Near-infrared (NIR) Single Photon Counting Detectors (SPADs)

Chong Hu, Minggou Liu, Joe C. Campbell & Archie Holmes

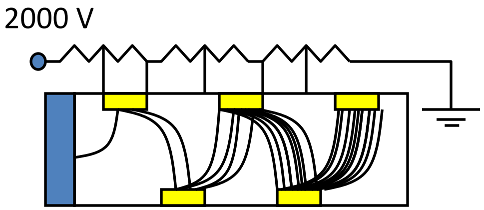
ECE Department

University of Virginia

Outline

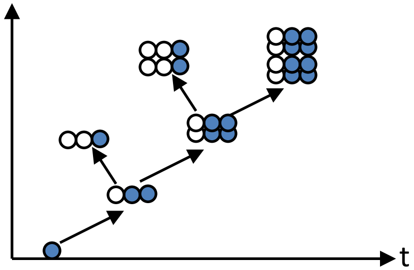
- ✓ Introduction to Single Photon Counting Detectors (SPADs)
- ✓ Current States of near-infrared SPADs
- ✓ Summary and Future Goals

PMT



- High gain
- Low dark current
- Low noise
- Low quantum efficiency
- Large, bulky
- Expensive
- High voltage
- Fragile
- Ambient light catastrophic

APD



- Electron & Hole avalanche multiplication

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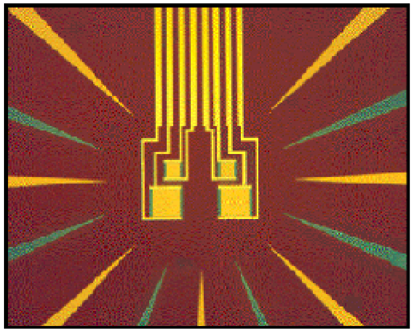
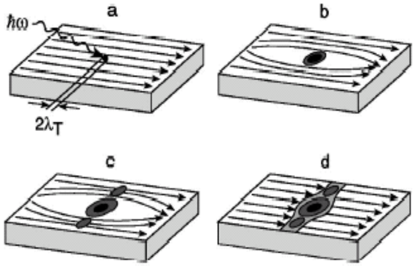
- Good efficiency
- Acceptable dark counts
- Afterpulsing

Superconductors





- Hotspot Generation and Resistive Barrier

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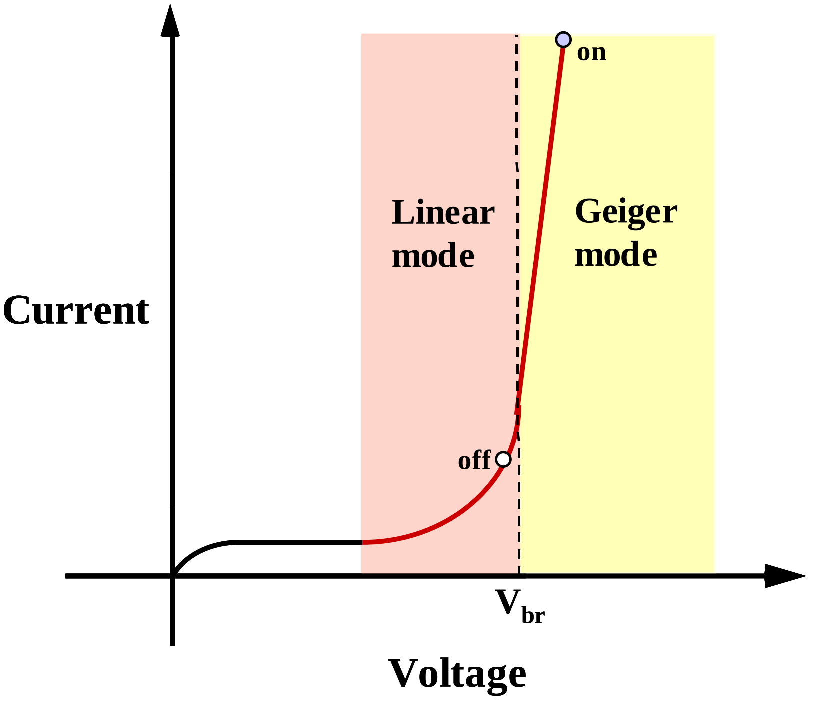
- High efficiency
- Low dark counts
- No afterpulsing
- T < 1K!!

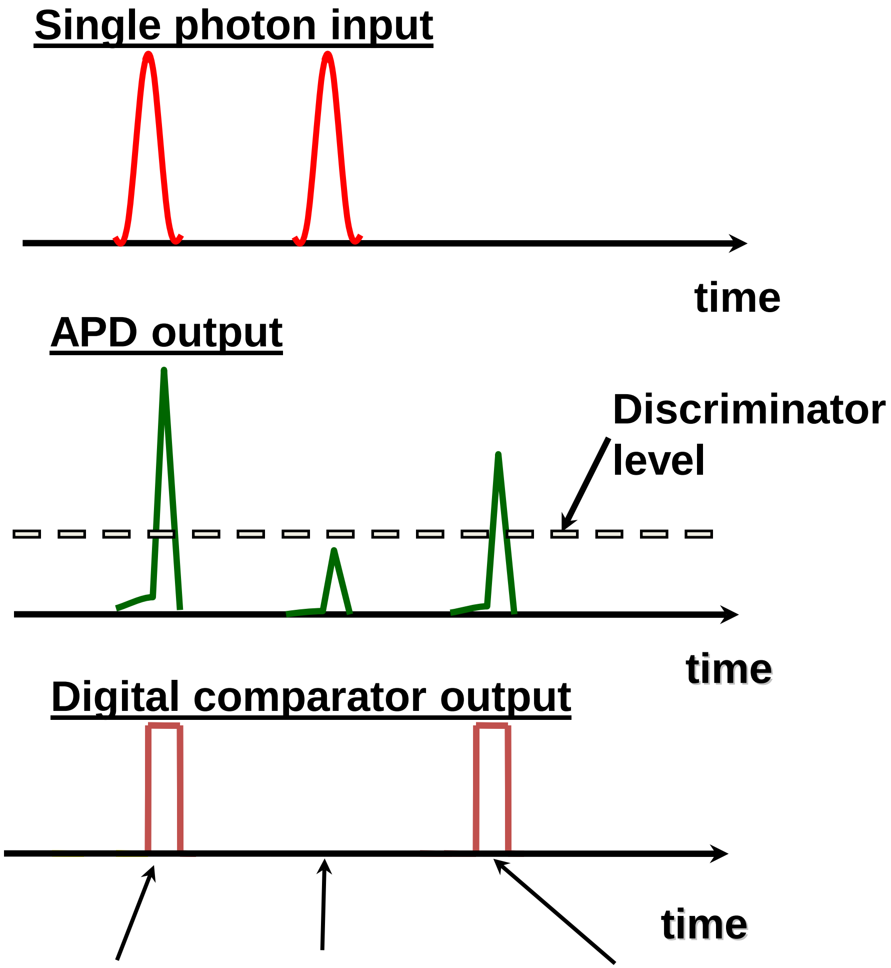
Geiger mode - APD functions as a switch

Analog		**Digital**
Responsivity	➡	Single photon detection efficiency
Dark current	➡	Probability of dark count

Concept of excess noise does not apply!



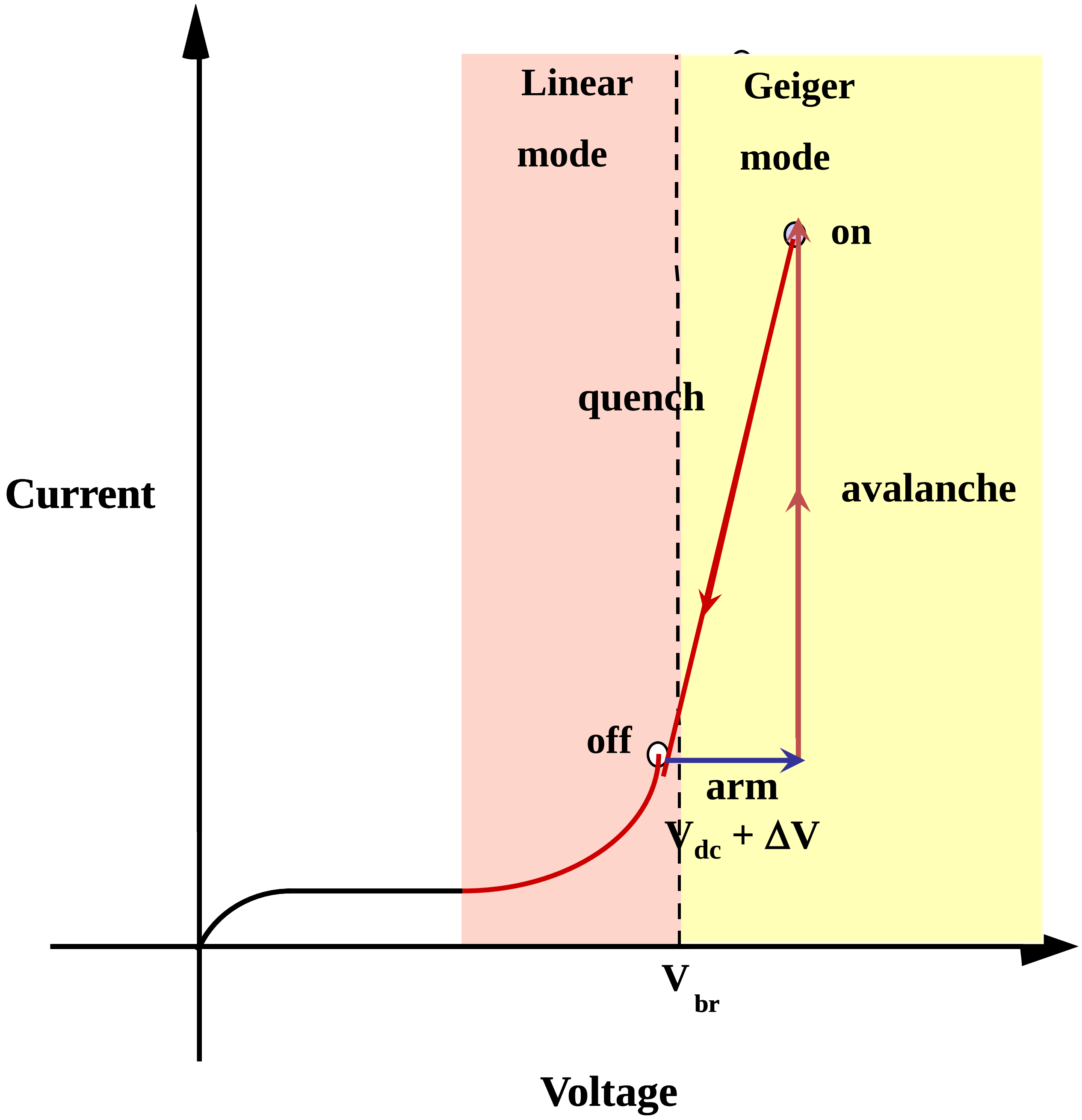
Geiger-mode operation



Successful single photon detection

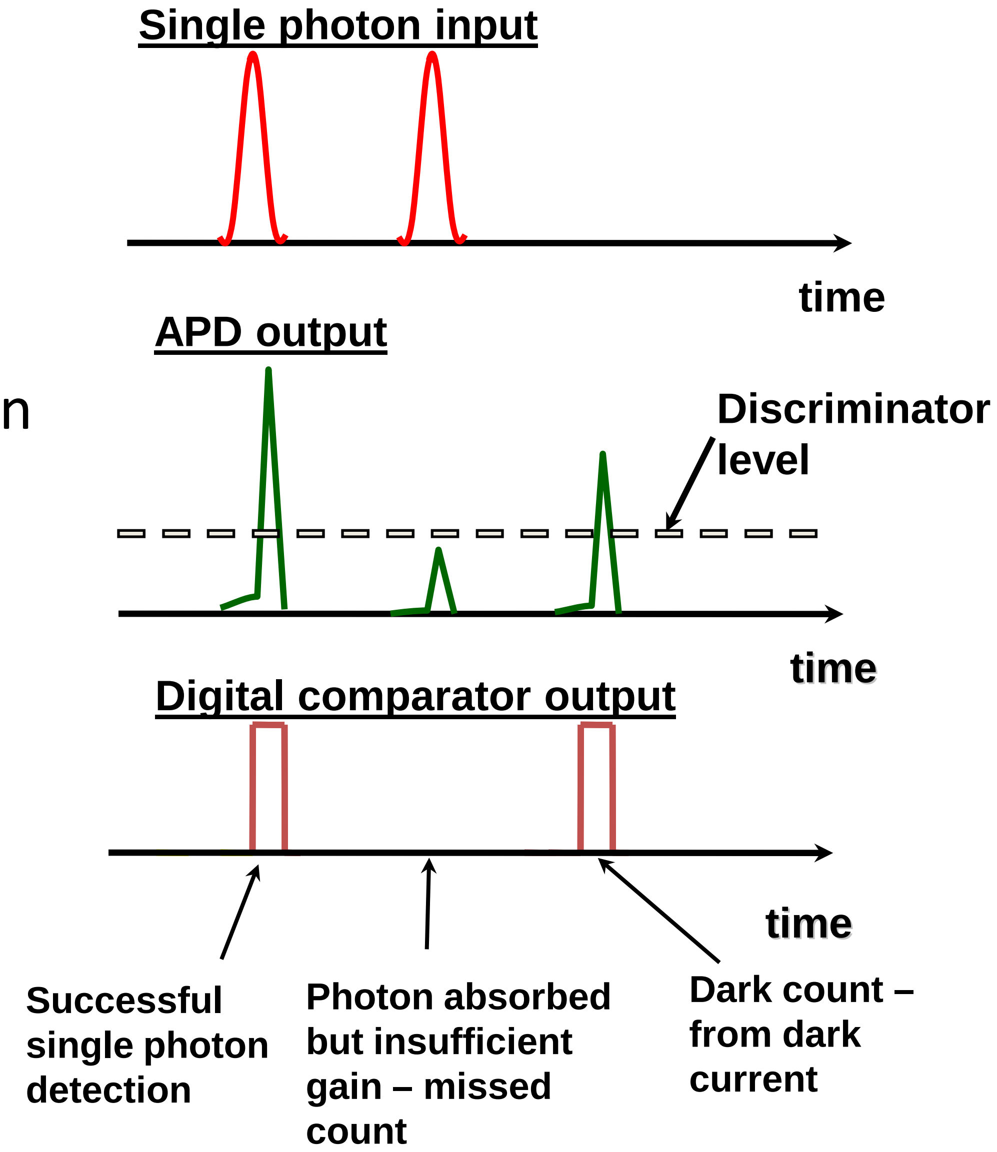
Photon absorbed but insufficient gain – missed count

