Title: Photon sensors

Speakers: Sae Woo Nam

Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 22, 2022 - 4:30 PM

URL: https://pirsa.org/22090025

Single Photon Detectors

Sae Woo Nam

NIST - National Institute of Standards and Technology

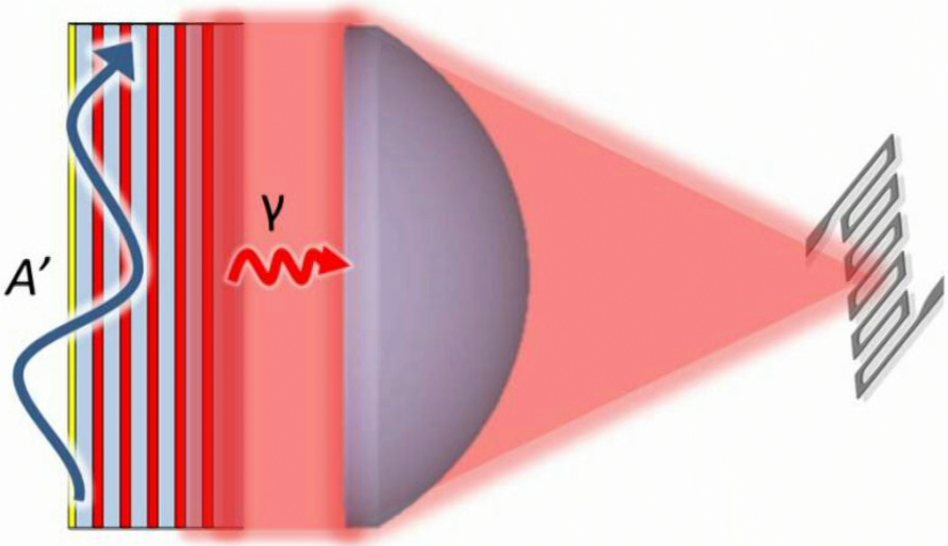
Outline

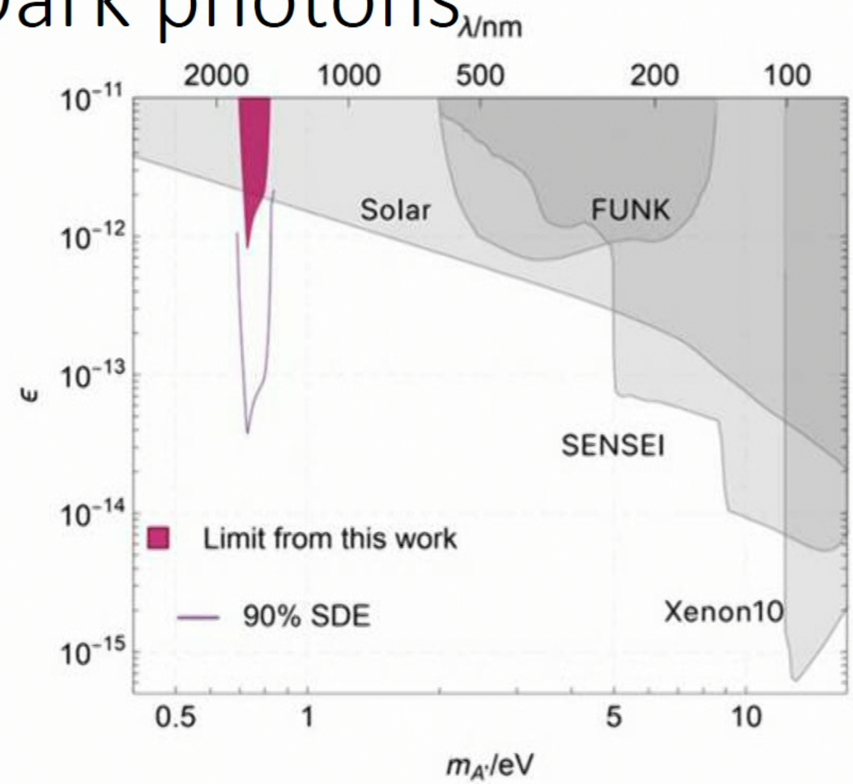
- Lecture 1: Physics of various Photodetectors
  - Motivation: Tabletop Experiments to detect DM
    - LAMPOST
    - ALPS
    - Comment on Signal to noise
  - Photon Detectors:
    - Metric / Specifications
    - Conventional
      - PMT
      - Avalanche Photodiodes
      - SiPM
    - Superconductors:
      - Superconducting Nanowire Single Photon Detectors
      - Transition-edge Sensors

Outline

- Lecture 2: Building LAMPOST
  - Cryogenics
  - Electronics
  - Optics
  - Detectors
  - Taking Data
  - What’s next?
    - Veto backgrounds
    - Calibrations

Motivation: LAMPOST, Dark photons



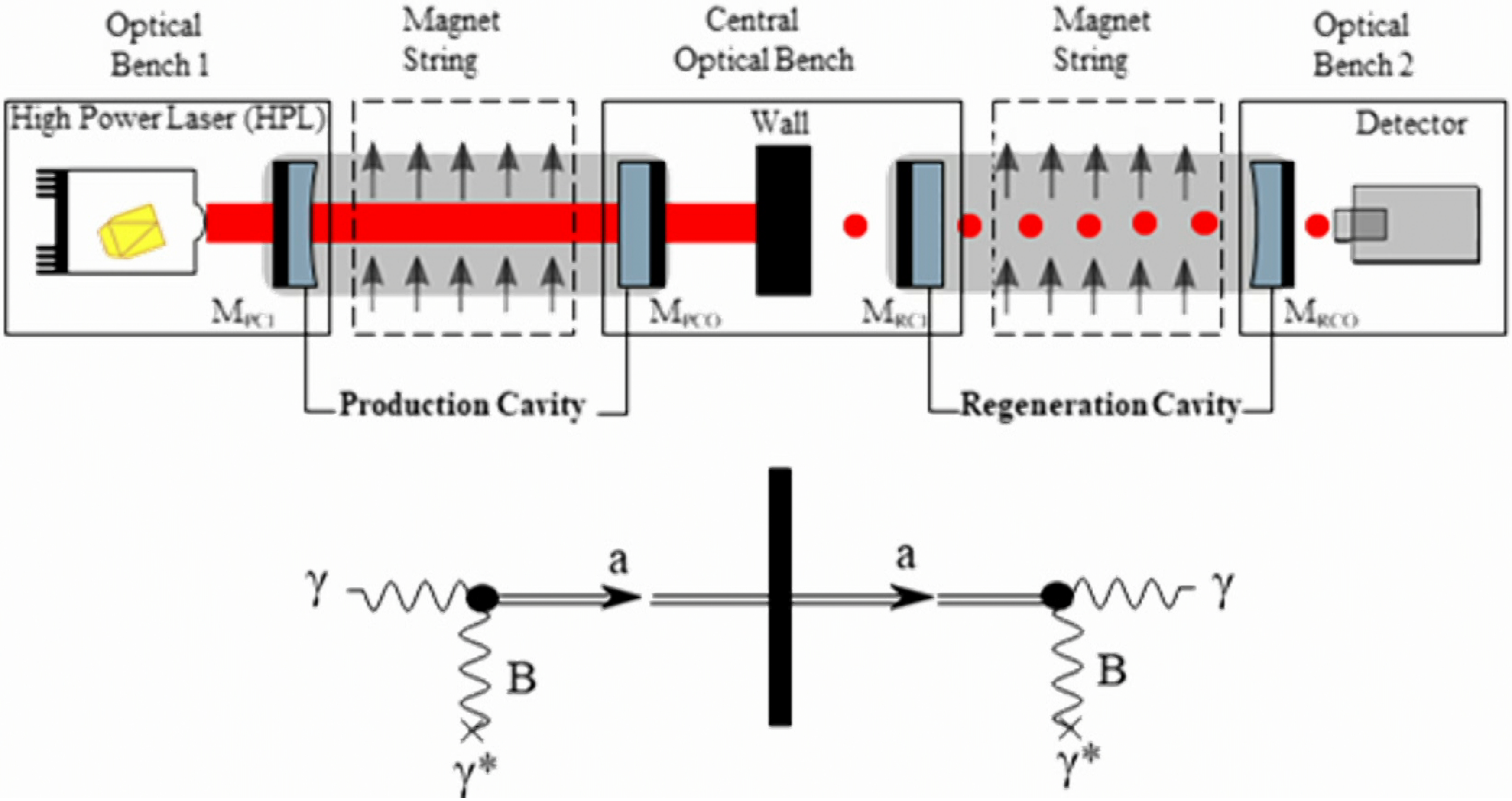


Transduction

https://doi.org/10.1103/PhysRevLett.128.231802

Jeff Chiles, Ilya Charaev, Robert Lasenby, Masha Baryakhtar, Junwu Huang, Alexana Roshko, George Burton, Marco Colangelo, Ken Van Tilburg, Asimina Arvanitaki, Sae Woo Nam, Karl K. Berggren

ALPS-II



Optical Bench 1
Magnet String
Central Optical Bench
Magnet String
Optical Bench 2
High Power Laser (HPL)
Wall
Detector
M_{PCI}
M_{PCO}
M_{RCI}
M_{RCO}
Production Cavity
Regeneration Cavity
γ
a
a
γ
B
B
γ*
γ*

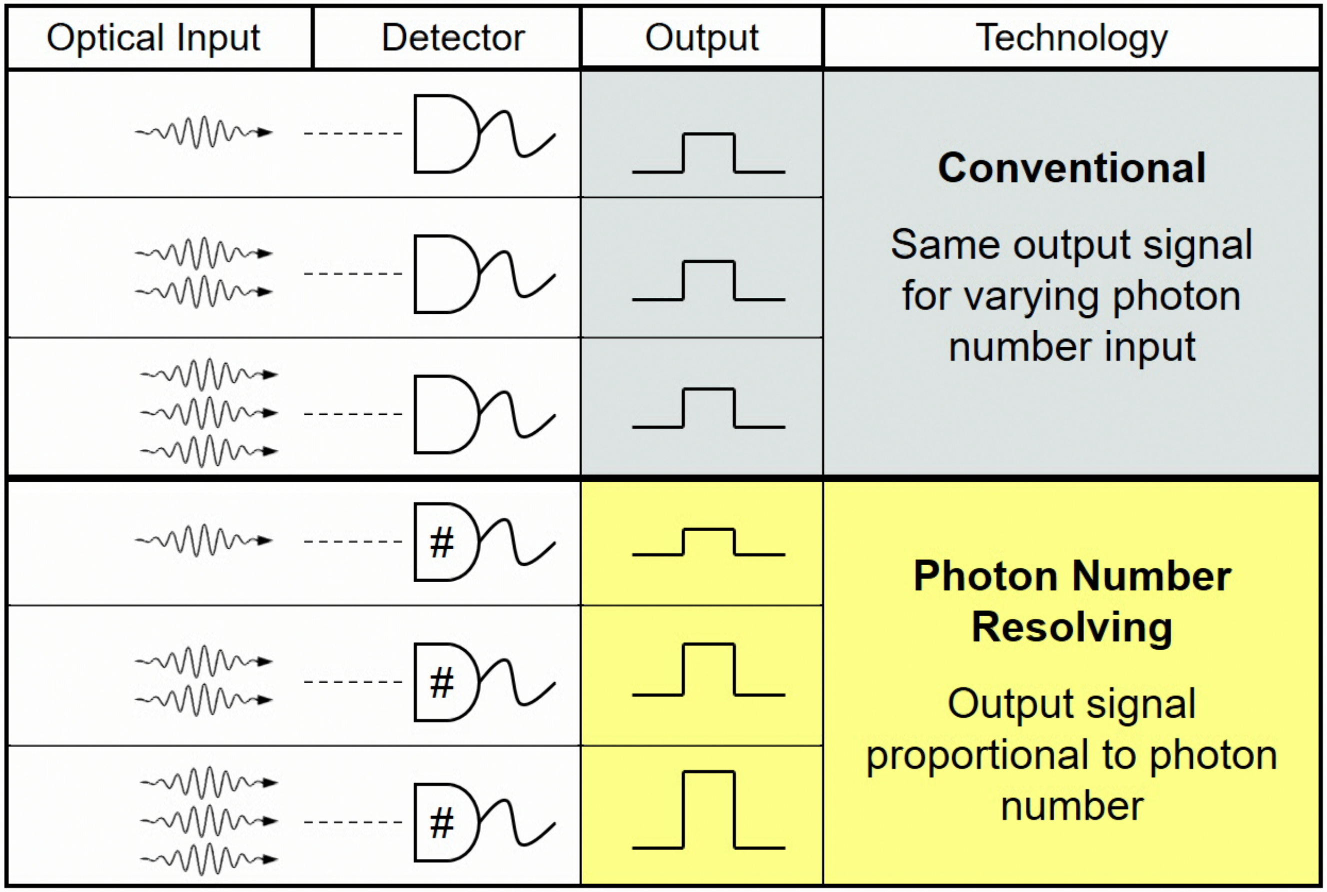
Single Photon Detectors - Properties

- High Quantum Efficiency (as close to 100%)
- Wavelengths: Narrow or Broadband (100nm to 10000 nm to 1mm???)
- Low Dark Count rate
  - No false counts
  - No afterpulsing
- Speed
  - Fast recovery
  - Low jitter
- Energy Resolving / Photon Number Resolving

Other considerations

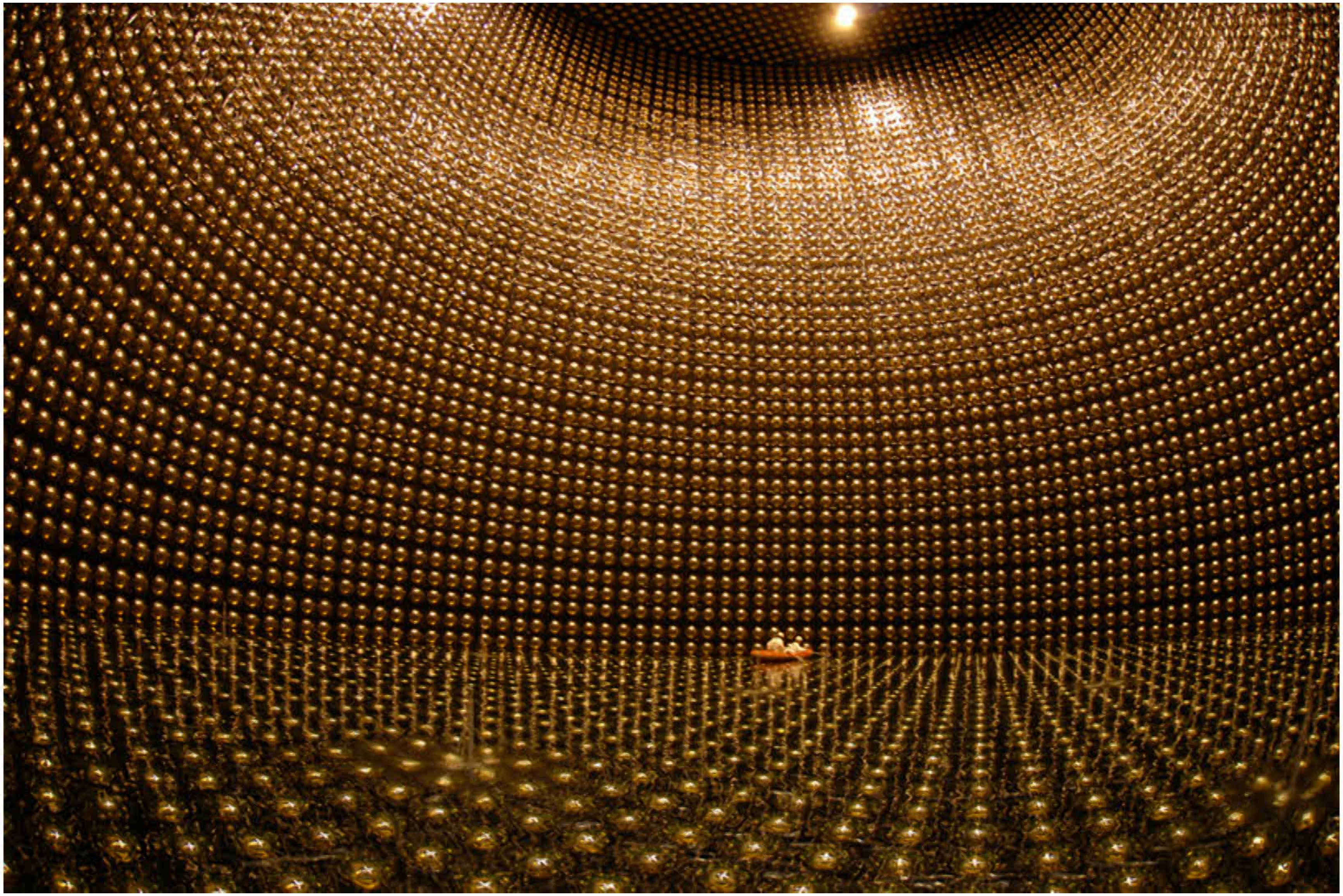
- SWaP
  - Size
  - Weight
  - Power
- Commercially available?
- Training / user friendly?
  - Do I need a PhD to operate this?
- Maintenance
- Robust… Is it easy to break?
- Price

Photon Counter vs. Photon Number Resolving

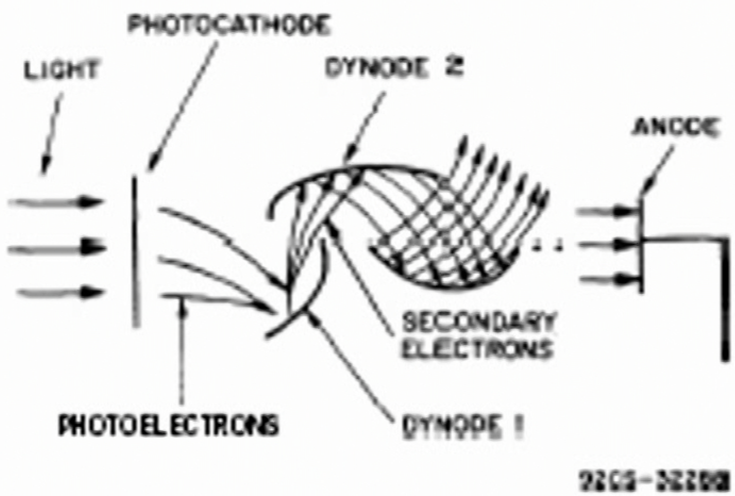


Single Photon Detector Technologies

- "Photon Counter"
  - **Photomultiplier Tubes**
  - **Avalanche Photodiodes**
  - Quantum Dots
  - Upconversion
  - **Superconducting Nanowire Single Photon Detector**
- "Photon Number Resolving"
  - N-splitters and photon counters
  - Photomultiplier
  - Visible Light Photon Counter / Solid State Photomultiplier
  - **Low Temperature Superconducting Detectors**



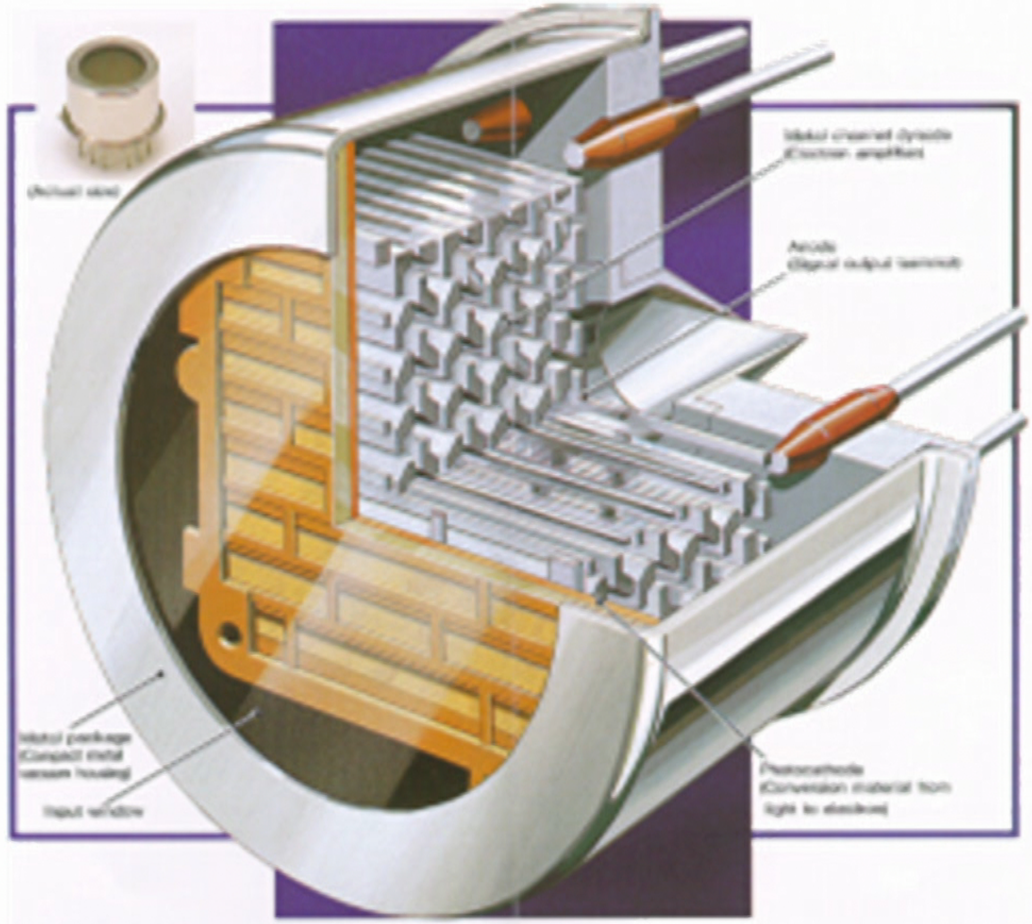
Photomultiplier Tube (PMT)



- Photoelectric Effect
- Secondary emission
- Photocathode determines sensitivity
- Afterpulsing
- Gain ~ 1 million

Wavlength	200-1700
Q.E.	Up to 50%
Dark Count	100 Hz – 100kHz
Count Rate	100 MHz
Timing	<1 ns

