Vienna 18th February 2019

The Silicon Photo-Multiplier

Status and Perspectives

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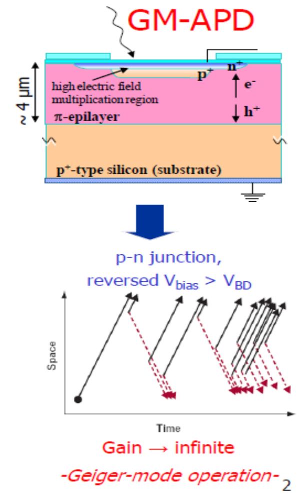
Overview

- Introduction to SiPM technologies
- Key features and performances → recent developments and trends
- Selected Applications

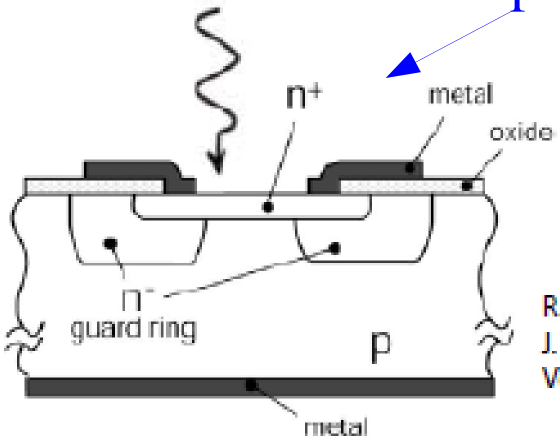
Single Photon Avalanche Diode (SPAD)



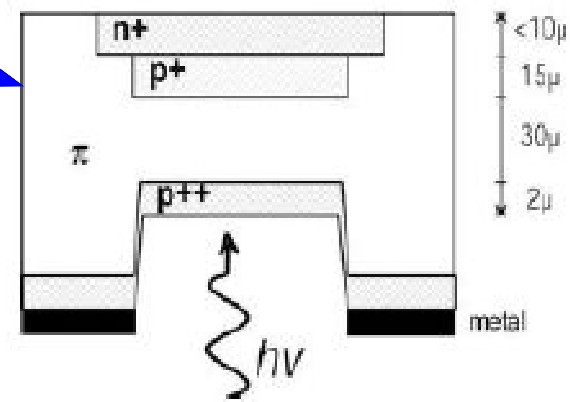
Various types of cell implementation

planar (shallow junction)

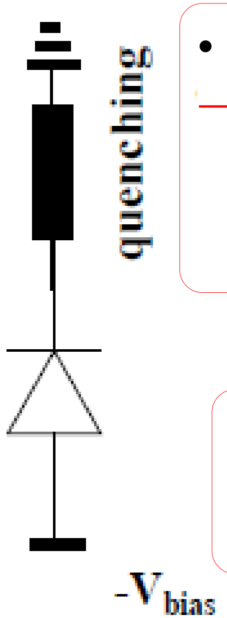
reach through



R.H. Haitz
J. Appl. Phys.,
Vol. 36, No. 10 (1965) 3123



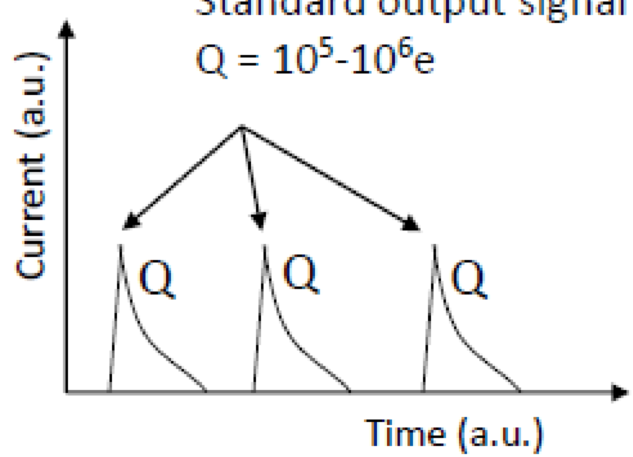
J.R. McIntire
IEEE Trans. Elec. Dev.
ED-13 (1966) 164



- Need **Quenching** and **Recharge**
  → various implementations
  - – Passive quenching: large resistance
  - – Active quenching: analog circuits

S. Cova & al., App. Opt. 35 (1996) 1956-1976

- Need **Arrays** for
  - Wide area
  - Multi-photon detection



Binary device

- If one or more simultaneous photons fire the GM-APD, the output is anytime a standard signal: $Q \sim C(V_{bias} - V_{BD})$
- GM-APD does not give information on the light intensity

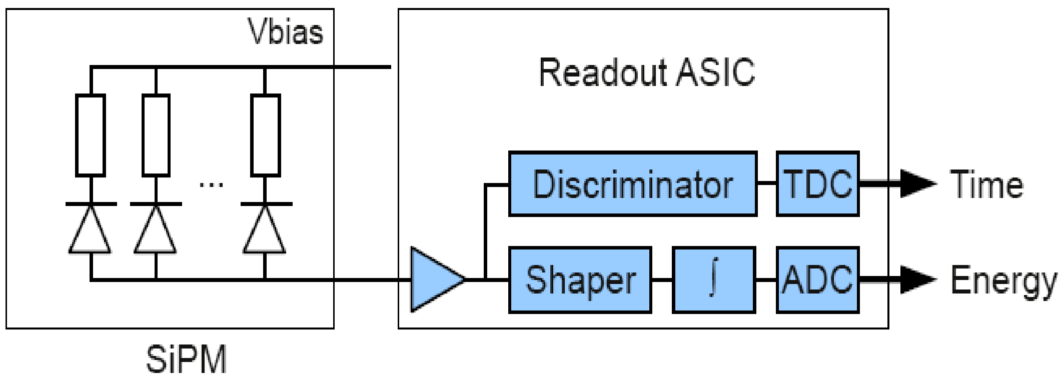
Arranging SPADs into packed matrices

Transition single SPAD → hundreds of GM-APD cells packed in arrays is not just design... need addressing new issues:

- Additional factor affecting the photo-detection efficiency (PDE):
  - the **fill factor** (FF) that for small cell size can be quite low
- How to control the **dark count rate** (DCR) because of
  - limited space for gettering techniques
  - high probability to include noisy cells in a device
- How to control the optical **cross-talk** (CT) among cells
- Production **yield** and **uniformity** affect performances
- Need choice of the **electronics** (integrated, external, hybrid, …)

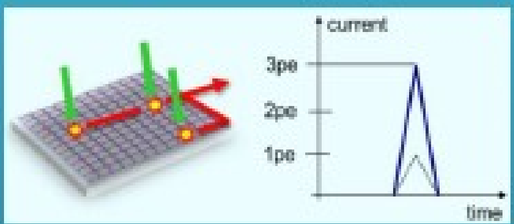
Analog and Digital SiPM

Analog Silicon Photomultiplier Detector

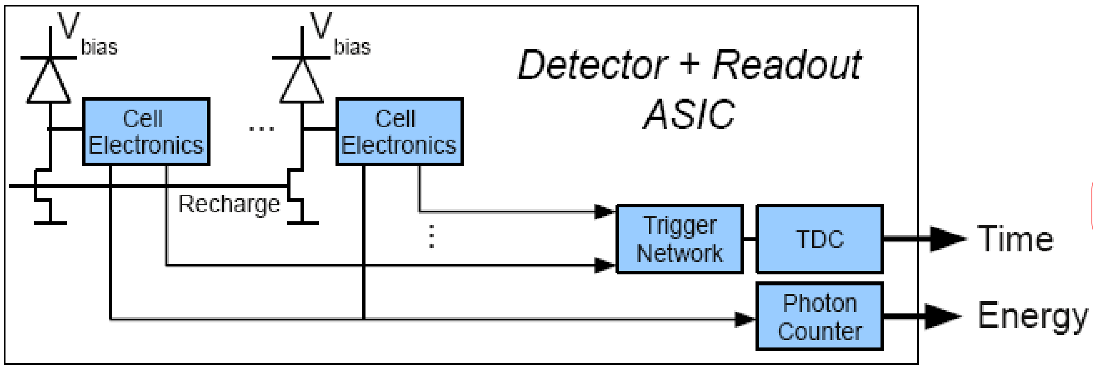


C.Pimonte - SENSE tech. forum 2018

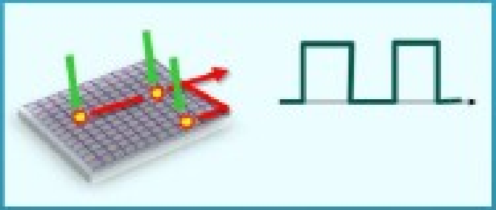
- SPADs are connected in parallel.
- Output analog signal is proportional to the number of photons.
- Custom technology (or CMOS).
- "Simple" technology, optimized SPAD performance.



Digital Silicon Photomultiplier Detector



- SPAD signal digitized at pixel level.
- Integrated digital architecture allows data processing on the sensor.
- CMOS technology.
- Optimized signal treatment, quenching/reset and processing.



d-SiPM:
- for each light pulse → output is: time-stamp and number of photons
- control of individual cells
- O(500ns) RO dead time (upon trigger)

SiPM development and production

Many institutes (R&D) and companies involved → competition...
prices still far (~x10) from asymptotic
production cost O(10€/cm²)

Courtesy of F.Acerbi and W.Ootani

• Single channel
Monolithic Devices
Surface → 1 cm²

• Multi-channel
Monolithic Arrays
Surface → several cm²

• Large choice in spectral sensitivity:
sensitivity from VUV to NIR

• Variety of commercial devices
• Easy customization

Some details about SiPM technology

- Micro-cells: **Custom** vs **CMOS**
- **Quenching** and **Reset** modes

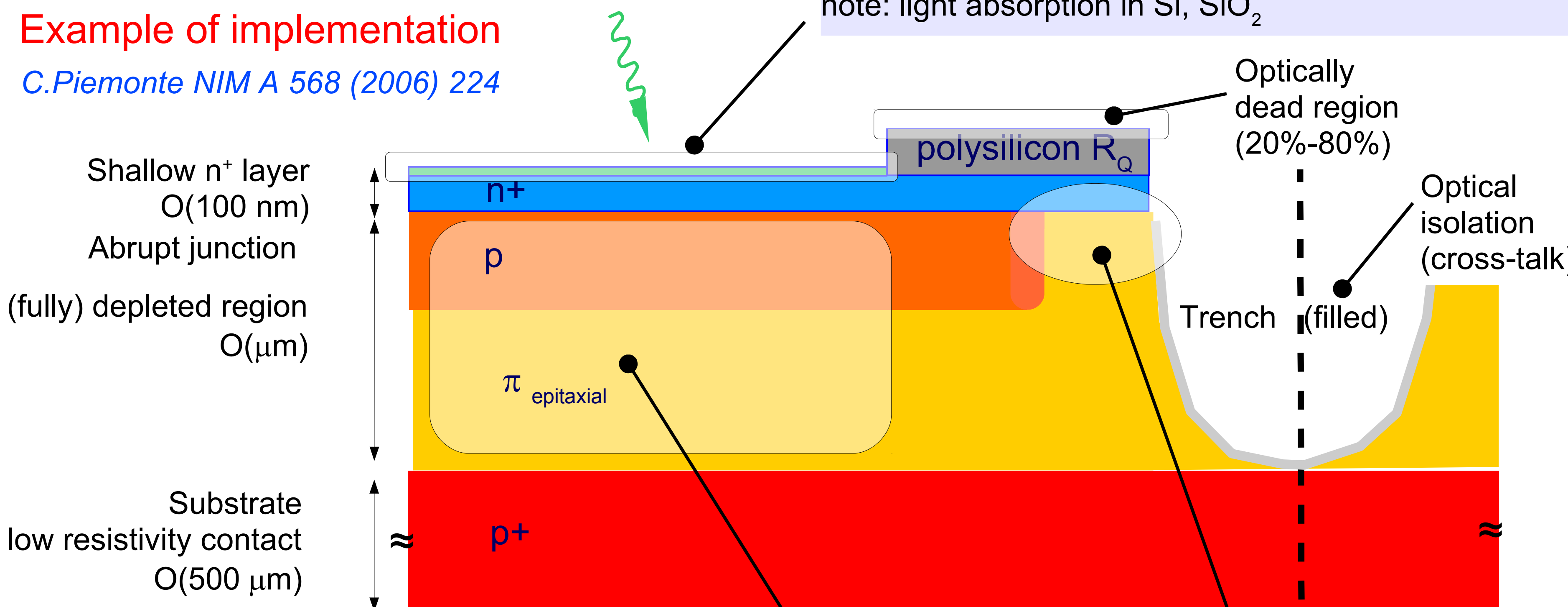
Close up of a cell – custom process

Shallow-Junction APD

Example of implementation

C.Piemonte NIM A 568 (2006) 224

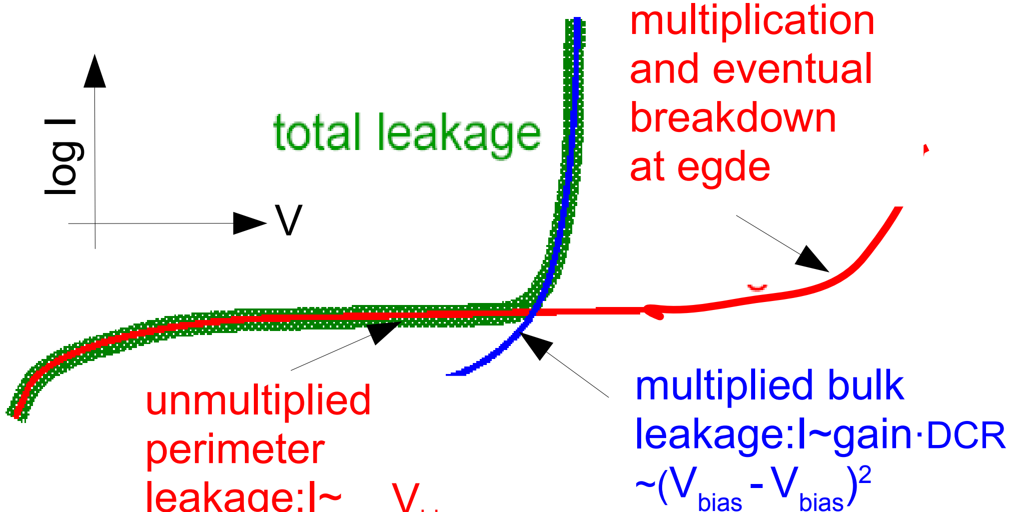
Optical window → Anti-Reflective Coating (ARC)
note: light absorption in Si, SiO_2



Active volume
- no micro-plasma's high quality epitaxial
- doping / E field profile engineering

Critical region
- Leakage current
- Surface charges
- **Guard Ring** for
  - preventing early edge-breakdown
  - isolating cells
  - tuning E field shape

→impact on Fill Factor



Close up of a cell - CMOS

Key elements for CMOS SiPMs
- **APD cell isolation** from CMOS circuitry
- **guard ring**
- **HV CMOS** extension against tunneling

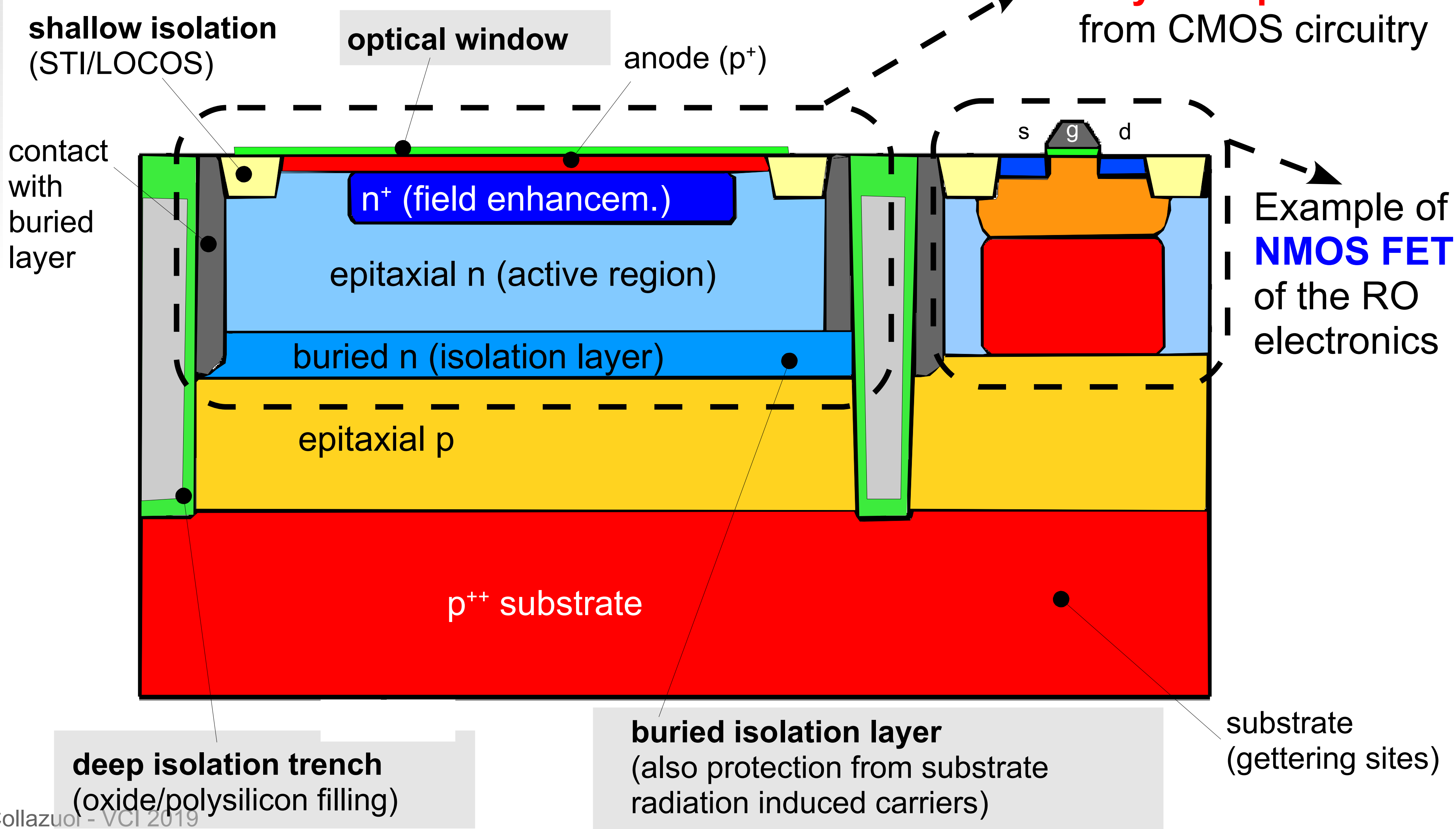
APD integration into CMOS

Example of implementation

from T.Frach - US patent 2010/0127314

Note
- extended CMOS processes exploited
- careful design of cell isolation and guard ring

APD cell isolated by multiple wells from CMOS circuitry



Silicon technologies for SPAD arrays

Custom technology

- possible both Planar and Reach Through
  → tune spectral sensitivity

- Control on shape of E field and cell insulation
  → high PDE
  → optimized timing resolution
  → low Dark Count Rate (DCR)
  → low After-Pulsing (AP)

- limited integration electronics
  (no libraries for complex functionalities
  and for deep-submicron features)
  → simple integrated electronics
  (few large MOS)
  → it limits array dimensions and fill factor

Ancillary electronics (quenching/readout):
→ completely external → **SiPM**
→ hybrid → **SPAD arrays**… complex fabrication

CMOS HV technology

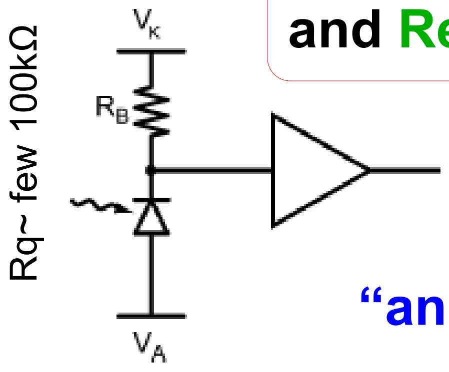
- only Planar structures
  → better UV/Blue sensitivity

- no optimization of shape of E field
  + high curvature sub-micron tech.
  → special care for guard ring (GR)
  (limited range of GR possible
  only STI demonstrated ok)

- fully supported sub-micron technology
  with models and libraries
  → electronics for quenching and readout
  → processing of large amount of data
  → high density → imaging
  → ultra-fast timing

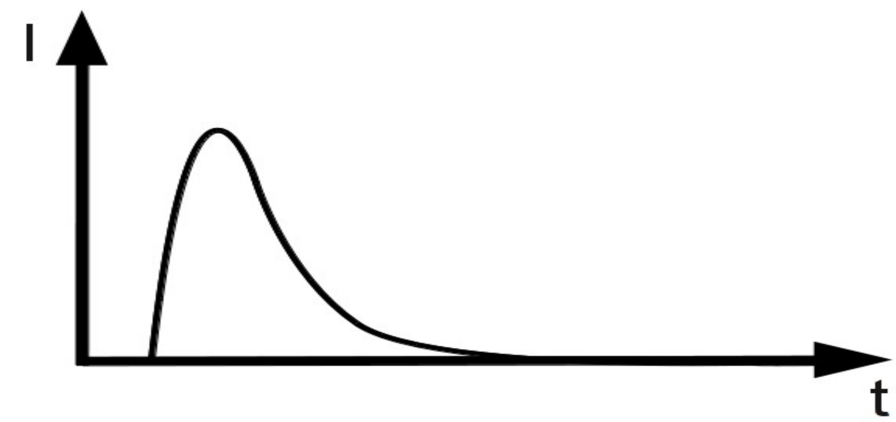
Ultrafast and/or **imaging**
monolithic SPAD arrays

Passive mode: resistor to **Quench & Recharge**



Passive Quenching and Reset

“analog” SiPM



- “Quenching resistor” regulates both **quenching** and **recharge**

- Simple concept but tricky to implement (high-ohmic resistors needed)

- Allows easy implementation of summation

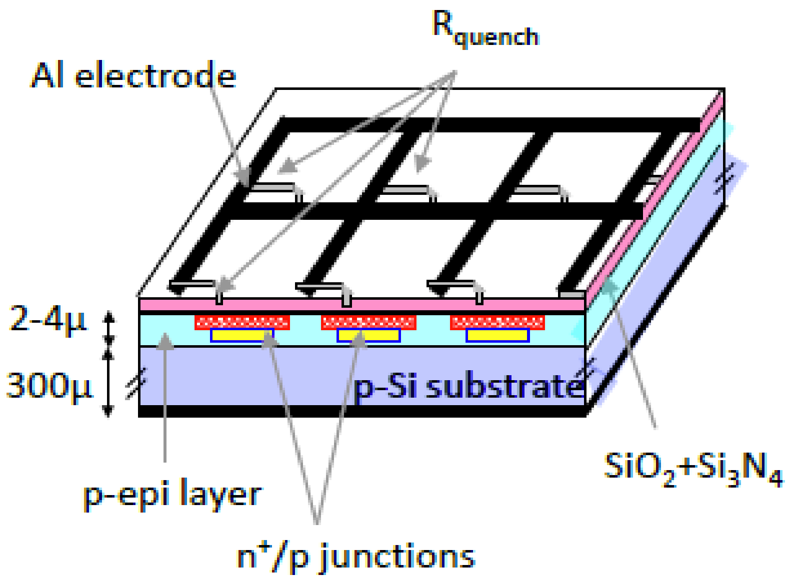
- **Constraints due to passive mode**: latch current level (20μA)
  → large charge developed before quenching
  → limited recharge current ($R_q \sim \Delta V/20\mu A$ for safe quenching → $I_r < 20\mu A$)
  (“long” recovery time: $\tau_r \sim Rq \times Cd$)

- Output signal compatible with that of PMTs → re-use of readout infrastructure

Array of passively decoupled GM-APD → "Analog" SiPM

Enormous progess in the last 15 years

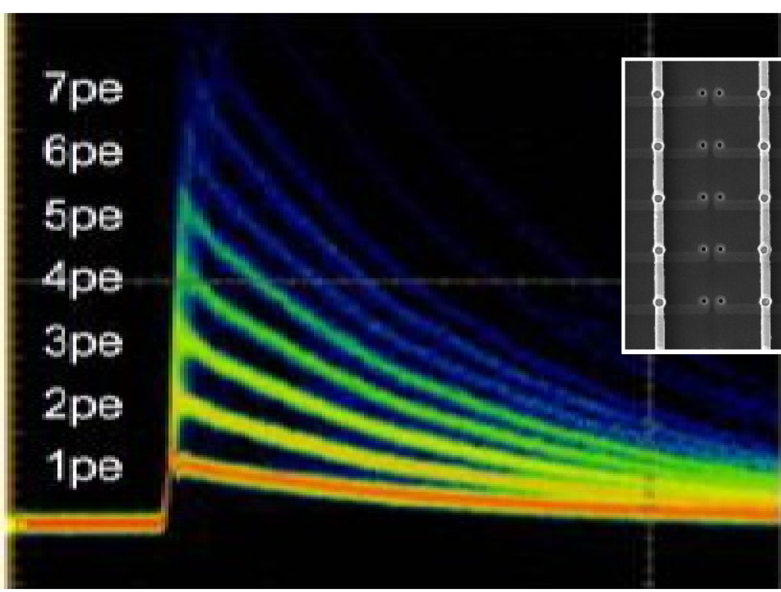
Single GM-APD gives **no information** on light intensity → use array of GM-APDs' first proposed in the late '80-ies by Golovin and Sadygov

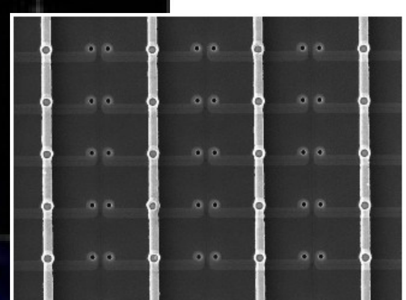


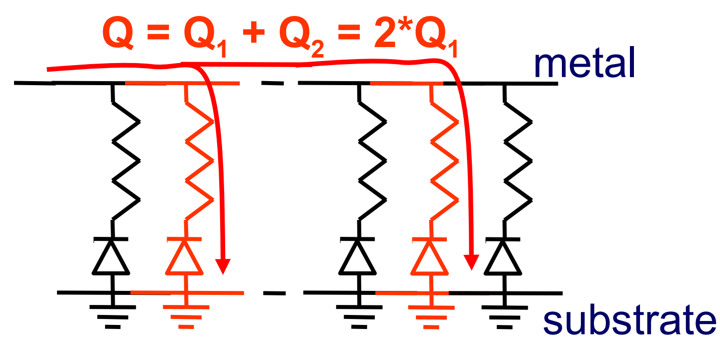
A SiPM is segmented in tiny GM-APD cells and connected in parallel trough a decoupling resistor, which is also used for quenching avalanches in the cells

Each element is independent and gives the same signal when fired by a photon

Σ of binary signals → analog signal







Output ∝ number incident photons

→ Linear response to multi-photon pulse

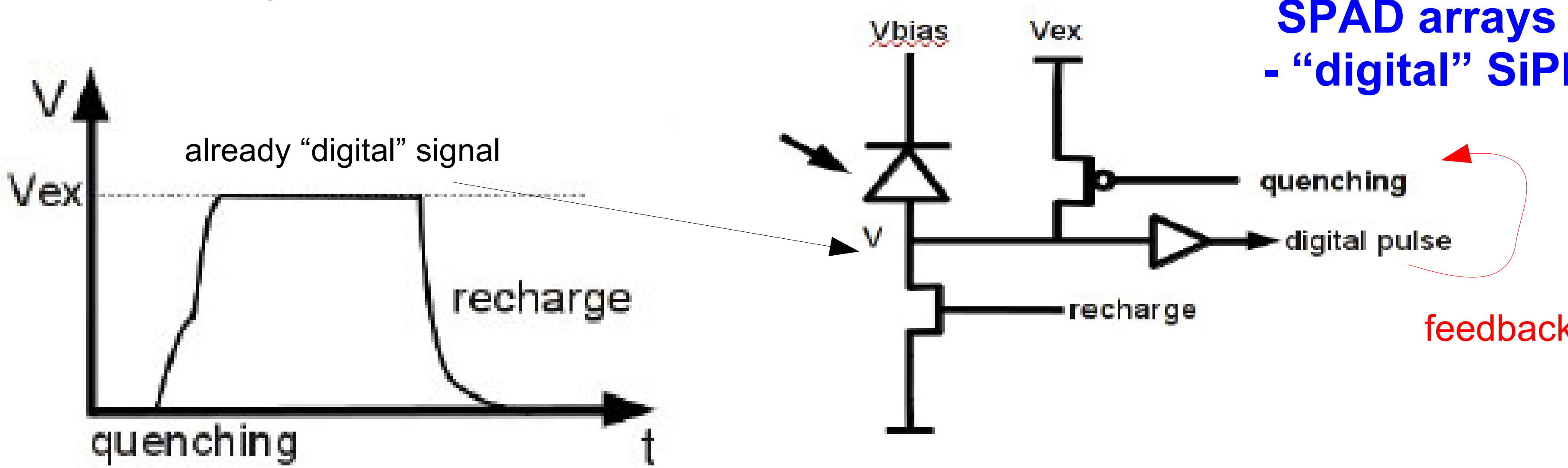
Active mode: transistors to **Quench** and **Reset**

- Sense the voltage at the diode terminal
- Use transistors to actively **discharge/recharge** the diode
  → controlled amount of charge → reduced after-pulsing and cross-talk
  → controlled (fast) recovery
- Flexibility: programmable timing possible, disabling of faulty cells
- Electronics area not active (unless 3D integ.): higher cost & lower fill factor
- Electronics exposed to radiation: hardness ?
- Fast digital signals (gate delays of ~30ps, rise/fall times ~90ps), low parasitics

Separation of **photon number**, **time of arrival**
and **position** information
right **at the detection element**
might potentially enable
new detector concepts

Active/Passive Quenching and Active Reset

SPAD arrays -
- “digital” SiPM

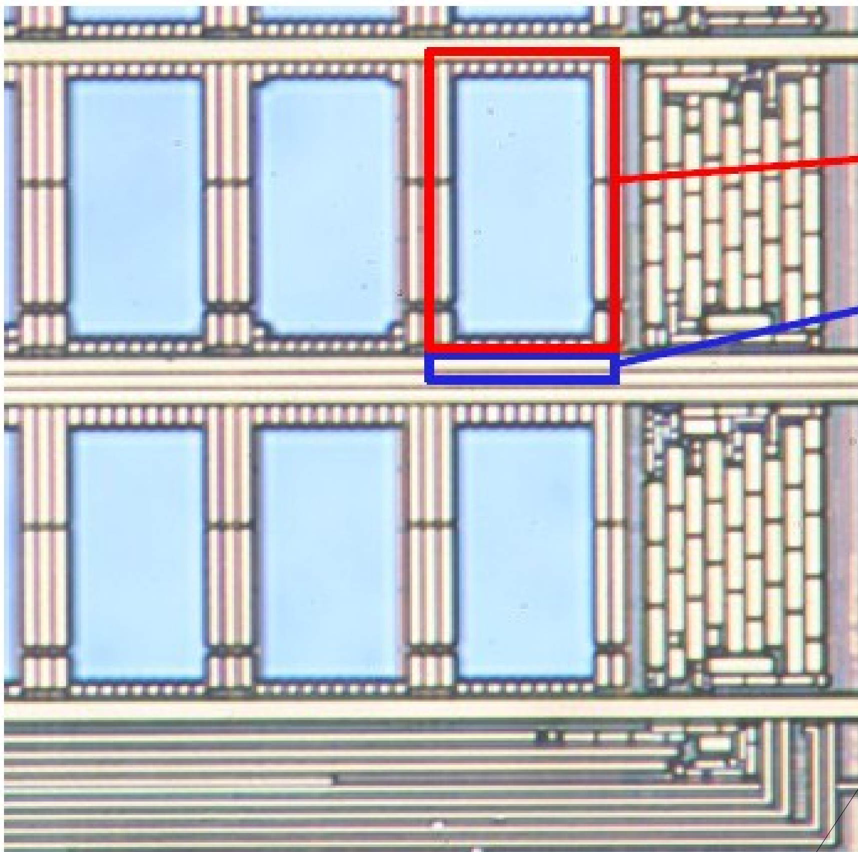


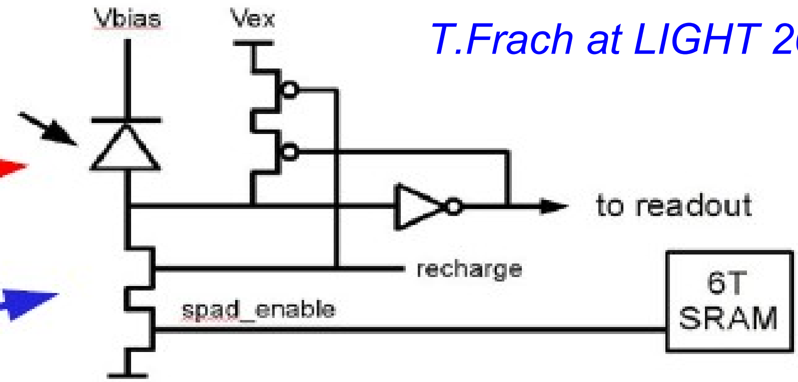
Active mode → “digital” SiPM

Philips Digital SiPM
APD cells & integrated electronics

- Cell area ~ 30x50μm^2
- Fill Factor ~ 50%

T.Frach at LIGHT 2011





- Cell electronics area: 120μm^2
- 25 transistors including 6T SRAM
- ~6% of total cell area
- Modified 0.18µm 5M CMOS
- Foundry: NXP Nijmegen

- reduced Fill Factor
- electronics exposed to radiation
→ additional radiation weakness

SiPM key features

Gain, Pulse shape (analog SiPM)
Dynamic Range, **Linearity**,
Energy Resolution

related to the recharge of the diode capacitance from V_{bd} to V_{bias} during the avalanche quenching time after I_{latch} is reached

Time resolution

related to cell structure and to avalanche propagation
...intrinsically SiPMs can be ultra-fast...

PDE (Photo-detection efficiency)

PDE = T ∗ QE ∗ P_{01} ∗ FF

T = transmission
QE = quantum efficiency
P_{01} = avalanche triggering prob.
FF = fill factor (effective)

Noise sources
→ thermally generated
Correlated noise:
→ after-pulsing,
→ cross-talk

pulses triggered by non-photo-generated carriers (thermal / tunneling generation in the bulk or in the surface depleted region around the junction)

carriers can be trapped during an avalanche and then released triggering another avalanche

photo-generation during the avalanche discharge. Some of the photons can be absorbed in the adjacent cell possibly triggering new discharges

Gain and Pulse shape (analog SiPM)

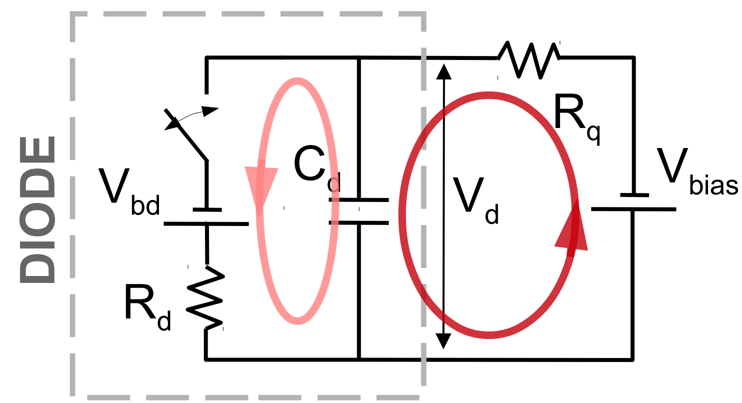
- Gain and related fluctuations
- Response non-linearity
- Tiny cell devices

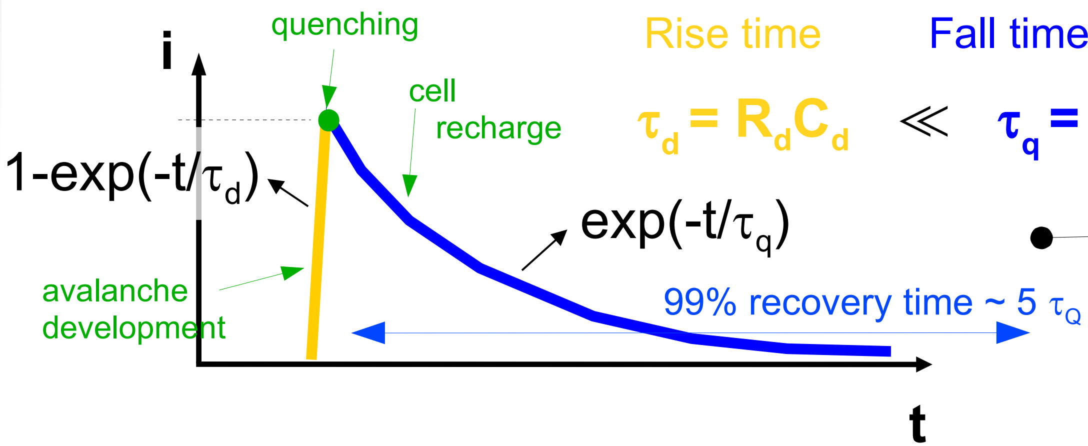
GM-APD Operation model – passive quenching

Diode (capacitor) fast discharge
and slow recharge

charge stored defines Gain
→ **Gain ~ C ΔV** (C is cell capacitance)
$\Delta V = V_{bias} - V_{bd}$ "Over-Voltage"

currents internal / external





Rise time Fall time (recovery)

$\tau_d = R_d C_d \ll \tau_q = R_q C_d$

pulse shape
(1st order approx)

Gain → linear with ΔV (≠ APD)
→ no multiplicatoin noise (≠ APD !!!)
→ independent of T at fixed ΔV (≠ APD)

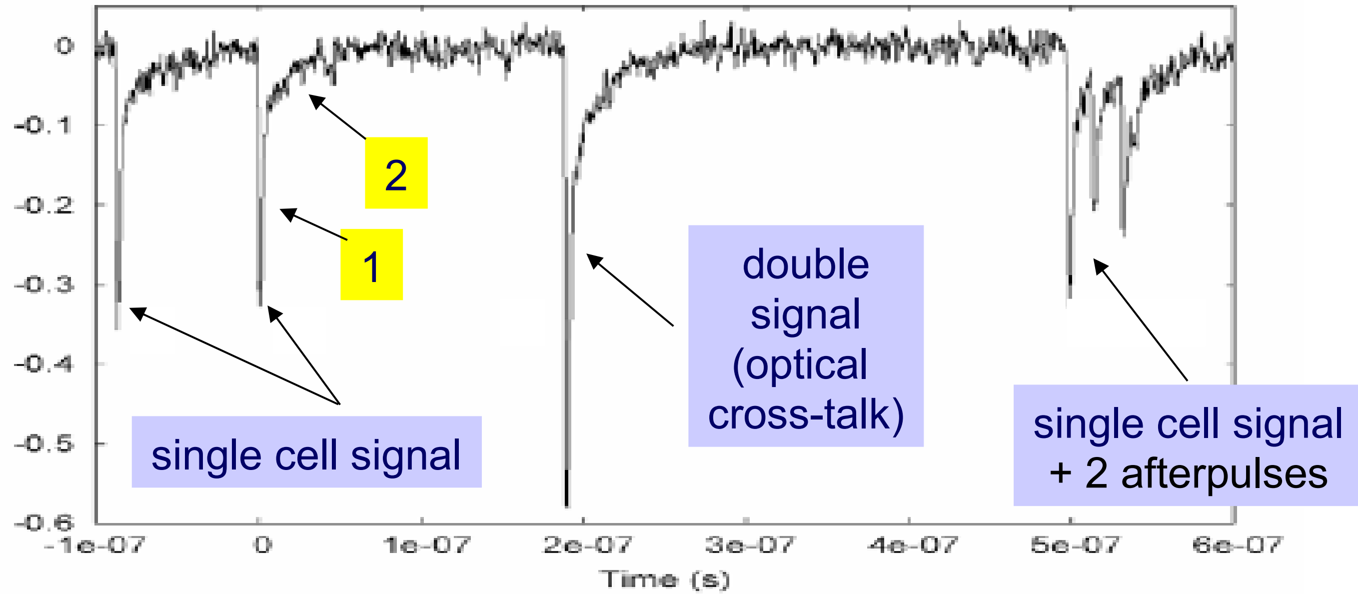
no multiplication noise !!!

Rise time T dependence (weak) due to R_d

Recovery time T dependence (strong) due to R_q
C_d is independent of T

Waveform, charge spectrum and gain

Waveform (Dark noise)

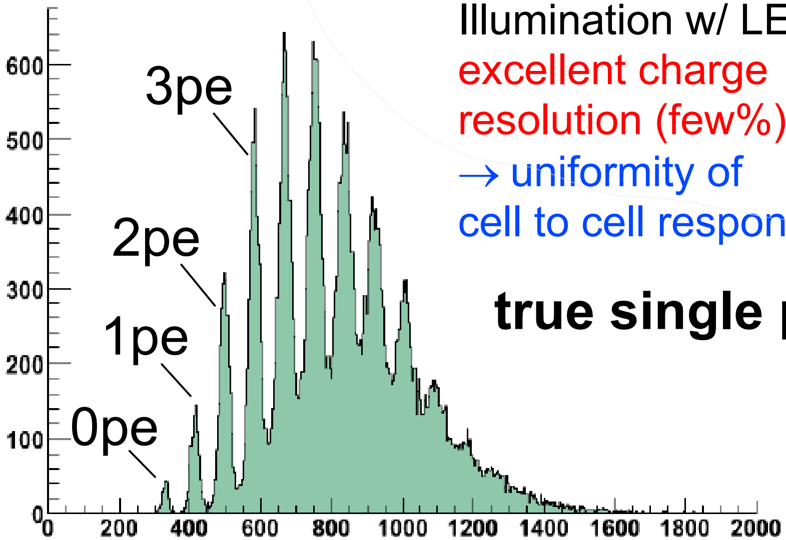


Pulse shape

1. fast component (parasitic transient)

2. slow component due to (99% recovery time ~100ns)

SER - Charge spectrum

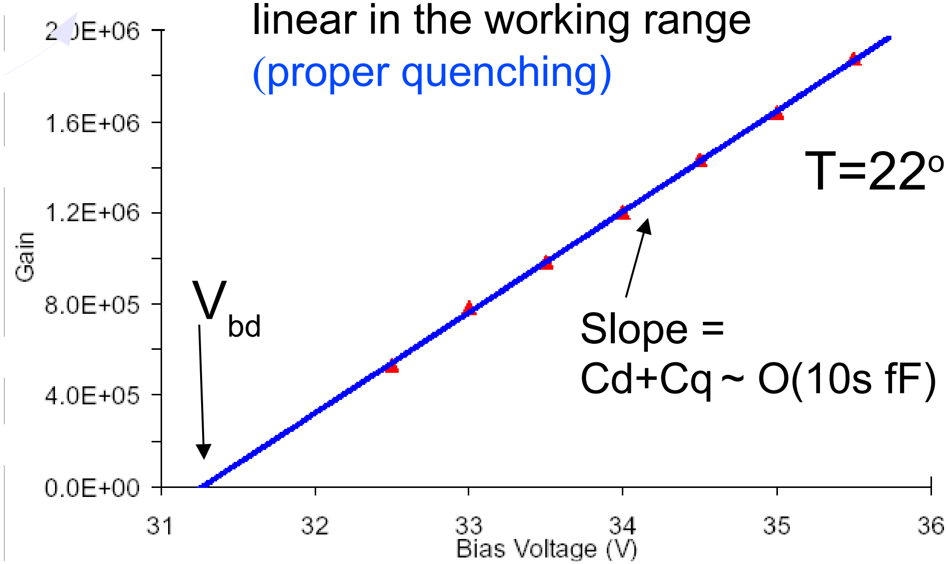


Illumination w/ LED
excellent charge resolution (few%)
→ uniformity of cell to cell response

true single ph.e

Gain

linear in the working range
(proper quenching)

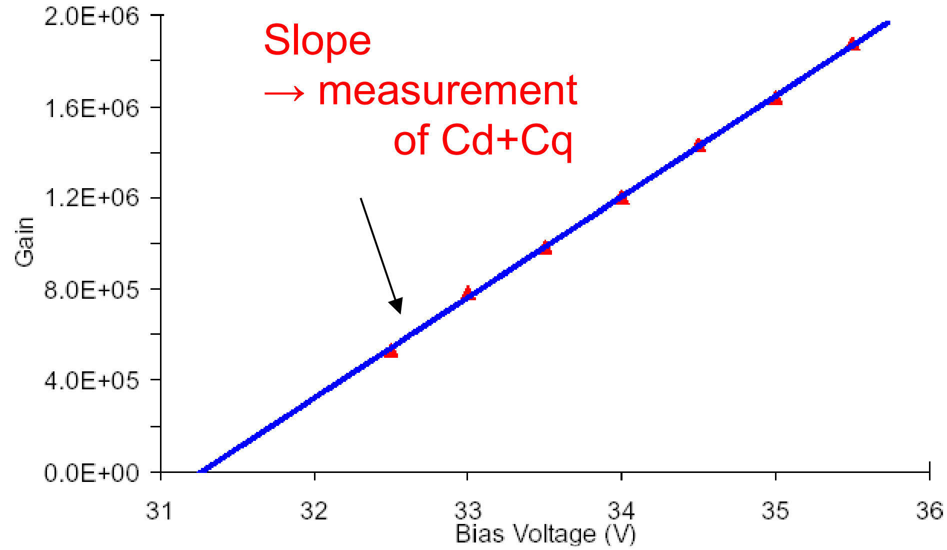


NOTE: gain easily measured
(… full charge integration)

Single Photon Resolution (SER) – Gain fluctuations

$$G = \Delta V (C_q + C_d) / q_e$$

→ Gain is linear if ΔV in quenching regime and under low intensity illumination

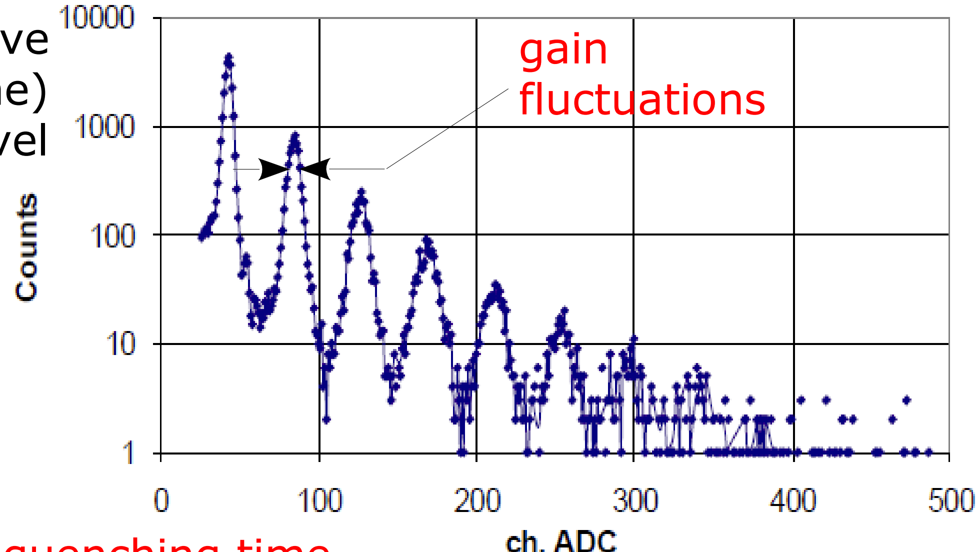


SiPM gain fluctuations (intrinsic) differ in nature compared to APD where the statistical process of internal amplification shows a characteristic fluctuations

$$\frac{\delta G}{G} = \frac{\delta V_{bd}}{V_{bd}} \oplus \frac{\delta C_{dq}}{C_{dq}}$$

cell to cell uniformity (active area and volume) control at % level

Integrated Charge Spectrum

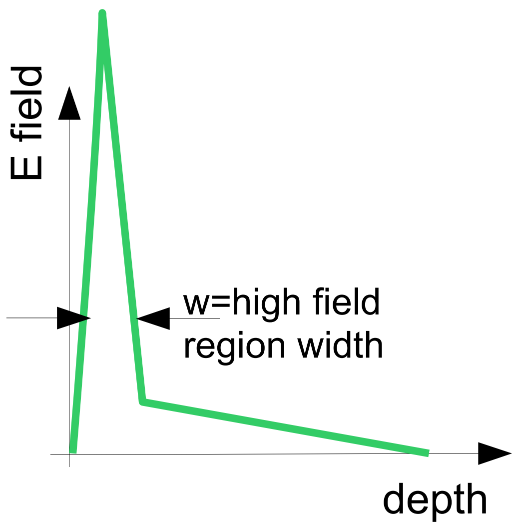


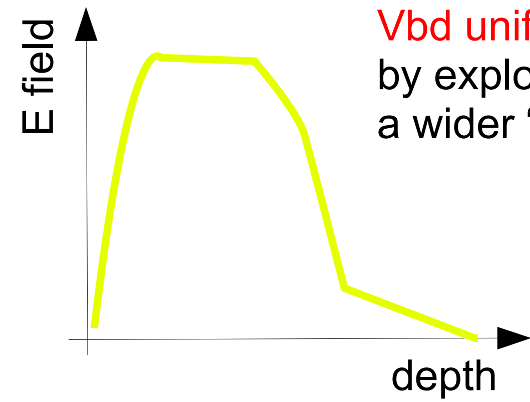
- doping densities (Poisson): $\delta V_{bd} \geq 0.3V$
  Shockley, Sol. State Ele. 2 (1961) 35
- doping, epitaxial, oxide (processing): $\delta V_{bd} \sim O(0.1V)$

In addition δG might be due to fluctuations in quenching time
… and of course after-pulses contribute too (not intrinsic → might be corrected)

Recent improvements in V_{bd} uniformity

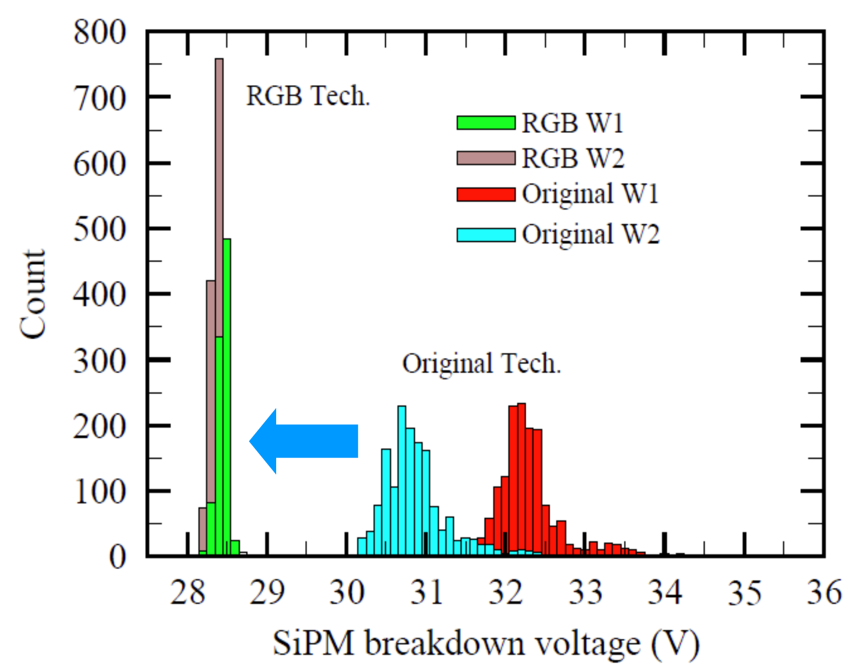
Engineering high electric field & depletion/drift layer profiles





Vbd uniformity easier
by exploiting lower field over
a wider “high field” region

Recent progresses in FBK-Advansid devices



→ Improved break-down voltage uniformity
- at wafer level
- among wafers

N.Serra: “Characterization of new FBK SiPM technology for visible light detection”, JINST 2013 JINST 8 P03019

Note: also improvement on T coefficient of V_{bd} → stability

Almost no intrinsic gain fluctuations...

→ accurate photon counting ?

→ perfect energy resolution ?

Almost no intrinsic gain fluctuations...

→ accurate photon counting ? …

→ perfect energy resolution ? …

… only up to some extent due to

- saturation effect → non linearity
- correlated noise → excess noise

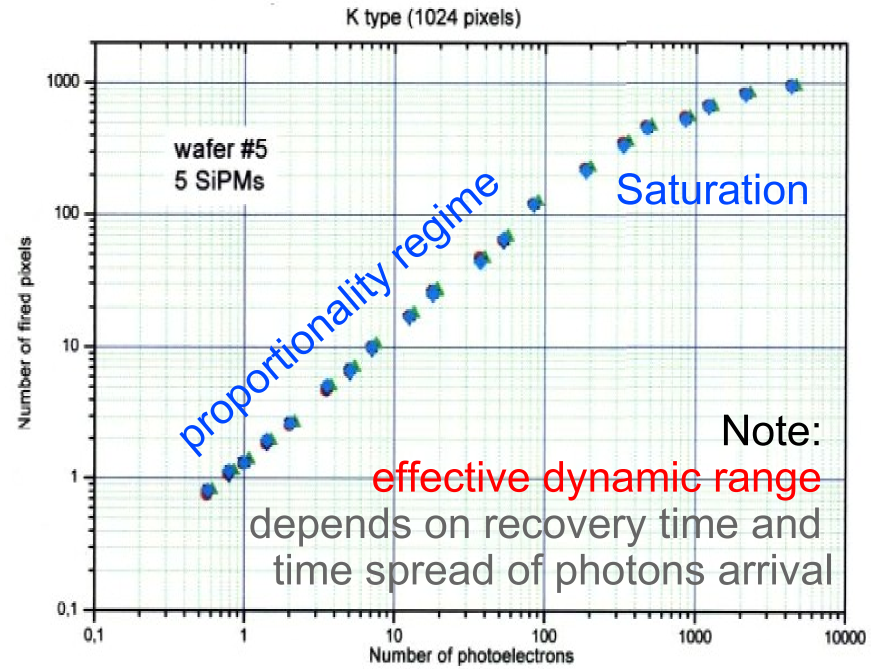
Response Non-Linearity

Non-proportionality of charge output w.r.t. number of photons (i.e. response) at level of several % might show up even in quenching regime (negligible quenching time), depending on ΔV and on the intensity and duration of the light pulse.