Dark count – from dark current


Linear
mode
Geiger
mode
on
quench
Current
avalanche
off
arm
$V_{dc} + \Delta V$
V_{br}
Voltage

Performance Parameters

- ✓ Photon detection efficiency (PDE)
  - ➢ The probability that a single incident photon initiates a current pulse that registers in a digital counter
- ✓ Dark count Rate (DCR)/Probability (DCP)
  - ➢ The probability that a count is triggered by dark current instead of incident photons



Single photon input

time

APD output

Discriminator level

time

Digital comparator output

time

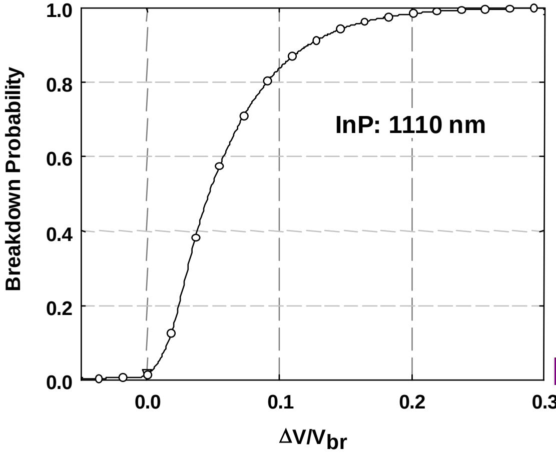
Successful single photon detection

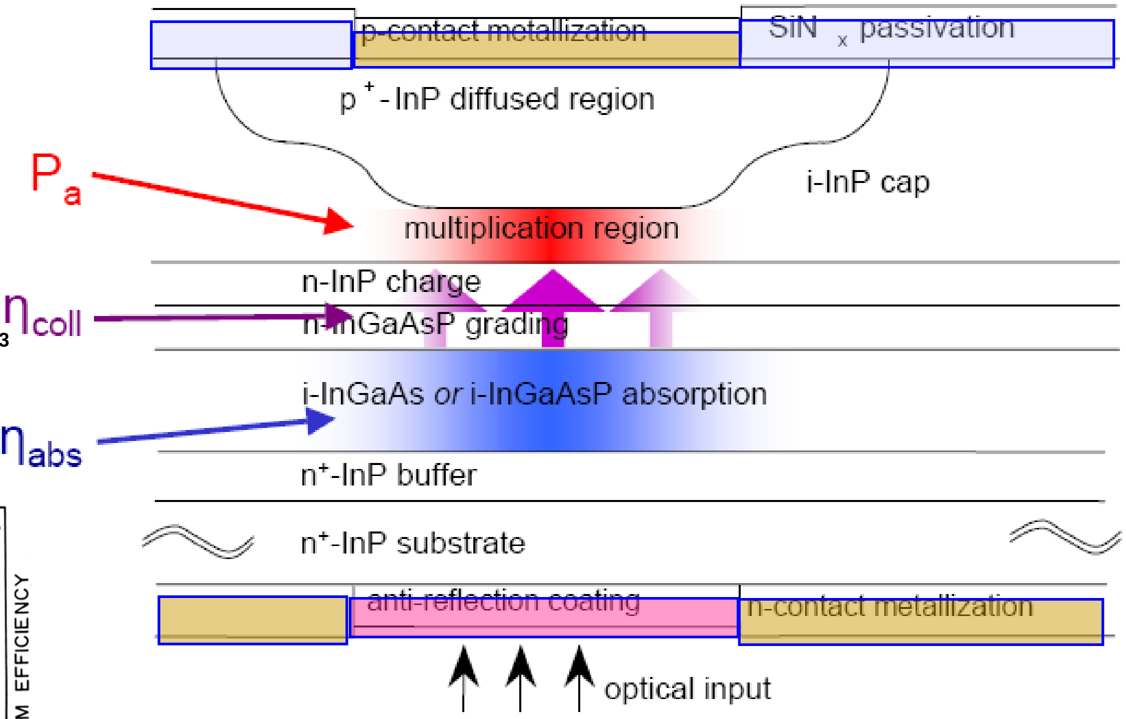
Photon absorbed but insufficient gain – missed count

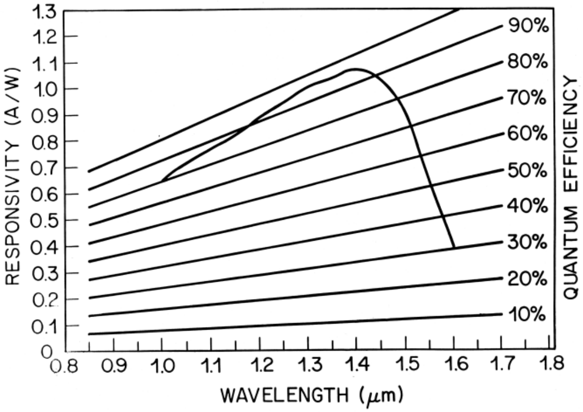
Dark count – from dark current

Photon Detection Efficiency

$$\eta_{PDE} = \eta_{external} \times \eta_{collection} \times P_{avalanche}$$



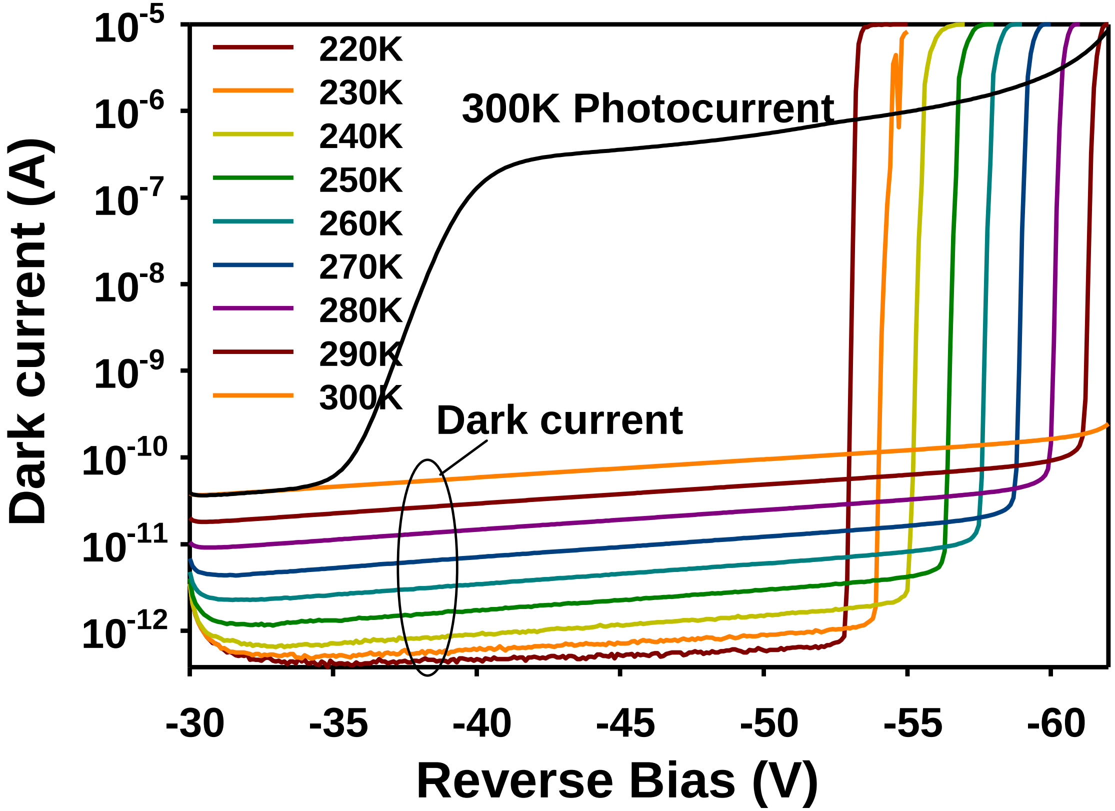




InGaAsP → **1.06, 1.3 μm**

InGaAs → **1.55 μm**

40μm-diameter In$_{0.53}$Ga$_{0.47}$As/InP



Dark current

- **0.18nA at 95% of V$_{br}$ at 297K**
- **0.15pA at 95% of V$_{br}$ at 200K**

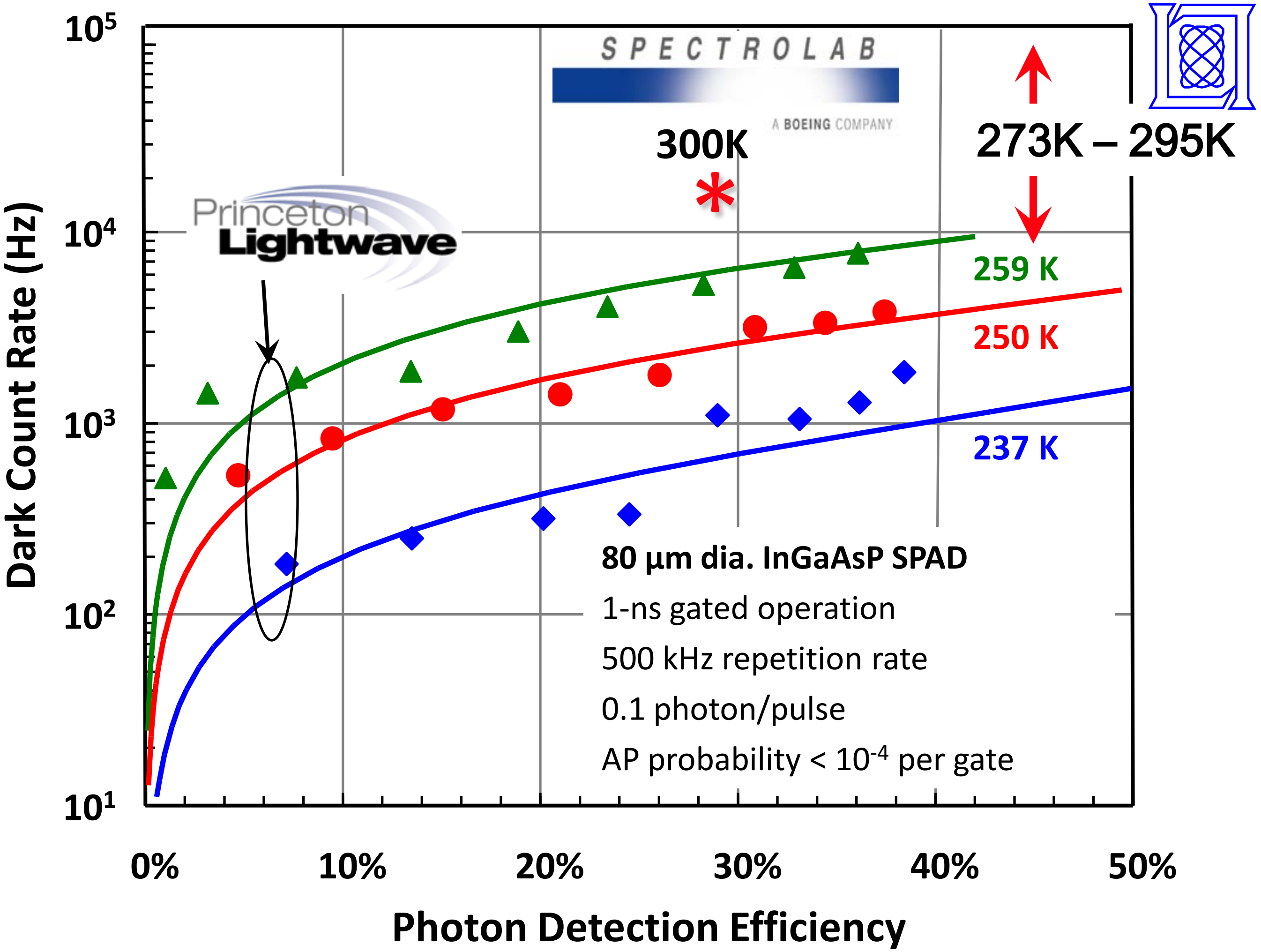
Good enough?

