# New generation of Photo-Detectors

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Overview: trends and selected examples in

- Vacuum based Photo-Detectors
- Gaseous PD's
- Solid State PD's

... as large overview as possible w/ few details

# Photo-Detectors family tree

## Gas
External photoemission

**gas photoionization**
(TMAE, TEA, ...)

and/or

**multiplication in gas**
by avalanche
(MWPC, GEM, ...)

## Vacuum devices
External photoemission

**secondary electron multiplication**

Dynodes:
- discrete (PMT)
- continuous dynode (channeltron, MCP)

Anode:
- multi-anode
- strip lines RF

**hybrid**
photocathode +

- multiplication by **ionization in Si** (HPD, HAPD, ...)

or

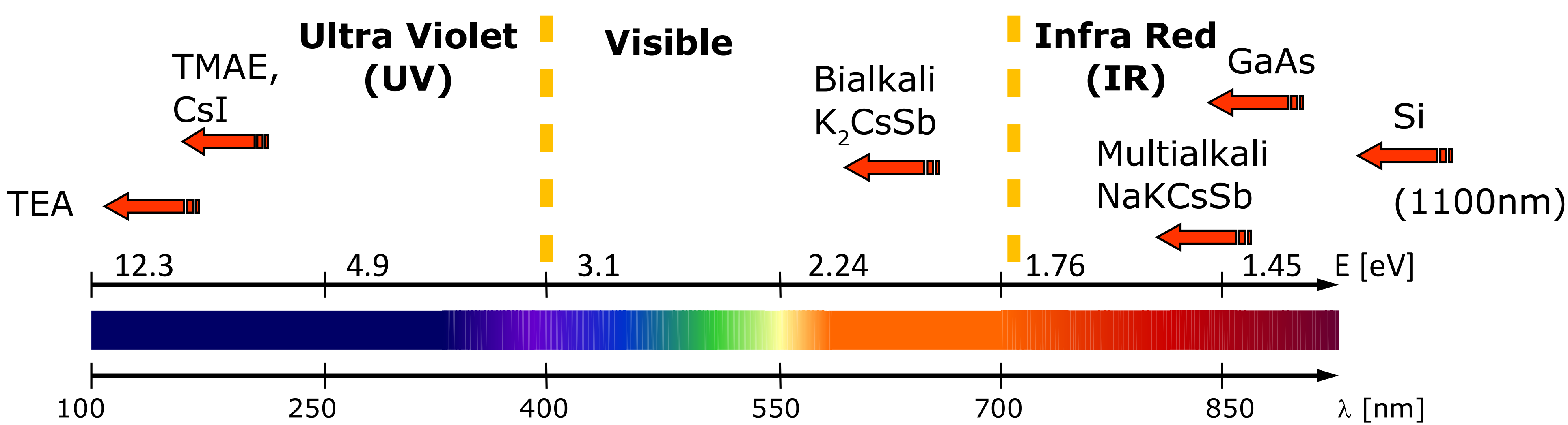
- multiplication by **luminescent anodes** (light amplifiers: SMART/Quasar, X-HPD, ...)

## Solid state
Internal photoemission

- PIN-Photo-diode
- APD, GM-APD (SiPM)
- Imaging CMOS, CCD

- Quantum well detectors
- Supercond. Tunnel Junc.

- Organic materials

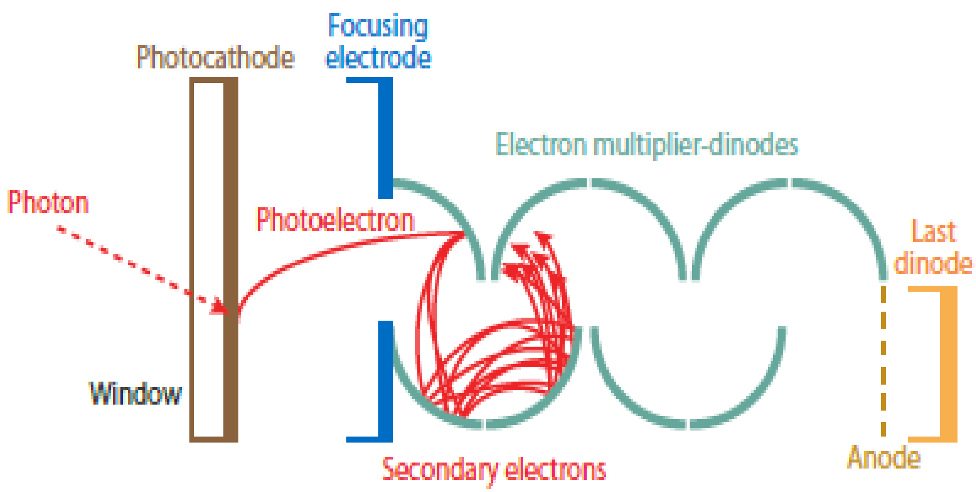


# New generation of Vacuum Photo-Detectors

# Vacuum Photo-detectors

Quite old device but still
many reasons for using it

- Large area
- High gain /Wide dynamic range
- Low noise
- Fast timing (MCP)
- Low price per unit area
- Weak T dependence




## Dissection

Most crucial element in any PMT type

1. Photo-cathode (PC)
   Efficiency, spectral response
2. Acceleration and Multiplication of photo-electron (Phe)
3. Signal pickup
   Multiplication elements / Anode

Alternative to dynodes
- Micro-channel plates
- Avalanche diode (HPD)
- SiPM (VSiPMT)
...

Fast Timing applications
- not covered (here)

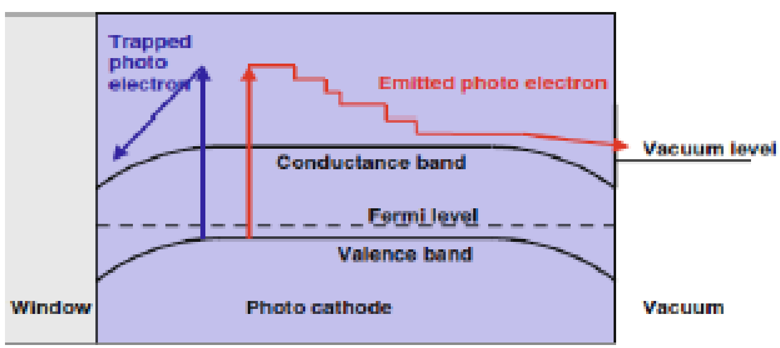
# Photo-cathodes

**1) Bi/Multi-alkali-antimonides**

→ K/Na + Sb in bulk + Cs/Rb at surface
→ poly-crystalline layers w/ high carrier lifetime
→ very good absorbers for photons 200-850nm
eg. $Na_3Sb$, $K_3Sb$ (Bialkali), $Na_2KSb$ (S20, S25)

Weak points:

- recombination centers in poly-crystalline struct.
- active layer directly deposited on window
  → electron sink due to outward band bending

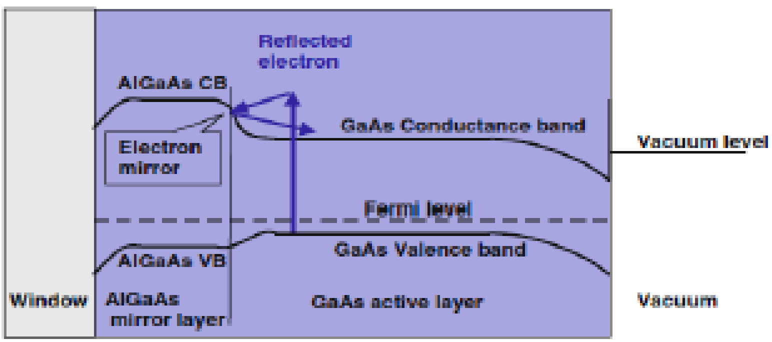



Examples:

- S20 has PEA (cutoff at 820nm)
  - only hot e- escape → thin layer (60nm)
  - low dark rate (<Khz/cm²)
- S25 has NEA (cutoff at bandgap, 890nm)
  - → thick layer (170nm)
  - higher dark rate (10KHz/cm²)

**2) III-V semiconductors**

→ GaAs, GaAsP bulk + Cs for NEA
→ very pure mono-crystalline layers
→ easy doping and hetero-junctions

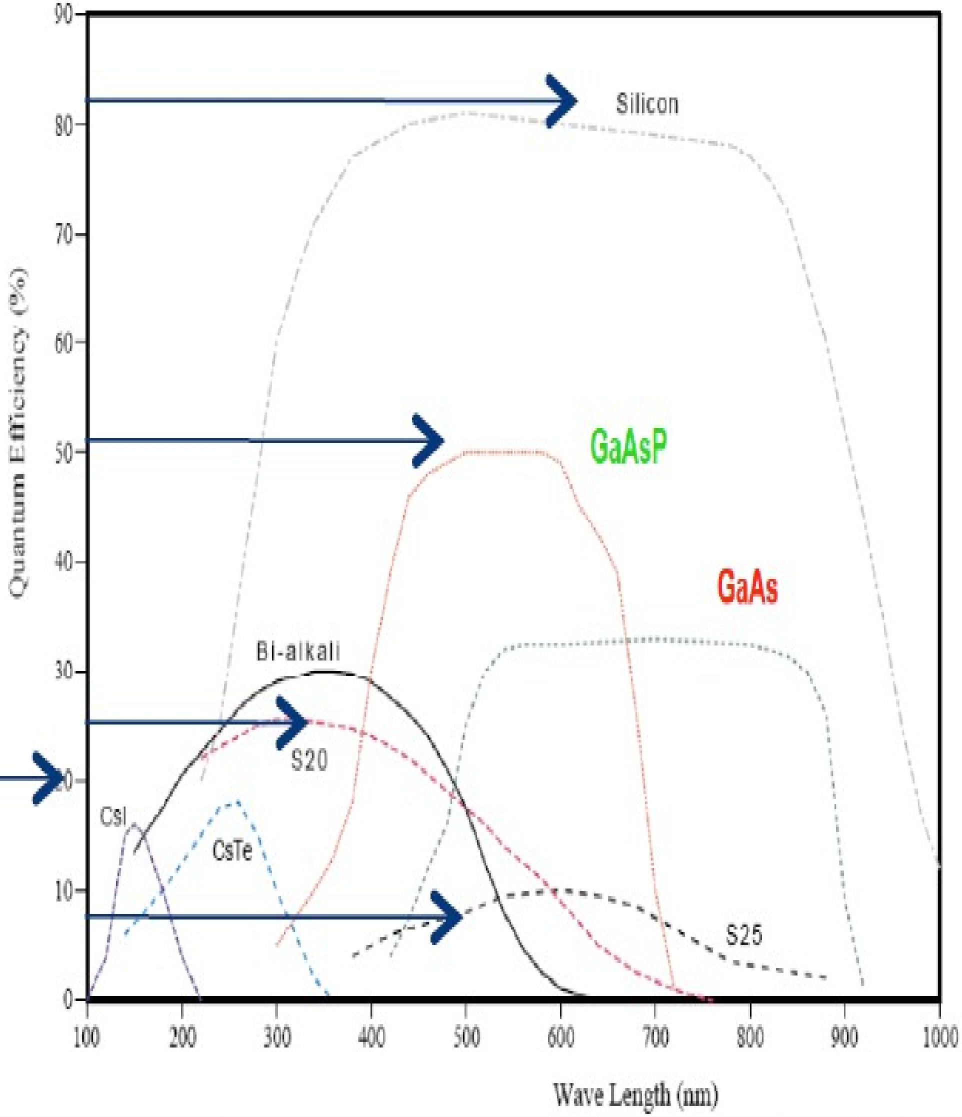



Weak points:

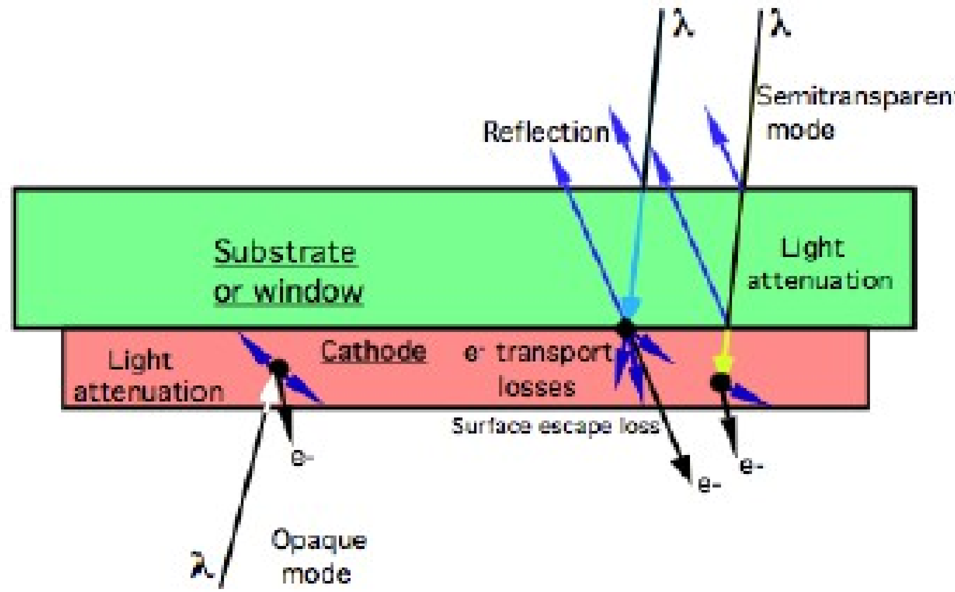
- extreme sensitivity to over-exposure and ion feed-back
- high dark rate (10KHz/cm²)

Note: alkali metals are very strong oxidizers
→ the smallest amount of $O_2$ or $H_2O$ totally burn any cathode
→ ultra high vacuum ($10^{-9}$ mbar) needed

# Photo-cathodes




Semitransparent (thin layer ☹)
on the entrance window
or
Reflective / opaque on internal substrate (thick layer ☺)



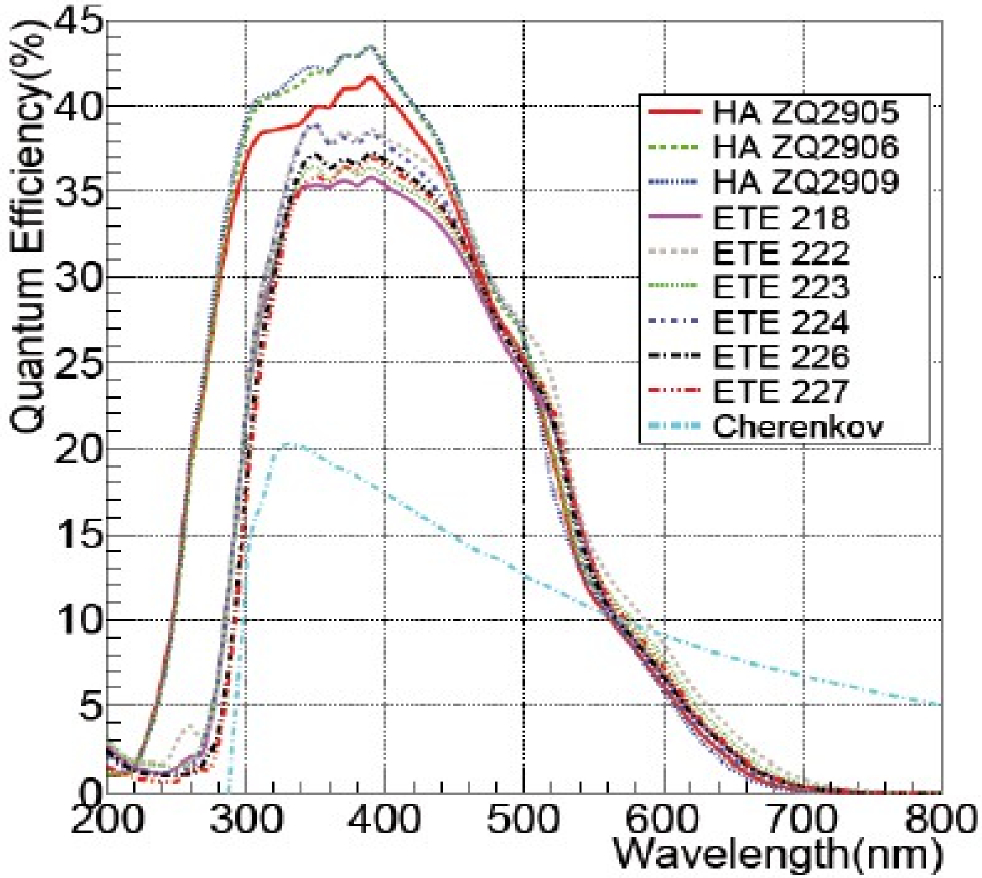

(poly)-crystalline
semiconductor materials

Photo-cathode: most crucial element in any PMT type
→ relatively complex working principles
→ complex construction → still **room for improvement** !
→ since last 10 years revived interest in R&D for new photo-cathodes

# New generation of Photo-cathodes

Strong press for new high QE photo-cathodes
from Astro-particle and large volume Neutrino experiments
Cherenkov light → sensitivity to single photon

PMT candidates for CTA




*R.Myrzoyan – Light Sensors for Astro-Particle physics – ICRR 2014*

Huge progresses for multi-alkali by Hamamatsu (Japan) and Electron Tubes Enterprises (UK)

- QE towards 40% (*)
- CE better than 90%

→ PDE x1.5 improvement

(*) due to "better crystallinity"

**Recent progress of photocathodes for PMTs**

*International Workshop on New Photon Detectors (PD09)*
*Shinshu University Matsumoto Japan*
*24-26 June 2009*

**Motohiro Suyama**[1]
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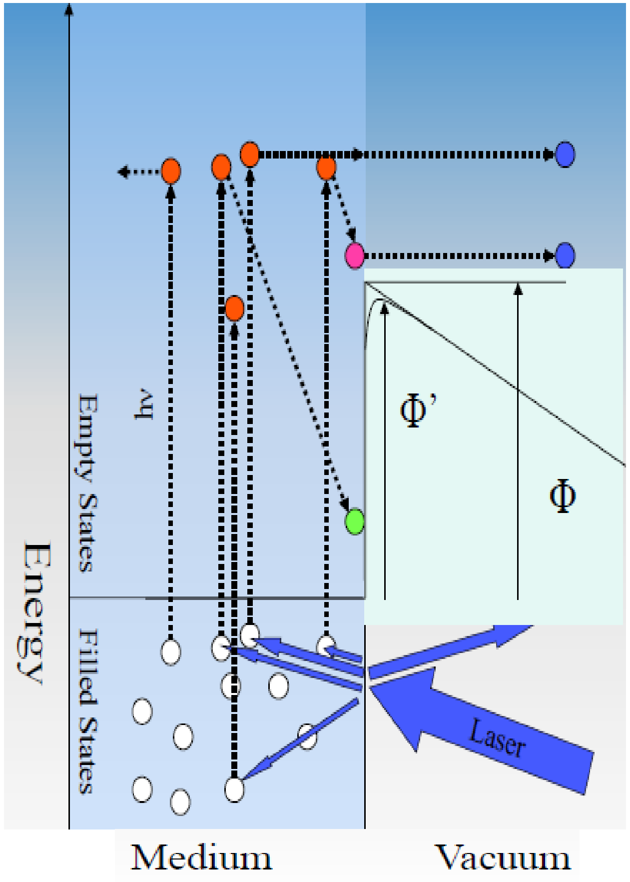
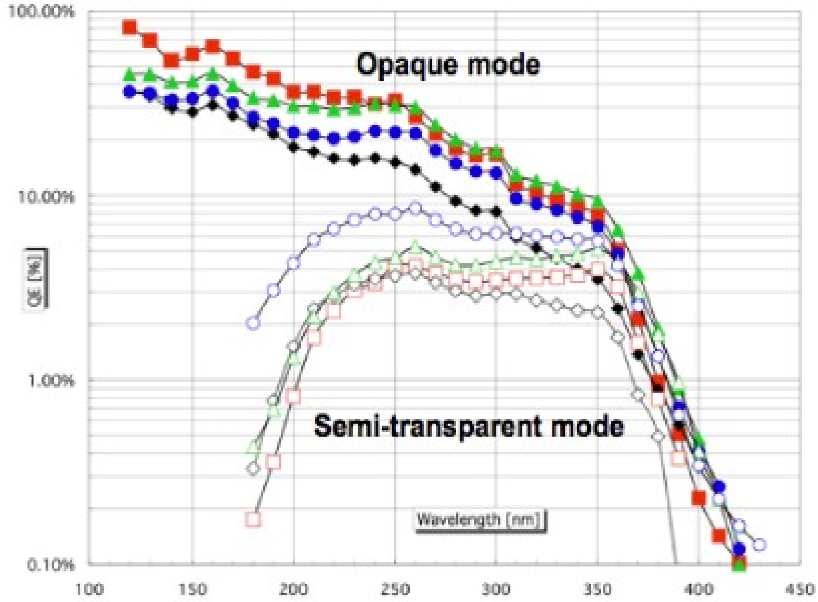
*M.Suyama PhotoDet 2009*

# New generation of Photo-cathodes

## "Open-source" developments by the LAPPD collaboration

*H.Frisch (U.Chicago), O.Siegmund (U.C.Berkeley), R.Wagner (ANL) et.al + industry*
*http://psec.uchicago.edu*



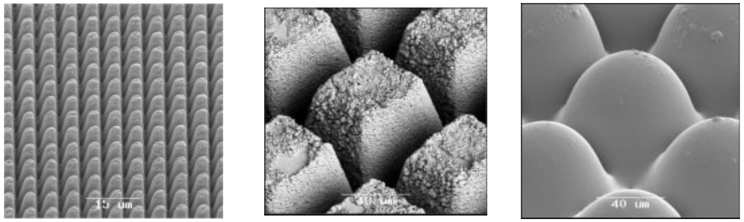

*O.Siegmund – Challenges in photo-cathode deposition for Large Area MCP Proximity Focus Devices – 2nd Photo-cathode workshop – Chicago 2012*

Opaque GaN
ALD MCP 25mmTube

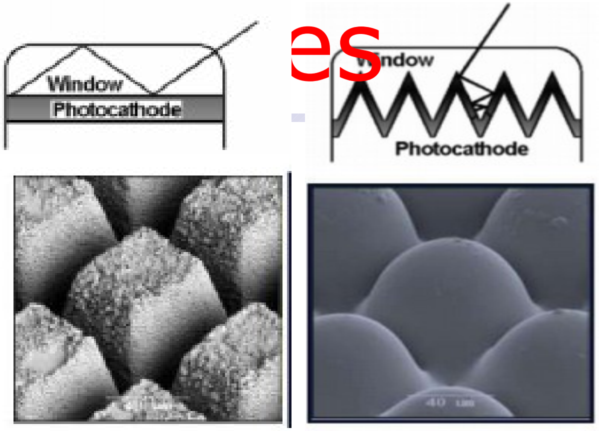
*J.Smedley – 2nd Photo-cathode workshop – Chicago 2012*

Reflectivity depends on angle of incidence and cathode thickness. Structuring of the photocathode can further reduce loss due to reflection.

