Geiger-mode APDs
(a.k.a. "SiPM")
(1)

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SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO

Plan of this lecture

1. Basic principle and performance of "SiPM"
2. Applications (HEP, nuclear/astro/medical)
    - Experience of using 60,000 MPPCs for T2K experiment
3. Future developments

Plan for today

1. Introduction
   - Photon detectors
2. Operation principle
   - From PD, APD to "SiPM"
3. Key parameters and performance
   - Signal generation

Introduction

Photon detectors

- **Needless to say,**
  - detection of photon is an important, elementary part of particle detection in a very broad field of application.

Photon detecto

sa

ph mpor
part of particle dete
eld of application.

Photon detectors

- Convert light to electric signal, with:
  - High efficiency
  - Multiplication: for detection of weak light (*single* photon in many cases).
  - Proportionality: need to know amount of light injected.

PMT (photomultiplier tube)

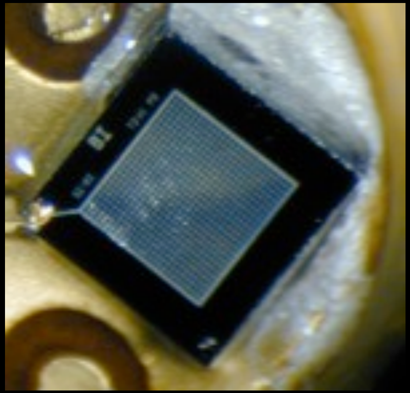
- Most commonly used in the field.
- Various types available depending on purpose. (size, sensitive wavelength, timing resolution, ...)

Great success of PMT

- PMTs are great device with excellent performance.
- To date, no device has performance to completely replace PMTs.
- However, recent development has yielded an interesting device, that is...

“Silicon Photo-multiplier”

- Known in many many names...
  - SiPM
  - MRS-APD
  - SPM
  - MPGM APD
  - AMPD
  - GM-APD
  - MPPC
  - .....
- Reflecting progress in many places in short time.



*Key development in Russia in 90s,
by Golovin, Sadygov, et al.

R&D over the world

Some (many) very likely missing..

Why so interesting?

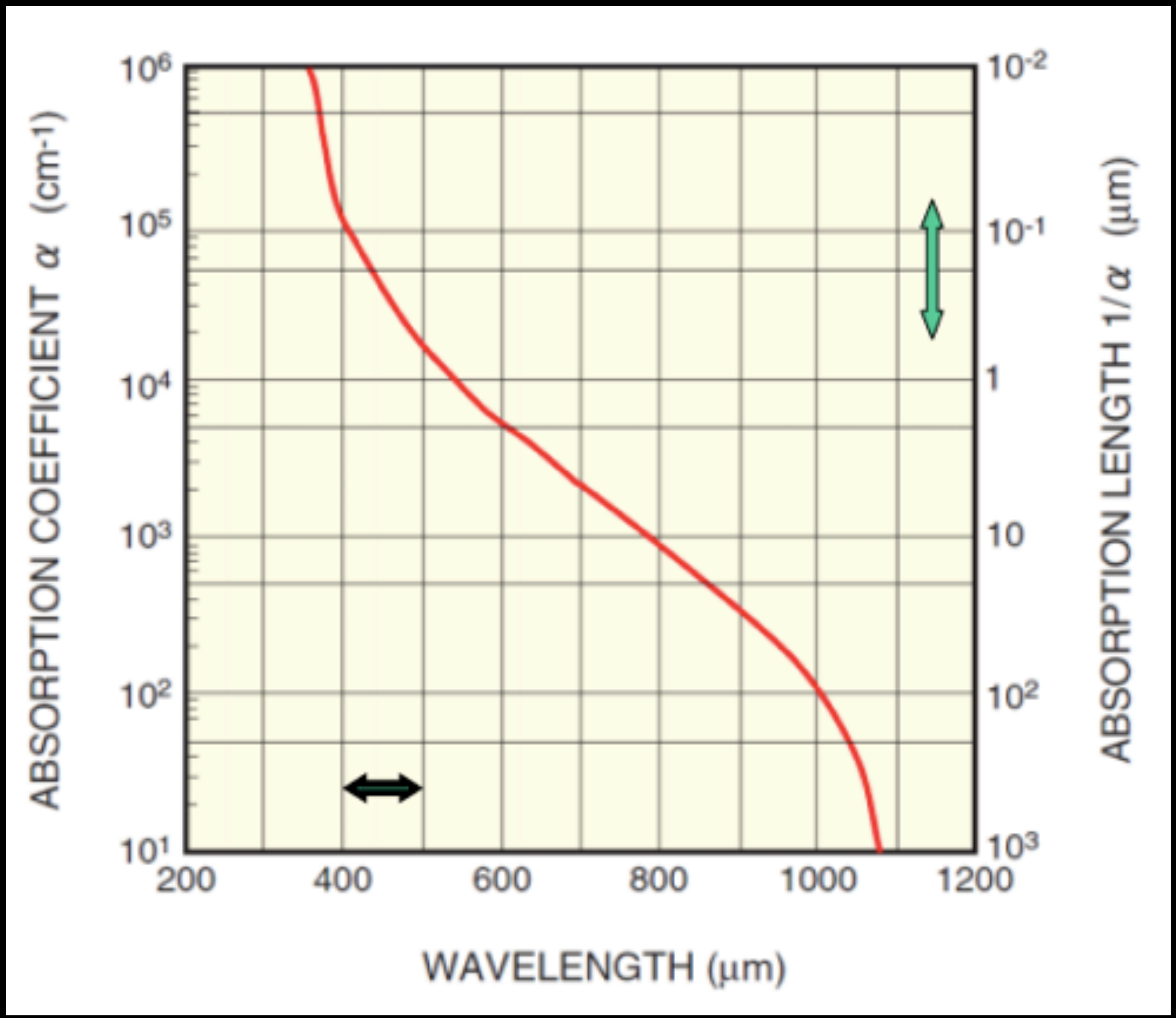
- Many advantages:
  - High (10^5-10^6) gain with low voltage (<100V)/power
  - High photon detection efficiency
  - Compact and robust
  - Insensitive to magnetic fields
- Although as many possible drawbacks *(at this moment)*:
  - Only small size (typically ~mm^2) available
  - High dark count rate (100kHz-1MHz/mm^2)
  - Optical cross-talk and after-pulse
  - ....

That's why I am giving this talk...

Operation Principle

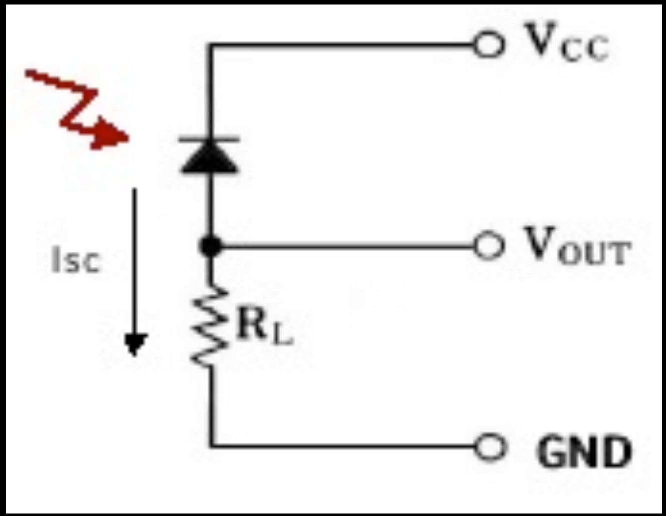
from basics of semiconductor photodetector

Photo absorption in Si

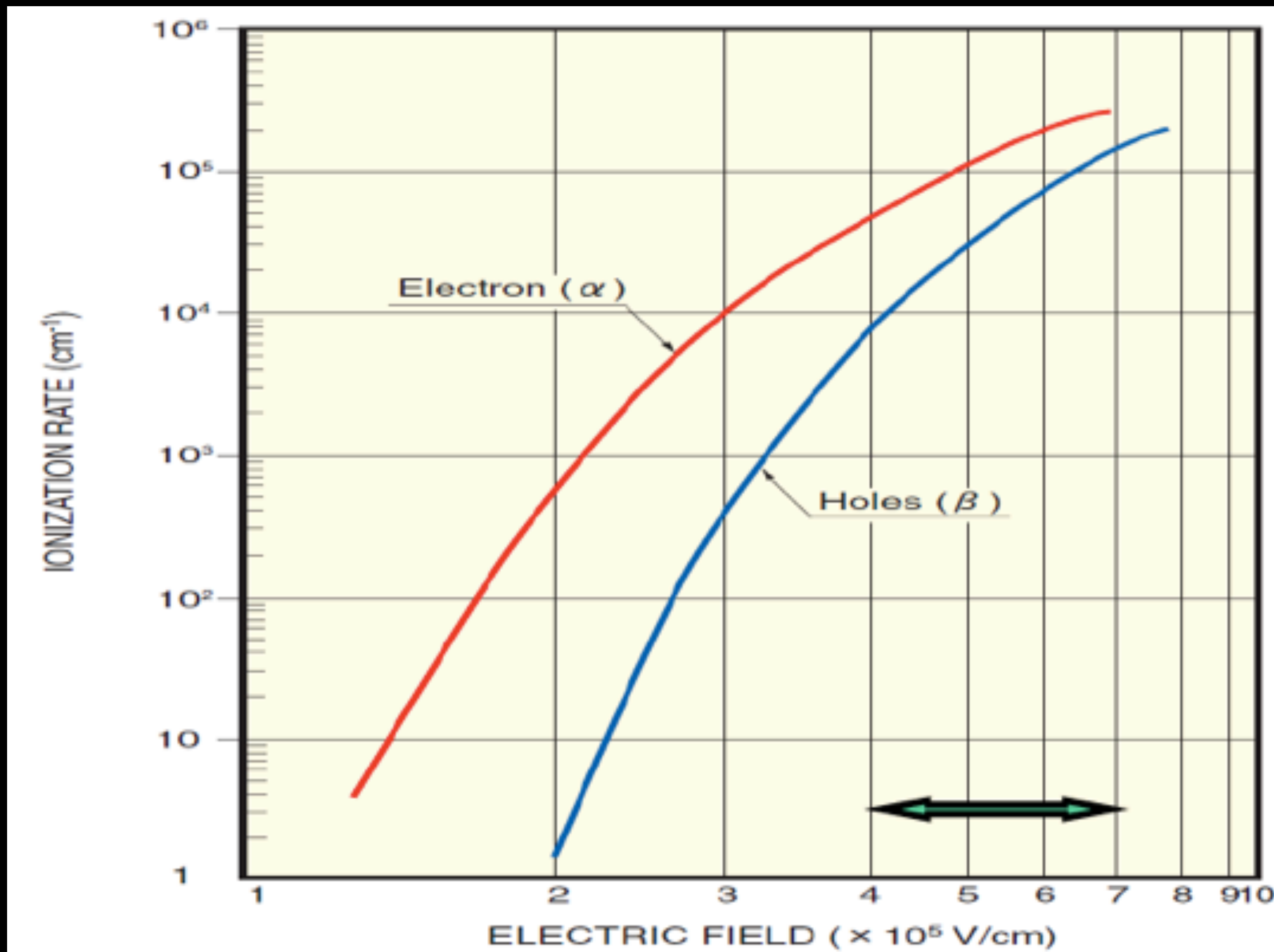


Photodiode

- p-n or p-i-n structure
- Photon creates electron hole pair near the surface
- Under reverse bias voltage, they can reach electrodes before recombination and give current proportional to the light intensity
- No amplification