1.06 µm SPADs: DCR vs. PDE

✓ **InGaAsP absorber lower generation-recombination dark current**

✓ **DCR approaching Si SPAD DCR with greatly increased PDE**

  ➢ **Si SPADs have PDE < 2% at 1.06 µm**



80 µm dia. InGaAsP SPAD

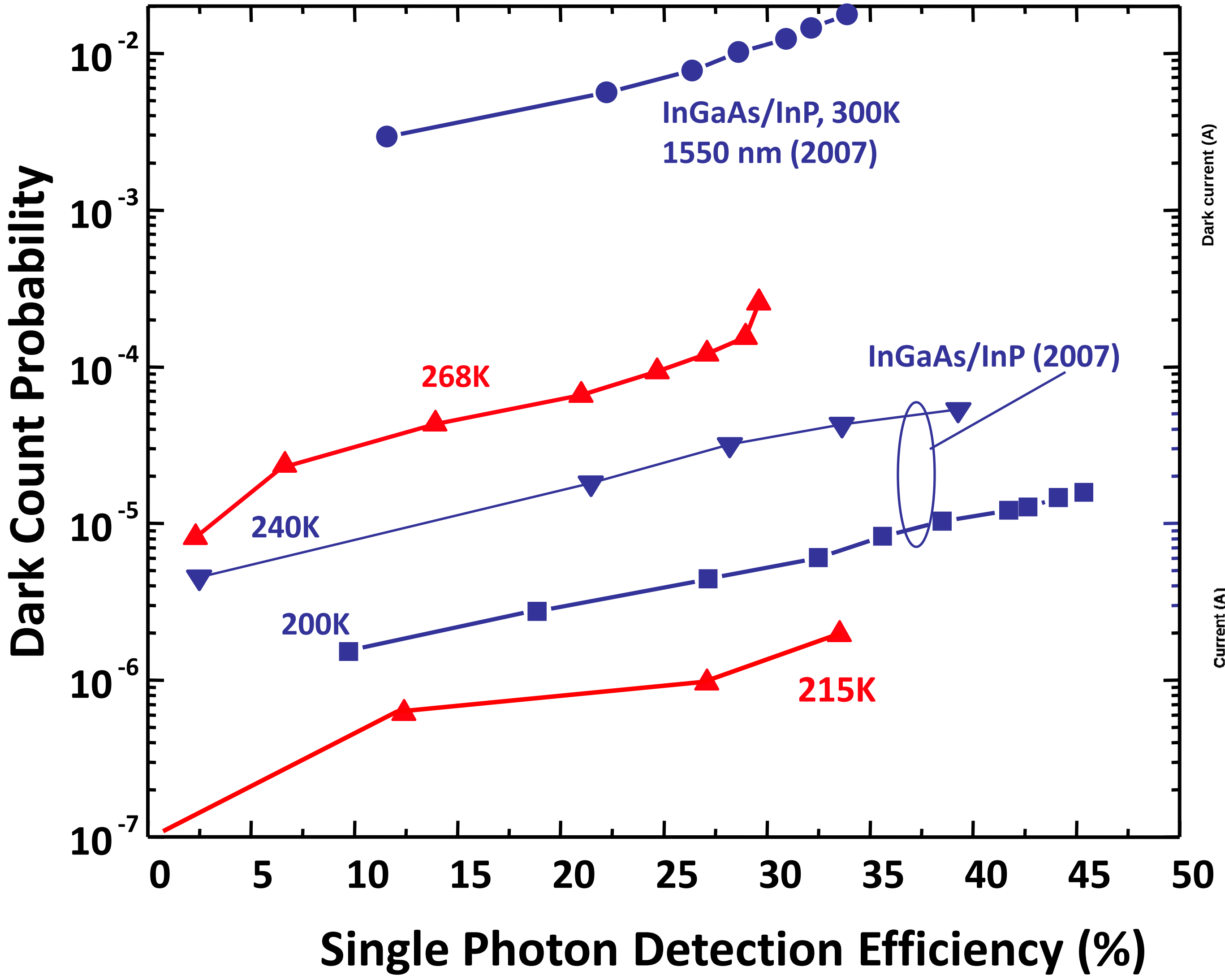
1-ns gated operation

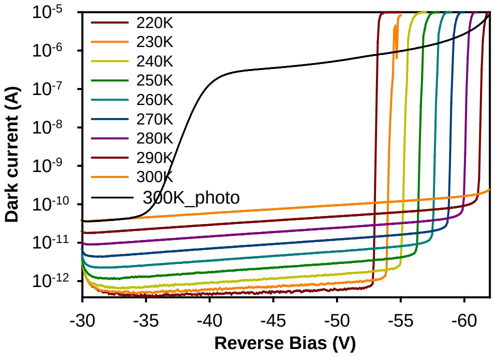
500 kHz repetition rate

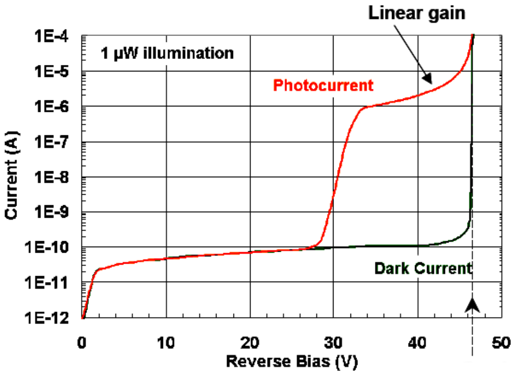
0.1 photon/pulse

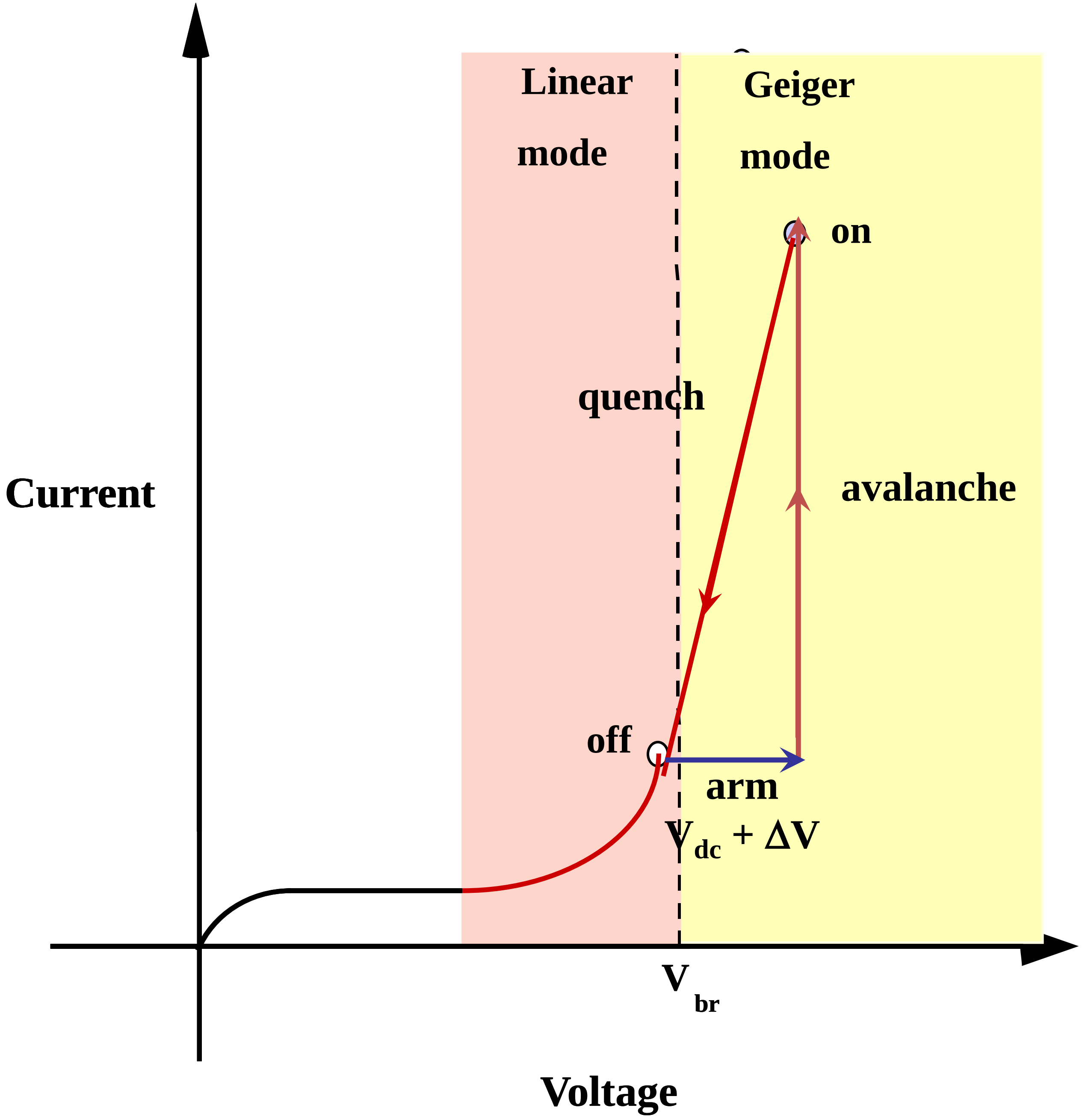
AP probability < 10^{-4} per gate

Dark Count Probability versus Photon Detection Efficiency







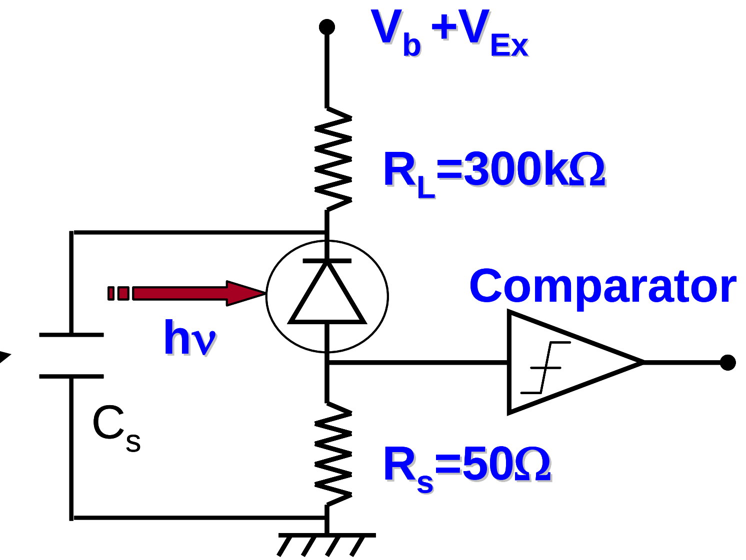

Linear
mode
Geiger
mode
on
quench
Current
avalanche
off
arm
V_dc + ΔV
V_br
Voltage

Quenching Techniques

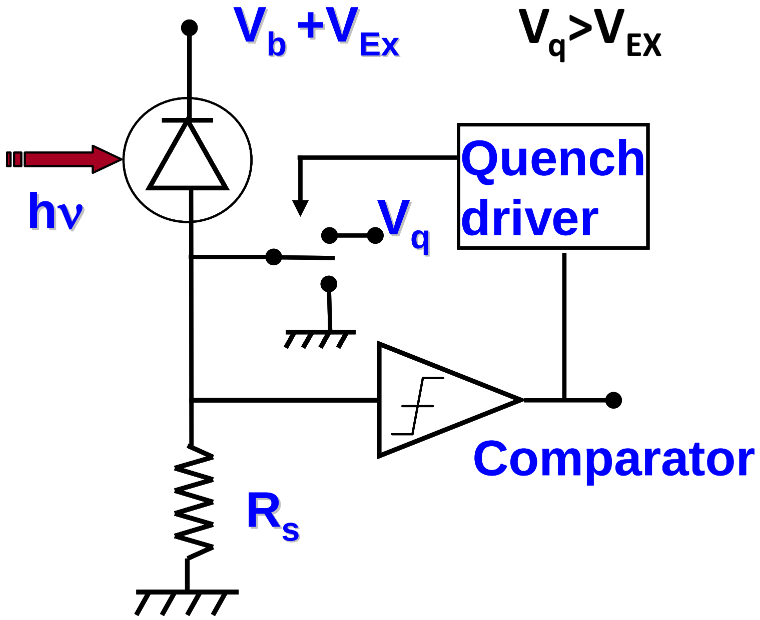
Quenching circuit

- Quench avalanche current
- Reset the device

- **Passive Quenching**
  - Quenched by discharging capacitance
  - Slow recharge

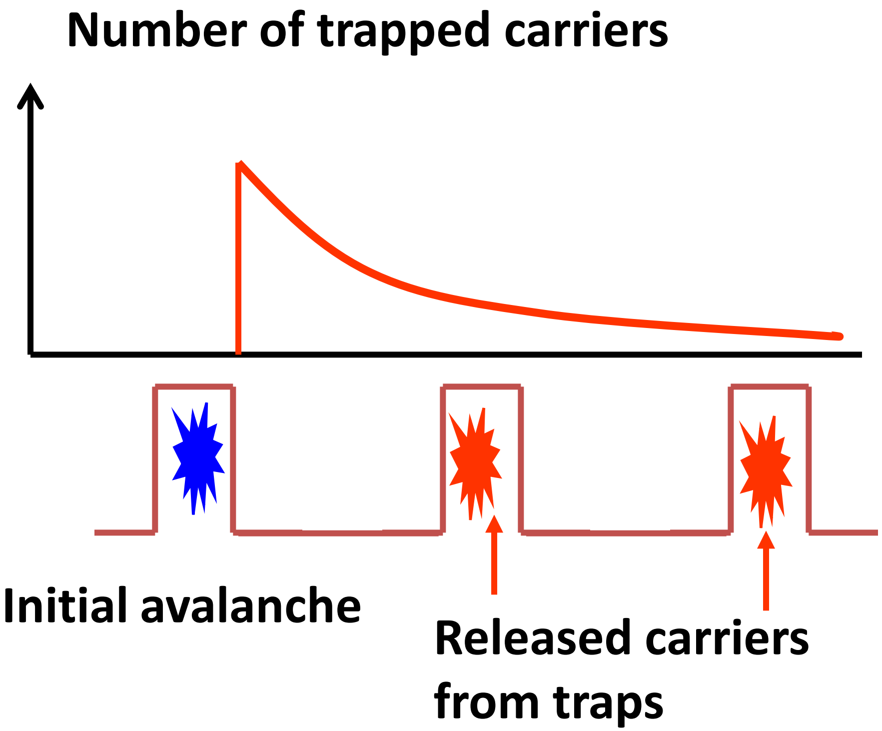


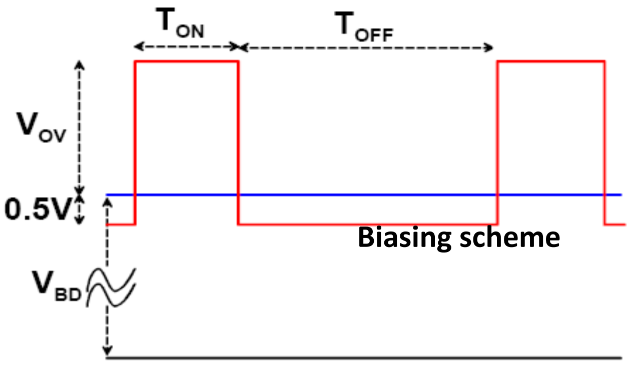
- **Active Quenching**
  - Raise the anode voltage
  - Quick recharge

