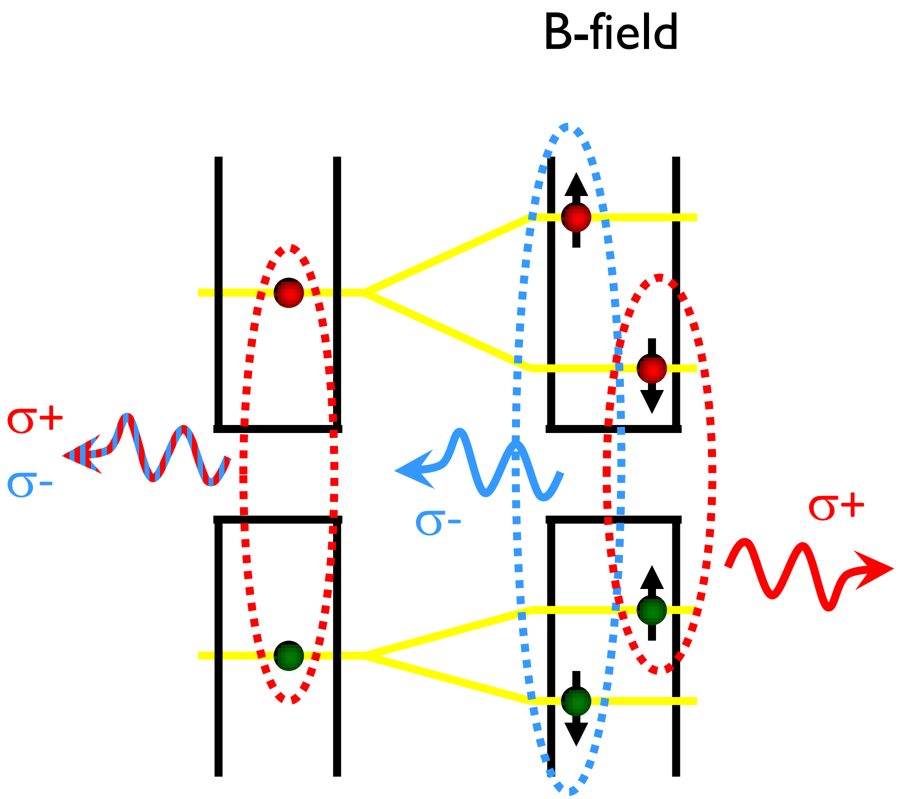


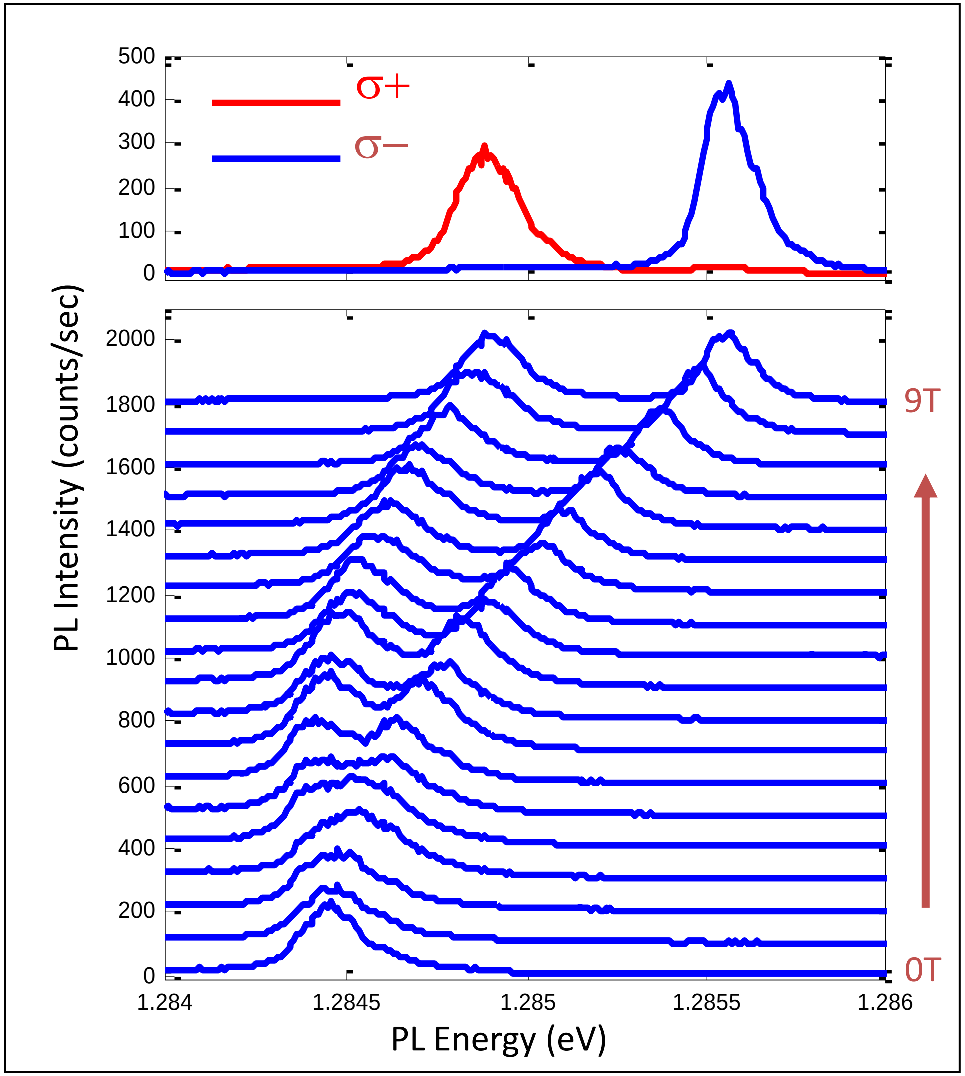
transfer efficiency ~ 100%

Collection efficiency enhancement

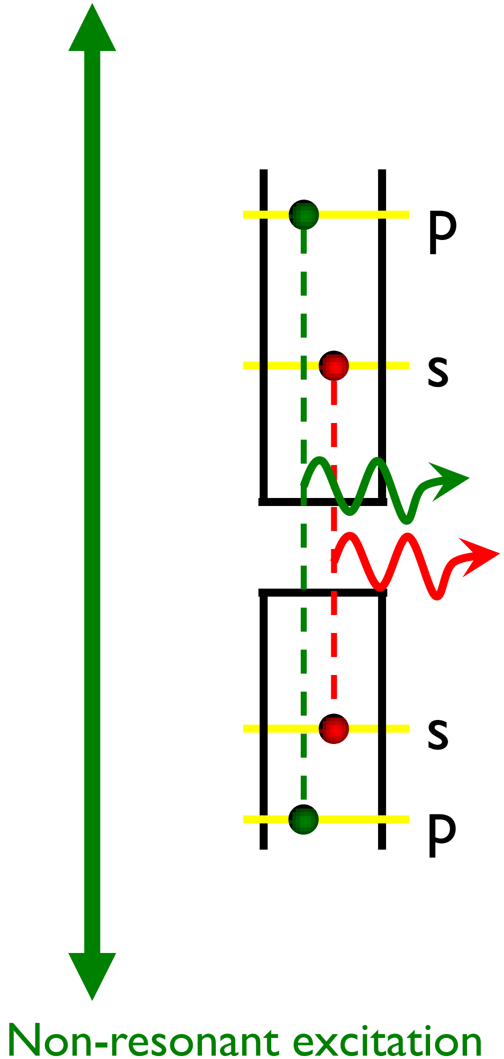


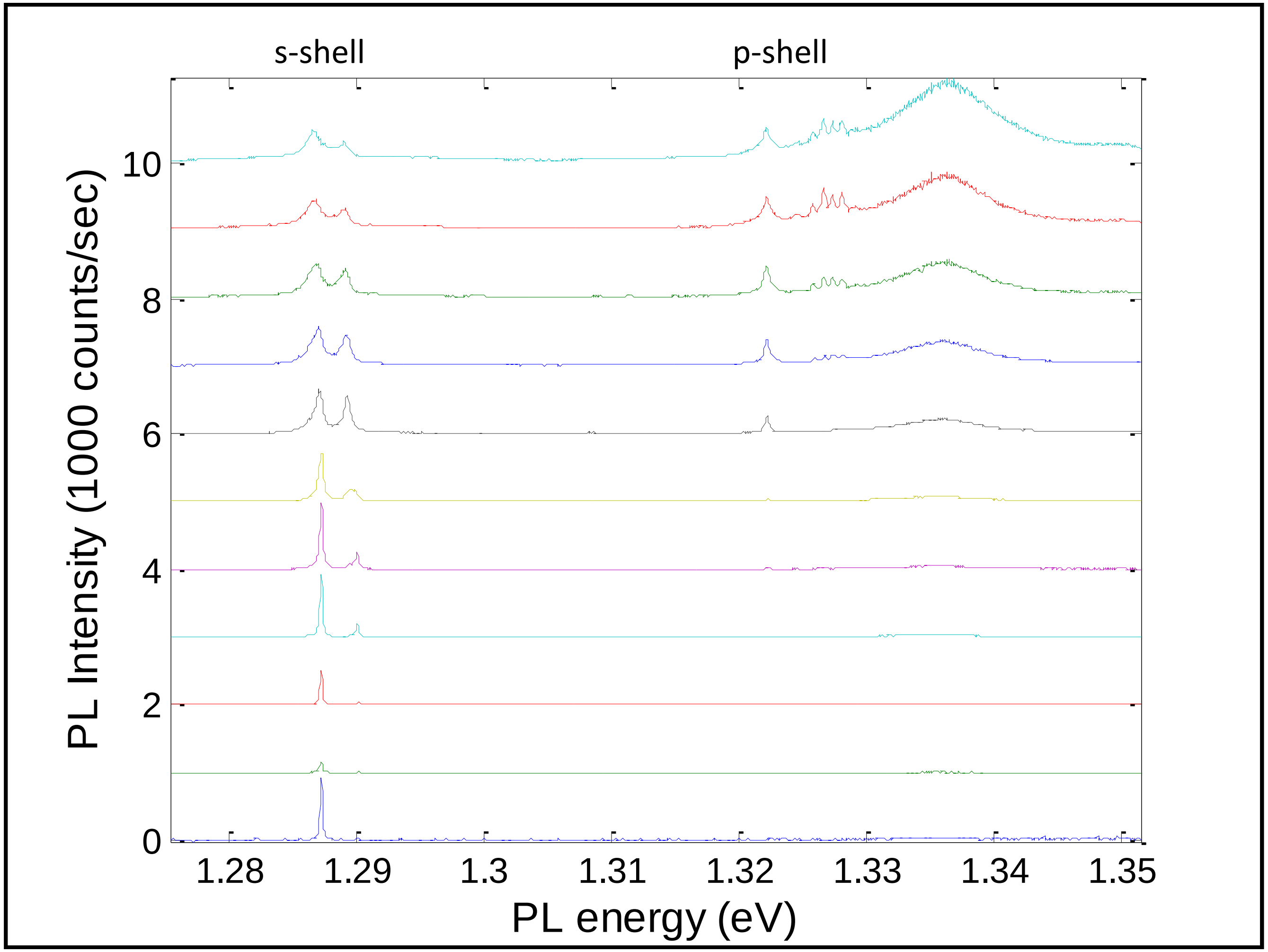
Probing intrinsic QD polarization



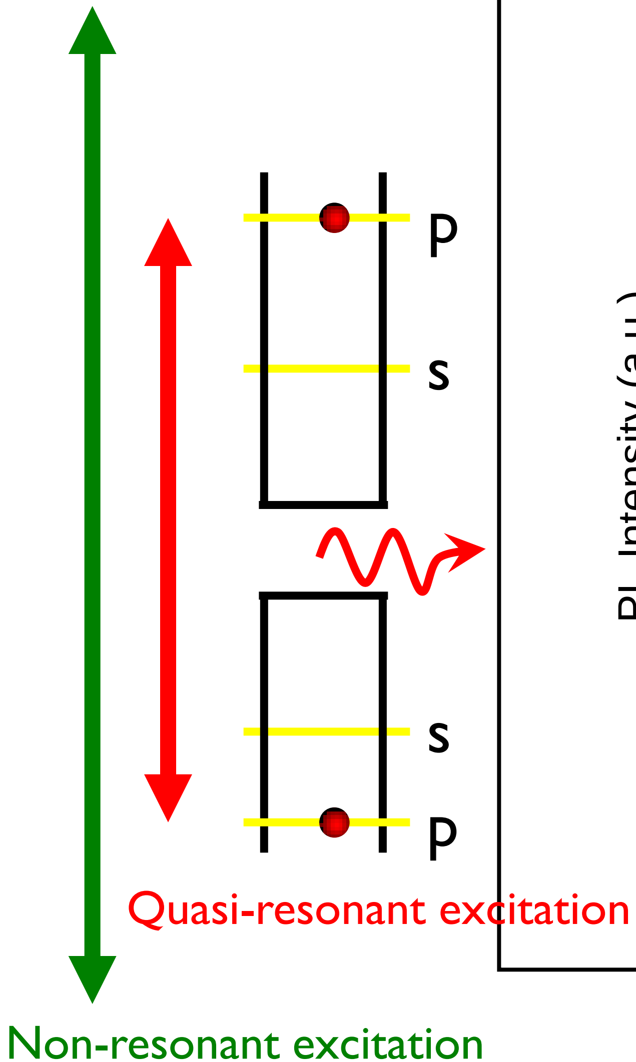


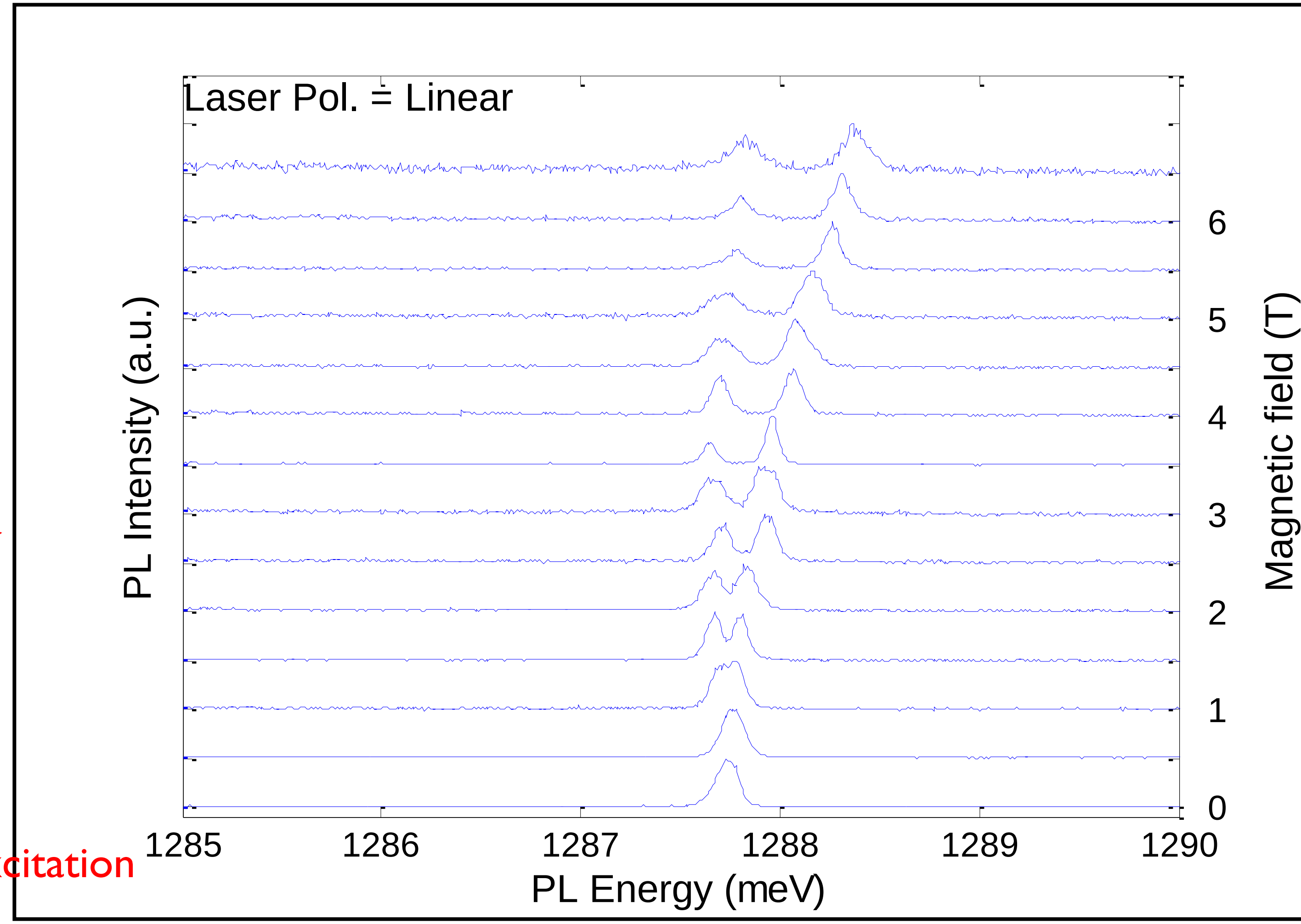
Excited states in the QD



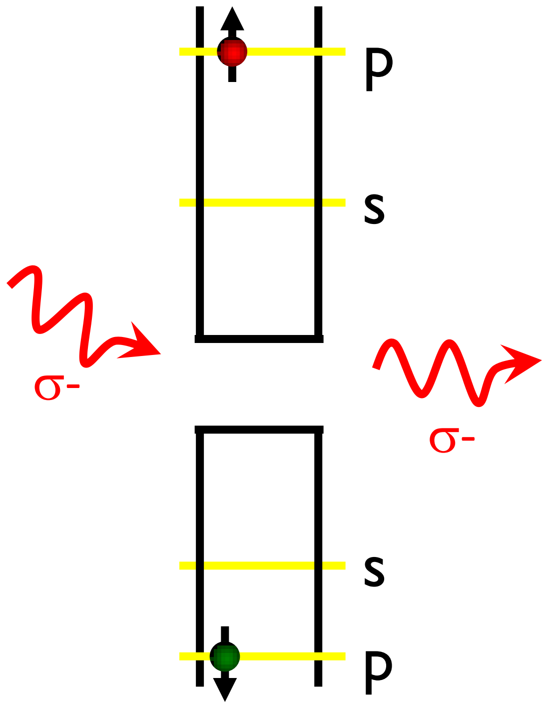


Quasi-resonant excitation

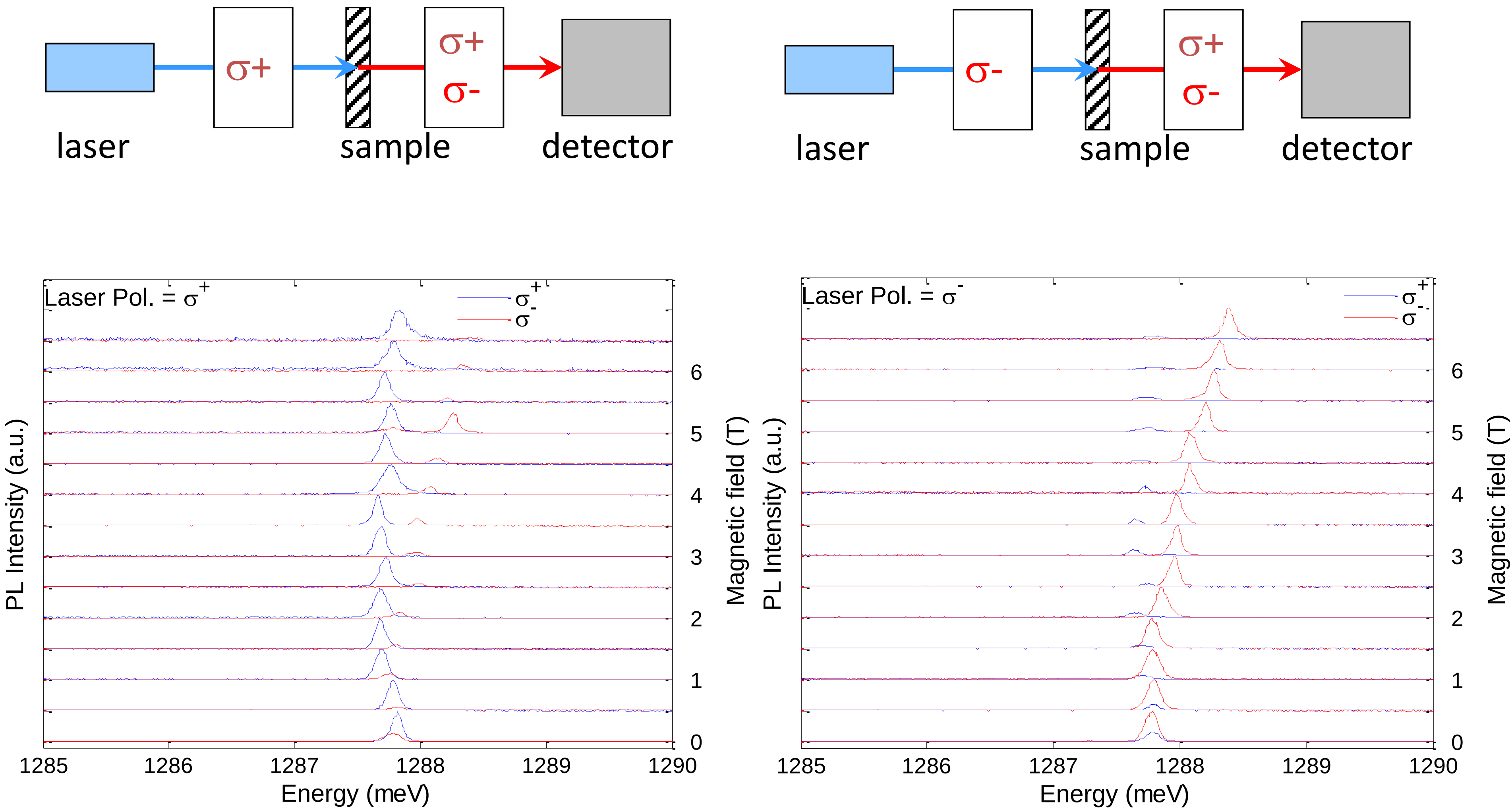




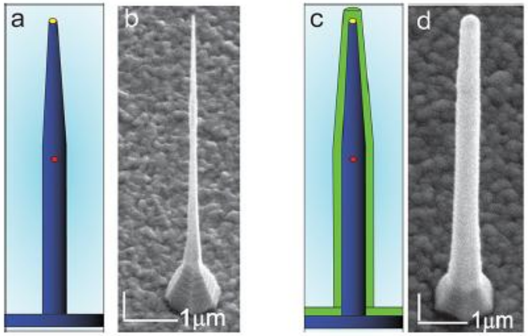
Addressing different spin states



Addressing different spin states

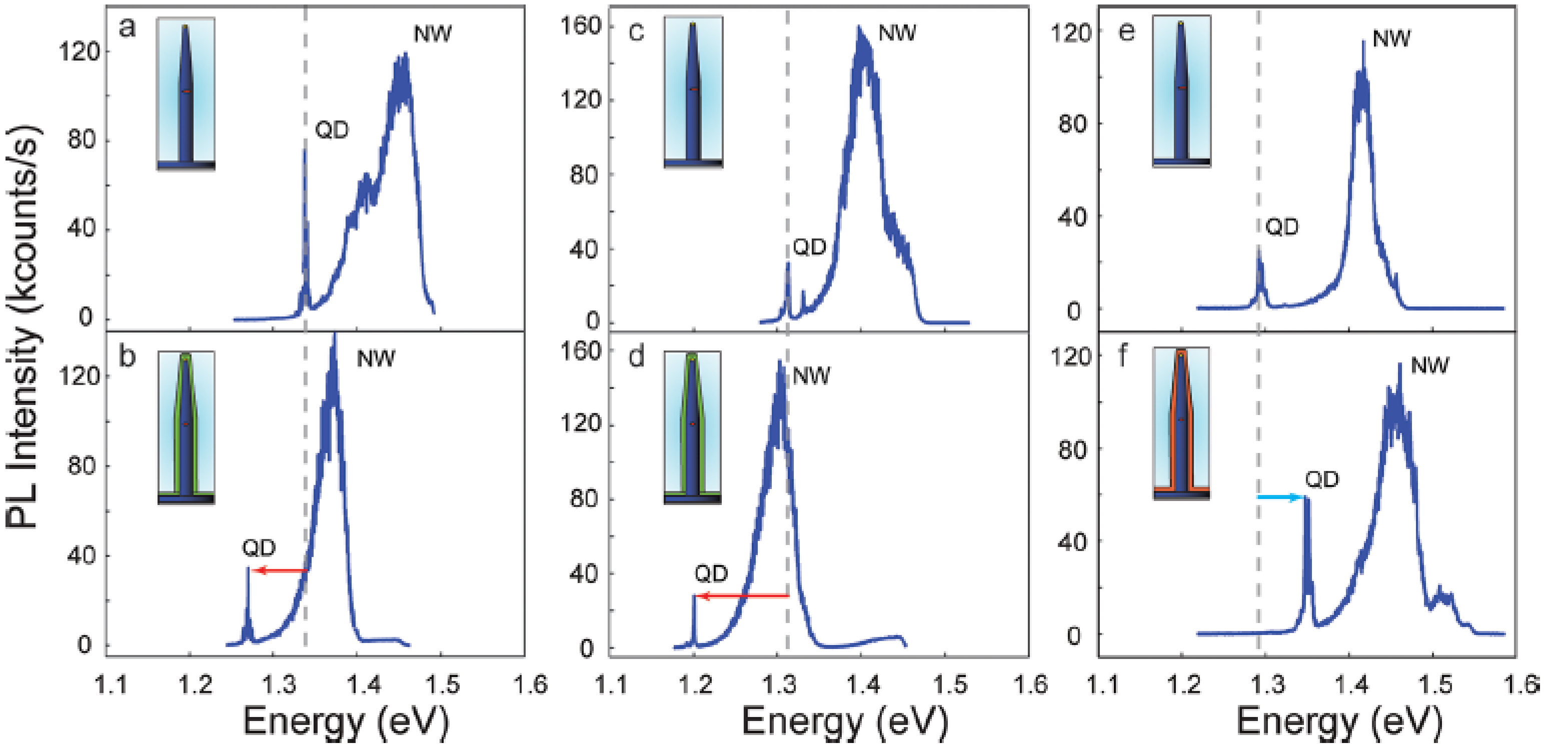


Strain tuning nanowire QDs



A dielectric shell induces a reversible emission shift of up to 100 meV.