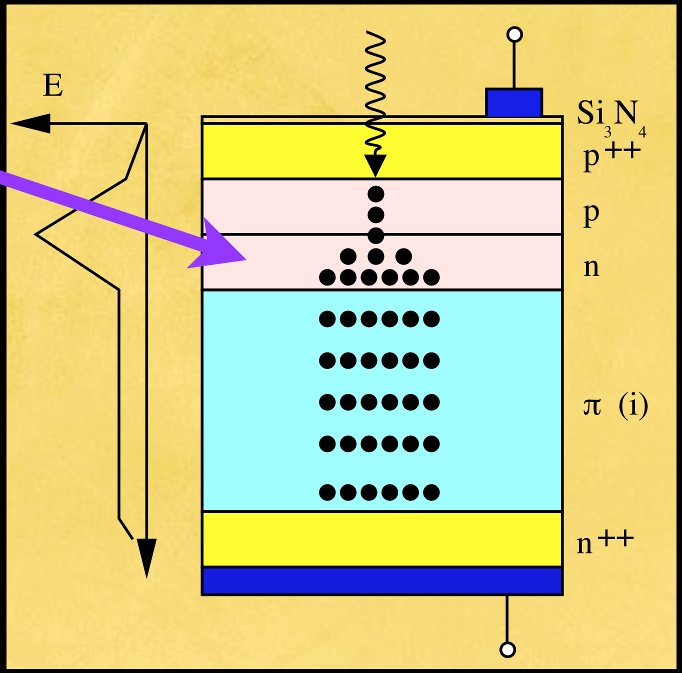
Ionization rate



Ionization coffient for avalanche Multiplication

Avalanche Photodiode (APD)

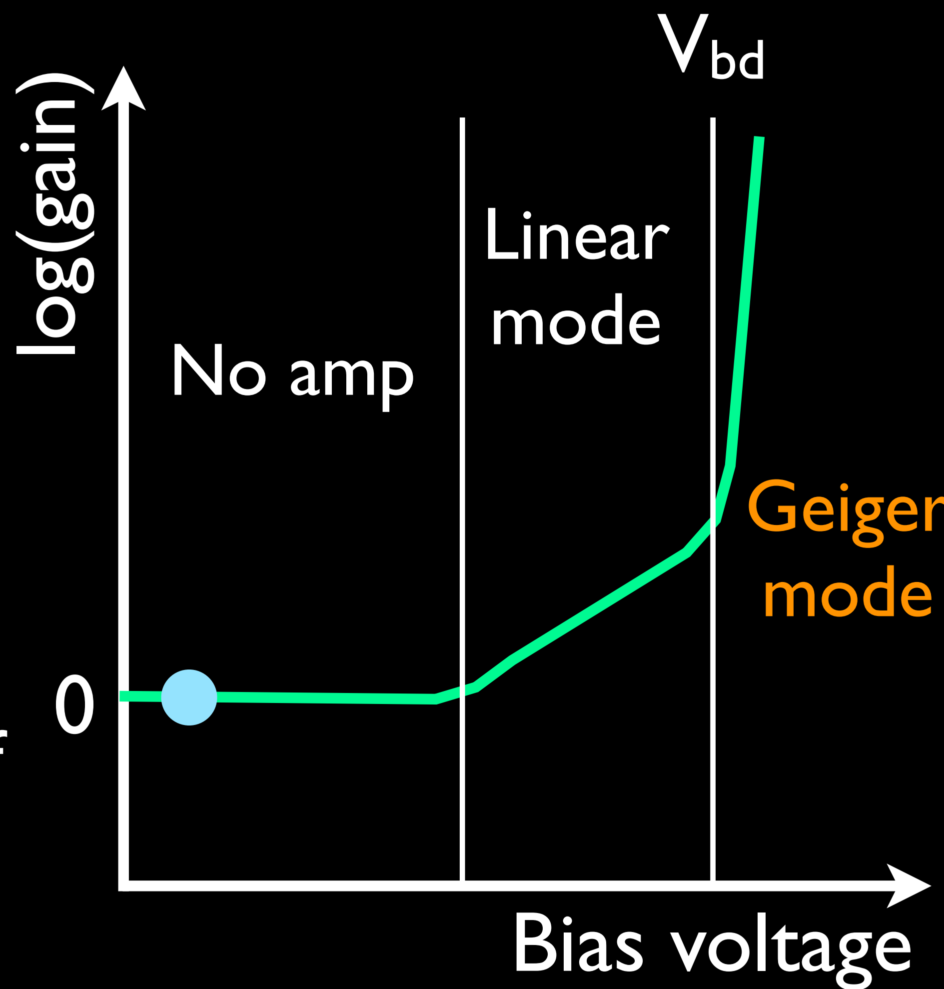
- Avalanche amplification in reverse-biased region
- Linear operation below breakdown voltage (V_{bd}): output charge ∝ number of e-h pairs ∝number of incident photons
  - Typical internal gain: 10-100 (~1000 in extreme case)



Schematics of APD for CMS-ECAL

Geiger-mode APDs

- Operation above the breakdown voltage
- Discharge 'quenched' by external register
- High internal gain
- Binary device
  - Same amount of charge regardless of number of incident photons
  - No proportionality



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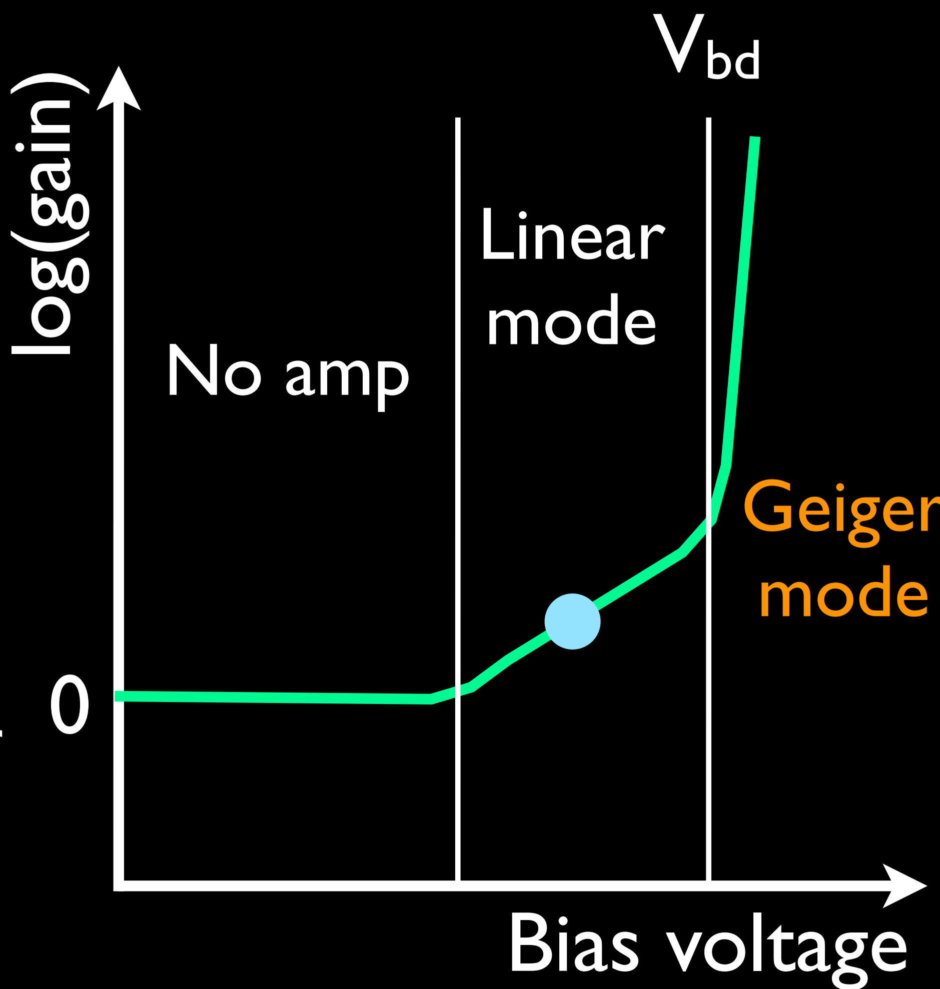

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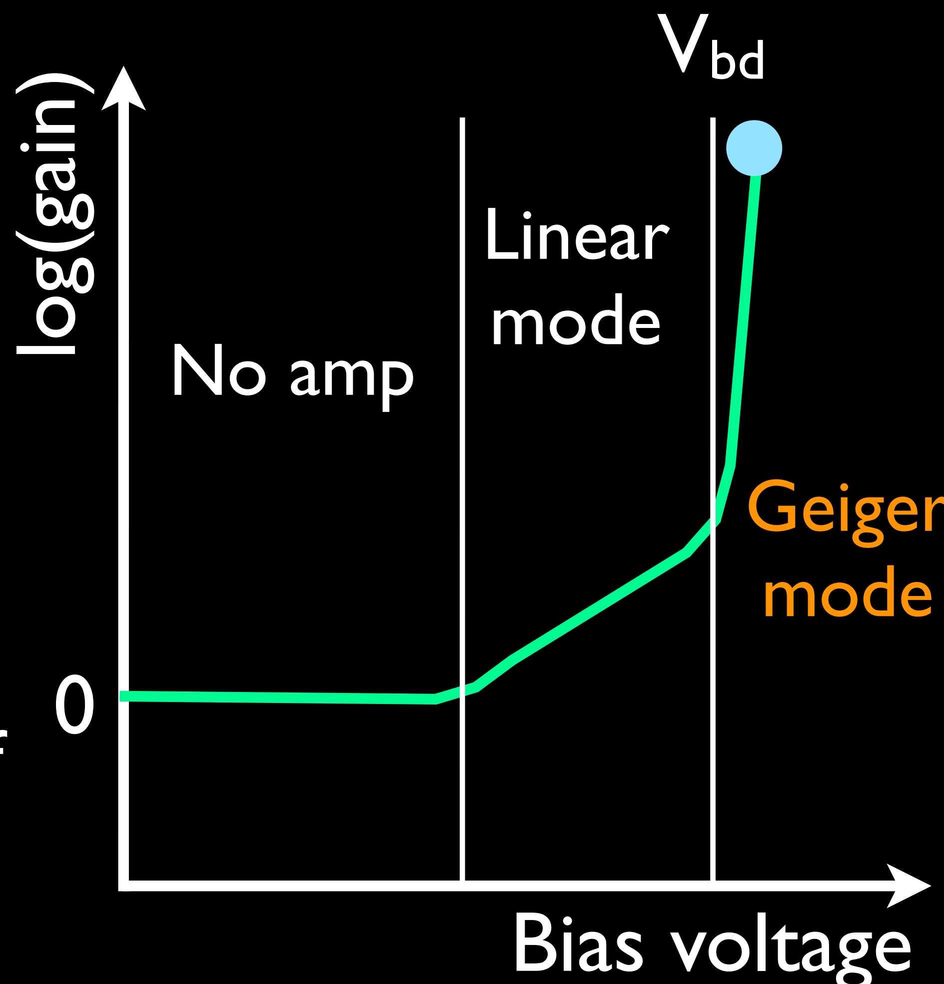
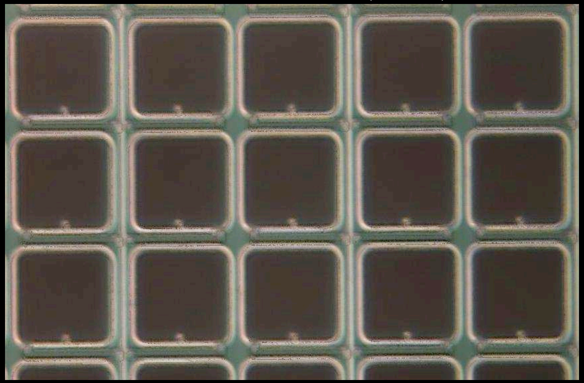
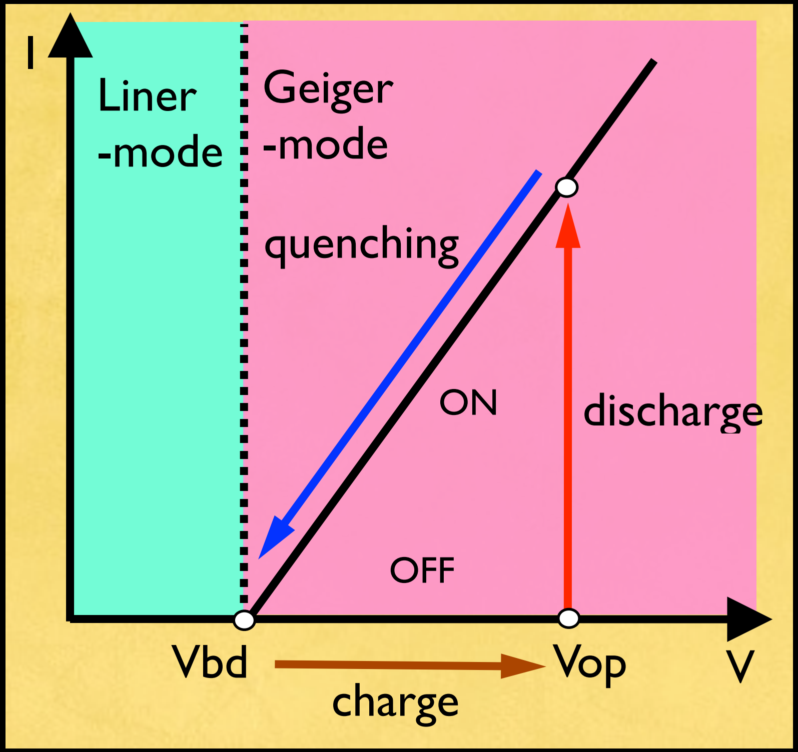


