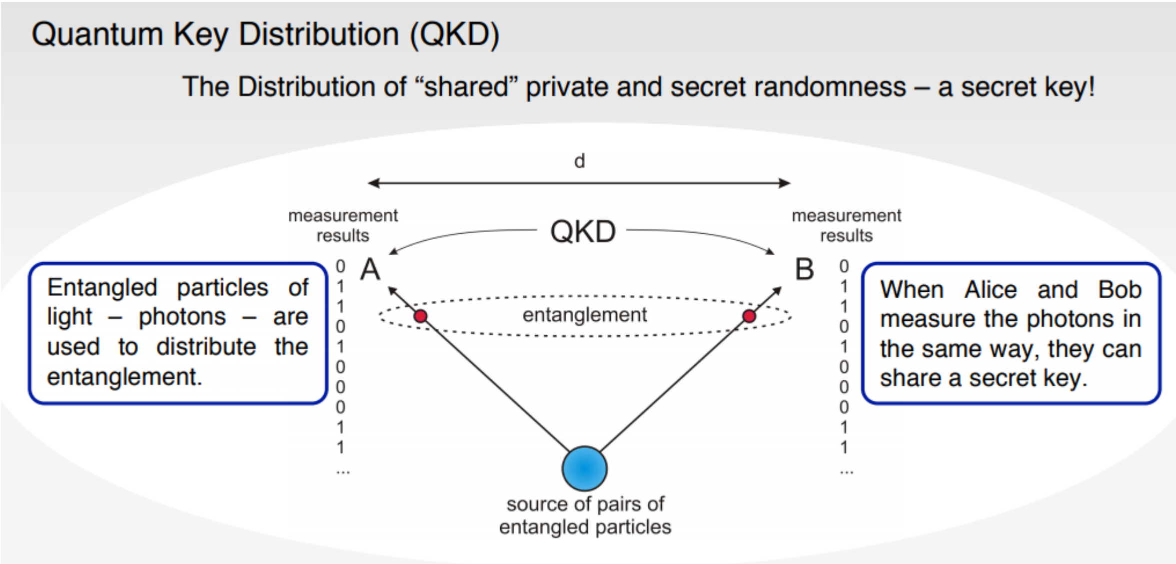
Lecture 6 – 26/03/2025

Quantum dots used as single photon emitters (SPEs)

- **Role of QD electronic structure for entangled photon sources**
- **Second-order correlation function ($g^{(2)}(\tau)$)**

Entangled photon sources for quantum communication



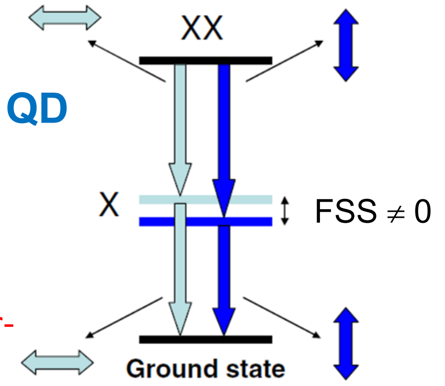
http://quantumrepeaters.eu/quantumrepeaters.eu/index.php/qcomm/

Transmitted data are encrypted and decrypted using an encryption algorithm and a secret key, which has been generated by quantum means, e.g., through the generation of entangled photons

Single QD engineered to have no fine structure splitting (FSS), i.e., same emission energy for polarization channels 1 & 2
⇒ The polarization of each photon cannot be determined by energy measurements (absence of "which-path" information)

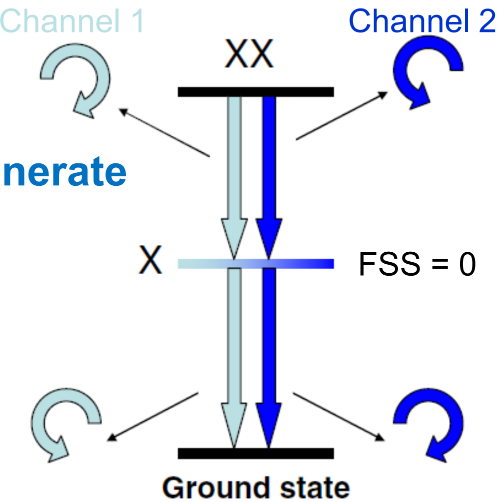
Quantum entanglement: *physical mechanism such that the quantum state of each particle of a group cannot be described independently of the state of the others*

Typical QD



Here, photon pairs are super-positions of cross-circularly polarized pairs, and are entangled

Degenerate QD

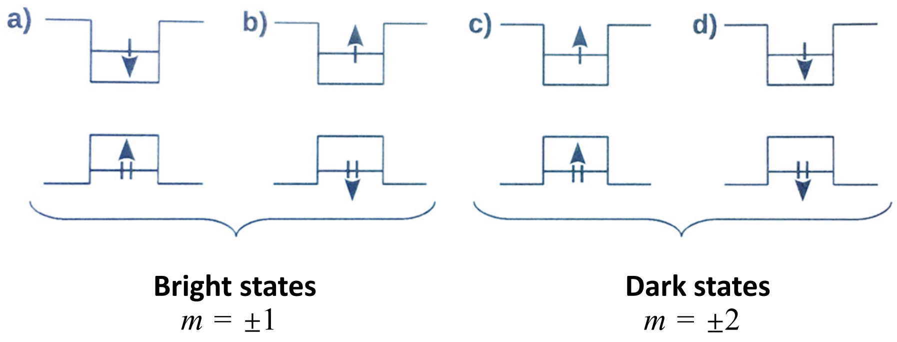


[1]R. J. Young *et al.*, N. J. Phys. **8**, 29 (2006). (> 240 citations)

Electronic structure of semiconductor QDs

In a QD, only the heavy hole band is considered with total angular momentum $m = \pm 3/2$ (i.e., light holes are out of the game)

Thus, an electron-hole pair is the combination of a hole ($\pm$3/2) and an electron ($\pm$1/2), with 4 possible states:



Exciton total angular momentum

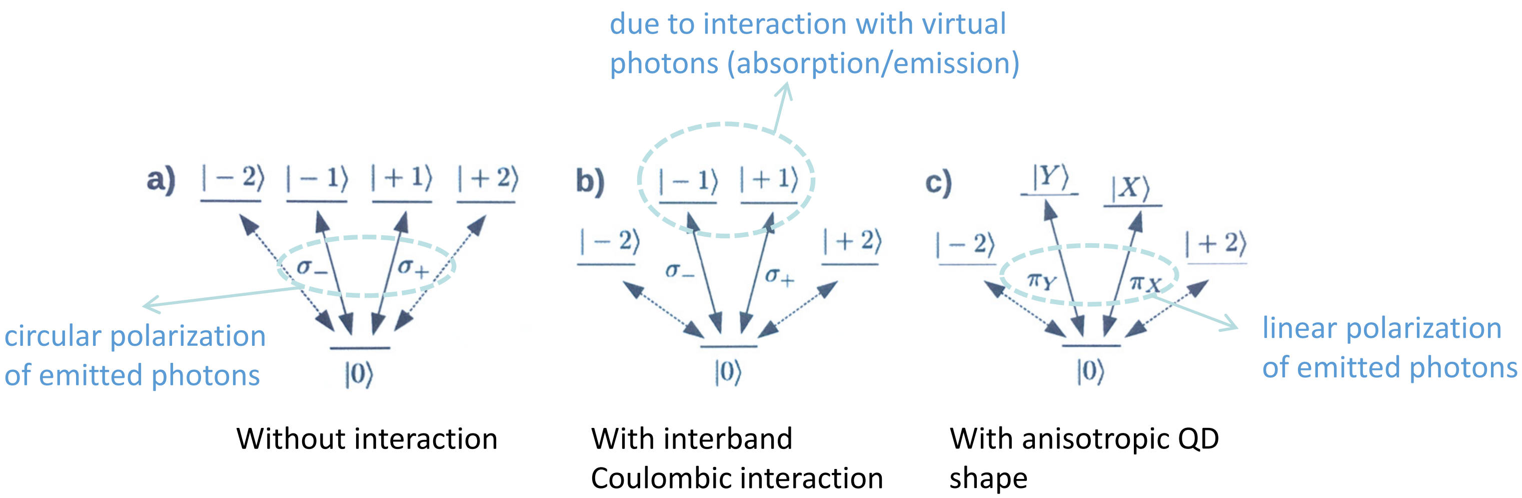
$$|+2\rangle = \left|+\tfrac{3}{2};+\tfrac{1}{2}\right\rangle \qquad m = +2$$
$$|+1\rangle = \left|+\tfrac{3}{2};-\tfrac{1}{2}\right\rangle \qquad m = +1$$
$$|-1\rangle = \left|-\tfrac{3}{2};+\tfrac{1}{2}\right\rangle \qquad m = -1$$
$$|-2\rangle = \left|-\tfrac{3}{2};-\tfrac{1}{2}\right\rangle \qquad m = -2$$

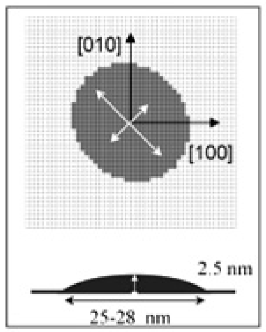
Total angular momentum conservation
($\Delta s = 0$, $\Delta m = \pm 1$ for the photons)

Due to the law of momentum conservation, the total angular momentum of a recombining e-h pair is equal to the angular momentum of the photon *with the additional condition of opposite spins for electrons and holes*

Electronic structure of semiconductor QDs

Electron-hole Coulomb interaction lifts the degeneracy of the 4 QD ground states:

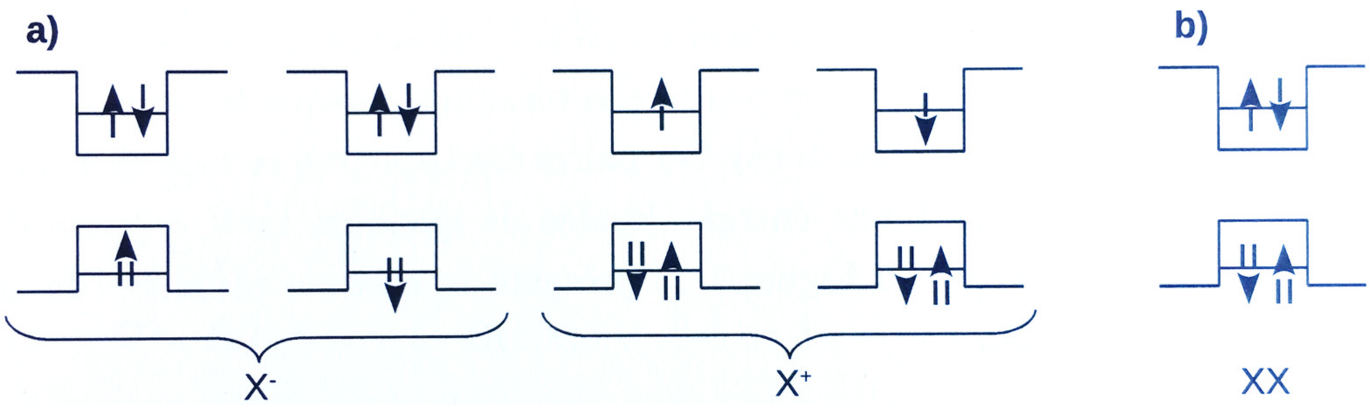




The splitting between bright states amounts to a few hundreds of μeV in InAs/GaAs QDs
⇒ This is the so-called fine-structure splitting (FSS)

Electronic structure of semiconductor QDs

Charged states and biexciton

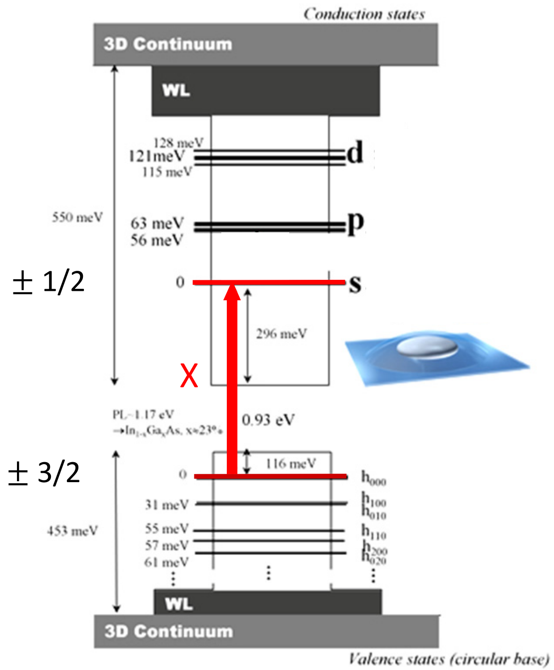


Charged excitons (also called *trions*) Biexcitons

interband coulombic interaction vanishes ⇒ fine-structure splitting (FSS) = 0, i.e., the exchange splitting at the level of a neutral exciton can be switched off by injecting an additional carrier

Physical Review B **65**, 195315 (2002). (> 880 citations)

Electronic structure of semiconductor QDs



Total angular momentum

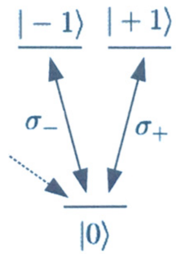
$|-2\rangle = |+\frac{3}{2};+\frac{1}{2}\rangle$ $m = +2$

$|+1\rangle = |+\frac{3}{2};-\frac{1}{2}\rangle$ $m = +1$

$|-1\rangle = |-\frac{3}{2};+\frac{1}{2}\rangle$ $m = -1$

Bright states

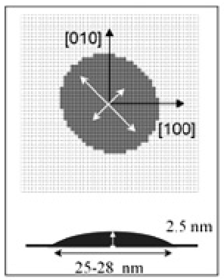
$|-2\rangle = |-\frac{3}{2};-\frac{1}{2}\rangle$ $m = -2$

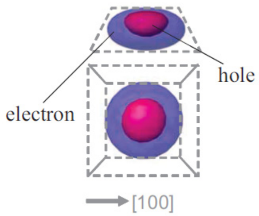


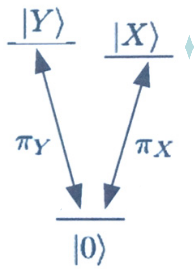
one e-h pair (exciton)

circular polarization

no e-h pair (empty dot)