Increasing the electron MFP will improve the QE. Phonon scattering cannot be removed, but a more perfect crystal can reduce defect and impurity scattering



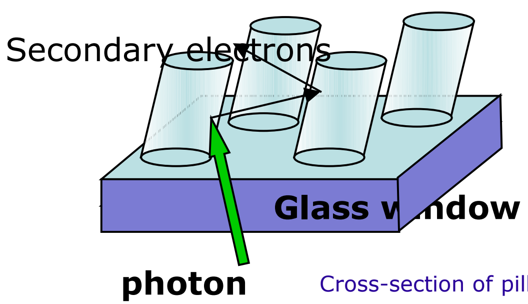
# New generation of Photo-c es

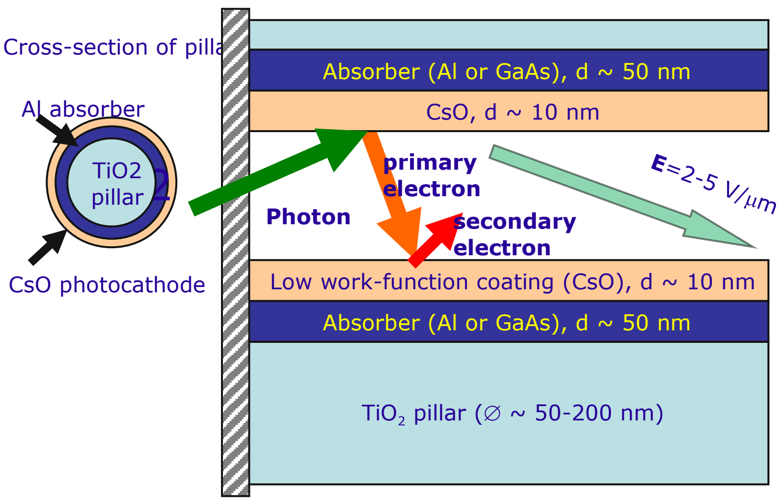


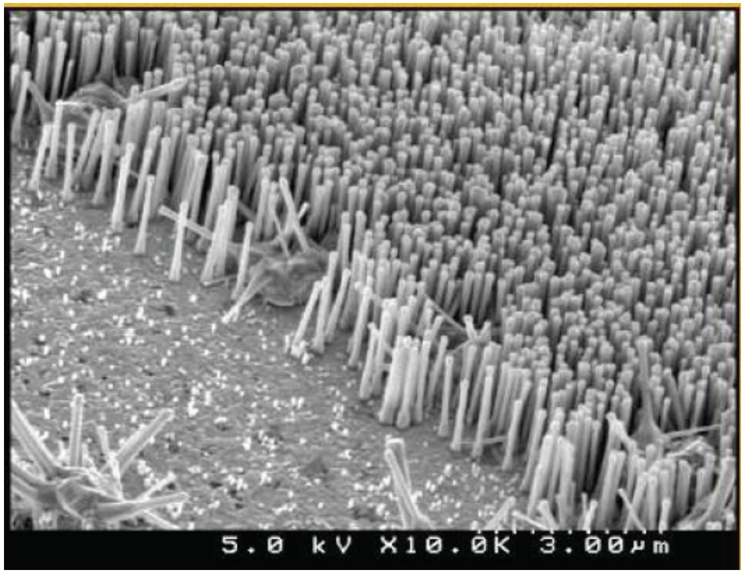

1) Search for new photo-cathode (PC) materials
- bi- and multi-alkali revisited (eg. $Li_2CsSb$)
- III-Nitrides (eg. GaN, $Al_xGa_{1-x}N$)
- II-VI (eg. ZnO, $Zn_{1-x}Mg_xO$)

2) Anti-reflecting structures

3) Electron emission enhancement
- Piezo-electrically enhanced photo-cathodes (no Cs;in air)
- Electric field assisted emission



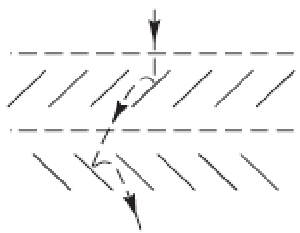



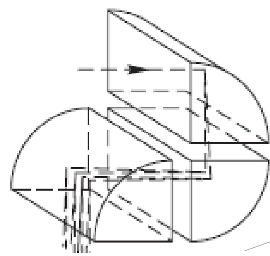

*LAPPD collaboration*
*→ 1st and 2nd Photo-Cathode Workshops (2009 and 2012 ) U.Chicago*

# Electron Multipliers

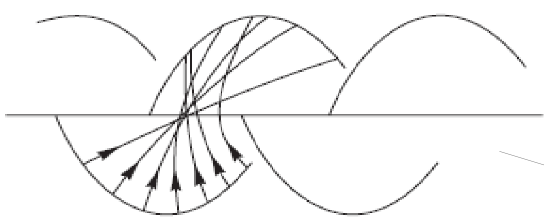
## discrete multiplication



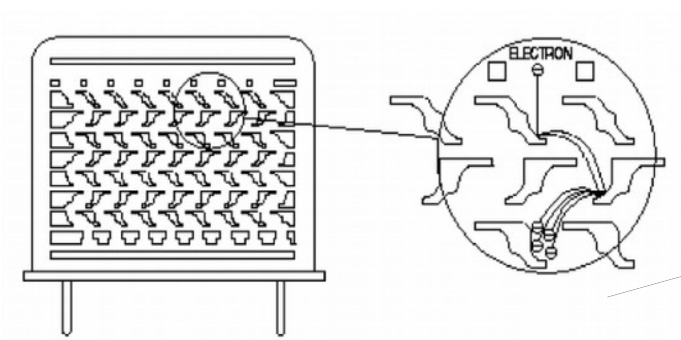
venetian blind



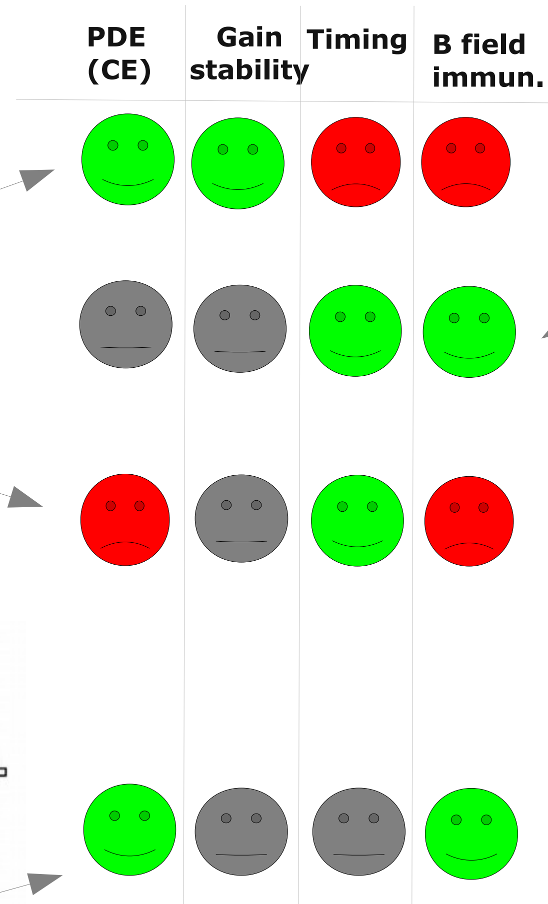
box & grid



linear focus

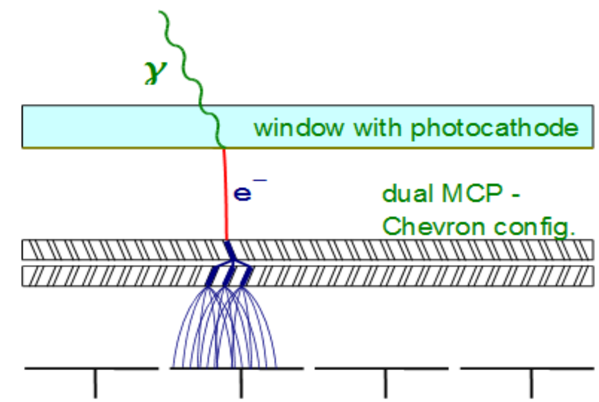


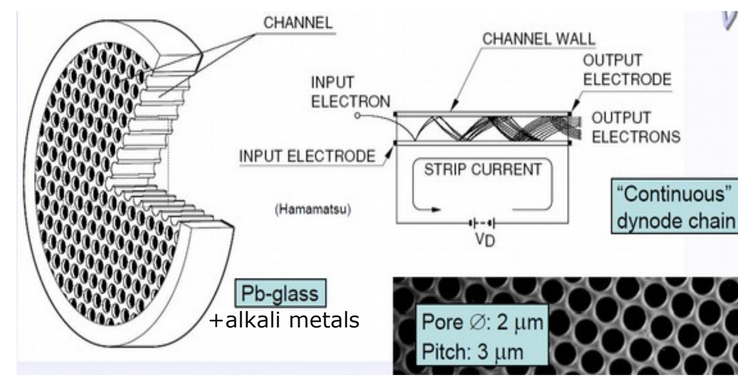

metal channel



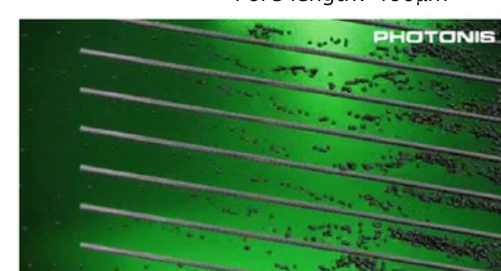

## continuous multiplication

micro-channel plate (MCP)




Pore length: 400µm



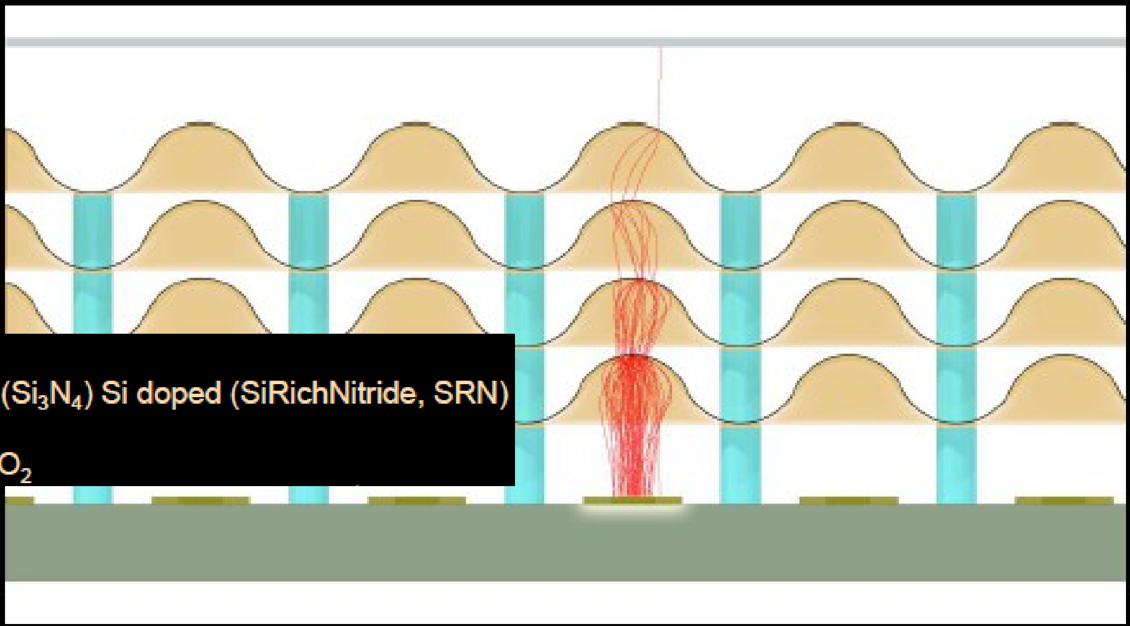

...plus a number of variants...

# New generation of Charge Multipliers

**discrete multiplication** Transmission dynodes revisited (new materials)

## A new single, free electron detector in vacuum

A pixelized detector for single free electrons in vacuum
with ps time resolution



diamond
SiNitride ($Si_3N_4$) Si doped (SiRichNitride, SRN)
CsI
doped $SiO_2$

Tipsy

transmission dynodes

Thin (~10 nm), planar dynodes, spaced ~ 30 μm

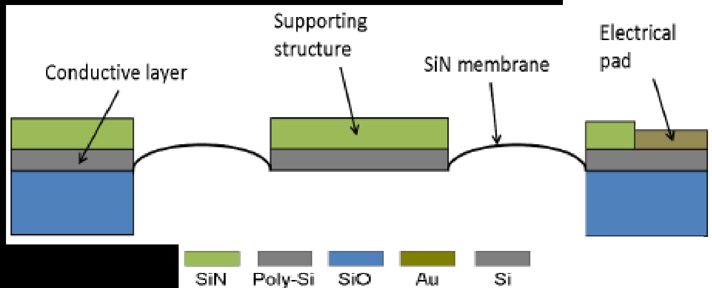
\+

CMOS pixel chip, square pitch ~ 55 μm

pixel chip

MicroElectronicMechanicalSystems 'MEMS' Technology
- ultra thin membranes
- Cone shape dynode section:

1. focusing electron from above
2. focusing emitted electrons
3. mechanically robust: larger diameter cones feasible

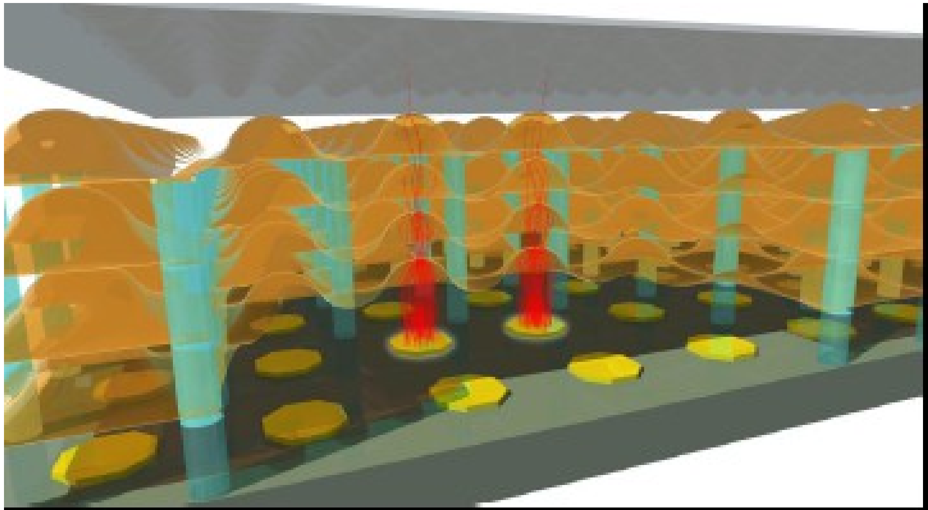



15 nm thin dynode material
Si Rich SiNitride (SRN)

*H.van der Graaf – The Tipsy soft photon detector - NDIP 2014*

# New generation of Charge Multipliers

**discrete multiplication** Transmission dynodes revisited (new materials)



## Timed Photon Counter
## TiPC, Tipsy

Fast: electron mobility is highest for free electrons in vacuum

Low noise: no bias current

- Thin, planar, light single soft photon detector
- Electron crossing time $t_c = D \sqrt{(2\ m/qV)}$ = 5 ps for V = 150 V, D = 20 μm
- Electron path: quite straight line towards next dynode
- 30 k e- enough for digital signal on pixel input pads: 7 dynodes adequate
- Signal response after 7 x 5 ps = 35 ps
- Time resolution determined by last electron crossing time: ~ 2 ps
- Spatial resolution determined by pixel granularity (55 μm x 55 μm)
- No noise from electron multiplier, no bias current from electron multiplier
- Radiation hard
- Operates in magnetic field

But:
- Secondary electron emission yield not known
- Very strong electric field between dynodes: Fowler-Nordheim limit ($10^9$ V/m)
- *QE limited by QE of classical photo cathode (20 – 40 %)!*

*H.van der Graaf – The Tipsy soft photon detector - NDIP 2014*

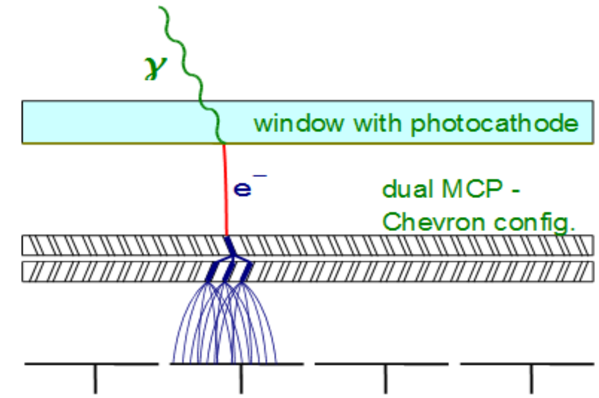
# Electron Multipliers - MCP

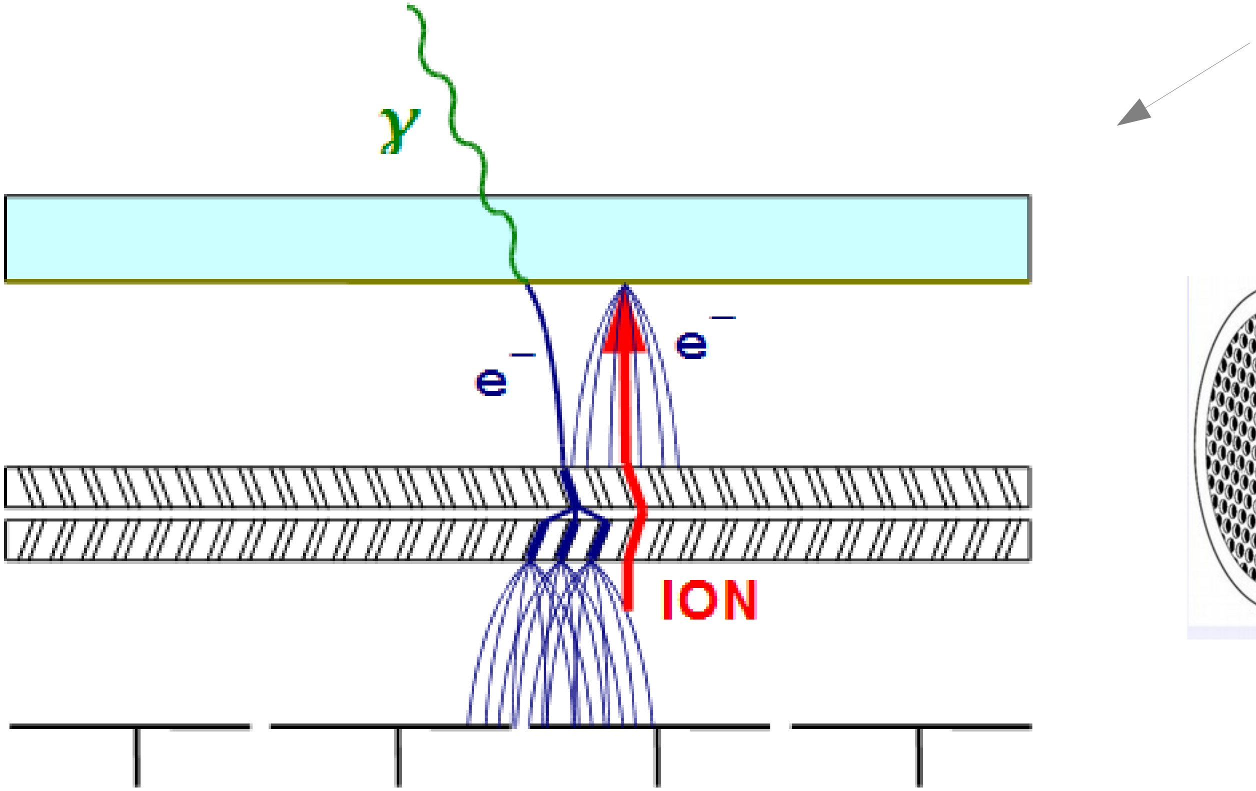
## Main problem: Ion Feedback (IFB)