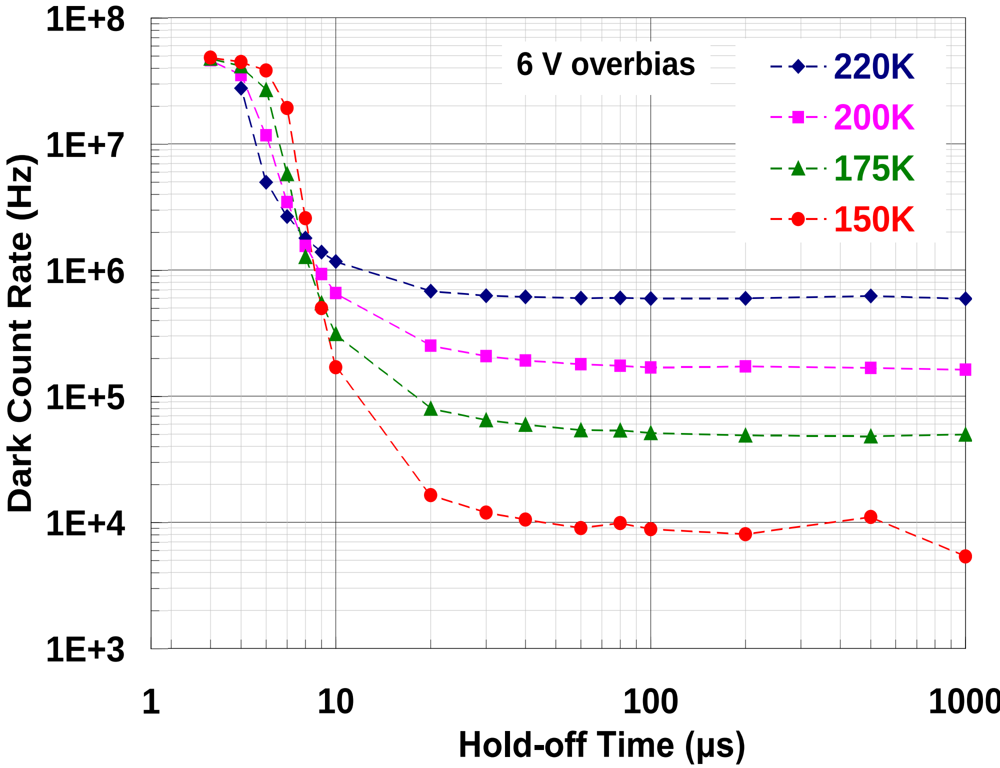


- **Gated Quenching**

Afterpulsing

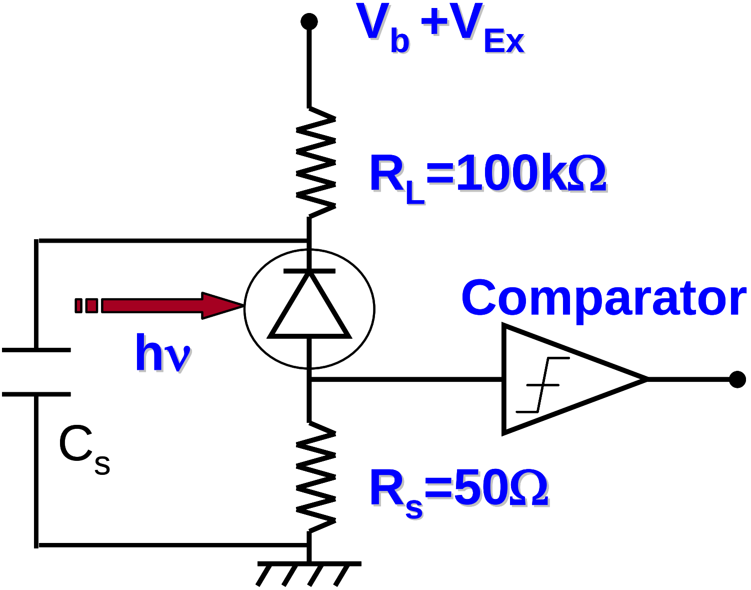


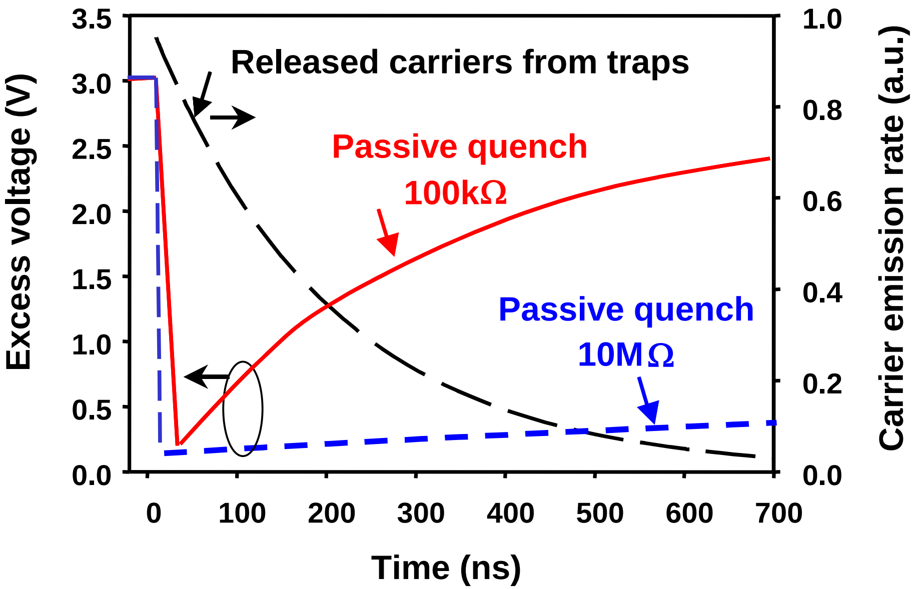




Reduction of Afterpulsing: Decreasing Charge Flow

Passive quenching





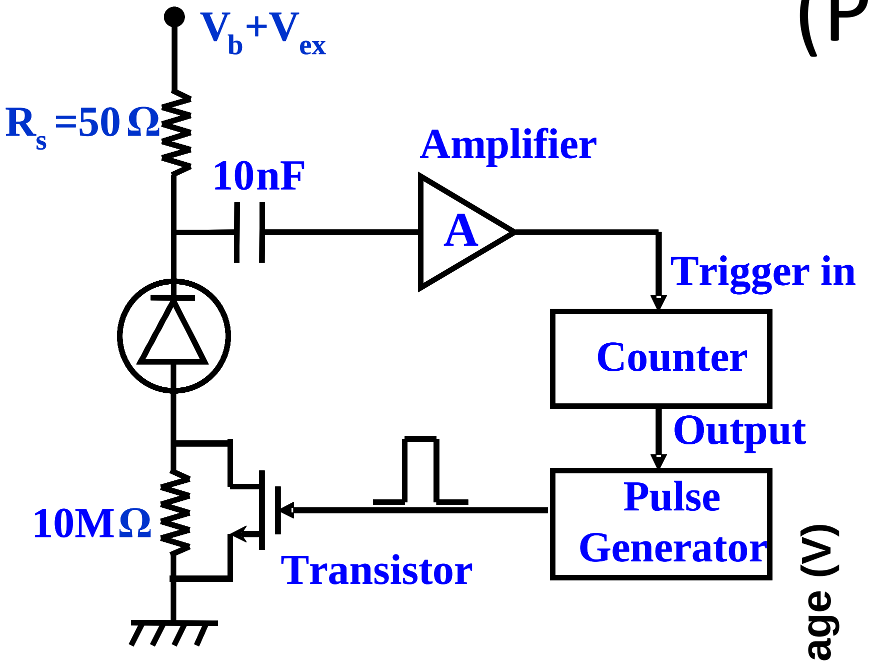
The total charges flowing through device:

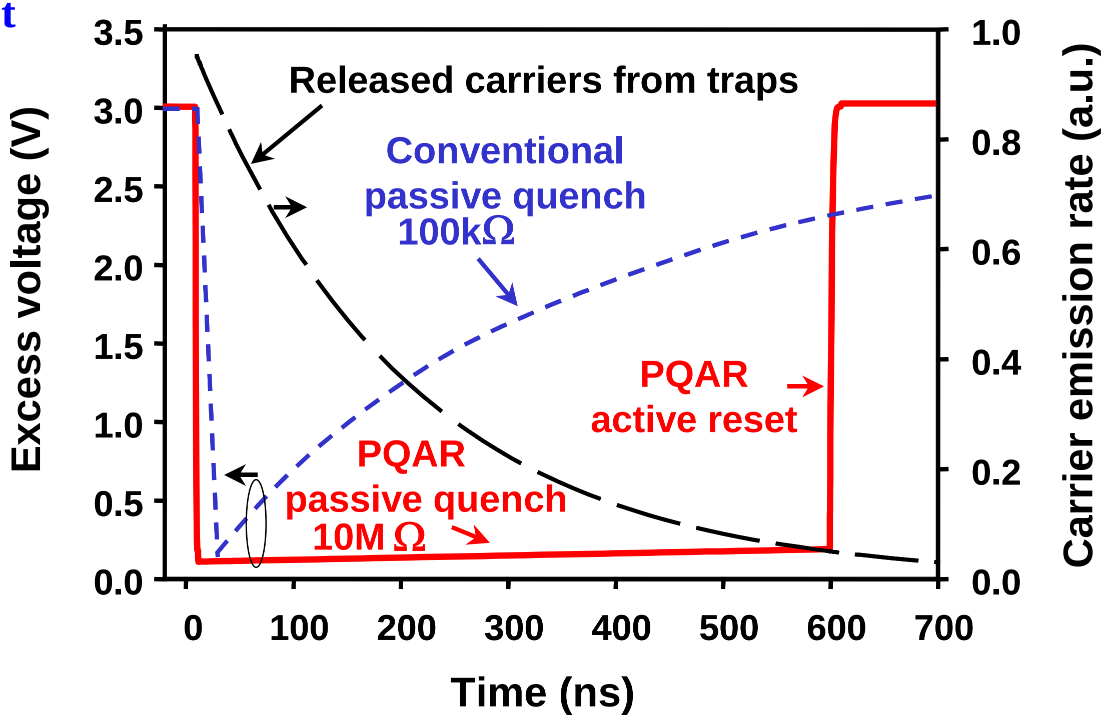
$Q=(C_s+C_d)V_{ex}$

C_d: device capacitance

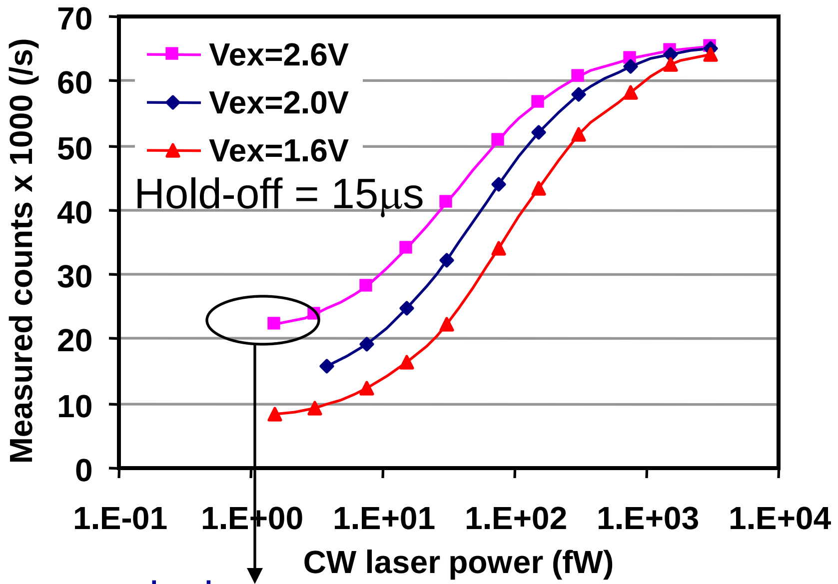
C_s: stray capacitance

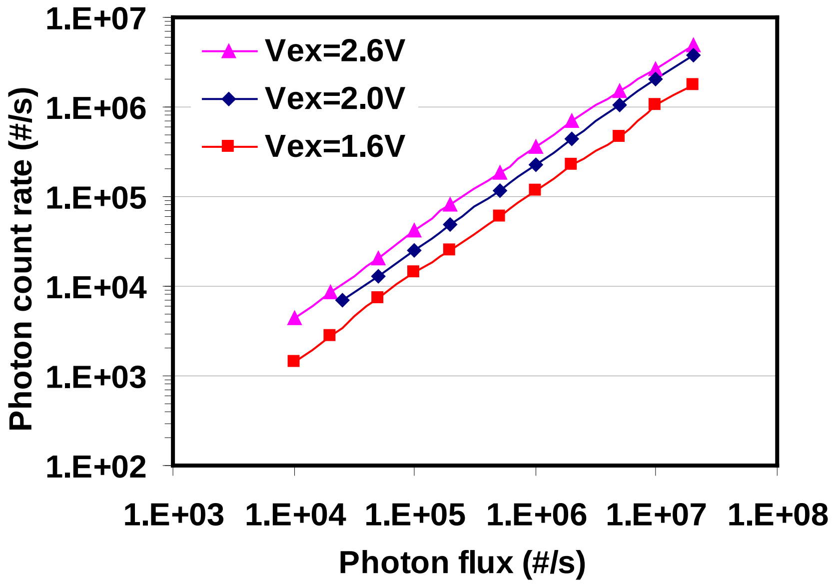
Passive Quenching with Active Reset (PQAR)

