Quantum Dot Devices for Single Photon Quantum Systems

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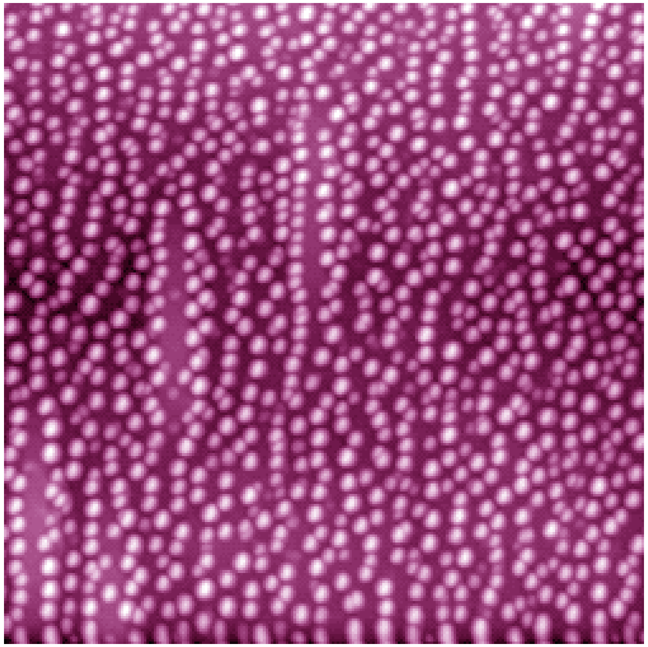
Boulder, Colorado

2007 SPIE Photonics West Invited Talk



2 µm x 2 µm Atomic Force Micrograph

I. Overview
II. Single Photon Sources
III. Single Photon Detectors
IV. Summary

Needs in Single Photon Quantum Systems

- **On-demand single photon sources**
  - **One and only one photon**
  - **High efficiency**
  - **Fast (short spontaneous emission lifetime)**
  - **Indistinguishable (spatial mode, polarization, transform-limited)?**

- **Single photon detectors**
  - **Fast**
  - **High quantum efficiency**
  - **Low dark count rate (no false positives)**
  - **Photon number resolving**
  - **No “afterpulsing”**
  - **Short “deadtime”**

Single Quantum Dot Single Photon Emitters

- Single photon is the fundamental particle for optical metrology
- Quantum radiometry: measure optical power by counting photons
- Quantum cryptography/quantum key distribution: provably secure method for communications
- Fundamental physics (quantum teleportation, Bell's inequality)
- Stepping stone for quantum optics and N-photonics, where N is an integer > 1 (linear optical quantum computing, Heisenberg limited interferometry)

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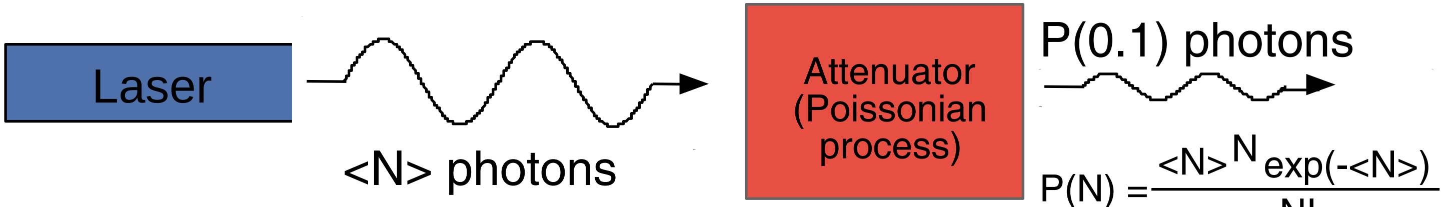
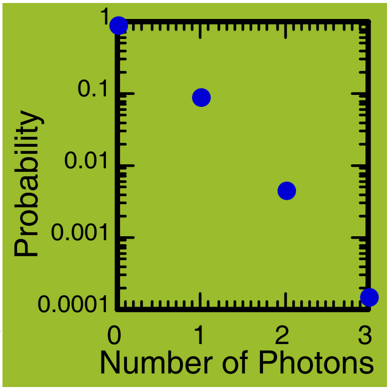
One Photon At a Time

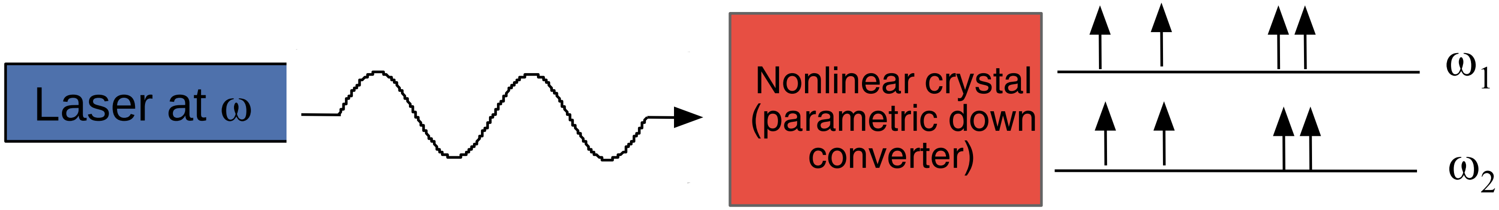
1) Attenuated laser beam



$$P(N) = \frac{\langle N\rangle^{N} \exp(-\langle N\rangle)}{N!}$$

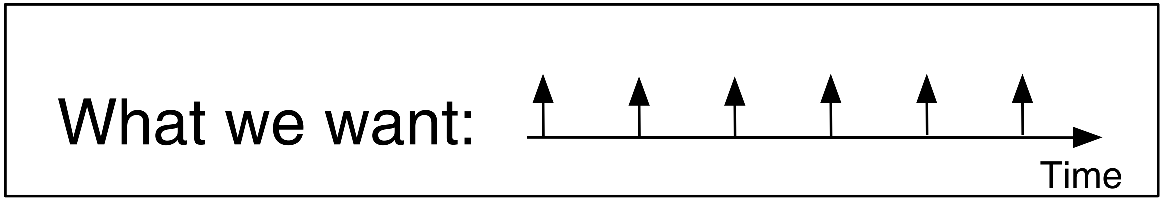


2) Optical parametric downconversion

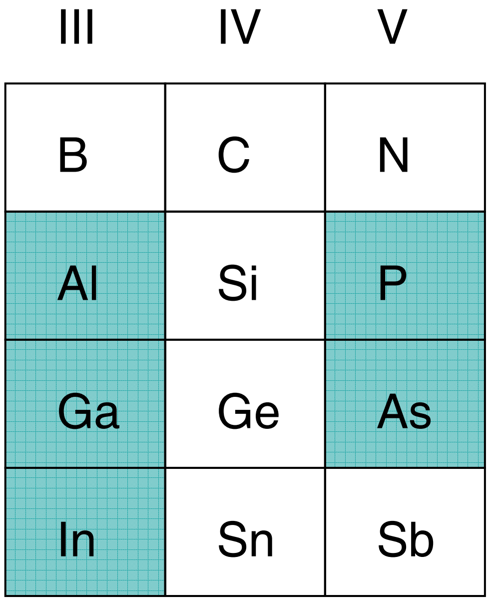


Extremely well-correlated photons generated

BUT... 1) Intensity noise due to Poissonian process (P(1) = 9%)
2) Sometimes get 2 photons (0.4%) or even 3 photons (0.02%)

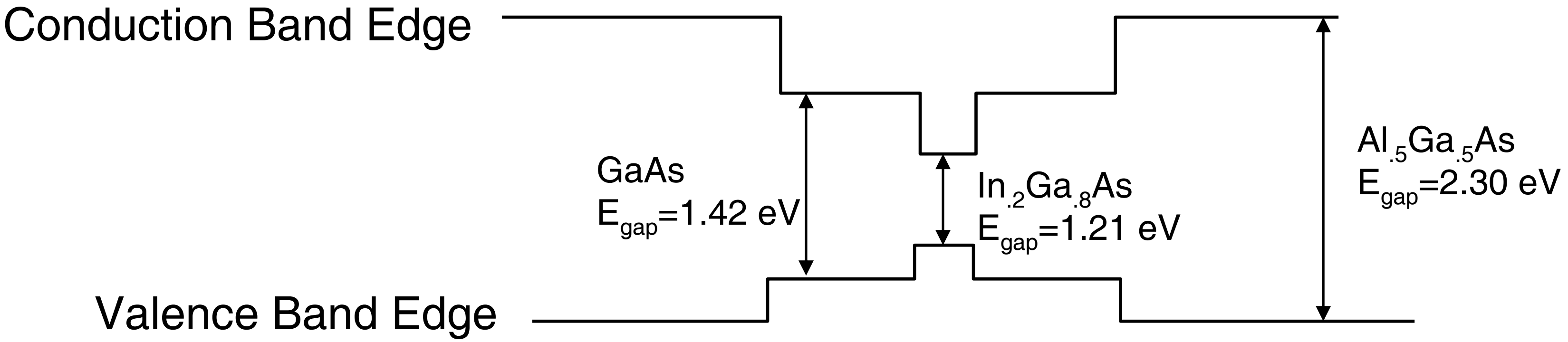


III-V Semiconductors



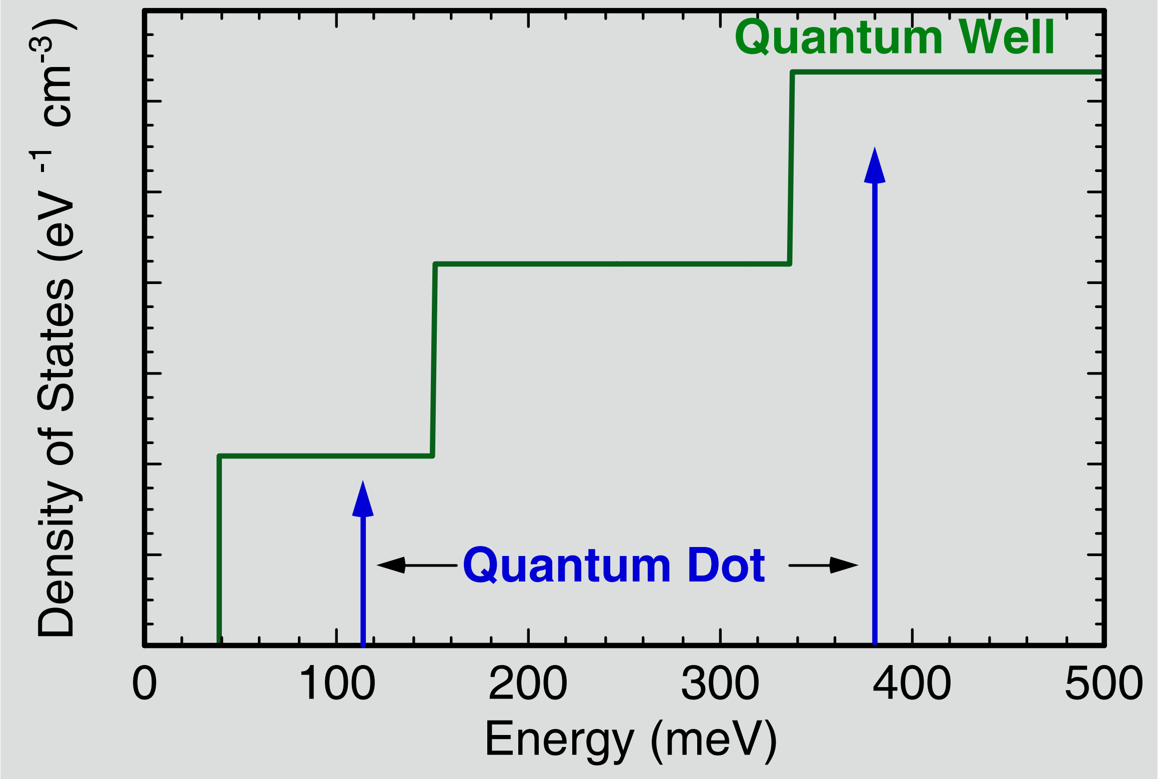
III	IV	V
B	C	N
Al	Si	P
Ga	Ge	As
In	Sn	Sb

- Heterostructures easily formed (Nobel Prize, 2000)
- RF electronics for wireless (cell phones, pagers,…)
- Optoelectronic devices-lasers, LEDS, photodiodes
- 2DEG used as Quantum Hall standard (working resistance standard) and cell phone amplifiers
- High quality epitaxial growth required



Semiconductor Quantum Dots

- Solid state realization of a quantum mechanical “particle-in-a-box”
- Density of states is discrete (*atomic-like*) instead of continuous



Quantum Dots <=> Atoms

- Improved devices such as laser diodes and optical amplifiers
- Novel devices such as single photon sources and detectors, optical memory, quantum logic gates

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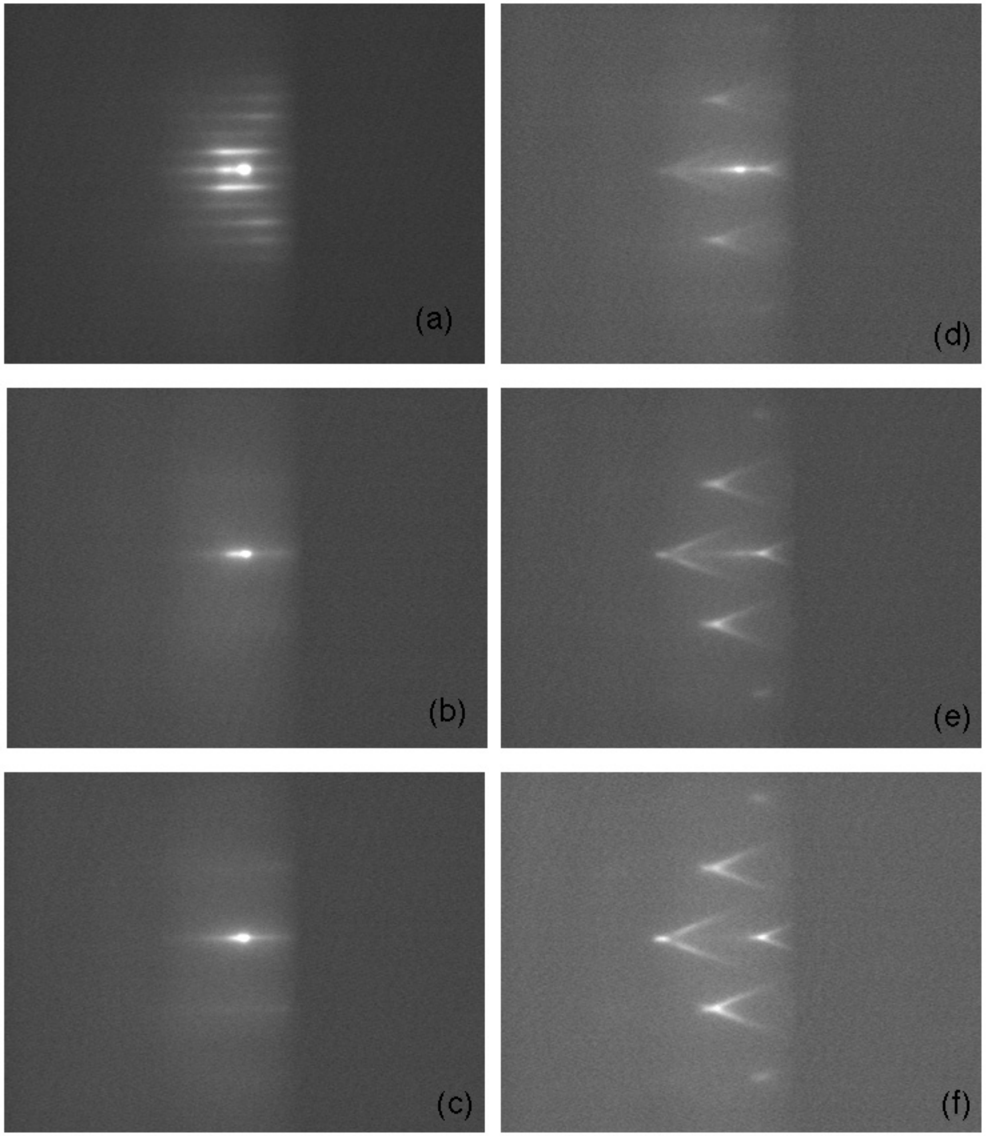
RHEED Transition



- Electron beam incident along [0-11]
- “Streaky” to “spotty” transition indicates 2D-to-3D growth transition (d)
- Mixture of chevrons and streaks indicates moderate dot density ($< 10^9$ cm^{-2})
- Chevrons indicate well-defined facet planes-{311} for these growth conditions

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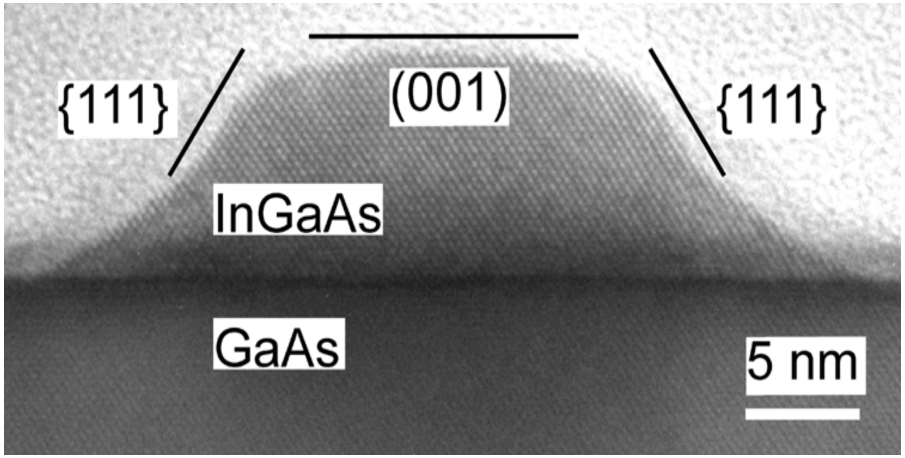
Quantum Dot Structural Characterization

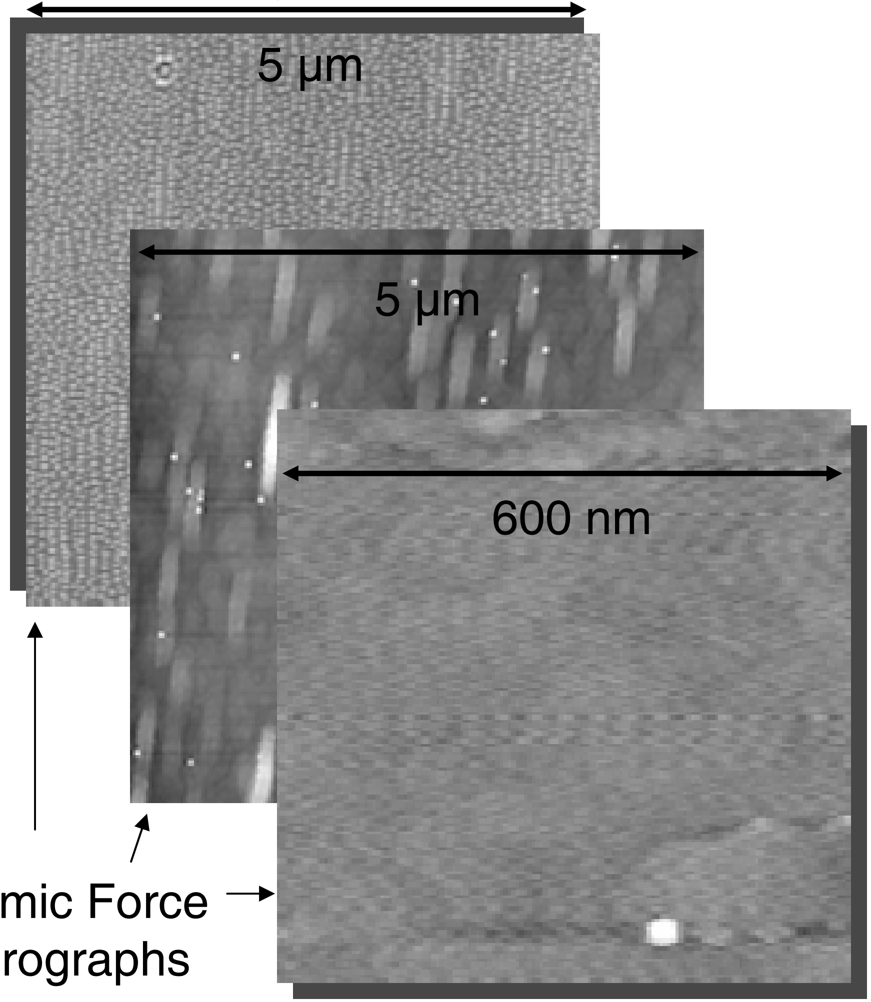


Transmission Electron Micrograph
(courtesy of A.G. Norman, NREL)