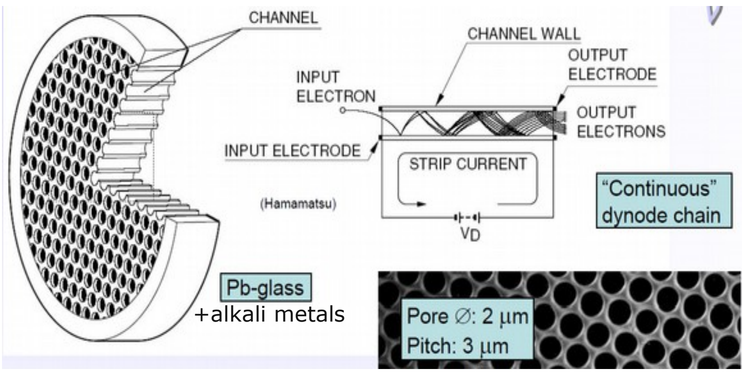
**continuous multiplication**

During the amplification process atoms of residual gas or desorbed travel back towards PC
→ secondary pulse
→ ion bombardment damages the PC → reducing QE
→ gain reduction

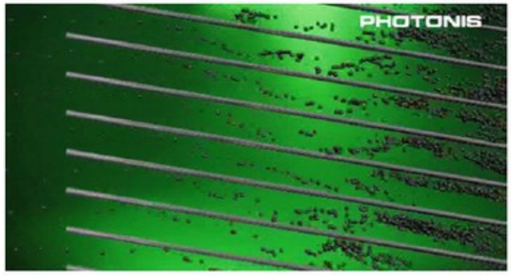
**micro-channel plate (MCP)**




Pore length: 400µm

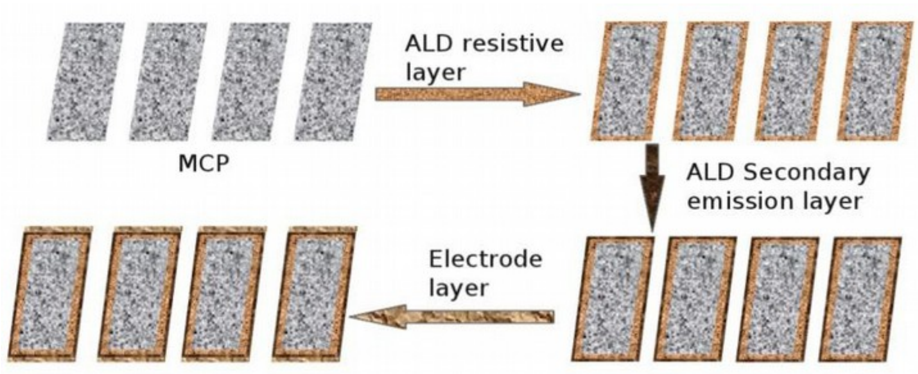


# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

Fast ageing due to IFB countermeasure (in addition to electron scrubbing):
1) make robust photo-cathodes (developed at BINP for FARICH)
2) investigate alternative MCP materials (borosilicate, Alumina, Silicon)
3) implement ion barrier films → Atomic Layer deposition (ALD)

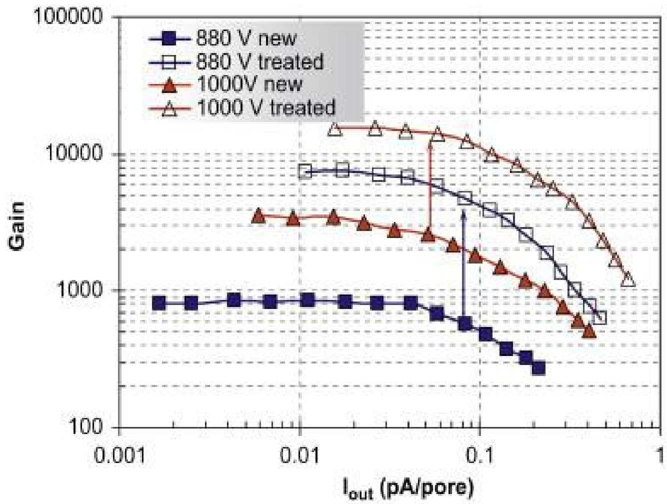
### Atomic Layer deposition (ALD)




**Three-step deposition process**
- Resistive layer
- Secondary emission layer
- Electrode layer

**Optimization of MCP resistance and SEE**
- Independently for each film
- For a given gain, lower operating voltage

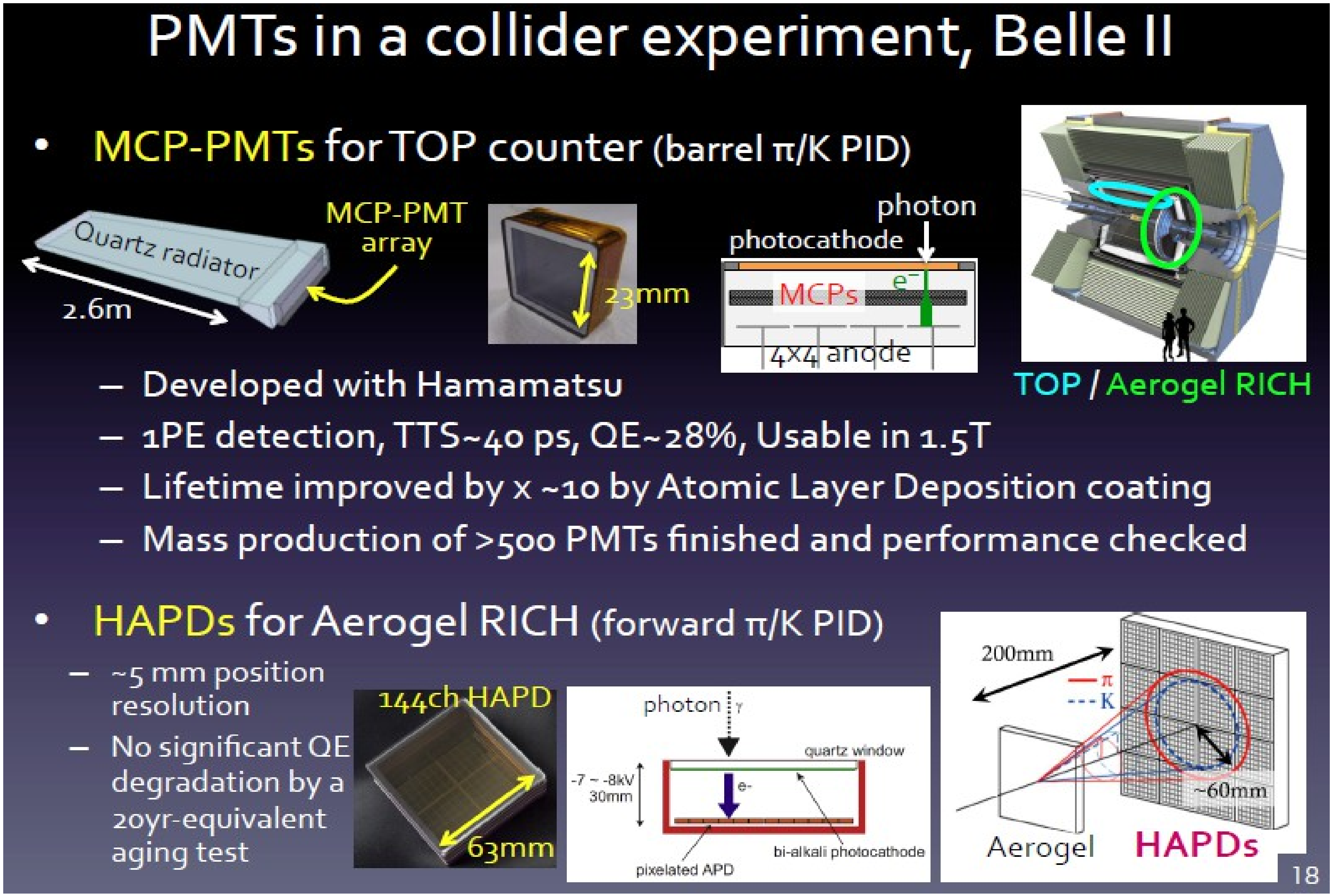
Allow use of insulating materials other than Pb-glass




*T.Gys – NDIP 2014*

# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)




Latest developments also within the TORCH project (Time of internally Reflected CHerenkov light) for low-p PID future LHCb upgrade

# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

### Key Issues for ALD Borosilicate MCPs

Current MCP devices have specific limitations due to the nature of the structure and processing of conventional MCPs. Atomic layer deposited (ALD) MCPs made on borosilicate substrates provide a unique way to improve on current devices or make new device types.

Borosilicate substrate:- Strong & clean compared with standard MCP glass

- Large areas can be made – large detectors for security applications
- Larger open area ratios – higher photon /electron/ion detection efficiency
- Low/no radioactive content – lower background for security applications
- Low outgassing – longer device lifetimes, shorter process/fab times
- High temperatures – deposit materials & cathodes not otherwise possible

Atomic layer deposition:- Decoupled from substrate, many materials possible

- Resistance tailored to suit – can make a wider range than standard MCPs allowing high local counting rates
- High secondary emissive layer – better pulse height at low gain, better gain
- Stable secondary emissive layer – faster gain burn-in, or none needed – very long lifetime & durability

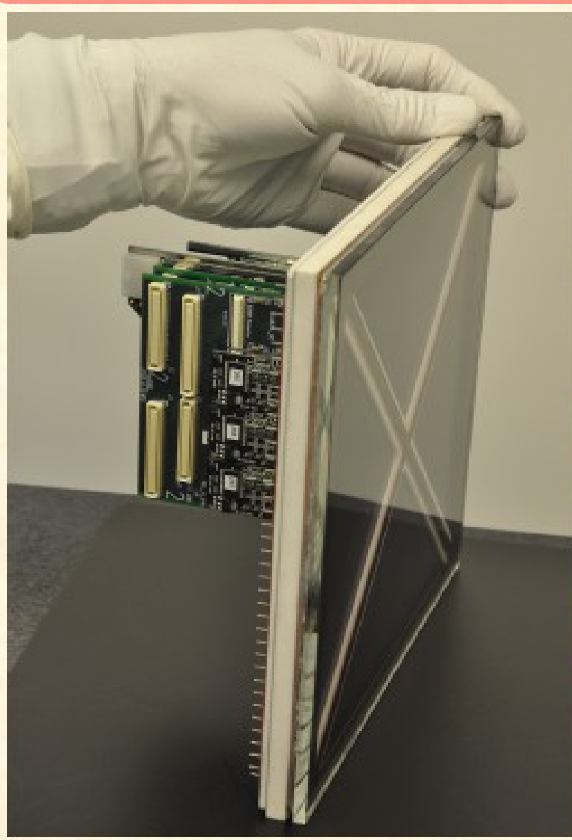
*O.Siegmund – Application of AL-Deposited MCP to imaging PD with High Time Resolution - NDIP 2014*

# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

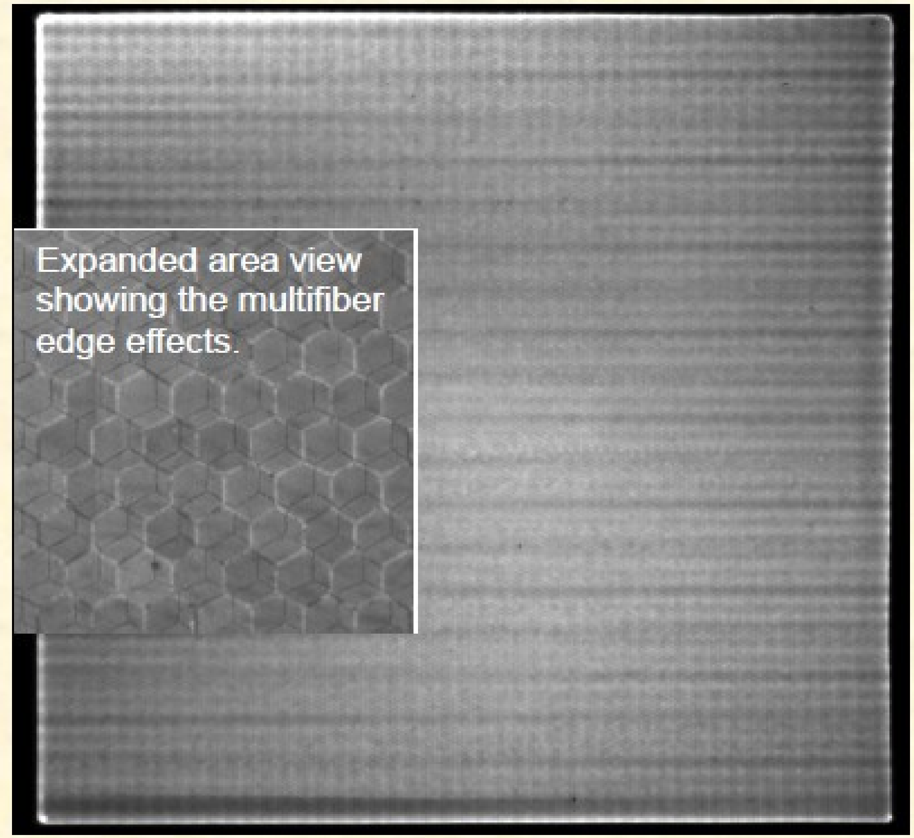
### 20cm ALD-MCP & Sealed Tube Development

LAPPD collaboration development of 20cm ALD MCPs and sealed tube with bialkali cathode and stripline anode for 2D imaging and <10ps timing.



Also see Incom poster.

First tube did not seal, making new tubes this summer




20cm, 20μm pore, $Al_2O_3$ SEY, MCP pair image with 185nm non-uniform UV illumination. Cross delay line photon counting anode. Image striping is due to the anode period/charge cloud size modulation.

*O.Siegmund – Application of AL-Deposited MCP to imaging PD with High Time Resolution - NDIP 2014*

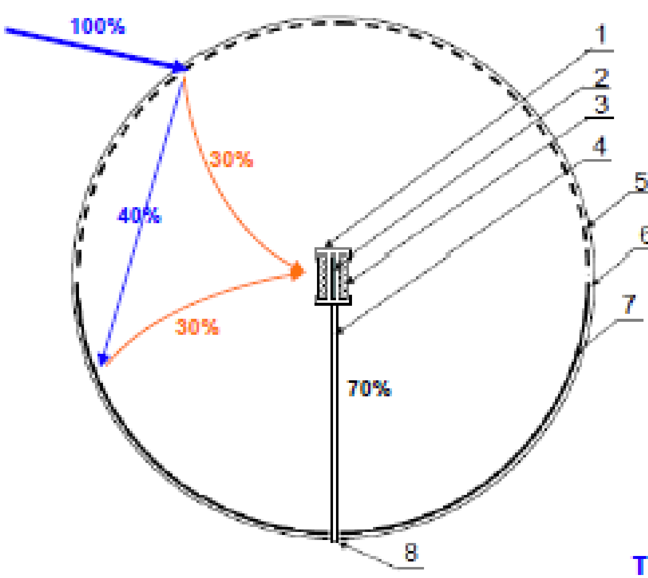
# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

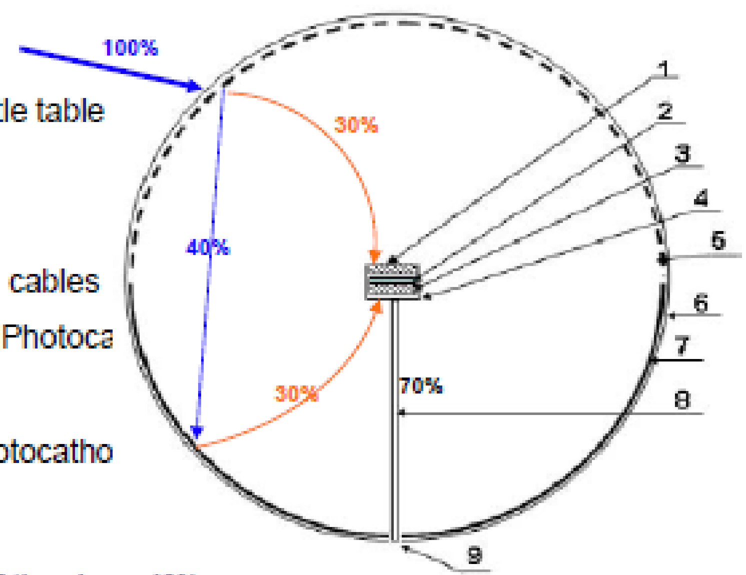
### MCP-PMT R&D in China → JUNO experiment

High photon detection efficiency + Single photoelectron Detection + Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain
2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) } ~ 4π viewing angle!




1.Insulated trestle table
2.Anode
3.MCP dodule
4.Bracket of the cables
5.Transmission Photoca
6.Glass shell
7.Reflection Photocatho
8.Glass joint




Transmission rate of the glass: 40%

Quantum Efficiency (QE) : of Transmission Photocathode 30% ; of Reflection Photocathode 30% ;

Collection Efficiency (CE) of MCP : 70%;

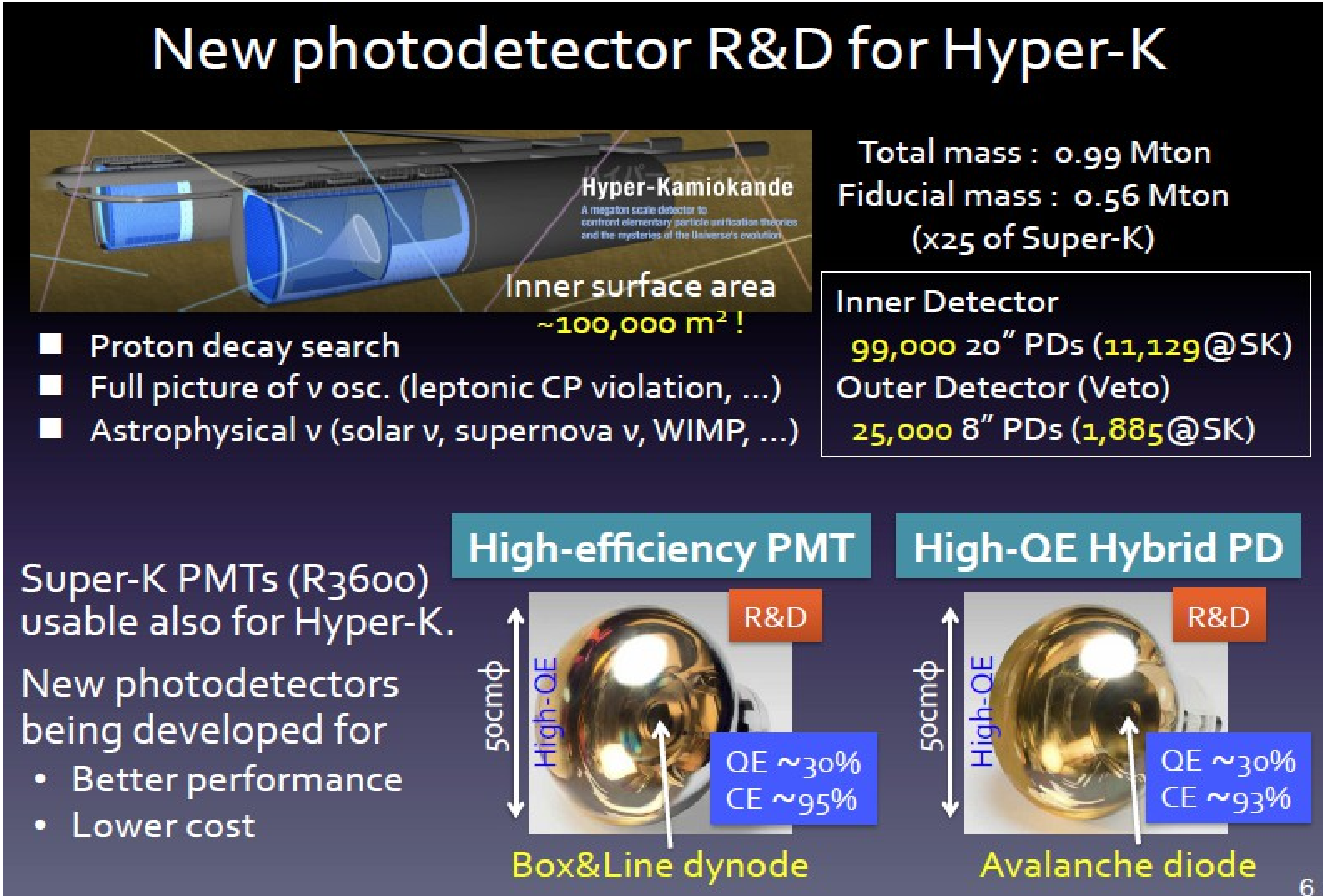
$$PD = QE_{Trans}{*}CE + TR_{Photo}QE_{Ref}{*}CE = 30\%{*}70\% + 40\%{*}30\%{*}70\% = 30\%$$