Main sources are:

- finite number of pixels
- finite recovery time
- after-pulses, cross-talk
- drop of ΔV during the light pulse in case of large signal current on series (ballast) resistances

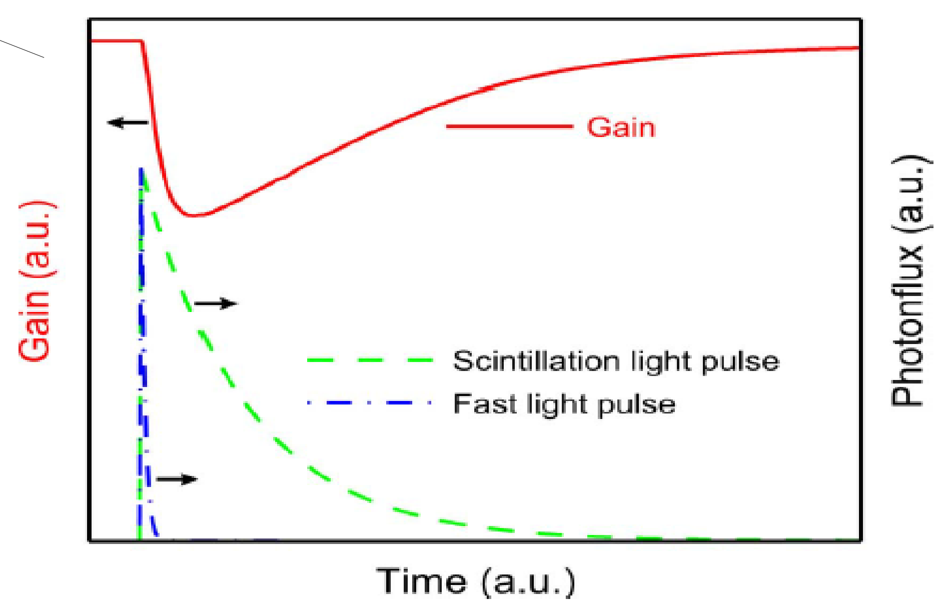
T.van Dam IEEE TNS 57 (2010) 2254
Detailed model to estimate non-lin. corrections



Note:
effective dynamic range depends on recovery time and time spread of photons arrival

Finite number of cells is main contribution in case number of photons ~ O(number of cells) (dynamic range not adequate to application)

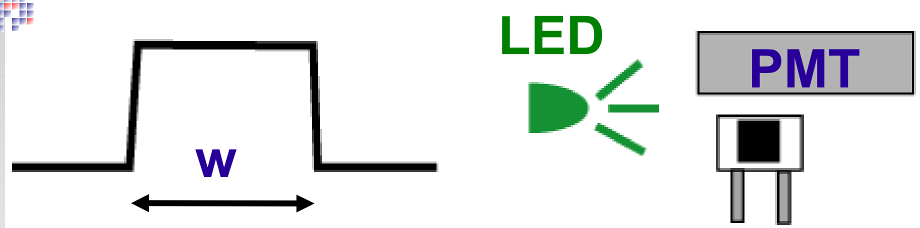
→ saturation
$$n_{fired} = n_{all}\left(1 - \exp\left(-\frac{n_{phot.} PDE}{n_{all}}\right)\right)$$
→ loss of energy resolution



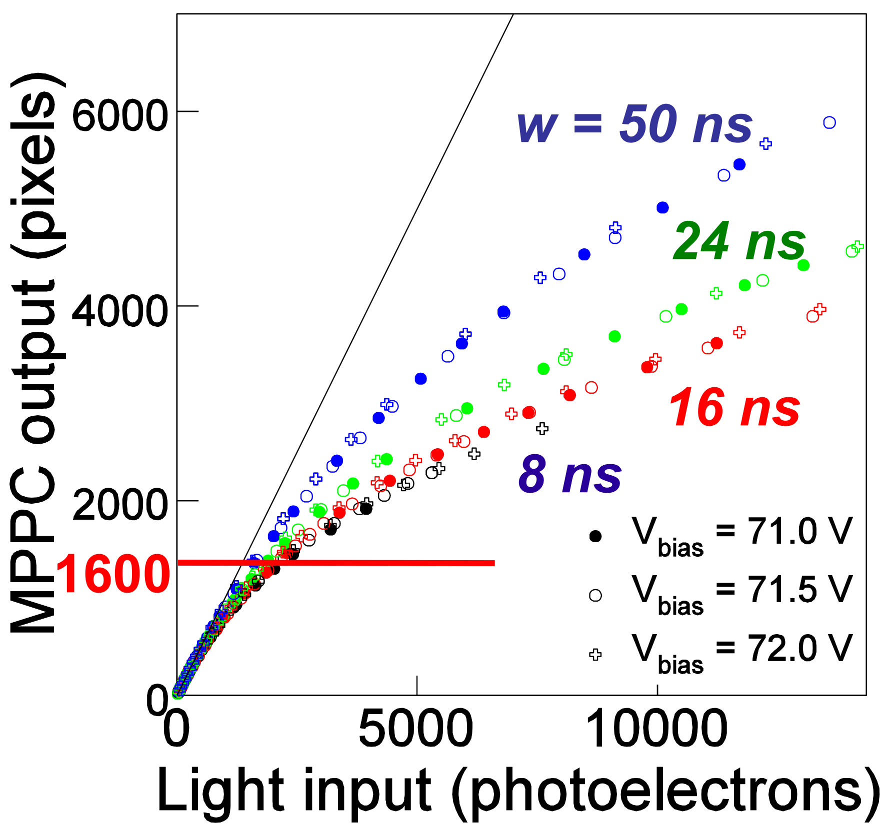
see Stoykov et al JINST 2 P06500 and Vinogradov et al IEEE NSS 2009 N28-3

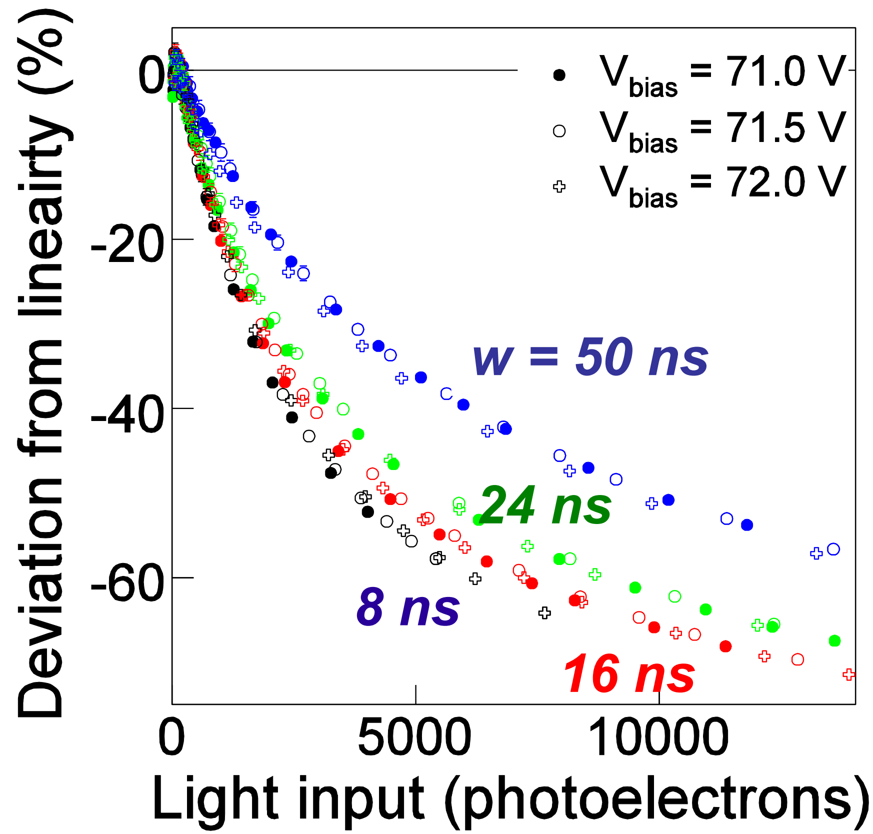
… Energy Calibration

S.Uozumi – PD07
Kobe - 27 June 2007



Response curves taken with various width of LED light pulses. (gate width = 100 ns)



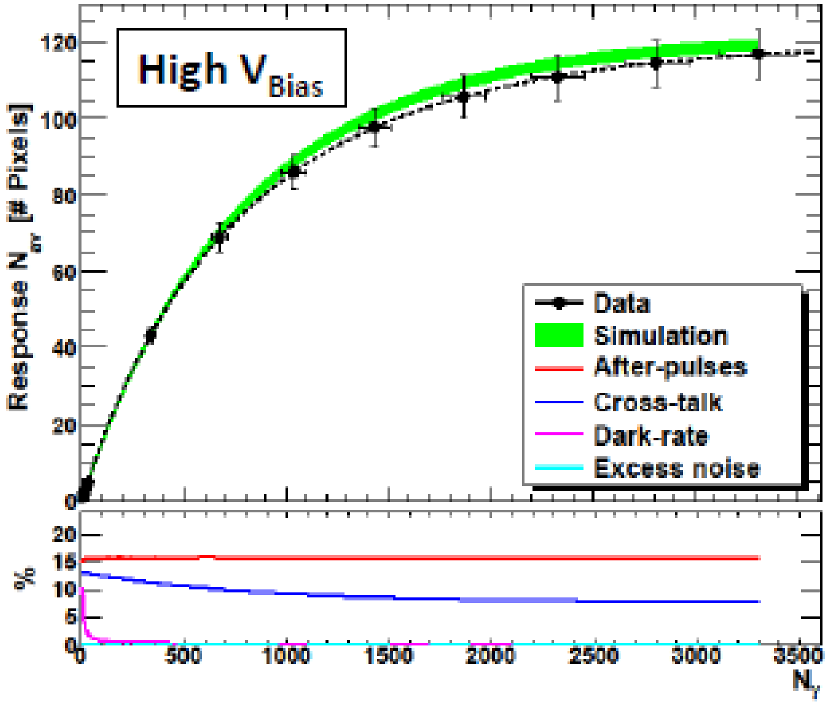


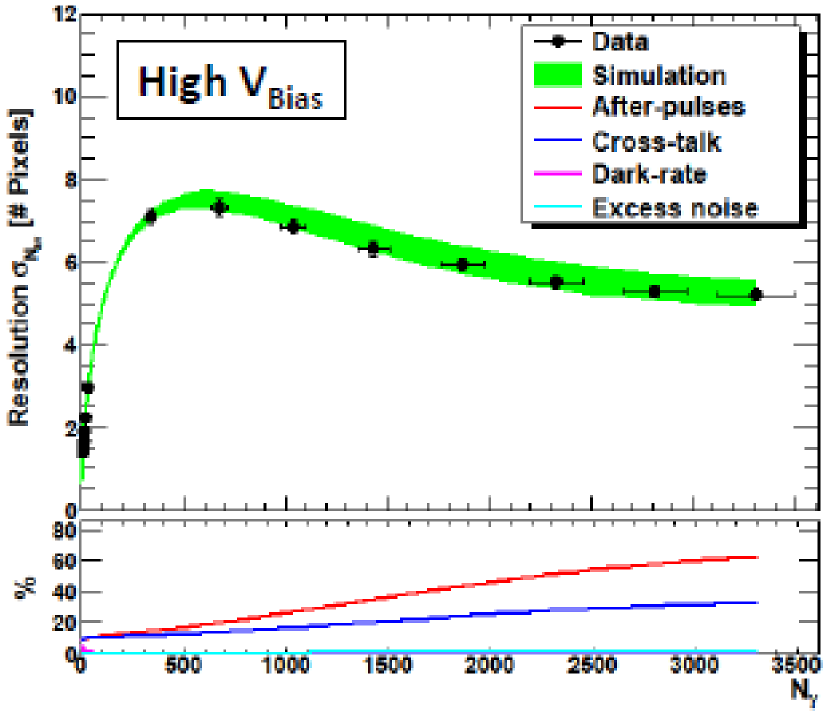
- Dynamic range is enhanced with longer light pulse
- Time structure of the light pulse gives large effects in non-linear region
- No significant influence with changing bias voltage
- Time structure of scintillator / WLS light emission must be mimicked by calibration system

Energy Resolution

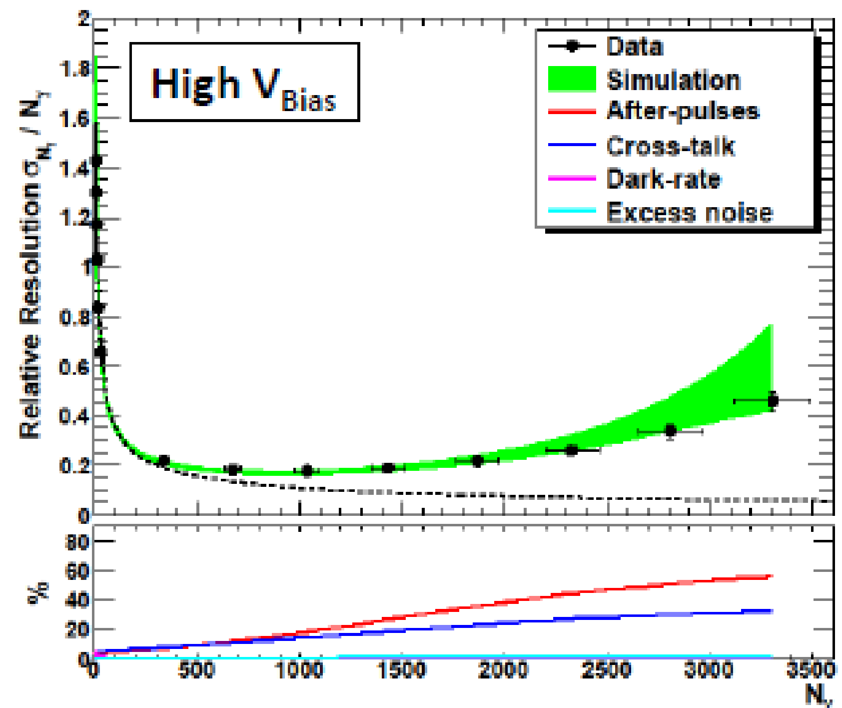
finite number of pixels: constraint
→ limit in resolving the number of photons

Note: Energy Resolution affected also by **correlated noise** (see later)





Eckert et al. Procs. of PhotoDet 2012



DR PDE, CT, AP

$$\frac{\Delta N_\gamma}{N_\gamma} \approx \frac{a}{N_\gamma} \oplus \frac{b}{\sqrt{N_\gamma}}$$

see also Musienko et al JINST 2 2007 P0600

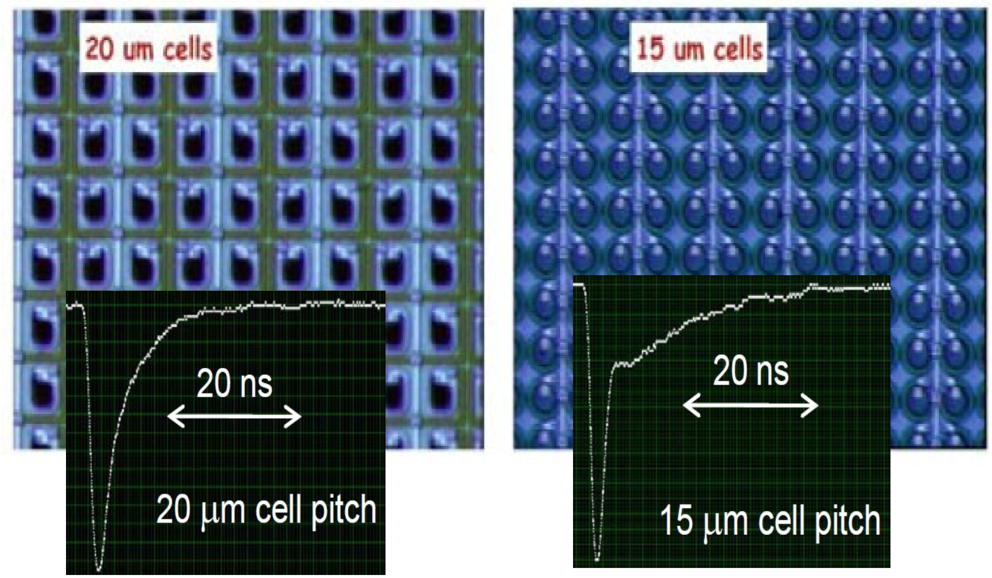
Tiny cells: wide dynamic range and more goods

Many small cell SiPM types available
→ **Fill Factor improving** (> 50%)

- tiny cells (→ 10-15μm)
  → HPK, FBK-Advansid, NDL, MPI-LL, …

- micro cells (→ μm)
  → Zecotek, Amplitication Techn.

tiny cell MPPC (2012) by Hamamatsu



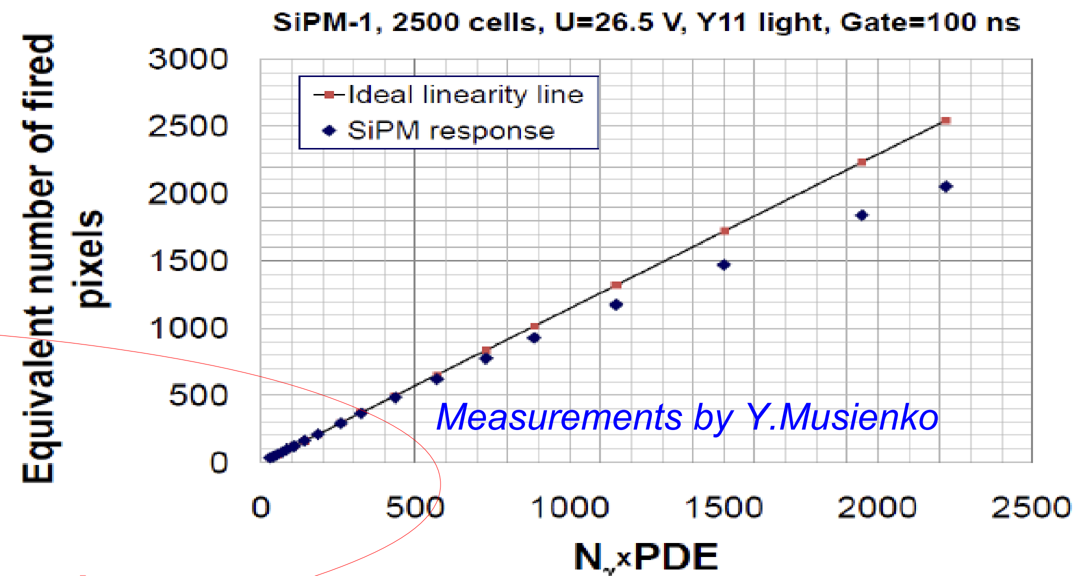
SiPMs NDL (Bejiing)

Zhang et al NIM A621 (2010) 116
Han at NDIP 2011

- type: n-on-p, Bulk Rq
- high cell density (10000/mm^2)
- fast recovery (5ns)
- low gain
- **better timing**

→ dynamic range

→ less after-pulsing
→ less cross-talk
→ mitigate effects of radiation damages



Tiny cells: wide dynamic range and more goods

PD18 workshop – Tokyo Dec 2018

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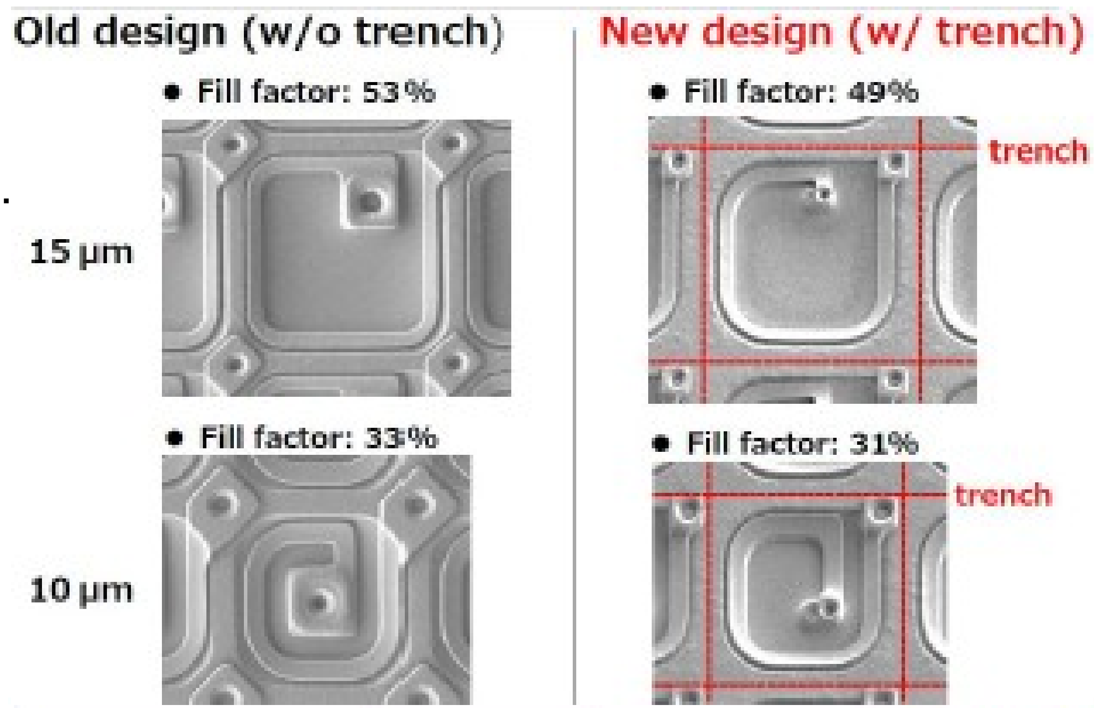
→ **Fill Factor improving** (> 50%)

- tiny cells (→ 10-15μm)
  → HPK, FBK-Advansid, NDL, MPI-LL, ..
- micro cells (→ μm)
  → Zecotek, Amplitication Techn.

tiny cell MPPCs (2018) by Hamamatsu



	S12571	S13360	S14160 (Latest)
Breakdown voltage	65 V	53 V	38 V
Trench isolation	none	Yes	Yes
Trench width	-	~ 1 μm	~ 0.5 μm
Fill factor	10μm: 33% 15μm: 53%	10/15μm no lineup	10μm: 31% 15μm: 49%

SiPMs NDL (Bejiing)

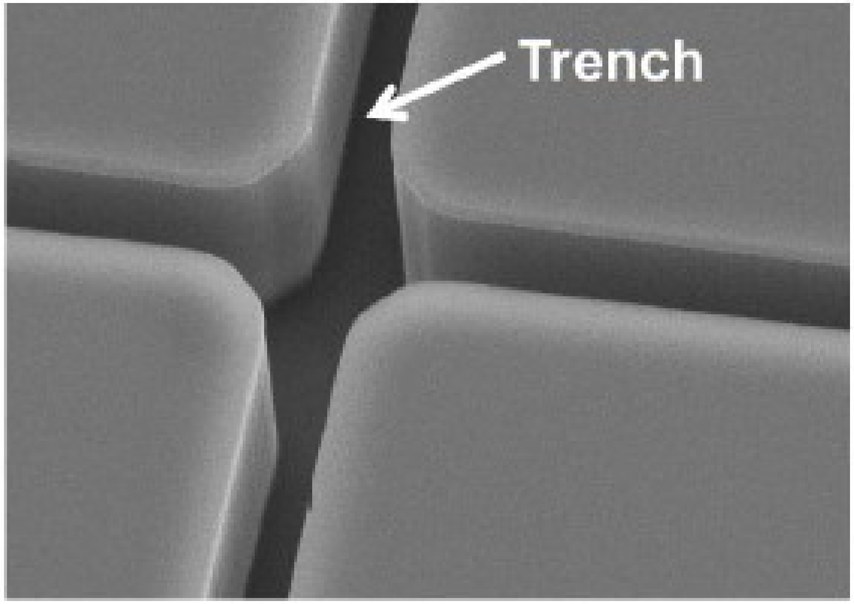
Zhang et al NIM A621 (2010) 116
Han at NDIP 2011

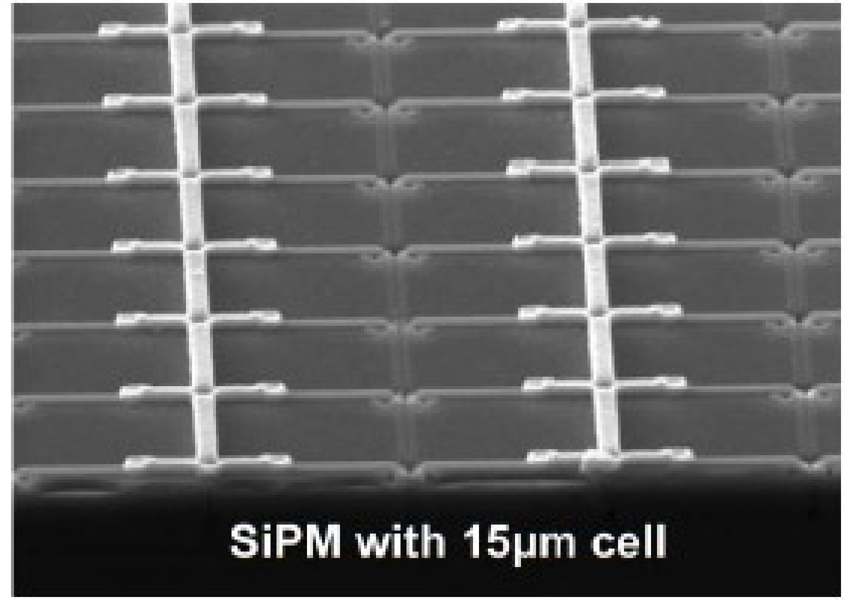
- type: n-on-p, Bulk Rq
- high cell density (10000/mm^2)
- fast recovery (5ns)
- low gain
- **better timing**

fast recovery, high cell density → **dynamic range**

low gain → **less after-pulsing**
→ **less cross-talk**
→ **mitigate effects of radiation damages**

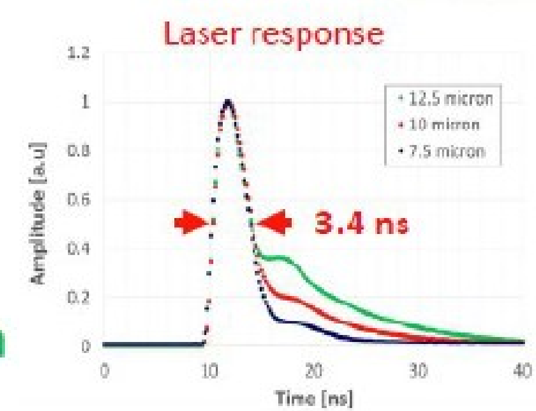
Tiny cells: better performances



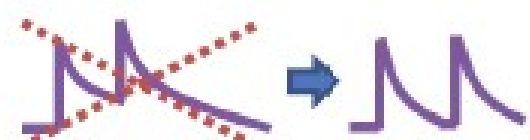


- Trenches between cells → optical and electrical cell isolation
- Dead border reduction → increased FF

Smaller cell size without FF reduction



- Small cells:
  - Gain reduction → afterpulsing and CT reduction
  - Larger dynamic range
  - Faster cell-signal → Reduce pile-up



Fabio Acerbi – NDIP 2017

SiPM equivalent circuit and pulse shape

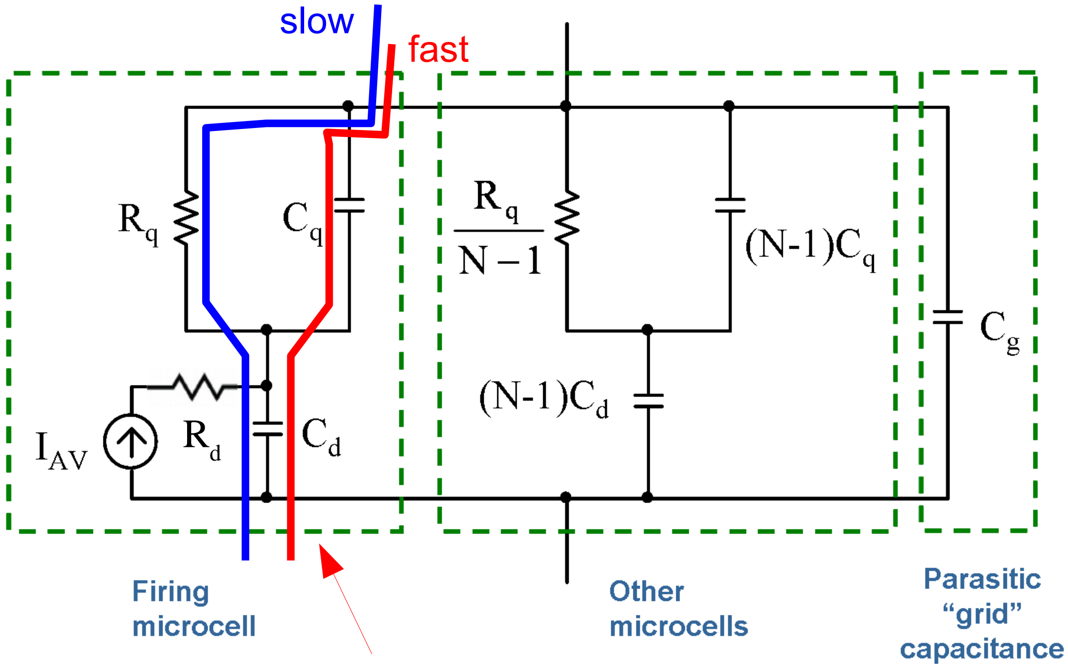
Single cell model → $(R_d||C_d)+(R_q||C_q)$

SiPM + load → $(||Z_{cell})||C_{grid} + Z_{load}$

Signal = slow pulse ($\tau_{d\,(rise)}, \tau_{slow\,(fall)}$) +
+ fast pulse ($\tau_{d\,(rise)}, \tau_{fast\,(fall)}$)

- $\tau_{d\,(rise)}$ ~ $R_d(C_q+C_d)$ (rising edge)
- $\tau_{fast\,(fall)}$ ~ $R_{Load}\ C_{tot}$ (fast; parasitic spike)
- $\tau_{slow\,(fall)}$ ~ $R_q\,(C_q+C_d)$ (slow; cell recovery)

F.Corsi, et al. NIM A572 (2007) 416
S.Seifert et al. IEEE TNS 56 (2009) 3726

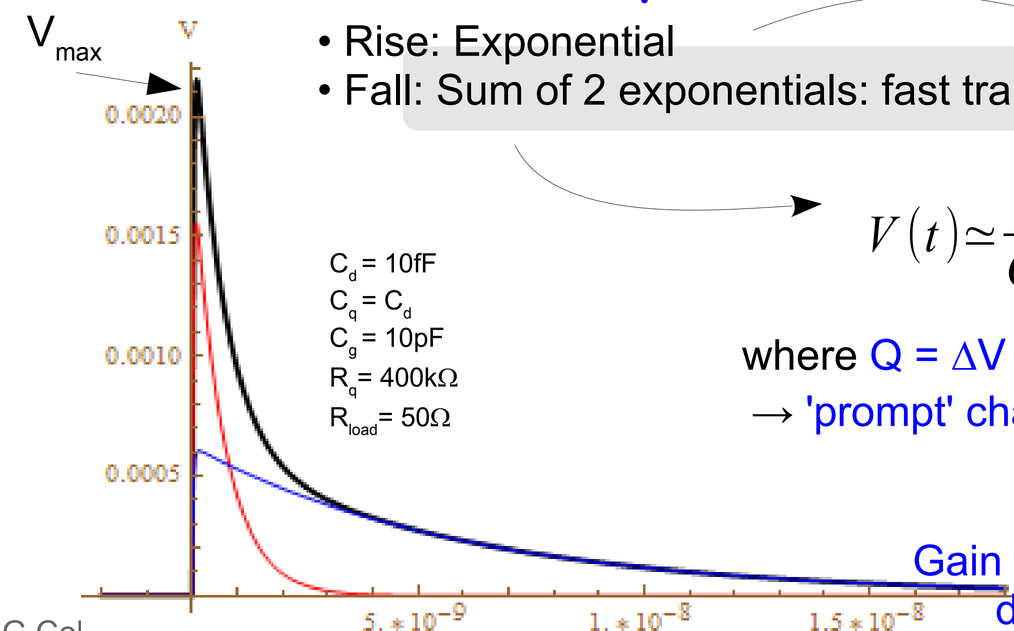


Cq → fast current supply path in the beginning of avalanche

Pulse shape

- Rise: Exponential
- Fall: Sum of 2 exponentials: fast transient + slow recovery

Space Charge Rd x Cd,q filtered by parasitic L & stray C (Low Pass) → $O(R_{load}\ C_{tot})$



$$V(t) \simeq \frac{Q}{C_q+C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{FAST}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q+C_d} e^{\frac{-t}{\tau_{SLOW}}}\right) \text{ for } R_{Load} << Rq$$

where $Q = \Delta V\ (C_q+C_d)$ is the total charge released by the cell
→ 'prompt' charge on C_{tot} is $Q_{fast} = Q\ C_q/(C_q+C_d)$

Gain still well defined: $$G = \int dt \frac{V(t)}{q_e R_{load}} = Q/q_e = \frac{\Delta V (C_d+C_q)}{q_e}$$

Pulse shape features

$$V(t) \simeq \frac{Q}{C_q+C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{fast}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q+C_d} e^{\frac{-t}{\tau_{slow}}}\right) = \frac{Q\,R_{load}}{C_q+C_d}\left(\frac{C_q}{\tau_{fast}} e^{\frac{-t}{\tau_{fast}}} + \frac{C_d}{\tau_{slow}} e^{\frac{-t}{\tau_{slow}}}\right)$$

Note: valid for low impedance load $R_{load} << Rq$

- $\tau_{fast} = R_{load}\ C_{tot}$
- $\tau_{slow} = R_q\,(C_q+C_d)$

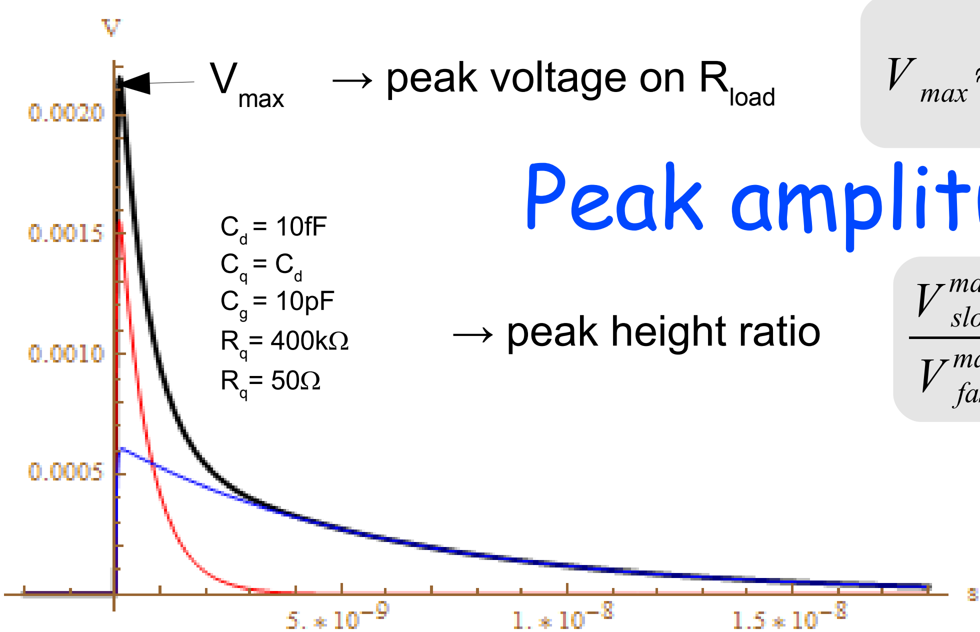
→ gain $G = \int dt \frac{V(t)}{q_e R_{load}} = Q/q_e = \frac{\Delta V(C_d+C_q)}{q_e}$ independent of R_q

Integrated charge

→ charge ratio $\frac{Q_{slow}}{Q_{fast}} \sim \frac{C_d}{C_q}$

V_{max} → peak voltage on R_{load} $V_{max} \approx R_{load}\left(\frac{Q_{fast}}{\tau_{fast}} + \frac{Q_{slow}}{\tau_{slow}}\right)$ dependent on R_q (increasing with $1/R_q$)

Peak amplitude or Initial Current



→ peak height ratio $\frac{V^{max}_{slow}}{V^{max}_{fast}} \sim \frac{C_d C_{tot} R_{load}}{C_q(C_q+C_d)R_q}$ increasing with C_d and $1/R_q$

Note: when C_{tot} large and R_{load} small
→ $R_{load}C_{tot}$ ~R_qC_{cell} → pole splitting for τ_{fast} / τ_{slow}

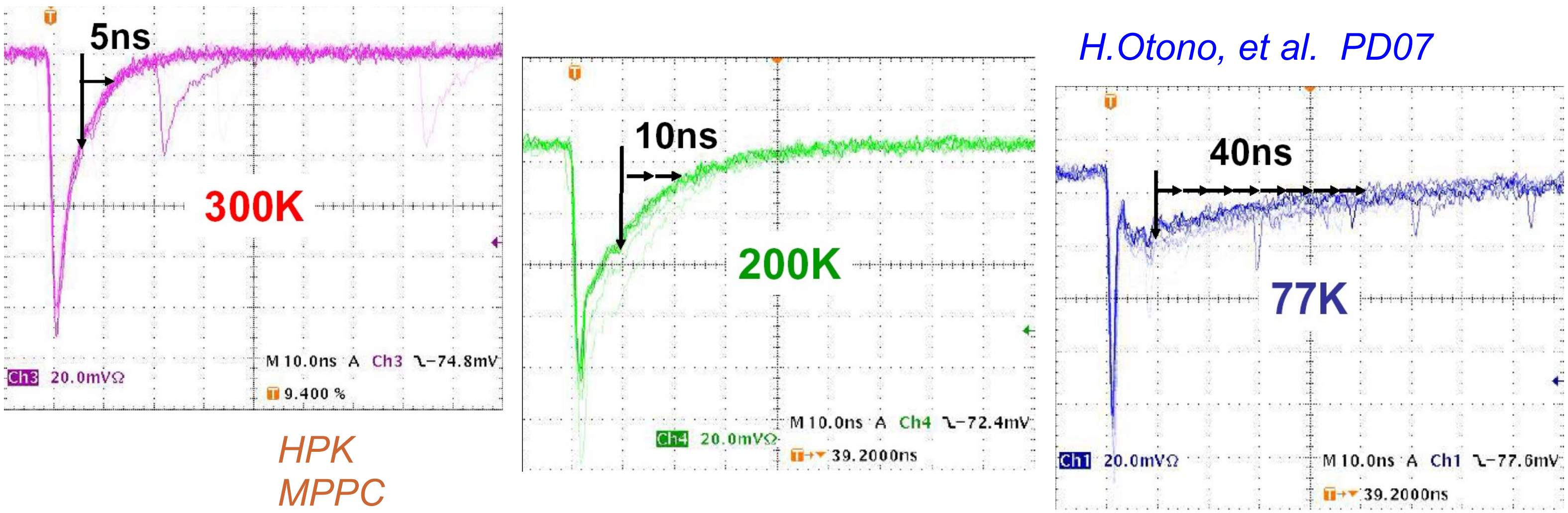
Pulse shape: dependence on Temperature

The two current components behave differently with Temperature

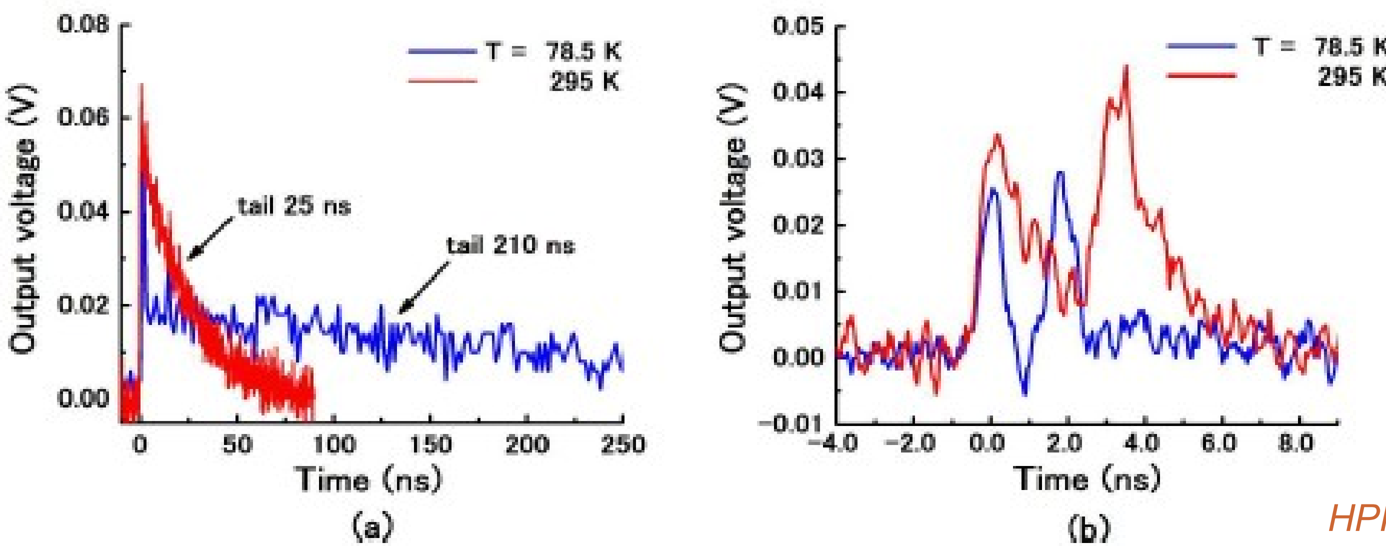
→ fast component is independent of T because C_{tot} couples to external R_{load}

→ slow component is dependent on T because $C_{d,q}$ couple to $R_q(T)$

H.Otono, et al. PD07



HPK MPPC



high pass filter / shaping
→ recover fast signals

HPK MPPC

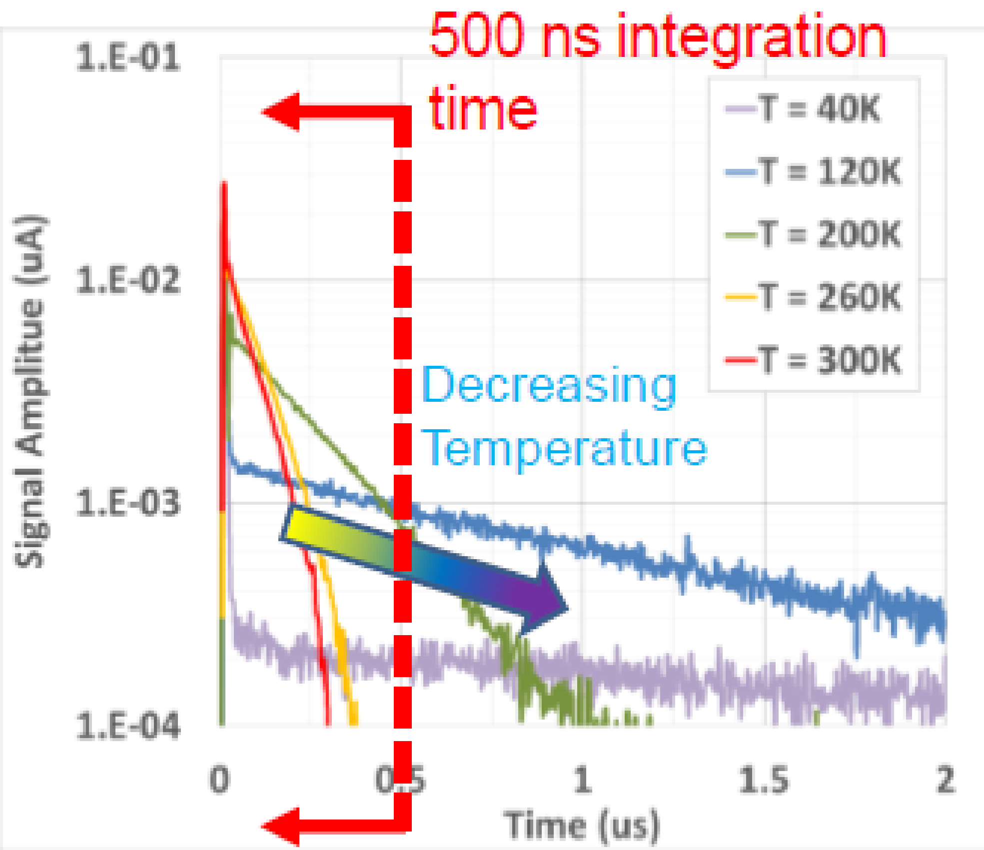
Fig. 2. (a) Output signals from the MPPC when no high-pass filter is used, and (b) output signals from the high-pass filter when two pulses were generated successively.

Akiba et al Optics Express 17 (2009) 16885

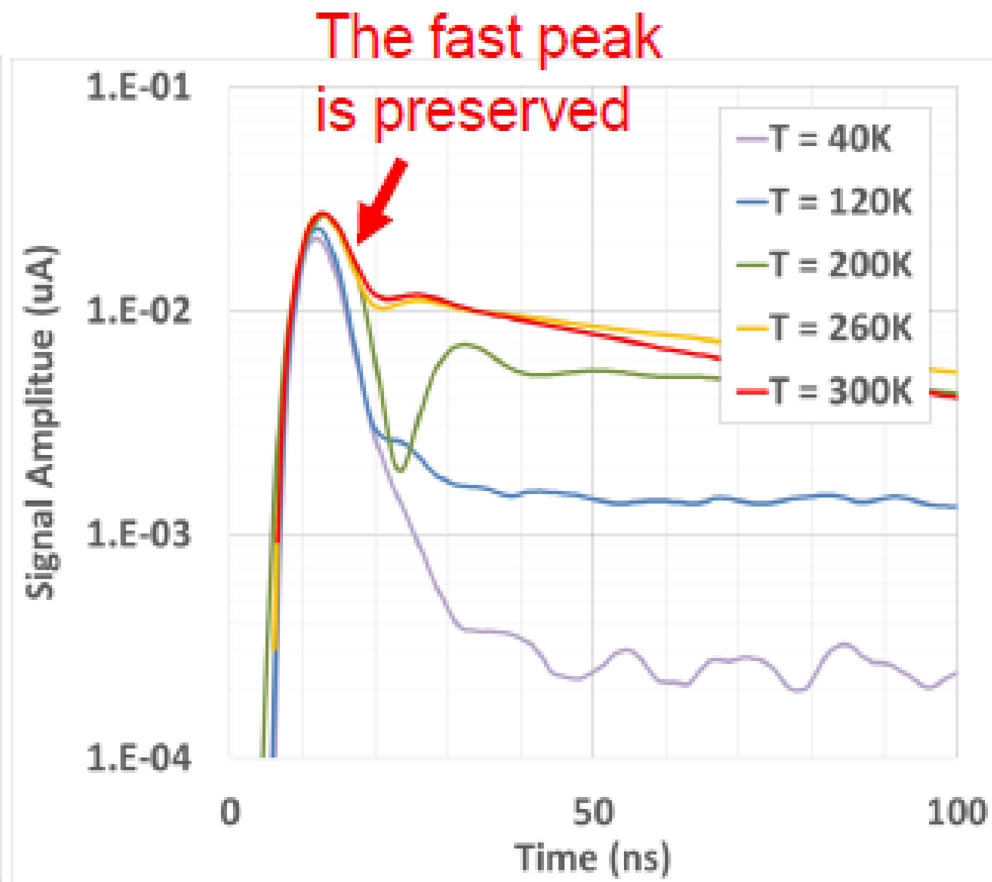
Pulse Charge vs Amplitude at low T

At low T fast peak is preserved, slow peak is not
→ Gain from integrated charge on limited time window G_Q < ideal G

Note: G is almost independent of T while G_Q is dependent on T
ostensible gain variation with temperature



Average SCR



Zoom of the first part of the SCR

SCR = Single Cell Response

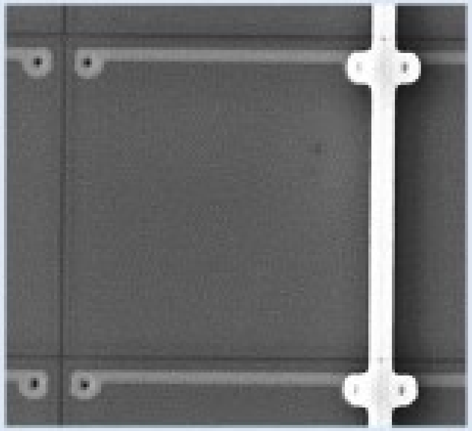
SiPM Quenching Resistor (Rq) Technologies

Integrated passive quenching Resistor
is required to quench the avalanche current
and to reset the SPAD after an event

Typical R_q =
500 kOhm – 1 MOhm

Different possible technologies….

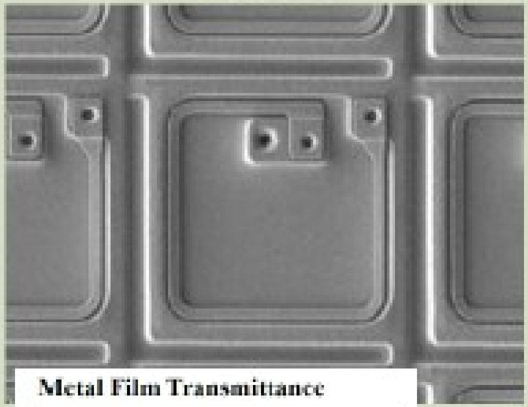
Poly Silicon Resistor
FBK, SensL, Ketek

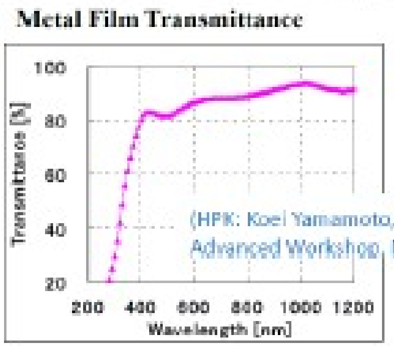


Cons.

- High temperature coefficient
- Additional microfab. process steps

Thin Metal Film Resistor





(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

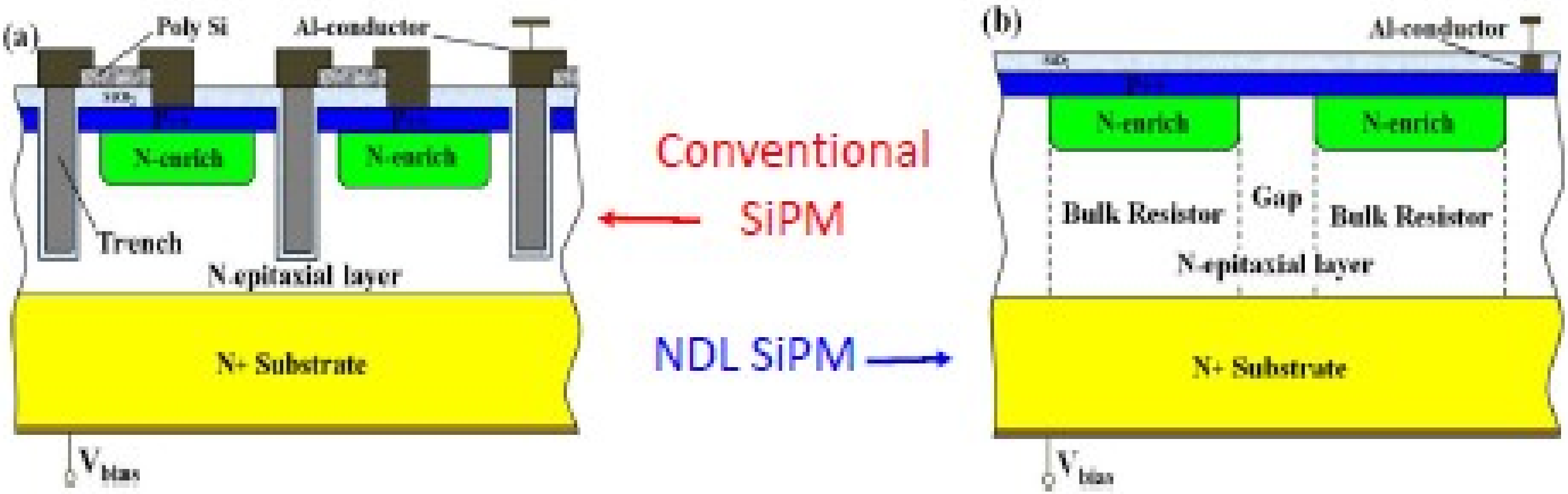
Pros:

- Low T coefficient
- Simpler processing
- Better tuning optical stack

SiPM Quenching Resistor – Bulk resistor (NDL)

… Alternative Approach (after Moser, Mirzoyan et al developing back-illuminated SiPM)

see Moser et al – PD07 Workshop and updates



Dejun Han – PD18 Workshop – Tokyo Dec 2018

Features

- The bulk resistor under each APD cell in the epitaxial layer is used as Rq
- A continuous cap resistive layer at the surface to connect all microcells

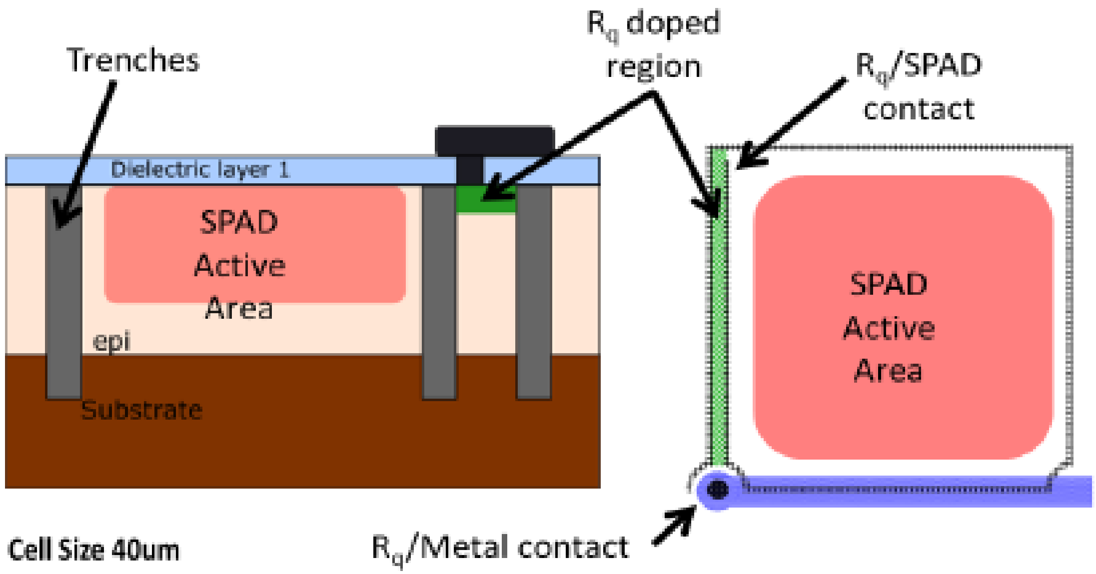
Advantages

- Tiny microcells (→ large dynamic range) with very high Fill Factor
- Simple fabrication technology (→ cost effective)
- Easy to implement charge division mechanism (→ position-sensitive SiPM)

. . .

SiPM Quenching Resistor – Silicon Resistor (FBK)

… Alternative Approach: Silicon Resistor (SiR-SiPM): quenching resistor integrated in the silicon substrate by means of a semi-conductive channel



- The resistor is realized by means of a **shallow doped region** and **confined between two trenches.**
- The silicon resistor is connected to the device by overlapping the shallow doped layer

Fill Factor	
NUV-HD	83 %
SiR	77 %

SiR-SiPM Advantages

- **Faster and cheaper fabrication process (30% less steps)**
- Simpler and more reliable fabrication process (no poly deposition; no Si/Poly contact)
- **Significantly reduced R_q dependence on the temperature**
- Small FF reduction
- **ARC is easily customizable** (single layer of oxide, no poly, reduced surface morphology)

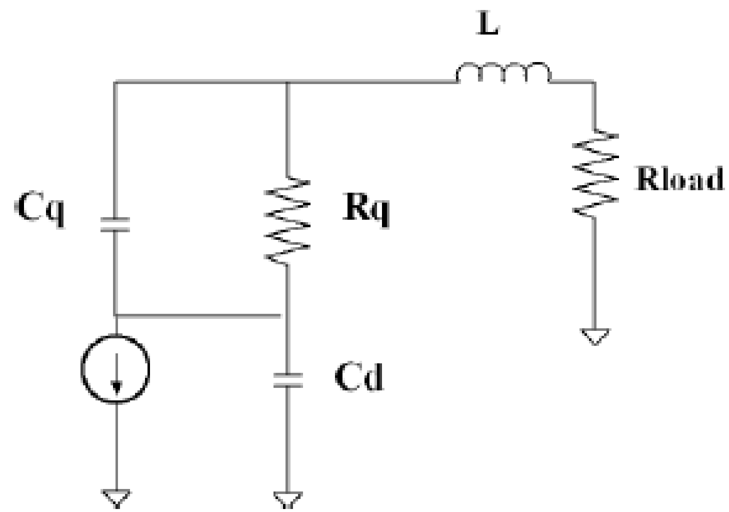
Fabio Acerbi – PD18 Workshop – Tokyo Dec 2018

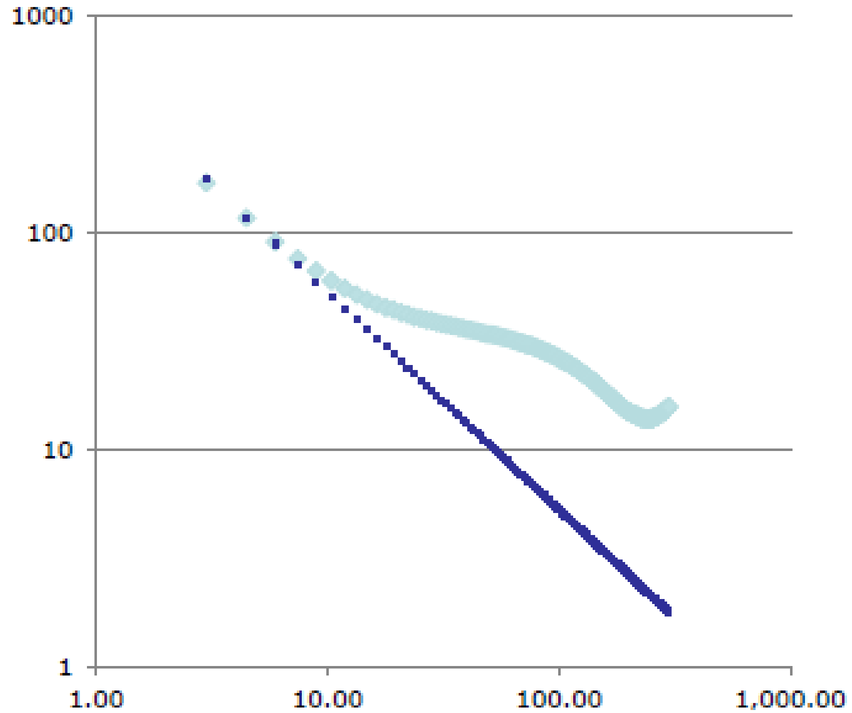
Pulse shape features: High Frequency reponse

- **RLC too simple, inaccurate at high frequency**
- **CdRqCqLR OK**
  - May better explain HF noise behaviour

C. de LaTaille – PhotoDet 2012

→ Ringing effect with low Z Front End !!!



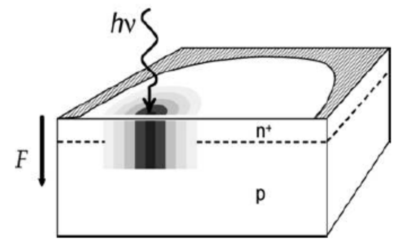


Measured impedance
MPPC HPK 3x3 mm
Line : C = 320 pF

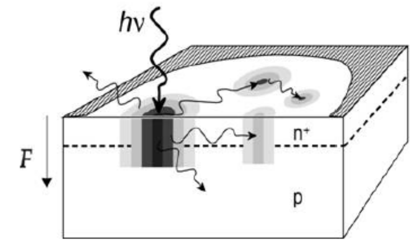
15 jun 2012 CdLT Photodet conference

Recent accurate electrical model & parameter extraction
→ *see Marano et al, IEEE TNS 61 (2014) 23*
→ *and Licciulli and Marzocca, IEEE TNS 63 (2016) 2517*

Timing



Multiplication assisted diffusion



Photon assisted propagation

- SiPM are intrinsically very fast

  Two timing components (related to avalanche developement)
  - prompt → gaussian time jitter below **100ps** (depending on ΔV, and λ)
  - delayed → non-gaussian tails up to **few ns** (depending on λ)

- Factors affecting practical timing measurements
  - Micro-cell structure (longitudinal and transverse electric field)
  - overall SiPM capacitance

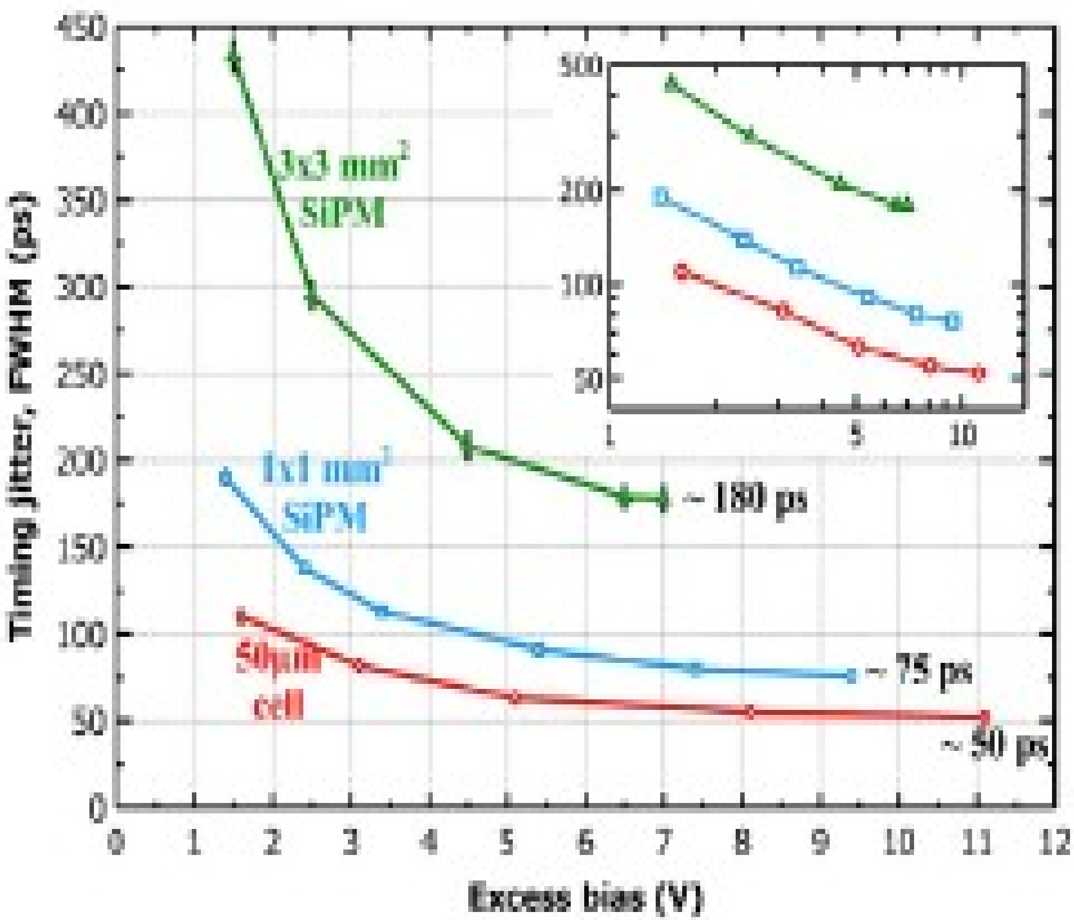
- Optimization of devices for timing applications
  - Micro-cell vs stray capacitance
  - Tiny cells !