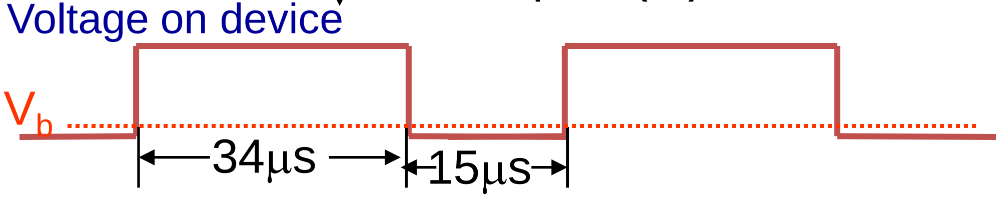




PQAR at 230K





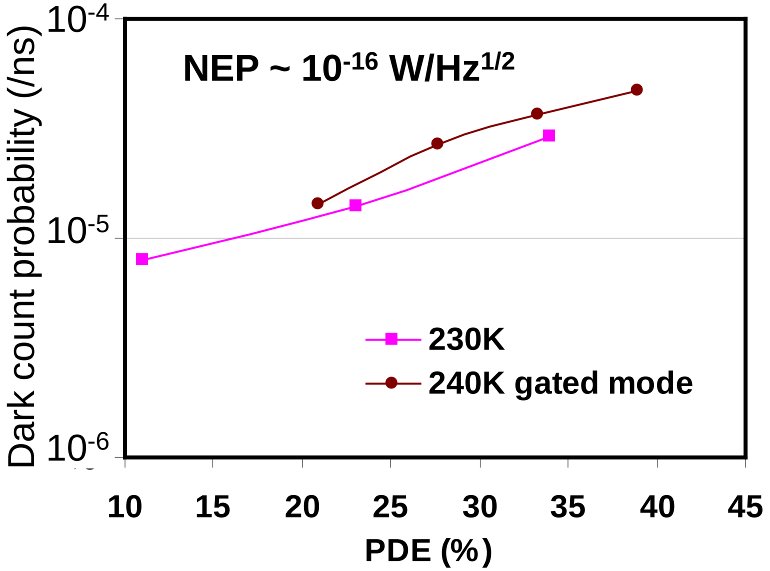


$$DCR = \frac{N_d}{1 - N_d \cdot \tau_{hold-off}} = R_d \cdot P_b$$

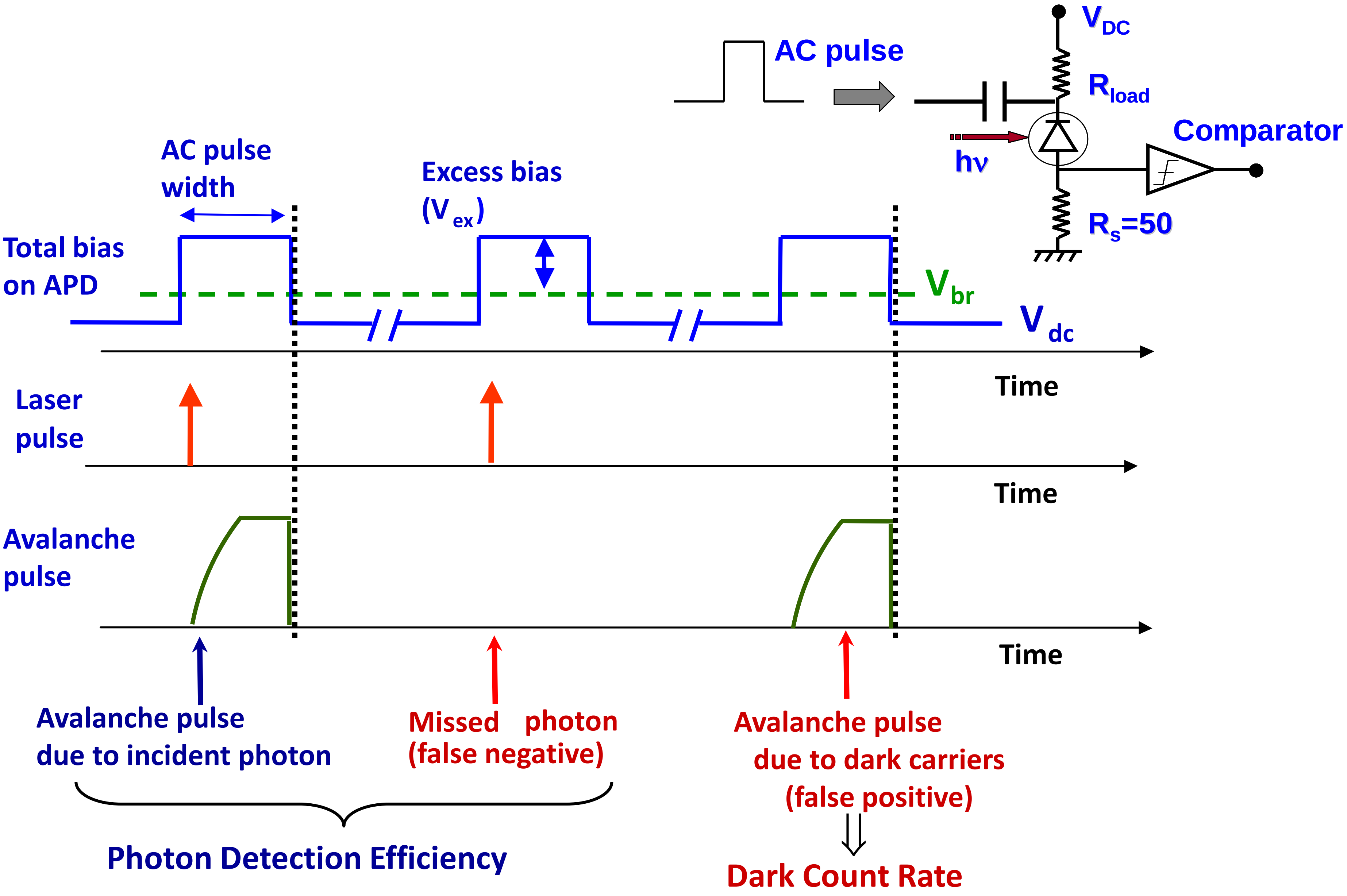
$$TotalCR = \frac{N_t}{1 - N_t \cdot \tau_{hold-off}} = (R_d + \Psi \cdot QE) \cdot P_b$$

$$PCR = TotalCR - DCR = \Psi \cdot PDE$$

Compare with gated mode results



Gated Quenching of a SPAD



Avalanche pulse due to incident photon

Missed photon (false negative)

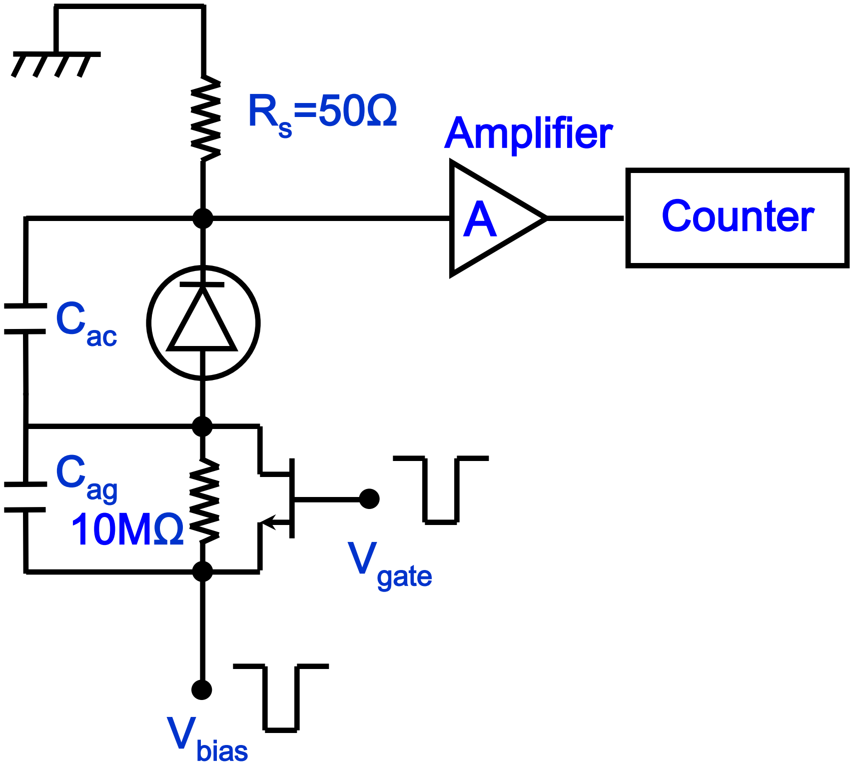
Photon Detection Efficiency

Avalanche pulse due to dark carriers (false positive)

⇓

Dark Count Rate

Gated-PQAR

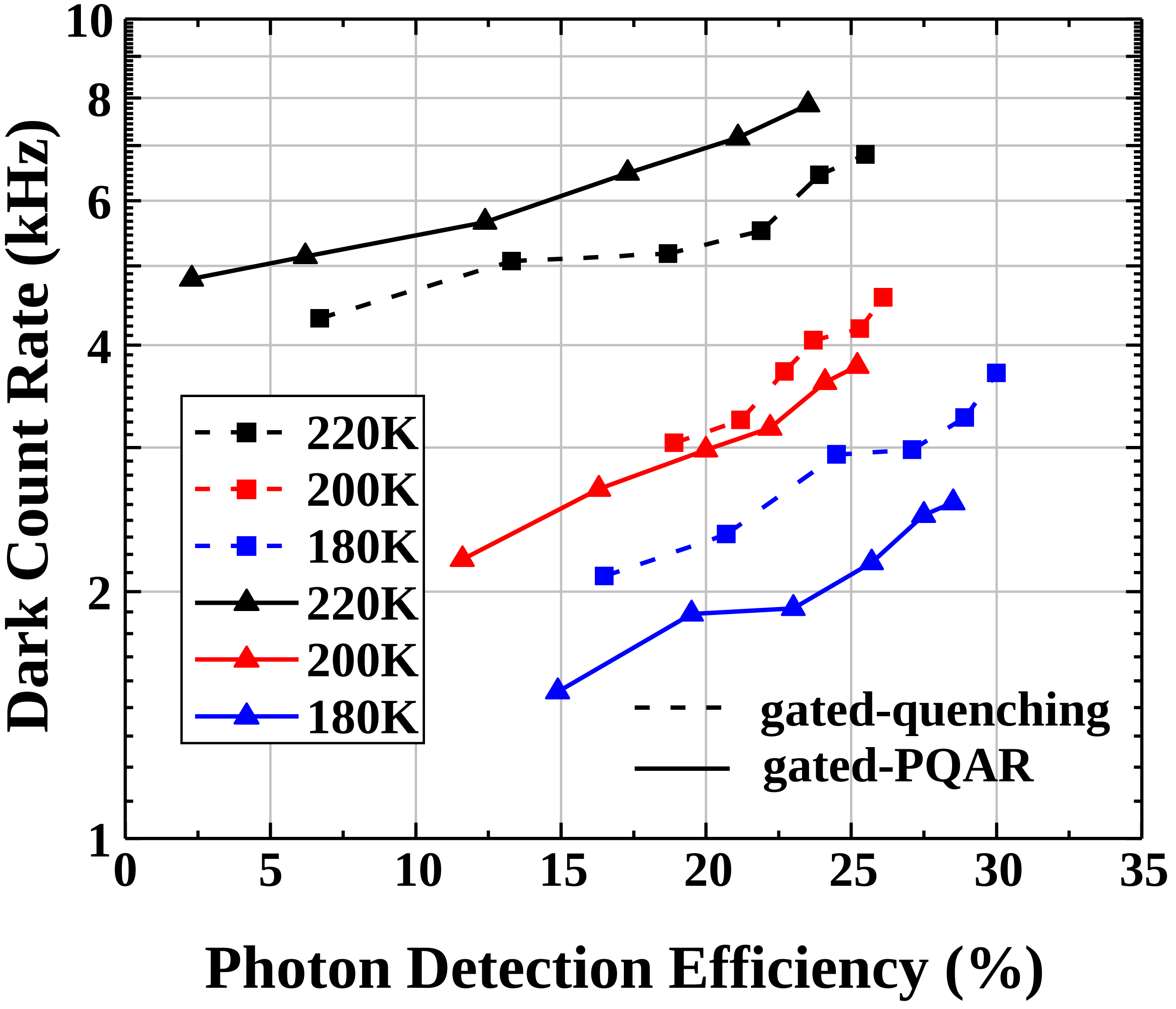


Compared to PQAR

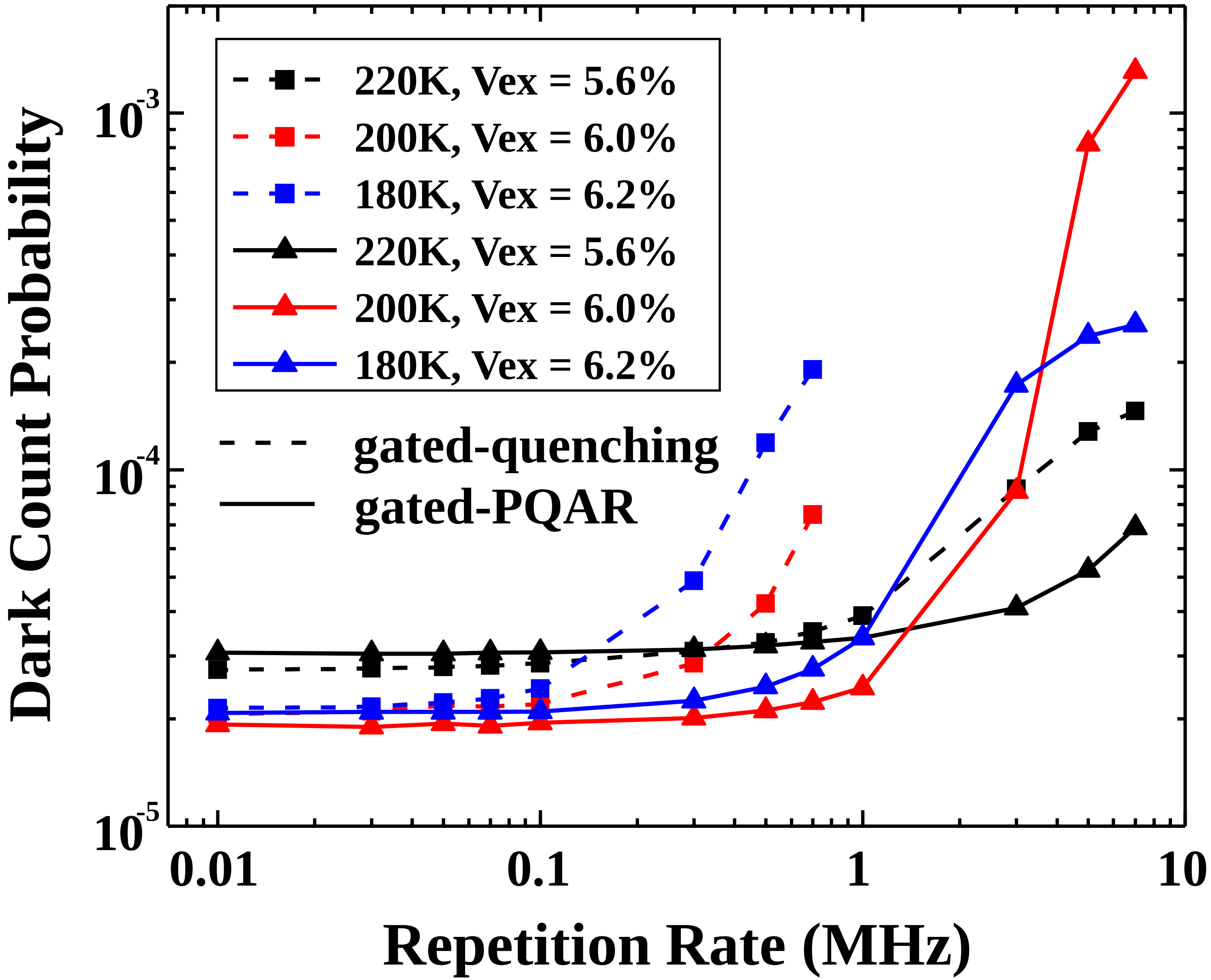
- **Suppressed dark counts by gated bias**
- **Reduced complexity**
- **Array operation: recharge together, quench separately**

The transistor can be HBT monolithically integrated on the SPAD, and the its gate/base input can be shared over the whole array.