**Photon Detection Efficiency: 15% → 30% ; ×~2 at least !**

*S.Qian – PhotoDet 2015*

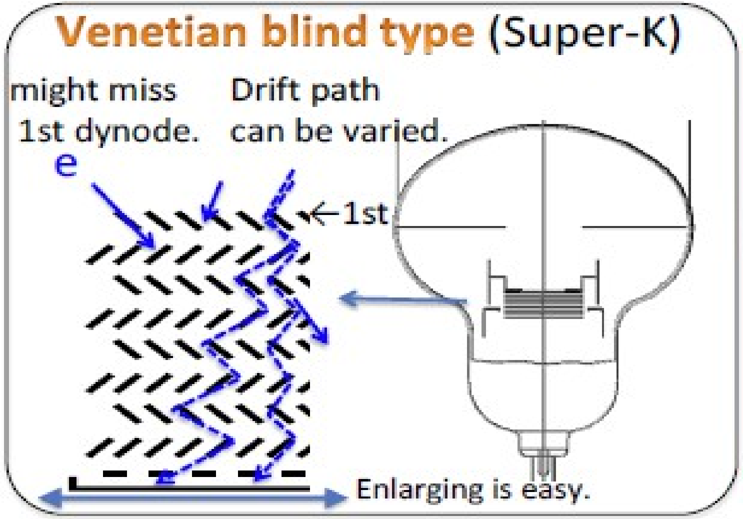
# New generation of Charge Multipliers

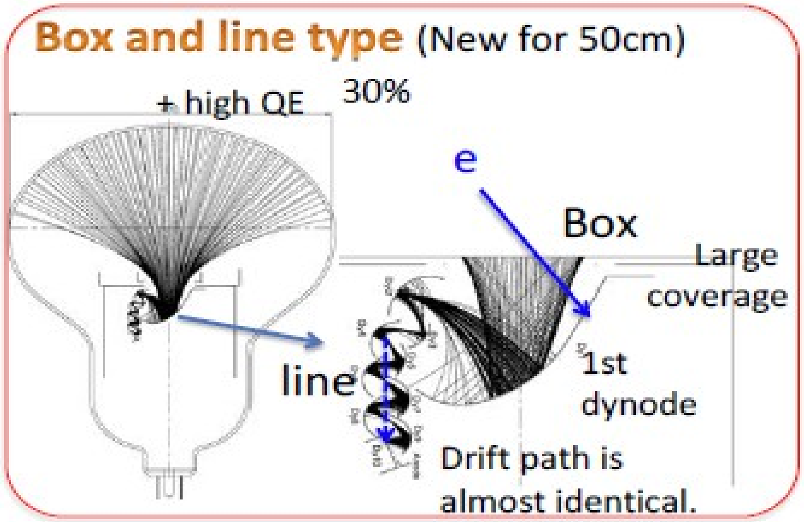
## Large area High Efficiency PMT's → B&L dynodes and HAPD

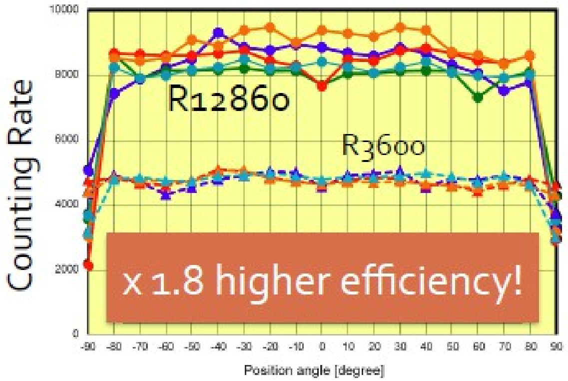



*S.Nakayama – Recent Progress in the developementof PMT's – PhotoDet 2015*

# New generation of Charge Multipliers



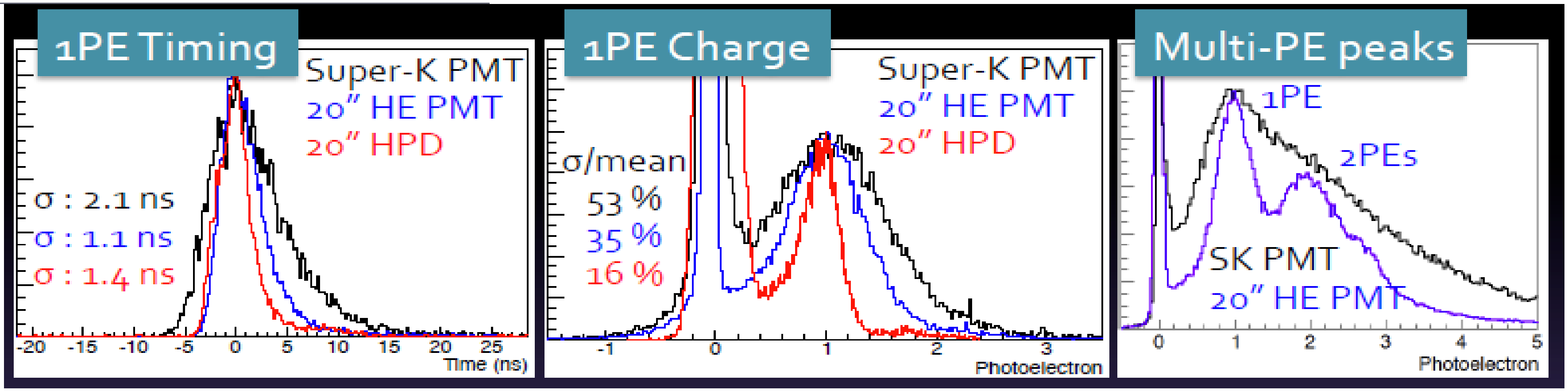




B&L type multiplication performs better:

1) Collection efficiency (wide first dynode)
2) Fast timing response (well defined e- path)

and have lower cost (simpler structure)

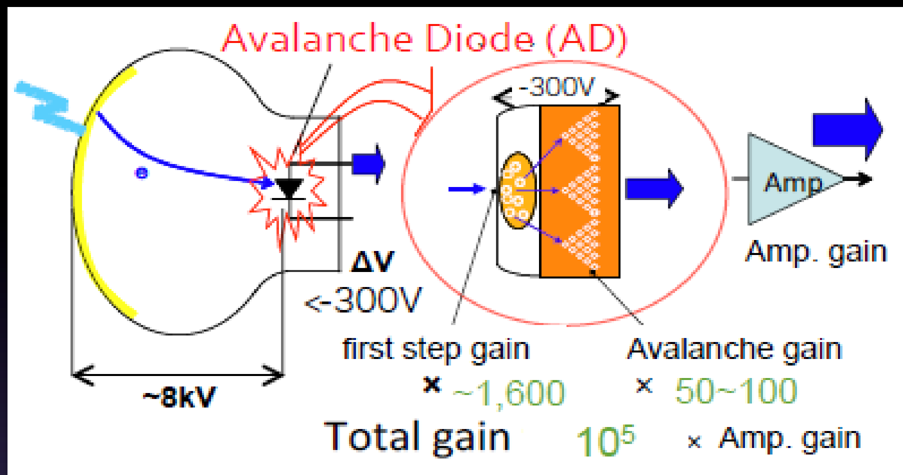


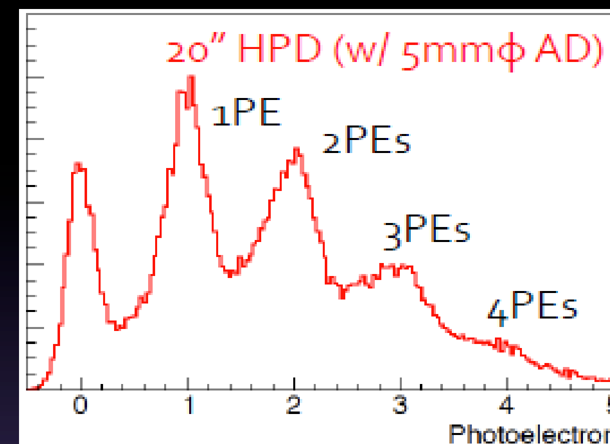
# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

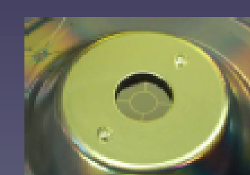
Hamamatsu R12850

### 20" HQE Hybrid Photodetector (HPD)



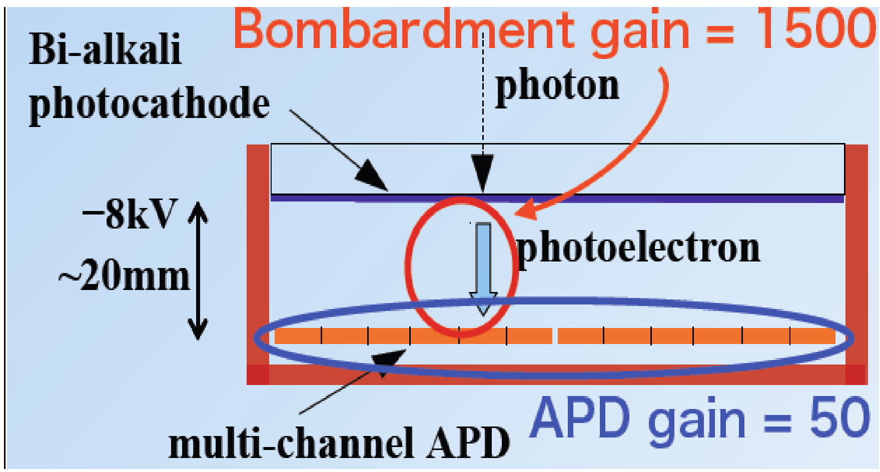

- 8" HPD prototype (5mmϕ AD) has shown good performance
- Low S/N ratio is an issue for 20" HPDs
  - Due to large junction capacitance (~800 pF) of a 20mmϕ AD
  - HPD with a segmented AD is under evaluation. Lower capacitance AD production is also being tried
  - Development of lower noise preamplifier is in progress



… thread-off high Collection Efficiency (large area APD) vs low noise (small area)

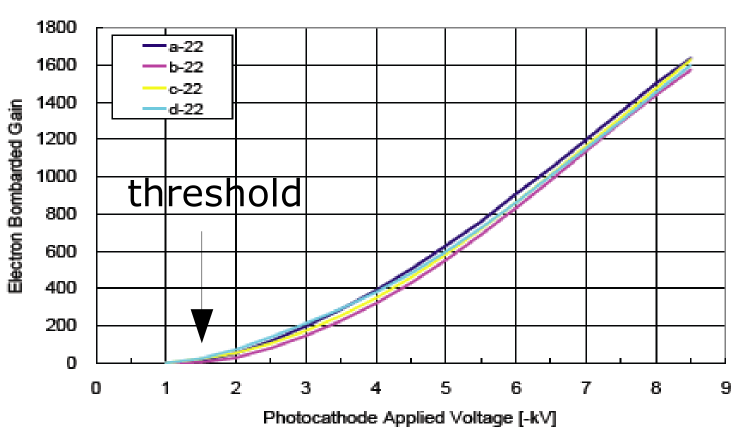
# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD → multi-channel

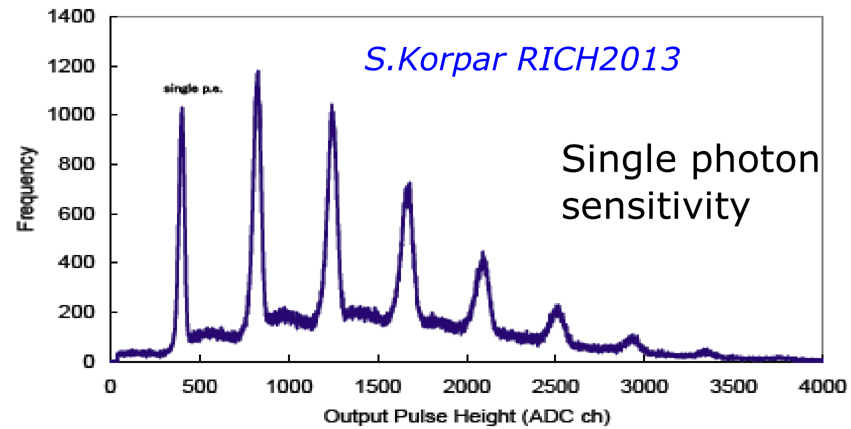


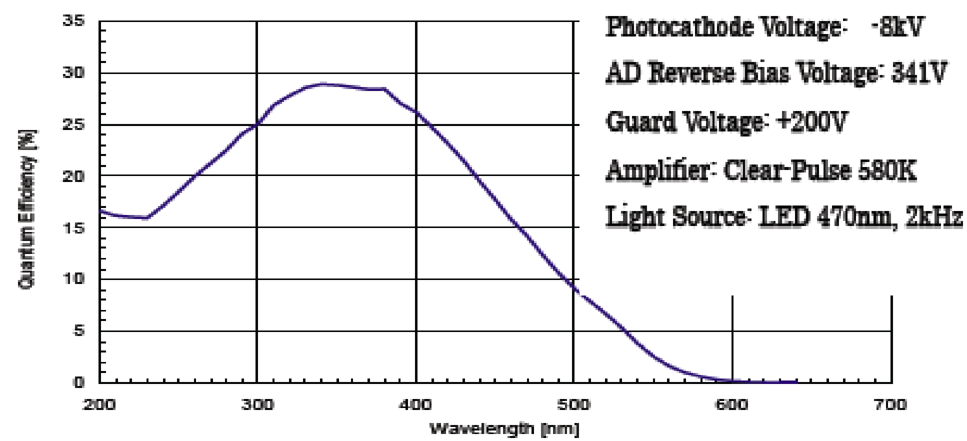

Total Gain ~ 7 $10^5$

Dedicated APD layout for
- kinematic E threshold
- protection against alkali
- HV insulation
- mitigate radiation effects




Development for
BELLE-II Aerogel RICH




*Y.Yusa at EPS 2013*

Note: improvement in timing resolution compared to same geometry PMT tubes (in particular for 8'' and 20'' devices *Y.Suda RICH2013*)

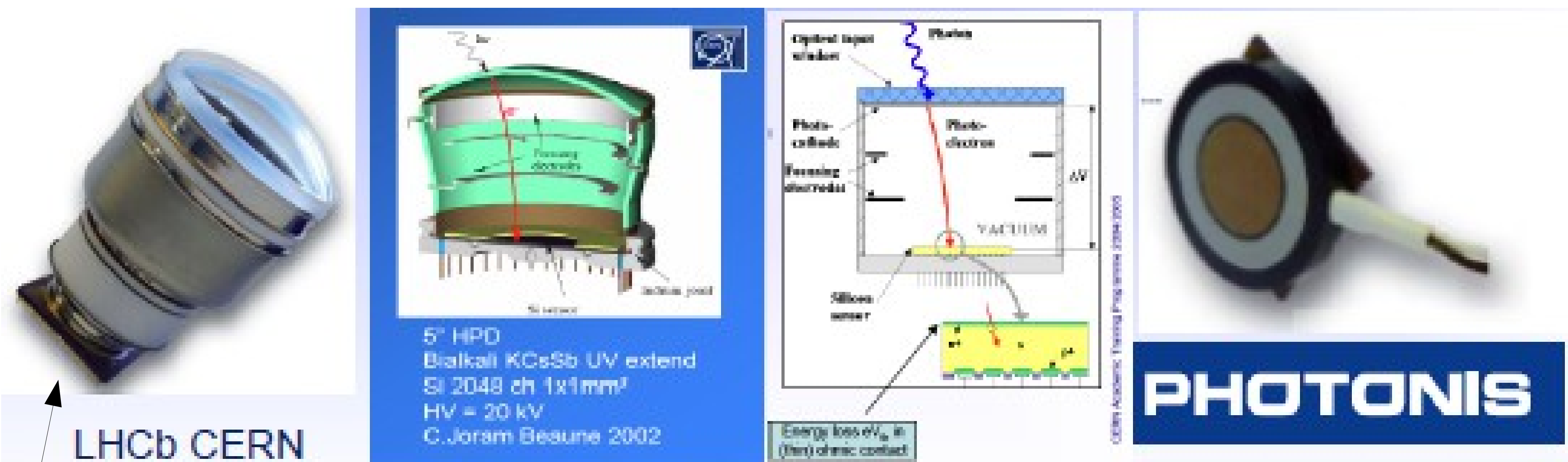
# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

- Si-Anode + RO Chip → HPD /ISPA tube
- APD → HAPD
- SiPM → VSiPMT
- Back thinned CCD → EBCCD
- Back thinned CMOS → EBCMOS

Large Area HPD / small number of pixels

Imaging / Megapixel devices



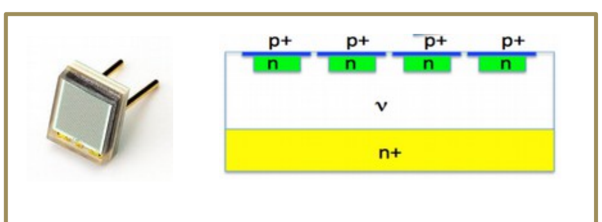

One the few relevant Photo-detector developments pushed by LHC

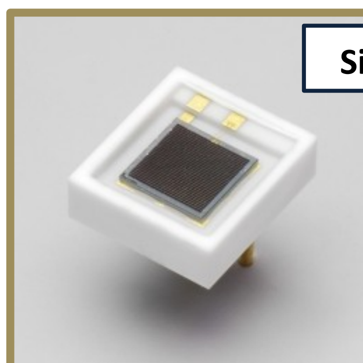
# New generation of Charge Multipliers

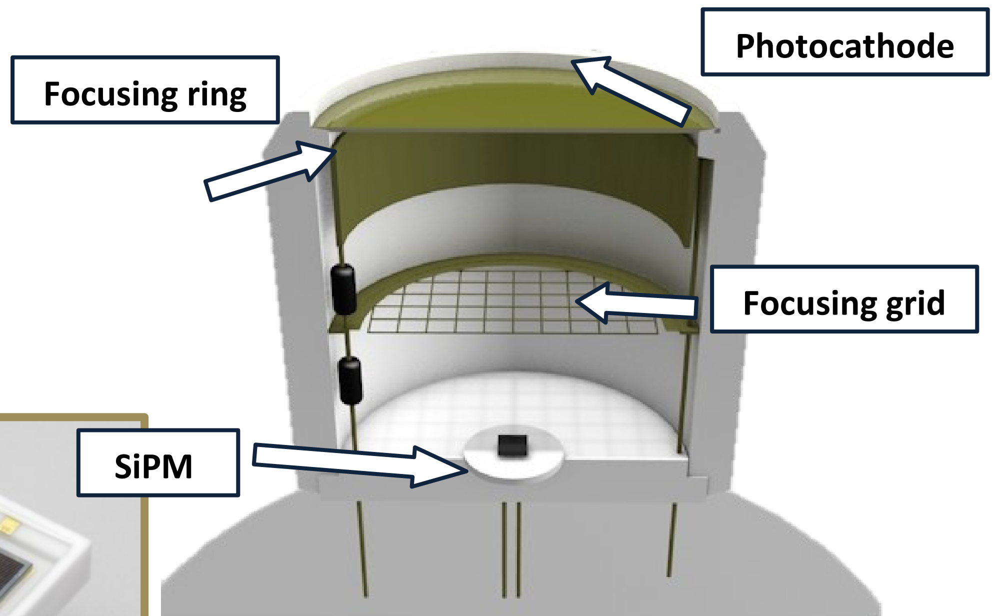
## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

## Vacuum Silicon Photo-Multiplier Tube

An innovative design for a modern hybrid photo-detector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope






increase the SiPM surface with SiPM performnces

The classical dynode chain of a PMT is replaced with a SiPM, acting as an electron multiplying detector.

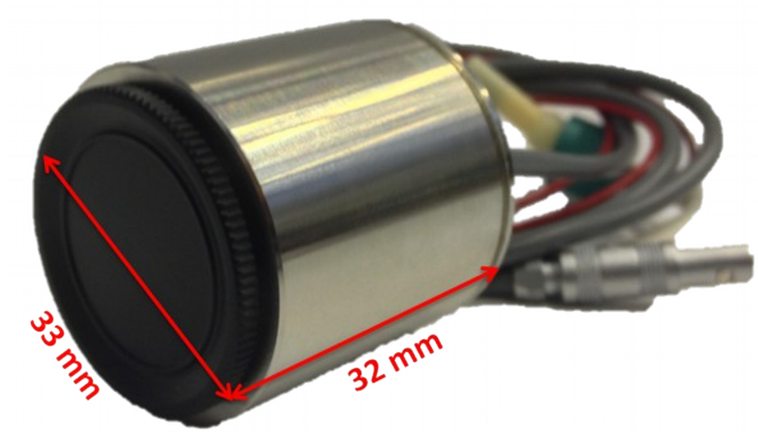
*GC. Barbarino et al*
*INFN - Napoli*

# New generation of Charge Multipliers

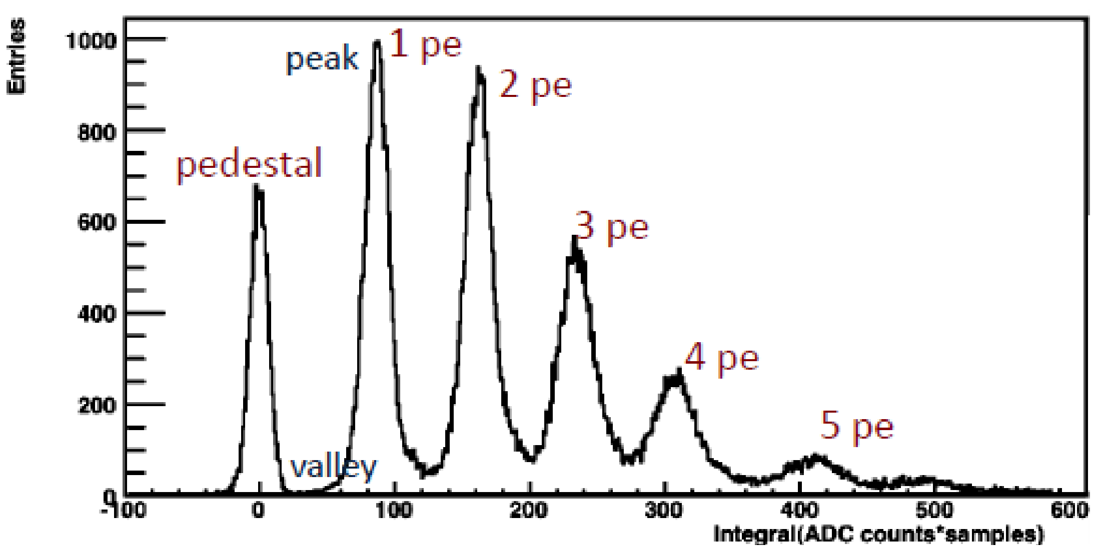
## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

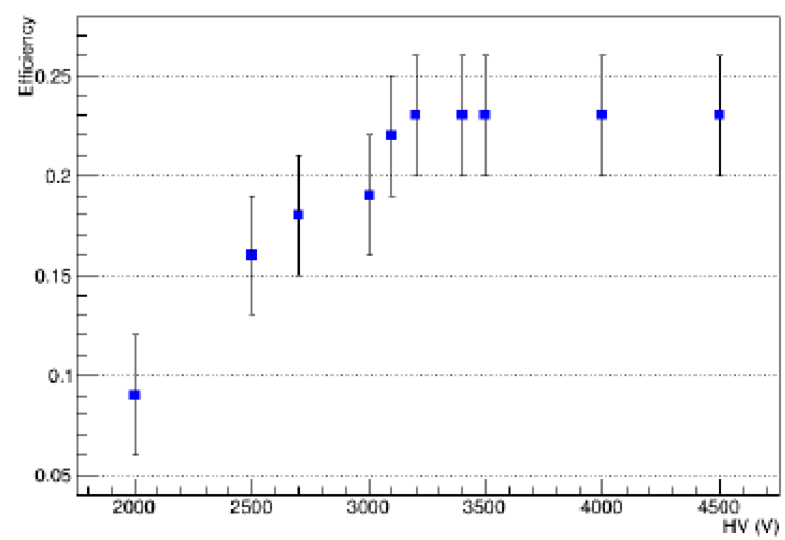
# VSiPM – industrial prototype

2013: Hamamatsu realized two industrial prototype, by arranging a no-windowed SiPM inside a commercial Hamamatsu HPD:  an outstanding proof of feasibility of the device.




