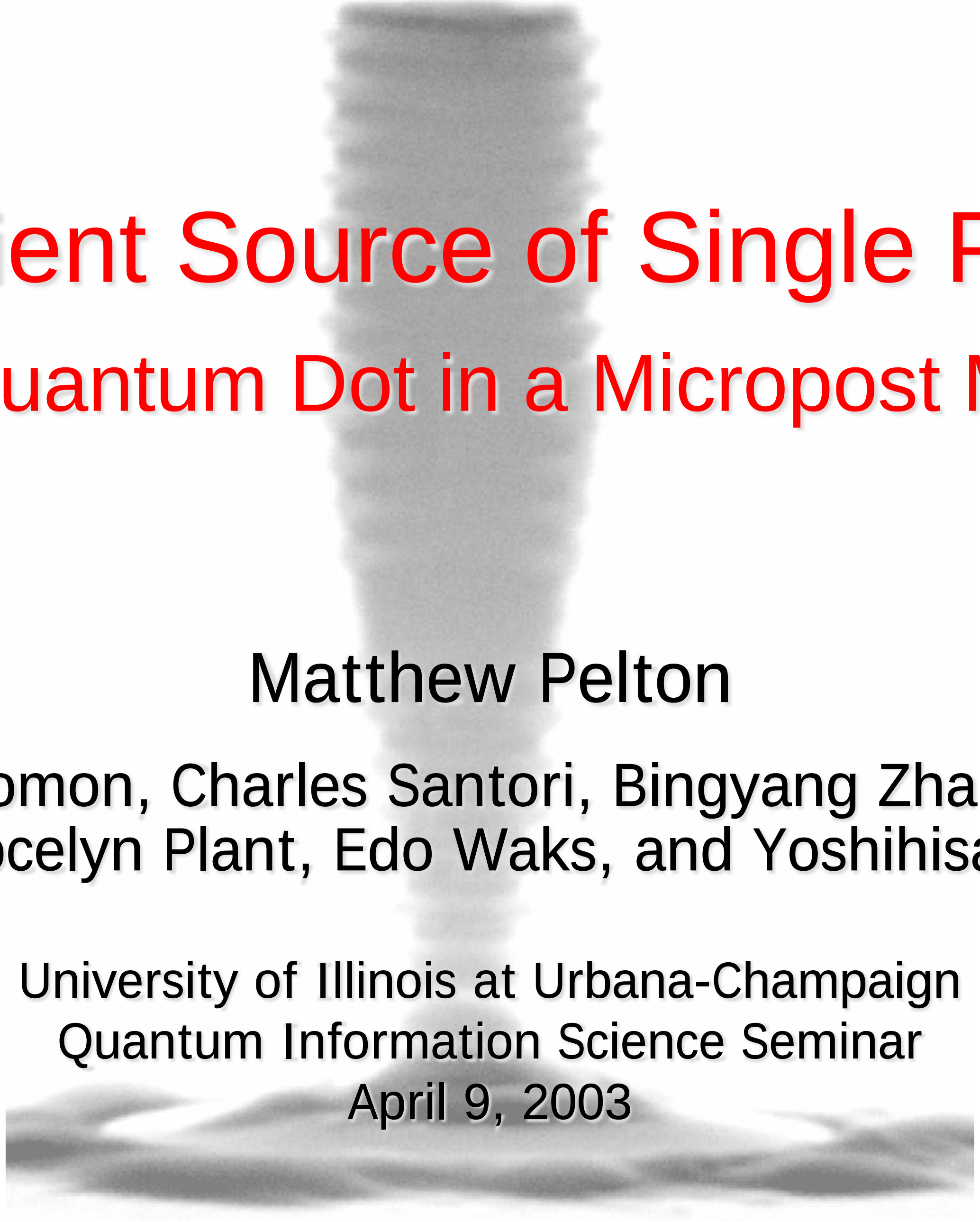
Roy Glauber (Nobel, 2005):
“A photon is what a photodetector detects.”



An Efficient Source of Single Photons:

A Single Quantum Dot in a Micropost Microcavity

Matthew Pelton

Glenn Solomon, Charles Santori, Bingyang Zhang, Jelena Vučković, Jocelyn Plant, Edo Waks, and Yoshihisa Yamamoto

University of Illinois at Urbana-Champaign
Quantum Information Science Seminar
April 9, 2003

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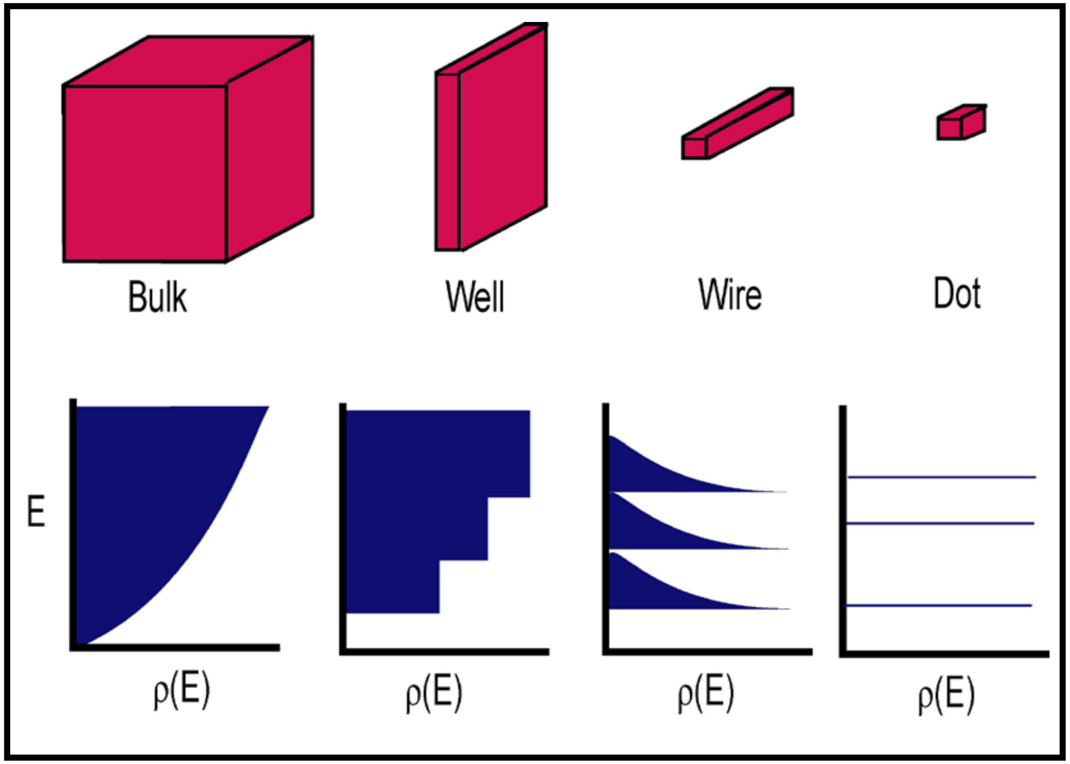
Quantum Dots

- Increasing number of confining dimensions leads to fully quantized density of states



Self-Assembled Quantum Dots

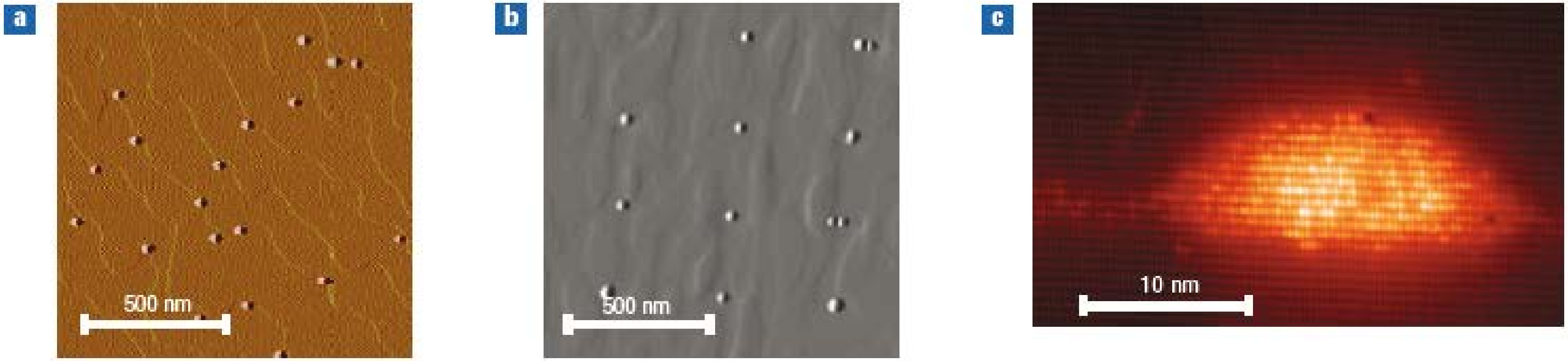


Figure 1 Self-assembled quantum dots. **a**, Image of a layer of InAs/GaAs self-assembled quantum dots recorded with an atomic-force microscope. Each blob corresponds to a dot with typical lateral diameters of 20–30 nm and a height of 4–8 nm. **b**, Atomic-force-microscope image of a layer of InAs quantum dots whose locations have been seeded by a matrix of nanometre-sized pits patterned onto the wafer surface. Under optimal conditions, up to 60% of the etch pits contain a single dot. Reproduced with permission from ref. 23. Copyright (2006) JSAP. **c**, Cross-sectional scanning-tunnelling-microscope image of an InAs dot inside a GaAs device. Image courtesy of P. Koenraad, Eindhoven.