Commercial Devices: Hamamatsu, Burle
~$20,000



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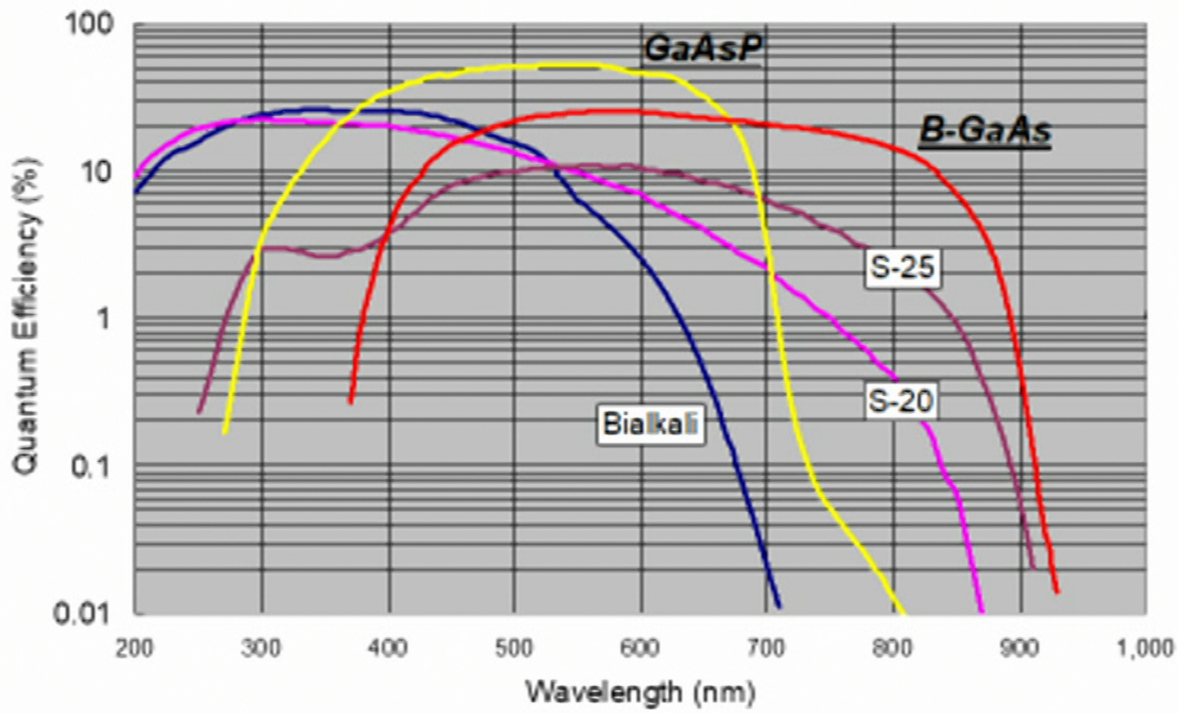
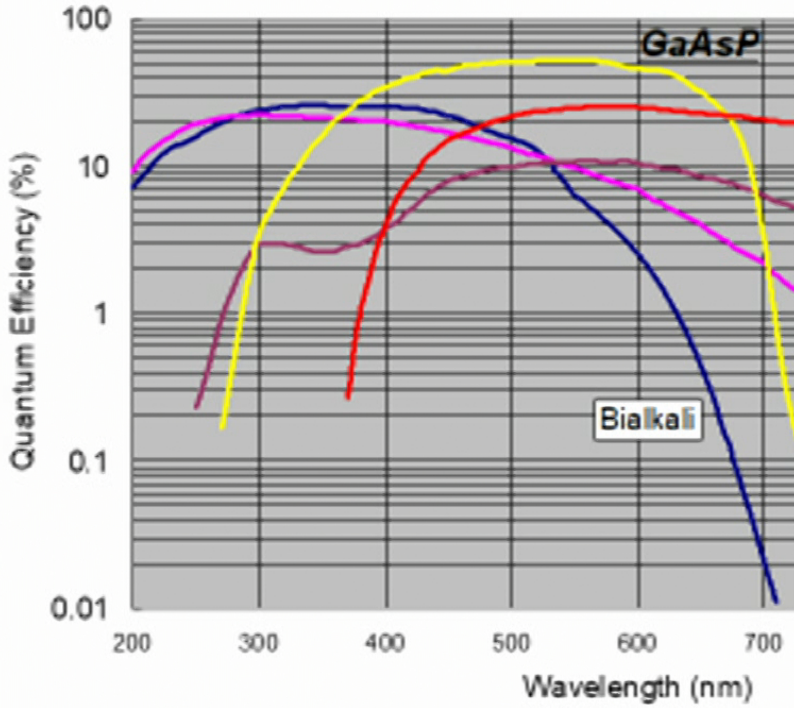
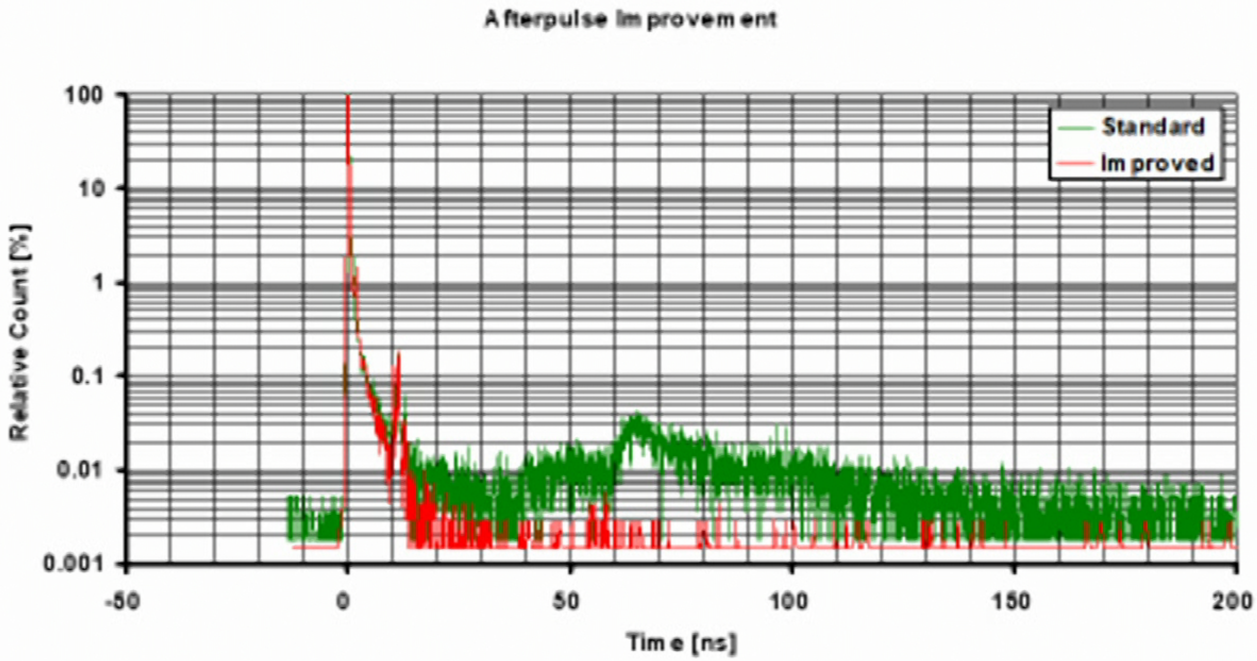
GaAsP & Blue Enhanced -GaAs



GaAsP & Blue Enhanced -GaAs

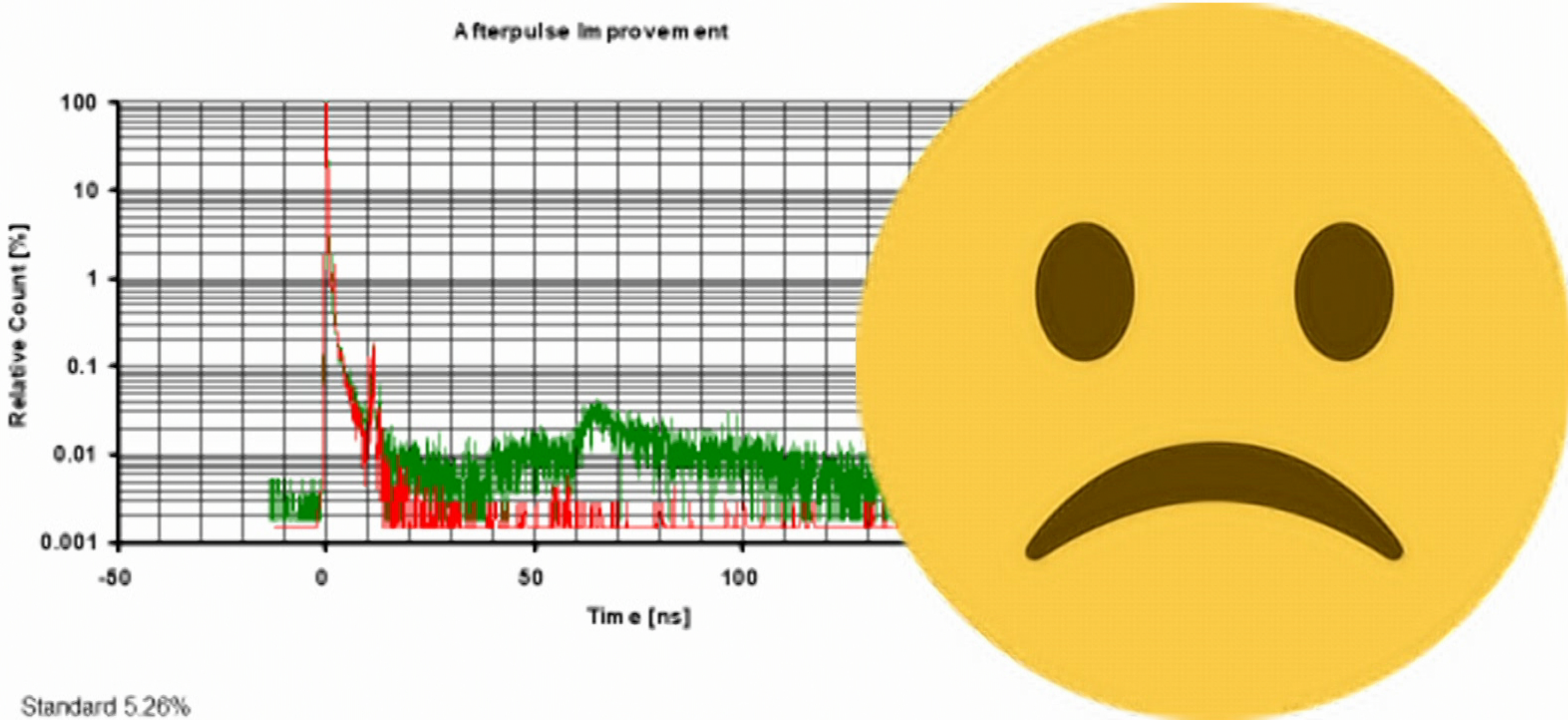


After pulsing Improvements



Standard 5.26%
Improved 0.95%

After pulsing Improvements



Standard 5.26%
Improved 0.95%

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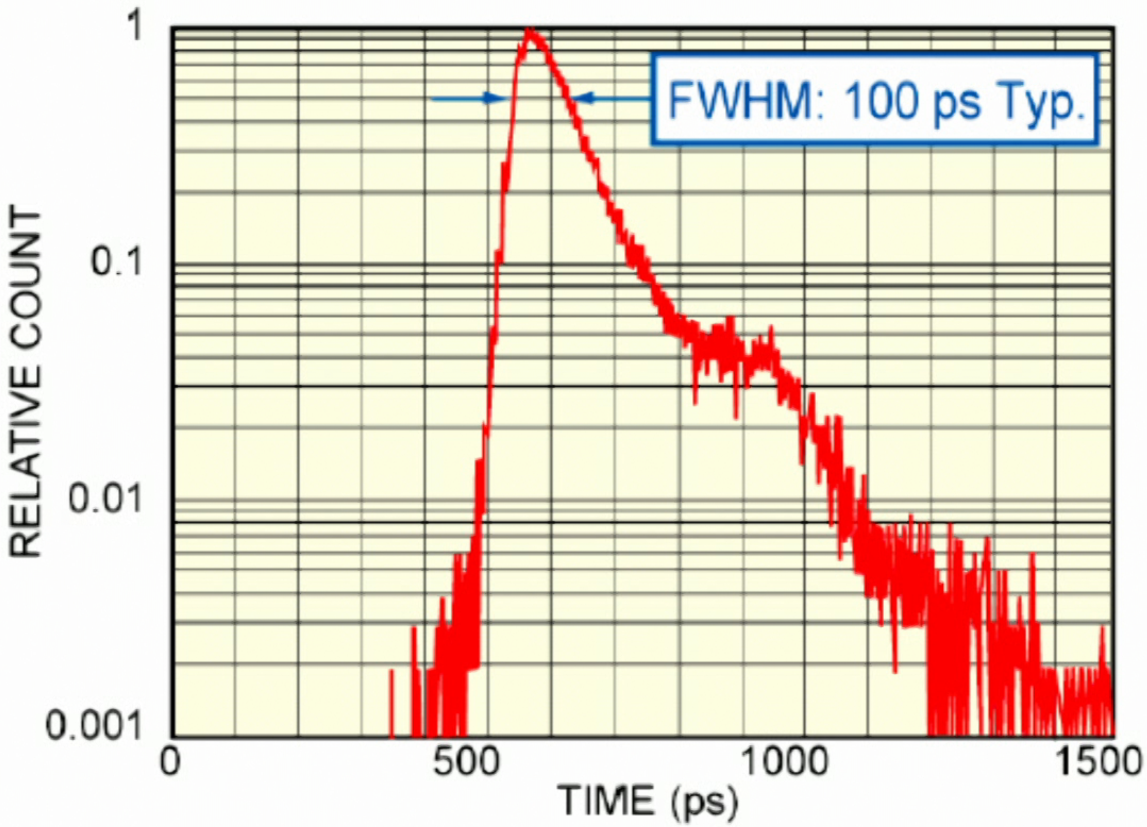
Jitter



FWHM: 100 ps Typ.
RELATIVE COUNT
1
0.1
0.01
0.001
0
500
1000
1500
TIME (ps)

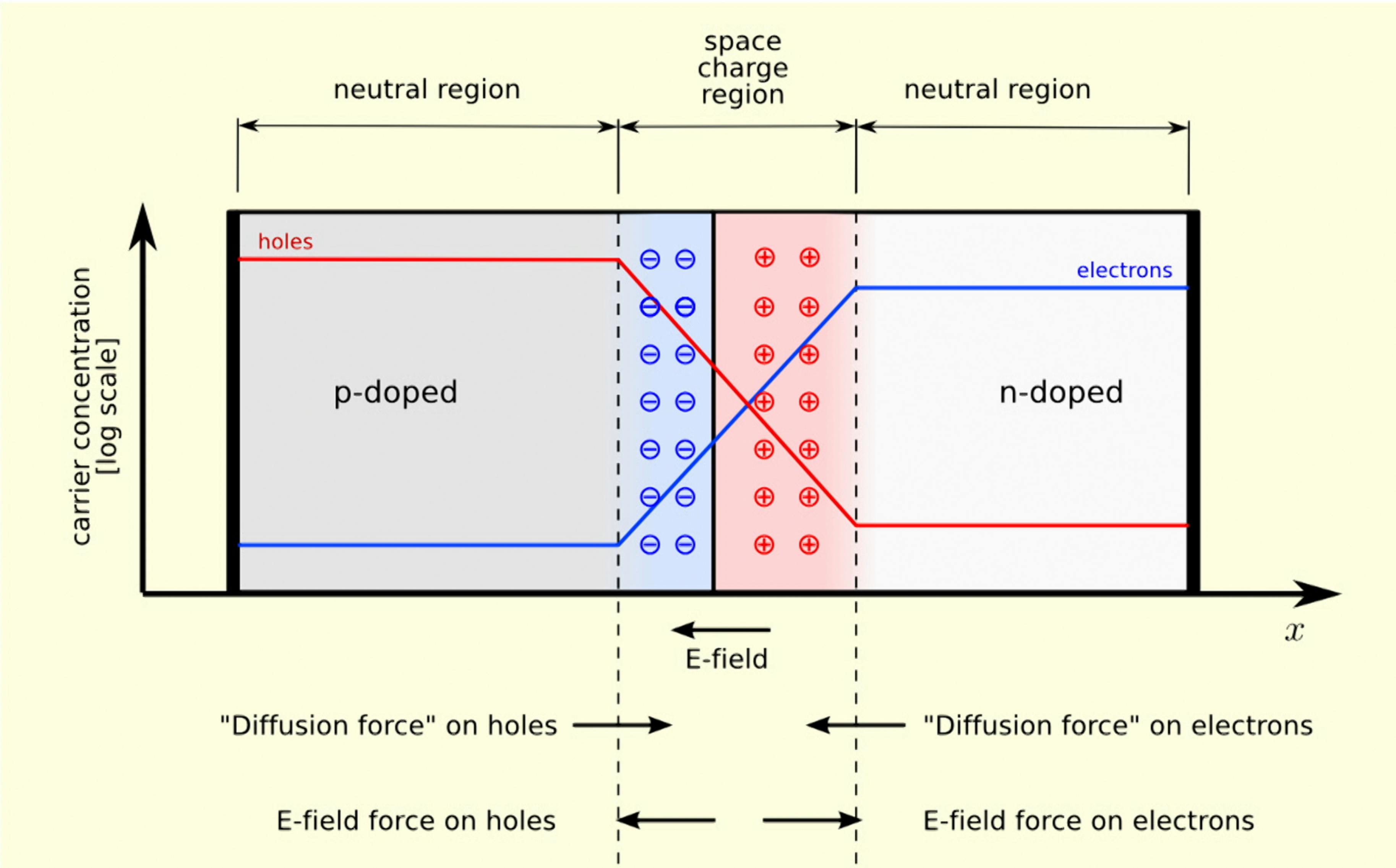
Avalanche Photodiodes (APD)

- Reverse Biased Diode
- Geiger Mode
- Impact Ionization continually amplifies uncontrollably
- Active/Passive Quench to reset
- Afterpulsing

Material	Si	InGaAs
Wavlength	300-1100 nm	1000-1700nm
Q.E.	70%	20%
Dark Count	100 Hz	10's kHz
Count Rate	5 MHz	100 kHz
Timing	1 ns	1 ns

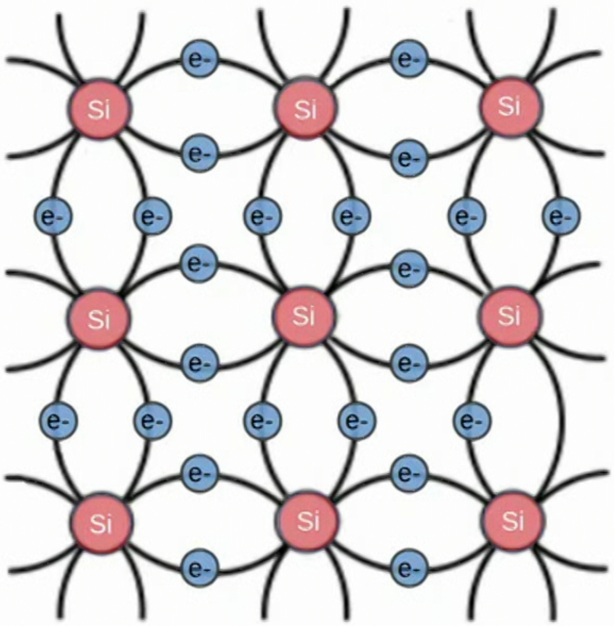
Research: UT-Austin, UCSD, NovaCrystals, UVA

Commercial Devices: Perkin Elmer, Sensors Unlimited, Amplification Technologies, JDS Uniphase, Fujitsu


space charge region
neutral region
neutral region
holes
electrons
p-doped
n-doped
carrier concentration [log scale]
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

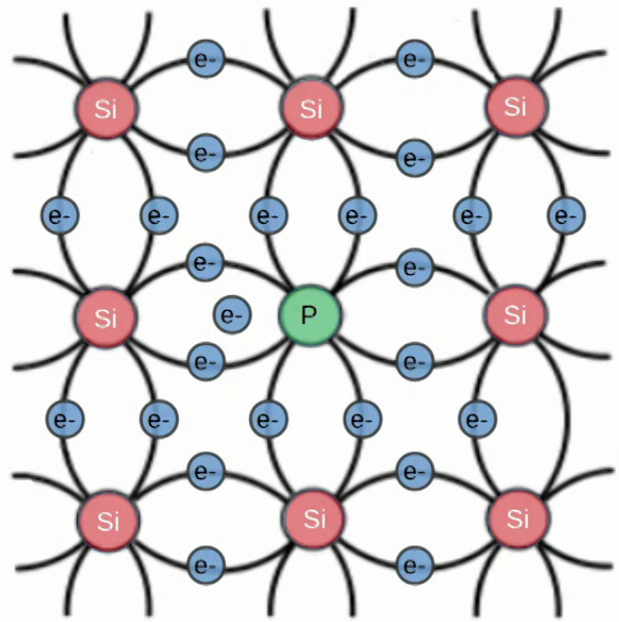
N-Doping example

Intrinsic



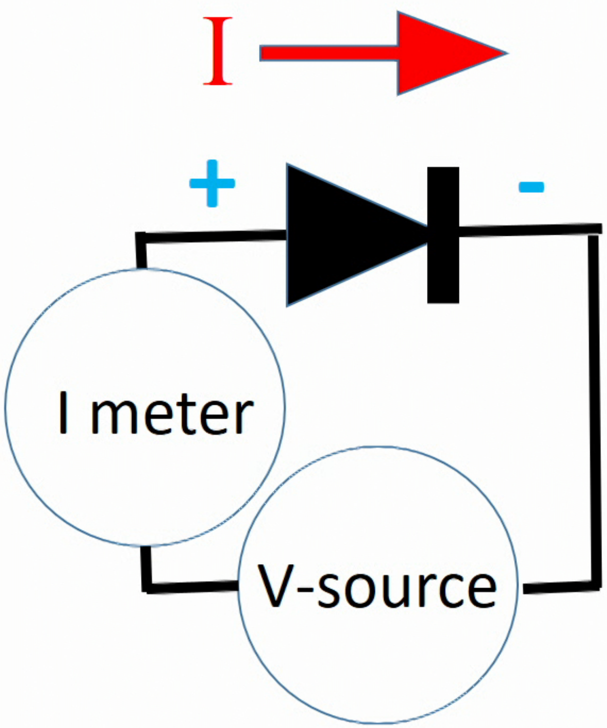
P-dopant	semiconductor	N-dopant
5 **B** Boron Metalloid	6 **C** Carbon Nonmetal	7 **N** Nitrogen Nonmetal
13 **Al** Aluminum Post-Transition Metal	14 **Si** Silicon Metalloid	15 **P** Phosphorus Nonmetal
31 **Ga** Gallium Post-Transition Metal	32 **Ge** Germanium Metalloid	33 **As** Arsenic Metalloid
49 **In** Indium	50 **Sn** Tin	51 **Sb** Antimony

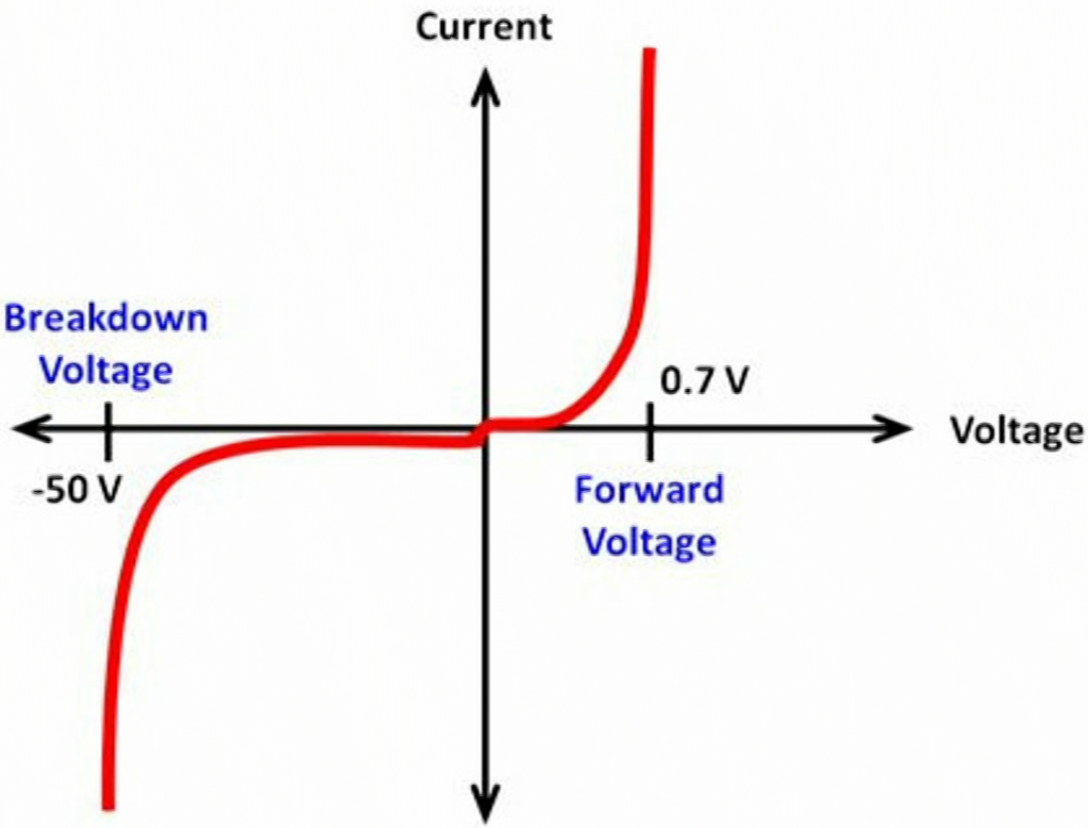
N-doped



Credit: Semiconductor Doping - Electronics Reference

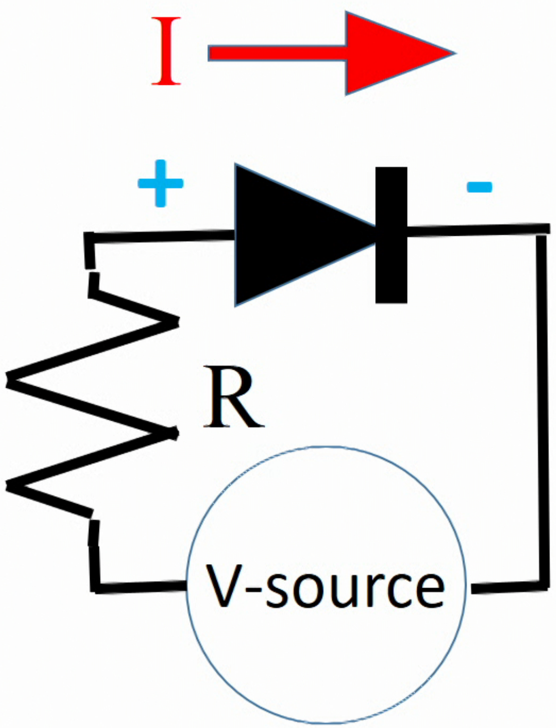
Diode: IV curve

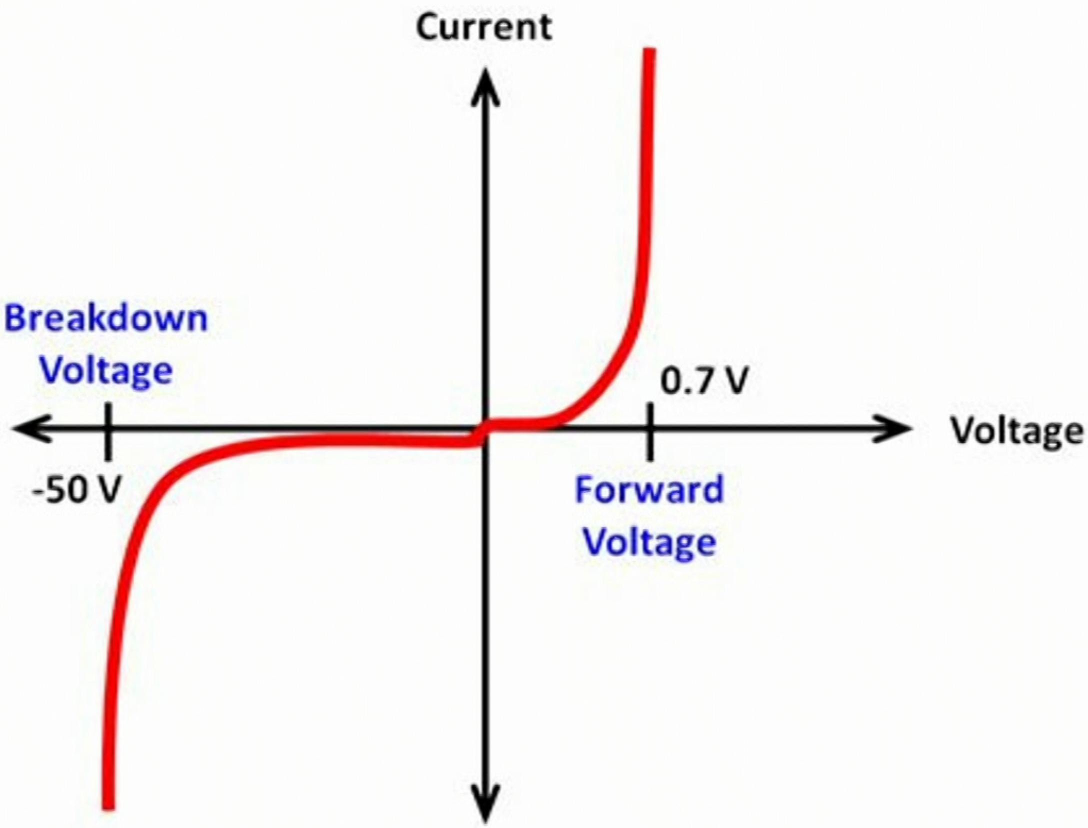




CREDIT: [Diodes: Everything You Wanted To Know And More (electronicsdesignhq.com)]