- Excellent photon counting capabilities
- Photon Detection Efficiency: ≈23% @ 407nm
- High gain: $10^5 \div 10^6$, HV-stable
- Good timing performances: TTS < 0.5ns
- Low power consumption: 5mW (amplifier stage)
- SPE resolution 17.8%
- Peak-to-valley ratio ≈65
- Efficiency is highly stable over 3200 V
- No need for high voltage stabilization



# New generation of Charge Multipliers

MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

## new VSiPM UV-Vis prototypes

1-3” Photo-Cathode VSiPMT devices
are under construction by Naples group
in collaboration with
Bari/CNR (photocathode)
FBK (e-SiPM for electrons)
National Industries (envelope, dom, tube)

“LEGO” prototype with
CsI based photocathode and Hamamatsu e-SiPM
→ tests ongoing at DAFNE UV source
results soon….. stay tuned!

*Naples project founded by INFN gr.5, ASI, STAR UNINA Federico II*

# Photo-detectors – specific applications

- High Pressure environment
- Operation in magnetic field
- Low Temperature
- Radio-purity

...

# Large Area & High Pressure

Km3Net experience:
Multi-PMT system with small PMTs (DOM)

Use small PMTs !
→ Photon counting
→ Small TTS
→ Negligible effects due to magnetic fields
→ Almost uniform coverage
→ High granularity (impr. background rej.)
→ Directional sensitivity (impr. recon.)
→ Several manufacturers of small PMTs

T2K-Naples R&D for a new multi-PMT
for TITUS and Hyper-K WCh detectors:
- New acrylic vessel to reduce the dark rate (radio-impure in glass vessels)
- PMT Read-Out system
- Other PD considered: VSiPMT, SiPM matrices, …

Km3Net DOM

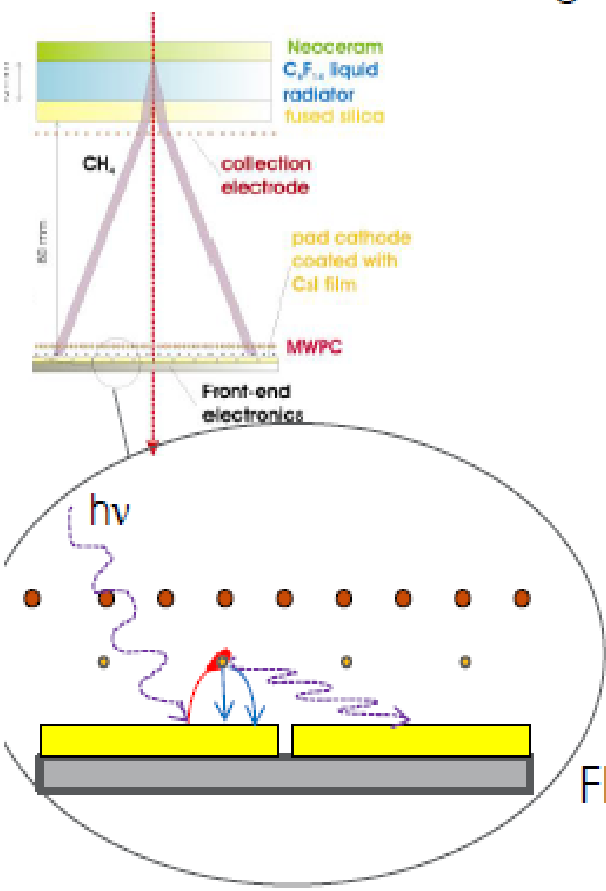
Photo-detectors and electronics arranged inside a pressure resistant vessel

# New generation of Gaseous Photo-Detectors

# Gaseous Photo-detectors (UV)

Large Area UV sensitive PD with CsI photo-cathode and MWPC readout
→ successful RICH detectors (stable operation and honest performance)

HMPID RICH




Single photon detection in CsI-MWPC

**Rate issues !**

- slow signal (ions)
- ion bombardment
- photon feedback

SINGLE PHOTON

CsI PC QE

SINGLE PHOTOELECTRON

photoelectron backscattering (GAS, E, P)

TOWNSEND AVALANCHE

gas gain (GAS, E, P) → ion bombardment, photon feedback

FRONT-END ELECTRONICS (ions signal)

- integration time → visible gain $A_0$
- noise → zero suppression thresh. $A_{th}$

$$\varepsilon_{det} = e^{-\frac{A_{th}}{A_0}}$$

SINGLE PHOTON HIT

detector instability

ageing

increase gain

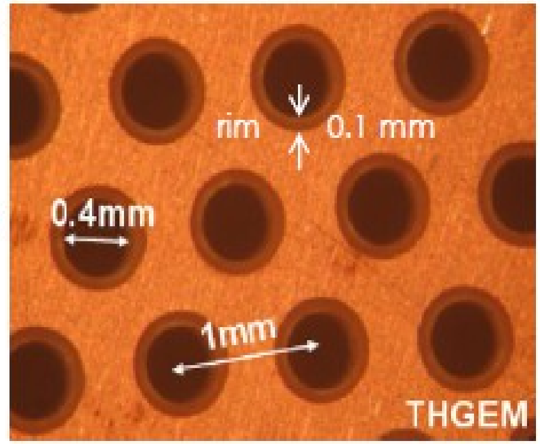
Reduce i.t.

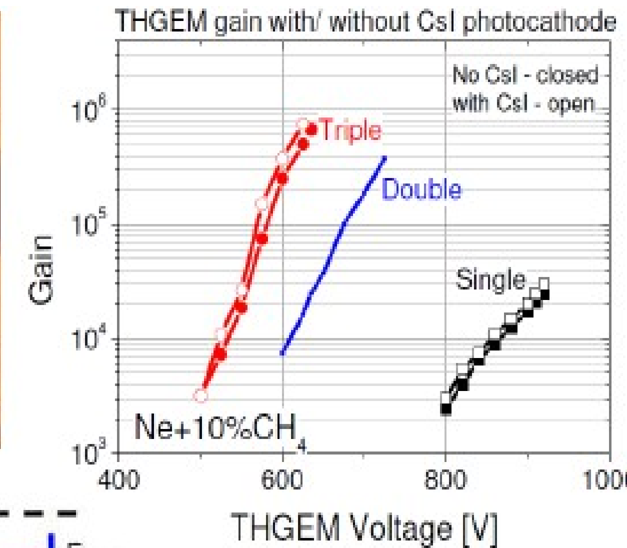
rate requirements

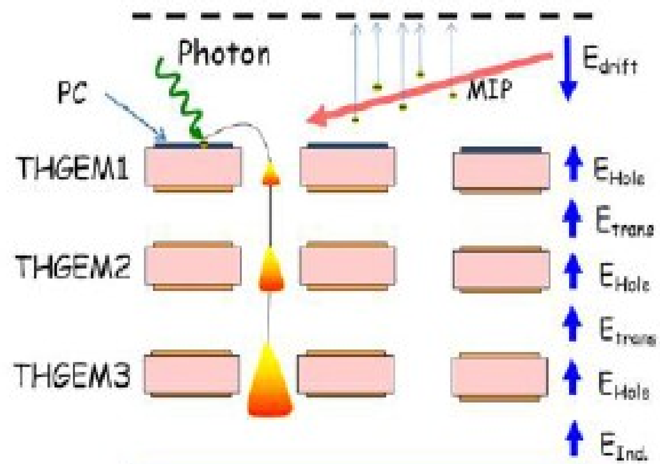
spatial resolution worsening

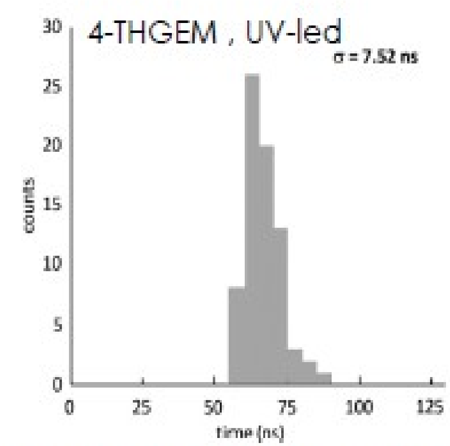
# New generation of GPDs → ThGEM

- GEMs operated in HEP experiments as tracking devices at gain ≤ $10^4$ (not enough for single photon)
- Thick-GEMs →
  - simple manufacturing (mech. drill. of PCB) and assembly
  - Hole diameter : 0.2 – 1 mm
  - Pitch : 0.5 – 5 mm
  - Thickness : 0.4 – 3 mm
  - Rim: 0 – 0.1 mm
  - mechanical robustness (also against sparks)
  - optimal alternative for single photon detection ( spatial resolution ≤ 1 mm)
  - large gain (~ $10^4$ /stage), 7-8 ns time resolution
- Extensive characterization by WIS, COMPASS, ALICE




R. Chechik et al., NIM A535 (2004) 303
C. Shalem et al.: NIM A558 (2006) 475 and NIM A558 (2006) 468
A. Breskin et al. ,NIM A598 (2009) 107
V. Peskov et al., JINST 5 (2010) P11004

M. Alexeev at al., NIM A 617 (2010) 396

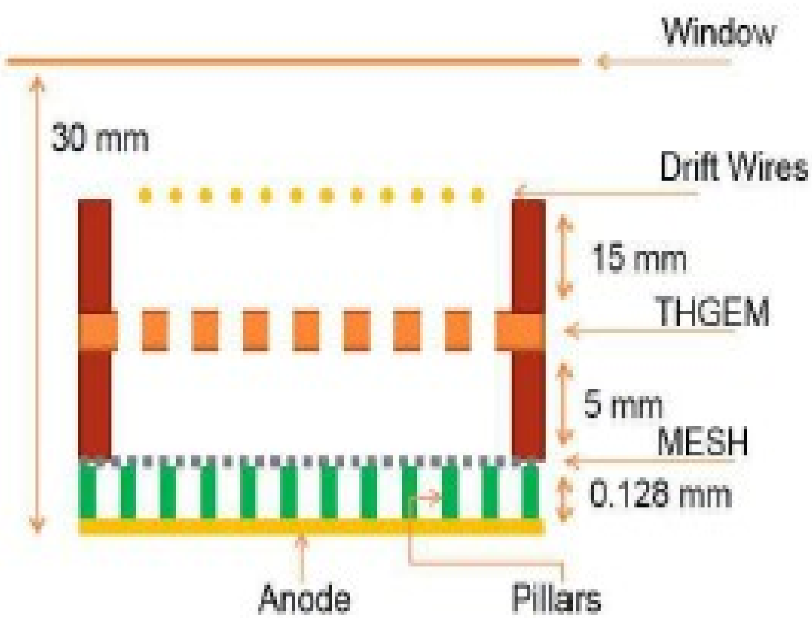
- Neon based mixtures (→ large gain at low HV) $CH_4$ or $CF_4$ (→ reduced ph.e backscattering)
- $E_{drift}$ and geometry → optimize ph.e transfer
- rim → stable operation without sparks

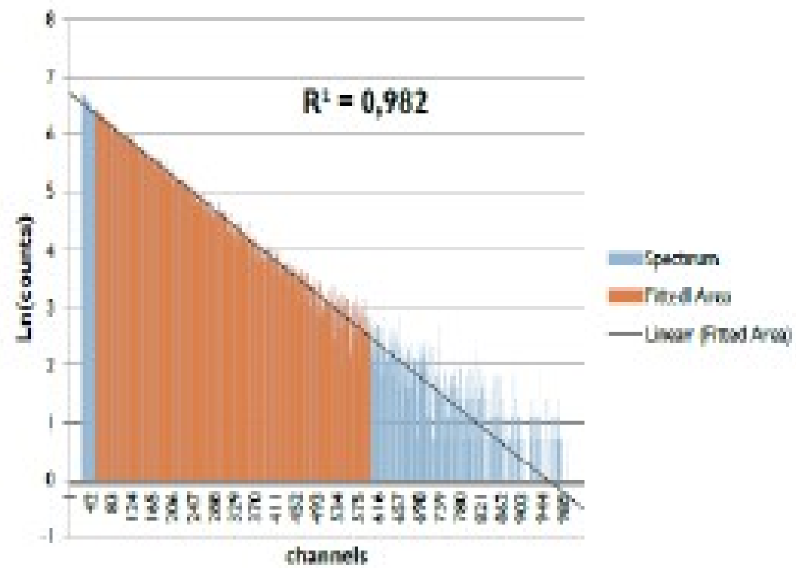
→ high gain (~$10^5$) high rate operation (100 Hz/cm$^2$) ... IBF still an issue (→ new structures)

# New generation of GPDs → Hybrids

## R&D for COMPASS RICH-1 upgrade

### Hybrid THGEM/MM




Gain ≈ 1.7E6

$V_{mesh}$ = 600 V
$E_{trans2}$ = 625 V/cm
$\Delta V_2$ = 1450 V
$E_{trans1}$ = 967 V/cm
$\Delta V_1$ = 1410 V
$E_{drift}$ = 0 V/cm

Rate ≈ 771 Hz

IBF ~ 4%

- Positive experience with large area MicroMegas
- Large suppression of IBF ( ~ $E_{mult}/E_{drift}$ )
- Spread of avalanche from THGEM pre-amplification → sharing of final amplification in various cells of MM, spark-free operation
- In Ar/CH4 total ΔV ~ 4 kV instead of 8 kV with triple THGEM + smaller no. of electrodes

*A. Di Mauro– Status and perspectives of GPD – RICH 2013*

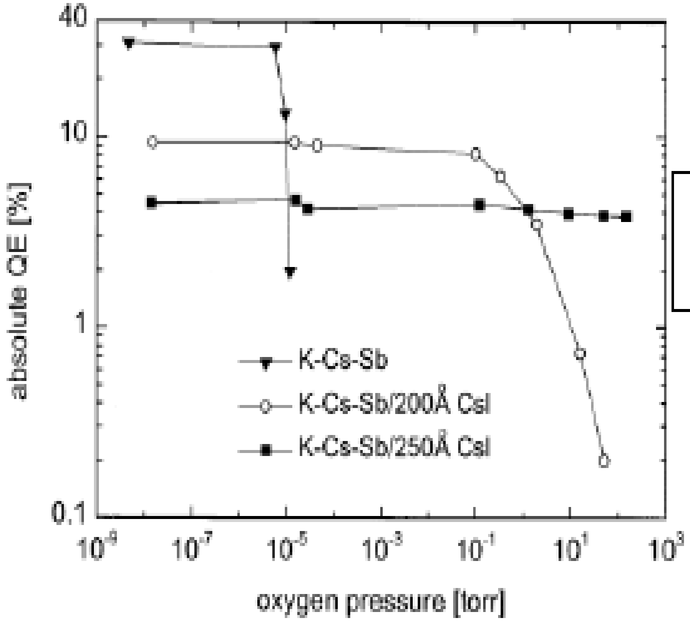
F. Tessarotto, talk at MPGD 2013 – Zaragoza 02/07/2013
S. Levorato, proceedings IEEE 2013

# New generation of GPDs → Visible

Operation in GPD of photoconverters sensitive in the visible range (e.g. alkali-antimony: Cs-Sb; bi-alkali: K-Cs-Sb, Na-K-Sb) is affected by:

- very high reactivity with $O_2$ and $H_2O$ (QE degradation)

Usage of very high purity gas systems, UHV material selection, operation in sealed mode, protective "nanofilms"




Low QE, works for $O_2$

E. Shefer et al.: NIM 433 (1999), 502; J. Appl. Phys 92 (2002), 4758

- large probability of ion-induced secondary electron emission: $\gamma^+ \sim 10^{-2}$

- Gas gain in "open geometry" detectors (MWPC) limited to $\sim 10^2$ for stable operation:

$$\gamma^+ G < 1$$

- In "close geometry" of hole-type MPGD with reduced IBF:

$$\gamma^+ \text{IBF } G < 1 \rightarrow G \sim 10^5 \text{ requires IBF} \sim 10^{-4}$$

*A. Di Mauro– Status and perspectives of GPD – RICH 2013*

# New generation of Solid State Photo-Detectors (SSPD)

Single / multichannel PDs

- PIN-Photo-diode
- APD
- SPAD
- GM-APD (SiPM)

Imaging devices / Megapixel

- CMOS, sCMOS
- CCD, EMCCD

Silicon

Compound semiconductors

Organic semiconductors

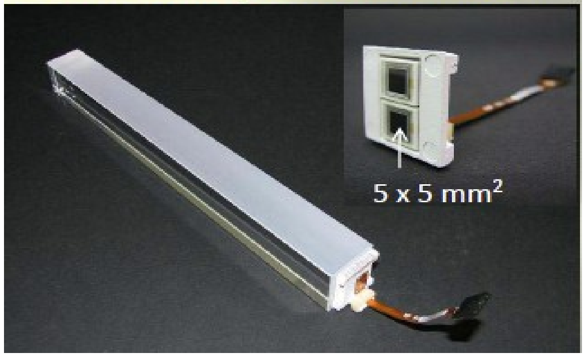
Carbon nanotubes

Superconductive Single Photon Detectors

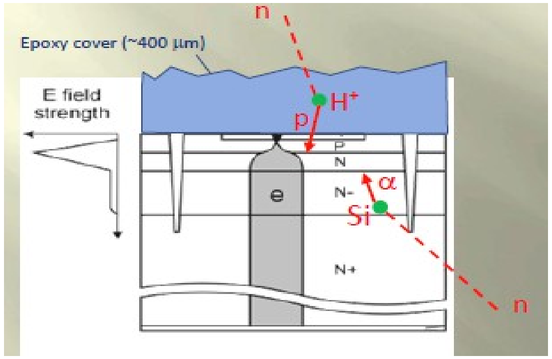
# SSPDs – APD – still largely in use

**>120.000 APD's in CMS**

Barrel: 2 x APD, Hamamatsu S8148



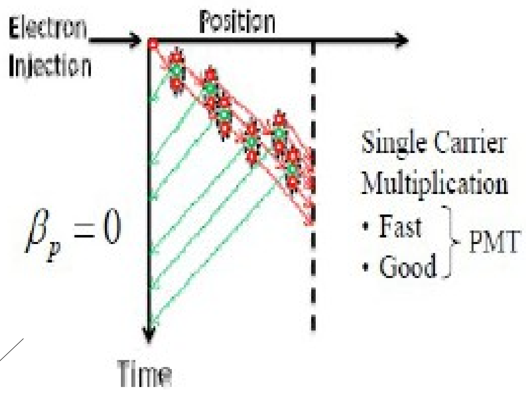

Good performance
(with anomalies)




APD biased for **low gain** M < 1/k

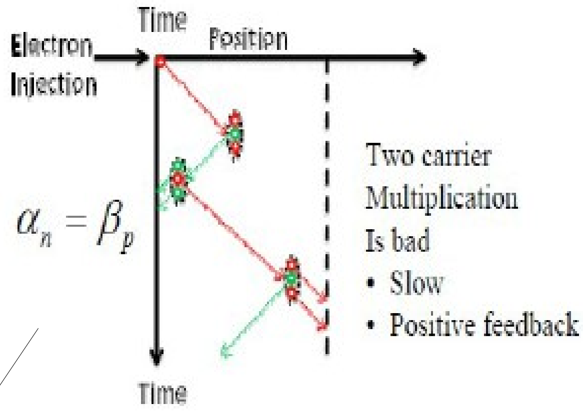
- fast exponential growing due to only electrons
- high number of carriers in high field region at given time:
  → small gain fluctuations
- Timing fluctuations are small: limited only by the length of depletion region
  → time resolution limited by electronics
  (high Amplification for low light signals)

Hayat et al J. Lightwave Tech. 24 (2006) 755
Fox et al Rev. Sci. Instr. 70 (1999) 1951




APD biased for **high gain** M > 1/k

- hole ionization events contribute
  → increase of gain is the result of small number of large pulses due to one or more hole ionization initiated secondary avalanches (ENF)
- low number of carriers in high field region at given time and hole ionization near cathode resulting in larger pulses
  → large gain fluctuations
- **slow buildup** and long pulse due to many carriers over long time
  → large timing fluctuations