“Semiconductor q. light sources”, A. Shields Nat. Phot. 2007

Advantages for single-photon source:

–Confined electron & hole levels

–Large oscillator strength

–Long-term stability

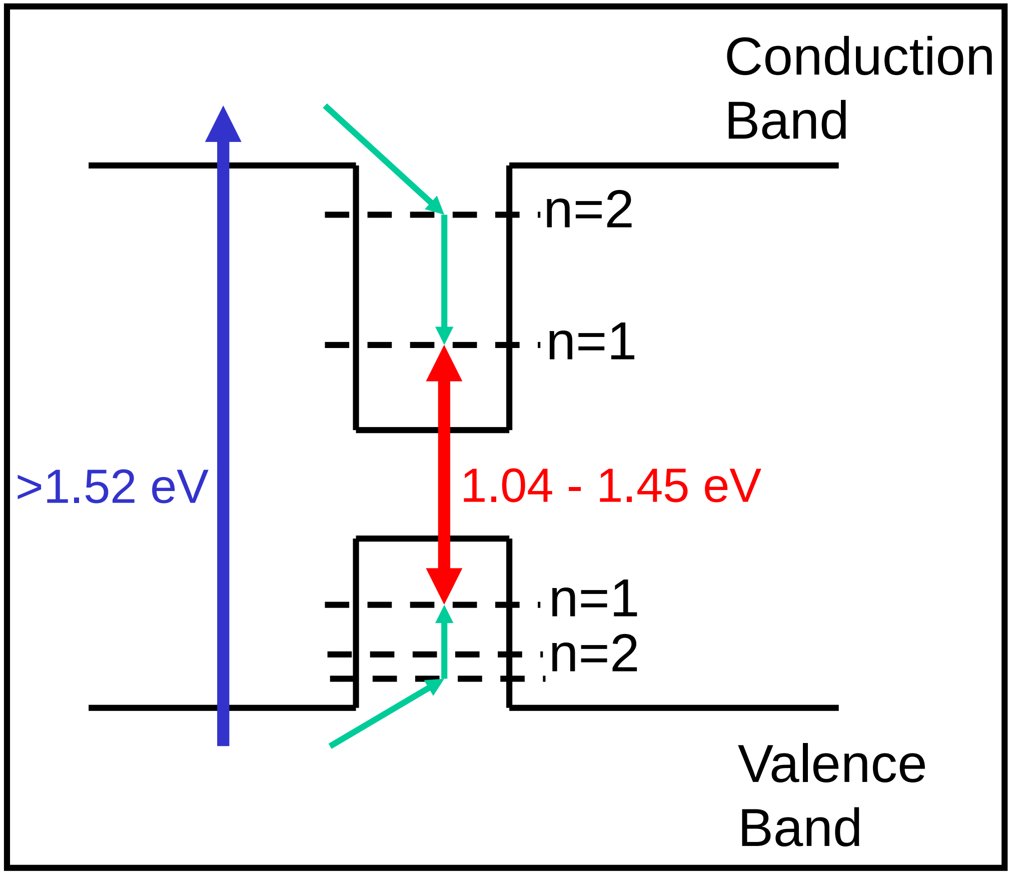
– High radiative efficiency

– Narrow emission bandwidth

– Possibility of incorporation into devices

Single-Dot Spectroscopy

- Dots isolated by etching microscopic mesas
- Electron-hole pairs excited in GaAs by laser pulse
- Carriers trapped in dots and relax to the ground state, where they recombine



Typical emission spectrum

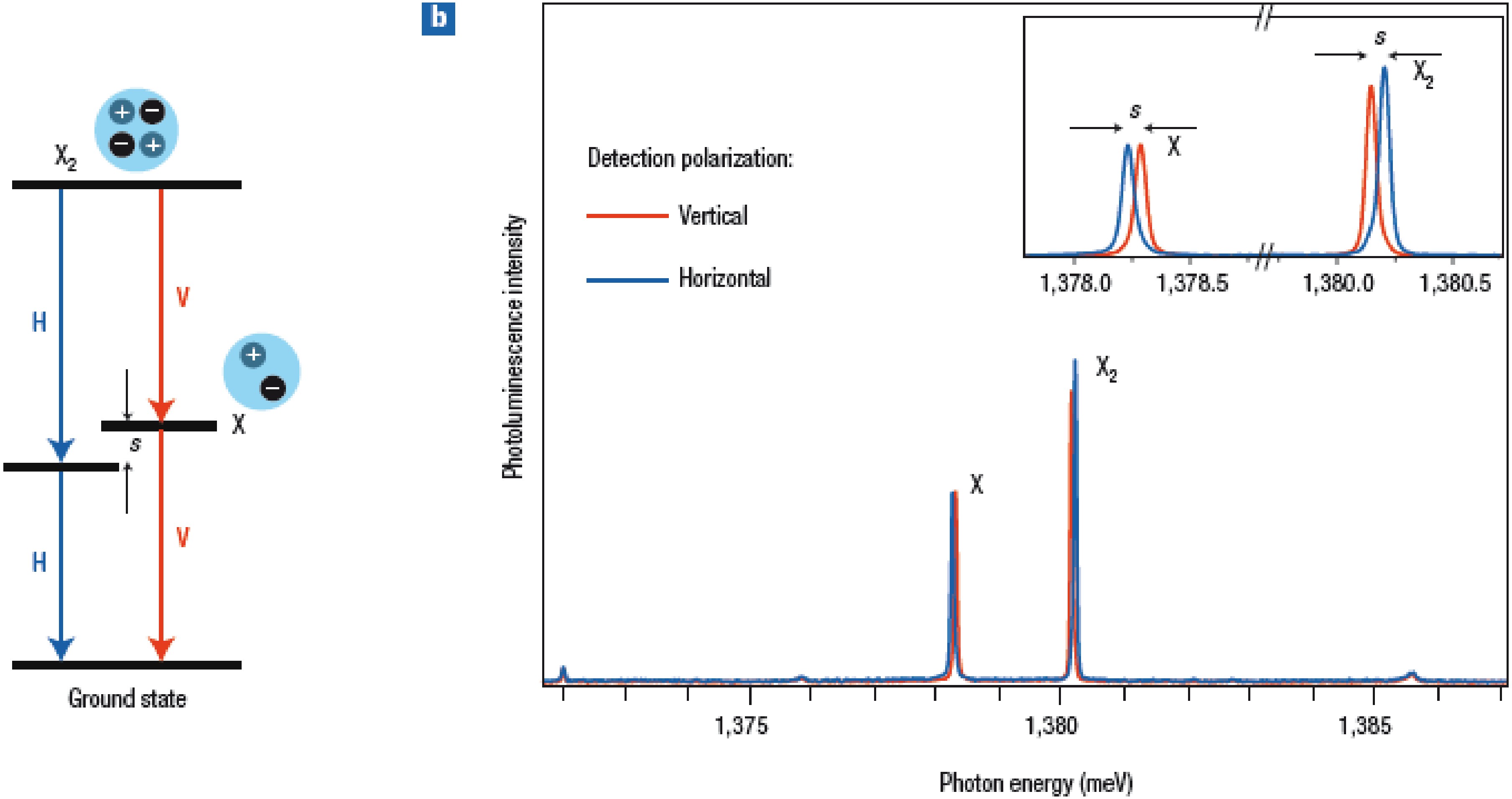


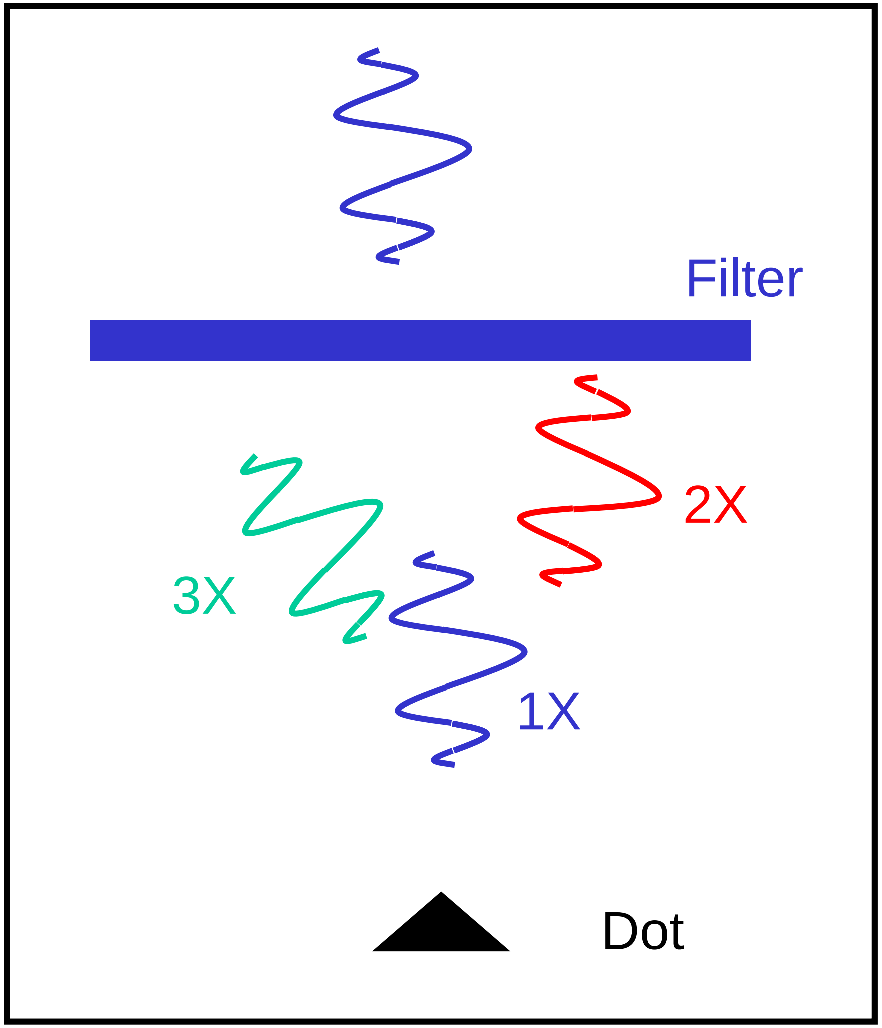
Figure 2 Optical spectrum of a quantum dot. **a**, Schematic of the biexciton cascade of a quantum dot. **b**, Typical photoluminescence spectrum of a single quantum dot showing sharp line emission due to the biexciton, X_2, and exciton, X, photon emitted by the cascade. The inset shows the polarization splitting of the transitions originating from the spin splitting of the exciton levels.