Areal Density and Height Control

1) Substrate temperature
2) Growth rate
3) Indium mole fraction
4) Amount of deposited material
5) Arsenic flux

Dense array: ~5×10^{10} cm^{-2}



Atomic Force Micrographs

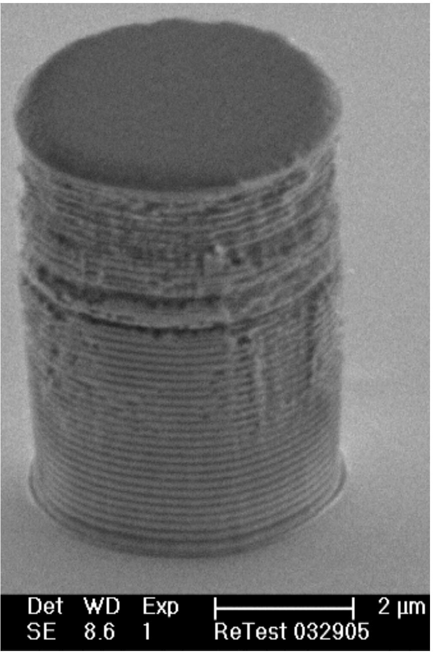
Sparse array: ~3×10^{8} cm^{-2}

Quantum Dot Single Photon *Sources* Studied with Superconducting Single Photon *Detectors*

Quantum dot single photon sources

Micropillar Cavity

Cavity-Enhanced Lifetime

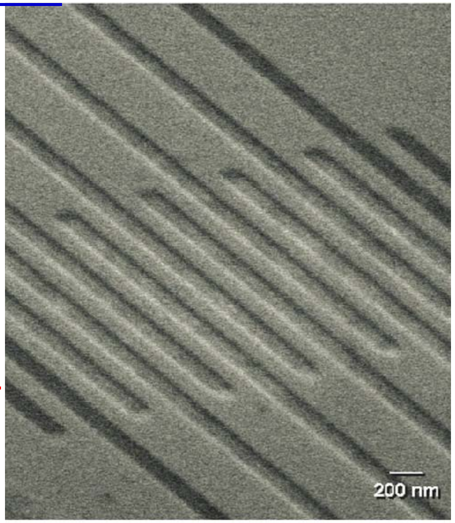


Superconducting single photon detectors

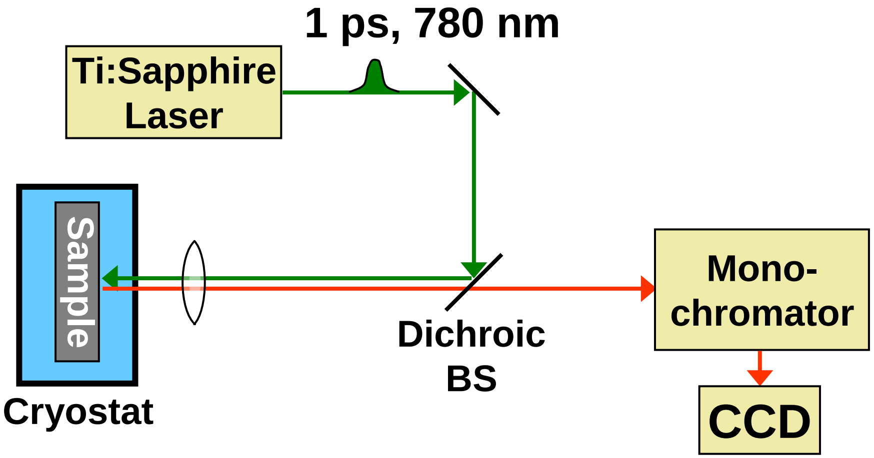
- **Lifetime measurements**
  - **- Low dark counts**
  - **- Gaussian response**
  - **- Sensitive beyond 1 μm**

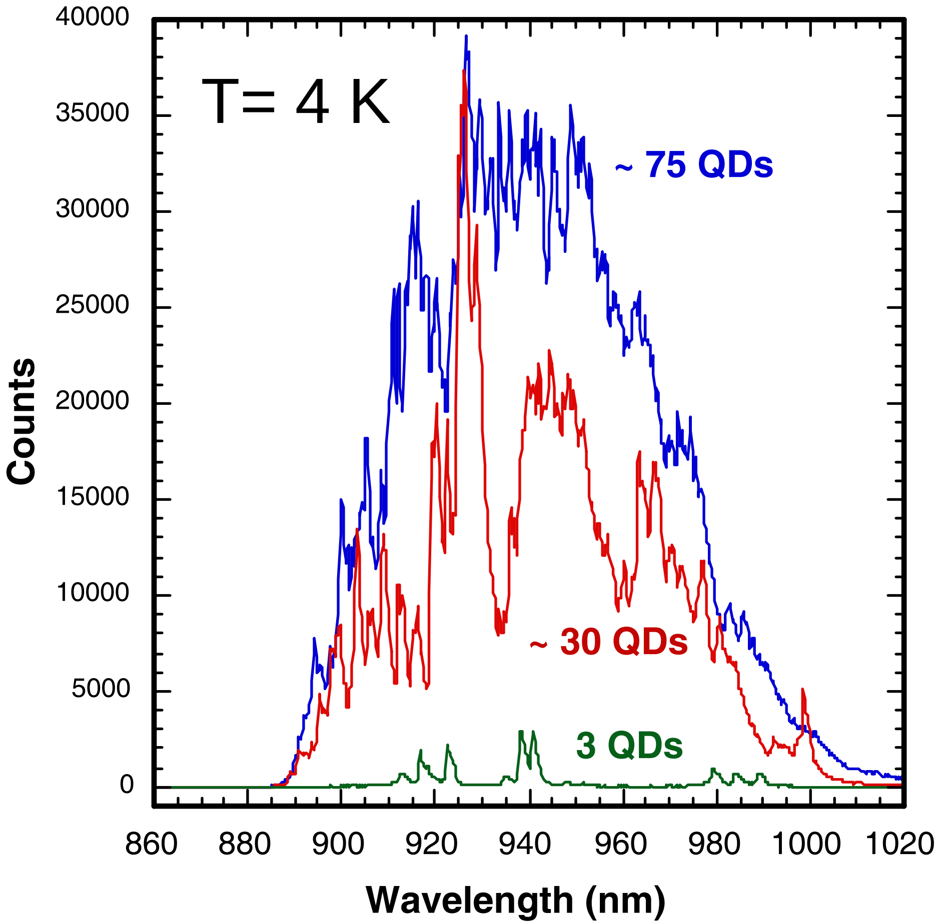
Demonstrate single photon emission

- **Avalanche photodiodes**
- **Superconducting detectors**



Experiment: Measure Spectrum





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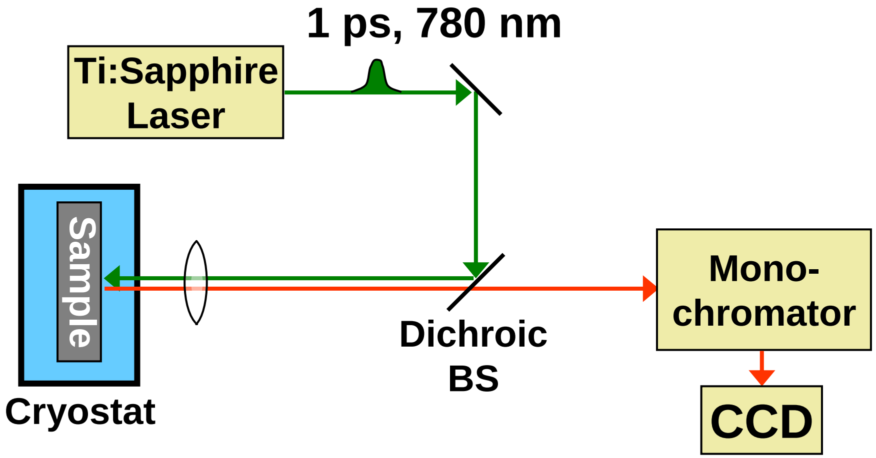
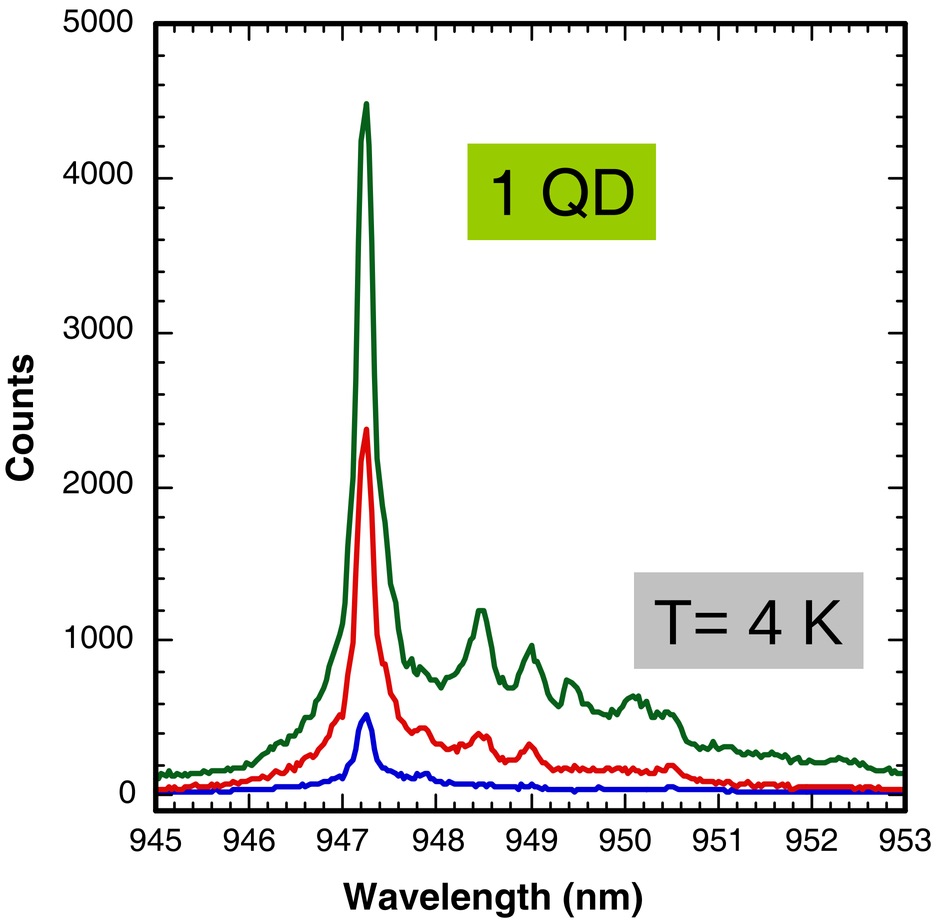
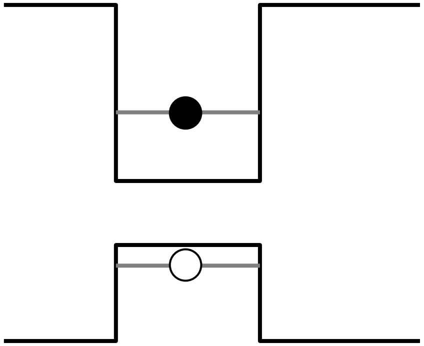
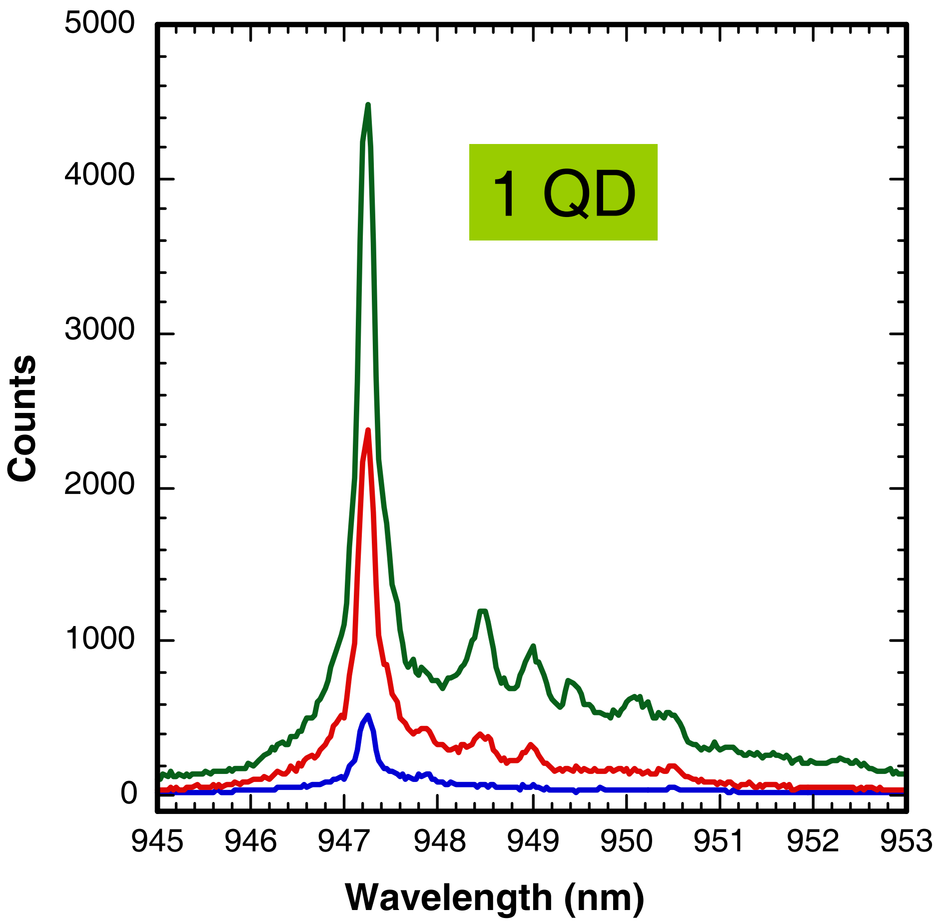