Gated Quenching and Gated PQAR



Gated Quenching and Gated PQAR



Conclusions

- ✓ Performance of Geiger-mode APDs is improving rapidly
  - ➢ Acceptable detection efficiencies and dark count probability levels
  - ➢ Getting a better control over the afterpulsing problem

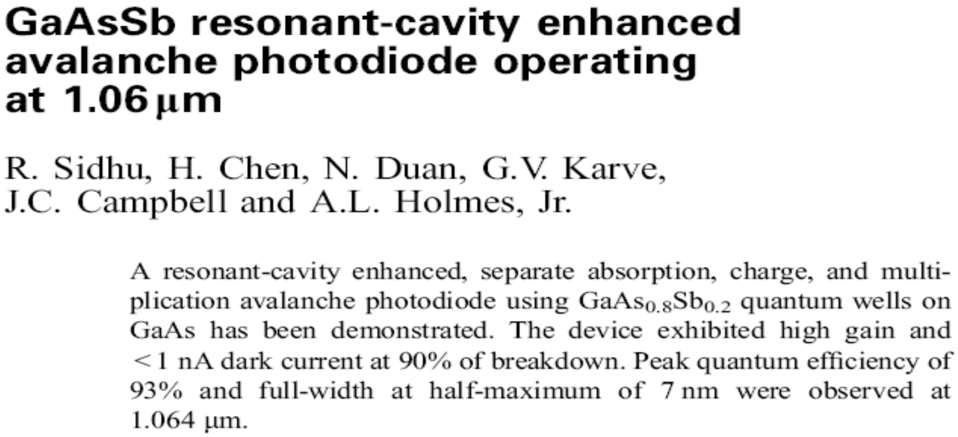
Future Goals

- ✓ Move closer to quantum limited detection
  - ➢ Dark Current → 0
  - ➢ Quantum Efficiency → 100%
  - ➢ Read Noise → 0

- ✓ Move to longer wavelengths

- ✓ Do photon number resolving

High QE Structure



GaAsSb resonant-cavity enhanced avalanche photodiode operating at 1.06 µm

R. Sidhu, H. Chen, N. Duan, G.V. Karve,
J.C. Campbell and A.L. Holmes, Jr.

A resonant-cavity enhanced, separate absorption, charge, and multiplication avalanche photodiode using $GaAs_{0.8}Sb_{0.2}$ quantum wells on GaAs has been demonstrated. The device exhibited high gain and <1 nA dark current at 90% of breakdown. Peak quantum efficiency of 93% and full-width at half-maximum of 7 nm were observed at 1.064 µm.

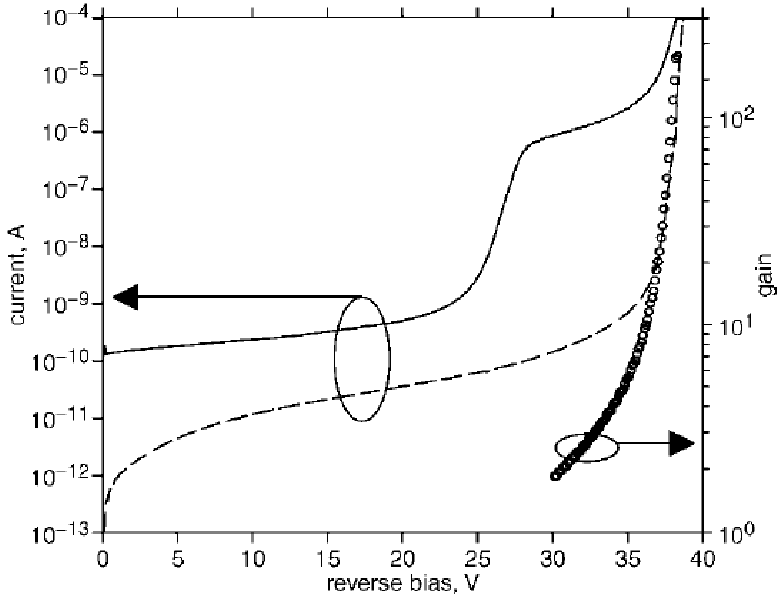


Fig. 2 *Photo-current, dark-current and DC avalanche gain against reverse bias, for 160 µm diameter mesa device*

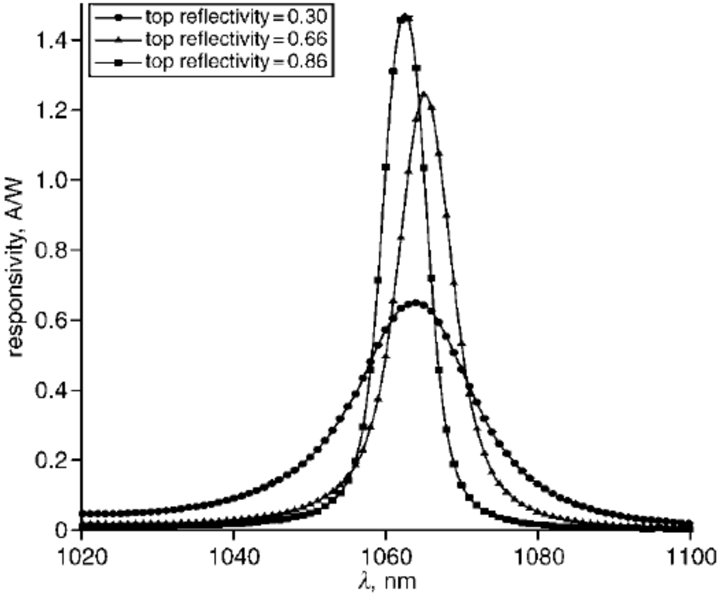
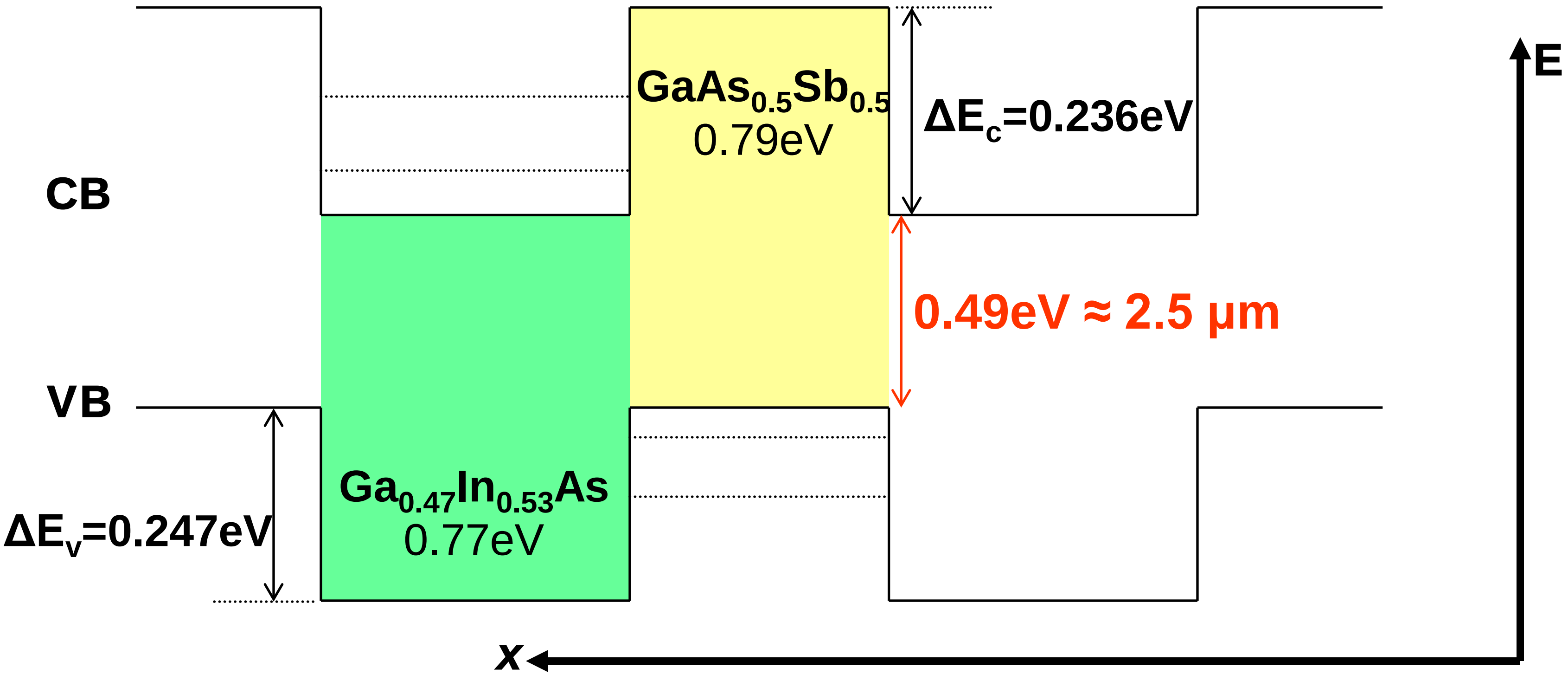


Fig. 3 *Measured responsivity against wavelength for device with no top mirrors (circles), one pair of top dielectric mirrors (triangles) and two pairs of top dielectric mirrors (squares)*

Type-II Quantum Wells (QWs)

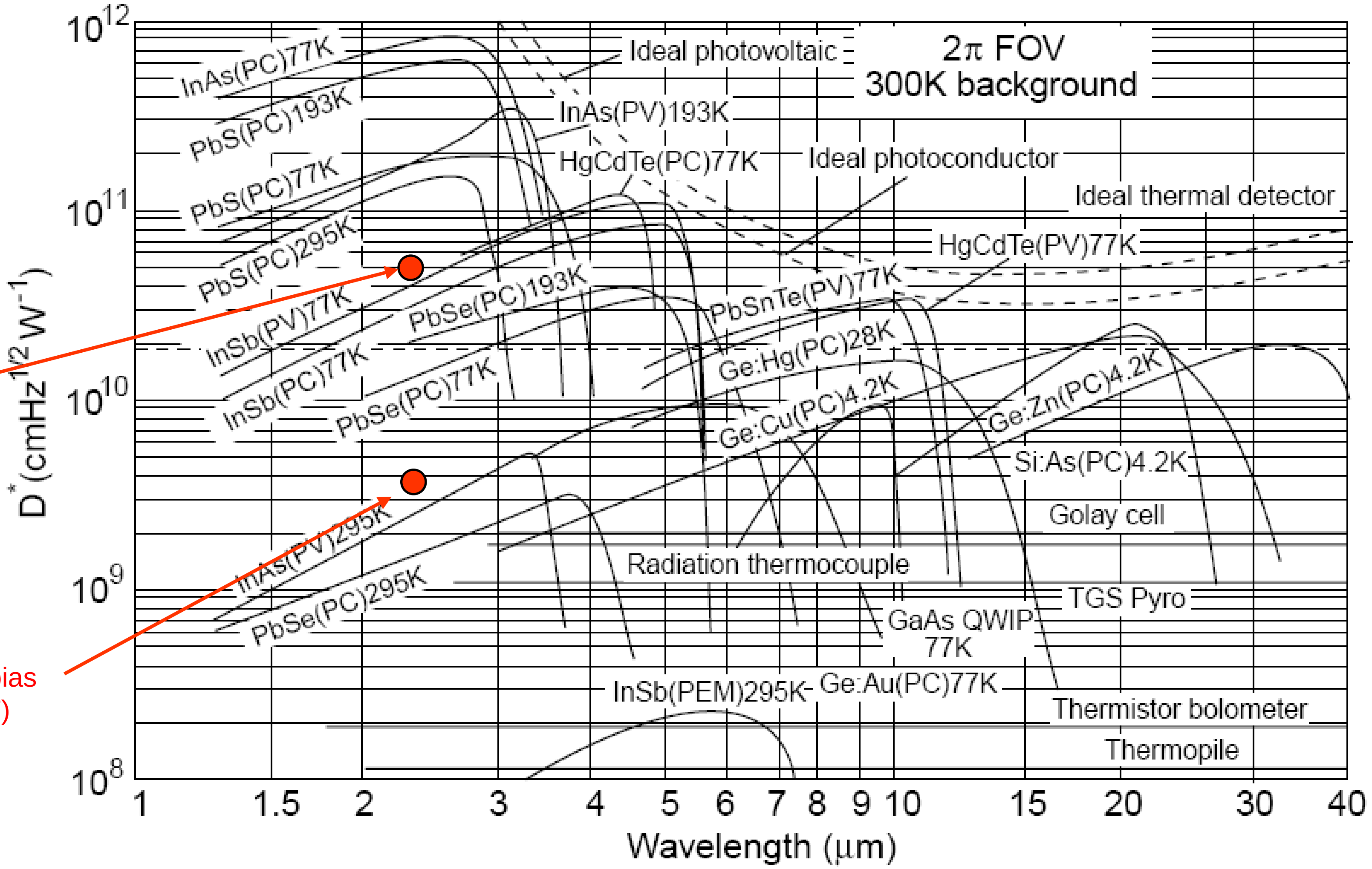
Formed between materials with staggered band line-ups