“Semiconductor q. light sources”, A. Shields Nat. Phot. 2007

Single-Photon Generation

- Excite with pulsed laser (eventually electrically...)
- For each pulse, the last photon will be emitted at a unique frequency
- Spectral filtering isolates regulated single photons

C. Santori, M. Pelton, G. S. Solomon, Y. Dale, and Y. Yamamoto, *Phys. Rev. Lett.* **86** (8), 1502 (2001).



Modified Spontaneous Emission

- Most photons are radiated into the substrate: Efficiency ~ 10^{-3}
- Linear elements can only redirect emission
- Changing density of available electromagnetic modes can change the rate of emission into useful directions
- Done using microscopic optical cavity: enhanced emission into resonant cavity modes

G. S. Solomon, M. Pelton, and Y. Yamamoto, *Phys. Rev. Lett.* **86** (17), 3903 (2001).

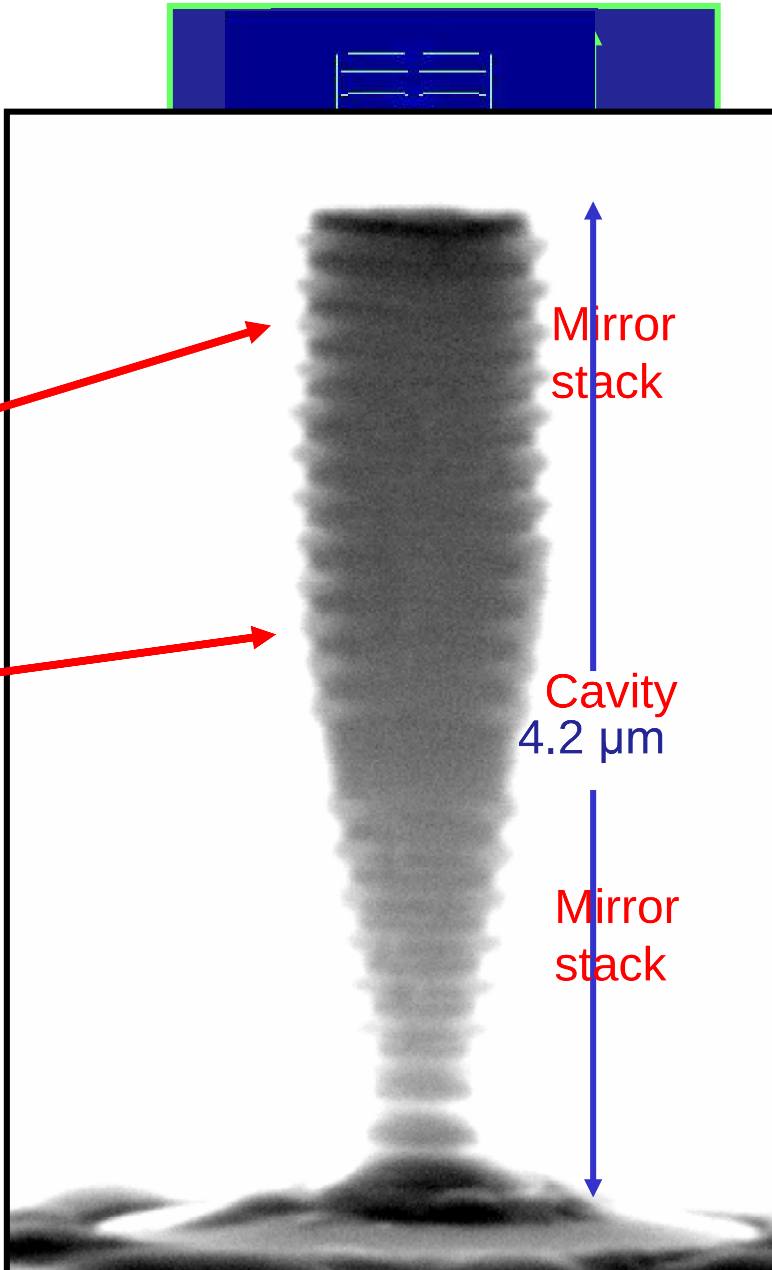
M. Pelton, J. Vučković, G. S. Solomon, A. Scherer, and Y. Yamamoto, *IEEE J. Quantum Electron.* **38** (2), 170 (2002).

Purcell Factor:

$$F_P = \frac{3Q}{4\pi^2}\frac{(\lambda/n)^3}{V}$$

Micropost Microcavities

- Planar microcavities grown by MBE
  - Stacks of alternating quarter-wavelength thick AlAs / GaAs layers
  - Separated by wavelength-thick GaAs layer
- Etched post acts as a waveguide
- Light confined in three dimensions



Various cavity-enhancement schemes

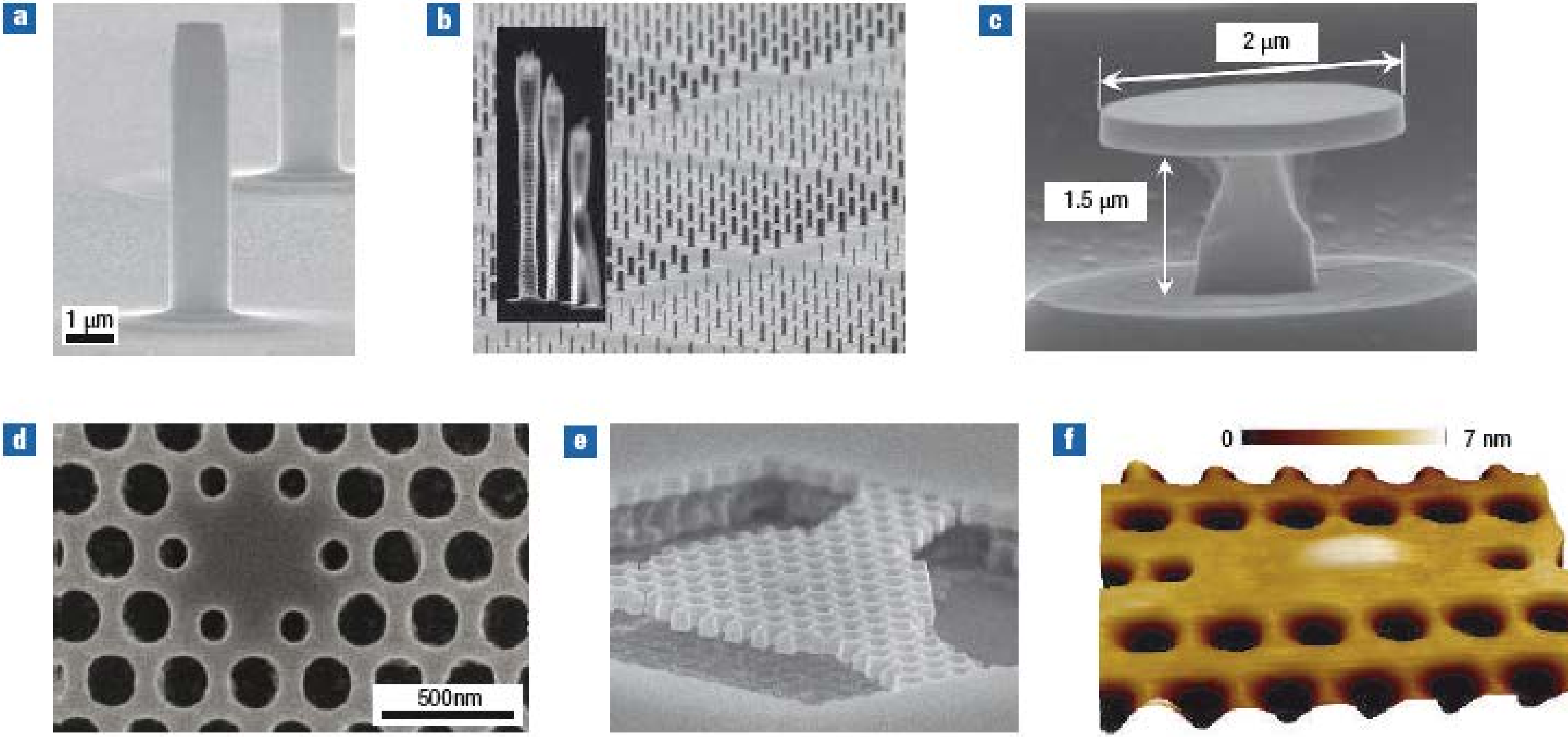
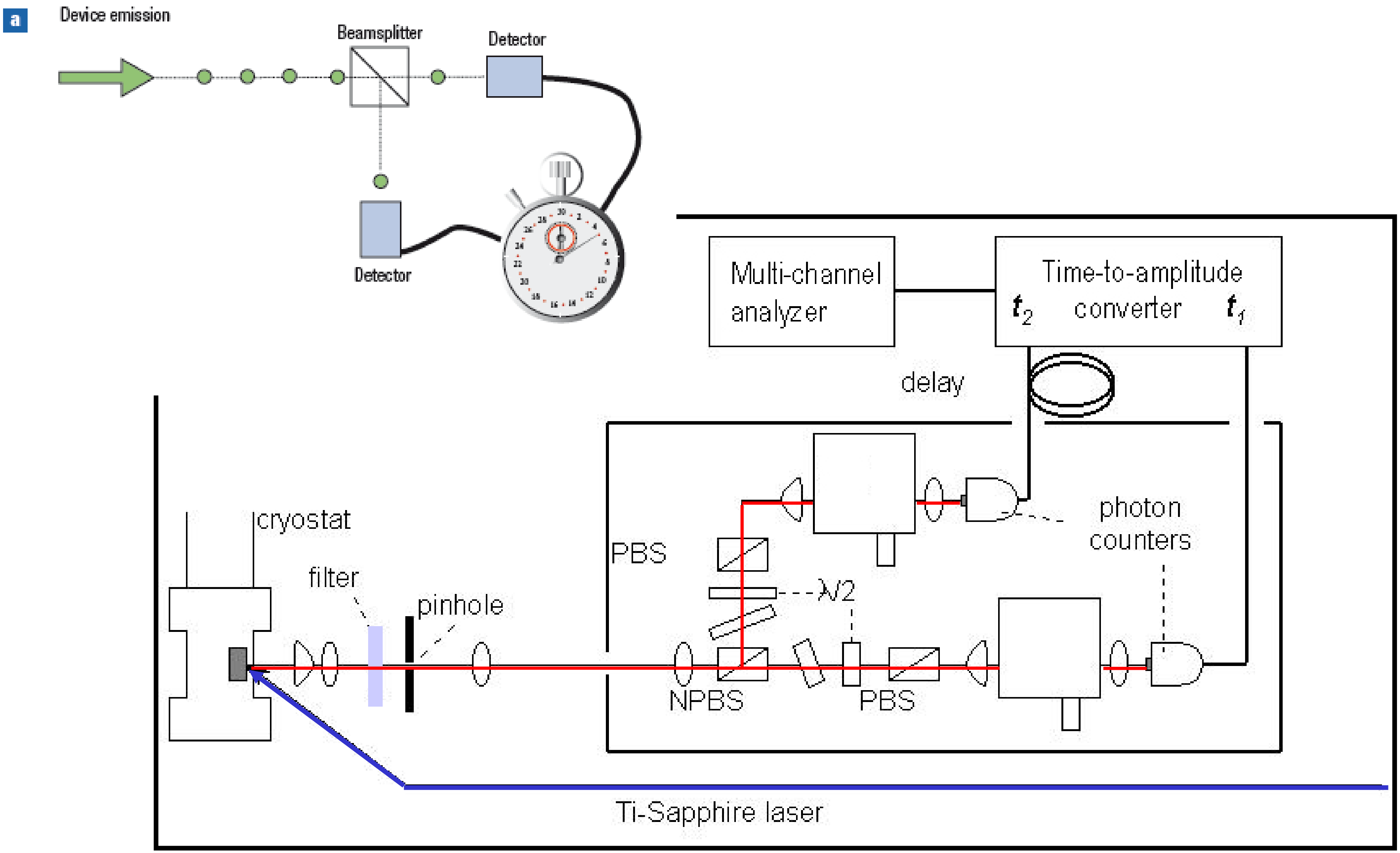