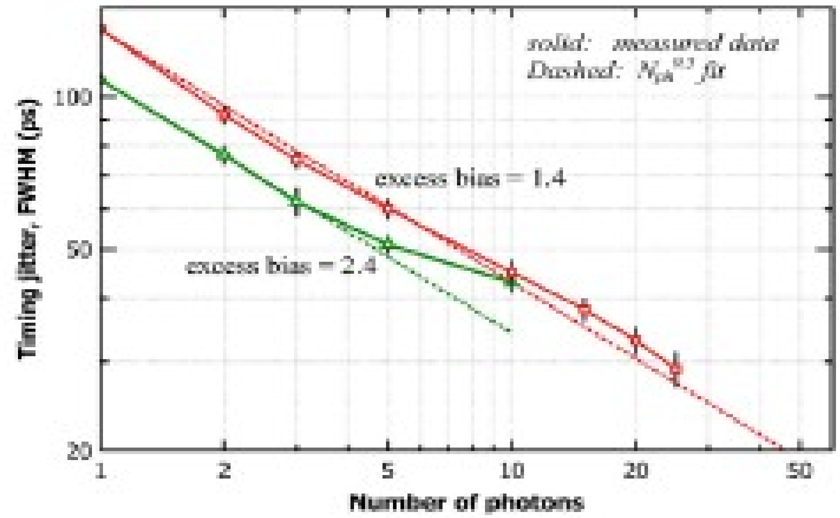
see also C.Betancourt at this Conference

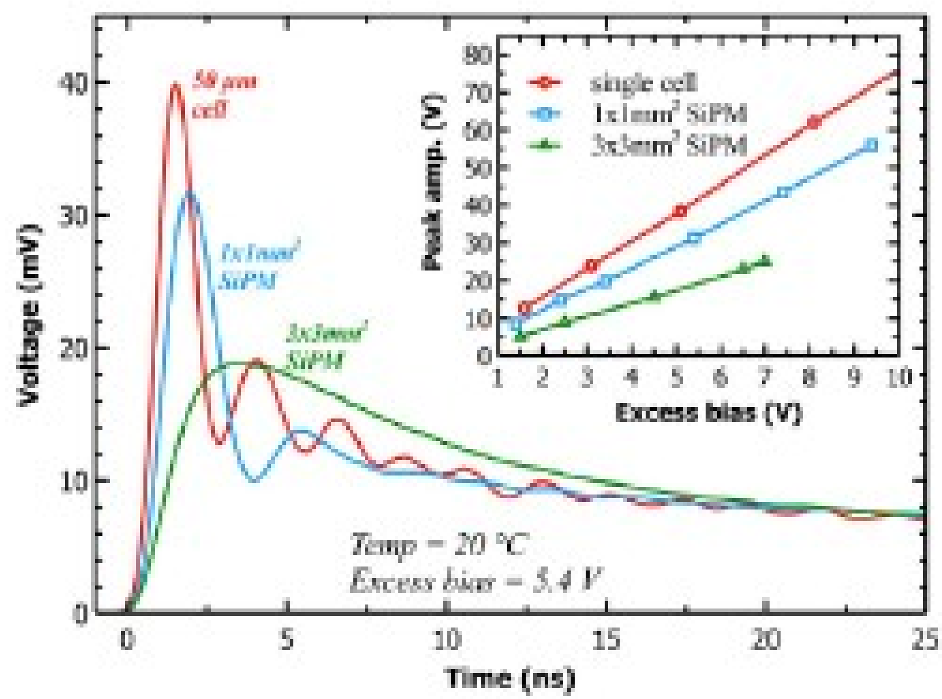
Factors affecting timing measurements

1) main contribution at **single cell level → lower field at cell edges**
(with single cell, single photon resolution below 20ps “easily” reached)

2) main contributions at **device level → capacitance**
+ X-talk and delayed pulses (multi-photon)
+ signal propagation: second order effect
+ device uniformity: negligible contribution



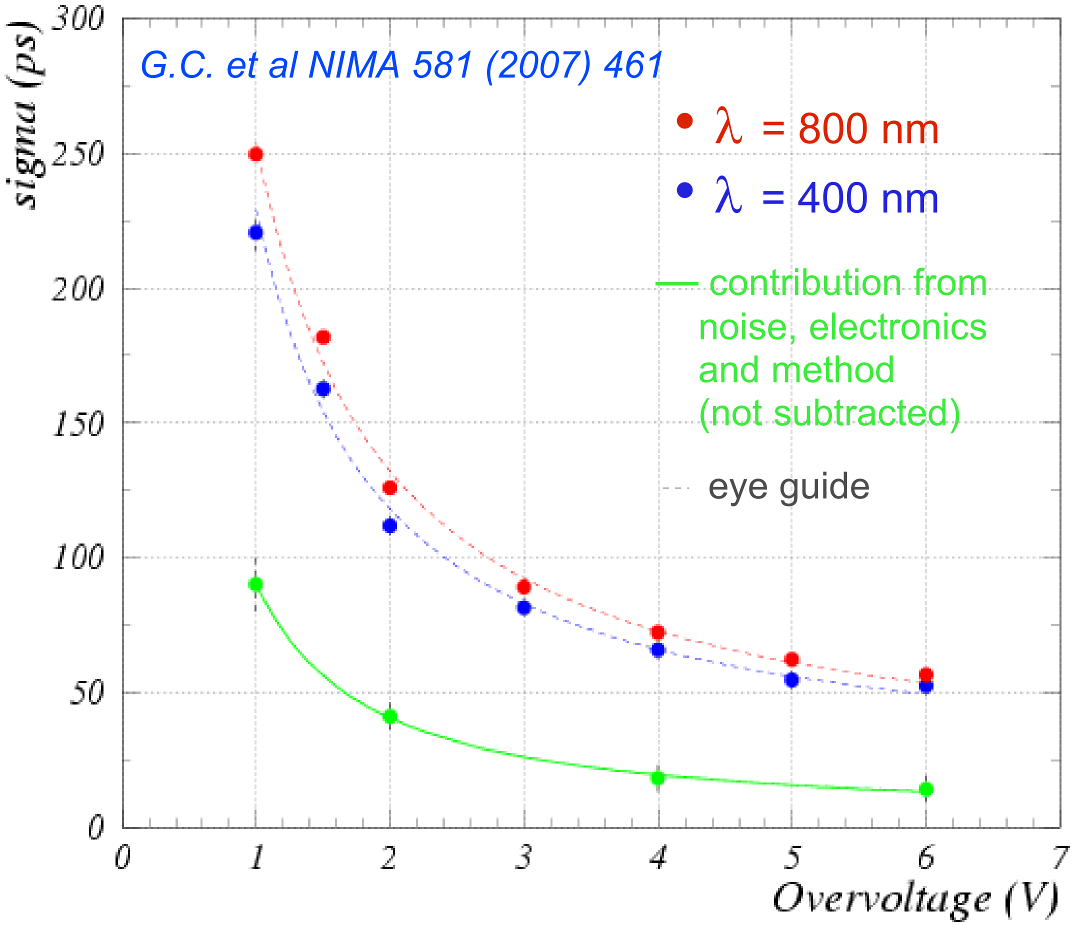


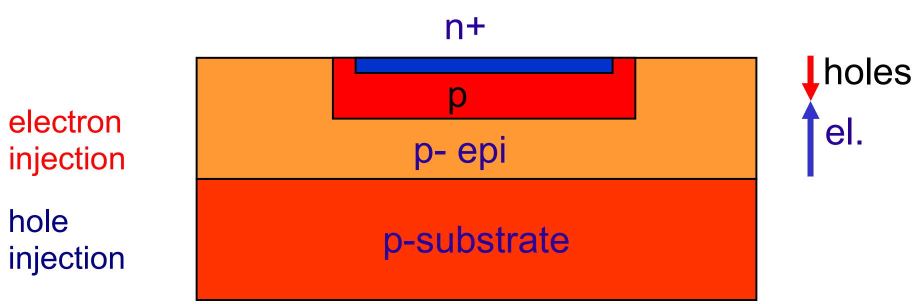


F.Acerbi et al IEEE TNS 61 5 (2014)

Single Photon Timing Resolution (SPTR)

timing measurement with femto-second laser, sampling at 20Gs/s and digital time filtering (optimized for SiPM)





GAUSSIAN timing fluctuations

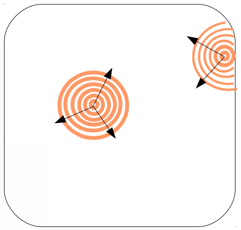
SPTR dependence on wavelength

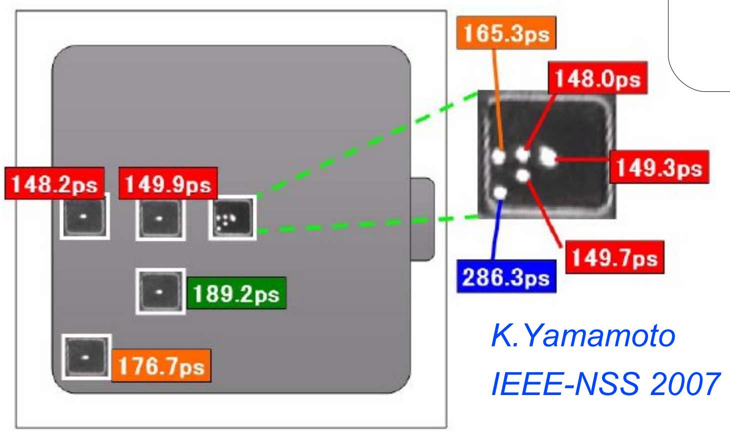
mixed effects of various factors:

- SiPM structure (p-on-n / n-on-p)
- depletion region depth
- high field region location

SPTR dependence on position

- lower field at edges → slower avalanche transverse propagation there
- Time delay across the SiPM can differ significantly and need to be equalized





Single Photon Timing Resolution

NOT-GAUSSIAN timing fluctuations

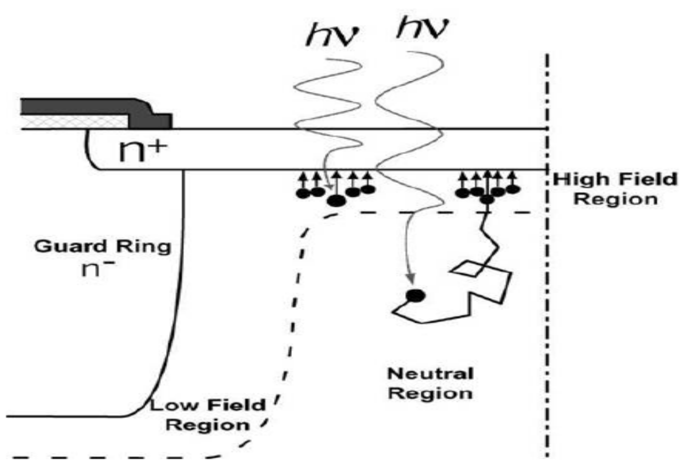
Time resolution of SiPM is not just a gaussian, but gaussian + tails (in particular at long wavelengths)

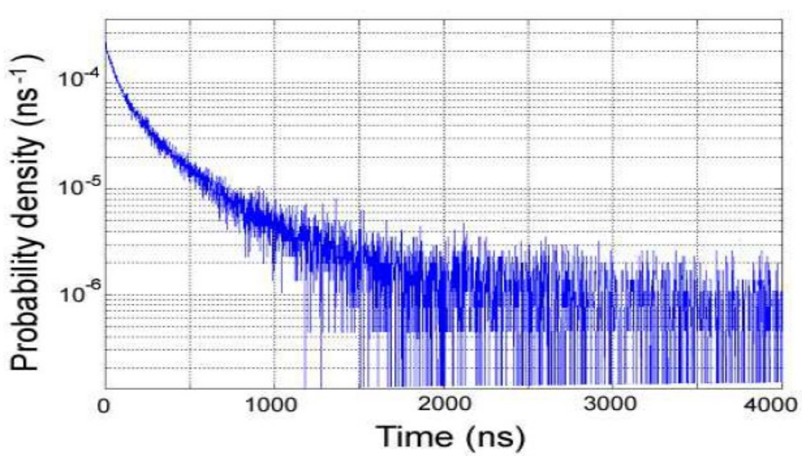
Gaussian + Tails (long λ)

rms ~ 50-100 ps ~ exp (-t / O(ns))

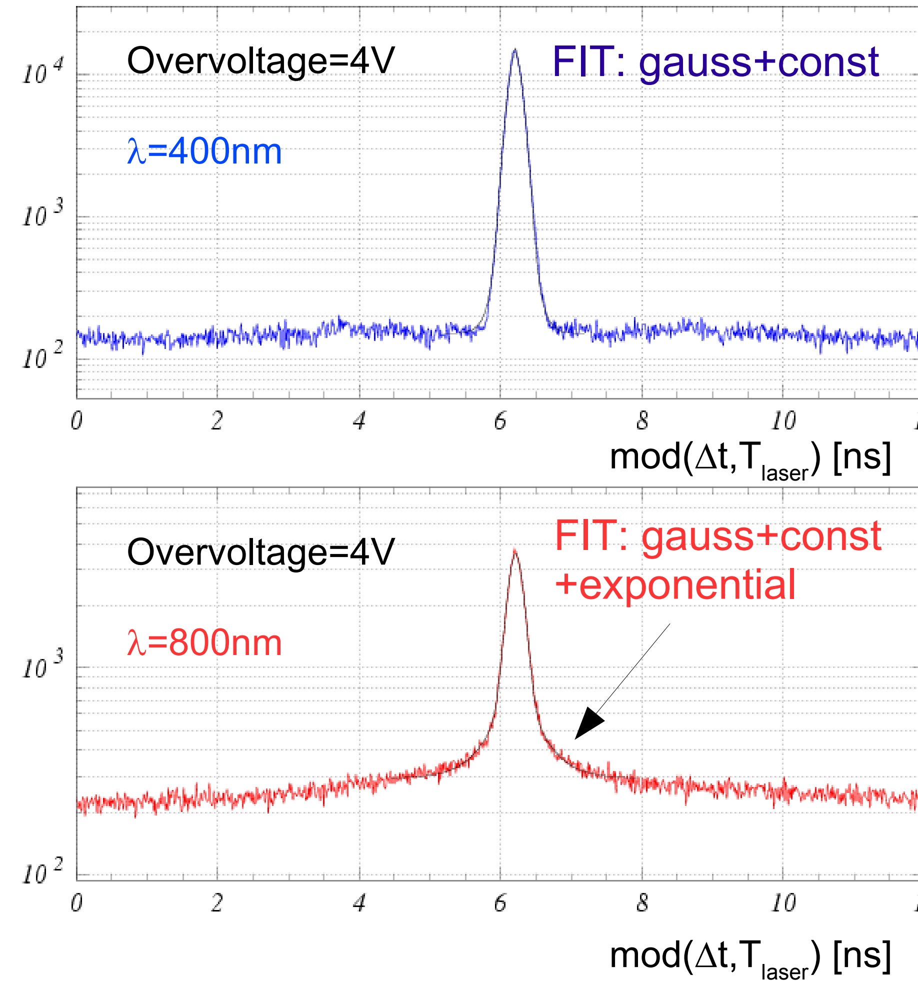
contrib. several % for long wavelengths

G.C. et al NIMA 581 (2007) 461



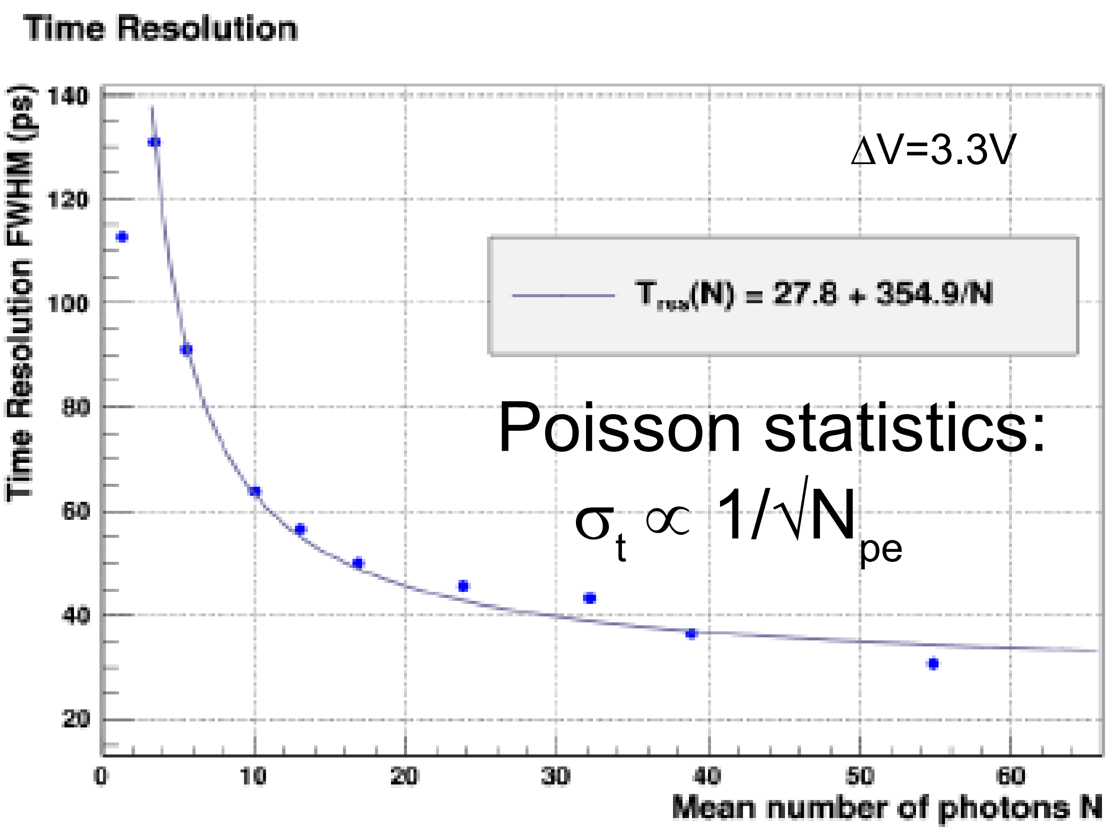


S.Cova et al, NIST Workshop on SPD (2003)



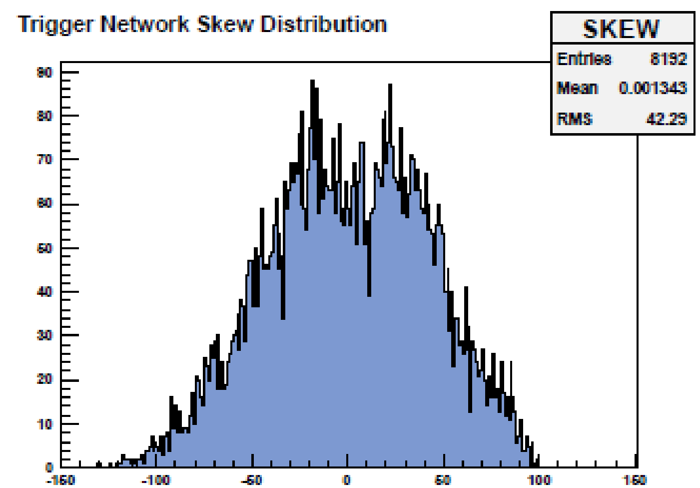
Distributions of the difference in time between successive peaks

Digital- SiPM timing resolution



Dependence on N_{pe} (simultaneous photons)

T.Frach at LIGHT 2011

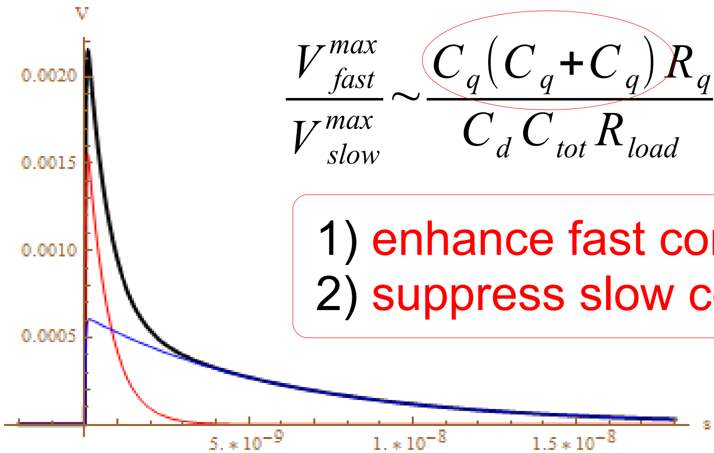


- Sensor triggered by attenuated laser pulses at first photon level
- Laser pulse width: 36ps FWHM, λ = 410nm
- Contribution to time resolution (FWHM):

  SPAD: 54ps, trigger network: 110ps, TDC: 20ps

- Trigger network skew currently limits the timing resolution

Optimizing signal shape for timing



$$\frac{V_{fast}^{max}}{V_{slow}^{max}} \sim \frac{C_q(C_q+C_q)R_q}{C_d C_{tot} R_{load}} \longrightarrow$$

1) enhance fast component
2) suppress slow component

Increasing C_q/C_d or/and R_q/R_{load}
→ spike enhancement → better timing
→ slow recovery tail suppressed
→ reduced baseline fluctuations

→ enhanced and well controlled amount of "parasitic" Cq

SensL SiPM architecture for fast timing

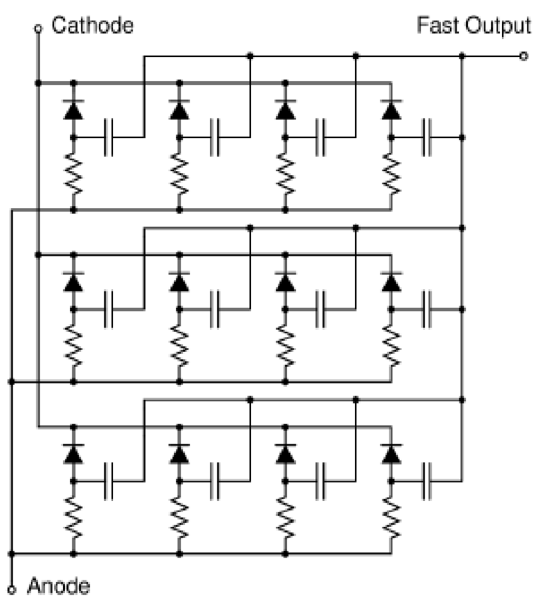
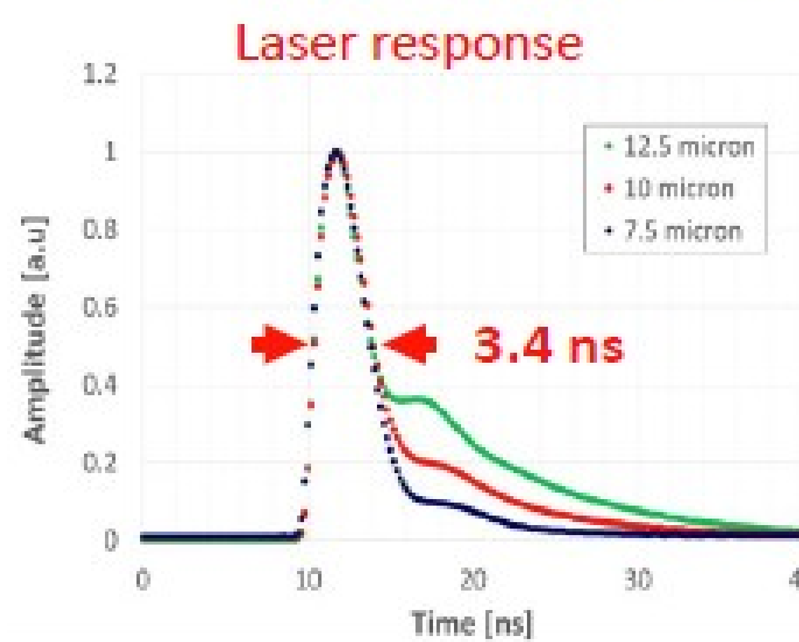


Figure 2: Concept schematic of the SensL fast output SiPM shown as an array of microcells connected in parallel (Courtesy of SensL [9].) Each diode symbol represents an individual p-n junction microstructure. Unlike standard SiPMs, each junction in the SensL device has a connection to a third electrode with a low capacitive coupling.

Tiny cells perform very fast timing



see also O'Neill et al - PhotoDet 2012

Photo-Detection Efficiency - PDE

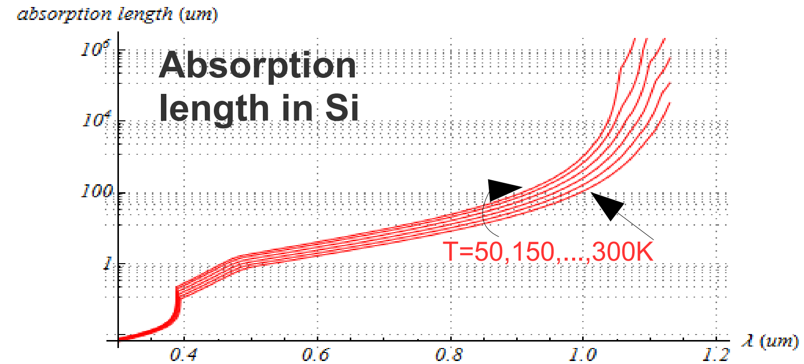
- Factors defining the spectral response shape
- Challenging spectral regions: VUV and NIR sensitive SiPM

see also J.Williams at this Conference

Photo-Detection Efficiency (PDE) → 4 factors

$$PDE = T \cdot QE \cdot P_{01} \cdot FF$$

T: entrance window transmission

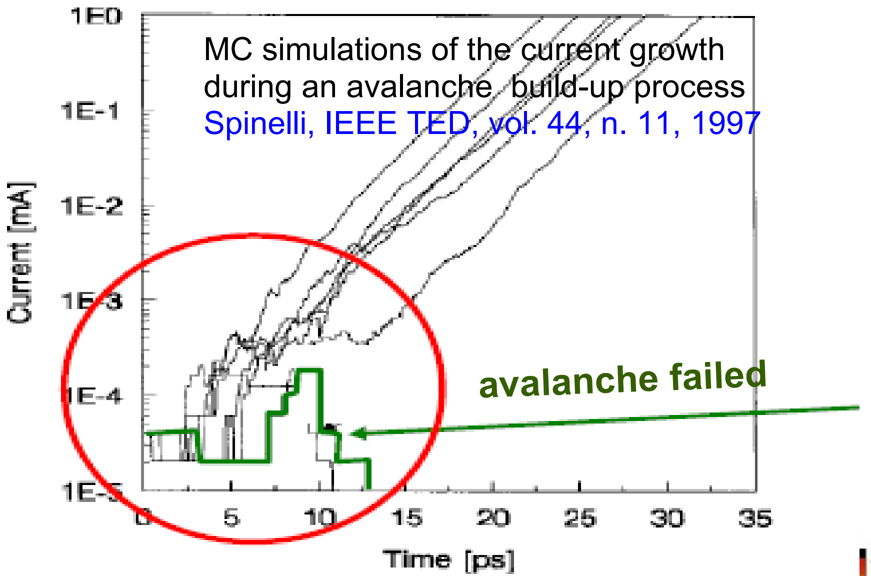


QE: carrier Photo-generation

probability for a photon to generate a carrier (in the **active region**) that reaches the high field region

→ λ and T dependent

→ ΔV independent if full depletion at V_{bd}



P_{01}: avalanche triggering probability

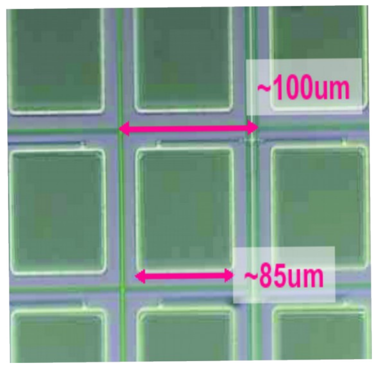
probability for a carrier traversing the high-field to **generate the avalanche**

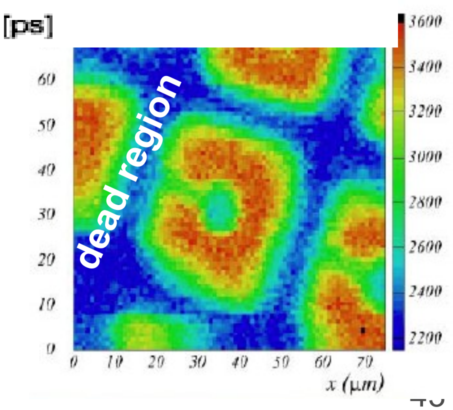
→ λ, T and ΔV dependent

FF: geometrical Fill Factor

fraction of dead area due to structures between the cells, eg. guard rings, trenches

→ negligible ΔV dependence (cell edges)



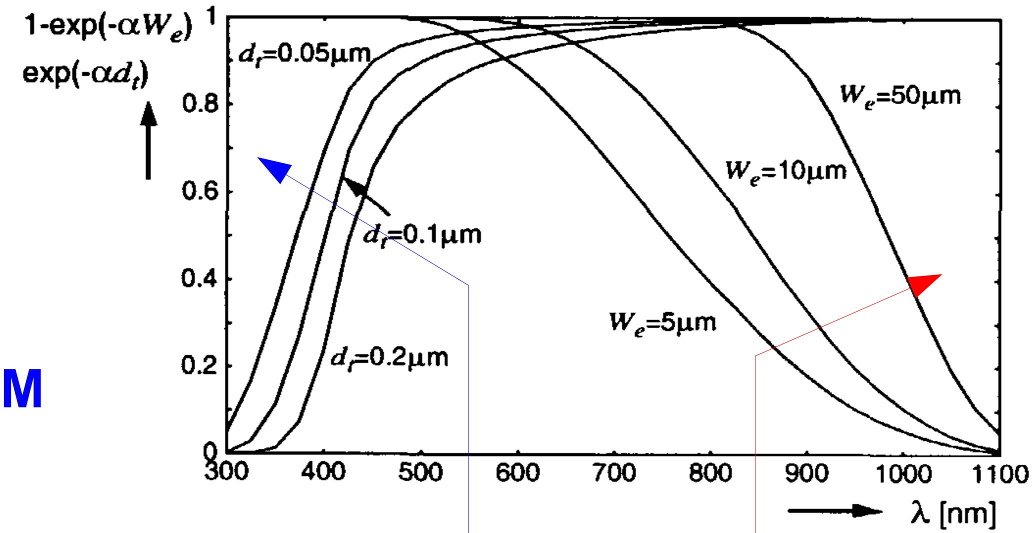


Transmission & QE → PDE shape vs λ

W.Knidt PhD Thesis 1999

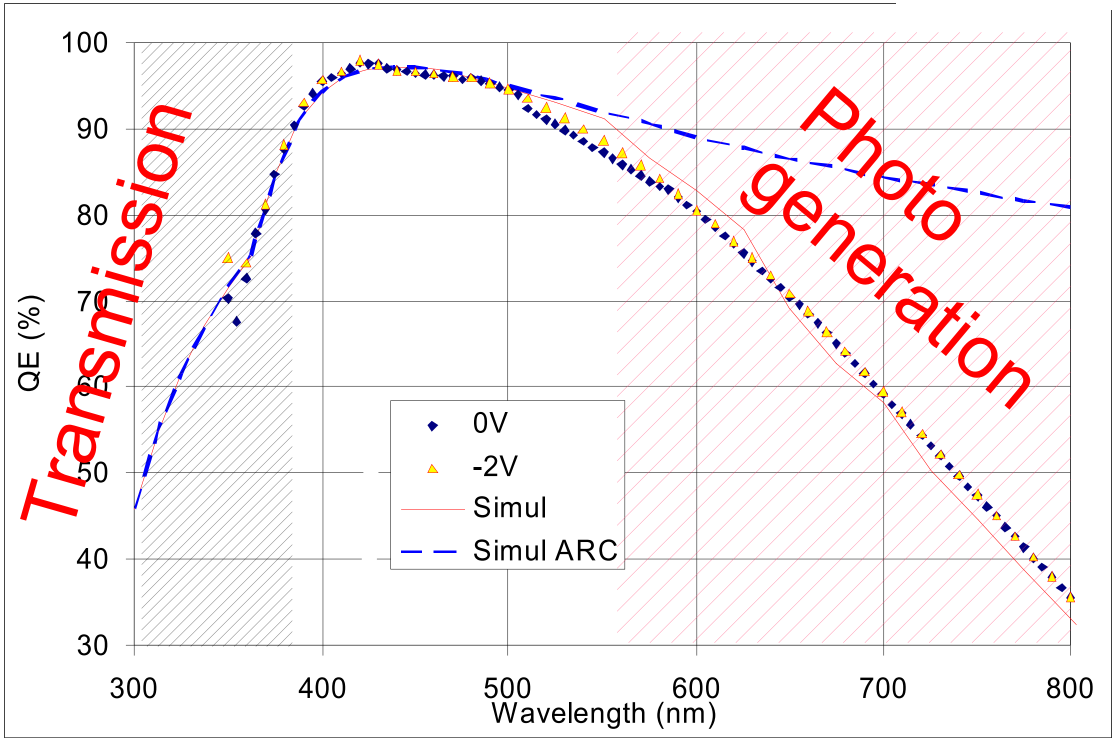
Limiting factors for short wavelengths:
- ARC Transmittance
- Superficial Recombination

Most critical issue for **VUV SiPM**



Decreasing thickness of top layer

Increasing thickness sensitive layer



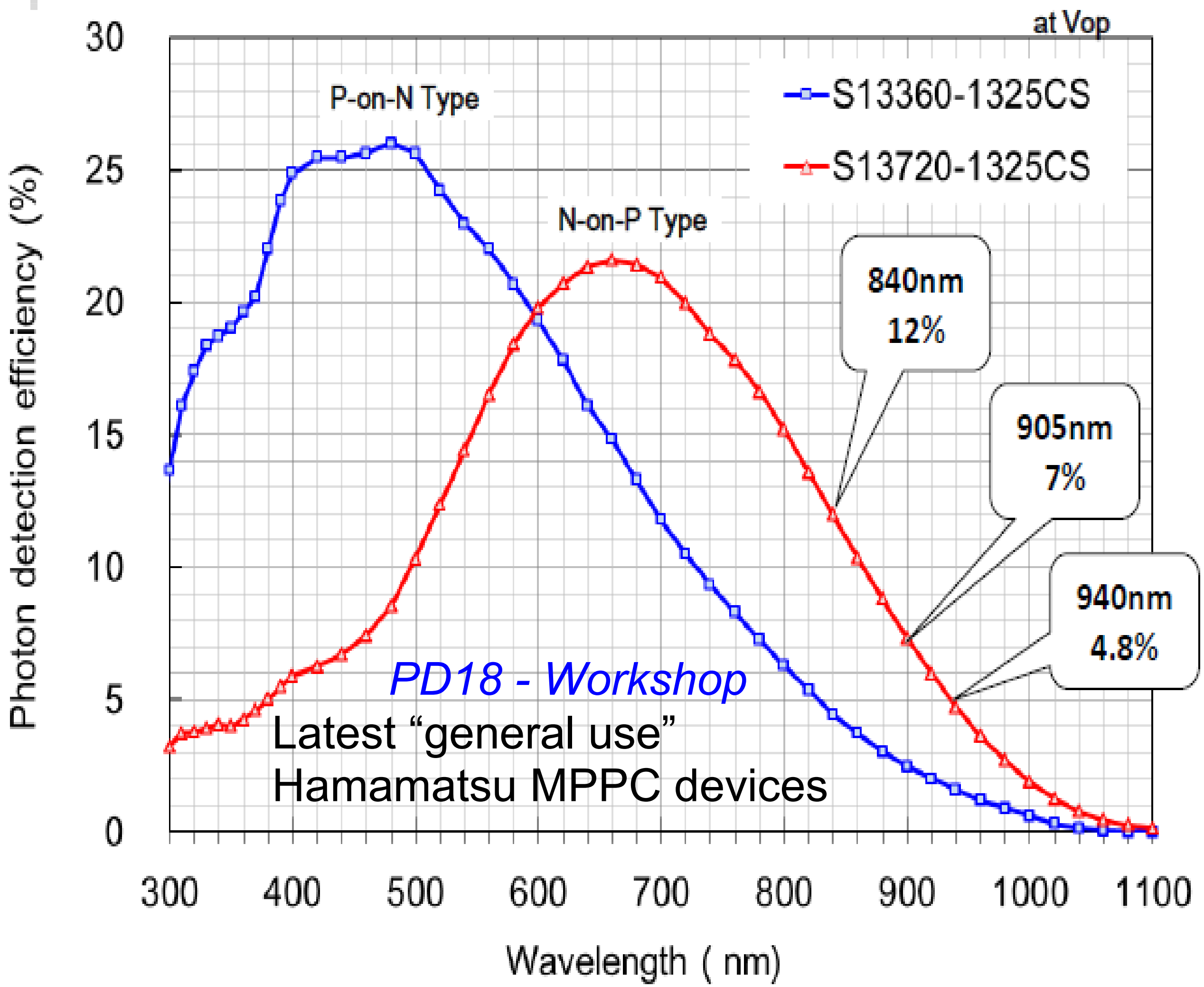
Limiting factors for long wavelengths:
- depth of π layer thickness or depleted region

Issue for **NIR SiPM**

FBK single diode (2006)

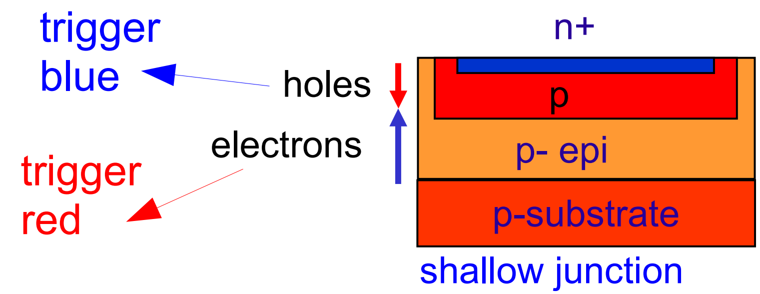
photo-voltaic regime ($V_{bias} \sim 0$ V)

Avalanche Triggering Probability → tuning PDE shape

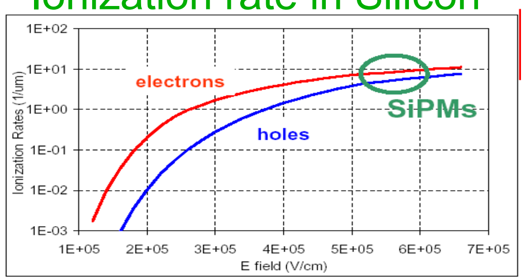


n-on-p structures

sensitivity peak → green-red

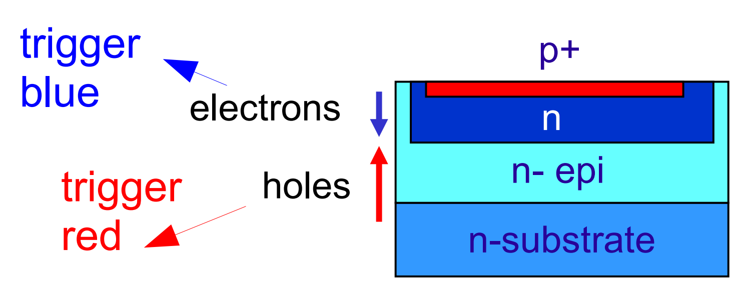


Ionization rate in Silicon



p-on-n structures

sensitivity peak → blue

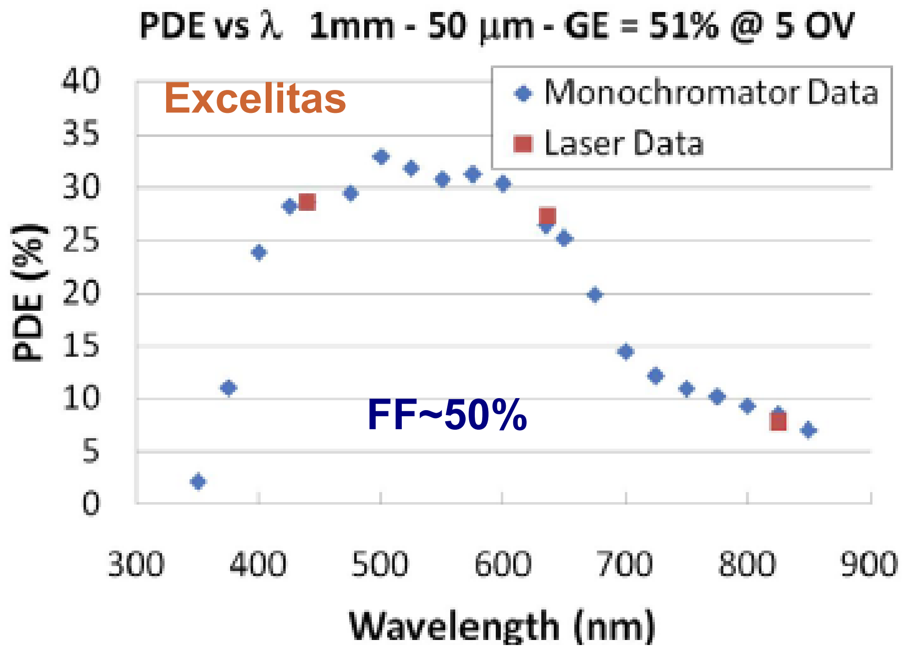


Tuning PDE spectrum:
(matching applications)

- structure type (shallow or reach trough)
- junction type (p-on-n or n-on-p)

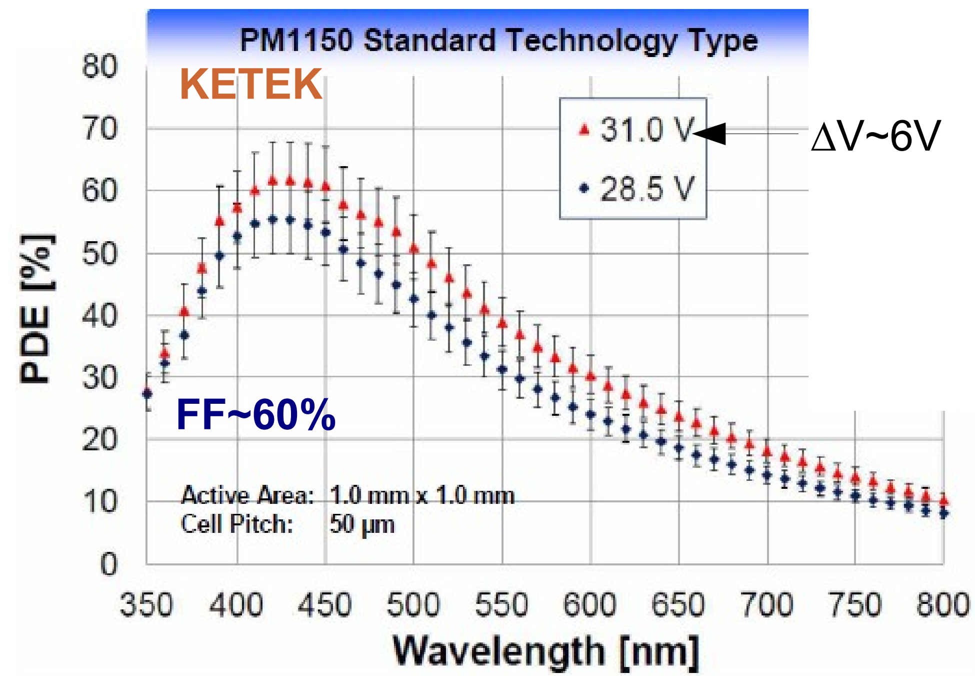
Avalanche Triggering Probability → PDE improving

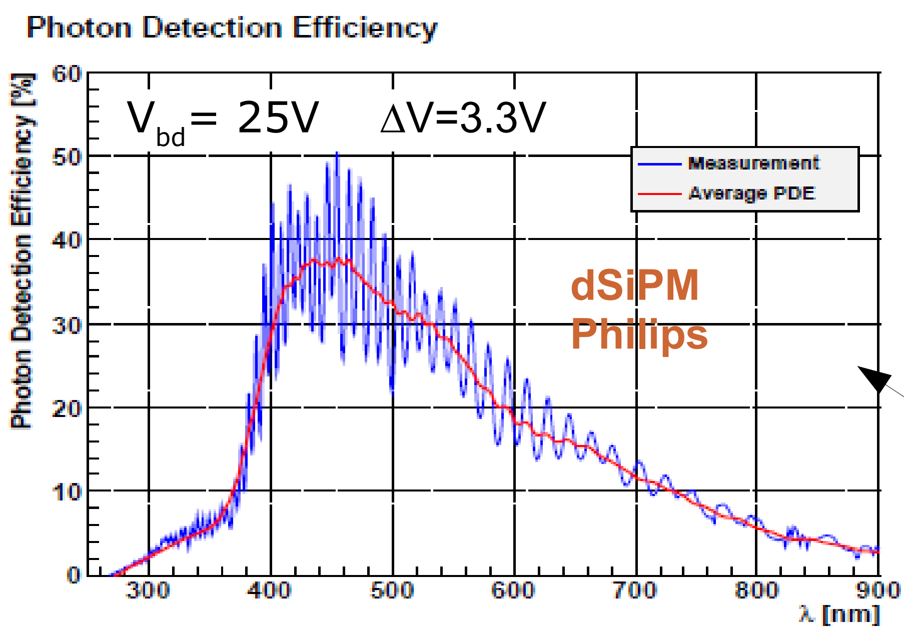
Barlow – LIGHT 2011



→ PDE peak constantly improving for many devices
→ every manufacturer shape PDE for matching target applications

F.Wiest – AIDA 2012 at DESY



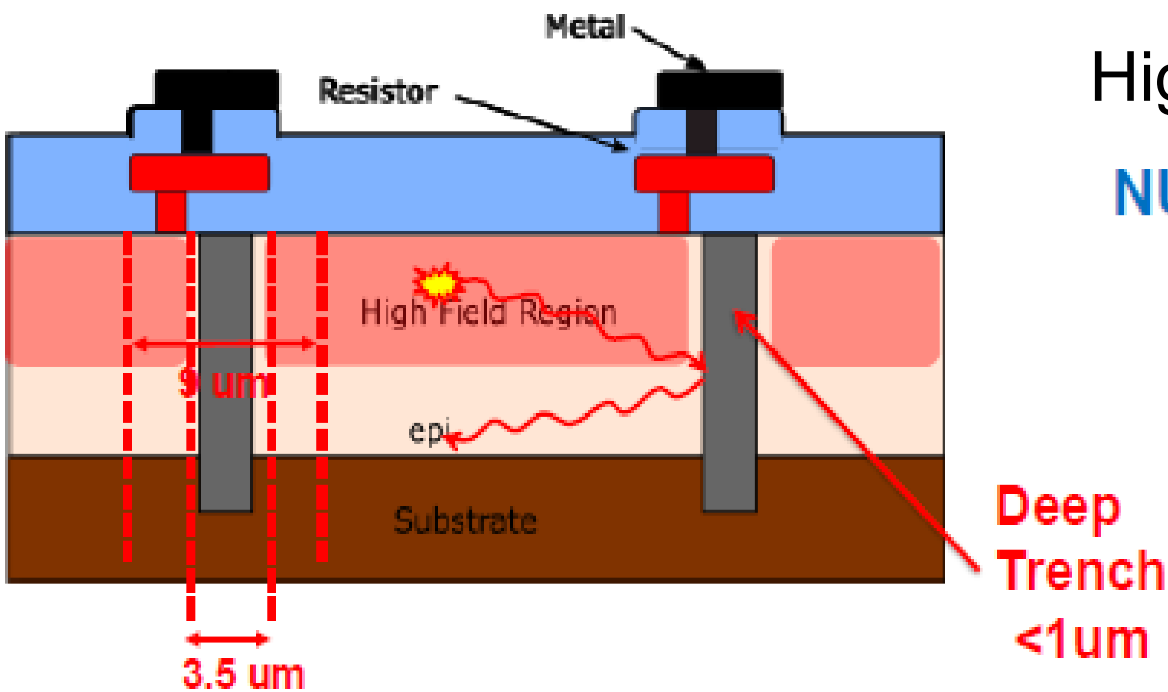


T.Frach 2012 JINST 7 C01112

Digital SiPM (Philips)
→ optical stack optimization can be improved
→ no anti-reflecting coating
→ potential improvement up to 60% peak PDE
Y.Haemish at AIDA 2012

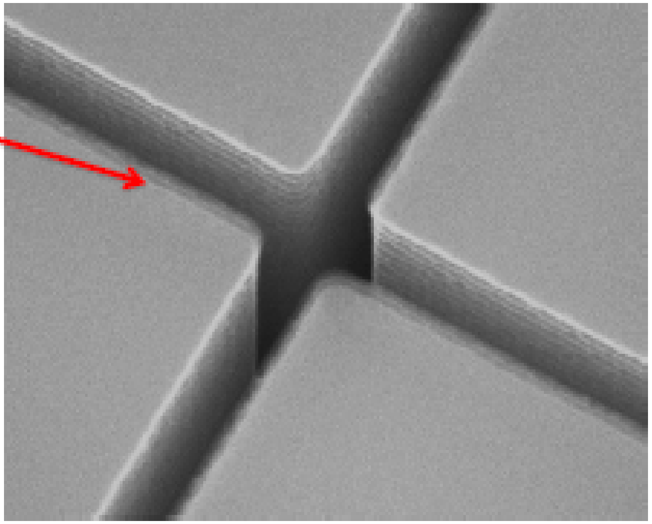
Fill Factor – Recent Improvements

- Narrow dead border region (virtual guard ring)
- Deep & narrow trenches (against cross-talk, see later)



High Density FBK tecnology

NUV-HD and RGB-HD SiPMs (2015)

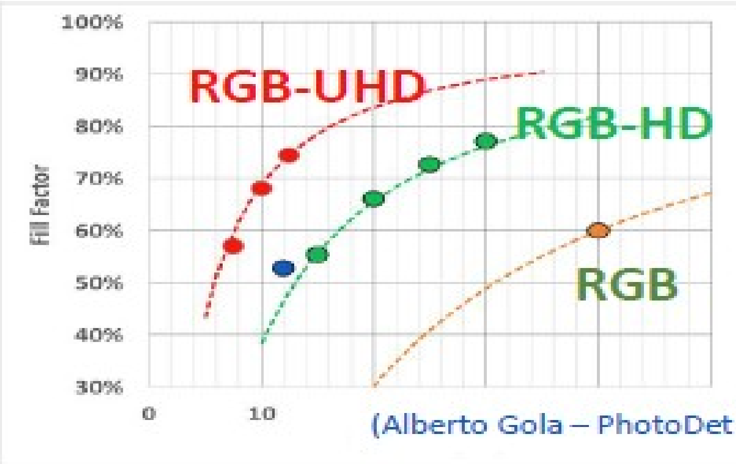


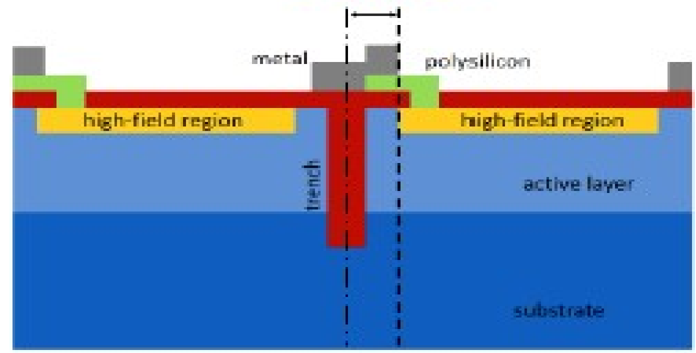
Make it simple: 9 lithographic steps

Courtesy – Giovanni Paternoster (FBK) – Oct 2018

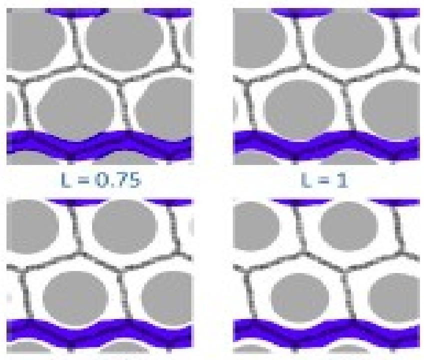
Fill Factor – Recent Improvements → HFF Tiny cells

(example FBK)

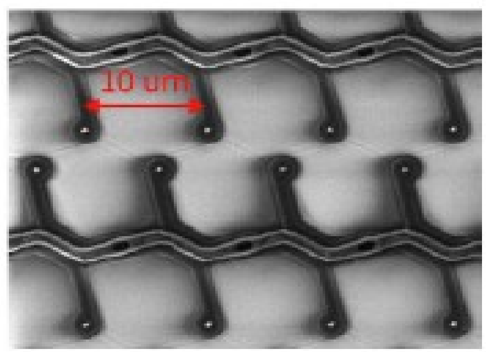




Cell sensitive area vs. trench width



Finished 10 μm cell pitch SiPM



Fill Factor vs. trench width

L (um)	Fill Factor
0.75	57.1%
1	48.8%
1.25	40.3%
1.5	32.6%

RGB-HD

cell pitch (μm)	cells/mm²
12	7000
15	4500
20	2500
25	1600
30	1100

RGB-UHD

cell pitch (μm)	cells/mm²
7.5	20530
10	11550
12	7400

- **High FF even for tiny cells**
- **Virtual Guard Ring** is the limiting factor
- Trench mitigates GR limitation

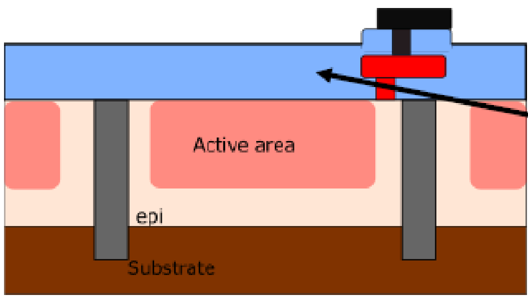
Extending SiPM Spectral Response

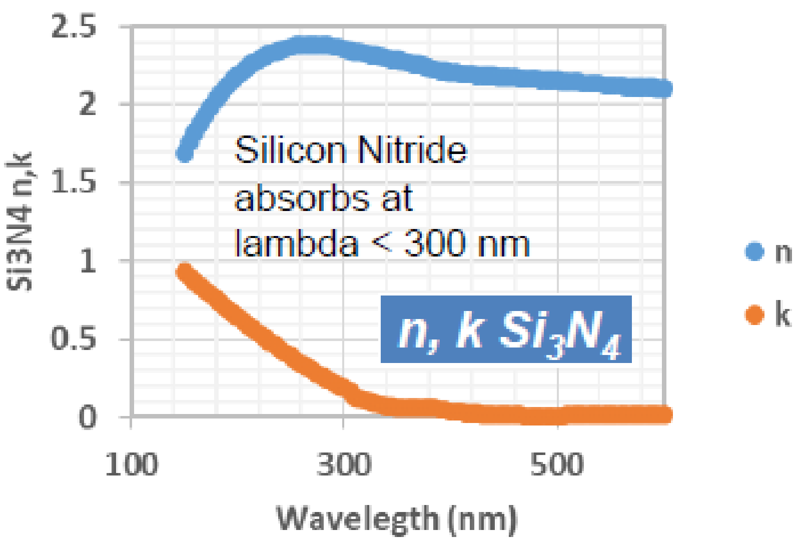
VUV and NIR sensitive devices

VUV SiPM - Challenges

Courtesy – Giovanni Paternoster (FBK) – Oct 2018

1. **Anti-Reflective Coating (ARC)**
   - VUV light can reflect on SiPM
   - VUV light is absorbed in the dielectric layers protecting the SiPM

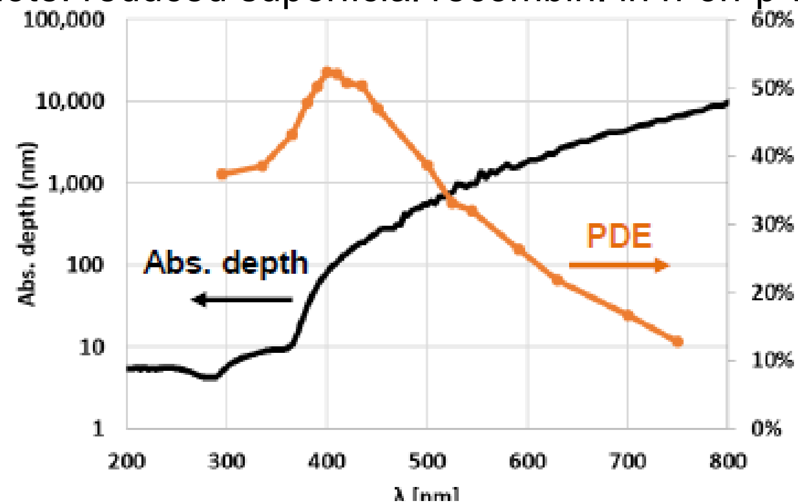




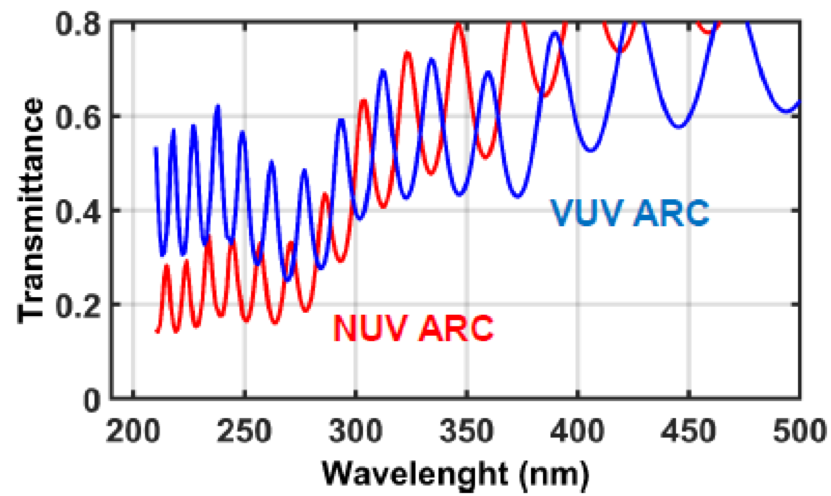
2. Ultra-shallow interaction depth in Silicon

(possible QE losses due to surface recombination).

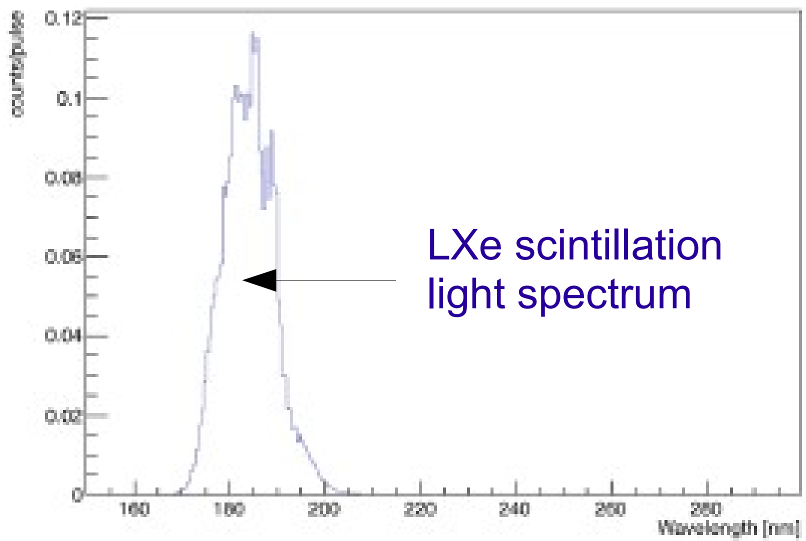
note: reduced superficial recombin. in n-on-p wrt p-on-n

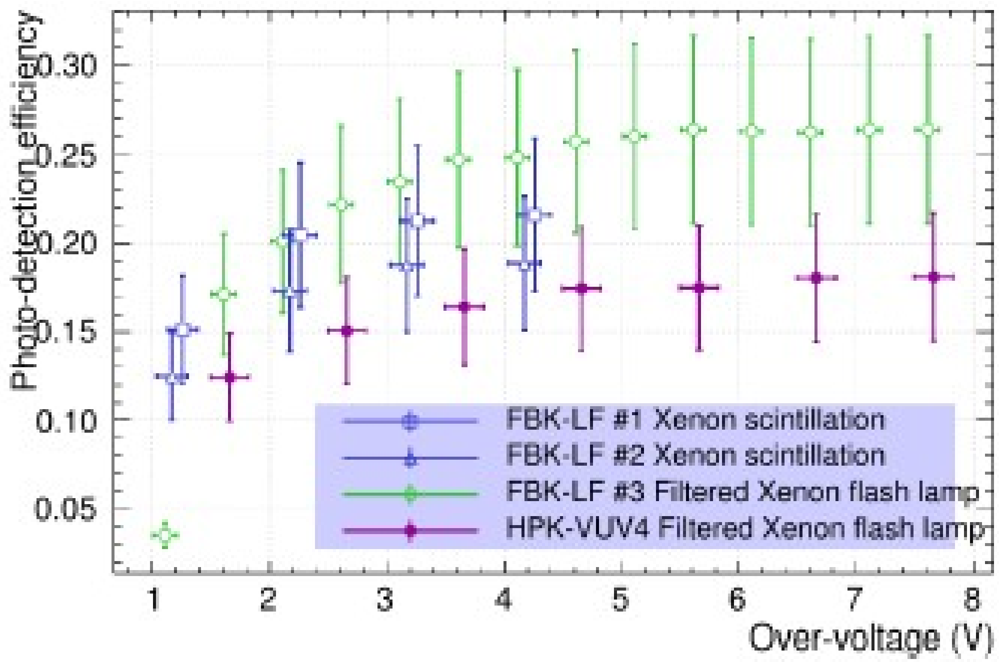


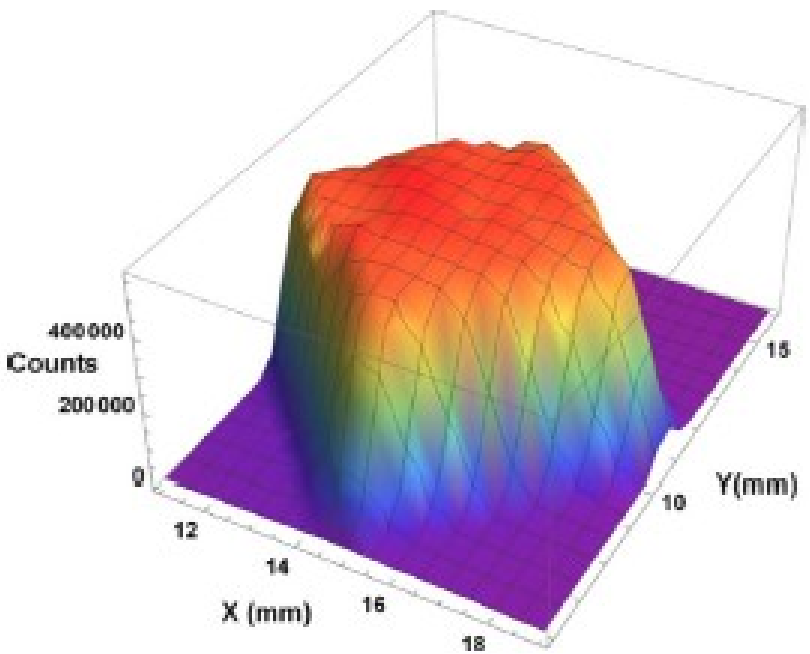
New VUV ARC:
- Elimination of SiN
- Preservation of the surface passivation quality



VUV SiPM – Characterization (λ ~ 175nm)





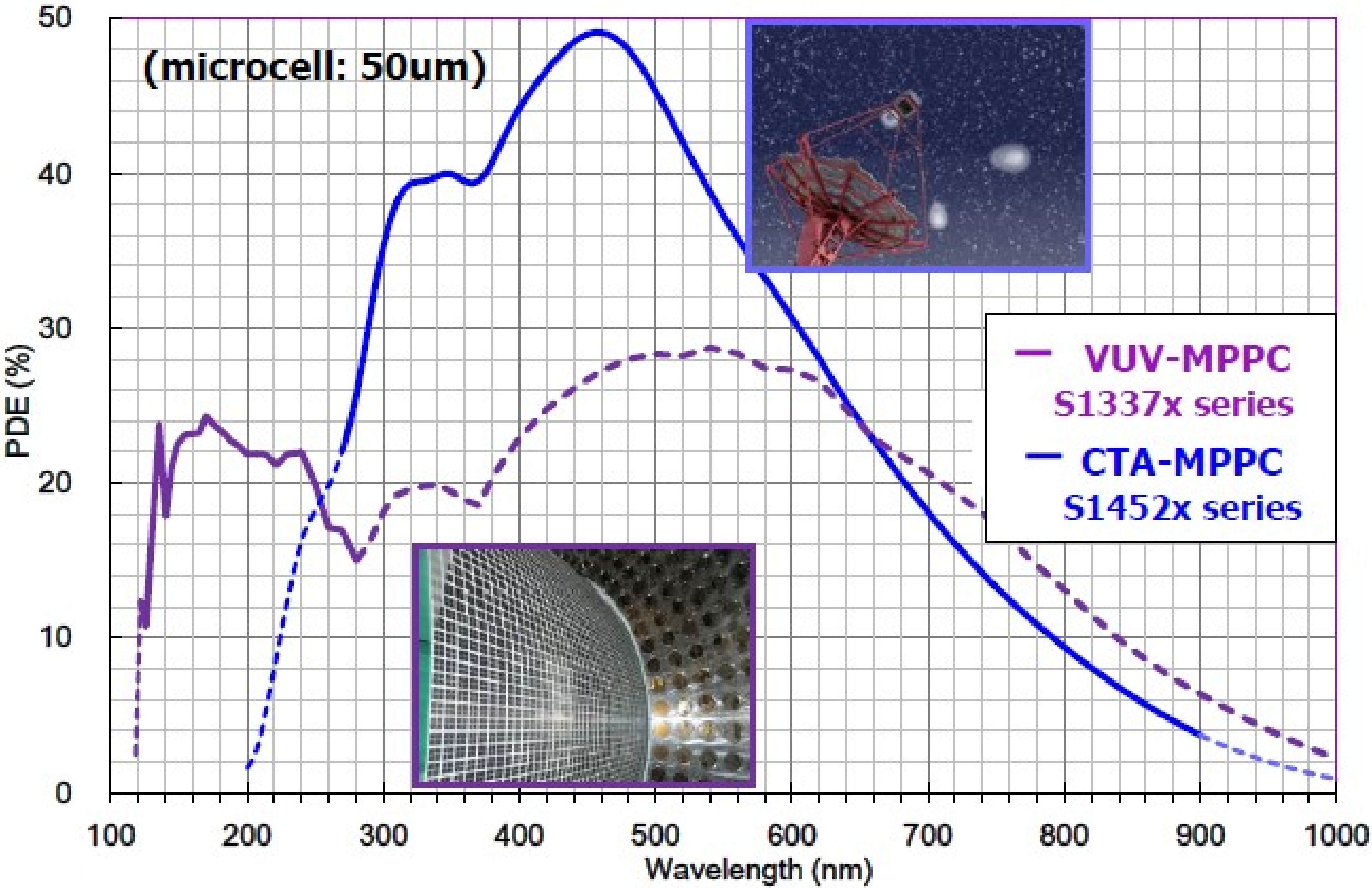


- PDE determined via mean number of detected photo-electrons
- Corrected for dark noise
- Devices: FBK 2016 LF & Hamamatsu VUV4
- Stanford: Xenon scintillation light TRIUMF: Xenon flash lamp

Michael Wagenpfeil (nEXO collaboration) – ICASiPM 2018

Hamamatsu recent
"MPPC for Scientific Applications"

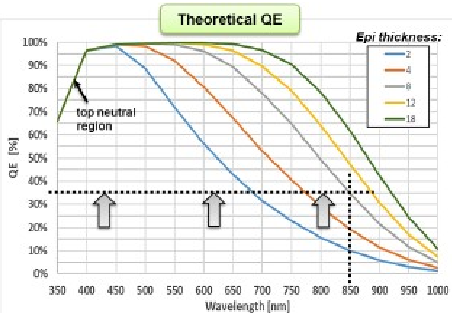
Koei Yamamoto (Hamamatsu) – PD18 Workshop – Dec 2018