Diode: IV curve + Load line





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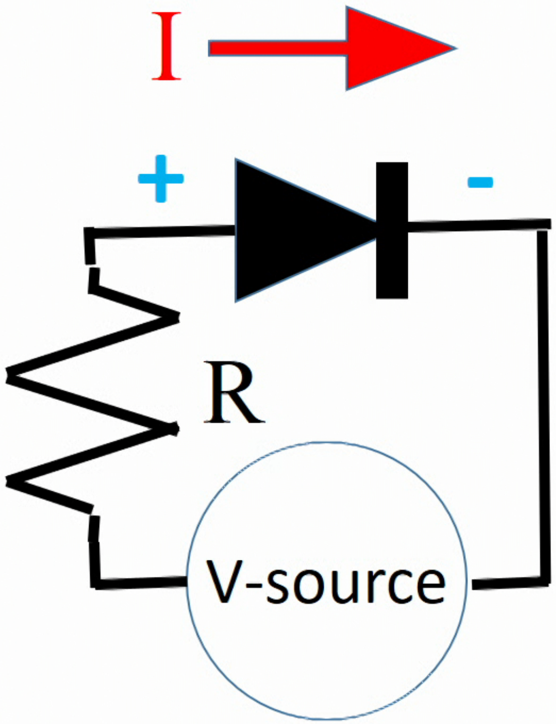


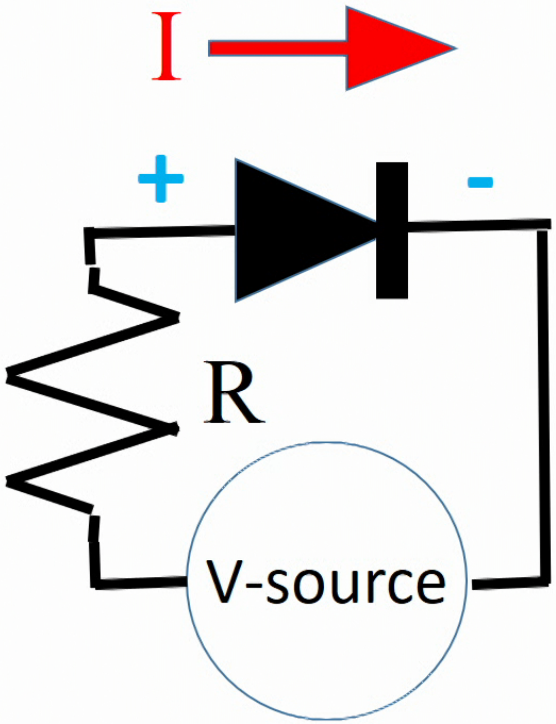
$$V_{source} = V_{resistor} + V_{diode}$$

$$V_{diode} = V_{source} - I_{diode}R$$

$$I_{diode} = -\frac{V_{diode}}{R} + \frac{V_{source}}{R}$$

CREDIT: [Diodes: Everything You Wanted To Know And More (electronicsdesignhq.com)]

Diode: IV curve + Load line



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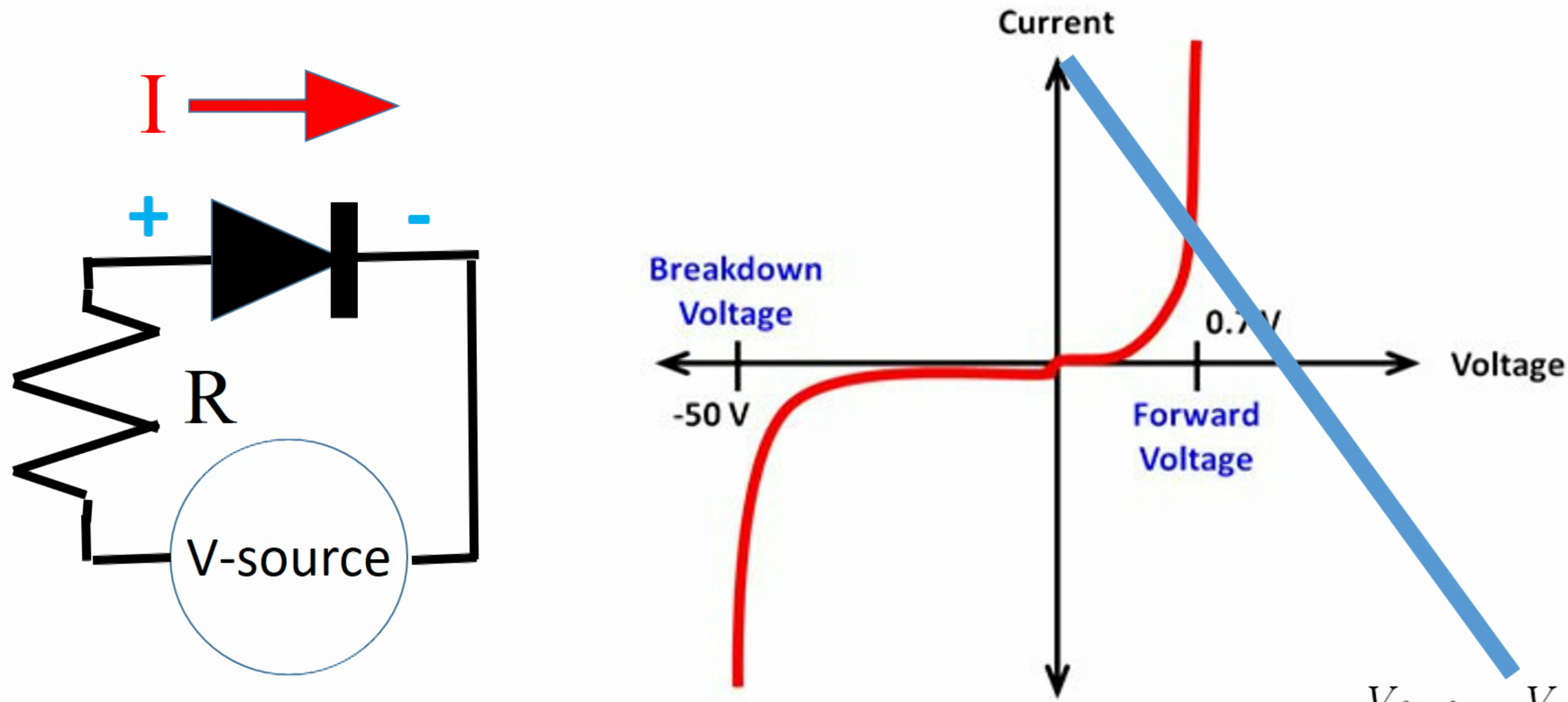


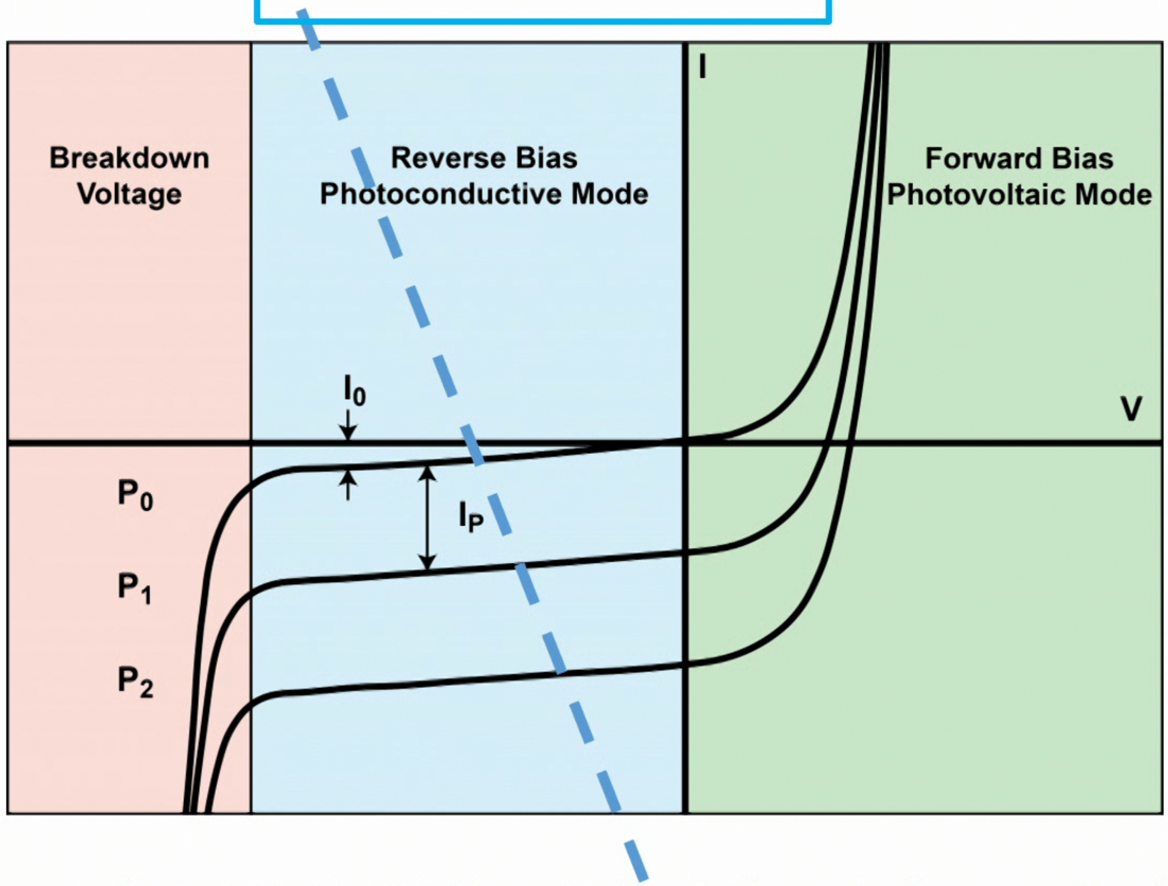
CREDIT: [Diodes: Everything You Wanted To Know And More (electronicsdesignhq.com)]

$$I_{diode} = -\frac{V_{diode}}{R} + \frac{V_{source}}{R}$$

Photodiode IV

- One photon creates one electron-hole pair
- Typical measures lots of photons per second
- Responsivity:
    - Amps/Watt

Bias Load Line



Credit: PHOTODIODE BASICS – Wavelength Electronics (teamwavelength.com)

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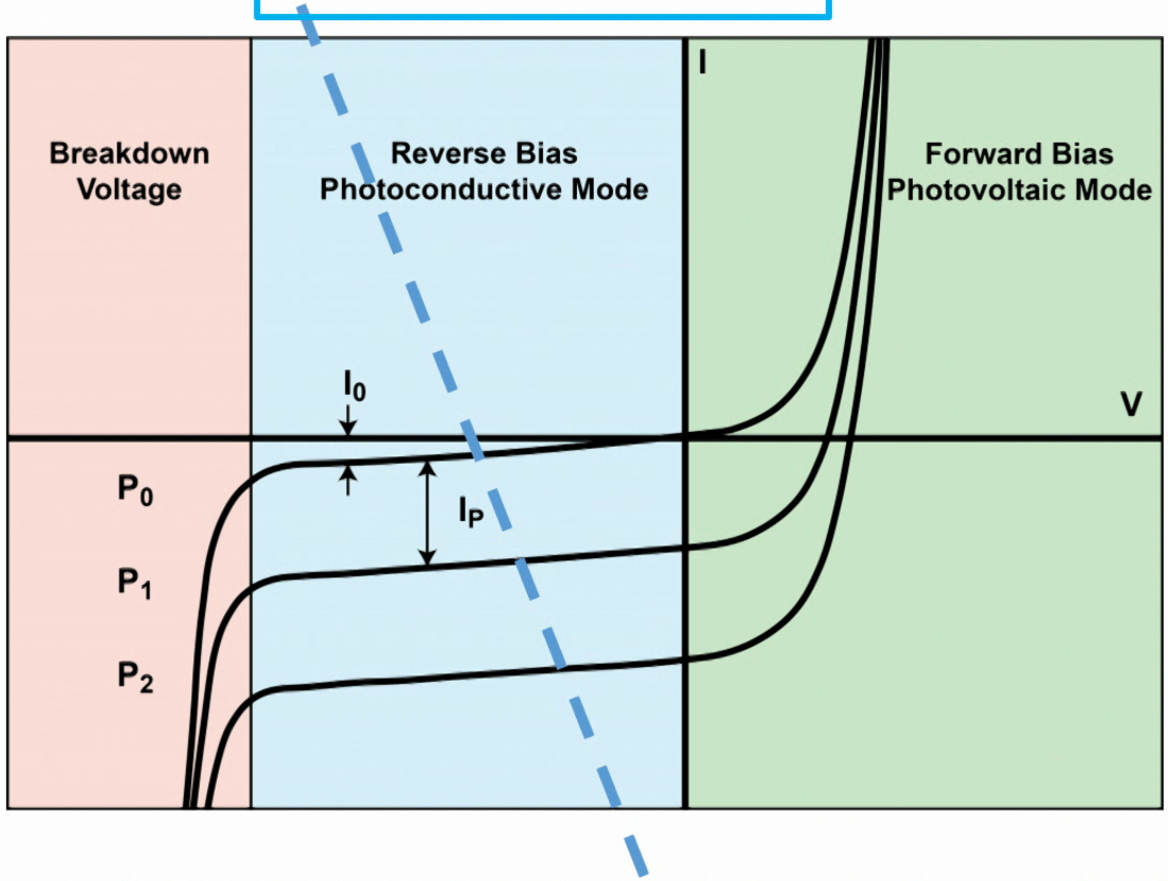
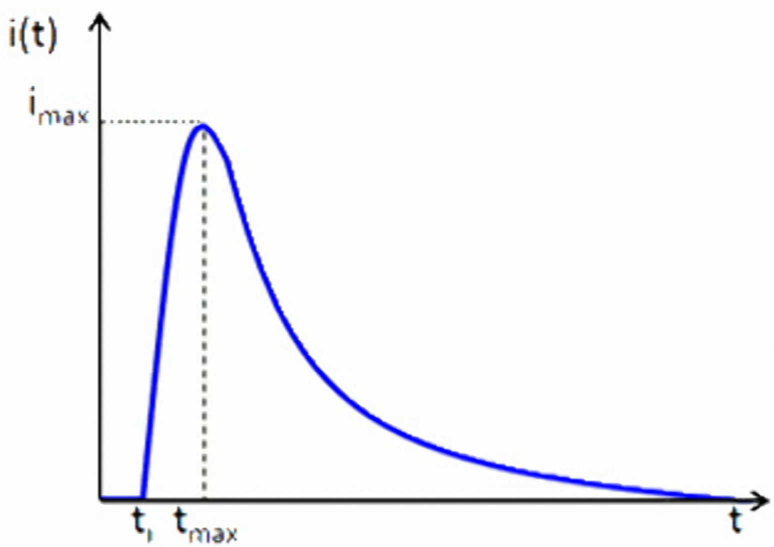


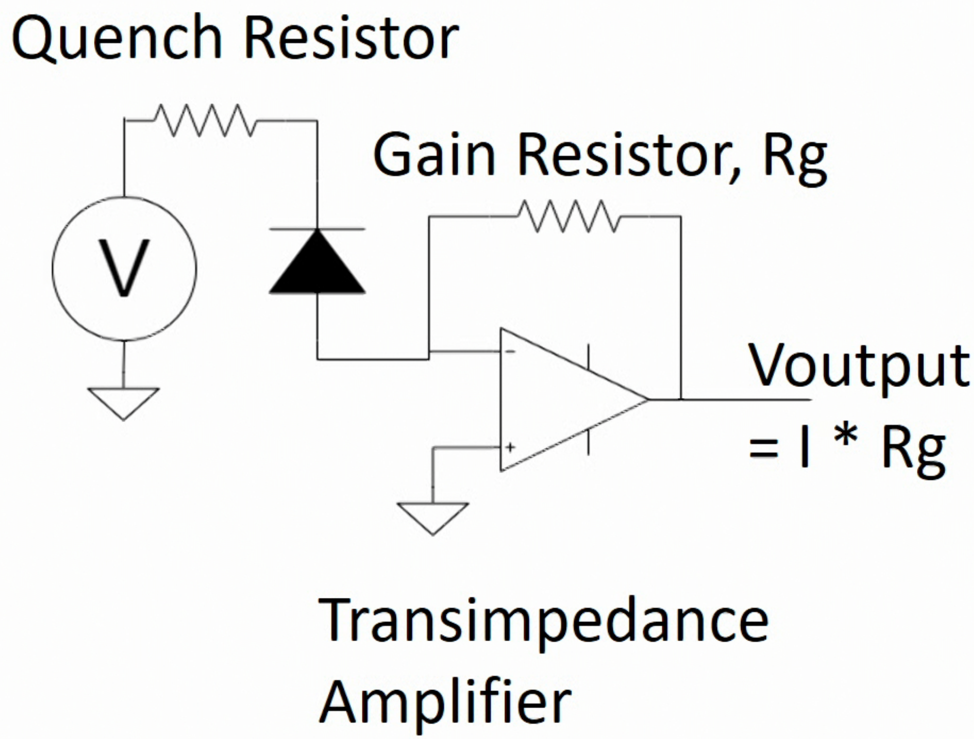
Credit: [PHOTODIODE BASICS – Wavelength Electronics (teamwavelength.com)]

Avalanche Photodetector

1. Voltage bias above breakdown
   This creates an electric field across the device
2. One photon is absorbed
3. Create an electron hole pair
4. Electron and holes drift apart in the electric field… hence a current
5. They are accelerated by field
6. Collide with other elecrons / holes created more pairs: Impact Ionization
   “Avalanche”
7. Moving charge creates a current
8. Current creates a voltage drop across the resistor, voltage across diode goes towards zero
   This is known an passive quenching

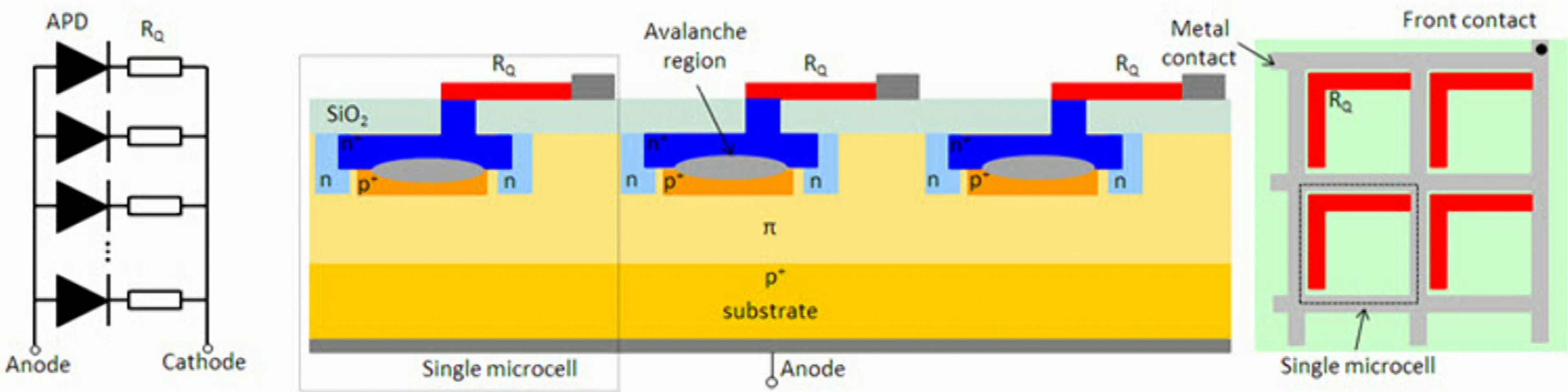
How do measure the current pulse from an APD?