Both blue and red shifts are possible.

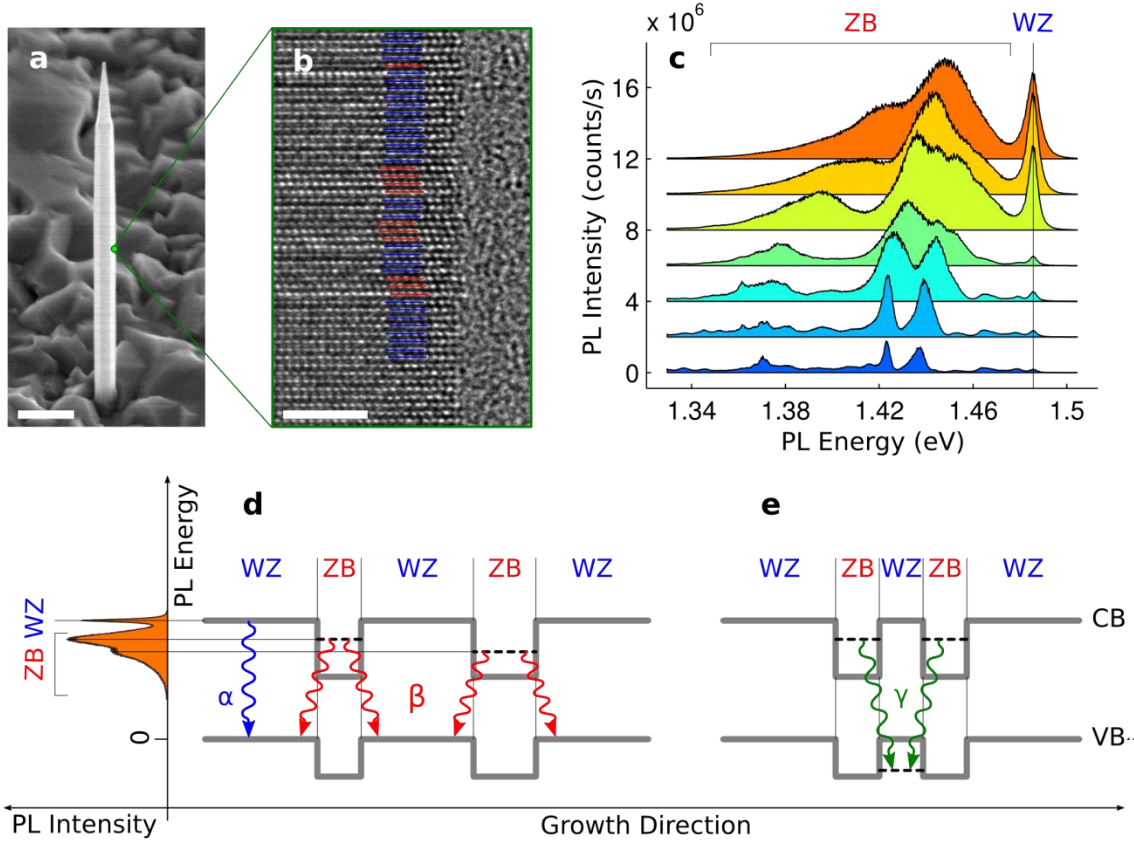


Tensile strain can redefine selection rules: Light Holes, **Nature Physics** 46, **10** (2014)

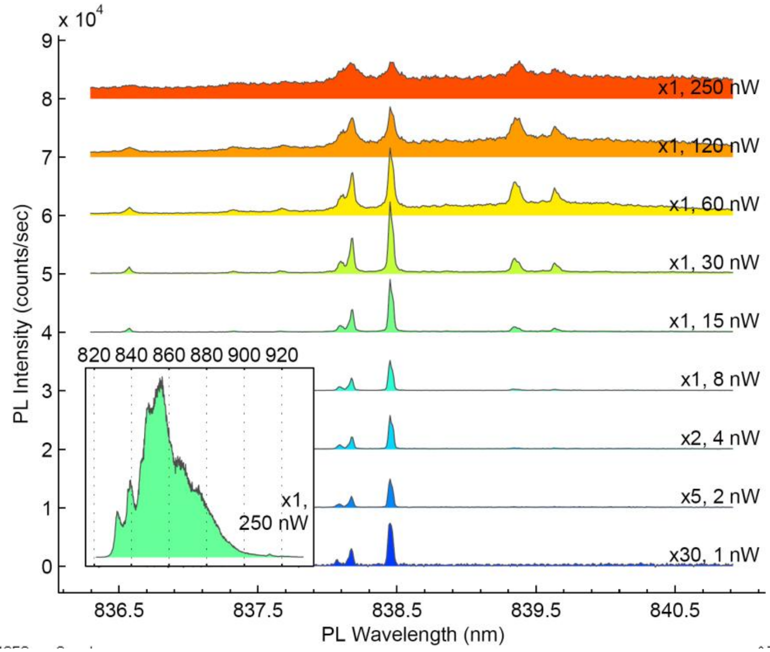
Yet another type of quantum dot: crystal phase quantum dots

Crystal phase quantum dots

InP nanowires, MBE grown (**J.-C. Harmand, G. Patriarche**, CNRS-LPN Marcoussis, France)

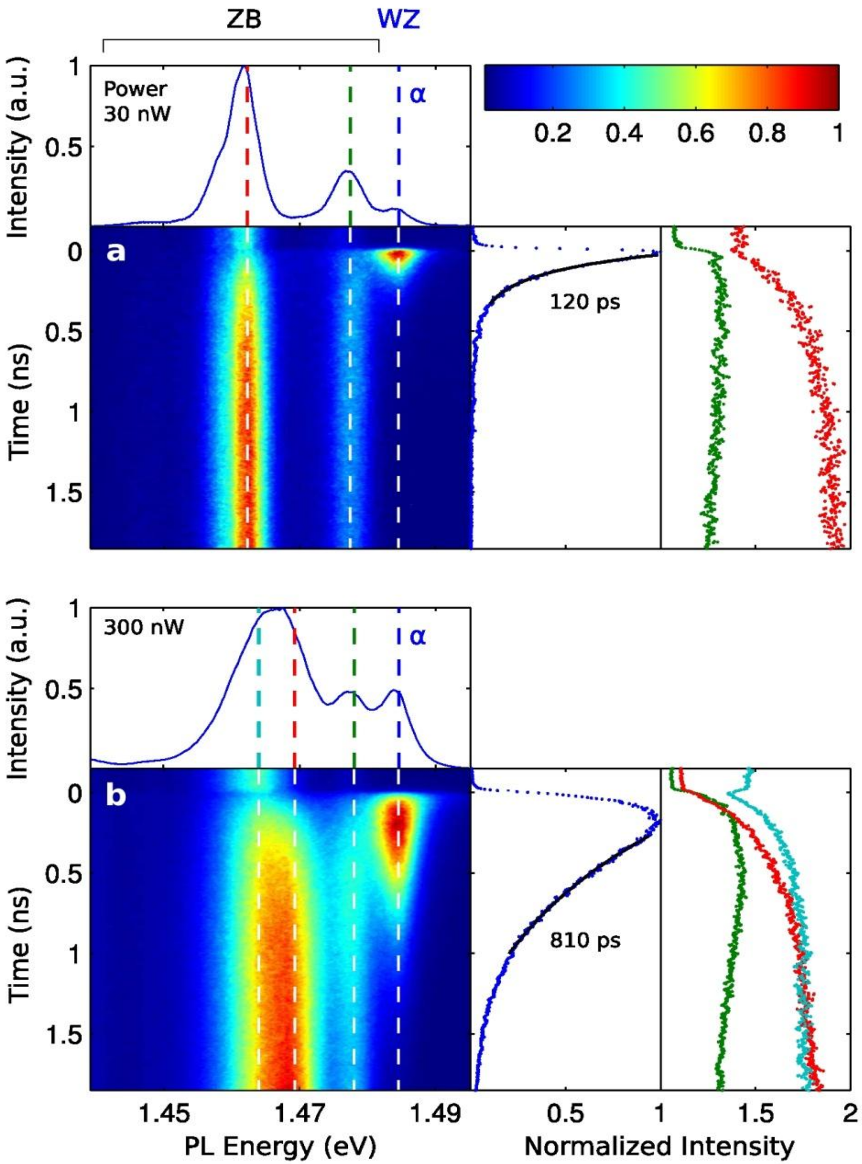


The Wurzite-Zincblende segments could define type II quantum dots.



Power dependent photoluminescence spectra reveal sharp lines (~ 50 μeV)

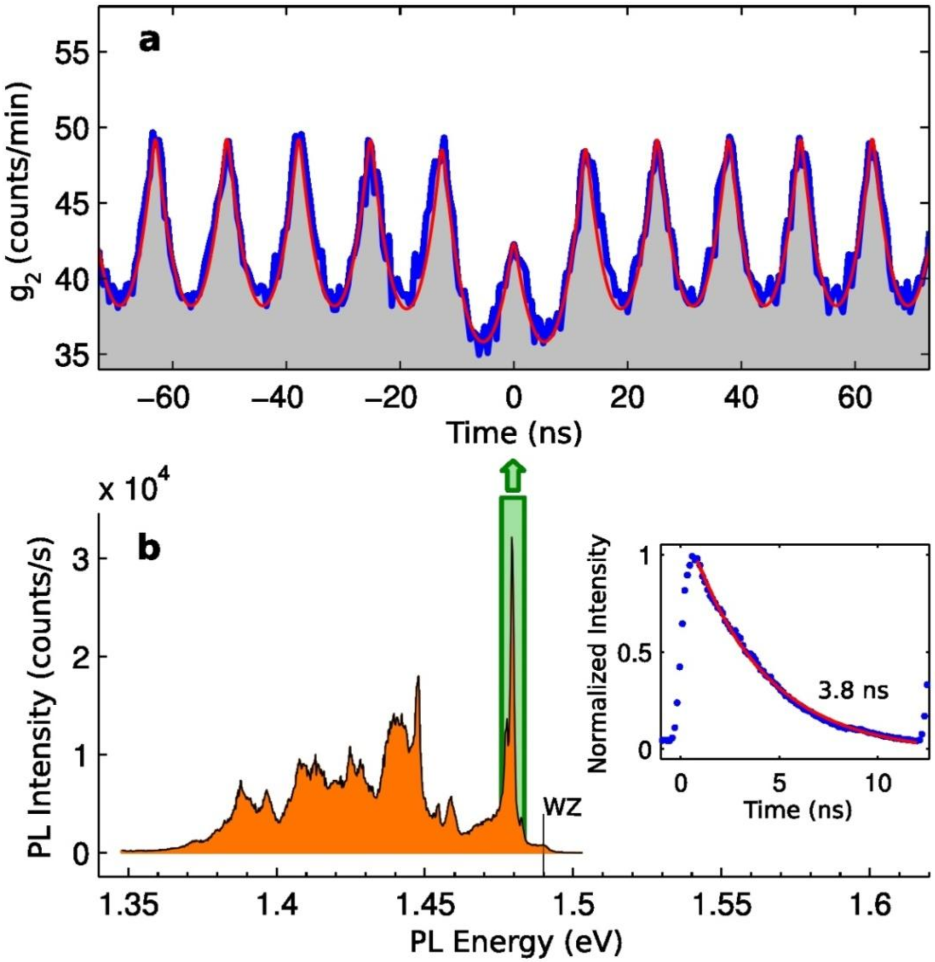
Crystal phase quantum dots: Time-resolved measurements



Time-resolved measurements reveal both long lifetimes and short lifetimes.

Type II transitions are expected to give longer lifetimes than type I.

Single photon emission from crystal phase quantum dots

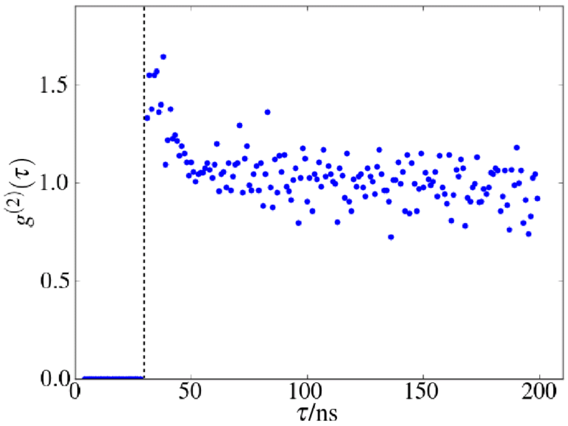


Correlations measurements reveal antibunching in the emission from the narrow spectra lines.

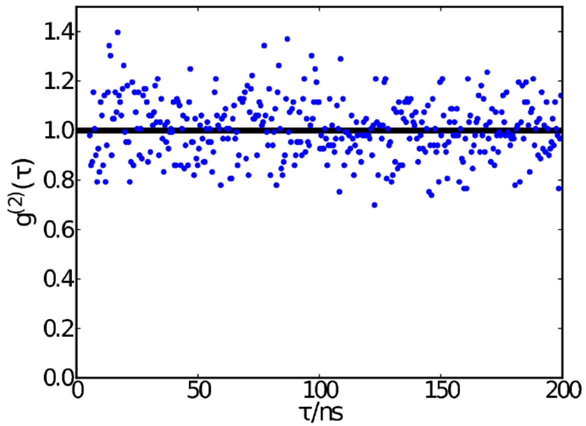
The pulsed correlation measurements are fitted with 4 ns lifetimes and 3 single emitters.

We have InP quantum dots in InP: homomaterial heterostructures.

Antibunching measurement with a single detector



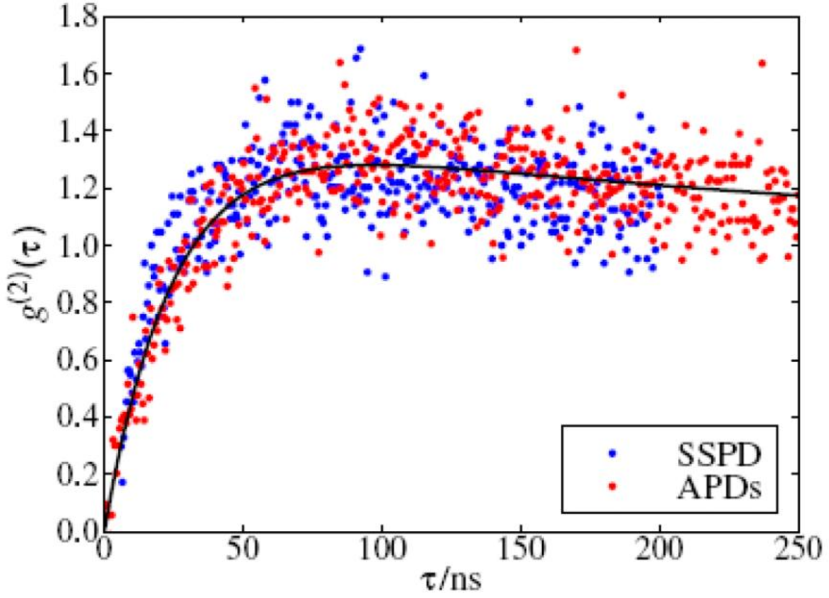
One APD



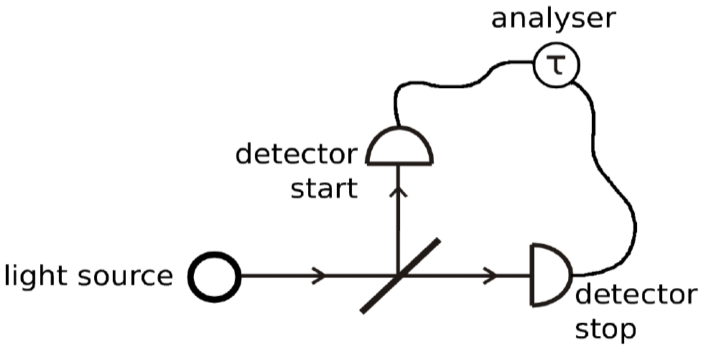
One SSPD

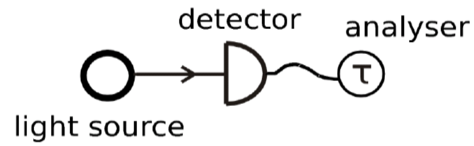
Measuring on a laser

Measuring on a NV center

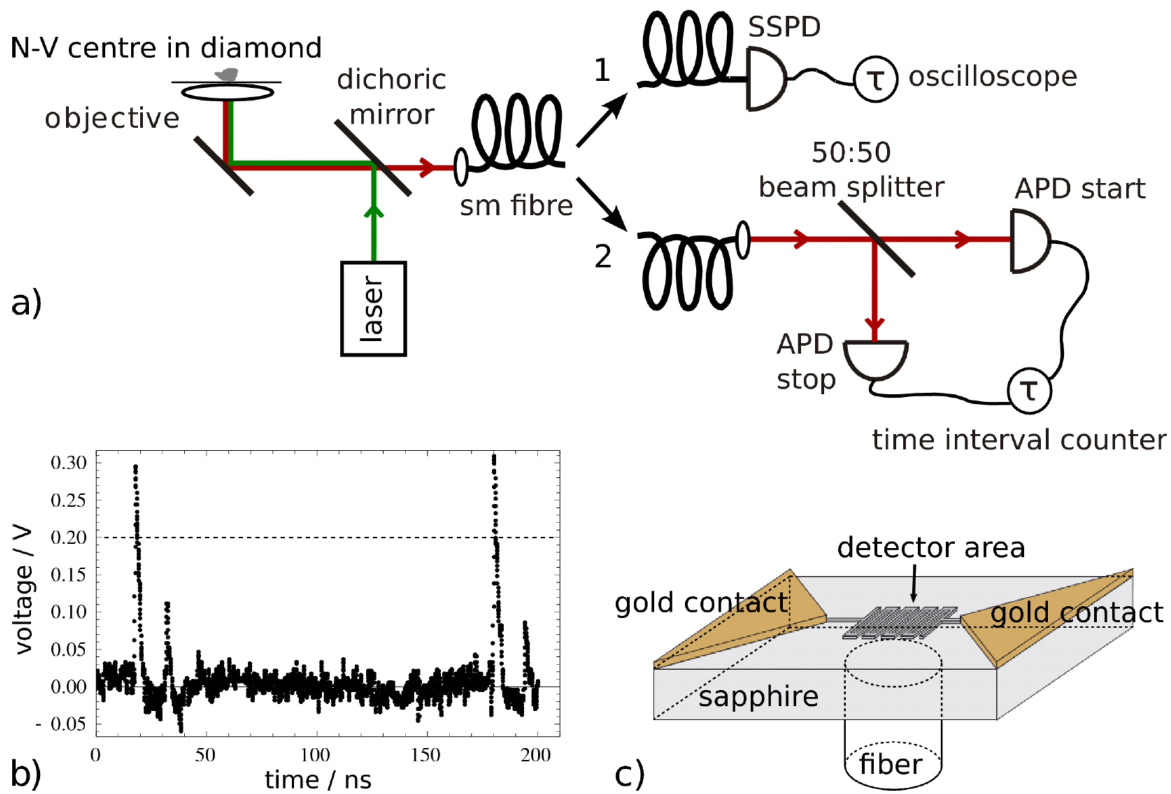


Antibunching measurement with a single detector



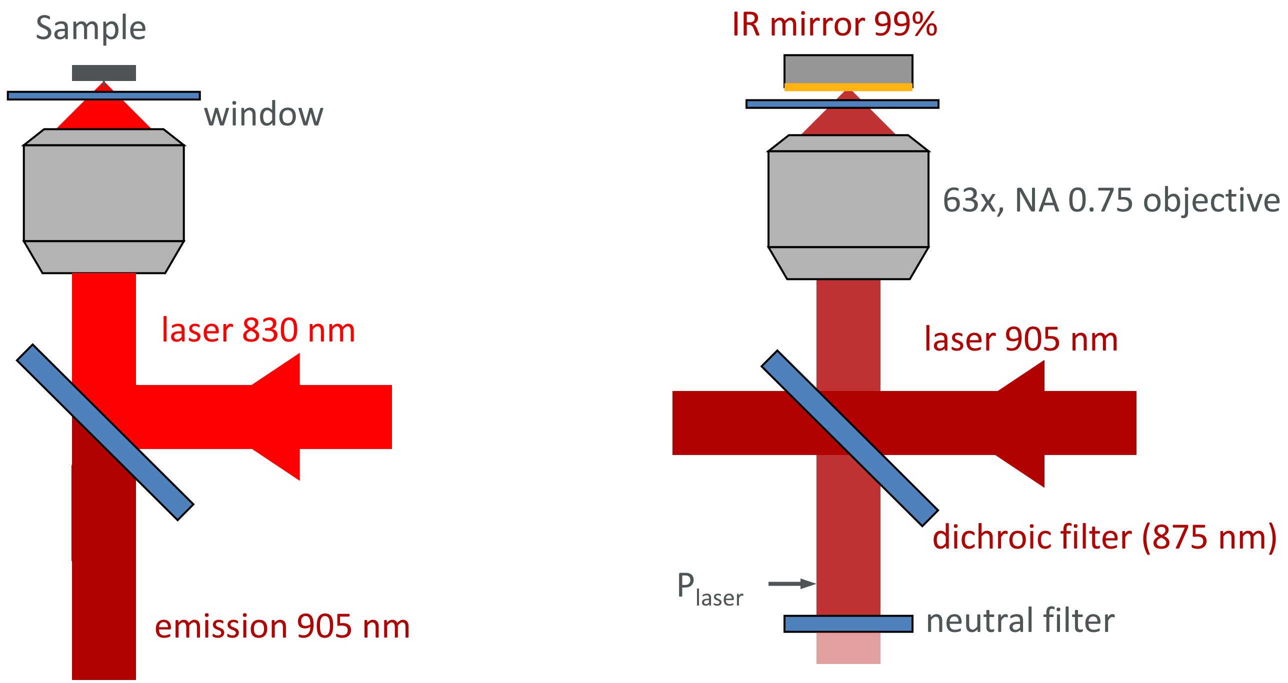


Do we really need two detectors?