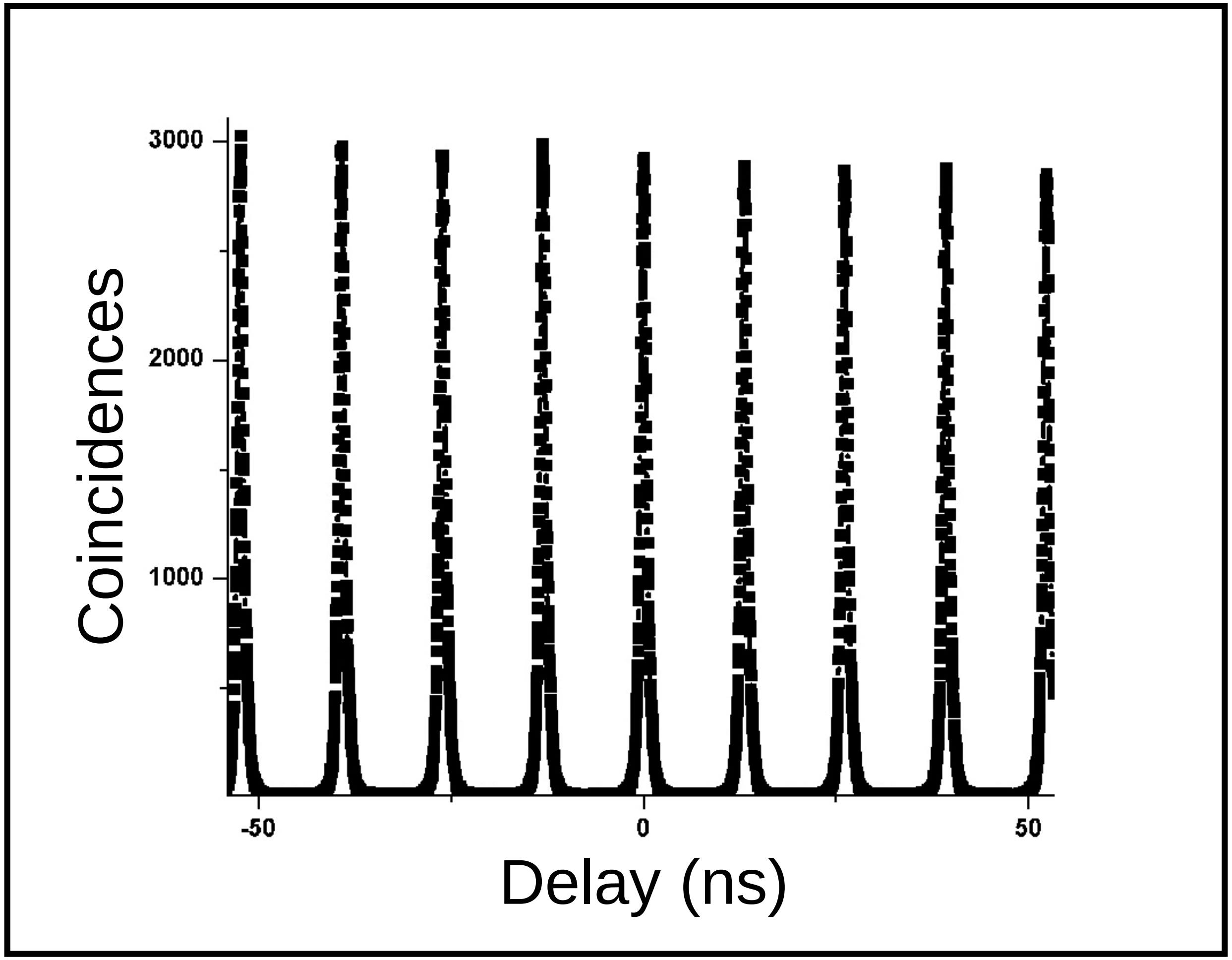
Figure 3 Scanning-electron-microscope images of semiconductor cavities. **a,b**, Pillar microcavities. **c**, microdisks. **d–f**, Photonic-bandgap defect cavities. The structures were fabricated at: **a**, University of Würzburg; **b,c,e**, CNRS-LPN (UPR-20); **d**, Univ. Cambridge; **f**, UCSB/ETHZ. (Image sources and permissions: **a**, Ref. 56. **c**, Ref. 51, copyright (2005) APS. **d**, Ref. 47, copyright (2006) AIP. **e,f**, Ref. 48)