Quantum Dot Photoluminescence

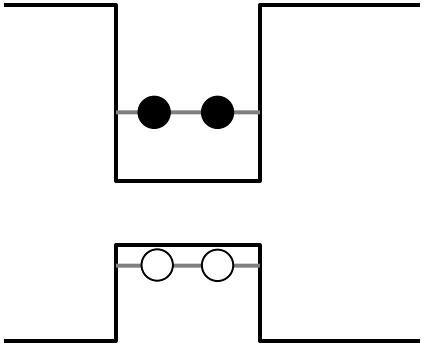
Exciton

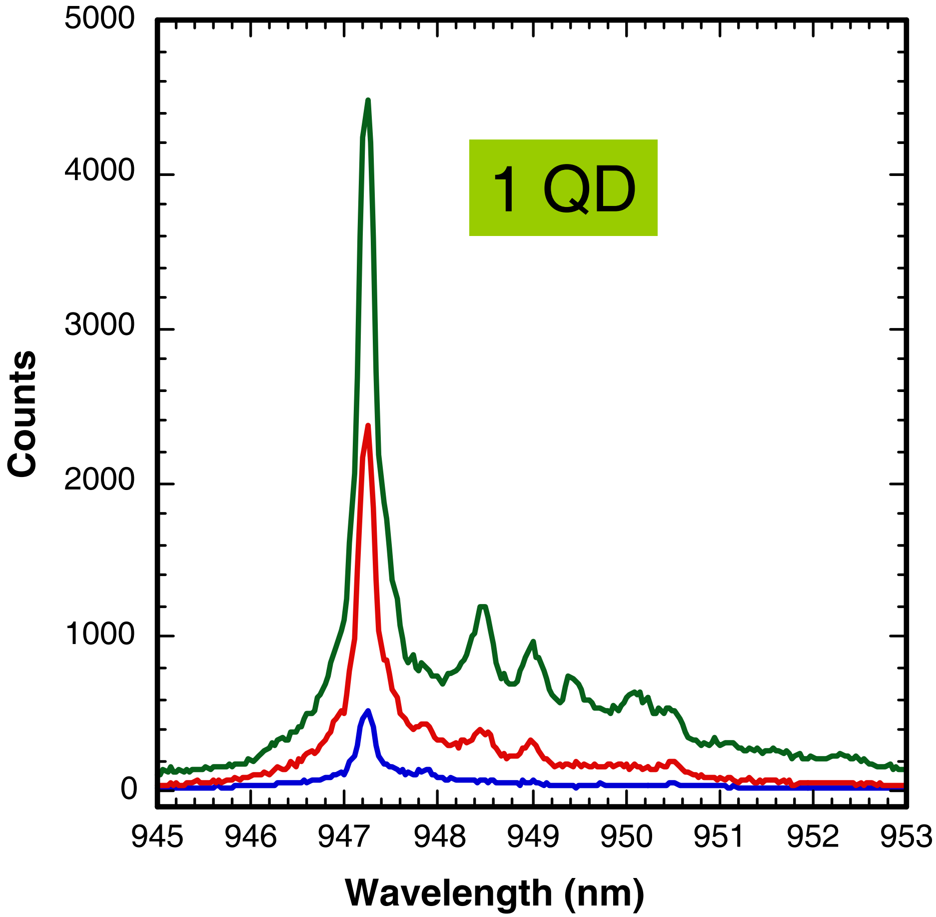




Quantum Dot Photoluminescence

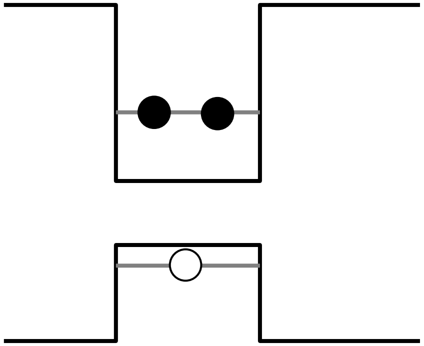
Biexciton

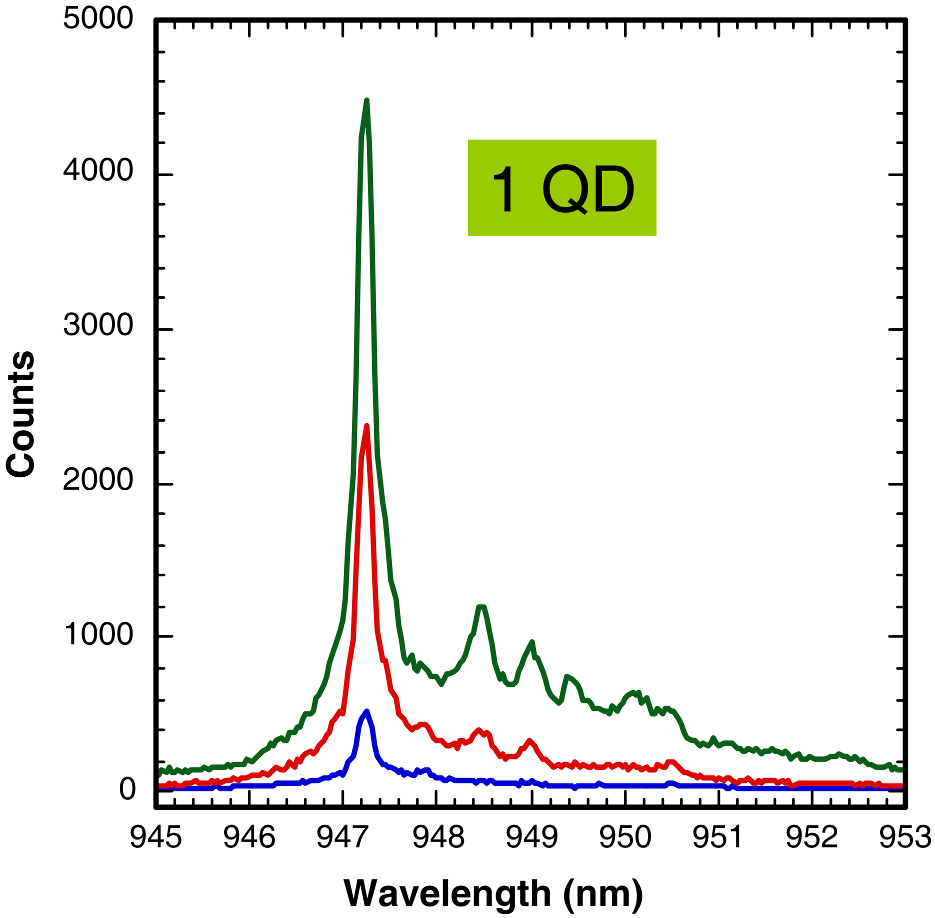




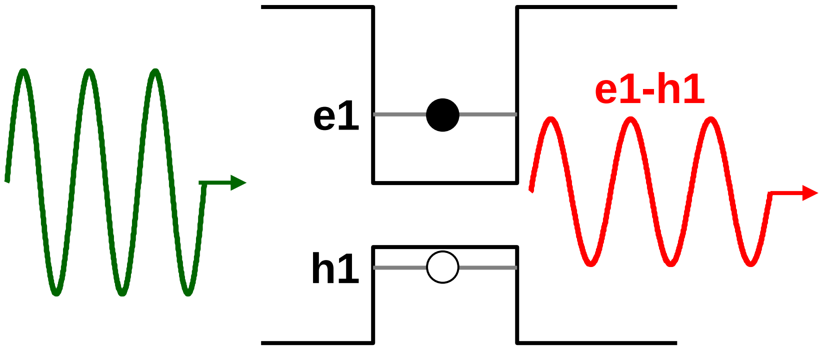
Quantum Dot Photoluminescence

Charged exciton





Optically-Pumped Single Photon Turnstile

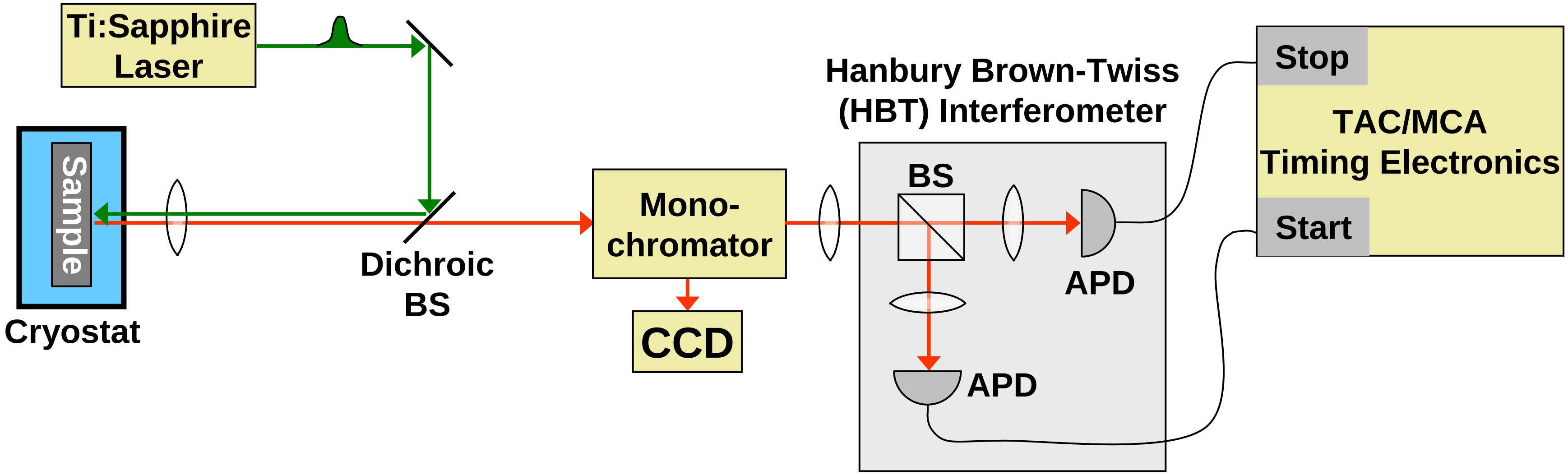


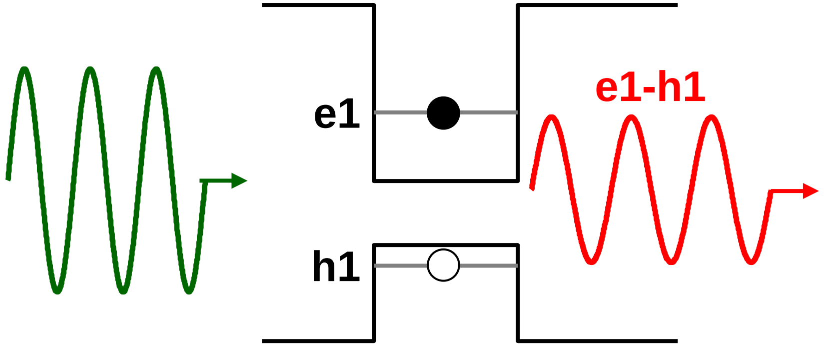
Many pump photons at 780 nm

One **photon out at 900 nm**

Each pump pulse generates *at most* one exciton with transition energy e1-h1

Optically-Pumped Single Photon Turnstile





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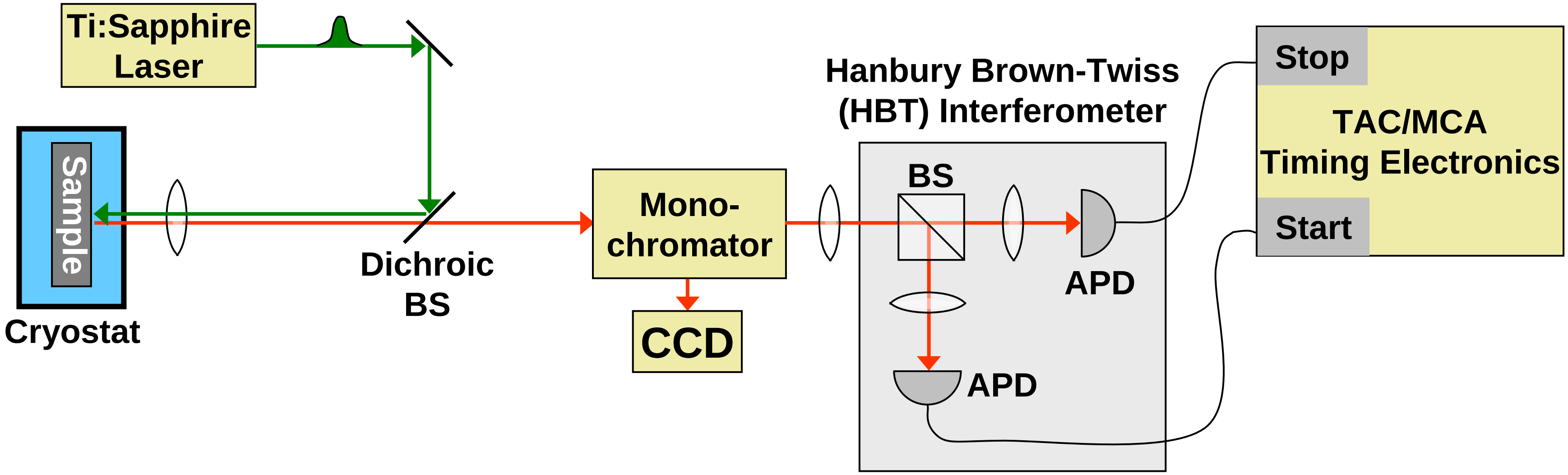
Optically Pumped Single Photon Turnstile



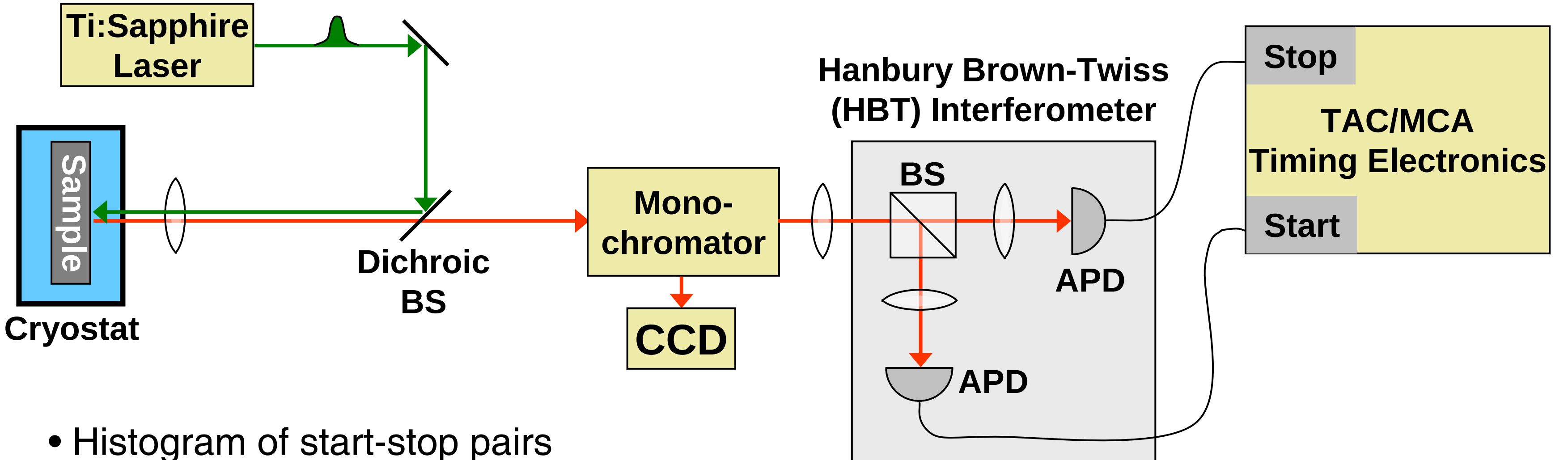
- **Hanbury Brown Twiss Interferometer:**
  - **Histogram of start-stop pairs**

    → 2nd order intensity correlation:

$$g^{(2)}(\tau) = \frac{<: I(t)I(t+\tau) :>}{< I(t) >^2}$$

  - **How often does QD emit more than one photon?**

Optically Pumped Single Photon Turnstile



Ti:Sapphire Laser

Cryostat

Sample

Dichroic BS

Mono-chromator

CCD

Hanbury Brown-Twiss (HBT) Interferometer

BS

APD

APD

Stop

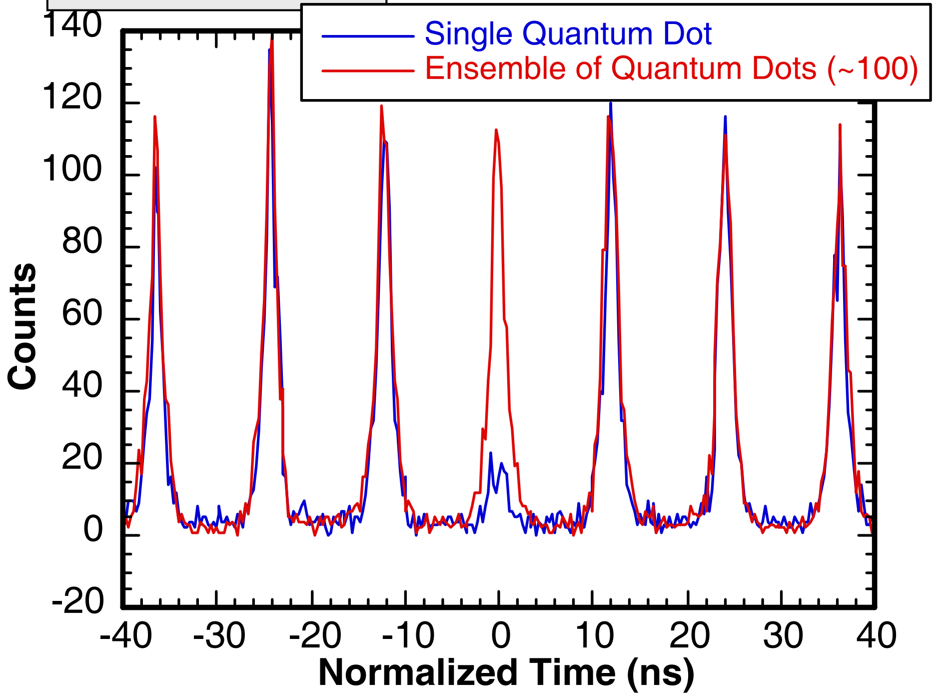
TAC/MCA Timing Electronics

Start

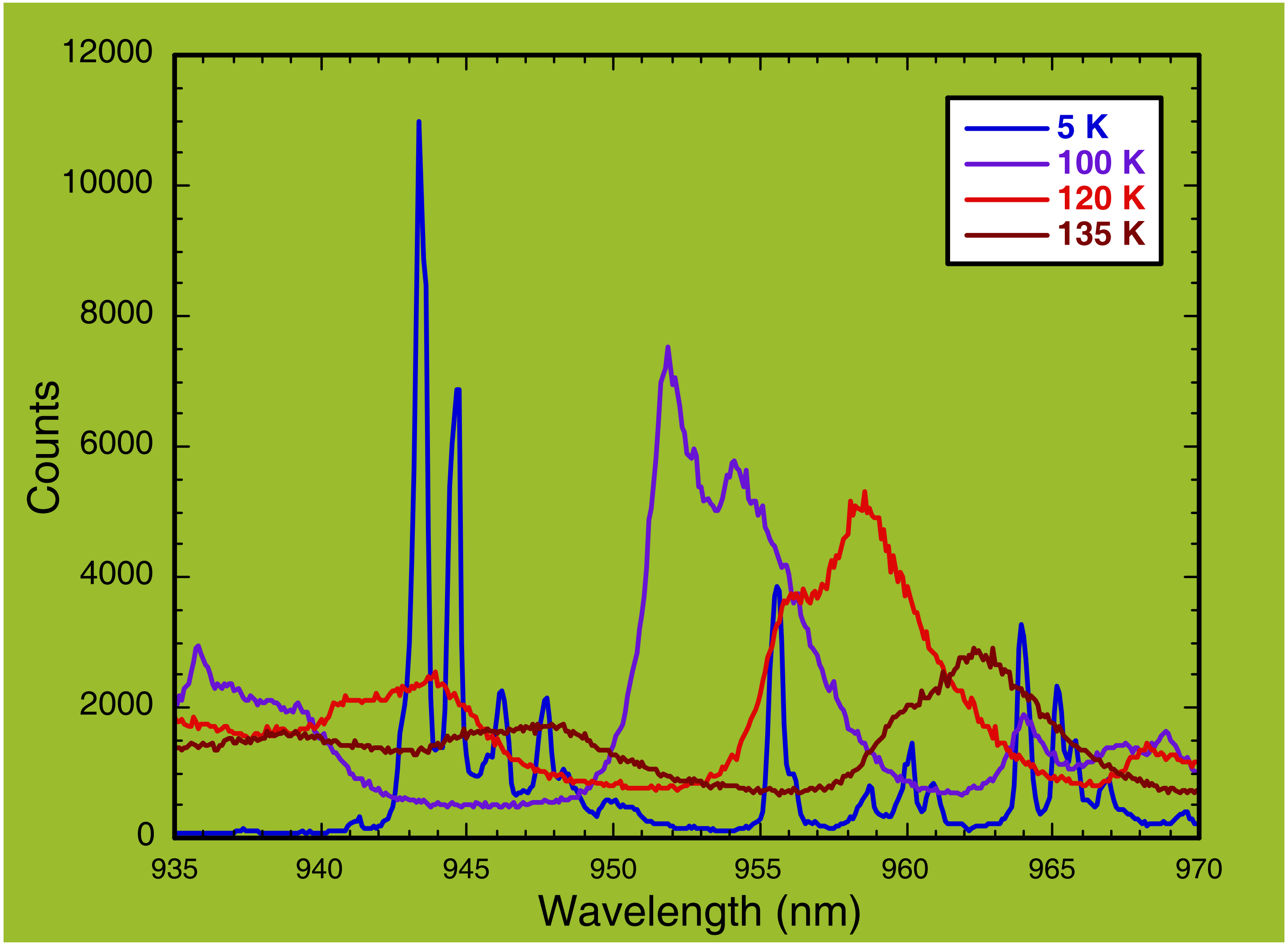
- Histogram of start-stop pairs corresponds to $g^{(2)}(\tau)$-second order intensity correlation

- Exciton emission from single QD exhibits strong anti-bunching; peak area < 20% of average peak area

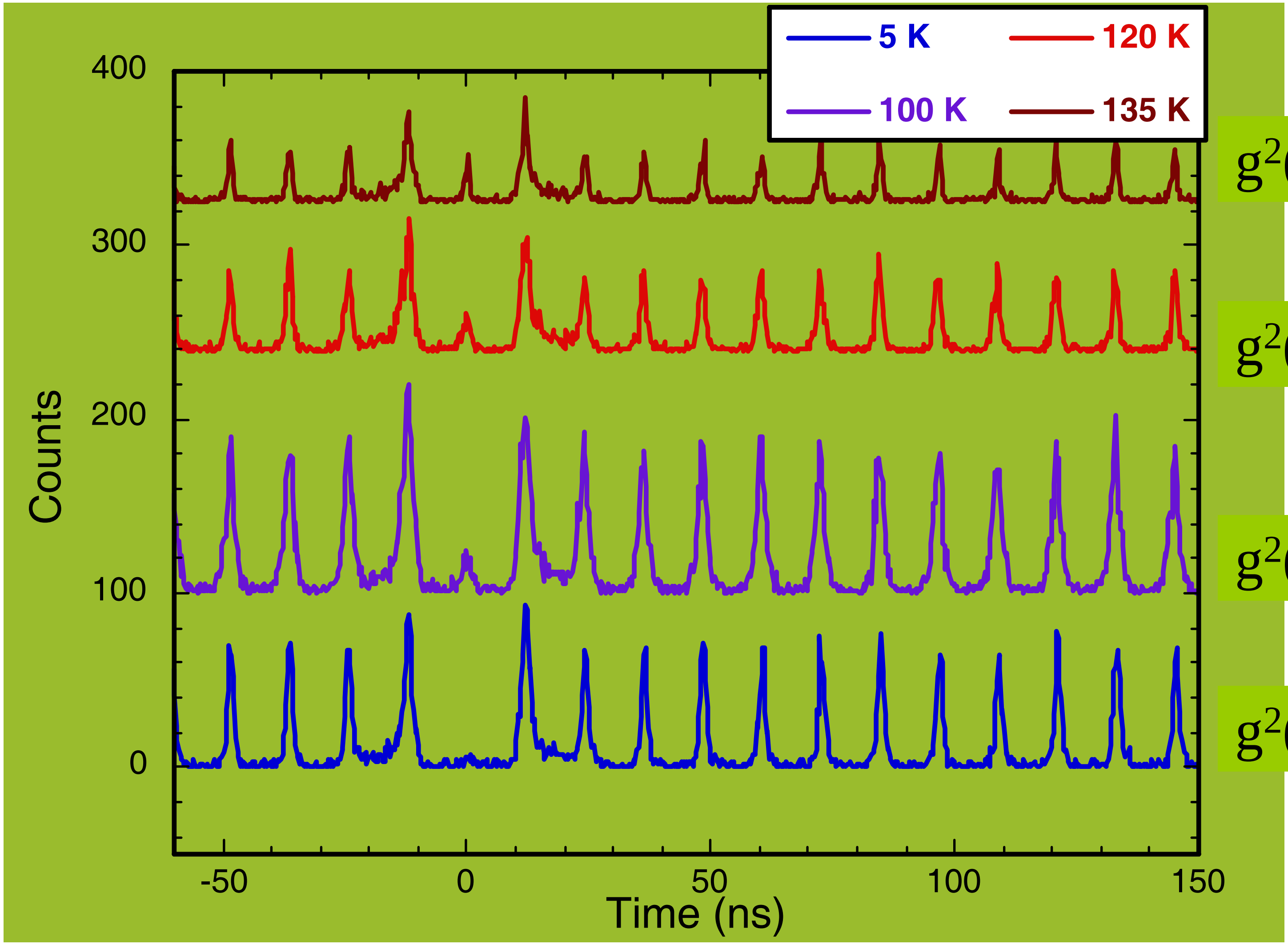
- Occasional multiphoton emission due to fast refilling of single exciton state under high optical excitation



