Silicon Photomultiplier (SiPM)
Status and Perspectives

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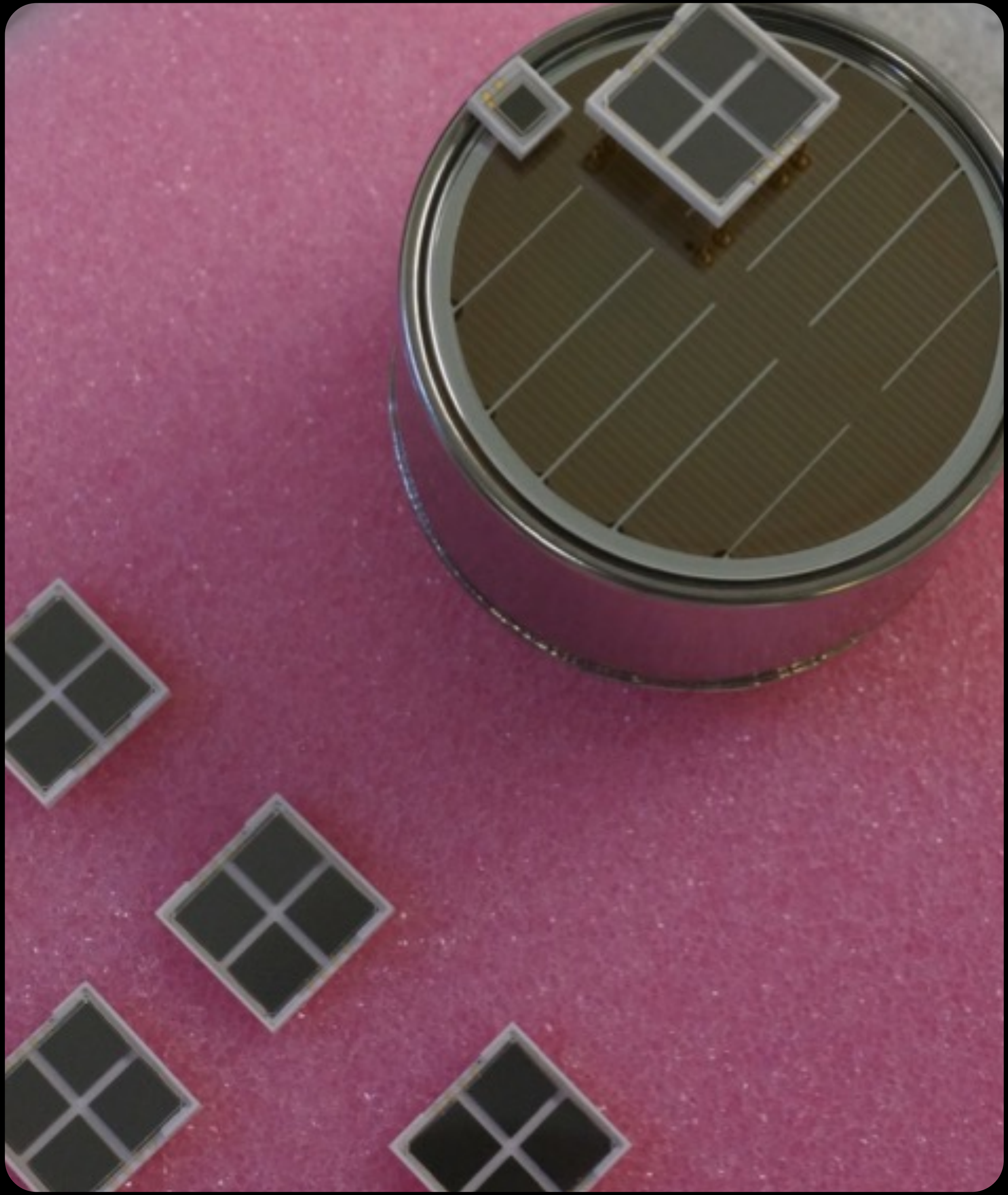
RD51 Academia-Industry Matching Event

Special Workshop on Photon Detection with MPGDs

June 10th, 2015 CERN

Contents

- Introduction
- Properties and Performance
- New Developments
- Application Examples
- Summary



Caveats

- I apologise that I can't cover everything on SiPM in this talk because of the limited time.
- Topics selection is (very much) biased by my personal interests.

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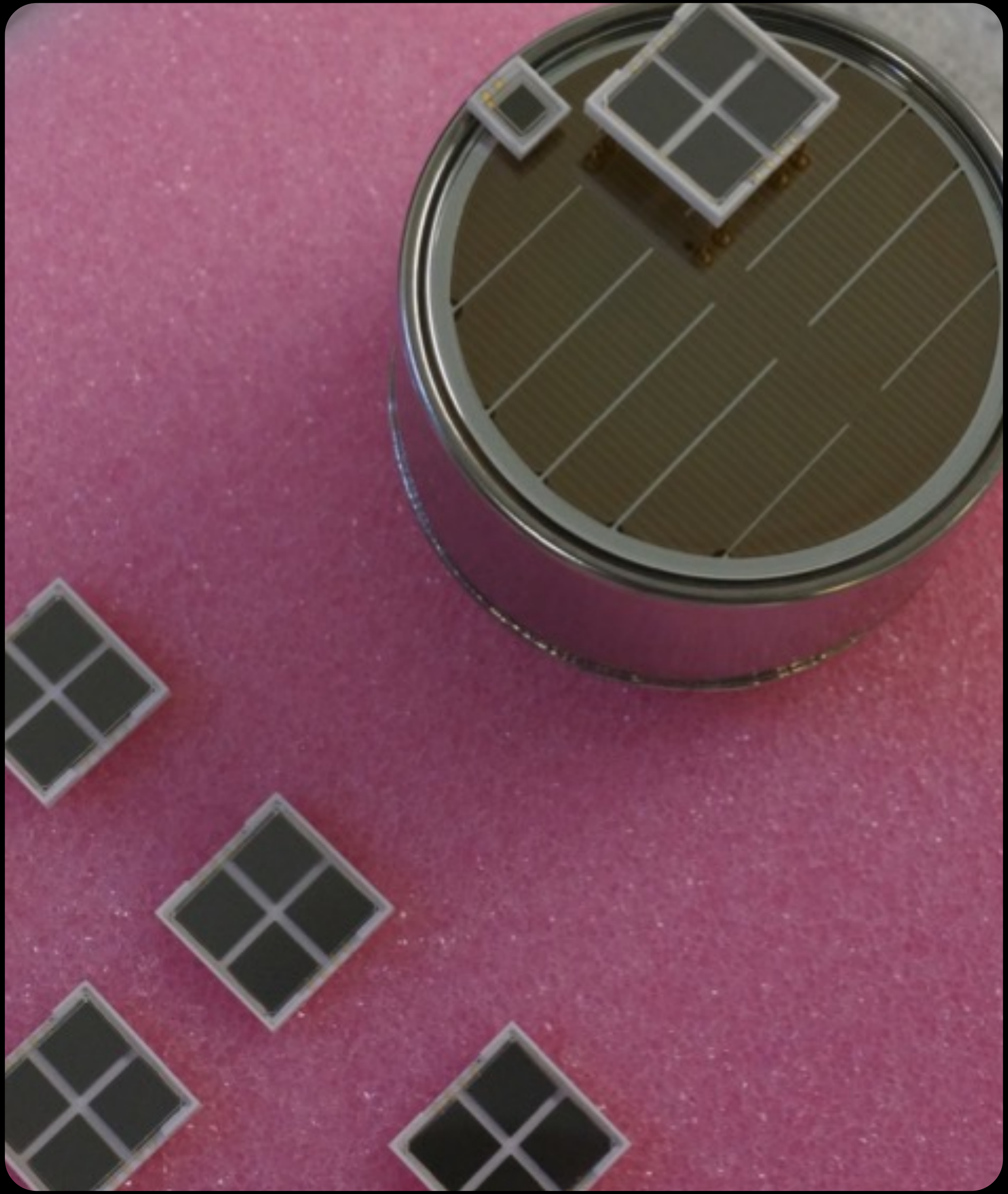
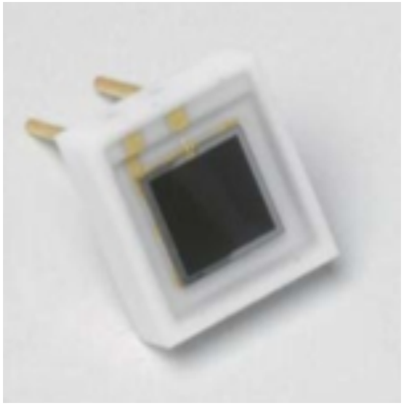
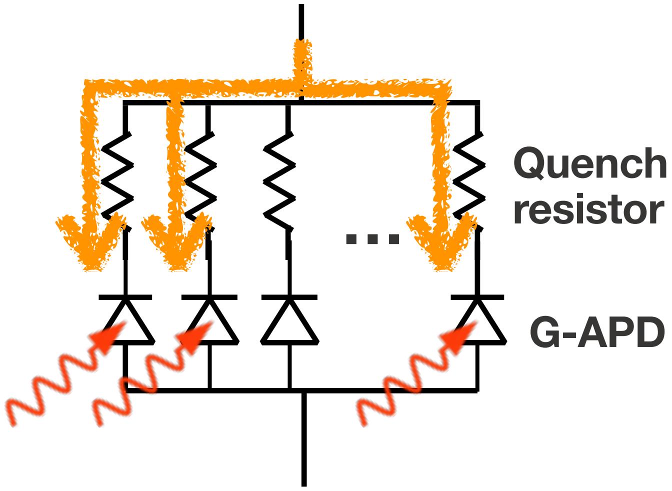
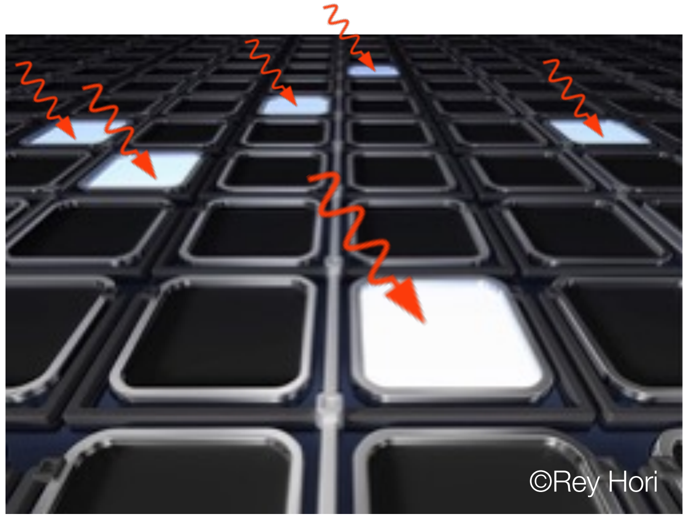


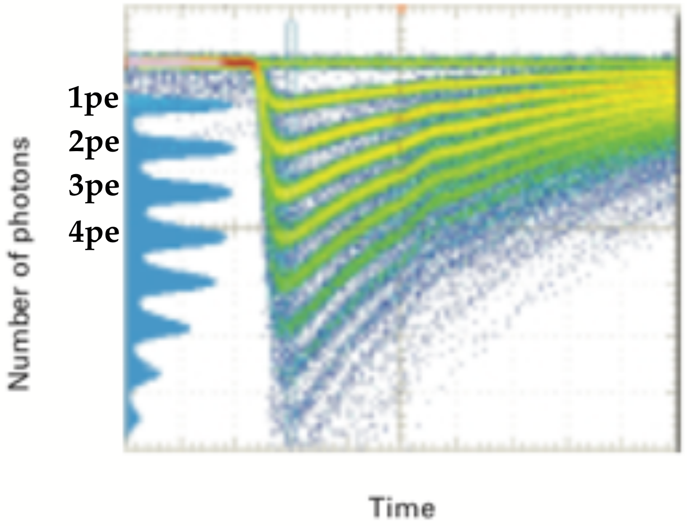
What Is Silicon Photomultiplier (SiPM)?

- SiPM = Multi-pixelated Geiger-mode APD (G-APD).
  - Tiny G-APD cells are connected in parallel together with resistor for self-quenching of avalanche
  - Each G-APD cell is a “binary” device. The same charge from each photon trigger.
  - SiPM output is a sum of signals from triggered G-APD cells.
- SiPM output is proportional to # of impinging photons
  - SiPM = “analogue” device.
- Pioneering works by Russian institutes in late 80ies (Golovin, Dolgoshein, Sadygov)



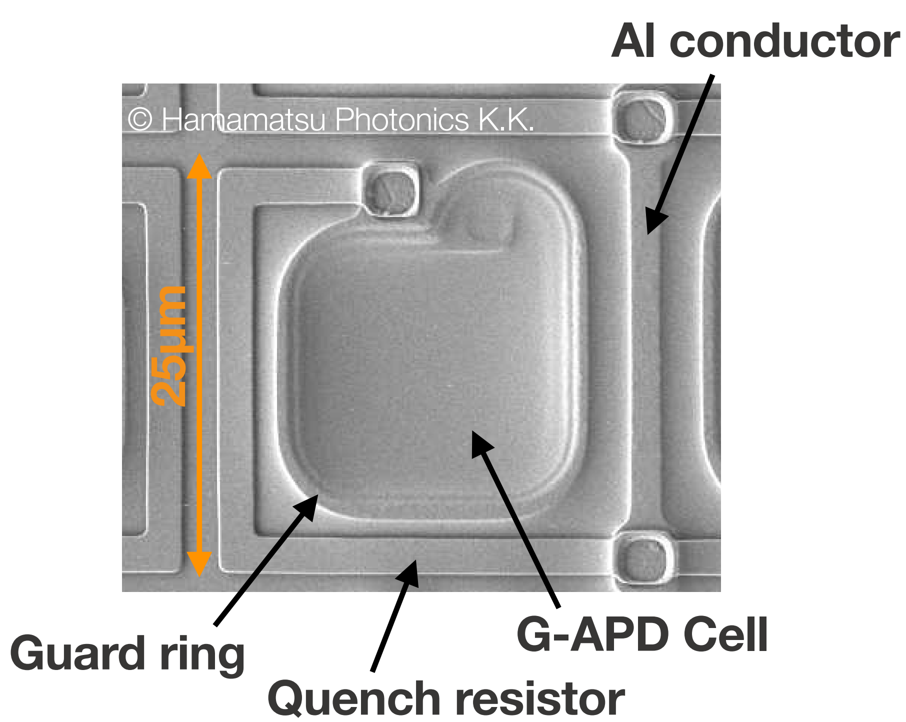


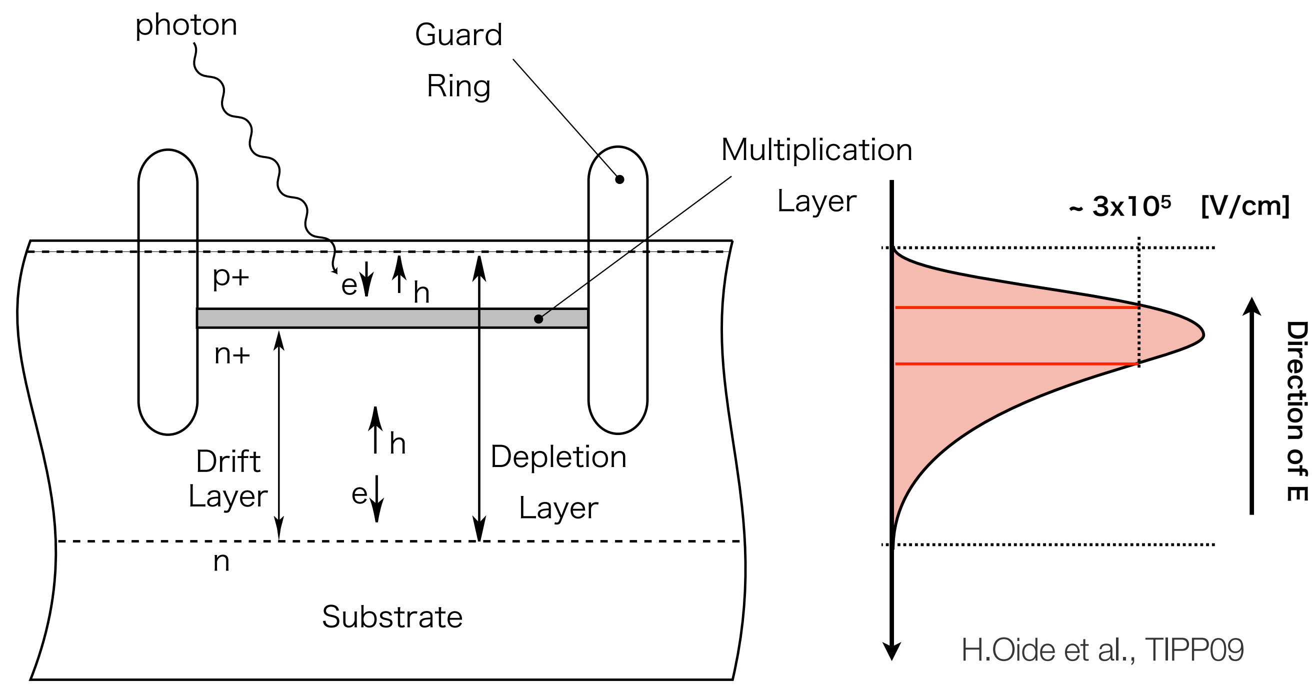


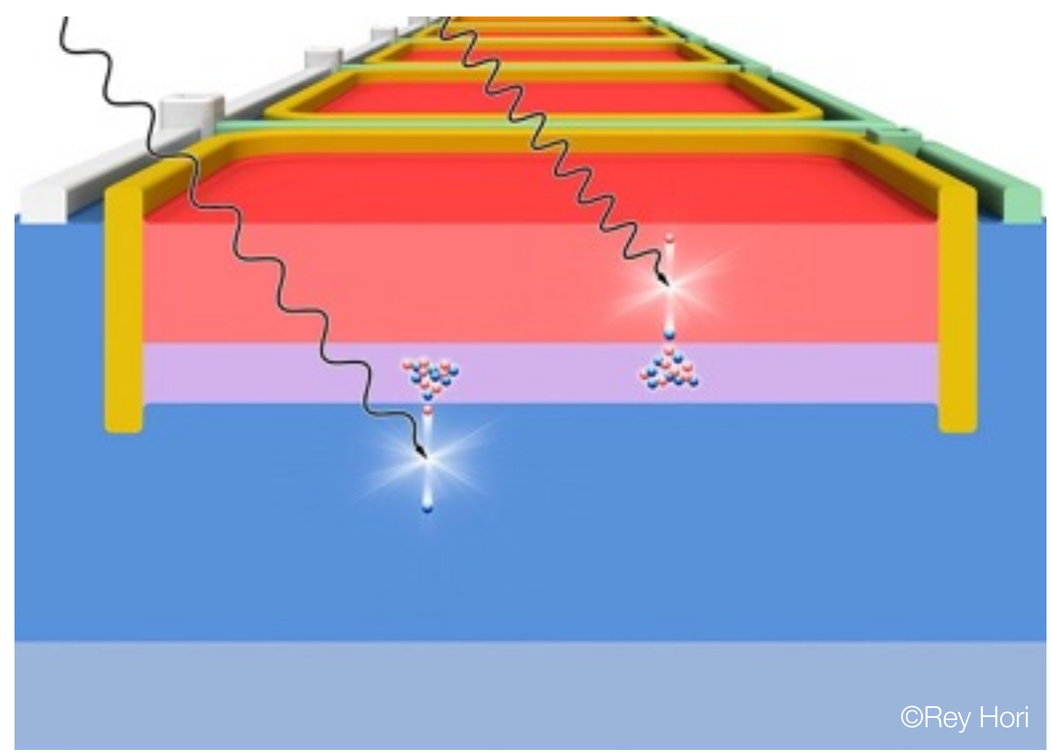


W.Ootani,“*SiPM, Status and Perspectives*”, *Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN*

Closer Look at Cell







SiPM: Basic Parameters

Sensor size (single)	1×1 - 6×6mm^2
Cell size (cell pitch)	10 - 100μm
Quench resistor	10k - 10MΩ
Internal gain	10^5 - 10^6
Photon detection efficiency (PDE)	20 - 50%
Time resolution (single photon)	O(100ps) (FWHM)
Dark noise rate	50k - 1M Hz/mm^2
Bias voltage	20 - 70 V

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Advantages of SiPM

- High photon detection efficiency
- High internal gain
- Insensitive to B-field
- Good single photoelectron resolution
- Fast (good timing resolution)
- Low bias voltage (<100V)
- Low power consumption
- Compact
- Low cost

Weak Points of SiPM

- Large sensor area is difficult.
- Temperature dependence
- Noise (dark noise + correlated noise)
- Radiation hardness
- Saturation for a large number of incoming photons

SiPMs from over The World

W.Ootani,"*SiPM, Status and Perspectives*", *Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN*

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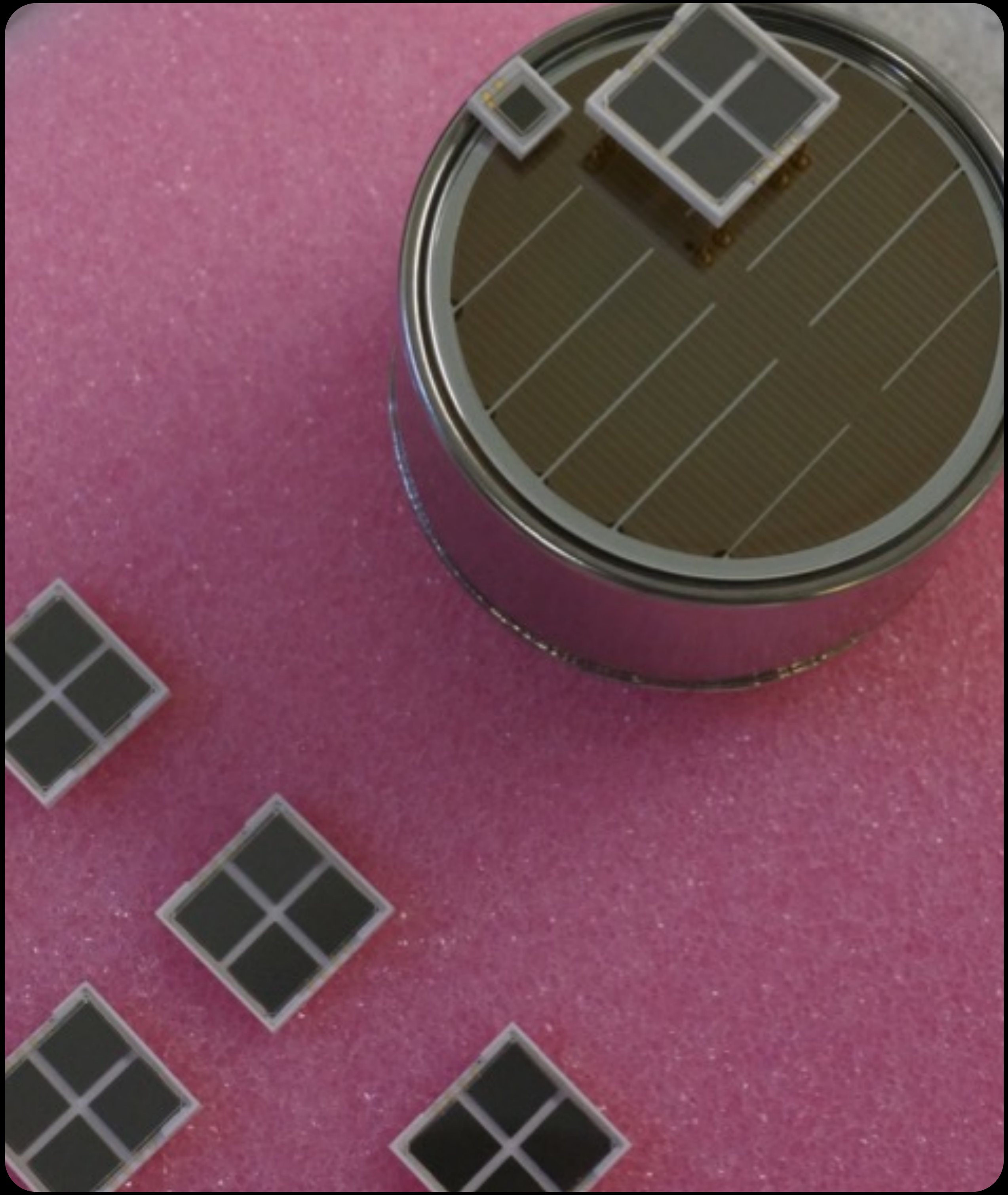
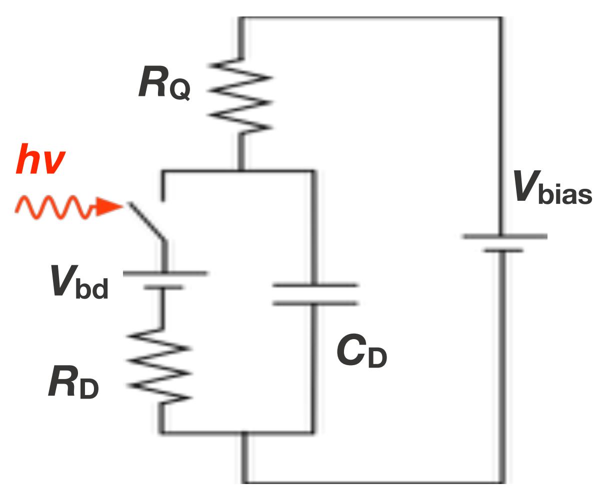