Experimental Setup



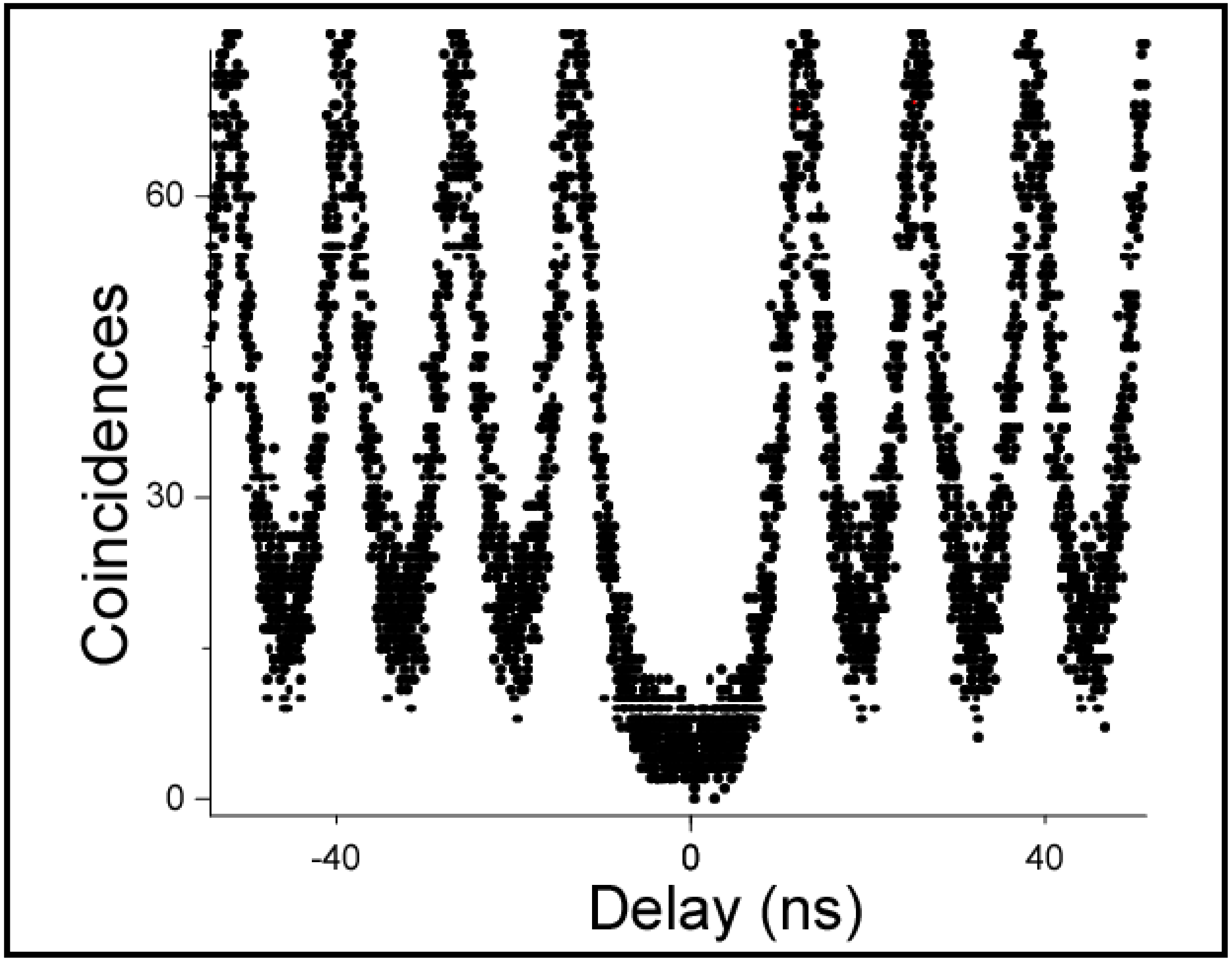
Poissonian Light

- Scattered laser light: all peak areas equal



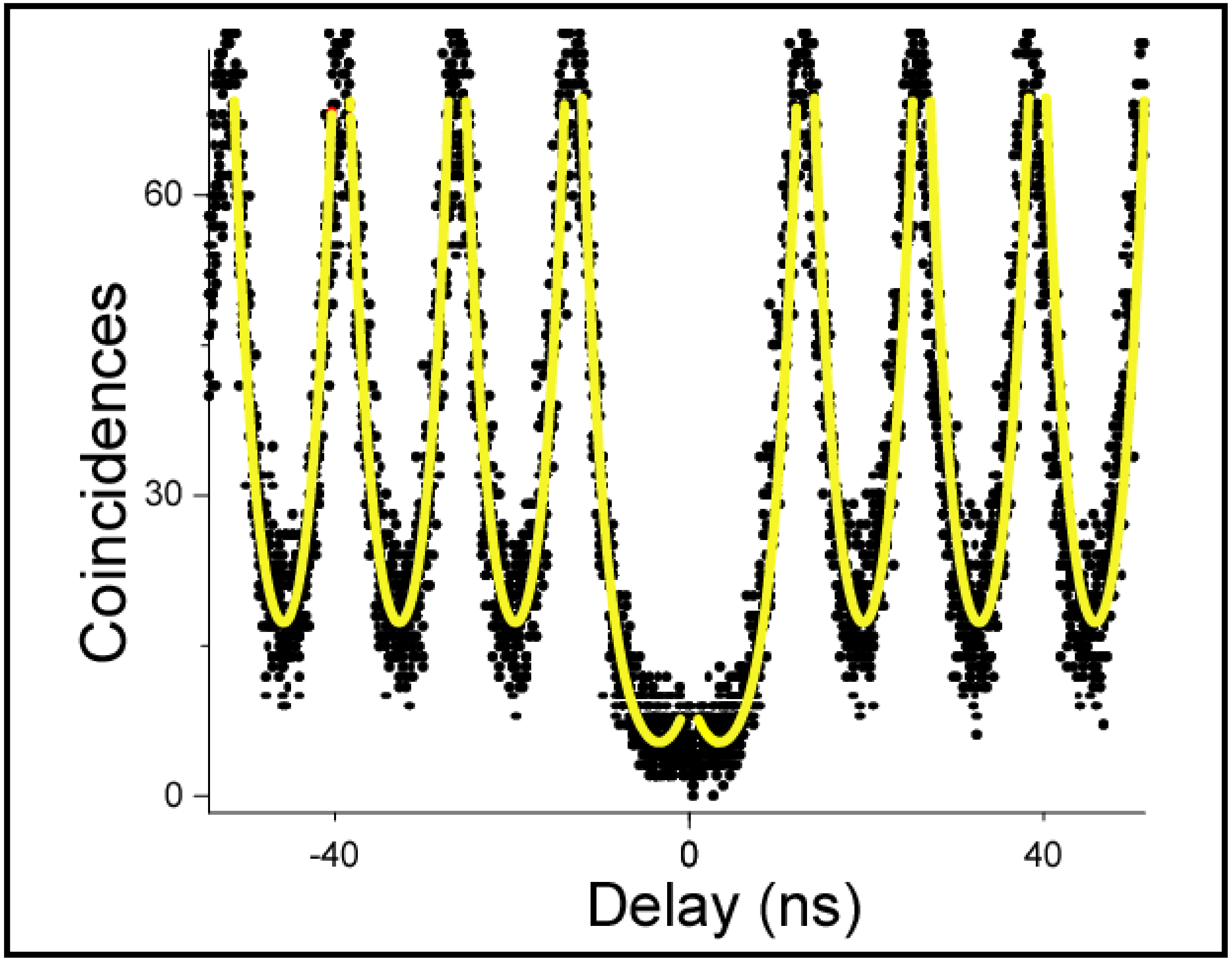
Antibunching

- Scattered laser light: all peak areas equal
- Light from dot: central peak area is small



Antibunching

- Fit uses measured quantum-dot lifetime and instrument response time

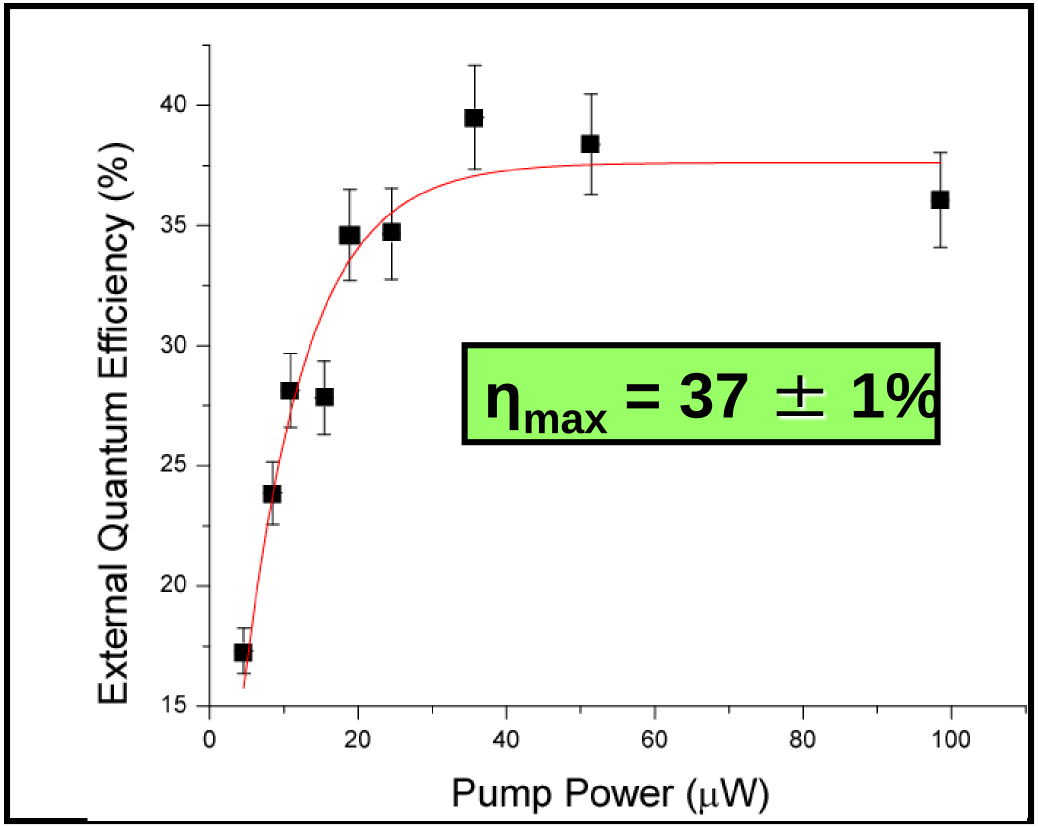


Efficiency

- Efficiency saturates as pump power increases:

$$\eta = \eta_{\max}\left(1 - e^{-P/P_{sat}}\right)$$

M. Pelton, et al., *Phys. Rev. Lett.* **89**, 233602 (2002).

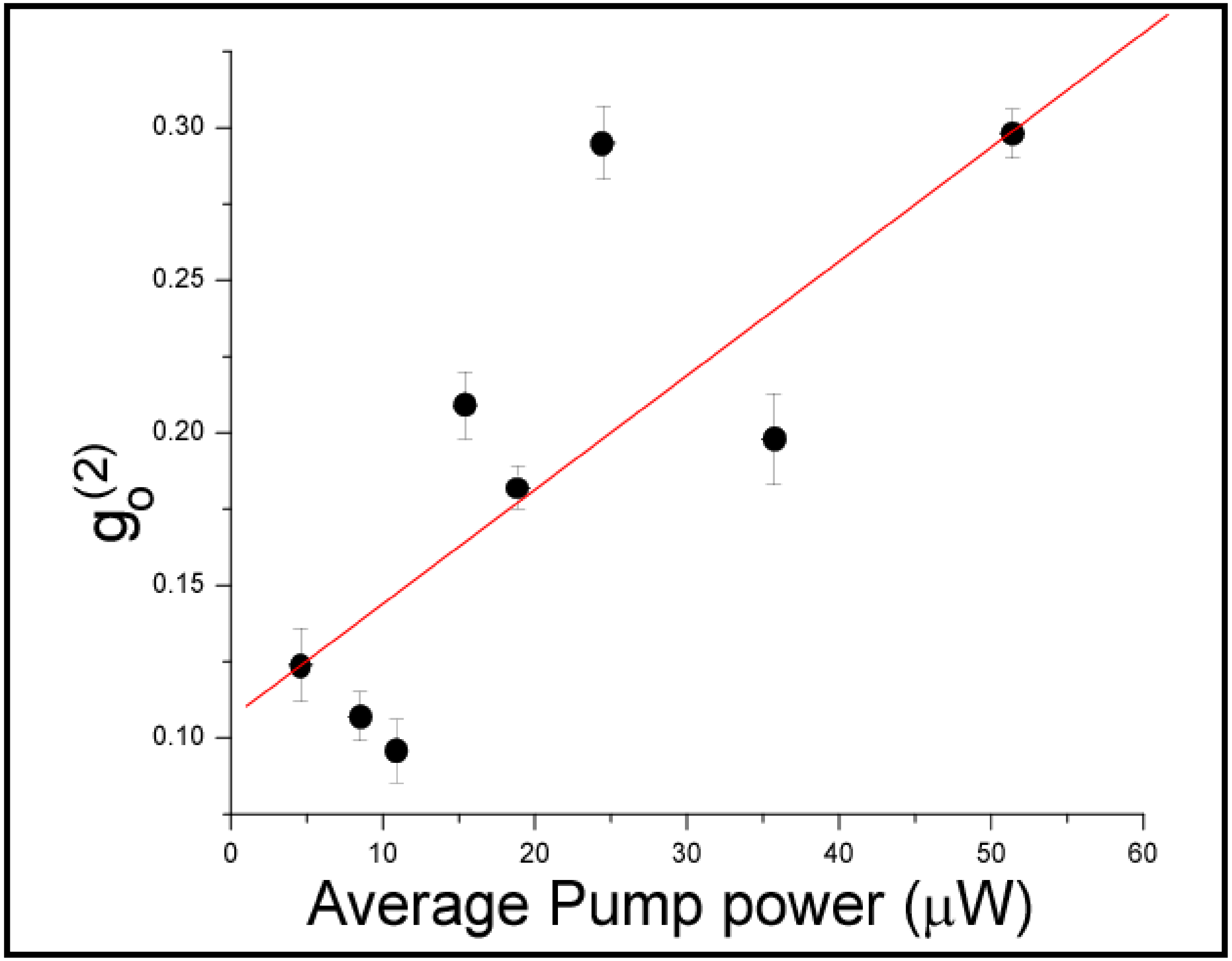


- Note: This is the efficiency to emit a photon, not for the photon to leave the cavity, nor to be collected into a single-mode fiber!

Question: why can’t we just work at high pump power?

Antibunching

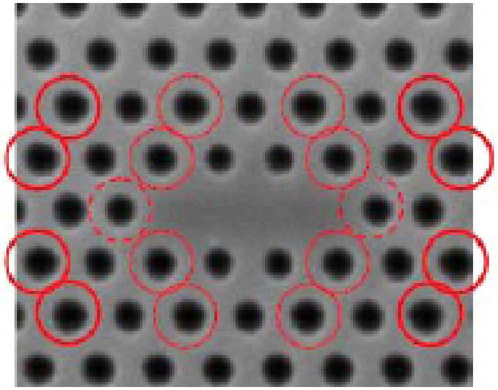
- Multi-photon probability increases with pump power
- Possibly due to excitation of other states

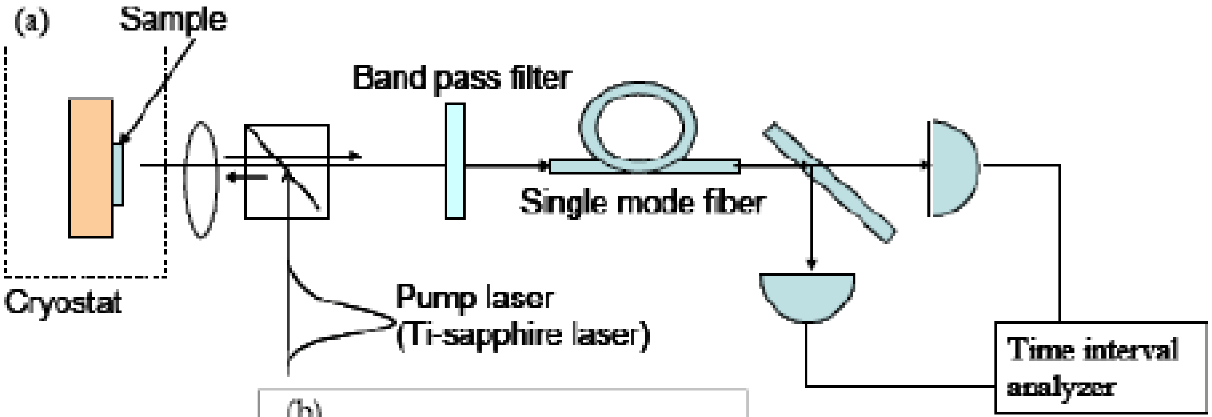


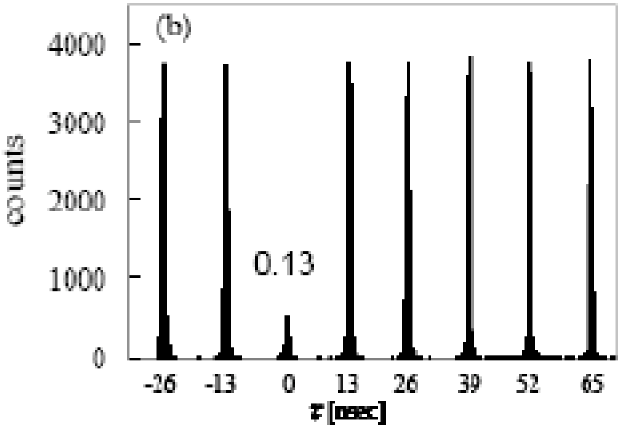
Problems…

- ~5K ☹
- Outcoupling low, but improving (>70% with quantum dot in photonic nanowire)
- λnon-ideal, and changes from dot to dot
  - now temperature and voltage-bias tuning...

High-brightness single photon source from a quantum dot in a directional-emission nanocavity







the coupling efficiency of the collected light into a single mode fiber improved 2x

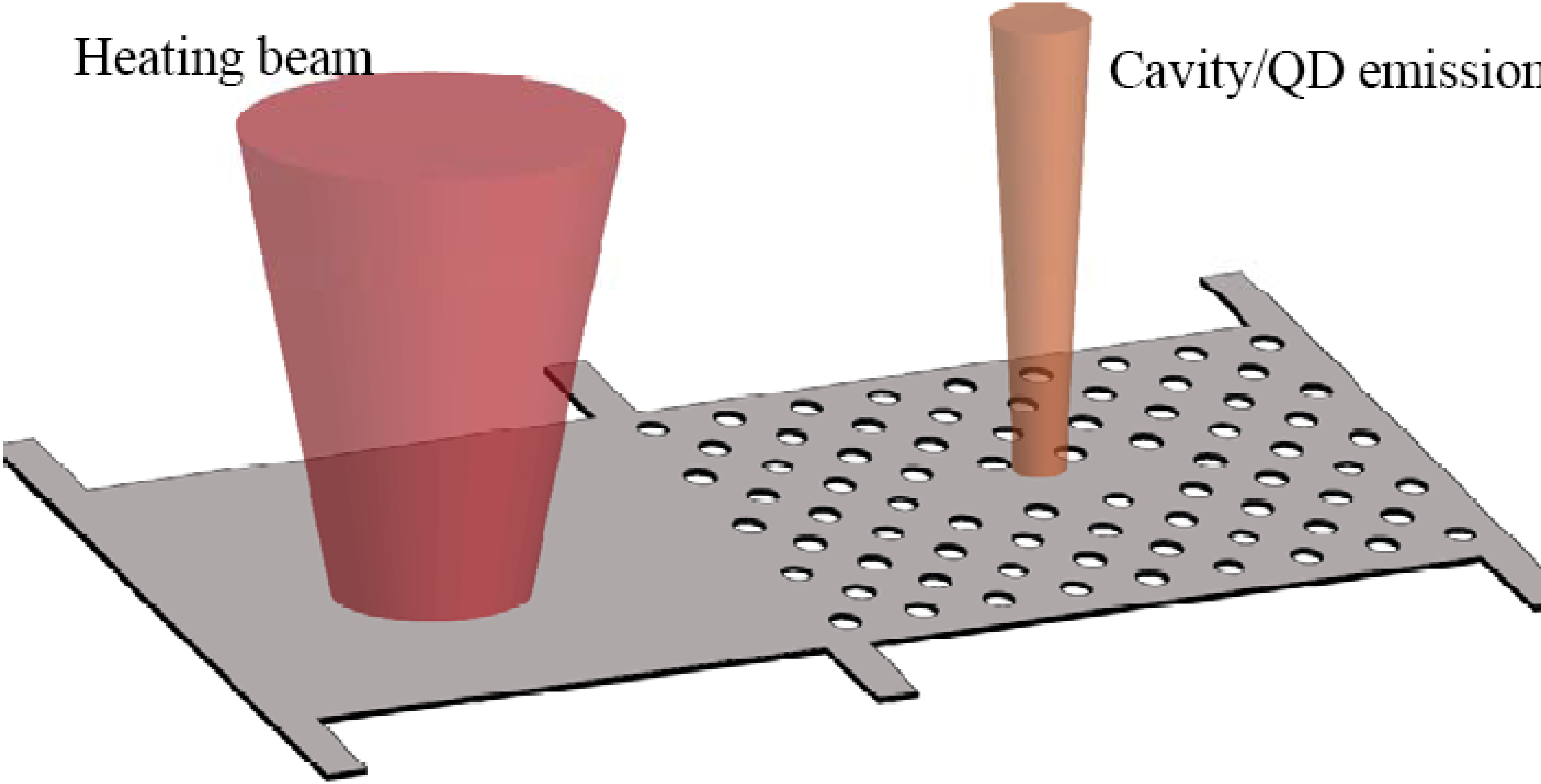
Mitsuru Toishi et al, *APL* (submitted)