Counting Photons with Geiger-mode APDs

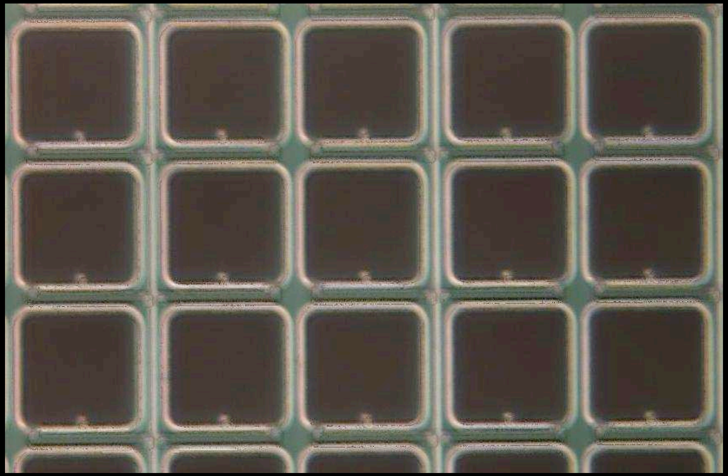
20-100μm (typ.)



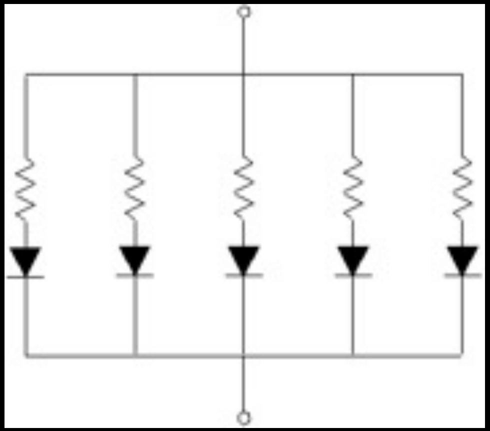
- Divide APD into *many small pixels*.
  - Each pixel works independently in Geiger mode.
- Incident photon 'fires' an APD pixel *but not others*
  - Output charge from one pixel: $Q=C_{pixel} \cdot (V_{op}-V_{bd})$
  - C_{pixel}~10-100fF and $\Delta V \equiv V_{op}-V_{bd}$~1-2V gives Q~10^5-10^6e



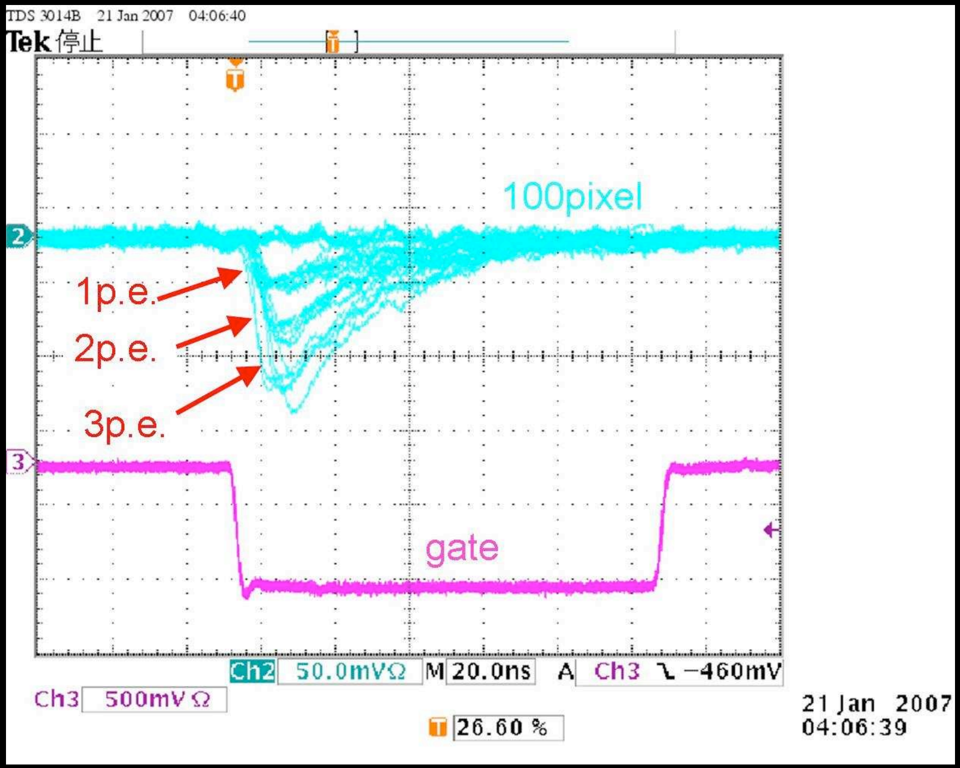
Operation of Multi-pixel Geiger-mode APDs

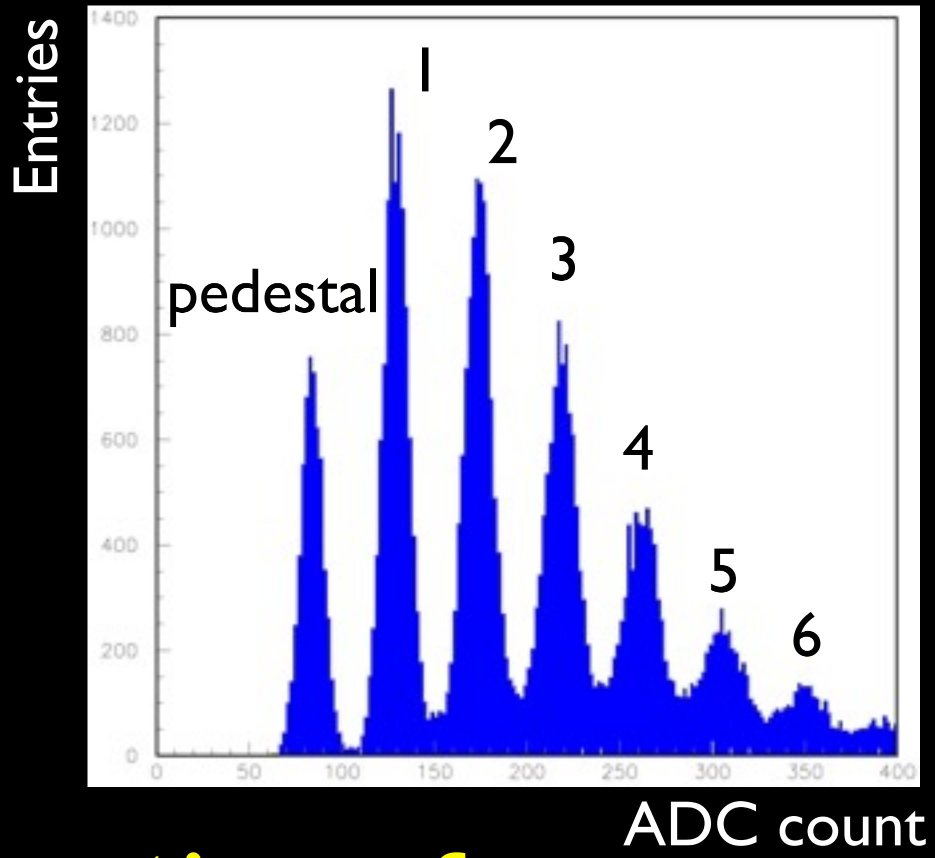


- All the pixels are connected in parallel
  - Taking sum of all pixels, one can know how many pixels are fired $\propto$ how many photons are incident !



Output from Multi-pixel Geiger-mode APD

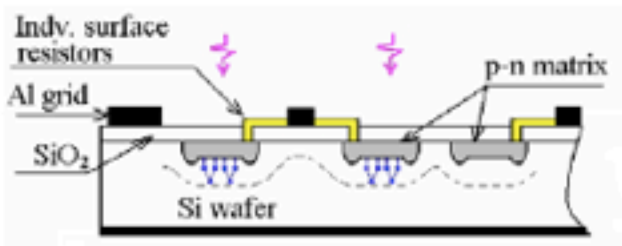


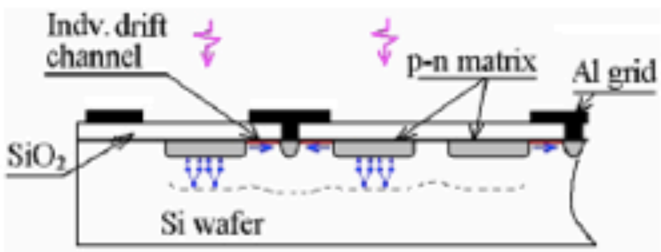


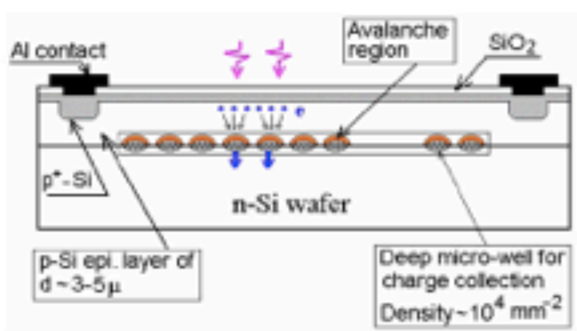
Clear separation of 1,2,3... photoelectron (p.e.) peaks!