Pulse Shape

- SiPM cell operation cycle (simplified model)
  - ① Photo-generation of carrier ➔ avalanche (switch ON)
  - ② Self-quenching (switch OFF)
  - ③ Re-charge cell



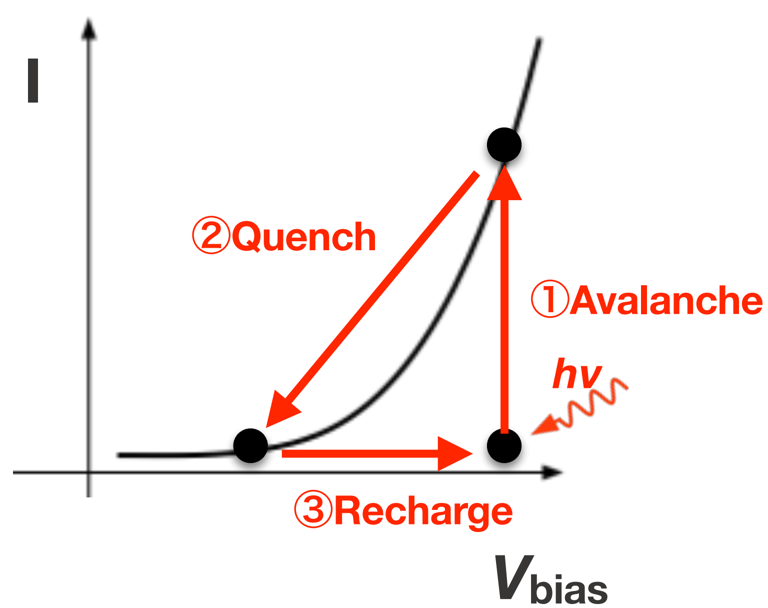
R_D: series resistance of micro-plasma in avalanche

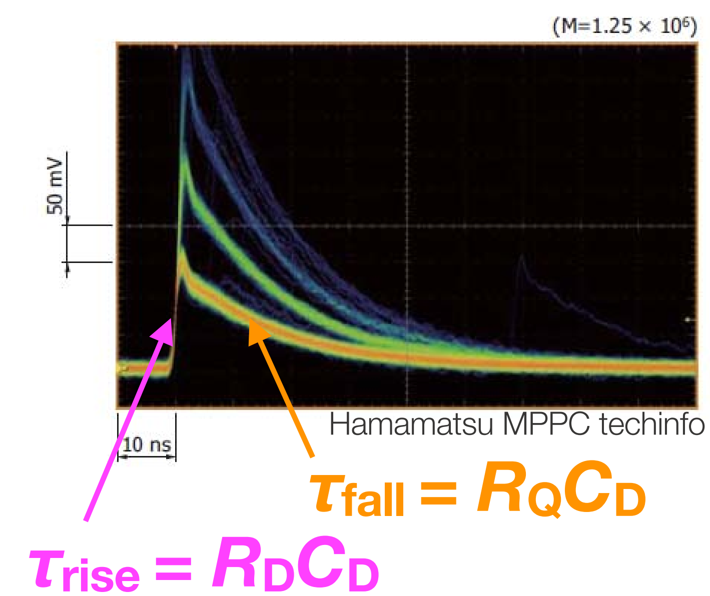
C_D: cell capacitance

V_{bd}: breakdown voltage

V_{bias}: bias voltage

R_Q: quench resistor





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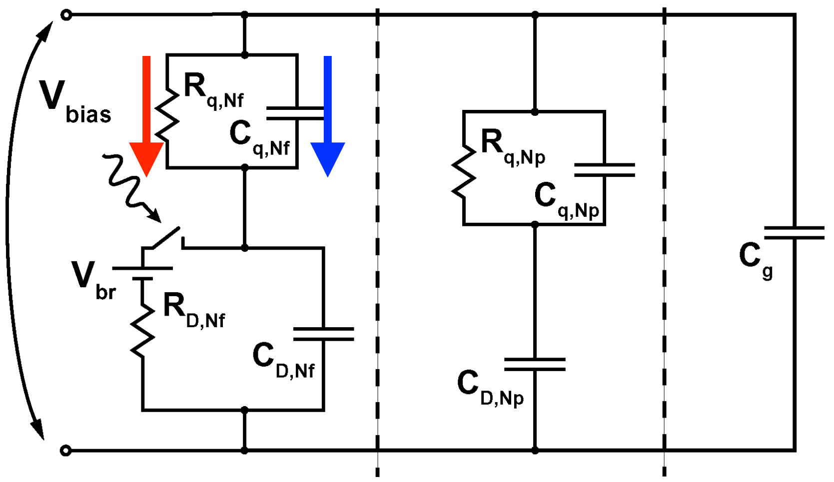
Pulse Shape

- More complicated response in reality due to
  - Parasitic capacitance of quench resistor
  - Parasitic capacitance of neighbouring cells
- Two components (fast and slow)
  - Slow: slow recharge through quench resistor (R_q)
  - Fast: fast discharge through parasitic capacitance of quench resistor (C_q)
    - Fast component is only visible in case of large R_q

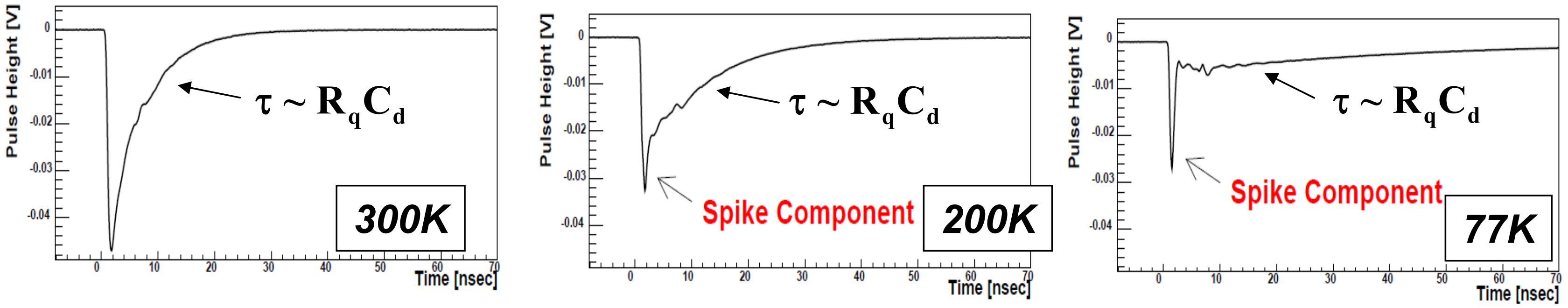
Equivalent circuit for SiPM



S.Seifert et al., IEEE TNS 56(2009)3726

	300K	200K	77K
R_q	0.21MΩ	0.40MΩ	1.68MΩ
C_q	22.1fF	22.0fF	22.1fF

H. Oide et al. PoS(PD07)007



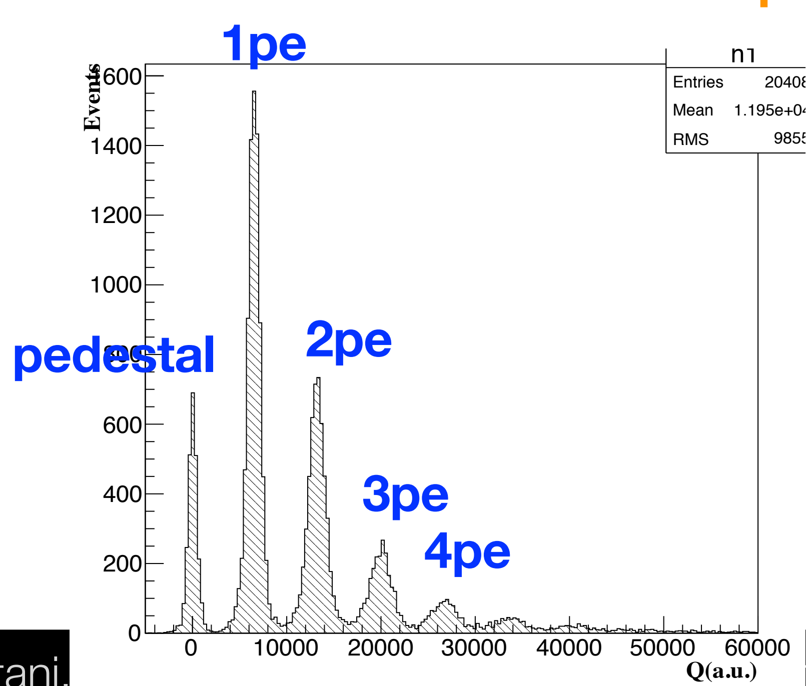
- Signal for light detection: Convoluted with light emission time distribution

Single Photoelectron Resolution

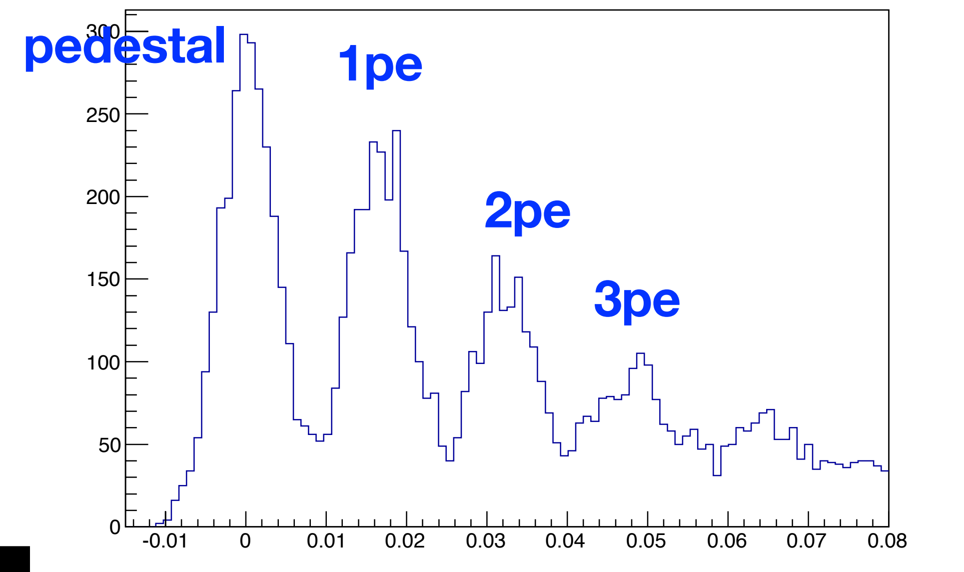
- Excellent single photoelectron resolution because of
  - High internal gain (= good S/N)
  - Good cell-to-cell gain uniformity
- Can be worsened by electrical noise and pileup due to dark noise and afterpulse
- Practically single photoelectron peak can not be resolved for >6×6mm^2 sensor area due to increasing dark noise

N.B. Good photoelectron resolution still possible for larger sensor size at low temp.

3×3mm^2 MPPC at room temp



12×12mm^2 MPPC at 165K (for MEG II)

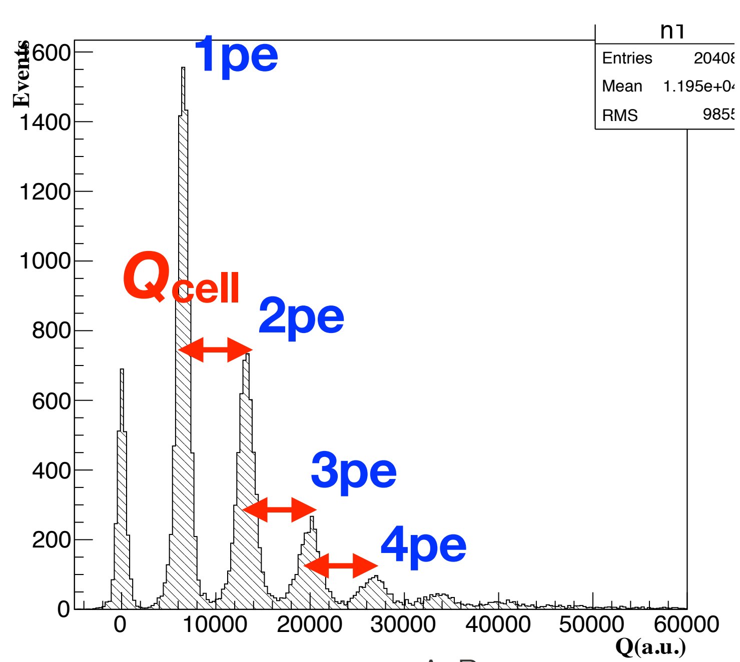


Gain

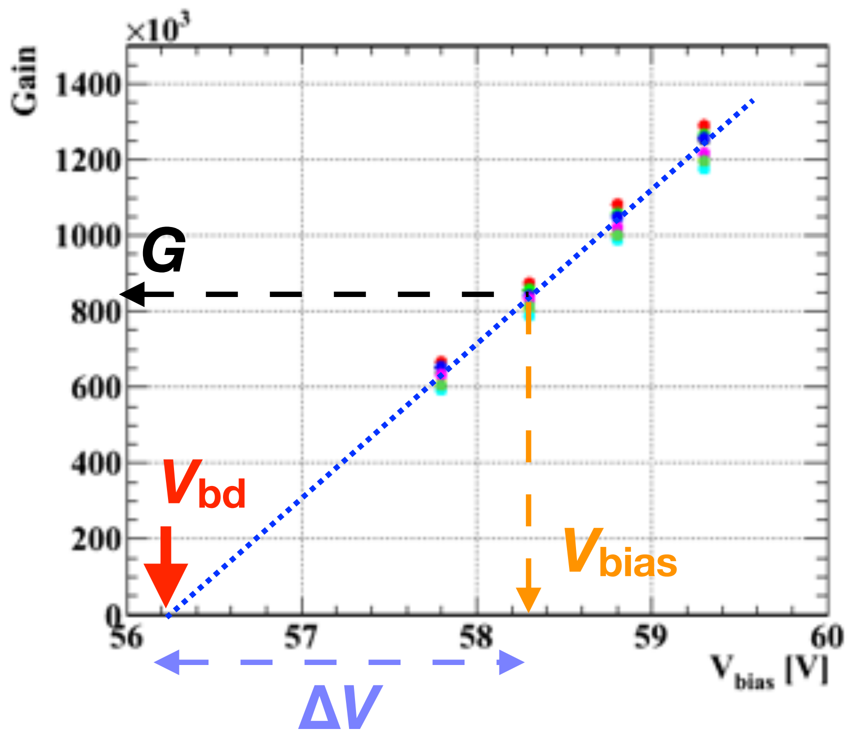
- High internal gain: 10^5-10^6
- Proportional to over-voltage ($\Delta V = V_{bias} - V_{bd}$)
- Easily measured from single photoelectron charge
- Gain fluctuation is quite small
  - Cell-to-cell uniformity on capacitance and V_{bd}
  - Small statistical fluctuation in avalanche multiplication (↔Poisson fluctuation in APD)

$$G = \frac{Q_{cell}}{e} = \frac{C_{cell}\Delta V}{e}$$

over-voltage $\Delta V = V_{bias} - V_{bd}$



A. Papa



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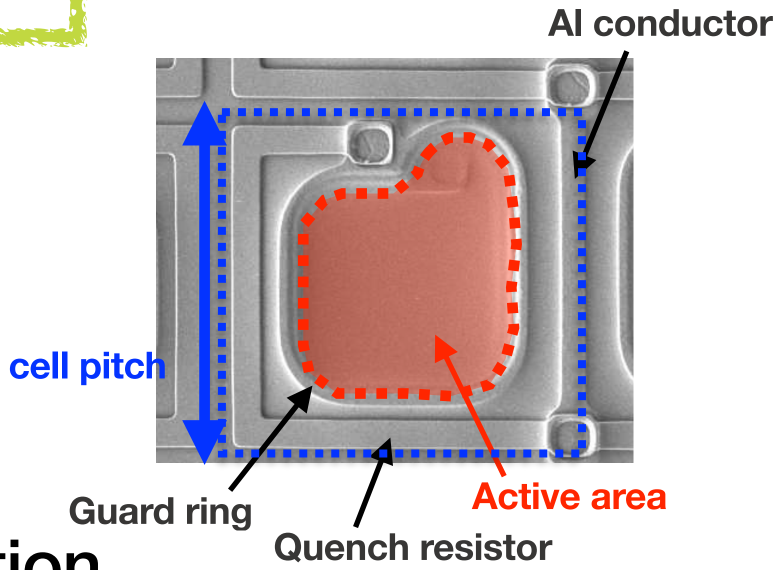
Photon Detection Efficiency (PDE)

$$PDE = \epsilon \times QE \times P_{trigger}$$

- ε (Fill factor)
  - Fraction of active area, typically 50-70%
  - Dead area due to signal line, guard ring, trench,…
- *QE* (Quantum efficiency)
  - Probability of photo-generation of carrier
  - Dependent on reflectivity on Si surface and absorption length in Si
- $P_{trigger}$
  - Probability for generated carrier to trigger avalanche



- Dependence on
  - λ
  - ΔV
  - temperature (small)

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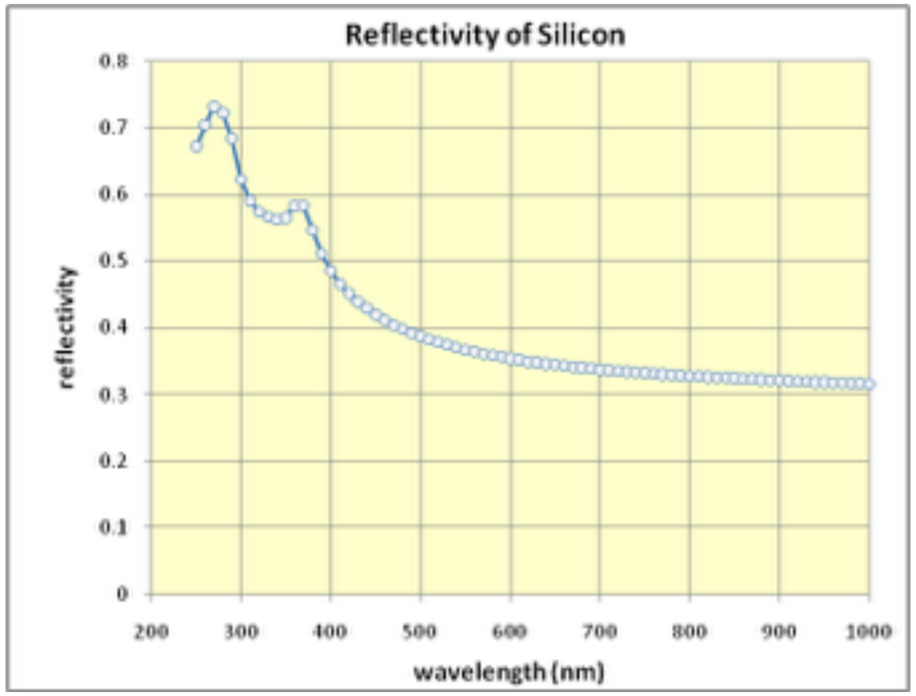
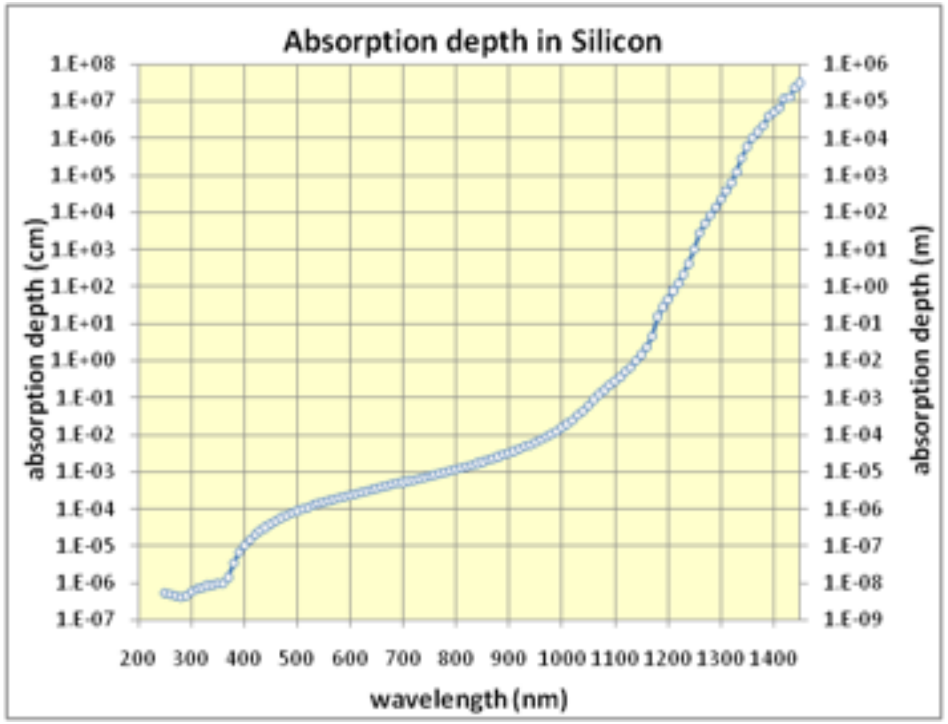
Photon Detection Efficiency (PDE)

Key parameters for QE

- Reflectivity on Si surface
  - Reflection can be somewhat reduced with AR coating.
- Absorption length in Si depends on λ



PV EDUCATION.ORG homepage



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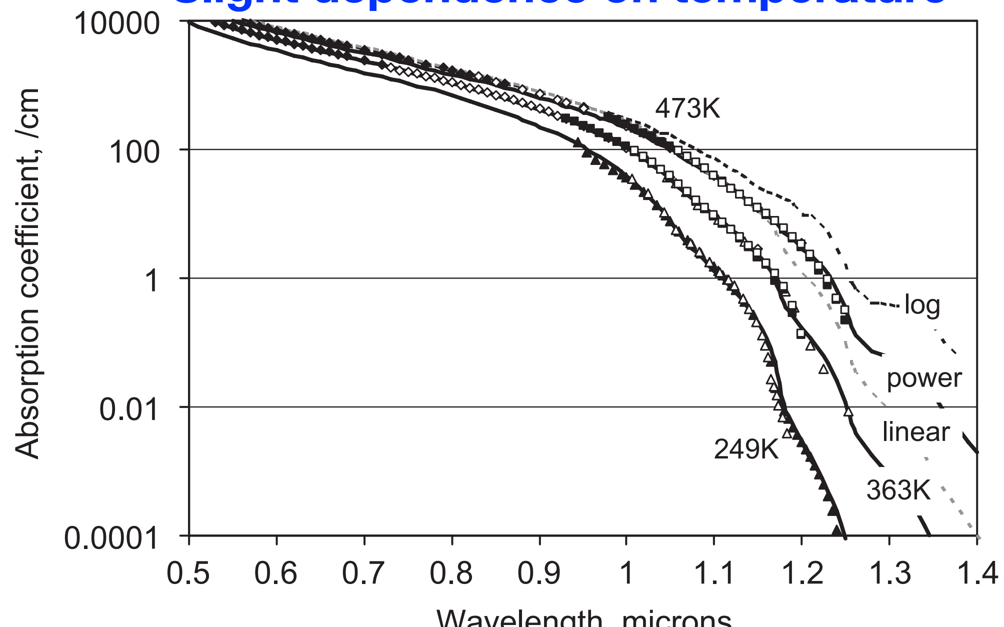
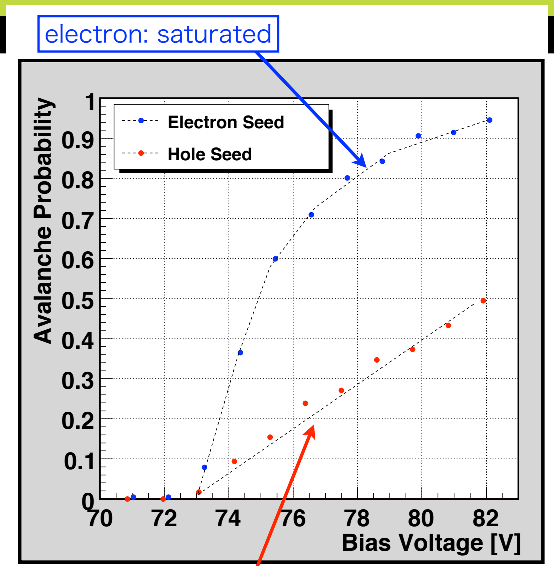
Slight dependence on temperature