Achieved $g^{(2)} = 0.04$

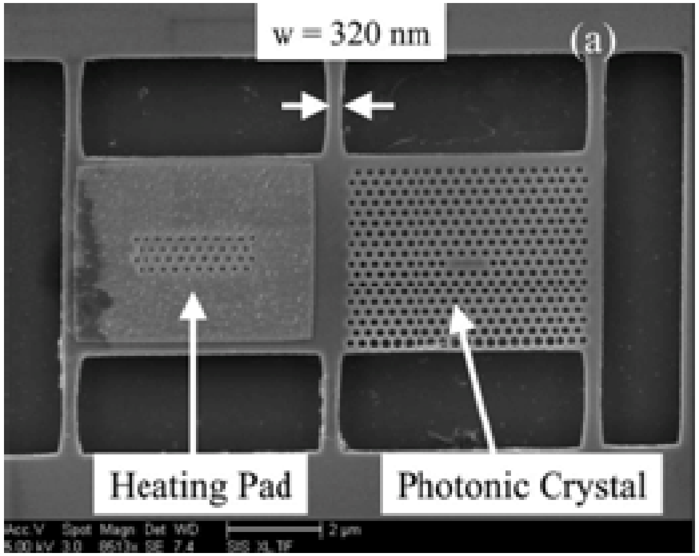
- Count rate ~70,000 photons/s after the single mode fibers on each of the detectors the HBT setup (80MHz repetition rate)
- Detector efficiency ~ 22% => the collection rate into SMF > 630,000 photons/s

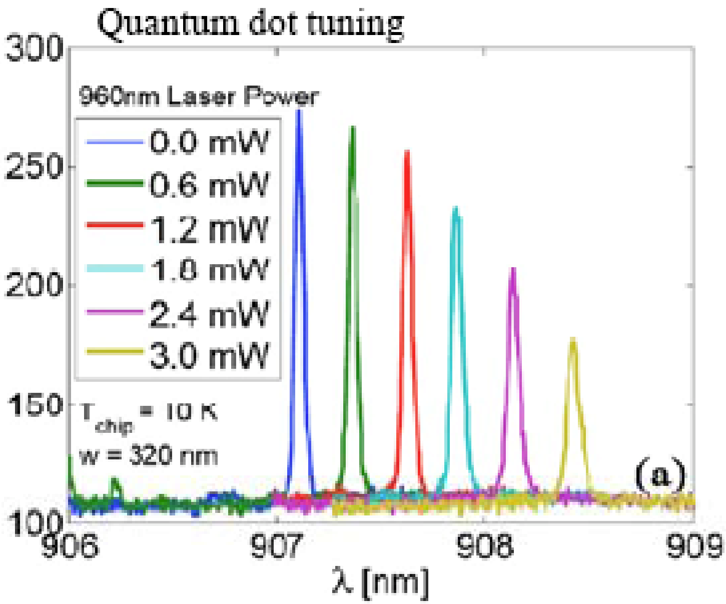
NOTE: $630{,}000/80 \times 10^6 = 0.8\%$ ☹

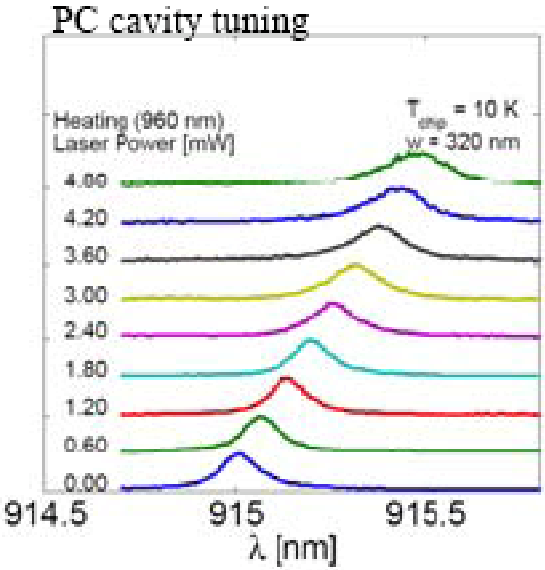
Local temperature tuning



Local temperature tuning




Quantum dot tuning


PC cavity tuning

More Problems…

- Off-resonant excitation typically causes
  - reduced purity (other carriers are recaptured, $g^{(2)}$ ↑)
  - reduced indistinguishability (from non-resonant inhomogeneous broadening of excited state)
  - uncontrollable time-jitter (from non-radiative relaxation from high-levels to emitting state)
- Resonant excitation
  - high purity & indistinguishability ☺
  - finite power needed to drive transition (“pi-pulse”) ☺
  - need to block pump light ☹
  - planar cavities typically have poor extraction efficiency ☹
- Electrical excitation: “single-photon LED”
  - background emission from non-dot layers → poorer $g^{(2)}$s

PRL 116, 020401 (2016) PHYSICAL REVIEW LETTERS week ending
15 JANUARY 2016

On-Demand Single Photons with High Extraction Efficiency and Near-Unity Indistinguishability from a Resonantly Driven Quantum Dot in a Micropillar

Xing Ding,[1,2,3] Yu He,[1,2,3] Z.-C. Duan,[1,2,3] Niels Gregersen,[4] M.-C. Chen,[1,2,3] S. Unsleber,[5] S. Maier,[5]
Christian Schneider,[5] Martin Kamp,[5] Sven Höfling,[1,5,6] Chao-Yang Lu,[1,2,3,*] and Jian-Wei Pan[1,2,3,†]

Scalable photonic quantum technologies require on-demand single-photon sources with *simultaneously* high levels of purity, indistinguishability, and efficiency. These key features, however, have only been demonstrated separately in previous experiments. Here, by *s*-shell pulsed resonant excitation of a Purcell-enhanced quantum dot-micropillar system, we deterministically generate resonance fluorescence single photons which, at π pulse excitation, have an extraction efficiency of 66%, single-photon purity of 99.1%, and photon indistinguishability of 98.5%. Such a single-photon source for the first time combines the features of high efficiency and near-perfect levels of purity and indistinguishabilty, and thus opens the way to multiphoton experiments with semiconductor quantum dots.

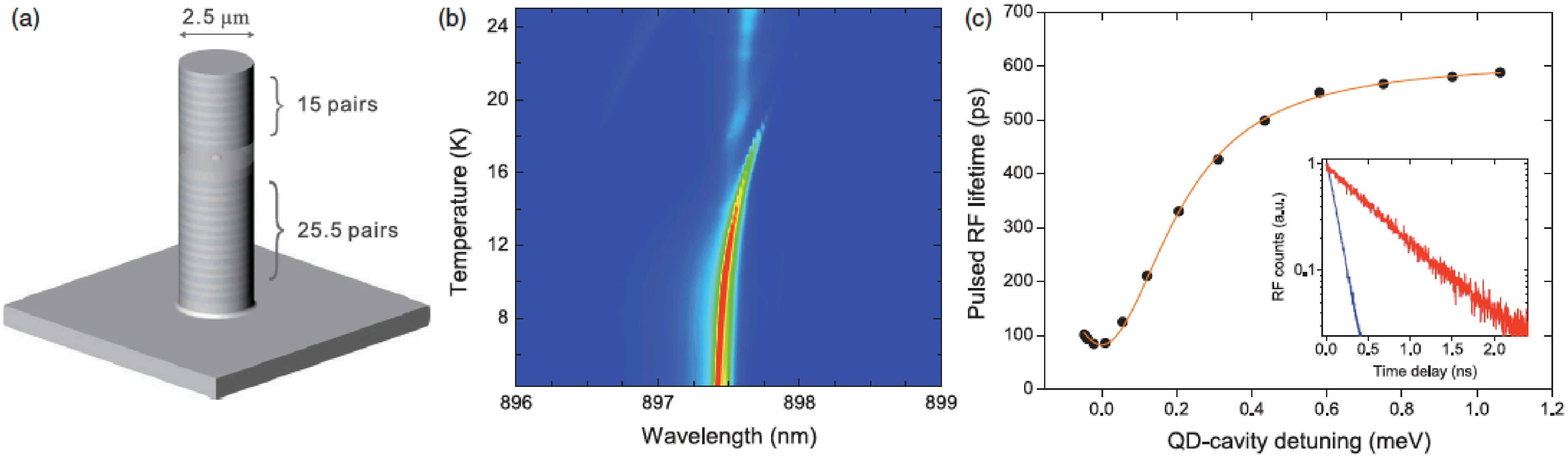
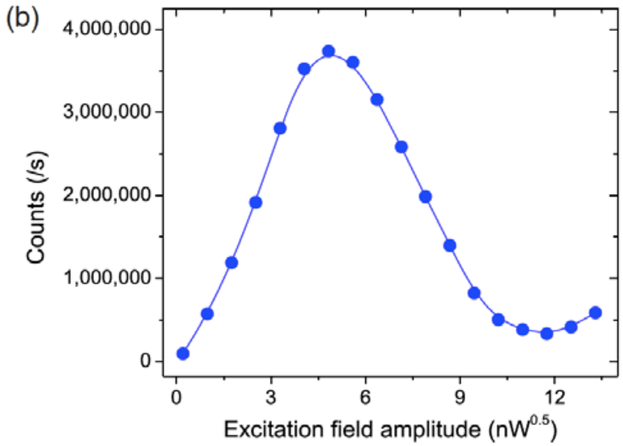