Temperature-Dependent PL



Temperature-Dependent Single Photon Operation



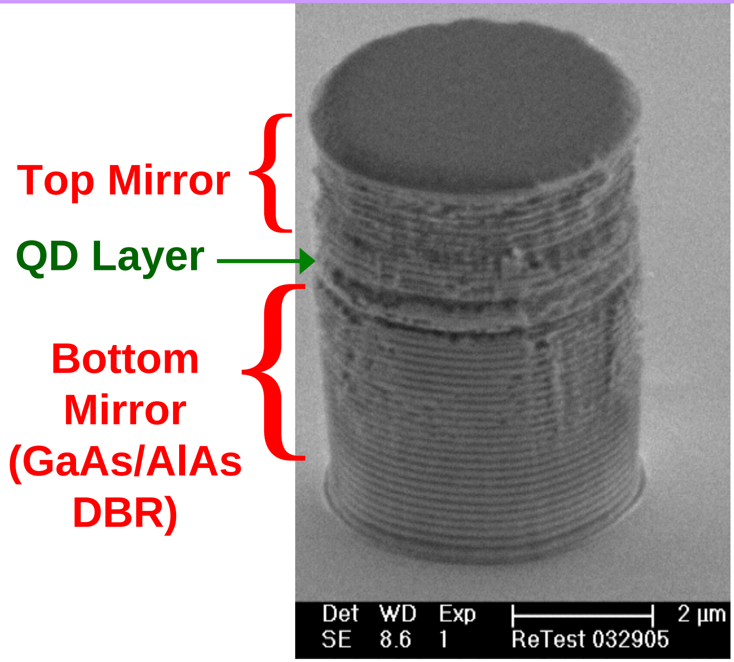
$g^2(0)=0.69$

$g^2(0)=0.48$

$g^2(0)=0.27$

$g^2(0)=0.09$

InGaAs Quantum Dots in Micropillar Cavities



- To isolate one QD:
  - Low density growth (1-10 μm^{-2})
  - Etch small pillars (1-10 μm^{2})
  - Spectral filtering

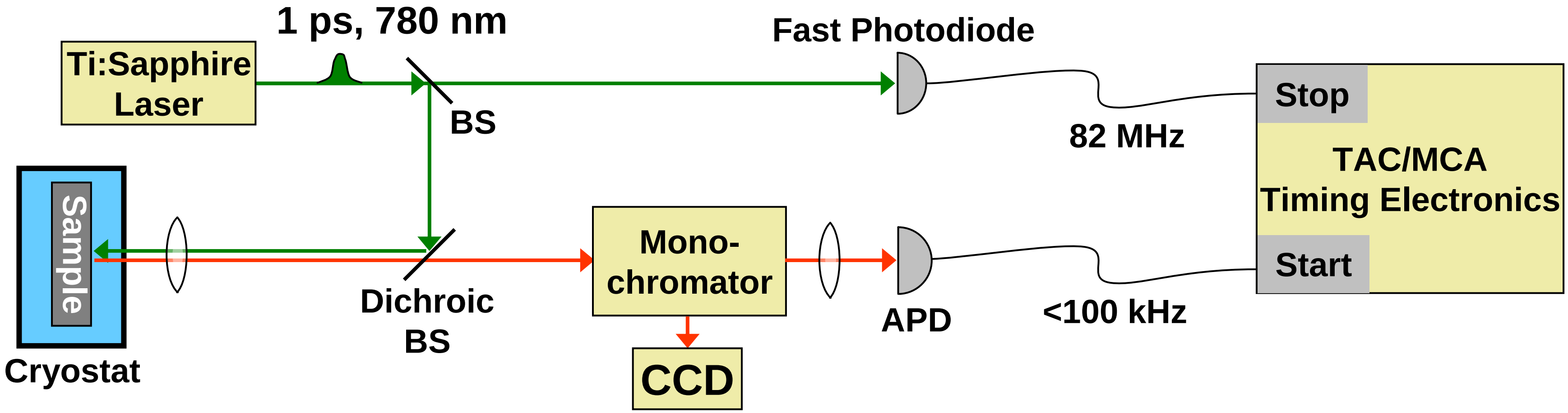
- Microcavity:
  - “Funnel” emission
  - Reduce lifetime (Purcell effect)

Purcell effect

$$\tau_{\text{Cavity}} \propto \frac{V \tau_{\text{Free}}}{Q\lambda^{3}}$$

→ Small pillars

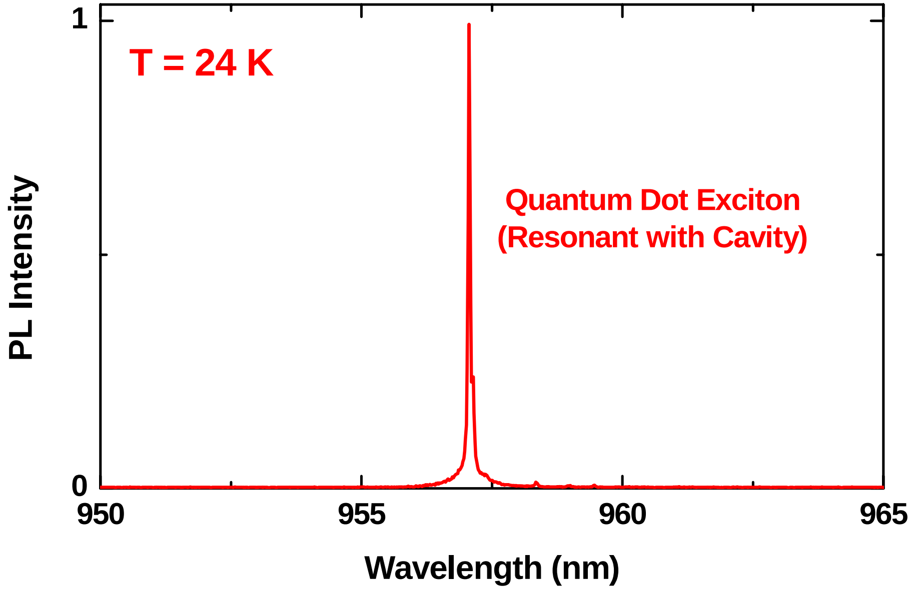
Experiment: Measure Lifetime

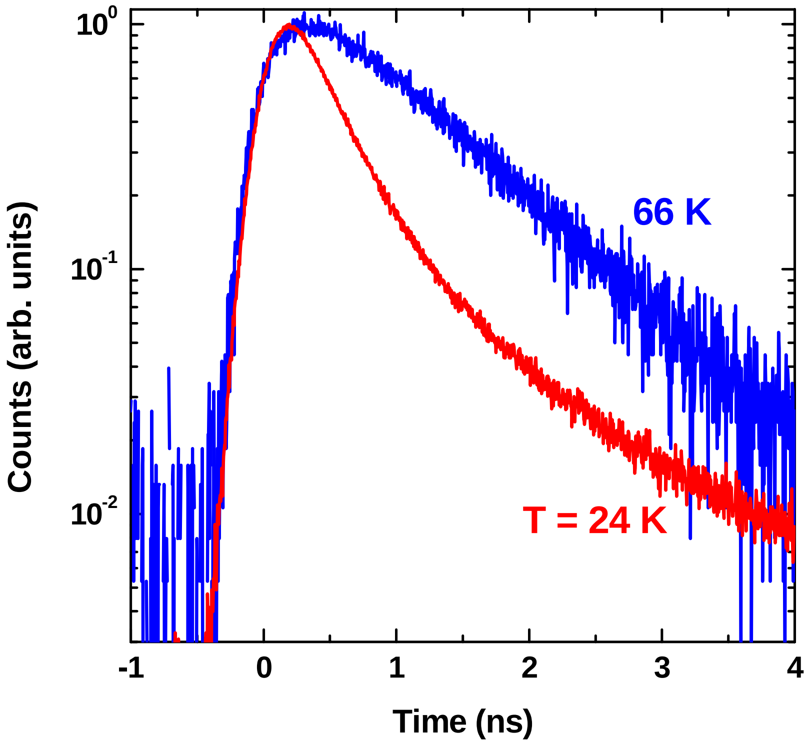


Time-Correlated Single Photon Counting (TCSPC)

- Single-photon sensitive detectors (APDs, PMTs, etc.)
- Time-to-Amplitude Converter (TAC) + Multichannel Analyzer (MCA)
- Ideal for weak sources (<< 1 detected photon/pump pulse)
- Time resolution down to ~40 ps
  - Single QD lifetimes ~100's – 1000's ps

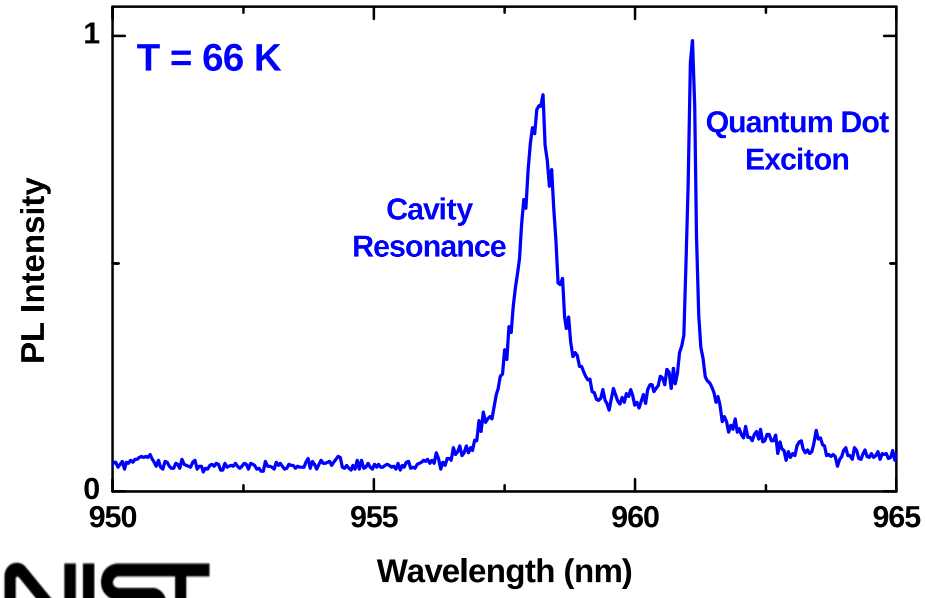
Cavity-Enhanced Emission





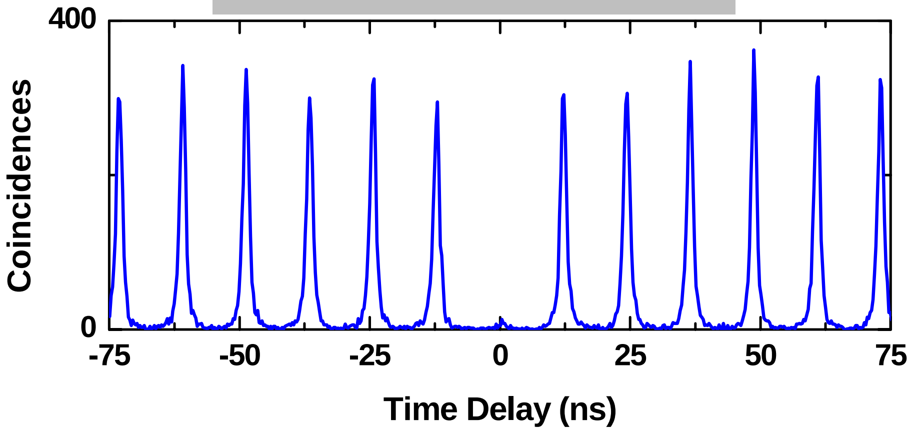
T$_1$ ≈ 450 ps @ 24 K (Better fit by a 2-exp decay)
T$_1$ ≈ 970 ps @ 66 K (Good single-exponential fit)

Dot-Cavity Detuning ~2.9 nm @ 66K



Cavity-Enhanced Emission

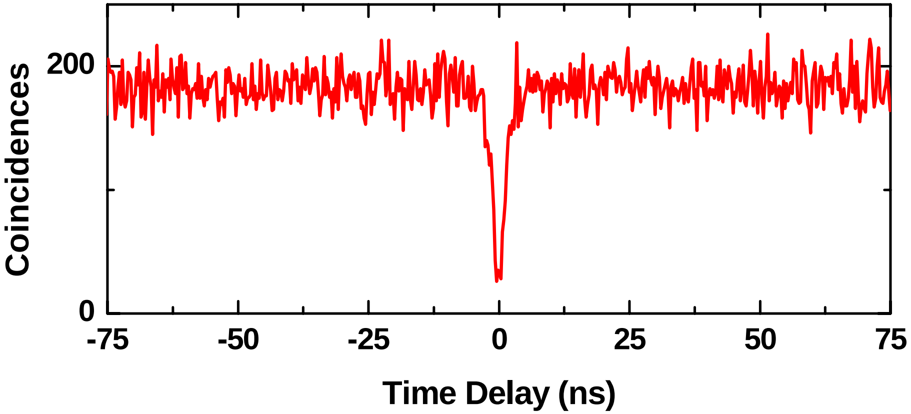
Pulsed excitation



$g^{(2)}(0) \approx 0.04$

~ 25 kHz per detector
~ 5 minutes acquisition time

CW excitation



$g^{(2)}(0) \approx 0.15$

~ 100 kHz per detector
~ 1 minute acquisition time

Summary: Single Photon Sources

- **Quantum dot single photon sources**
  - **Micropillar cavities**
    - **Decreased spontaneous emission lifetime**
- **Superconducting single photon detectors**
  - **Low timing jitter + Gaussian profile**

    → Improved lifetime measurements
  - **Infrared response (>1 μm)**

    → Single photon source characterization in telecom regime

Single Photon Detectors

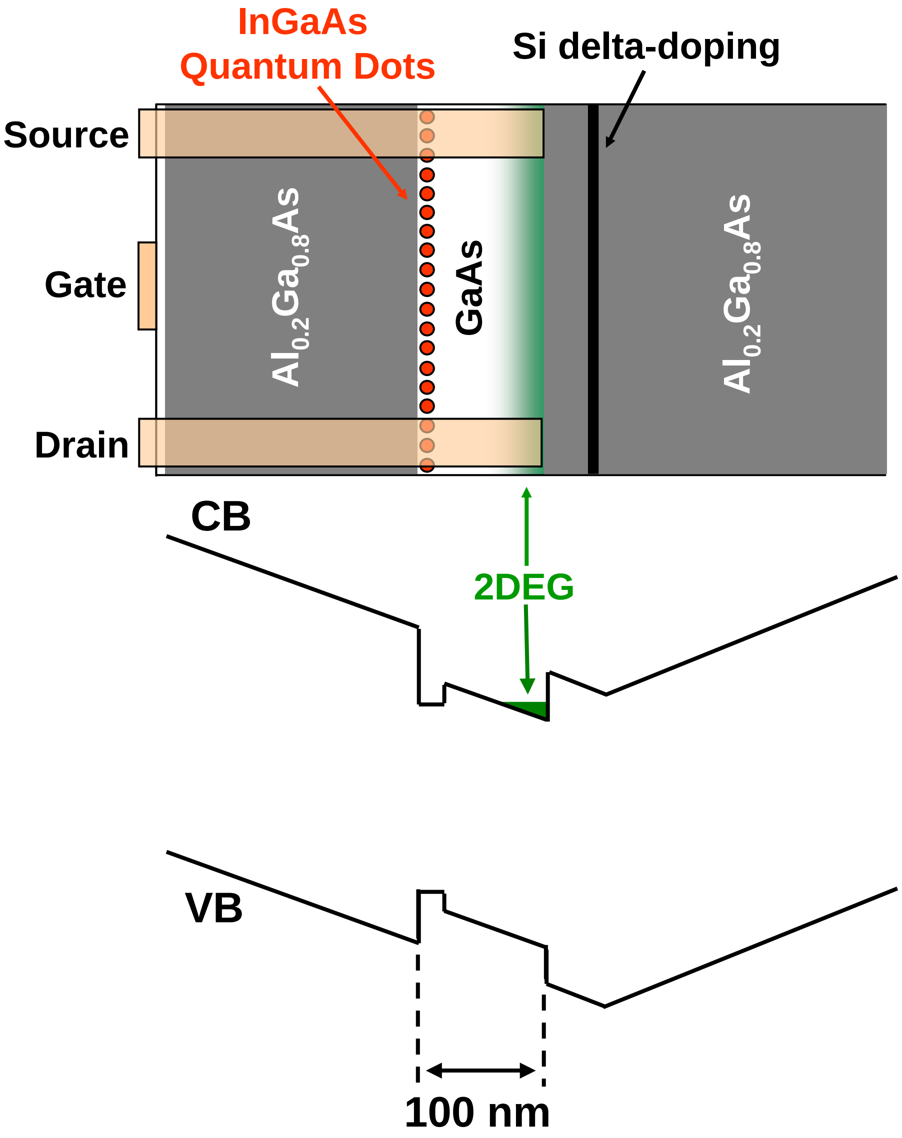
- Commercially available:
  - Photomultiplier tubes (PMTs)
  - Single photon avalanche diodes (SPADs)-Si or InGaAs

- Research labs:
  - Superconducting detectors
    - NbN SSPD-very fast
    - Transition edge sensor (TES)-PNR, highest QE
  - Semiconducting
    - Visible light photon counter (VLPC)
    - Quantum dot optically-gated field effect transistor (QDOGFET)

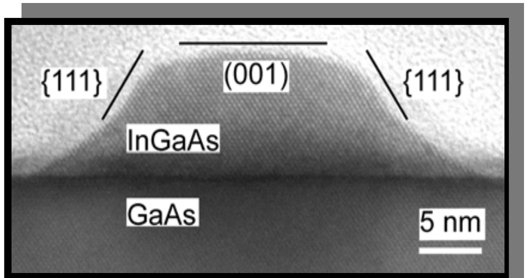
QDOGFET Advantages

- Wavelength tunable by choice of epitaxial layers
- Insensitive to blackbody radiation
- High temperature operation (at least 77 K)
- Low jitter (< 10 ps?)
- No high field region -> no breakdown flash or afterpulsing
- "Burst mode"-can detect several photons before reset required

QDOGFET Introduction



Here we use a layer of ***semiconductor quantum dots*** as an optically addressable floating gate in a modulation-doped FET.