Measurement in
O. Benson group, Berlin

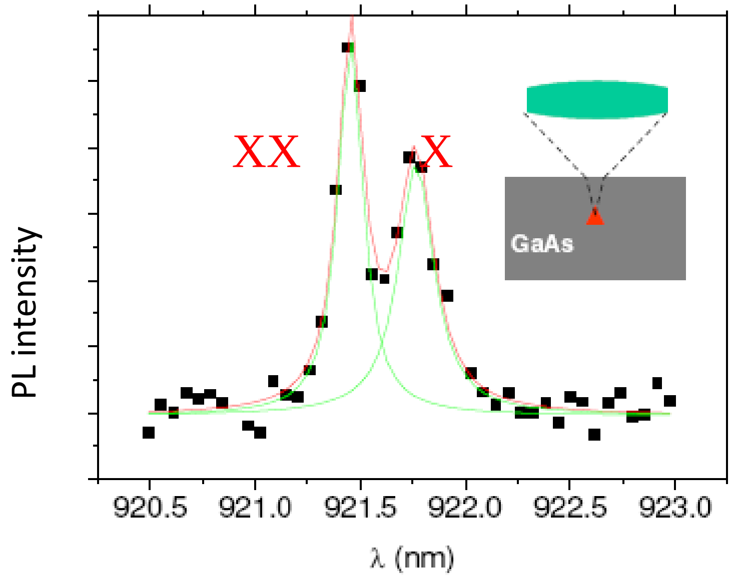
Calibration procedure for the SPS efficiency measurement

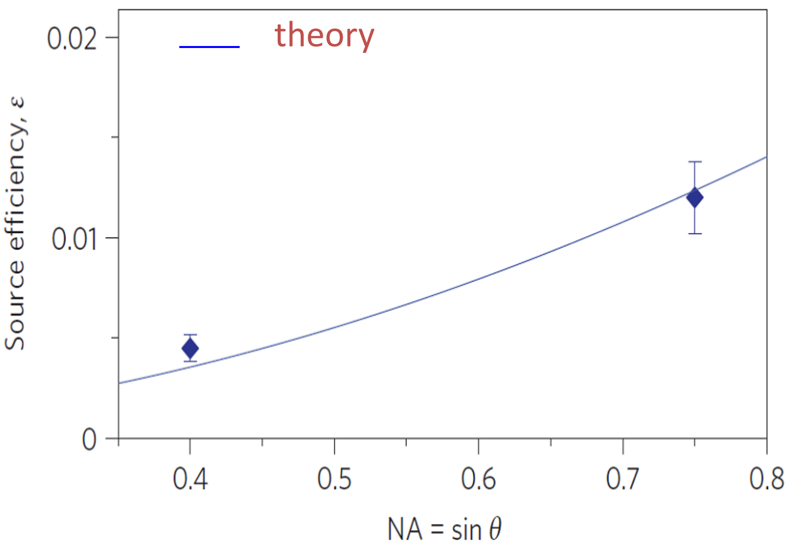


- Attenuated laser beam as reference source at the QD emission wavelength
- The reflection of the laser mimics the broad radiation pattern of the SPS

Calibration procedure for the QD-SPS efficiency (2)

- A single QD in unpatterned GaAs as reference SPS

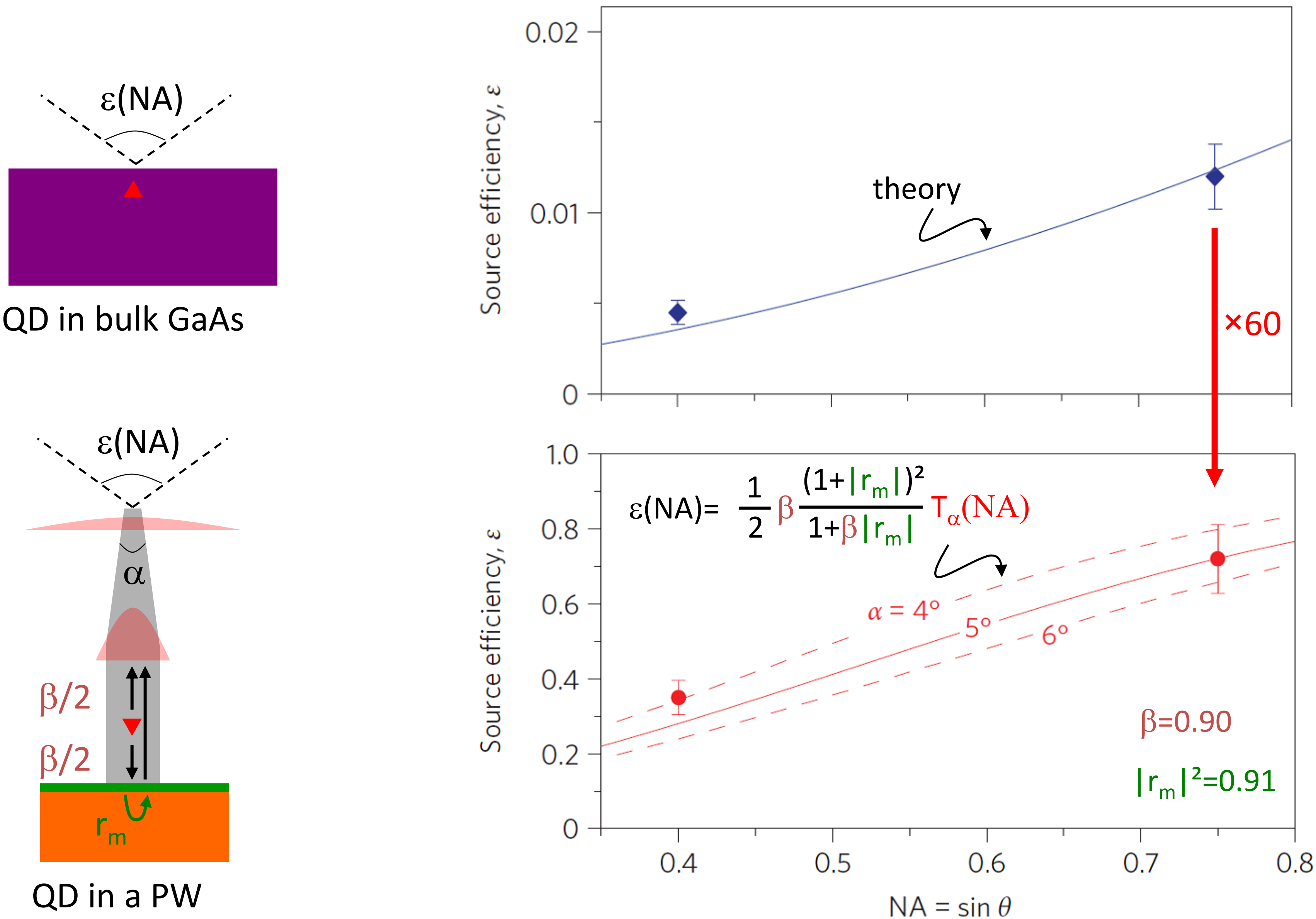




- Measured efficiency ~ **1.2 ± 0.2 % for NA=0.75**

  0.45 ± 0.1 % for NA=0.4
- … in excellent agreement with calculations

A high-efficiency single-photon source



Assets of photonic wire SPS

o One can get simultaneously

- a high efficiency (0.72 photon per pulse)
- $g^{(2)}(0) < 0.01$

J Claudon et al,

Nature Phot. 4, 174 (2010)

o Many other assets related to the broadband SE control

_ Spectrally tunable QD SPS

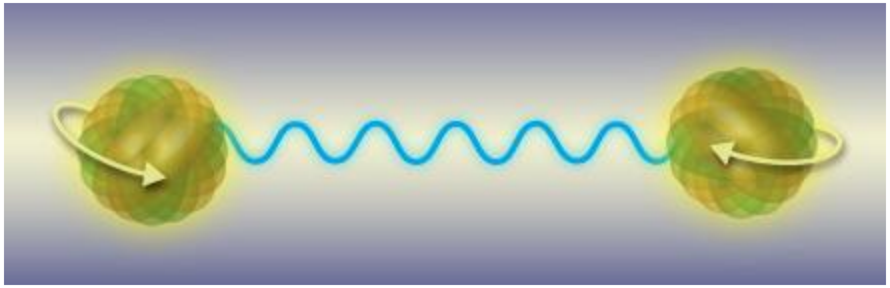
_ Single-mode SPS exploiting a non-monochromatic emitter

F-center in diamond, QD at high temperature…

_ Efficient source of entangled photon pairs

Bottom up quantum dots and nanowires

Beyond single photons: pairs of entangled photons.

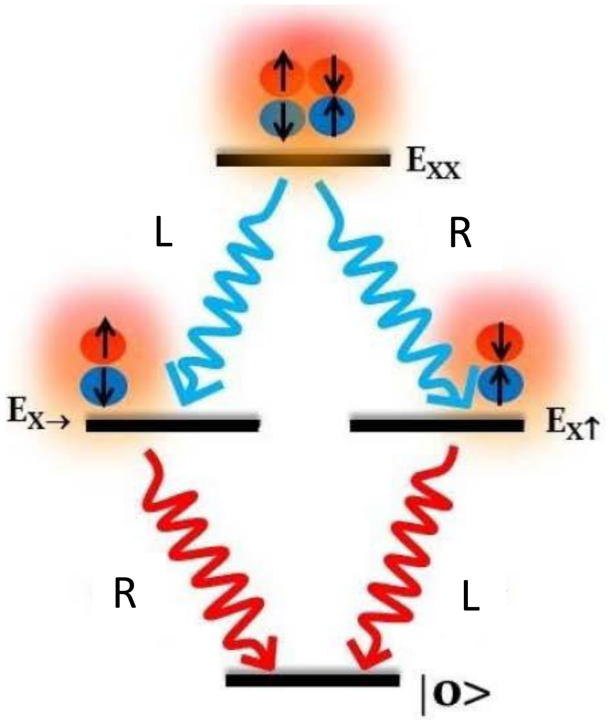


Concept of quantum entanglement was brought up by A. Einstein.
Measurement on one particle reveals information about the other.

For example: |HV> + |VH>

Entanglement is an important resource for quantum technology.

Entangled photons due to NW symmetry



$$|\Phi^+\rangle = (|R\rangle|L\rangle + |L\rangle|R\rangle)/\sqrt{2}$$

$$|\Phi^+\rangle = (|H\rangle|H\rangle + |V\rangle|V\rangle)/\sqrt{2}$$

Nanowire Quantum Dots as an Ideal Source of Entangled Photon Pairs

Ranber Singh and Gabriel Bester

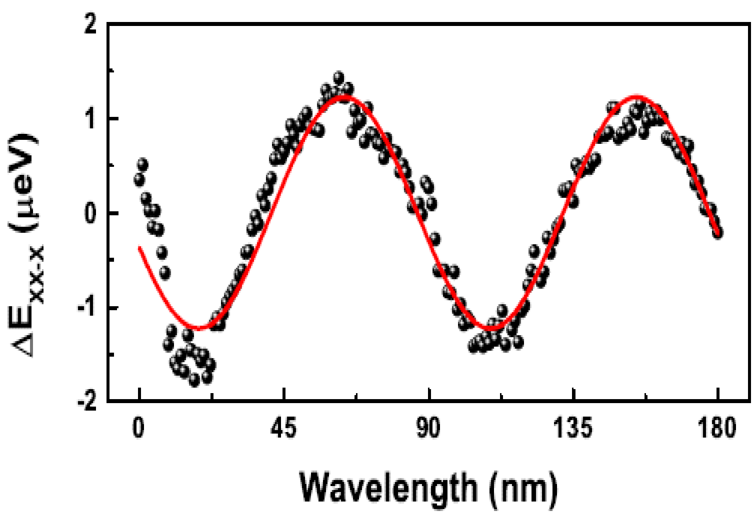
Max Planck Institute for Solid State Research, D-70569 Stuttgart, Germany

(Received 10 March 2009; published 3 August 2009)

We predict that heterostructure quantum wires and [111] grown quantum dots have a vanishing fine-structure splitting on the grounds of their symmetry, and are therefore ideal candidates to generate entangled photon pairs. We underpin this proposal by atomistic million-atom many-body pseudopotential calculations of realistic structures and find that the vanishing fine-structure splitting is robust against possible variations in morphology.

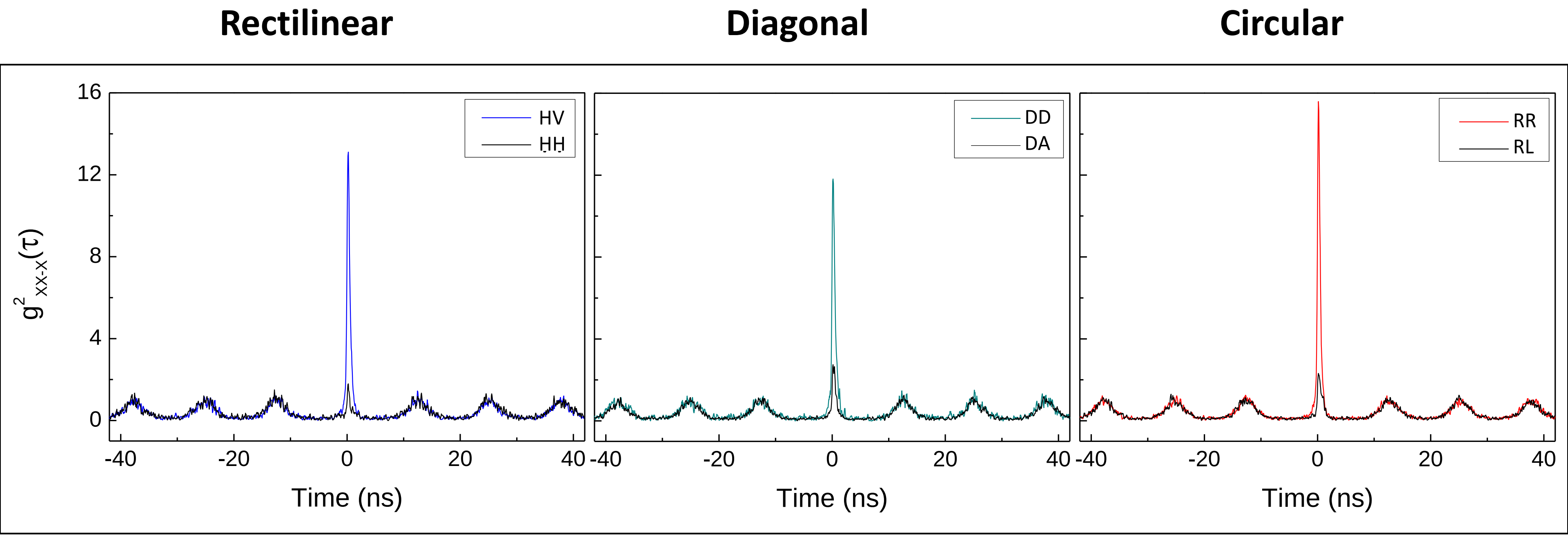
- Zero fine-structure splitting predicted

R. Singh and G. Bester, PRL 103, 063601 (2009)



- Measured fine-structure splitting of 1 μeV

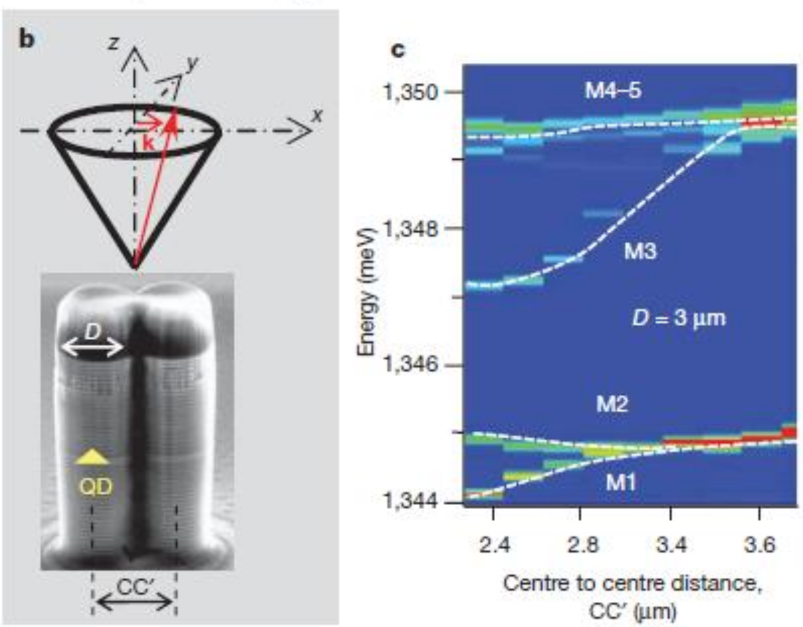
Entangled photon pairs generation



- **We observe a different quantum state than for self-assembled quantum dots**
- **The quantum state is most like |HV>+|VH>**
- **Fidelity: 0.86**

Nature Communications 5298, **5** (2014)

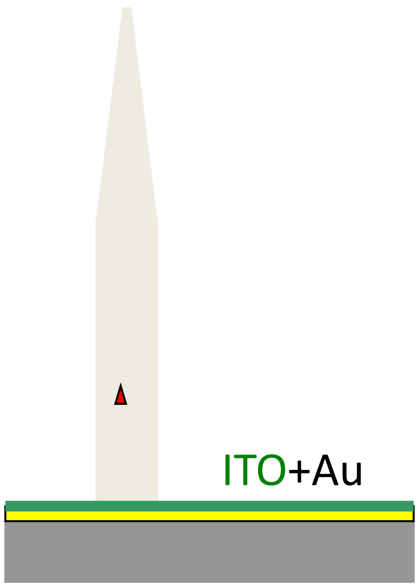
Photonic wires as sources of entangled photon pairs (?)



Single QD in a photonic molecule

P Senellart et al, CNRS/LPN, Nature 2010

Efficiency : 0.35 x 0.35 ~ 12%



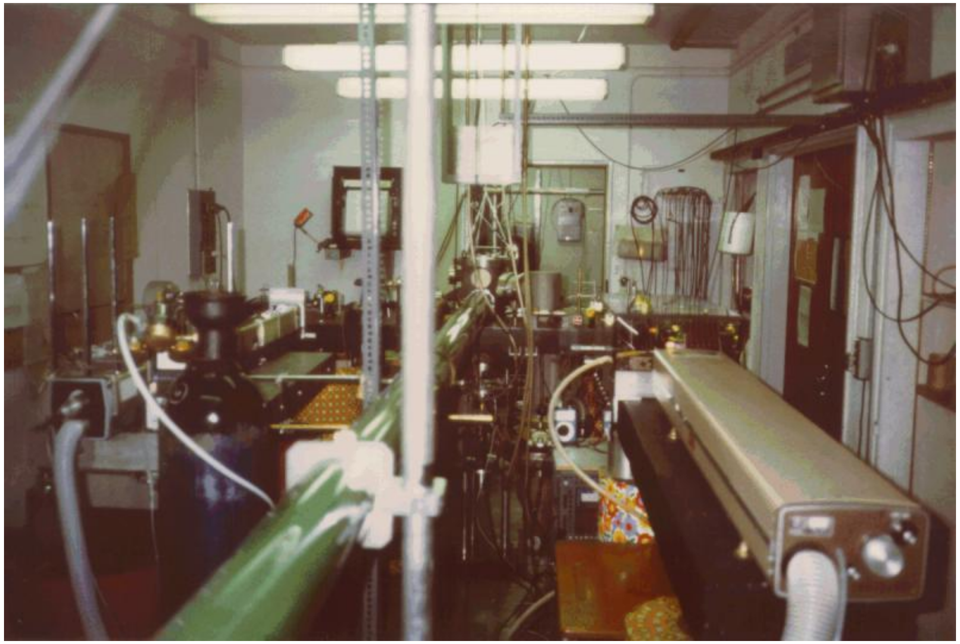
Single QD in a photonic wire

Potential efficiency :

0.9 x 0.9 ~ 80%

The first demonstration of quantum entanglement was performed by Alain Aspect 30 years ago using an atomic cascade to generate pairs of entangled photons. The experimental apparatus was bulky.

Orsay's source of pairs of entangled photons (1981)



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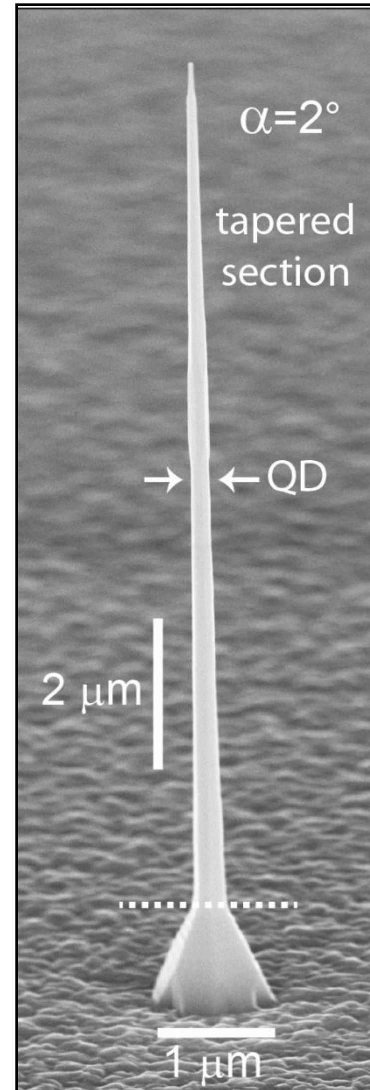


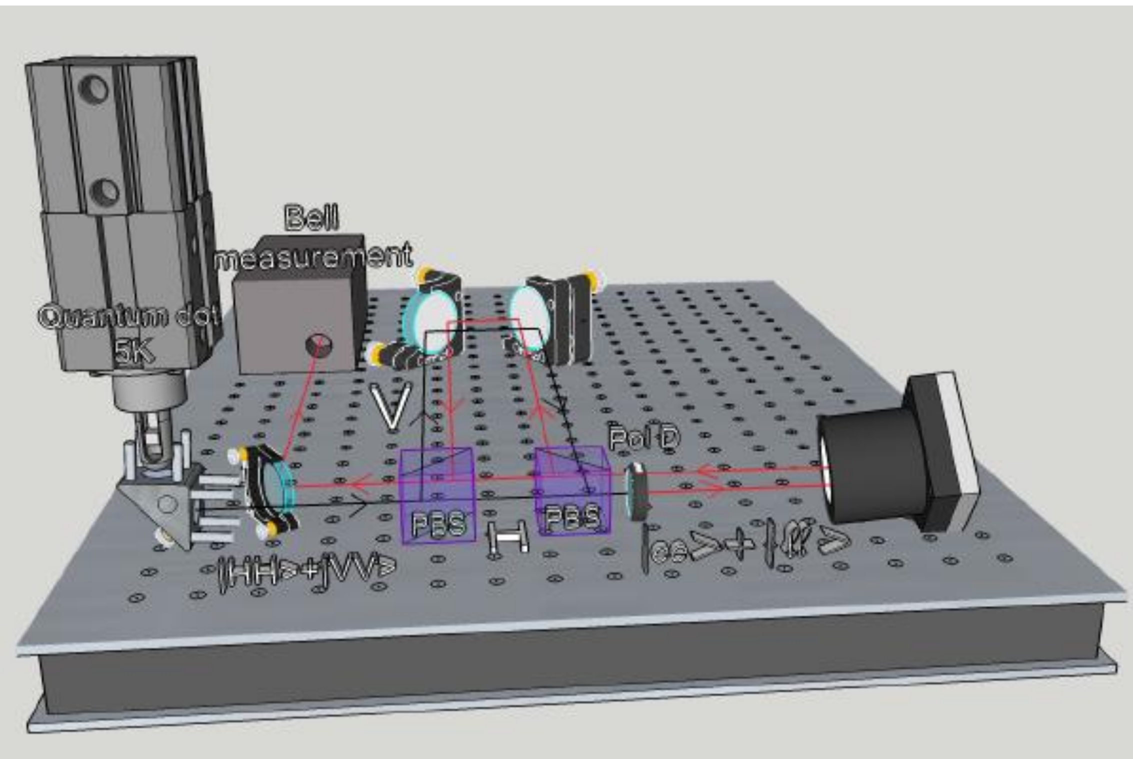
Beyond polarization entanglement: time bin entanglement

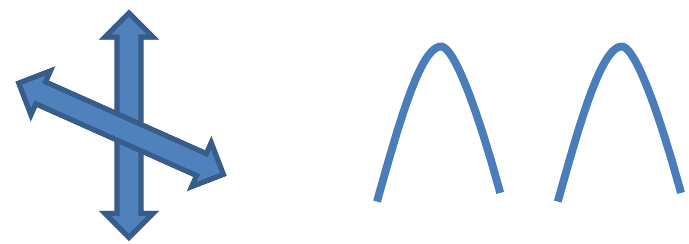
Other measurables than polarization can be entangled. For instance, a photon can be in a superposition of two emission times (like a cat can be in a dead and alive superposition).
This enables time-bin entanglement.