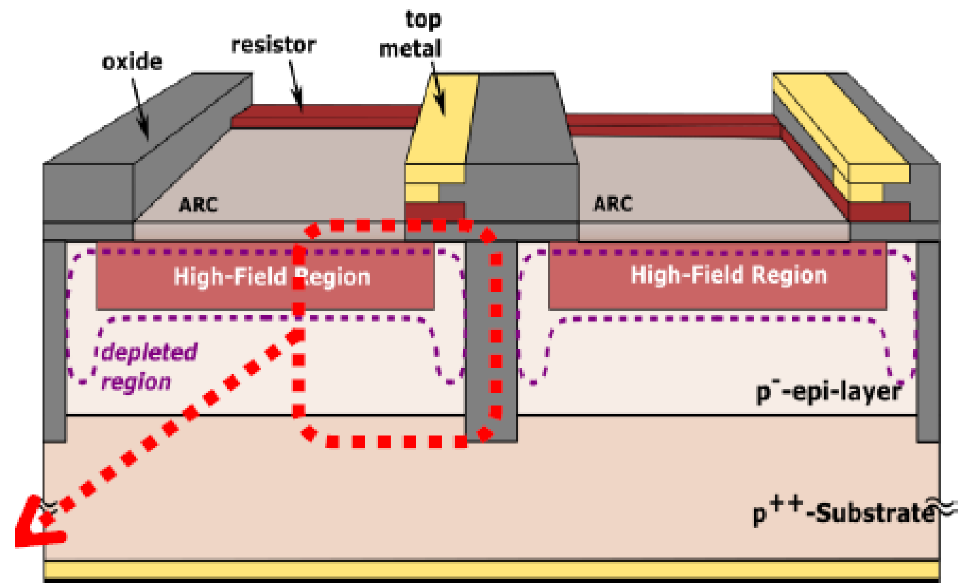


NIR SiPM - Challenges

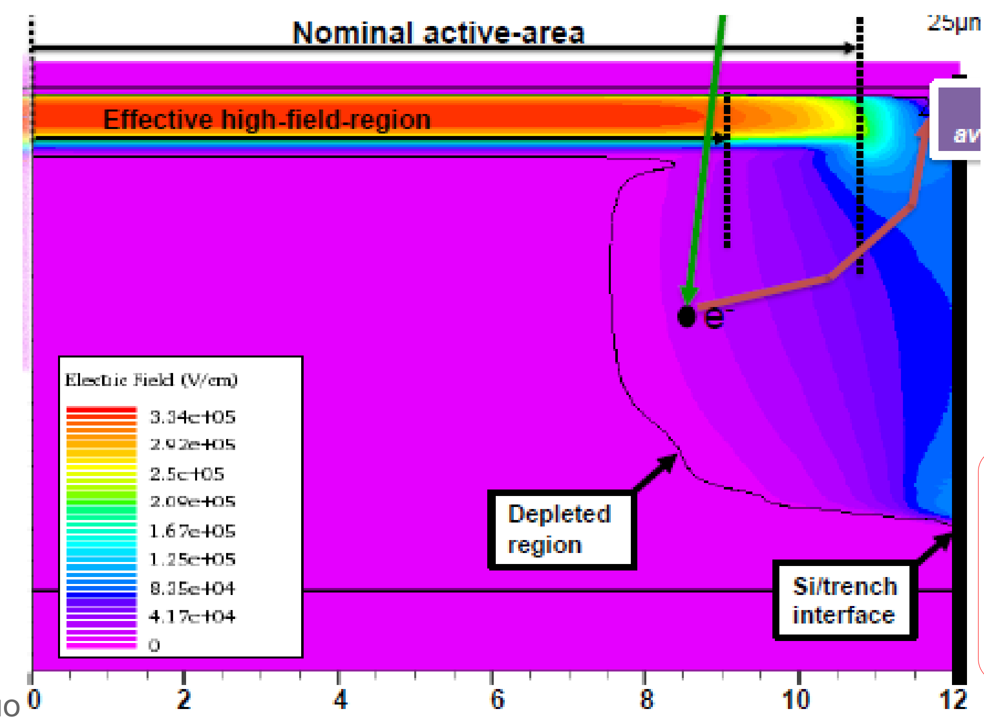
Fabio Acerbi (FBK) – NDIP 2017

- Increase **PDE** at long wavelength
  - Thicker epitaxial layer
  - Deeper trenches for cell electrical isolation
- In SiPM → High FF has to be preserved (also at high depth)
  - This is not a SPAD → *NIR sensitive SiPM is more challenging*
  - The inactive border of the cell can be very important → to be reduced
- Breakdown voltage should stay low
  - Keeping the low temperature dependence *(important in industrial and automotive app.)*





Acerbi et al, 2018 10.1109/JQE.2018.2802542

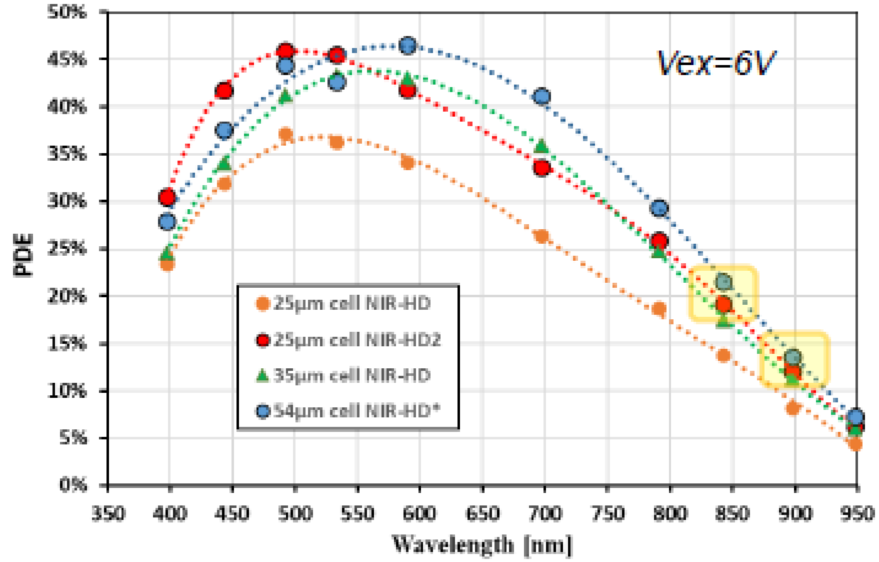


Two "**border effects**" → **reduced eff. FF**
1. High-Field region narrower than nominal
2. Lateral depletion below HF → lateral drift

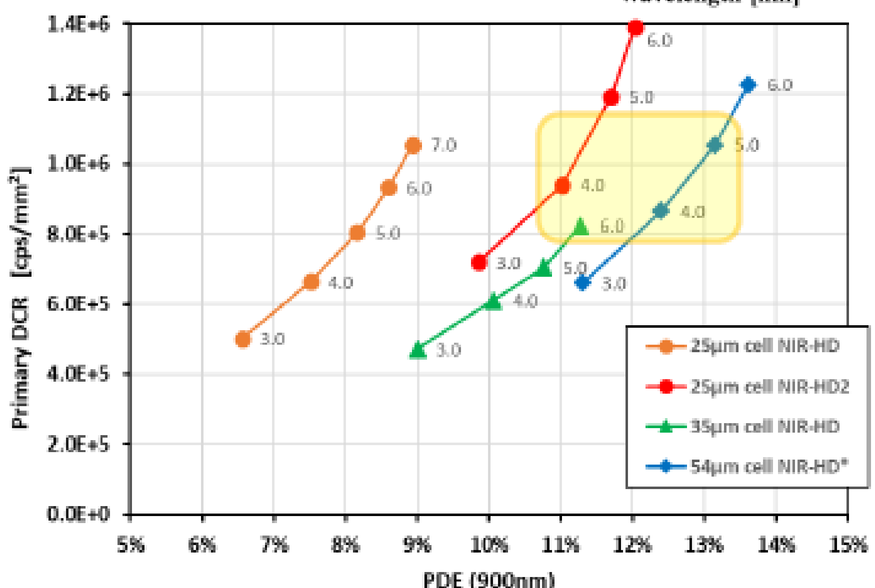
NIR SiPM – first results FBK

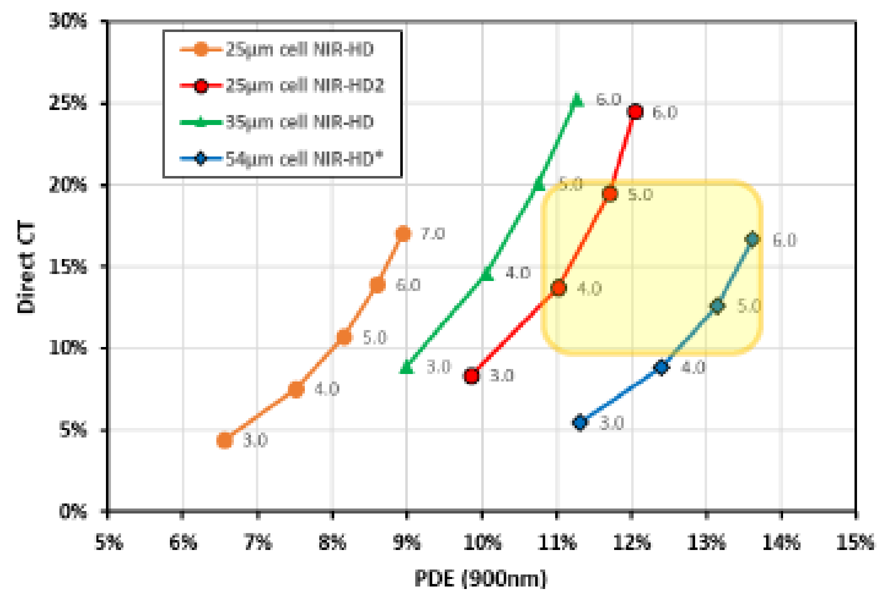
Fabio Acerbi (FBK) –
PD18 Workshop – Dec 2018

- **Modified doping profile → improved thick epi structure:**
  - Enhancement of the effective high field region (but not close to trench, to avoid higher noise !)
  - Reduction of the lateral depletion



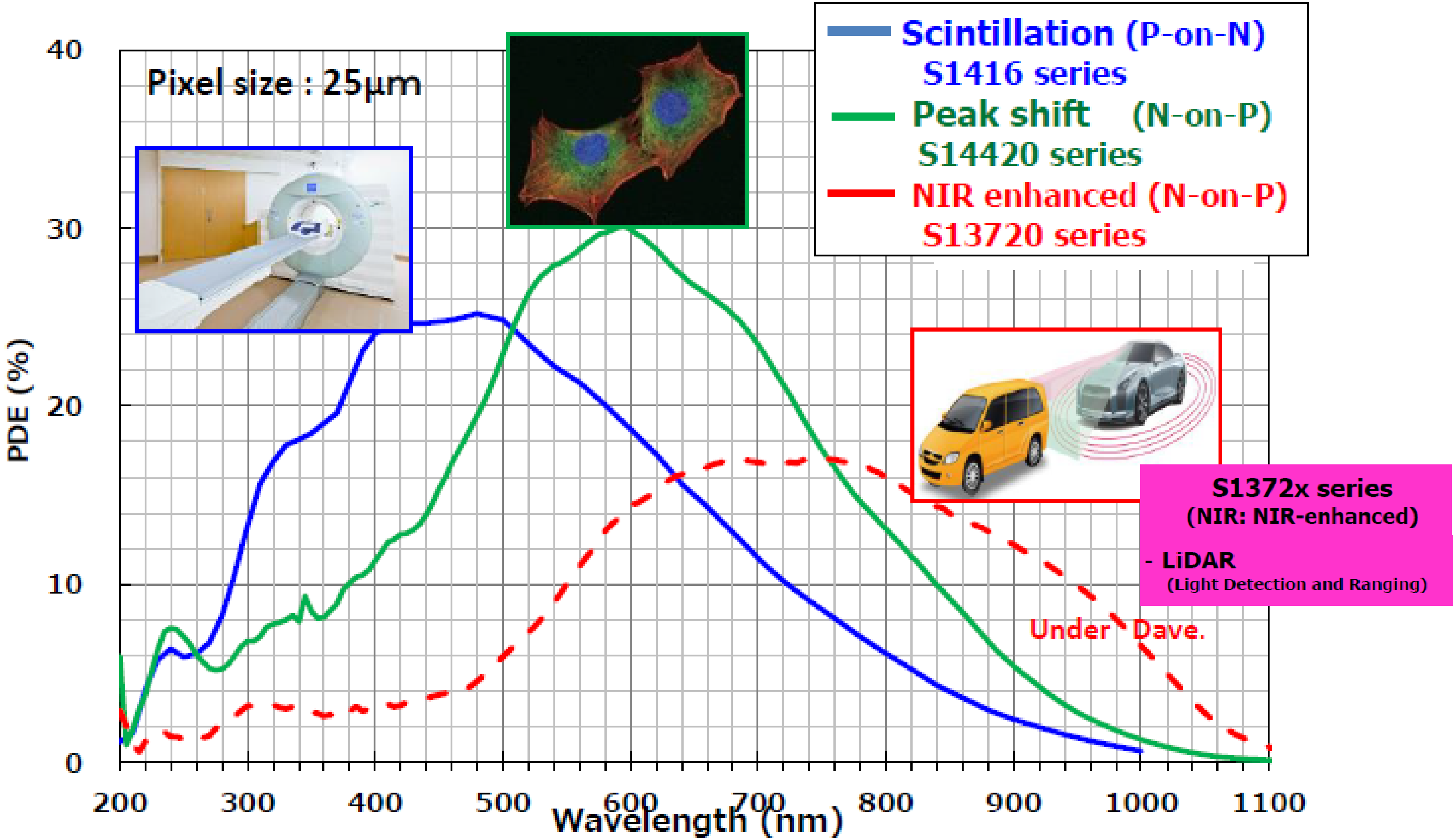
- **New NIR-HD technology:**
  - Primary DCR in the order of ~1Mcps/mm²
  - Direct CT: ~10÷20%
  - With a PDE:
    17% ÷ 20% @850nm
    11% ÷ 13% @900nm





Hamamatsu recent "MPPC for Industrial Applications"

Koei Yamamoto (hamamatsu) – PD18 Workshop – Dec 2018



Dark noise for present NIR SiPMs (first generation) ~ 1MHz/mm^2

Noise in SiPM

Primary noise
→ dark counts

→ Single photo-electron noise

Correlated “excess” charge
→ After-pulsing
→ Optical Cross-Talk

→ Worse Photon-counting and Energy resolution

Dark Noise in SiPM

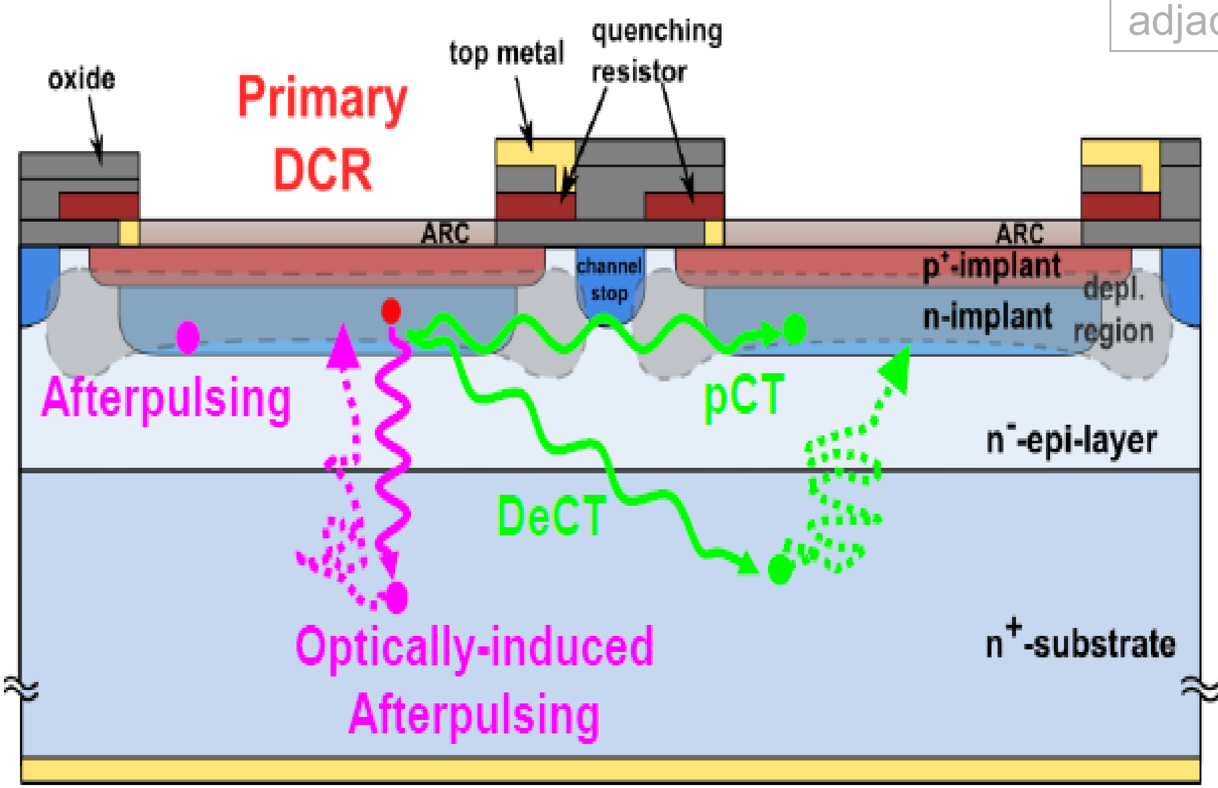
Primary noise
→ dark counts

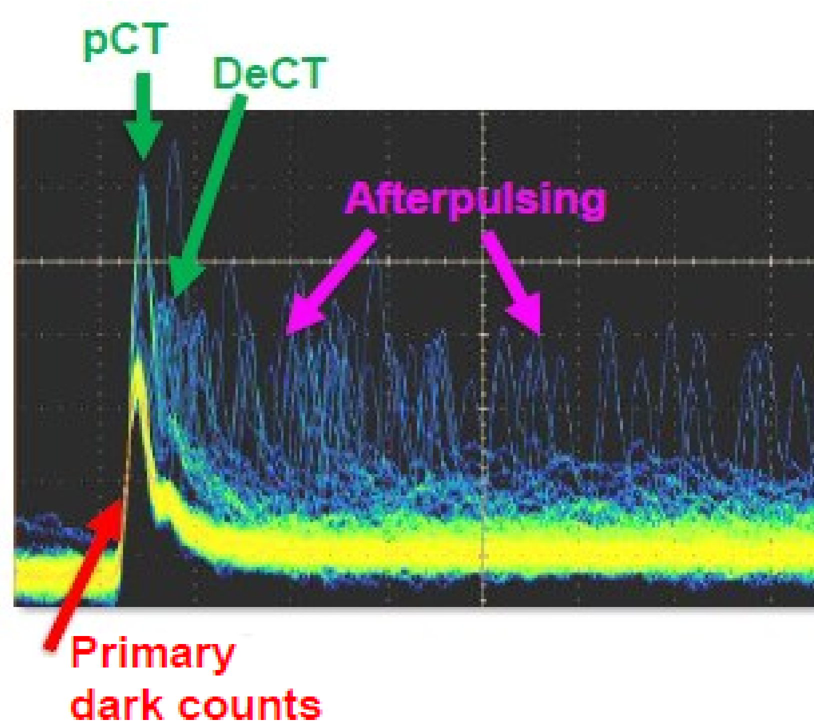
pulses triggered by non-photo-generated carriers (thermal / tunneling generation in the bulk or in the surface depleted region around the junction)

Correlated "excess" charge
→ After-pulsing
→ Optical Cross-Talk

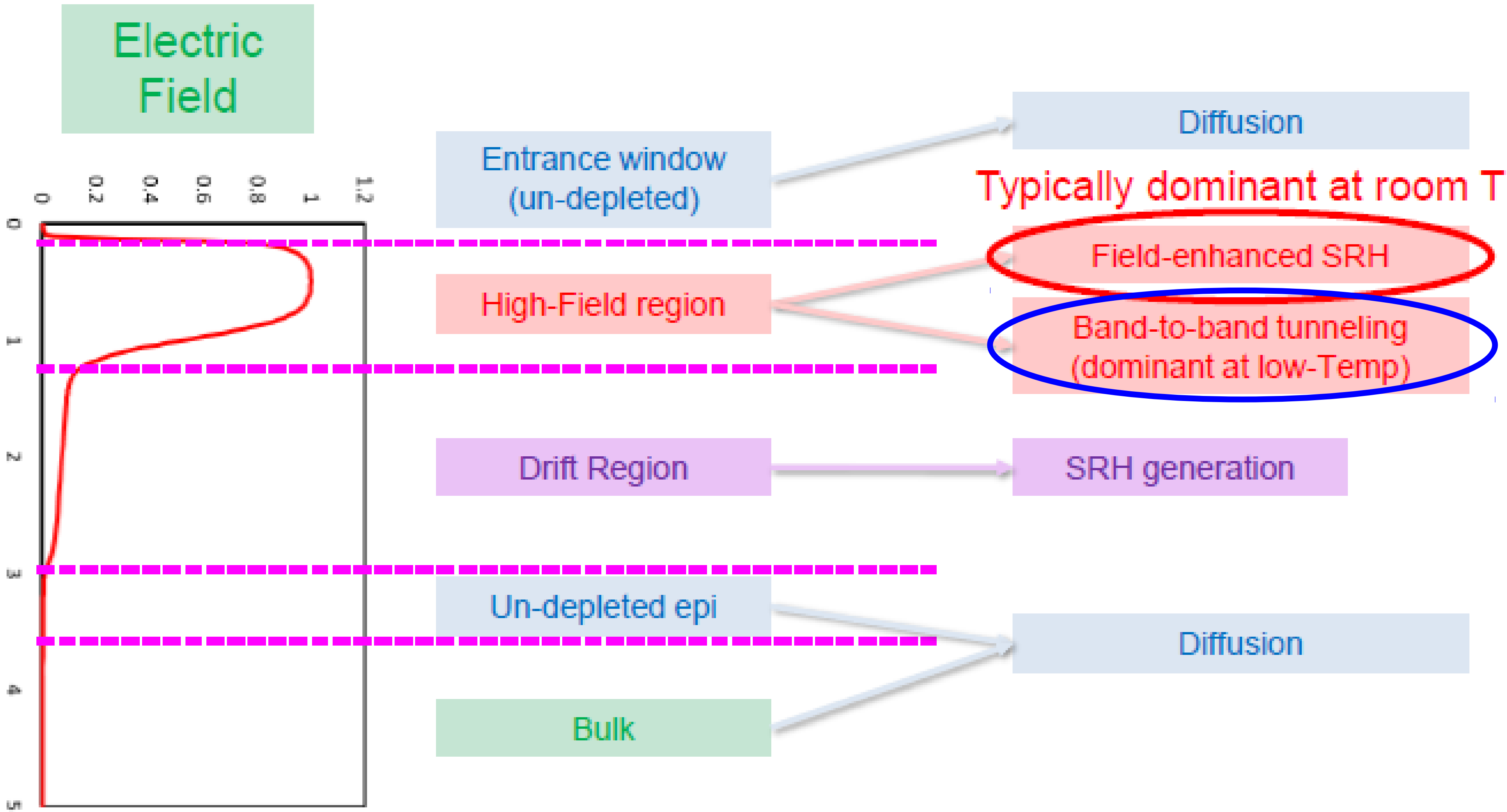
carriers can be trapped during an avalanche and then released triggering another avalanche

photo-generation during the avalanche discharge. Some of the photons can be absorbed in the adjacent cell possibly triggering new discharges





Sources of Dark Counts

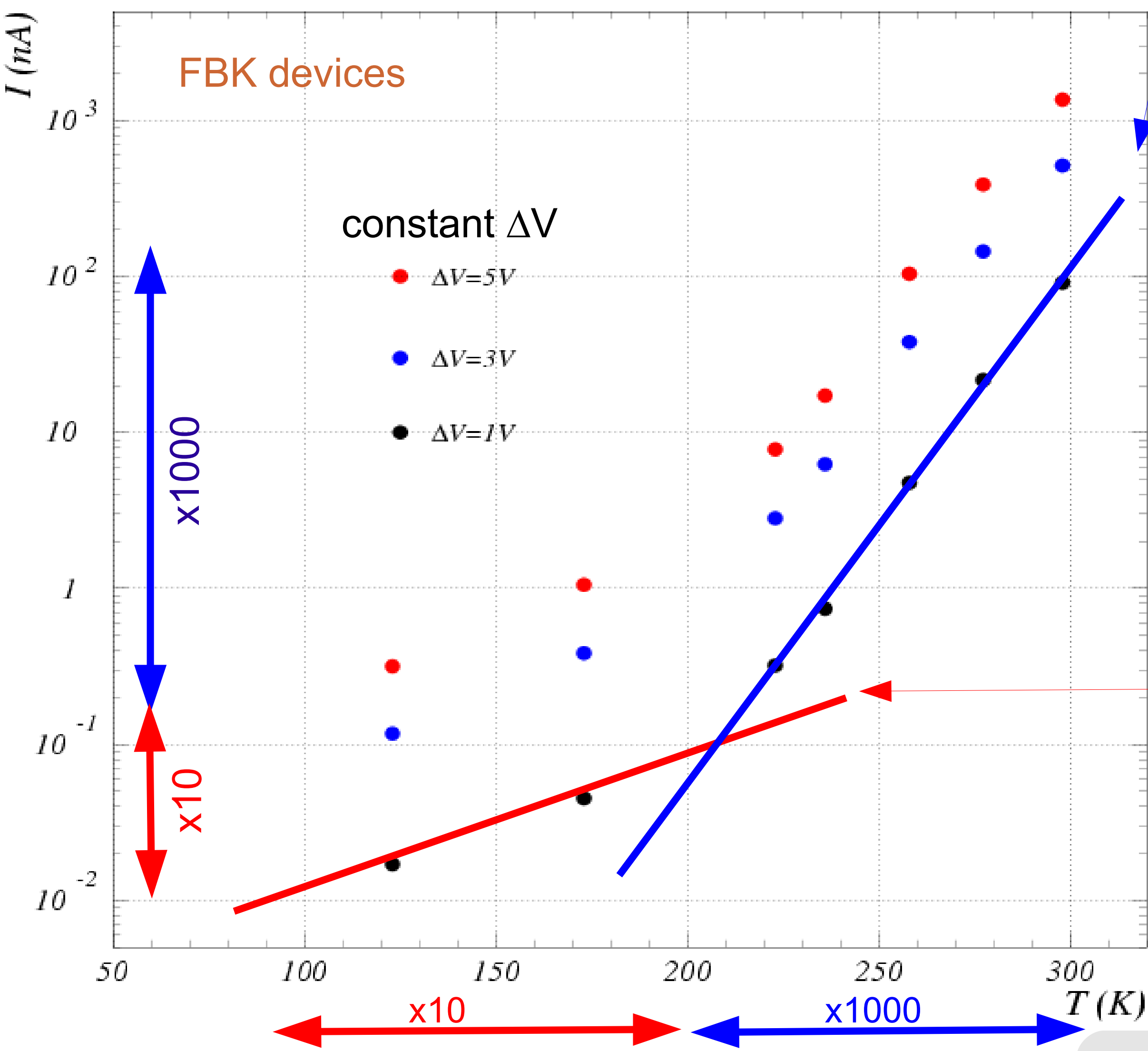


All these components have different dependence on device parameter and on temperature..

Courtesy – Alberto Gola – ICASiPM 2018

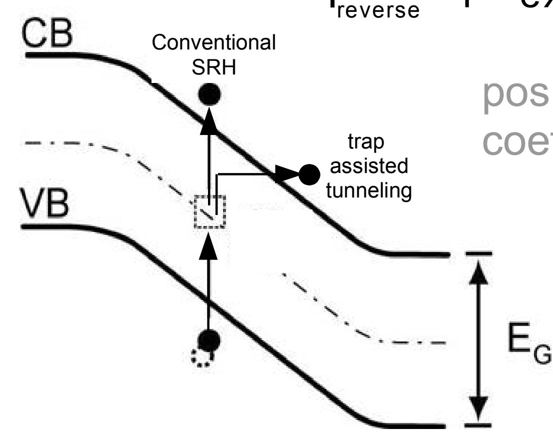
Sources of Dark Counts → Dark current vs T

Noise mainly comes from the high E Field region
(no whole depletion region)



1) Generation/Recombination SRH noise (enhanced by trap assisted tunneling)

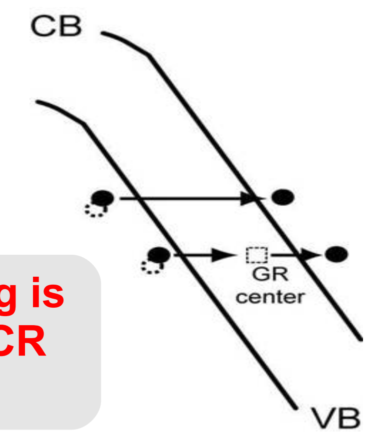
$$I_{reverse} \sim T^{1.5} \exp \frac{-E_{act}}{K_B T}$$



positive T coefficient

2) Band-to-band Tunneling noise (strong dependence on the Electric field profile)

negative T coefficient

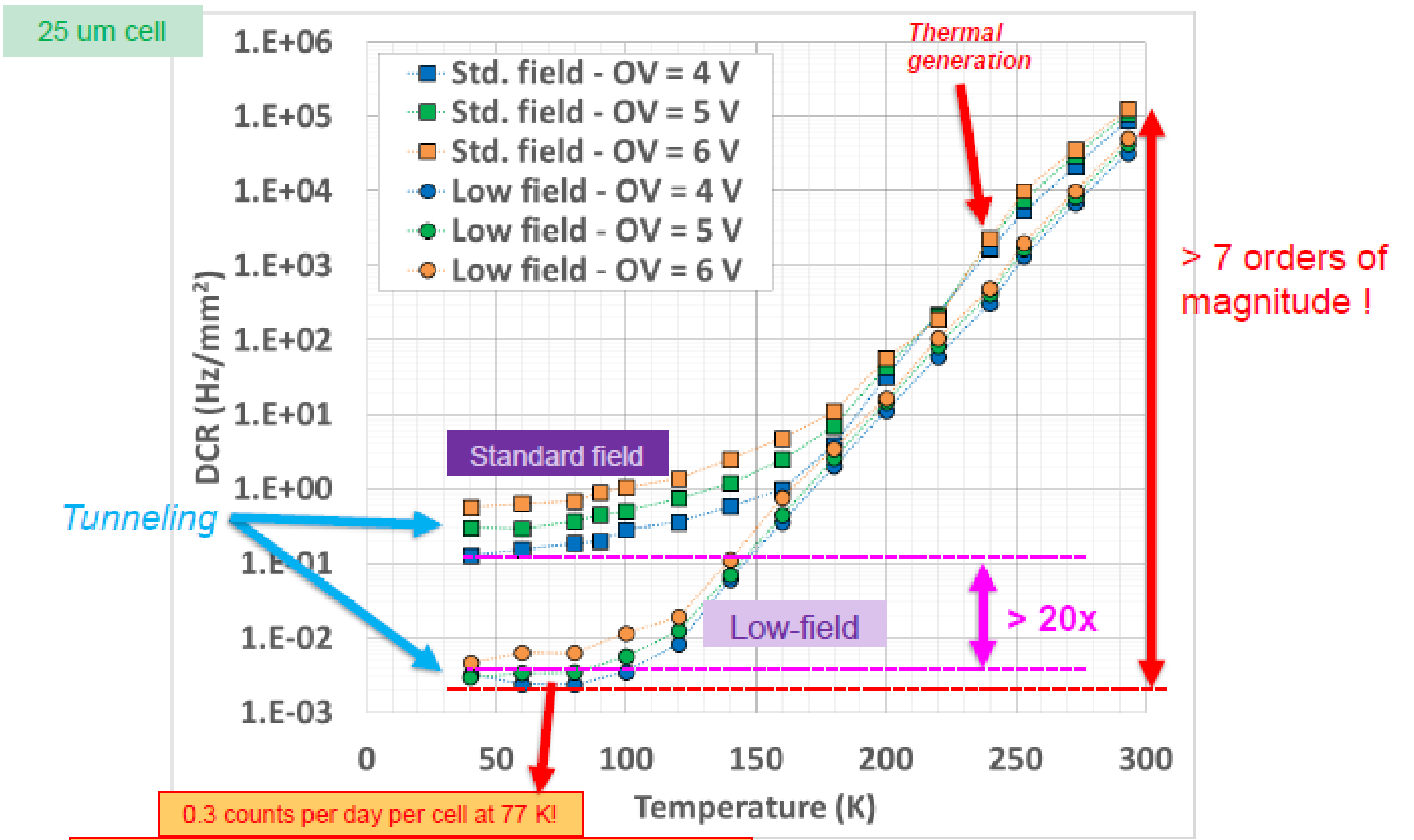


Tunneling noise dominating for T<200K
(sharp high E field region → higher noise)

E field engineering is crucial for min. DCR (esp. at low T)

FBK NUV SiPM optimized for cryogenic operation

Alberto Gola – IEEE NSS-MIC 2015
and Fabio Acerbi - PD18

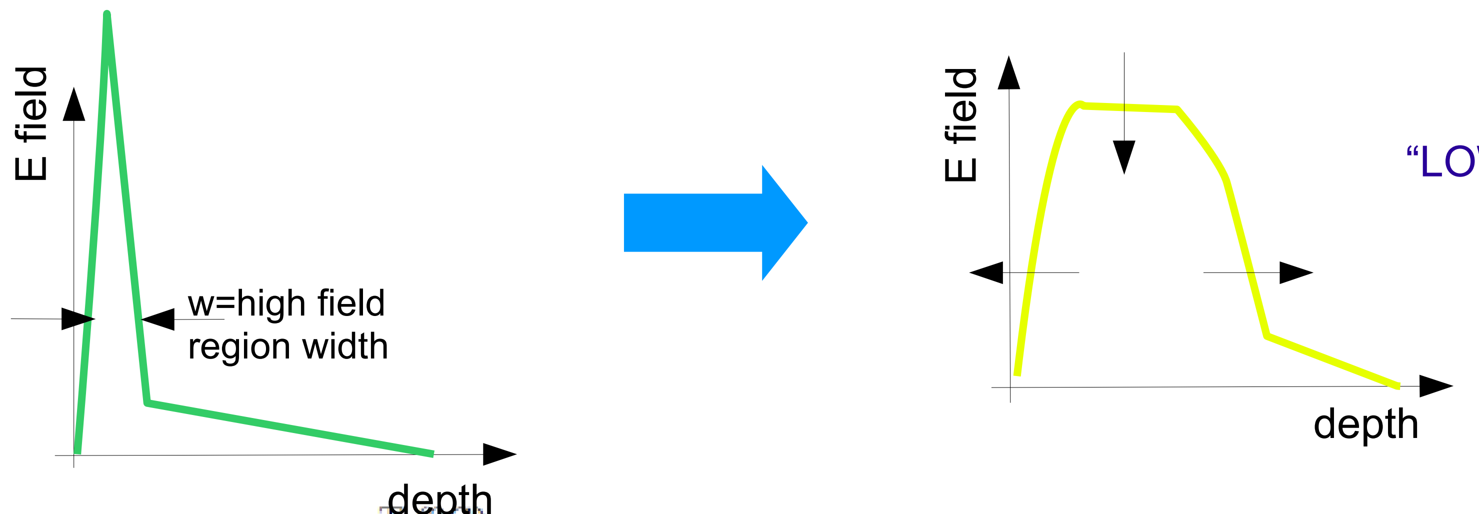


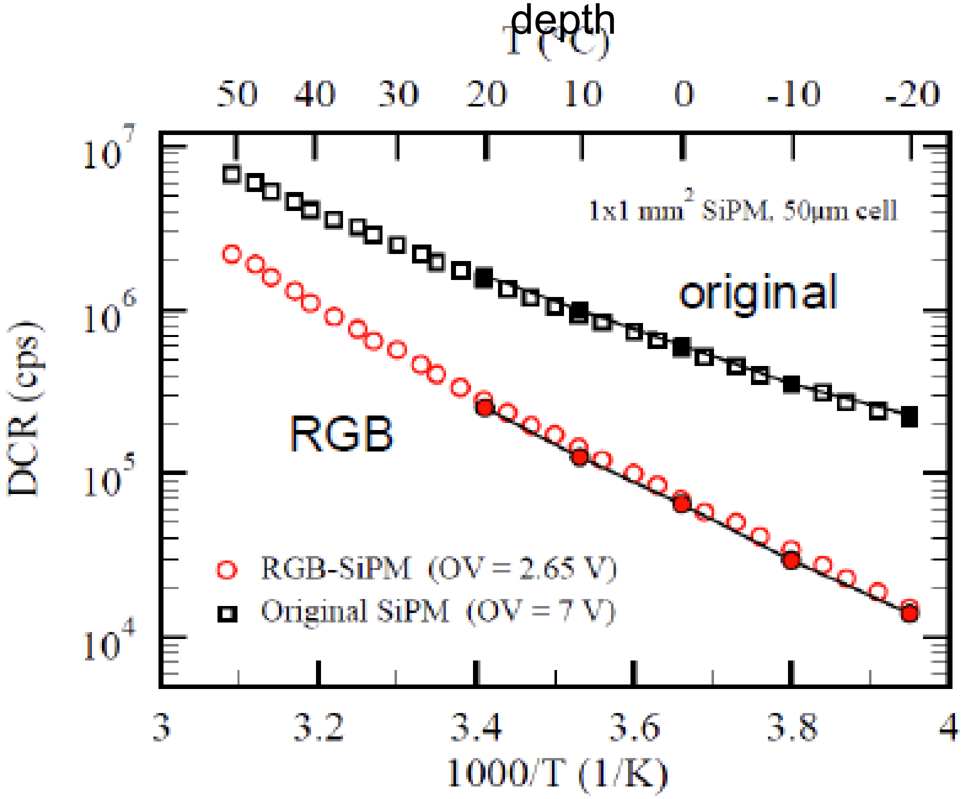
0.3 counts per day per cell at 77 K!

A 10x10 cm² SiPM array would have a total DCR < 100 cps!

Recent improvements to reduce Dark Count Rate

Engineering high electric field & depletion/drift layer profiles

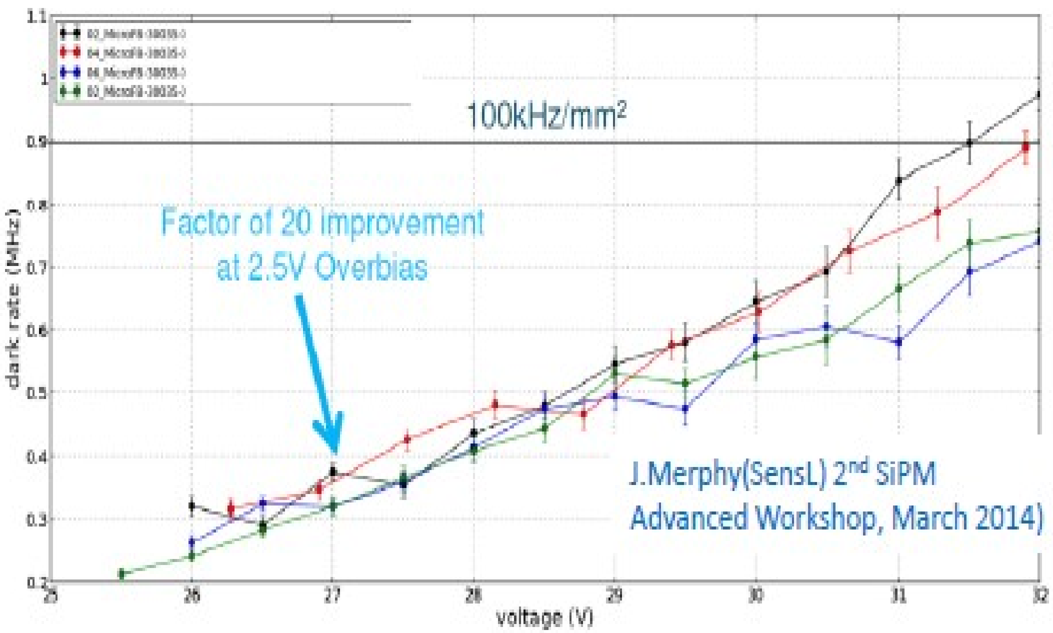




RGB has a much lower noise and a steeper temperature dependence:

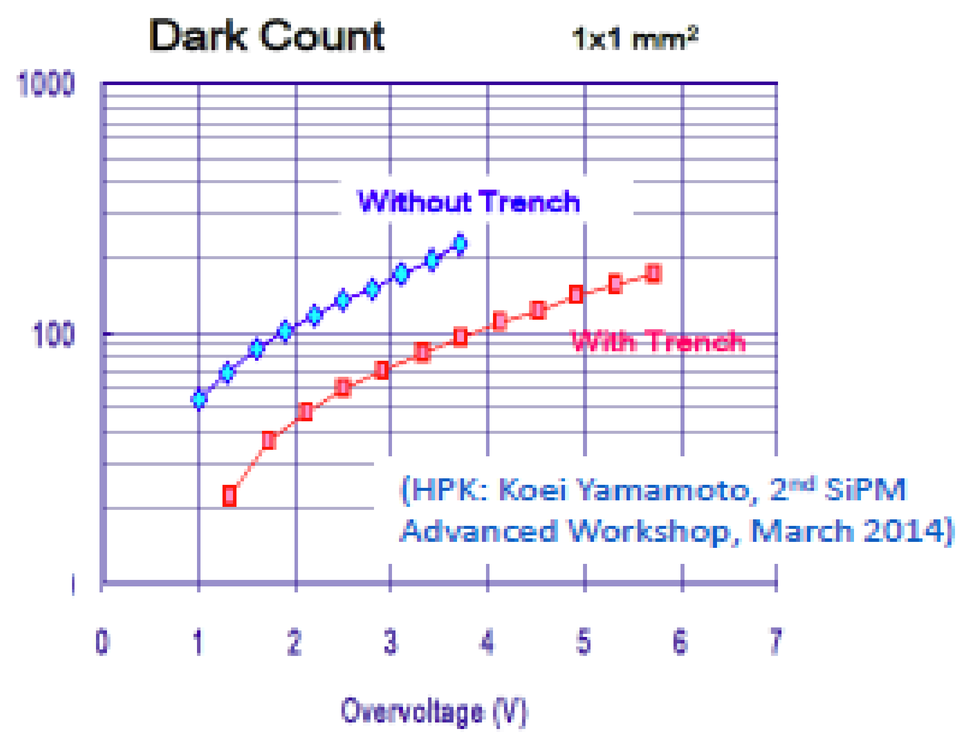
→ **less tunneling**

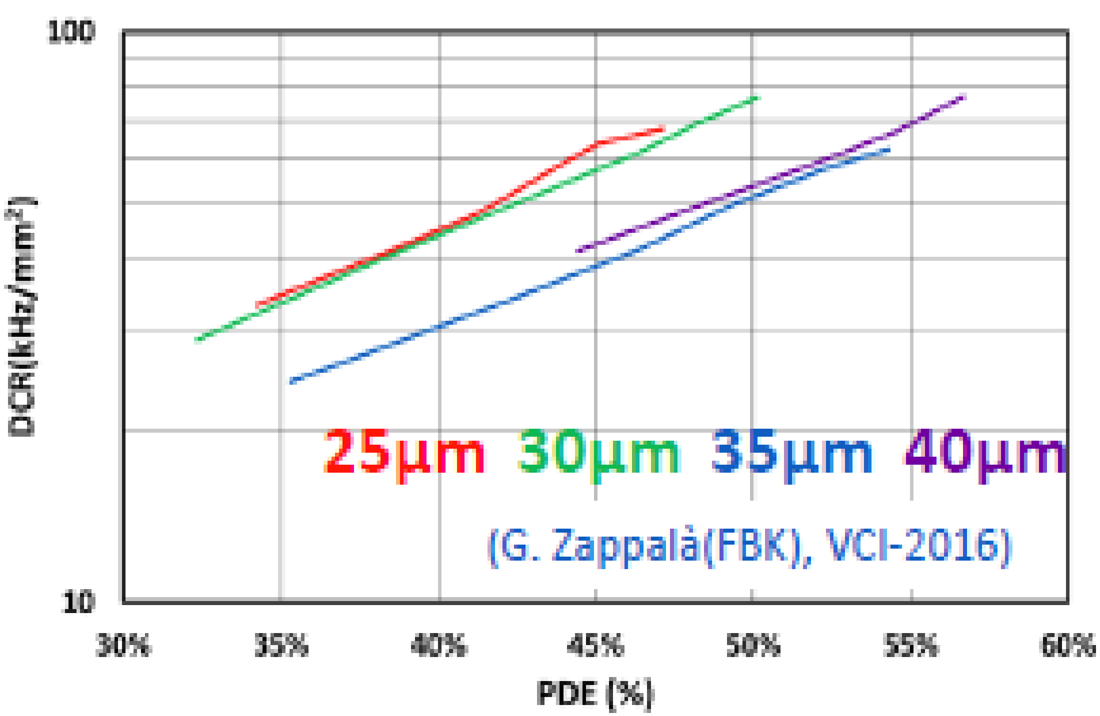
Recent improvements to reduce Dark Count Rate



Critical issues:

- quality of epitaxial layer
- gettering techniques
- Electric field → tunneling

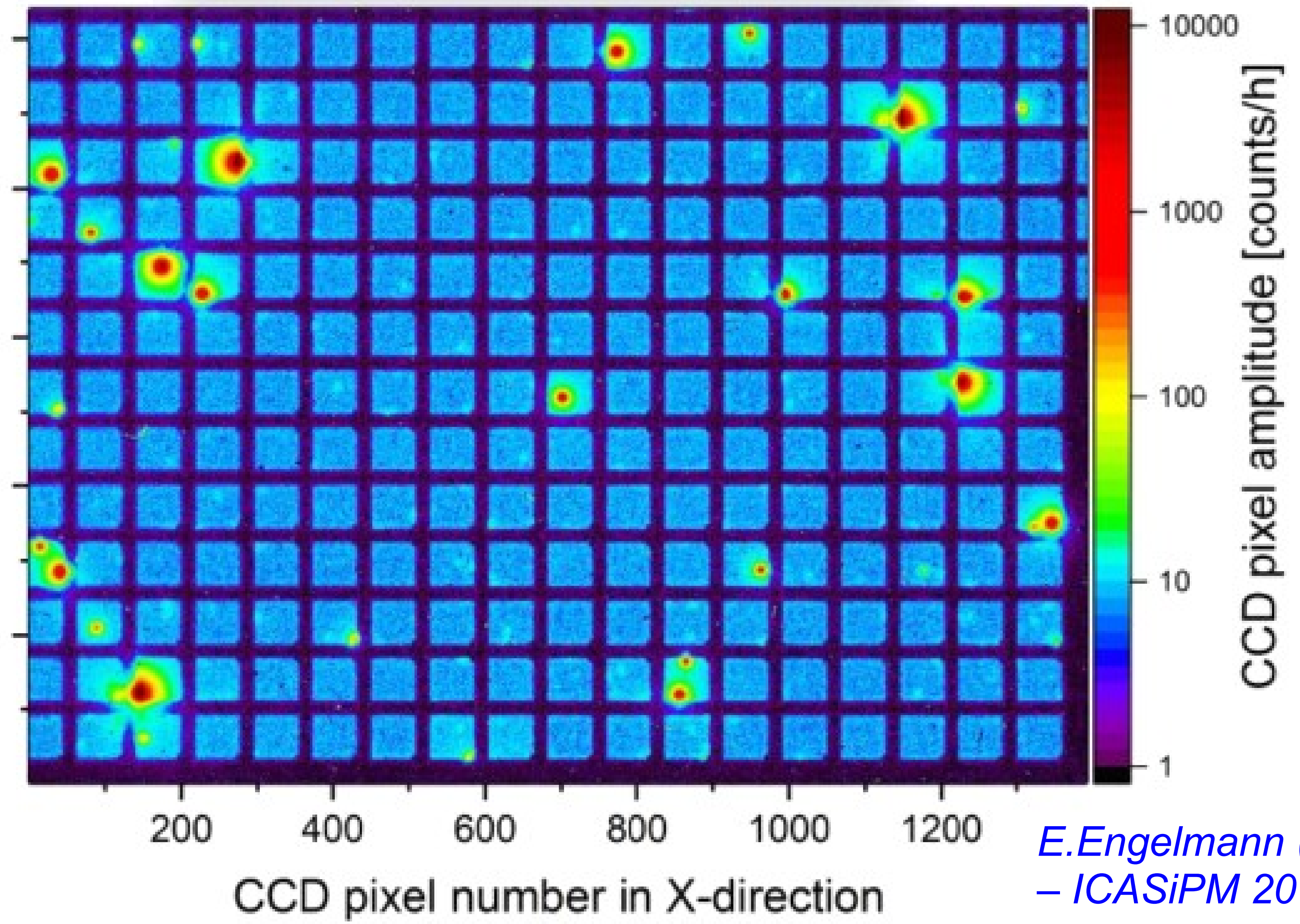




Many devices feature DCR at the level of ~30kHz/mm² (T_{room}) in extended over-voltage range ! (factor x30 decrease in 10 years...)

Map of hot pixels observer with a CCD…

Most of the DCR noise generated by few high noise cells



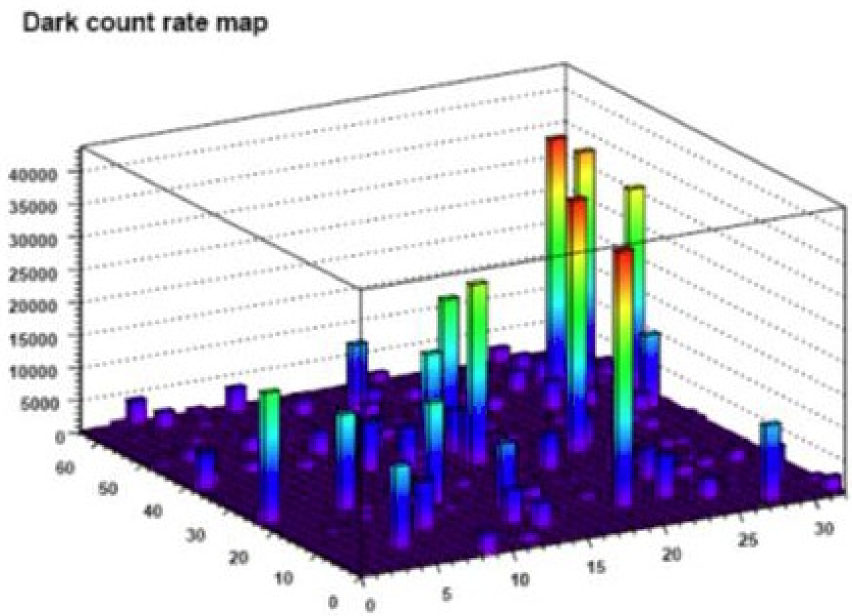
E.Engelmann (KETEK) – – ICASiPM 2018

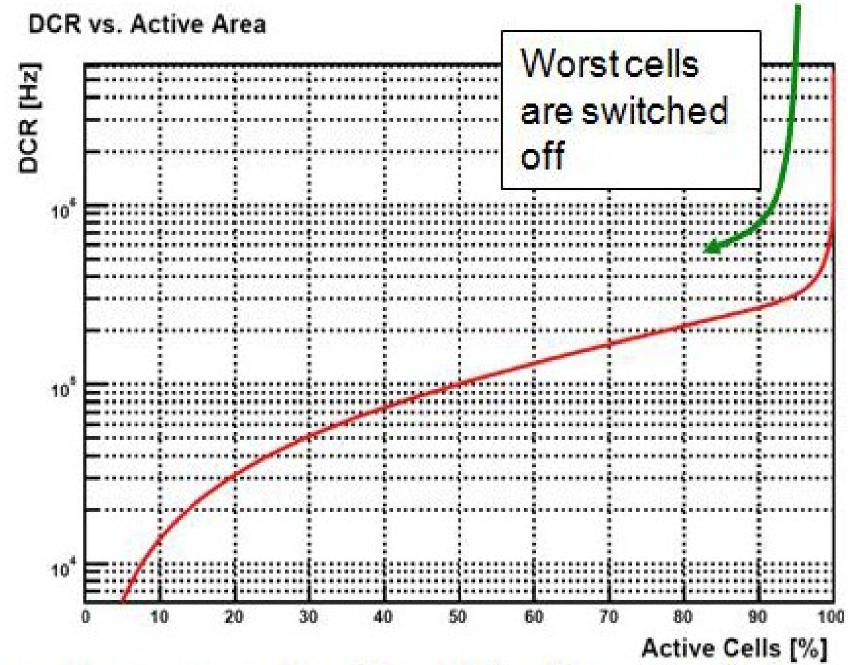
… and yes: avalanche does emit photons !

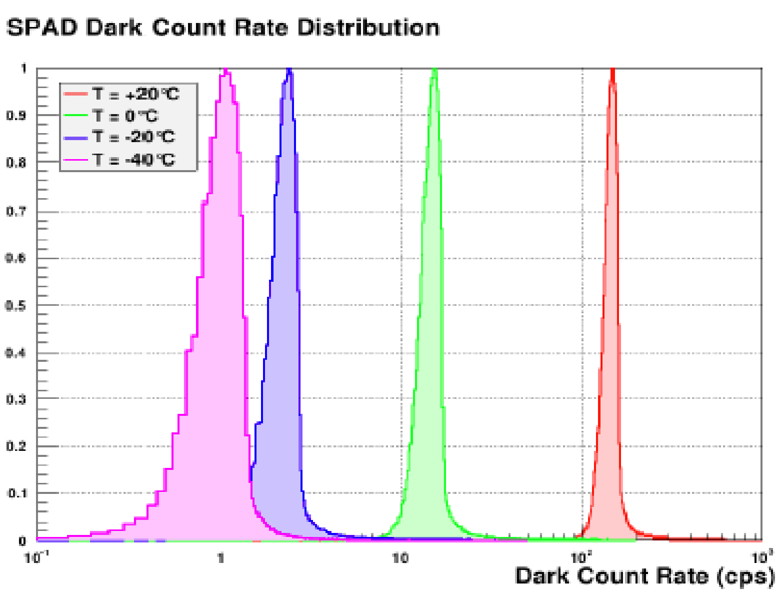
DCR - digital-SiPM (Philips)

T.Frach at Heraeus Seminar 2013

Control over individual SPADs enables detailed device characterization







- Over 90% good diodes (dark count rate close to average)
- Typical dark count rate for ΔV=3.3V ~150 Hz/diode at 20°C
- Low DCR ~1-2 Hz/diode at -40°C

Can disable bad cells (eg 10%) …
… loose in PDE (10% relative)

Correlated Noise in SiPM

Primary noise
→ dark counts

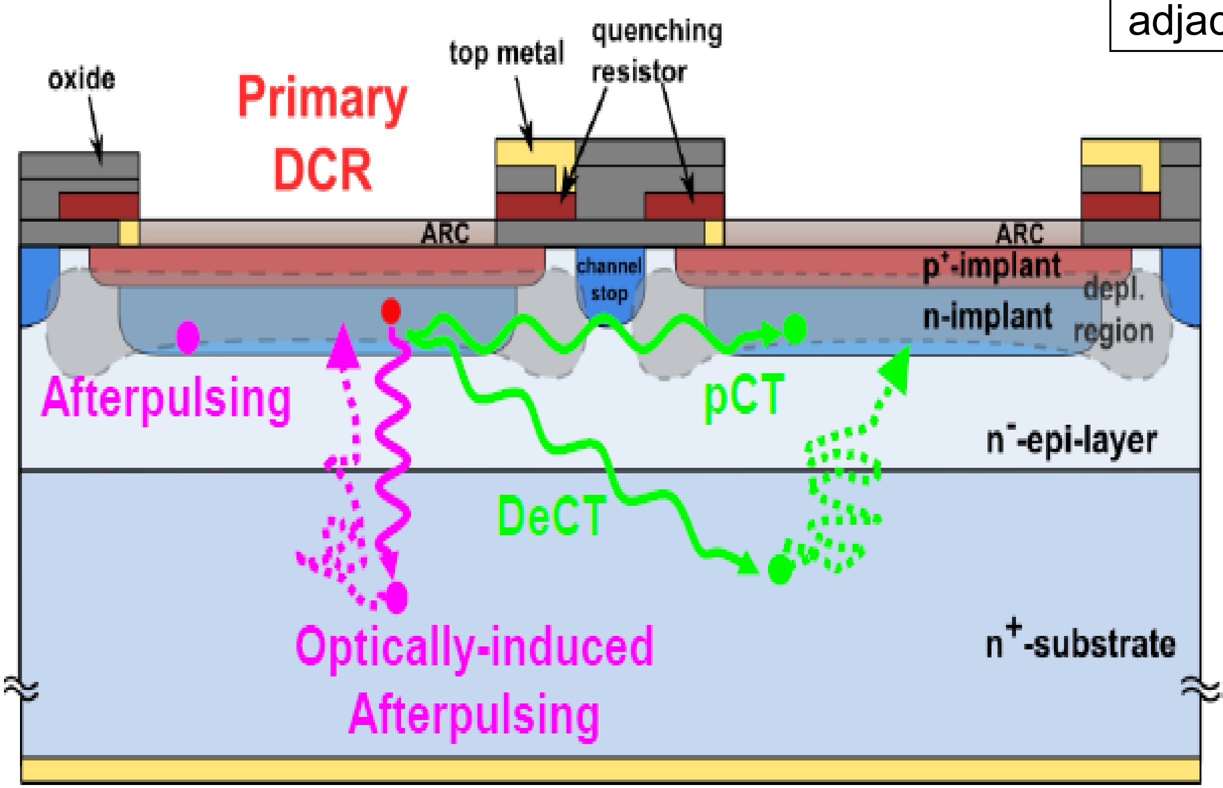
pulses triggered by non-photo-generated carriers (thermal / tunneling generation in the bulk or in the surface depleted region around the junction)

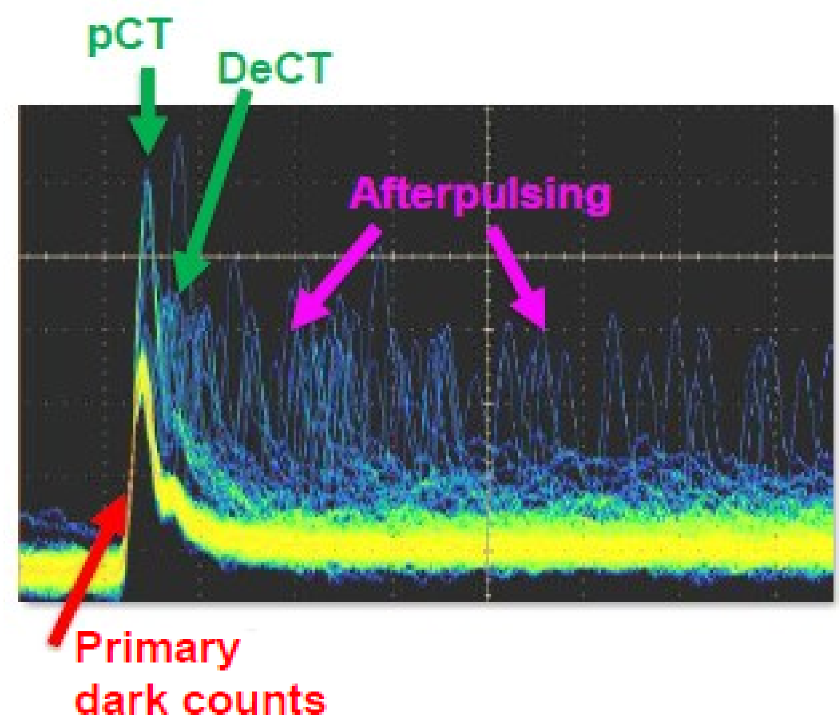
Correlated "excess" charge

→ After-pulsing
→ Optical Cross-Talk

carriers can be trapped during an avalanche and then released triggering another avalanche

photo-generation during the avalanche discharge. Some of the photons can be absorbed in the adjacent cell possibly triggering new discharges





Optical Cross-Talk

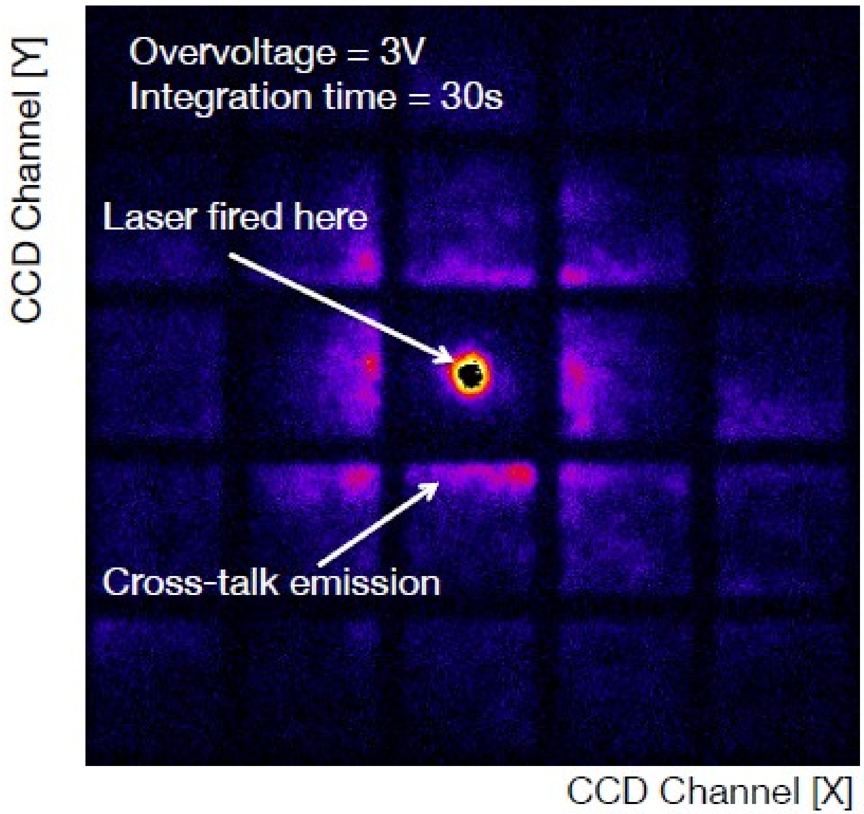
Cross-Talk observed
by Light Emission Microscopy
Derek Strom – PD18

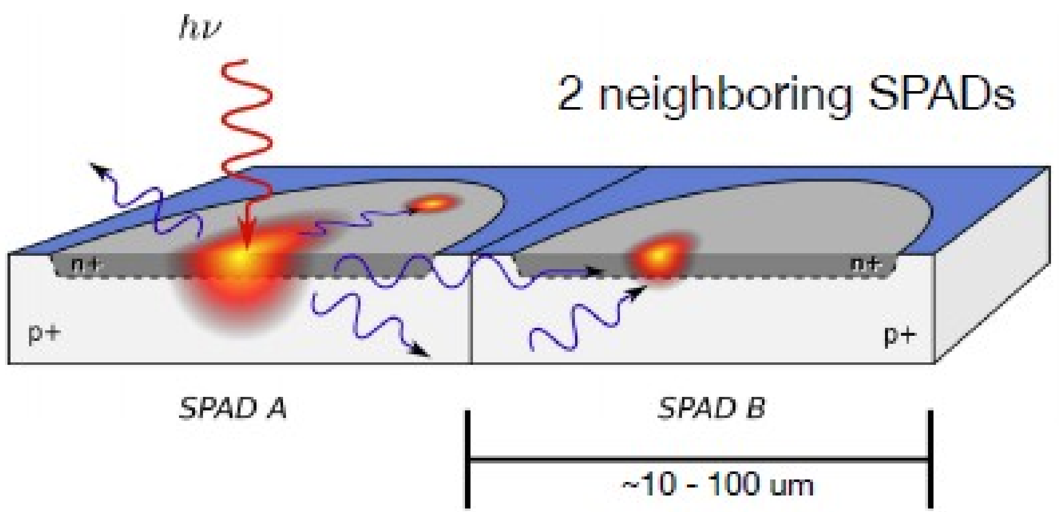
Carriers' luminescence (spontaneous direct relaxation in the conduction band) during the avalanche: probability 3.10^{-5} / carrier to emit photons with E>1.14eV

A.Lacaita et al. IEEE TED (1993)

Few 10s of photons (NIR spectrum) are emitted per avalanche, which can induce avalanches in neighboring cells

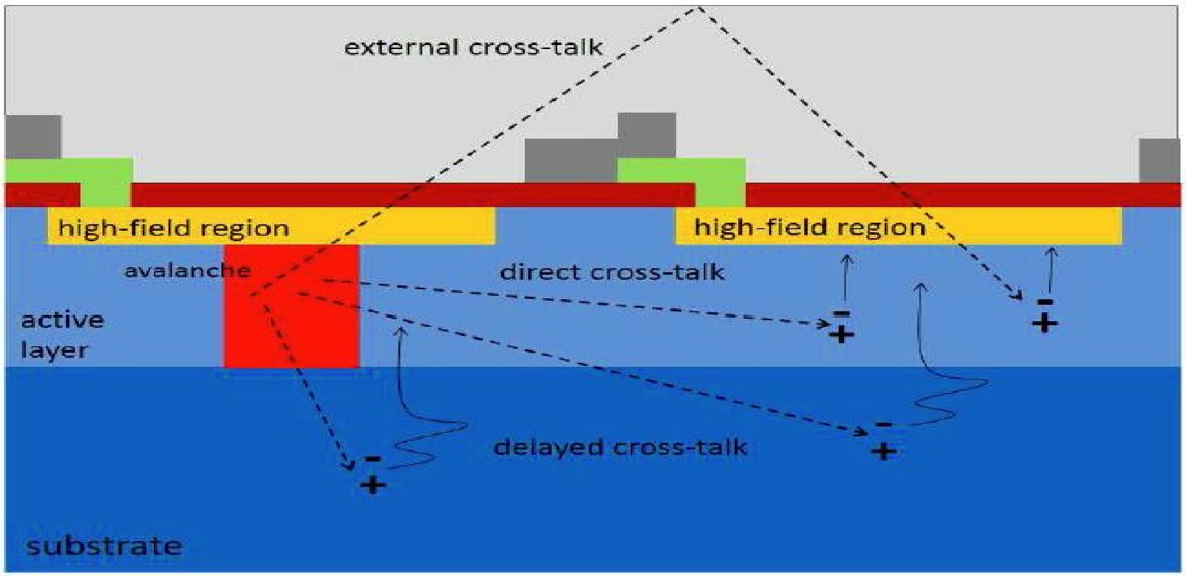
Depends on distance between high-field regions
ΔV^2 dependence on over-voltage:
- carrier current during avalanche $\propto \Delta V$
- gain $\propto \Delta V$





- Add to Gain fluctuations → Excess Noise Factor
- … Worse Q resolution and photon counting
- … Fake trigger

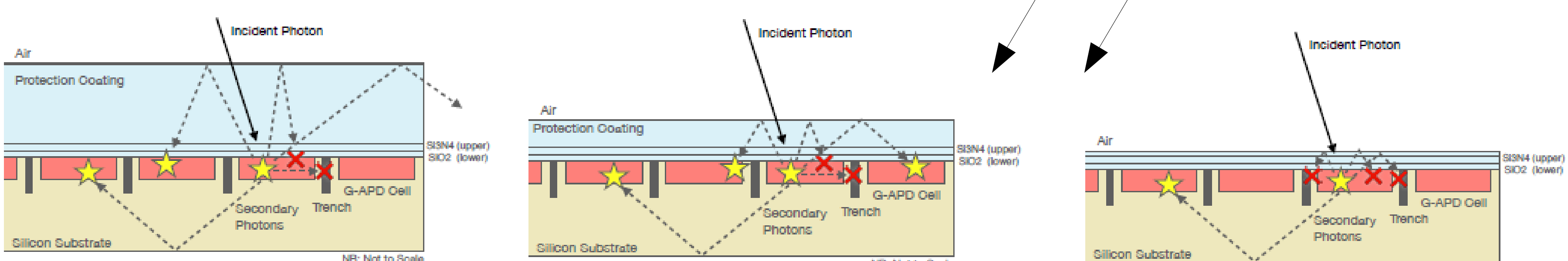
Optical Cross-Talk – various types



...many paths for optical cross-talk ...