SiPM: Silicon Photomultiplier

- Bunch of Silicon APDs in parallel
- Currents from each APD (cell) add together



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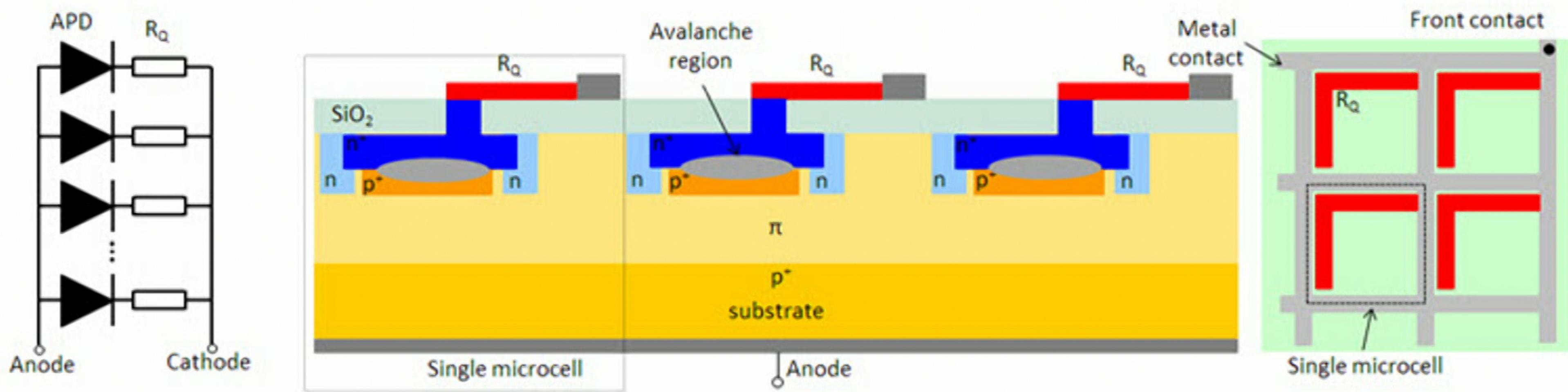
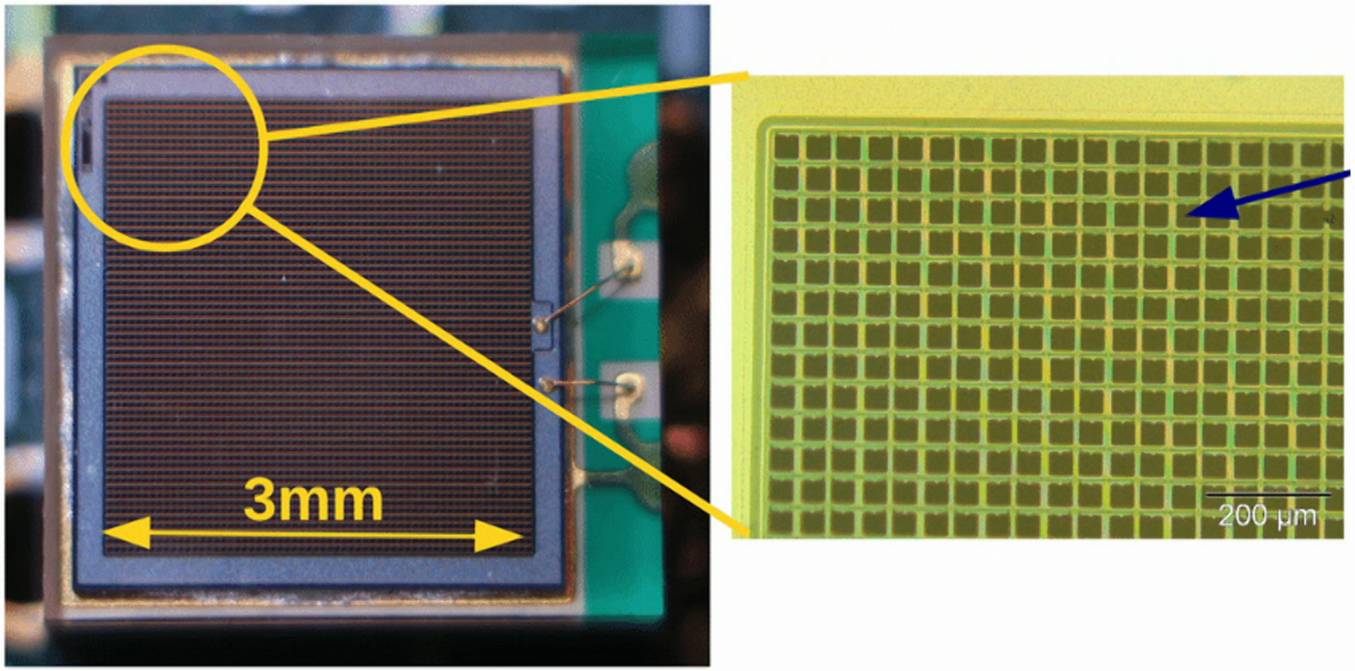
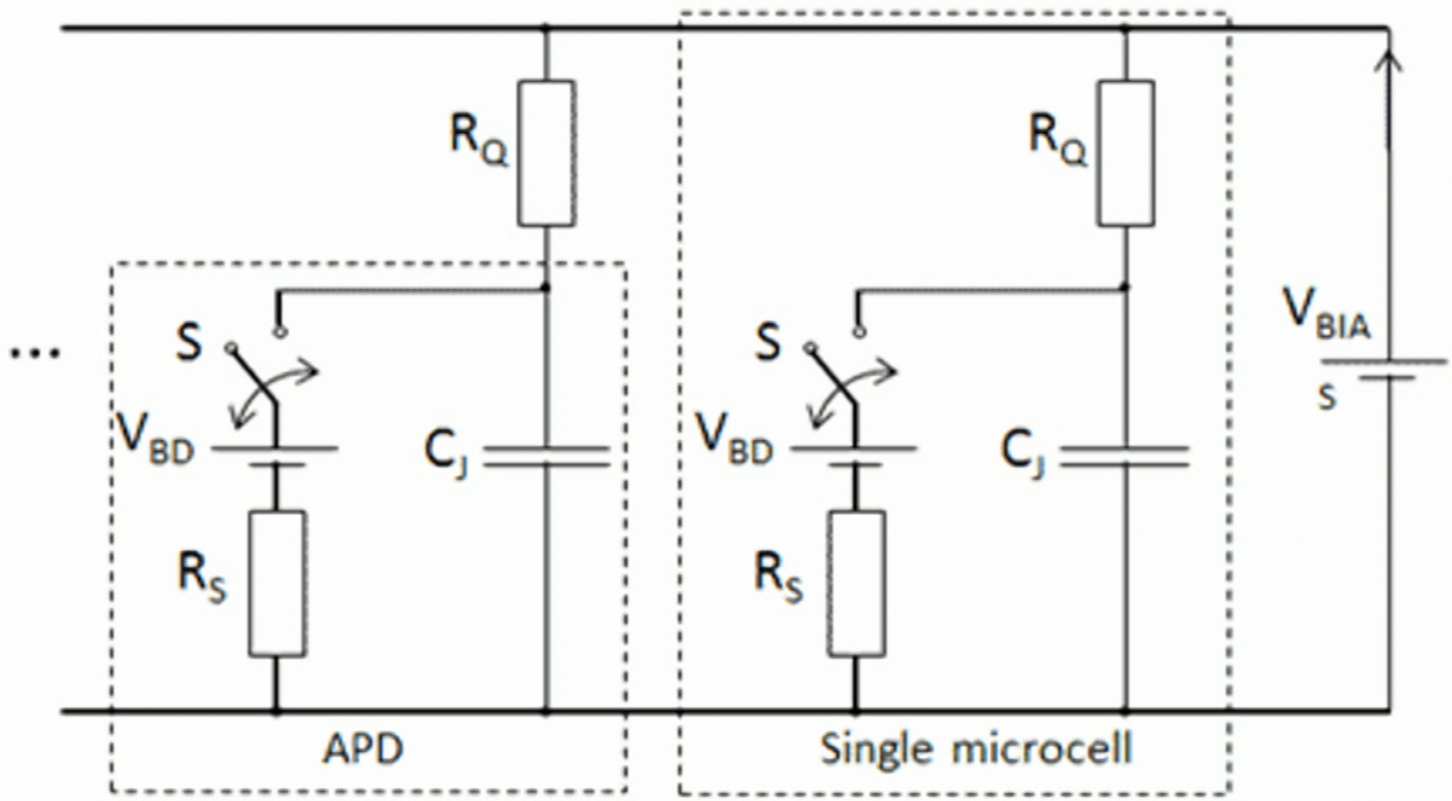




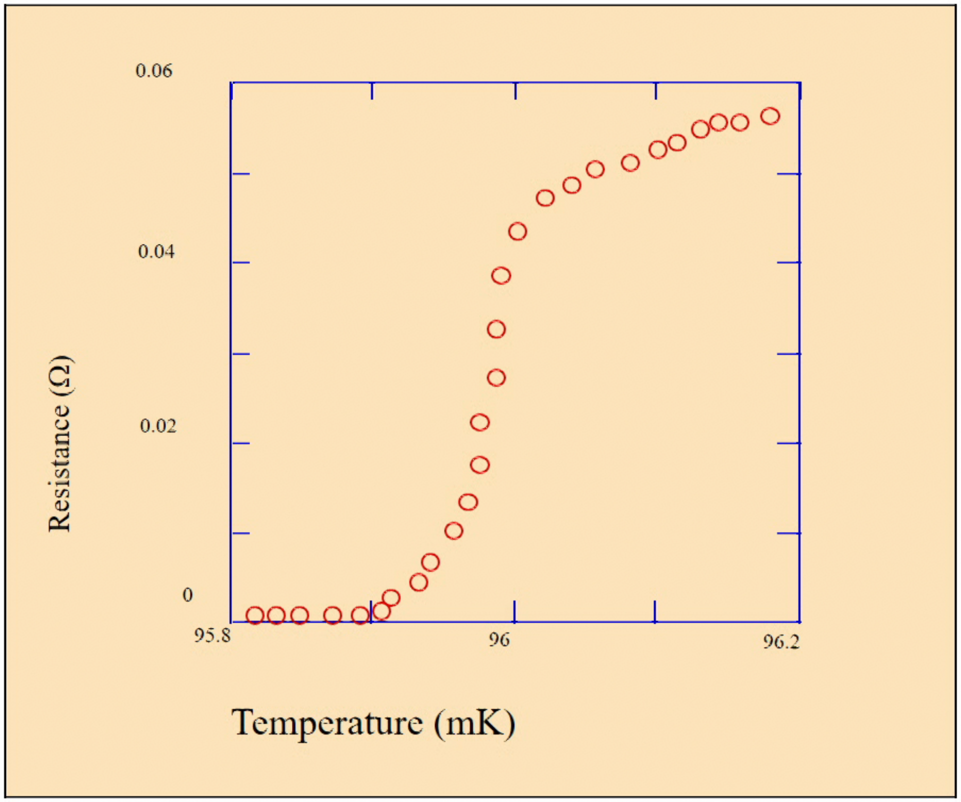
CREDIT: DOI:10.1088/1361-6560/ab7b2d

Circuit Model of SiPM



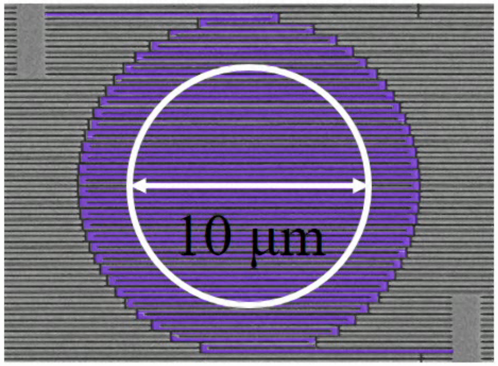
What is an SiPM and how does it work? | Hamamatsu Photonics

Superconductivity



- Electrical resistance goes to zero at a critical temperature Tc
- Critical Current Ic or density Jc above which there is resistance below Tc
- Critical Field Hc
- Electrons in the superconducting ground state form Cooper pairs
- Excitations above the ground state are known as quasi-particles, energy ~ 2Δ

Superconducting Nanowire Single Photon Detector (SNSPD)



Wavelength	200-10000nm
Q.E.	approach 100%
Dark Count	1 per day
Count Rate	100 MHz
Timing	<100 ps

Break supercondu crivity to get a signal that is suitable to measure

Energy scale for excitations in the superconductor is 1000x smaller

Research: MIT, JPL, NIST, ANL
Commercial: Photonspot, Quantum Opus

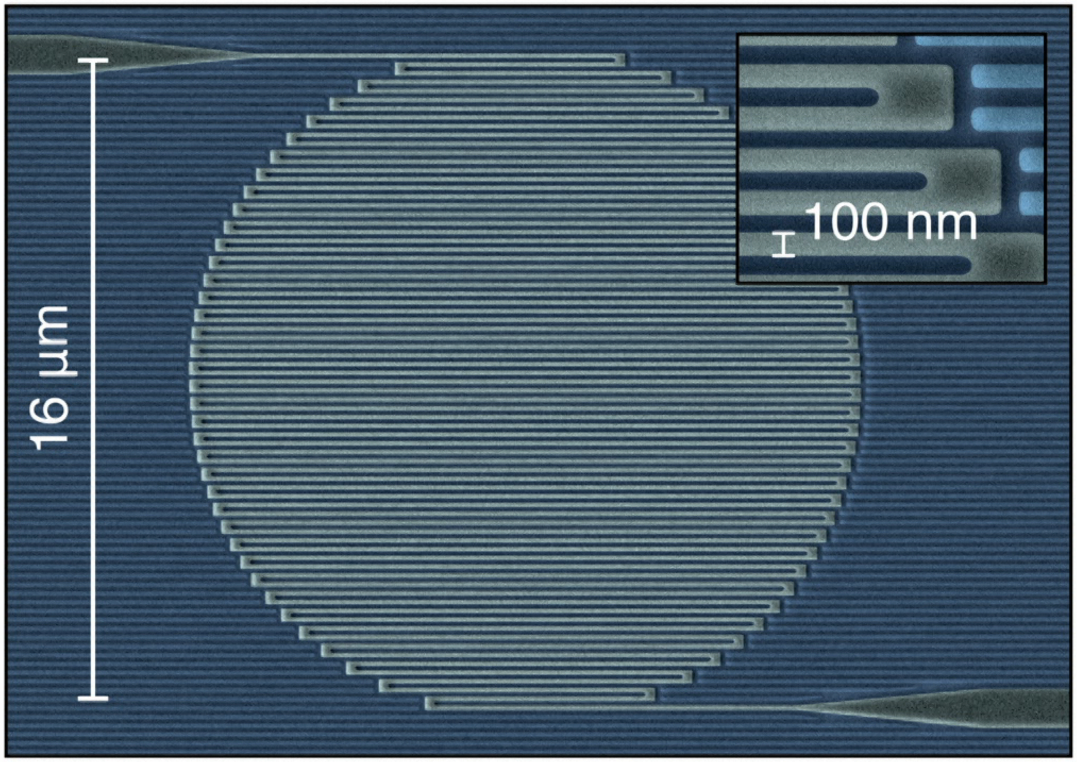
Superconducting Devices Fabrication Facility

- **2700 sq ft class 100 space**
- **I-line 5x lithography**
- **E-beam lithography**
- **Reticle generation**
- **Sputter deposition (x2)**
- **ECR PECVD deposition**
- **LPCVD (x2)**
- **Thermal oxide / diffusion (x2)**
- **Thermal deposition (x2)**
- **RIE (x2)**
- **Plasma etching**
- **Ion mill etching**
- **3 inch wafers**

Superconducting Fabrication Facility

Superconducting Nanowire Single-Photon Detector

- Meandered wire of superconducting thin film with a small bias current

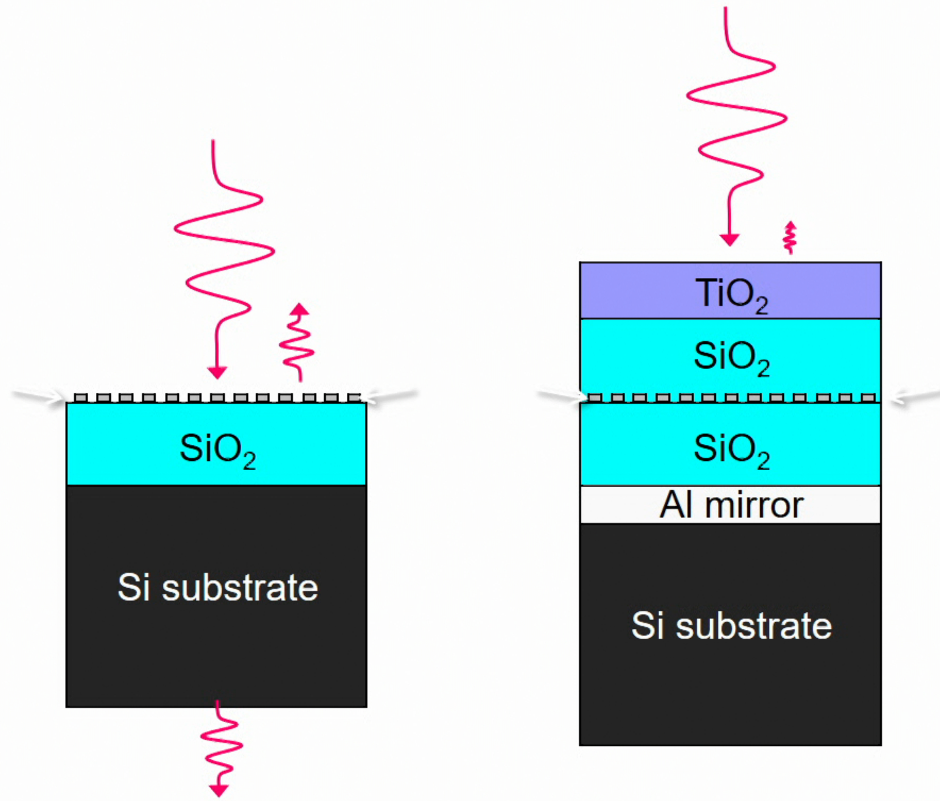


V. Verma (NIST)

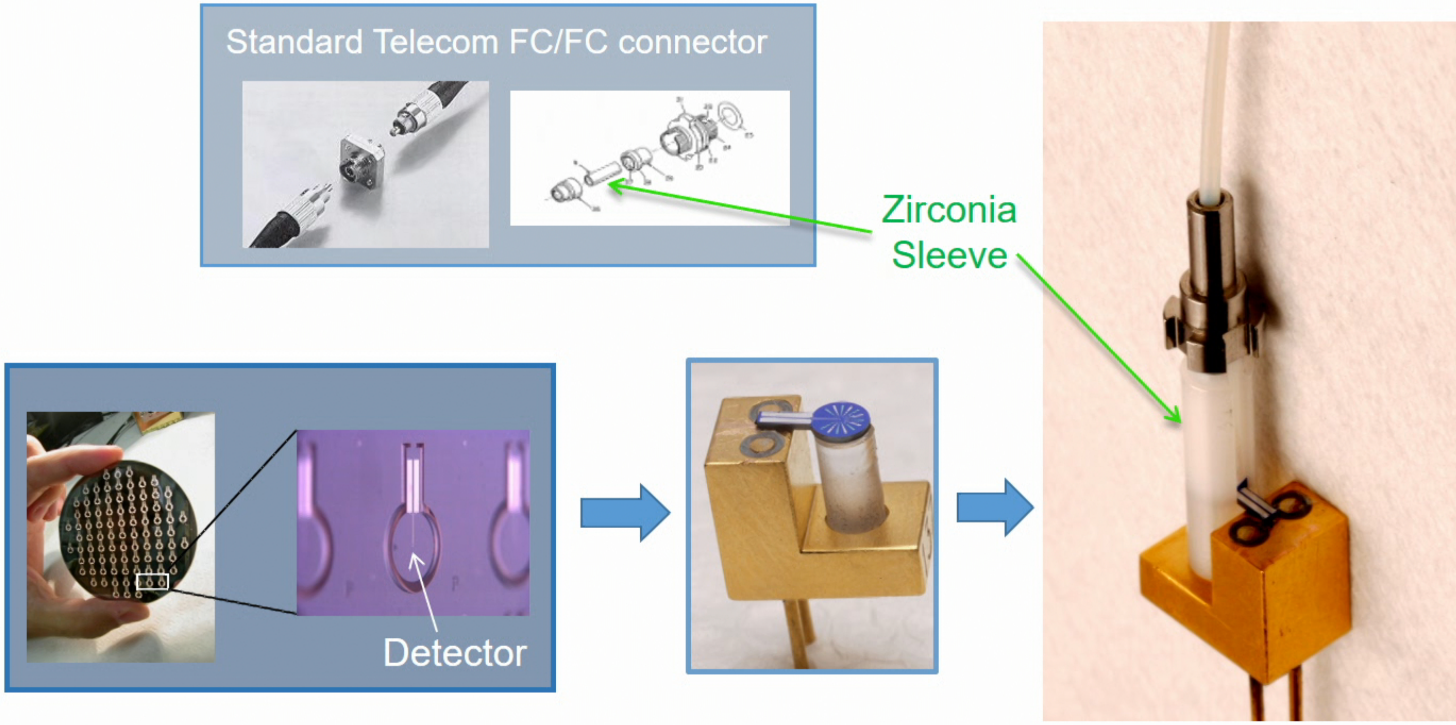
Conventional:
NbN, NbTiN
Tc ~ 10K

Amorphous:
W-Si, MoSi,
MoGe
Tc ~3K

Increasing Absorption: Optical Stack Design



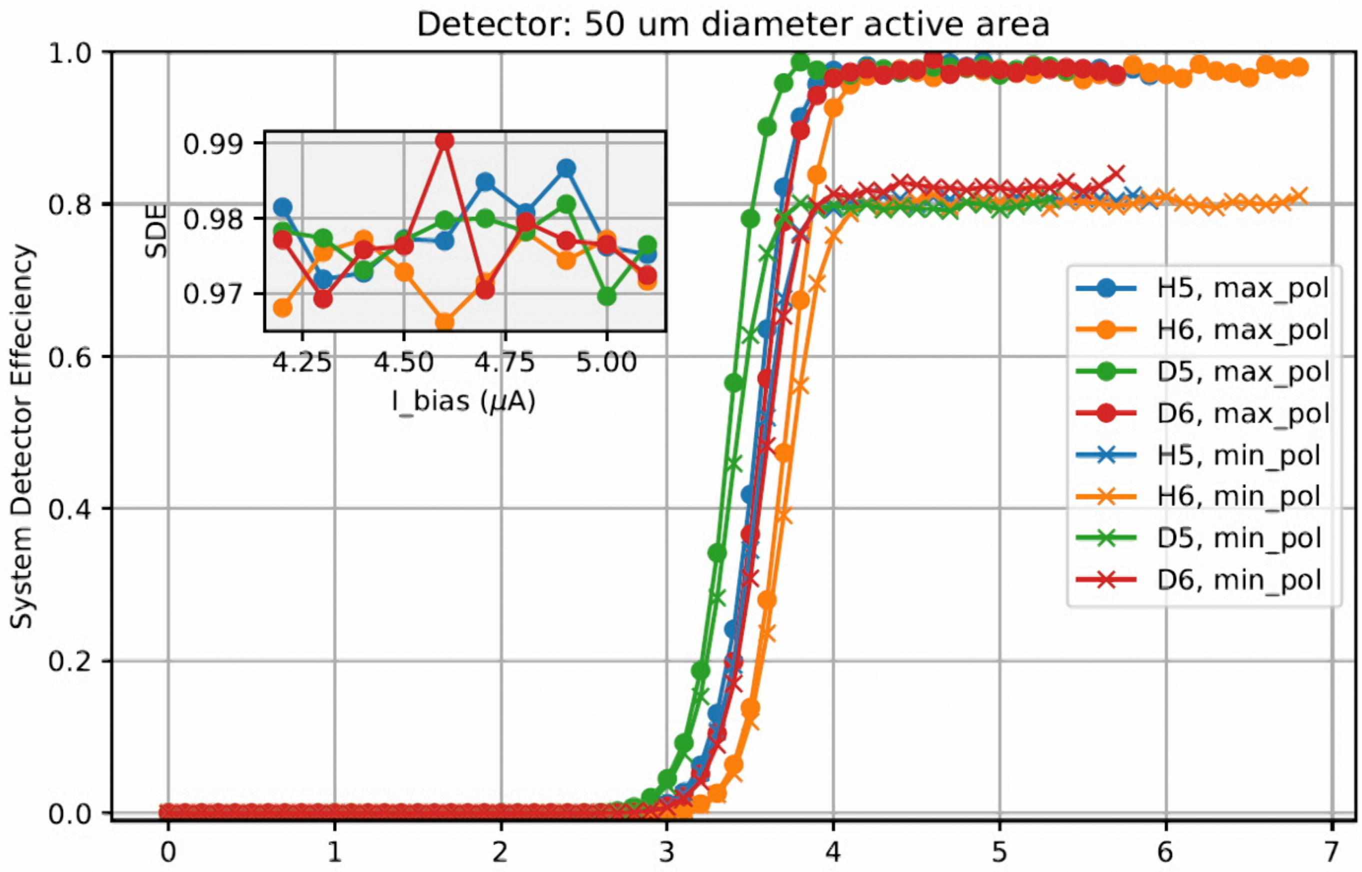
Self-Aligned Packaging



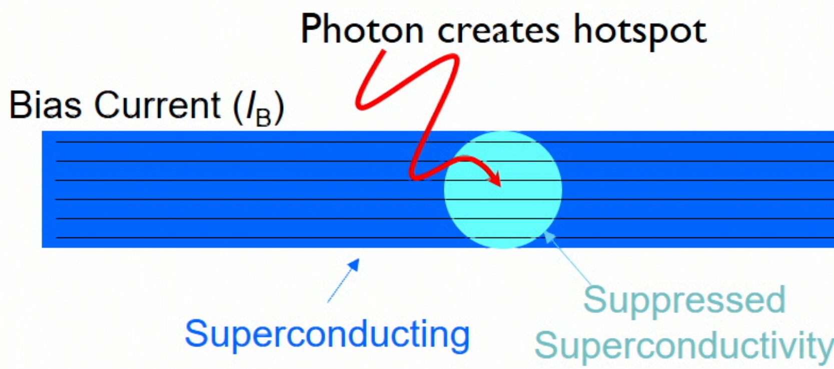
Coupling loss consistently < 1%

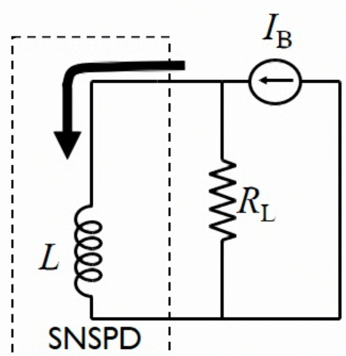
A. J. Miller et al., *Optics Express*, **19**, 9102 (2011)