[@ room temperature]

Types of G-APDs







- CPTA/Photonique (Moscow and Geneva)
- MEPhI/Pulsar (Moscow, Russia)
- Amplification Technologies (Orlando, USA)
- Hamamatsu Photonics (Hamamatsu, Japan)
- SensL (Cork, Ireland)
- RMD (Boston, USA)
- MPI Semiconductor Lab. (Munich, Germany)
- FBK-irst (Trento, Italy)
- ST-Microelectronics (Catania, Italy)
- ……

- Z. Sadygov (JINR, Dubna, Russia)

- Zecotek (Singapore)

D.Renker, PD09

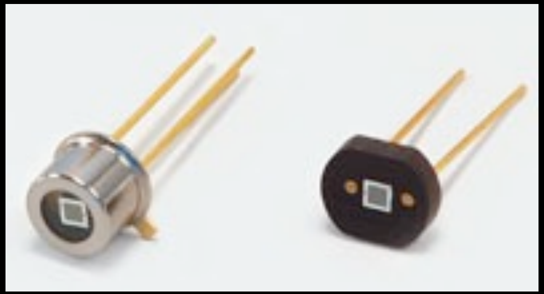
Comparison of photo-sensors

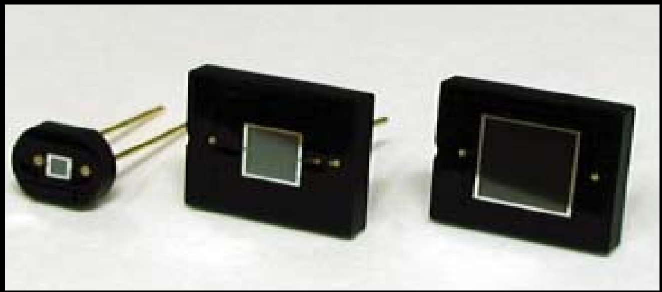
	PMT	APD	`SiPM'
Gain	10^6-10^7	~100	10^5-10^6
Operation voltage(V)	1-2k	300-500	<100
Active area	~>100cm^2	~10mm^2	~1mm^2
Dark count (Hz)	<1k		0.1-1M
Photon detection efficiency (blue-green)	20-30%	75-80%	20-50%
Magnetic field	x	o	o tested to 7T

Example:
Hamamatsu MPPC

MPPC by Hamamatsu

- Structure based on CMS-APD
  - n+-substrate
    - Lower noise
    - Sensitivity to short wavelength
- Currently on catalogue:
  - 1x1/3x3 mm^2 active area
  - 25/50/200 μm pixel pitch
  - Metal/ceramic package or surface mounted





MPPC lineup

Pixel size: 25/50/100μm

Catalogue spec

Electrical and optical characteristics (Typ. Ta=25 °C, unless otherwise noted)

Parameter	Symbol	S10362-11			Unit
		-025U, -025C, -025P	-050U, -050C, -050P	-100U, -100C, -100P	
Fill factor [*1]	-	30.8	61.5	78.5	%
Spectral response range	λ	320 to 900			nm
Peak sensitivity wavelength	λp	440			nm
Photon detection efficiency [*2] (λ=λp)	PDE	25	50	65	%
Operating voltage range	-	70 ± 10 [*3]			V
Dark count [*4]	-	300	400	600	kcps
Dark count Max. [*4]	-	600	800	1000	kcps
Terminal capacitance	Ct	35			pF
Time resolution (FWHM) [*5]	-	200 to 300			ps
Temperature coefficient of reverse voltage	-	56			mV/°C
Gain	M	2.75×10^5	7.5×10^5	2.4×10^6	-

Parameters and performance

Basic response
(signal generation)

Gain

$$Q=\sum C(V-V_{bd}).$$

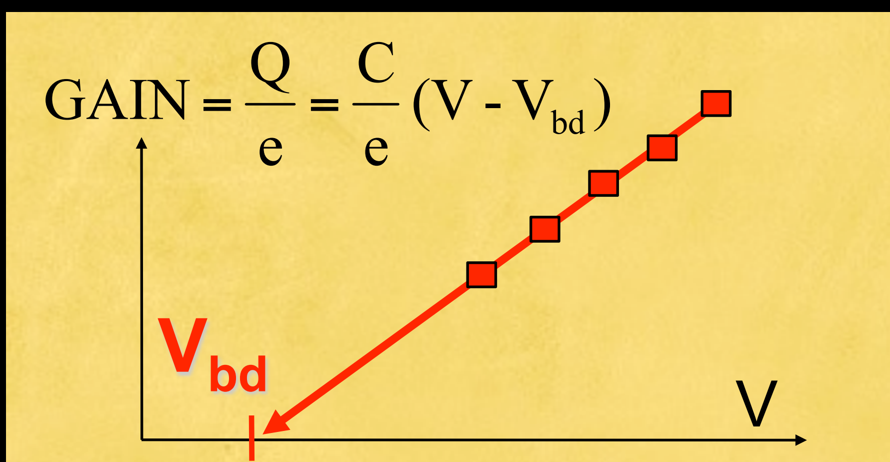
- C: capacitance of one pixel
- V: applied voltage
- V_{bd}: breakdown voltage.
  - V-Vbd called 'overvoltage (ΔV)'.
- Gain $\equiv$ Q/e : 10^5-10^7.
  simple or no amplifier required.

High gain

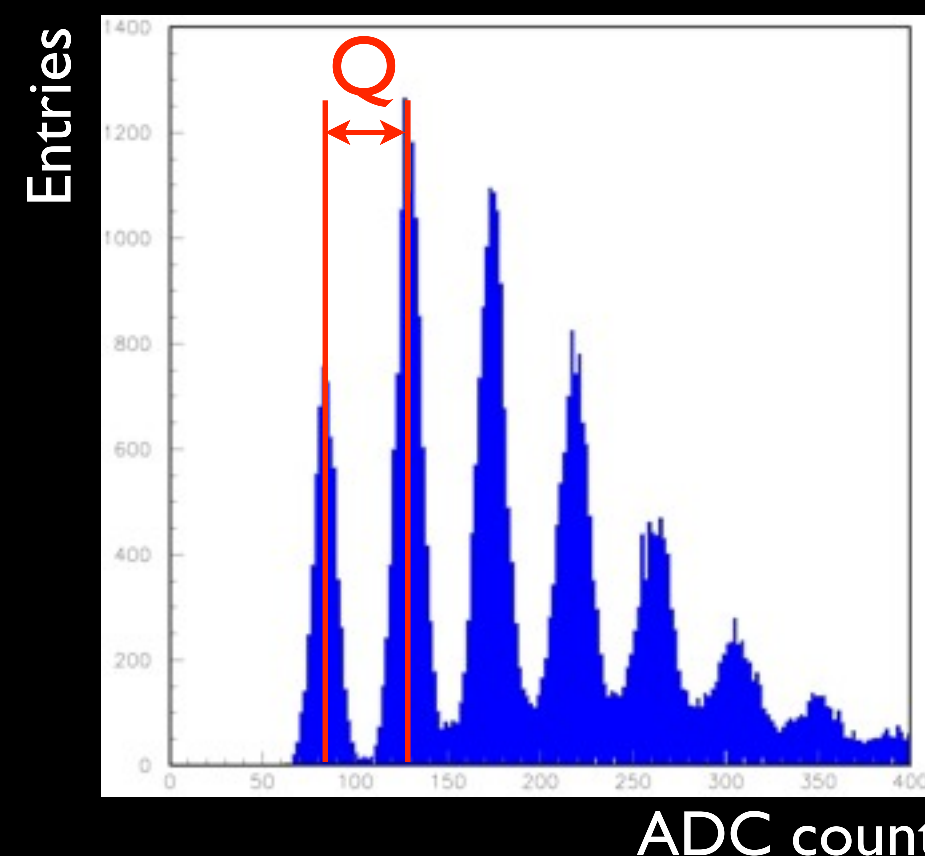
- Large amplification in thin layer
  - No nuclear counter effect.
    - Charged particle produces just 1pe equivalent charge.
  - No avalanche fluctuation.
    - Small excess noise factor (in principle, see later discussion) in contrast to APD.