- *F.Retiere – PD12*
- *A.Ferri - IPRD 2013*

Effect		**Countermeasure**
(1) Direct Cross-Talk	→	deep trenches + Poly-Si filling
(2) Delayed CT	→	buried junction (to avoid out-diffusion)
(3) External CT	→	thin coating (if any…) & care to ext surfaces

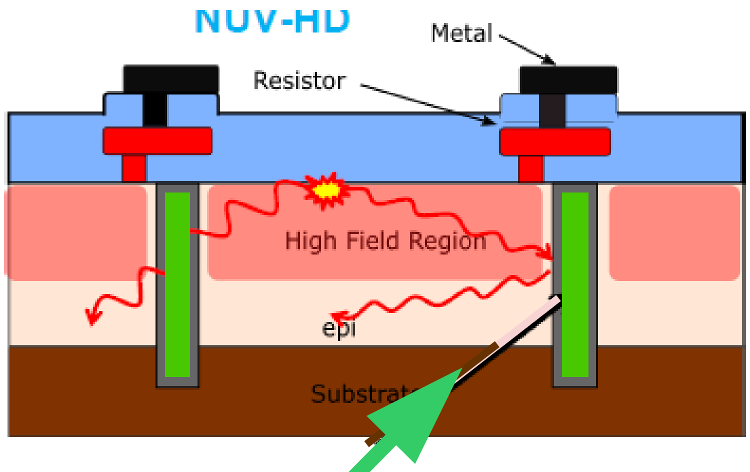


Y.Nakamura PD18 – Tokyo 2018

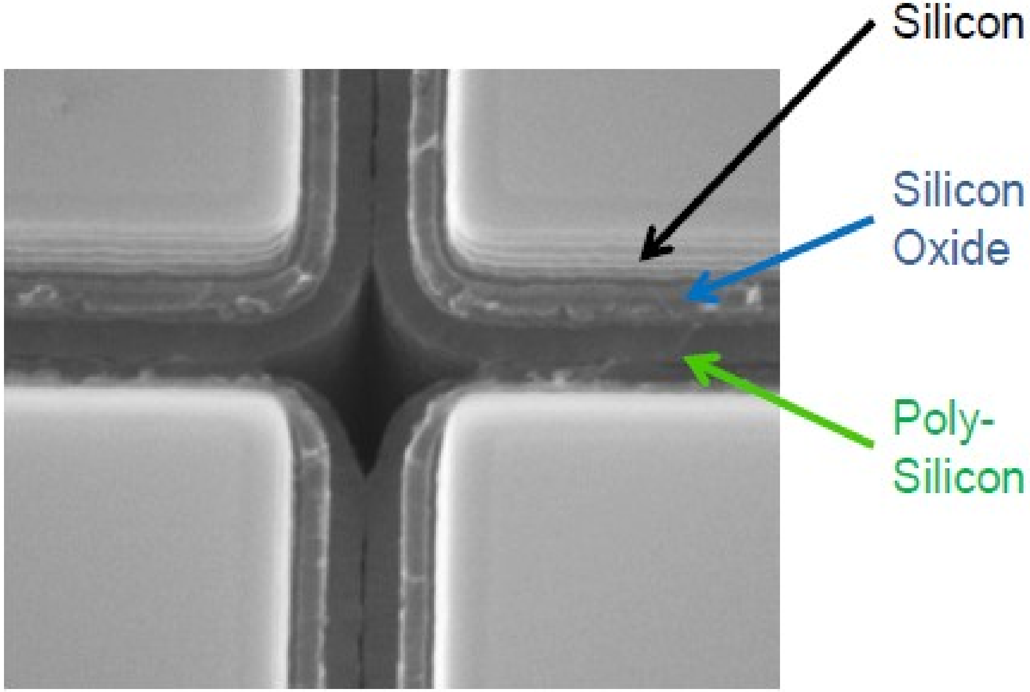
Optical Cross-Talk mitigation: FBK recipes

(1) Poly-Si Trench filling

- SiO2/Poly-Si/SiO2 stack in the trenches
- the materials composing the stack show high-contrast refractive indexes, increasing reflection of light
- high-doped poly-Silicon layer aids to absorb part of the light due to free carriers absorption



through
ches



(2) Substrate with reduced carrier lifetime

- Buried layer for reducing out-diffusion form un-depleted region

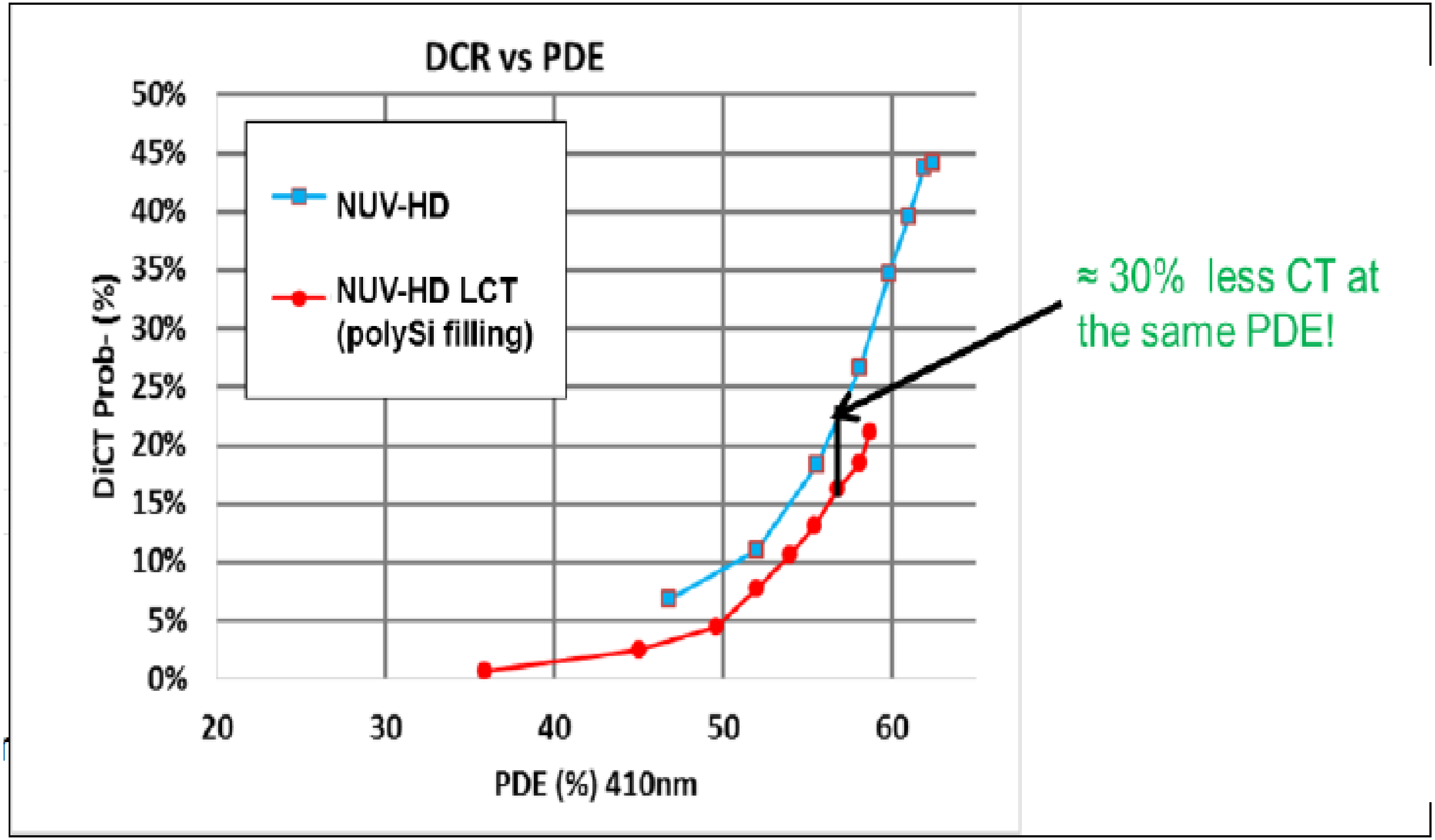
→ reduction of any type delayed noise (AP, DeCT)

Courtesy – Giovanni Paternoster (FBK) - 2018

Optical Cross-Talk mitigation

FBK SiPM develoment for CTA

(Cross-Talk mitigation crucial for Cherenkov applications)



Courtesy – Giovanni Paternoster (FBK) - 2018

After-Pulsing

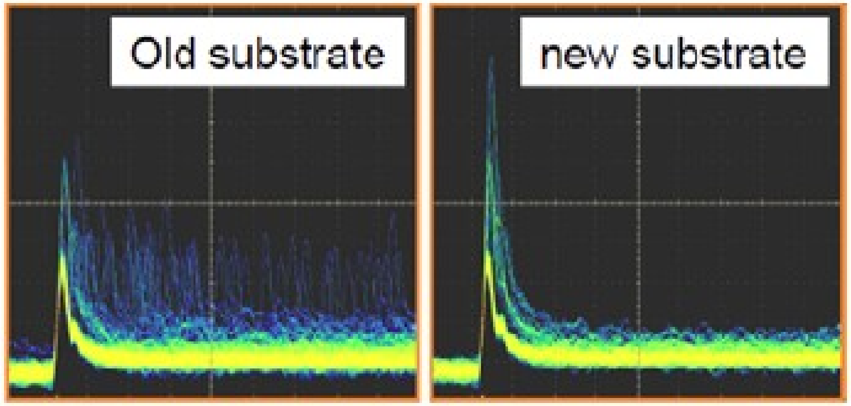
Delayed correlated noise: 2 sources

(1) Delayed release of trapped carrier

• Some carriers from primary avalanche are trapped in a deep trapping level in energy band gap → delayed release → trigger another avalanche

→ Solution: Better **quality of substrate and epi. layer** (minority carrier lifetime reduced x100)

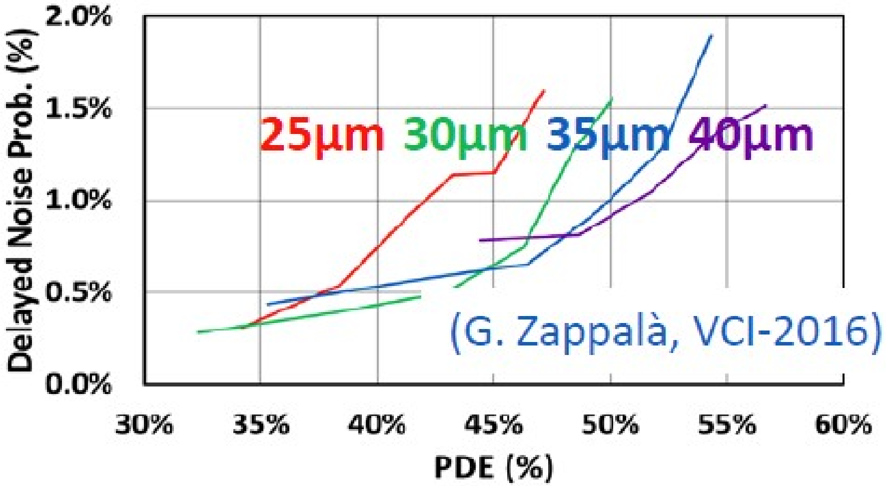
Hamamatsu MPPC 2013



(2) Delayed optical cross-talk

→ Solution: Buried layer to block delayed carrier diffusion from substrate

FBK SiPM 2016

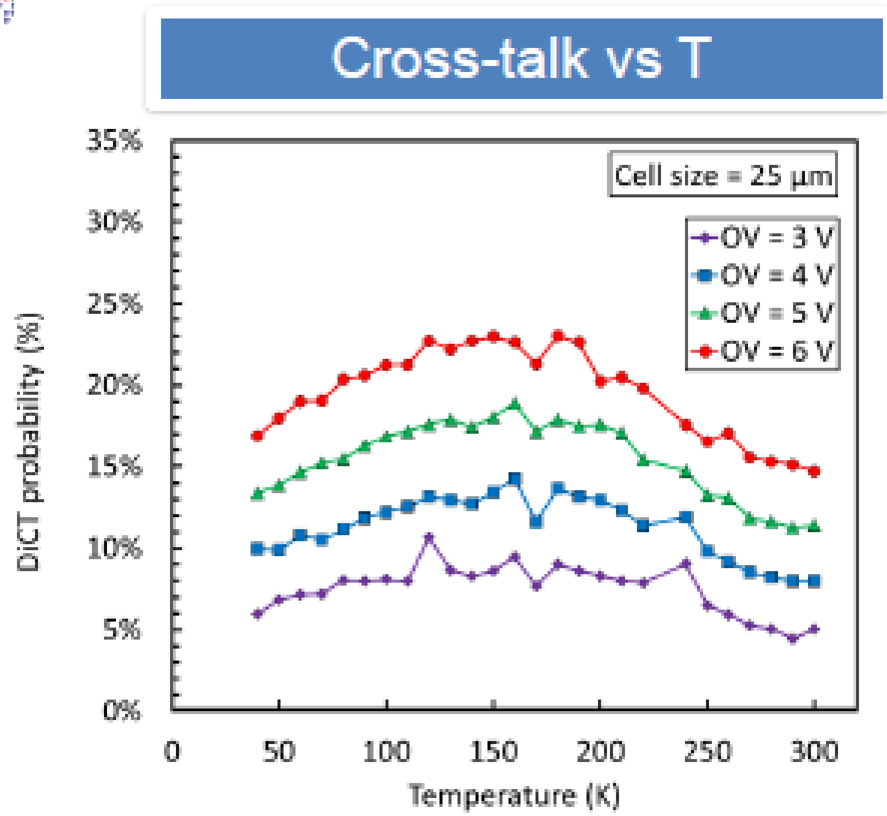


Note: most of delayed carriers are emitted when the cell is still partially discharged (after the primary avalanche)

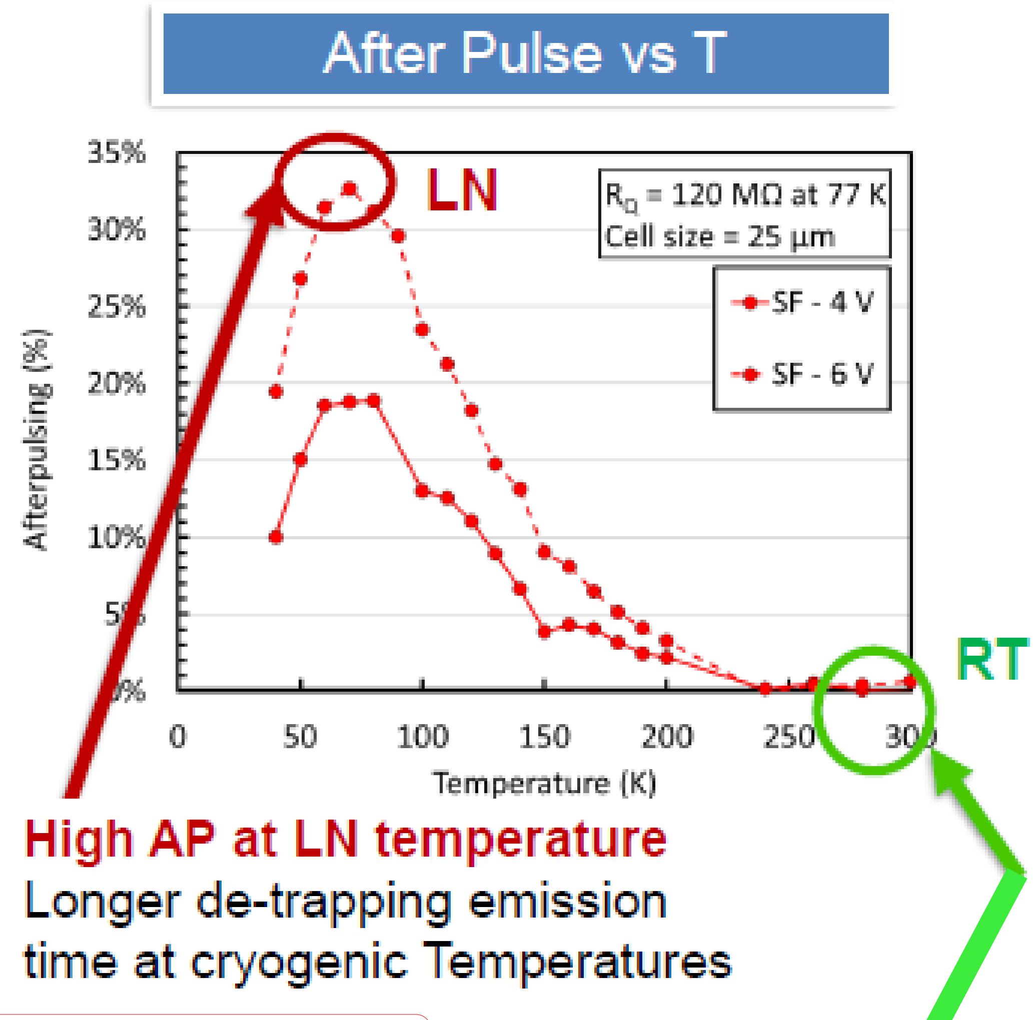
→ (A) long recovery time hides After-Pulsing !

→ (B) low T: longer recovery counterbalances longer emission times … down to ~100K…

After-Pulsing at low Temperature



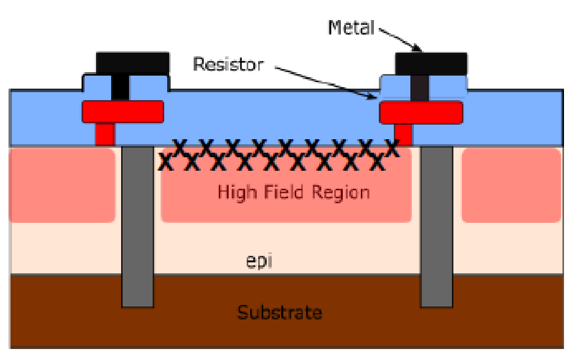
Weak dependence of CT on T



High AP at LN temperature
Longer de-trapping emission time at cryogenic Temperatures

Courtesy – Giovanni Paternoster (FBK) - 2018

Hypotesis:
Trapping centers located at top interface

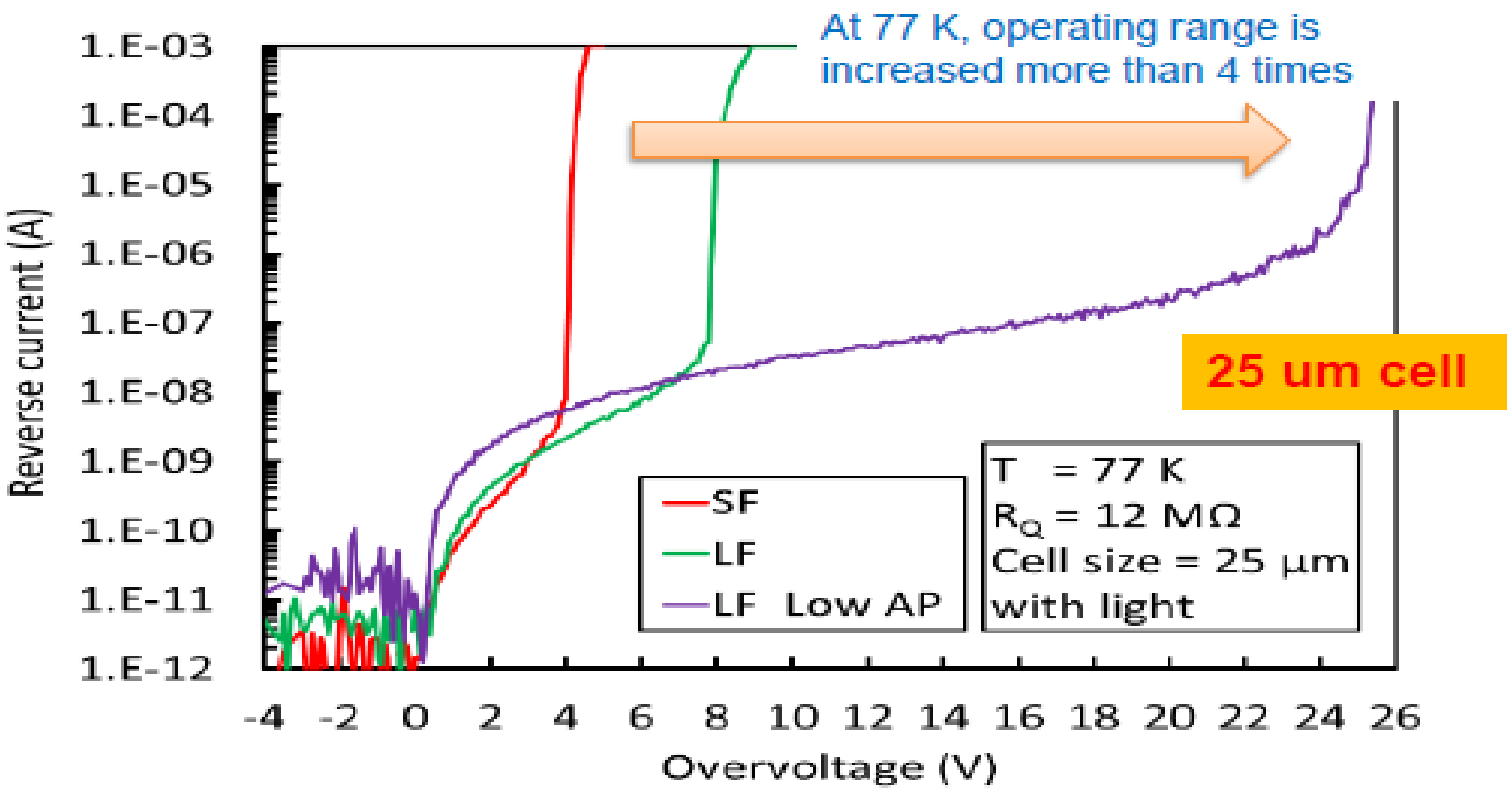


AP negligible at RT
carriers are emitted by trapping centers when the microcells is still partially discharged after the primary avalanche

DCR & AP & CT Knock-down at low T
→ allow operating SiPM at very high gain

Afterpulsing can significantly increase at low temperatures because of **increment of deep-levels de-trap time constants!**

Solution: Low-field + modified dopant concentrations in the microcell
→ significantly reduced afterpulsing probability at cryogenic temperatures.



Fabio Acerbi (FBK) – PD18 – Tokyo 2018

Radiation Hardness

- Being a silicon device with **internal multiplication** SiPM is very prone to damage due to radiation effects

- Due to intrinsic gain the effect of **increased of dark current** and **correlated noise** are dominant wrt other radiation damage effects like depletion region modification

see also R.Klanner at this Conference

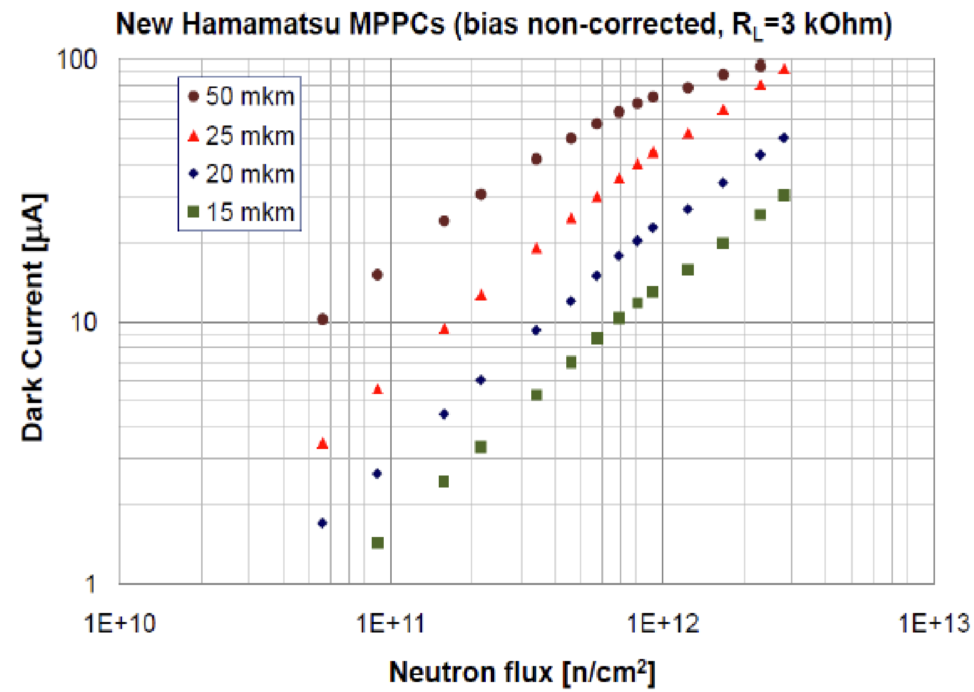
Radiation damage: effects on SiPM

Main effects

1) Significant DCR increase
2) Correlated noise (AP & CT) increase
3) Reduction of PDE ~10%
4) Small increment of Vbd

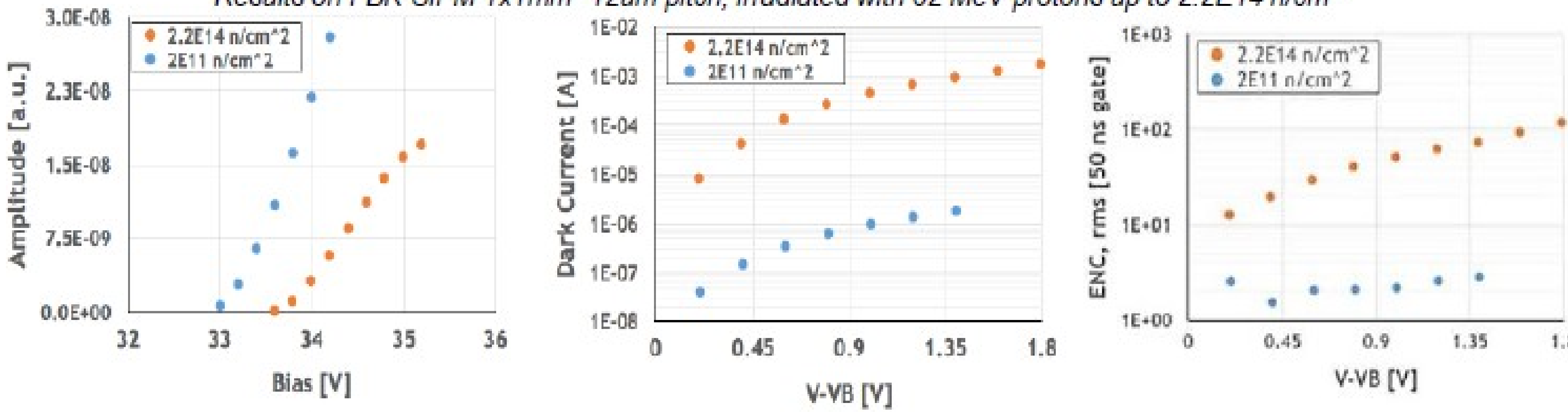
Performance loss

A) SiPM are still working at 10^{14} n/cm^2
B) photon counting lost at 10^{11} n/cm^2



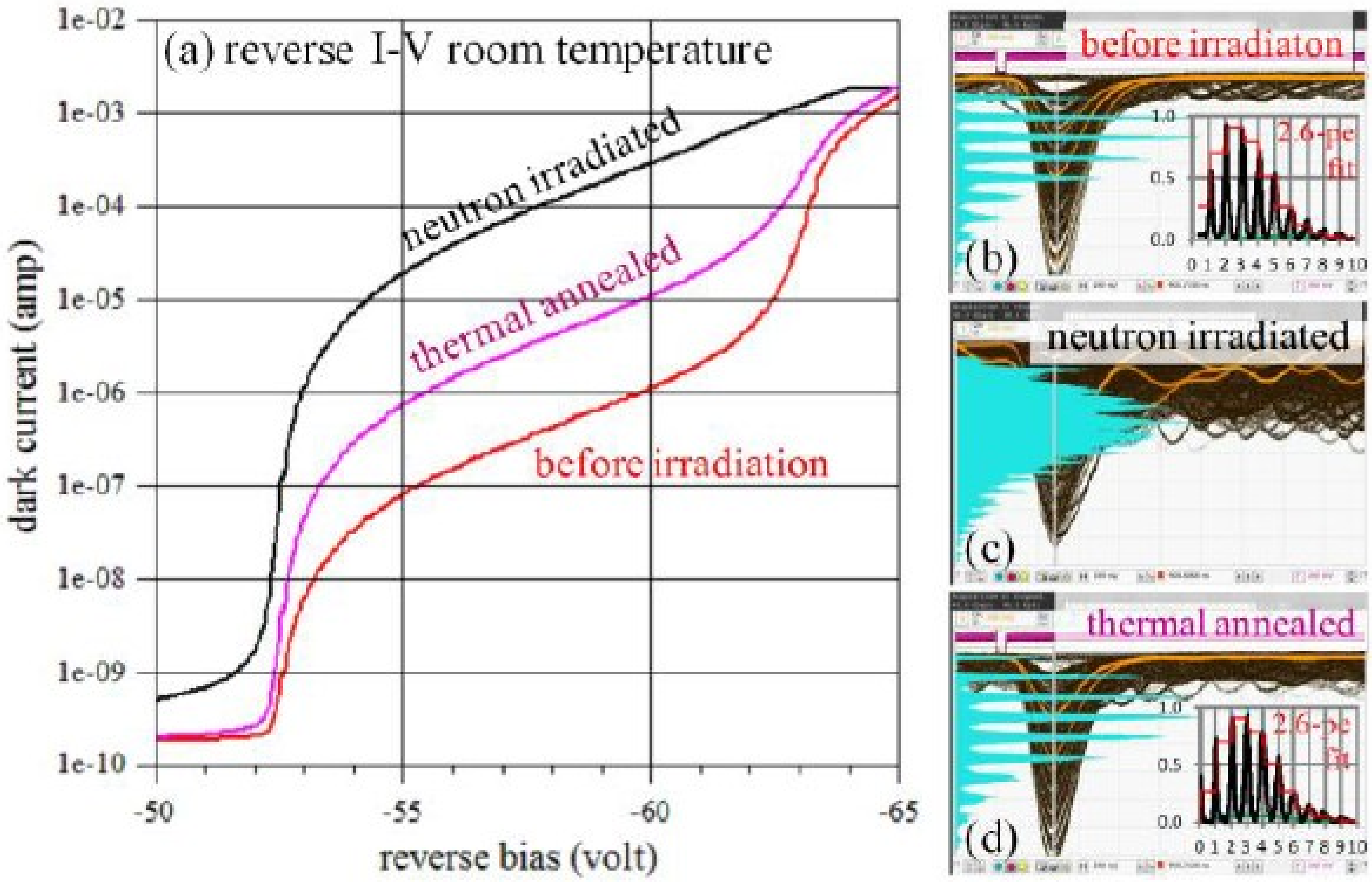
Review by Y.Musienko - SENSE TechForum 2018

Results on FBK-SiPM 1x1mm² 12um pitch, irradiated with 62 MeV protons up to 2.2E14 n/cm²



Radiation damage: annealing …

T.Tsang et al – JINST 11 (2016) P12002



High T (+250°C) annealing + forward biasing (SiPM current reaching 10mA) of devices irradiated up to $\Phi_{eq}=10^{12}/cm^2$

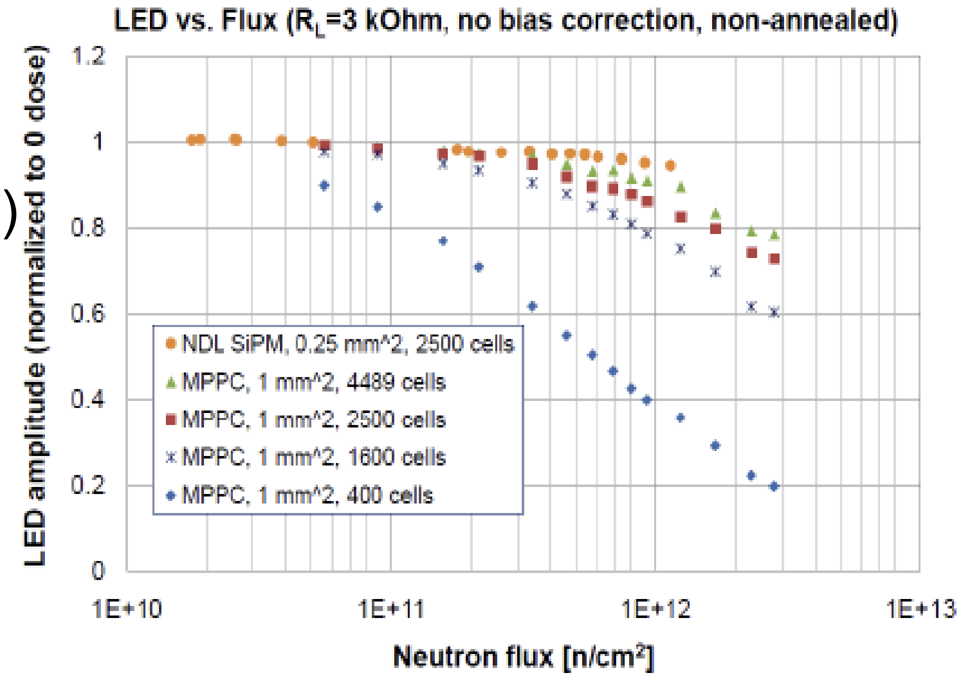
→ x20 reduction of the DCR

→ Single photo-electron resolution recovered with cooling to -50°C

Trends to improve radiation hardness

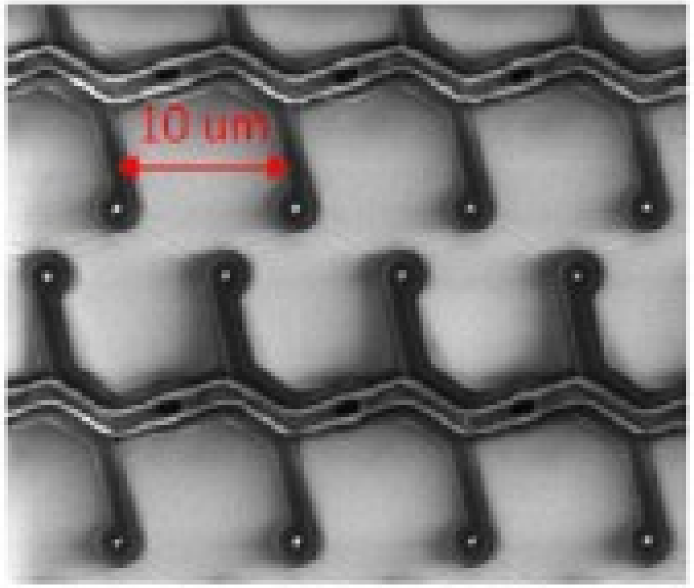
1) DCR increase is equivalent to reduction of effective PDE (high occupancy) → **tiny cell SiPM** are better suited for radiation harsh environments:

- lower fraction of “dead” cells due to DCR
- smaller Cd → reduced recovery time
- smaller gain → reduced charge trapping



2) Cooling is more effective if $\partial V_{bd}/\partial T$ and $\partial DCR/\partial T$ are large → **low-electric-field** & wider HF region

3) Optimization of the $SiO_2/S_3N_4/Si$ interface to reduce light losses in entrance window and avoid trapping → **Bulk, Metal film or Silicon resistor SiPM**



Selected Applications

- Fine 3D Tracking (w/ plastic scint.)

  see talk by P.Saba at this Conference

- Fast Calorimetry (w/ crystals scint.)

  see also R.Donghia, A.Papa, F.Ferri talks at this Conference

- Timing → ToF, Lidar

  see also S.Gundaker, M.Nishimura, talks at this Conference

- Low Temperature & Large Area

see also W.Ootani ICASiPM 2018 - "Readout techniques for Cryogenic SiPMs"

see also A.Razeto FEE 2018 - "Large Area SiPM readout"

↓

SiPM "ganging" schemes

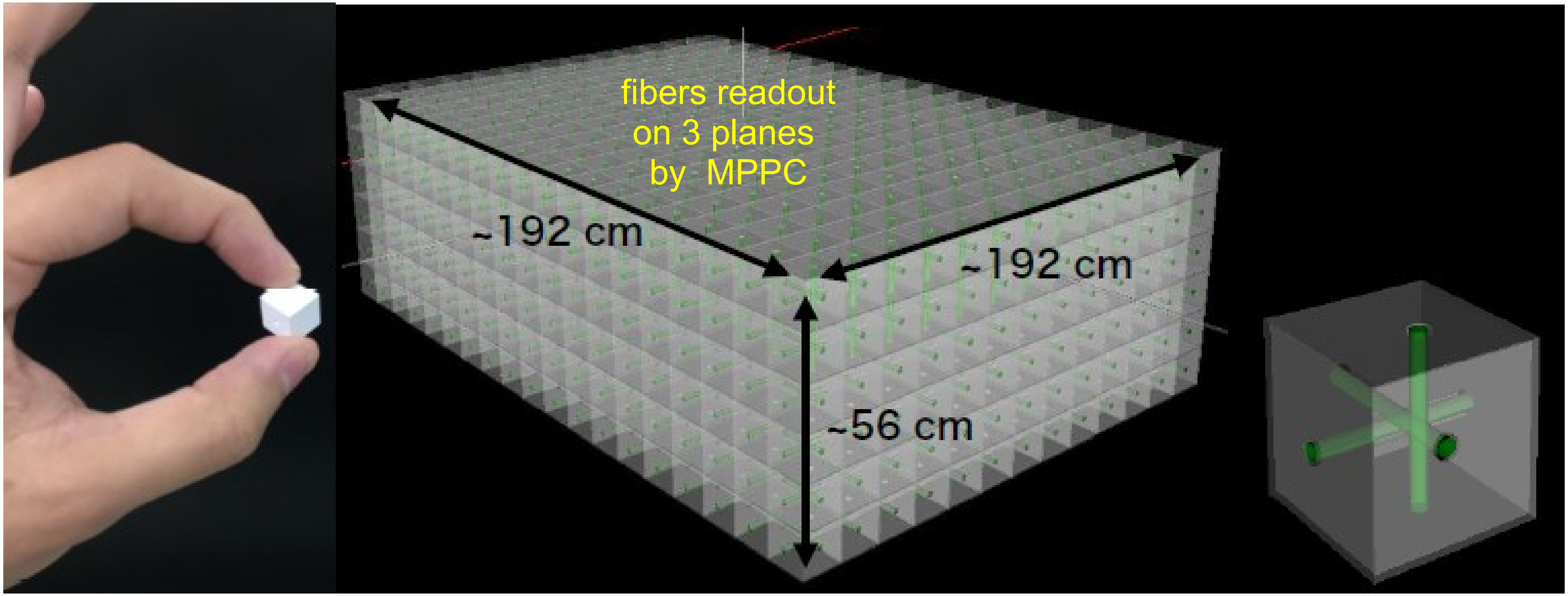
3D tracking with scintillator

see talk by Parsa Saba at this conference

T2K upgrade → neutrino active target and fine grained 3D scintillator tracker

A novel plastic scintillator detector with new structure

- Proposed in 2017 for the T2K near detector upgrade [JINST 13 (2018) P02006]



- Optically independent ~2,000,000 scintillator cubes (1 cm^3) w/ 3 holes
- Three orthogonal projections with ~60,000 MPPCs via WLS fibers

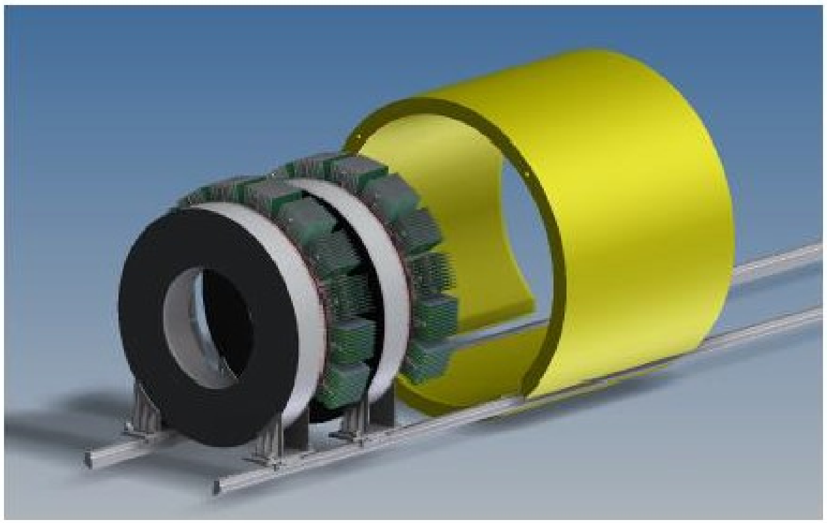
→ Large active target (~2 t), Fine granularity, 4π acceptance

BaF2 readout with SiPM

see talk by Raffaella Donghia at this conference

Coherent conversion of muons into electrons (CLFV)

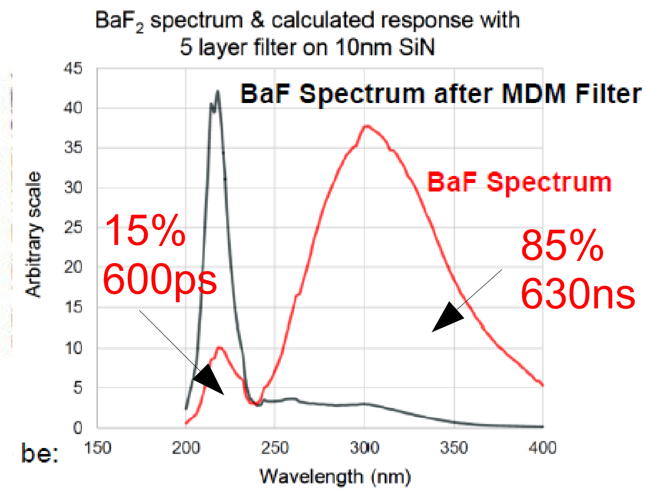
Mu2e calorimeter



- Array of BaF_2 crystals readout by SiPMs
- 1 T Magnetic Field at the SiPM level
- Radiation hardness
- Fast timing, high spatial and energy resolution are required

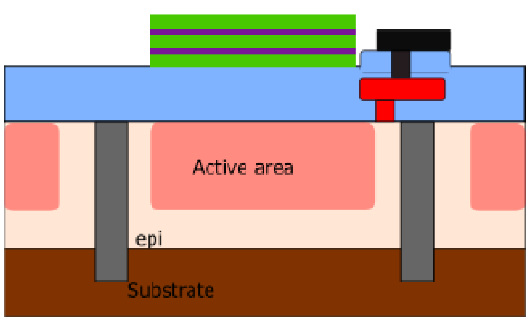
BaF_2 is the fastest inorganic scintillator

- Two emission components: a fast component and a slow component
- Fast component luminescence is peaked at 220nm

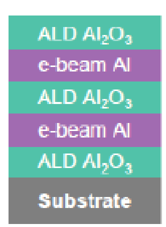


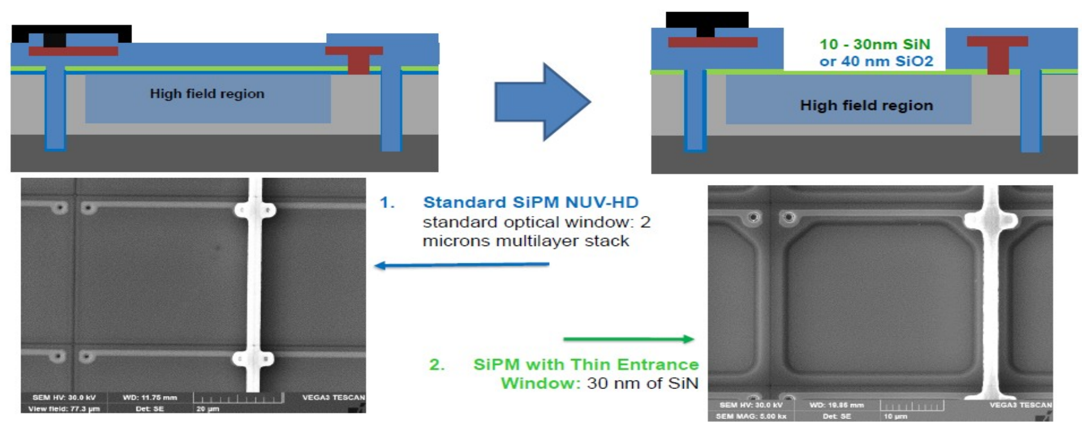
Proposed Solutions:

SiPM with integrated MDF solar blind Filter



Five layer MDF



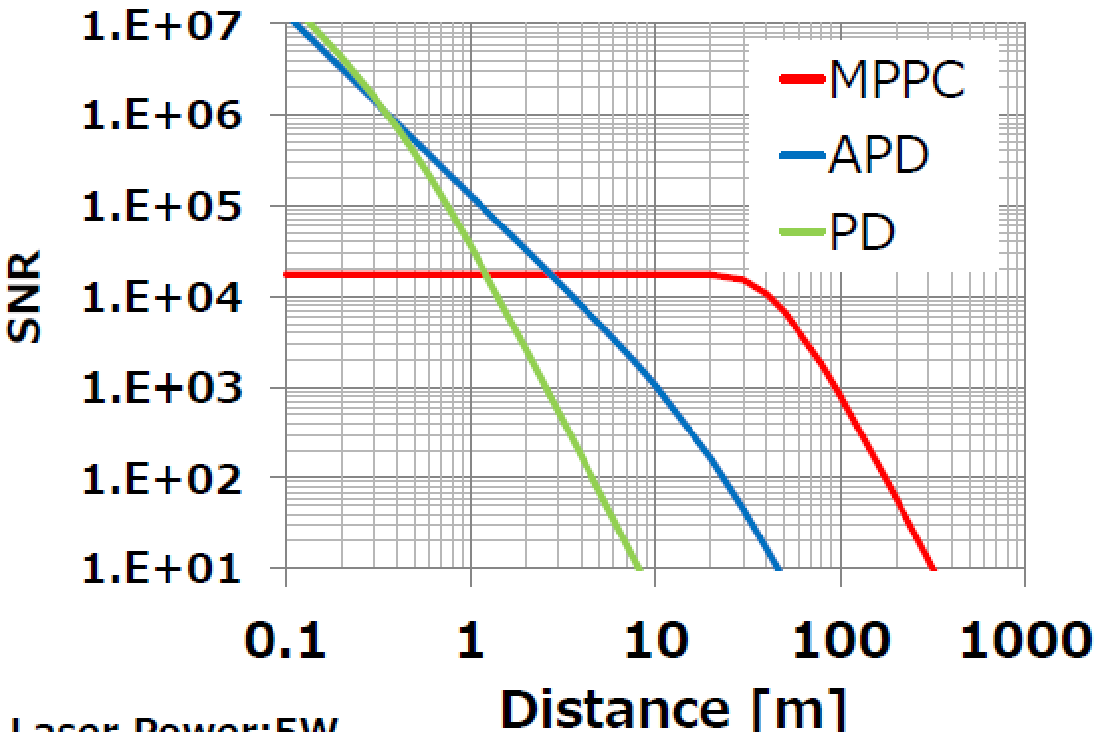


Timing - Lidar

Requirements of ADAS

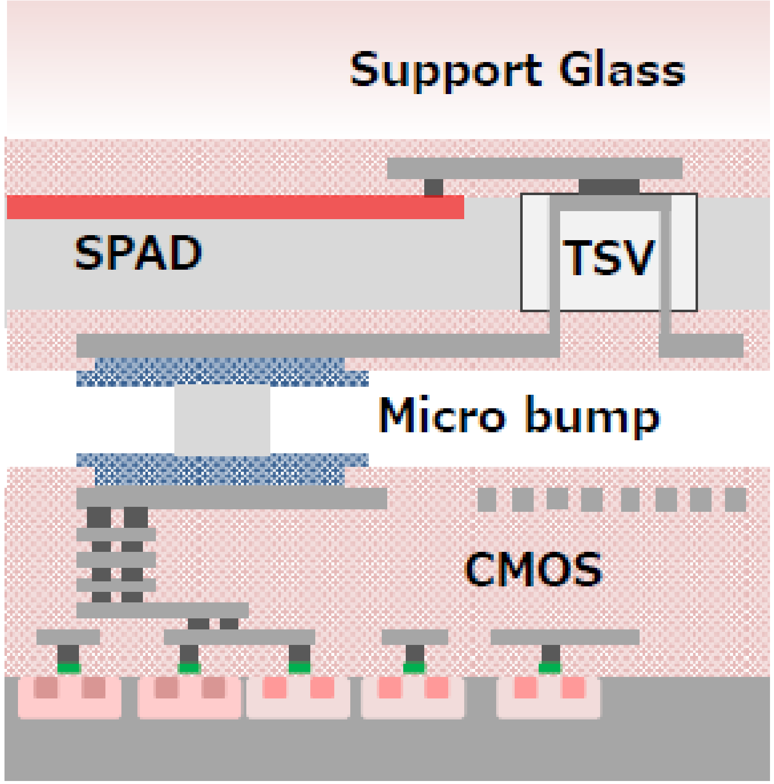
- High NIR sensitivity (800 nm ~ 1.06 μm)
- Wide dynamic range
- Fast response
- Low timing jitter

MPPC make possible to extend 10times longer distance

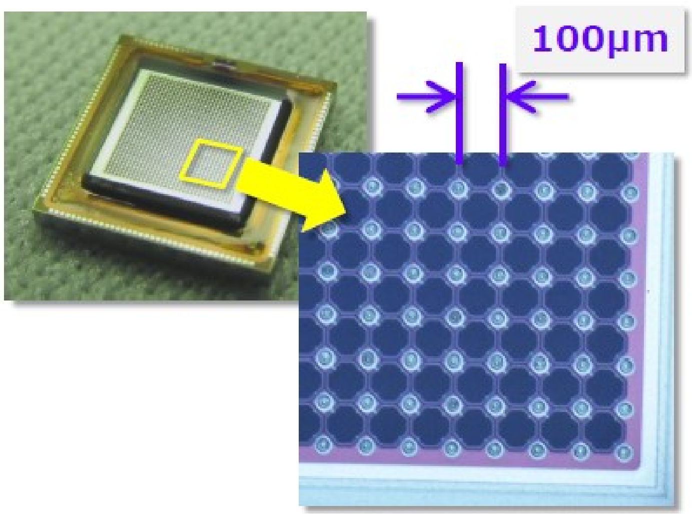


Laser Power:5W

Hamamatsu Hybrid module

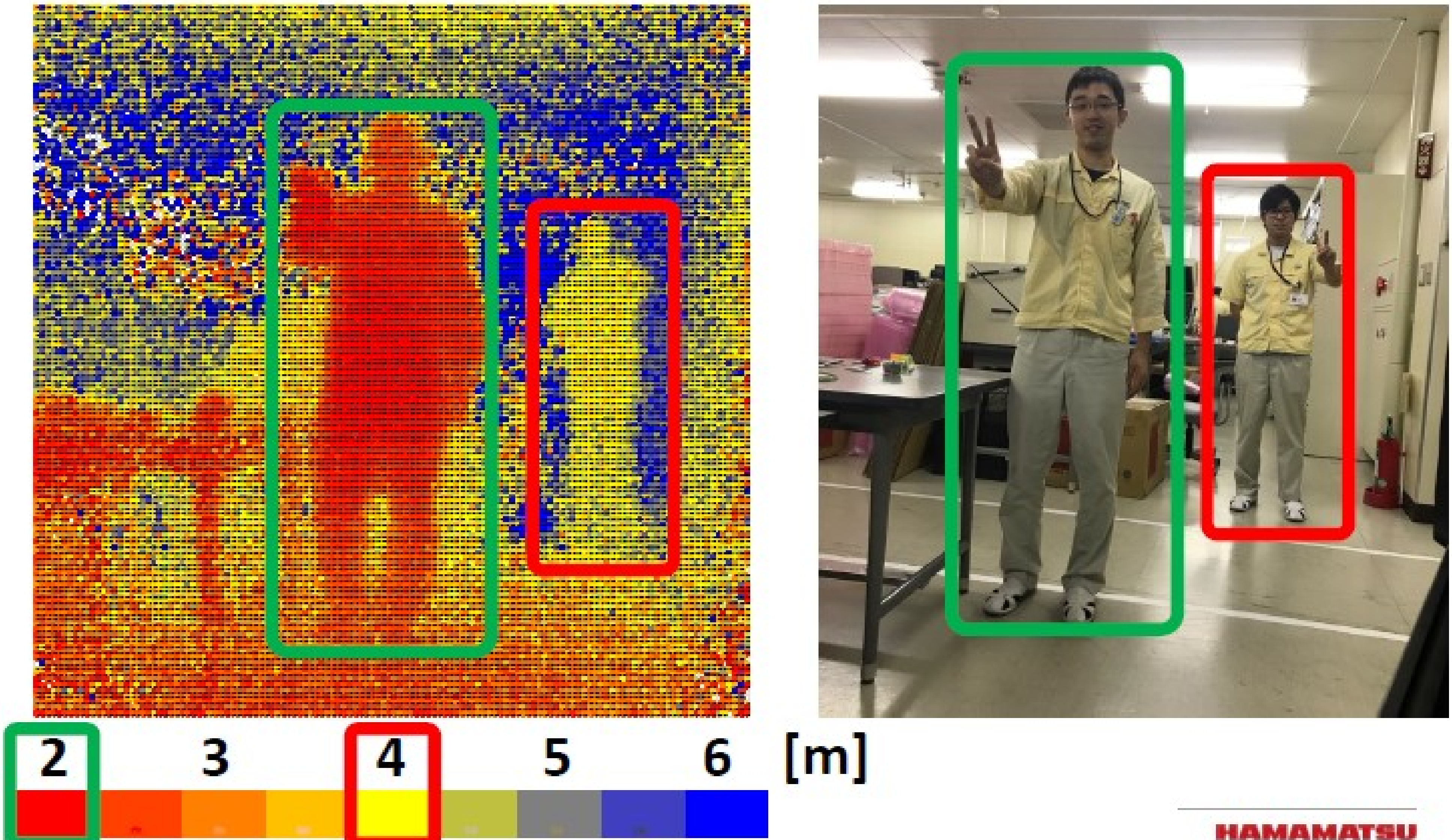


Sectional view



Timing - Lidar

Distance image acquisition experiment

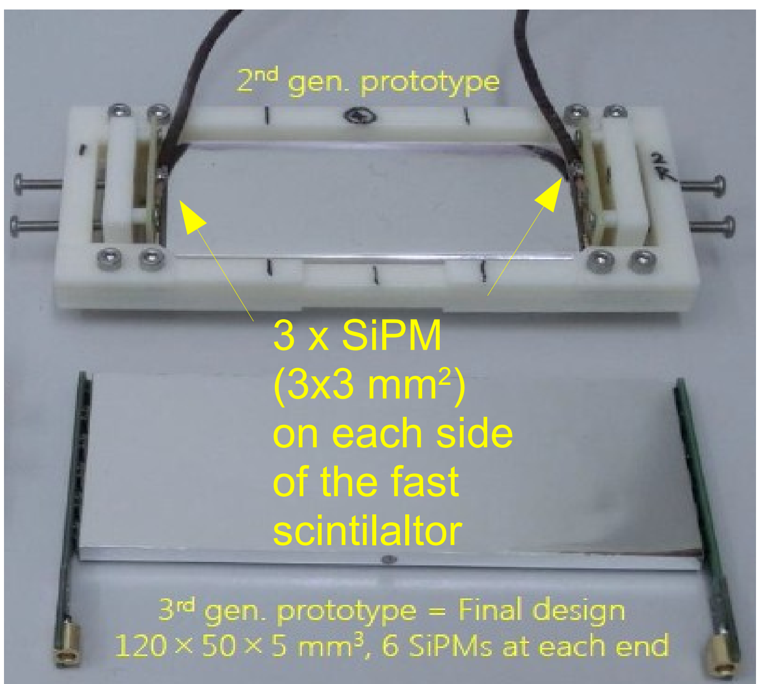


HAMAMATSU
PHOTON IS OUR BUSINESS

Timing: fast counter MEG-II

Requirements:

- collecting many photons by combining a few SiPM to form a single channel
- low sensor capacitance



Summary

- SiPM-based scintillation counters can provide <30 ps time resolution
  - Intrinsic resolution of σ=**15 ps**/$\sqrt{E/(1\ \mathrm{MeV})}$ is achievable with a single small counter
  - More importantly, SiPM application allows flexible design of your detectors
  - ⇒ Multiple measurements of a particle time, improving closely as **1/**$\sqrt{N_{\mathrm{hit}}}$
- R&D for the MEG-II Timing Counter was completed
  - 30-ps resolution was demonstrated
  - Tested first ¼ detector in 2015

Timing: fast counter MEG-II

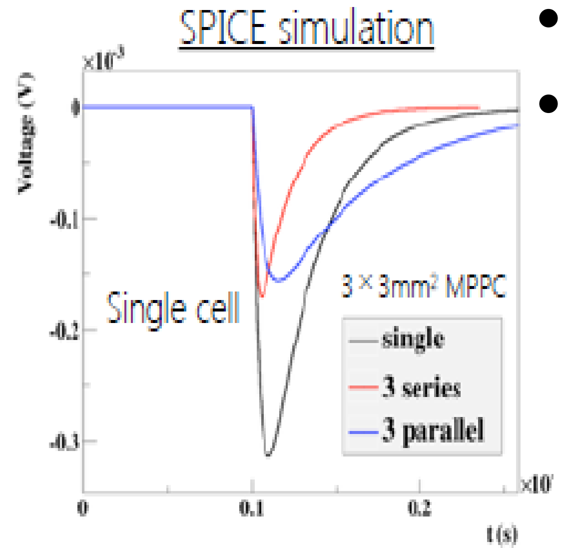
Combining n SiPMs in Series

→ less channels and also
- less Capacitance
- less Signal (Q)
- faster rise/fall signal fronts

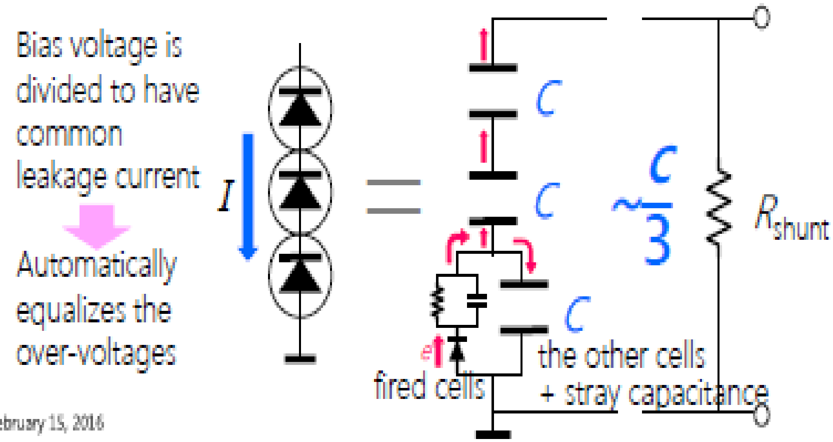
… by factor n

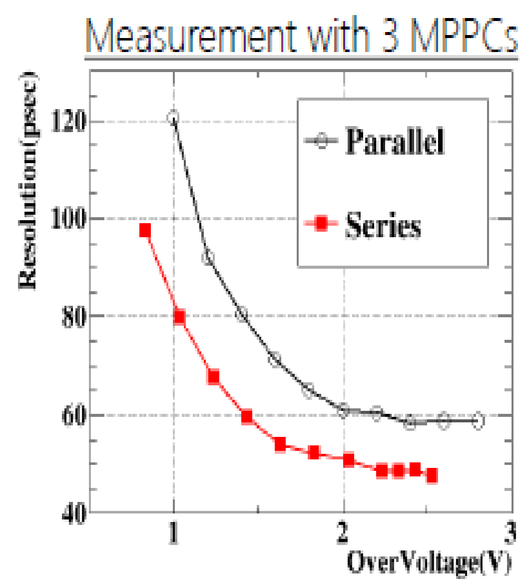
- SiPMs have high capacitance
  - Terminal capacitance ~300 pF for 3×3 mm² SiPM
- This forms a slow RC time-constant with amplifier input impedance
  - 3×3 mm² : 300pF × 50Ω = 15 ns
  - 3×9 mm² : 900pF × 50Ω = 45 ns !!