Bias versus Efficiency / counts



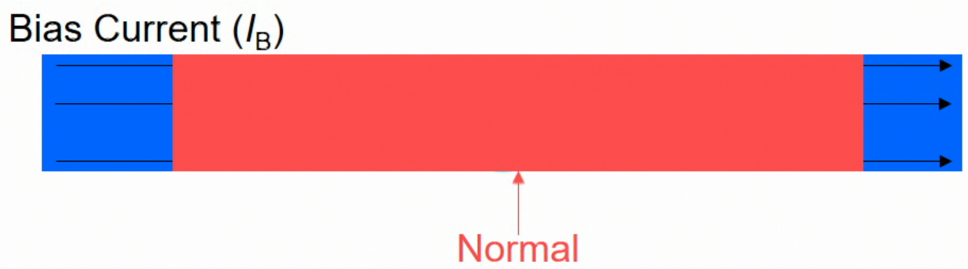
Superconducting Nanowire Single-Photon Detector

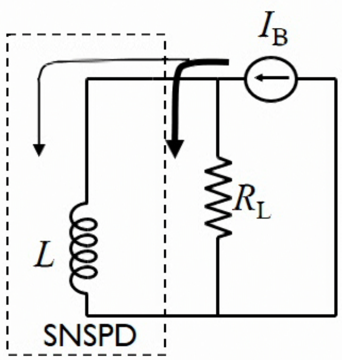




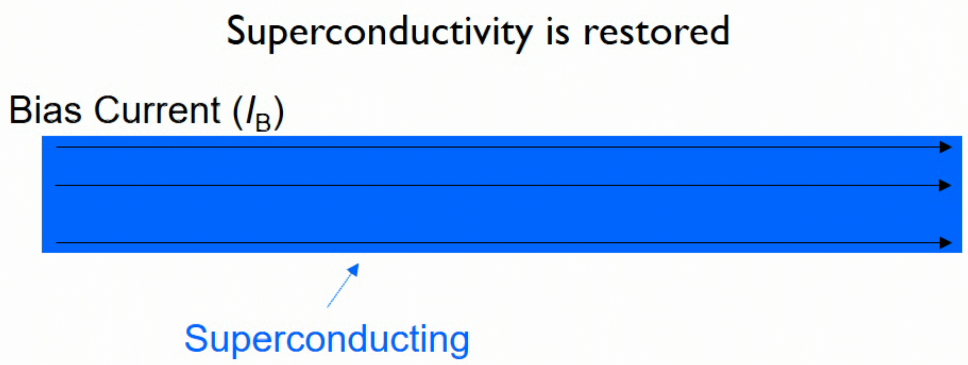
Anomalously, large Inductance, L

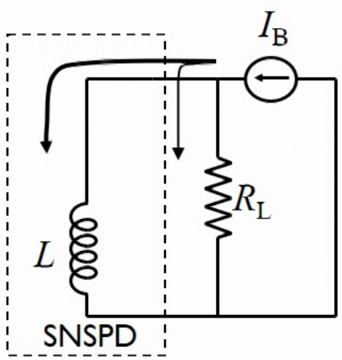
Superconducting Nanowire Single-Photon Detector





Superconducting Nanowire Single-Photon Detector





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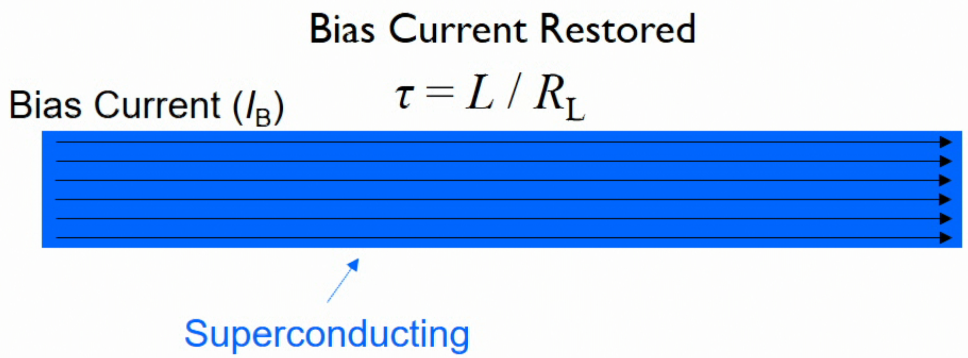
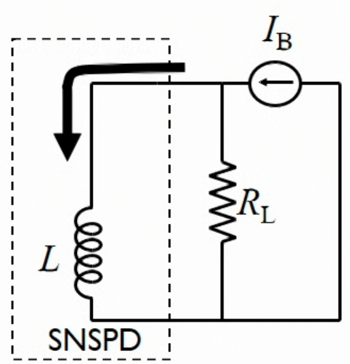
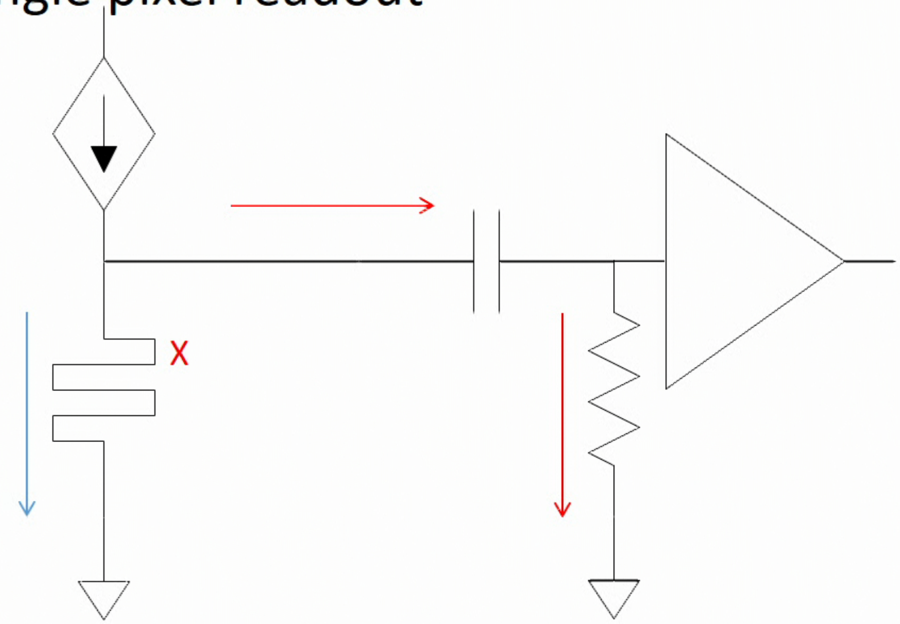




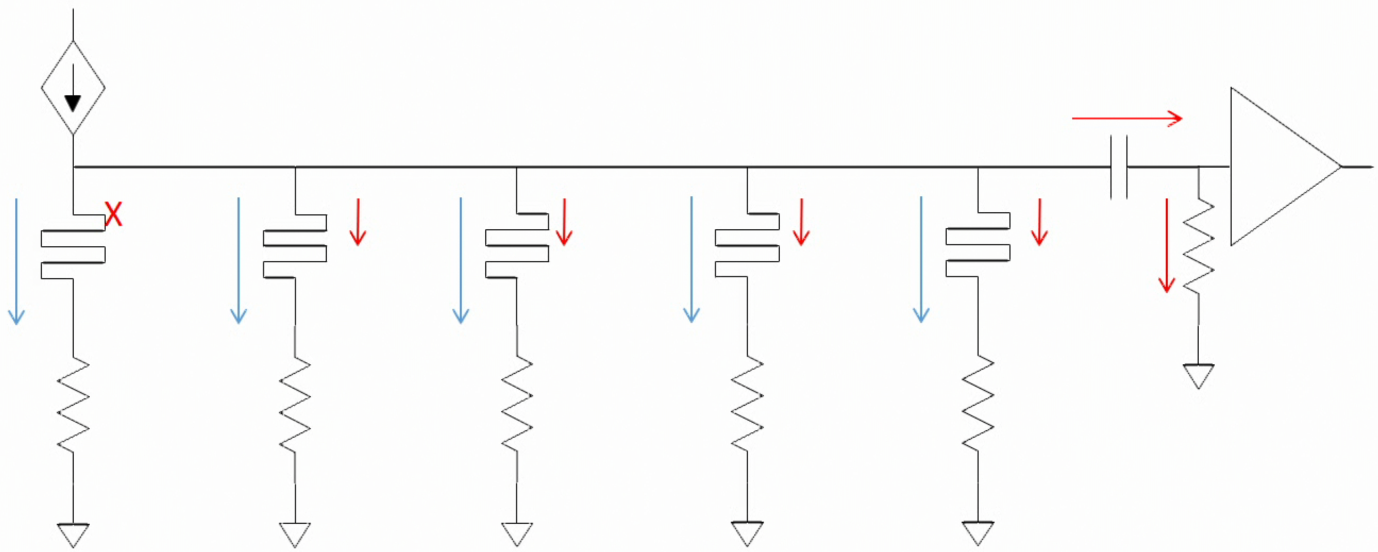
Scalable readout

- Conventional Single pixel readout



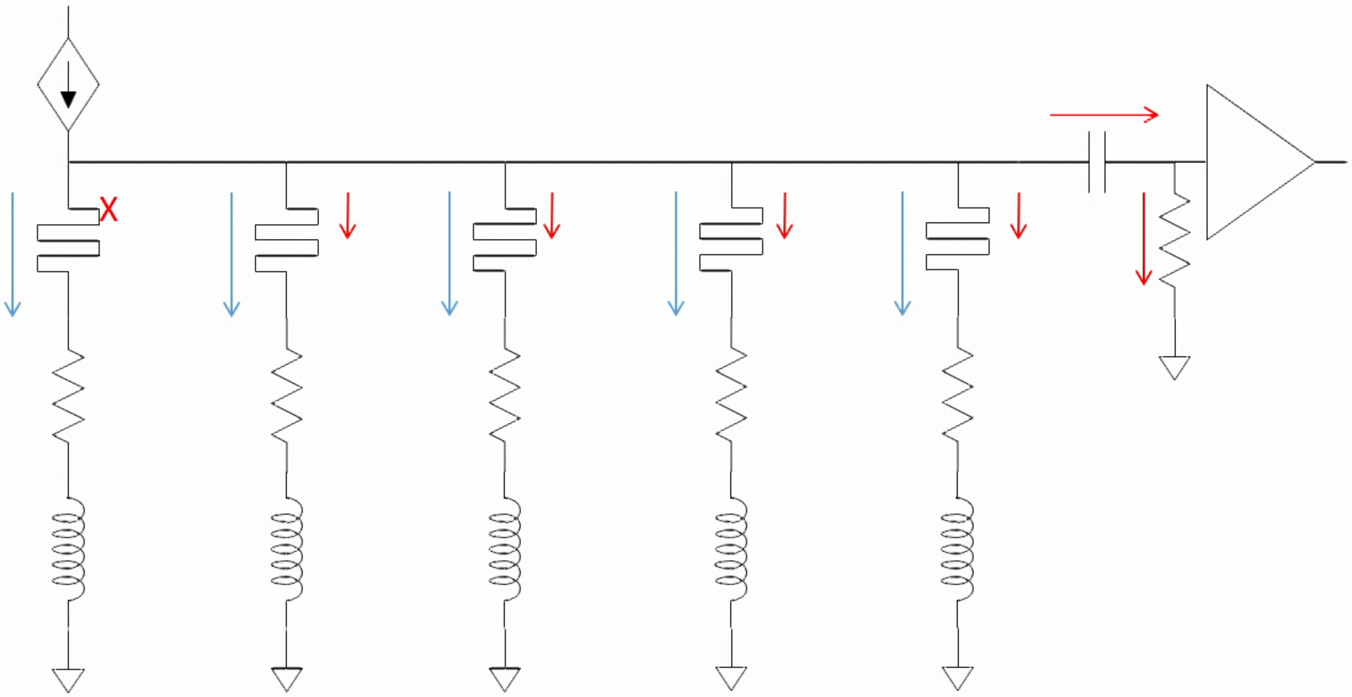
Scalable readout

- One wire to readout multiple pixels

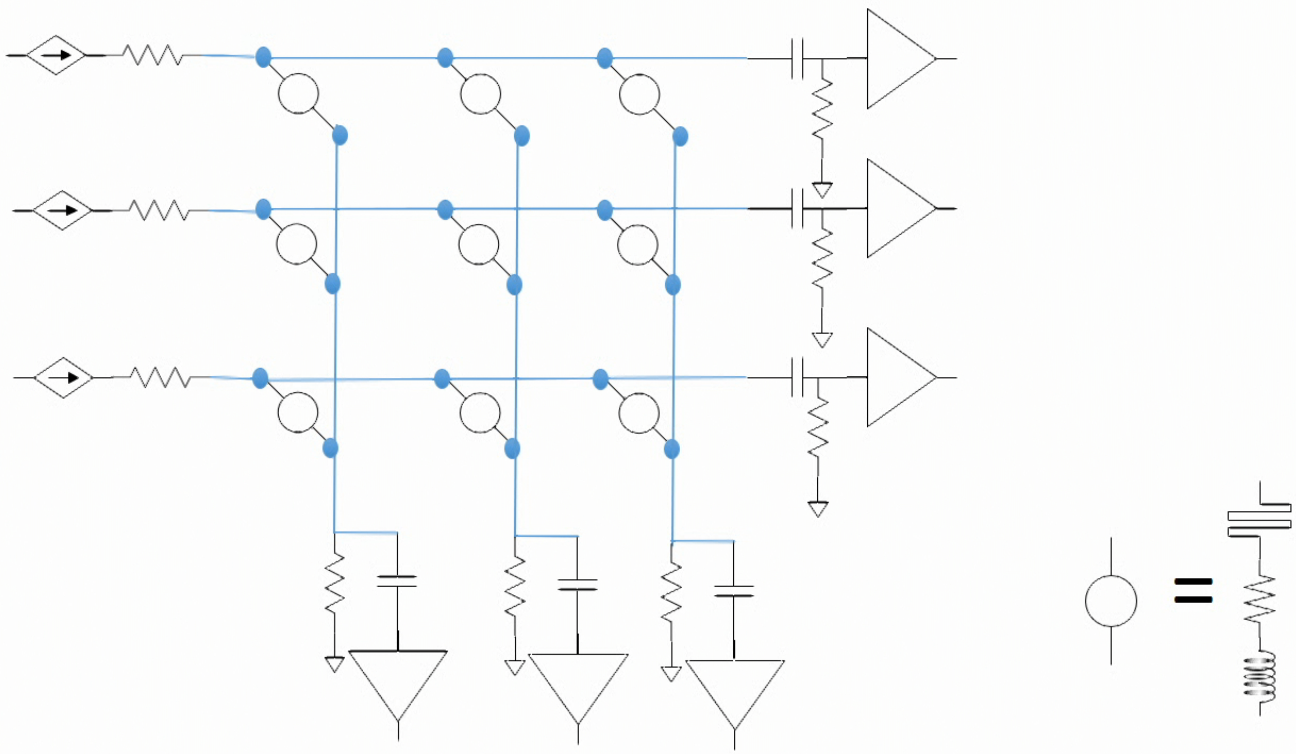


Scalable readout

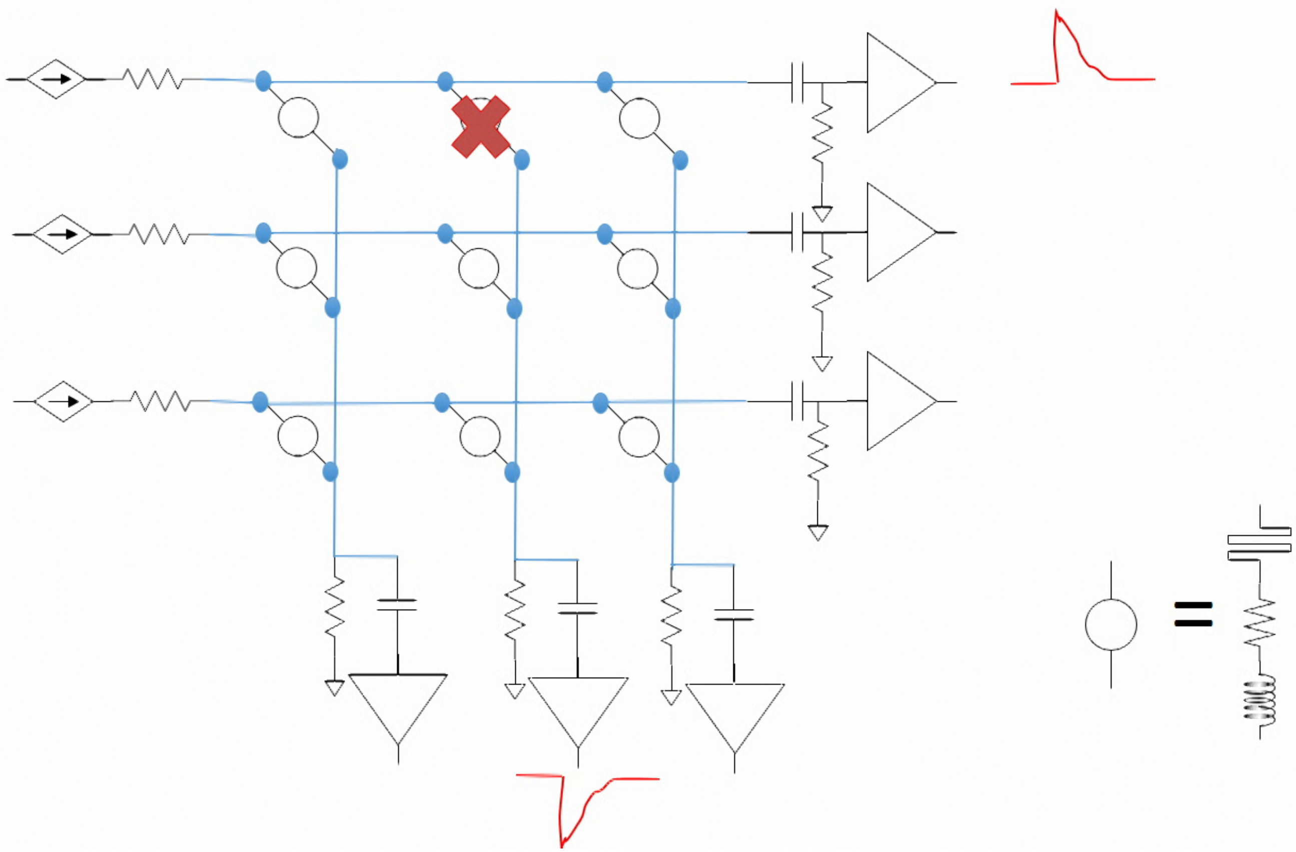
May need additional impedance to reduce leakage to other pixels



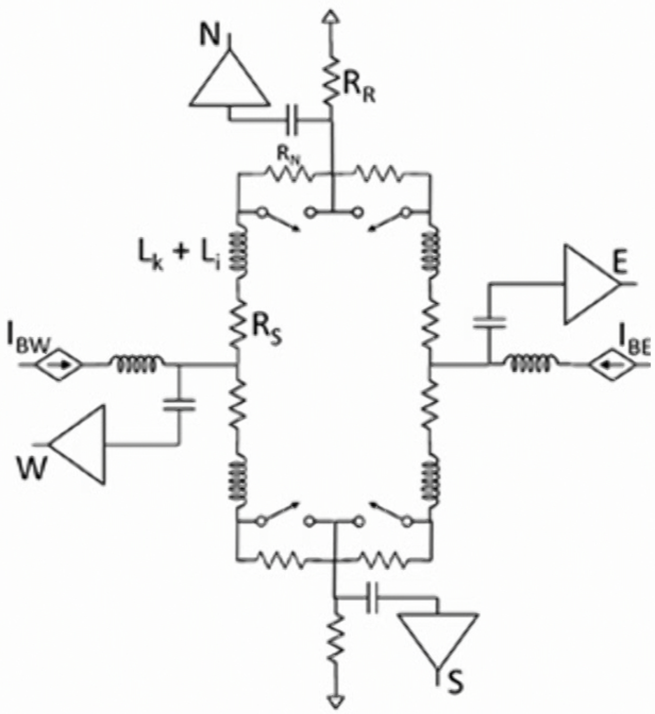
Scalable readout



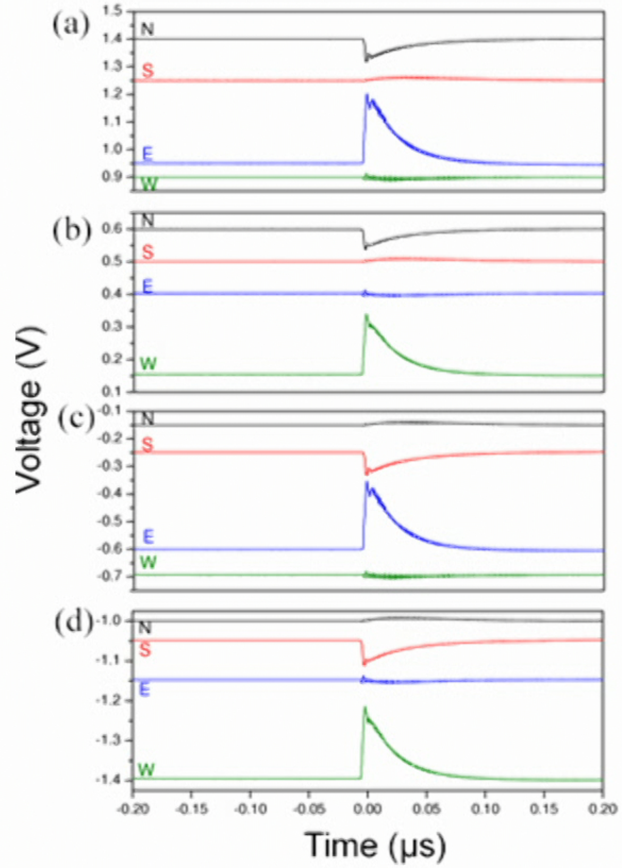
Scalable readout



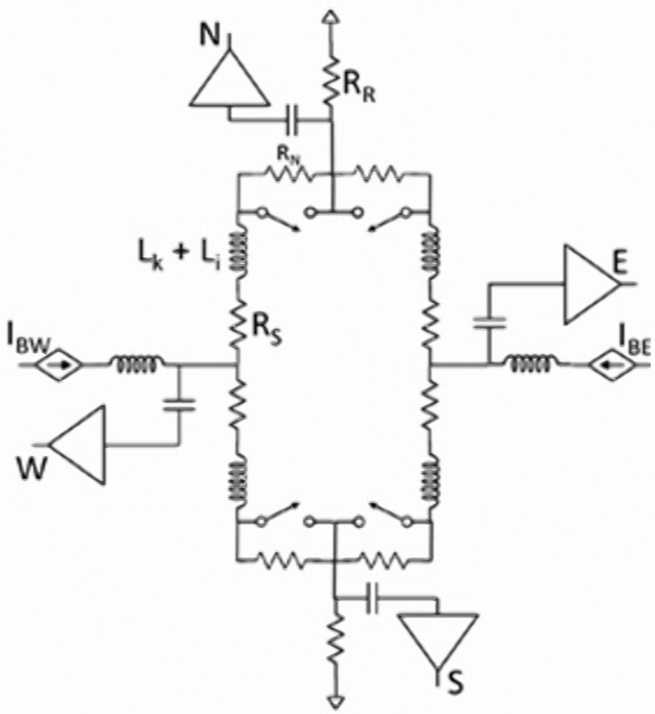
2x2 demonstrated



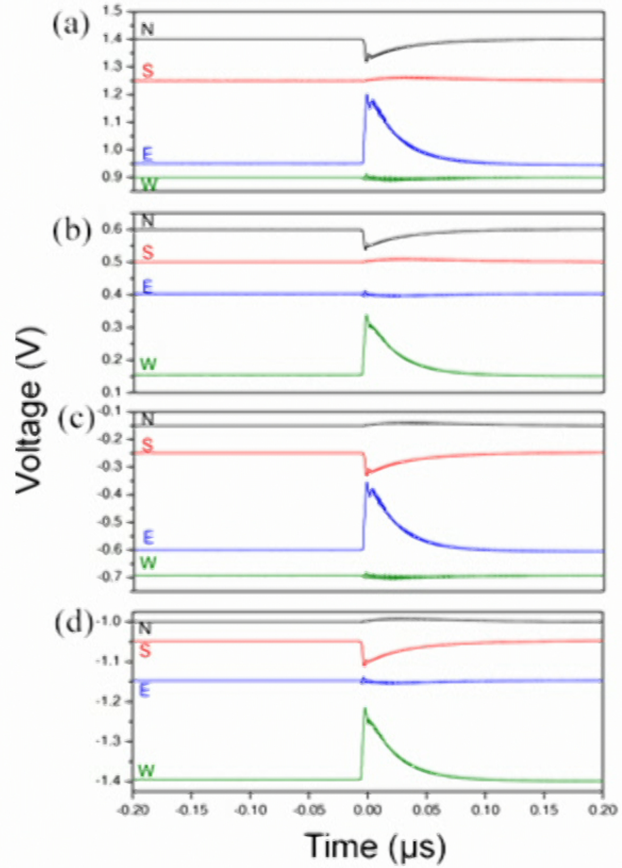
(b)