Time-bin entangled photon pairs on demand

We generate **time-bin entanglement on-demand** with a quantum dot by conversion from polarization entanglement.

Quantum dots in pyramids from Emanuele Peluchi, Tyndall Institute, Ireland.

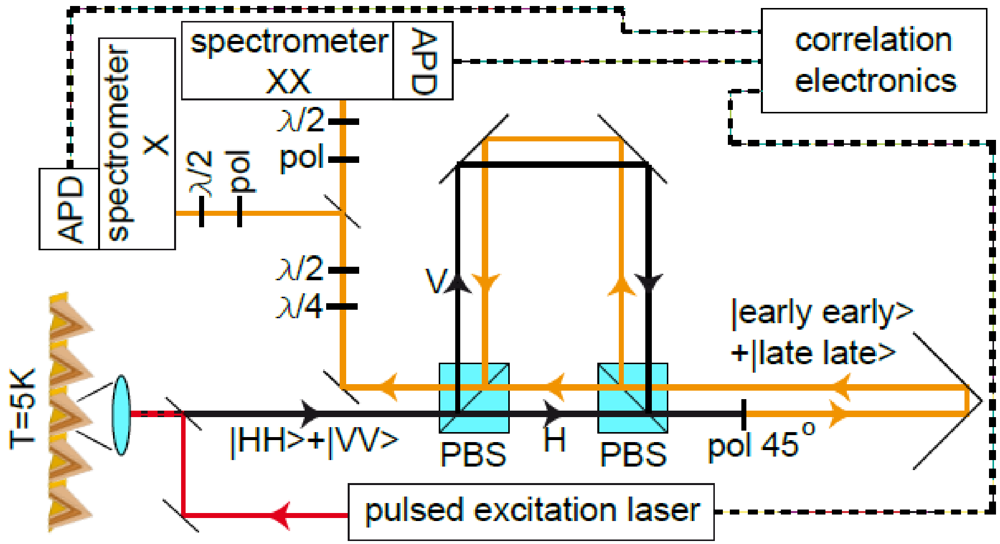


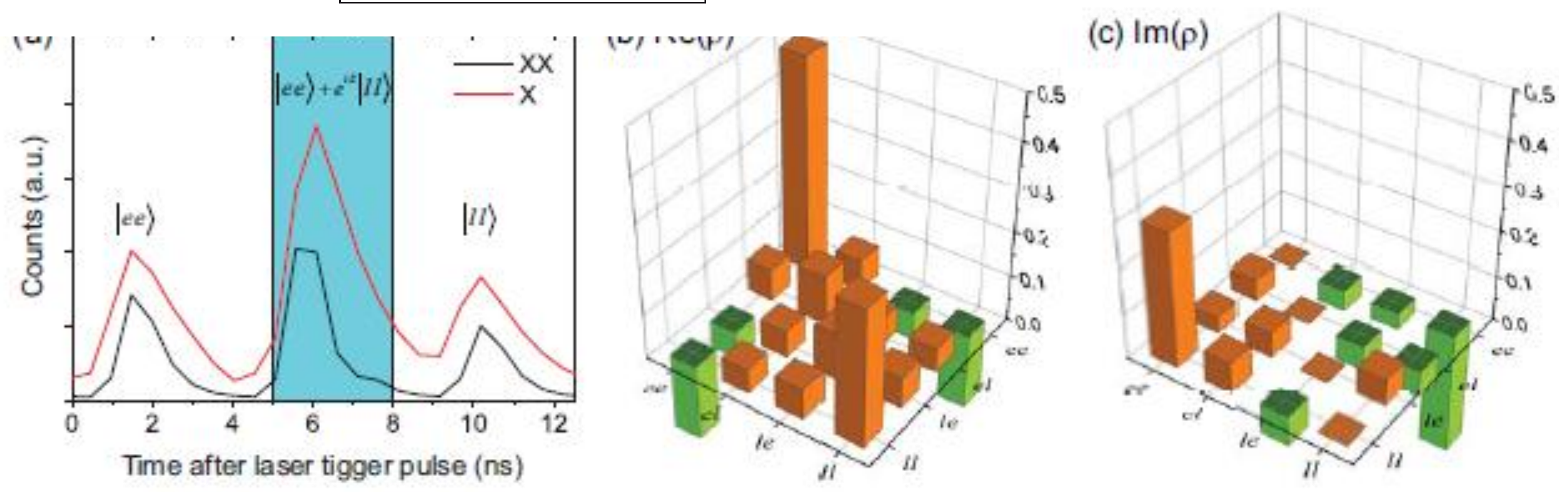


Polarization superposition is turned into early-late superposition.

Transmitting time-bin entangled states does not require polarization conservation
-> good for plasmonics circuits

Time-bin entanglement on demand

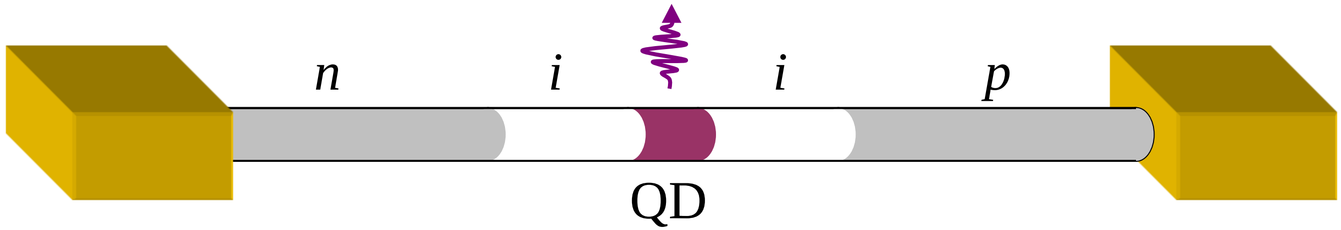


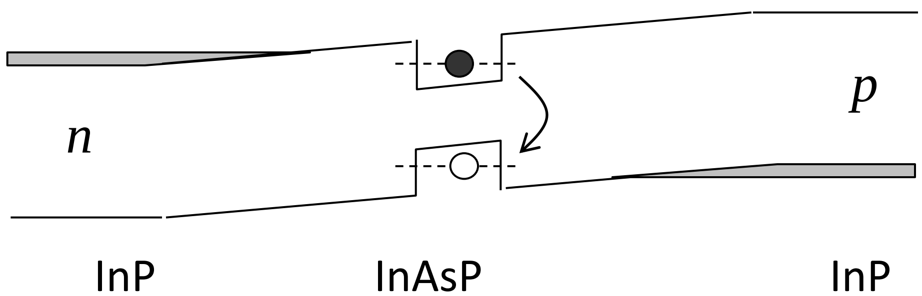


The fidelity to $(|ee\rangle + e^{0.672\pi i}|ll\rangle)/\sqrt{2}$ is 0.74 ± 0.02.

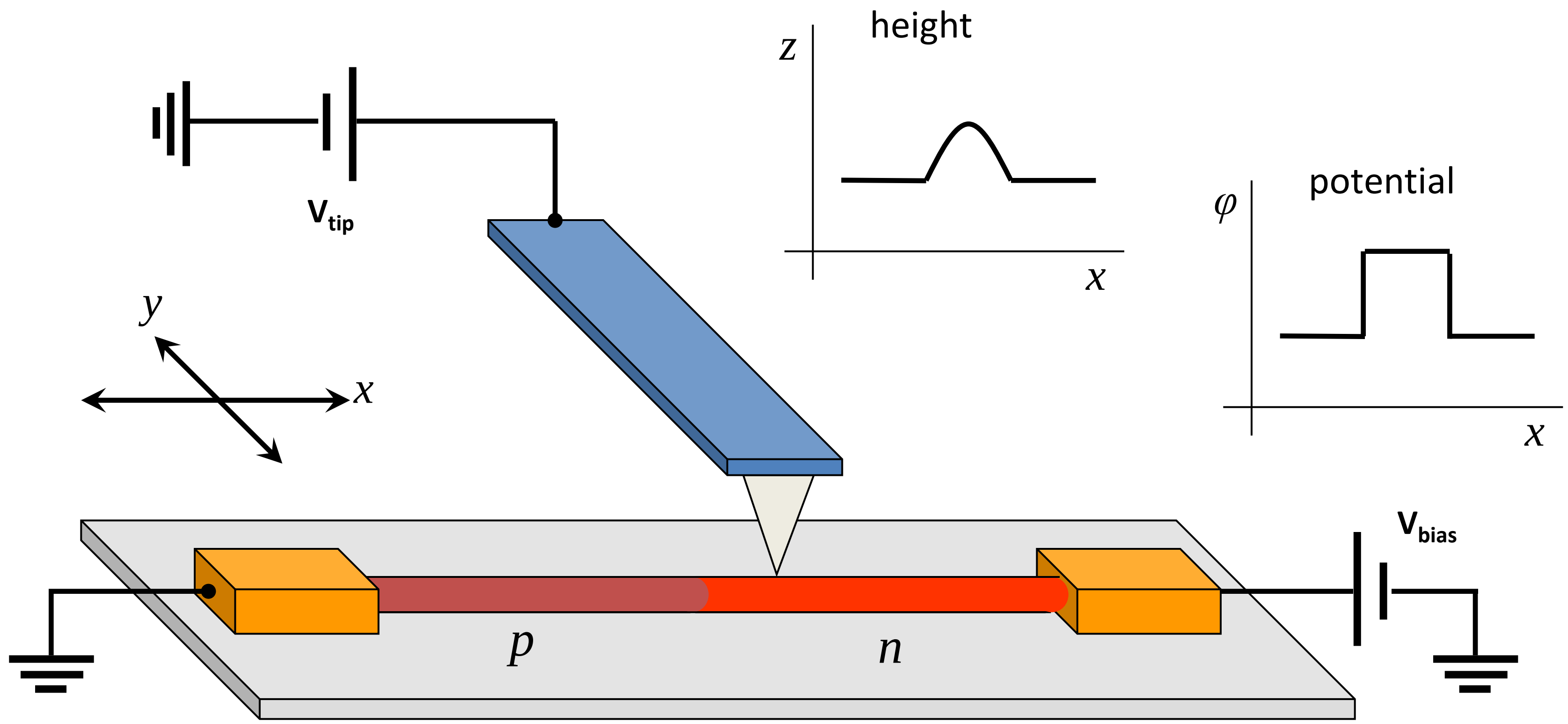
Electrically contacted nanowires: a nanowire LED

An electrically pumped source of single photons:
a quantum dot in a pn junction



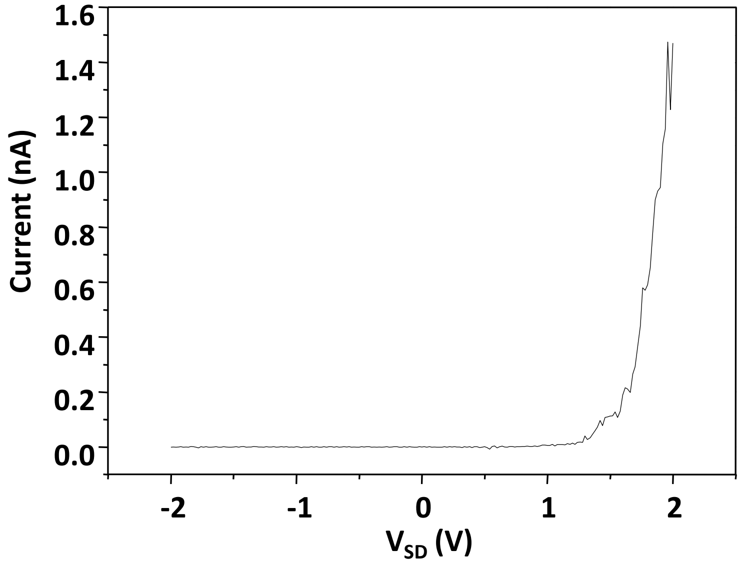


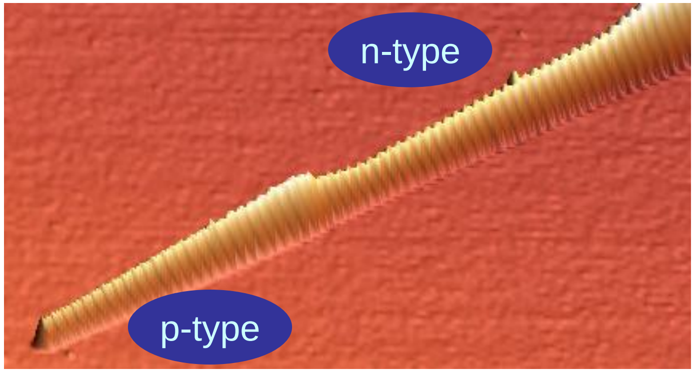
Surface potential measurement

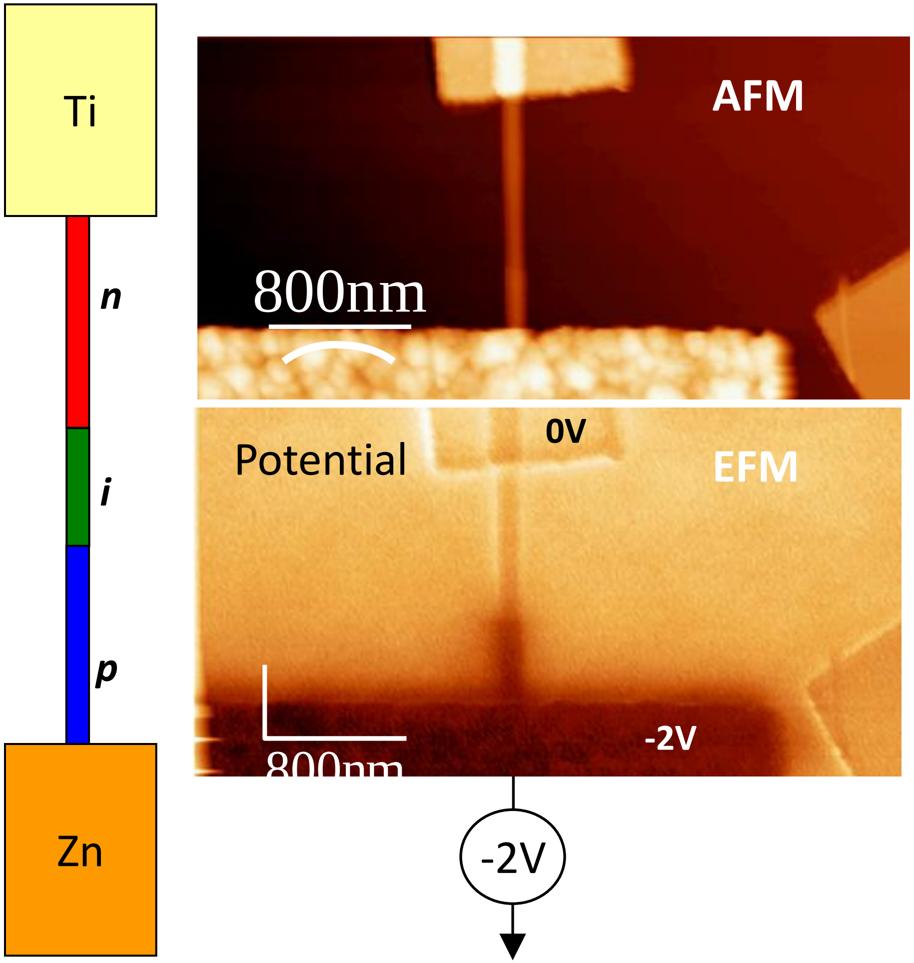


→ measures band-bending of the *p-n* junction

Scanning surface potential shows the pn-junction

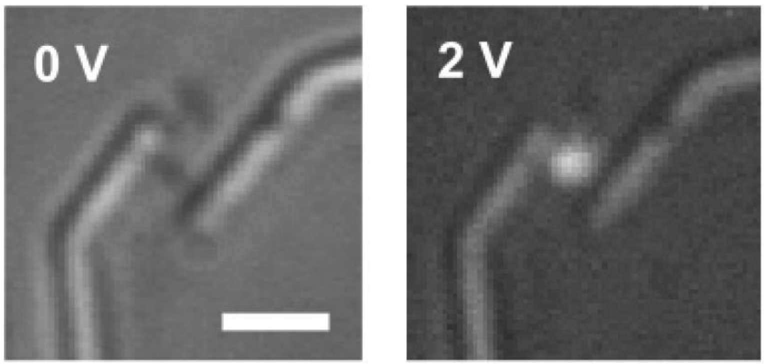


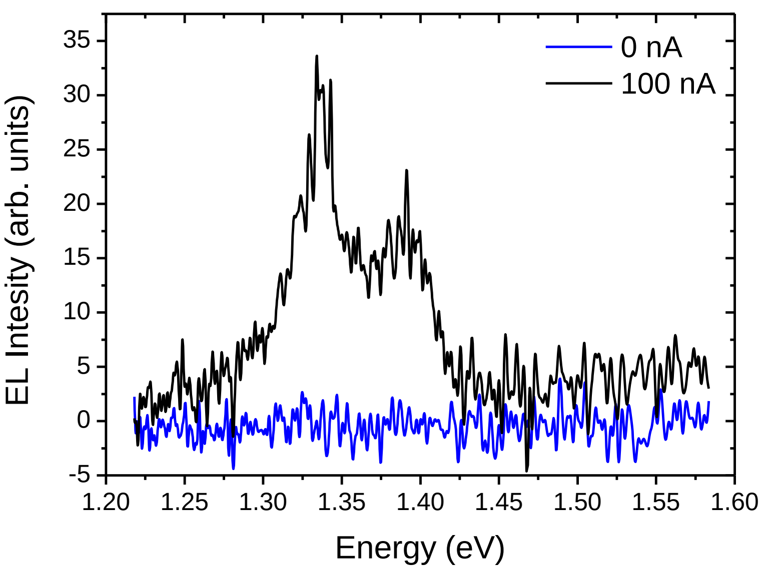




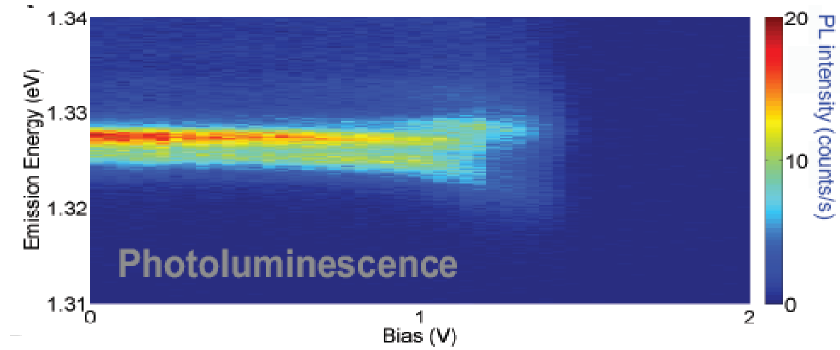
p-i-n QD LED electroluminescence and photocurrent

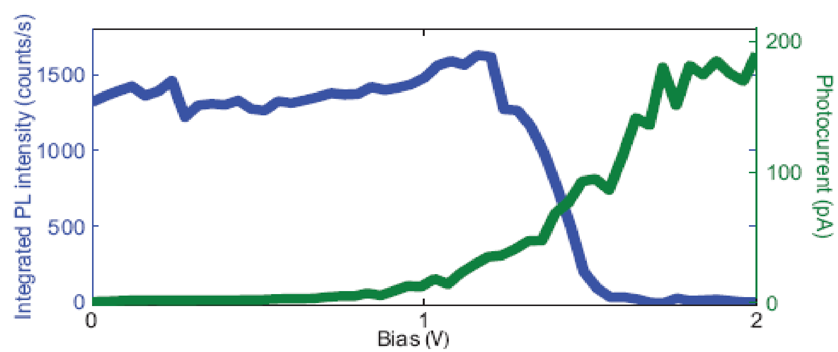
Electroluminescence

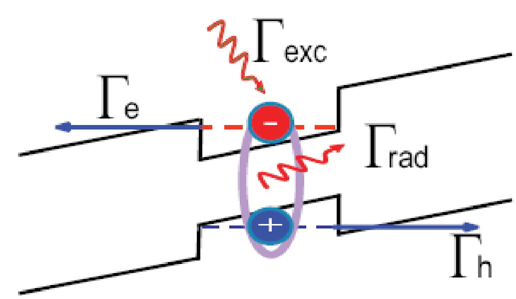




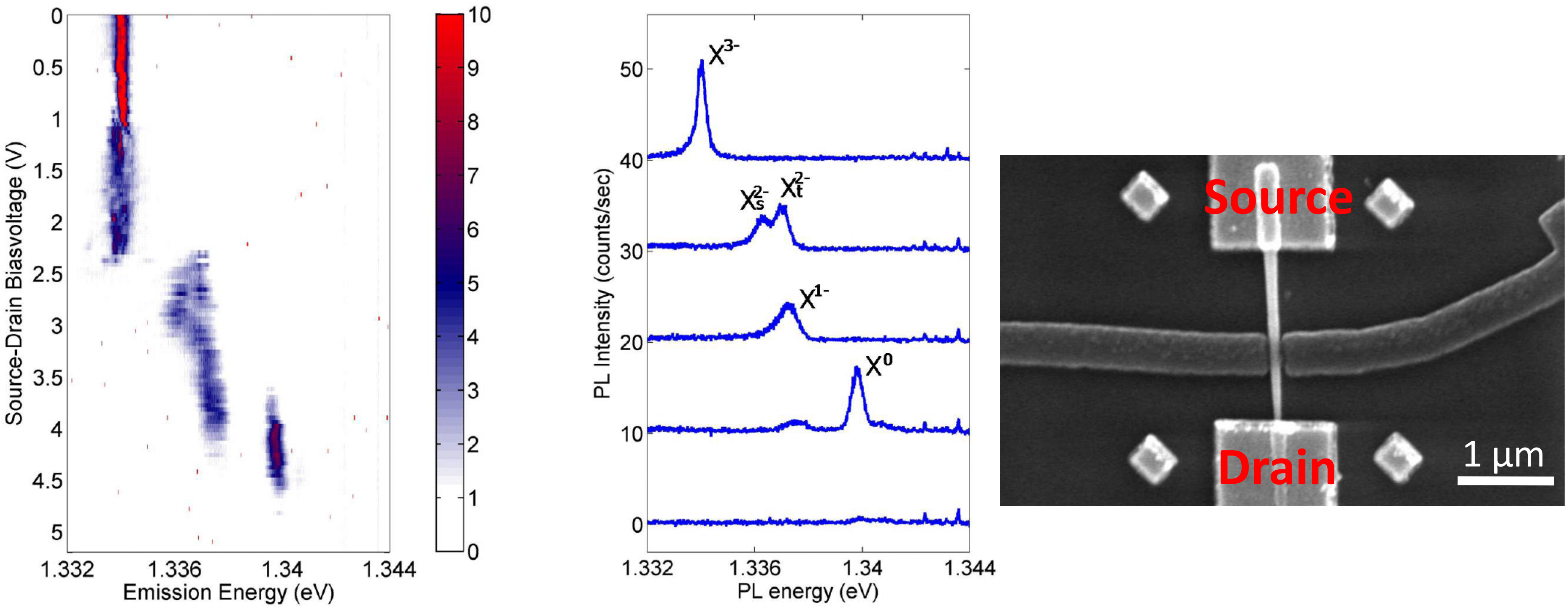
Photocurrent





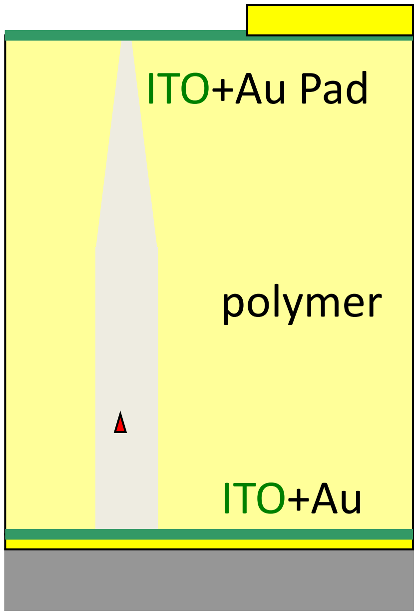


Gated nanowire quantum dot



A source-drain bias enables a controlled charging of the quantum dot, observed by photoluminescence.