Fine structure splitting

linear polarization

Fine-structure splitting (FSS) in QDs

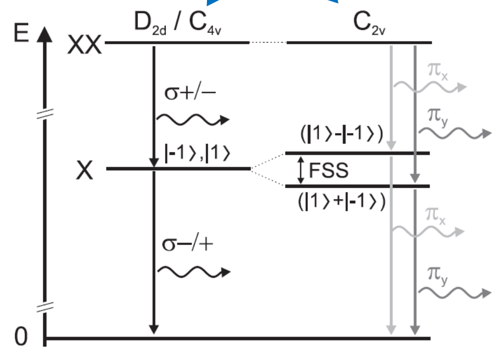
PRL 95, 257402 (2005) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2005

Size-Dependent Fine-Structure Splitting in Self-Organized InAs/GaAs Quantum Dots

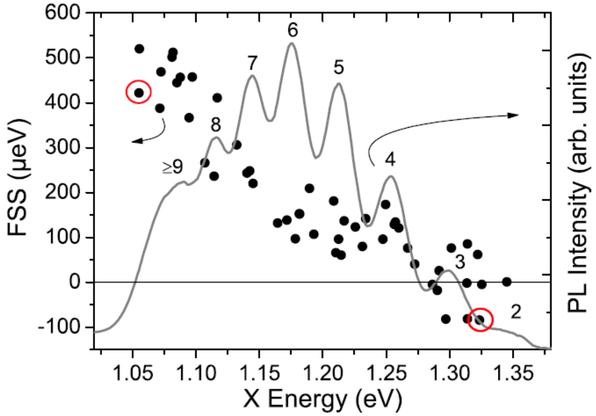
R. Seguin, A. Schliwa, S. Rodt, K. Pötschke, U. W. Pohl, and D. Bimberg
Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany

(> 270 citations)

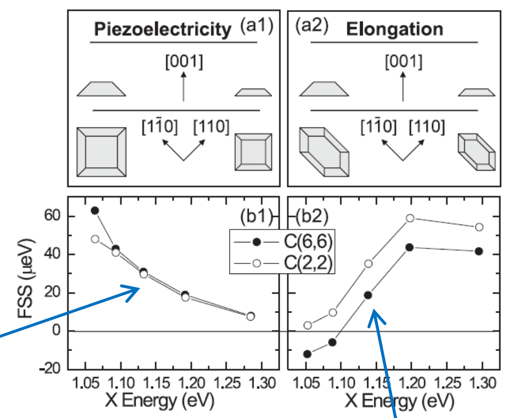
Confinement potential symmetry



QDs/matrix	FSS [μeV]	Setup
InAs/GaAs	110–180	μPL
InAs/GaAs	≤140	μPL
InAs/GaAs	40	FWM
InGaAs/GaAs	30–150	μPL
InGaAs/GaAs	10–42	Transmission
InGaAs/GaAs	8–36	Pump & probe
InGaAs/GaAs	6–96	FWM
InAs/AlGaAs	500–1000	μPL



What is governing the FSS?



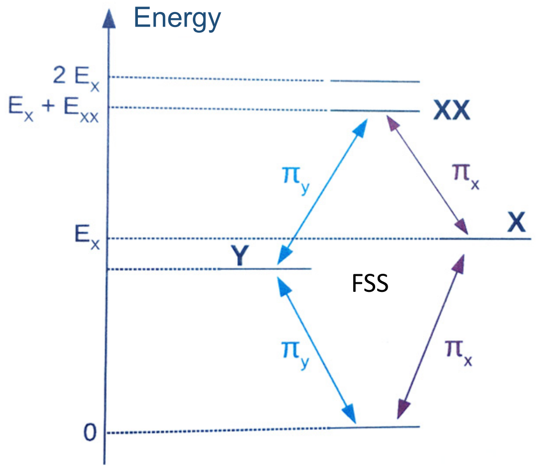
With piezoelectricity

Without piezoelectricity

- Qualitative agreement when including piezoelectric effects
- Elongation ruled out

Electronic structure of semiconductor QDs

Measuring the fine structure splitting



X $|+1\rangle = |+\frac{3}{2}; -\frac{1}{2}\rangle$

Y $|-1\rangle = |-\frac{3}{2}; +\frac{1}{2}\rangle$

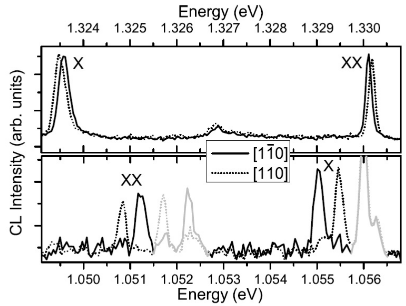
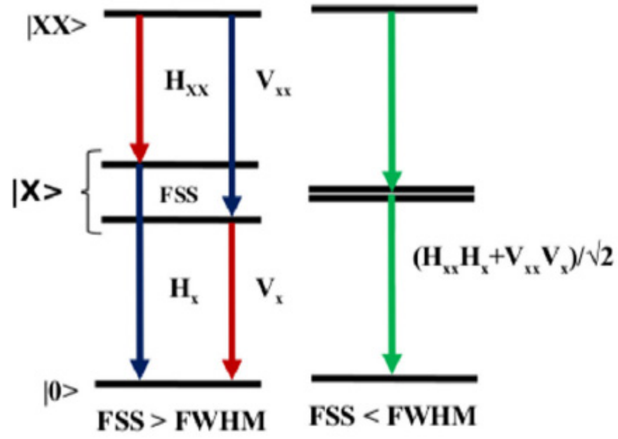
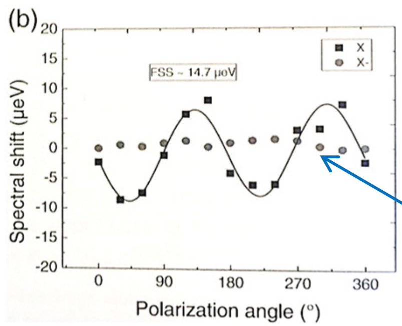


FIG. 2: Polarized spectra for two different QDs emitting at high and low energies are shown. The FSS is −80 and 420 μeV, respectively. Gray lines in the lower panel originate from charged excitonic complexes not considered in this Letter.

Phys. Rev. Lett. **95**, 257402 (2005)

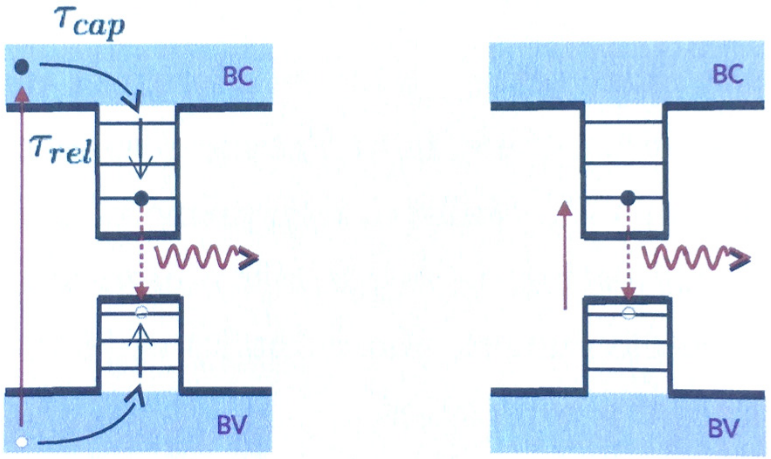




The FSS can only be measured if the emission linewidth of the QD is smaller than the energy separation