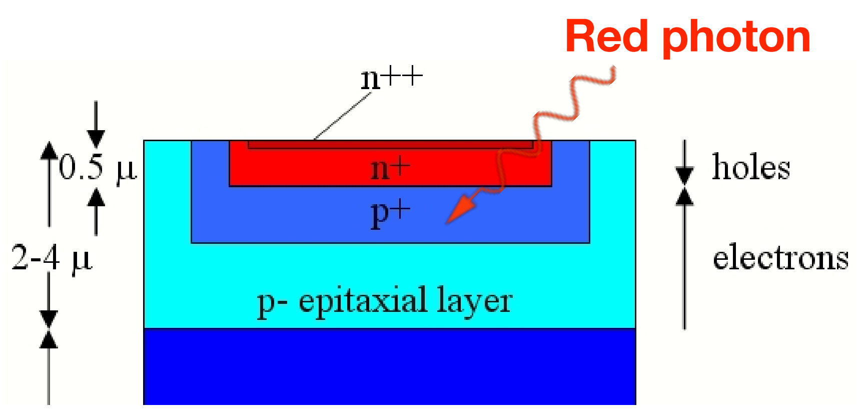
Solar Energy Materials & Solar Cells 92 (2008) 1305– 1310

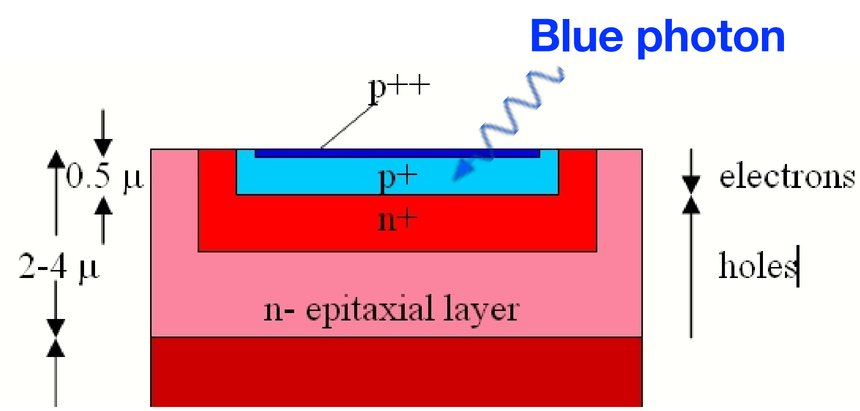
Photon Detection Efficiency (PDE)

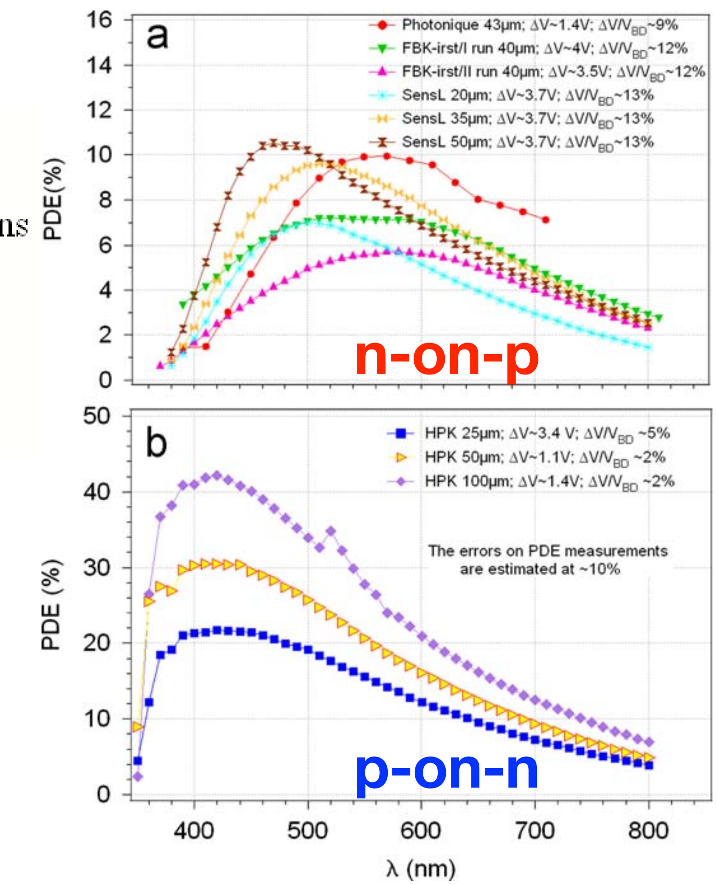
- $P_{trigger}$ (electron) >> $P_{trigger}$ (hole)
  - ➔ Higher PDE for carrier generated in p+ layer
- λ-dependence of absorption length in Si
  - ➔Different λ-dependence of PDE depending on depth of p+ layer.



H. Otono, et al., PANIC08







N. Dinu et al., NIMA 610(2009)423

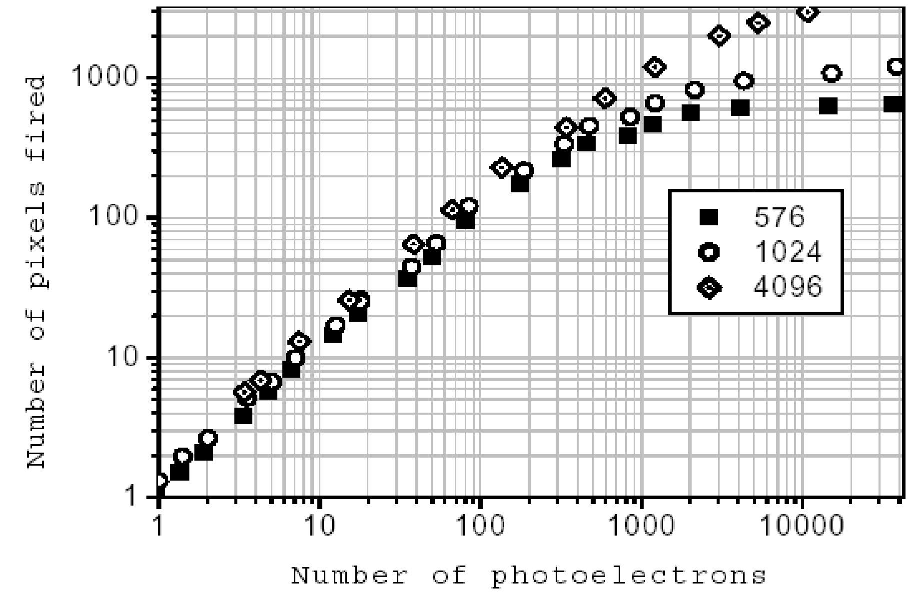
n-on-p structure
➔ Green/Red sensitive

p-on-n structure
➔ Blue sensitive

Linearity/Saturation

- Good linearity as long as $N_{pe} < N_{cell}$
- Non-linearity (saturation) caused by finite number of cells
- Limiting factors
  - Incoming photon intensity
  - Cell size
  - Recovery time
- Need careful correction for many photons
- How to mitigate saturation ➔ smaller cell

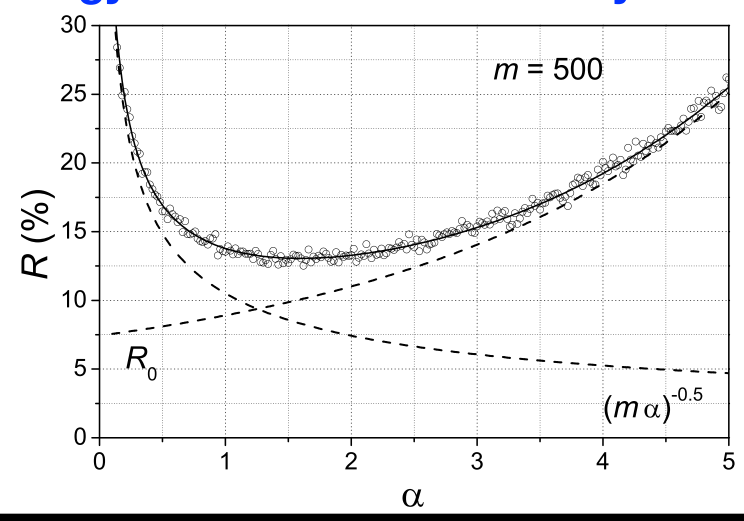
Response functions for the SiPMs with different total pixel numbers measured for 40 ps laser pulses



B. Dolgoshein, TRD2005

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

Energy resolution worsened by saturation (Simulation)



***m*: N_{cell}**

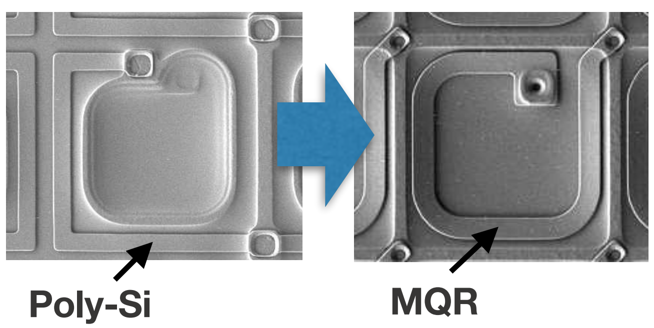
***n*: N_{photon} × PDE**

$\alpha = n/m$

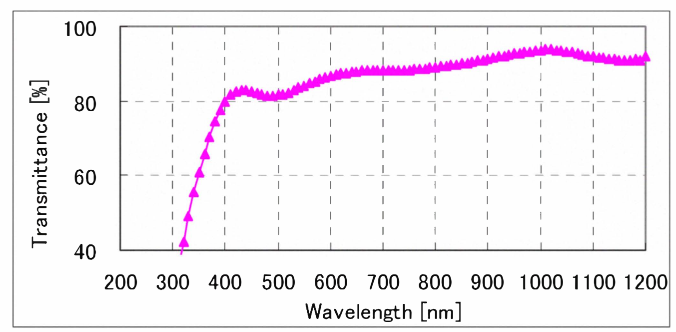
A. Stoykov, et al., JINST 2 P06005

Small Cell SiPM

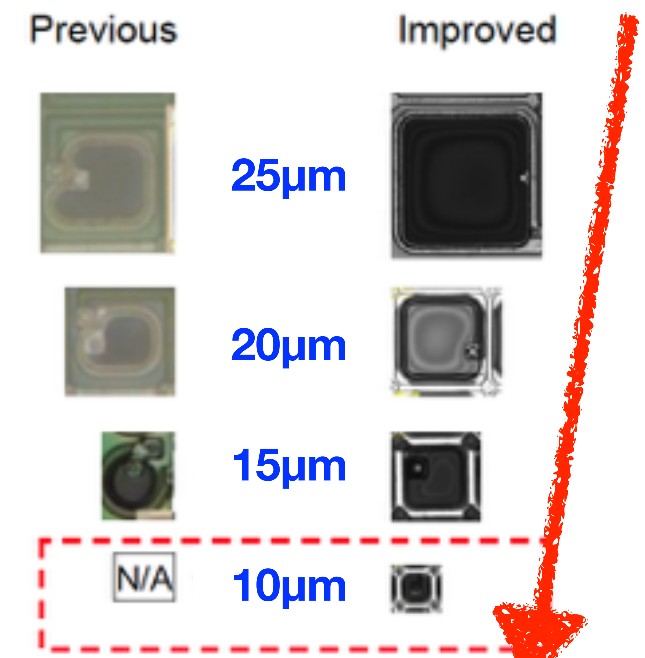
- 10μm cell pitch for Hamamatsu MPPC
  - Fill factor improved by metal quench resistor (MQR)
  - Thin MQR (⇐ transparent to light) over active area!



K. Sato et al., IEEE TNS 2013

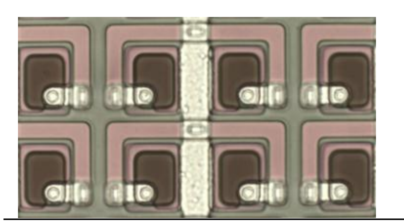


T.Nagano et al., IEEE TNS 2011

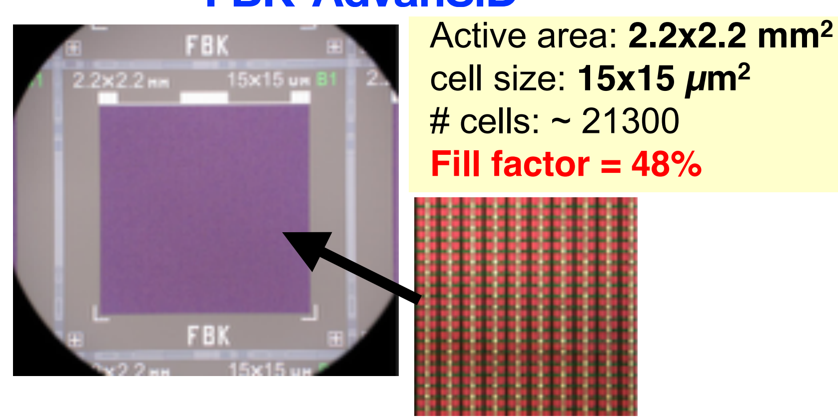


- 15μm cell pitch for KETEK and AdvanSiD

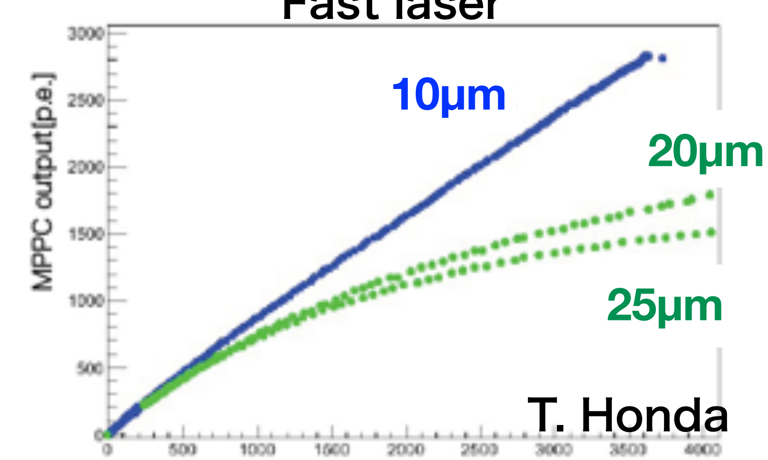
KETEK



FBK-AdvanSiD



Fast laser



- Micro-cell: Micro-pixel APD (MAPD) from Zecotek
  - Up to 40,000 cell/mm^2

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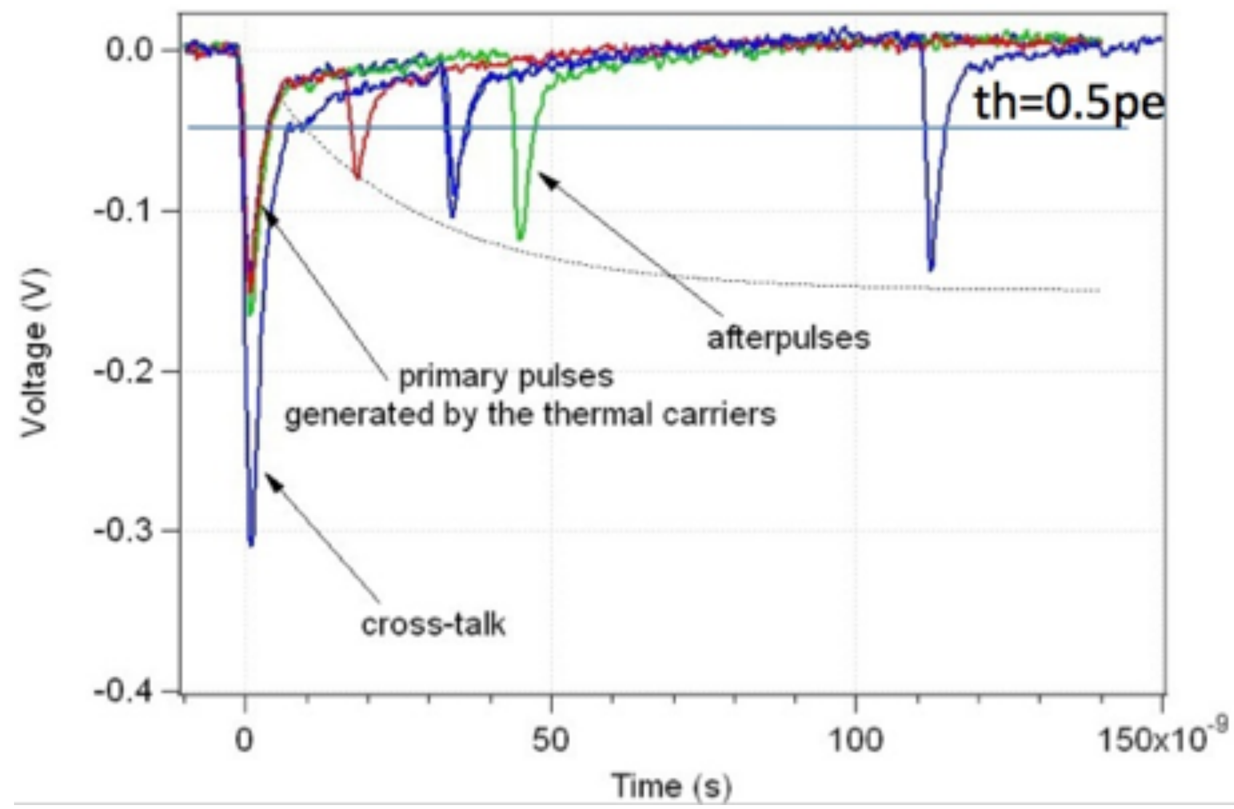
Noise in SiPM

Intrinsic noise source of SiPM

- Dark noise
  - Thermally generated carrier
  - Random
- Correlated noise
  - Optical cross-talk
  - After-pulsing



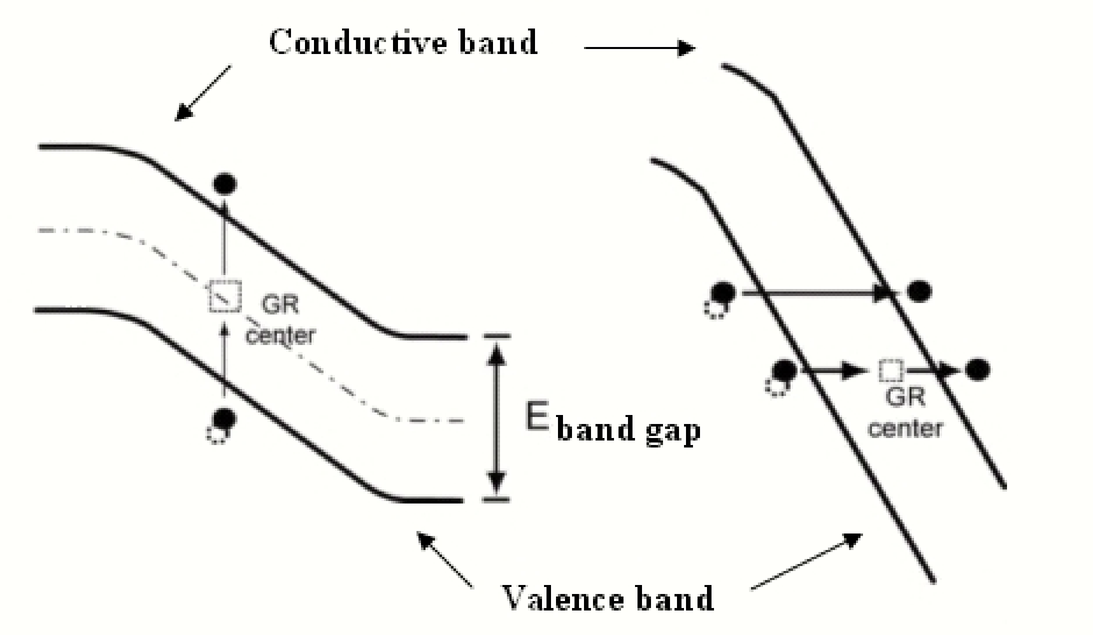
- Correlated noise increases gain fluctuation and thus increases excess noise factor (ENF).
  - Energy resolution is deteriorated with increased ENF.

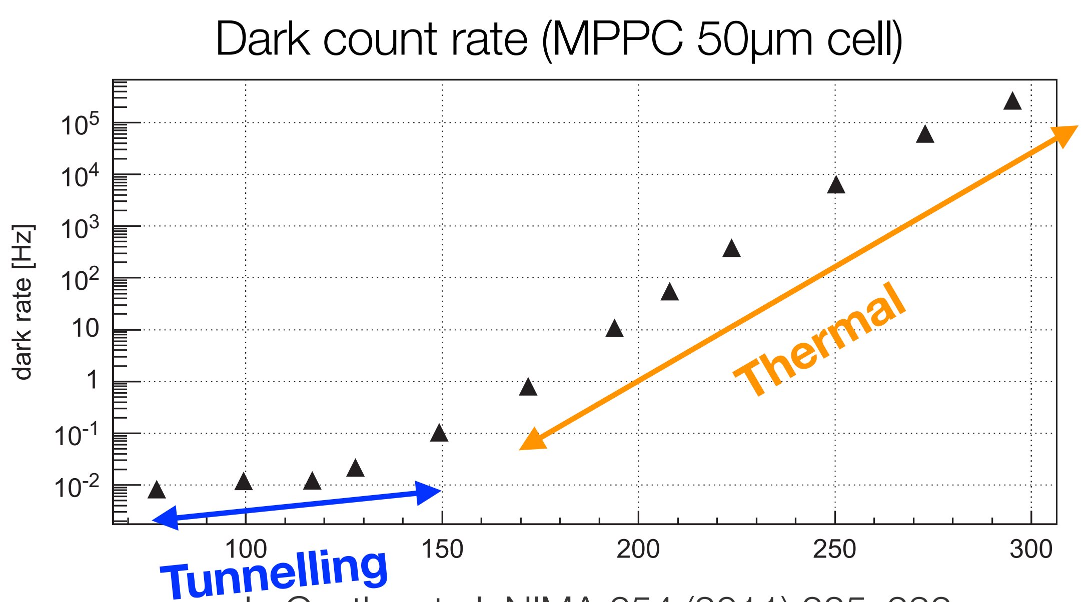
$$ENF = 1 + \frac{\sigma_G^2}{G^2}$$

W.Ootani, "*SiPM, Status and Perspectives*", *Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN*

Dark Noise (Dark Count)

- Signal from avalanche triggered by randomly generated carrier
- Two sources
  - Thermal generated
    - Dominates at room temperature
    - Drastically reduced at low temperature (A factor of two every 8 deg. temperature drop)
  - “Field-assisted” generation (Tunnelling)
    - Dominates at T<200K