Gain&V_{bd}: most basic parameters

- Gain of MPPC can be measured with well-separated p.e. peaks: Gain=Q/e

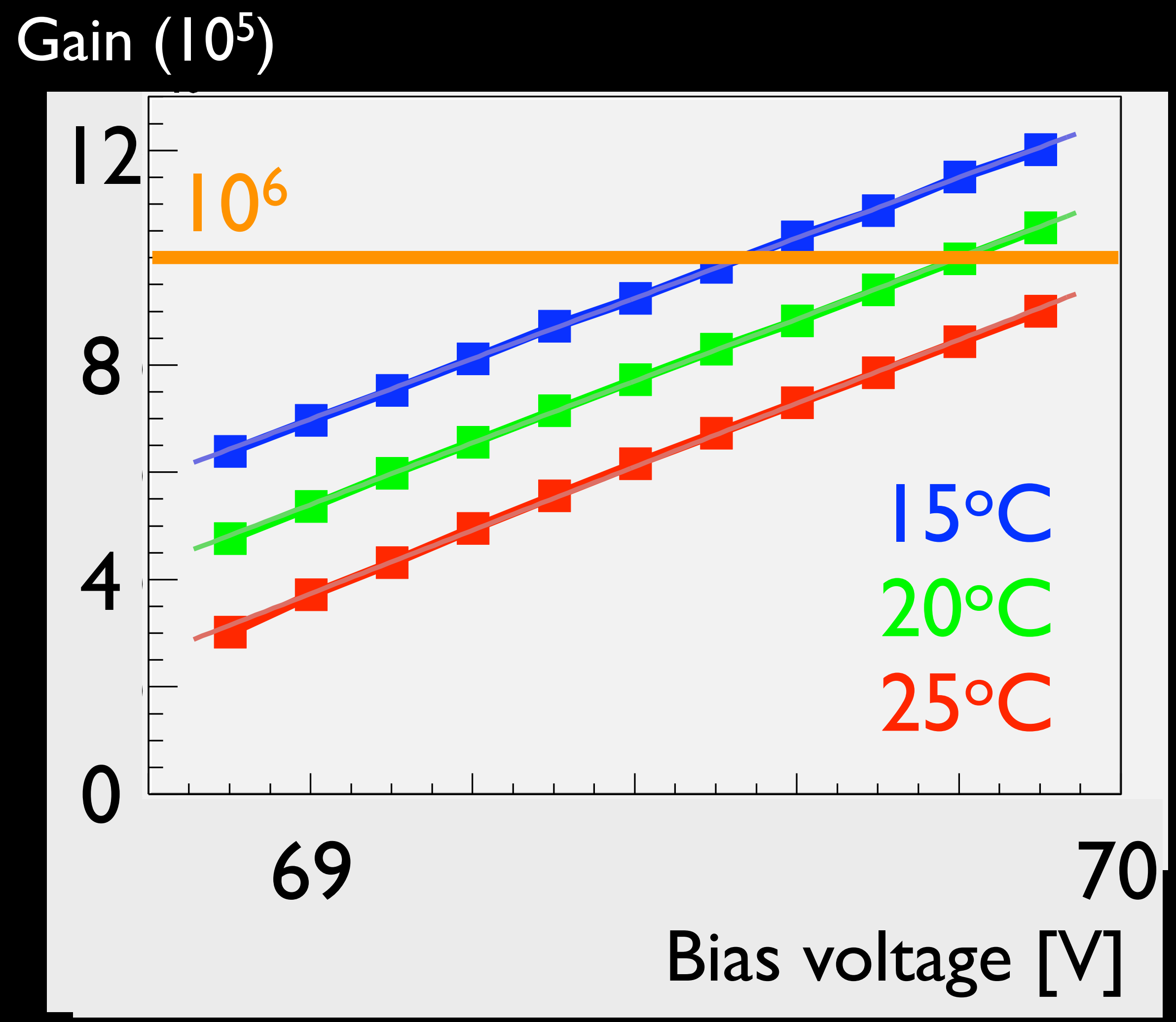


- Using linear relation, breakdown voltage (V_{bd}) also derived

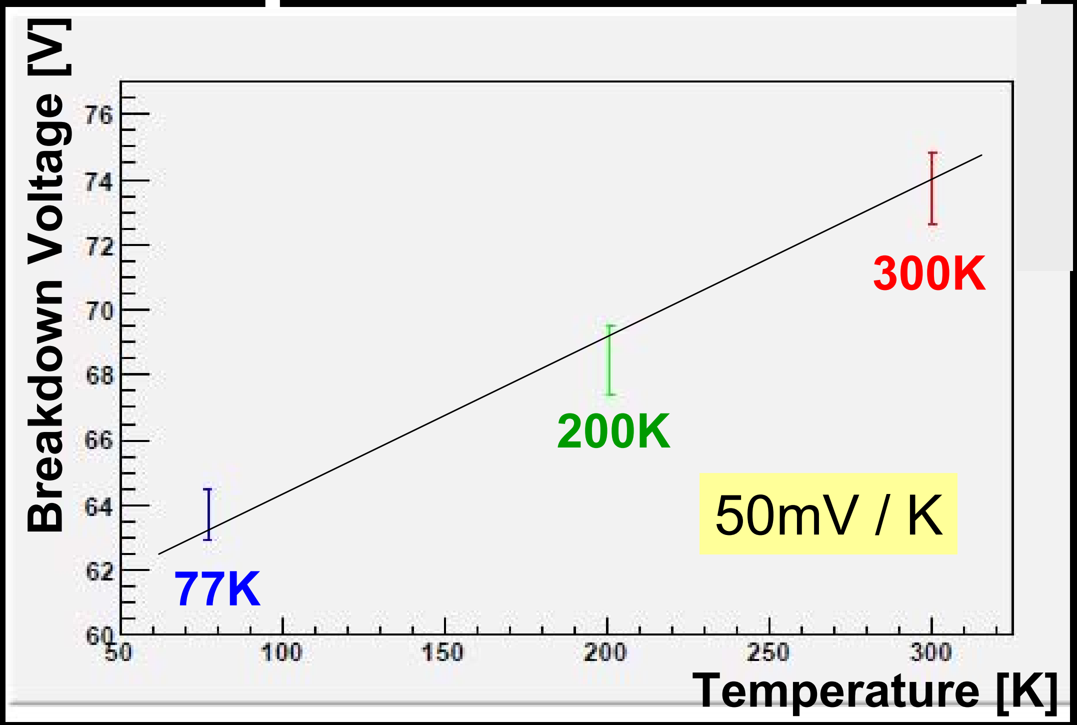


Measured gain

- MPPC has >>10^5 gain at room temperature, with V<<100V.
- Gain is (linearly) dependent on ΔV.
  - dM/dV~X%.



Temperature dependence



H. Otono @PD07

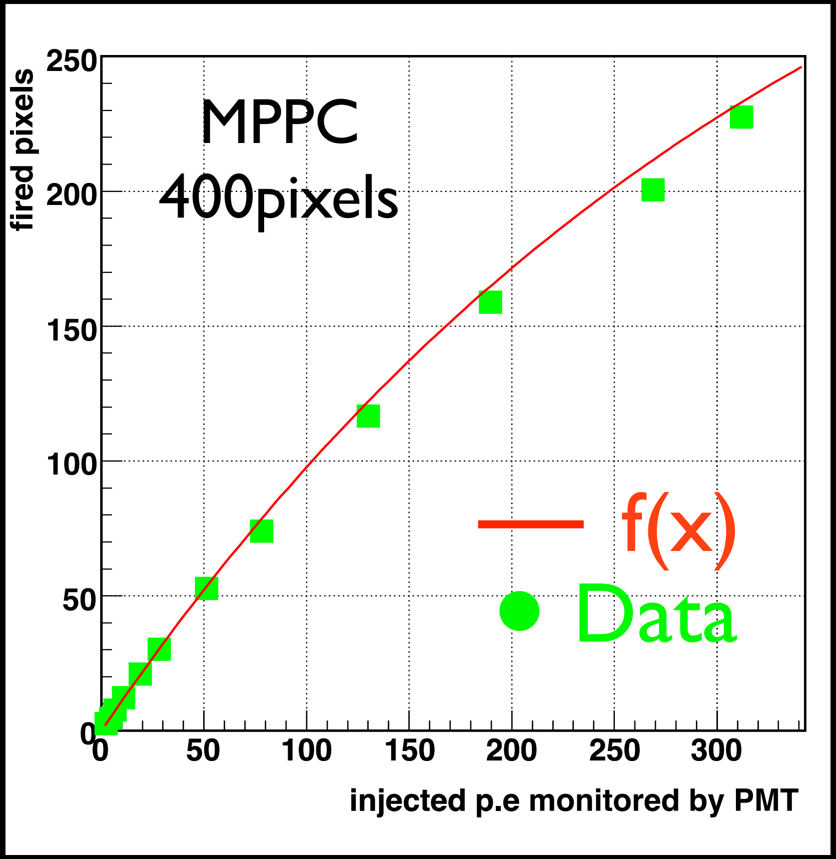
1600 pixel

(Also many measurements around room temperature)

- Many parameters of MPPC are known to depend on 'over-voltage' $\Delta V \equiv V - V_{bd}$
- V_{bd} linearly depends on temperature dVbd/dT~-50mV/K

Linearity / saturation

- If more than one photon enter the same pixel, it gives only signal equal to that of one photon.
- The output signal is proportional to the number of *fired* pixel, when the number of incident photon is small.



$$f(x)=N_{pix}\times[1-\exp(N_{inc}\cdot PDE(1+c)/N_{pix})]$$

c: cross-talk and afterpulse

Photon detection efficiency (PDE)

- PDE consists of three factors:
  - Geometrical factor (fill factor): ε_{geom}

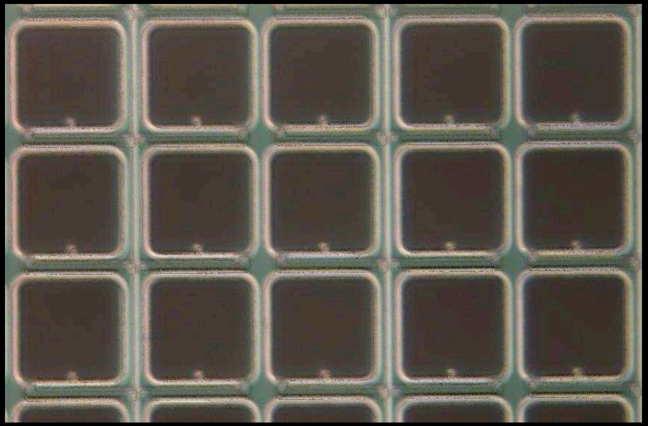
    ➡Determined by design
  - Quantum efficiency : QE

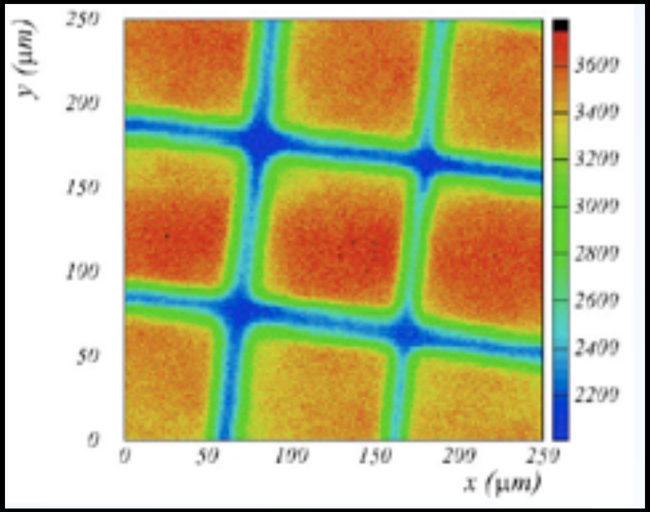
    ➡Dependent on wavelength
  - Avalanche trigger probability : ε_{trig}

    ➡Dependent on overvoltage

Geometric fill factor

- Determined by the design
  - Need some space for isolation, resistors, ...
  - Smaller pixel means less active region
- 30.8/61.5/78.5 % for 25/50/100μm MPPC