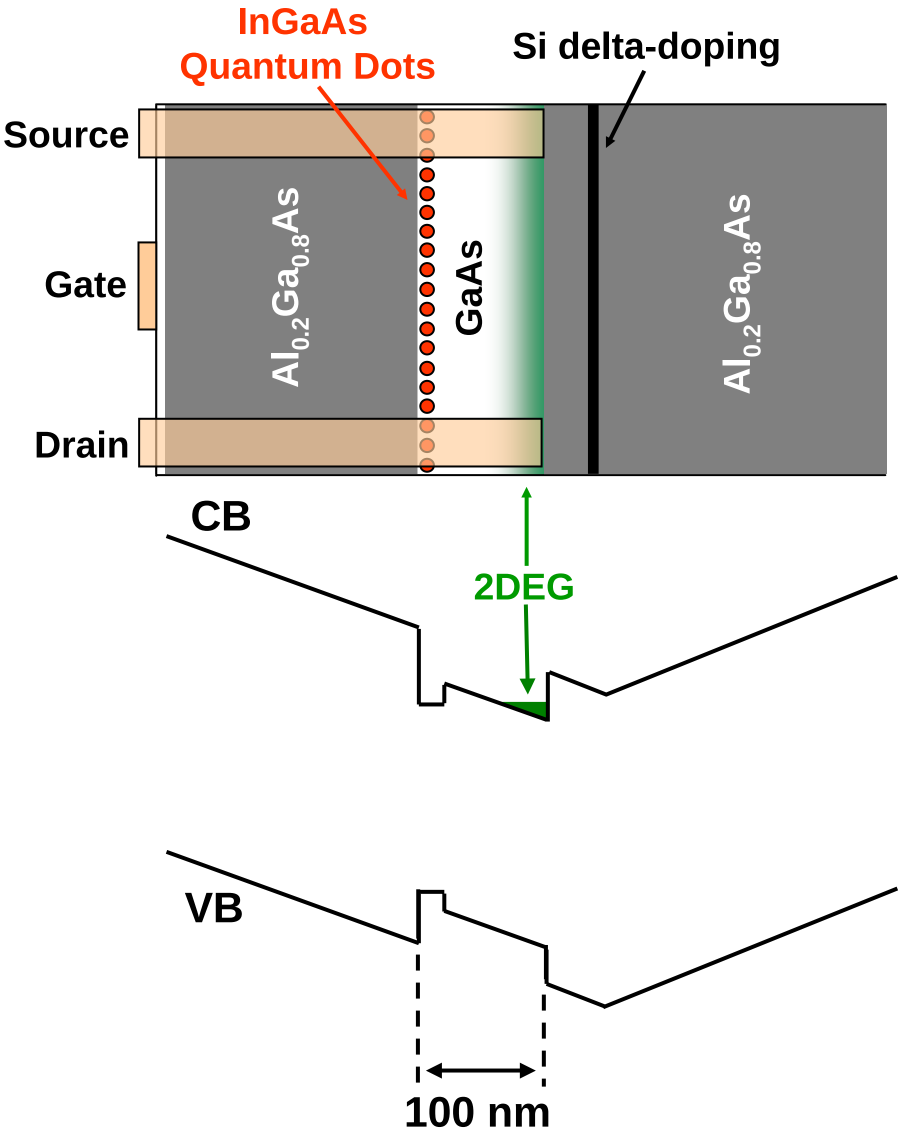


TEM (A.G. Norman, NREL)

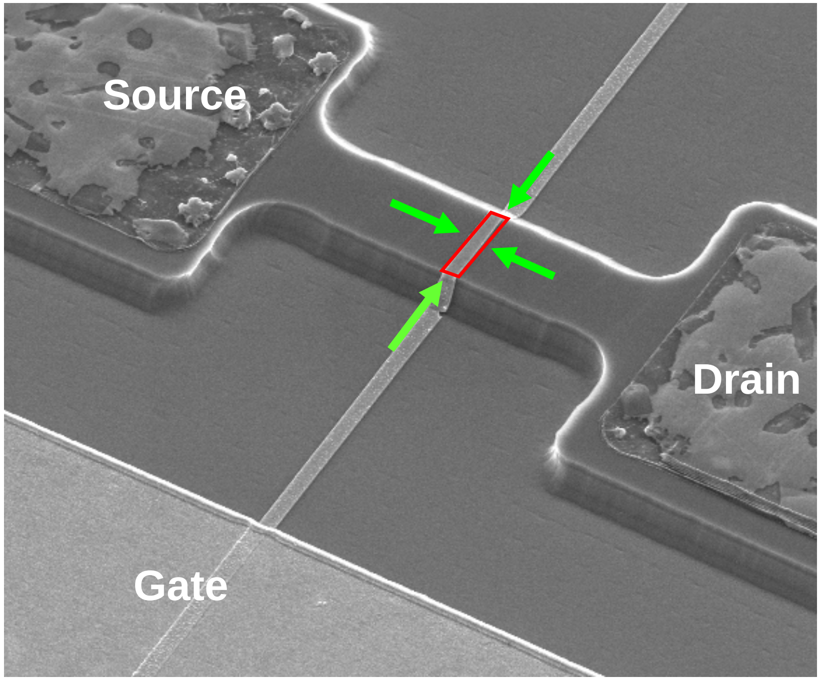
Detector Exhibits:

- **Single-photon sensitivity**
- **Linear response**
- **Low dark counts**
- **~70% Internal Quantum Efficiency**

QDOGFET Introduction



SEM Image

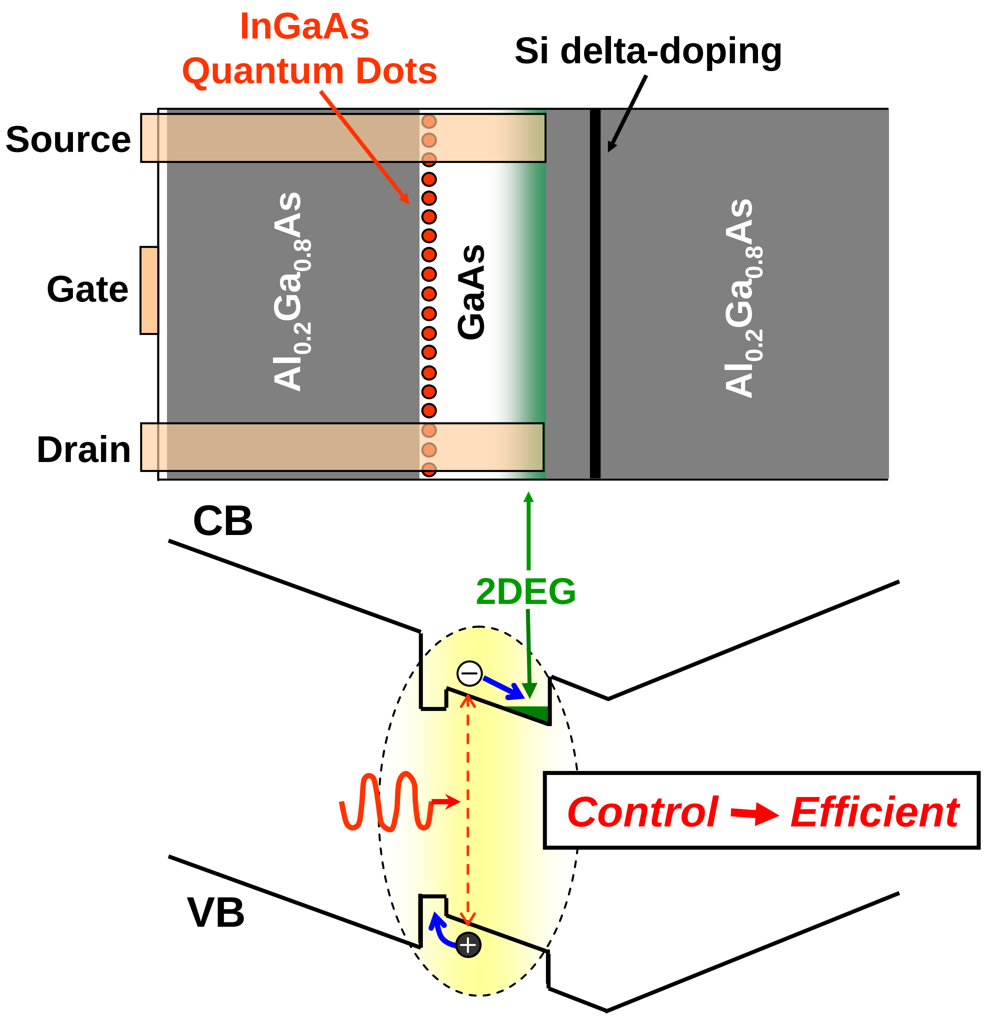


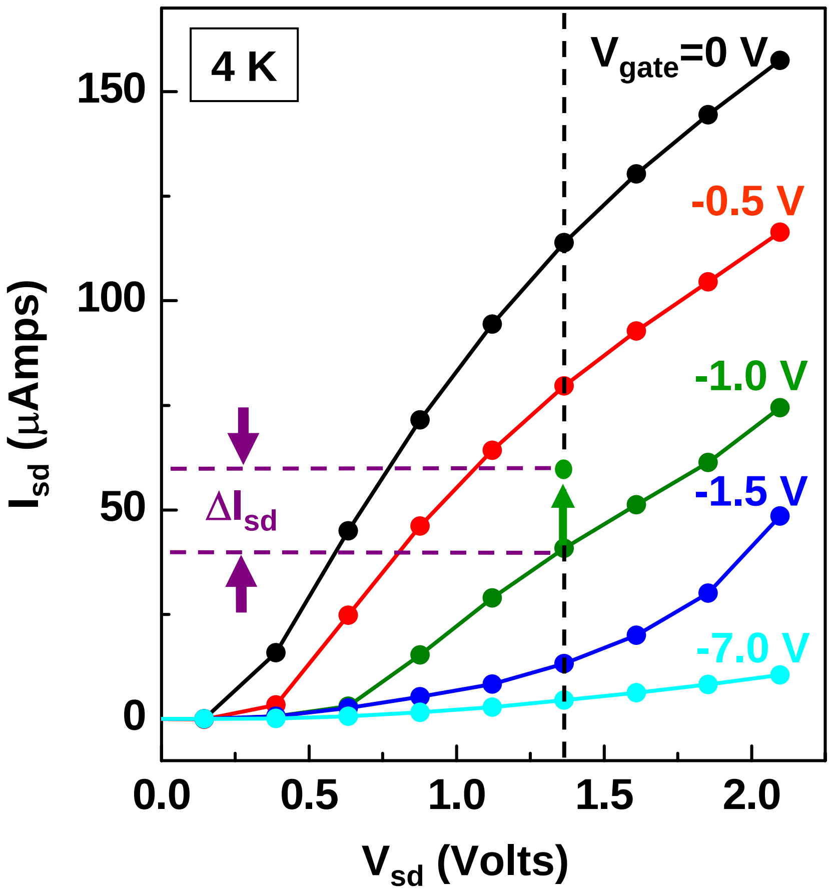
0.7 μm x 3.9 μm Active Region

QD Density: 400-500 QDs/μm^2

~1000 QDs in Active Region

QDOGFET Introduction

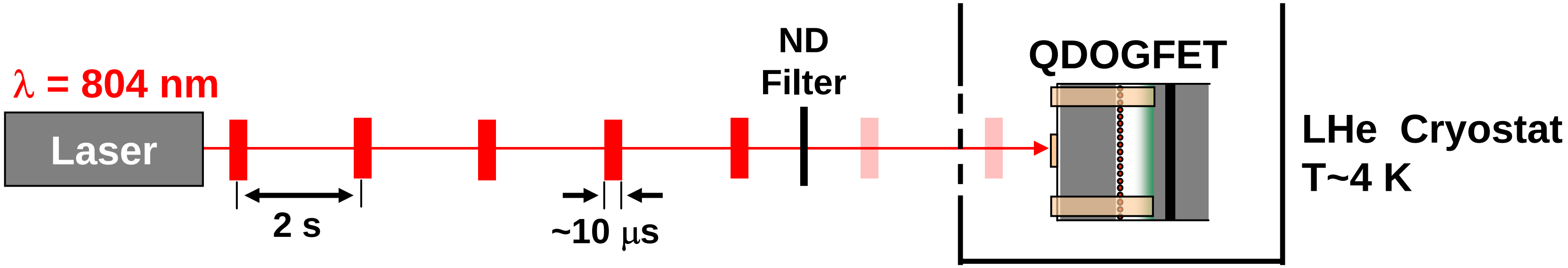




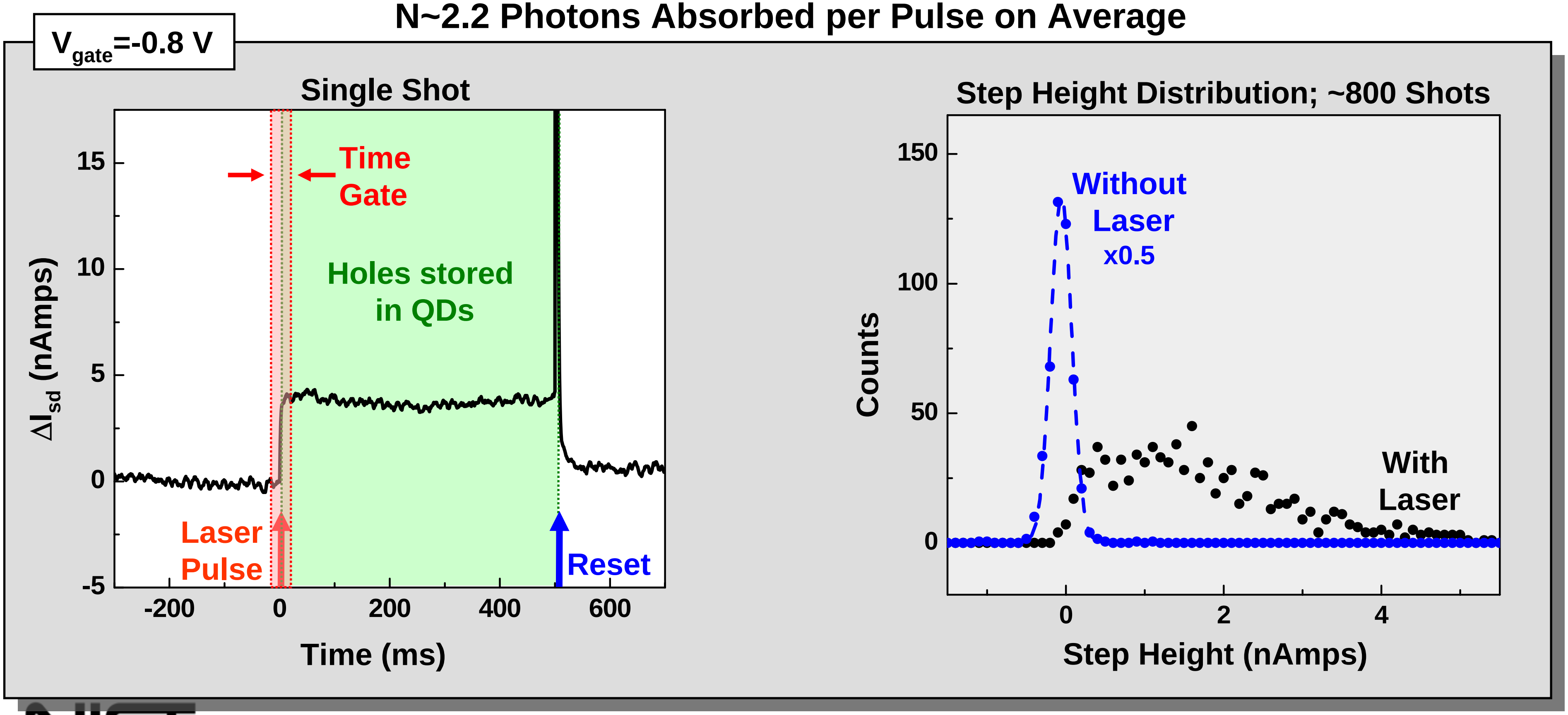
- ✓ Photon excites electron-hole pair in GaAs
- ✓ Hole trapped by quantum dot; electron joins 2DEG

- ✓ Charged QD screens internal field effectively changing V_{gate}
- ✓ *Persistent* change in I_{sd}
- ✓ Device reset by forward biasing gate

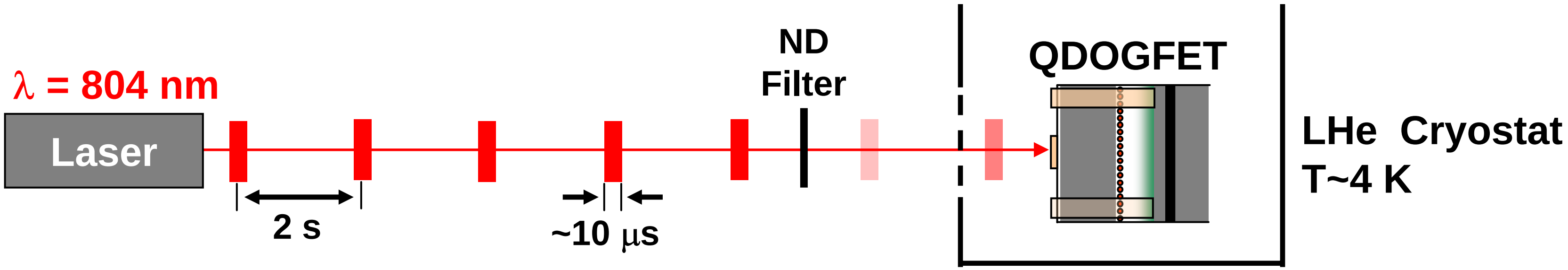
Experimental Investigation



N~2.2 Photons Absorbed per Pulse on Average



Experimental Investigation



N~2.2 Photons Absorbed per Pulse on Average

V_{gate}=-0.8 V

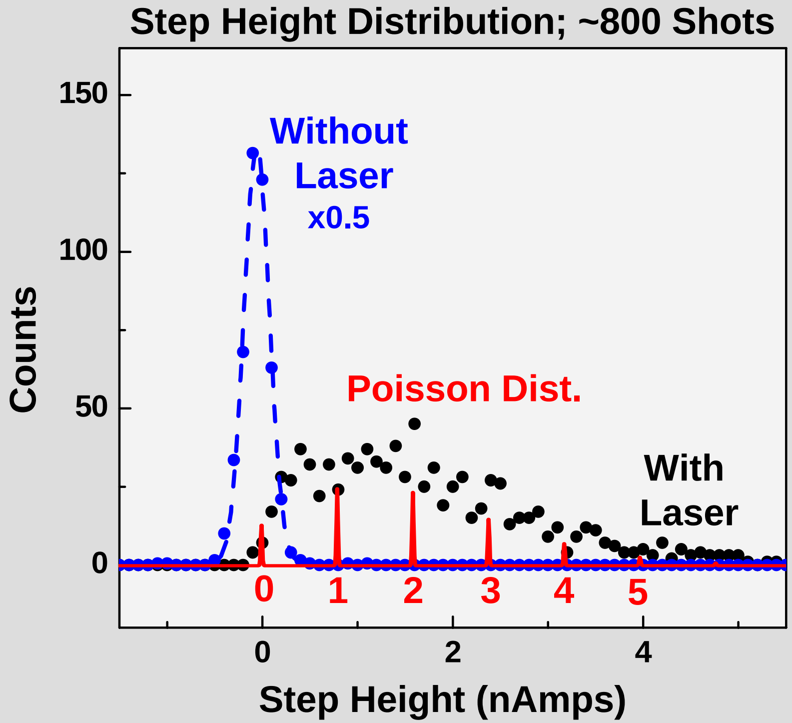
- **Asymmetric distribution**
  ➞ *Poisson statistics*

- **Distribution statistics indicate number of holes trapped by QDs on average**

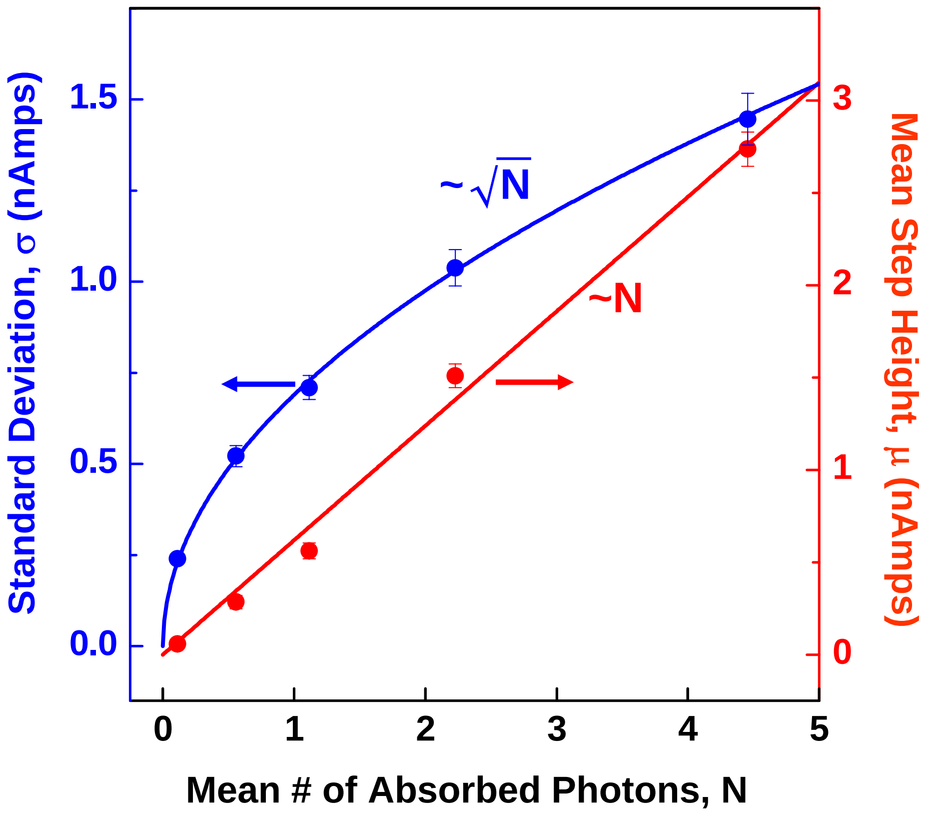
  $(\mu/\sigma)^2$ ~ 1.9 Trapped Holes per Pulse