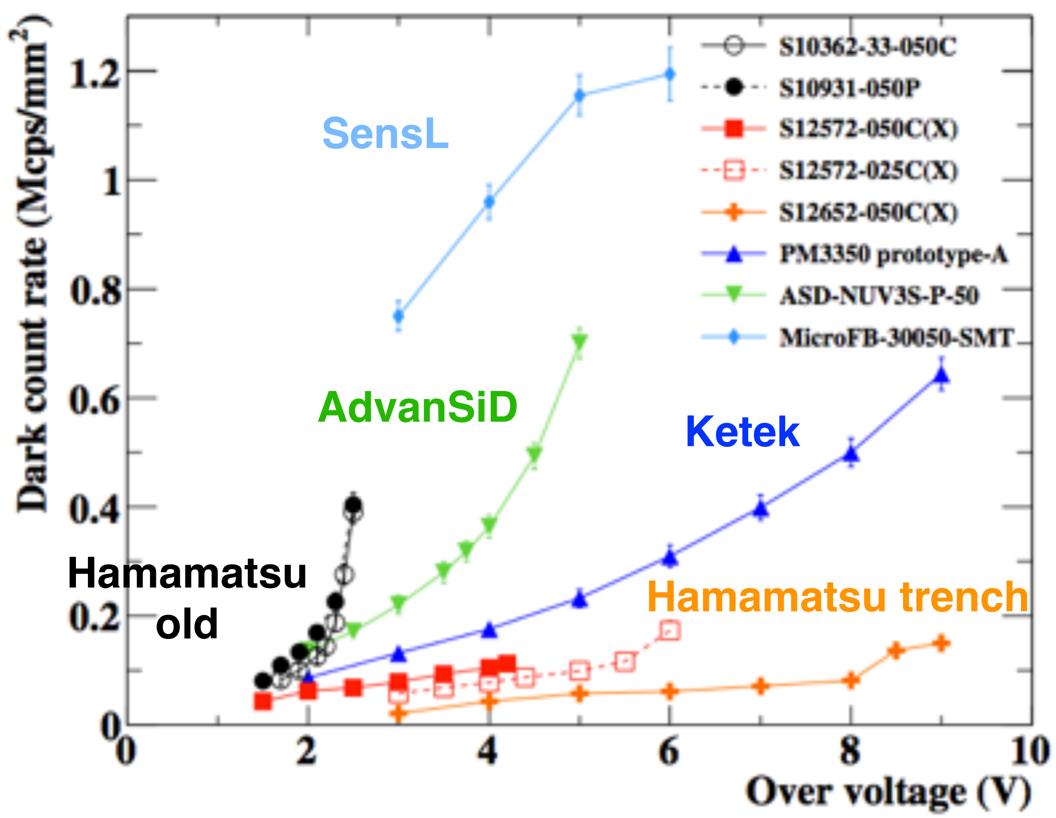




J. Csathy et al. NIMA 654 (2011) 225–232

Dark Noise (Dark Count)

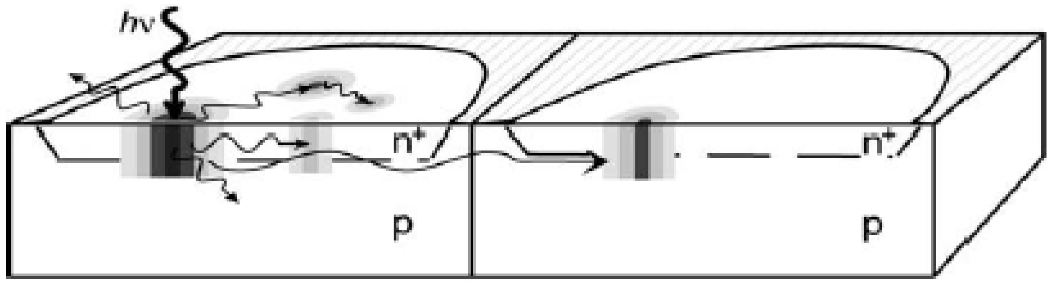
- Dark count rate improved as <50kHz/mm^2 for recent devices
  - Improved wafer quality
  - Improved processing of epitaxial layer
  - Impurity getter
- Easy solution: Setting higher threshold (>1pe, 2pe, …)



P. W. Cataneo, WO, et al. IEEE-TNS 61(2014)2657

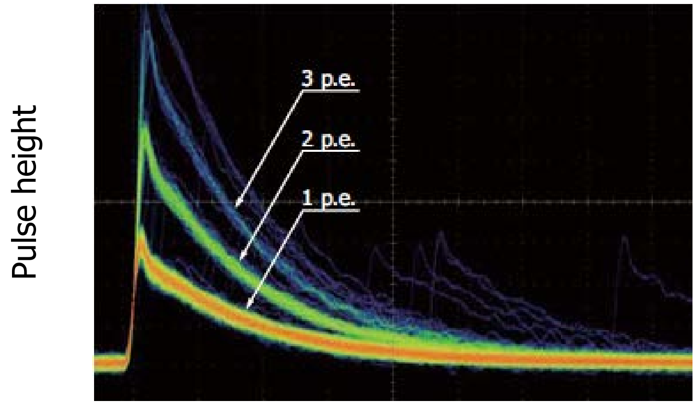
Optical Cross-talk

- NIR luminescence during avalanche:
  - **~3 photons generated for 10^5 carriers** (A. Lacaita et al.,IEEE TED 1993)
- Photon can generate carrier in neighbouring cell and then induce another avalanche.
- Superimposed on the primary pulse at the same timing.

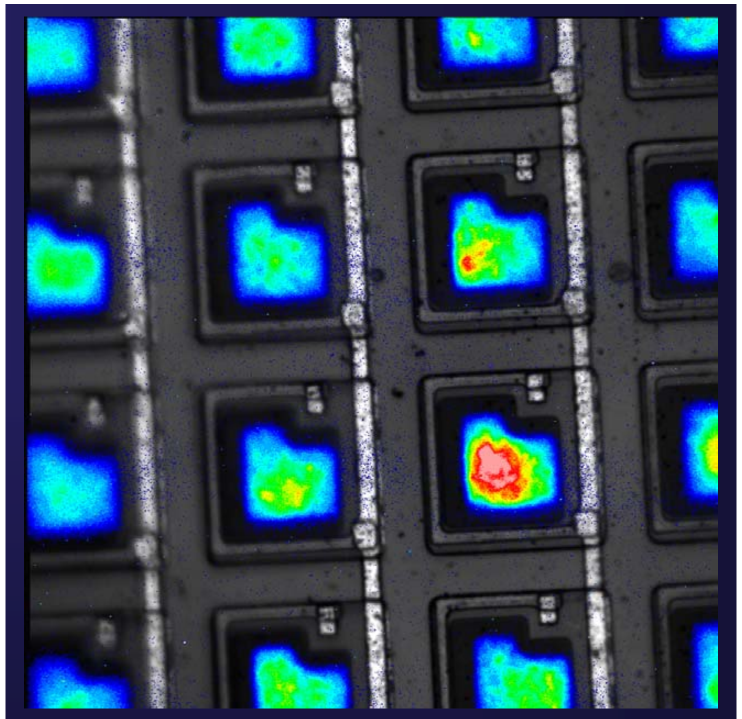


A. Lacaita et al., IEEE TED 2013

Optical crosstalk superimposed on primary pulse



Hamamatsu MPPC techinfo

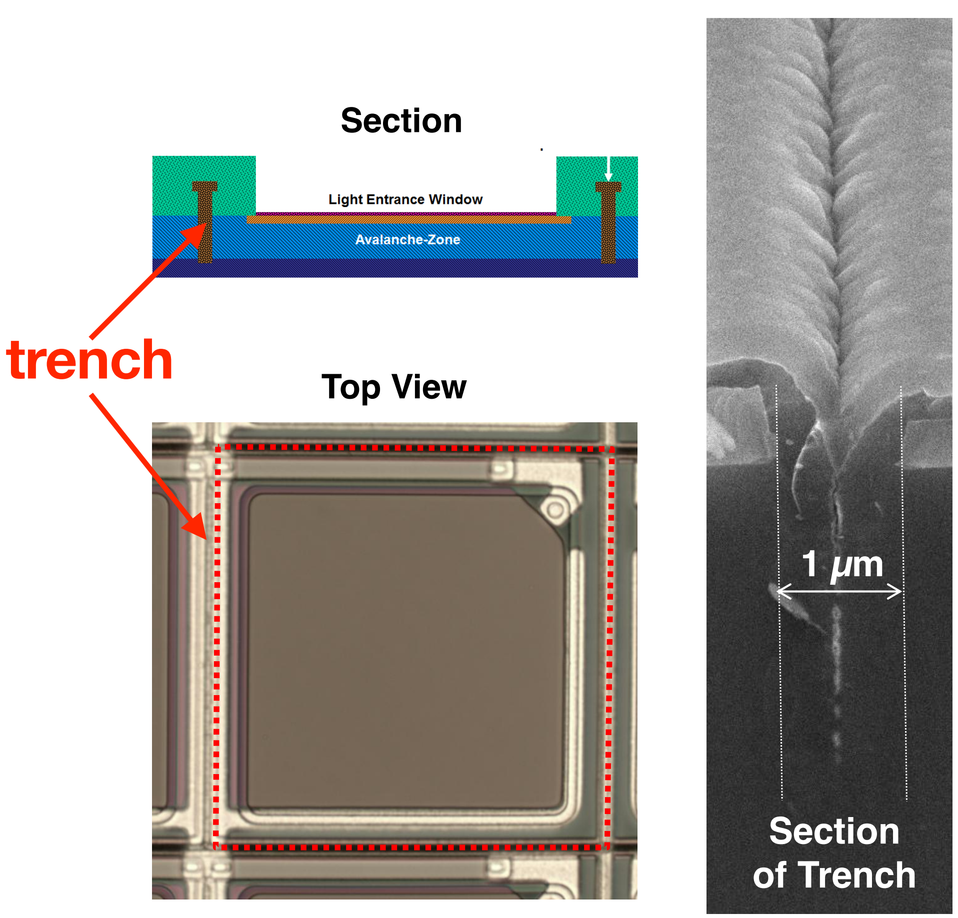


Emission microscopy picture of a prototype SiPM

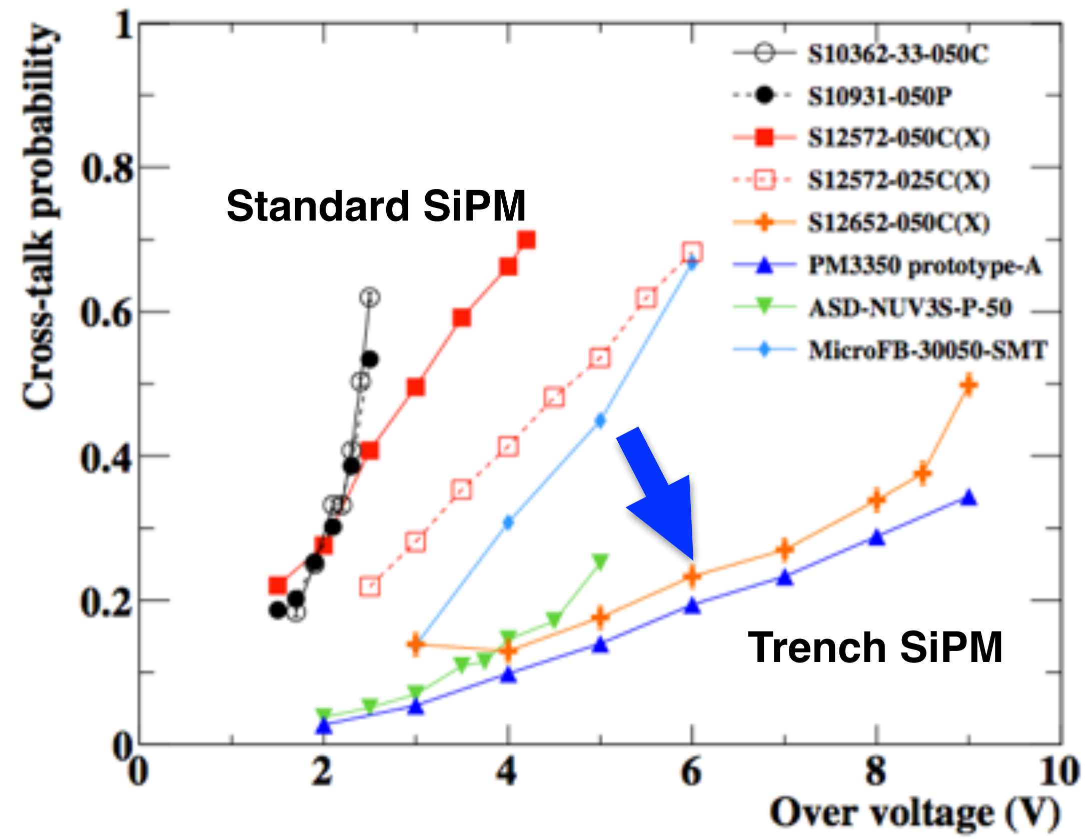
N. Otte, SNIC2006

Optical Cross-talk

- Optical cross-talk can be reduced by
  - Lower bias voltage (at the cost of lower gain/PDE)
  - Smaller cell
  - Cell isolation by trench filled with opaque material



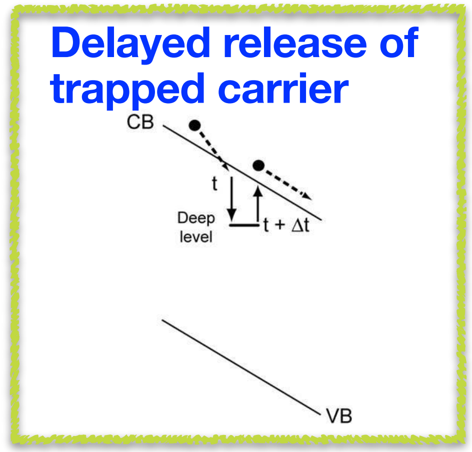
F. Wiest et al., PhotoDet2012

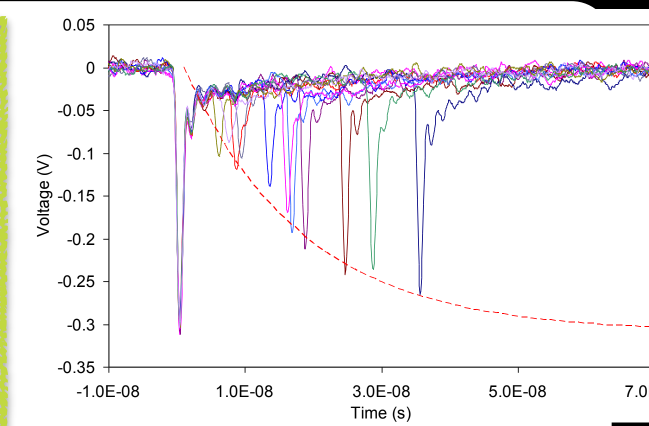


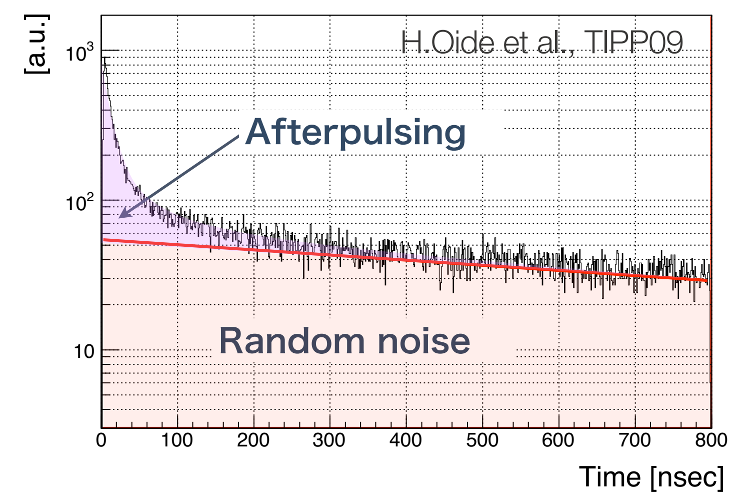
P. W. Cataneo, WO, et al. IEEE-TNS 61(2014)2657

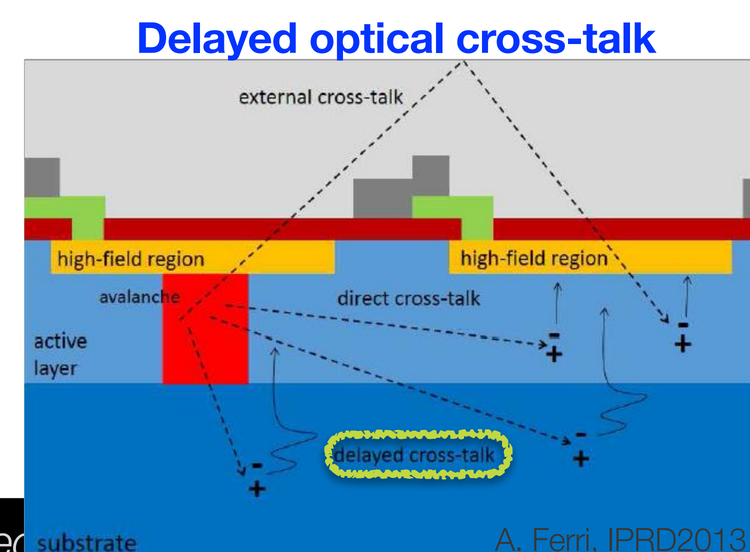
After-pulsing

- Delayed correlated noise
- Two sources
  - **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
    - ΔV^2 dependence ($N_{carrier} \propto \Delta V$, $P_{trigger} \propto \Delta V$)
    - Solutions
      - Better quality of wafer and epi. layer
      - Reduced gain
  - **Delayed optical cross-talk**
    - Solutions: Buried junction to block delayed carrier diffusion from substrate









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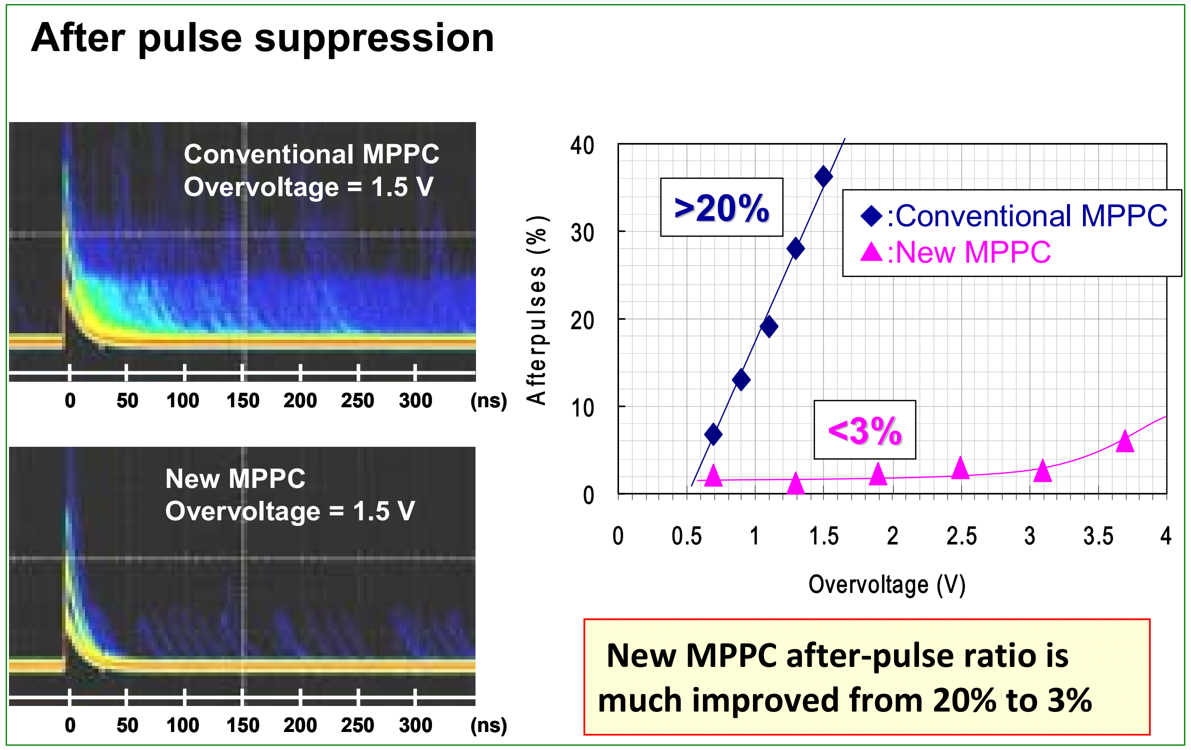
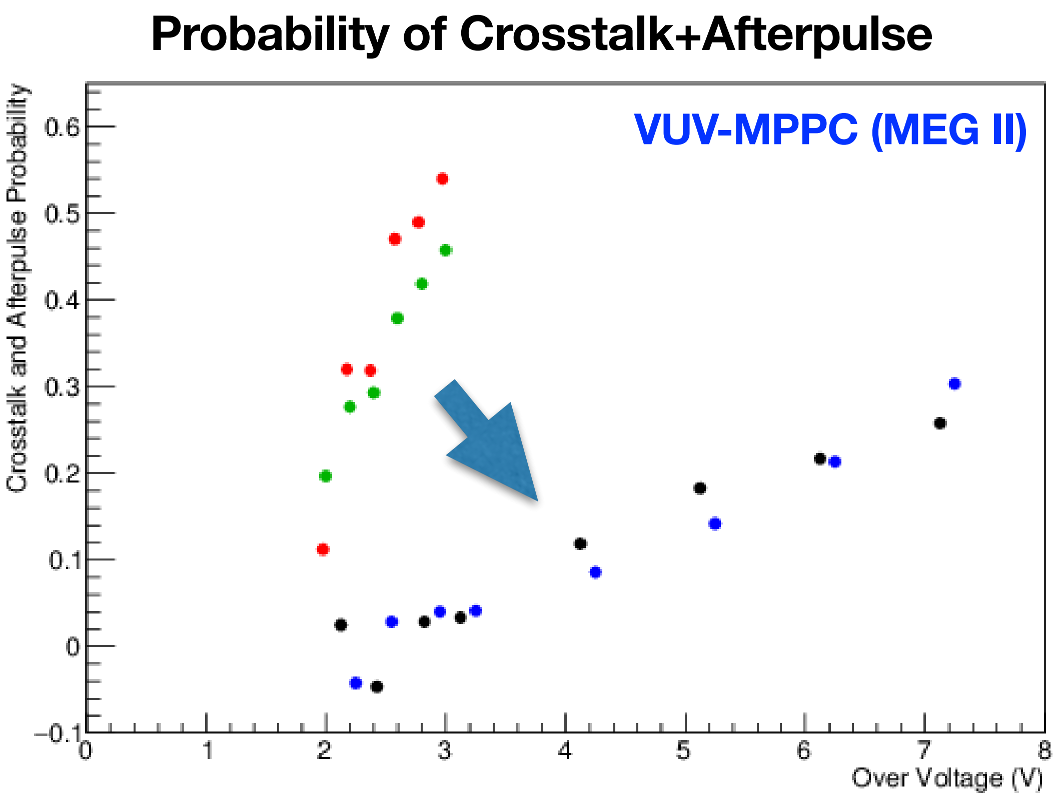
After-pulsing

- After-pulsing drastically reduced for recent Hamamatsu MPPC



K. Sato, et al.,VCI2013

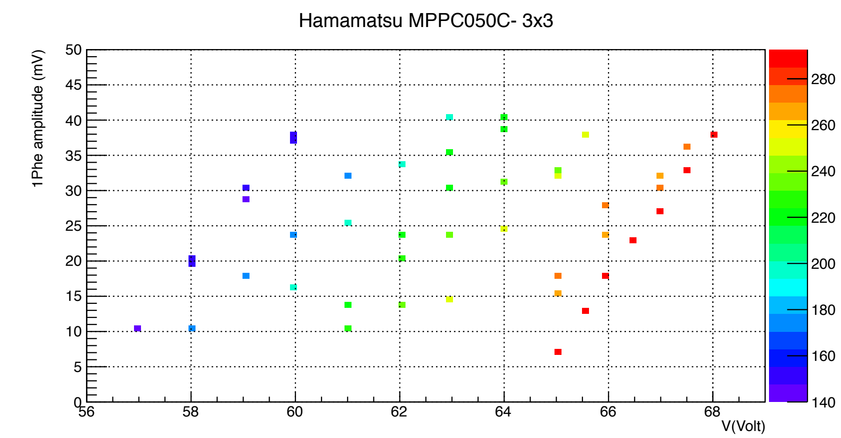


- Both cross-talk and after-pulsing drastically reduced at the same device!
- Bonus: Operational at higher bias voltage ➔ higher gain/PDE

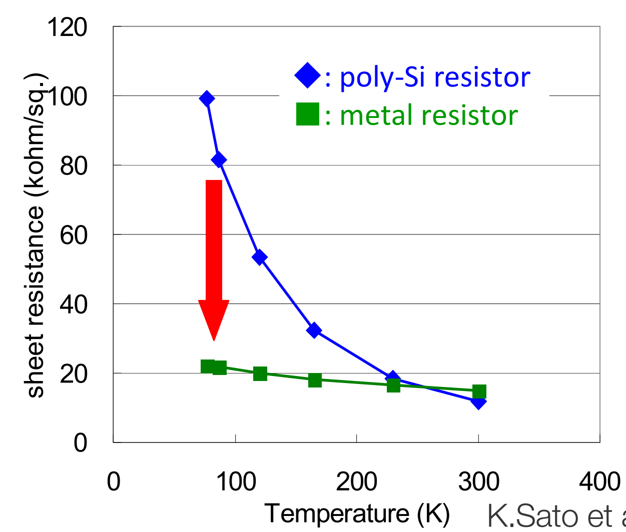
W.Ootani,"*SiPM, Status and Perspectives*", *Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN*