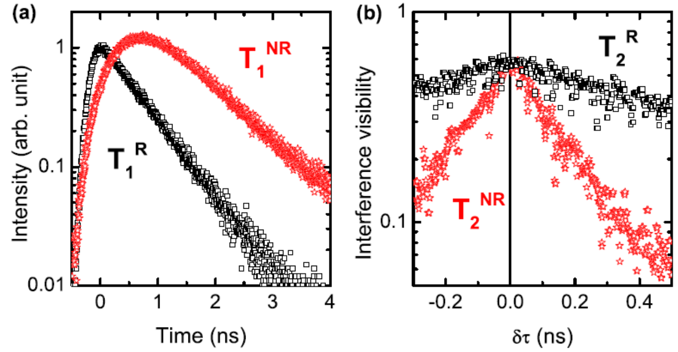
Quenching of the exchange splitting for the trion

Resonant versus nonresonant excitation



Nonresonant excitation (NR):
laser energy > E_g barrier
$\tau_{cap} \approx \tau_{rel} \approx$ 1-5 ps
Few electron-hole pairs created

Resonant excitation (R):
laser energy ≈ X energy
One electron-hole pair created
(Pauli blocking)



Radiative lifetime

$T_1^{NR} = 850\ ps$
$T_1^{R} = 670\ ps$

$T_2^{NR} = 200\ ps$
$T_2^{R} = 950\ ps$

Dephasing time

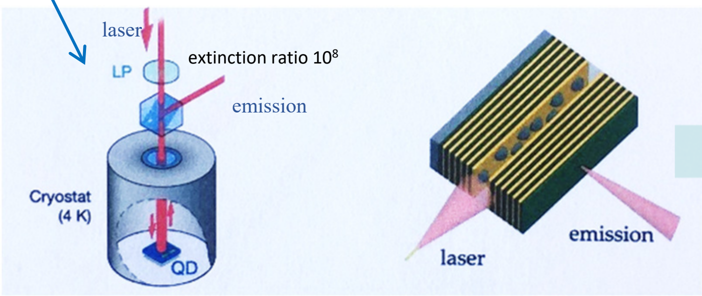
Capture and relaxation processes induce photon decoherence ($T_2 \downarrow$)

Phys. Rev. B **90**, 041303(R) (2014)

In the limit of high quality InAs/GaAs QD, at low T(K), the homogeneous linewidth is given by the relationship $\Gamma = \frac{2\hbar}{T_2^R}$ with T_2^R the dephasing time of radiative origin (= 630 ps at 7 K (slide 13, Lecture 5), i.e., Γ ~2.1 μeV)

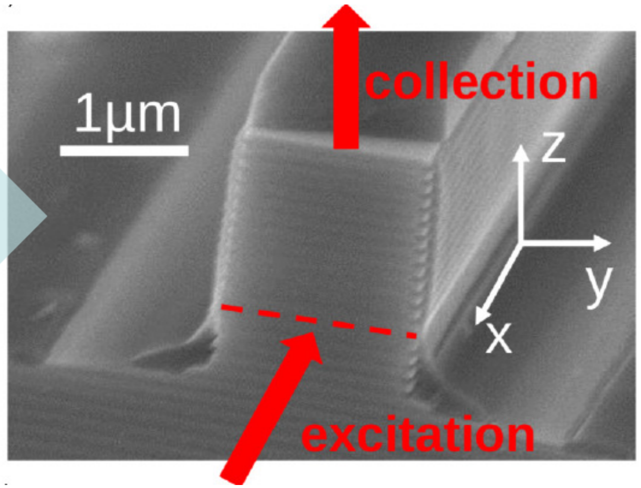
Resonant excitation: experimental setup

Use of two crossed polarizers to separate the laser from the QD emission



Polarization selection — Nature **525**, 222 (2015)

Spatial selection — Phys. Rev. Lett. **114**, 067401 (2015)



PHYSICAL REVIEW B **90**, 041303(R) (2014)

Number of photons per laser pulse: $N = \lambda P / hc\,\nu_{rep} \sim 10^4 - 10^5 \Rightarrow$ 1 photon from the dot

Repetition rate of the laser

Need a special experimental setup to discriminate QD photons from laser ones

Control of the fine-structure splitting

APPLIED PHYSICS LETTERS **90**, 011907 (2007)

Control of fine-structure splitting of individual InAs quantum dots by rapid thermal annealing

D. J. P. Ellis,[a)] R. M. Stevenson, R. J. Young, and A. J. Shields
Toshiba Research Europe Limited, Cambridge Research Laboratory, 260 Science Park, Milton Road, Cambridge CB4 0WE, United Kingdom

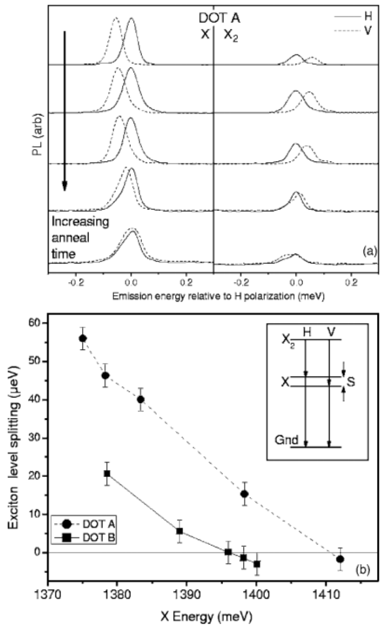
P. Atkinson and D. A. Ritchie
Cavendish Laboratory, Cambridge University, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom

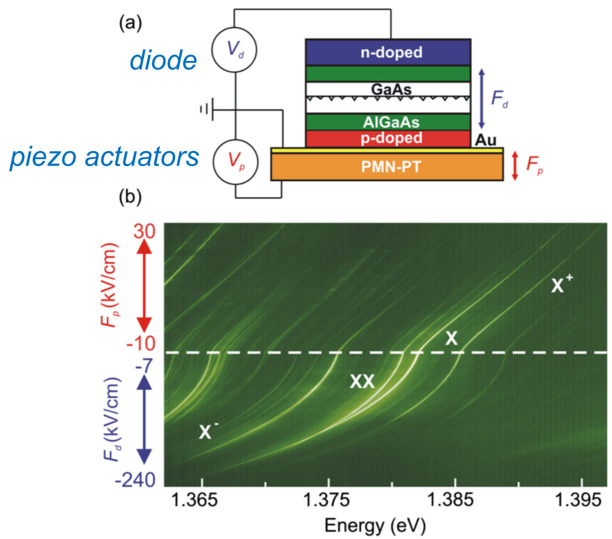
Selected for a Viewpoint in *Physics*
PRL **109,** 147401 (2012) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2012

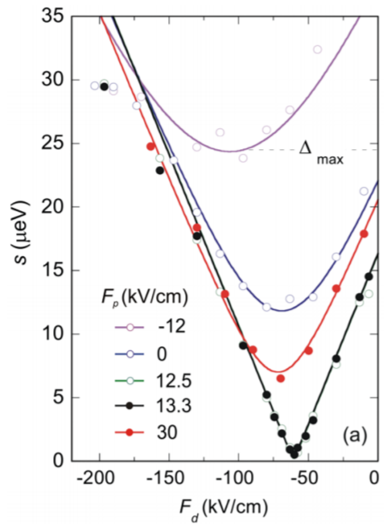
Universal Recovery of the Energy-Level Degeneracy of Bright Excitons in InGaAs Quantum Dots without a Structure Symmetry