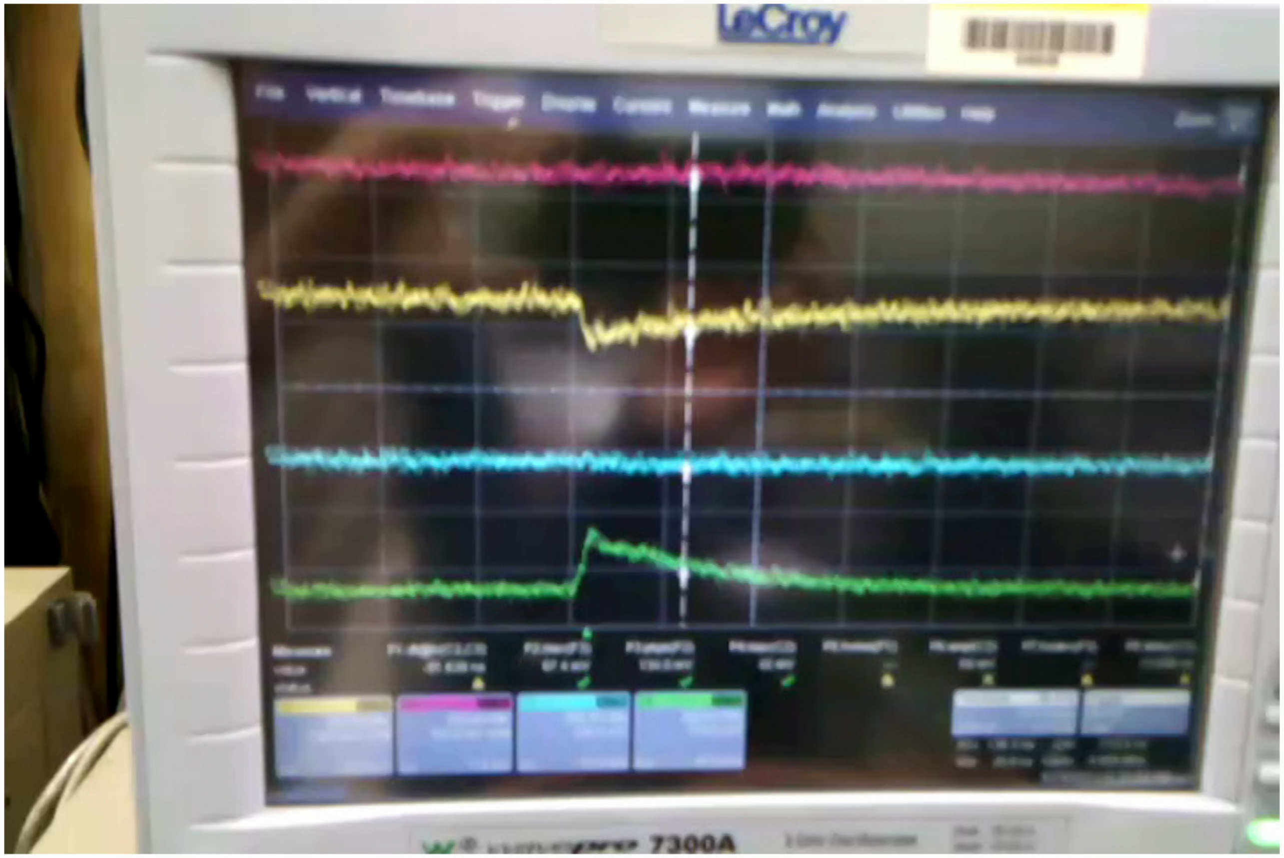
2x2 demonstrated



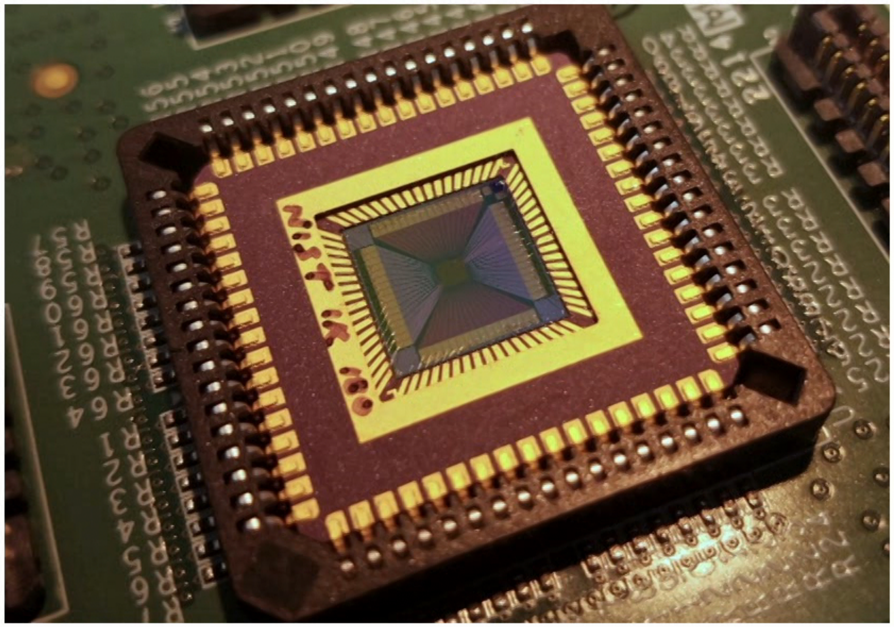
(b)

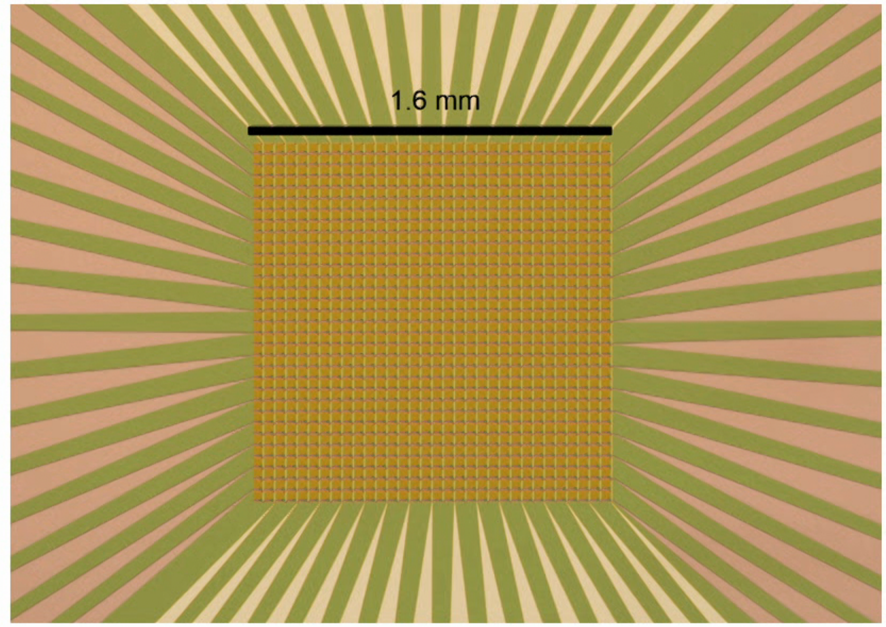


Scalable readout

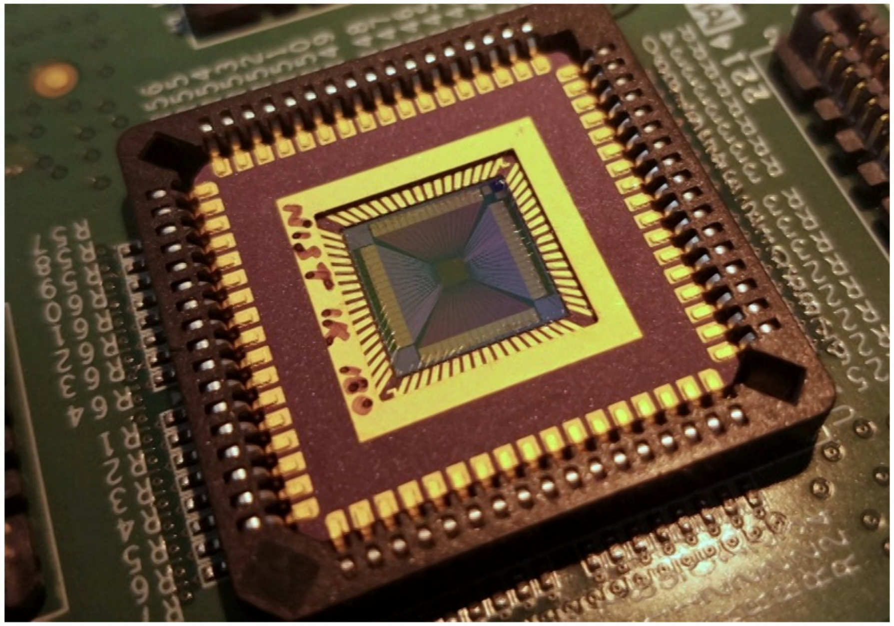


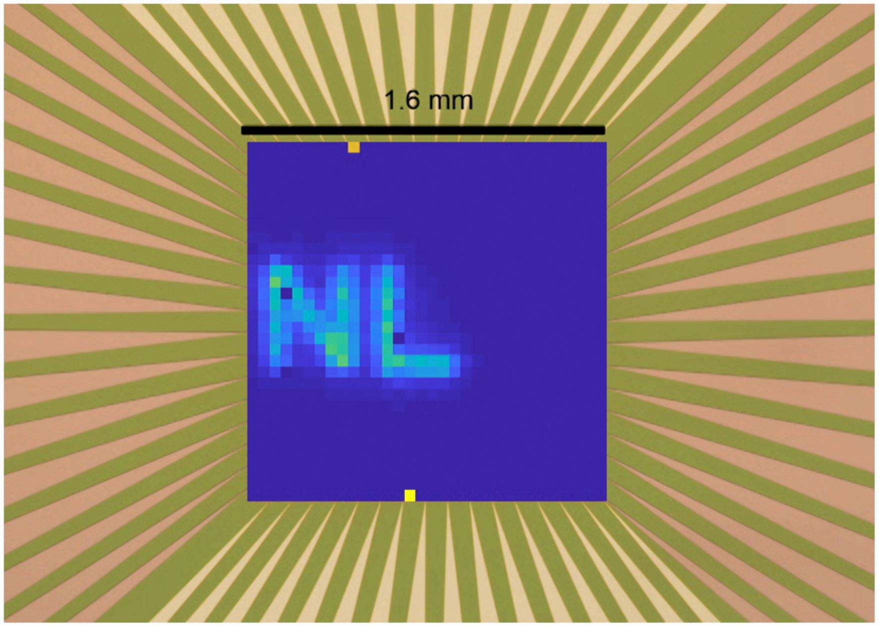
Larger Areas: N^2 pixels with 2N readout





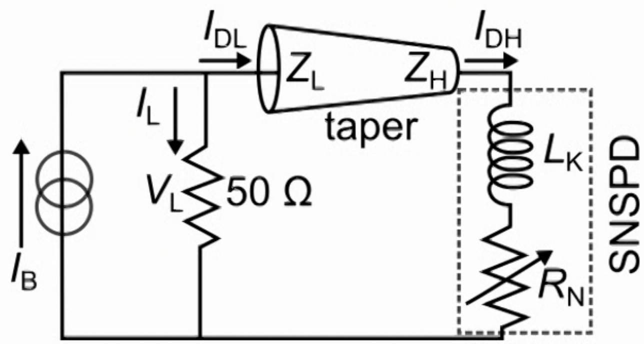
Larger Areas: N^2 pixels with 2N readout

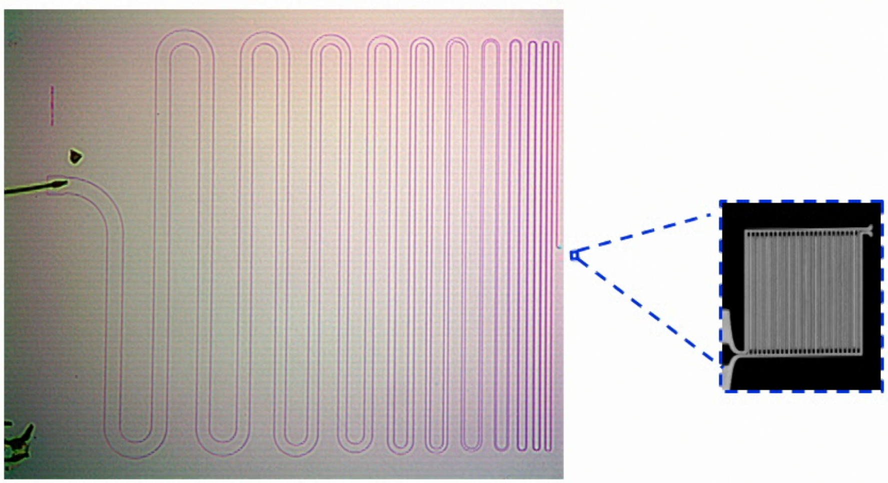




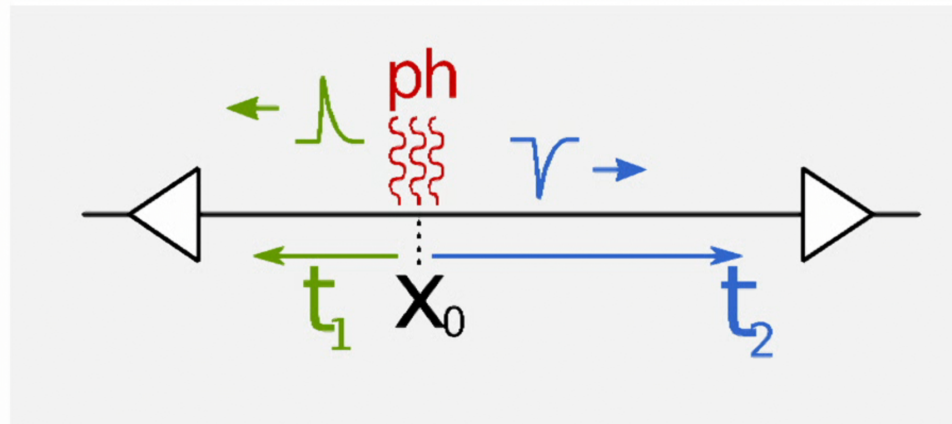
JPL

Taper readout





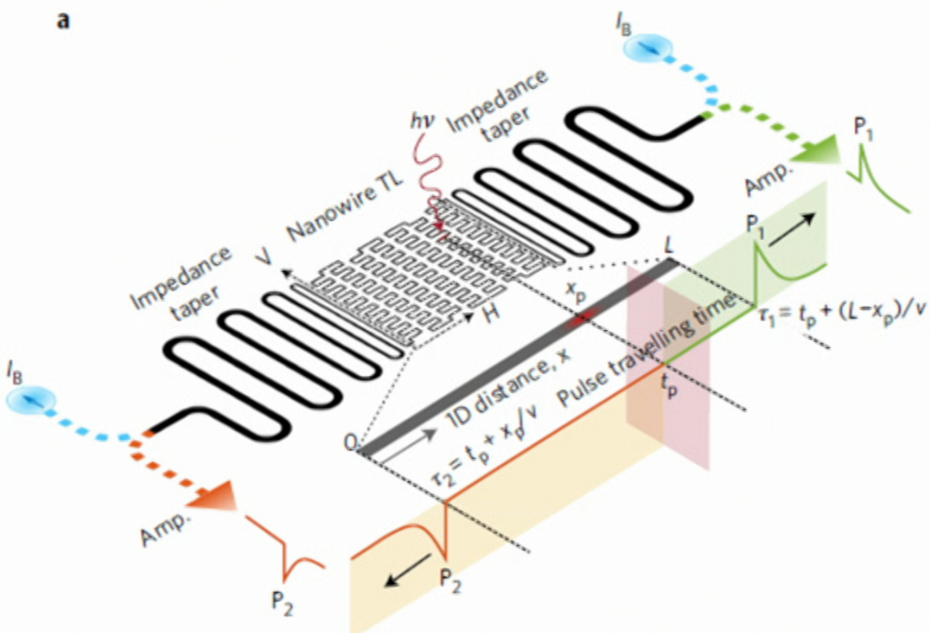
Transmission line imager



- Use relative time delay to determine where a photon is detected
- Requires dual readout

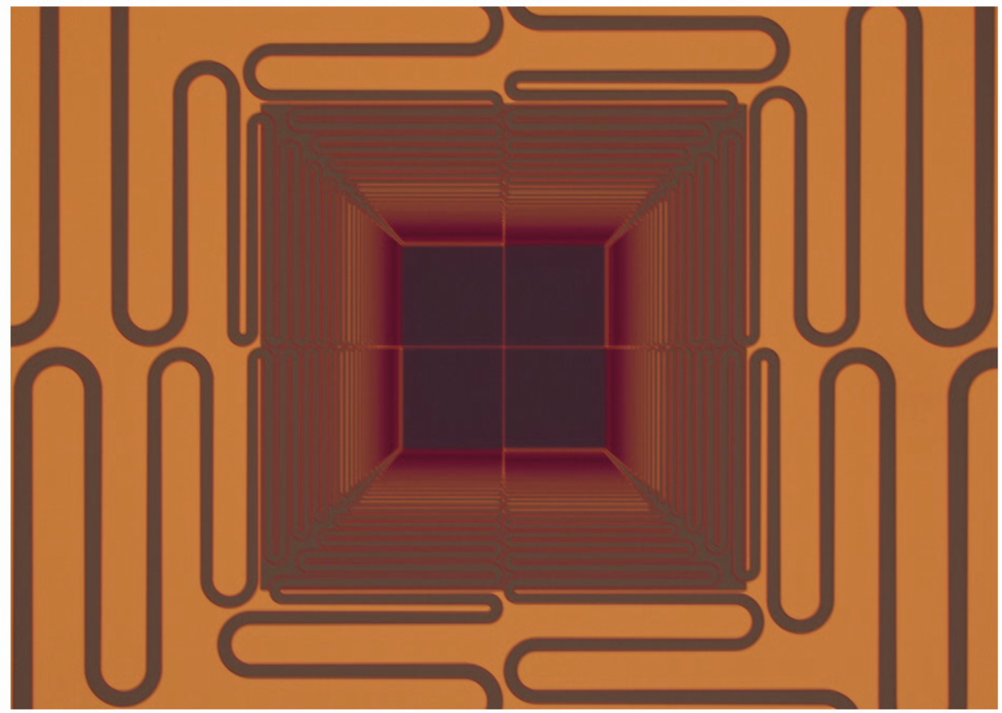
Q. Zhao et. al, Nature Photonics 11, 247 (2017)

Delay line imager



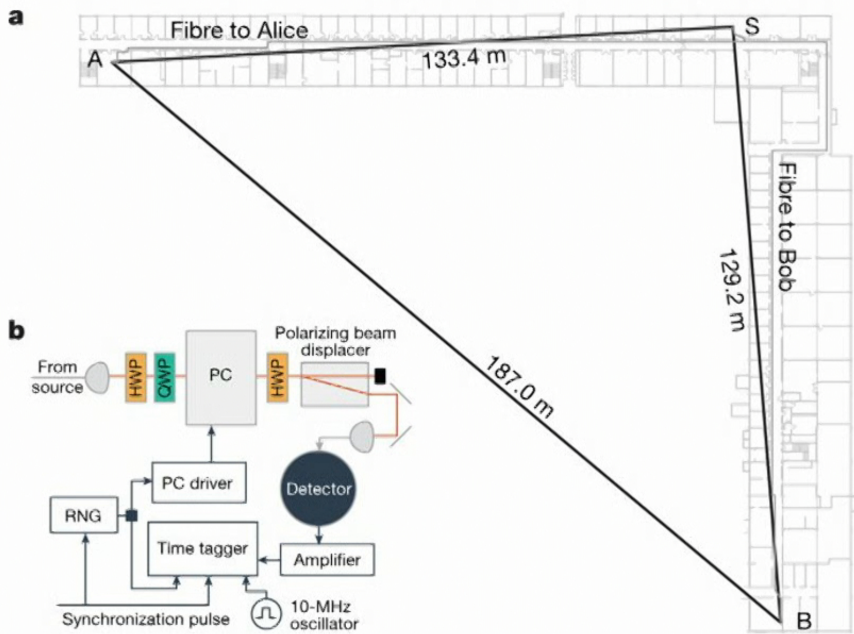
Q. Zhao et. al, Nature Photonics 11, 247 (2017).

NIST Quad Delay line imager



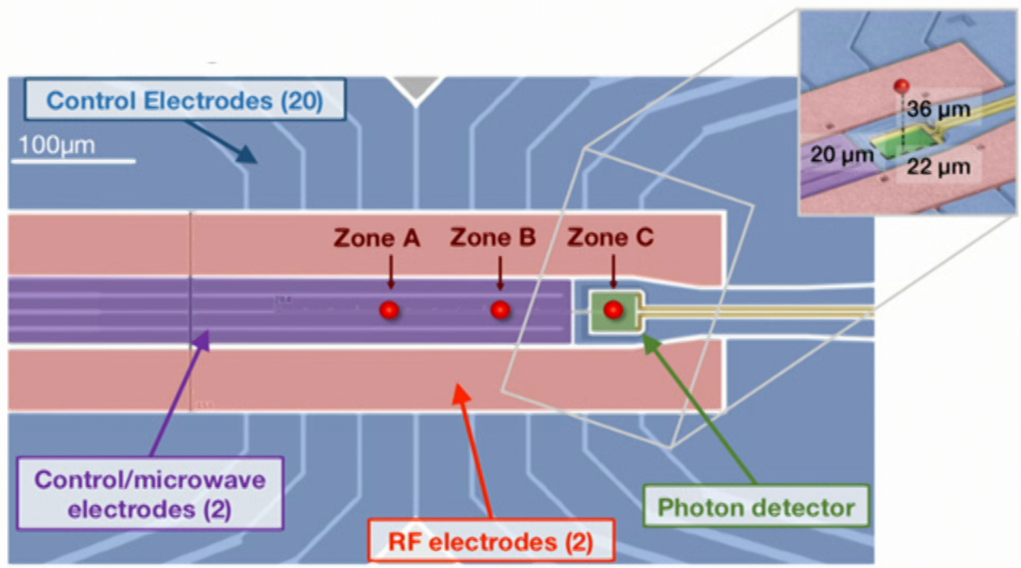
Loophole-free Bell Tests
Quantum certified RNG

Bierhorst et al, Nature, 556, pg 223–226 (2018)

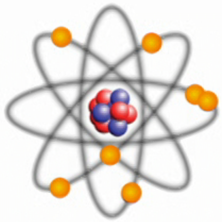


Ion Traps QIP

Slichter et al. , Opt. Express 25, 8705-8720 (2017)



^{229}Thorium

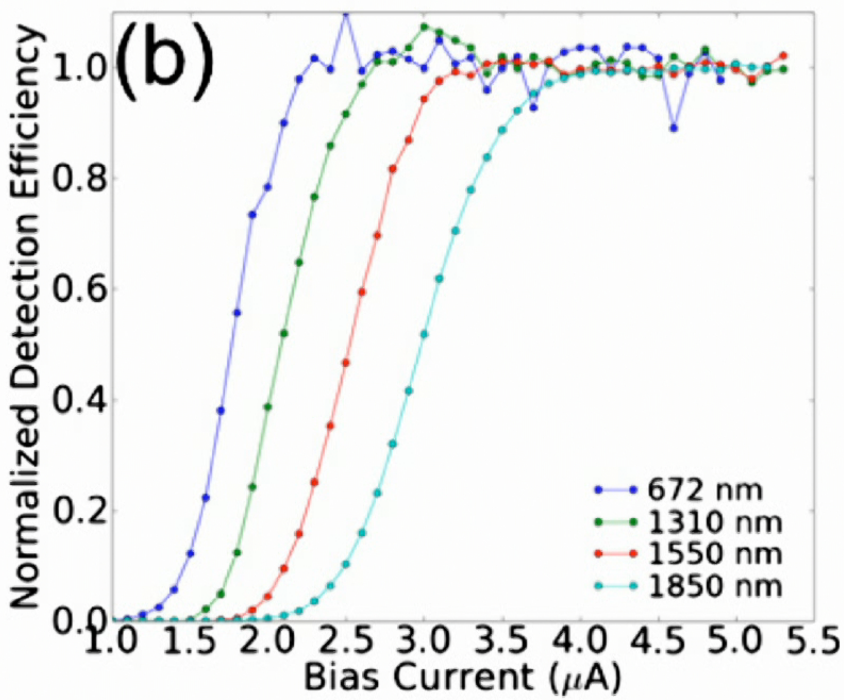


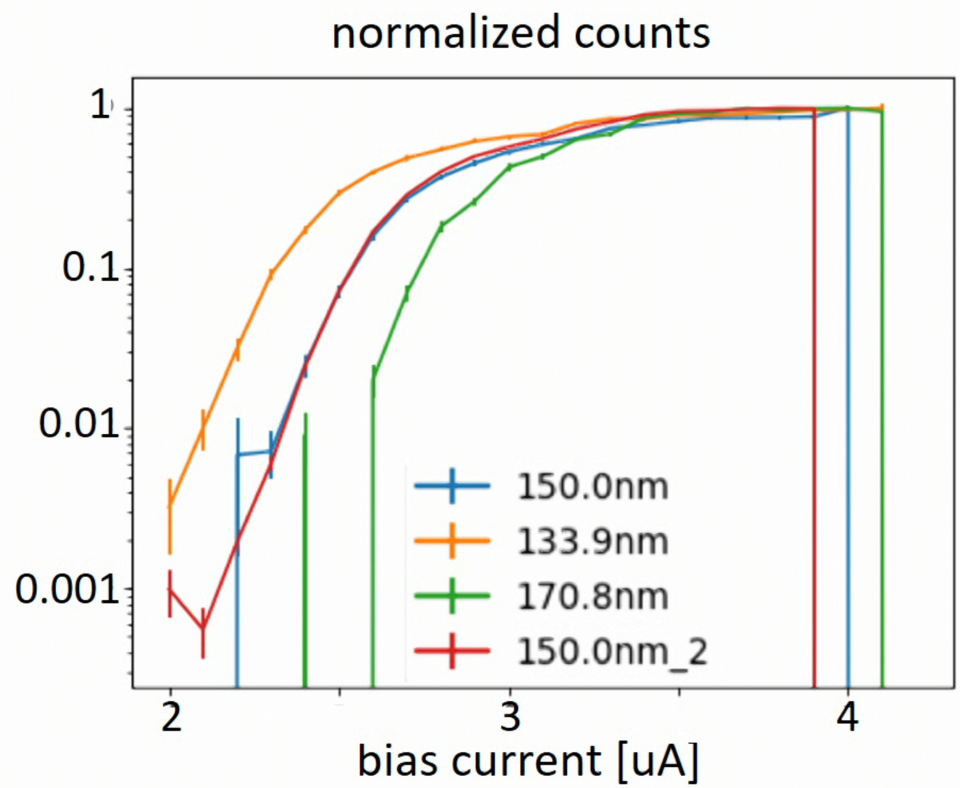
- Th229 nuclear isomer is long lived (30 minutes or more), has a narrow linewidth,
  - Beck *et al*, 7.8 eV +/- 0.5 eV
  - Seiferle *et al*, 8.3 eV +/- 0.2
- Nuclear clock would be a much more sensitive measurement of alpha-dot
- The measurement uncertainty in the energy is too large to scan carefully with a laser
  - Need <50 meV uncertainty

ΔE [eV]	Year
< 100	1976
1 (4)	1990
3.4 (1.8)	2003
7.6 (0.5)	2007
6 – 18	2016
8.3 (0.2)	2019

UCLA and LMU

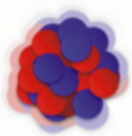
Statistical measurement of Energy





Where do we get Thorium 229?