Towards plug-and-play electrically-pumped SPS (1)

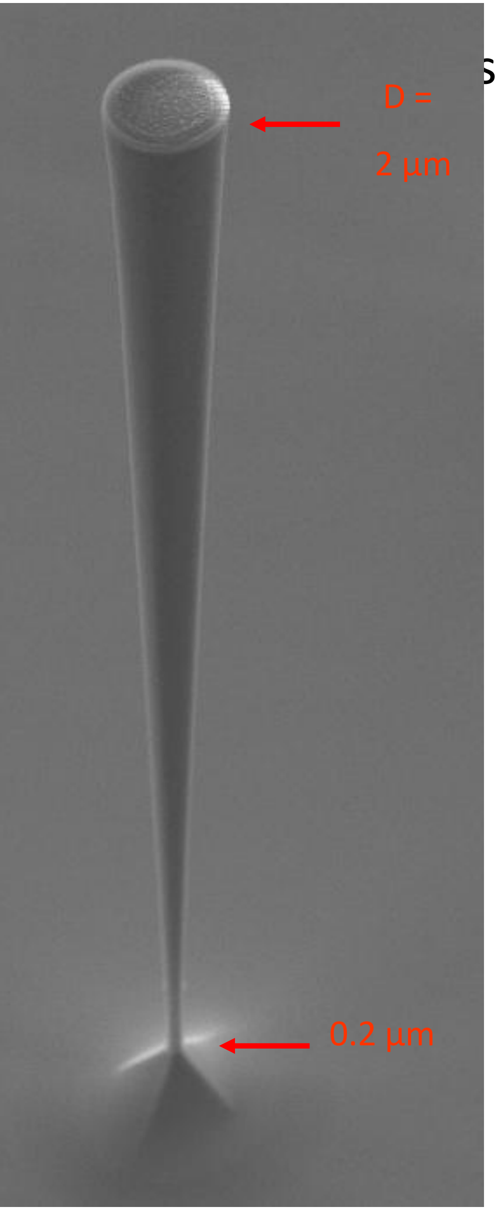


ε > 0.8 for optimized structure

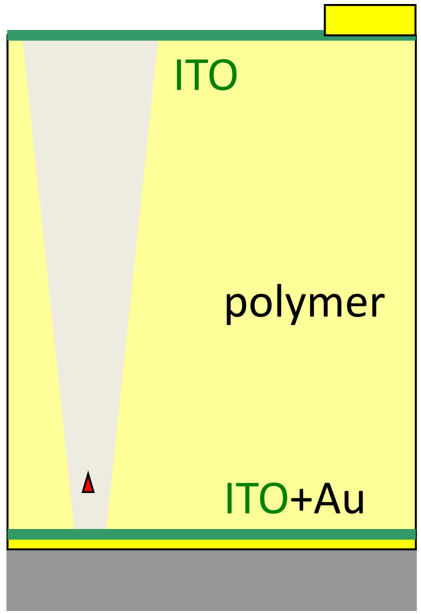
Gregersen et al, Opt. Exp. 2010

… but tricky process!

.



s plug-and-play electrically-pumped SPS (2)



Adiabatic mode expansion inside the photonic wire

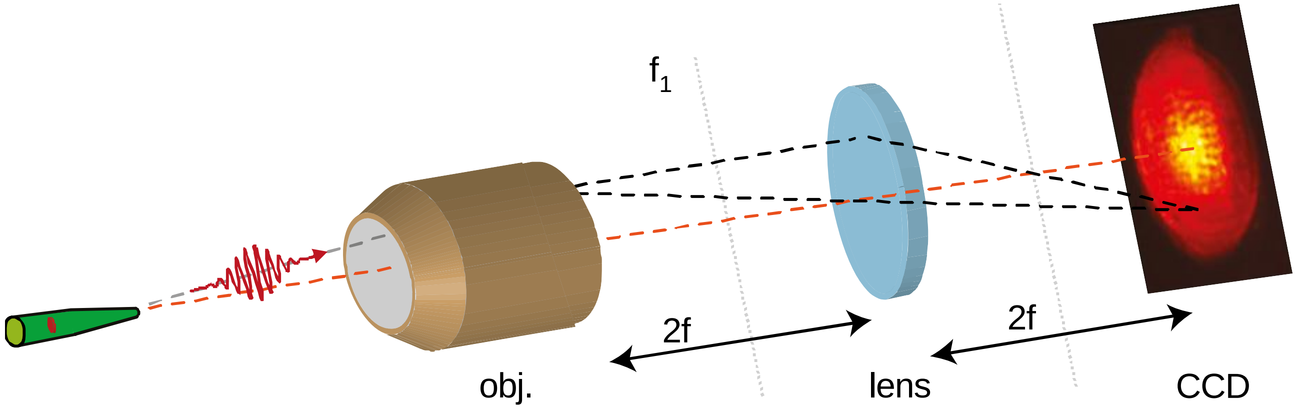
Easier contacting process

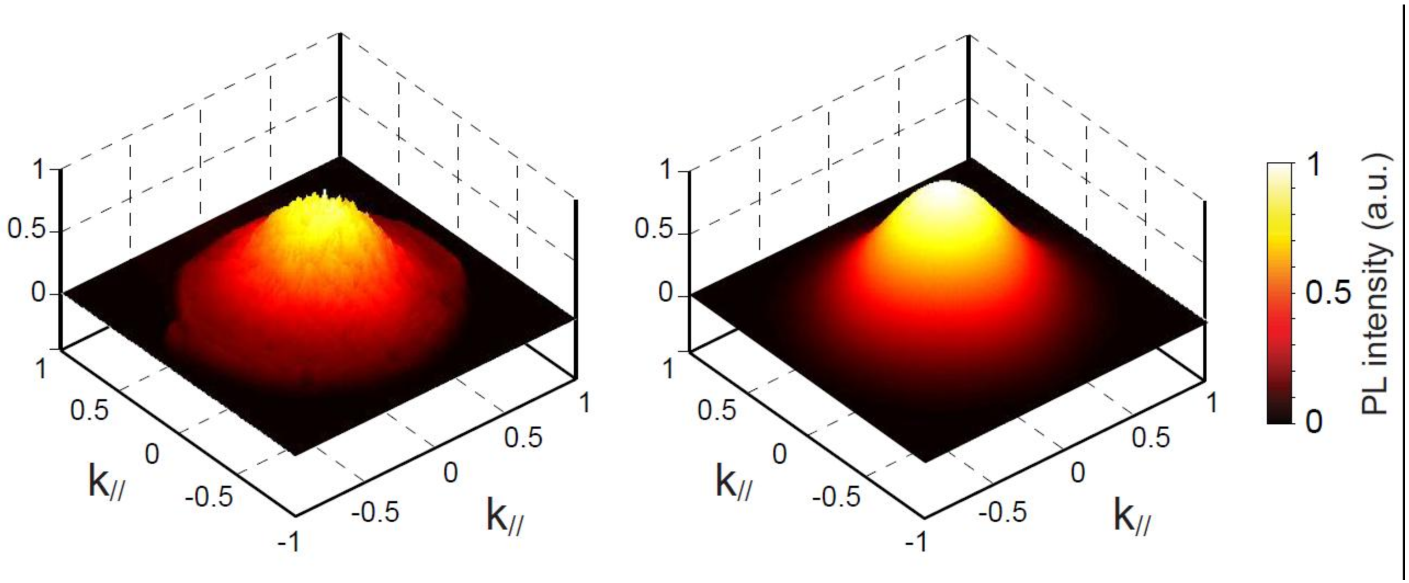
$\varepsilon > 0.9$ for optimized structure

Gregersen et al, Opt. Exp. 2010

CEA+DTU patent 2010

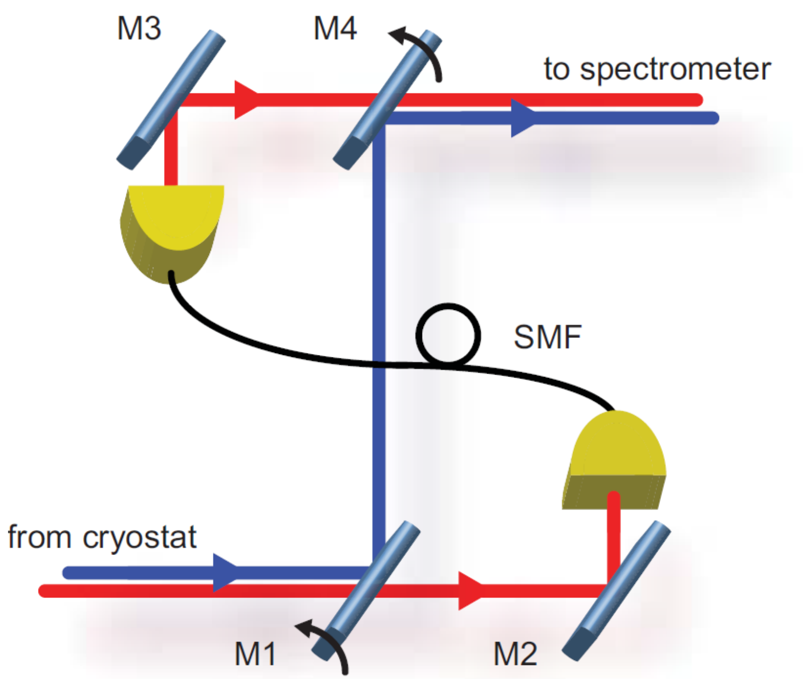
Far field emission profile

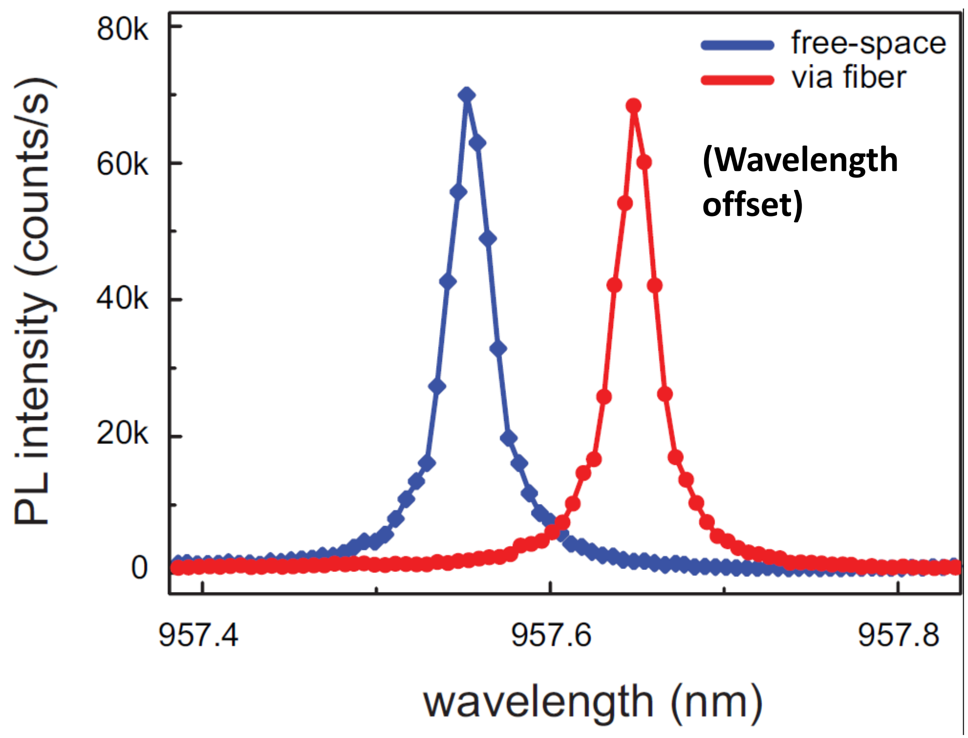




- 98 % overlap with Gaussian mode

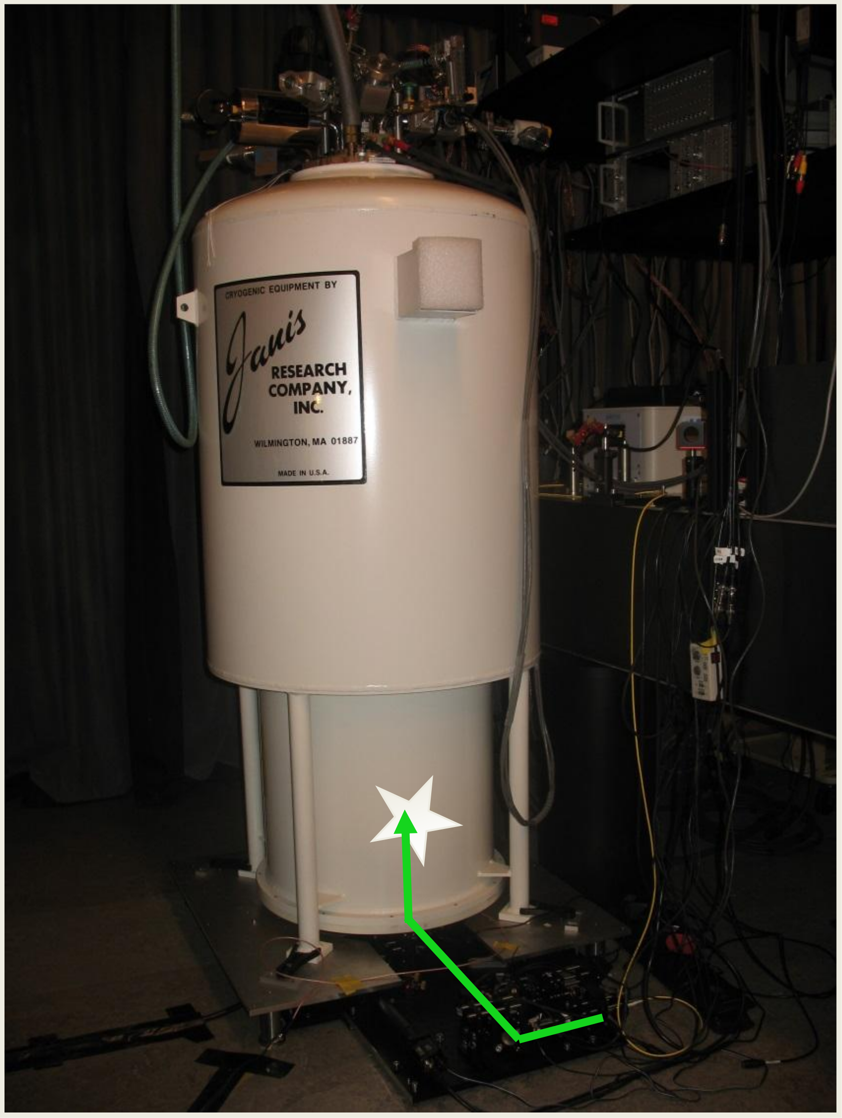
Coupling to single-mode fibers





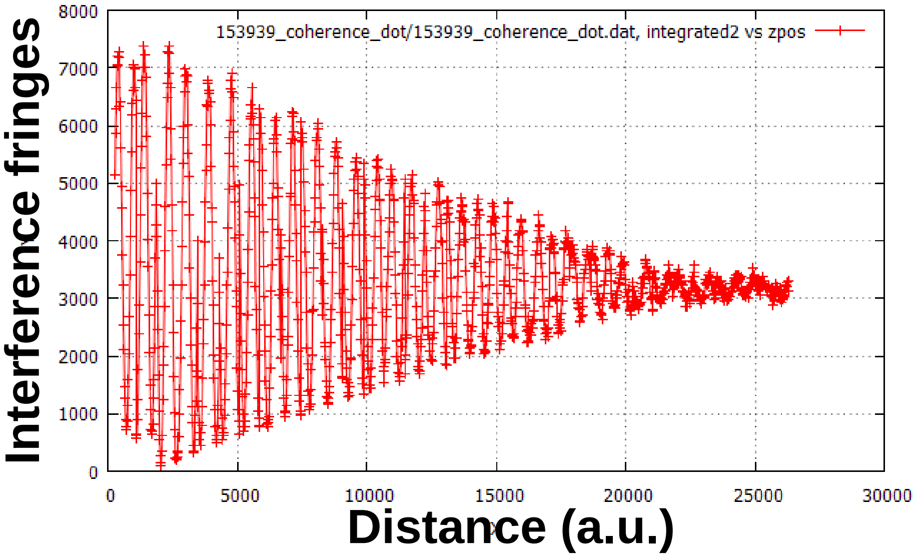
- **Excellent coupling to a single-mode fiber**
- **93 %**
- **Count rates as high as 460,000 counts/s measured on single-photon detector**

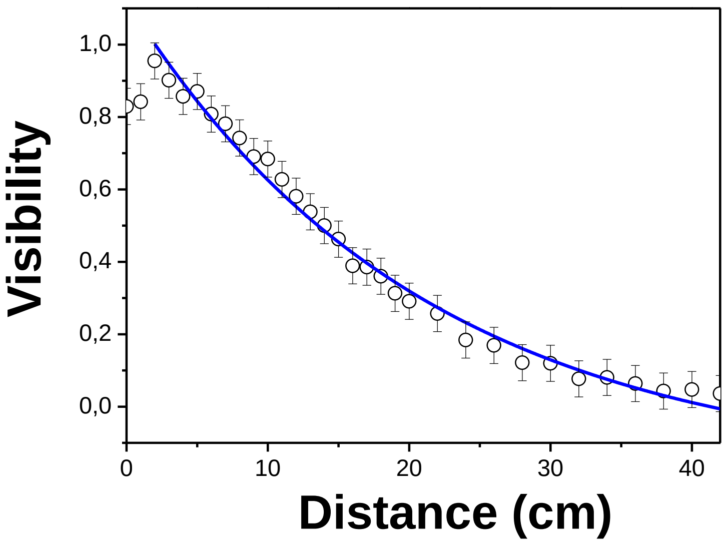
Enhancing the coherence



Cool down to 300 mK to suppress thermally activated dephasing processes.

QD coherence at 300 mK





- Coherence at 300 mK → 23 cm
- Linewidth of 415 MHz → ~1.7 μeV
- Improvement by factor of ~2 compared to 4 K

Coherence improves at lower temperatures.

Detection at the nanoscale

The challenge of detecting single photons.

History of single photon detection

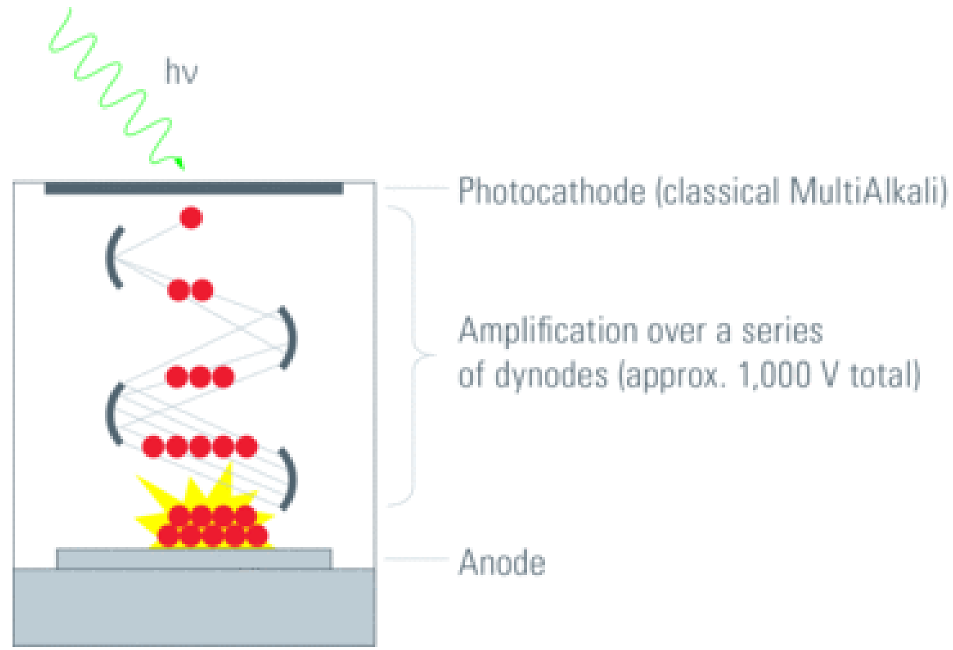
Photomultiplier tubes (PMTs)

Avalanche Photodiodes (APDs)

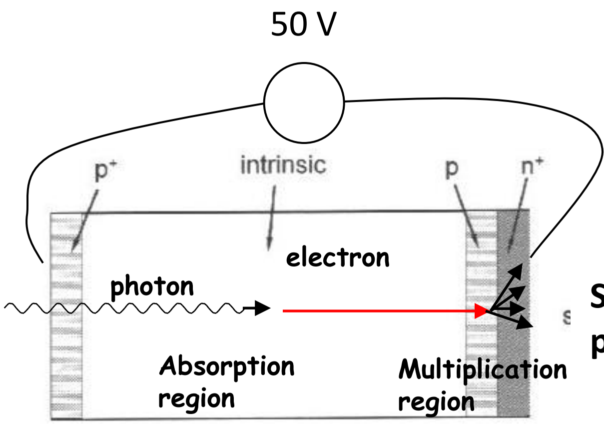
Superconducting single photon detectors (SSPD)

Photomultiplier tubes

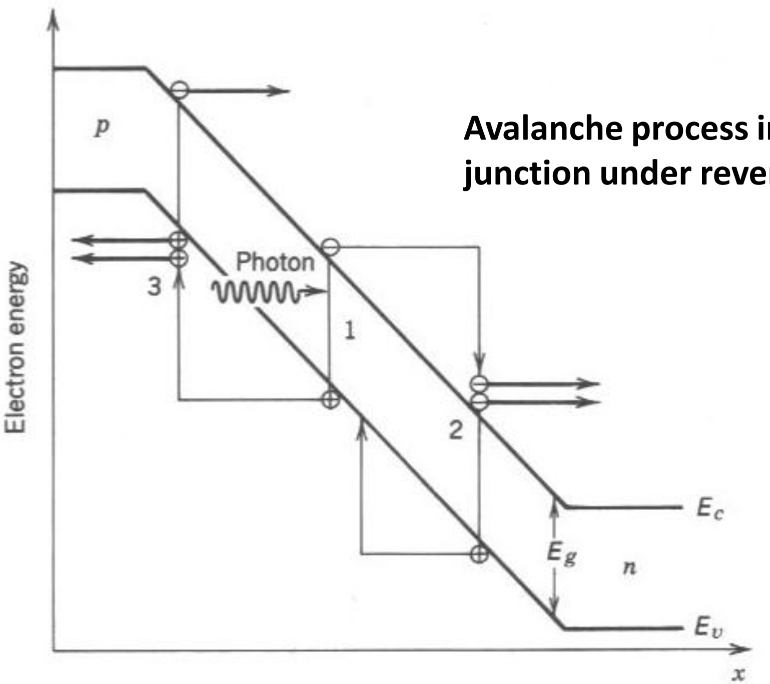
First single photon detectors. Still used for UV detection.
A photon releases an electron which is accelerated, subsequent stages yield multiplication.



Avalanche photodiodes



Structure of an avalanche photodiode.



Avalanche process in a pn junction under reverse bias.

The avalanche process gives huge gain: **single photons can be detected.**

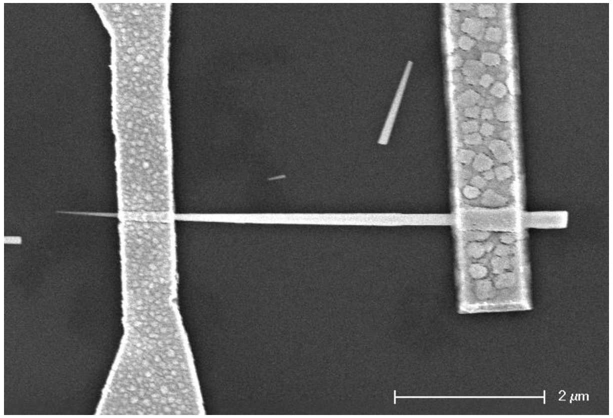
Very fast process, useful for communications.