  → *One of limitations for large area SiPMs or array of SiPMs with parallel connection*



- This large capacitance works as capacitive coupling when connected **in series**





February 15, 2016
YUSUKE UCHIYAMA

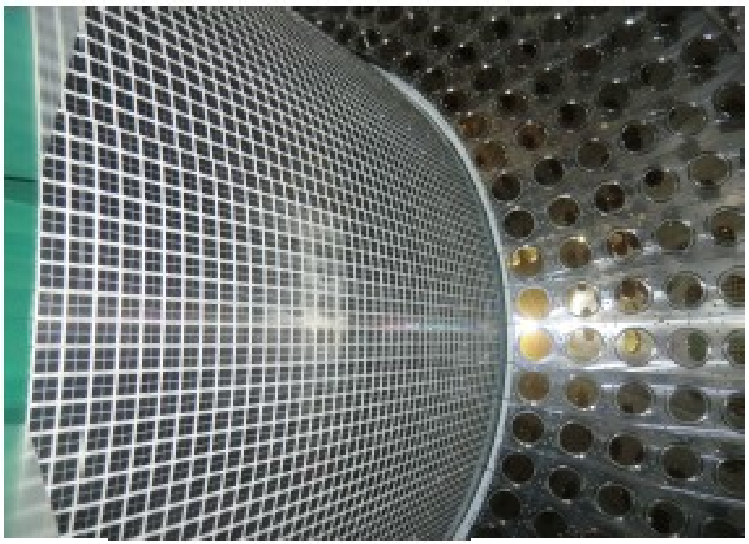
Large Surface Cryogenic SiPM readout - VUV

MEG-II

LXe scintillation light detection (175nm) by VUV-MPPC

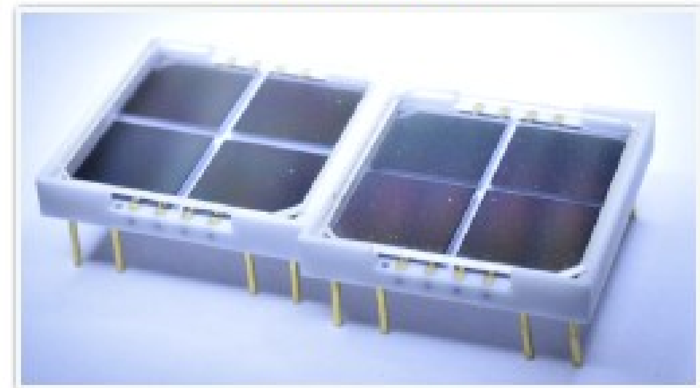
- Highly granular readout w 4092 × VUV-MPPC (140mm^2 each)
- Covering 0.92m^2 area with coverage of 62%

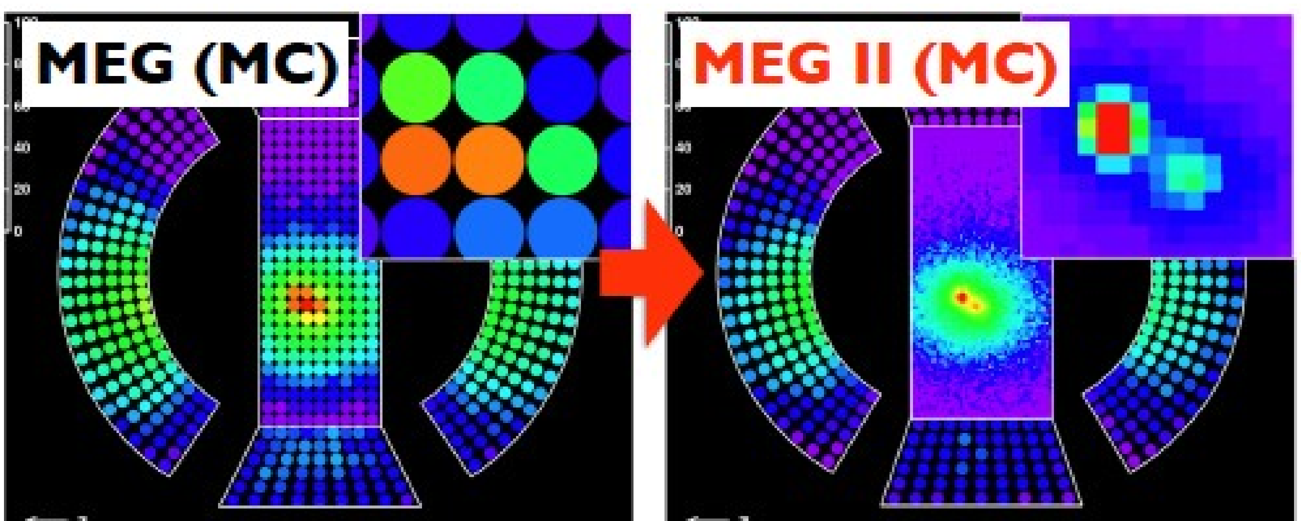
→ MPPC development Hamamatsu



Aim is at improving **Energy and Position Resolution**

S10943-4372





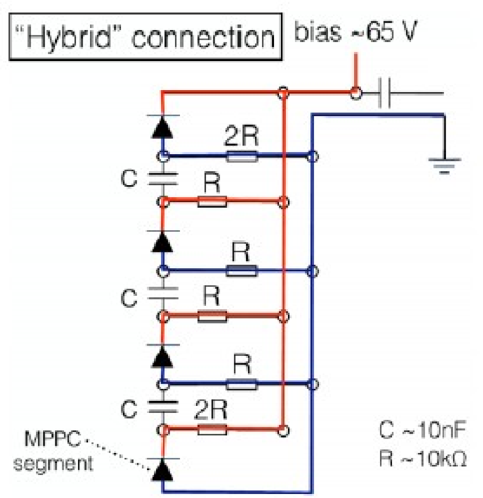
Requirements and constraints

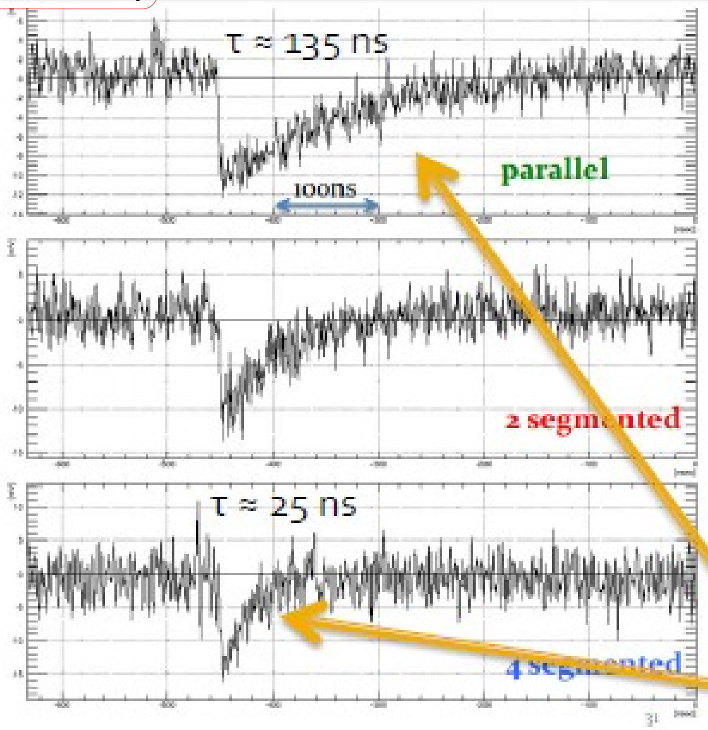
- High granularity
- Need both good S/N (energy)
- Need high speed (timing)
- No amplification at cryogenic T

MEG-II ganging

Passive ganging of 4 sensor segments (6×6mm^2 each)

- Series connection employed (timing ↔ S/N)





$\tau_{i2} \simeq \tau_{FAST}$
$\tau_{d2} \simeq \tau_{SLOW}$

Assuming:
N= 40k
Rq = 1 MΩ
Rs = 50 Ω
Cd = 30 fF
F = 5

Ctot changes !

τ_{d2} = 30 ns
$\tau_{i2}{}^{P}$ ≈ 120 ns
$\tau_{i2}{}^{S}$ ≈ 20ns

- indeed it's "Hybrid" connection:

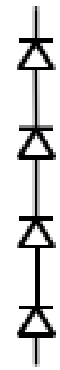
→ Series connection for signal
→ Parallel connection for biasing

- At Cryogenic T **dark rate too low for enforcing auto-balancing** of over-voltage
  - over-all common Leakage current would fix V biases at different over-voltages)
  - Bias uniformity provided by the resistor network

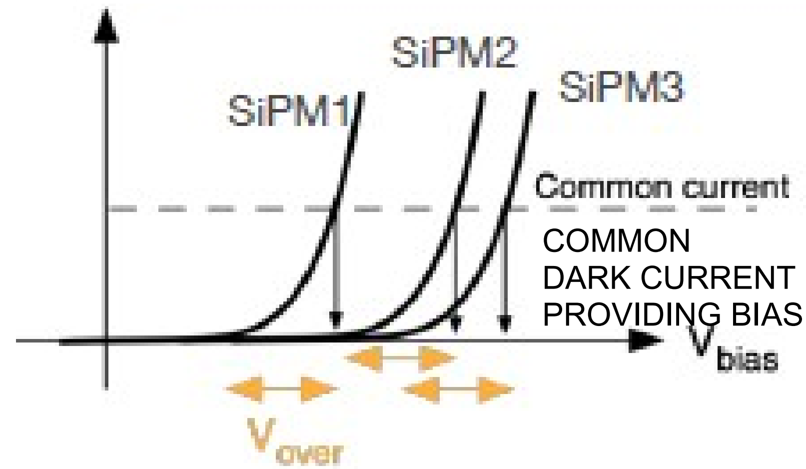
- High bandwidth signal transmission on coaxial-like signal line (50Ω)
  + Waveform sampling (DRS4) at room temperature

Parallel or Series ?

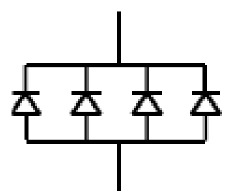
Series
- Both charge and amplitude reduced (signal gain reduced)
- Reduced capacitance → fast signal
- Better for timing
- Generally lower noise but not S/N
- Automatic over-voltage adjustment even with different breakdown voltages
- Need higher bias voltage (× N)

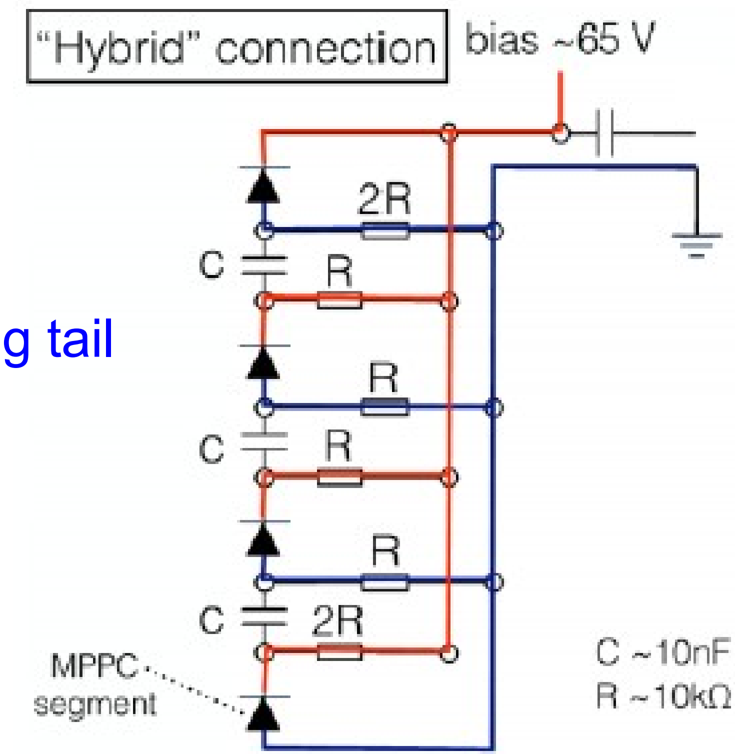


Automatic Over-Voltage Adjustement



Parallel
- Charge preserved, but amplitude reduced
- Increasing capacitance (x N) → slow rise and long tail
- Not optimal for timing and high rate
- Need to group SiPMs w/ same breakdown V



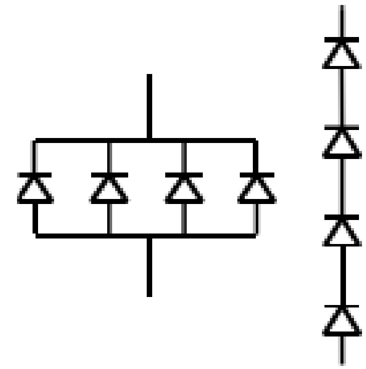


Hybrid
- Connected in series, but with decoupling capacitor in between
  → Series connection for signal
  → Parallel connection for bias (no bias via I_{dark} at low T)
- Common bias voltage

After Ootani – ICASiPM 2018 and A.Razeto – PD18 (modified)

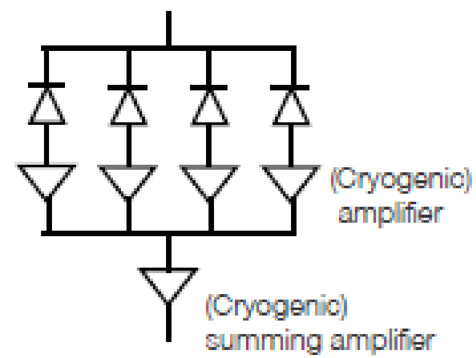
SiPM ganging: several choices...

… depending on requirements and constraints
- Speed, S/N, granularity, # of readout cables, cost, …



Passive ganging
- Parallel or Series (Hybrid at Low T)
- Simpler … but…
- Need signal transmission over long cable → worse S/N

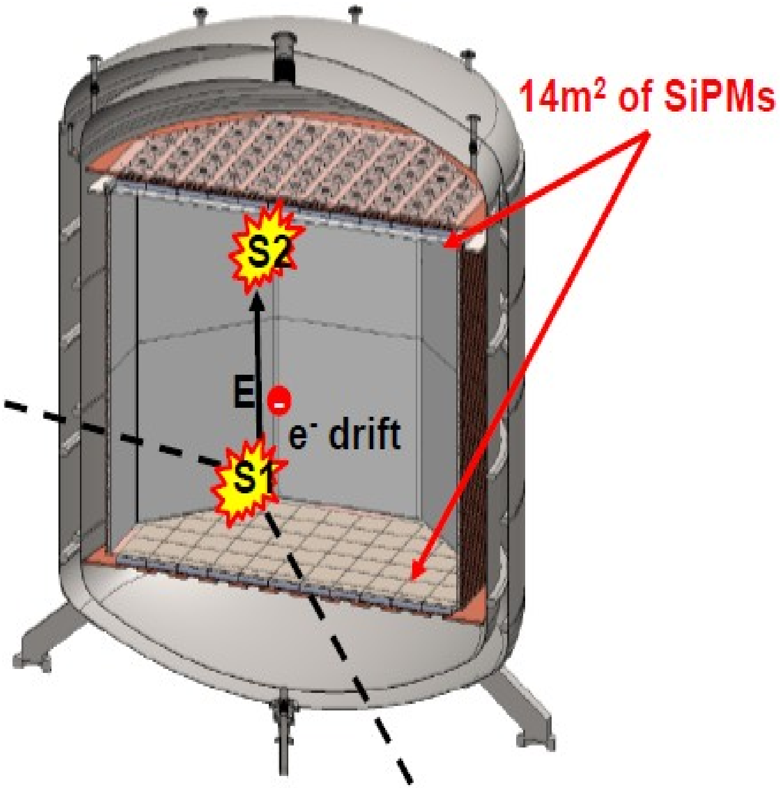
Active ganging (option for Cryogenic applications)
- Better S/N and timing … but …
- Need cryogenic amplifier
- Power consumption & Cooling
- Bubbling due to local heat
- Additional radioactivity near active detector volume
- Influence on purity of liquid



Combination of active and passive ganging

After Ootani – ICASiPM 2018 (modified)

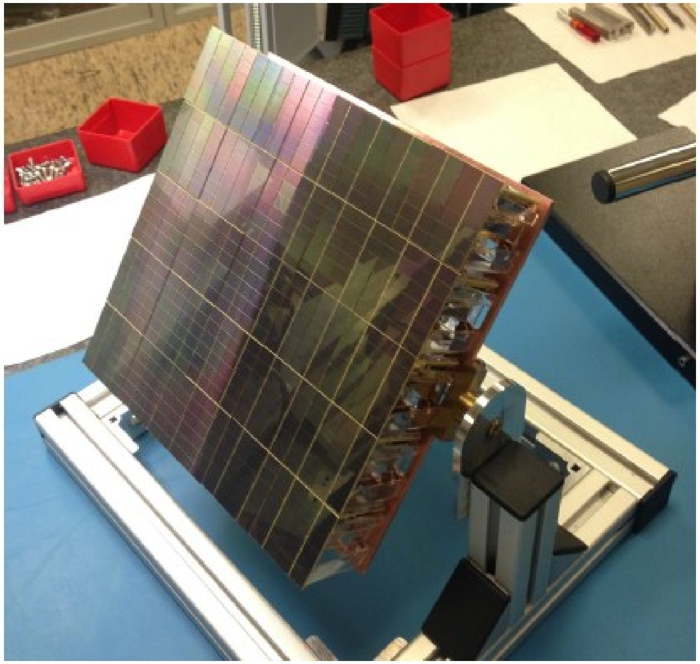
Large Surface Cryogenic SiPM readout



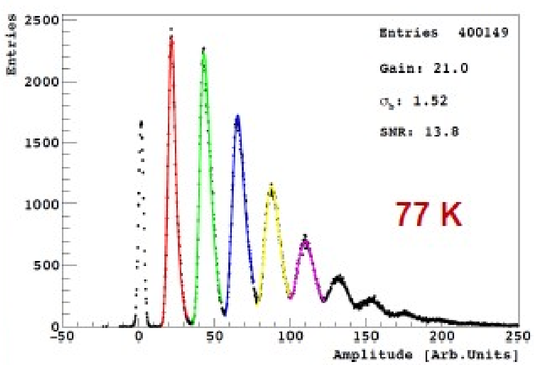
DARKSIDE

- Dark matter search experiment with 20t of LAr
- Operating at ~77K
- $14m^2$ of SiPM in TPC (+veto)
- Blue light detection with WLS (TPB)
- Granularity crucial

First Motherboard, 625 cm^2 area, ~90% covered by SiPM



First results with $24cm^2$ single readout channel tile !!!



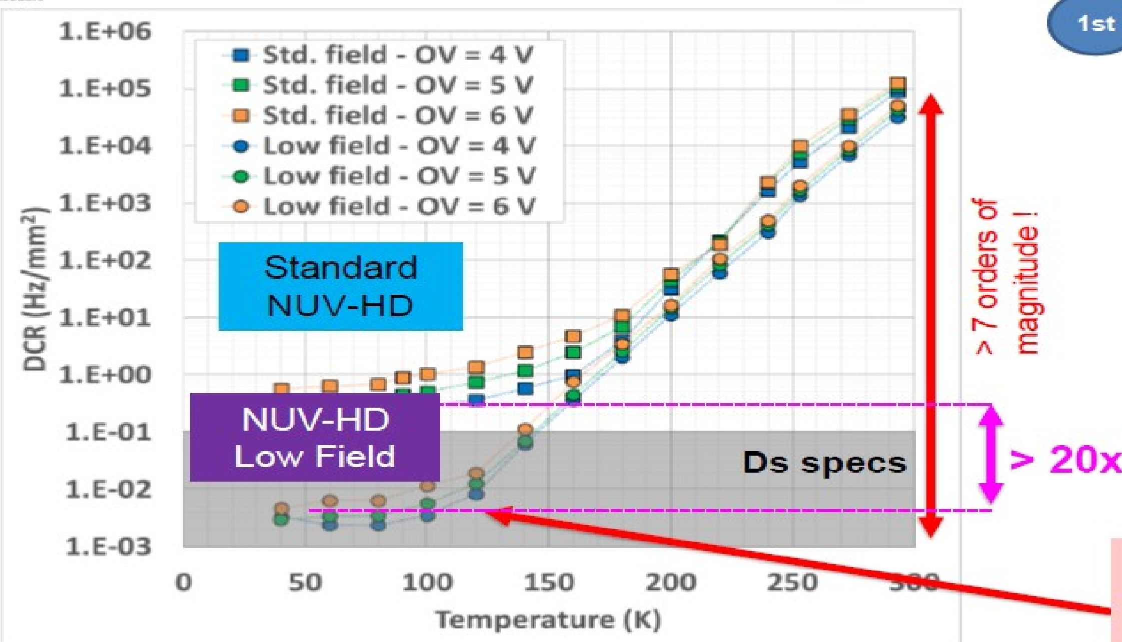
DS-20k module specs.

- Surface = $25cm^2$
- PDE > 45% at 420nm
- Noise hits ~ DCR = $8cps/cm^2$
- Timing ~ 10ns
- Dynamic Range > 50pe
- SNR > 8 over BW ~ 30MHz

FBK SiPM development for DARKSIDE

F.Acerbi – PD18
and G.Paternoster

NUV-HD-cryo: DCR



1st improvement **NUV-HD Low Field**

Re-designed multiplication region doping profiles:
- Lower Electric Field
- Wider depletion region

Lower generation via Tunneling effect

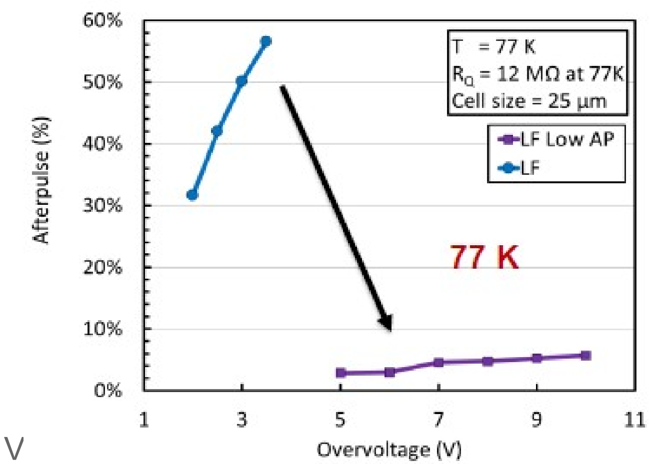
0.3 counts per day per cell at 77 K!

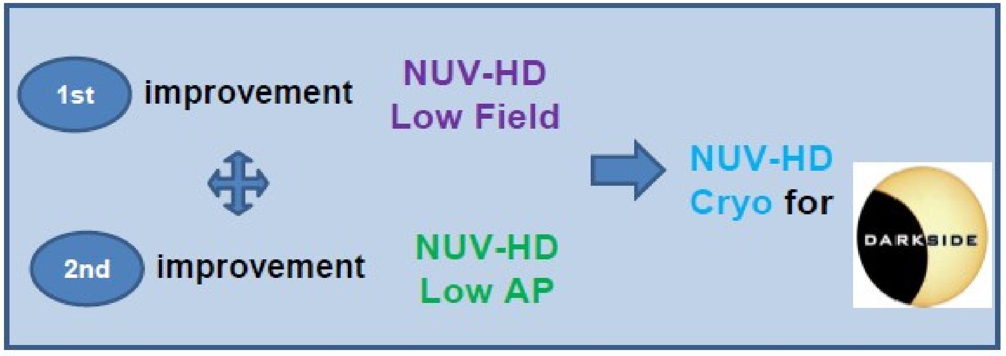
A 10x10 cm² SiPM array would have a total DCR < 100 cps!

2nd improvement **NUV-HD Low AP**

Re-designed surface junction doping profiles:
- Improved surface passivation

NUV-HD-Low AfterPulsing





DARKSIDE ganging

Ganging: passive+active

Passive (sum at ~ virtual ground)

- $1cm^2 \rightarrow 6cm^2$
- 3 parallel branches of 2 SiPMs in series (2s3p)

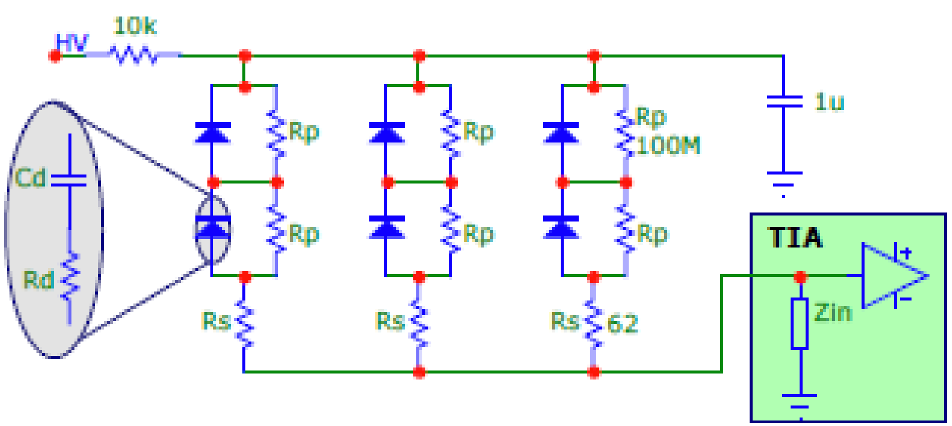
Active

- $6cm^2 \rightarrow 24cm^2$
- Cryogenic trans-impedance amplifier

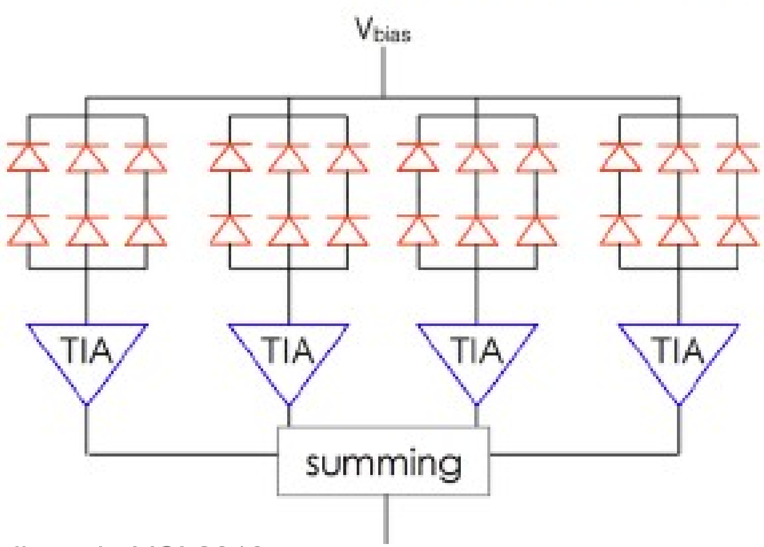
TIA amplifier wrt CSA or OPA is "shorter", allows fast signals and ultra-low noise

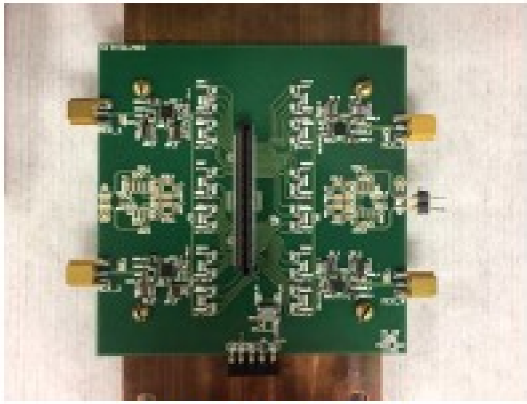
2S3P configuration is a tradeoff experimentally found to optimize SNR and Bandwidth

Passive ($1cm^2 \rightarrow 6cm^2$)



Active ($6cm^2 \rightarrow 24cm^2$)





arXiv:1706:04220

SiPM Bias

- precision R voltage divider
- divider current compromise
  - to be > leakeage current
  - minimize shot noise

see talk "Cryogenic Applications" A.Razeto – PD18 – Tokyo

Large Surface Cryogenic SiPM readout - VUV

nEXO

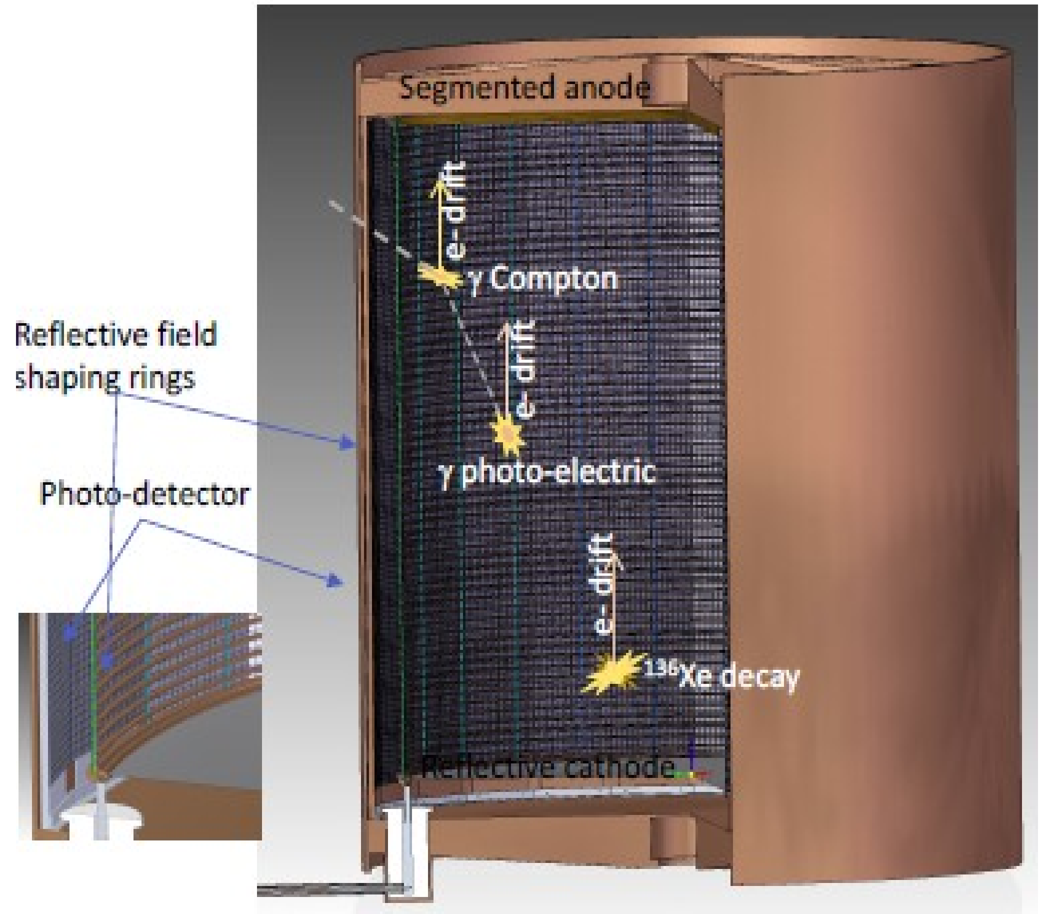
- TPC Filled with LXe
- 4-5 m^2 SiPM
  - Single VUV photon sensitive (**175nm**)
    - >15% efficiency
    - <20% correlated noise
    - <50 mHz/mm^2 DCR
  - Very low radioactivity
    - Silicon is generally very radiopure

GOAL:

energy resolution

$$\frac{\sigma}{Q_{\beta\beta}} < 0.01$$

for the 0νββ decay of ^{136}Xe (2458.07±0.31 keV)



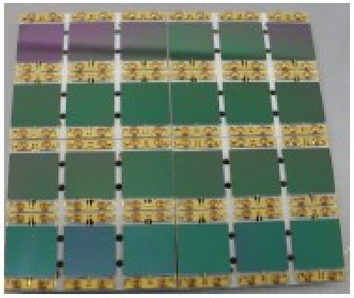
SiPM light detection at barrel of nEXO

- **VUV-SiPMs** covering 4-5m^2
- Single photo-detector active area >1cm^2
- Noise < 0.1pe per channel

Two options under study for SiPM readout

- Cryogenic **analogue** readout
- Cryogenic **digital** readout
- Very low power consumption <1W

Prototype large area SiPM array (24SiPMs, 24cm^2)



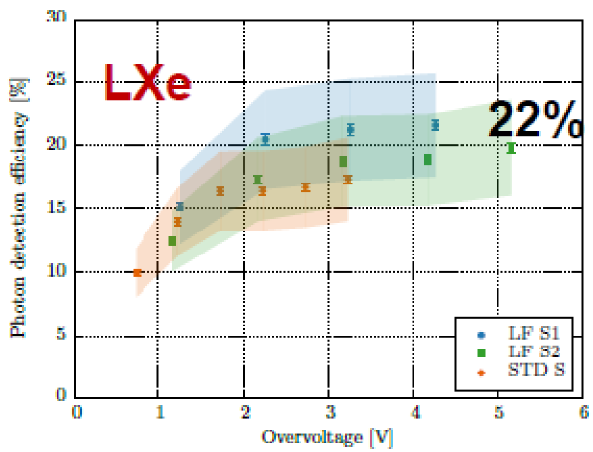
nEXO - VUV analog SiPM

Courtesy G.Paternoster FBK

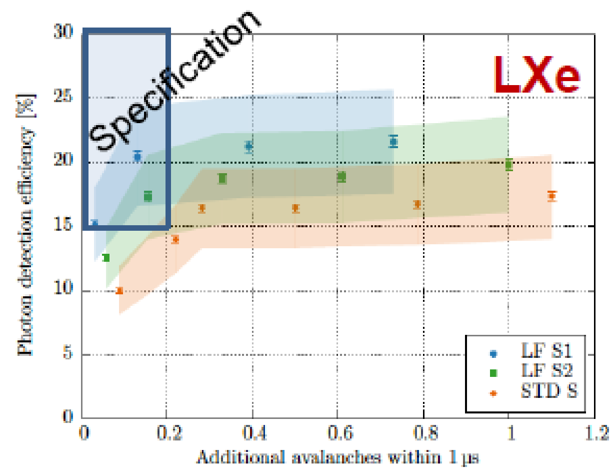
FBK development

characterization TRIUMF

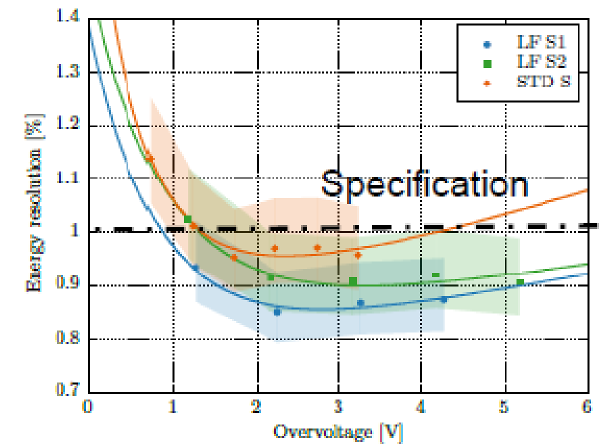
PDE vs OV

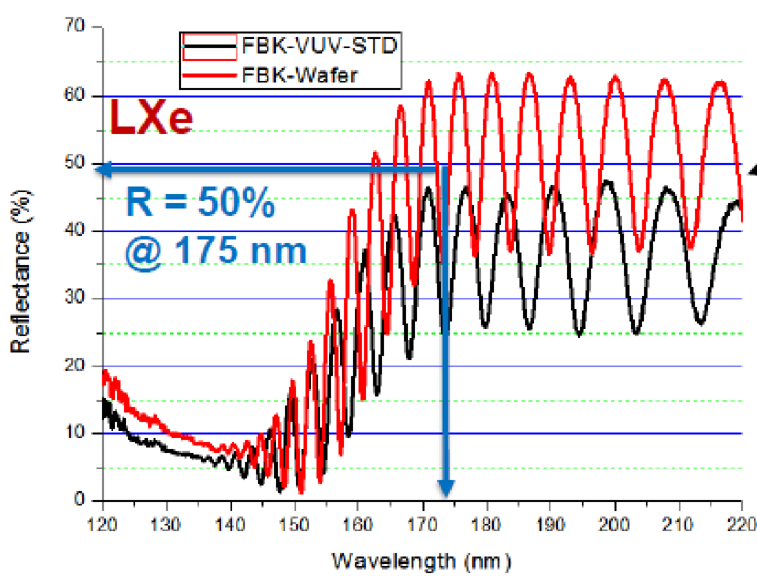


PDE vs Correlated Noise



Expected E resolution with FBK SiPM





- The main limiting factor is still the VUV light reflection on the SiPMs

  50% of the light is lost by reflection

nSi=0.7
nSiO2=1.6
nLXe=1.66

Next Steps to reduce reflectivity

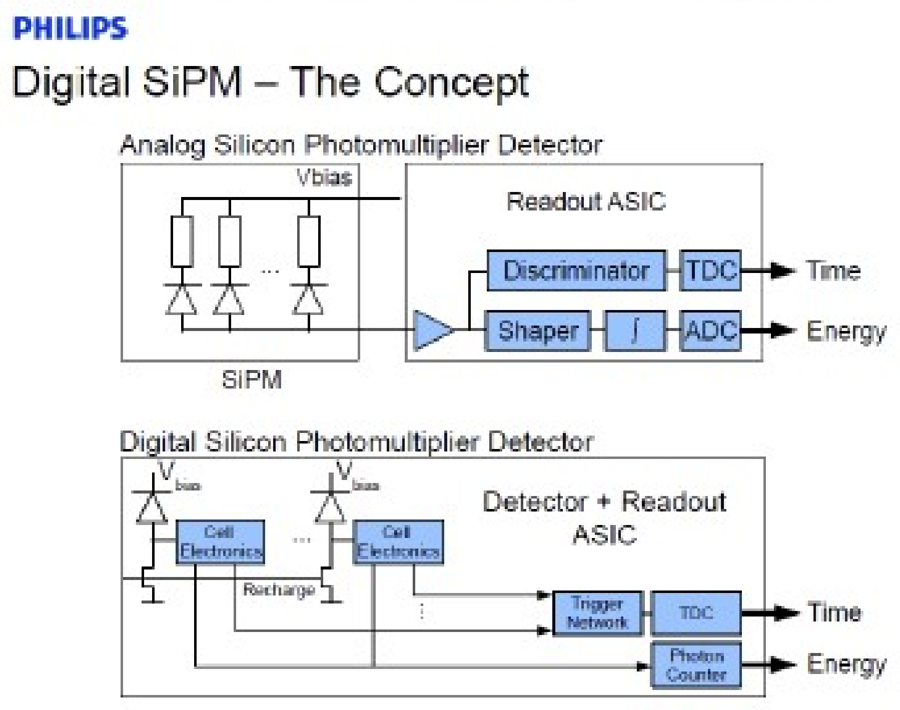
- Conventional low-loss dielectric filters are not available in this wavelength range.
- Metal-dielectric UV band pass filters under investigation

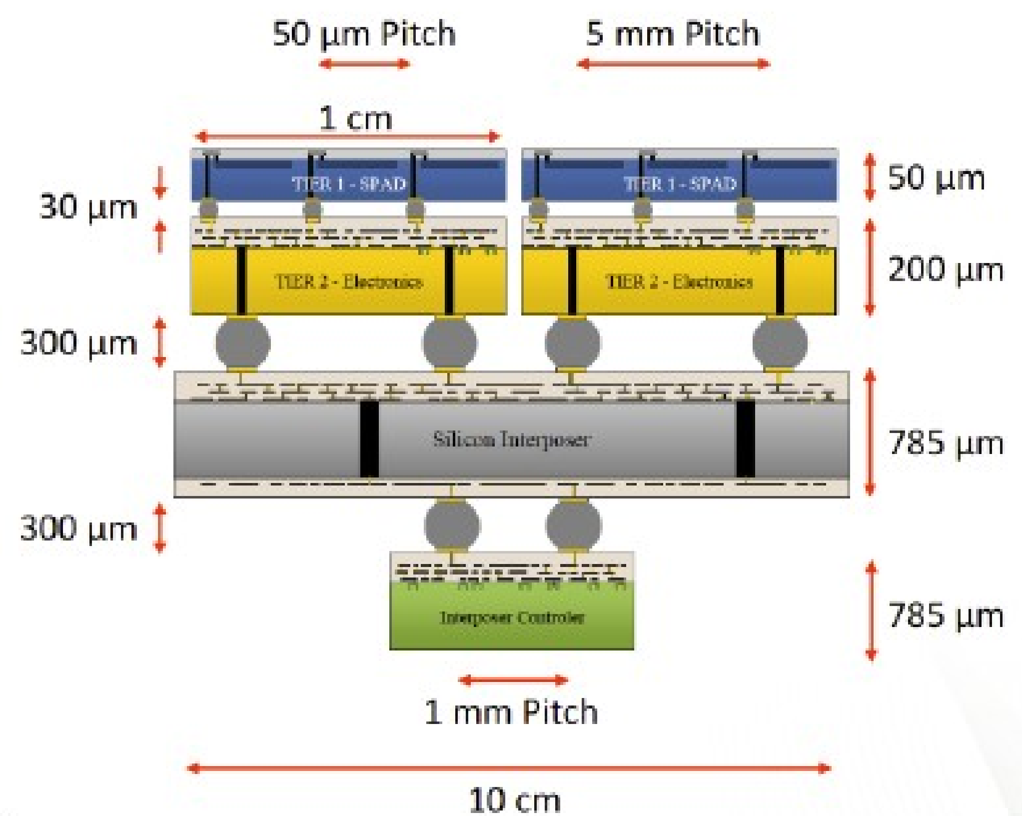
nEXO - 3D integrated digital SiPM

Development {

- **Digital SiPM**
  - On-cell digitisation
  - Low power consumption
  - Easier for large scale integration
- **3D-dSiPM: 3D integration to minimise dead area**
  - Tier1: SPAD
  - Tier2: electronics
  - Tier3: Data aggregator and trigger circuit

see “3D integrated digital SiPM” F.Retiere – TIPP17

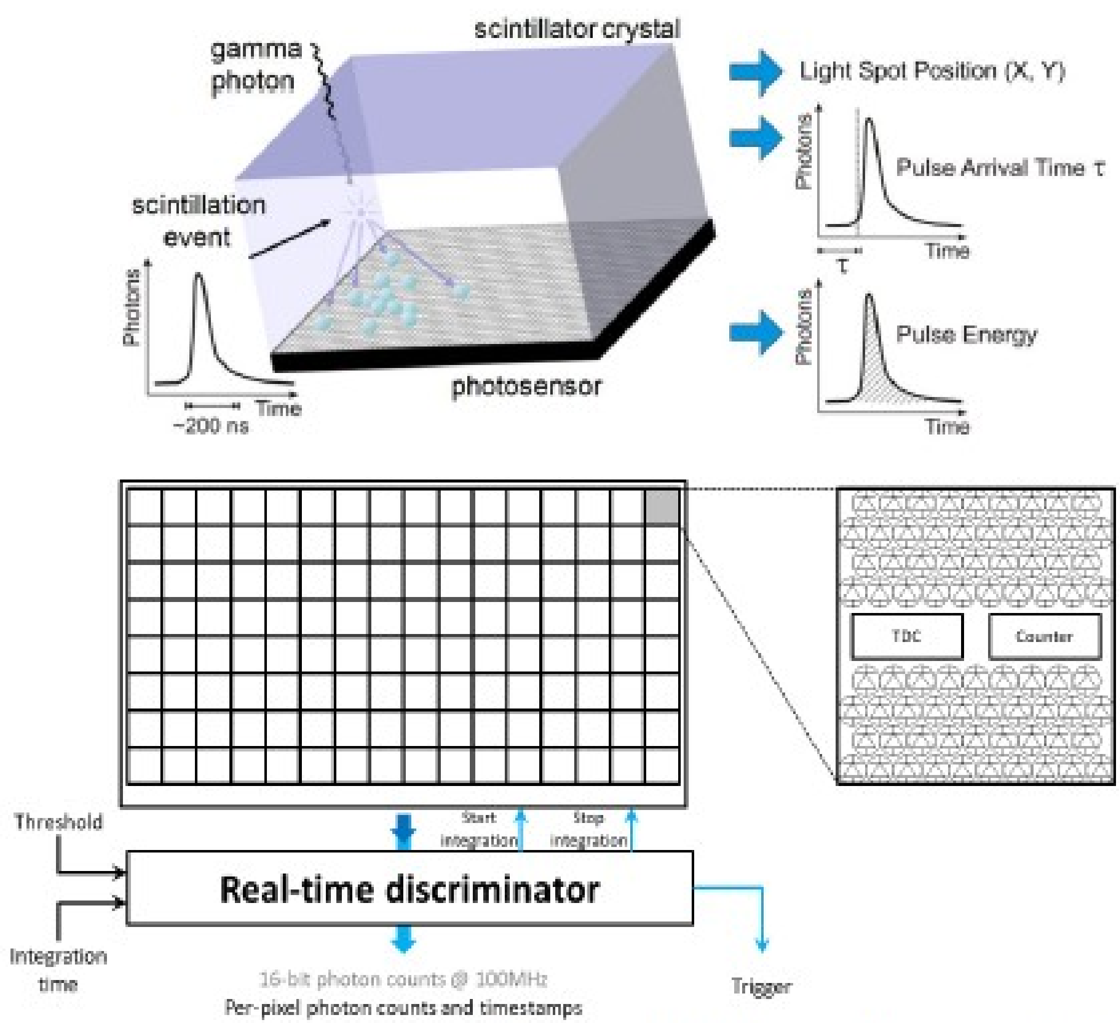


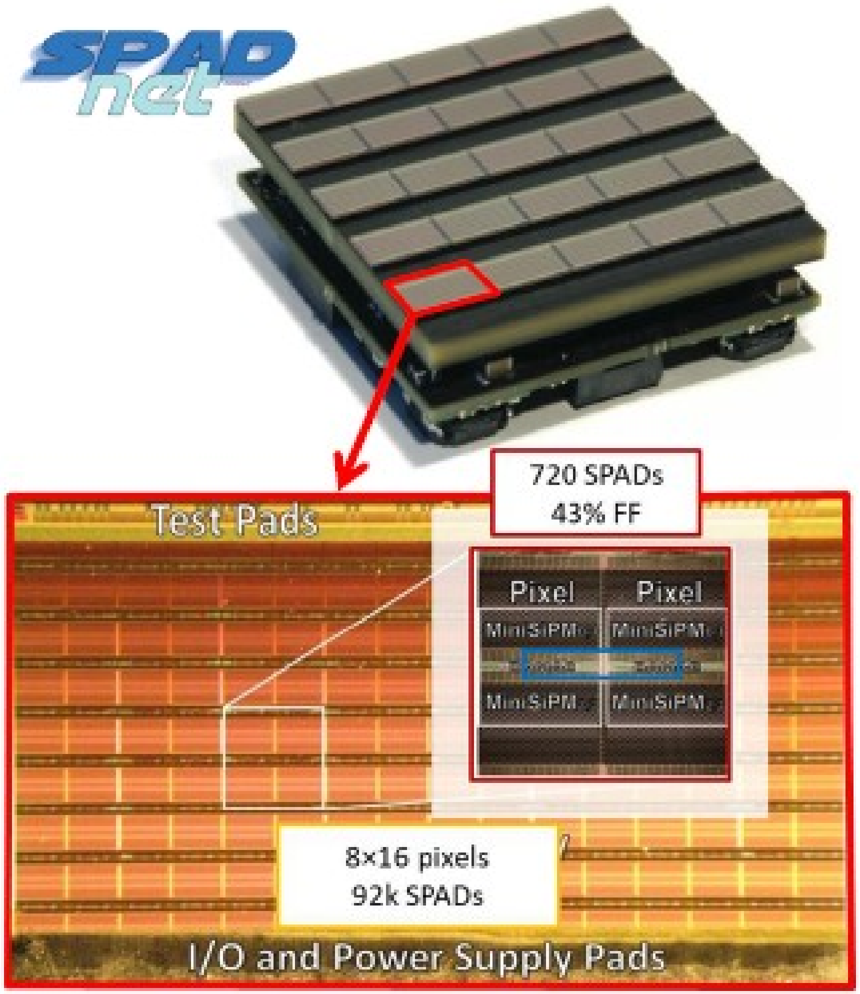


Latest trends d-SiPM

Digital SiPM (D-SiPM) System-on-Chip (SoC)

Source: slides from L.Gasparini, presented at CERN 2018





2 acquisition phases → 2 operating modes

- *Before γ :* Single-channel D-SiPM with real-time discriminator
- *After γ:* 2D array of D-SiPMs with photon counters and TDCs

Summary of SiPM features

Main features of a SiPM are:

- Sensitivity to extremely low photon fluxes
  providing proportional information with excellent resolution
  and high photon detection efficiency

- Intrinsically low jitter time response
  sub-ns risetime and jitter below 50ps (single ph.e)

- Single Photon noise @ few kHz & Correlated noise @ % level

- Limited radiation tolerance

More features:

- Insensitive to magnetic fields (up to 15T) and EM pickup
- robust and compact and stable over long term
- low bias voltage (<100V)
- low power consumption ($<50\mu W/mm^2$)
- little sensitivity to charged particle traversing the device
- tolerate accidental illumination, and illumination with no bias
- low cost per unit area

Conclusions

- Impressive progress in SiPM technology over the last 15 years

- In terms of both performance and cost it become mature technology which is employed in many projects also because of its flexibility: fine tuning for application

- Weak features (DCR, AP, CT, …) remarkably improved and still there is room for improvement (radiation hardness...)

- Spectral sensitivity range extended towards VUV and NIR (… IR too by InGaAs MPPC)

- Excellent performances at low temperature allow applications involving very large area (several m^2) readout by SiPM

Thanks for your attention

Additional material →

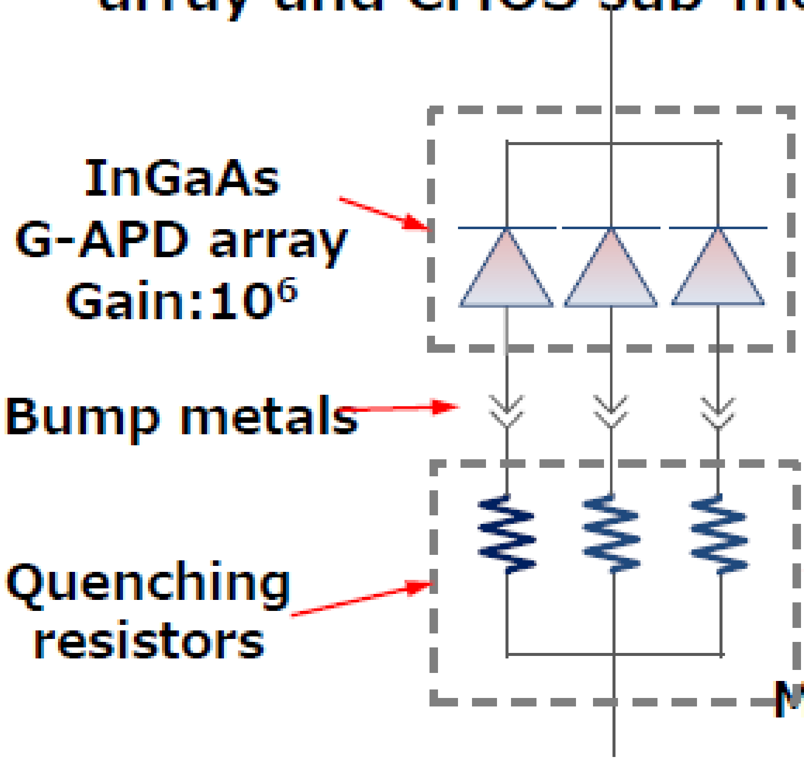
Novel types of SiPM

- Other semiconductors micro-cell avalanche mode
  → InGaAs-PM, SiC-PM, GaAs-PM
- Position sensitive SiPM

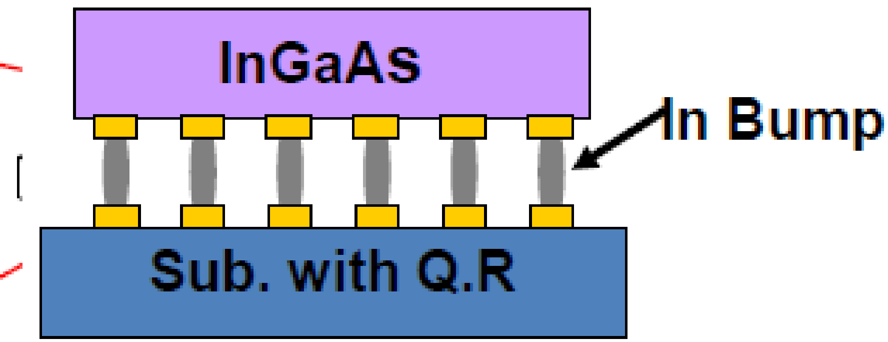
Other types of SSPM → IGA-MPPC

Koei Yamamoto (hamamatsu)
PD18 Workshop – Dec 2018

InGaAs-MPPC composed of InGaAs Geiger-mode APD array and CMOS sub-mount passive quenching circuits.



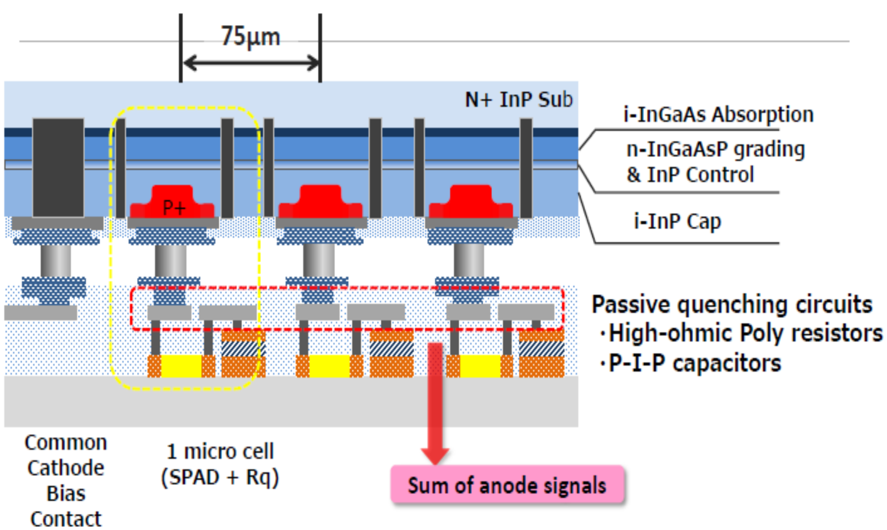
Active area size : 1㎜□~
Micro pixel size : Φ10~40um



Merit

G-APD : fast response & high gain
MPPC : possible to discriminate dark pulses
active quenching : after pulsing reduction

Anode signals from each micro cell are summed and read out as a current signal.