^{233}U

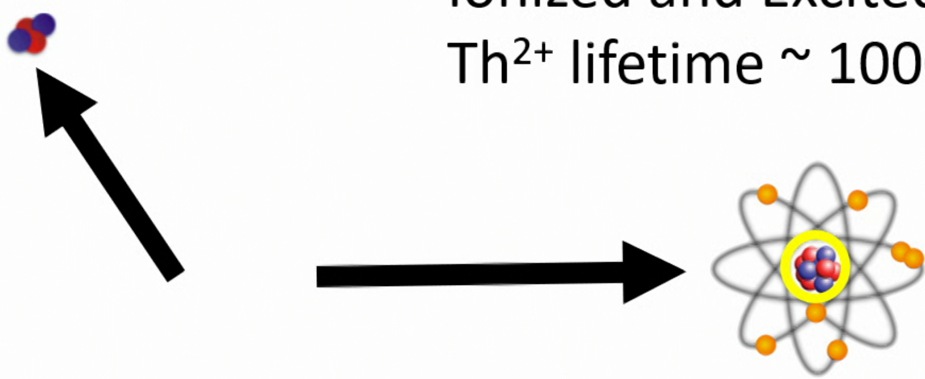


Where do we get Thorium 229?

Alpha Particle

Ionized and Excited ^{229}Th

Th^{2+} lifetime ~ 1000 seconds

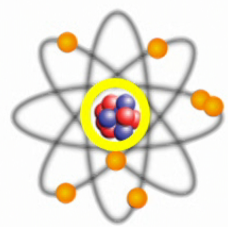


Where do we get Thorium 229?

Alpha Particle

Ionized and Excited ^{229}Th

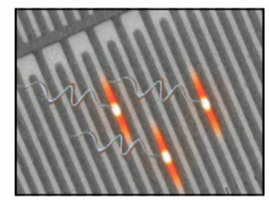
Th^{2+} lifetime ~ 1000 seconds



Lifetime is 10 μs

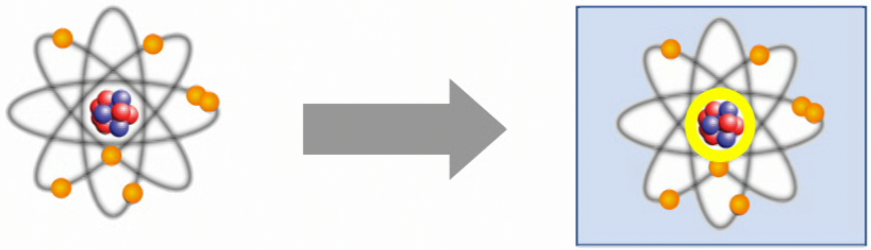
Internal

Conversion

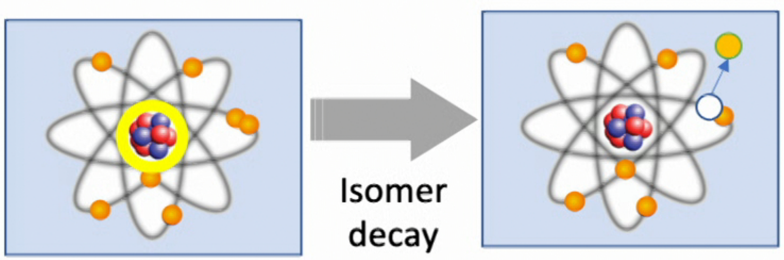


What does the nanowire detector observe?

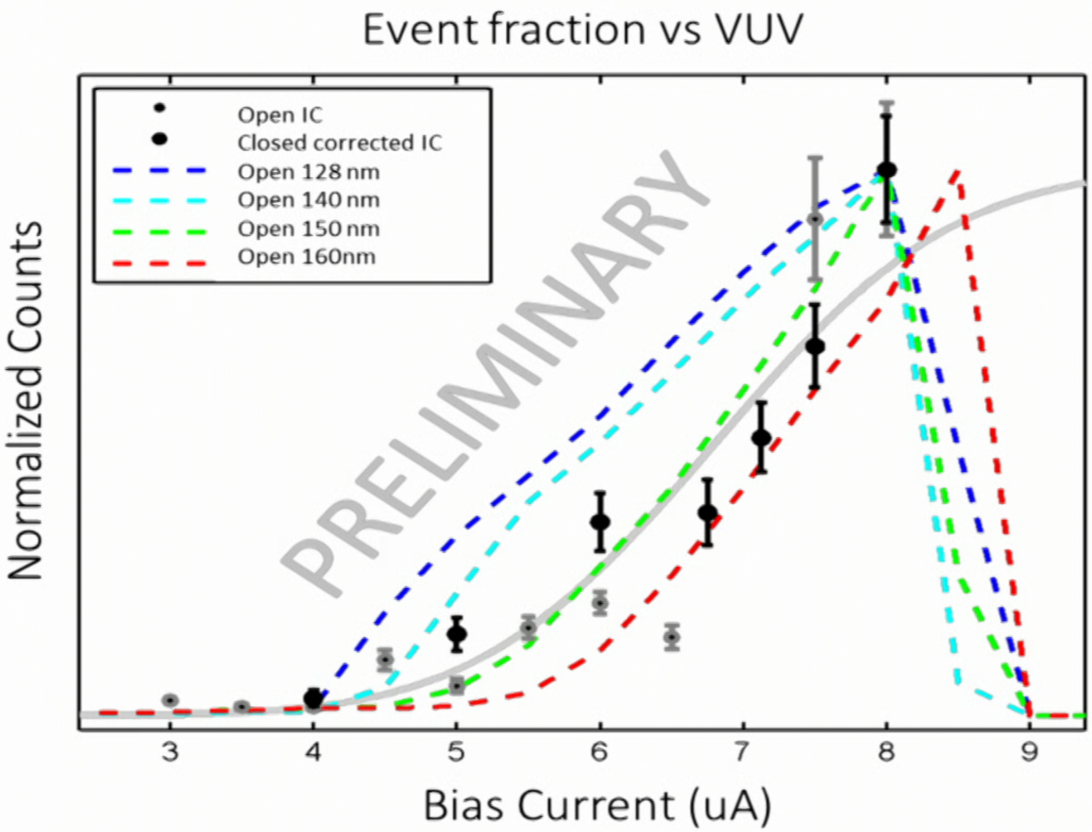
1. Th229 Ion impacts the detector and causes a click



1. ~2% of the Th229 ions are in the nuclear isomer state.   In metals, the lifetime is ~ 10usec, we should see a second click from the internal conversion ***in the same place***

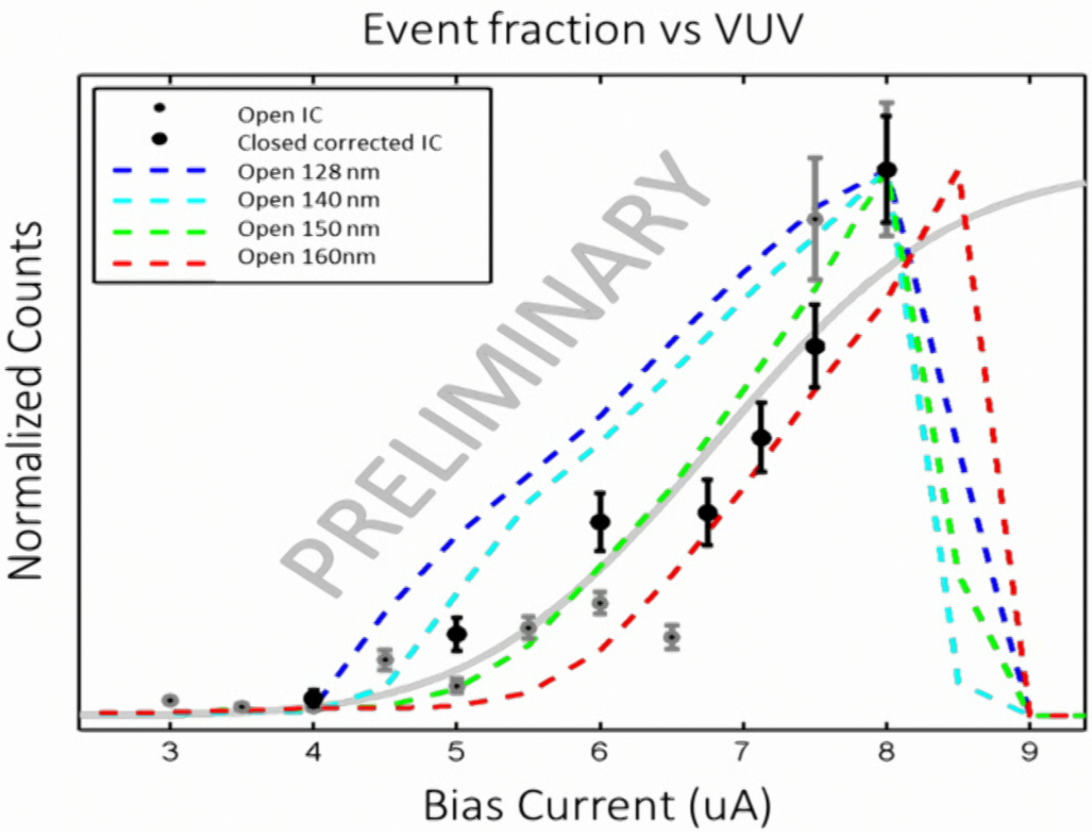


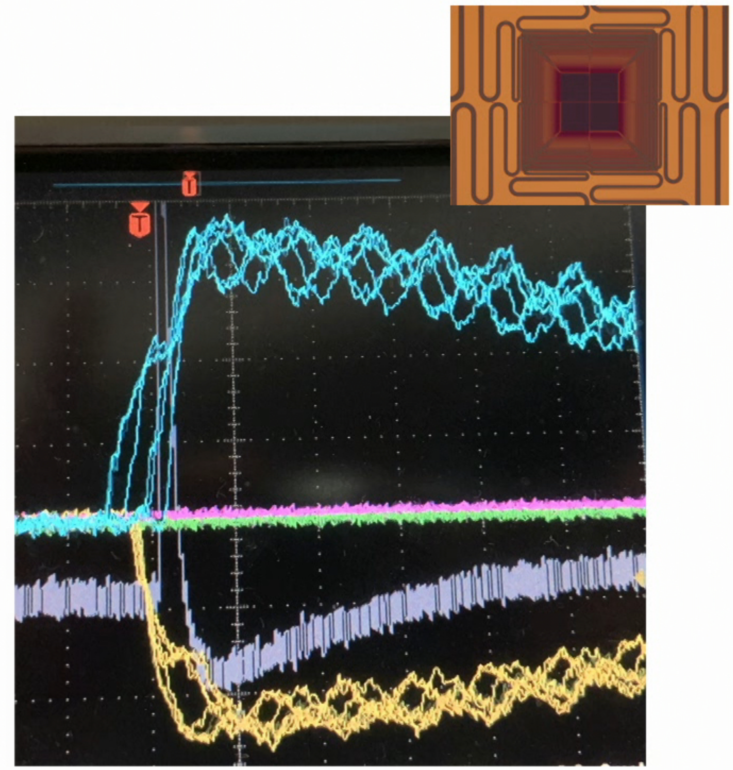
Preliminary Data indicates we see Thorium isomer decay



UCLA | AMO | Hudson Lab
Quantum interactions and fundamental physics

Preliminary Data indicates we see Thorium isomer decay





UCLA | AMO | Hudson Lab

Quantum interactions and fundamental physics

State of the Art (before 2000's)

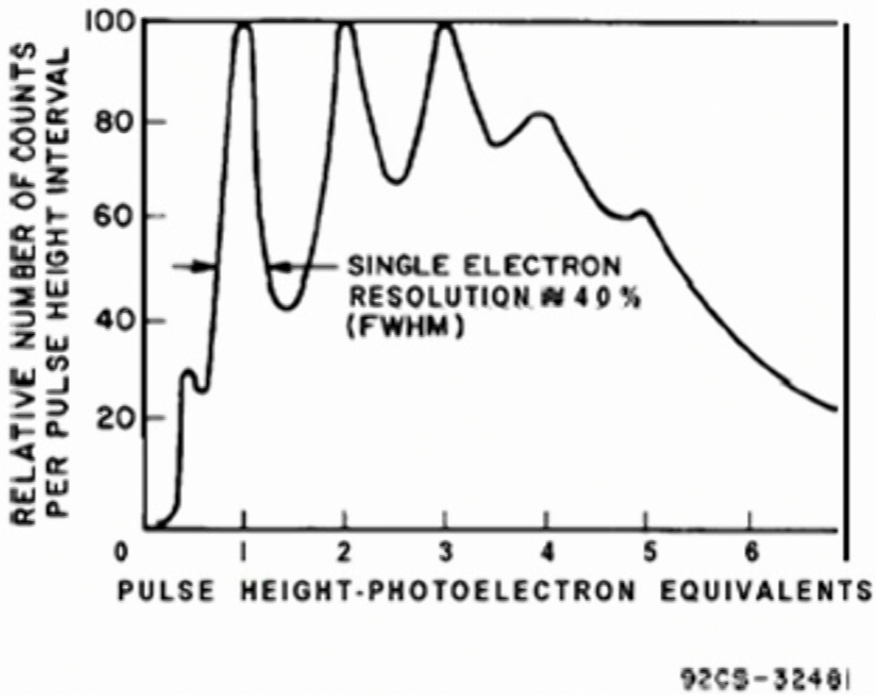
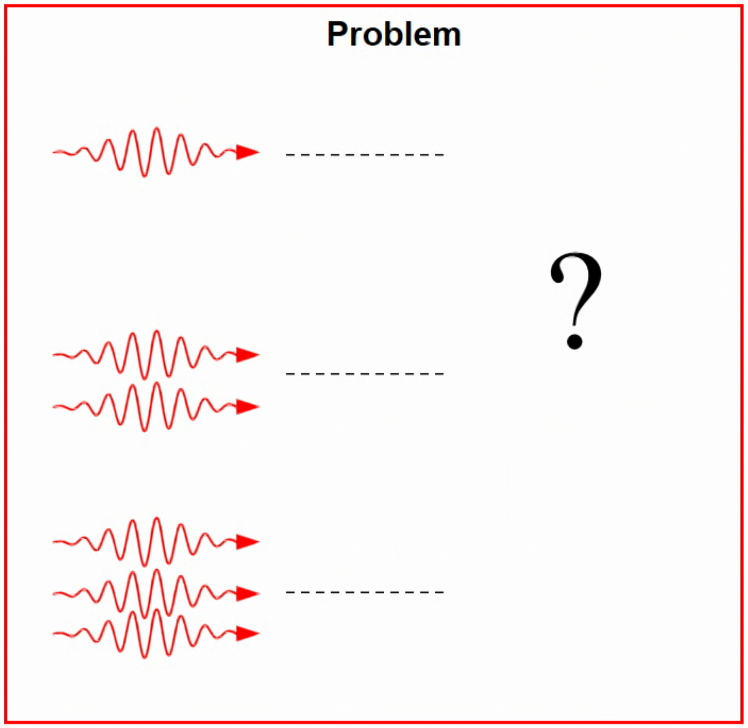
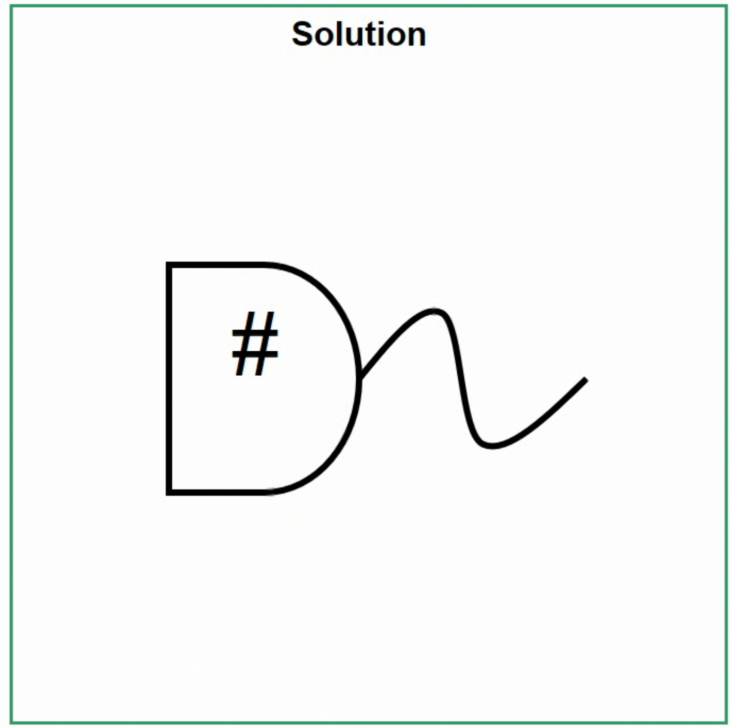


Fig. G-8 - Typical photoelectron pulse-height spectrum for a photomultiplier having a GaP first dynode.

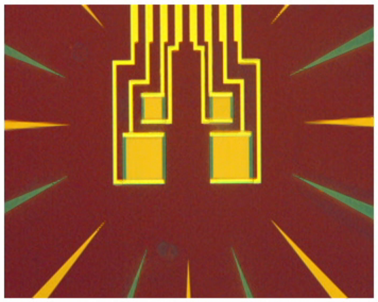
- Efficiency not close too 100%
- There is non-trivial amount of error in identifying "1" vs "2"

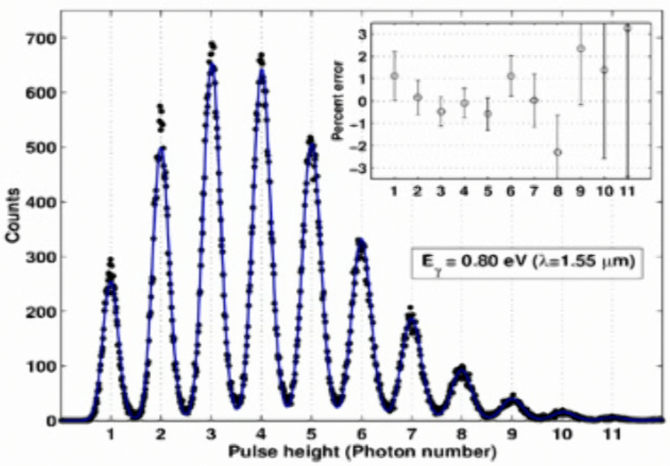
How do you make a Photon Number Resolving detector?