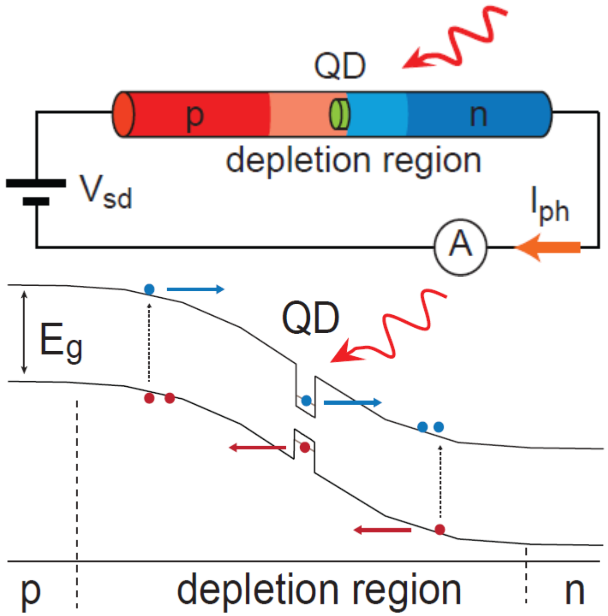
The photons are absorbed in the intrinsic region.

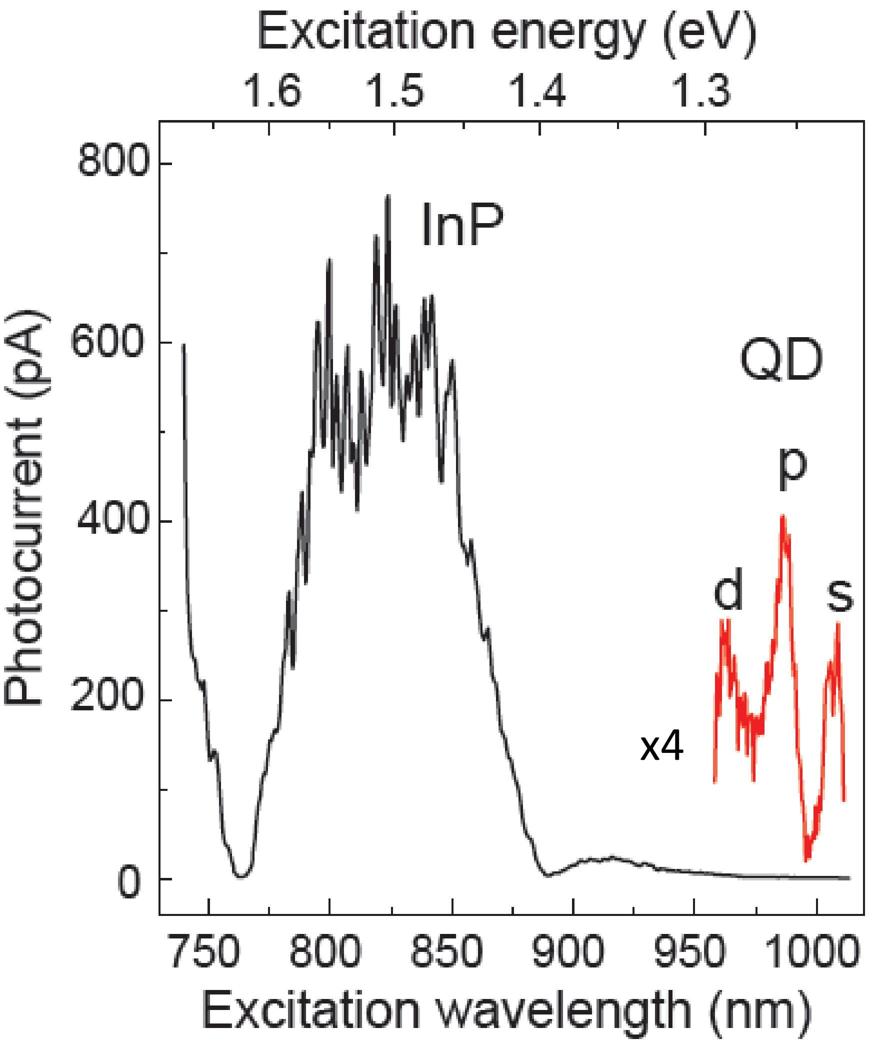
The generated electrons are driven towards the pn junction.

Under high reverse bias, amplification (impact ionization) takes place in the pn junction.

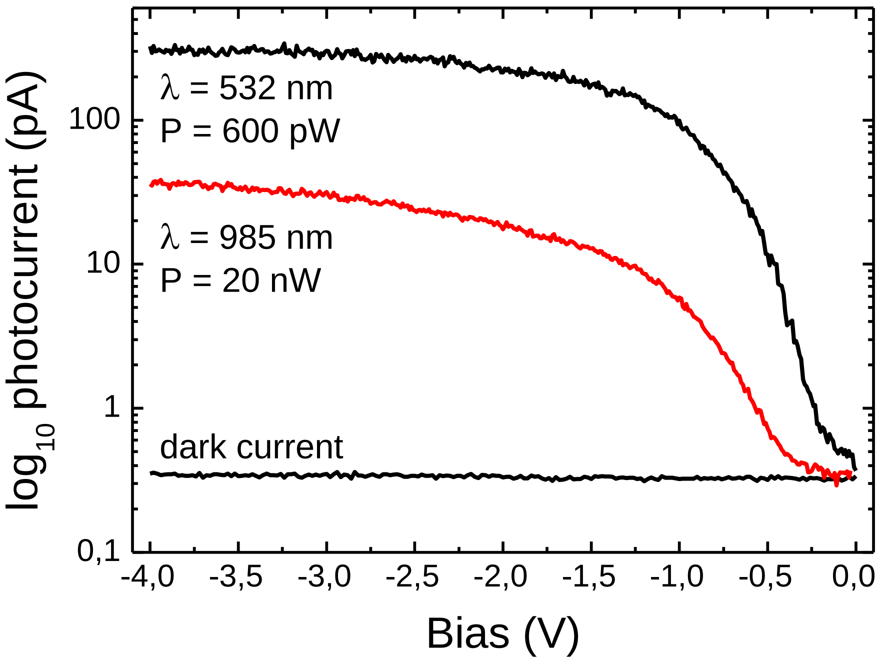
Quantum dot in a nanowire APD

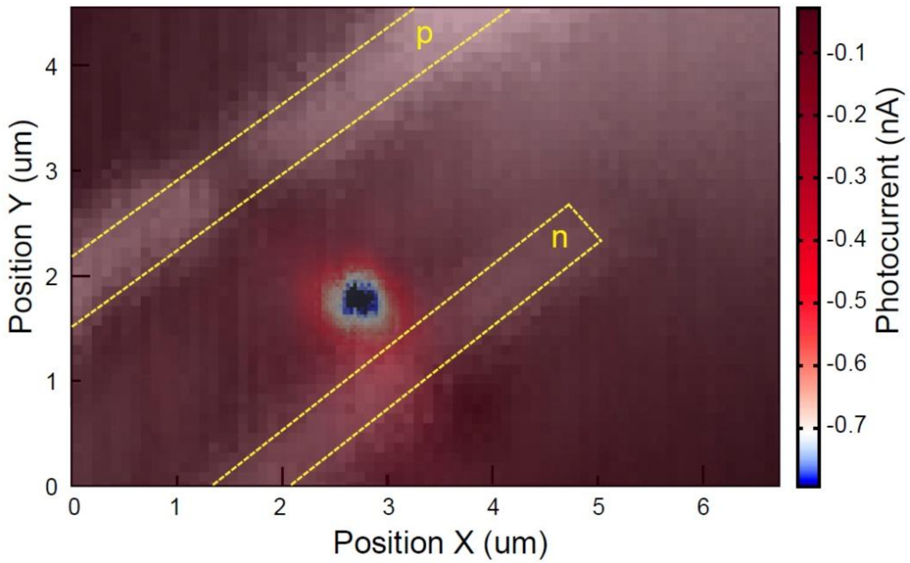






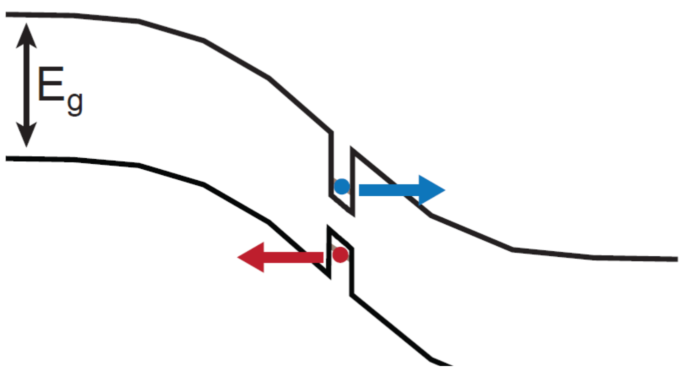
Resonant photodetection in the QD





- Resonant excitation in the QD p-shell
- Multiplication in the nanowire

Separated absorption and multiplication regions
Giving a gain of 37200



Signal above noise level with only **2 photon absorbed.**
Single photon detection with a single nanowire APD is within reach.

Nature Communications 1266, **3** (2012) **Nature Photonics** 455, **6** (2012)

Crucial parameters for detectors

Detection efficiency

Time resolution

Dark noise

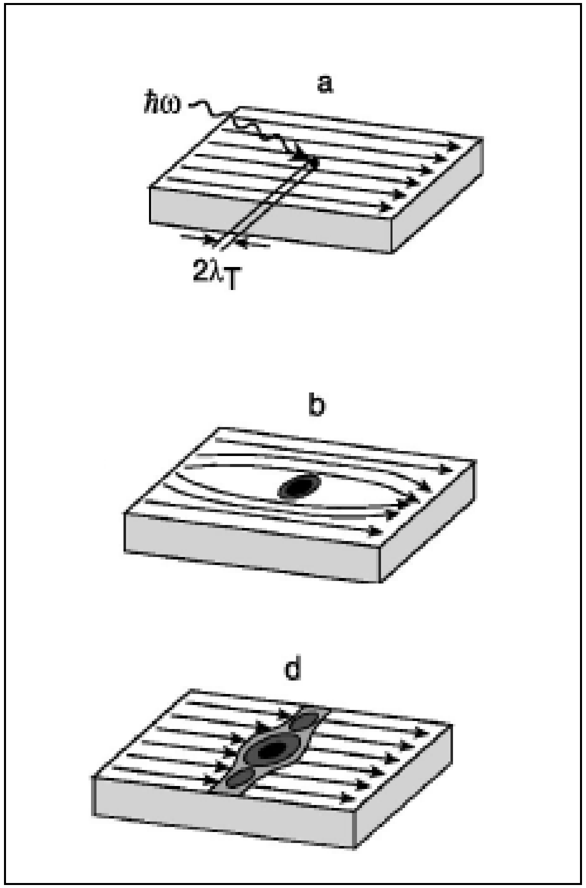
After pulsing

Photon number resolution

Superconducting single photon detectors

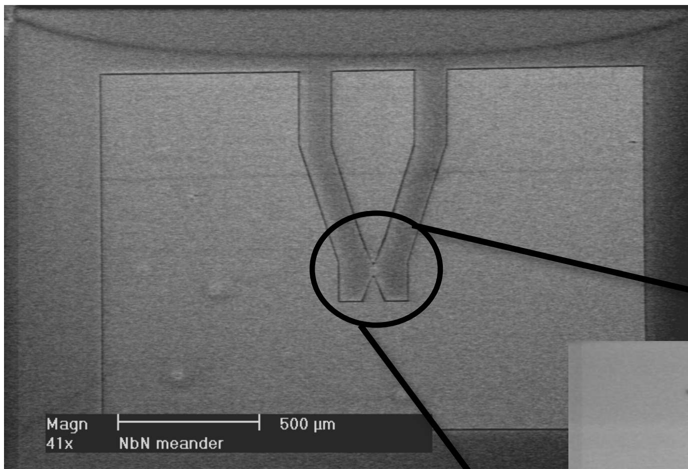
Invented by **G. Goltsman** (Moscow State Pedagogical University) and **R. Sobolweski** (Rochester University, USA)

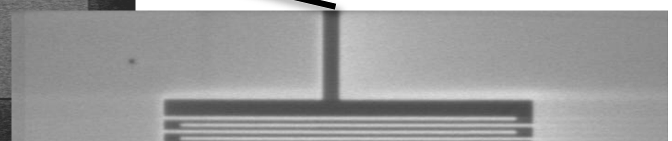
- **Detection from UV to IR**
- **High time resolution (30 ps)**
- **Short dead time (4 ns)**
- **No afterpulsing**
- **Very low dark counts**
- **Easy implementation**
- **Photon number resolution possible**
- **Could detect single plasmons on chip**

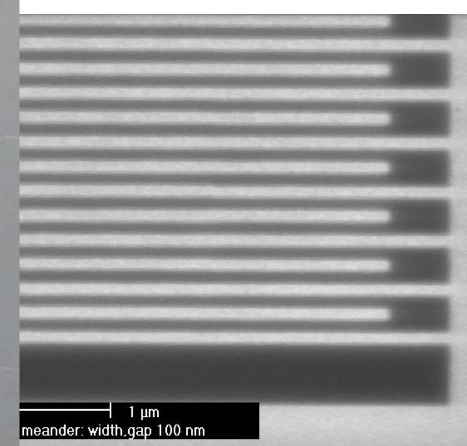


Superconducting detectors

- Start from thin film (4-6 nm thick)
  - NbN on sapphire
  - NbTiN on silicon
- Nb/AuPd contacts by lift-off technique
- Define meander by e-beam and etching
- Pigtail to an optical fiber



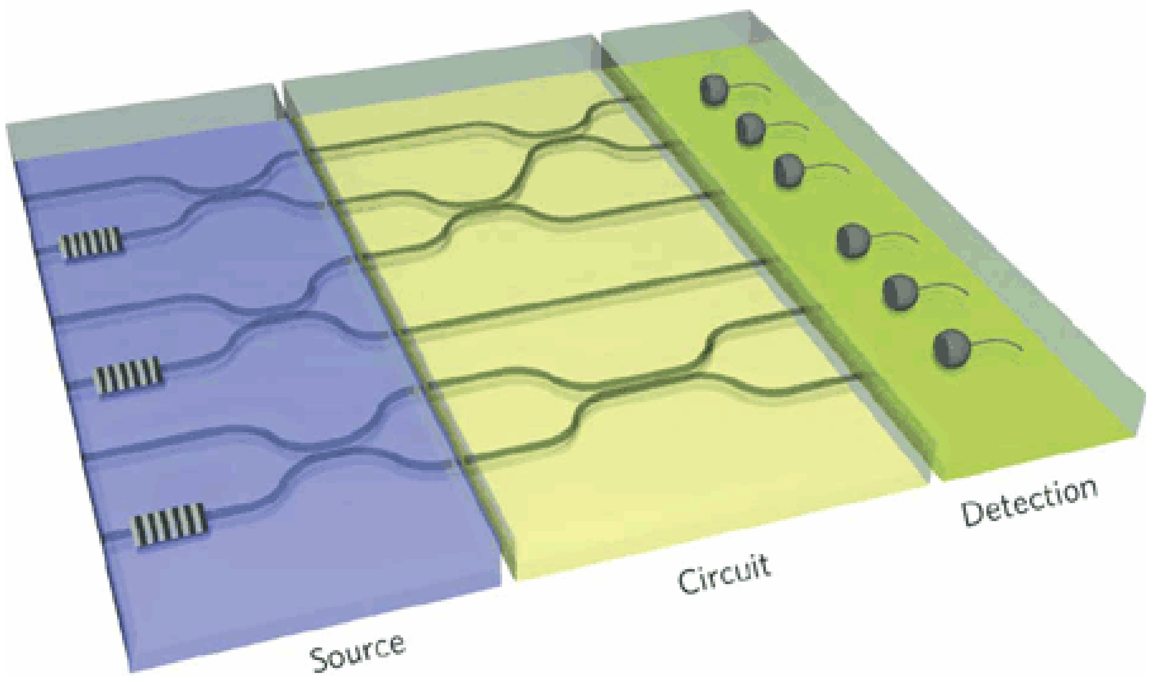




Quantum optics on a chip

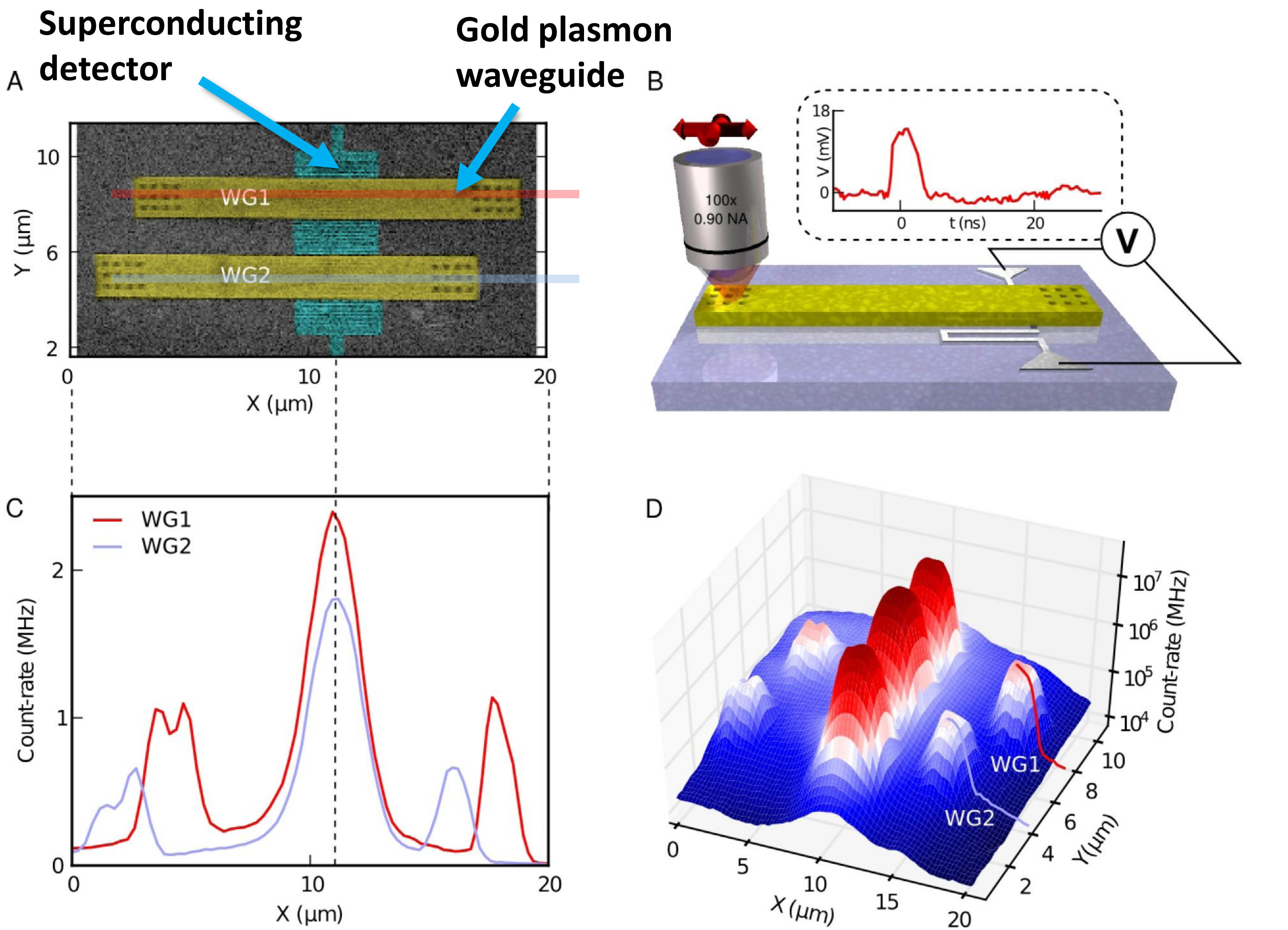
We can now bring together our nanoscale sources of photons, our waveguides and our detectors to make quantum circuits, all on a chip.

Manipulating light at the nanoscale

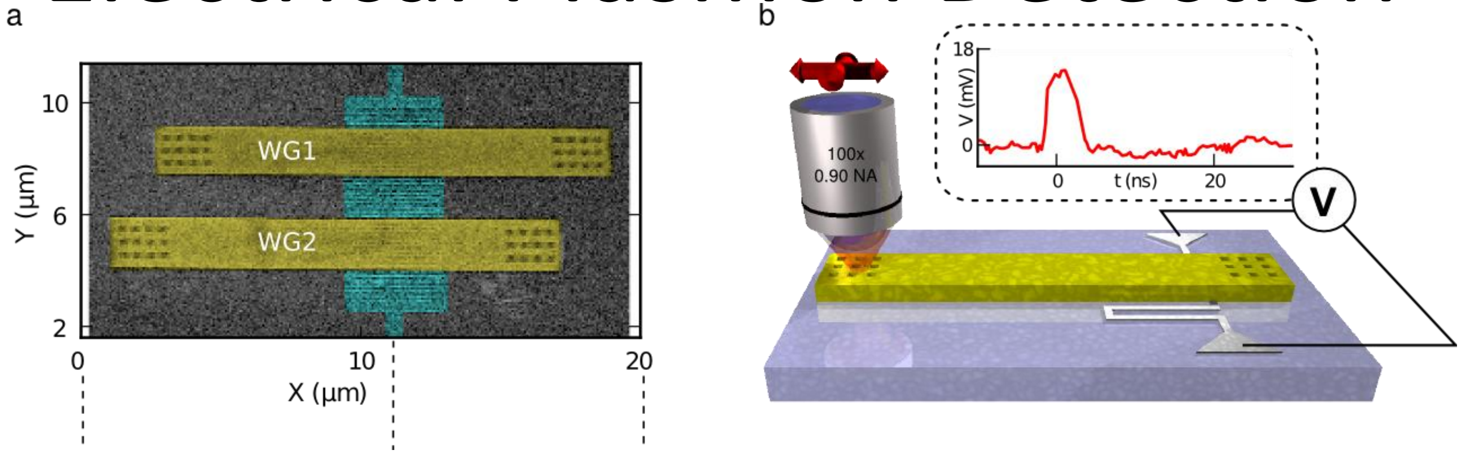


Towards quantum optics experiments all on a chip.
Requires integration of quantum sources, waveguides and detectors.