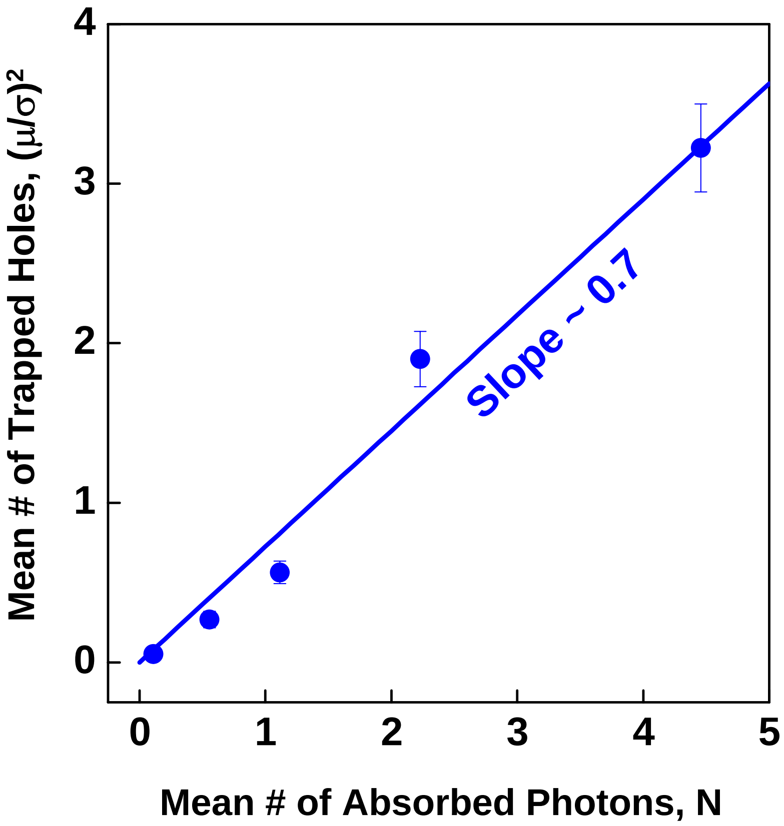
- **Single-photon sensitivity**

  Noise ~ 0.5 photon


Step Height Distribution; ~800 Shots

Detector Quantum Efficiency





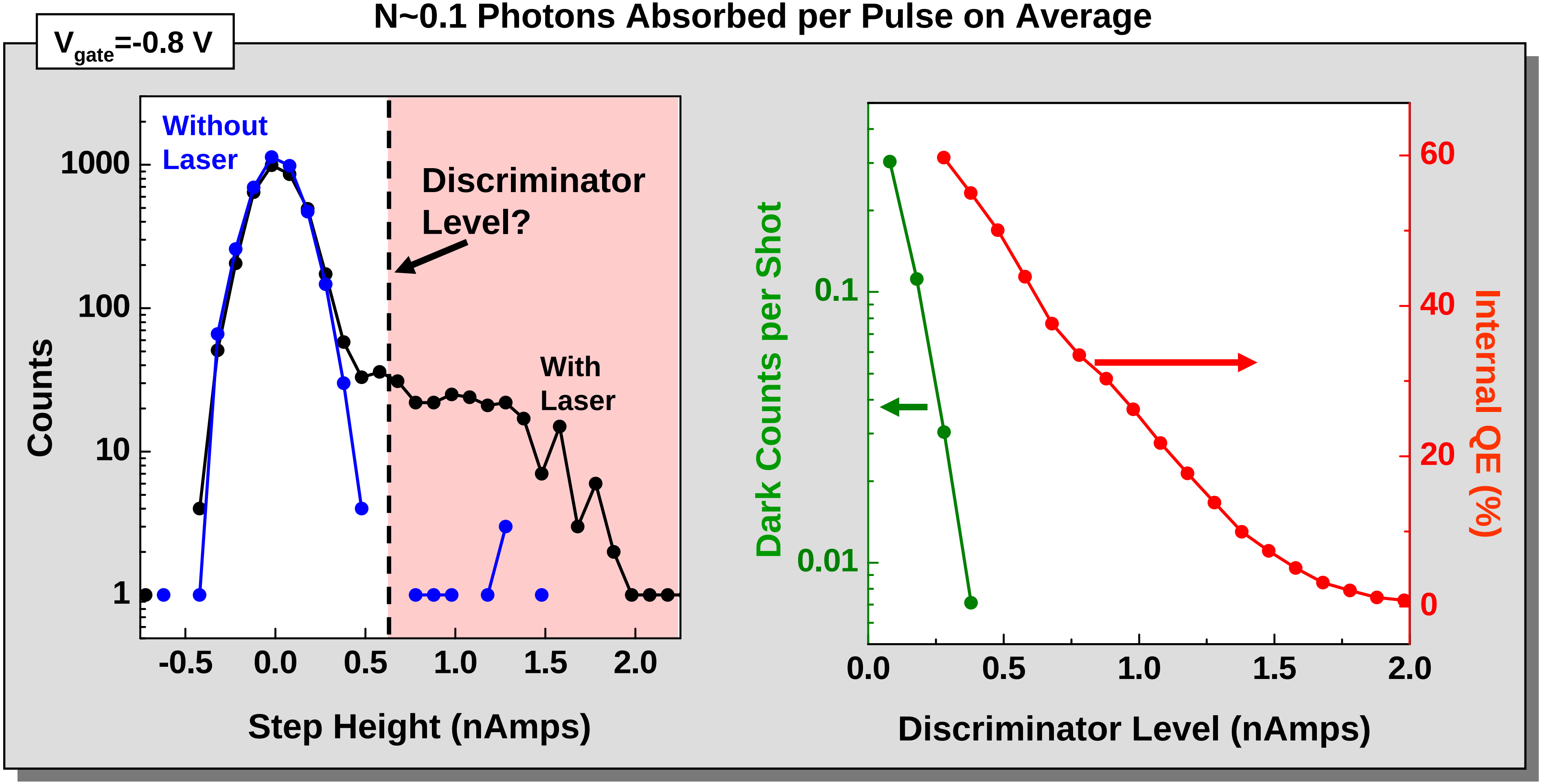
~70% Internal Quantum Efficiency

~3% External Quantum Efficiency

-Limited by ~40% gate transmission
& ~10% absorption of GaAs region

Single-Photon Detection Analysis

N~0.1 Photons Absorbed per Pulse on Average

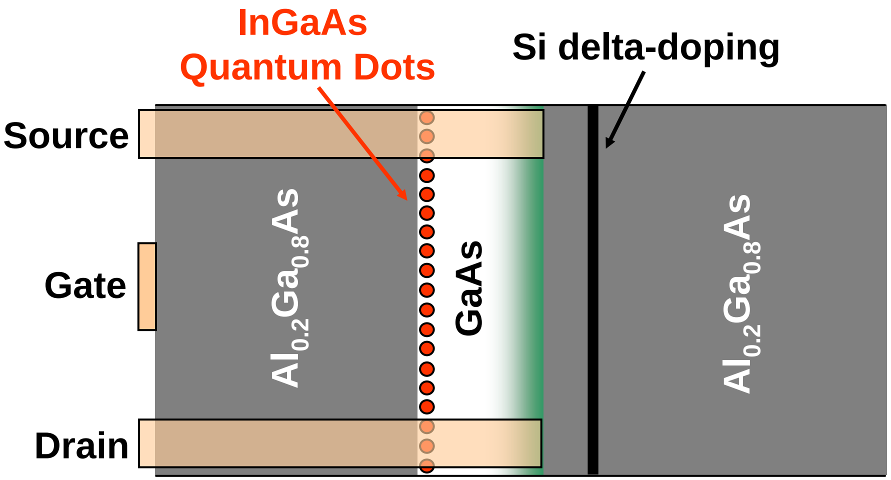


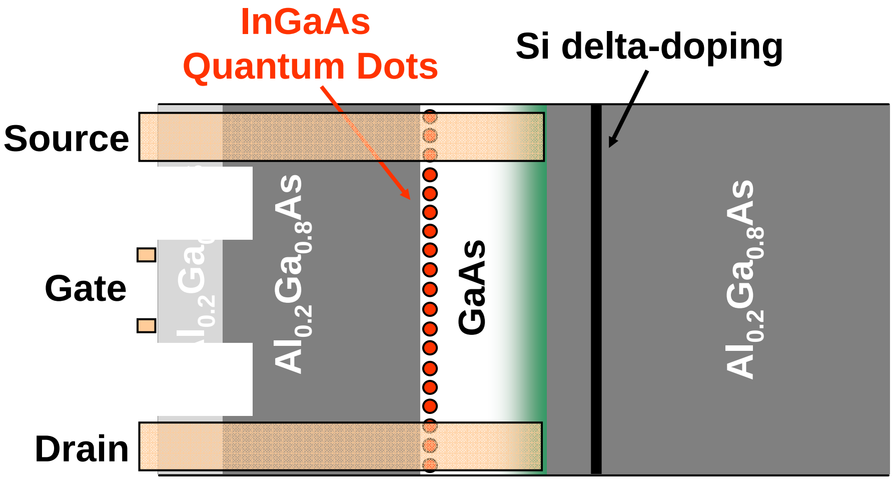
Low Dark Count Operation

Work in Progress: Improved Quantum Efficiency

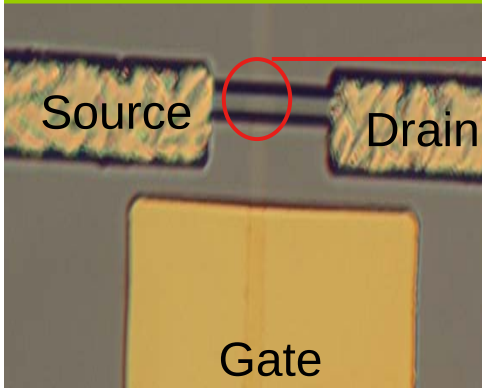
Problem: Semitransparent gate (Pt, 4 nm) only 40% transmission

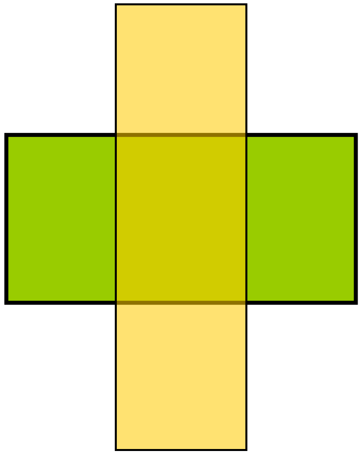
Solution: Transparent gate of doped semiconductor



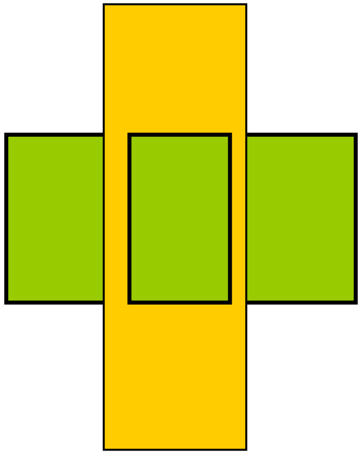


Top view Photo



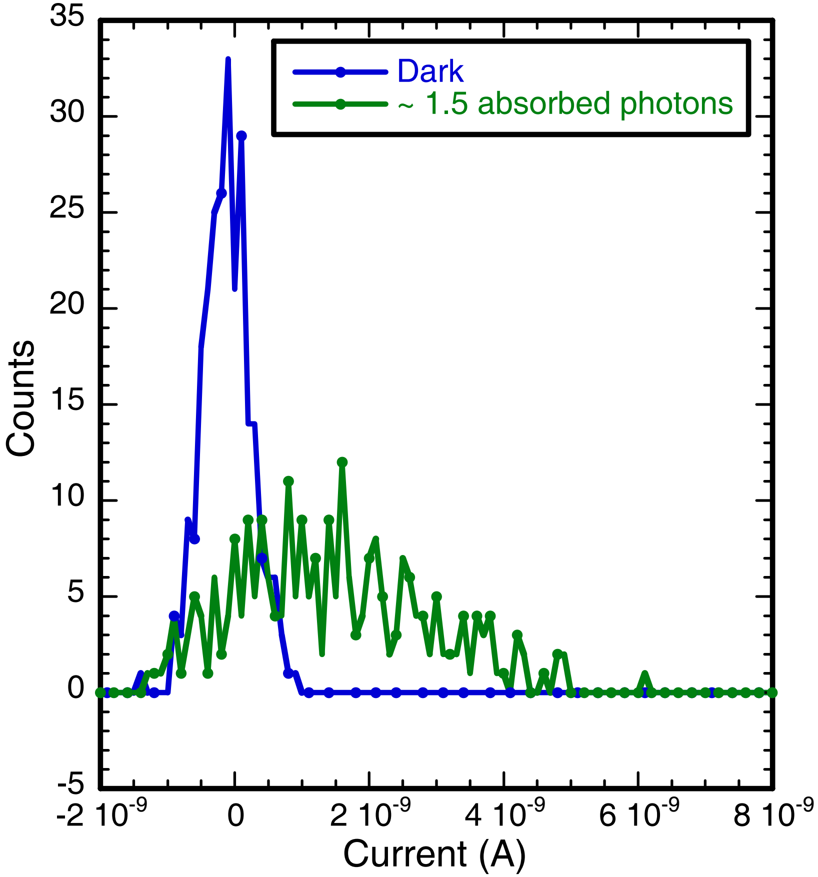


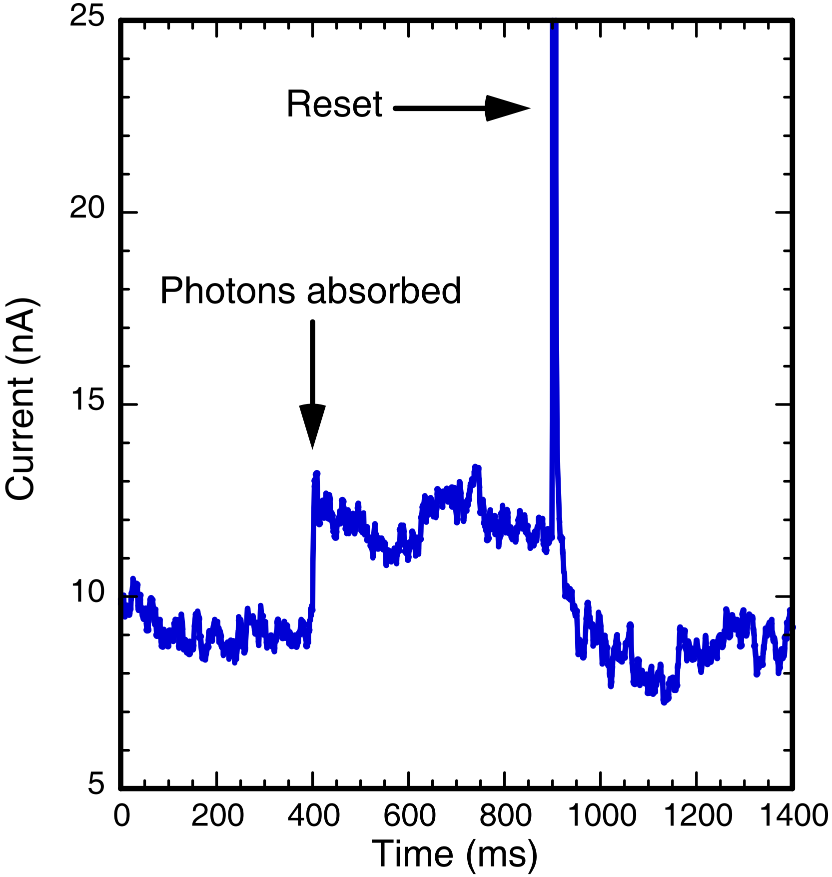
Semitransparent Gate



Transparent Gate

Work in Progress: 77 K Measurements





Noise(77 K) ~ 0.4 photons (std dev), ~3X Noise(4 K)

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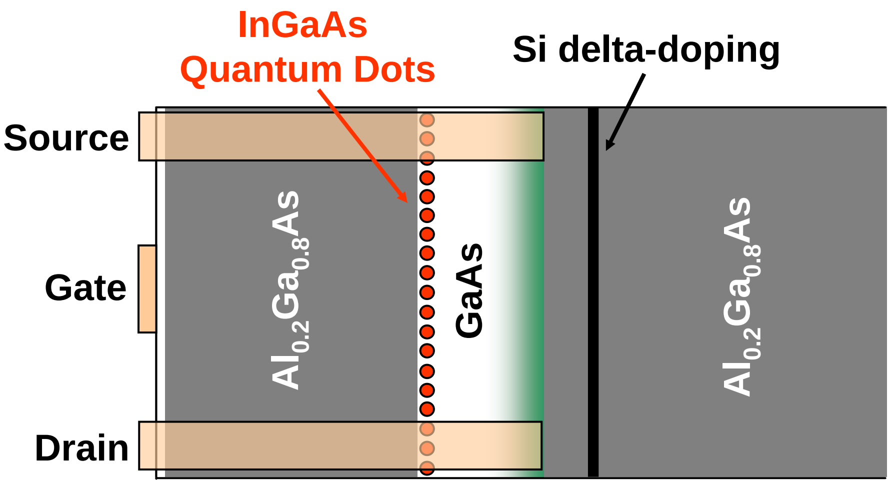
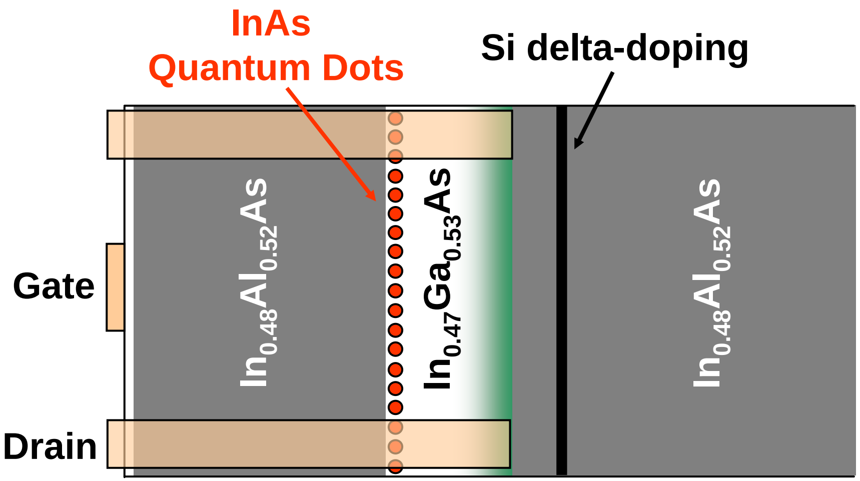
1310/1550 nm Device Design