Temperature Dependence

- In general, SiPM has to be operated at controlled temperature. ☹
- Temperature dependence of SiPM
  - Breakdown voltage
    - $\Delta V_{bd} / \Delta T$ = 55mV/deg (MPPC), 25mV/deg (AdvanSiD)
    - Gain can be drastically changed when temperature varies, if V_{bias} is not adjusted accordingly.
  - Dark count rate
    - ×2 reduction every 8deg temp. reduction
  - Quench resistor
    - Signal shape can be changed.
    - Improved by using metal quench resistor instead of poly-Si (Hamamatsu MPPC)



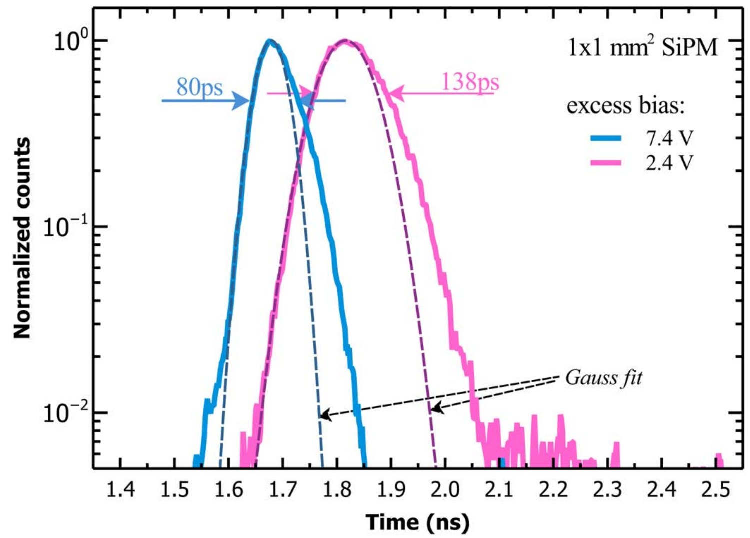
A. Papa



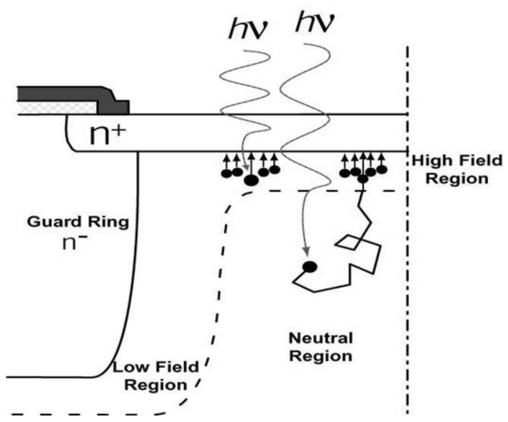
K.Sato et al., VCI2013

Timing Resolution

- SiPM signal charge generated in very thin layer (~a few μm)
- SiPM has an excellent Single Photon Time Resolution (SPTR).
  - Major component: Gaussian jitter ~O(100ps) (FWHM)
  - Minor slow tail (~O(ns)) from carrier drift from neutral region

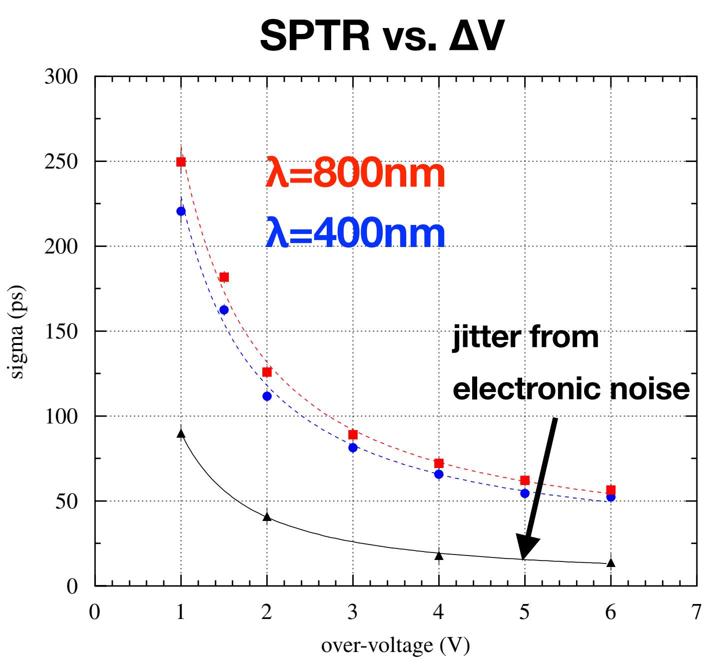


F. Acerbi et al., IEEE-TNS 61(2014)2678

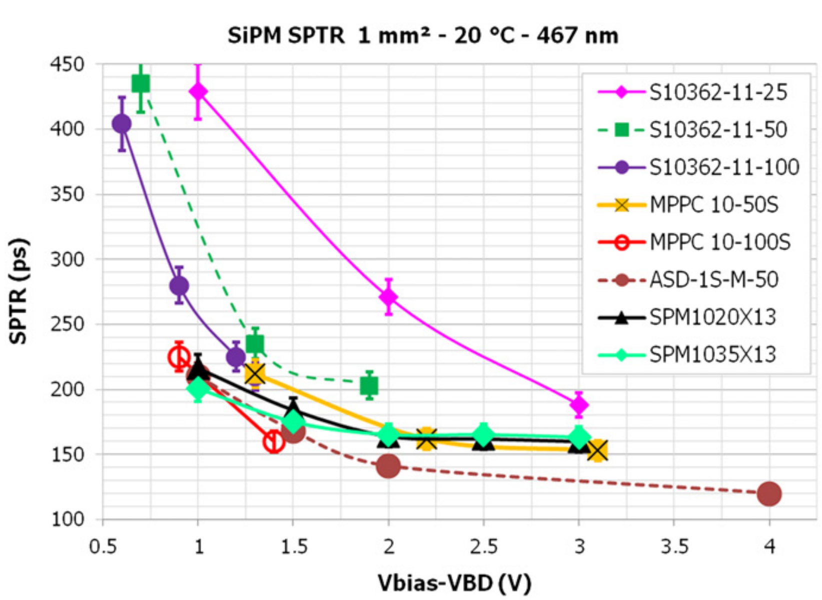


S. Cova et al., NIST Workshop on Single Photon Detectors 2003

- Strong dependence on ΔV, weak dependence on λ



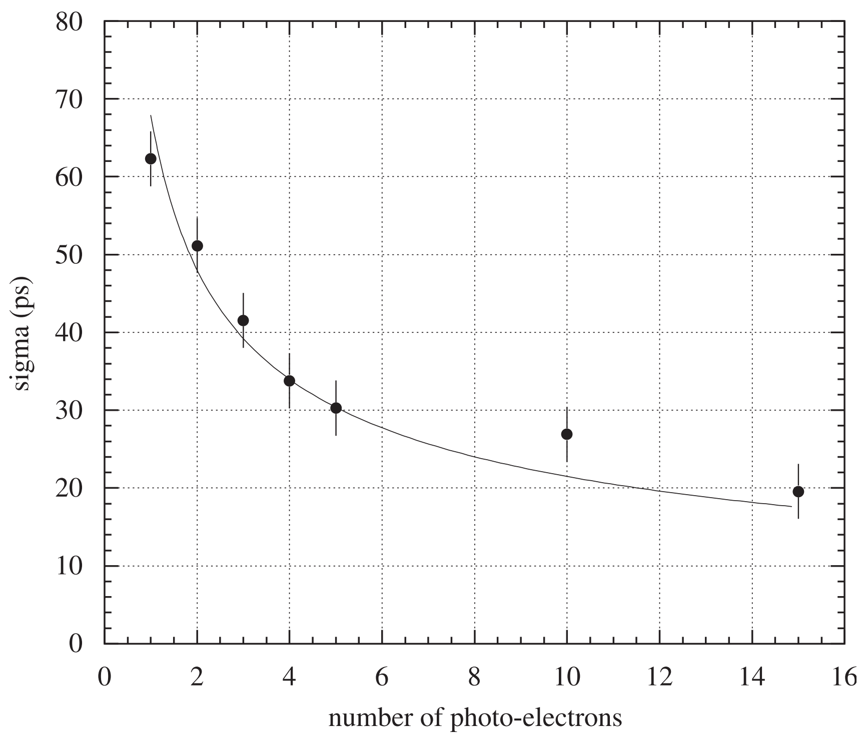
G. Collazuol et al., NIMA 581(2007)461



V. Puill et al., NIMA 695(2012)354

Timing Resolution

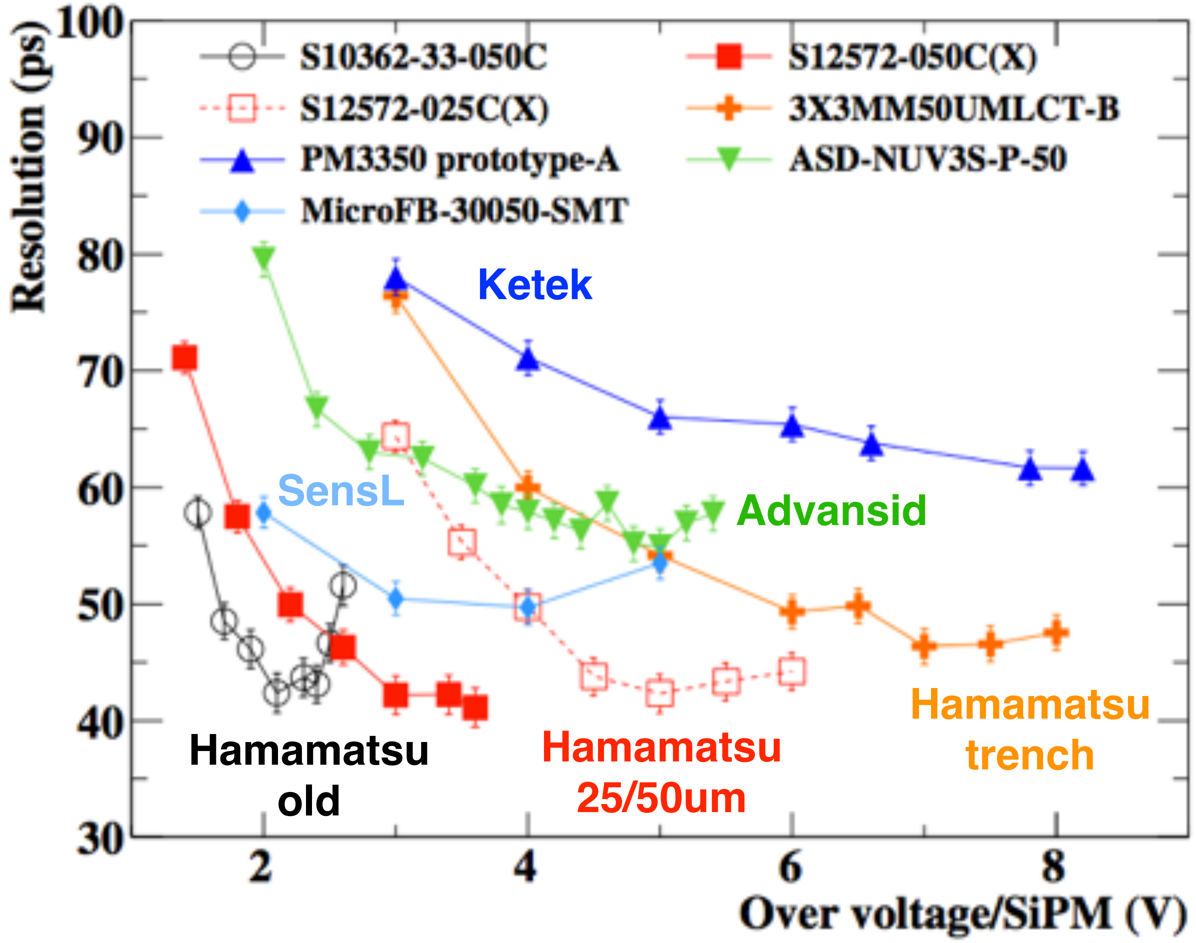
- Timing resolution for many photons



G. Collazuol et al., NIMA 581(2007)461

Fast plastic scintillator (BC422 60×30×5mm^3) readout by 6 SiPMs

P. W. Cataneo, WO, et al. IEEE-TNS 61(2014)2657

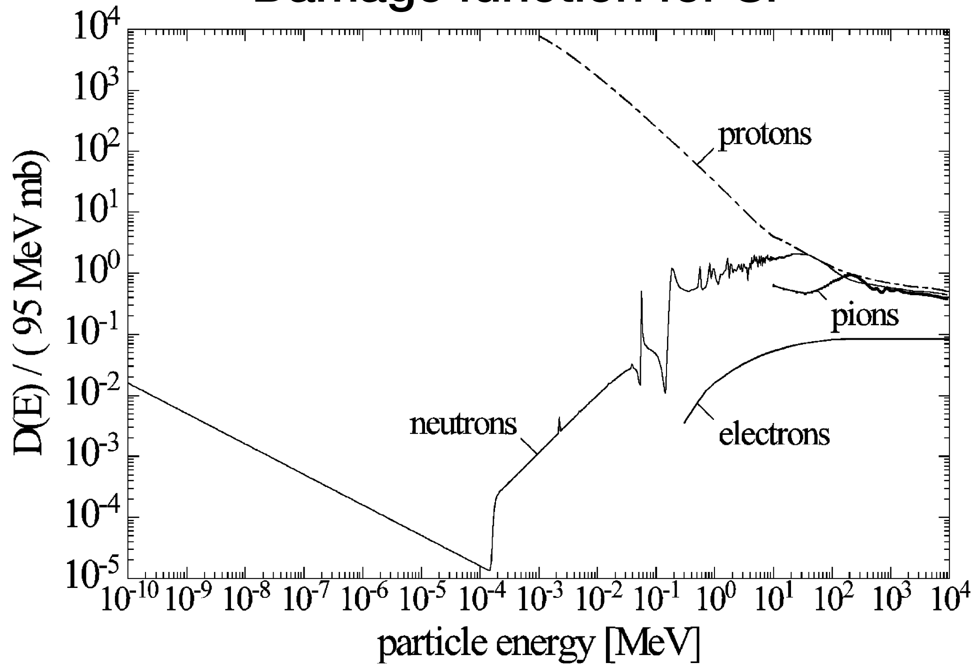


- Better resolution at higher ΔV (gain, PDE, SPTR)
- Saturated due to dark noise or after-pulsing

Radiation Hardness

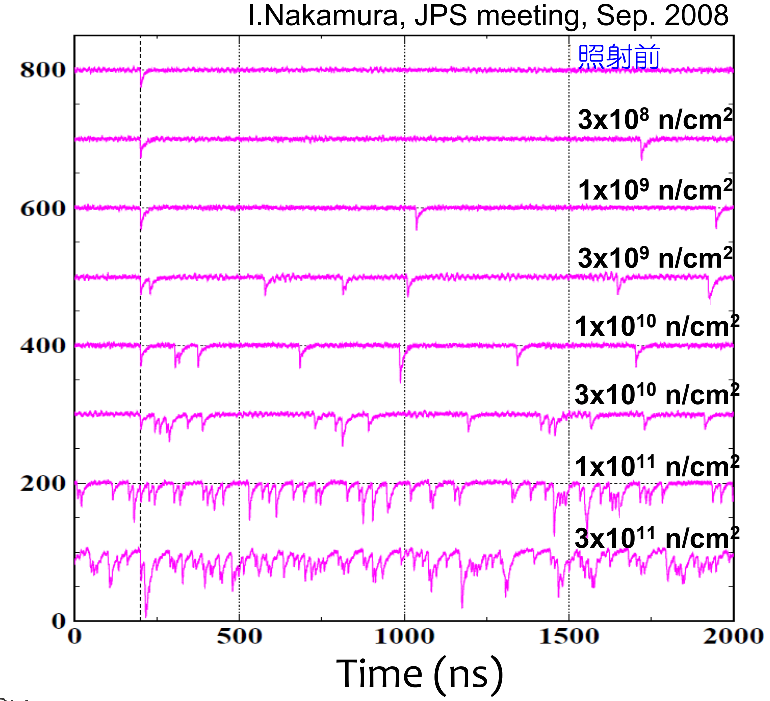
- Radiation damage of SiPM
  - Neutron, Proton → Bulk damage by Non-Ionizing Energy Loss (NIEL)
  - γ-ray, X-ray → Damage of Si-SiO_2 interface by inoizing energy loss → Charge trap at interface
- Effect of radiation damage
  - Increase of dark noise
  - Change in breakdown voltage, gain and PDE

Damage function for Si

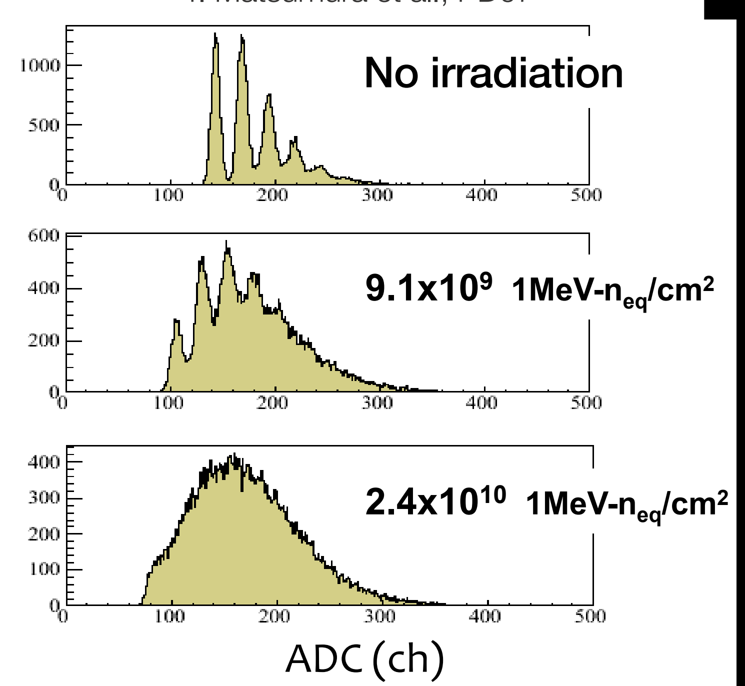


G. Lindstrom, et al., NIMA 426(1999)1

I.Nakamura, JPS meeting, Sep. 2008



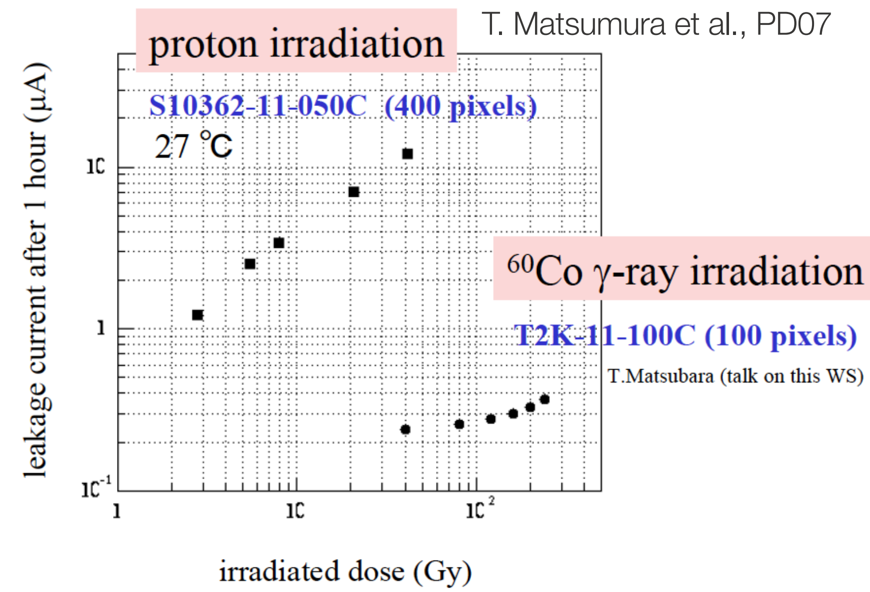
T. Matsumura et al., PD07



Radiation Hardness

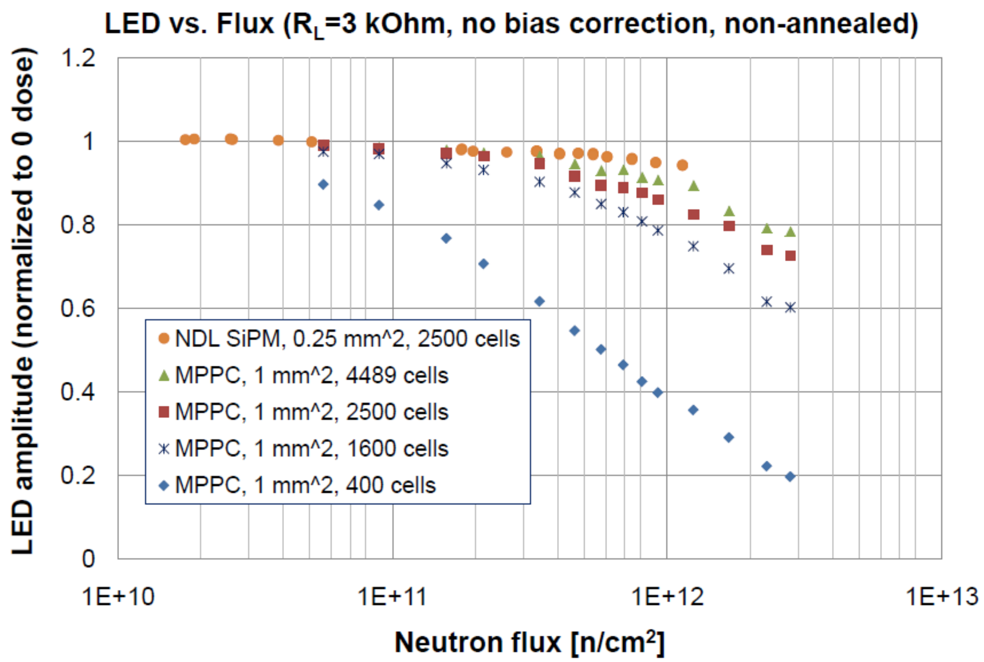
Effect of radiation damage

- Neutron/proton
  - $>10^{8}$ 1MeV-n_{eq}/cm^2: increase of dark noise
  - $>10^{10}$ 1MeV-n_{eq}/cm^2: loss of single photoelectron resolution
- γ-ray
  - ~200Gy: local breakdown
- Damage effect for proton: 1-2 orders larger than γ-ray