Transition-edge Sensor



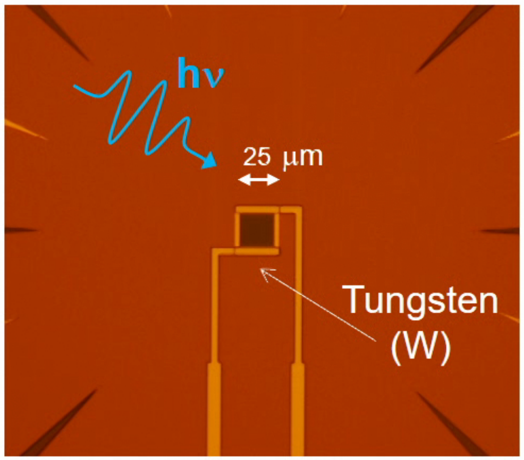


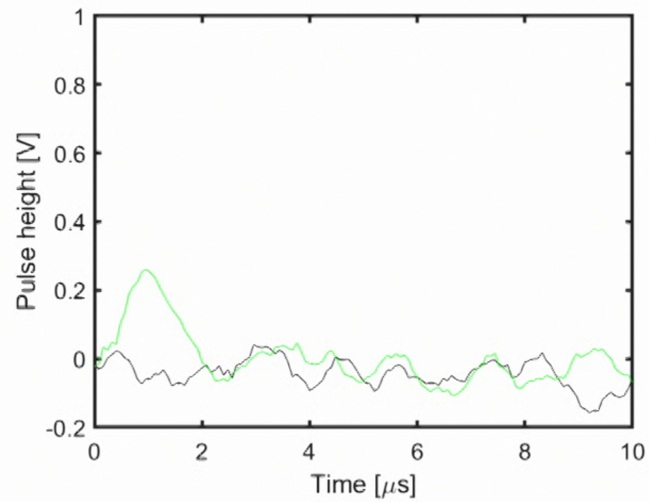
Wavlength	200-1700 nm
Q.E.	>98%
Dark Count	0
Count Rate	1 MHz
Timing	~1 μsec

Research: NIST, AIST

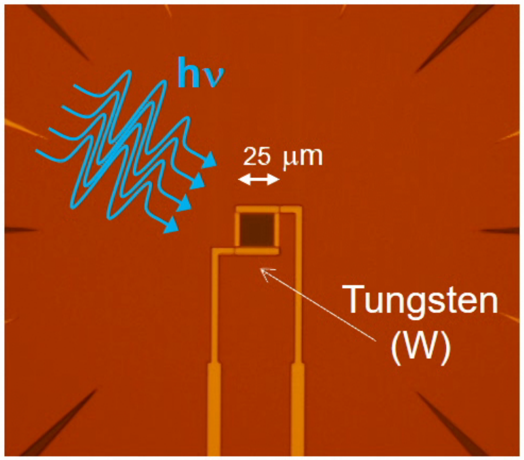
Commercial: Xanadu (Toronto)

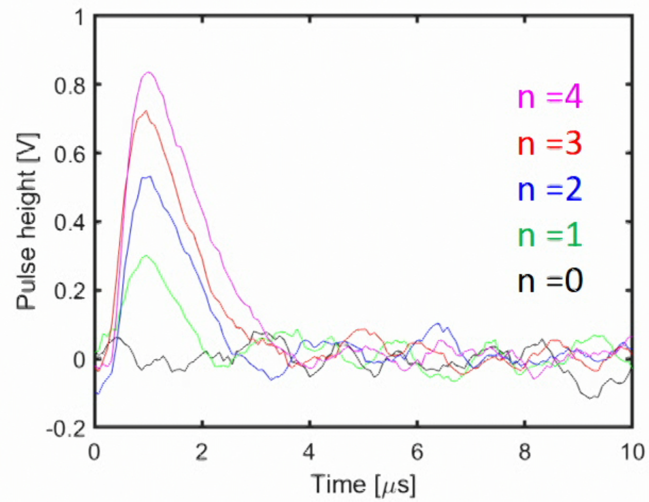
Optical Transition-Edge Sensor Photon-Number Resolving





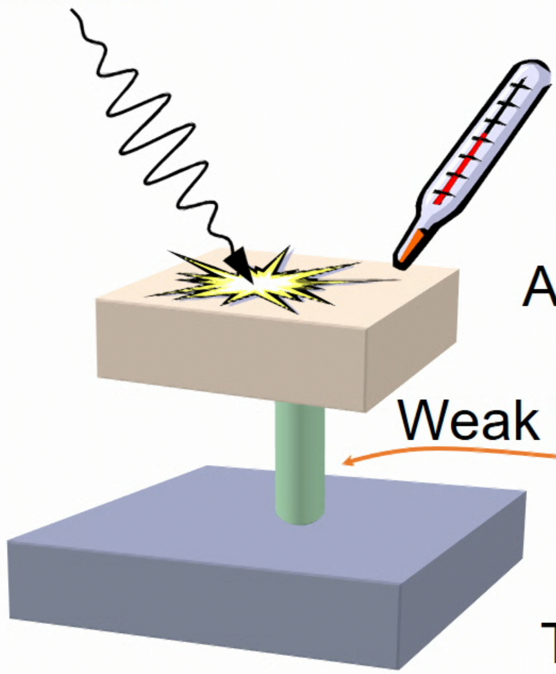
Optical Transition-Edge Sensor Photon-Number Resolving

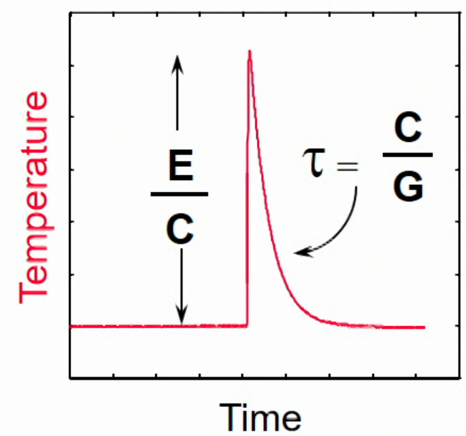




- Calorimetric operation (not avalanche)
- Output signal is proportional to incoming photon energy
- Enables distinction of photon number
- Can be made with high detection efficiency
- Recovery time can be ~μS

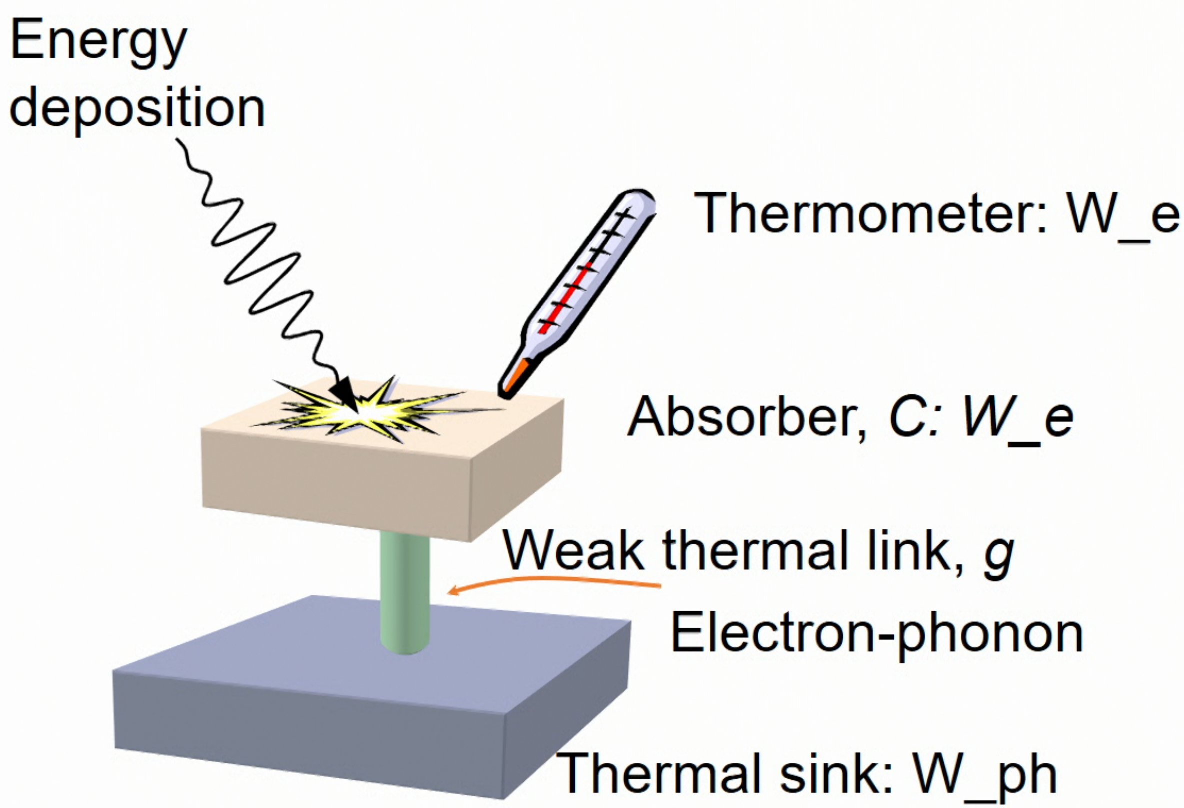
Simple Microcalorimeter





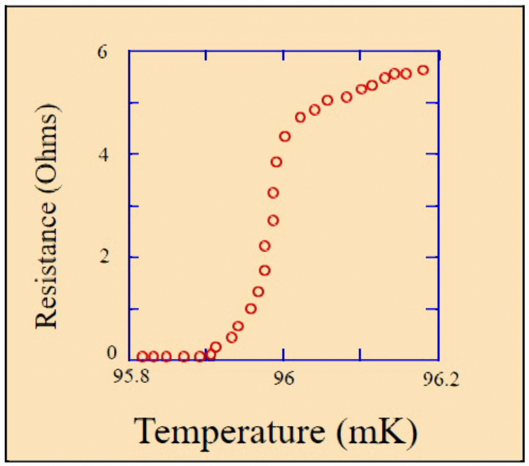
$$C\frac{d(\Delta T)}{dt} + G\Delta T = E\delta(t)$$

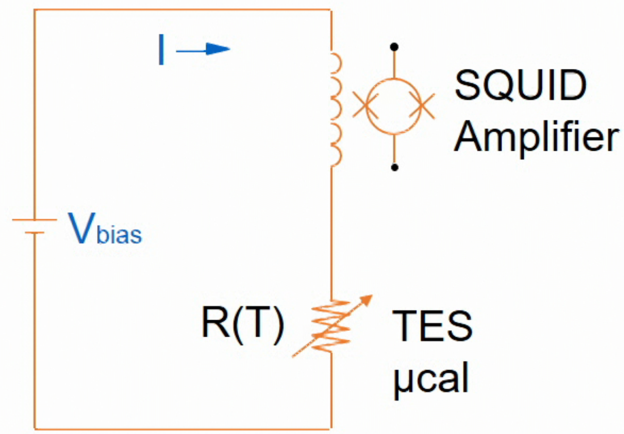
Optical TES



- The entire microcalorimeter is in the W device
  - Thermometer
  - Weak thermal link
  - Thermal heat sink
- The energy of a single photon is so small that the heat capacity needs to be very tiny to get a measureable change in Temperature
- Physics forces the Temperature to be < 1K

Voltage-Biased TES





Superconducting Transition-Edge Sensor (TES)

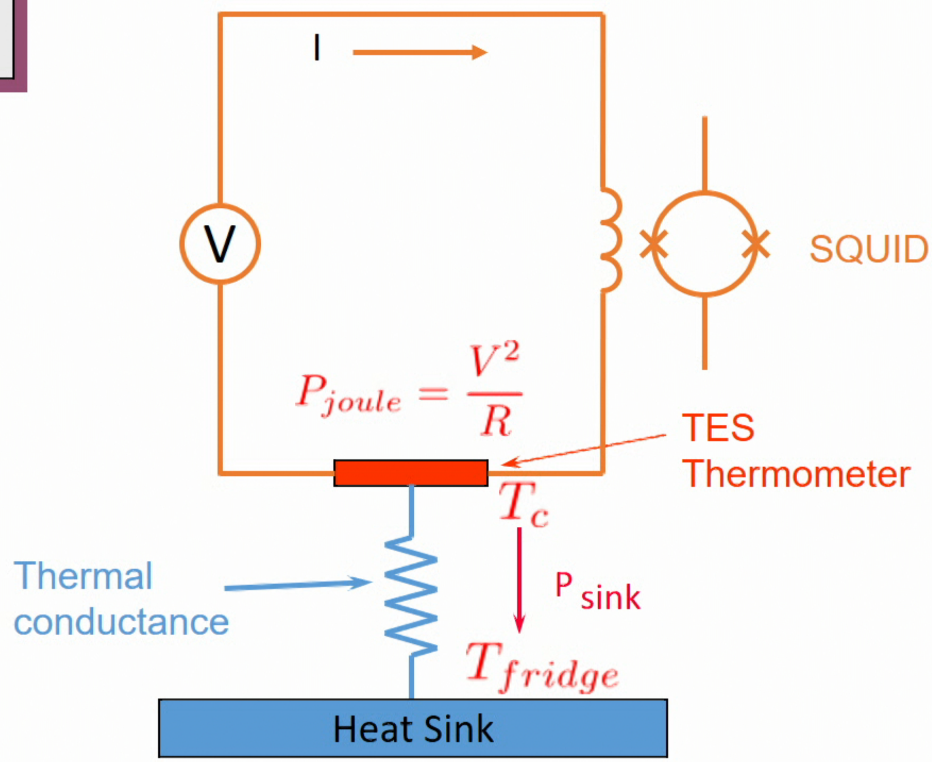
Temperature Self-Biasing

As the film cools, R → 0 , and P_{joule} increases.

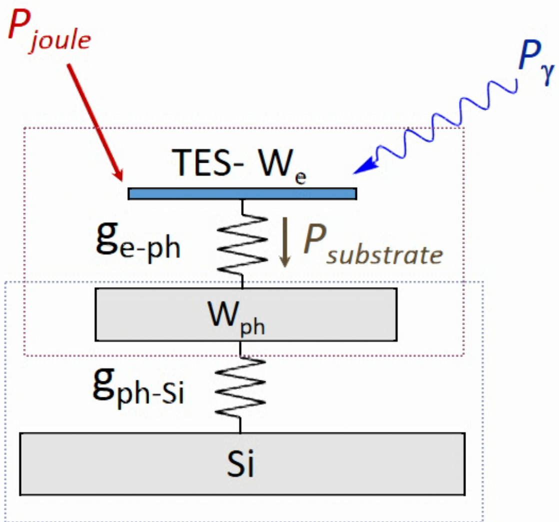
In stable equilibrium

$$\frac{V^2}{R} = P_{sink}$$

Temperature Self-Regulation



Thermal Model/Theory



$g_{e\text{-}ph} \ll g_{ph\text{-}Si}$

$T_{electron} \sim 175$ mK

$T_{phonon} = T_{Si} \sim 60$ mK

Electrothermal Feedback (ETF)

In equilibrium: $P_{substrate} = P_{joule}$

$$\kappa\,(T_e^{\,n} - T_{ph}^{\,n}) = I_{sensor} \cdot V_{sensor}$$

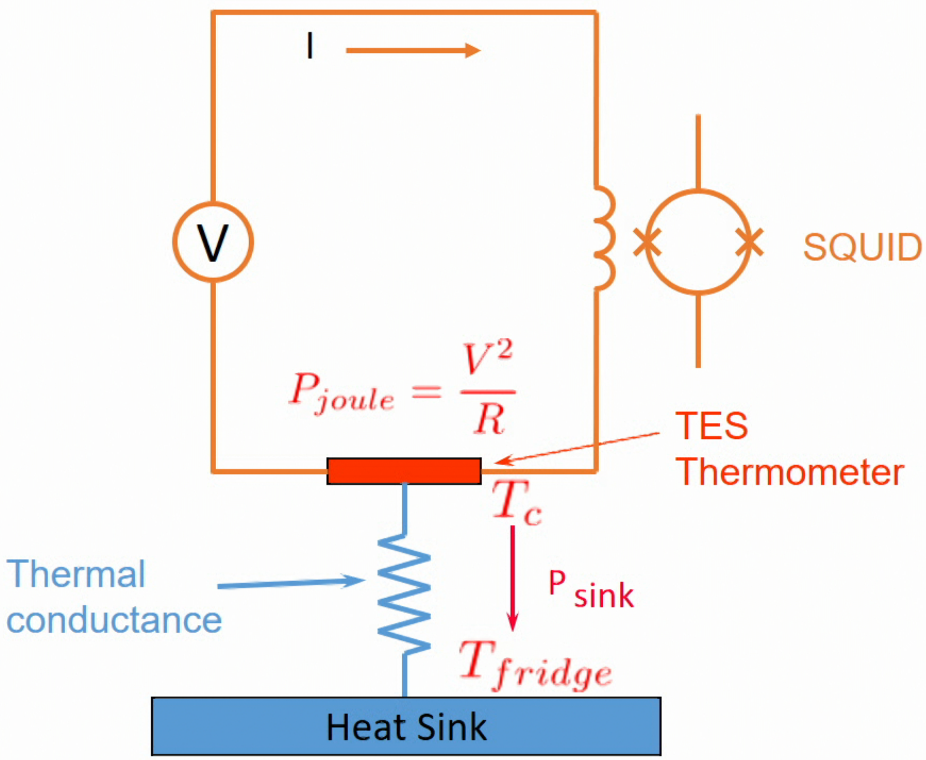
When a photon is absorbed:

$$C\frac{dT_e}{dt} + \kappa\,(T_e^{\,n} - T_{ph}^{\,n}) = \frac{(V_{sensor})^2}{R_{sensor}} + P_{\gamma}$$

Material and Tc Dependent

Bias Dependent

TES Electrical circuit



$$C\frac{dT_e}{dt} + \kappa\left(T_e^{\ n} - T_{ph}^{\ n}\right) = \frac{\left(V_{sensor}\right)^2}{R_{sensor}} + P_\gamma$$

$$\boxed{L\frac{dI}{dt} = V - IR(T,I)}$$

$$\alpha = \frac{\partial ln(R)}{\partial ln(T)} \qquad \beta = \frac{\partial ln(R)}{\partial ln(I)}$$

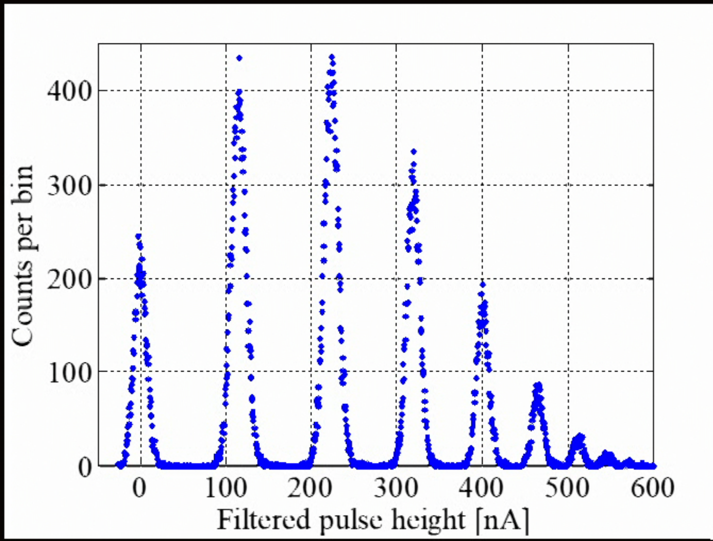
- Heat Capacity C and Inductance L can form a n “LC” oscillator
- Low R_sensor and High L can cause oscillations that are underdamped

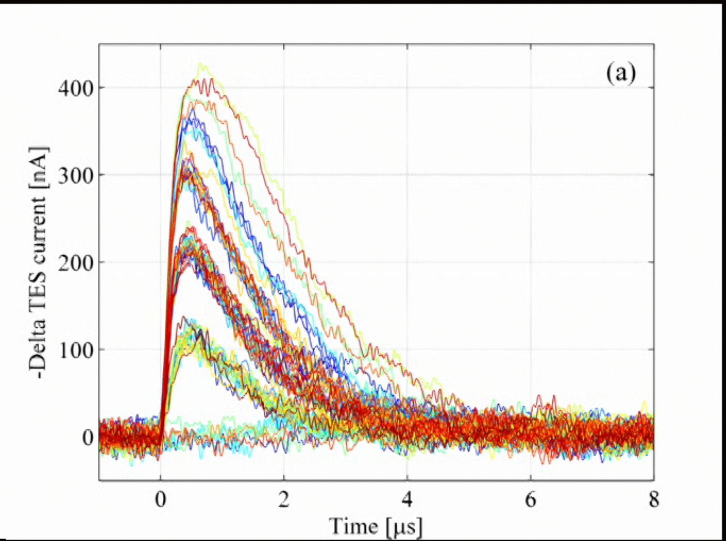
805 nm Optimized Device

> 98 % System Detection Efficiency

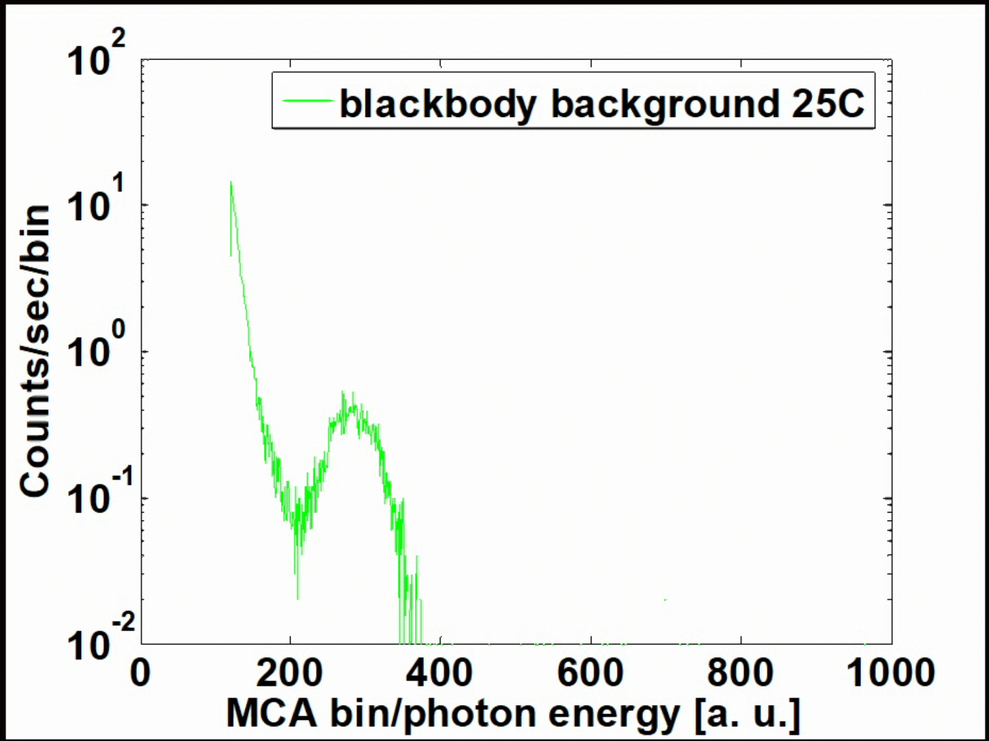
Pulse-Height Distribution
805 nm photons

TES response to 805 nm photons
Recovery times < 1 μs

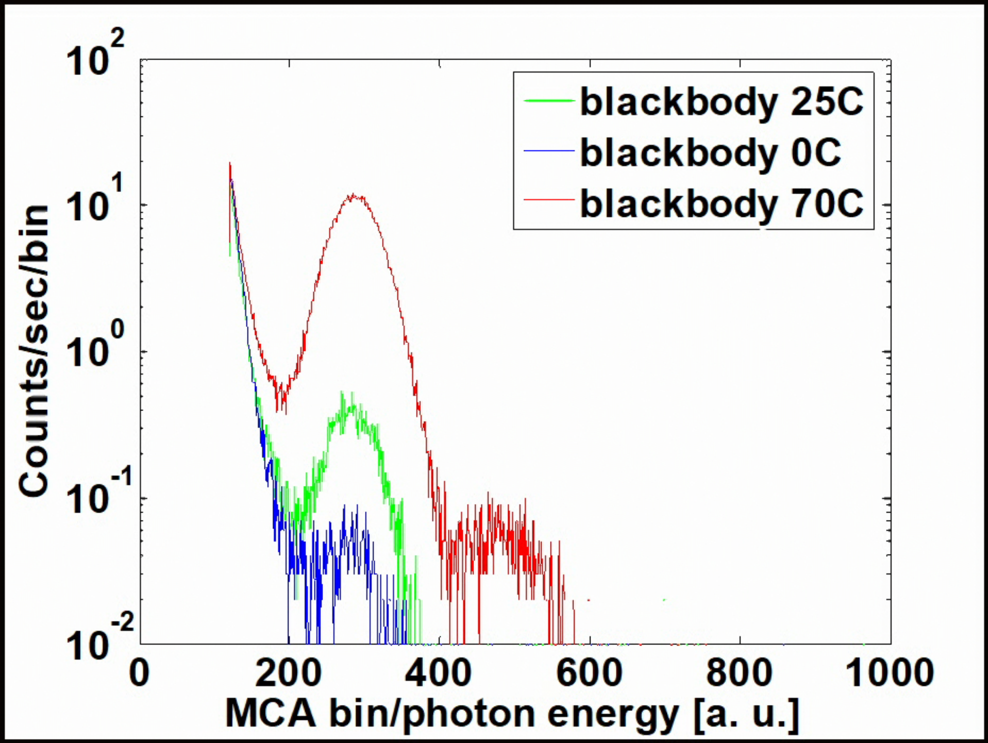




Background Limited Photon counting



Background Limited Photon counting



Conventional Single-Photon Detectors

	Wavelength Range	QE (%, max)	DCR (cps)	Jitter	Max Count Rate (cps)
PMT (visible)	400-900 nm	40	100	300 ps	10×10^6
PMT (IR)	1000-1600 nm	2	200K	300 ps	10×10^6
Silicon (thick)	400-1050 nm	65	25	400 ps	10×10^6
Silicon (thin)	400-1000 nm	49	25	35 ps	10×10^6
InGaAs APD	950-1600 nm	20	75K	350 ps	10×10^3

- Commercially available
- Relatively inexpensive

M. D. Eisaman, J. Fan, A. Migdall, and S. V. Polyakov, Rev. Sci. Instrum. 82, 071101 (2011)

Low Temperature Physics = High Performance

	Wavelength Range	QE (%, max)	DCR (cps)	Jitter	Max Count Rate (cps)
W-TES (NIST)	UV-1850 nm+	>98%	<<1	10-100 ns	100×10^3
SNSPD: NbN	UV-5 um	>90%	100-1000	~3 ps	100×10^6
SNSPD: WSi	UV-5 um	~98%	$<<10^{-5}$	~5 ps	10×10^6

TES: Transition Edge Sensor
SNSPD: Superconducting Nanowire Single Photon Detector

- No afterpulsing problems
- Excellent prospects for longer wavelengths

Key takeaways

- TES is an electrical and thermal device
- When energy is absorbed by the TES
  - It primarily cools by reducing the amount of Joule heating…
  - This means that the integral over time of the voltage bias * drop in sensor current will be proportional to the incoming energy.
  - Only ~40% of the incoming energy ends up getting extracted by Joule power. The remaining 60% is lost to the substrate almost immediately by athermal phonons.