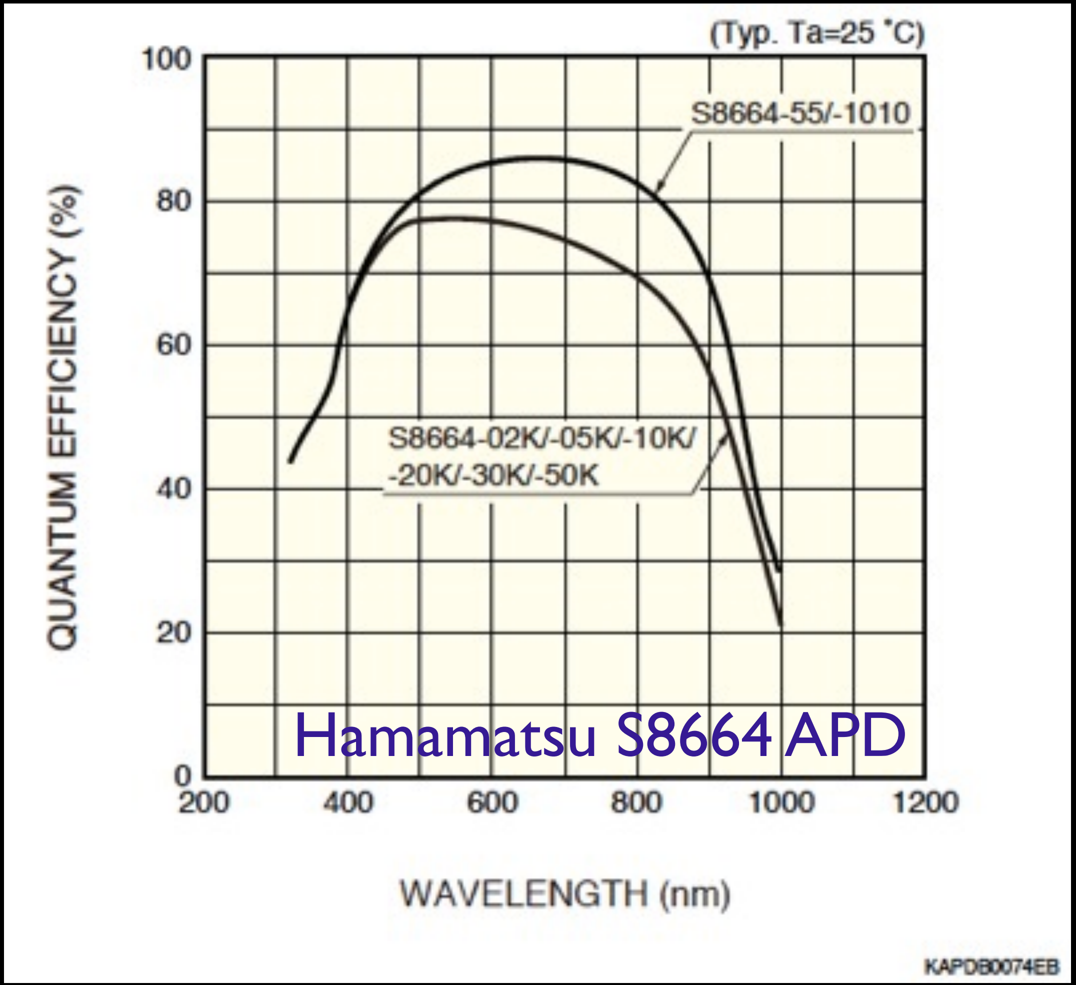




S.Korpar, PD09

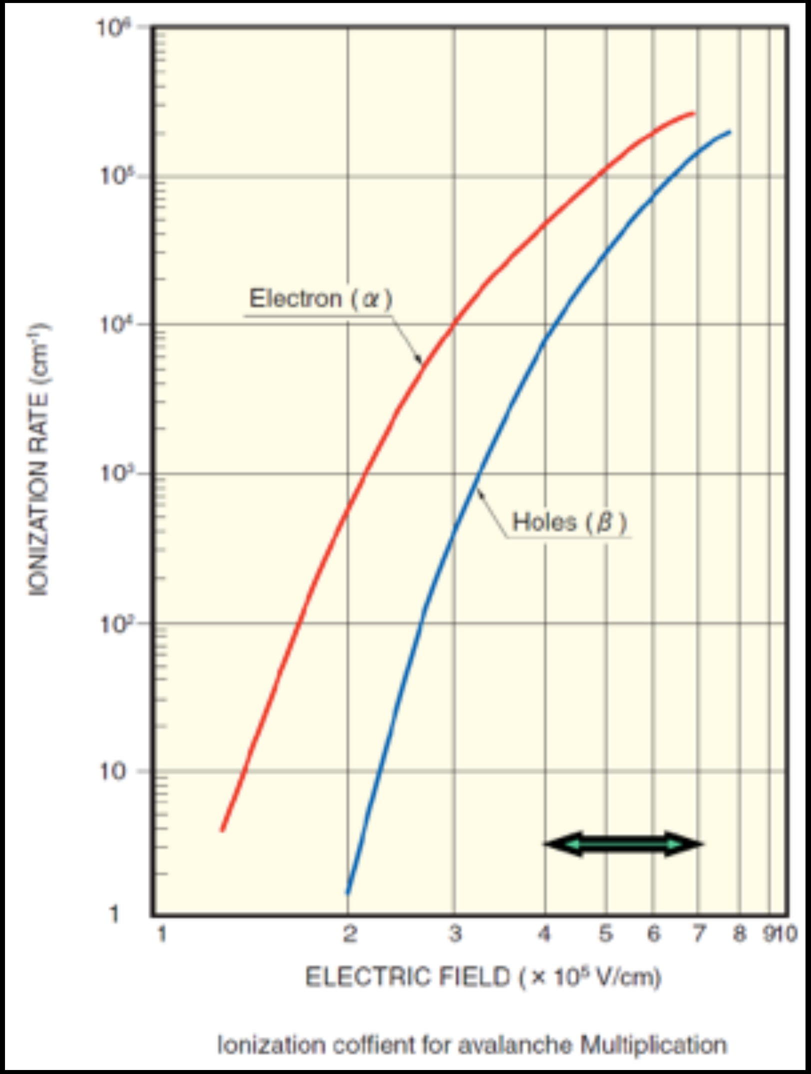
QE

- QE for APD can be as high as 80-90%.

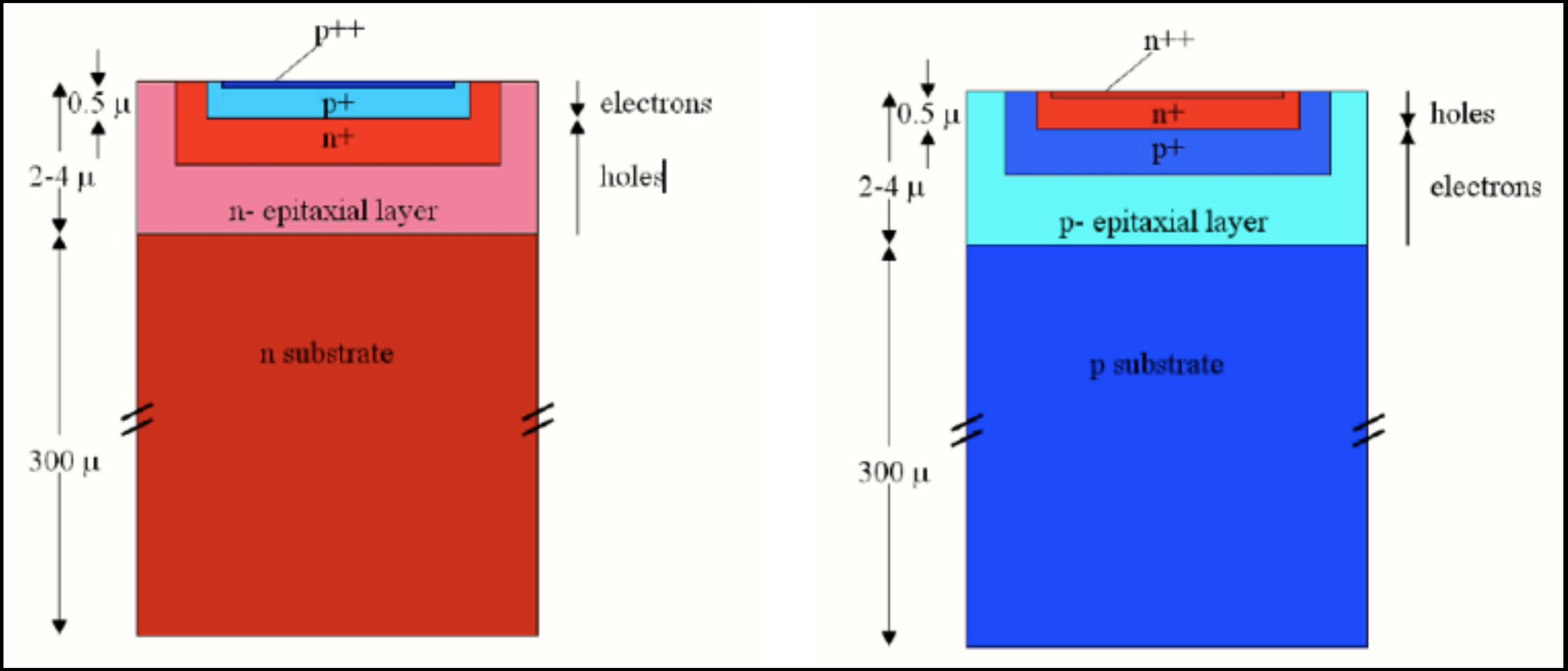


Trigger probability

- ε_{trig} depends on the position where carrier is created.
- Electron has better probability to trigger a breakdown.
- Photon converted in p-layer has larger ε_{trig}.
- Wavelength dependence determined by structure.



Structure



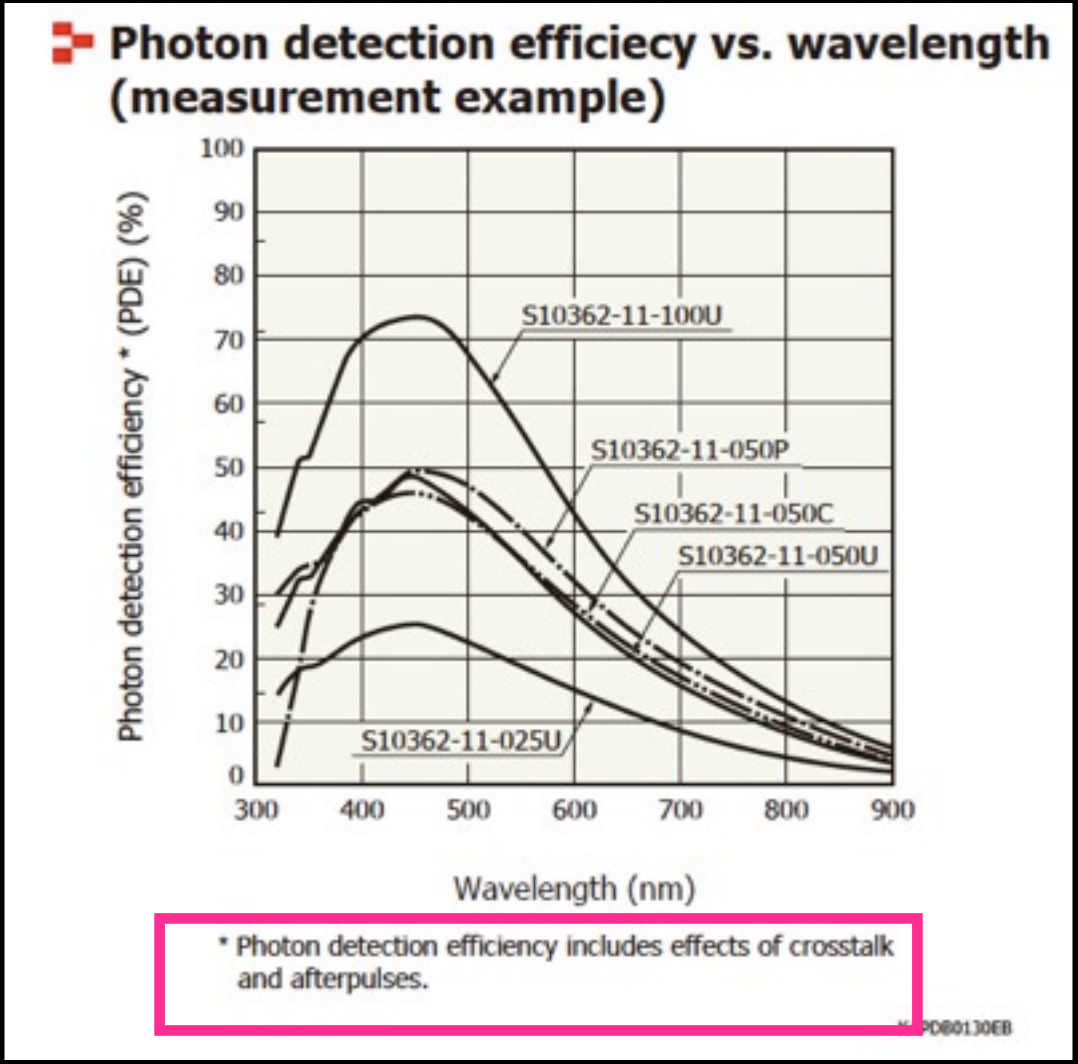
p-on-n

Shallow p region
⇒ blue sensitive

n-on-p

deep p region
⇒ red sensitive

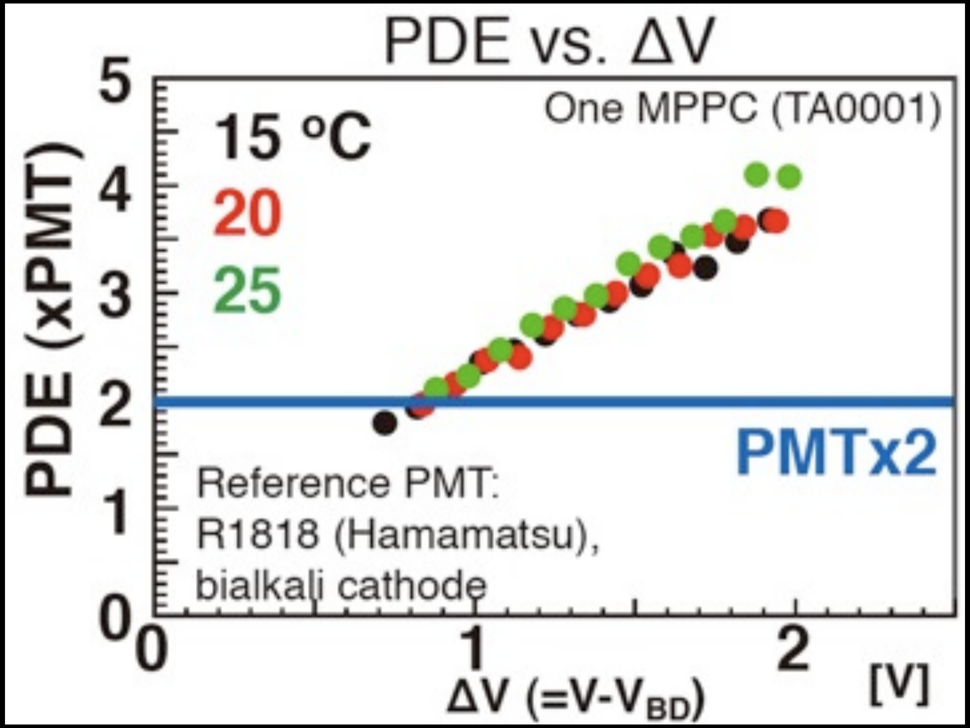
PDE from MPPC catalogue



Includes crosstalk & afterpulse
(20-30% overestimate)

PDE

- Avalanche triggering probability ε_{trig} has large dependence on ΔV.
- It makes the overall PDE dependent on ΔV.
- Large ΔV gives better PDE, but limitation due to dark count, cross-talk, afterpulse (discussed later).