R. Trotta,[1,2,*] E. Zallo,[1] C. Ortix,[3] P. Atkinson,[1,4] J. D. Plumhof,[1] J. van den Brink,[3] A. Rastelli,[1,2,†] and O. G. Schmidt[1]
[1]*Institute for Integrative Nanosciences, IFW Dresden, Helmholtzstrasse 20, D-01069 Dresden, Germany*
[2]*Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Altenbergerstrasse 69, A-4040 Linz, Austria*
[3]*Institute for Theoretical Solid State Physics, IFW Dresden, Helmholtzstrasse 20, D-01069 Dresden, Germany*
[4]*Institut des NanoSciences des Paris, UPMC CNRS UMR 7588, 4 Place Jussieu Boite courier 840, Paris 75252 Cedex 05, France*
(Received 7 June 2012; published 1 October 2012)

(> 140 citations)





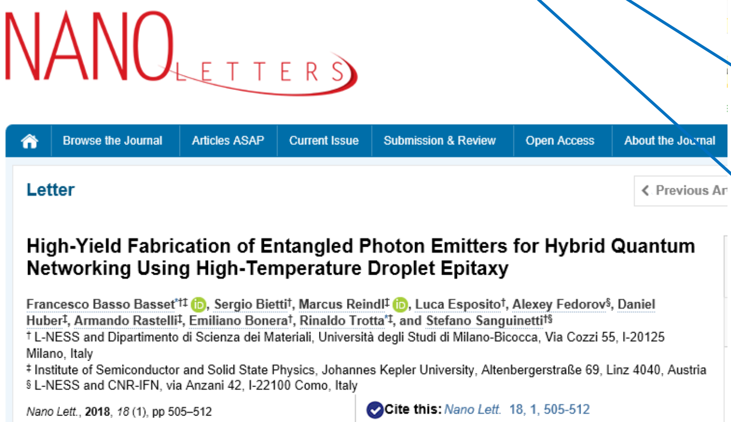


Same trend as in slide 7!

Entangled photon sources

Isotropic GaAs quantum dots obtained from liquid Ga droplets further exposed to As form GaAs islands

To cancel the FSS



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Letter

Previous Ar

High-Yield Fabrication of Entangled Photon Emitters for Hybrid Quantum Networking Using High-Temperature Droplet Epitaxy

Francesco Basso Basset†‡, Sergio Bietti†, Marcus Reindl‡, Luca Esposito†, Alexey Fedorov§, Daniel Huber‡, Armando Rastelli‡, Emiliano Bonera†, Rinaldo Trotta†‡, and Stefano Sanguinetti†§
† L-NESS and Dipartimento di Scienza dei Materiali, Università degli Studi di Milano-Bicocca, Via Cozzi 55, I-20125 Milano, Italy
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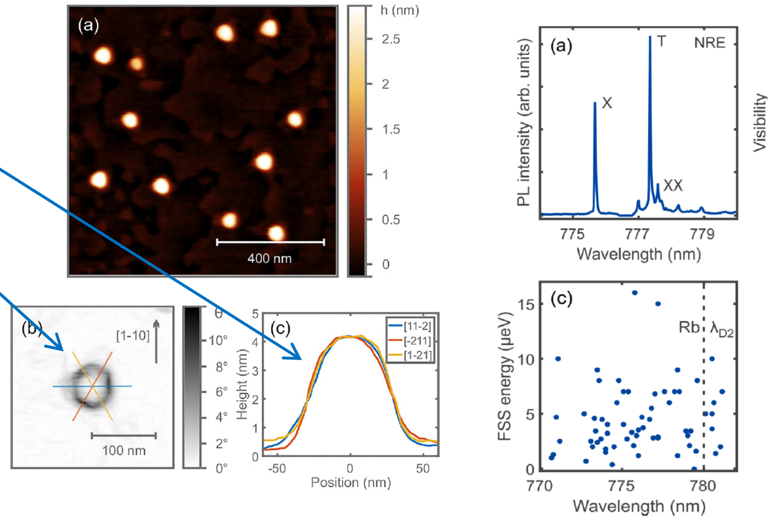
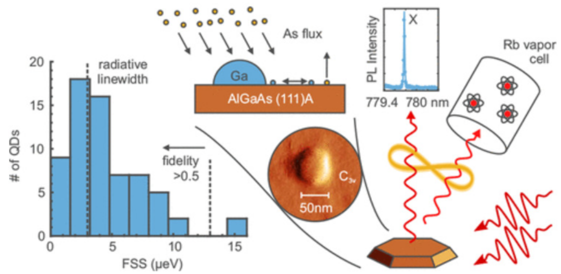
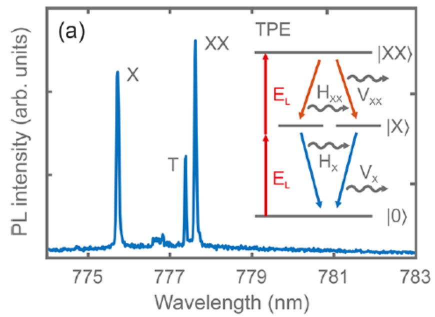
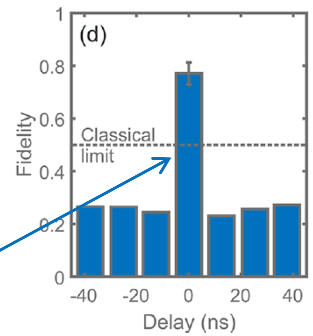
Nano Lett., 2018, 18 (1), pp 505–512
Cite this: Nano Lett. 18, 1, 505-512









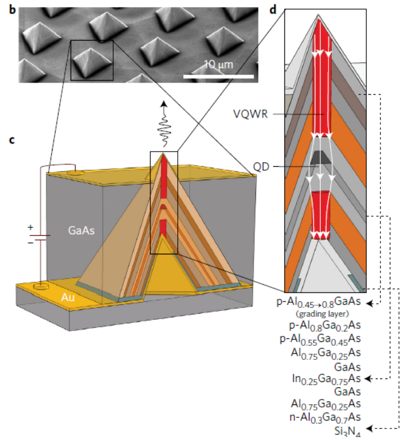
Fidelity to the expected maximally entangled Bell states ⇒
important figure of merit for an entangled quantum light source

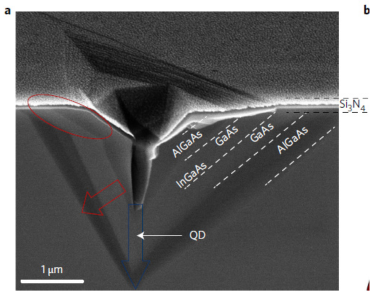
Entangled photon sources

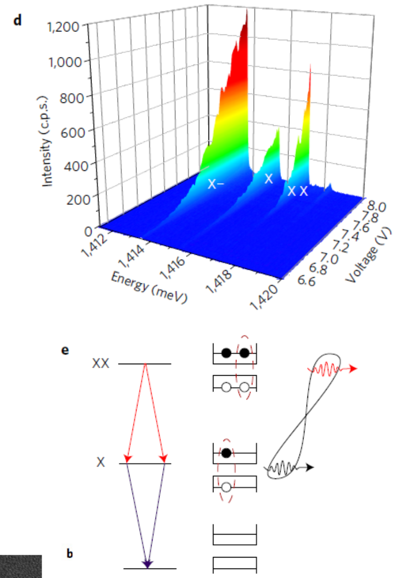
ARTICLES
PUBLISHED ONLINE: 31 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.203
nature photonics