Superconducting plasmon detector

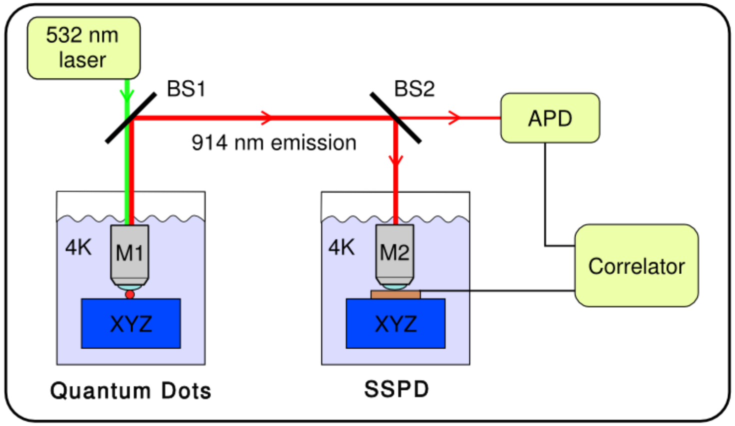


Electrical Plasmon Detection



Electrical ***Single*** Plasmon Detection

a



Quantum dot from Glenn Solomon, NIST

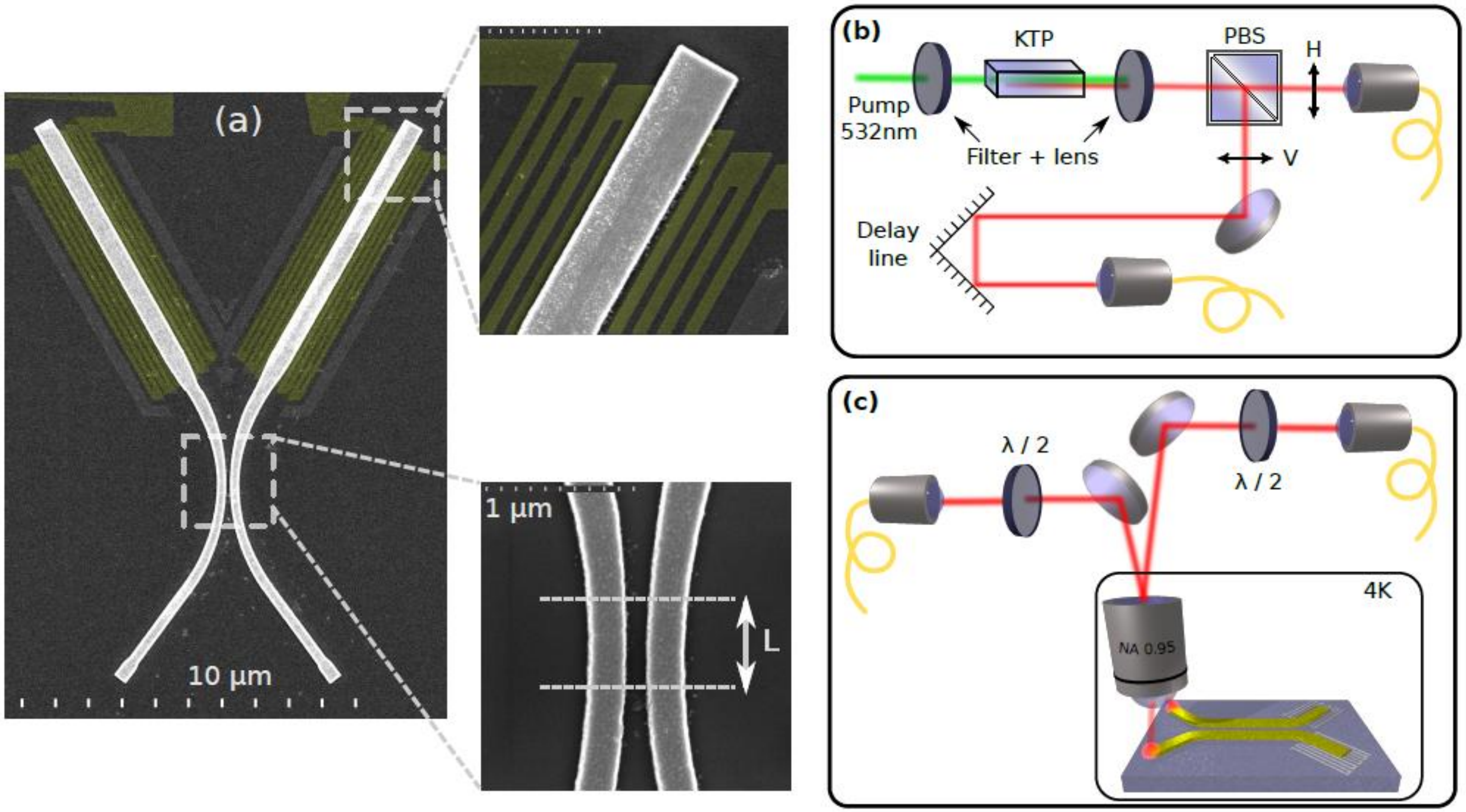
What is really Quantum here?

Quantum Interference

- Indistinguishable photons impinging on a beam splitter
  - → Bunching (or lack of coincidences)

|ψ>

Hong-Ou-Mandel plasmonic interferometer



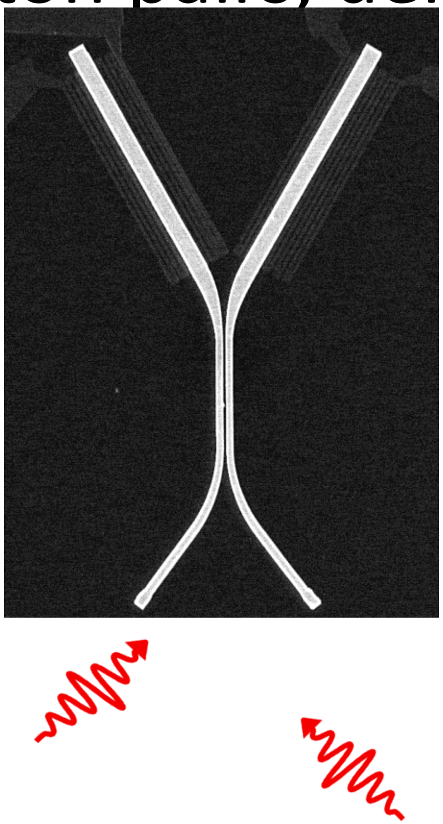
Plasmonic waveguides made of gold nanowires.

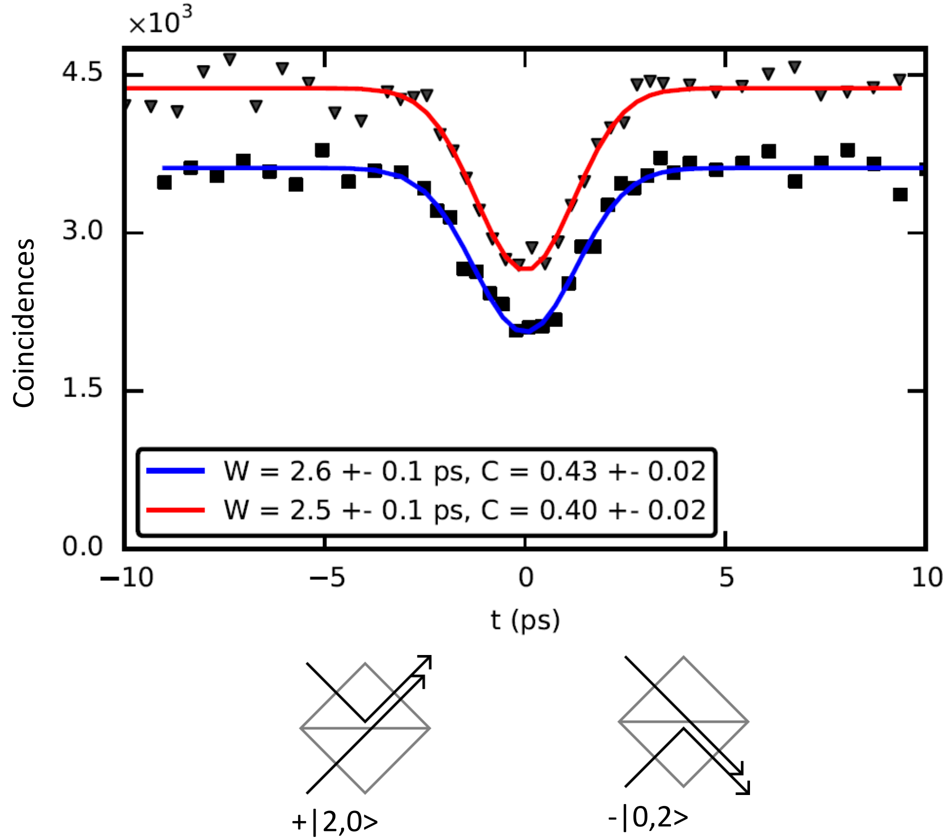
Single photon (plasmon) detectors made of NbN nanowires.

-> A complete Hanbury-Brown Twiss interferometer in 10 x 15 microns.

Correlation Measurements

Photon pairs, delay 1



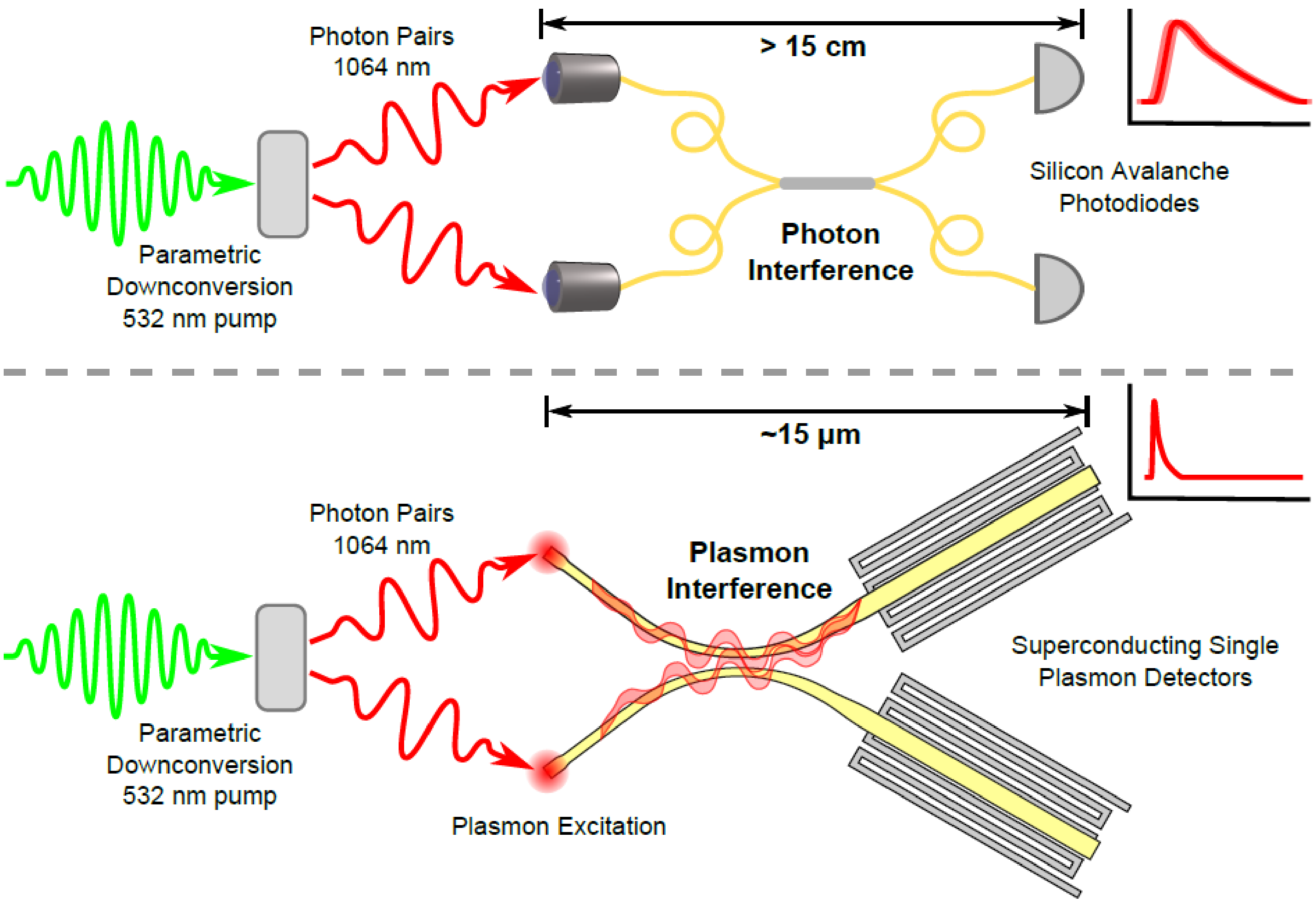


The dip in correlations demonstrates the bunching of indistinguishable plasmons.
-> Hong-Ou-Mandel effect demonstrated for plasmons.

Nature Nanotechnology 719, **8** (2013)

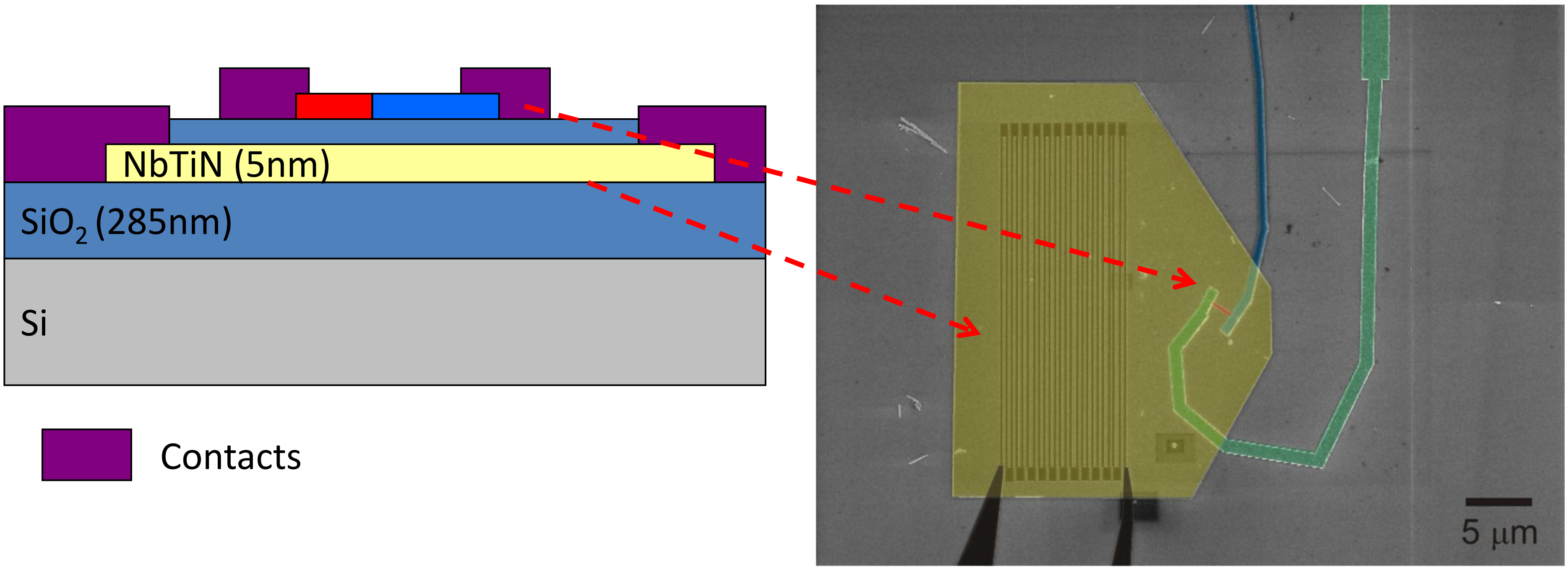
Quantum optics beyond the diffraction limit

Hong-Ou-Mandel interference is a coherent quantum effect based on quantum indistinguishability.



On chip single photon emission and detection

To maximize the detection efficiency we are fabricating an SSPD in the vicinity of a Quantum LED nanowire

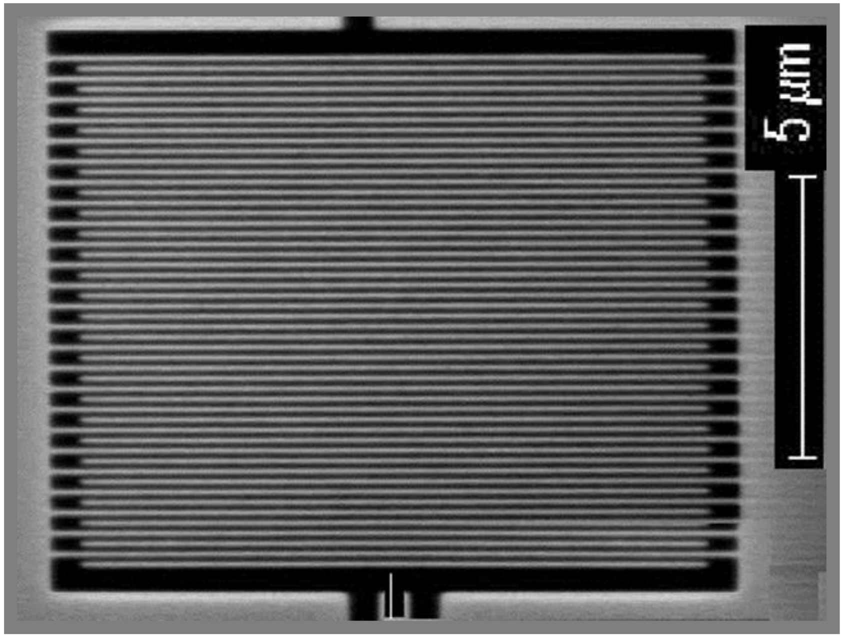


SINGLE QUANTUM
Excellence in photon detection

Our Mission

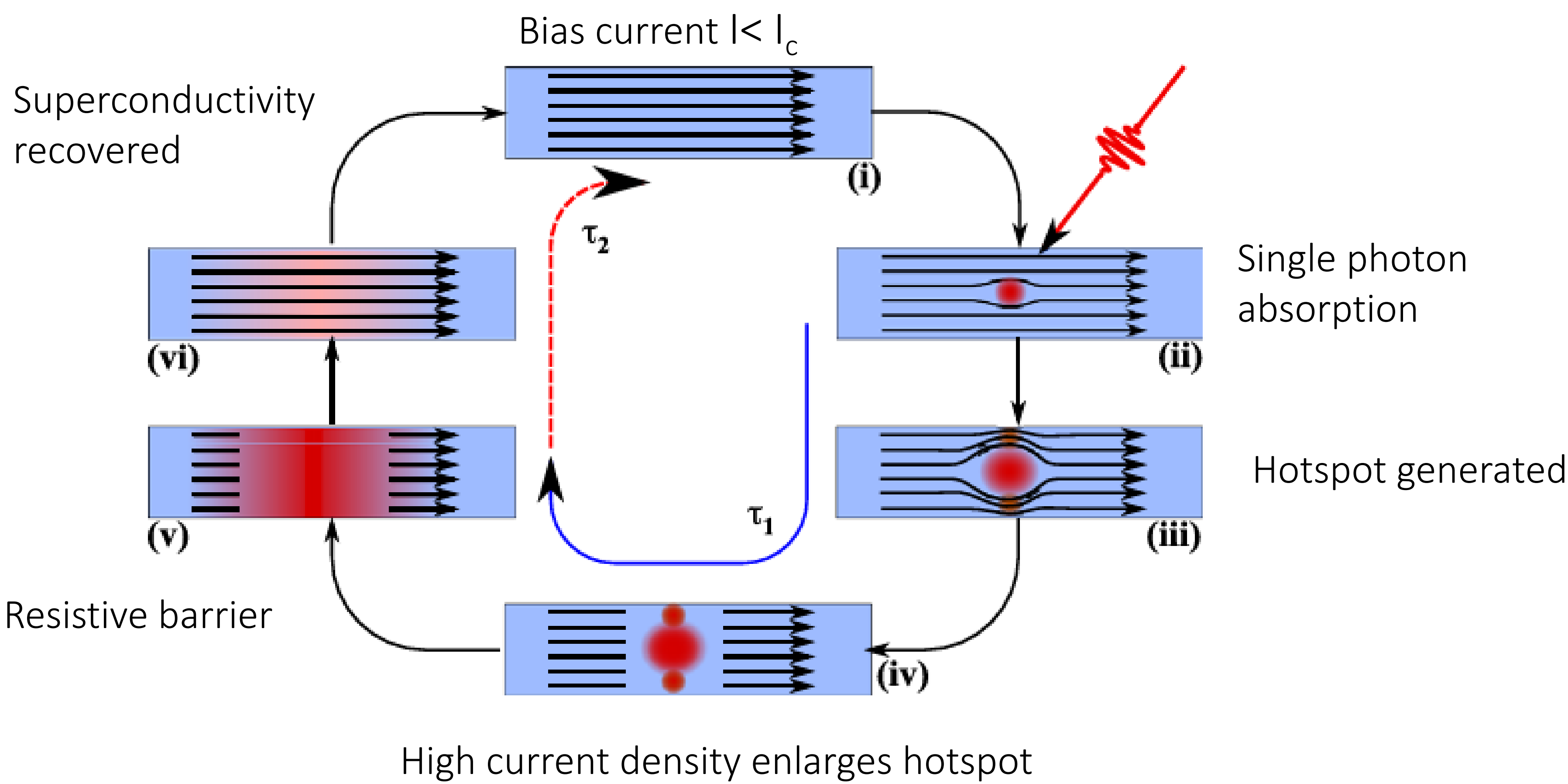
To develop the best photon detectors for scientific research and industrial applications

Superconducting Nanowire

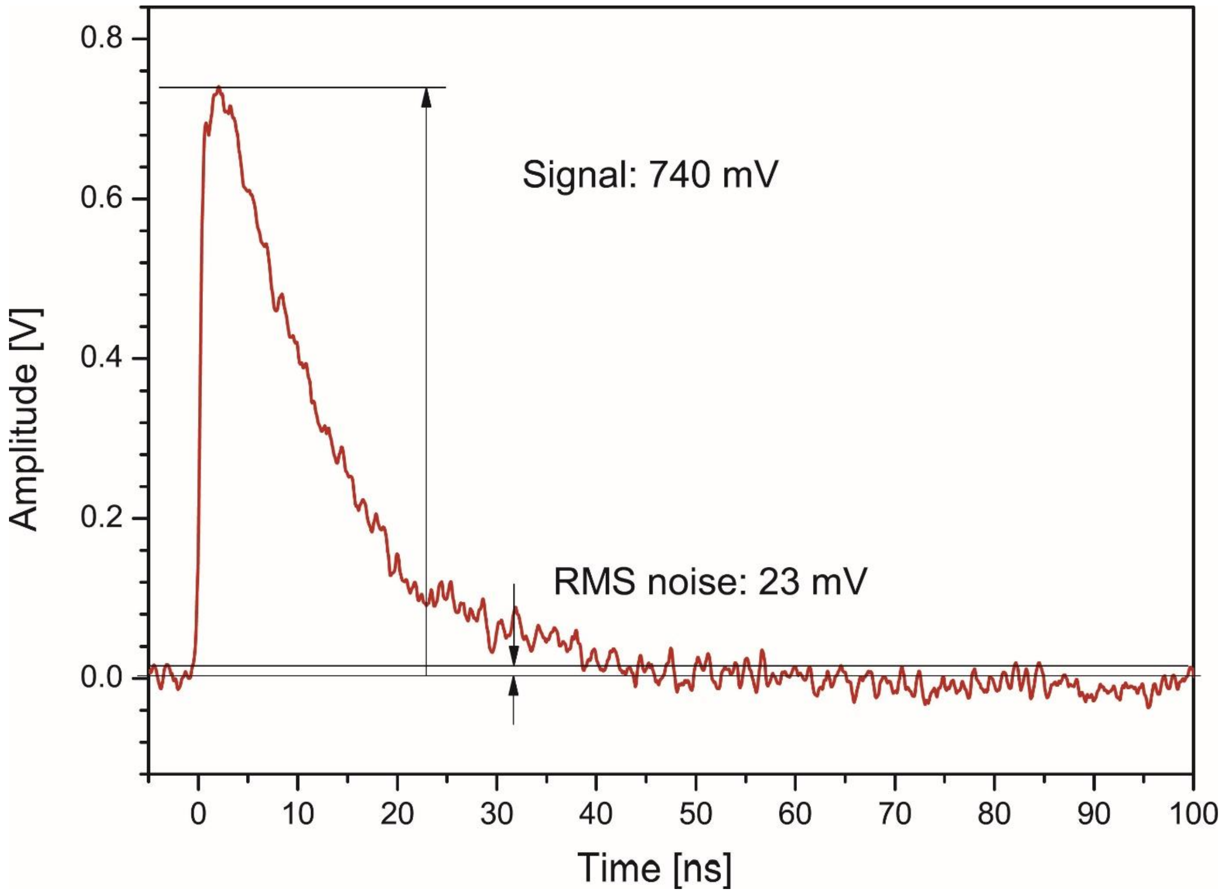


- Geometry: meander nanowire
- Critical current: I_c
- Absorbtion of photon: transition to normal state

Single Photon Detection



Output Voltage Pulse



SINGLE QUANTUM
Excellence in photon detection

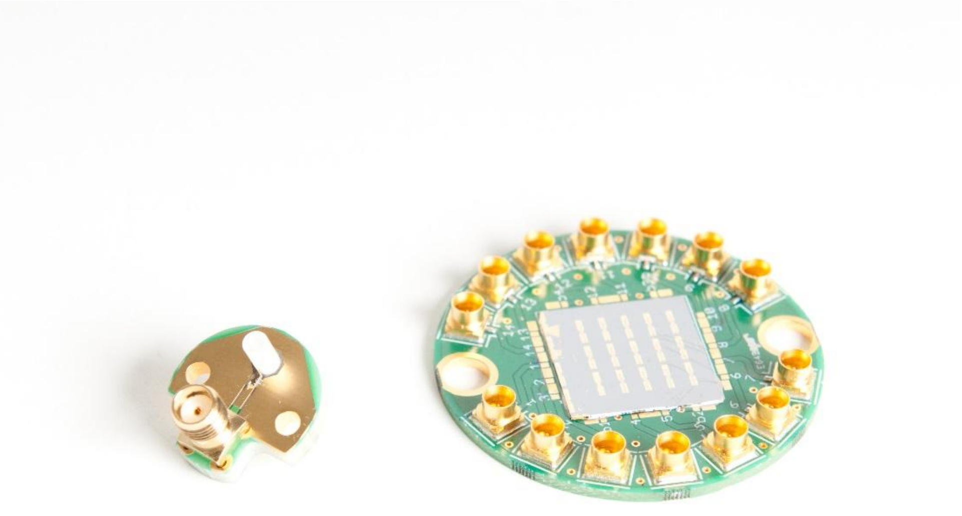
Closed-cycle single photon detection system