$E_{gap}(\mathrm{GaAs\text{-}4K}) = 815$ nm

$E_{gap}(\mathrm{In_{0.47}Ga_{0.53}As\text{-}4K}) = 1450$ nm

$E_{gap}(\mathrm{In_{0.47}Ga_{0.43}Al_{0.10}As\text{-}4K}) = 1550$ nm

Conclusions and Future Work

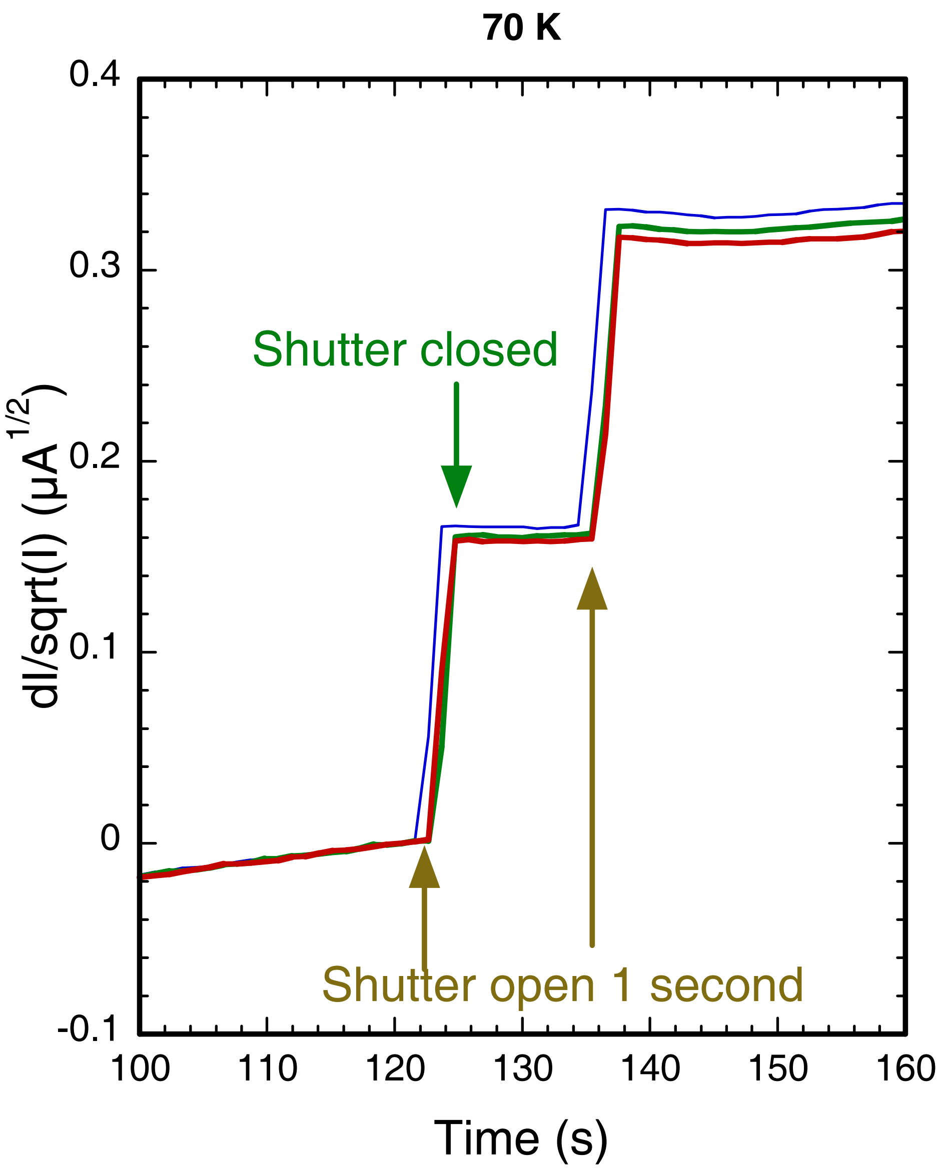
We have demonstrated:

- **Time-gated, single-shot, single-photon detection using a QDOGFET**
- **Internal QE: ~70% (External QE of 3% limited by gate transmission and absorption of GaAs region)**
- **Low dark-count operation**
- **Linear response with flux, capability to measure mean photon number from a weak Poissonian source**

Still to come:

- **Single-shot Photon Number Resolution**
- **High-speed operation**
- **Increased QE (resonant cavity, optimized GaAs thickness)**
- **Higher temperature operation**
  (Persistent Photoconductivity: hrs @ 150K – Finley *et al*. APL 1998)
- **Modified structures for communications wavelengths**
- **Larger area devices for better free space and fiber coupling**

Burst Mode



- Many single photon pulses can be detected without having to reset the device (thousands of QDs available for charge storage)

- Minimizes detector dead time due to reset

Future Directions (aka Postdoc Opportunities)

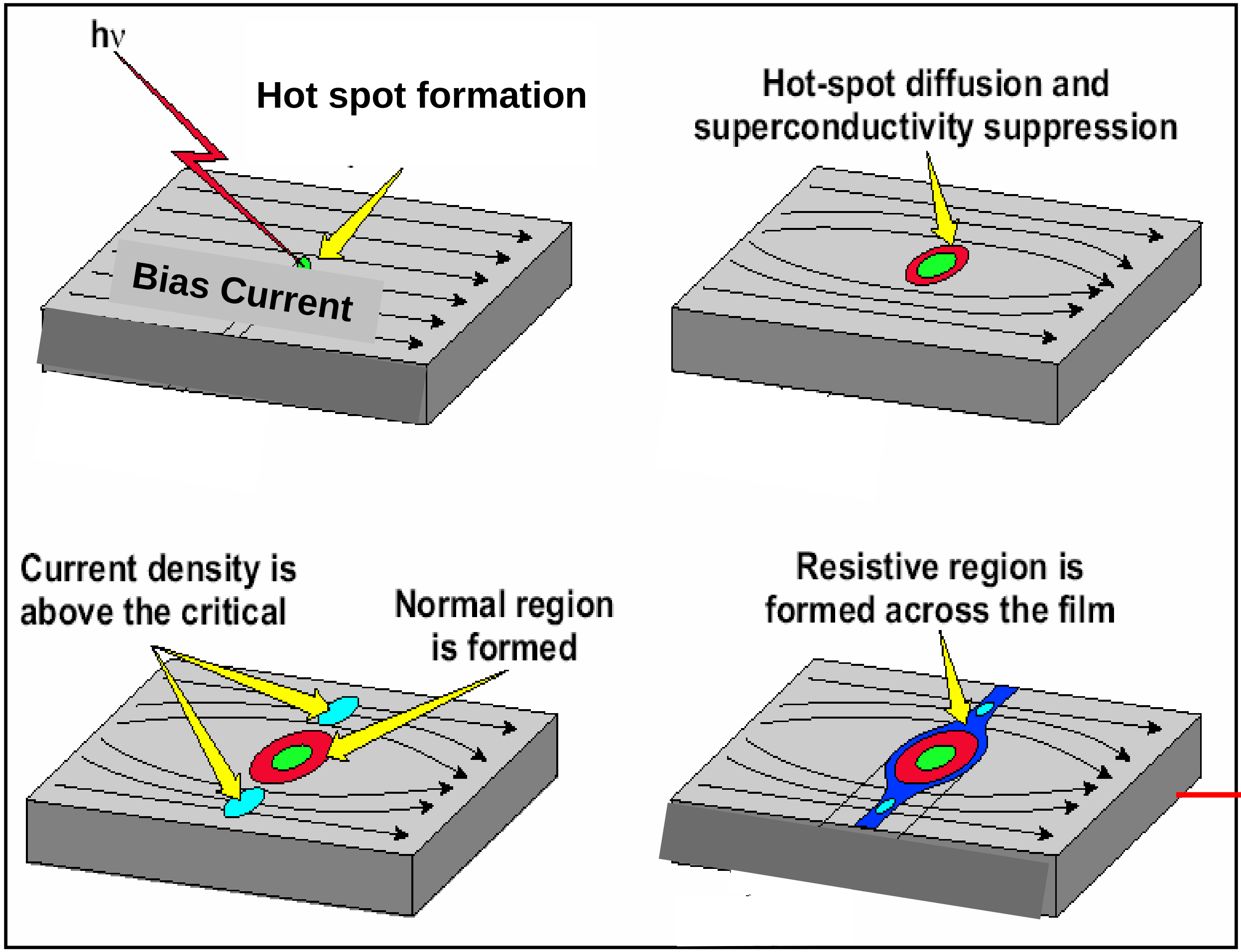
- Single photon source measurements at ~ 1300/1550 nm
- Indistinguishable photons from single QDs
- Engineered quantum states of light (NOON states, Schrödinger cat states)
- Temperature-dependent SHB
- Exciton-biexciton coherence

Superconducting Single Photon Detector (SSPD)

Superconductor: Zero resistance below critical

- **Temperature (T_c)**
- **Current density (J_c)**

Zero Voltage Drop →

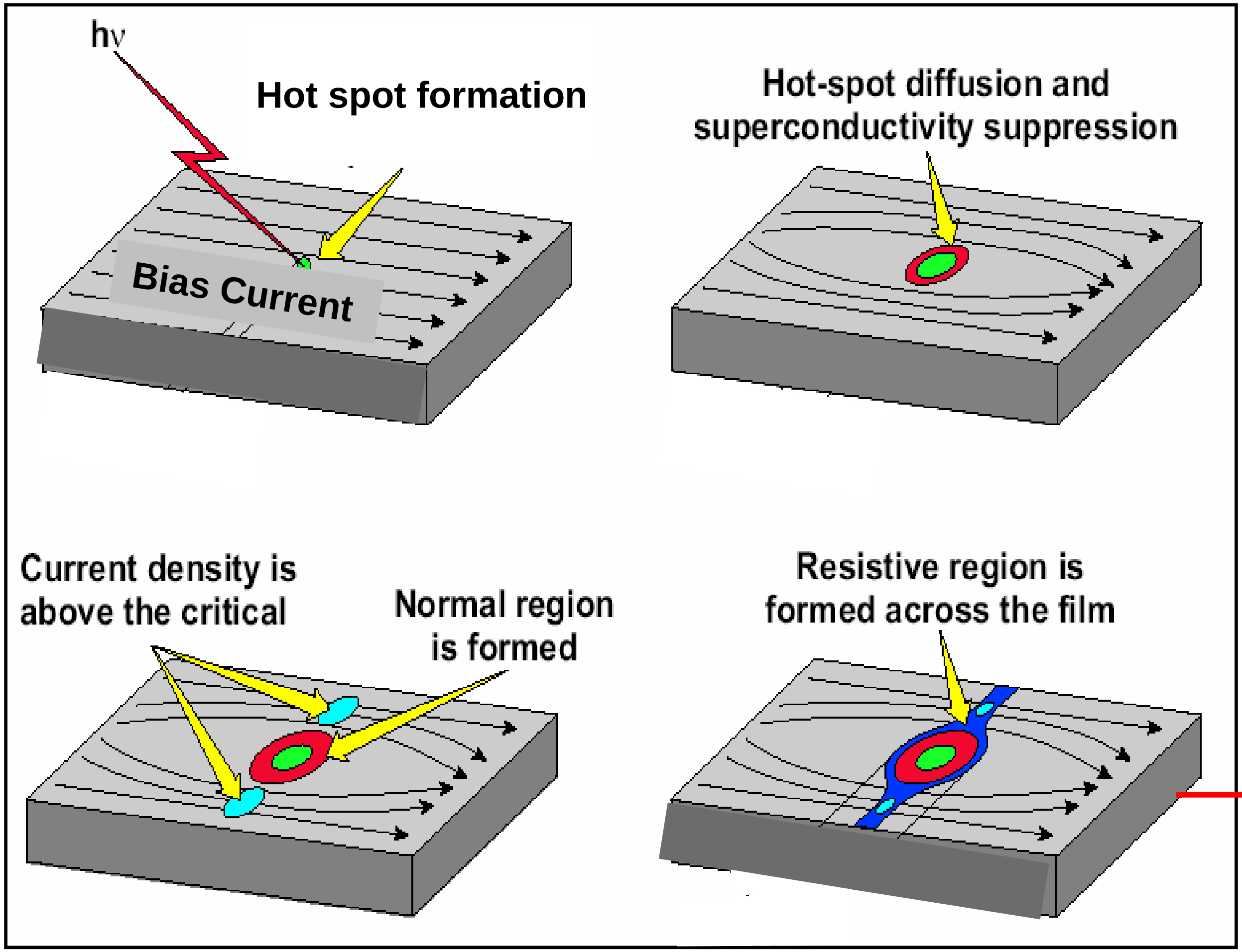


→ **Voltage Pulse Out**

Superconducting Single Photon Detector (SSPD)

Niobium Nitride (NbN)

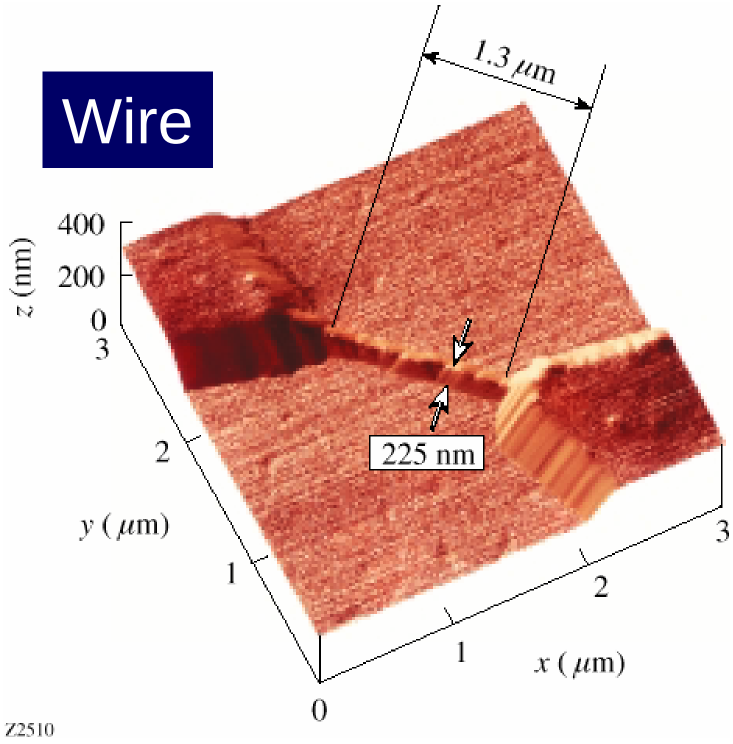
- T_c = 10 K
- Strong absorption
- Fast relaxation (ps)
- UV to Mid-IR

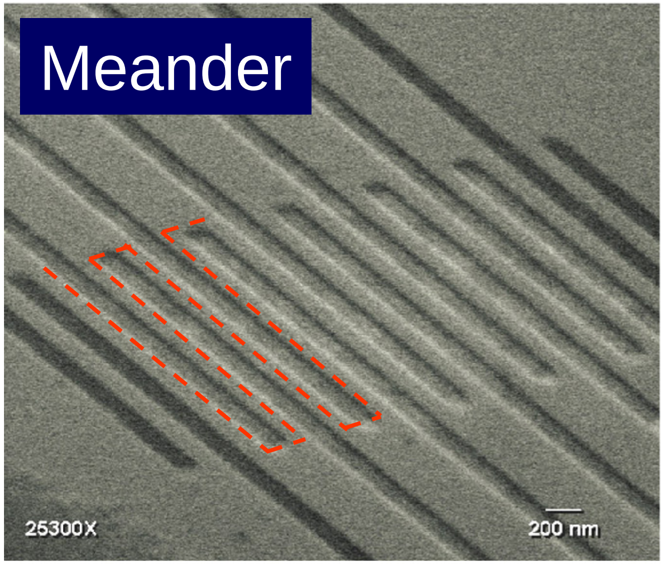


Zero Voltage Drop

Voltage Pulse Out

Superconducting Single Photon Detector (SSPD)





Pioneered in Moscow & Rochester

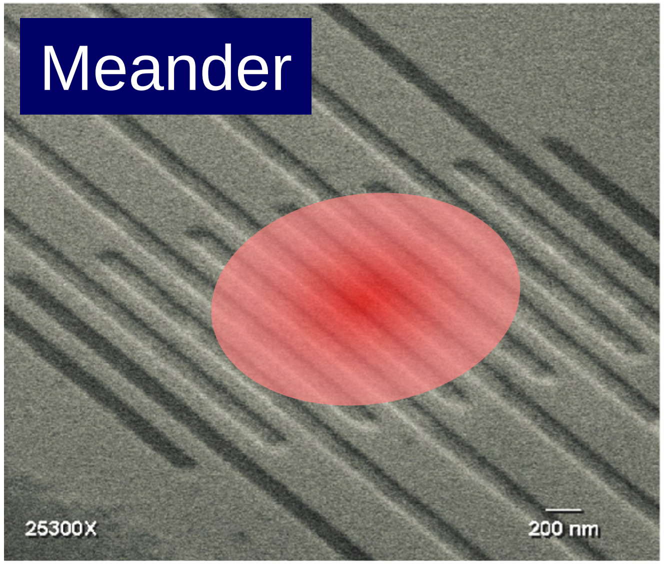
•1 GHz	**•Range 400 nm – 5 μm**
•20 ps jitter	**•QE up to 20% (visible)**

•Gol'tsman, APL 79, 705 (2001)
•Verevkin *et al.*, J. Mod. Optics 51, 1447 (2004)

Superconducting Single Photon Detector (SSPD)

Our devices:

- **Packaged in a commercial cryogen-free refrigerator (~4 K)**
- **Fiber coupled**
- **Detection Efficiency**
  - **~2% @ 900 nm**
  - **~1% @ 1550 nm**
  - **(Includes fiber coupling losses)**



3.5-nm-thick devices with 0.5 filling factor. Active area 10 x 10 μm^2

- **Hadfield *et al.*, Optics Express <u>13</u>, 1086 (2005)**

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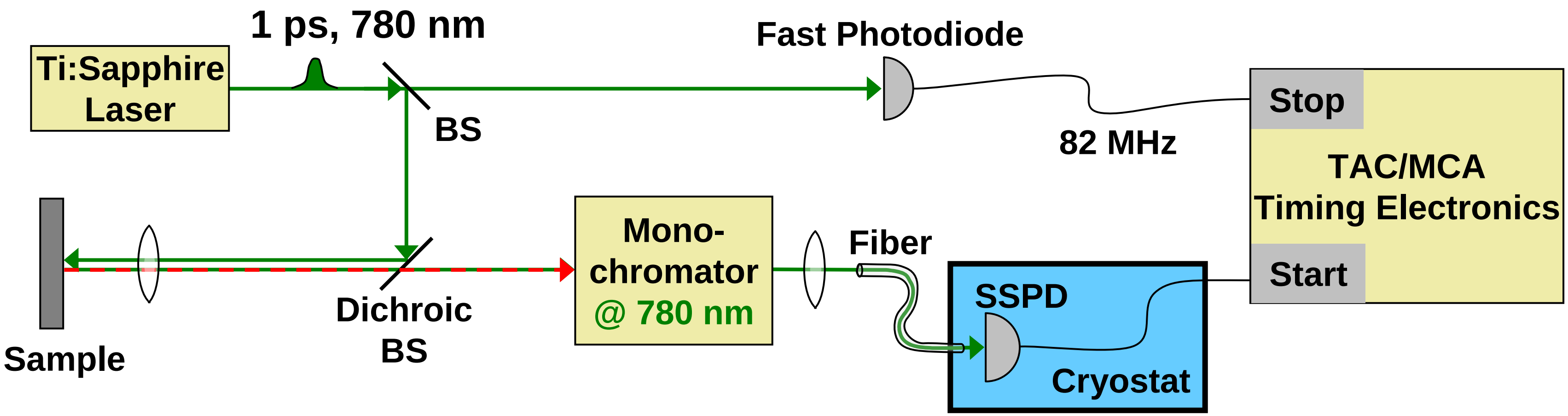
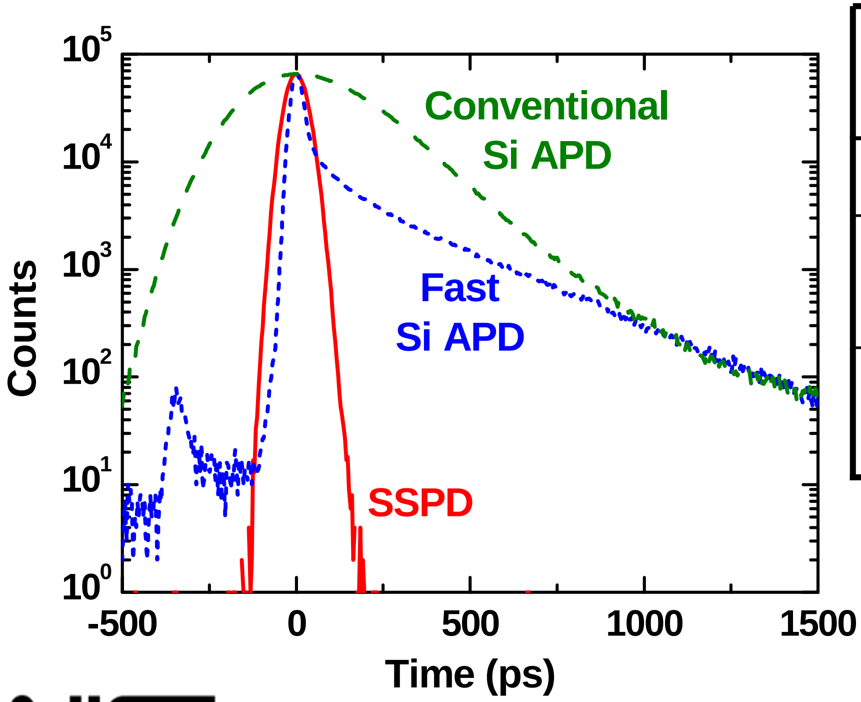
Instrument Response Functions