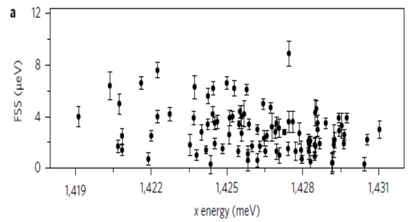
Selective carrier injection into patterned arrays of pyramidal quantum dots for entangled photon light-emitting diodes

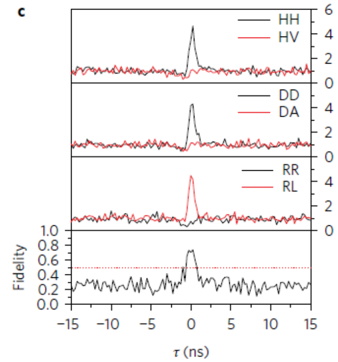
T. H. Chung[†], G. Juska*[†], S. T. Moroni, A. Pescaglini, A. Gocalinska and E. Pelucchi







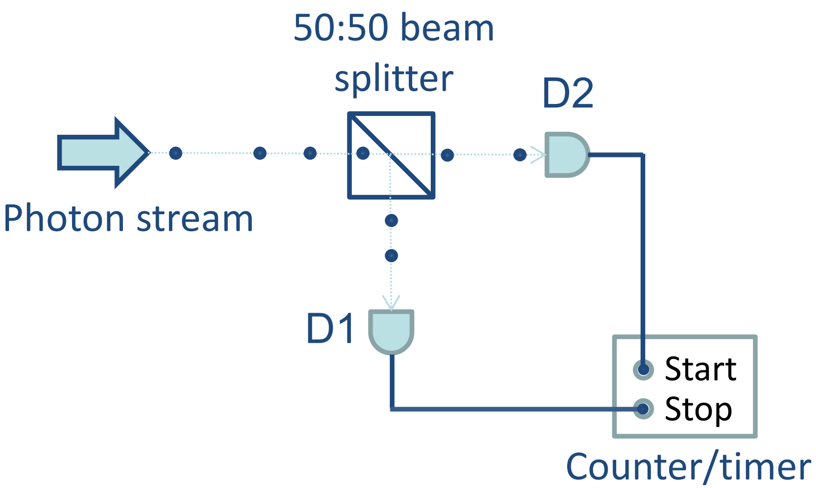




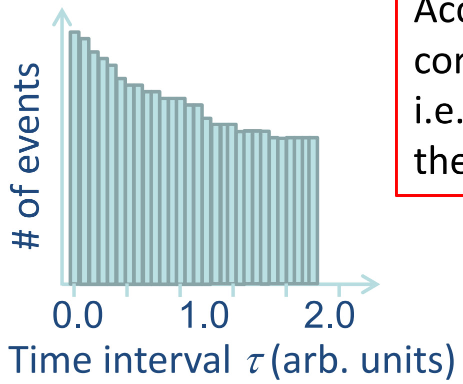
$(1/\sqrt{2})(|DD\rangle + |AA\rangle) = (1/\sqrt{2})(|RL\rangle + |LR\rangle)$, where $|R\rangle = (1/\sqrt{2})(|H\rangle + i|V\rangle)$, $|L\rangle = (1/\sqrt{2})(|H\rangle + i|V\rangle)$, $|D\rangle = (1/\sqrt{2})(|H\rangle + |V\rangle)$ and $|A\rangle = (1/\sqrt{2})(|H\rangle + |V\rangle)$ are the right/left-hand circular, diagonal and antidiagonal polarization states, respectively.

Photon statistics as a tool to assess coherence

Hanbury Brown-Twiss experiment

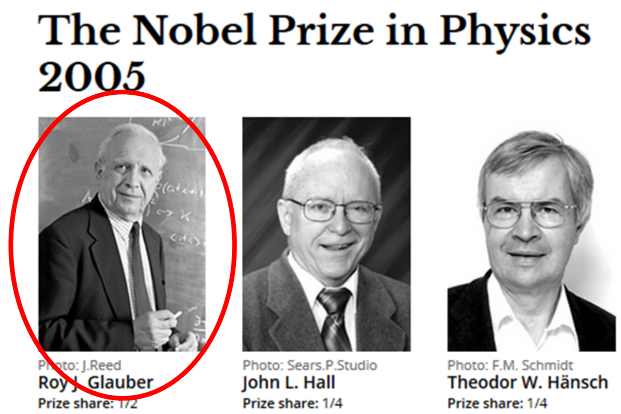


Histogram



Access to 2nd-order correlation function, $g^{(2)}(\tau)$, i.e., intensity fluctuations in the photon field

- Bunched (chaotic) light: $g^{(2)}(0) > 1$
  Thermal light
- Coherent light: $g^{(2)}(0) = 1$ (random)
  Laser light
- Antibunched light: $g^{(2)}(0) < 1$
  SPEs (ideal SPE, $g^{(2)}(0) = 0$)

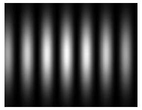


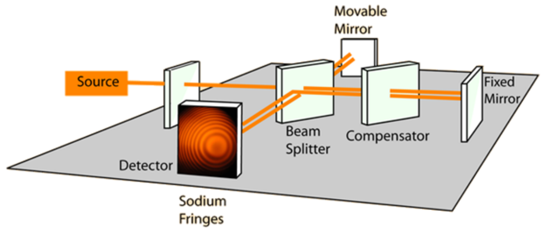
Some insights into the 2nd order coherence function

1st order coherence function: *quantifies electric field fluctuations in time*

$$g^{(1)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}(t+\tau)\rangle}{\langle |\mathcal{E}(t)|^2\rangle}$$

$$\text{visibility} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = |g^{(1)}(\tau)|$$





2nd order coherence function: *quantifies intensity fluctuations in time*

$$g^{(2)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\mathcal{E}(t)\rangle}{\langle \mathcal{E}^*(t)\mathcal{E}(t)\rangle\langle \mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\rangle} = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle\langle I(t+\tau)\rangle}$$

Hanbury Brown and Twiss, Nature **177**, 27 (1956). (> 2030 citations)
Hanbury Brown and Twiss, Nature **178**, 1046 (1956). (> 850 citations)

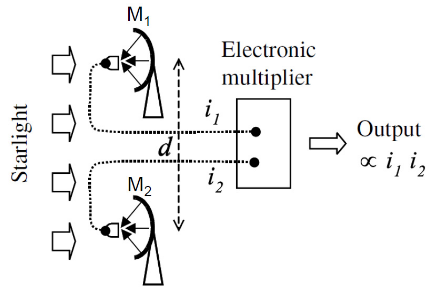
Quantum state describing here a set of quantum emitters

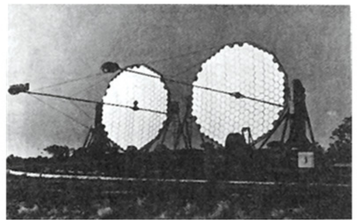
For a given number *Fock state* |*n*> satisfying the bosonic commutation, the zero time-delay correlation becomes[1]

$$g^{(2)}(0) = \frac{n(n-1)}{n^2}$$

[1]I. Aharonovich *et al.*, Rep. Prog. Phys. **74**, 076501 (2011).