**Low gain**
→ Hybrid PM
→ fast timing applications

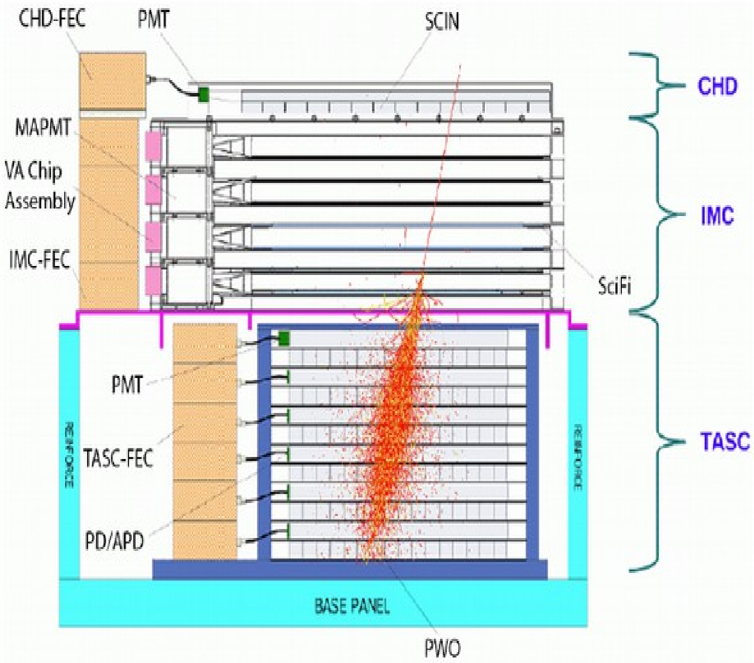
Devices with high multiplication noise are not good for single photon counting

***Single photon counting is possible, but at low temperature (T~77K) and with slow electronics (PDE~20%)***

A. Dorokhovet.al.,JournalMod.Opt. v51 2004 p.1351

# SSPDs – APD – still largely in use

**APDs in Space** based instrumentation




The CALET experiment on the ISS station

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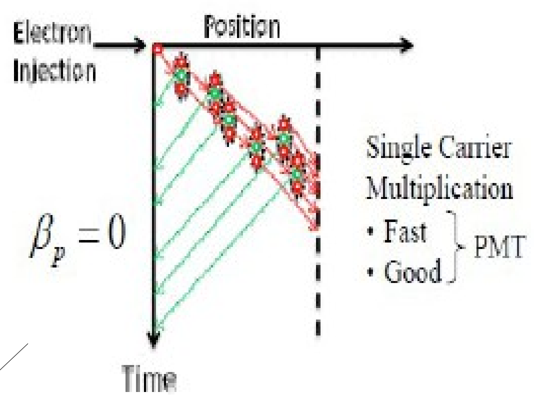
Hayat et al J. Lightwave Tech. 24 (2006) 755
Fox et al Rev. Sci. Instr. 70 (1999) 1951

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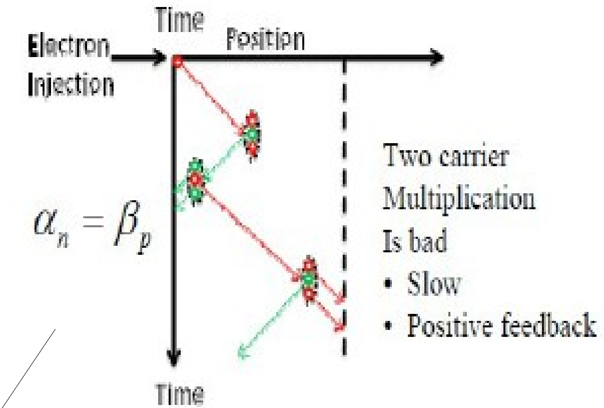


**Low gain**
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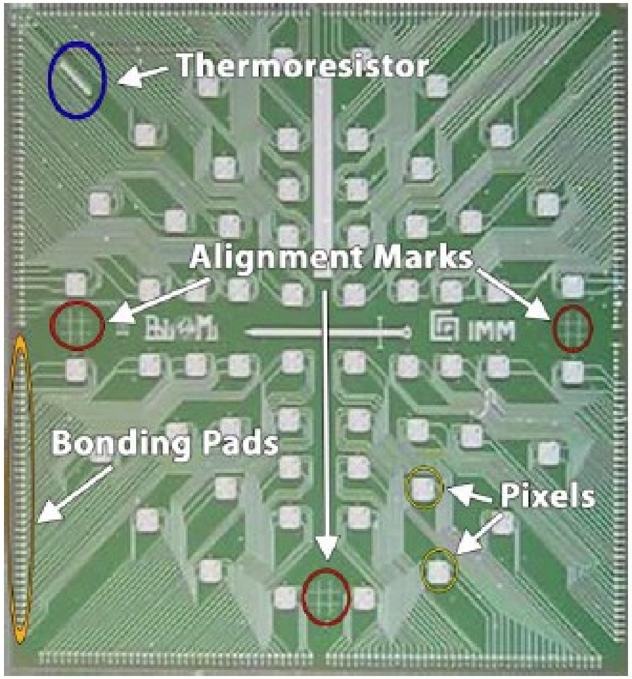
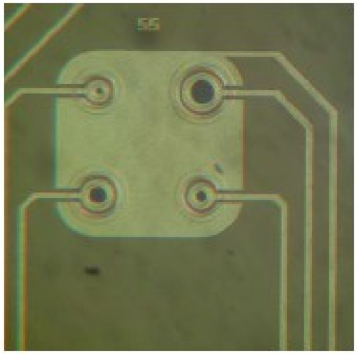
***Single photon counting is possible, but at low temperature (T~77K) and with slow electronics (PDE~20%)***

*A. Dorokhovet.al.,JournalMod.Opt. v51 2004 p.1351*

# SPAD Arrays with electronics "integrated"

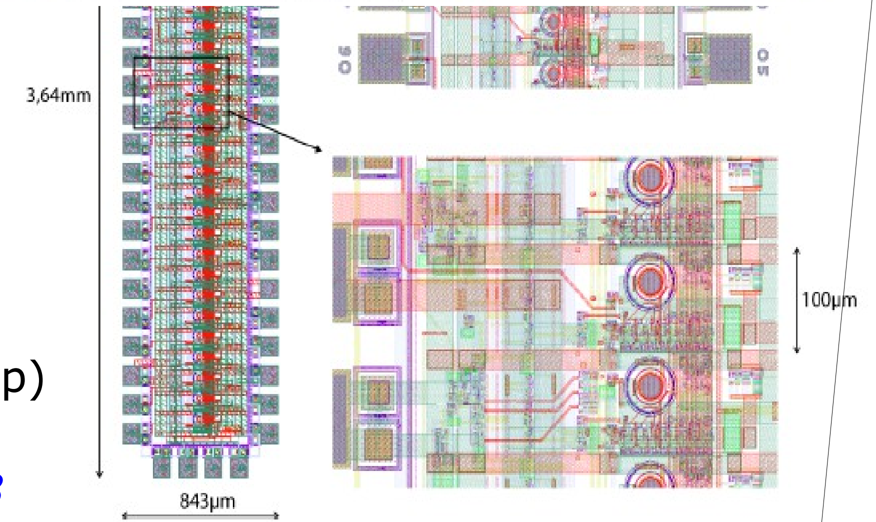


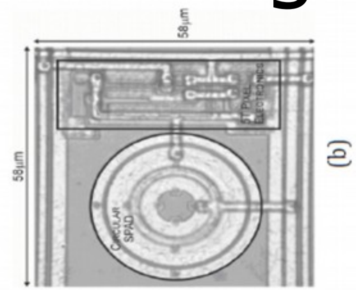

- quenching
- reset
- read-out



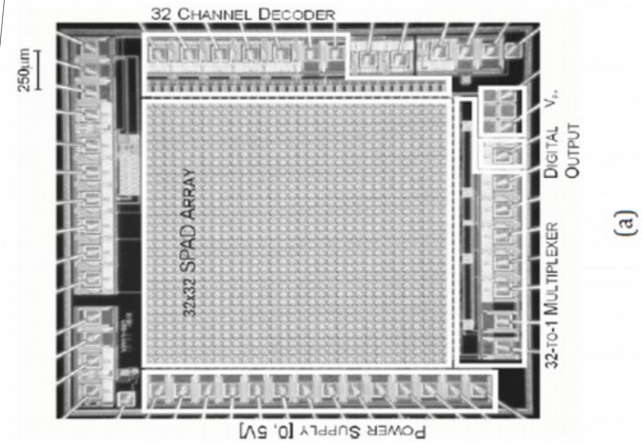
- Cova, Lacaita, Zappa et al since early 90-ies (Politecnico Milano group)

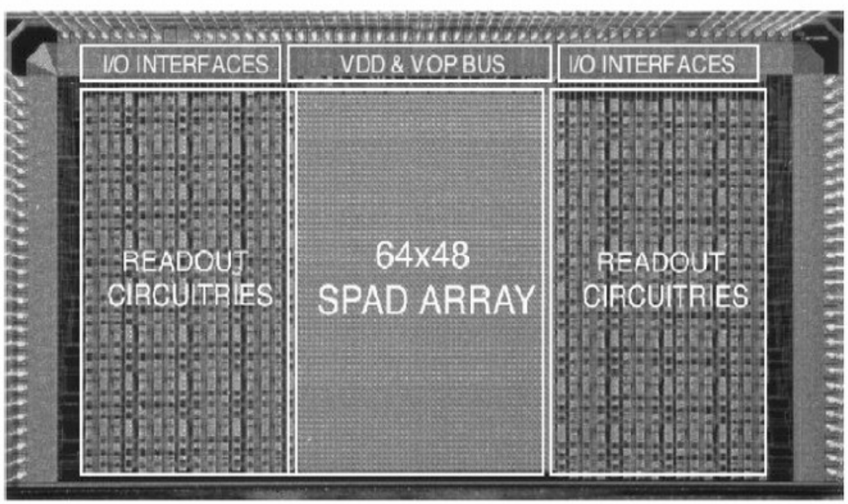
*Guerrieri, NDIP 2008*




*Niclass, PhD Thesis EPFL (2008)*



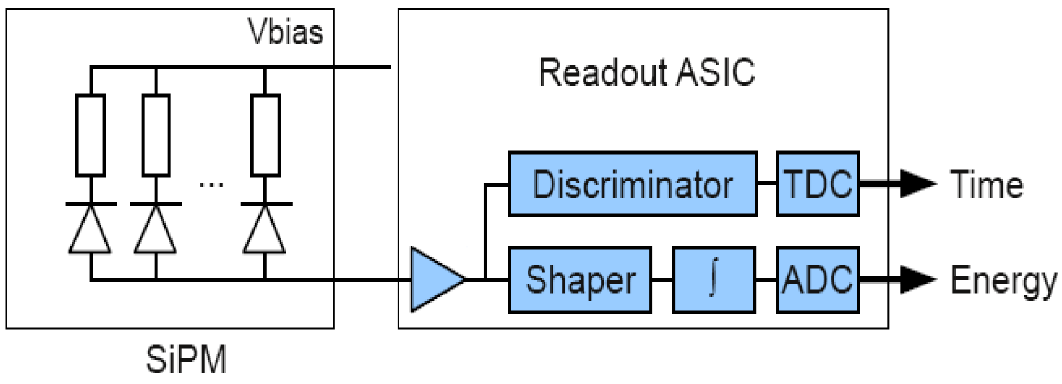




- *Charbon, Rochas, Niclass, et al (EPFL Lousanne group)*

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

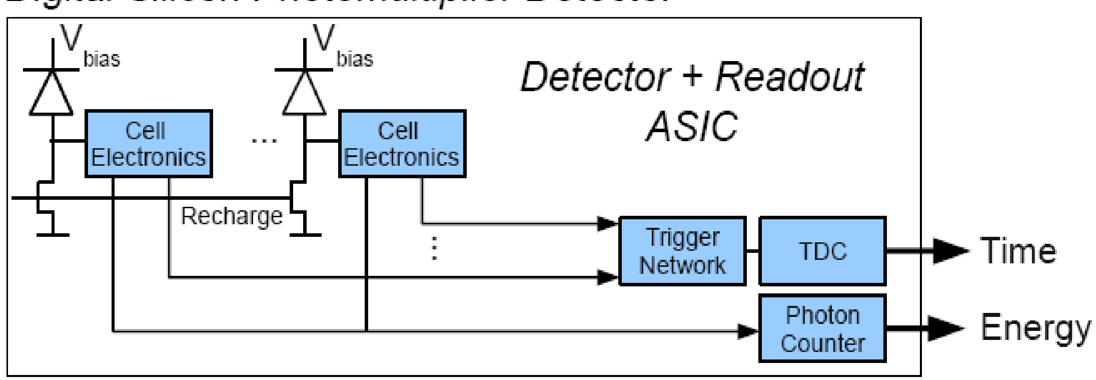
# Digital vs Analog SiPM

*Analog Silicon Photomultiplier Detector*



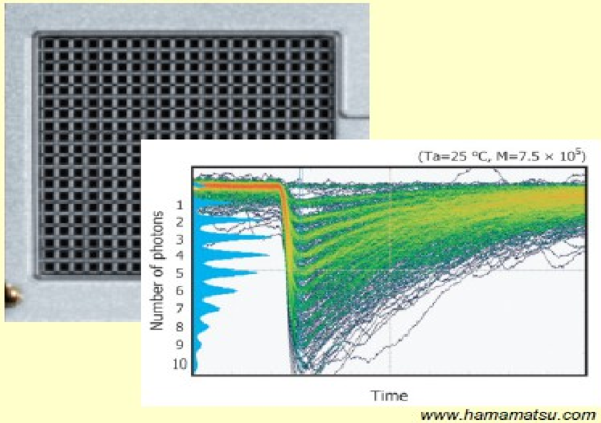

*T.Frach - Heraeus Seminar 2013*

*Digital Silicon Photomultiplier Detector*



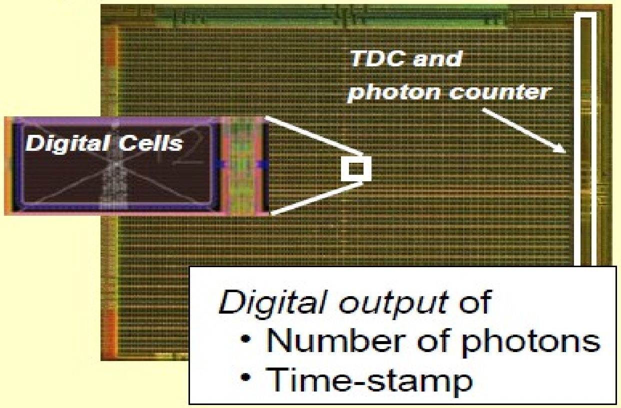

d-SiPM:
- for each light pulse → output is: time-stamp and number of photons
- control of individual cells
- O(500ns) RO dead time (upon trigger)

## Analog SiPM




- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

## Digital SiPM




- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

## Trends and optimal operation of Analog SiPMs:

- tiny cells
- low Temperature

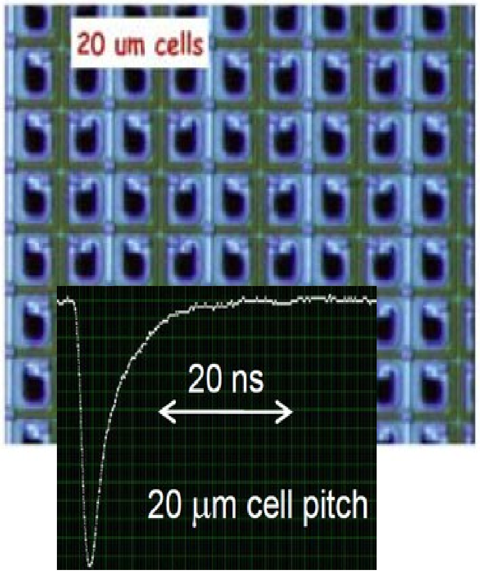
# Trends in analog SiPM – tiny cells

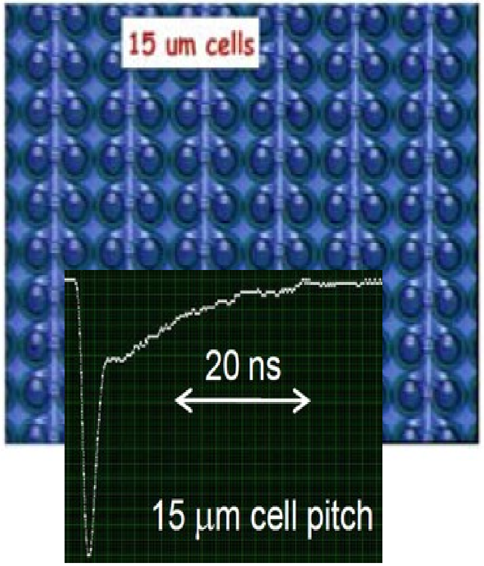
## Tiny cell → better performances

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

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

tiny cell MPPC (2012) by Hamamatsu



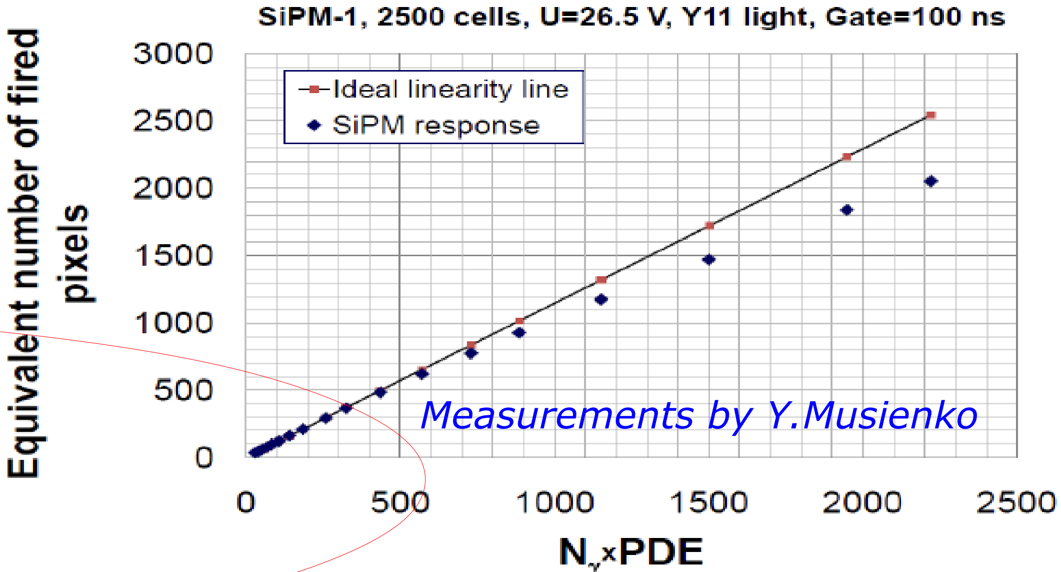

SiPMs NDL (Bejiing)

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

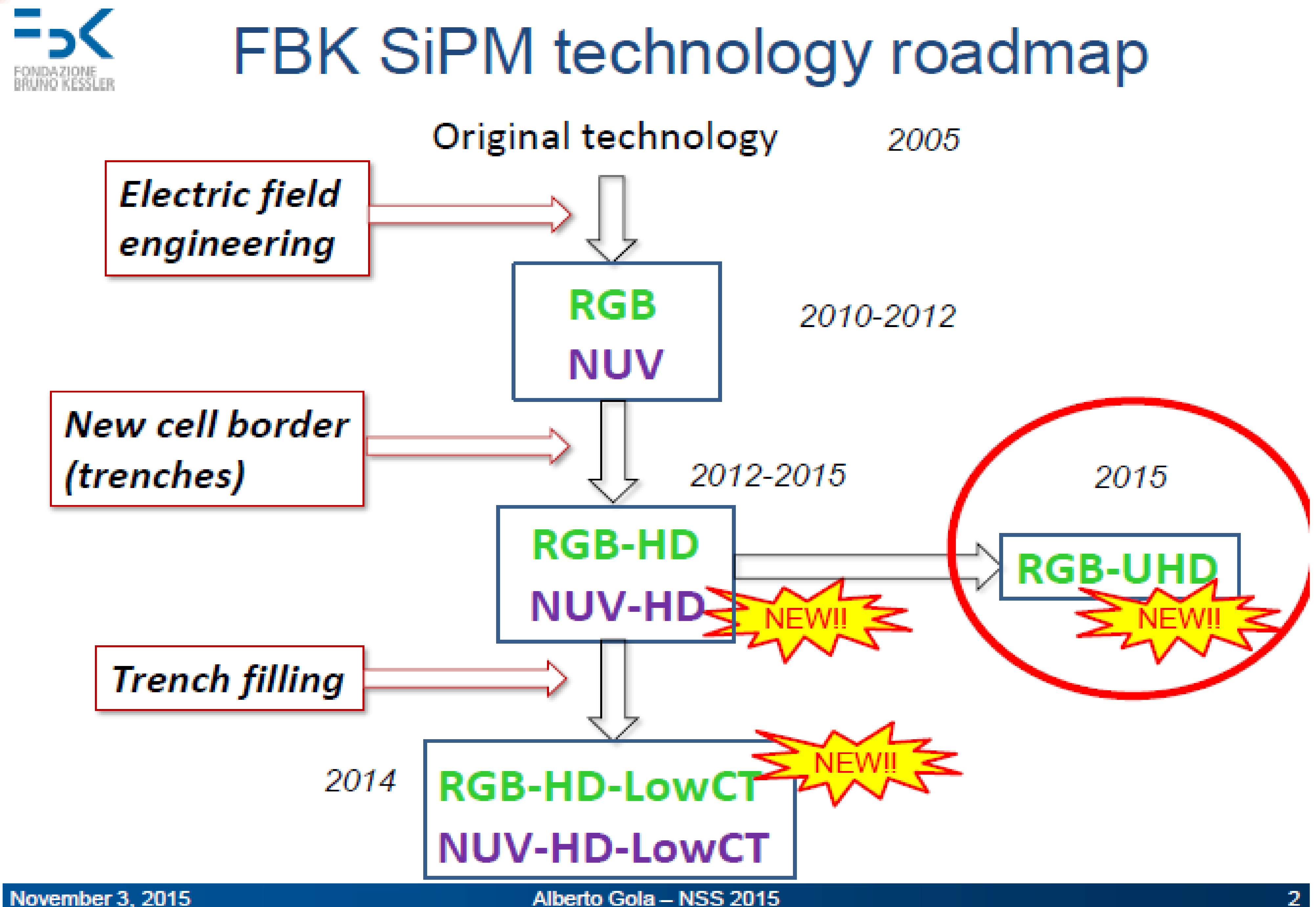
- type: n-on-p, Bulk Rq
- high cell density (10000/mm$^2$)
- fast recovery (5ns)
- low gain
- **better timing**

→ **dynamic range**

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



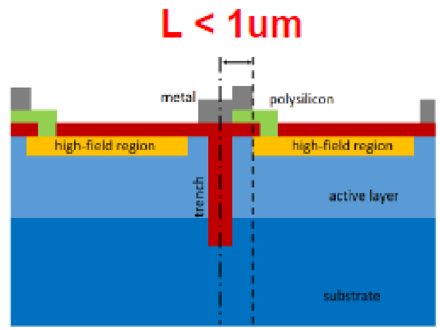
# Trends in analog SiPM – tiny cells



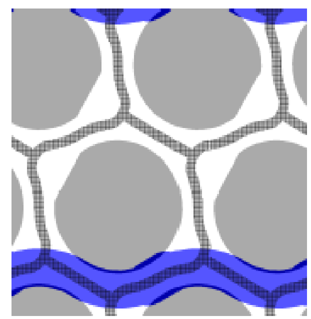
# Trends in analog SiPM – tiny cells

Reduction of all the feature sizes
- Contacts
- Resistor
- ..