Possible solution for radiation hardness

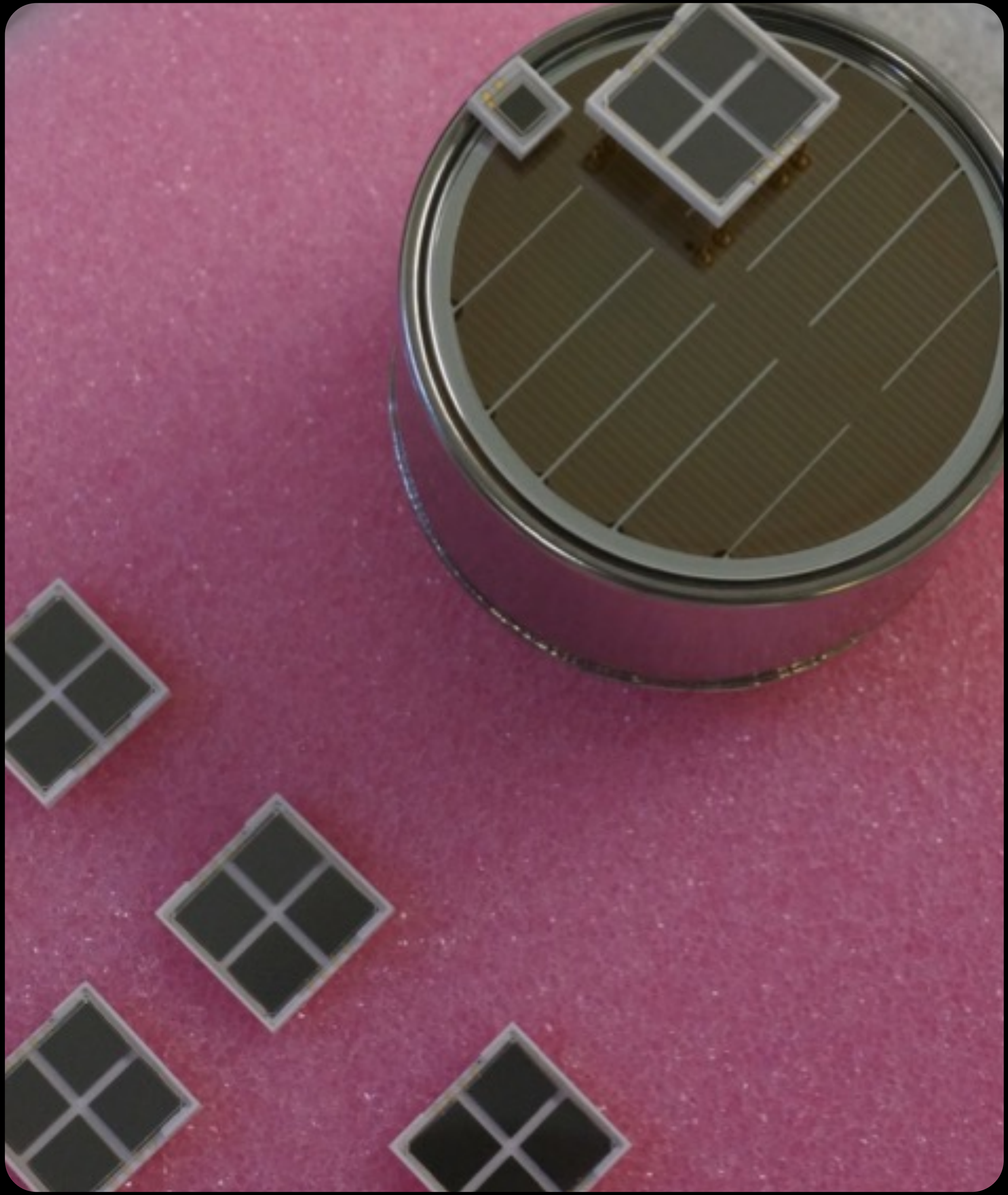
- Reduce volume to be damaged
  - Thinning down epitaxial layer ← smaller cell
  - Thinning down substrate
- Better insulator material for surface damage?
- Other material? Not "Si"PM any more…



Y. Musienko, CERN SiPM workshop 2011

Contents

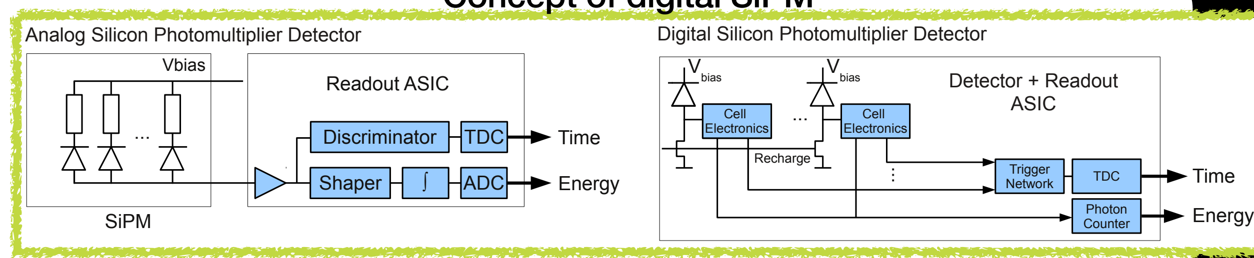
- Introduction
- Properties and Performance
- **New Developments**
- Application Examples
- Summary

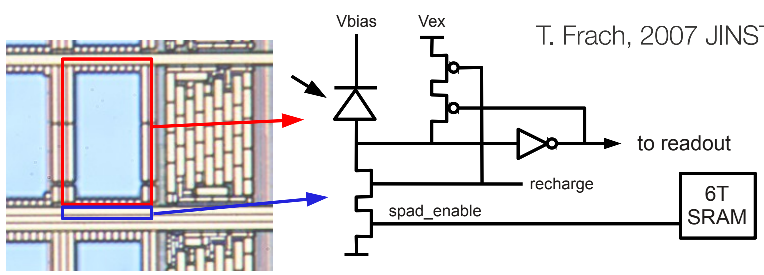


Digital SiPM

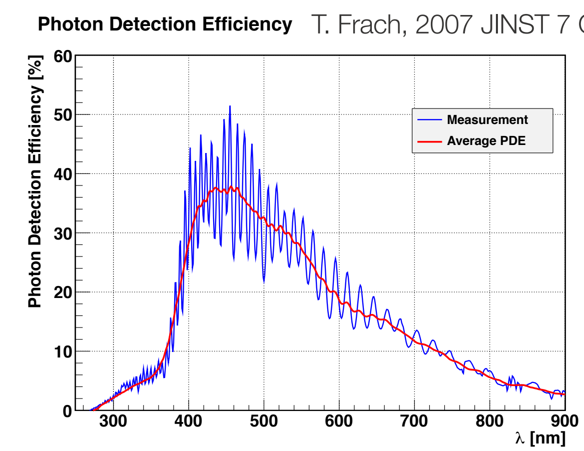
- Digital SiPM (dSiPM) from Philips
  - G-APD arrays with integrated electronics
  - Features
    - Counting # of fired cells
    - Time stamp of first fired cell (per die)
    - Cell-by-cell active control ➔ disable hot cell
    - Active quenching

Concept of digital SiPM

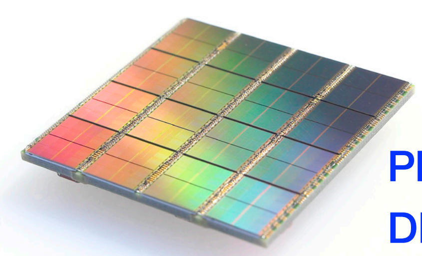




T. Frach, 2007 JINST 7 C01112

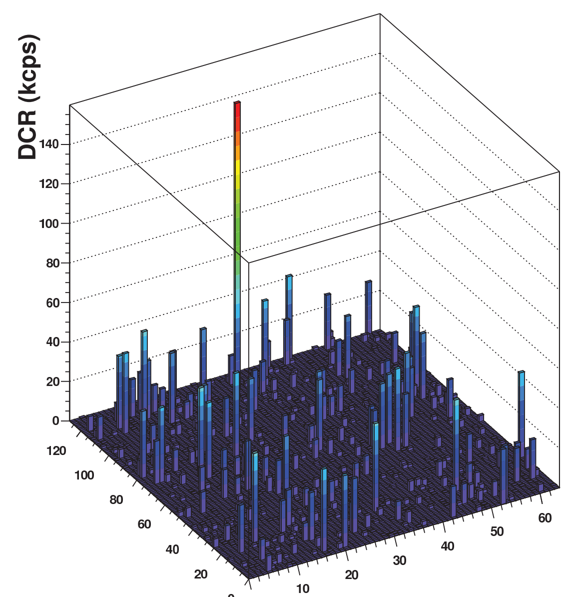


T. Frach, 2007 JINST 7 C01112

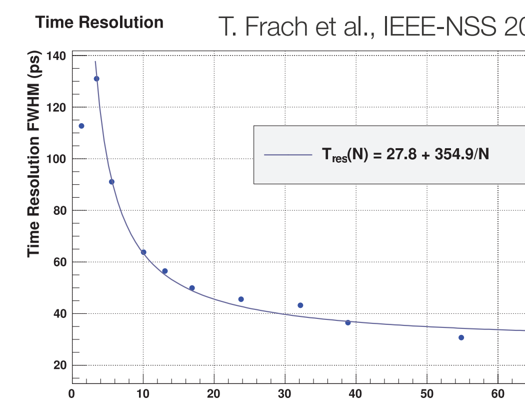


Philips digital SiPM
DPC6400-22-44 (DPC3200-22-44)

Dark noise rate distribution



T. Frach et al., IEEE-NSS 2009

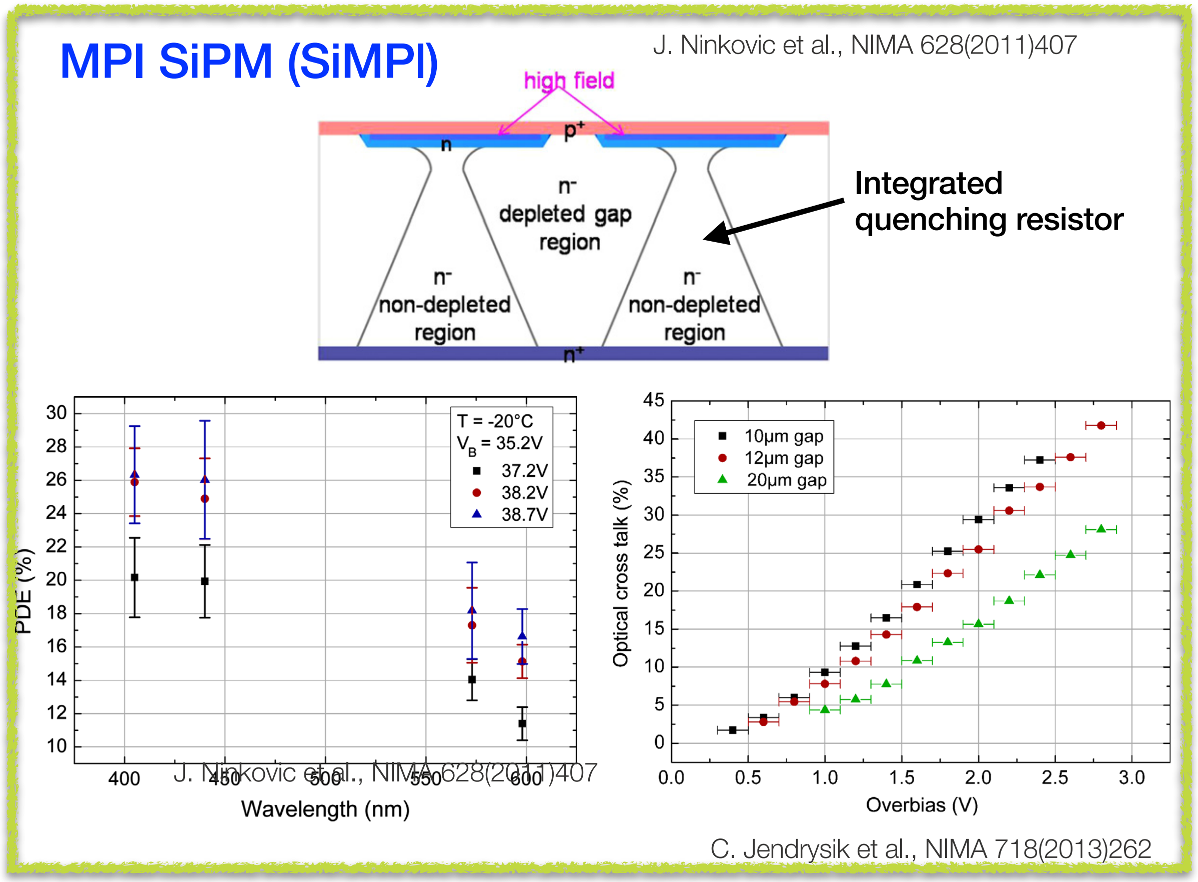


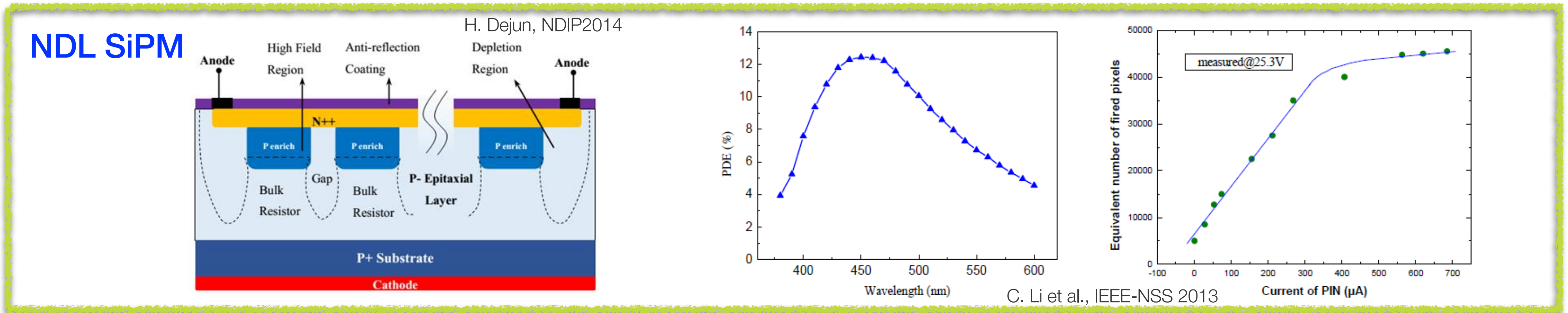
T. Frach et al., IEEE-NSS 2009

Outer dimensions	32.6×32.6 mm²
Pixel pitch	4×4 mm²
Pixel active area	3.9×3.2 mm²
# of cells	6936(3200)
Cell size	59.4×32(64) mm²
Pixel fill factor	54(74) %
Tile fill factor	75(55) %
Operational bias voltage	27±0.5 V

SiPMs with Bulk Integrated Resistor

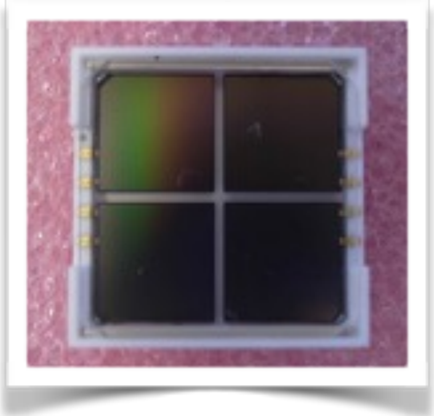
- Quenching resistor is integrated in Si bulk.
  - Advantages
    - High fill factor
    - Simpler processing
    - Flat surface ➔Easier implementation of anti-reflecting coating)
    - Higher cell density (smaller cell)
    - Less optical cross-talk
  - Issues
    - Need thicker wafer for vertical R length
    - Long recovery time
    - Worse radiation hardness?

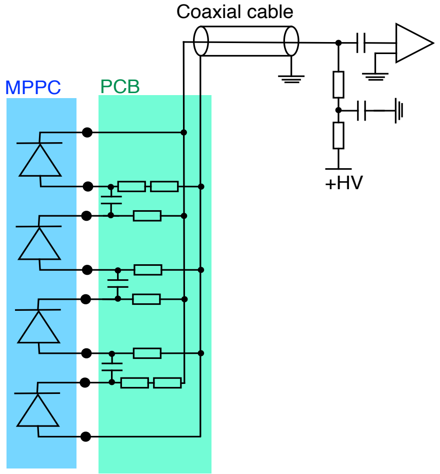




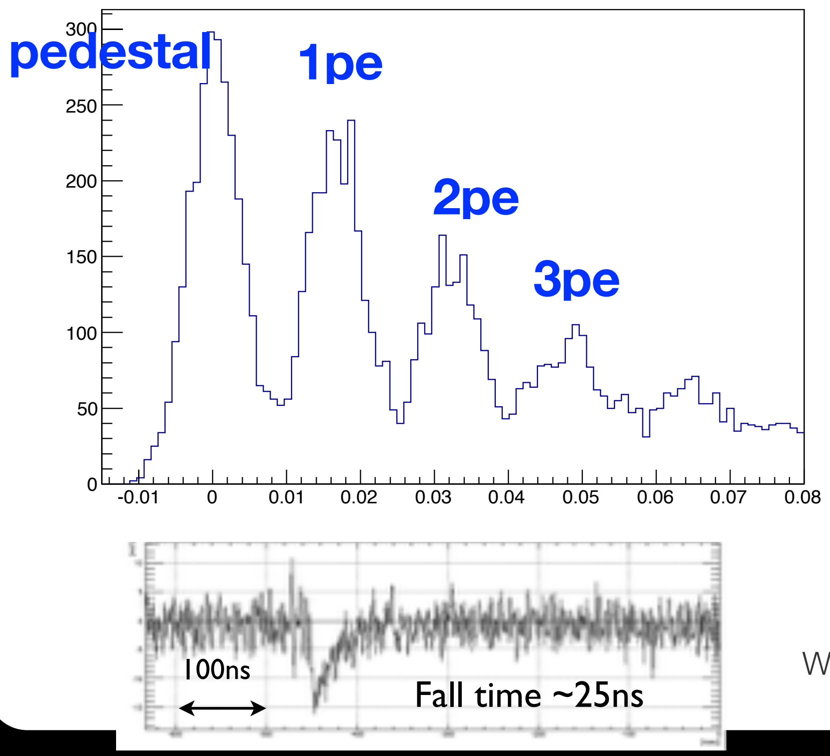
SiPM for Deep UV Light

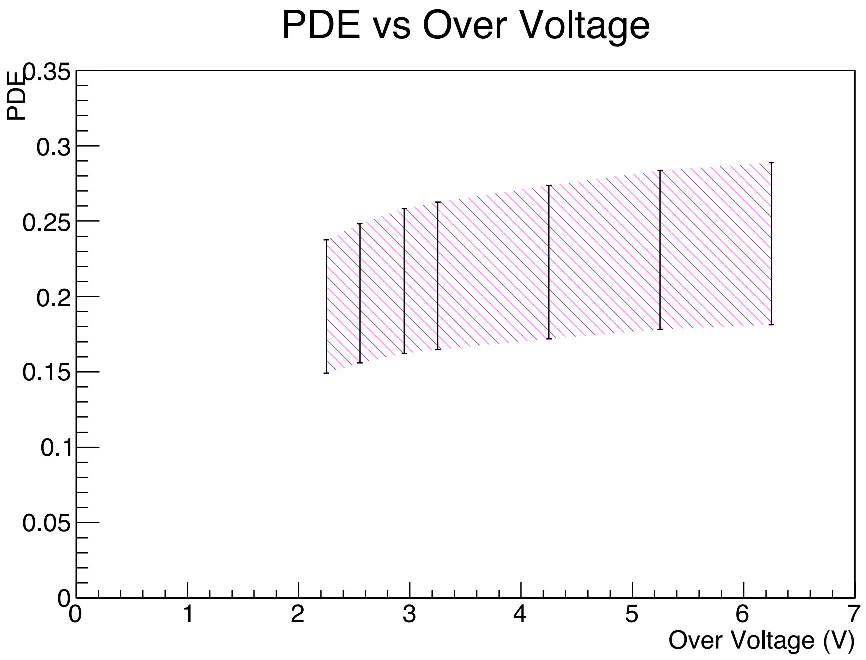
- DUV-sensitive MPPC developed for MEG II LXe detector
  - Hamamatsu MPPC S10943-4372
  - PDE≳20% at λ=175nm
  - 12×12mm^2 (discrete array of four 6×6mm^2 chip)
  - 50μm cell pitch
  - Metal quench resistor
  - Suppression of after-pulsing/cross-talk
  - Operational at LXe temp. (165K)





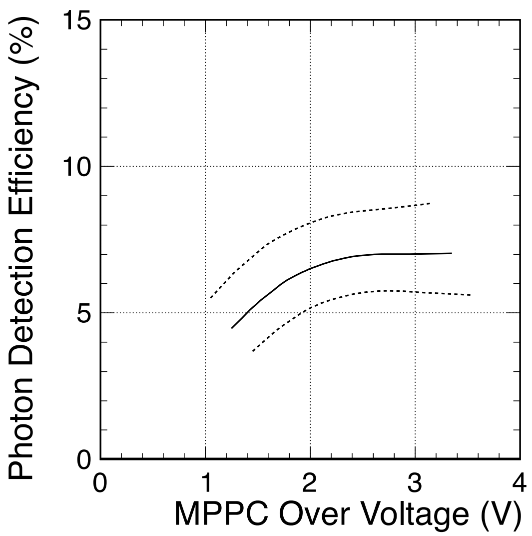
Four segment chips connected in series on readout PCB





WO et al., NIMA 787(2015)220

Same technology applied for LAr (λ=128nm, T=87K)



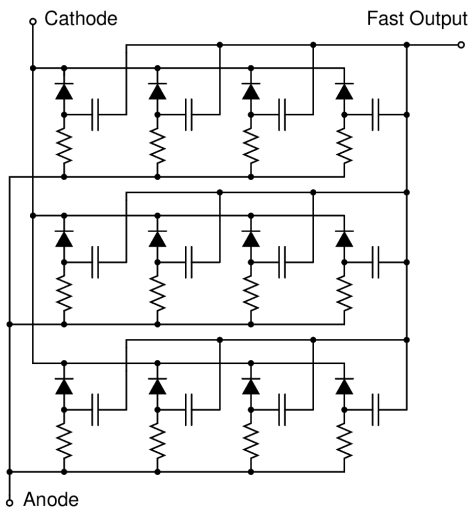
T. Igarashi et al., arXiv:1505.00091

W.Ootani,"*SiPM, Status and Perspectives*", *Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN*

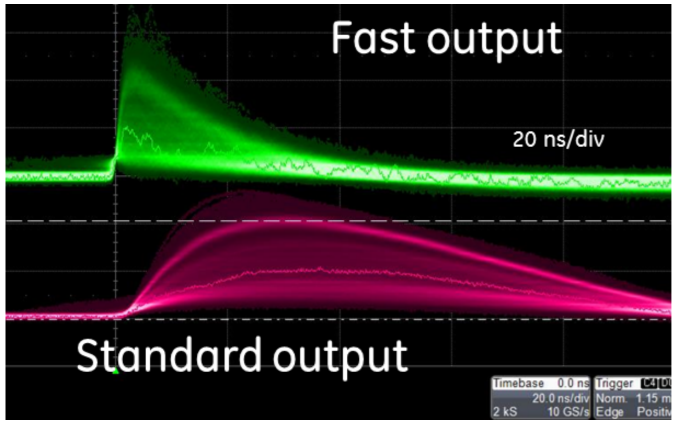
Other New Developments

- New implementation in SensL SiPM for fast timing
- Separate fast output in addition to standard output

"Fast output" scheme in SensL SiPM



Pulse shape for SensL SiPM with fast output coupled to LYSO



S. Dolinsky et al., IEEE-NSS 2013

A proposal for new SiPM structure

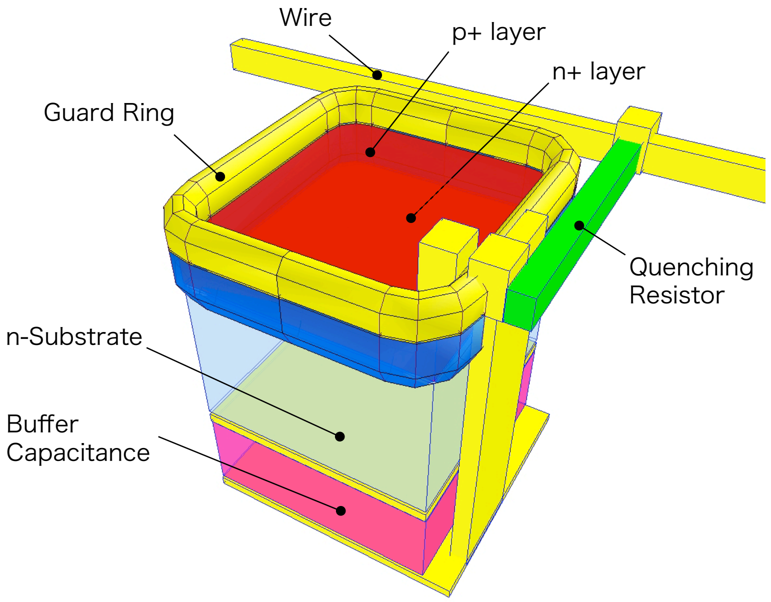
H. Oide et al., TIPP09

- Thinning depletion layer
- Additional buffer capacitance parallel to p-n junction