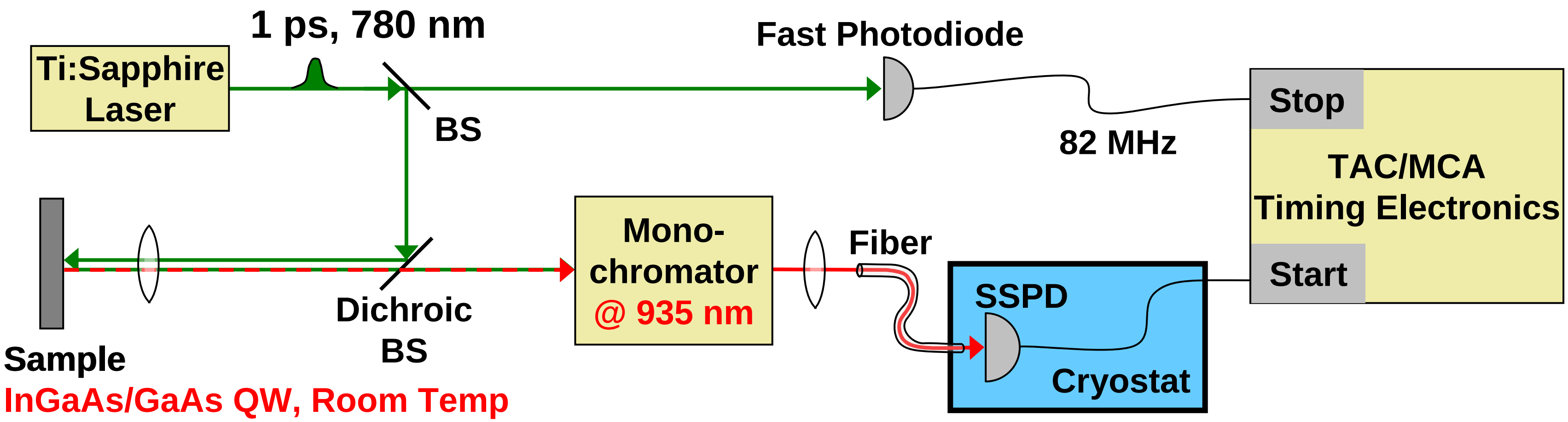
Detector	IRF (FWHM)	Efficiency @ 900 nm	Dark Counts
Convt'l APD	350 ps	38%	~50 Hz
Fast APD	40 ps Long tail	5%	~50 Hz
SSPD	65 ps Gaussian!	2%	~30 Hz

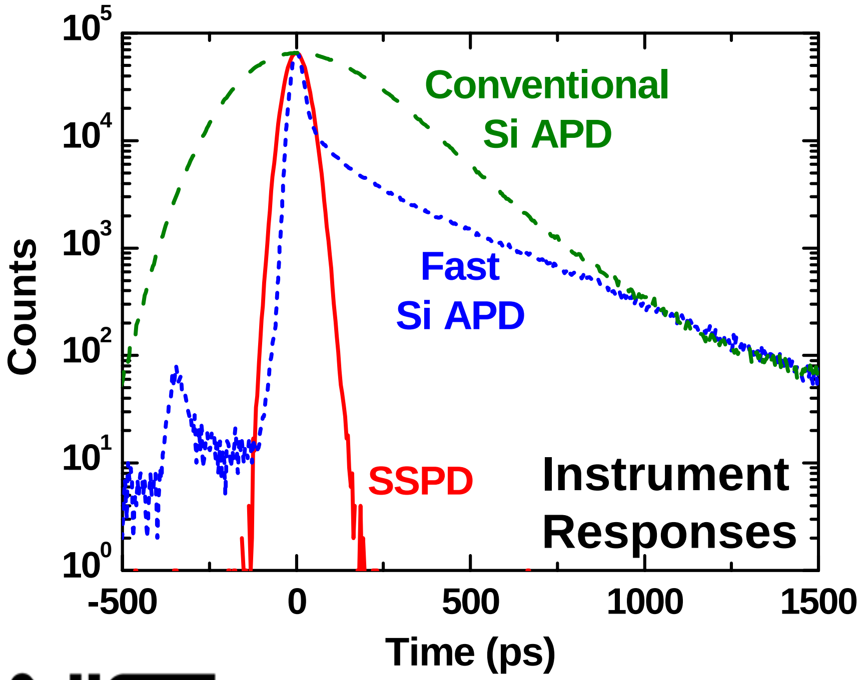
Gaussian response + Few dark counts

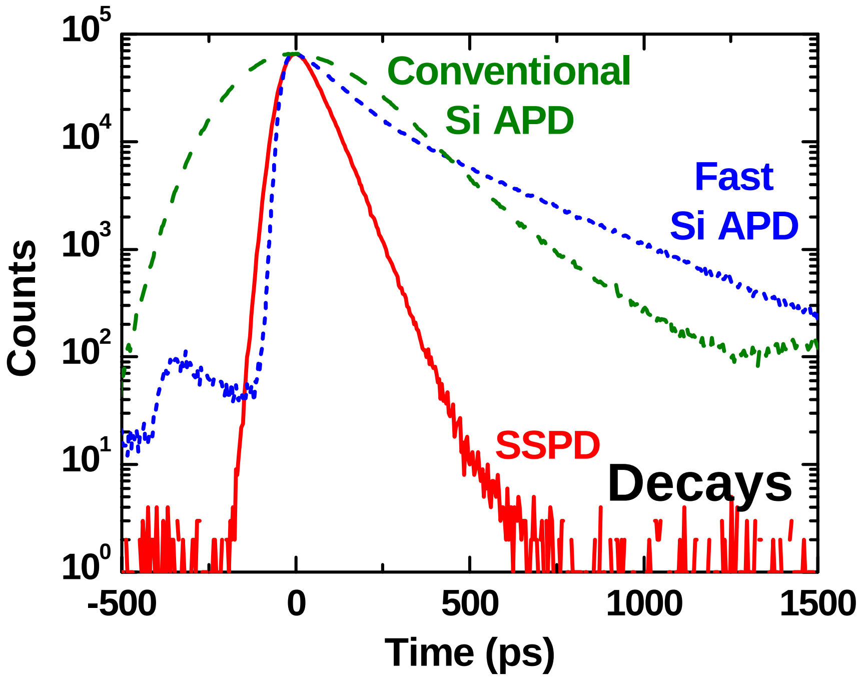
→ Tolerate low efficiency

→ Identify multiexponential processes

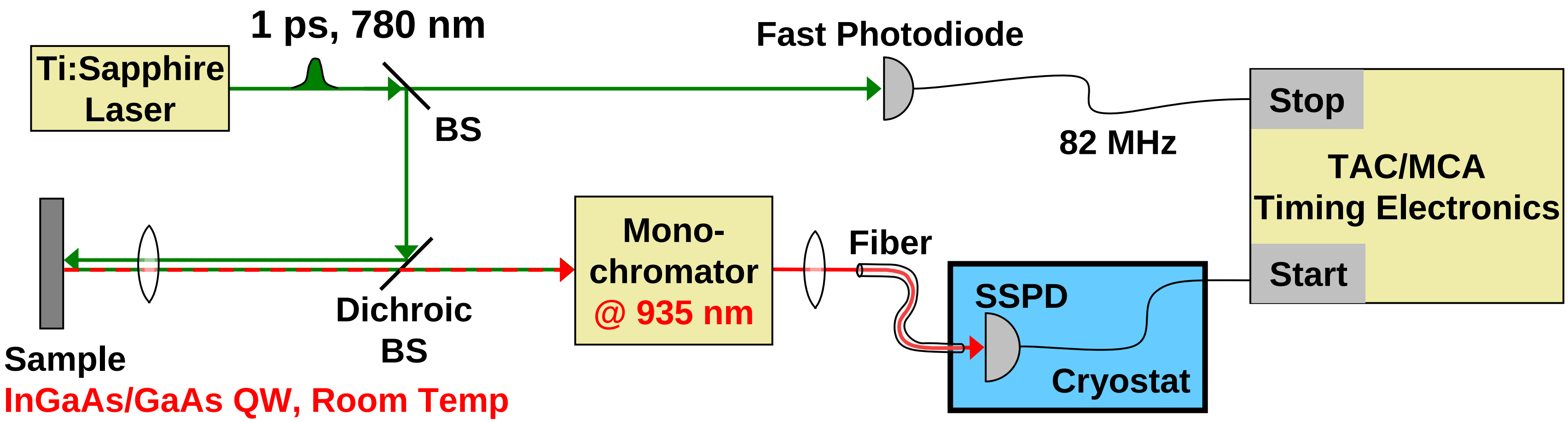
Lifetime Measurements

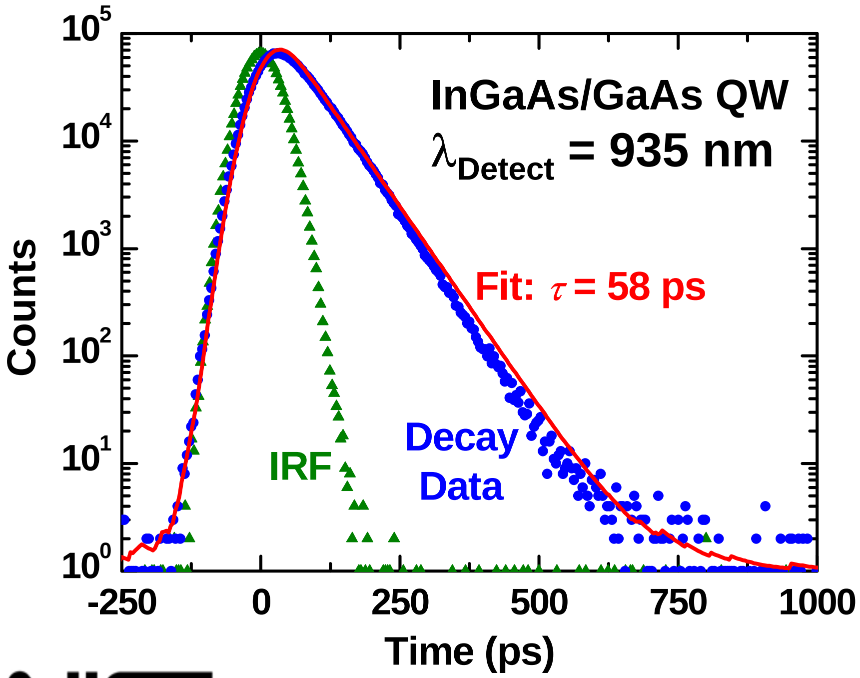


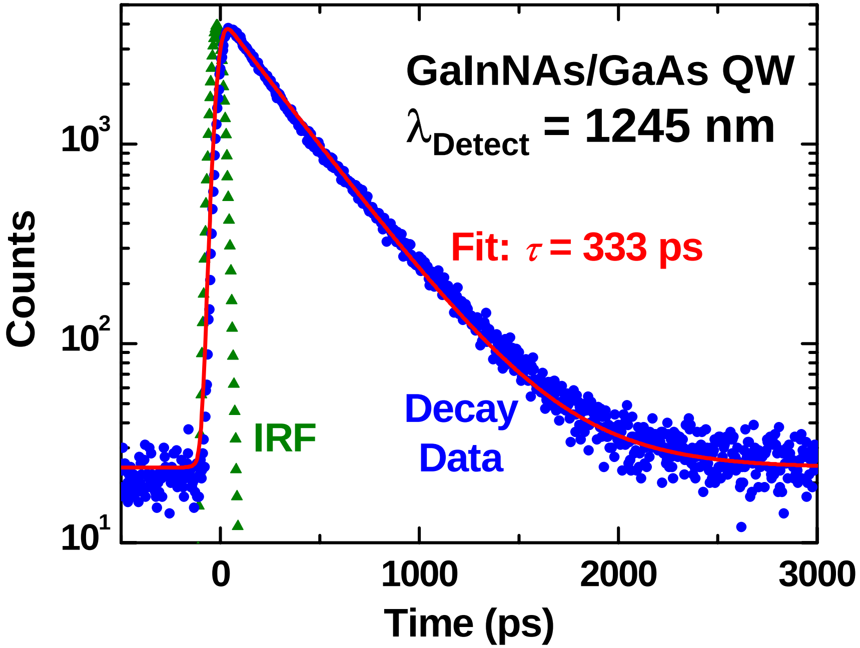




Instrument Response Functions

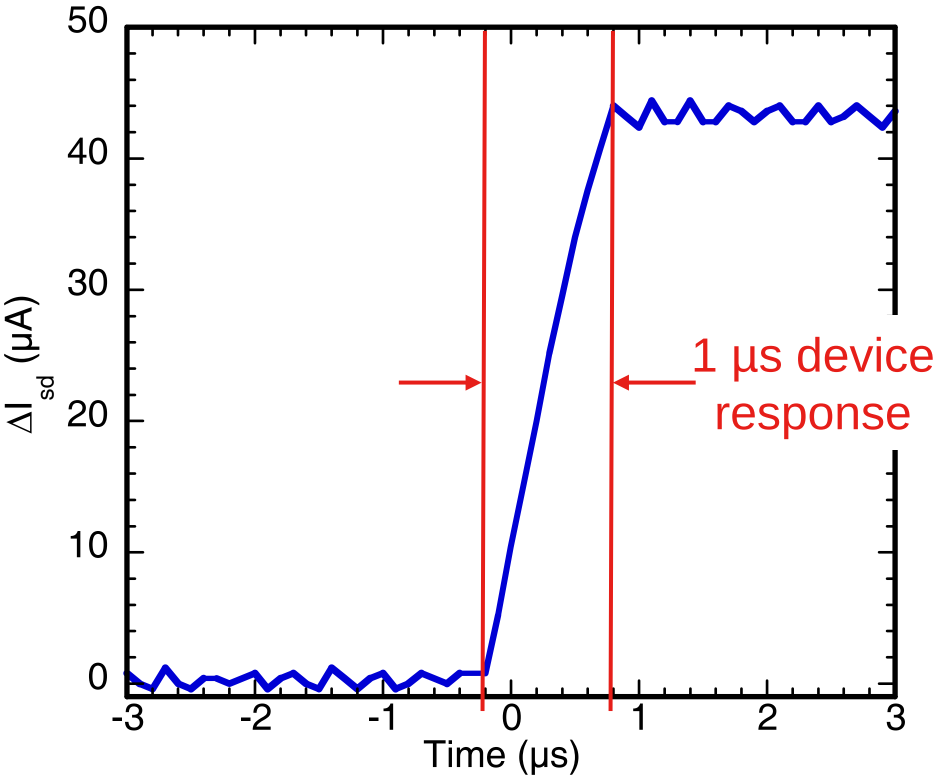






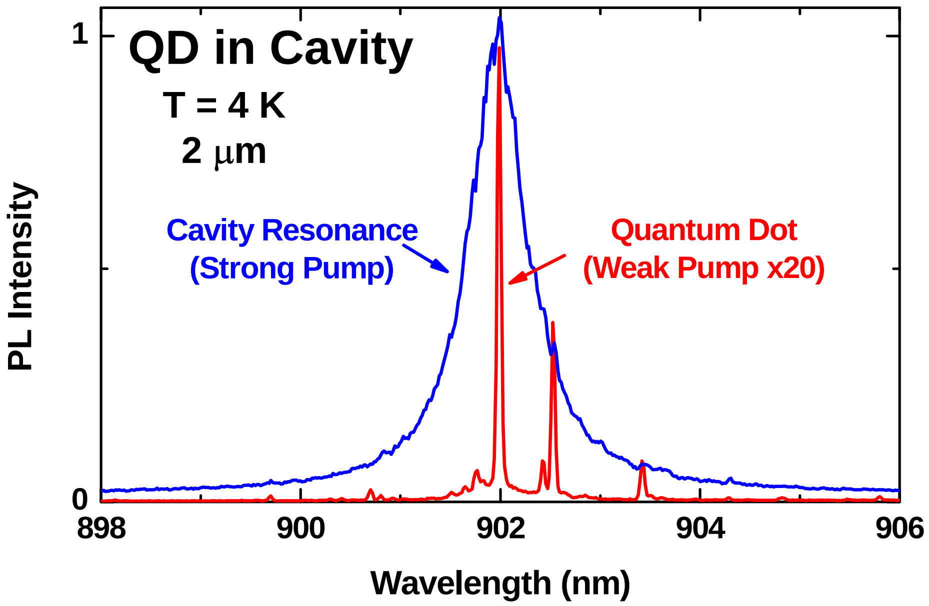
- SSPD works where Si won't ($\lambda > 1$ μm)!

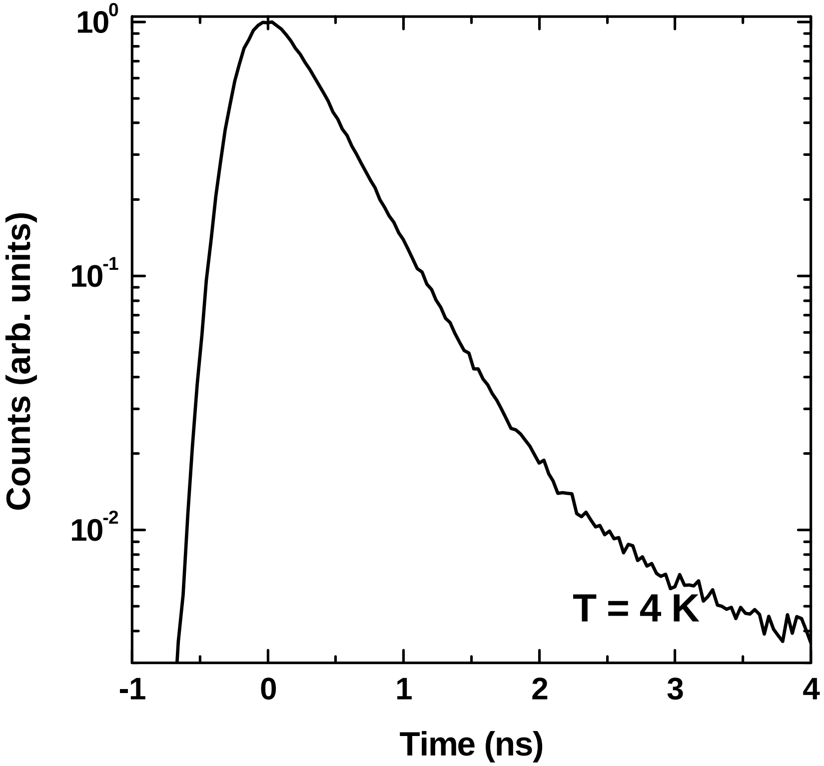
Work in Progress: High Speed Measurements



- Demonstrates device can respond to fast pulse
- Next step: implement fast amplifier

Cavity-Enhanced Emission





Cavity-Enhanced Emission