Reduction of the active-to-border distance (L)



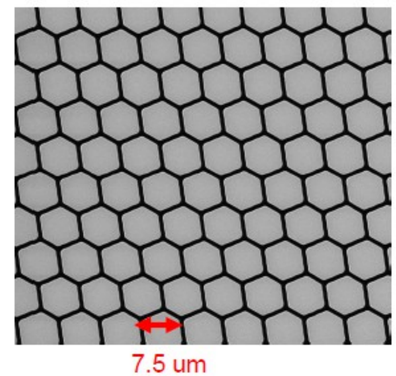

Circular active area (smallest cells)
- No corners (with lower field)
- Hexagonal cells arranged in honeycomb configuration



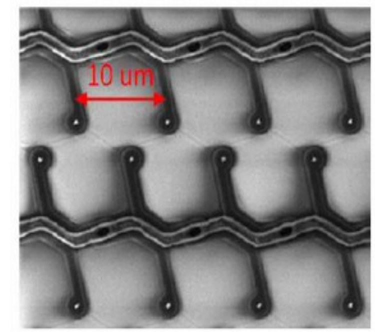
Lower Rq
- For even faster recharge

## UHD technology

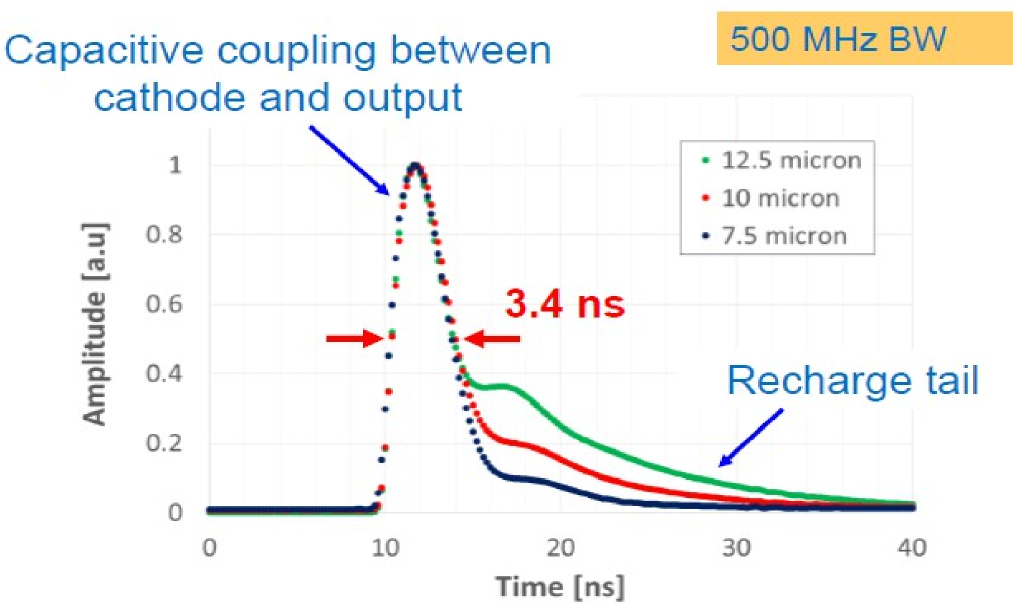
SEM images

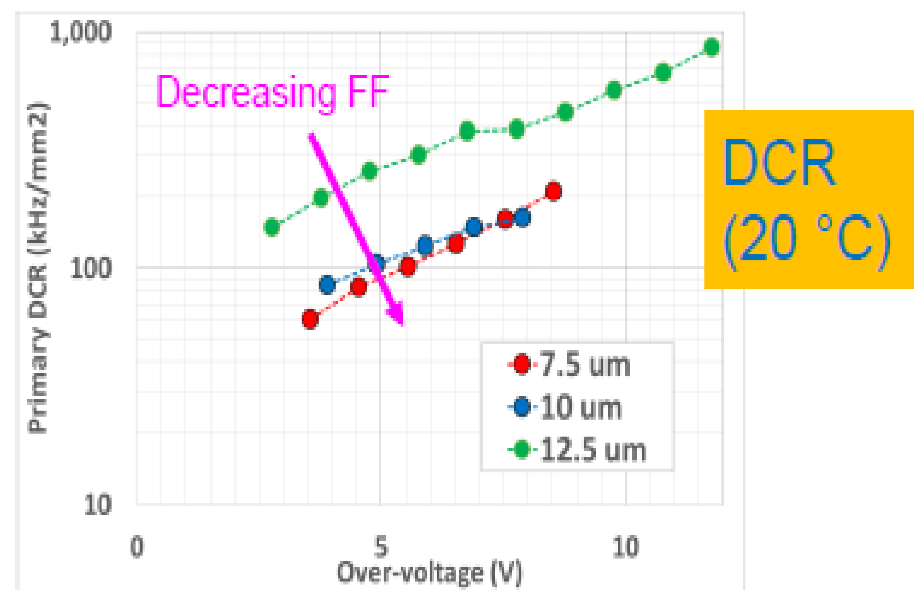



Microcells separated by trenches (7.5 um)




Finished SiPM (10 um)



# Trends in analog SiPM – tiny cells

## UHD technology

Reduction of all the feature sizes
- Contacts
- Resistor
- ..

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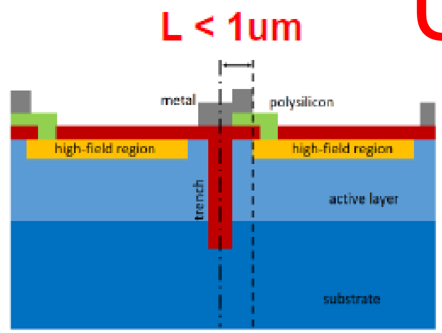


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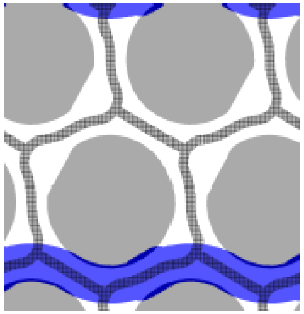
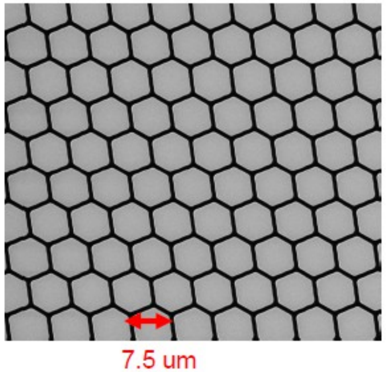
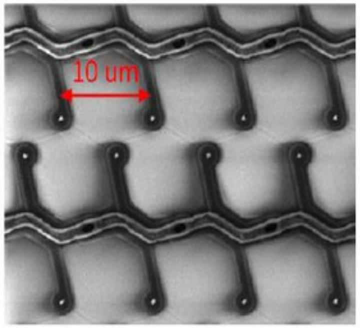


Lower Rq
- For even faster recharge

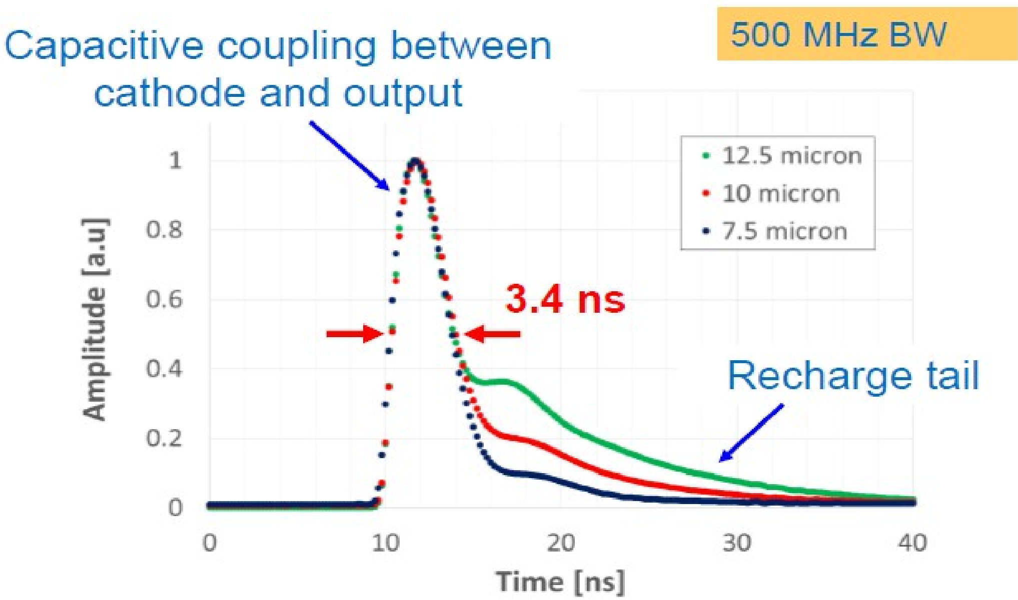
SEM images

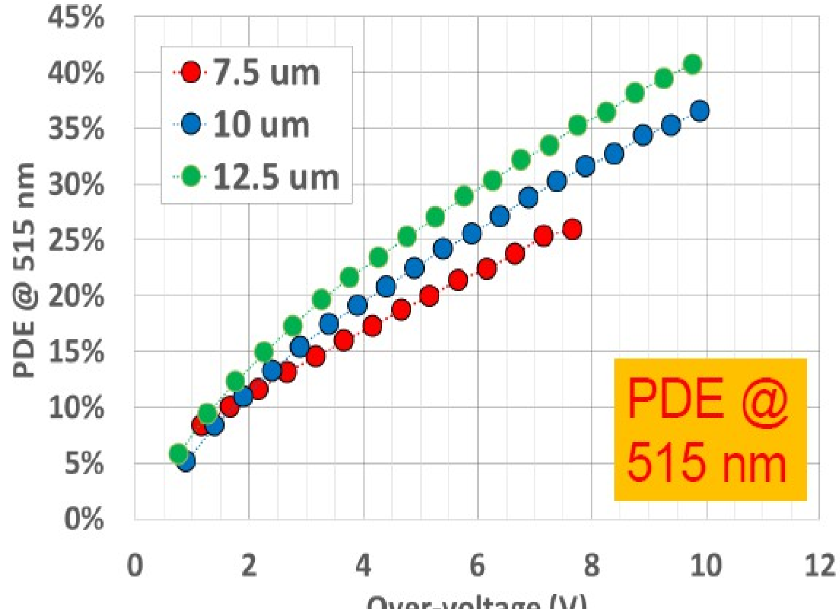



Microcells separated by trenches (7.5 um)




Finished SiPM (10 um)



# Trends in analog SiPM – tiny cells

## Measurements after Irradiation

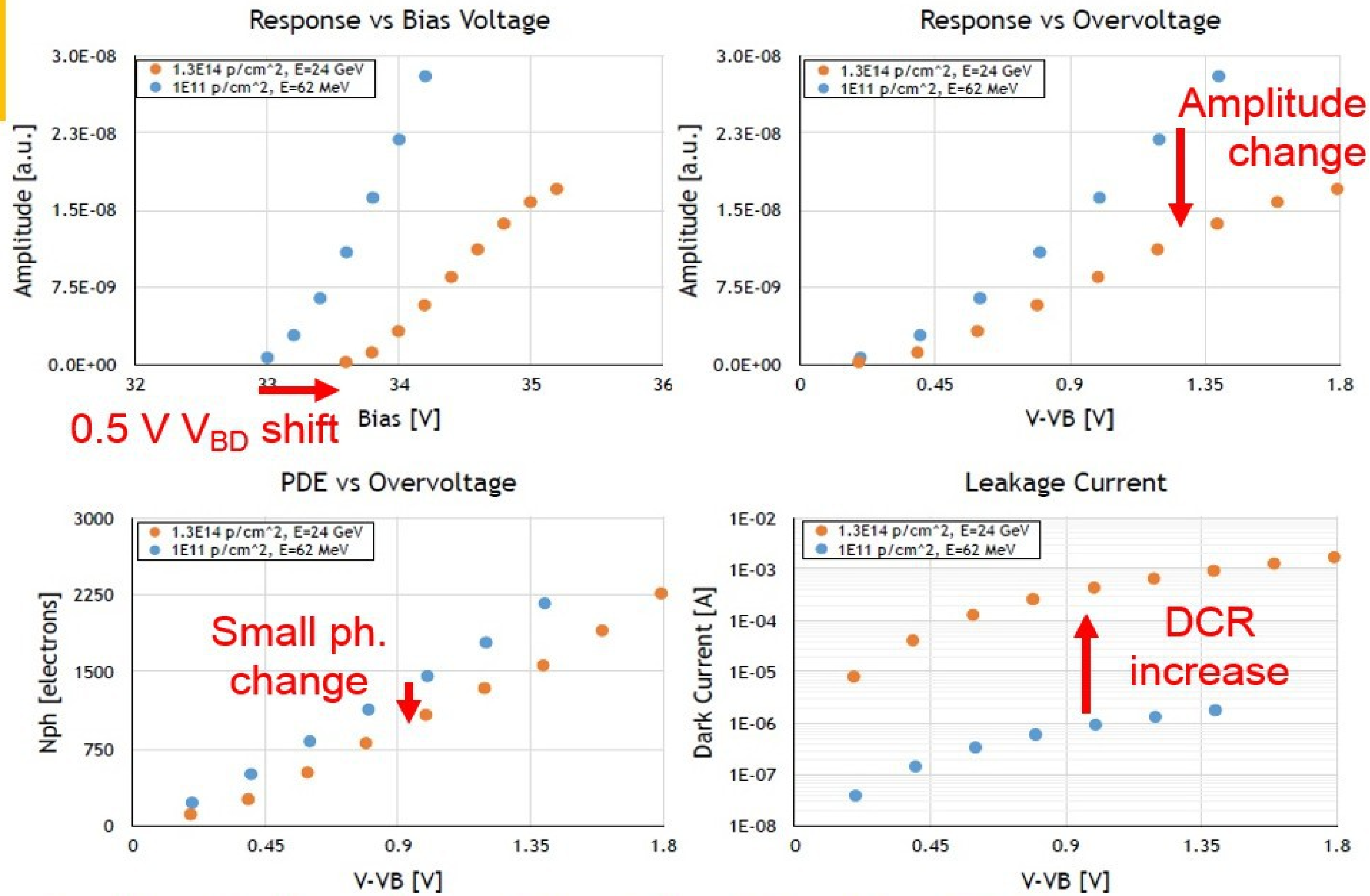
FONDAZIONE BRUNO KESSLER

### - FBK 1 mm$^2$ 12 micron cell with thin epitaxial layer

**~2.2E14 1 MeV eq. n/cm$^2$**

Measured at T= 23 Celsius

- Small bias shift of 0.5V
- Low PDE change
- Dark current 1 mA/mm$^2$
- Gain reduction due to self heating of the device




Presented by A. Heering at the Pisa Meeting 2015

# Applications of tiny cells

## Calorimetry

- **CMS calorimeter Phase II Upgrade** → R&D funding.
- Reduced non-linearity at high energy thanks to high cell density and fast recharge time.
- Reduced correlated noise.

## Applications requiring radiation hardness

- Small cells are less sensitive to the effects of radiation damage.
- CMS calorimeter Phase II Upgrade.

## Prompt Gamma Imaging in Proton Therapy

- Requires larger dynamic range with respect to typical SiPM applications in medical imaging (PET, SPECT..).
- High-rate.

# Trends in analog SiPM – low T

## Functional characterization of NUV-HD FBK Silicon Photomultipliers from 300 K to 40 K

[1]Alberto Gola, [1]Fabio Acerbi, [1]Alessandro Ferri, [2]George Korga, [3]Andrea Mandarano, [1]Giovanni Paternoster, [1]Claudio Piemonte, [4,5]Alessandro Razeto, [1]Veronica Regazzoni, [4]Davide Sablone, [3]Claudio Savarese, [1]Nicola Zorzi

FONDAZIONE BRUNO KESSLER

### Devices Under Test

INFN Istituto Nazionale di Fisica Nucleare

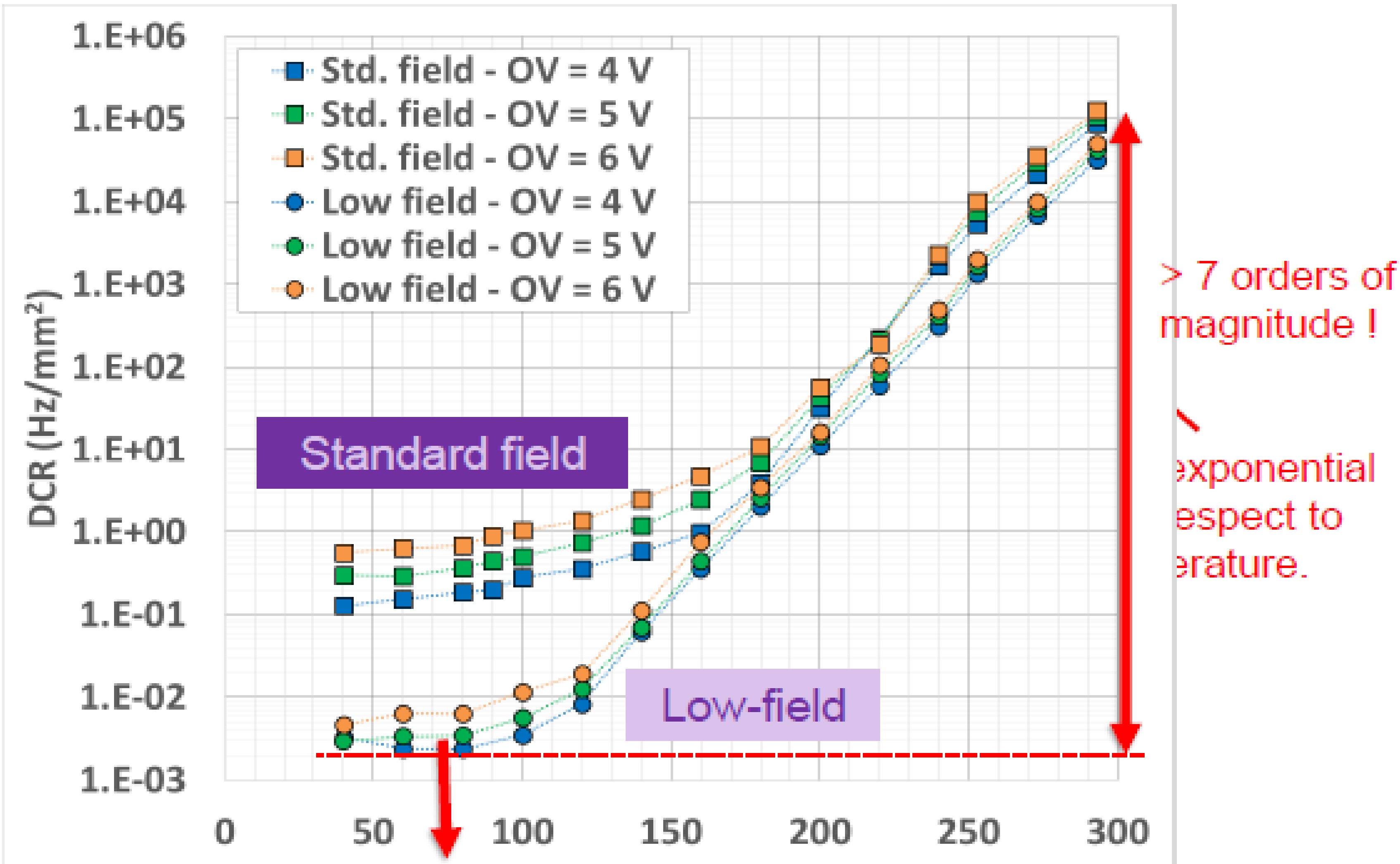
| Parameters (@ room T) | RGB-HD Std. field | NUV-HD Std. field | NUV-HD Low-field |
|---|---|---|---|
| Cell Size | 25 μm | 25 μm | 25 μm |
| Fill Factor | 73% | 73% | 73% |
| Breakdown Voltage | 28 V | 26.5 V | 32 V |
| Max PDE | 45% | 50% | 50% |
| Peak PDE λ | 550 nm | 410 nm | 410 nm |
| DCR (20°C) | < 300 kHz/mm² | < 150 kHz/mm² | < 150 kHz/mm² |
| DiCT | 20% | 25% | 25% |
| DeCT + AP | 20% | 2% | 2% |