➔

- Reduced dark noise and afterpulse
- Better radiation hardness
- Higher gain

$$G = (C_{\mathrm{diode}} + C_{\mathrm{buffer}})\Delta V / e$$



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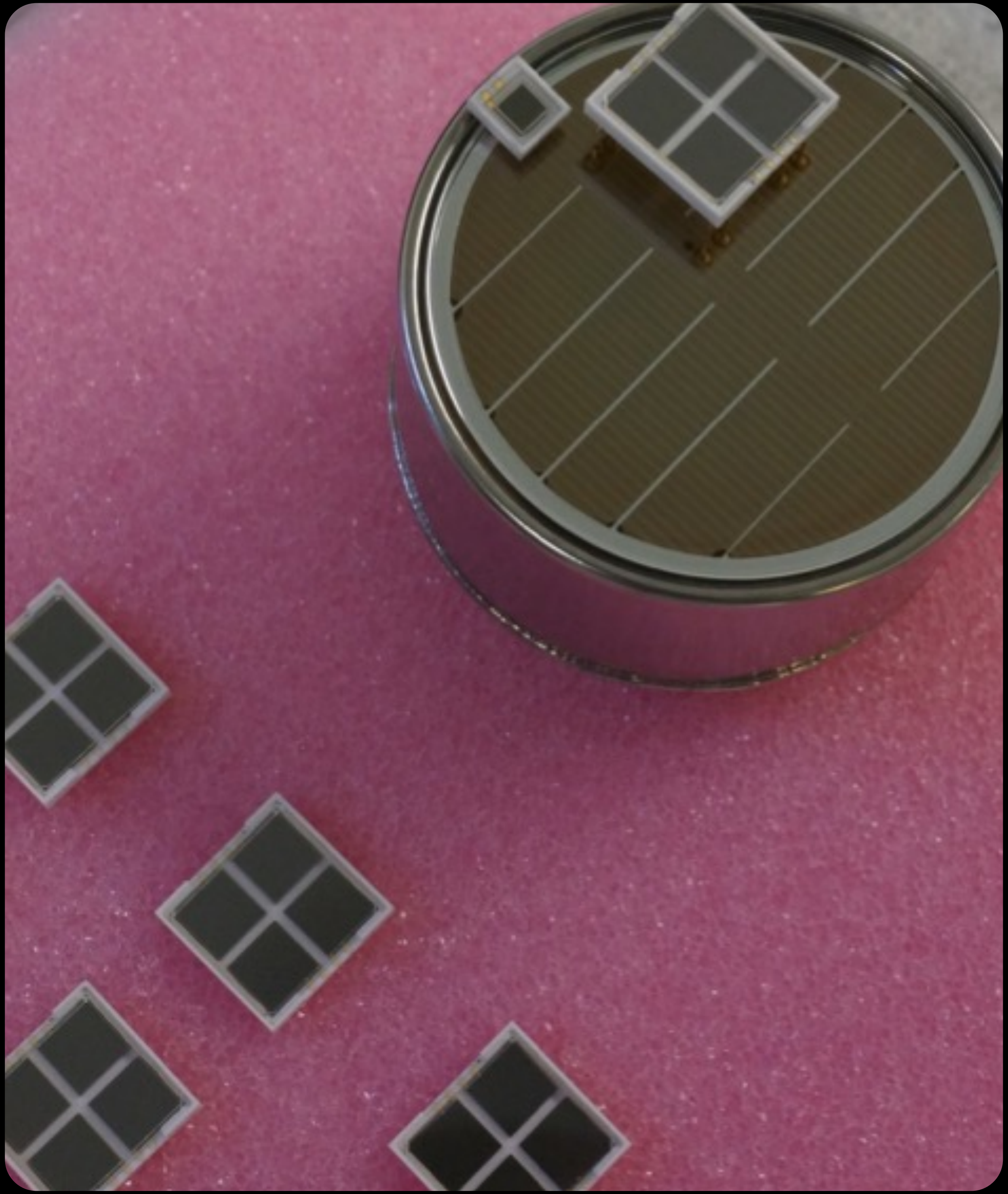
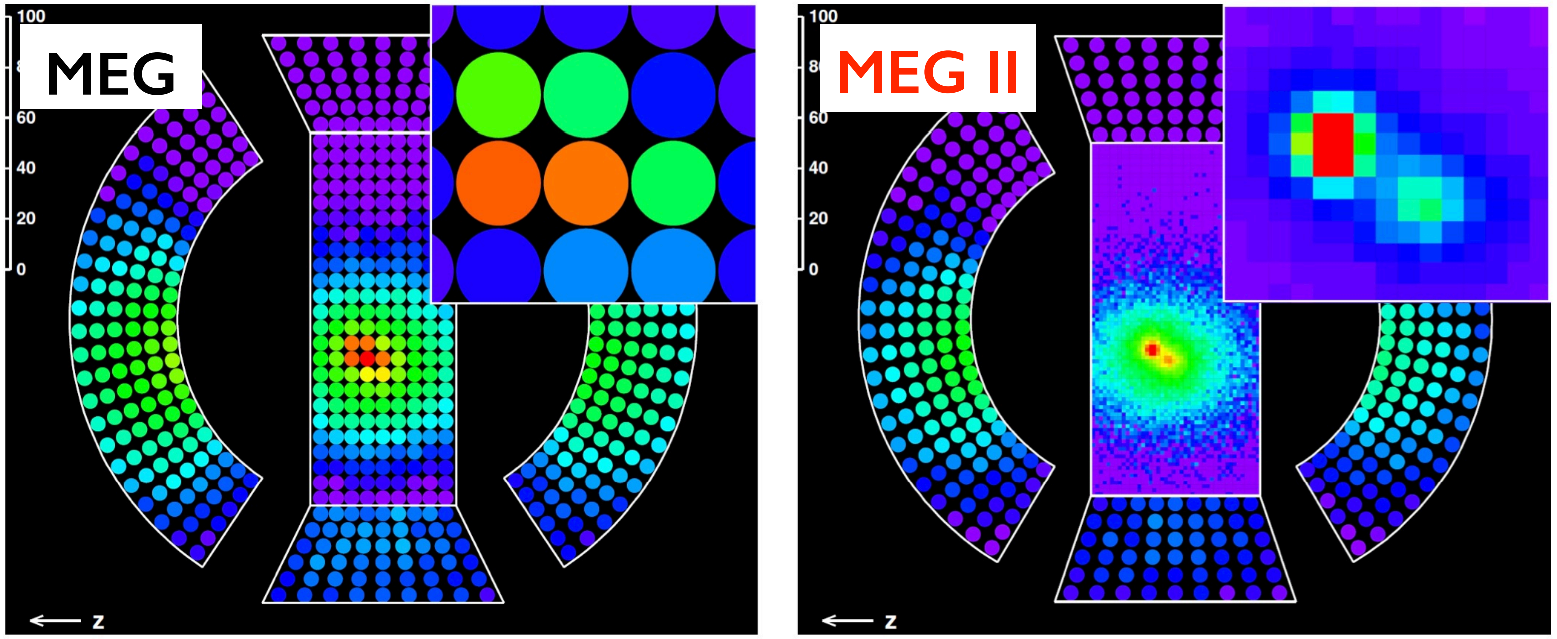
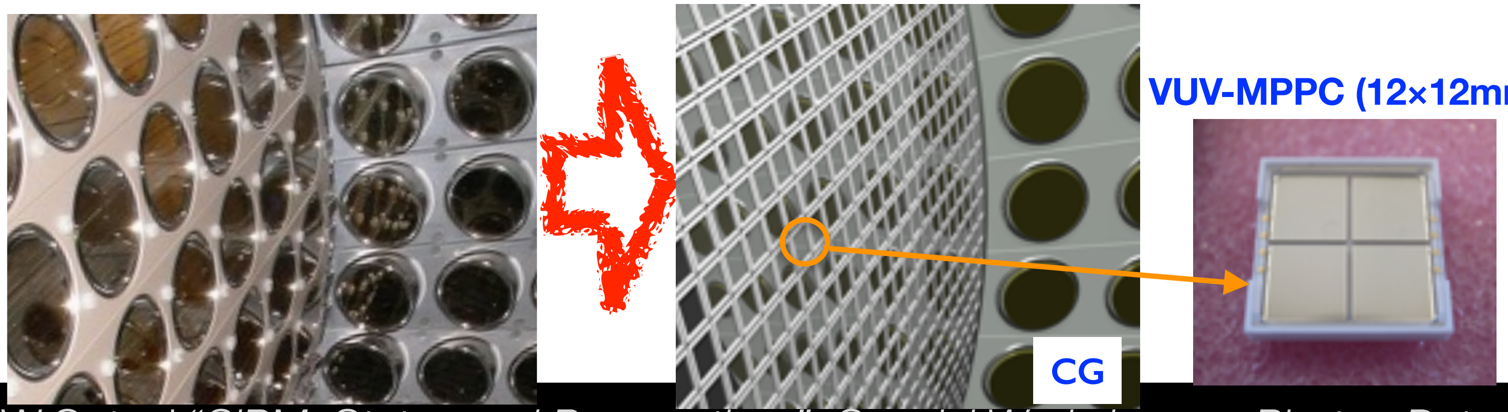


MEG II LXe Detector

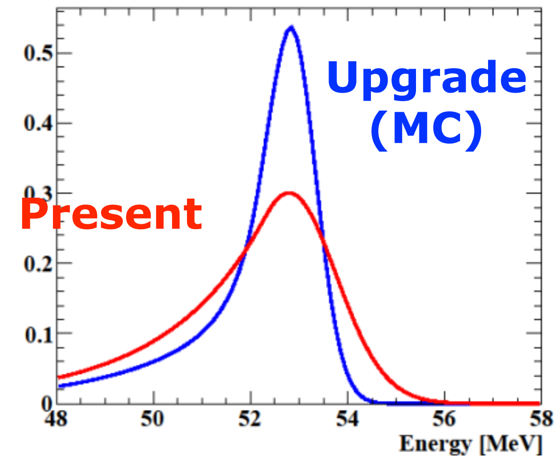
- Upgrade for LXe Detector in MEG experiment to measure 52.8MeV γ-ray from μ→eγ decay
- Highly granular scintillation readout with VUV-MPPC
  - 256 PMTs (2 inch) replaced with 4092 VUV-MPPCs (12×12mm²)
- Construction to be finished within 2015

MEG II Proposal: arXiv:1301.7225
WO et al., NIMA 787(2015)220

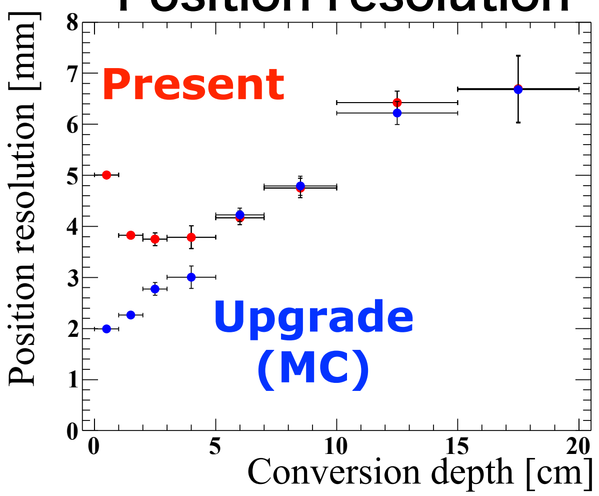




Energy resolution



Position resolution



W.Ootani,"*SiPM, Status and Perspectives*", *Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN*

T2K: Neutrino Oscillation Experiment

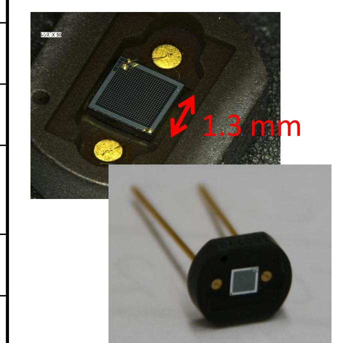
- A large number of MPPCs totalling ~56,000 used in several detectors in T2K.
- Working fine for several years
- # of bad channel < 0.28% incl. problem of readout electronics

A. Minamino, Next generation photosensor worksop 2010

Item	Spec
Active area	1.3 x 1.3 mm^2
Pixel size	50 x 50 μm^2
Num. of pixels	667
Operation voltage	70 V (typical)
PDE @ 550nm	~ 25 %
Dark count (Gain = 7.5 x 10^5)	< 1.35 Mcps @ 25 deg. (Thre. = 0.5 p.e.)
Num. of device	56,000

S10362-13-050C

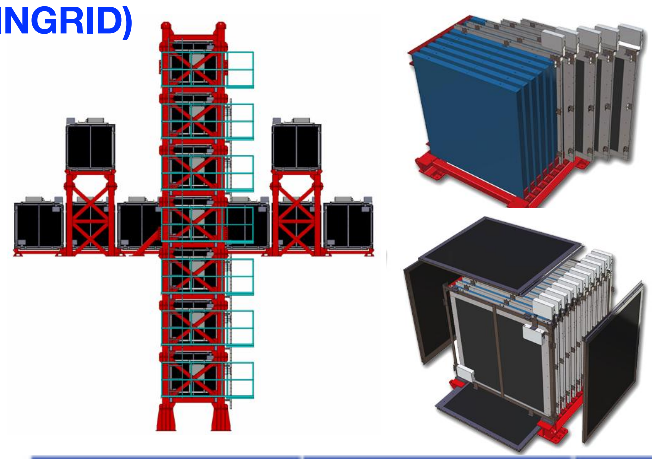
Developed for T2K



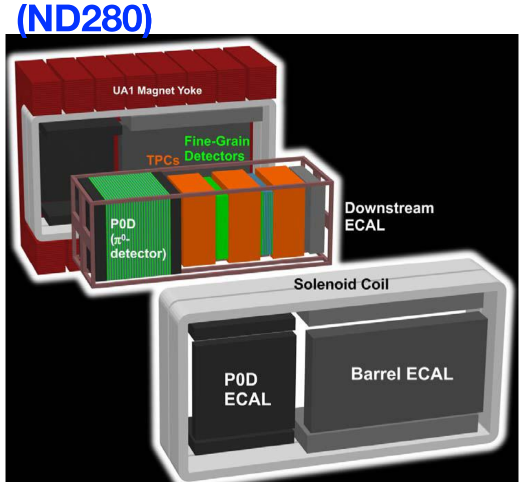
Produced by Hamamatsu Photonics

17

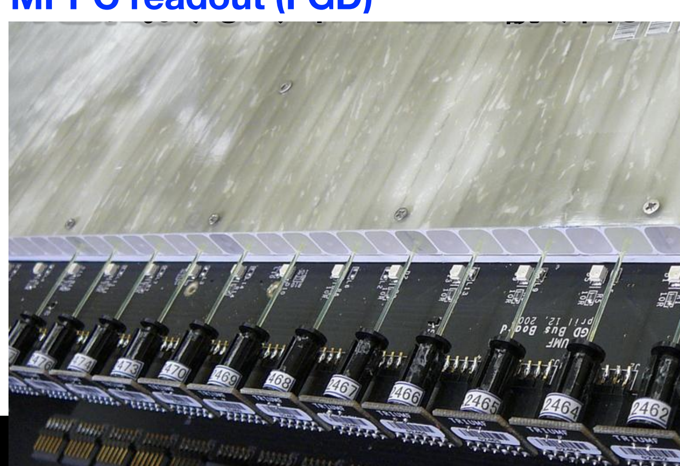
T2K on-axis near detectors (INGRID)



T2K off-axis near detectors (ND280)



MPPC readout (FGD)

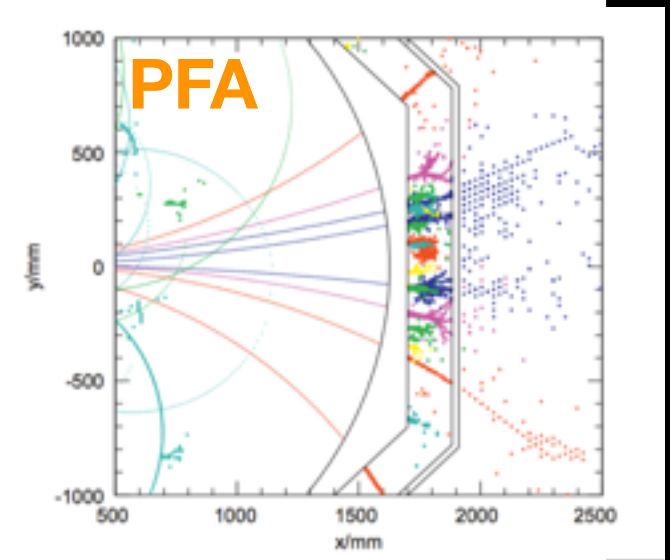


T. Kikawa, Next generation photosensor worksop 2012

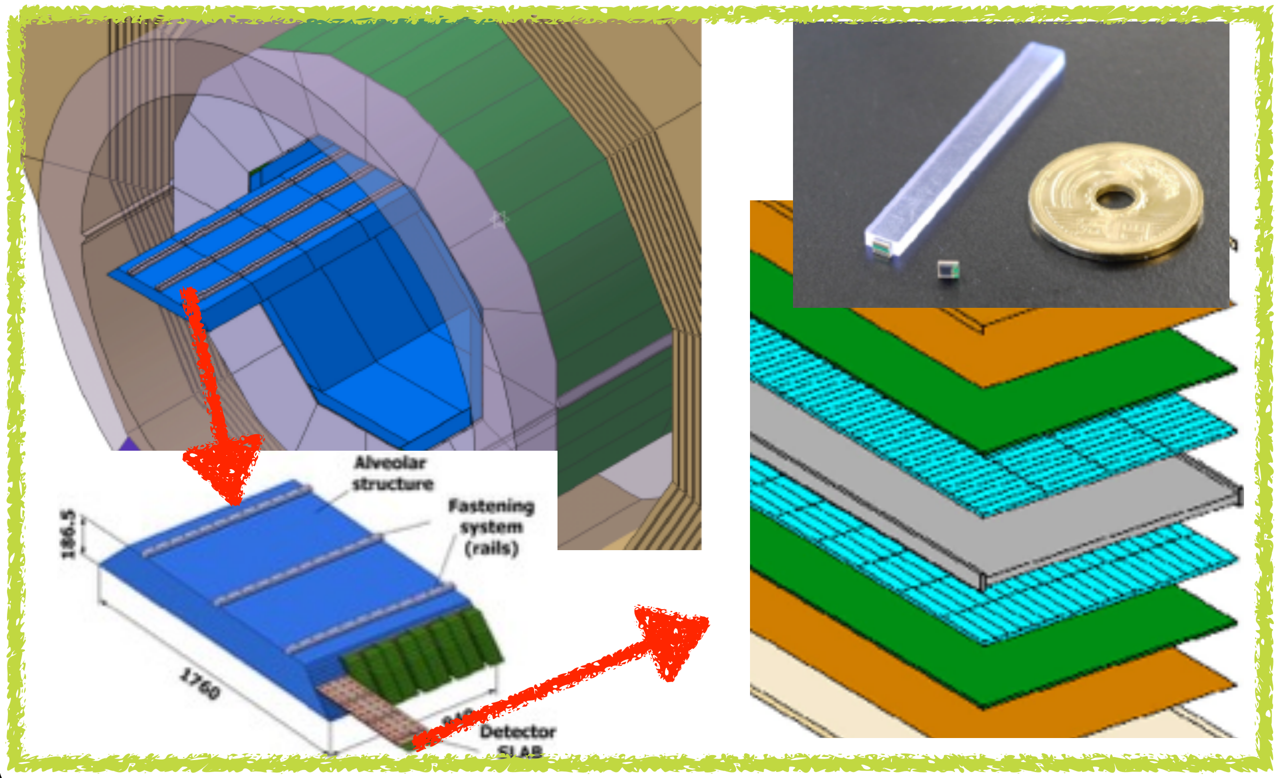
Detector	# of ch	# of bad ch		Fraction of bad ch	
		2010	2012	2010	2012
INGRID	10796	18	37	0.17%	0.34%
FGD	8448	20	20	0.24%	0.24%
ECAL	22336	35	58	0.16%	0.26%
P0D	10400	7	28	0.07%	0.27%
SMRD	4016	7	15	0.17%	0.37%
計	55996	87	158	0.16%	0.28%

ILD Scintillator Calorimeters

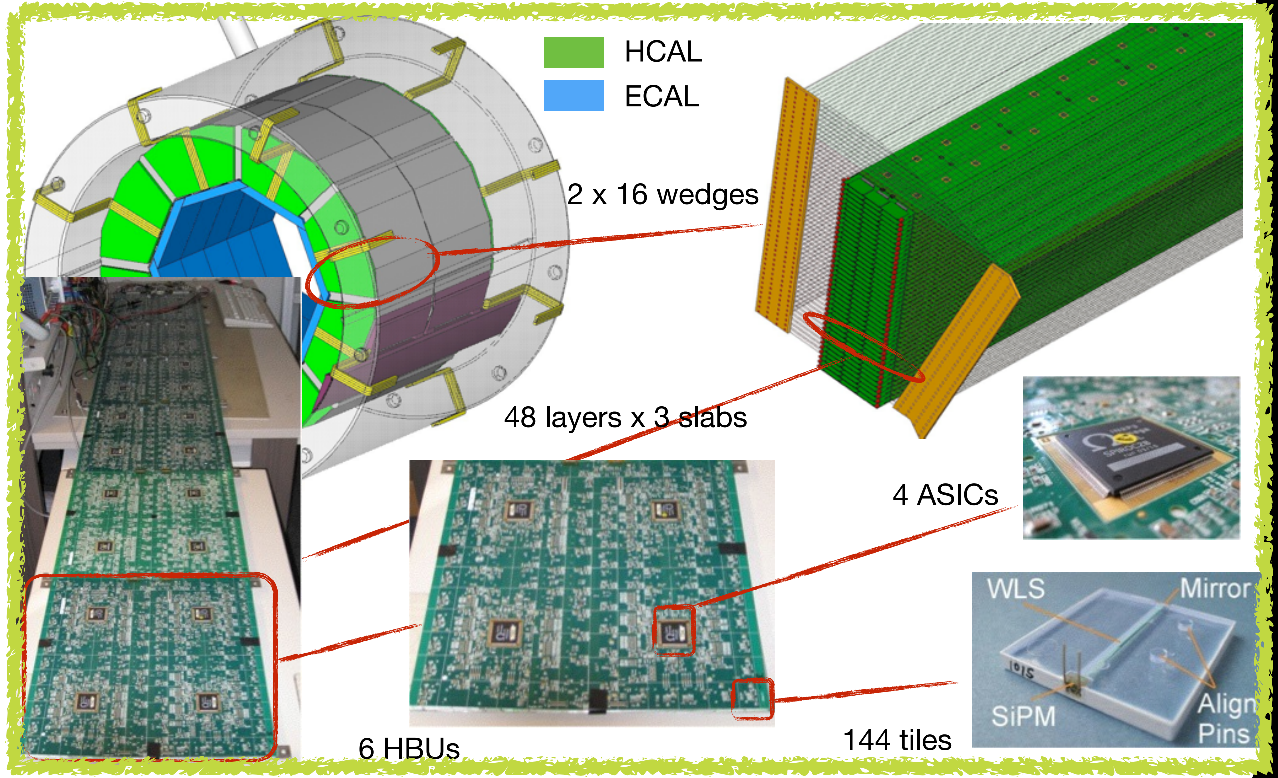
- Highly granular calorimeter for ILC detector based on Particle Flow Algorithm (PFA).
  - AHCAL: ~10^7 × ($30×30×3mm^2$ scinti. cell + SiPM)
  - ScECAL: ~10^7 × ($5×45×2mm^2$ scinti. strip + SiPM)
- SiPM technology allows
  - SiPM and readout electronics are integrated in active volume
  - Calorimeters in solenoid field of 4T



ScECAL



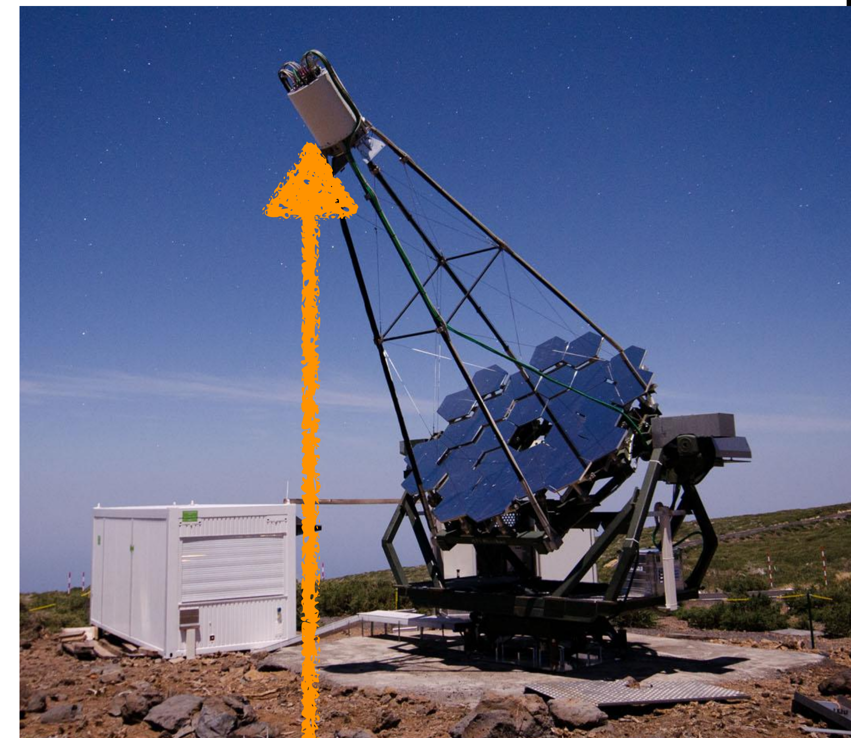
AHCAL



W.Ootani,"*SiPM, Status and Perspectives*", *Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN*