# *n* of quantum emitters	$g^{(2)}(0)$
1	0
2	0.5
3	0.667

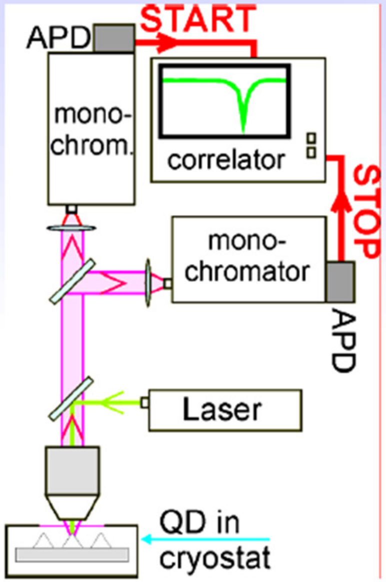


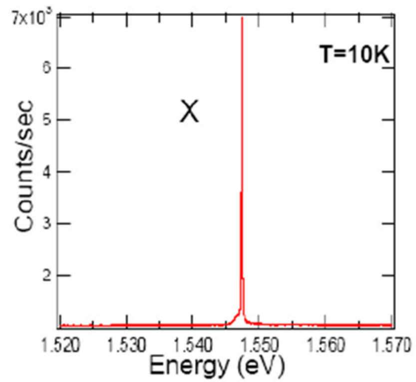


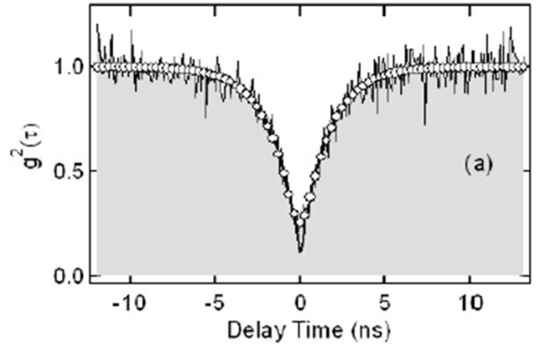
➡ $g^{(2)}(0) < 0.5$ for ensuring true single photon emission

Single photon emission from QDs

Hanbury Brown and Twiss interferometry







$$g^{(2)}(\tau) = \frac{\langle n(t)n(t+\tau)\rangle}{\langle n\rangle^2}$$

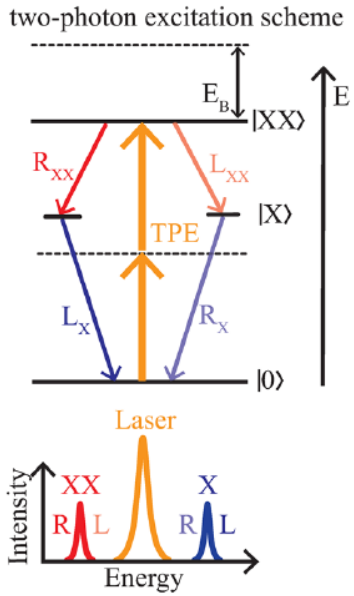
2nd order correlation function

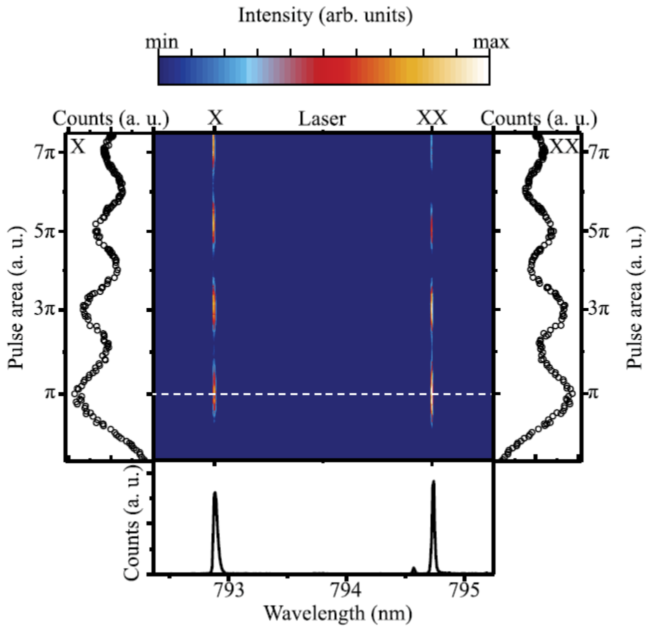
- Single QDs are readily selected and probed
- Photon antibunching observed at X lines

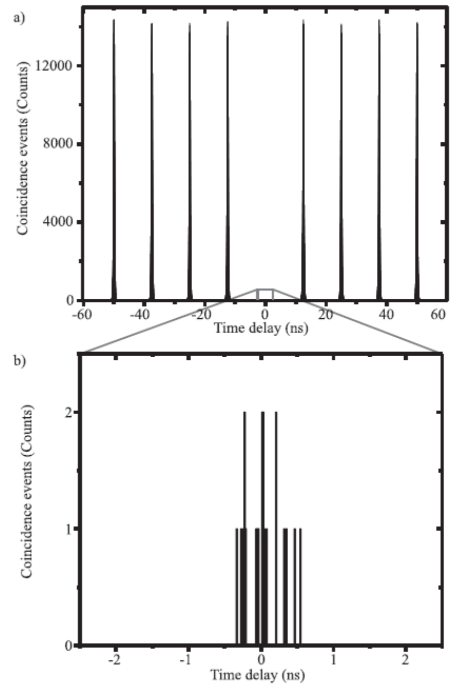
Photon antibunching

Two-photon resonant excitation of the biexciton

Reduce decoherence and multi-photon emission[1]







Laser spectral width of 260 μeV and pulse length of 7 ps

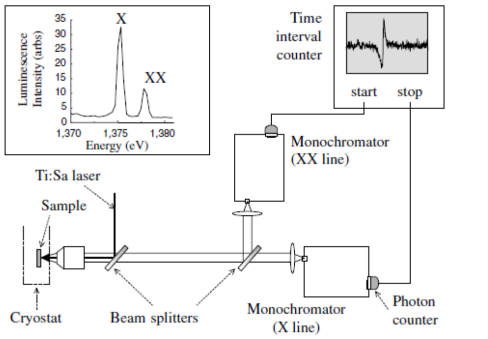
$$g^{(2)}(0) = (7.5 \pm 1.6) \times 10^{-5}$$

Low background noise

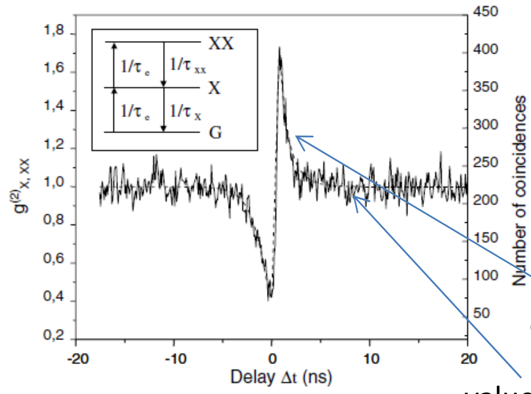
[1] L. Schweickert *et al.*, Appl. Phys. Lett. **112**, 093106 (2018). (> 210 citations)

Quantum cascade of photons in quantum dots[1]

Experiment highlighting the potential of single dots as an efficient source of single photons (quantum information applications)



Hanbury-Brown & Twiss setup with *λ selective arms*



Cross-correlation function of X and XX photons (cw experiment)

$$C^{(2)}_{X,XX}(\Delta t) = \int_0^{T_m} n_{XX}(t)\, n_X(t+\Delta t)\,dt$$

time interval between two consecutively detected photons

exponential decay ≡ exciton lifetime

value of accidental coincidences, $g^{(2)}_{X,XX} = 1$

Biexciton/exciton as sources of pairs of correlated single photons

Spectral filtering allows isolation of a single photon by a single dot (antibunching → single photon nature of exciton emission)