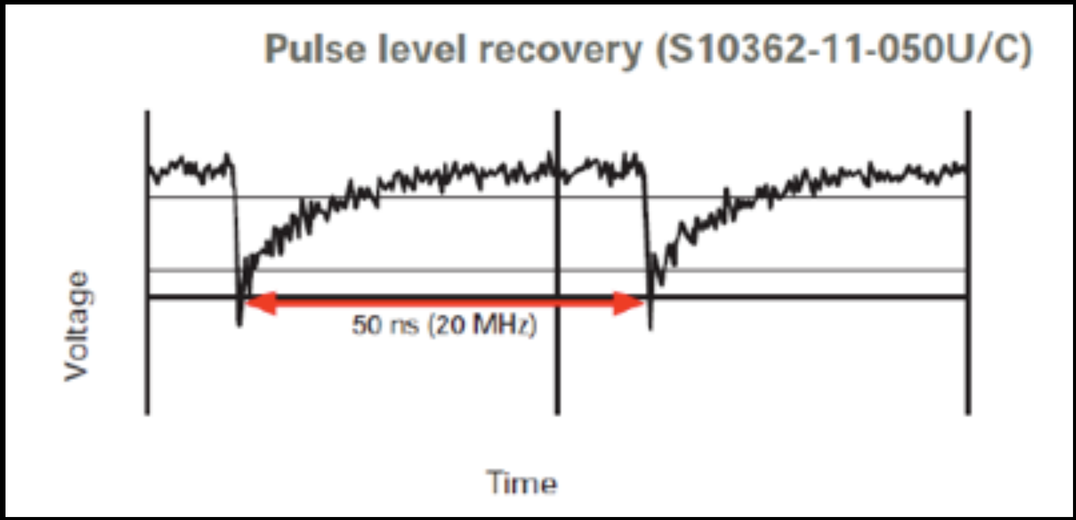
MY, NDIP08

Pixel size: consideration

- Larger pixel gives better PDE. (fixed area of dead region)
    - Total area limited by dark count rate
      → number of pixel smaller
      → saturation against large number of photons.
- Tradeoff b/w PDE and linearity.

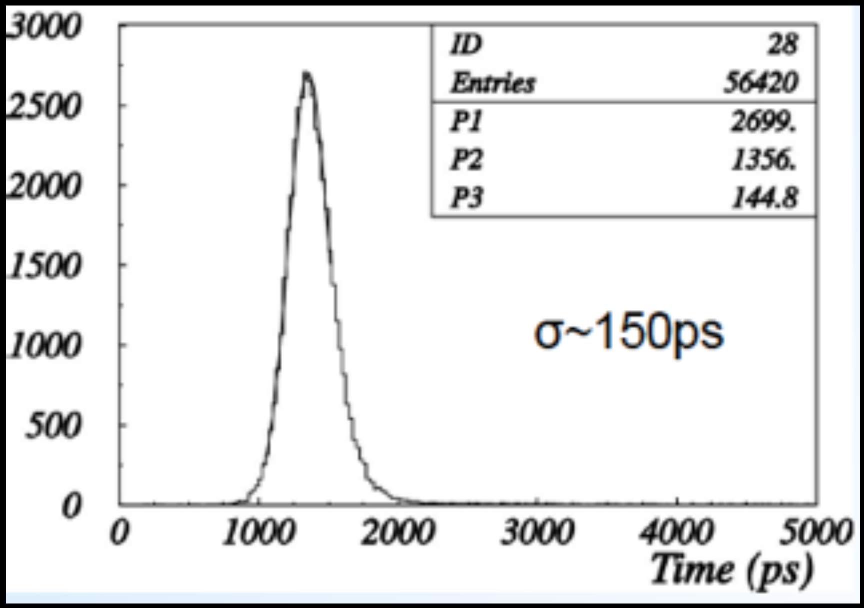
Pulse shape and recovery

- Signal 'rise time' usually very fast (~a few ns).
- Fall time / pixel recovery time determined by recharging through RC.
  - Larger pixel size = large C, longer recovery



Timing resolution

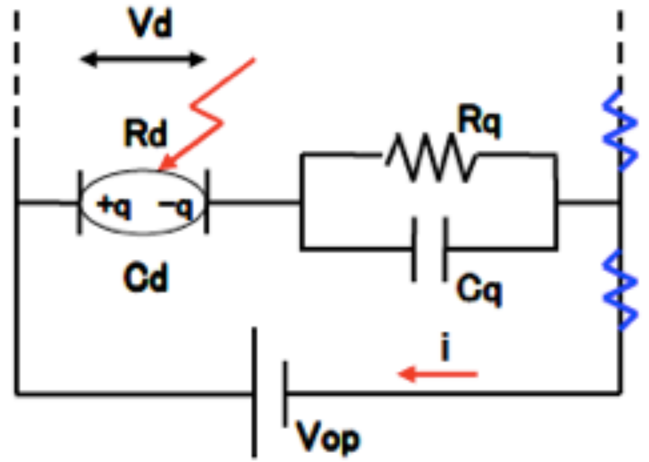
- Fast breakdown process in thin (a few μm) multiplication layer.
  - Timing resolution expected to be very good even with single photon.



S.Korpar, PD09

For improvement of timing resolution

< Equivalent circuit of MPPC by Otono et al.>



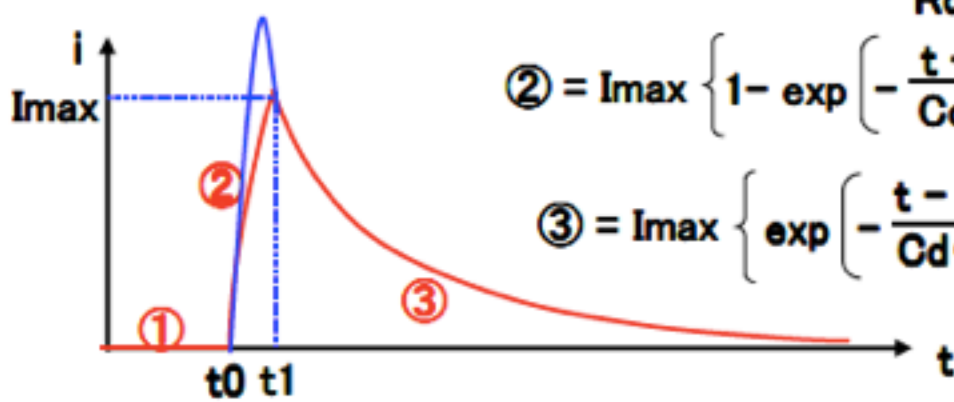
Rq >> Rd

■ Suppose Vd down to Vbr

$$I_{max} = \frac{V_{op} - V_{br}}{R_q}$$

$$② = I_{max}\left\{1 - \exp\left(-\frac{t - t_0}{C_d \cdot R_d}\right)\right\}$$

$$③ = I_{max}\left\{\exp\left(-\frac{t - t_1}{C_d \cdot R_q}\right)\right\}$$



■ Add Cq effect, pulse height is larger as spike shape

Actual device has trace resistance (Rtr)

For good timing resolution,

< Each pixel >

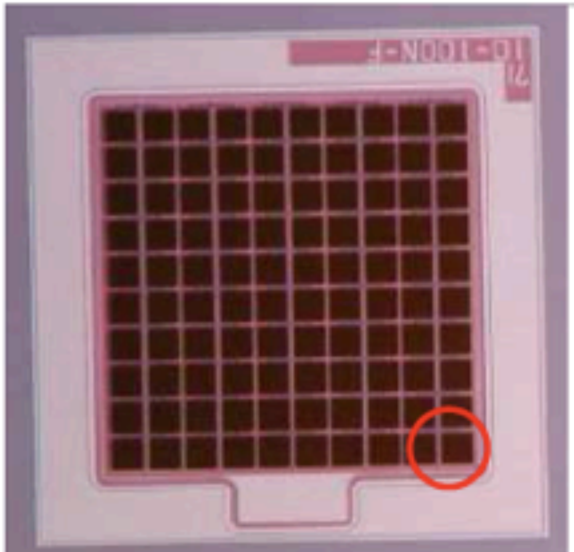
1) Better to large Imax
   ΔV (Vop-Vbr) ⇒ larger
2) Better to small rise time
   Cd ⇒ smaller
3) Better to large Cq effect

< Whole pixels >

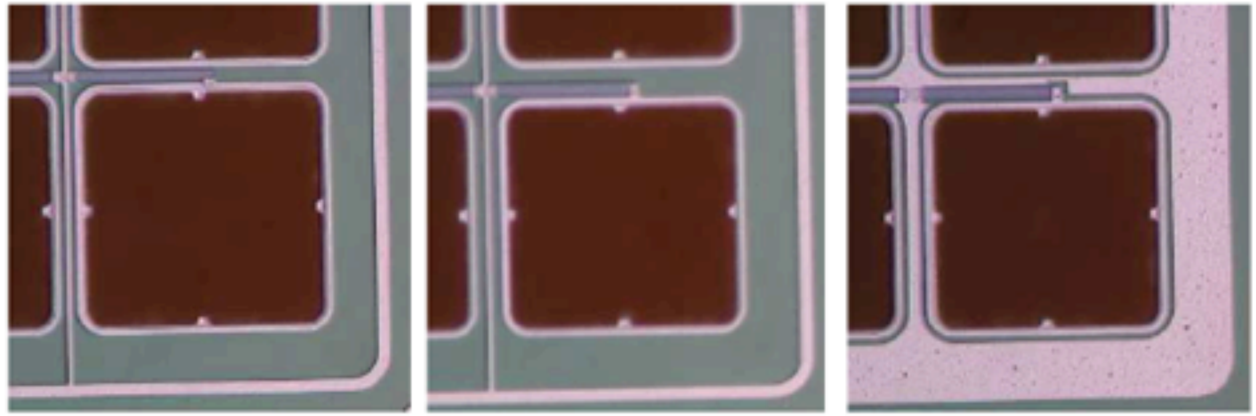
1) Better to small and uniform Rtr
2) Pixel characteristic(GAIN, Rq,Cq,Rd,Cd,・・・) should be uniform