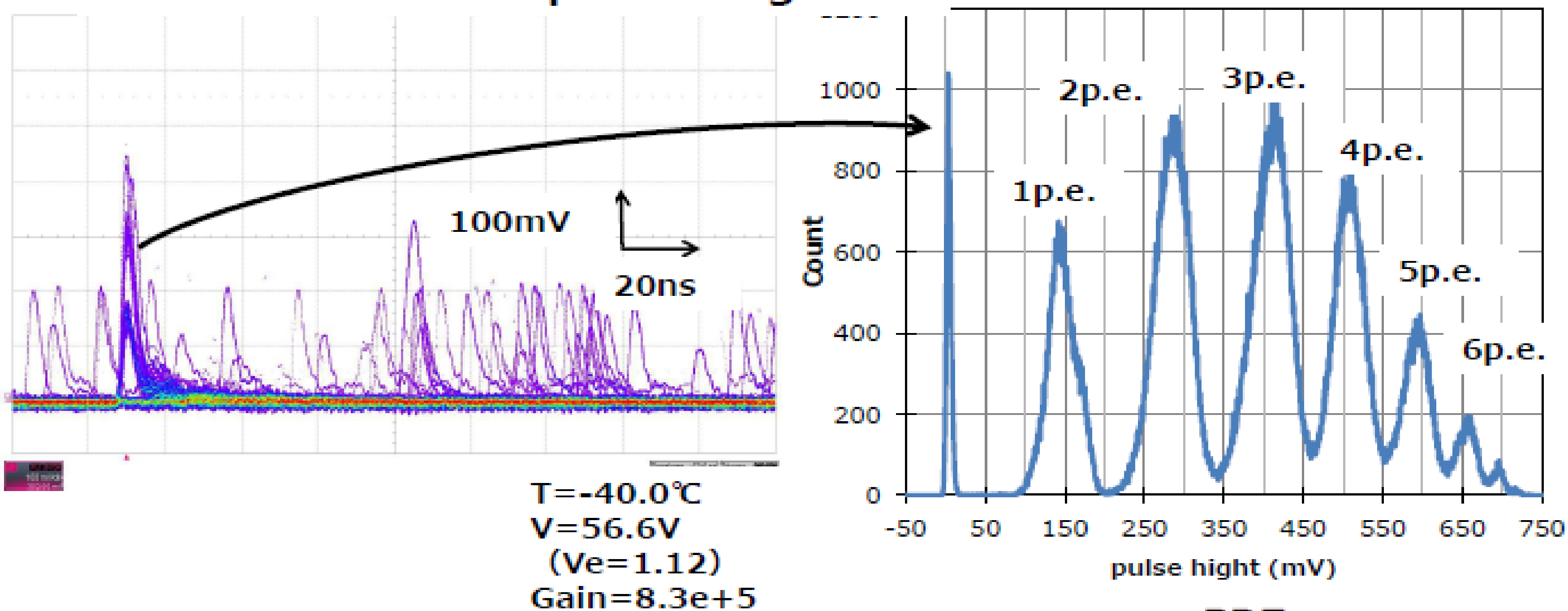
Problem

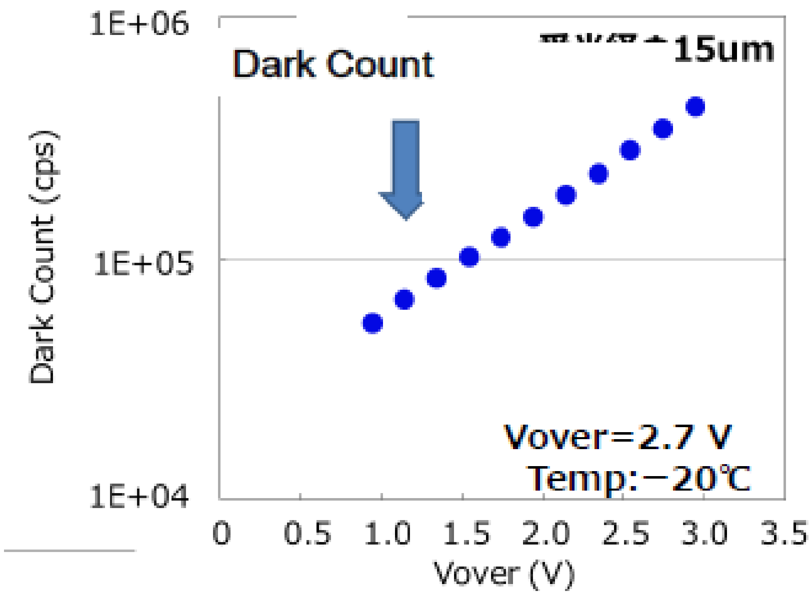
Have to develop Back illuminated type

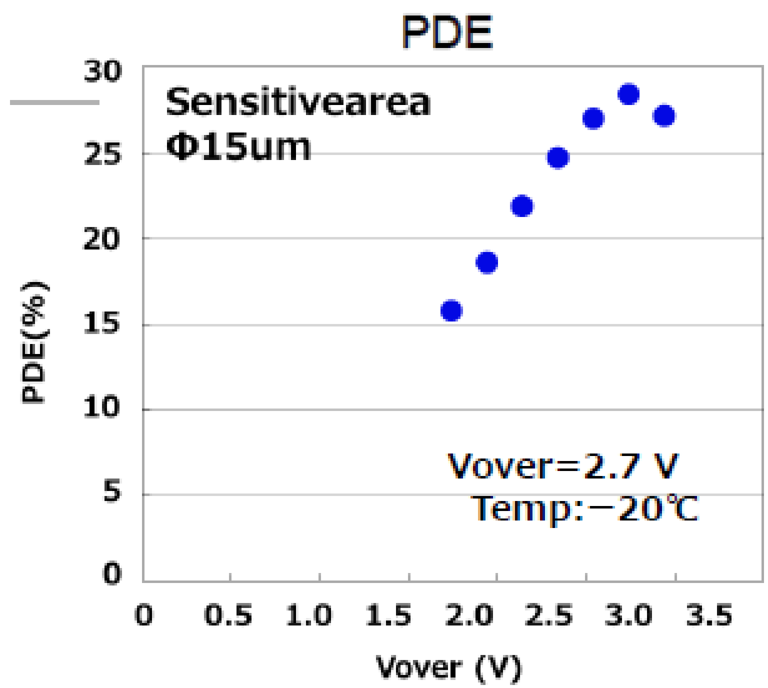
Other types of SSPM → IGA-MPPC

Koei Yamamoto (hamamatsu)
PD18 Workshop – Dec 2018

Count numbers of pulse height



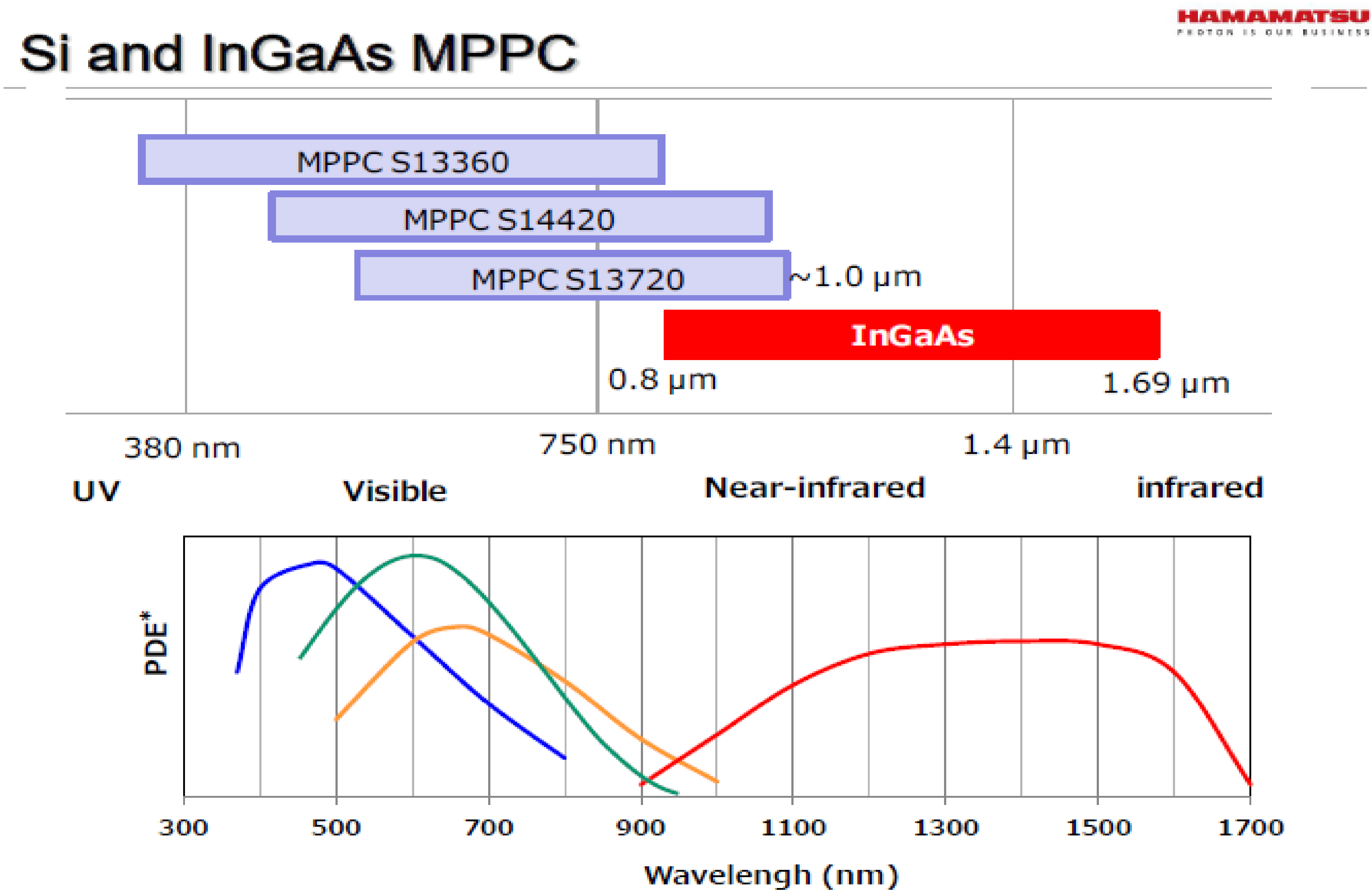




Other types of SSPM IGA-MPPC

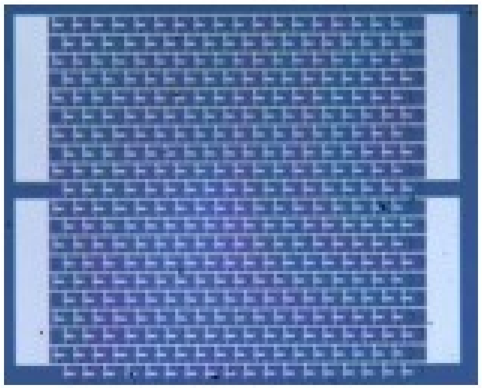
Koei Yamamoto (Hamamatsu)
PD18 Workshop – Dec 2018

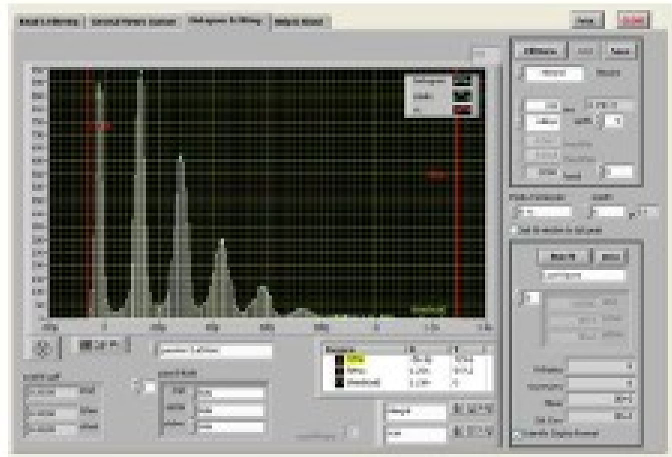
Si and InGaAs MPPC

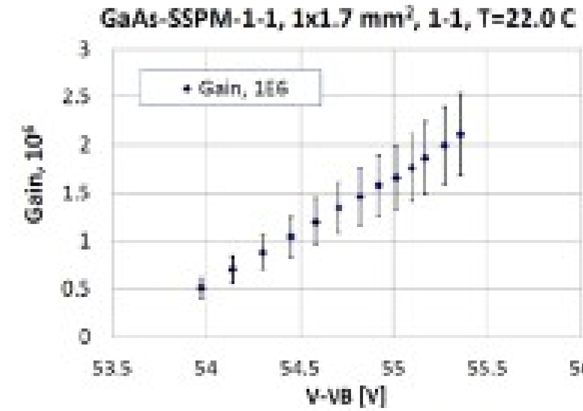


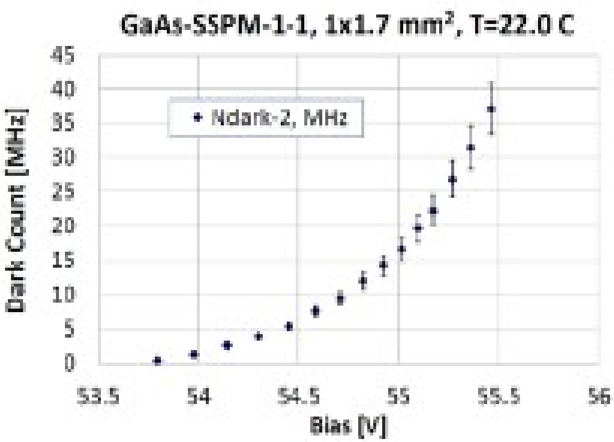
Other types of SSPM → GaAs-PM

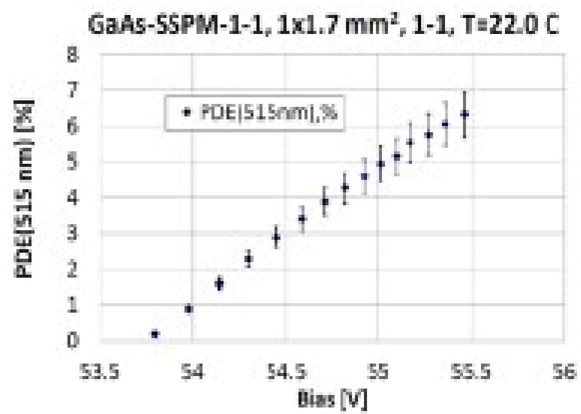
LightSpin Photomultiplier Chip™

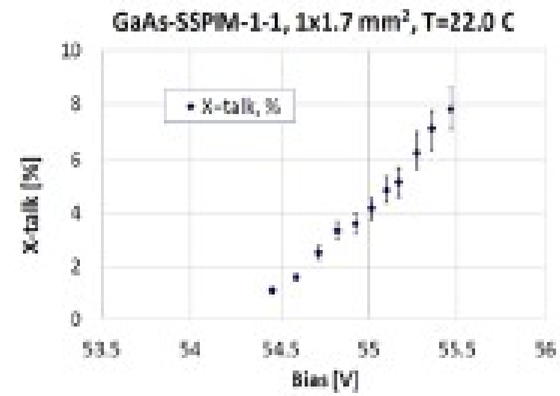


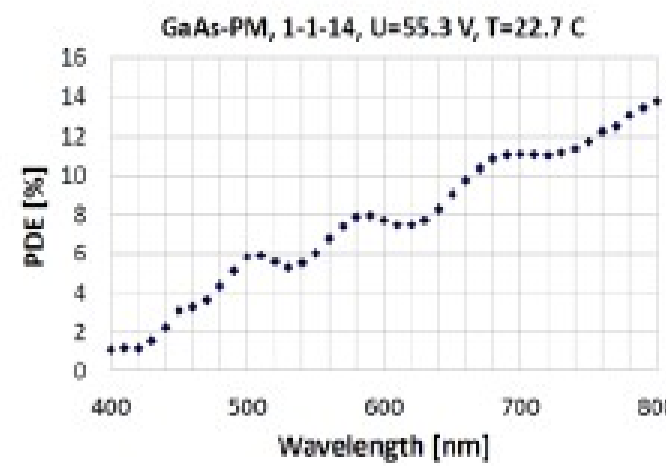






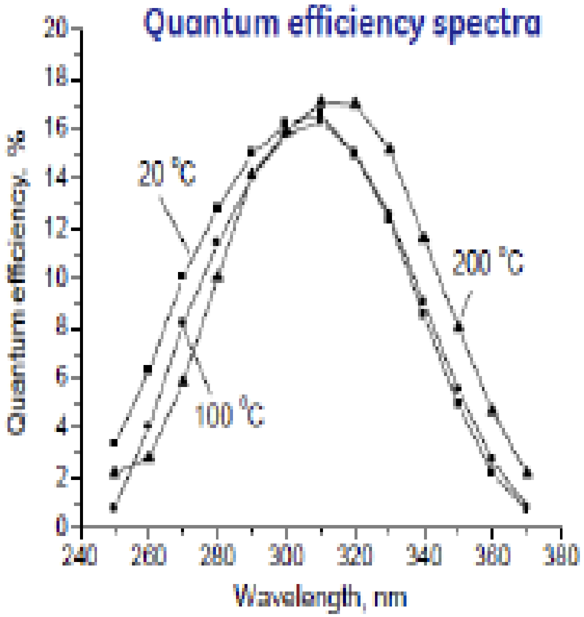






Wide bandgap (1.42 eV): potentially can be more radiation hard than silicon. Timing with GaAs SSPM can be also better (high mobility of electrons and holes, fast avalanche development – direct semiconductor)

Other types of SSPM → SiC-PM

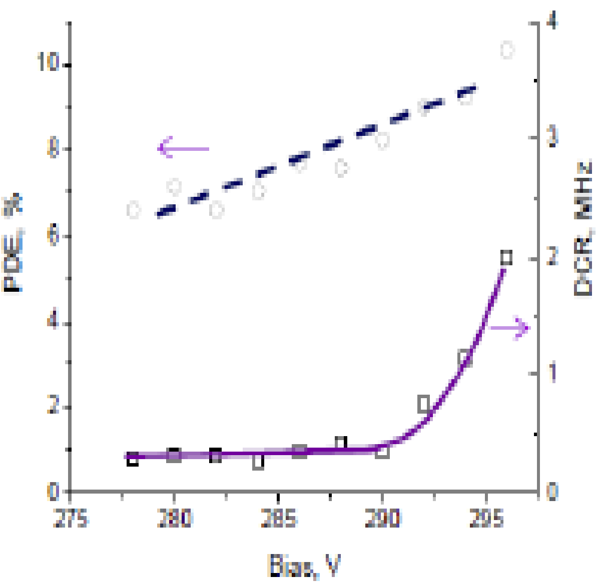


Advantage of SiC: it has
larger bandgap than Si (3.26eV)
→ Lower leakeage current
→ higher operating T
→ Higher sensitivity to UV

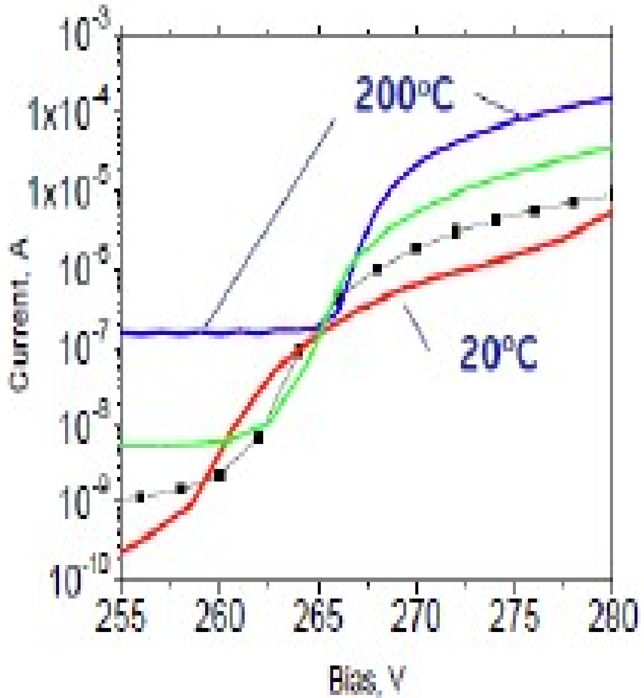
Packaged SiC SSPM

Active area: 4x4 mm²
Pixel size: 60 um
16 sub arrays
Area of sub-array: 1x1 mm²

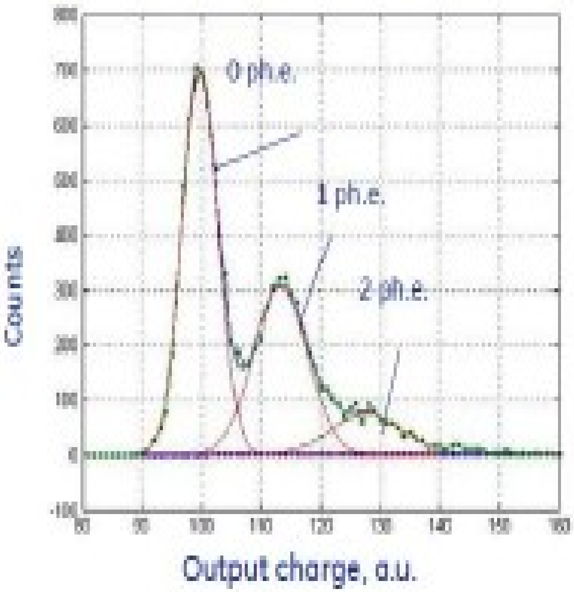
Photodetection efficiency and dark count rate as functions of voltage bias



Dark current vs. temperature



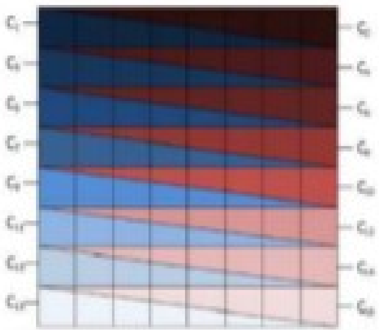
Single Photoelectron spectrum recorded for SiC-PM with 256 pixels (1 mm²)



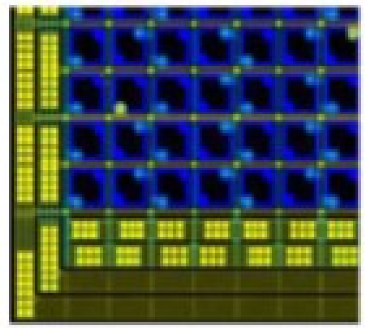
S.Dolinsky, GE, NDIP-2014

Position sensitive SiPM

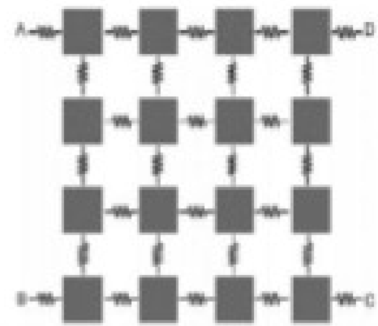
SeSP Uni. of Aachen, Germany [1]



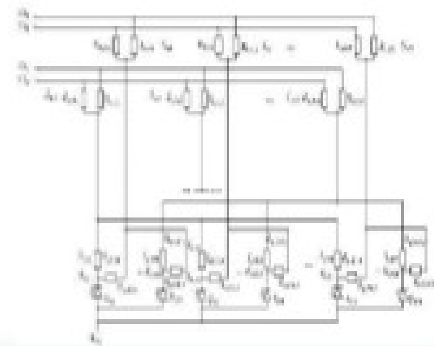
ISiPM Univ. of Heidelberg, Germany[2]



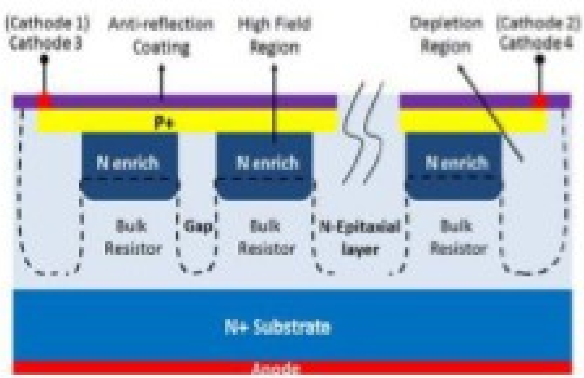
PS-SSPM RMD, USA [3]

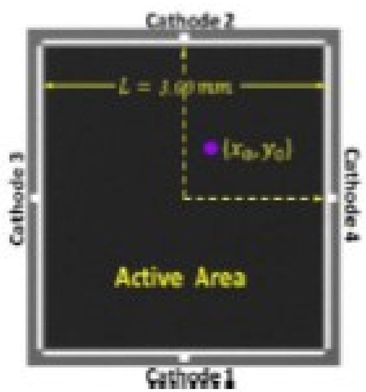


LG-SiPM FBK, Italy [4]



NDL EQR-SiPM → CRL-SiPM [5]





References

[1] Omidvari, N. and V. Schulz, IEEE Transactions on Nuclear Science, 2015. 62(3): p. 679-687.
[2] I., S., et al. IEEE SENSORS. 2013.
[3] J., P.S., et al., IEEE Transactions on Nuclear Science, 2014. 61(3): p. 1074-1083.
[4] Berneking, A., et al., NIM:A, 2018. 888: p. 44-52.
[5] Zhao, T., et al., IEEE Electron Device Letters, 2017. 38(2): p. 228-231.

Source:
Y. Peng @ICASiPM 2018, Schwetzingen

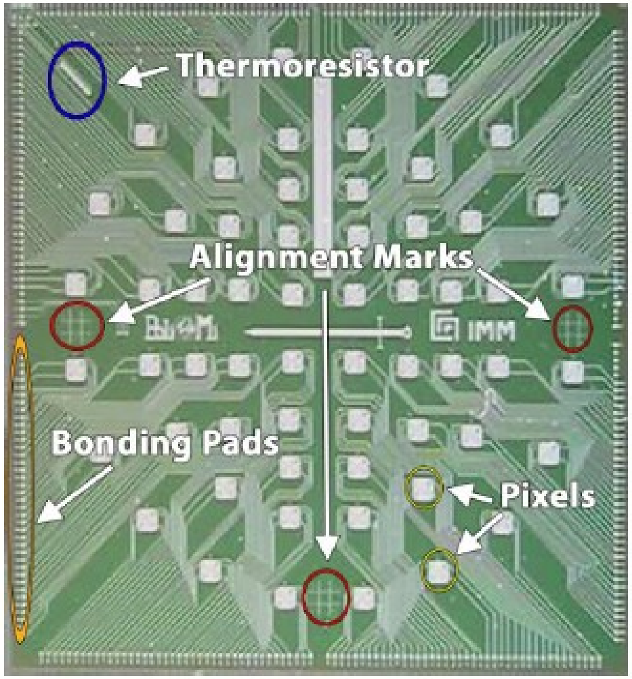
Increasing interest for Position-sensitive SiPMs:

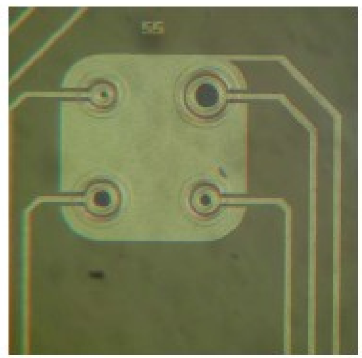
- Useful for small-animal PET
- Interest for imaging secondary scintillation light in TPCs
- Possibly many other applications

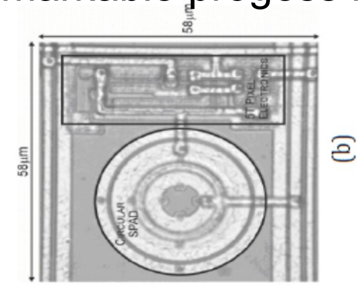
SPAD Arrays w/ electronics "integrated" → "Digital" SiPM

Remarkable progess in the last 20 years

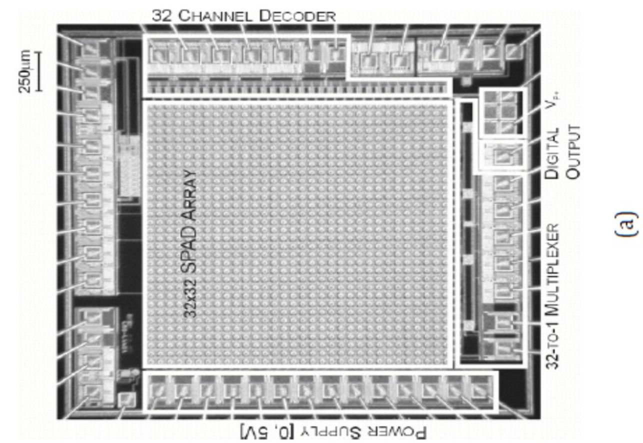
- quenching
- reset
- read-out





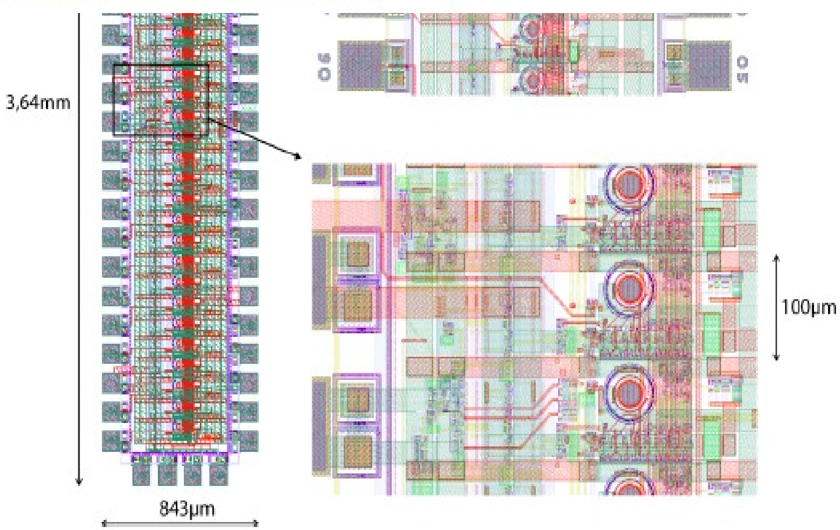


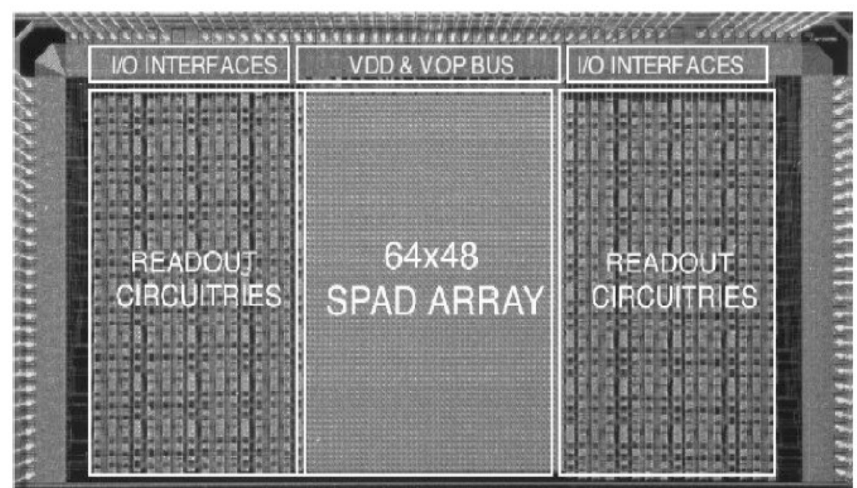
Niclass, PhD Thesis EPFL (2008)



- Cova, Lacaita, Zappa et al since early 90-ies (Politecnico Milano group)

Guerrieri, NDIP 2008

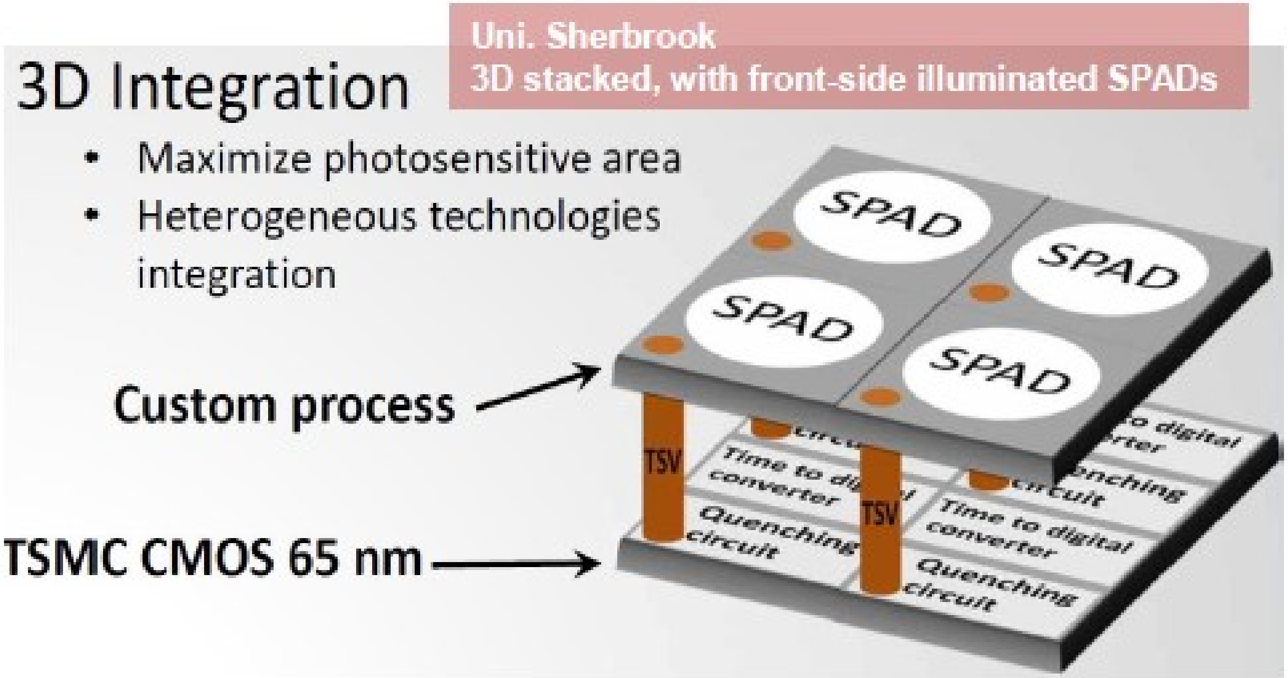


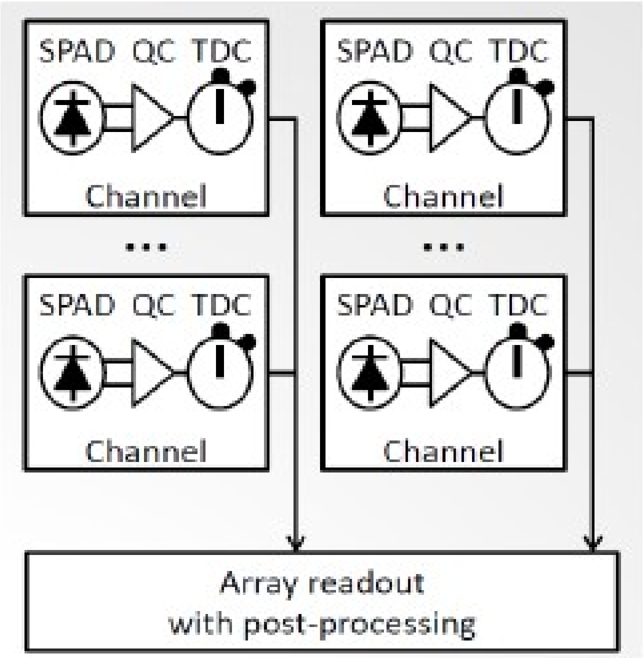


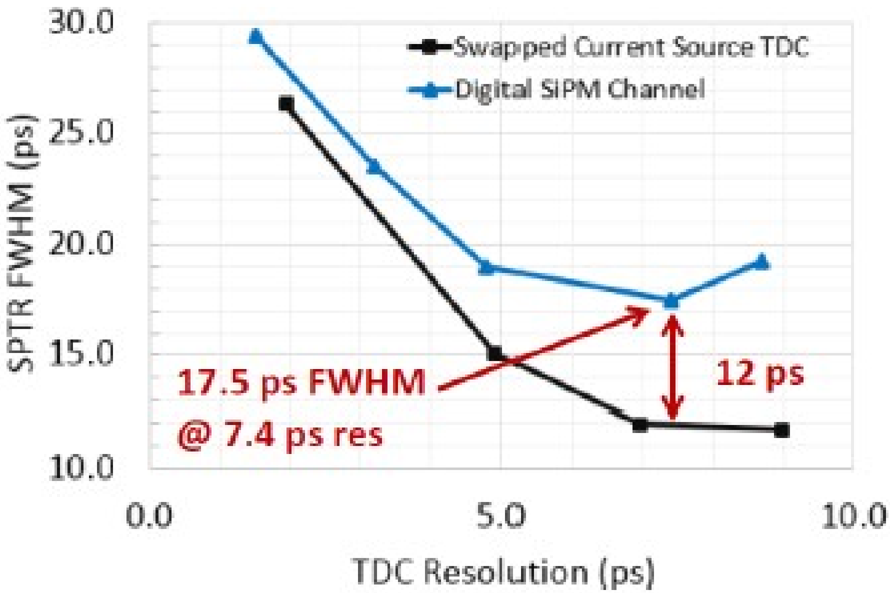
- *Charbon, Rochas, Niclass, et al (EPFL Lousanne group)*

See also:
- *Kindt et al*
- *Jackson et al*
- *Staples et al*

Latest Trends d-SiPM







Optimized custom technology for SPADs

+

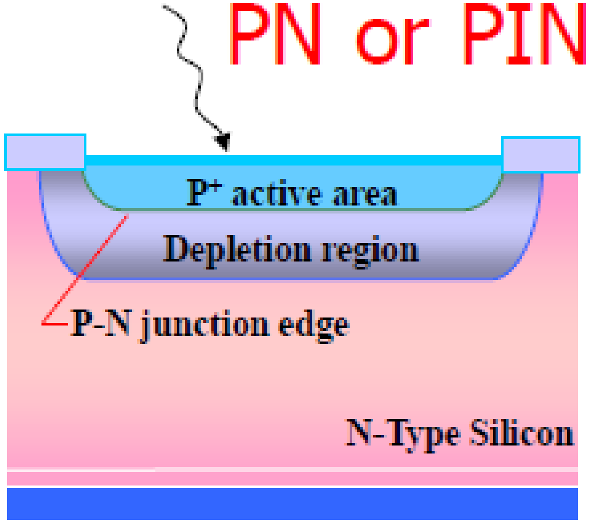
CMOS advanced tech. for quenching and processing.

- Focused on best TDC and timing performances
  - Obtained <20ps FWHM single-photon time resolution on one channel.

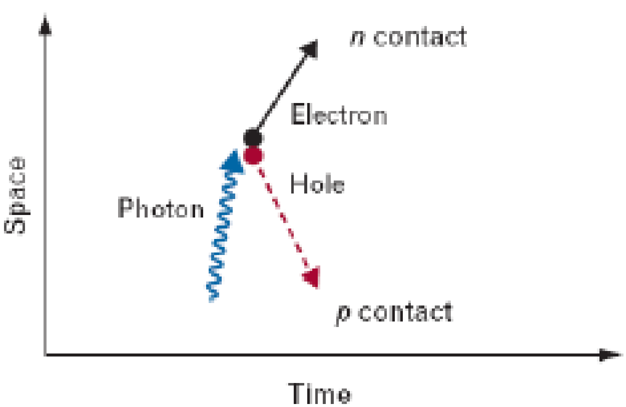
source F.Acerbi - PD18

SiPM building block → Geiger Mode APD

PN or PIN

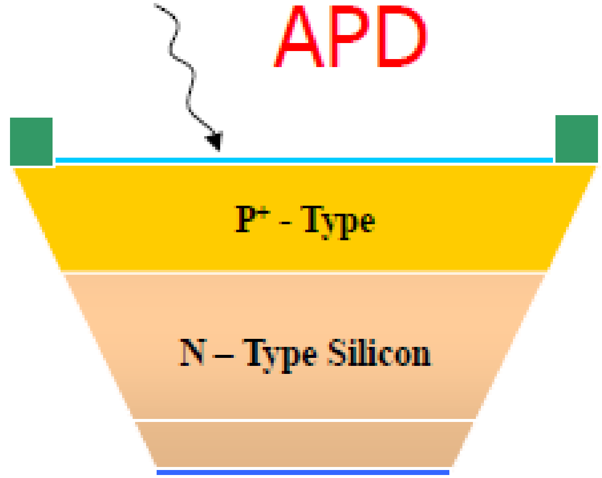


p-n junction,
reversed V_{bias} – 0-3 V

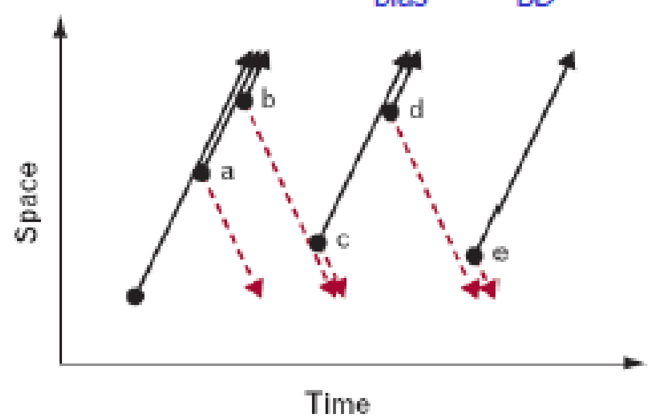


Gain = 1

APD



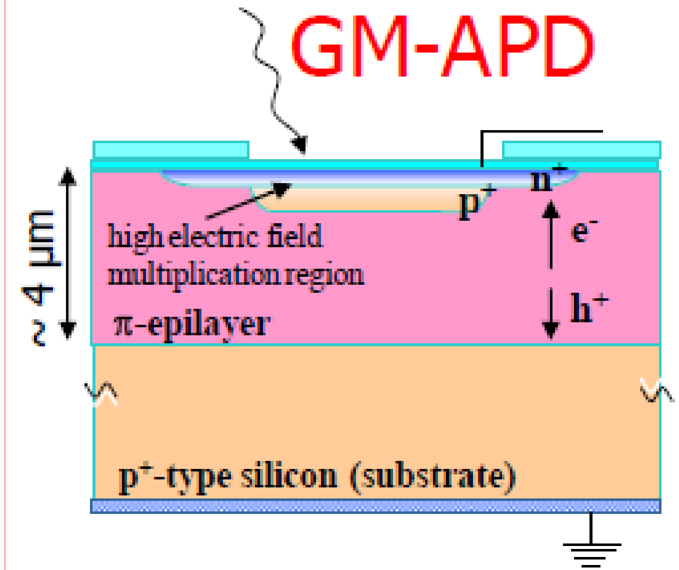
p-n junction,
reversed $V_{bias} < V_{BD}$



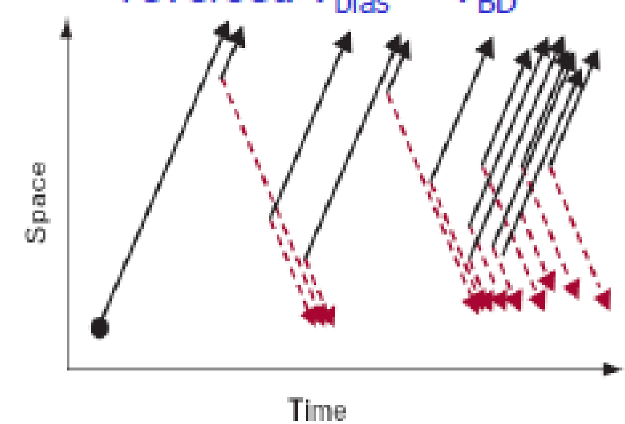
Gain = M (~ 50-500)

- linear mode operation-

GM-APD



p-n junction,
reversed $V_{bias} > V_{BD}$



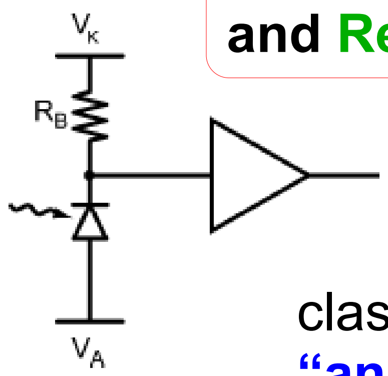
Gain → infinite

-Geiger-mode operation-

N.Dinu Ecole Microelectronique IN2P3 2013

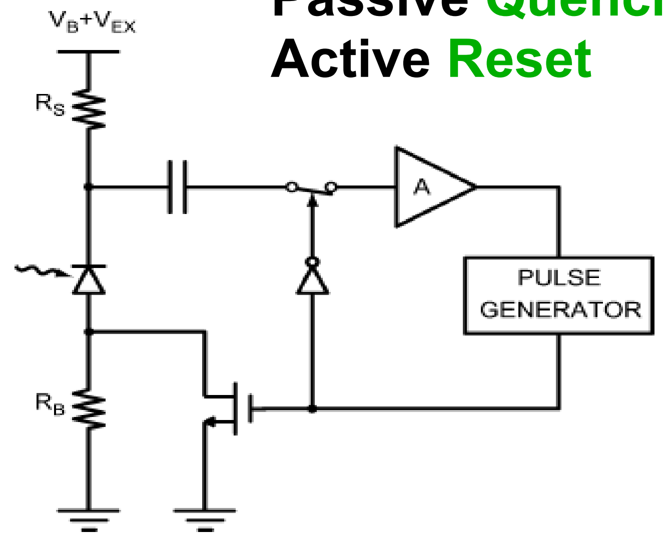
Passive / Active quenching and recharge

Passive Quenching and Reset

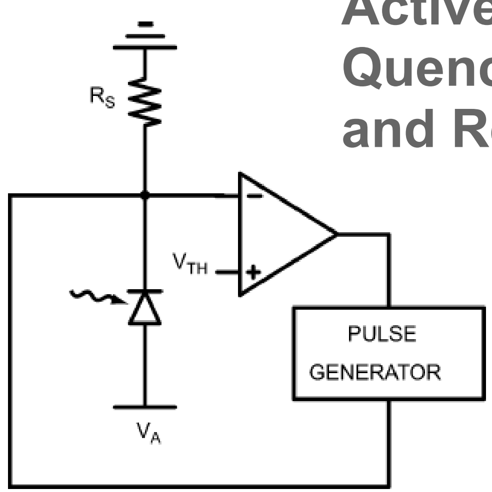


classical
“analog” SiPM

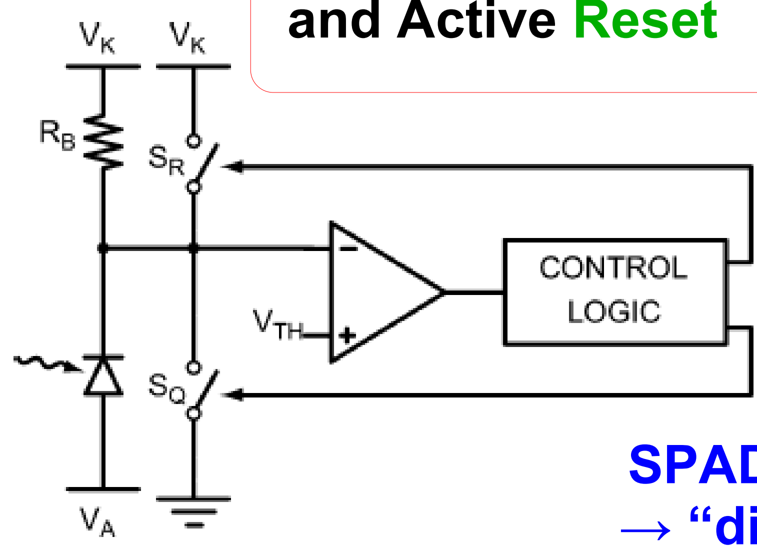
Passive Quenching
Active Reset



Active Quenching and Reset



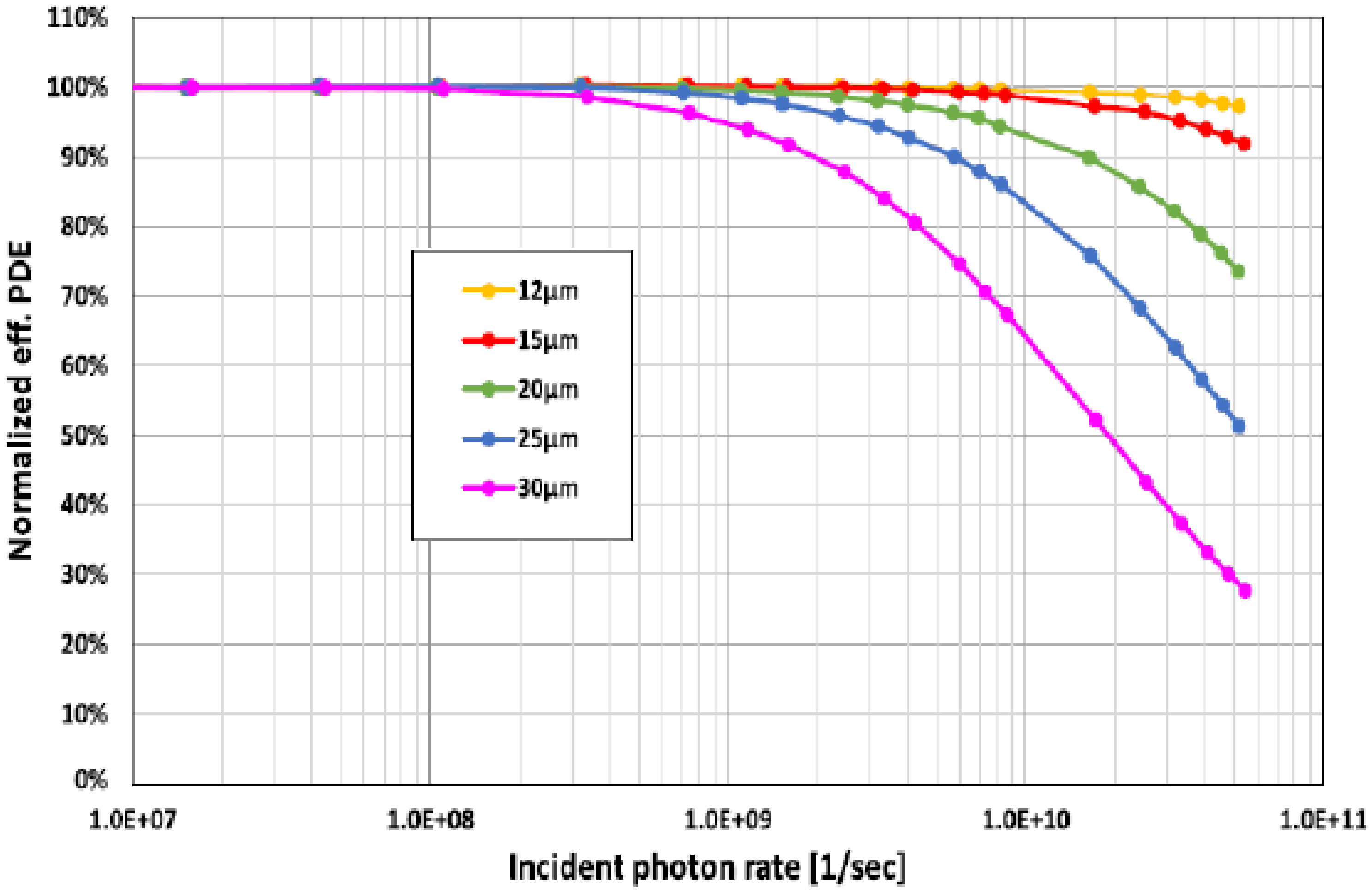
Active/Passive Quenching and Active Reset



SPAD arrays → → “digital” SiPM

Gallivanoni et al IEEE TNS 57 (2010) 3815

Tiny cells



Smaller cells → higher linearity:
higher number of cell per area
& faster recharge of each cell
& lower correlated noise.

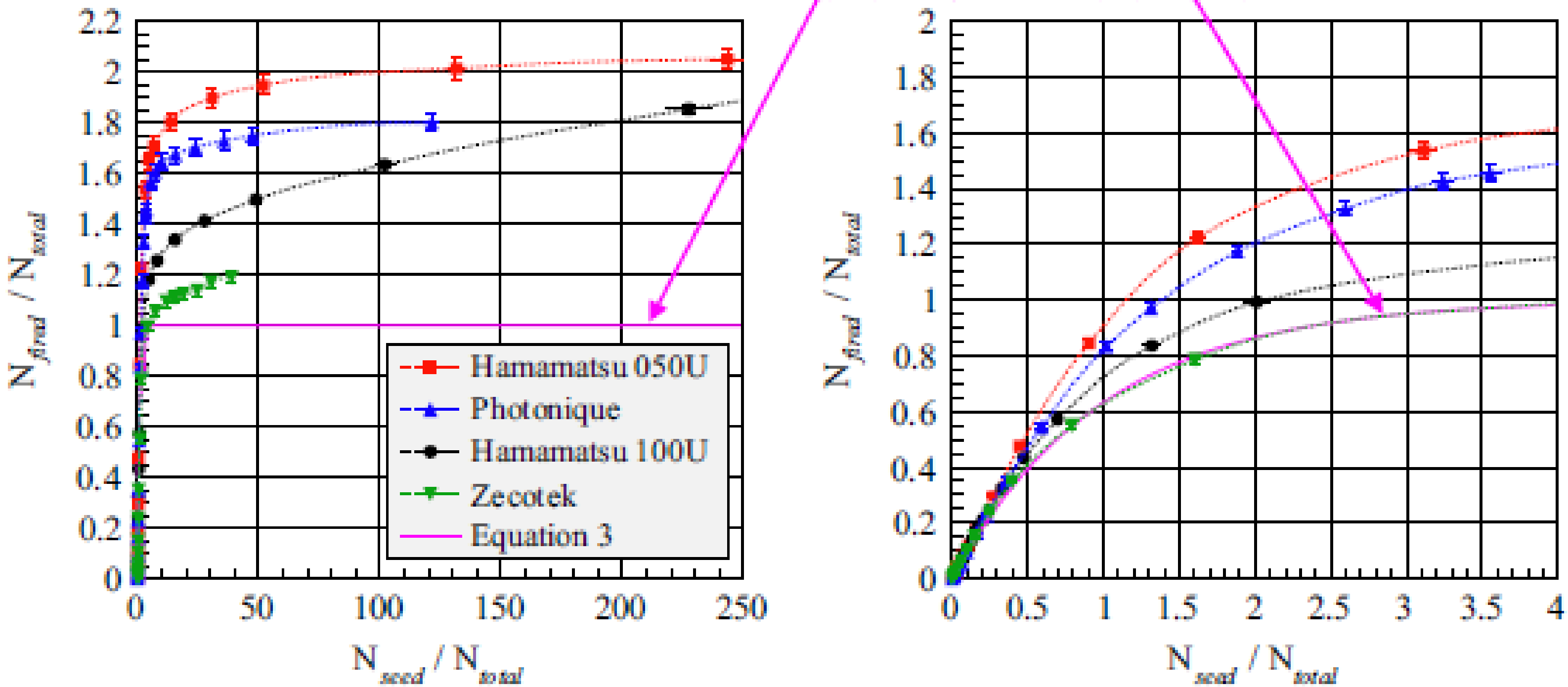
*** Measured on RGB-HD technology*
(from I-V curve, vs extracted photon rate from calibrated photodiode)

Fabio Acerbi – PD18 Workshop – Tokyo Dec 2018

Over-saturation ?

- Some reports on over-saturation
  - $N_{fired} > N_{cell}$ with fast laser (32ps pulse width → No chance of cell recovery)
- Still to be understood

$$N_{fired} = N_{cell}\left(1 - e^{\frac{-N_{photon}PDE}{N_{cell}}}\right)$$



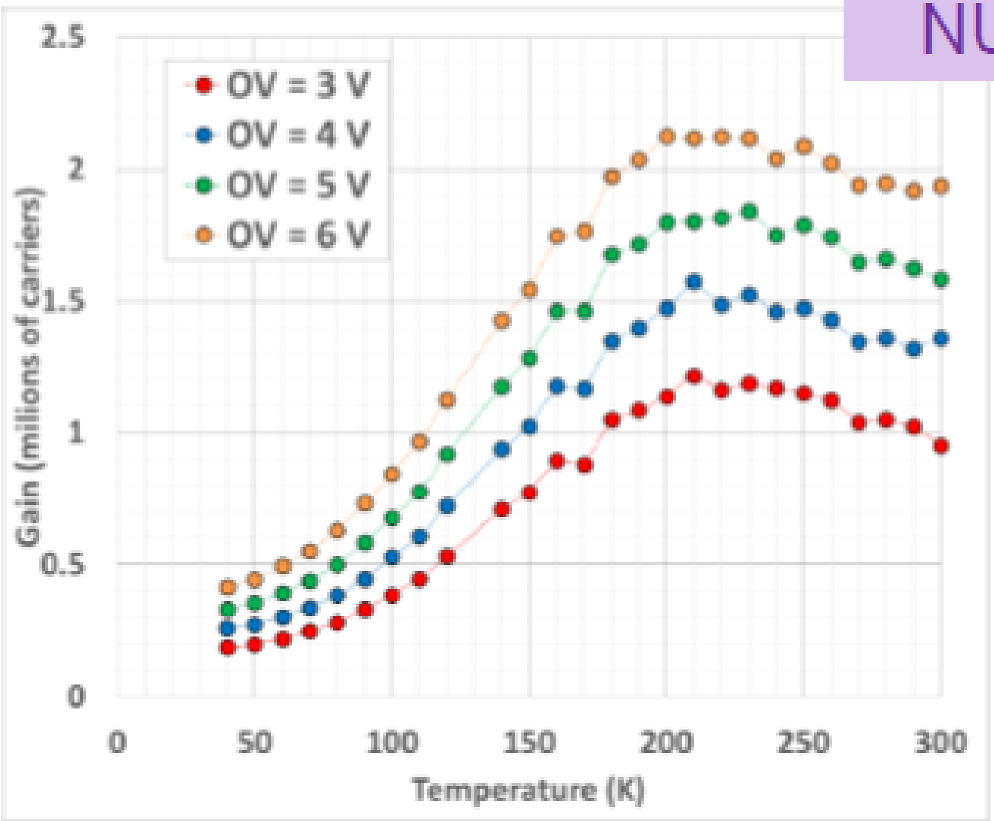
L. Gruber et al. NIMA737 (2014) 11

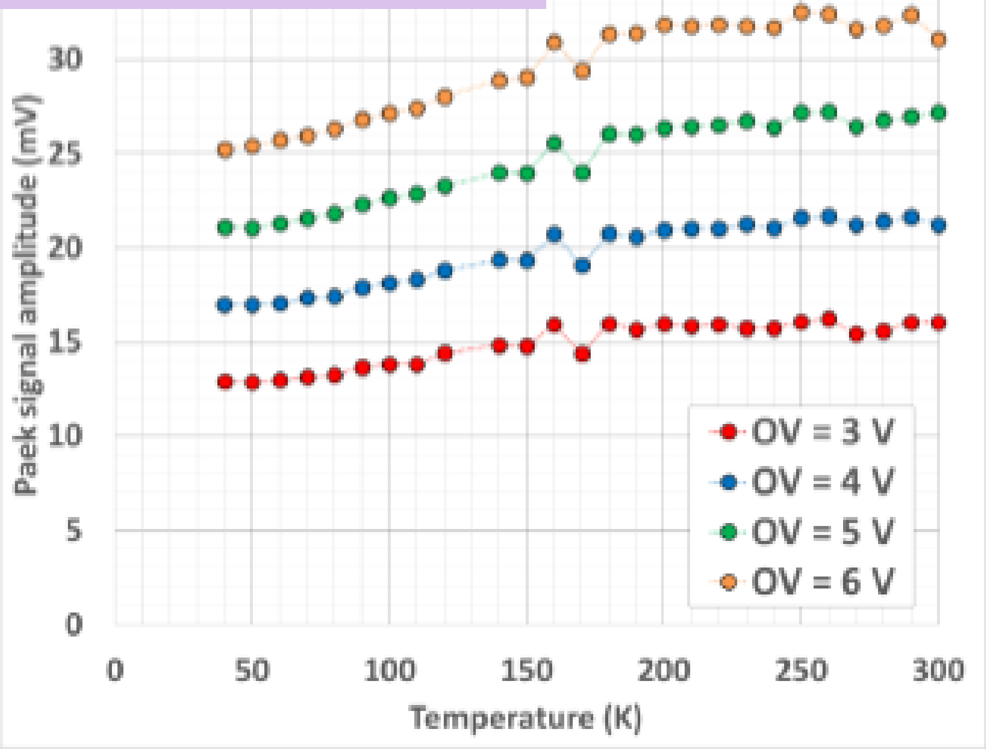
W.Ootani – RD51 – PD Workshop 2015

Pulse Charge and Amplitude vs T

- Fast peak amplitude is preserved
- Charge integrated within fixed window depends on T
  (ostensible gain variation with temperature)

NUV-HD Low-field





G_Q SiPM Gain
500 ns gate

SCR Amplitude

Timing jitter: prompt components

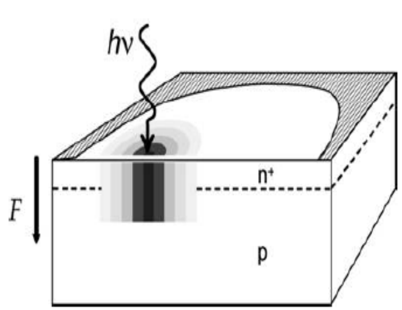
1) Prompt component: gaussian with time scale O(100ps)

Statistical fluctuations in the avalanche:

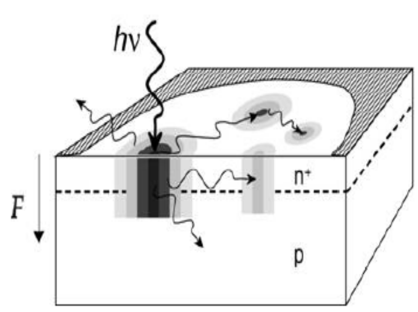
- **Longitudinal** build-up (minor contribution)
- **Transversal** propagation (main contribution)

- via multiplication assisted diffusion (dominating in few μm thin devices)
A.Lacaita et al. APL and El.Lett. 1990

- via photon assisted propagation (dominating in thick devices – O(100μm))
PP.Webb, R.J. McIntyre RCA Eng. 1982
A.Lacaita et al. APL 1992



Multiplication assisted diffusion



Photon assisted propagation

Fluctuations due to
a) impact ionization statistics

b) variance of longitudinal position of photo-generation: finite drift time even at saturated velocity
note: saturated ve ~ 3 vh
(n-on-p are faster in general)

→ Jitter at minimum → **O(10ps)**
(very low threshold → not easy)

Fluctuations in shock-wave due to
c) variance of the transverse diffusion speed v_{diff}

d) variance of transverse position of photo-generation: slope of current rising front depends on transverse position

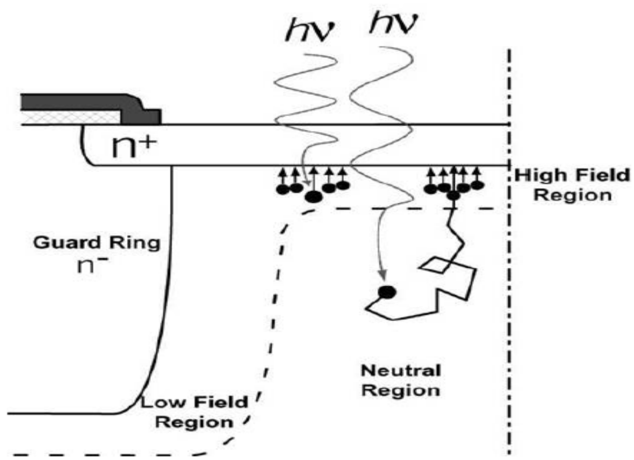
→ Jitter → **O(100ps)**
(usually threshold set high)

Timing jitter: delayed components

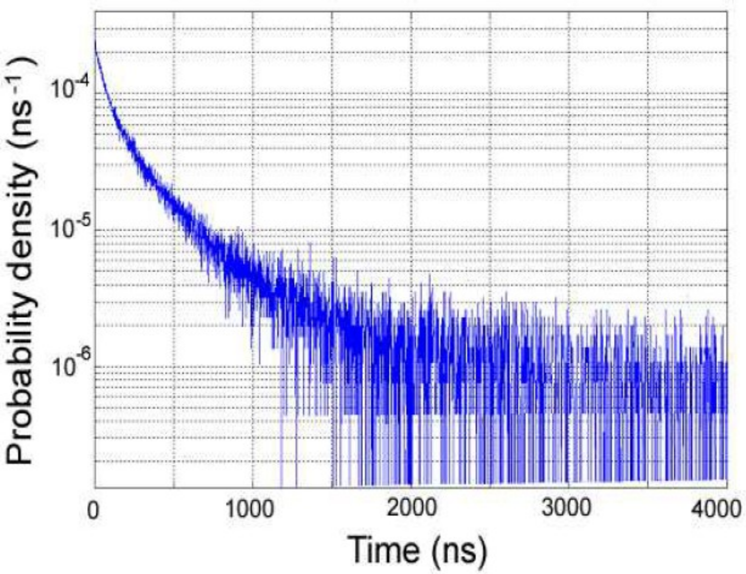
2) delayed component: non-gaussian tails with time scale O(ns)

Carriers photo-generated in the neutral regions above/beneath the junction and reaching the electric field region by diffusion

G.Ripamonti, S.Cova Sol.State Electronics (1985)



S.Cova et al. NIST Workshop on SPD (2003)



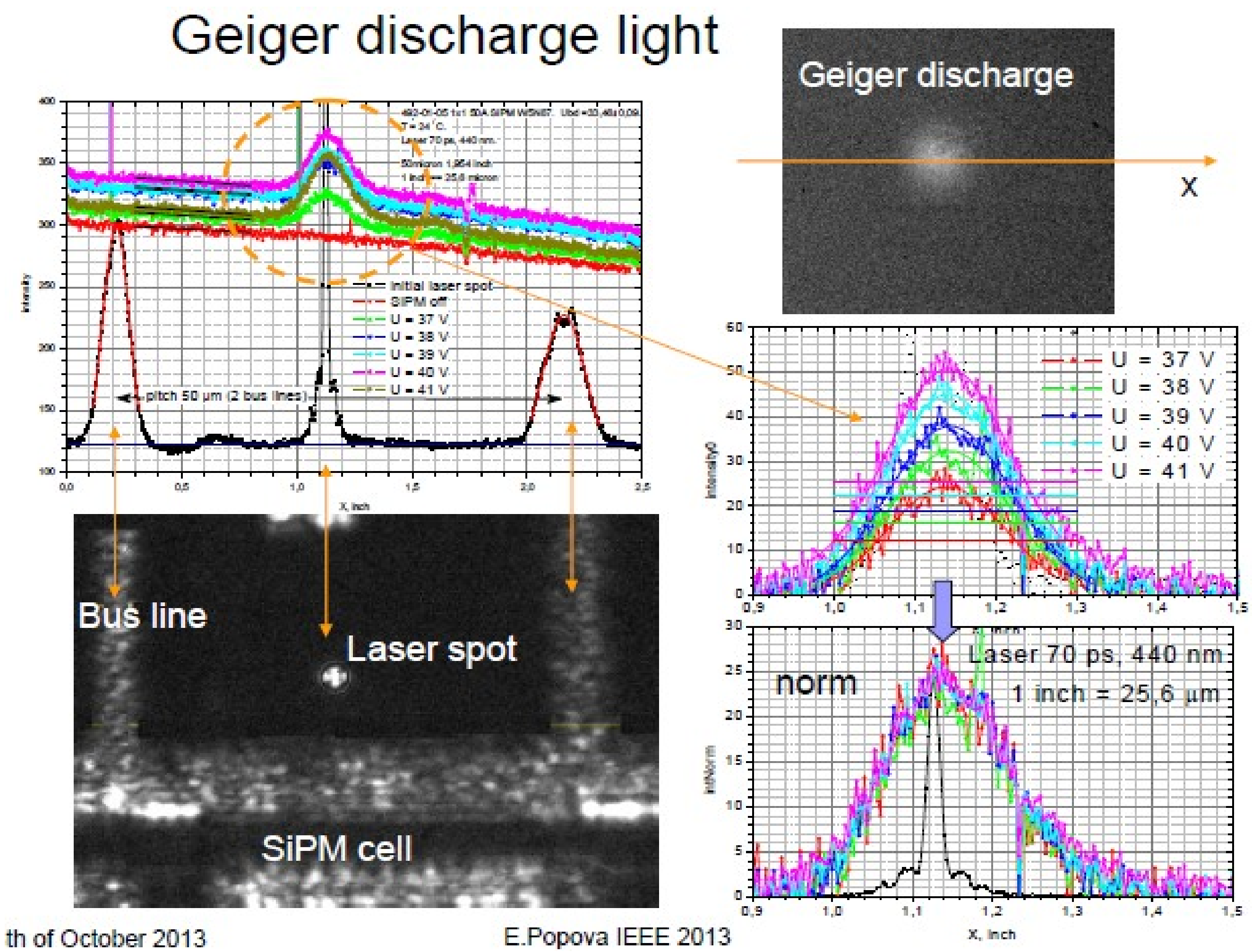
S.Cova et al. NIST Workshop on SPD (2003)

tail lifetime: $\tau \sim L^2 / \pi^2 D$ ~ up to some ns
L = effective neutral layer thickness
D = diffusion coefficient

→ **Neutral regions** underneath the junction : timing tails for long wavelengths
→ **Neutral regions** in APD entrance: timing tails for short wavelengths

Discharge transverse size in SiPM

Interesting measurements and hybrid model of avalanche development and signal formation by R.Mirzoyan et al (*see E.Popova at IEEE NSS 2013*)



Spot size of Avalanche

1) O(10)μm

2) independent of over-voltage

3) mild dependence from cell size

Timing at low Temperature

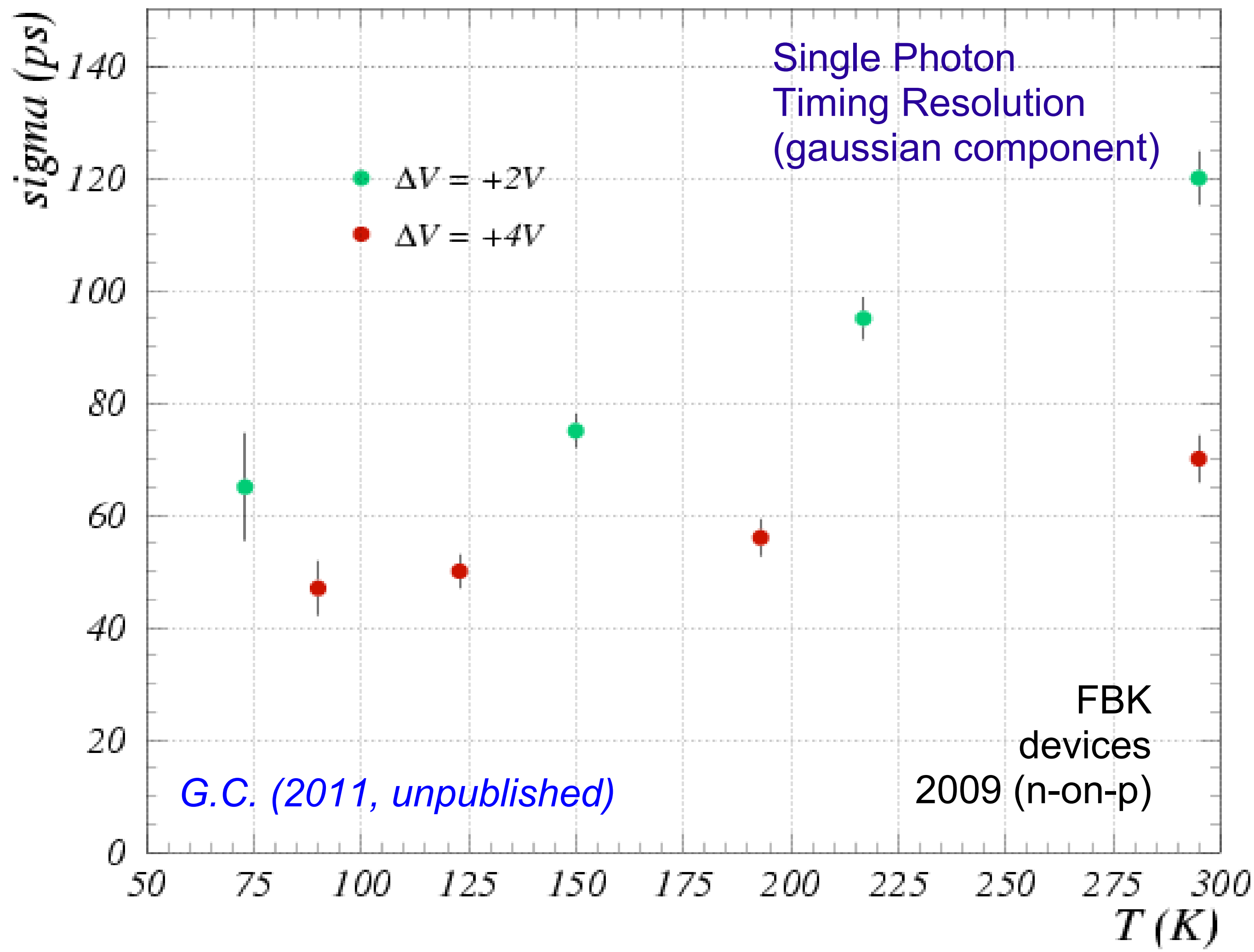
Timing: improves at low T

Lower jitter at low T due to higher mobility: → a) avalanche process is faster; b) reduced fluctuations

(Over-voltage fixed)

Note:

$$\frac{dI}{dt} \sim \frac{\sqrt{D}\uparrow}{\downarrow R_{sp}\sqrt{\tau}\downarrow}$$



New accurate measurements of SPTR at low T are welcome !!!