Eos X10 CS

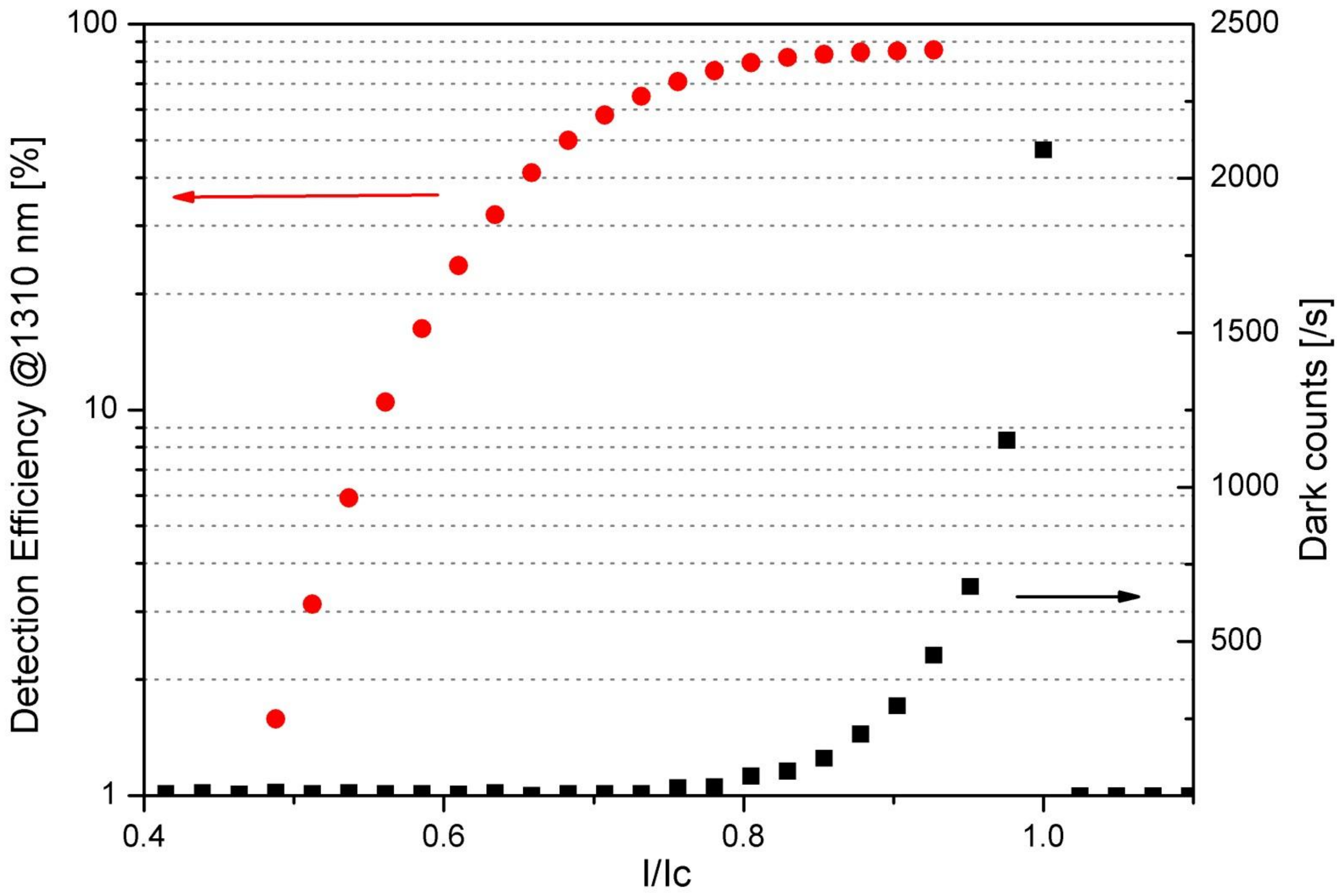
- 2 to 4 detection channels
- Closed-cycle cryostat
- Water- or air- cool compressor
- Dedicated software

Unique Features of our SNSPDs

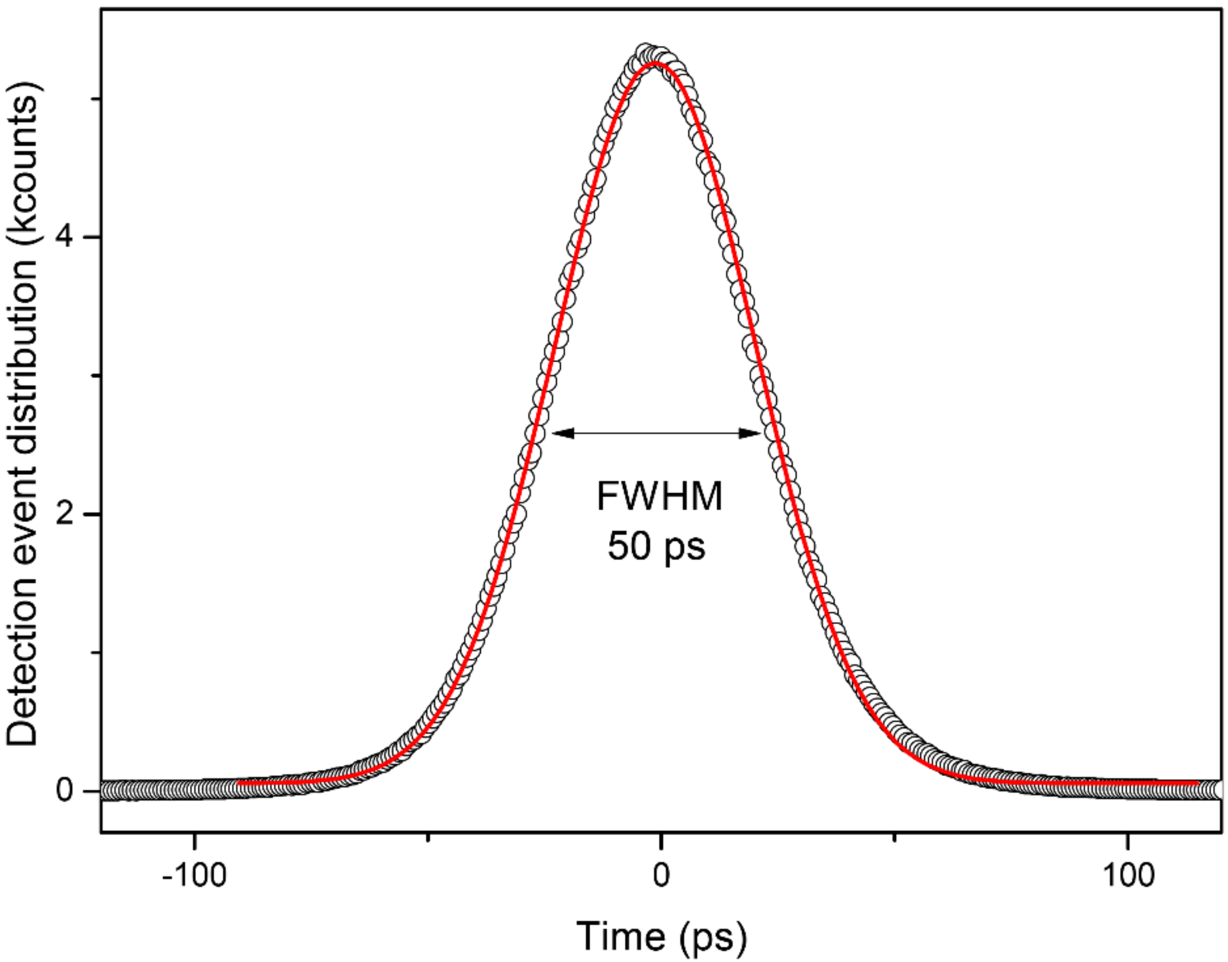
- Sensitive from UV to MIR
- Highest efficiency for NIR
- Short dead time
- High time resolution
- Low noise



Detection Efficiency vs Dark Counts



Timing Jitter



Closed-cycle cryogenic cooling

- No liquid helium consumption
- Easy to use, plug and play
- Continuous operation > 10,000 hours
- Base temperature: 2.5 K

Fiber-Coupled Detector Chips

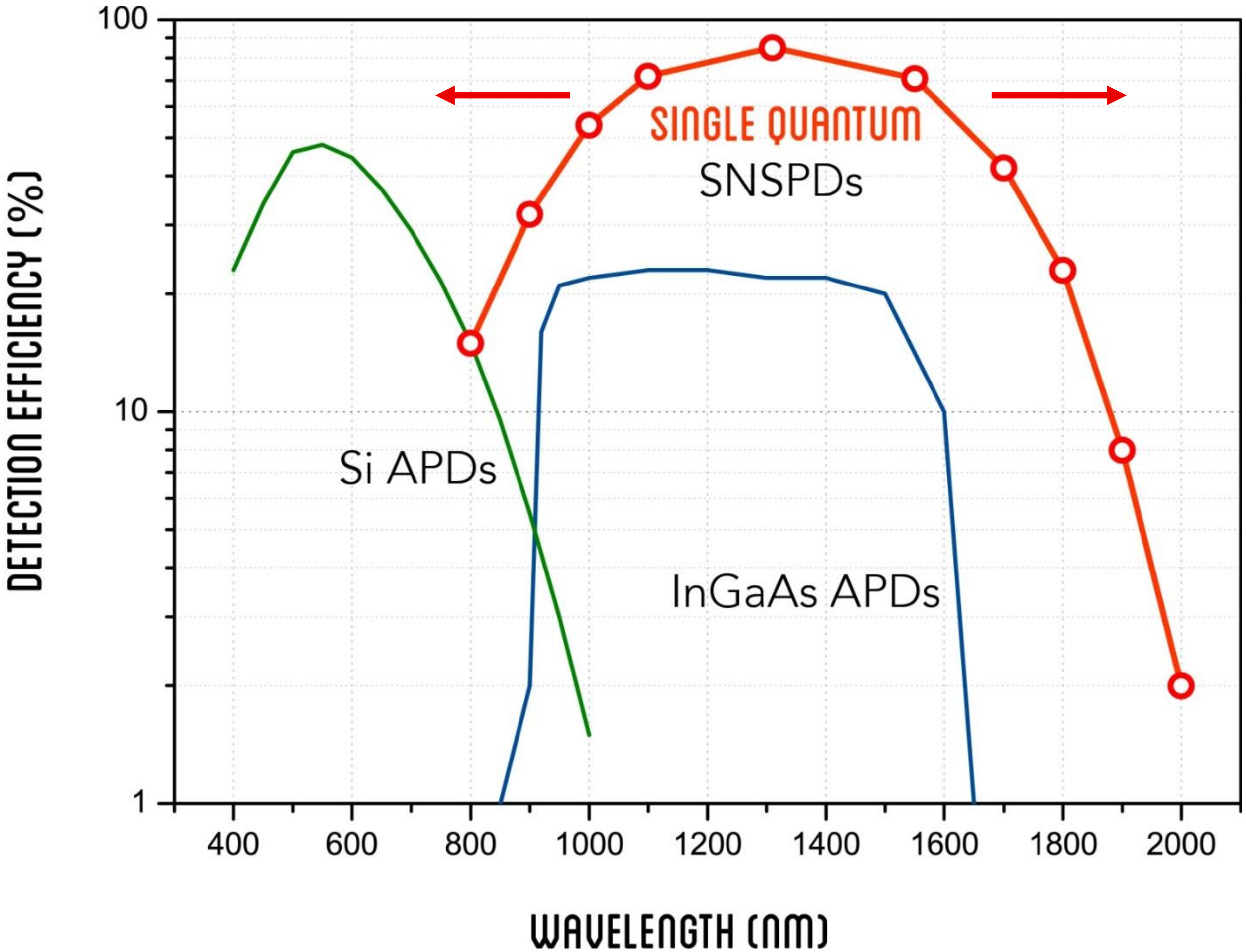
Robust, efficient, compact

Complete solution

Electronic driver Argos 410

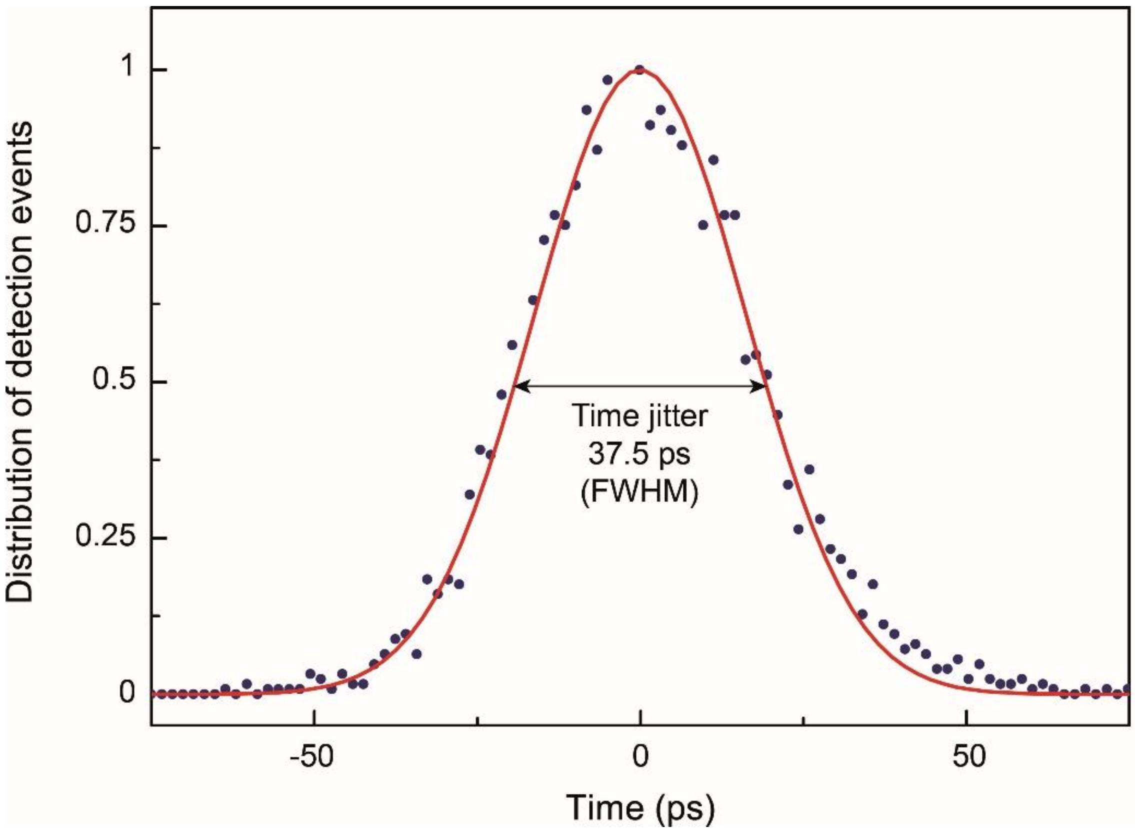
Single Quantum driver software

SNSPD vs. APDs



High time resolution

Cryogenic first-stage amplifier: timing jitter ≤ 40 ps



Coming soon

- More detection channels
- Ultra-low dark counts < 100 Hz
- Multimode fiber coupling
- Extended wavelength sensitivity
- Automatic input polarization control

Application 1:

near- and mid-infrared spectroscopy

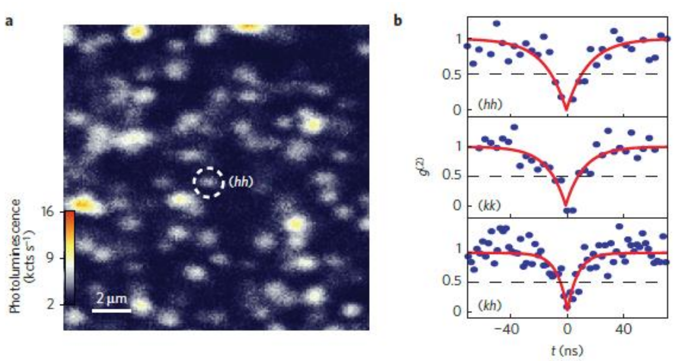
LETTERS

PUBLISHED ONLINE: 1 DECEMBER 2014 | DOI: 10.1038/NMAT4144

nature materials

Isolated electron spins in silicon carbide with millisecond coherence times

David J. Christle[1,2], Abram L. Falk[1], Paolo Andrich[1,2], Paul V. Klimov[1,2], Jawad Ul Hassan[3], Nguyen T. Son[3], Erik Janzén[3], Takeshi Ohshima[4] and David D. Awschalom[1,2]*



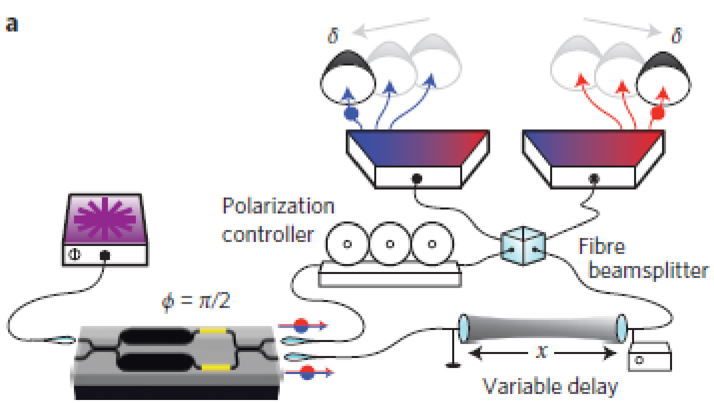
Detection of the infrared luminescence of single defects in silicon-carbide to demonstrate their quantum behavior.

Application 2:
quantum computing

LETTERS
PUBLISHED ONLINE: 15 DECEMBER 2013 | DOI: 10.1038/NPHOTON.2013.339
nature photonics

On-chip quantum interference between silicon photon-pair sources

J. W. Silverstone[1], D. Bonneau[1], K. Ohira[2], N. Suzuki[2], H. Yoshida[2], N. Iizuka[2], M. Ezaki[2], C. M. Natarajan[3], M. G. Tanner[4], R. H. Hadfield[4], V. Zwiller[5], G. D. Marshall[1], J. G. Rarity[1], J. L. O'Brien[1] and M. G. Thompson[1]*



Measuring the interference of single photons propagating in complex integrated circuits as the first step towards a photonic quantum computer.

Application 3:
laser remote sensing

Kilometer-range, high resolution depth imaging via 1560 nm wavelength single-photon detection
Aongus McCarthy et al.
Optics Express, Vol. 21, Issue 7, pp. 8904-8915 (2013)

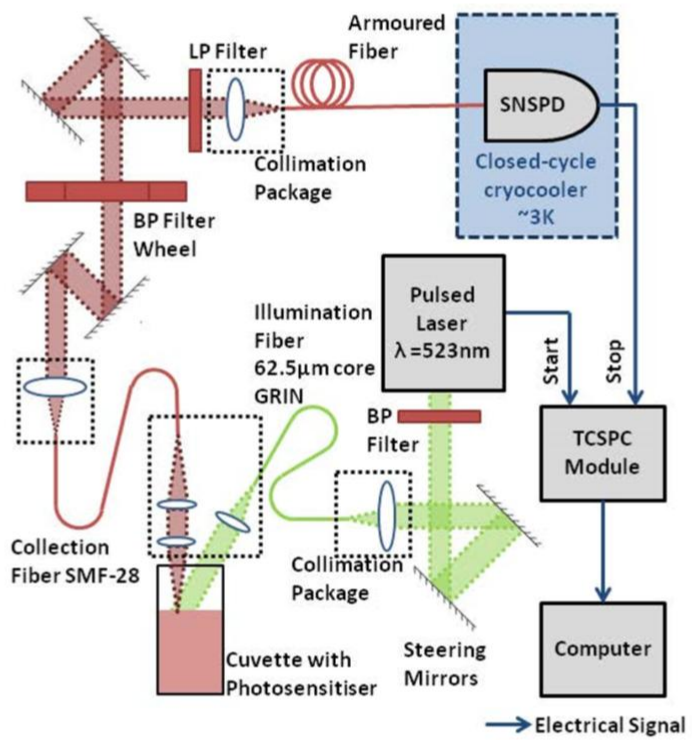
High-sensitivity detection enabling remote laser communication and sensing at infrared eye-safe wavelengths, applied in deep space communications, Earth observation, and sensing.

Application 4:
biomedical imaging

Singlet oxygen luminescence detection with a fiber-coupled superconducting nanowire single-photon detector

Nathan R. Gemmell et al.

Optics Express, Vol. 21, Issue 4, pp. 5005-5013 (2013)

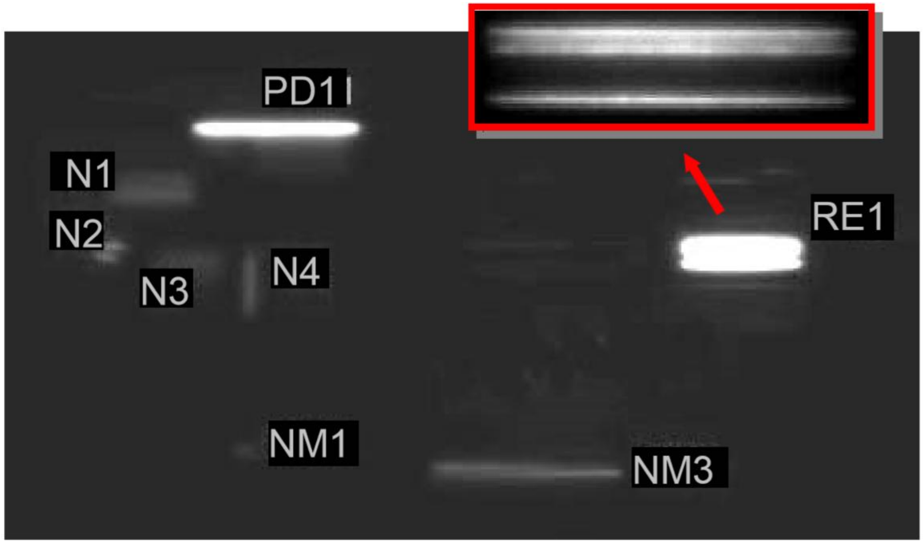


Detection of singlet oxygen luminescence for minimally-invasive endoscopic and intraoperative treatments.

Application 5:
failure analysis in CMOS technology

CMOS circuit analysis with luminescence measurements and simulations

F. Stellari et al.
IBM Watson Research Center & DEIB
28th European Solid-State Device Research Conference
Florence, Italy, 24-26 Sep. 2002



Optical inspection as a powerful and versatile method for localizing and identifying defects and failures in integrated circuits.

12 systems installed worldwide

- **Now**
  12 detection systems sold worldwide
  total revenue > 1M€
  9 employees

Single Quantum

- 2007
  Zwiller group at TU Delft
  started research on SNSPDs

- 2011
  Dutch valorization grant
  for a value of 25.000€

- 2012
  Single Quantum incorporated

Scientific Excellence for Most Demanding Applicaions

- ✓ Upgrade-able systems
- ✓ Satisfied customers worldwide
- ✓ Continuous innovation
- ✓ Dedicated customer service

www.singlequantum.com

Nano-optics offers opportunities for:

Generating, manipulating and detecting light at the single photon level.
Both fundamental physics and technological applications are emerging

Reinier Heeres, Sander Dorenbos, Iman Zadeh: Quantum detectors
Michael Reimer, Gabriele Bulgarini, Maaike Bavinck, Barbara Witek: Nanowire QD
Marijn Versteegh, Klaus Jons, Andreas Fognini, Lucas Schweickert: Hybrid QD