PD09 International Workshop on new photon-detectors

100um pitch Samples



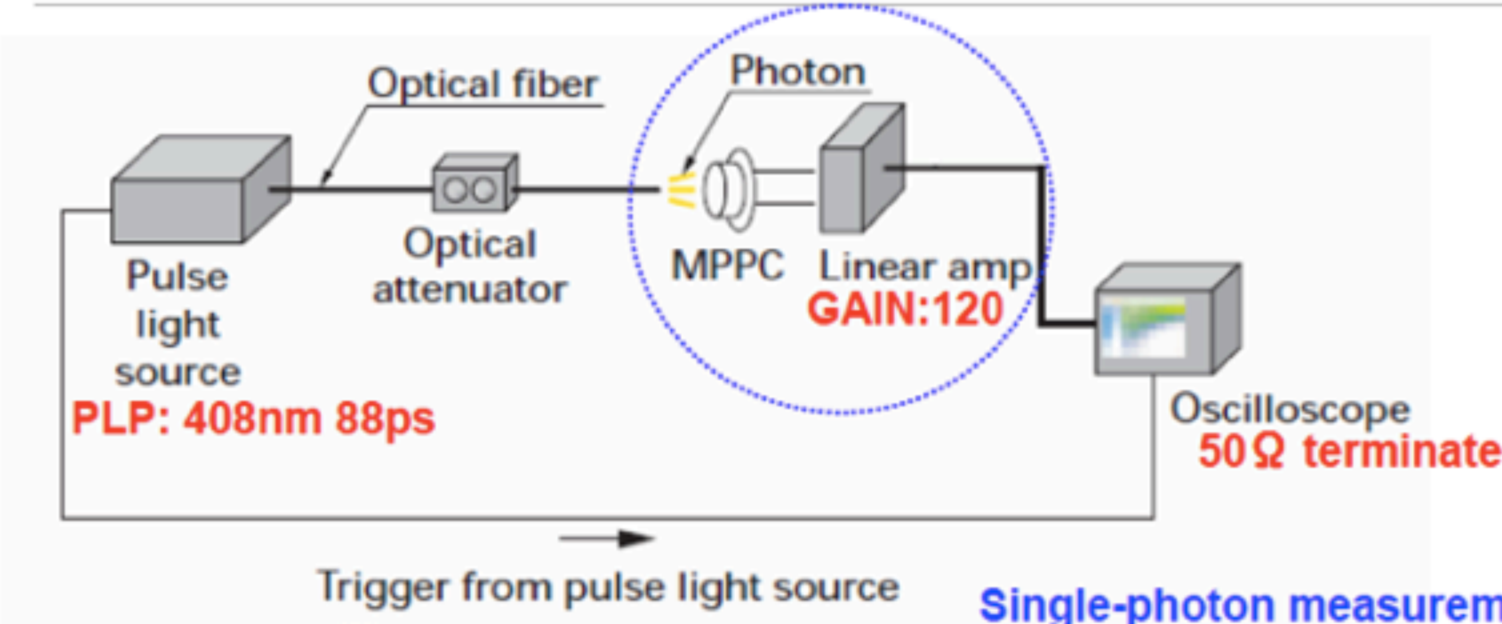
Quenching resistance = 115KΩ by forward IV curve

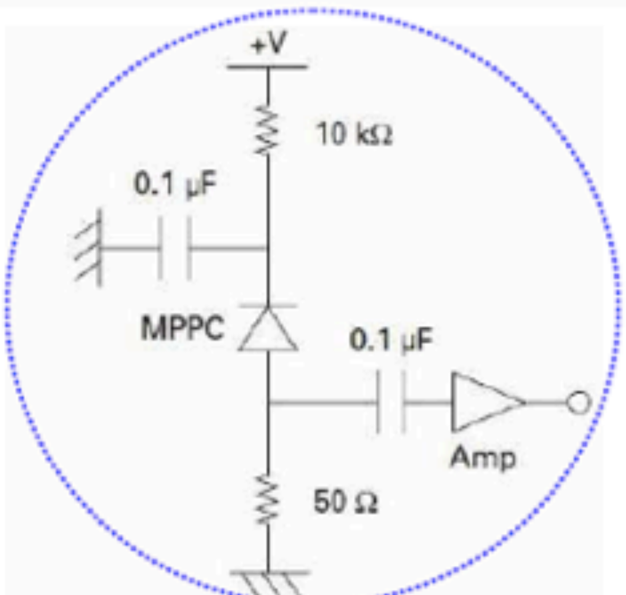


Sample name	10-100N-F (STD)	10-100S-F (Small pixel)	10-100S-FS (Wide trace)
Fill factor	78 %	72 %	72 %
ΔV(Vop−Vbr) #1	1.02 V	1.18 V	1.18 V
Dark count at Vop	1075 Kcps	1089 Kcps	1243 Kcps
Pixel capacitance (Cd) #2	373 fF	323 fF	325 fF
Stray capacitance / pixel #3	17 fF	37 fF	61 fF
PDE at Vop , 440nm	79.7 %	76.2 %	77.6 %

#1 : Vop is at 2.4E06 #2 : by GAIN vs VR curve #3 : Ctotal / 100 – Cd at 25℃

Measurement setup for timing resolution





Single-photon measurement : with Amp.

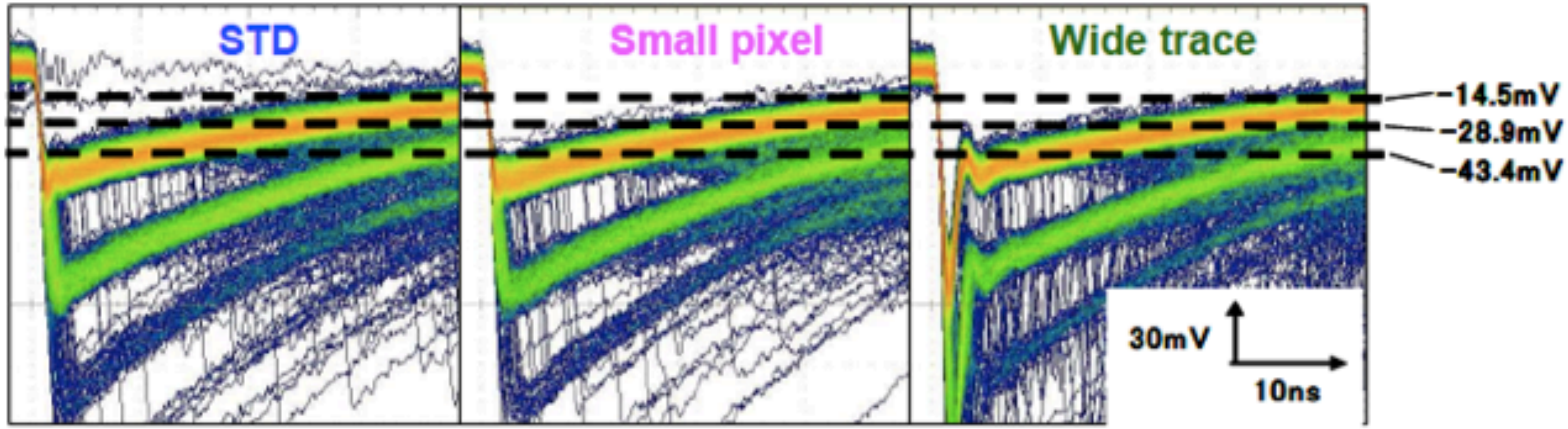
Multi-photon measurement : without Amp and bias resistance change to 1KΩ.

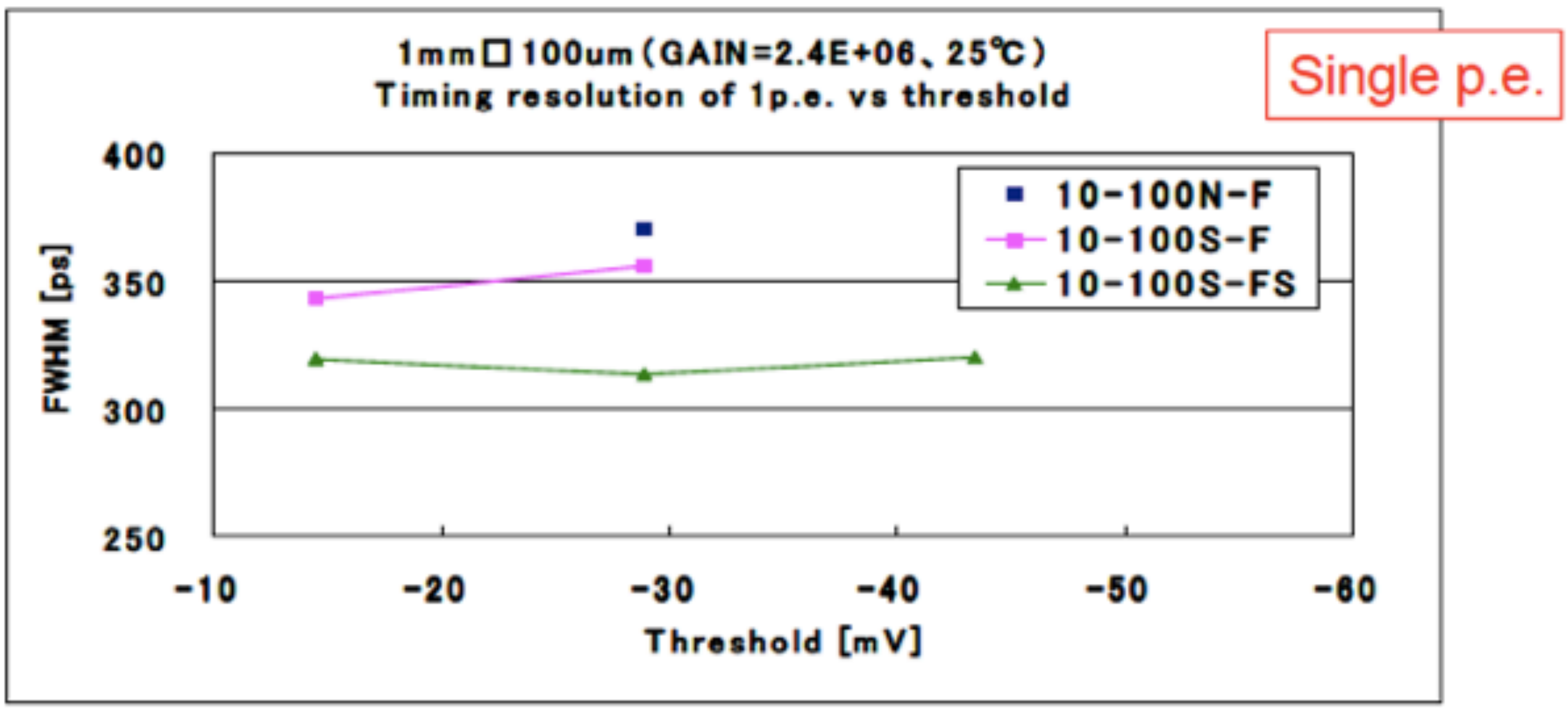
1) Measure the time when pulse height is setting threshold level

2) Repeat 10K time and plot histogram

3) Gaussian fit and get timing resolution

Timing resolution of 100um pitch MPPCs





Summary and next

- Today's topics
  - Introduction
  - Signal generation: Gain, PDE, timing
- Tomorrow:
  - Dark noise, cross-talk, afterpulse
  - Radiation damage, device stability
  - Devices on the market