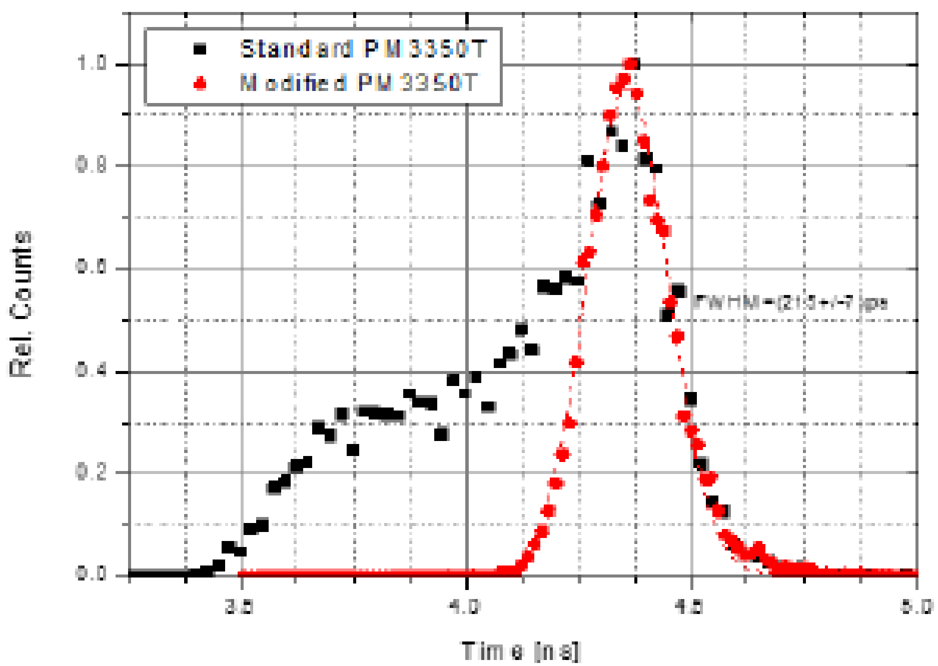
Single Photon Timing Resolution (SPTR)

Time delay across the SiPM area can differ significantly and need to be equalized

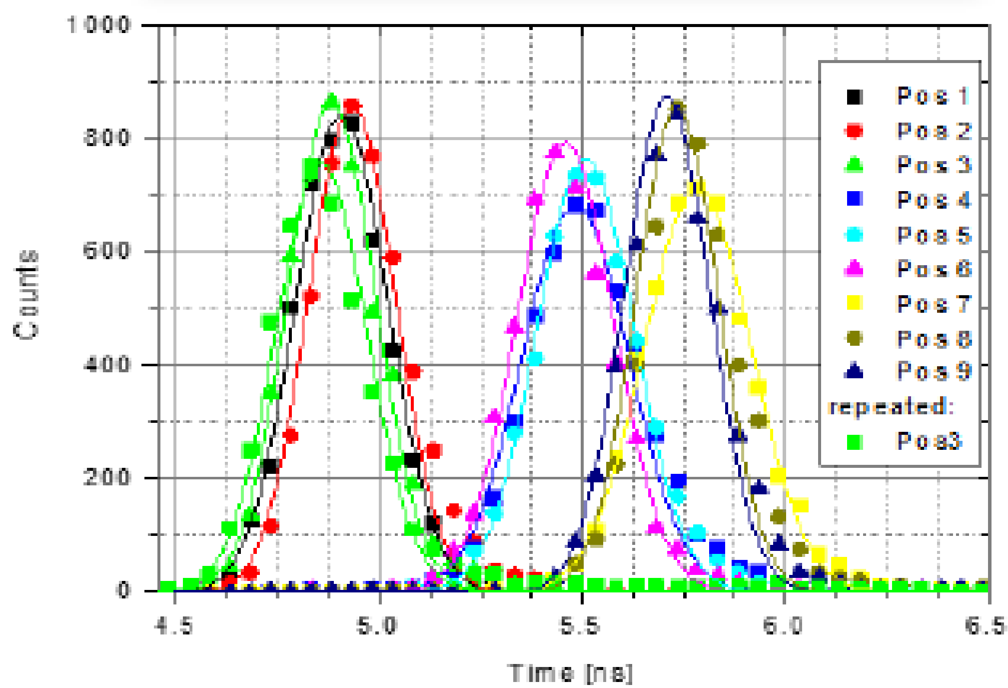
S.Kopar – VCI 2016

KETEK

SPTR measurements

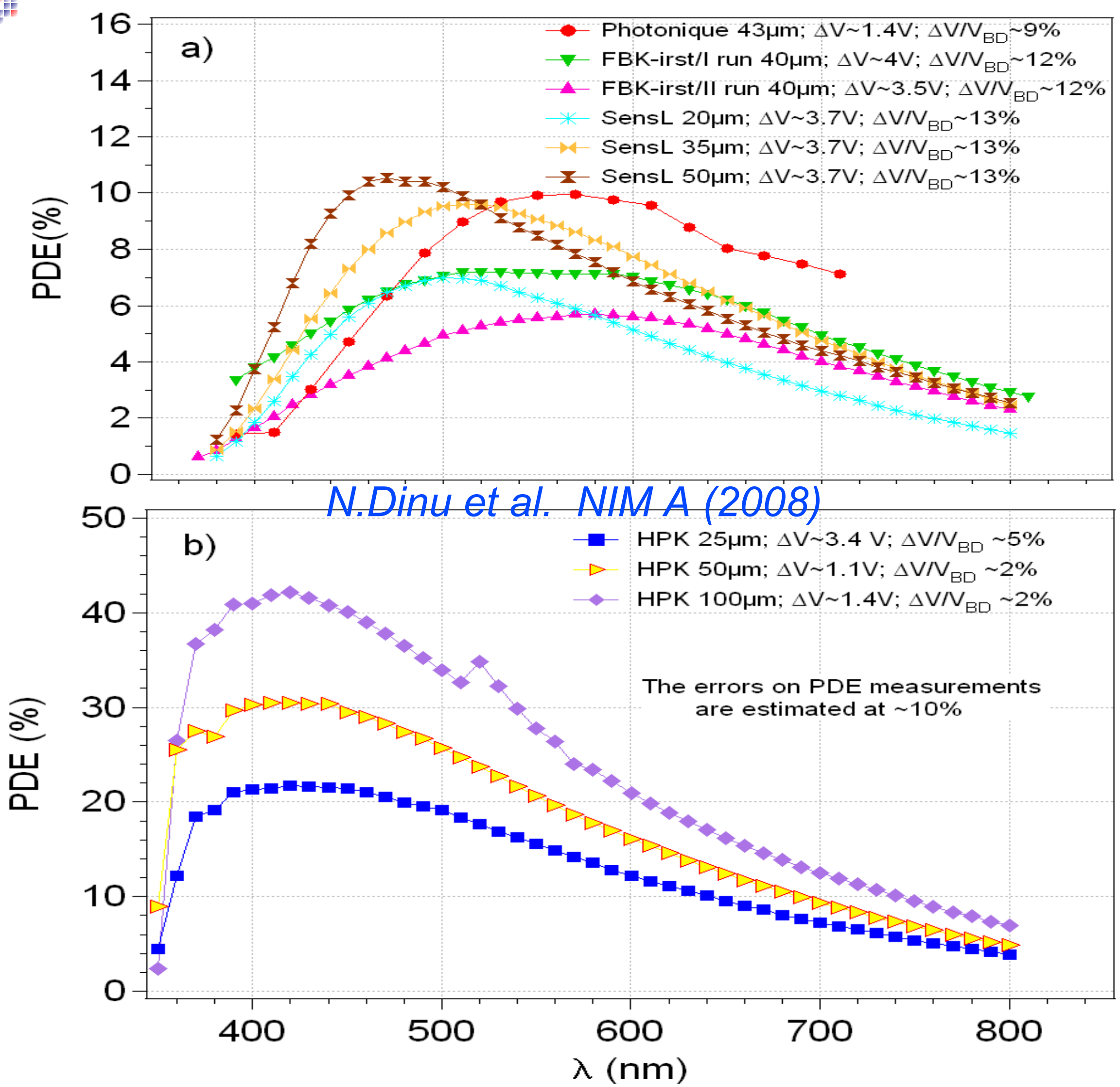


Localized SPTR measurements



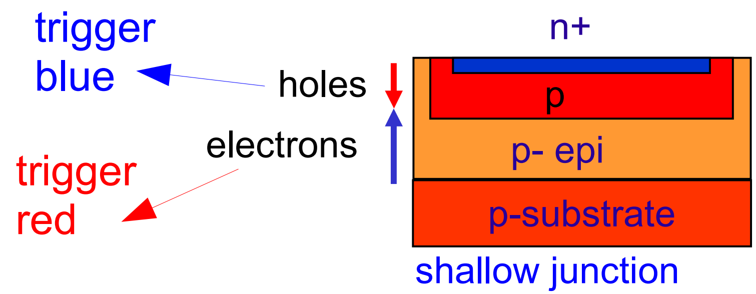
Avalanche Triggering Probability → tuning PDE shape

main PDE absolute scale differences due to Fill Factor

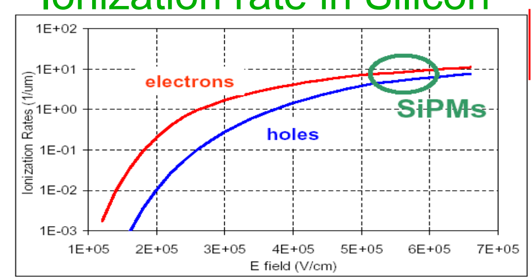


n-on-p structures

sensitivity peak → green-red

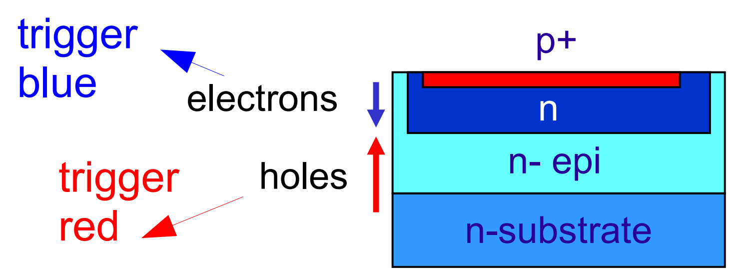


Ionization rate in Silicon



p-on-n structures

sensitivity peak → blue



Tuning PDE spectrum:
(matching applications)

- structure type (shallow or reach trough)
- junction type (p-on-n or n-on-p)

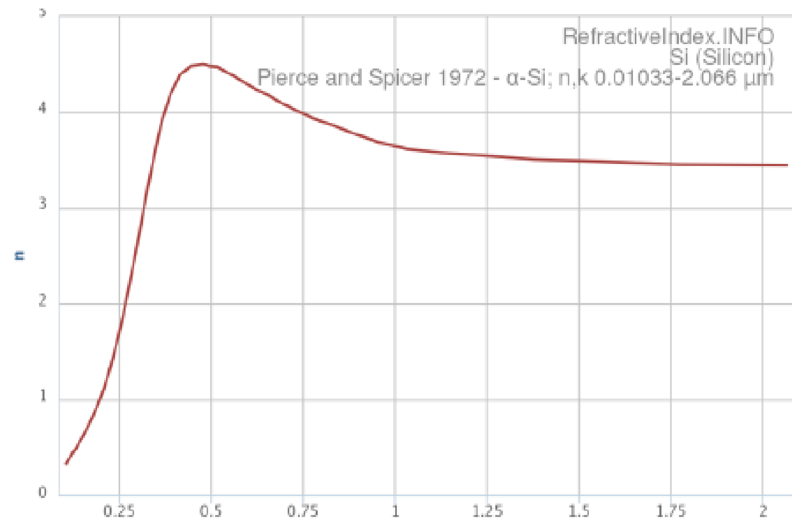
Physics at entrance window → short wavelengths !!!

Transmission/Reflection

- medium-Silicon refraction index mismatch
  → large reflection at interfaces
- Passivation layers (n~1.5) partially mitigate
  (depending on wavelength)

➡ Multilayer Anti-Reflective Coating (ARC)
to optimize light transmission (>90%)

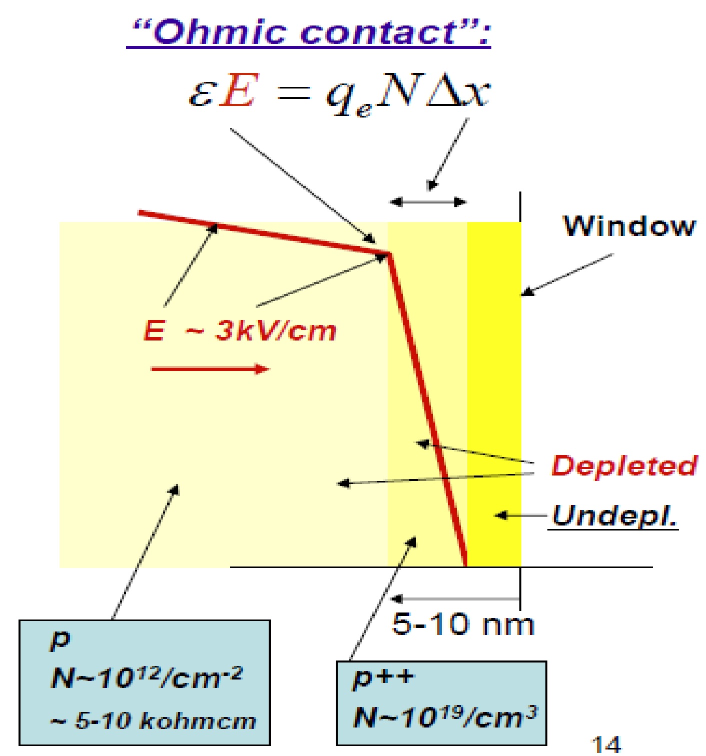
Refraction index of Si (amorphous)



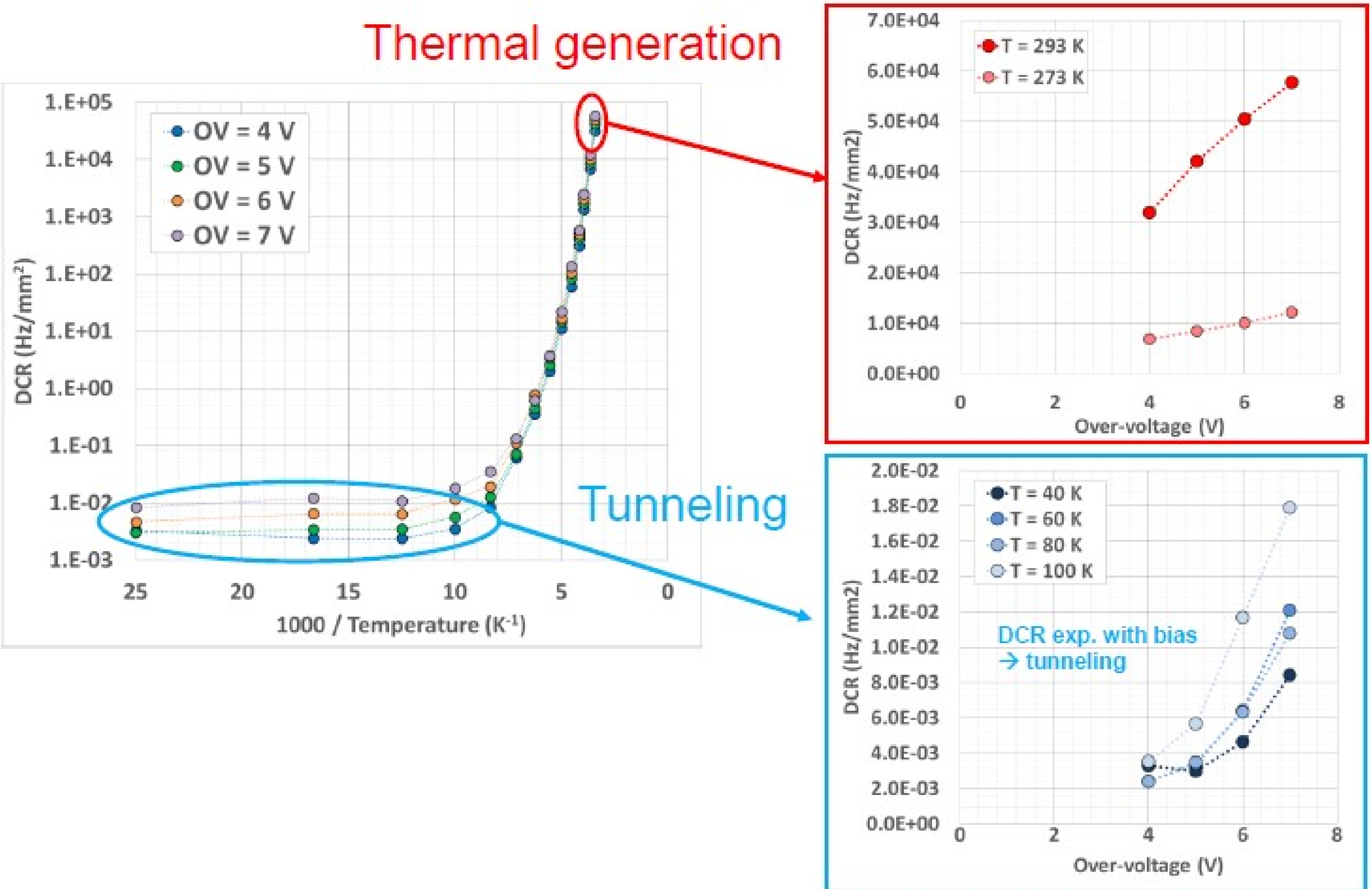
Absorption/Recombination

- Passivation and ARC
  → absorption losses
- Electrode region: partially un-depleted
  → recombination losses

➡ highly doped layer to terminate the field
and leave a thin conductive layer at the surface



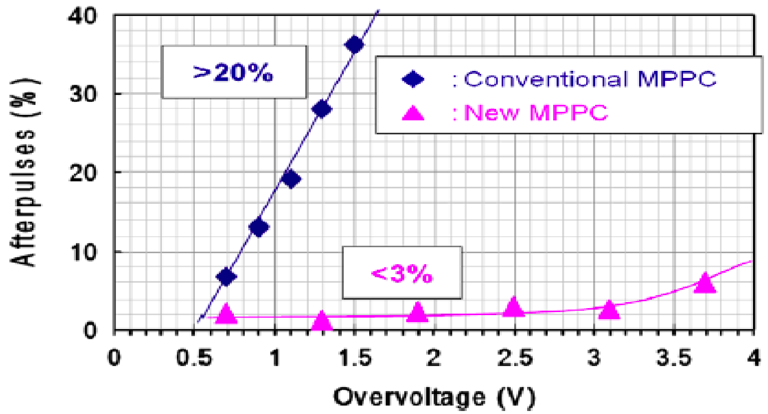
Tunneling vs Thermal Generation DCR

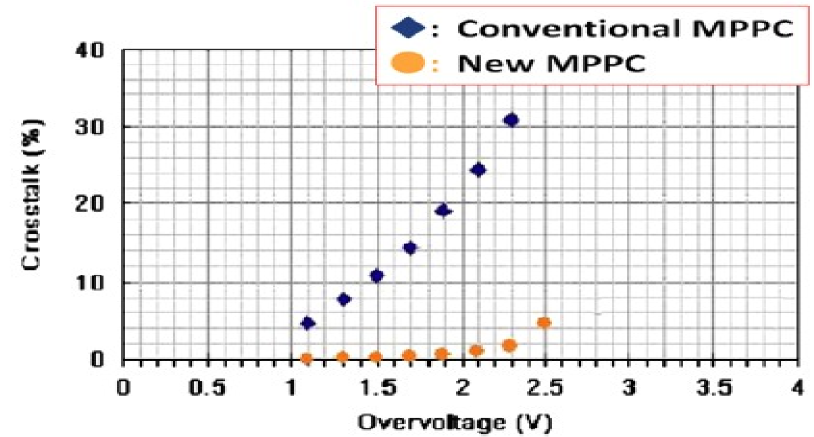


Fabio Acerbi – PD18 Workshop – Tokyo Dec 2018

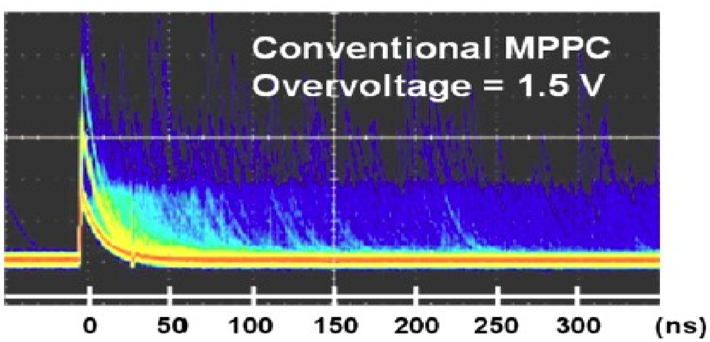
Reduced CT and AP from Hamamatsu (since 2013)

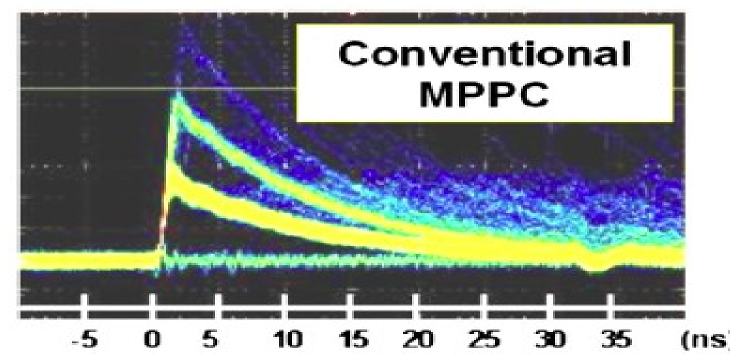
Reduced After-pulsing / Cross-Talk rates

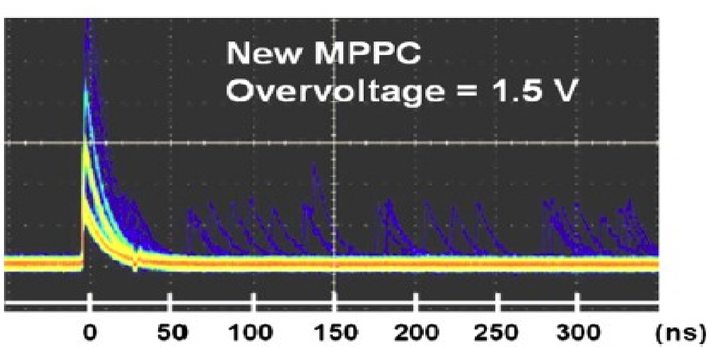


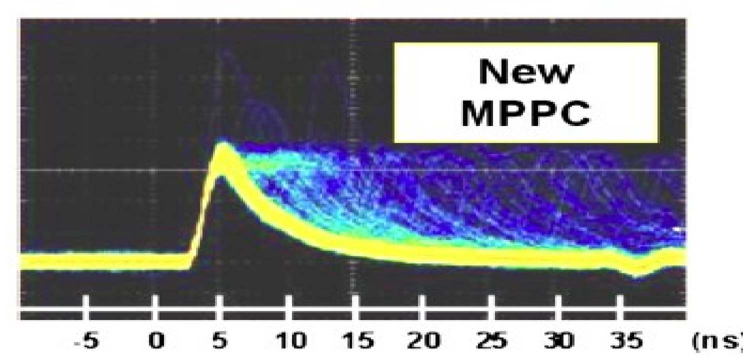


trench
type
device





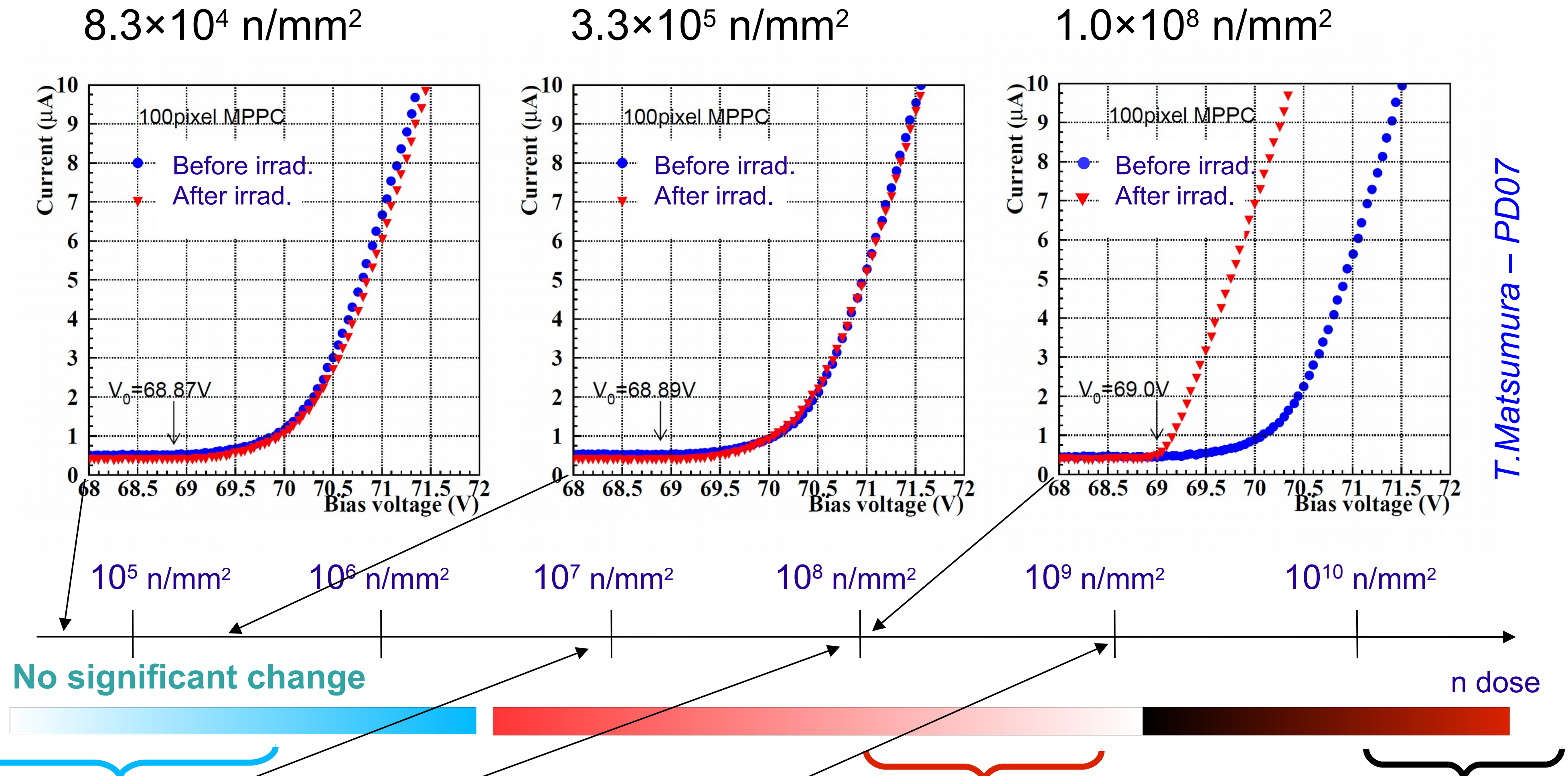


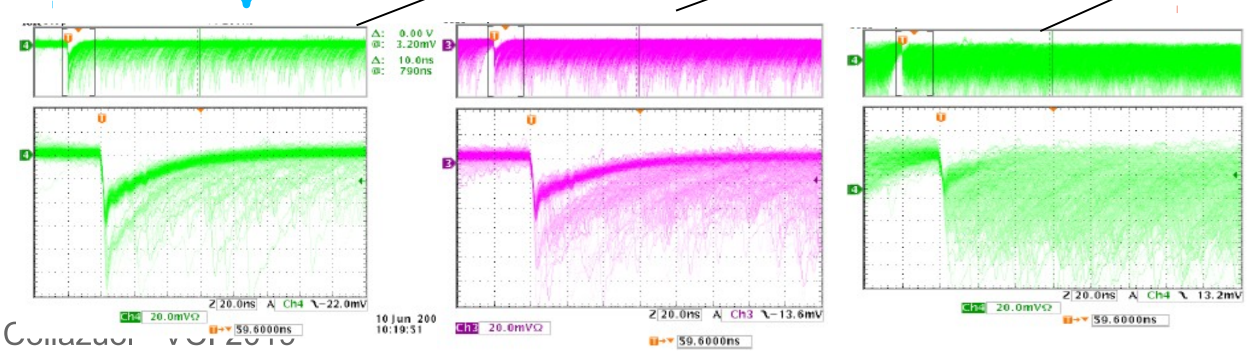


K.Sato et al VCI 13 – Vienna 2013

Radiation damage: neutrons (0.1 -1 MeV)

Photon counting capabiliy is lost at 10^{11} n_{eq}/cm^2





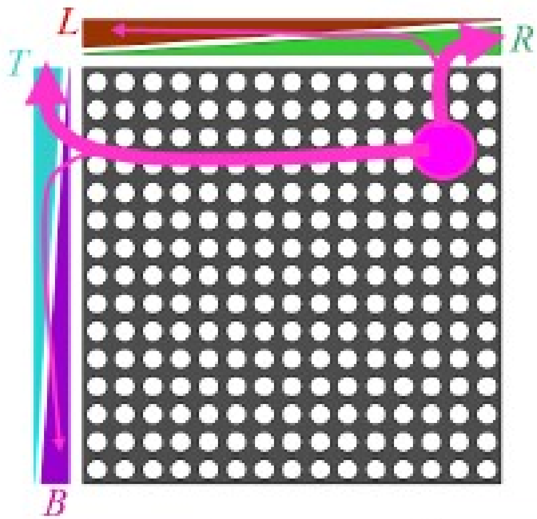
I-V drastically change.
Signal pulse is still there,
but continuous pulse height.
(No photon-counting capability)

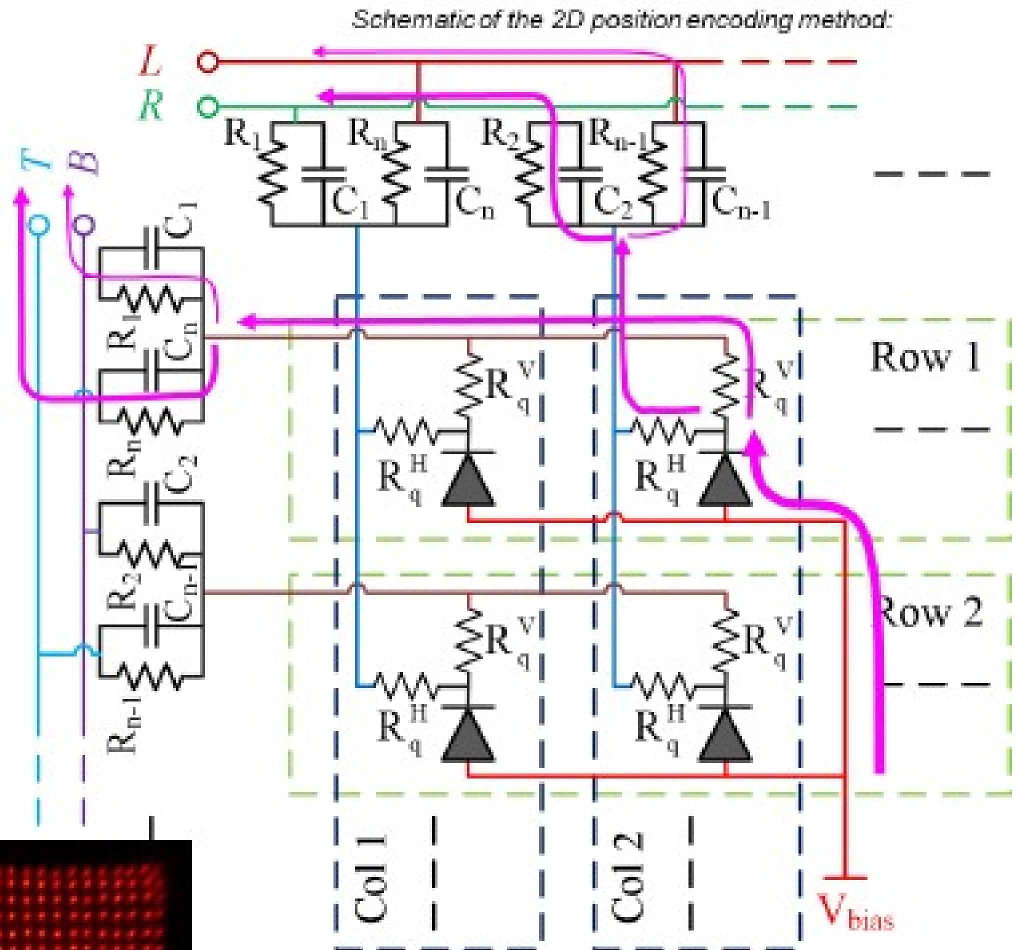
No signal

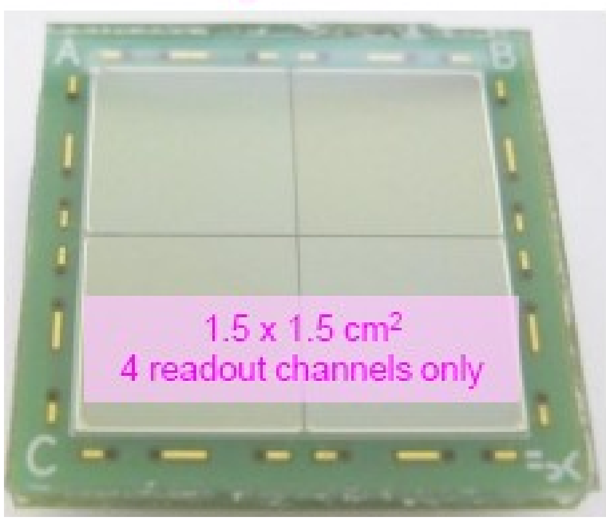
Nakamura at NDIP08

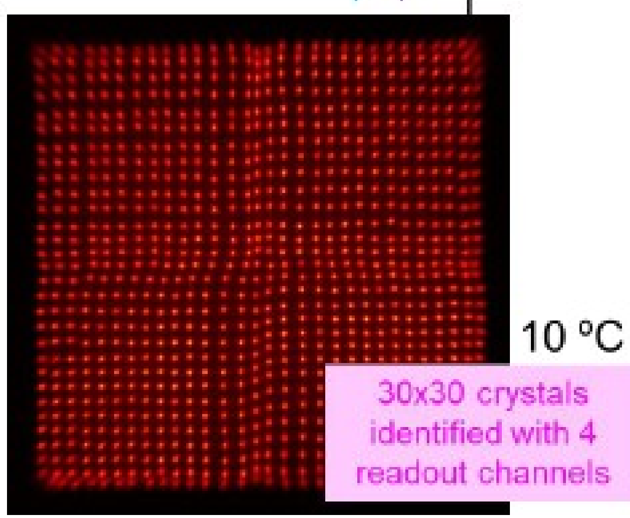
Position sensitive – example (FBK)

- 4 outputs to encode the interaction position of photons.
- Charge division through 2 different quenching resistors and different dividers.





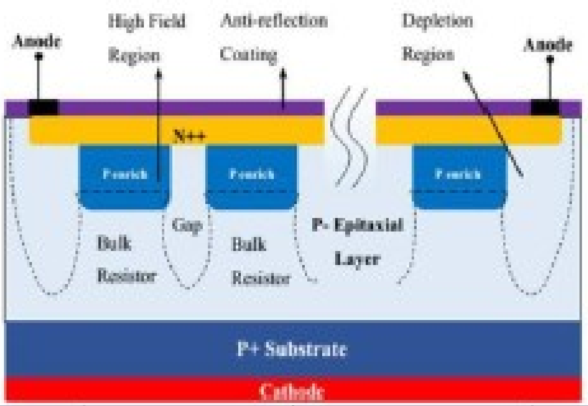




- New: 8x8mm² device produced.
  TILE of total 1.5x1.5 cm² tested with pixelated scintillator.

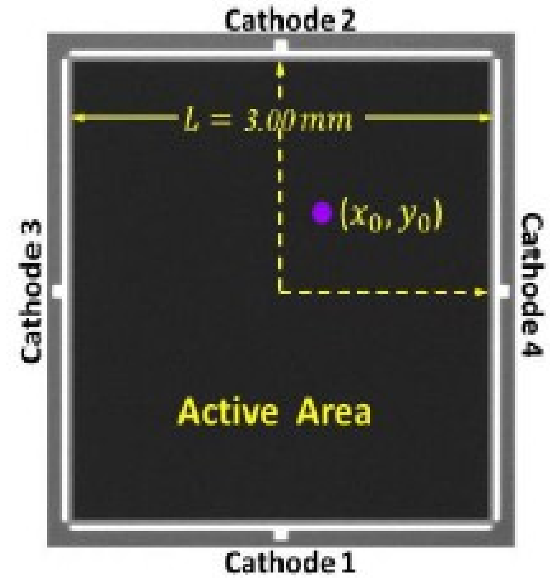
C. Piemonte, S.R. Cherry et al IEEE MIC 2015

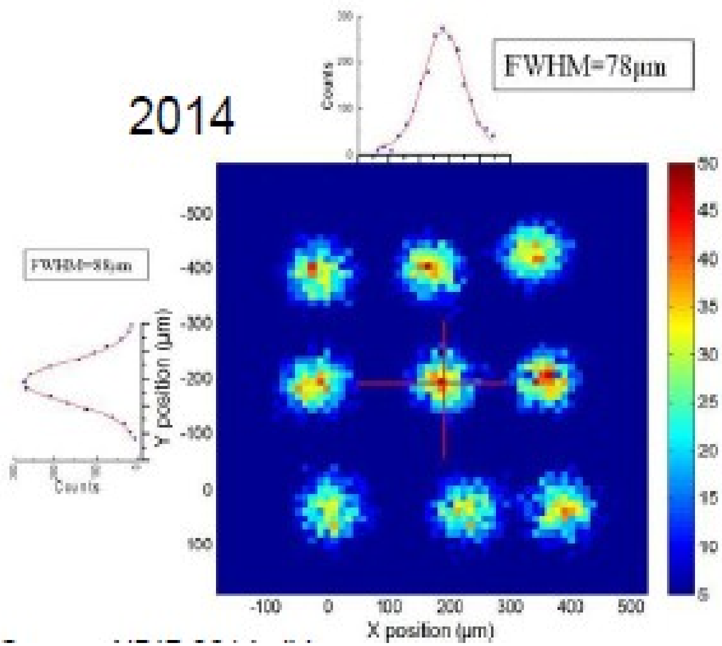
Position sensitive – example (NDL)

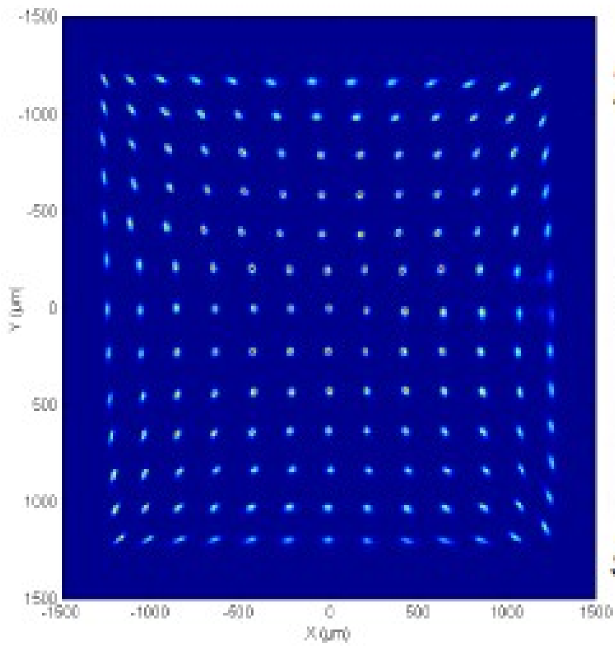


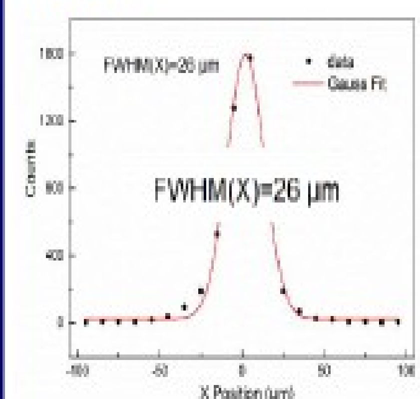
Thanks to the common shallow implant: possible readout from 4 cathodes!

Series	Description	Cell number per pixel	Pixel active area(mm^2)
11-1010C	Regular	10000	1.0 × 1.0
11-3030C	Regular	90000	3.0 × 3.0
11-2727PS	Position Sensitive	76730	2.77 × 2.77









Source: ICASIPM 2018 slides

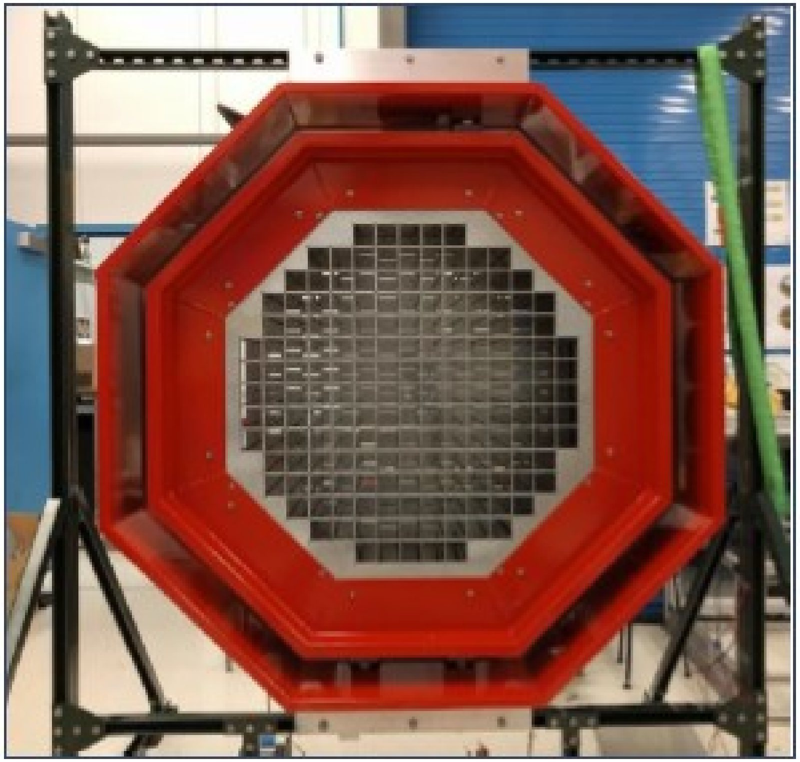
source F.Acerbi - PD18

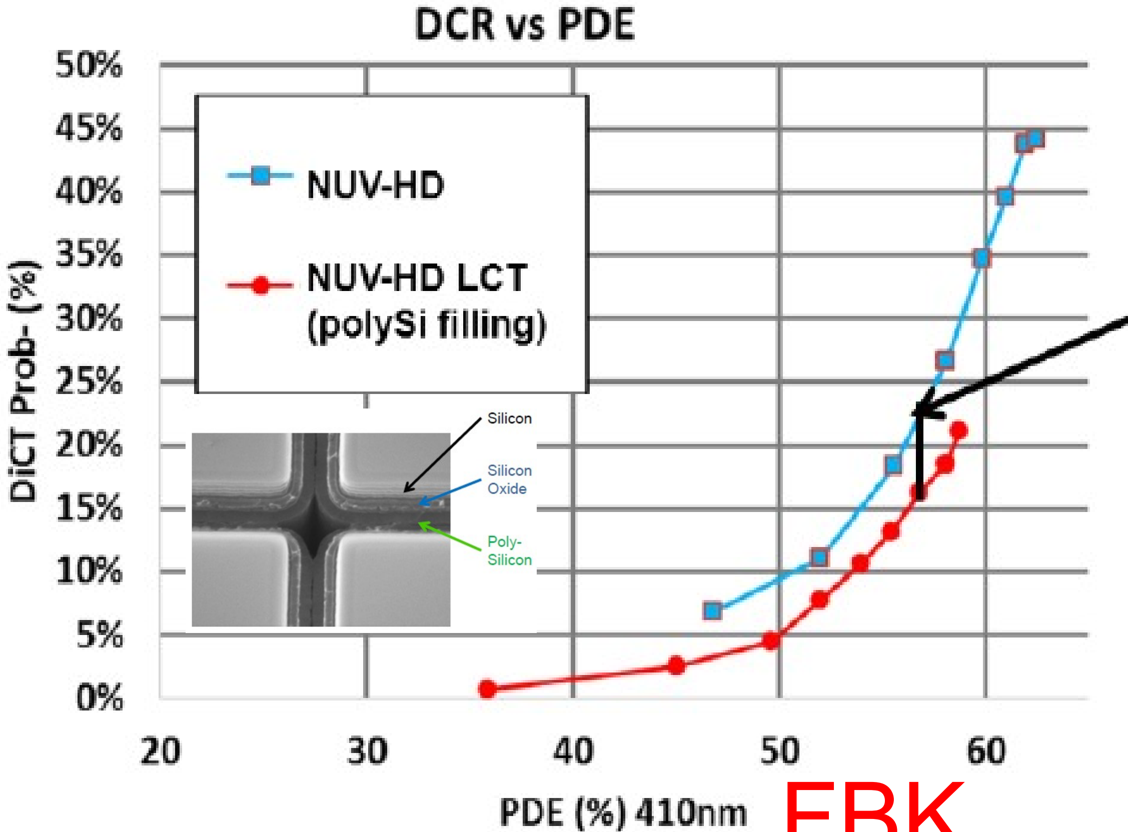
Cherenkov – CTA

Poly-Si Trench filling

- SiO2/Poly-Si/SiO2 stack in the trenches
- the materials composing the stack show high-contrast refractive indexes, increasing reflection of light
- high-doped poly-Silicon layer aids to absorb part of the light due to free carriers absorption

The Schwarzschild-Couder Telescope Prototype for CTA





FBK devel. for CTA

- Module area: 54x54 mm^2 → 4 matrices of 16 SiPMs (6x6 mm^2)
- Significant amount of night sky background light
- PDE optimized for spectral region 300-600 nm → NUV-HD SiPMs
- Mandatory to **minimize Cross-Talk against fake triggers rate**

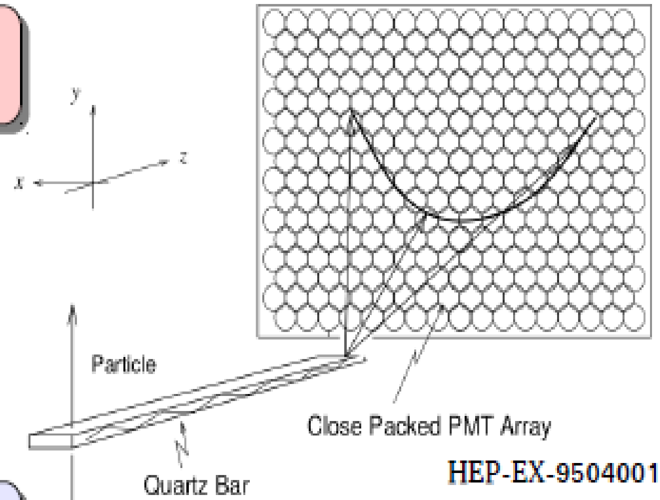
Cherenkov – an FDIRC for CR Space Physics

JE Suh, PS Marrocchesi et al RICH 2016

A Digital FDIRC Prototype for Isotopic Identification in Astroparticle Physics

DIRC
(Detection of Internally Reflected Cherenkov light)

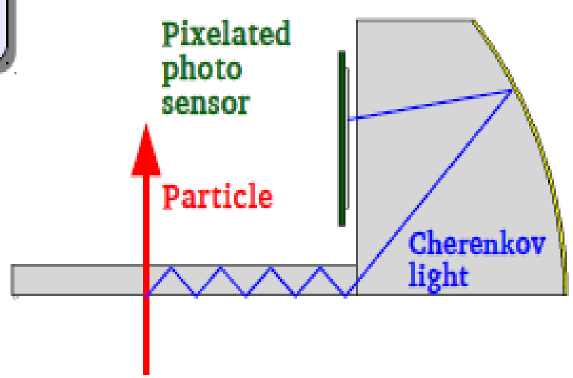
- Radiator bar + wall of PMTs
- Pinhole effect
- π/K separation
- BaBar, Belle, PANDA ...

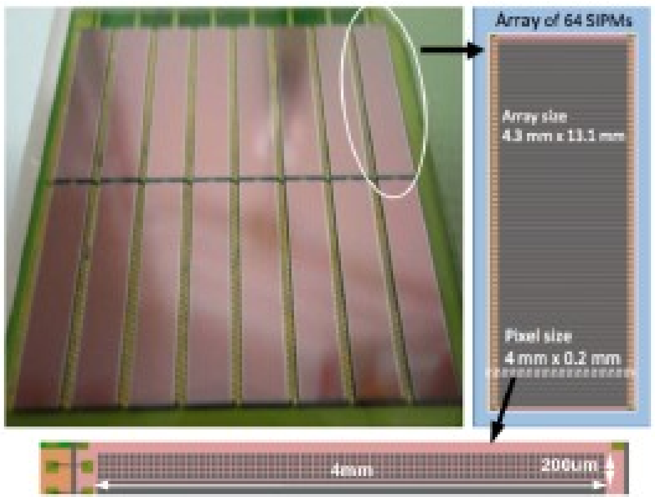


HEP-EX-9504001

FDIRC
(Focusing DIRC)

- Radiator bar + Focusing Mirror + Pixelated photo sensors
- Isotopic separation in cosmic -rays

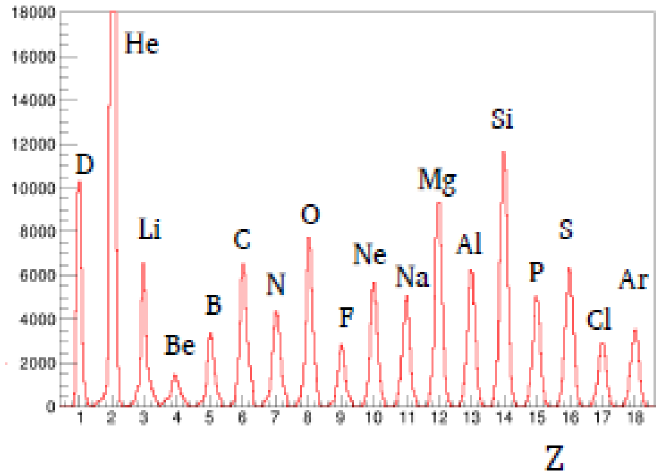




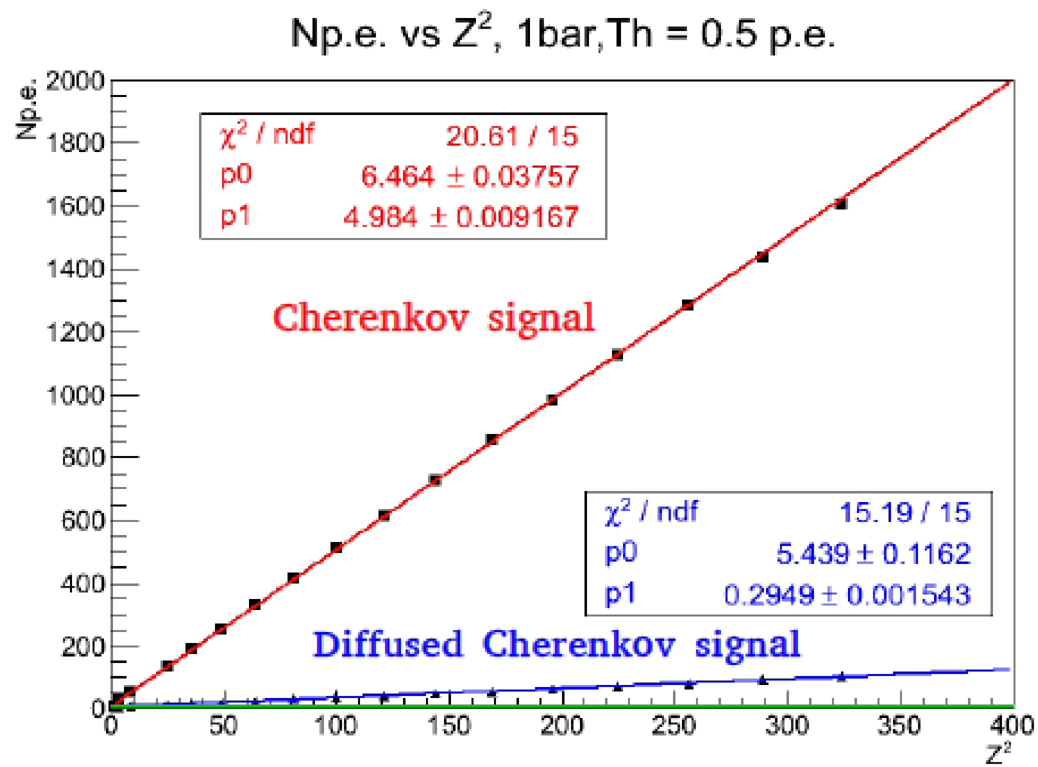
- 64SiPMs x 16 modules (1024 SiPMs)
- Developed at FBK Trento
- Uniform V_{bd} and gain spread for 16 arrays of SiPMs
- DCR (<100kHz/mm²)
- PDE ~ 35% @ 420nm, (OV 4.4V)

Cherenkov – FDIRC

PS Marrocchesi et al RICH 2016

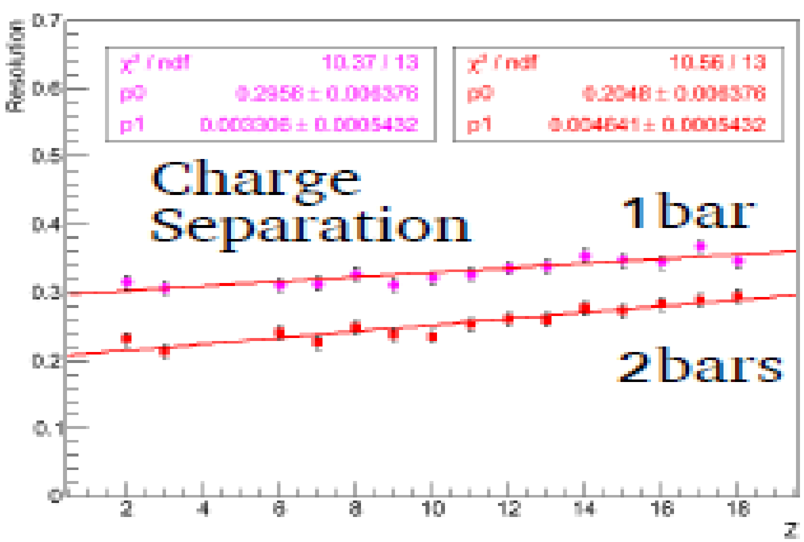


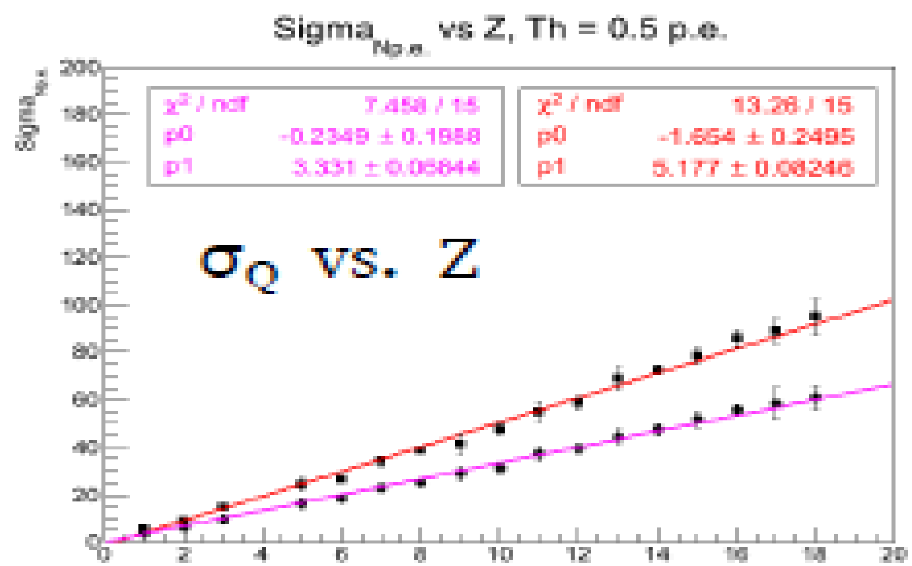
charge tagging



Integrated Cherenkov signal

1 bar

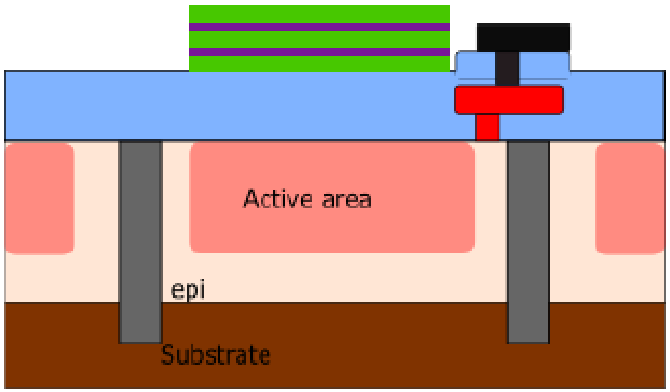




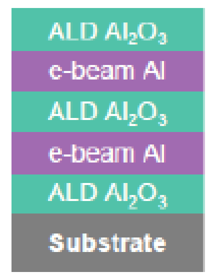
BaF2 readout with SiPM

Proposed Solutions:

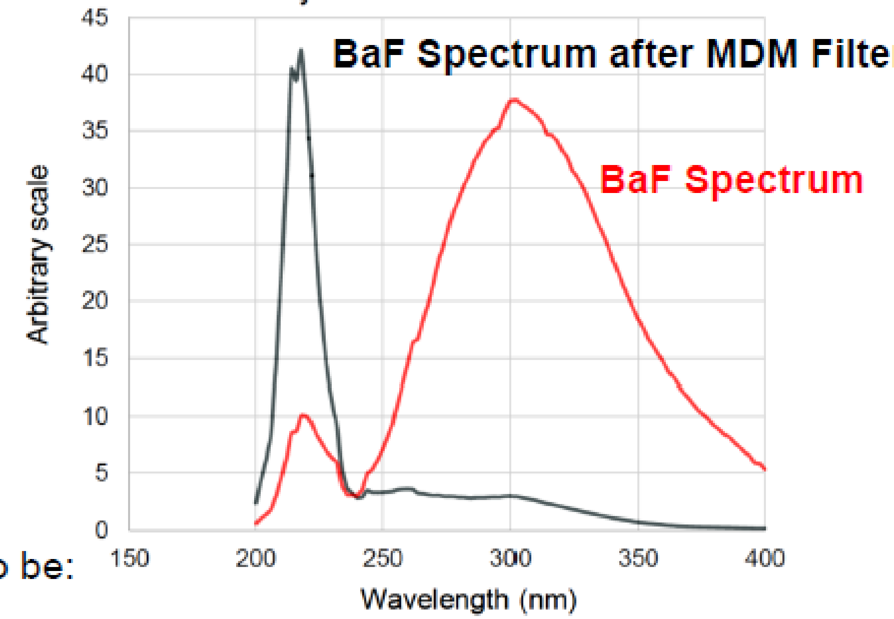
SiPM with integrated MDF solar blind Filter



Five layer MDF



BaF_2 spectrum & calculated response with 5 layer filter on 10nm SiN



The SIPM optical entrance window must be redesigned in order to be:

- Ultra-thin (less than 30 nm)
- Made of a single dielectric film (SiN or SiO_2)
- Extremely uniform at wafer level (few nanometers)
- Should preserve the SiPM