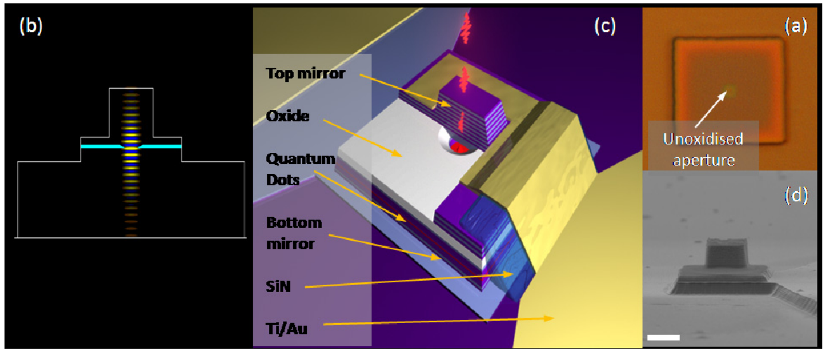
Cross-bunching ($\Delta t > 0$, i.e. XX 1st, X 2nd) and cross-antibunching ($\Delta t < 0$, when X photon is detected, system ≡ ground state, probability of detecting XX photon → 0)

Quantum efficiency for photon pair production in QDs >> efficiencies atomic cascades and parametric fluorescence (but operation limited to liquid He temperature)

Traditional sources of entangled photons

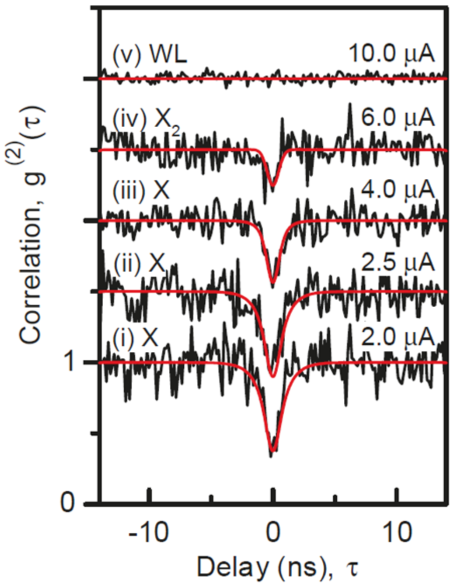
[1]E. Moreau *et al.*, Phys. Rev. Lett. **87**, 183601 (2001). (> 300 citations)

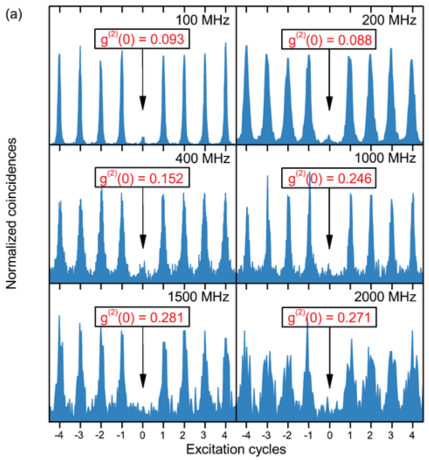
Electrically-driven QD-based single photon emitters



Cambridge + Toshiba UK

Z. L. Yuan *et al.*, Science **295**, 102 (2002). (> 1030 citations)





Single photon emission up to excitation repetition rates of 2 GHz

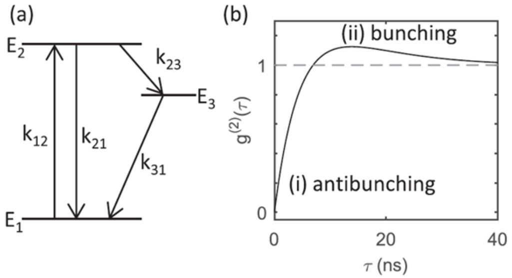
F. Hargart *et al.*, Appl. Phys. Lett. **102**, 011126 (2013).

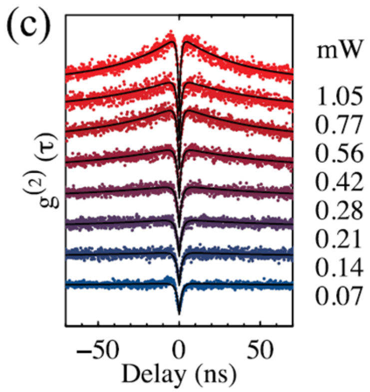
Alternative solid-state single photon emitters

Deep-level defects in:

OPERATE AT 300 K BUT NOT AS BRIGHT AS QDs

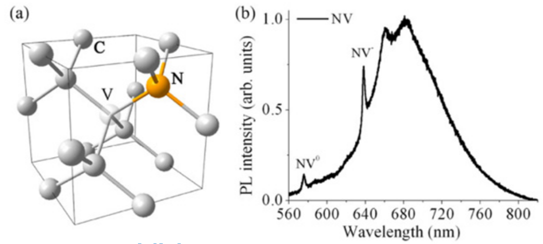
SiC[1]



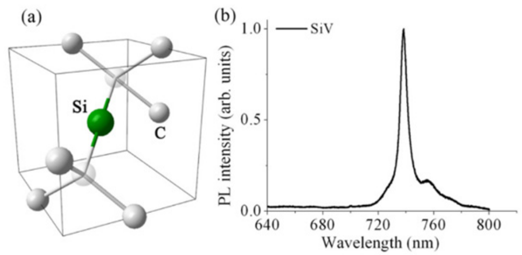


[1]A. Lohrmann *et al.*, Rep. Prog. Phys. **80**, 034502 (2017).

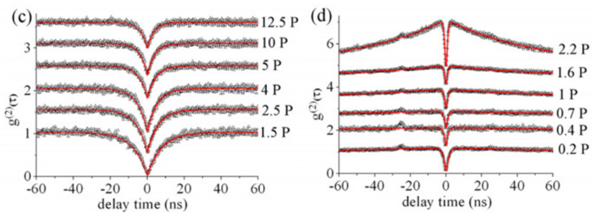
Diamond[2]



NV⁻ centers

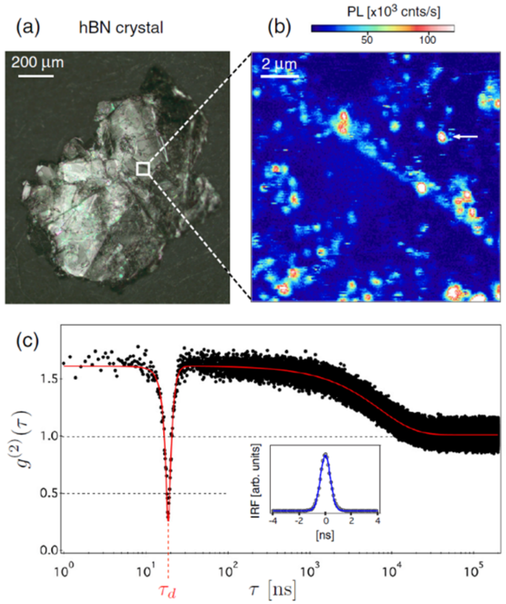


SiV⁻ centers



[2]I. Aharonovich *et al.*, Rep. Prog. Phys. **74**, 076501 (2011).

hBN[3]



[3]L. J. Martínez *et al.*, Phys. Rev. B **94**, 121405(R) (2016).