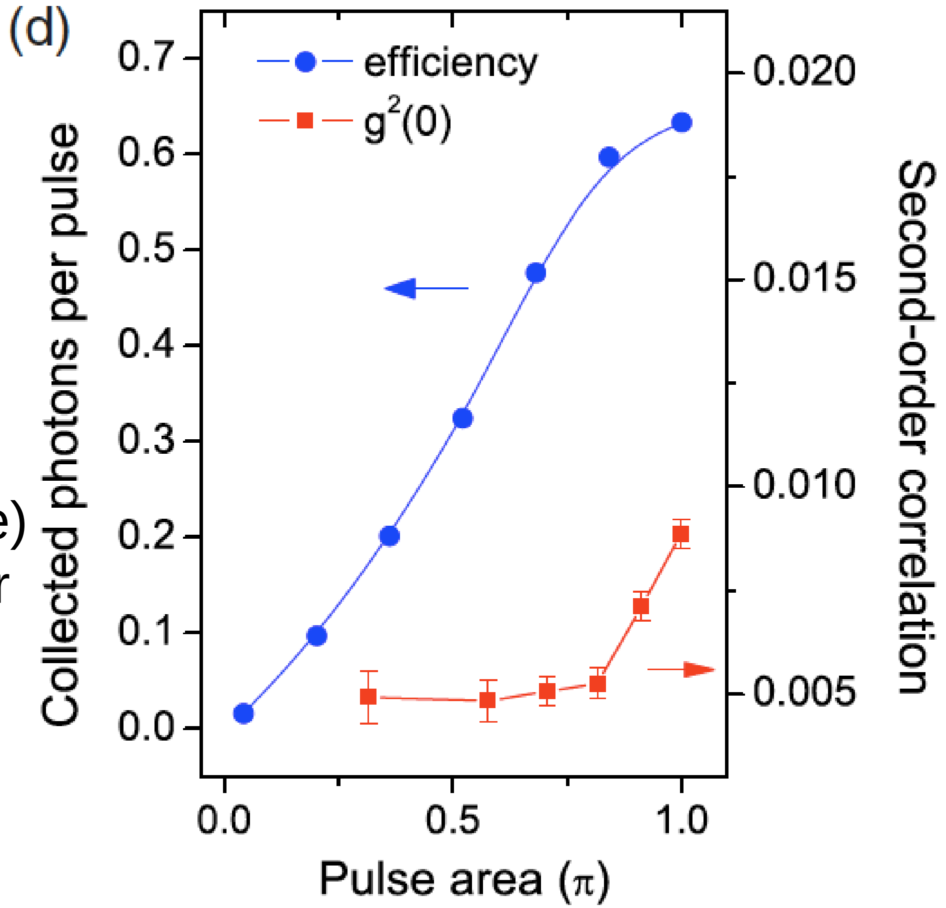
FIG. 1. Purcell-enhanced QD-micropillar system. (a) An illustration of a single QD embedded in a micropillar. The QD is grown via molecular beam epitaxy, embedded in a λ-thick GaAs cavity and sandwiched between 25.5 lower and 15 upper DBR stacks. Micropillars with 2.5 μm diameter were defined via electron beam lithography [18]. (b) 2D intensity (in log scale) plot of temperature-dependent microphotoluminescence spectra. The excitation cw laser is at 780 nm wavelength and the power is $\sim$3 nW. (c) Pulsed RF lifetime as a function of QD-cavity detuning by varying the temperature. The time-resolved data are measured using a superconducting nanowire single-photon detectors with a fast time resolution of $\sim$63 ps. The orange curve is a fit using the standard theoretical formula from Ref. [19]. The inset shows two examples of time-resolved RF counts at QD-cavity resonance and at far detuning.

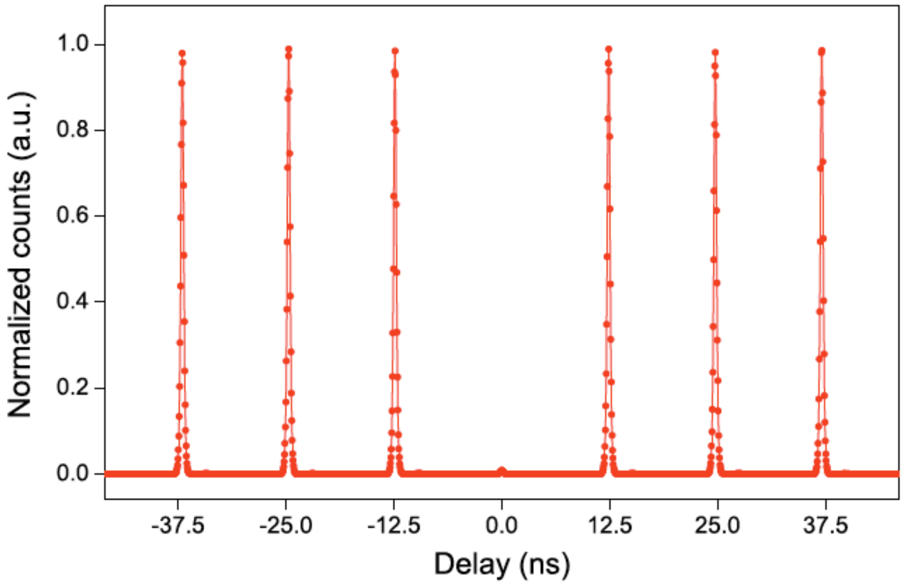
Achieved Q ~6100 → $F_{purcell}$ = 6.3(4)

→ decay reduced from 590ps to 84 ps



Rabi oscillation (resonance fluorescence)
→ peak excitation for 24 nW laser power



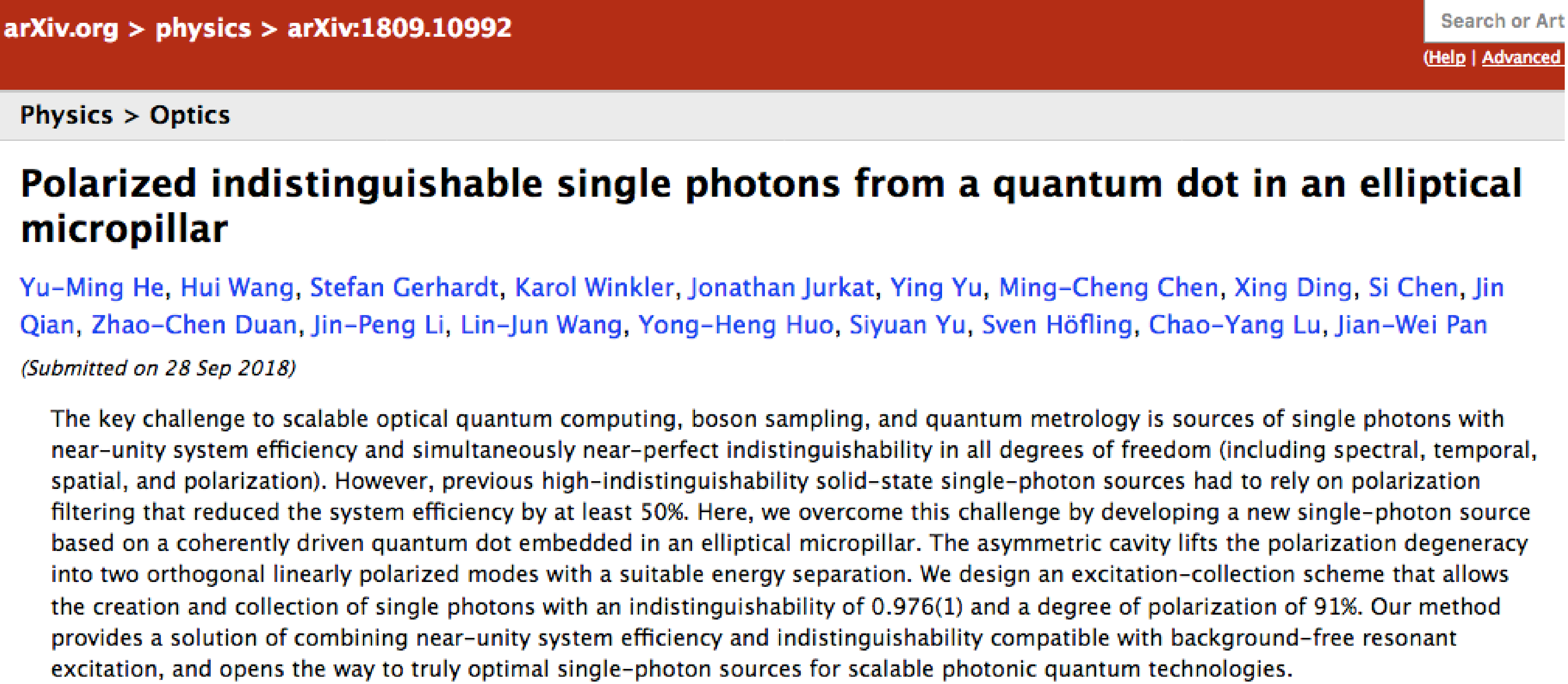


Measured $g^{(2)}$ as low as 0.005

Actual efficiency = $3.7\text{x}10^6$/81MHz

= 4.6% (~15% if we divide out $\eta_{detector}$)

Note: They used a polarization filter to block the pump (~10^7 extinction) → automatic 50% loss



arXiv.org > physics > arXiv:1809.10992

Physics > Optics

Polarized indistinguishable single photons from a quantum dot in an elliptical micropillar

Yu-Ming He, Hui Wang, Stefan Gerhardt, Karol Winkler, Jonathan Jurkat, Ying Yu, Ming-Cheng Chen, Xing Ding, Si Chen, Jin Qian, Zhao-Chen Duan, Jin-Peng Li, Lin-Jun Wang, Yong-Heng Huo, Siyuan Yu, Sven Höfling, Chao-Yang Lu, Jian-Wei Pan

(Submitted on 28 Sep 2018)

The key challenge to scalable optical quantum computing, boson sampling, and quantum metrology is sources of single photons with near-unity system efficiency and simultaneously near-perfect indistinguishability in all degrees of freedom (including spectral, temporal, spatial, and polarization). However, previous high-indistinguishability solid-state single-photon sources had to rely on polarization filtering that reduced the system efficiency by at least 50%. Here, we overcome this challenge by developing a new single-photon source based on a coherently driven quantum dot embedded in an elliptical micropillar. The asymmetric cavity lifts the polarization degeneracy into two orthogonal linearly polarized modes with a suitable energy separation. We design an excitation-collection scheme that allows the creation and collection of single photons with an indistinguishability of 0.976(1) and a degree of polarization of 91%. Our method provides a solution of combining near-unity system efficiency and indistinguishability compatible with background-free resonant excitation, and opens the way to truly optimal single-photon sources for scalable photonic quantum technologies.

For the end users in quantum information, it is the single-photon system efficiency that ultimately matters. For instance, a system efficiency above 50% is necessary for the boson sampling[2] to show quantum advantages over classical computers. While our current single-photon source has overcome the 50% loss due to polarization filtering, its final system efficiency is about 15%, which is mainly limited by the Purcell factor of 3.4, scattering loss (~20%) due to imperfect micropillar sidewall, single-mode fiber coupling loss (~30%), and transmission loss (~47%) in the optical setup. Future work