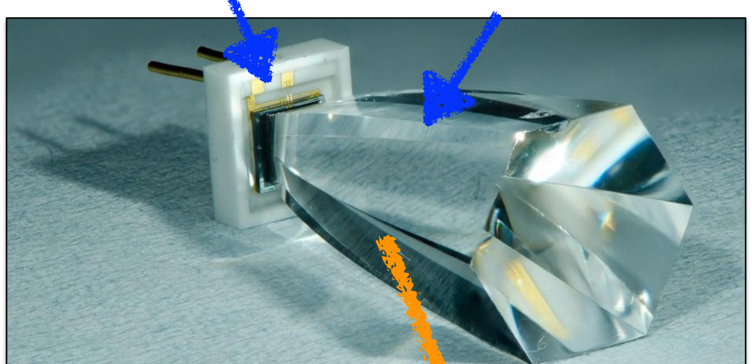
FACT: First G-APD Cherenkov Telescope

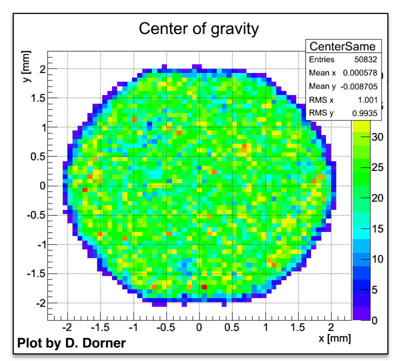
- SiPM-based camera for Imaging Atmospheric Cherenkov Telescopes (IACTs)
- 1440 pixel modules based on MPPC with light collecting cone.
- Integrated electronics: trigger and digitisation (DRS4 chip)
- First operation on Oct. 11, 2011 (full moon)

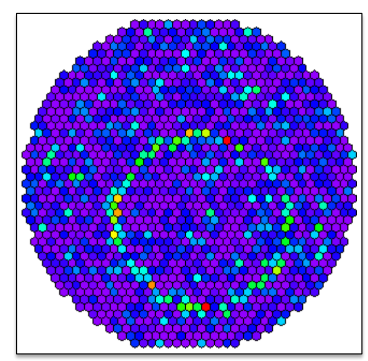


MPPC S10362-33-050C

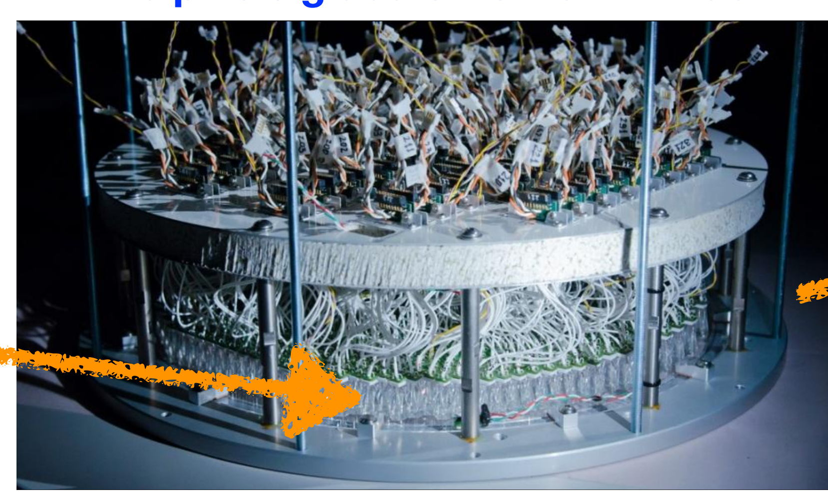
Ligt collecting cone (injection moulded PMMA)

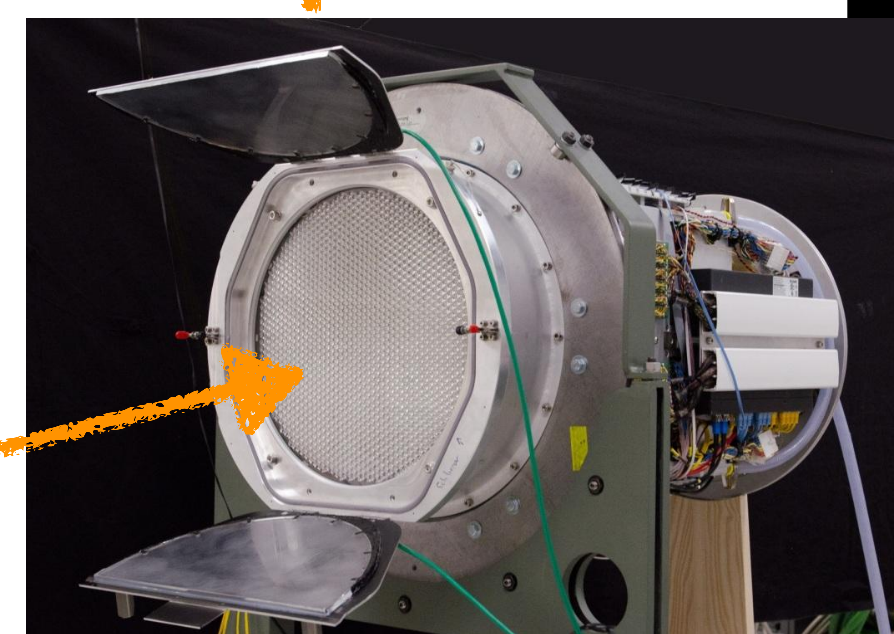






1440 pixels glued onto front window





Th. Krähenbühl, Photodet2012

Summary

- Vast progress in development of SiPM technology since last two decades.
- SiPM technology is mature enough in terms of both performance and cost to be employed in many projects.
- Many advantages, while some weak points to be overcome.
  - Dark noise
  - Correlated noise
  - Saturation
  - Radiation hardness
  - Temperature dependence
  - Limited sensor area
- Many new developments and new applications are on-going.

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  - Correlated noise 😊
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  - Radiation hardness 😥
  - Temperature dependence 😥
  - Limited sensor area 😐
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  - Saturation 😐
  - Radiation hardness 😥
  - Temperature dependence 😥
  - Limited sensor area 😐
- Many new developments and new applications are on-going. 😊

Thank you for your attention!

Questions?

More complete reviews

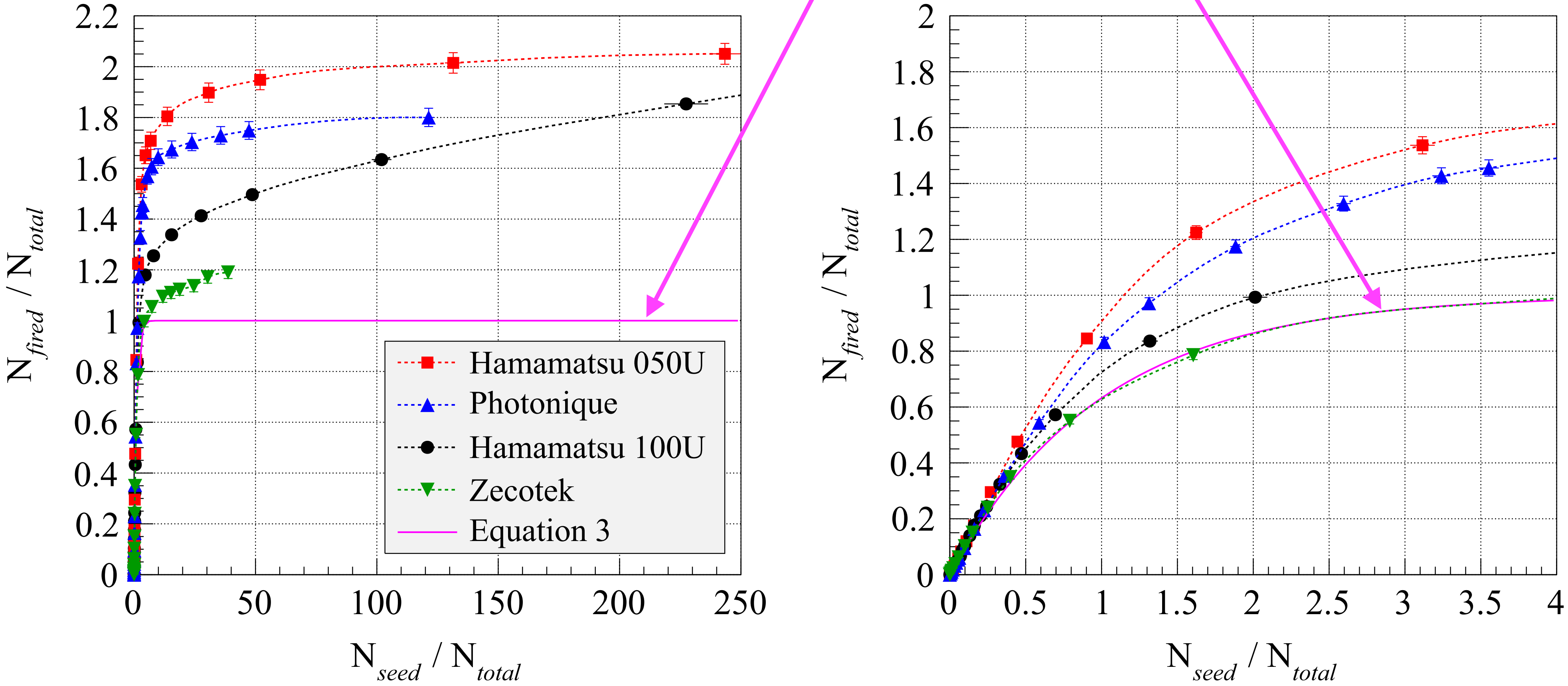
- V. Puill, *“Tutorial SiPM”, NDIP2014*
- G. Collazuol, *“Status and Perspectives of Solid State Photo-detector”, RICH2013*

Backup

Over-Saturation?

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

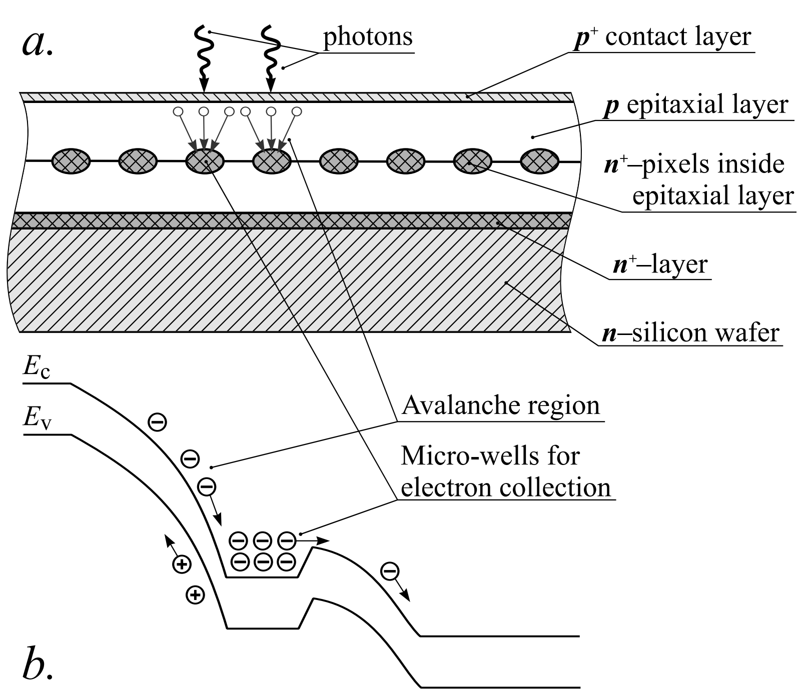
$$N_{\text{fired}} = N_{\text{cell}}\left(1 - e^{\frac{-N_{\text{photon}}PDE}{N_{\text{cell}}}}\right)$$



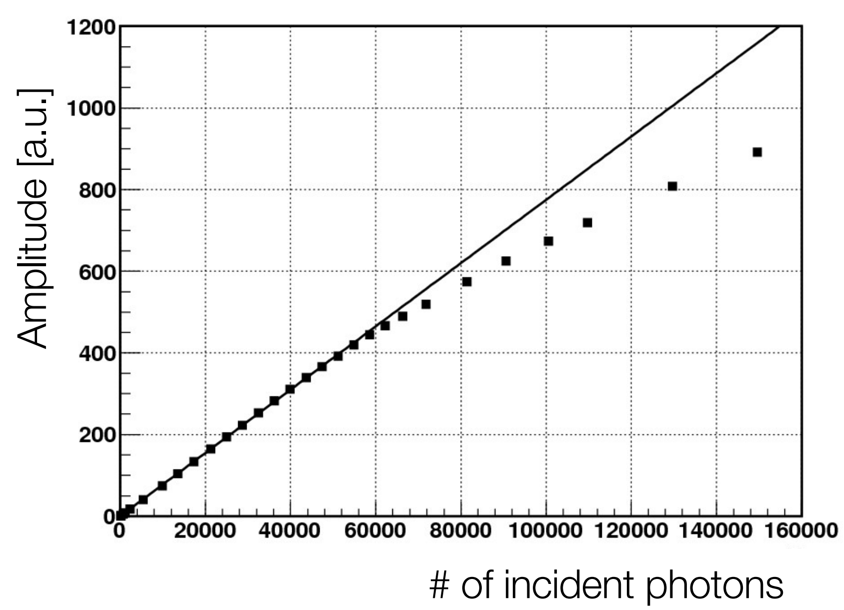
L. Gruber et al. NIMA737 (2014) 11

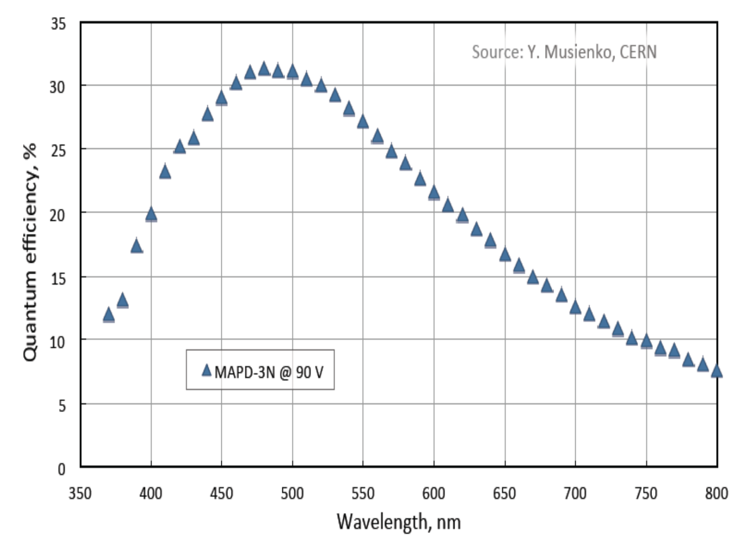
Even Smaller… Micro Cell SiPM

- Micro-pixel APD (MAPD) from Zecotek
  - Cells inside epitaxial layer
  - No quenching resistor. Directly biased p-n junction under each cell is used to quench avalanche instead.
  - up to 40,000 cells/mm^2



135000 cells (3×3mm^2) = 15000 cells/mm^2





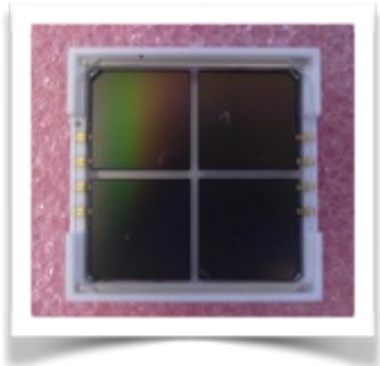
Measured by Y. Musienko (CERN)

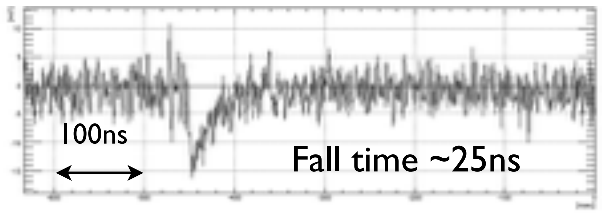
Z.Sadygov, et al., Tech. Phys. Lett. 36(2010)528

Large Area Sensor

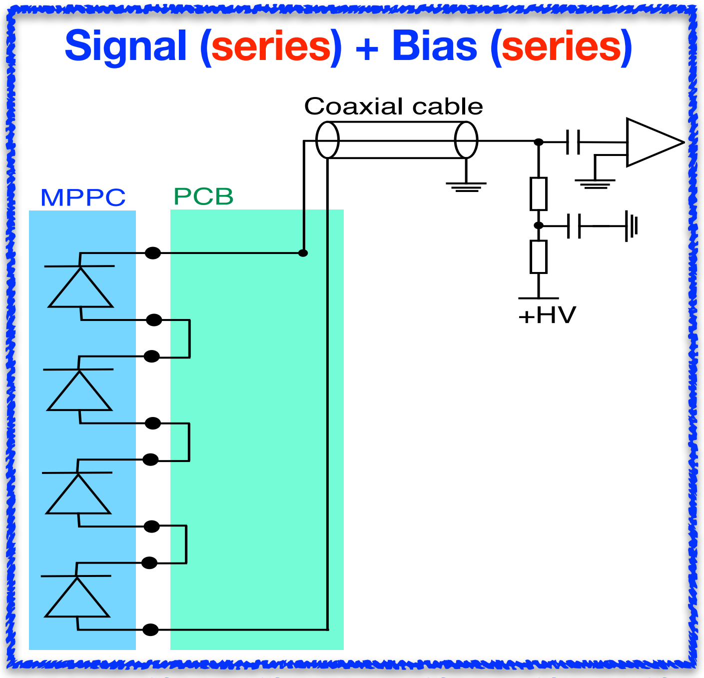
- SiPM sensor area is limited by dark noise and sensor capacitance.
- Cost per unit area is already comparable to PMT!
- Solutions for large area sensor
  - Array
    - Discrete or monolithic
    - Need individual channel readout
  - Series connection of multiple sensors
    - Working as a single sensor ➔ Reduction of # of readout channel
    - Reduced sensor capacitance
    - Need operation at low temp to reduce dark noise

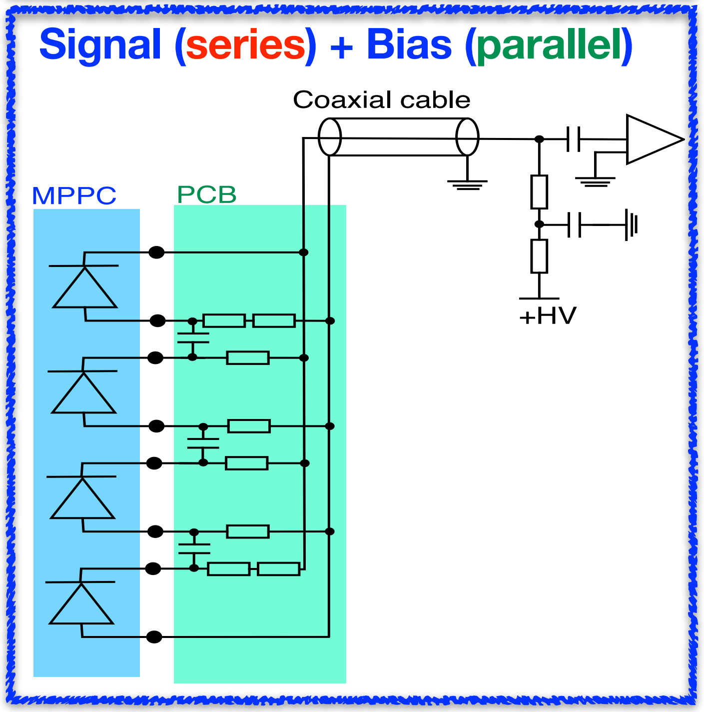
Hamamatsu VUV-MPPC (total area 12×12mm², four segments)





Series connection of SiPM segments





WO et al., NDIP2014

MEG II Pixelated Scintillator Detector

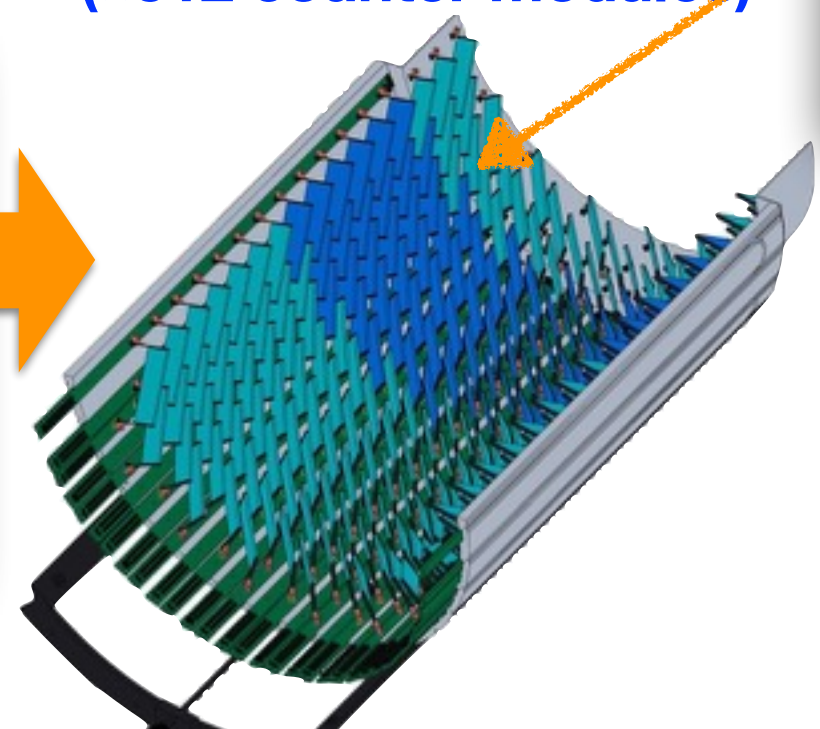
- Timing counter for 52.8MeV positron from μ→eγ decay in MEG II
- ×512 fast scintillator plates, each of which is readout by multiple SiPMs connected in series
- Excellent timing resolution of 30-40ps demonstrated with prototype
- To be constructed in 2015

MEG II Proposal: arXiv:1301.7225
WO, NIMA 732(2013)146
M. De Gerone, WO et al. JINST9(2014)C02035
P. W. Cattaneo, WO et al., IEEE-TNS 61(2014)2657

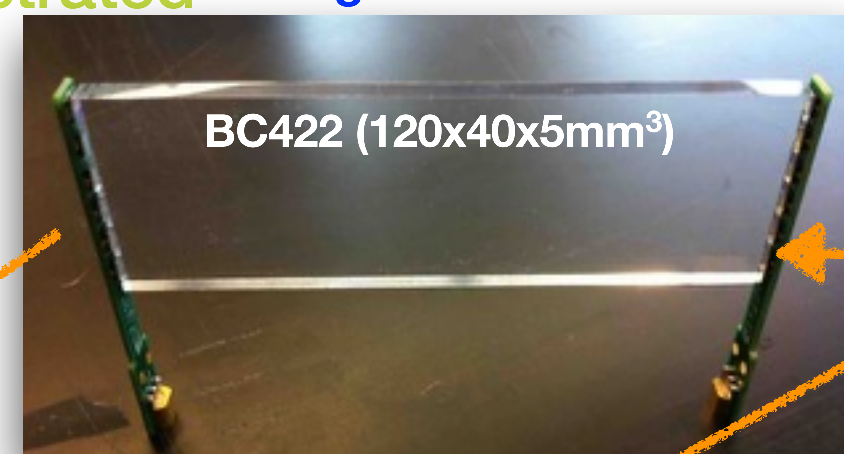
MEG timing counter

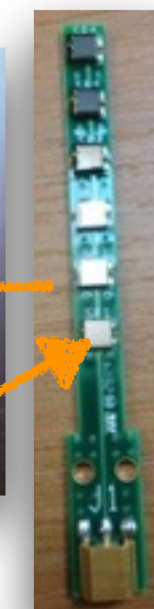
Plastic scintillator bar ($40x40x900mm^3$) + PMT

MEG II timing counter (×512 counter modules)



Single counter





6 SiPMs connected in series
(AdvanSiD AMSASD-NUV3S-P50, 3×3mm², 50μm)

V_{bd} distribution for ~4000 SiPMs