- ✓ Electrons and holes are confined in adjoining layers
- ✓ Spatially indirect absorption and emission
- ➢ **Smaller effective bandgap for long-wavelength operation**



Where we are now (pin devices)

Rogalski, A., Progress in Quant. Elec., 27(2-3), pp 59 (2003)

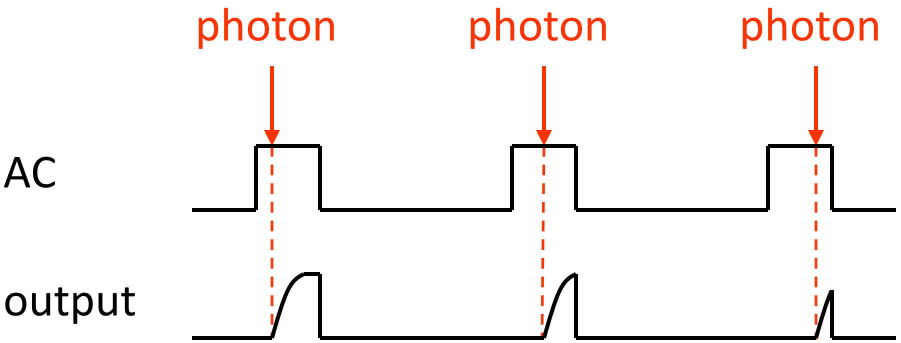


-2 V bias
(200K)

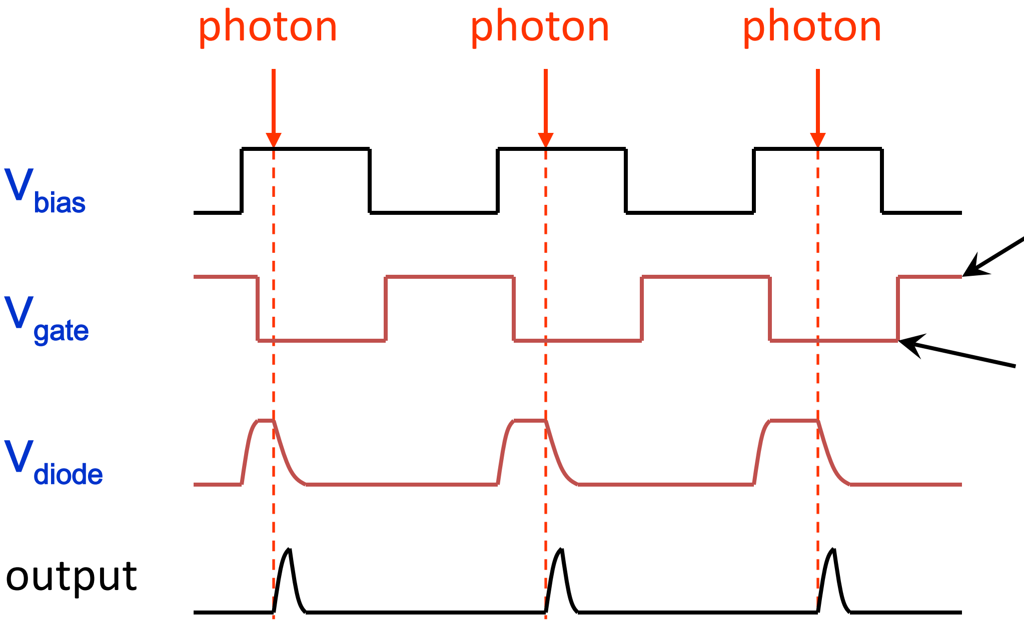
-2 V bias
(RT)

Gated-PQAR for Synchronized Detection

Gated Quench



Gated-PQAR



Transistor on: low resistance for fast reset

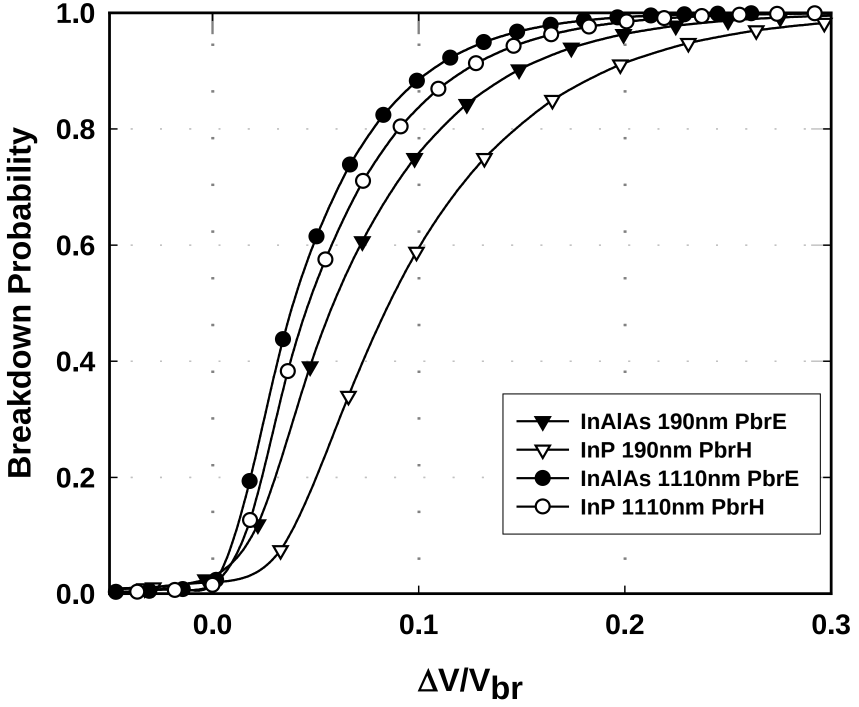
Transistor off: high resistance for fast passive quench

Compared to gated quench

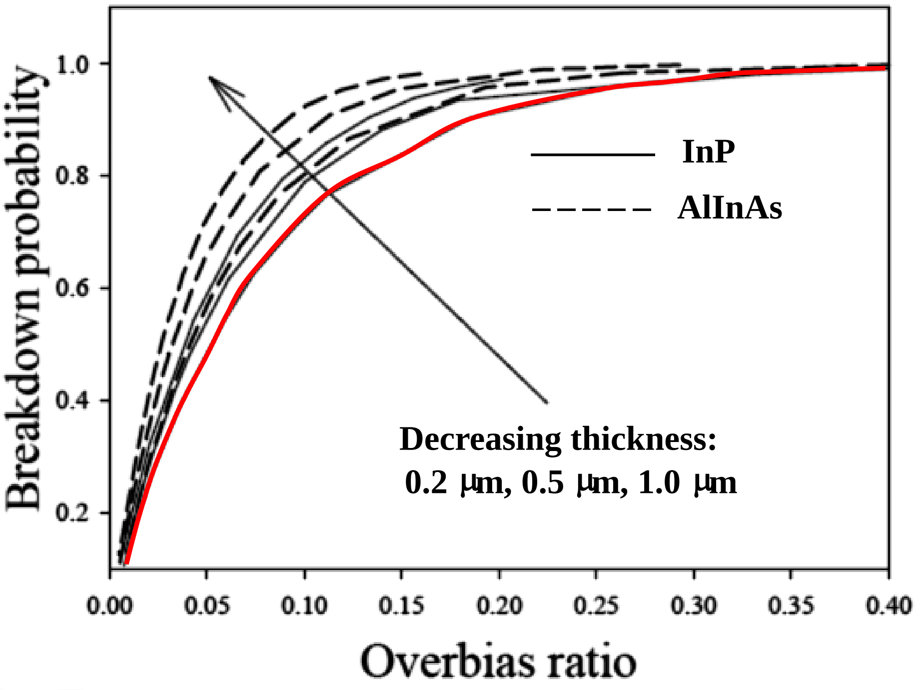
- **Comparable circuit complexity**
- **Wider AC pulses: easier to generate and synchronize**
- **Uniform output pulse shape, good for photon-number-resolution with multiplexing**

Questions??

Simulated Breakdown Probabilities

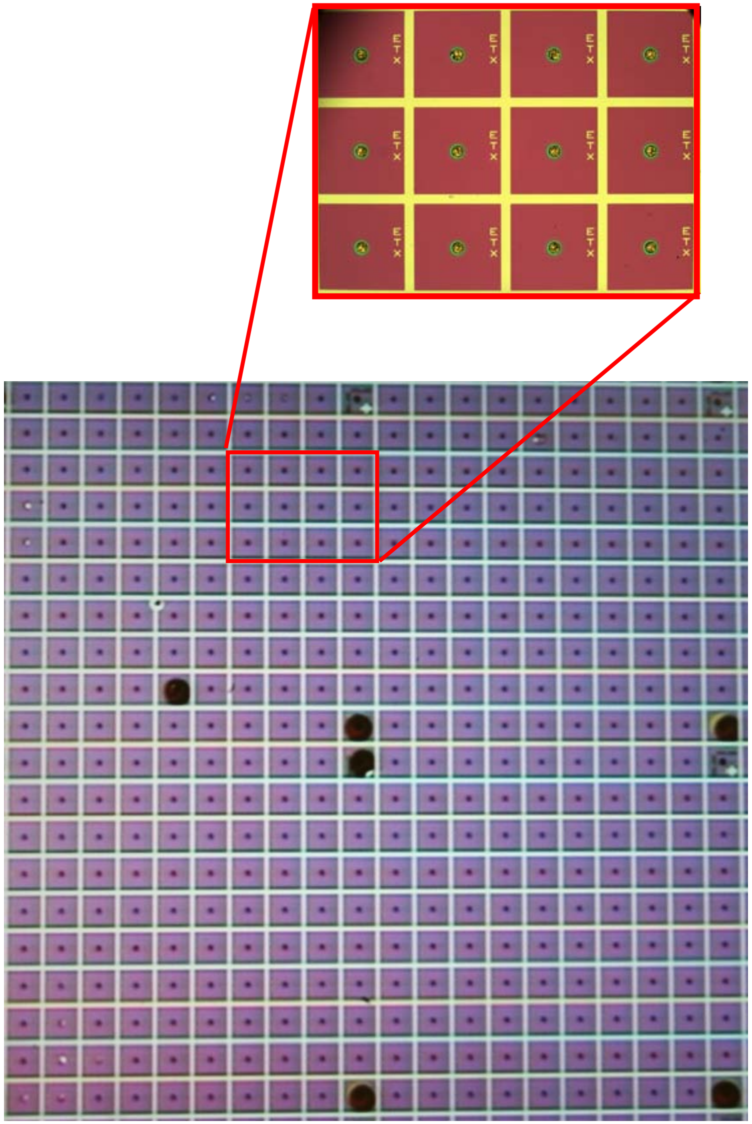


J. P. R. David, University of Sheffield

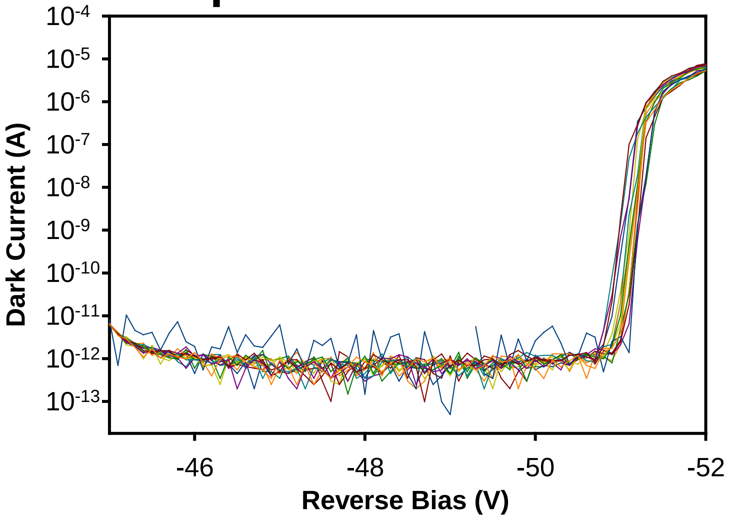


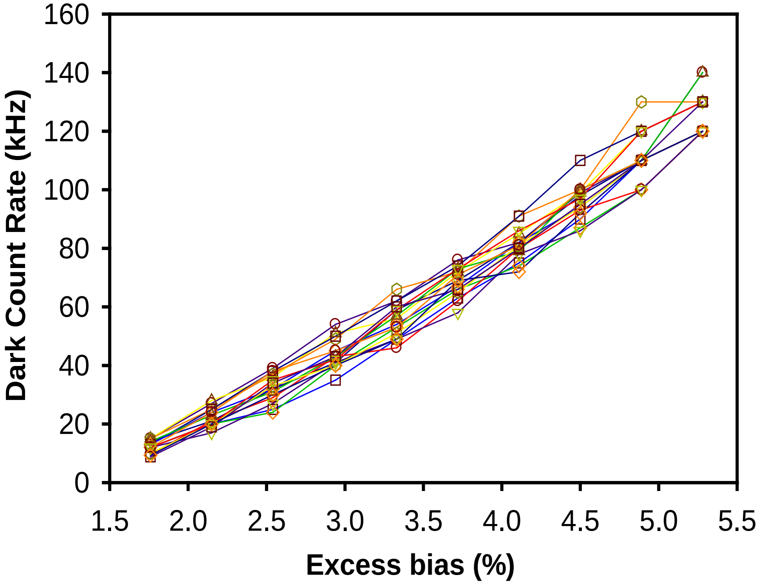
Decreasing thickness:
0.2 µm, 0.5 µm, 1.0 µm

- **20 x 20 Array – 98% yield**

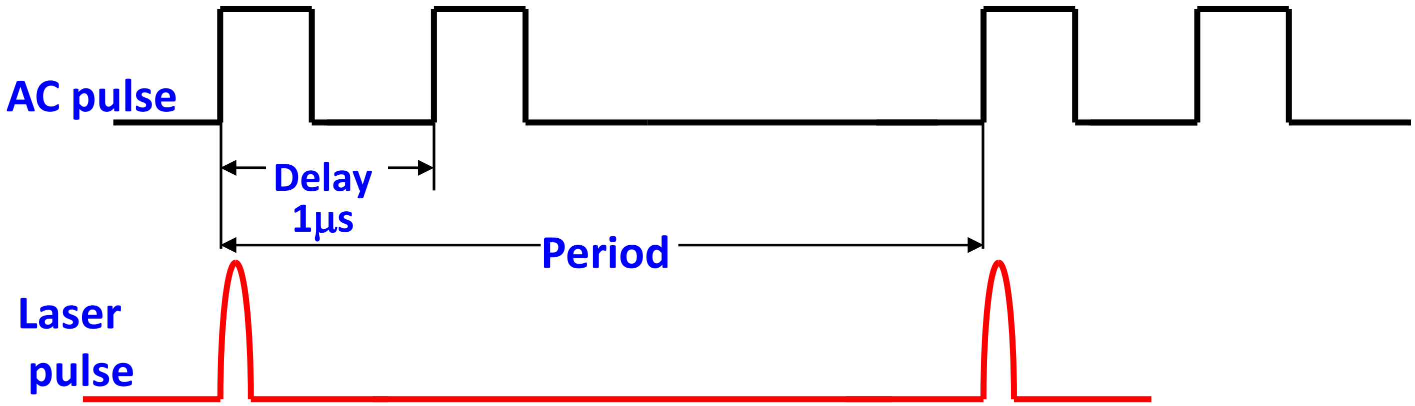


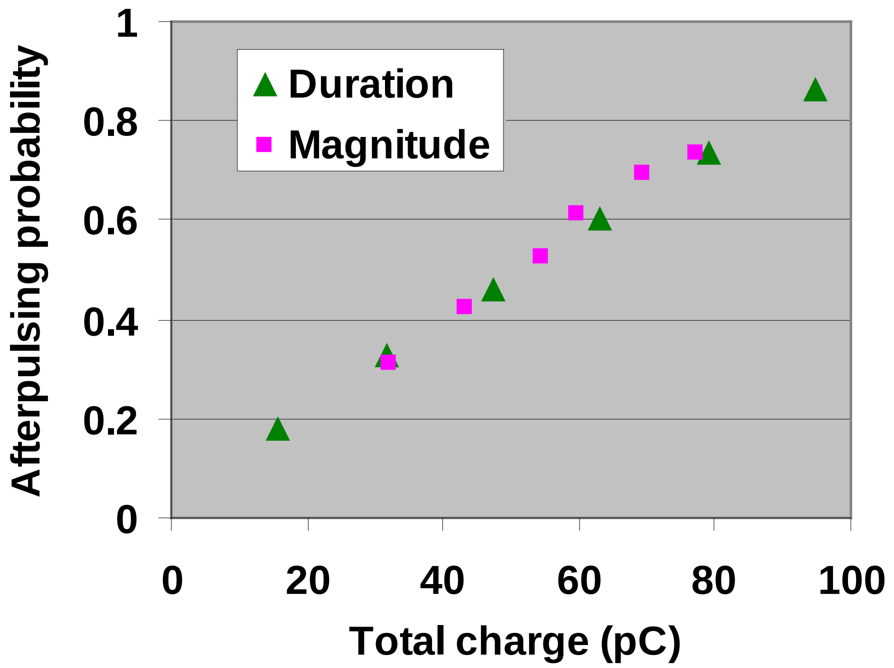
- **4 x 4 Subarray – uniform single-photon response**



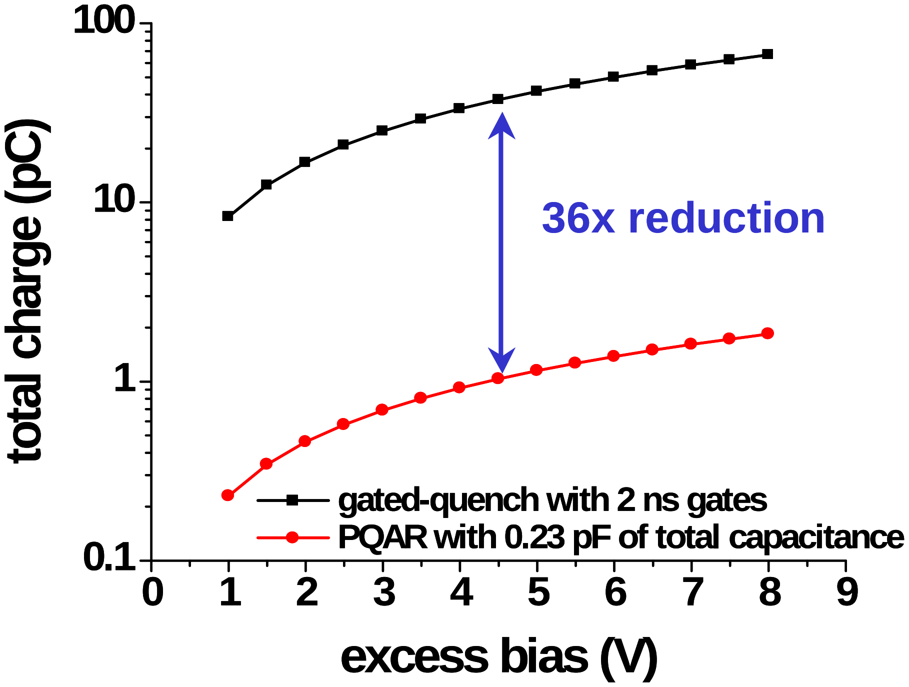


Afterpulsing Probability vs. Total Charge

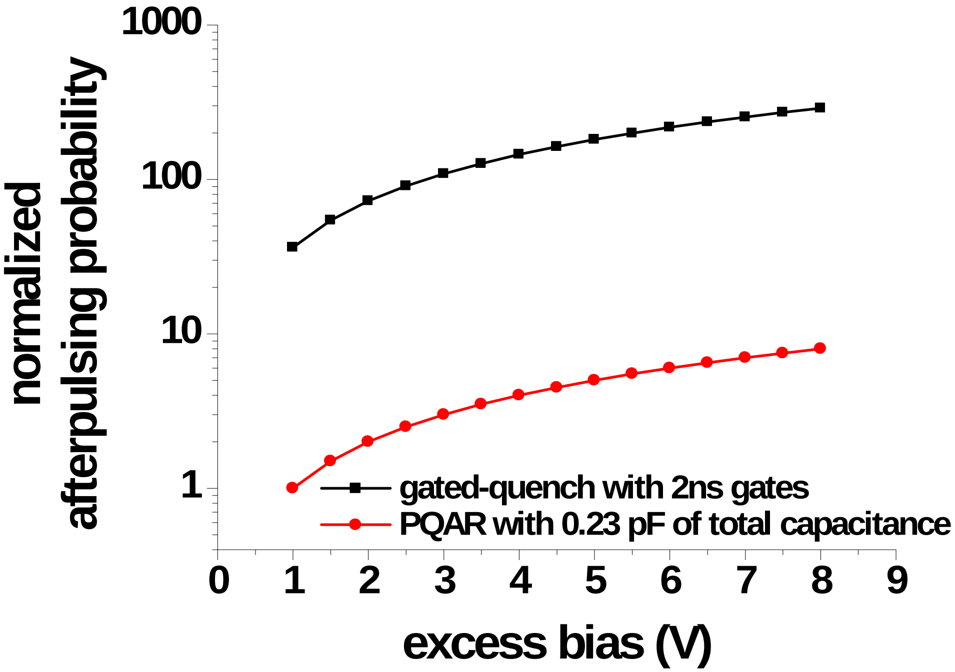




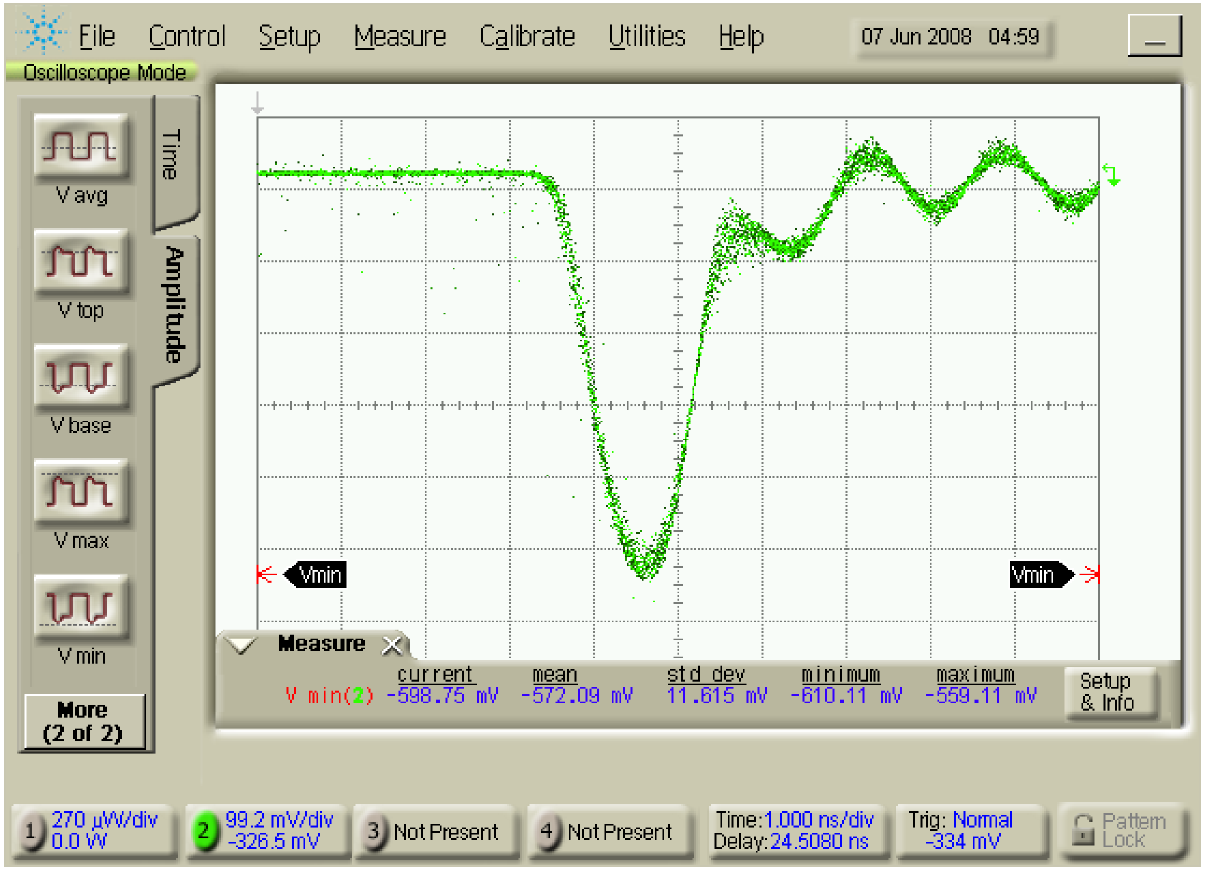
Total Charge Flow



36x reduction



“Effective Excess Noise Factor”



07 Jun 2008 04:59

	current	mean	std dev	minimum	maximum
V min(2)	-598.75 mV	-572.09 mV	11.615 mV	-610.11 mV	-559.11 mV

1 270 µW/div 0.0 W

2 99.2 mV/div -326.5 mV

3 Not Present

4 Not Present

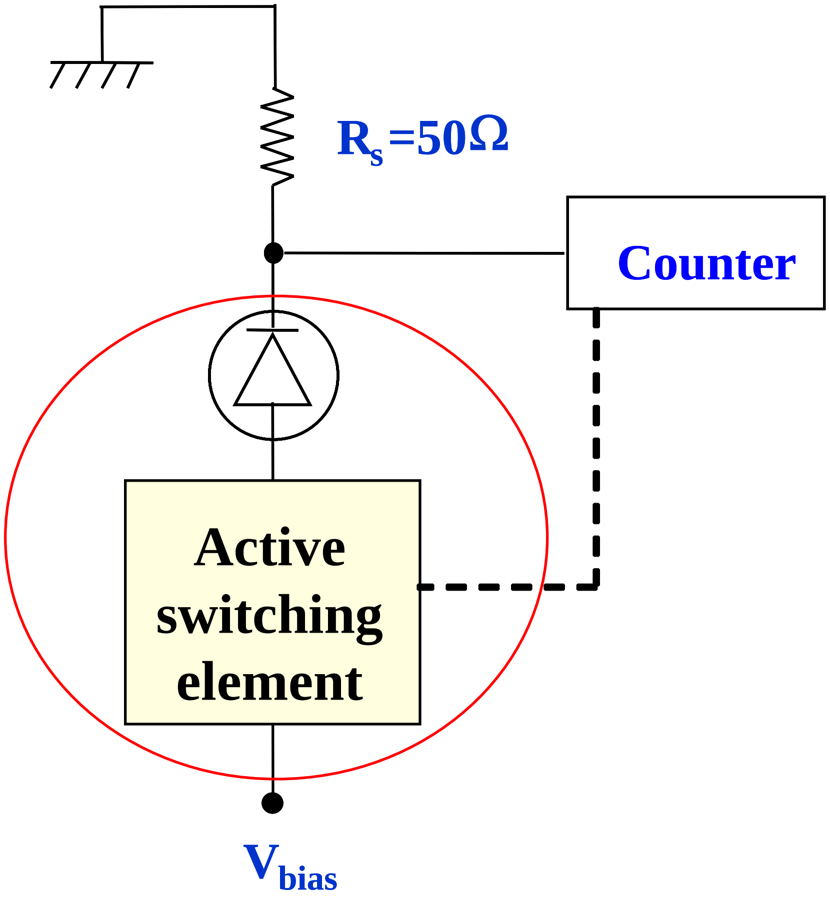
Time:1.000 ns/div Delay:24.5080 ns

Trig: Normal -334 mV

$$\textbf{Effective excess noise factor } \equiv 1+\frac{\sigma^2(\text{peak signal})}{<\text{peak signal}>^2}$$

$$=1+\left(\frac{11.6mV}{572mV}\right)^2 = 1.0004$$

Pixel Level Monolithic Integration of Active Switching Elements



- **Reduced parasitics**
- **Faster quenching**
- **Reduced afterpulsing**
- **Increased transmission and sampling rates**
- **Packaging advantages**