Tested Devices

Optimized for low temperature operation

# Trends in analog SiPM – low T

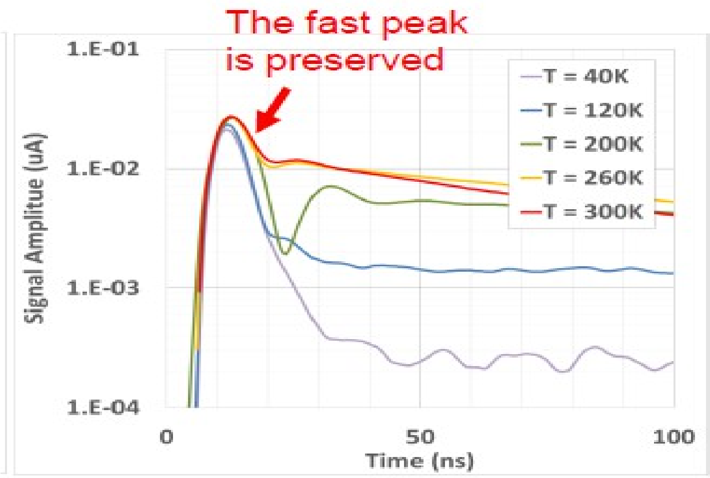
## DCR / mm² vs. Temperature



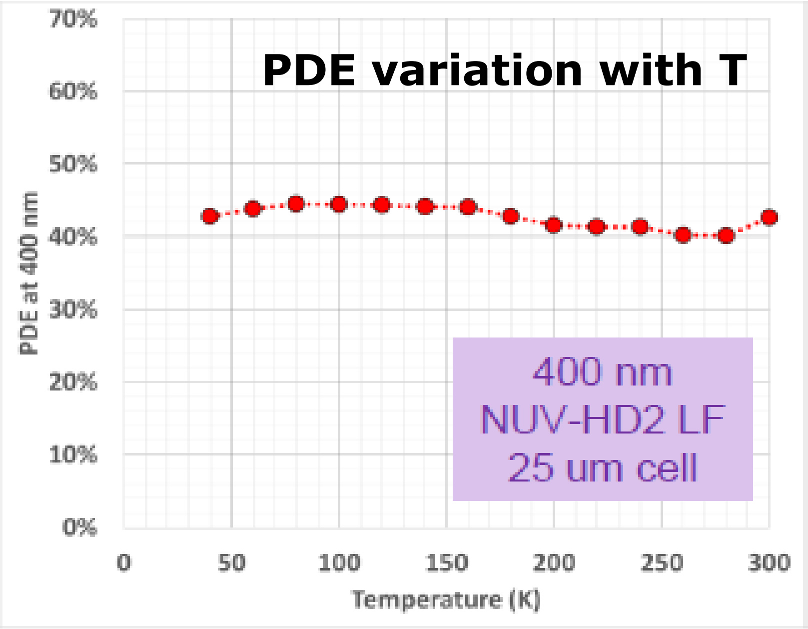

A 10x10 cm² SiPM array would have a total DCR < 100 Hz!

# Trends in analog SiPM – low T

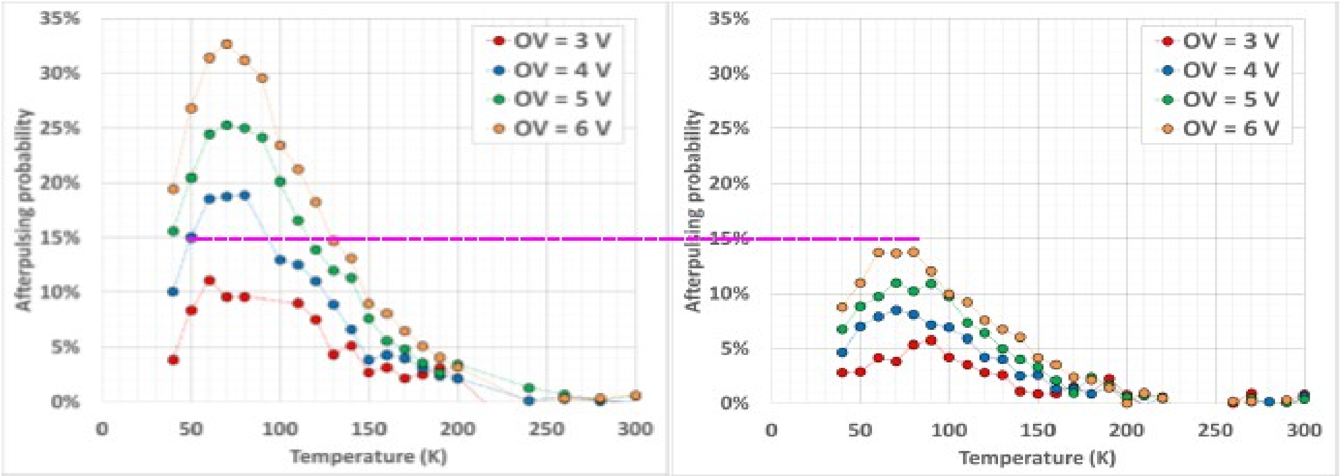
**Signal shape**




Zoom of the first part of the SCR




**After-pulsing**




Standard field

Low-field

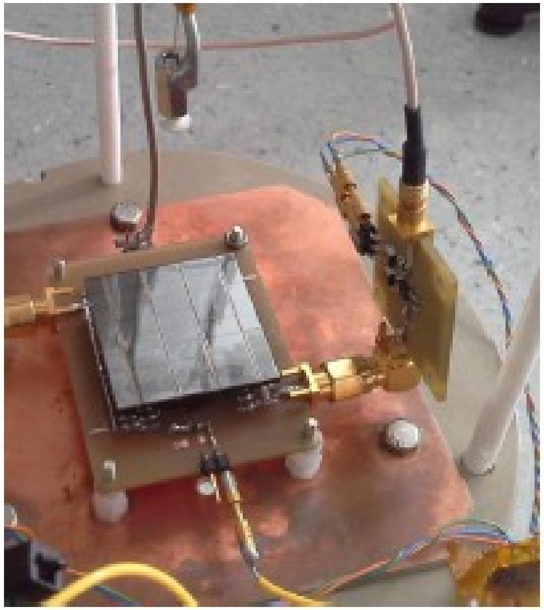
# Trends in analog SiPM – low T

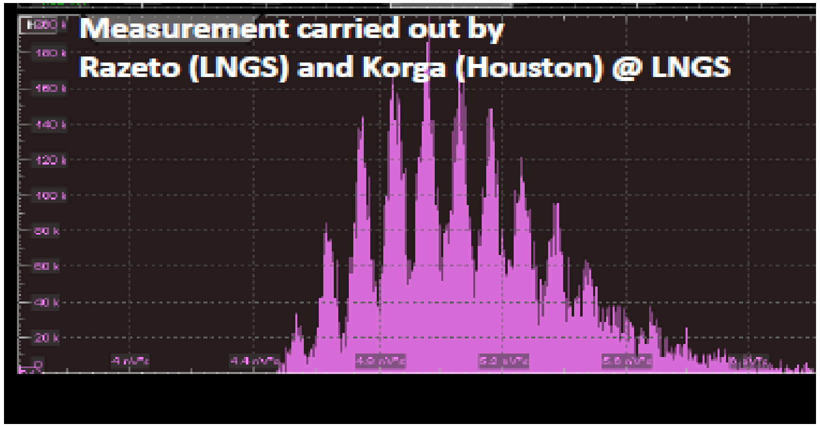
The DCR of the NUV-HD LF is extremely low: < 10 mHz / mm$^2$.

It is possible to build 100 cm$^2$ SiPM tiles with DCR < 100 Hz!

The correlated noise is under control, also thanks to the increase of the recharge time constant. The signal amplitude is not attenuated at cryogenic temperatures.

It is possible to readout a 10 cm$^2$ SiPM tile with one electronic channel, obtaining relatively fast signal and photon counting capability.





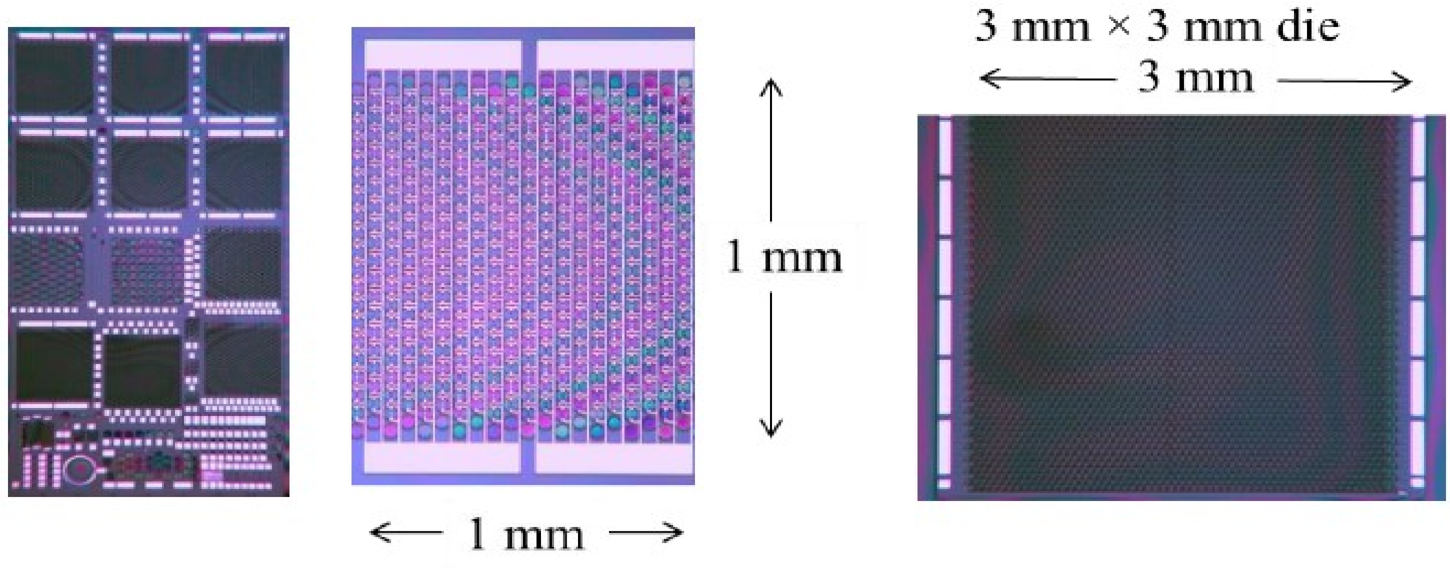

**Single-photon spectrum visible!!**
- low noise
- very uniform behavior of the SiPMs!!

# GM-SSPD
# w/ compound semiconductors

# New generation of SSPDs – Compound

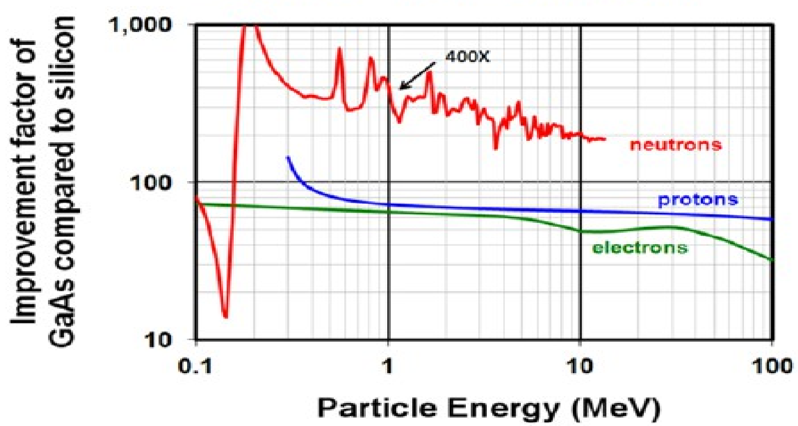
## GaAs Photomultiplier Chips™

*Harmond - NDIP 2014*

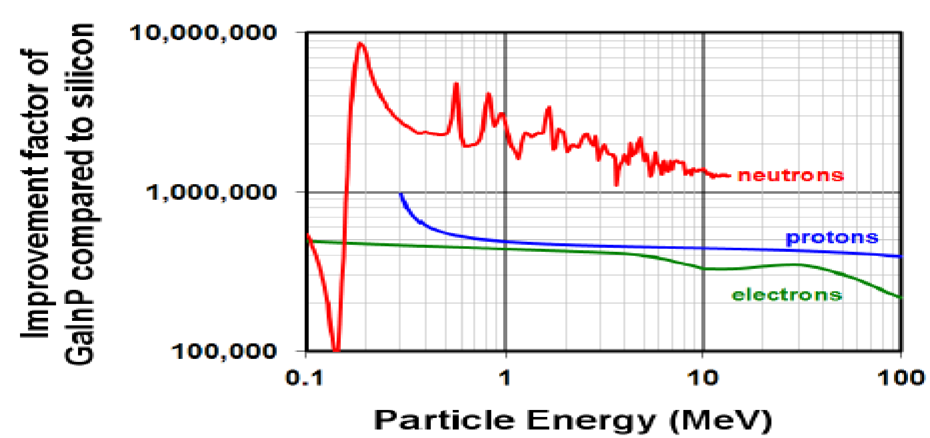



LightSpin Technologies, Inc. 16

### Radiation Hardness GaAs vs. silicon

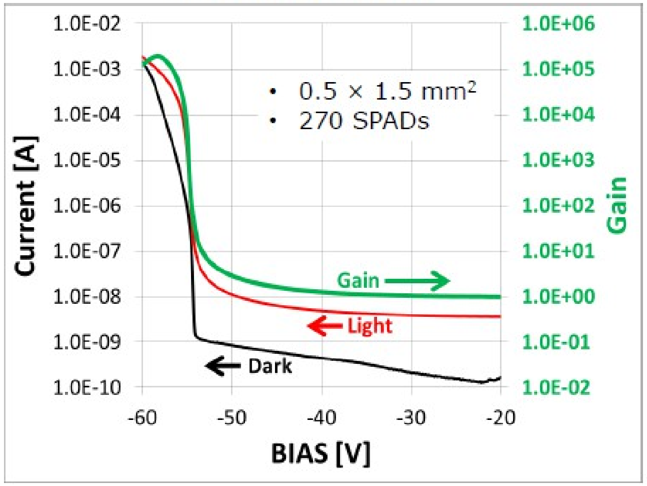



### Radiation Hardness GaInP vs. silicon

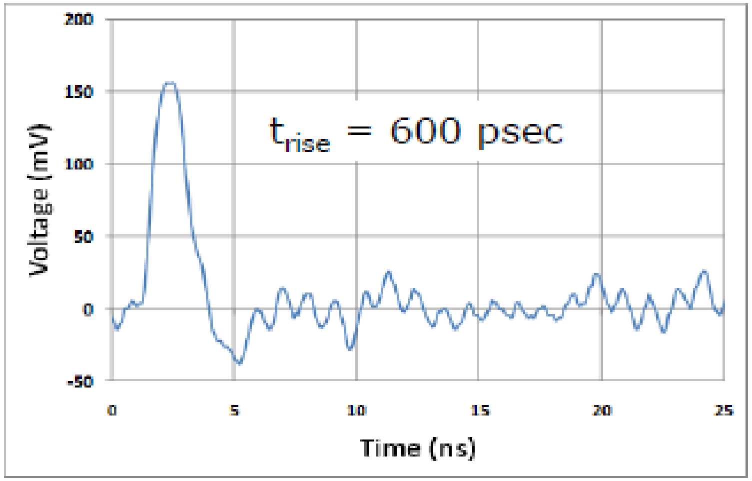


# New generation of SSPDs – Compound

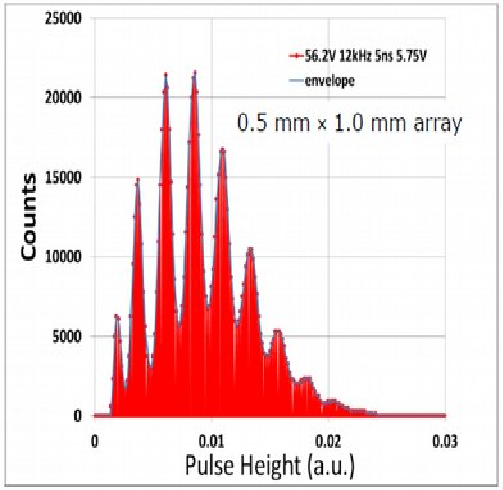
I-V curves




Packaged 1.0 mm × 1.0 mm array

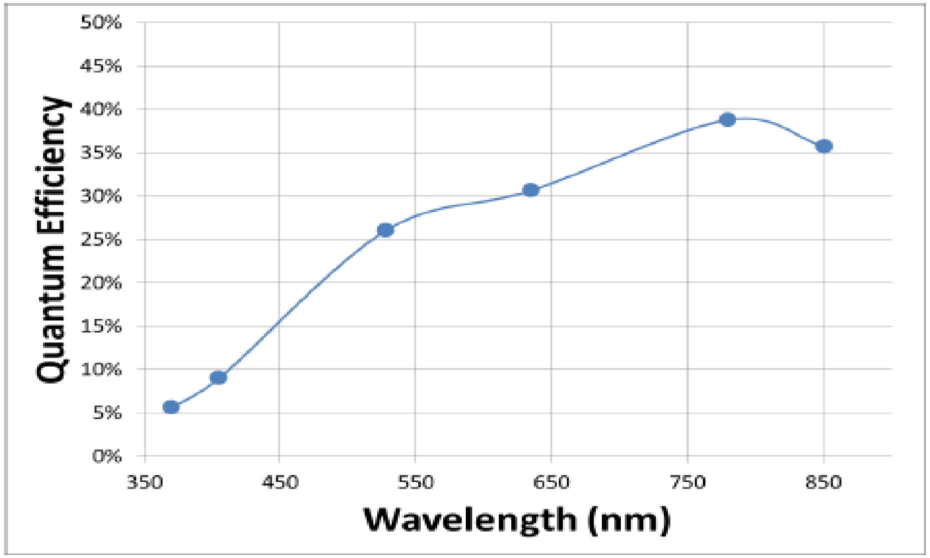



Photon Number resolving

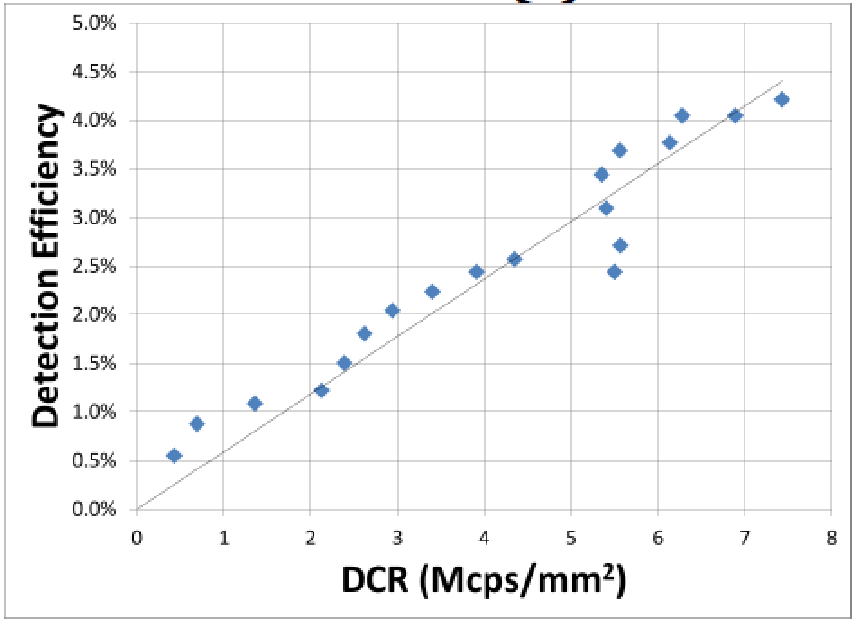



*Harmond - NDIP 2014*

Quantum Efficiency




DE vs. DCR @ 770 nm



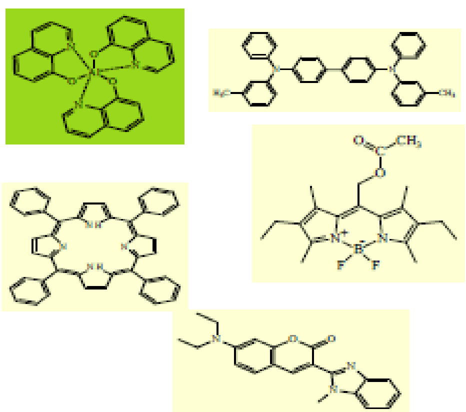

LightSpin Technologies, Inc.

# Organic Semiconductors

# SSPDs – Organic Semiconductors

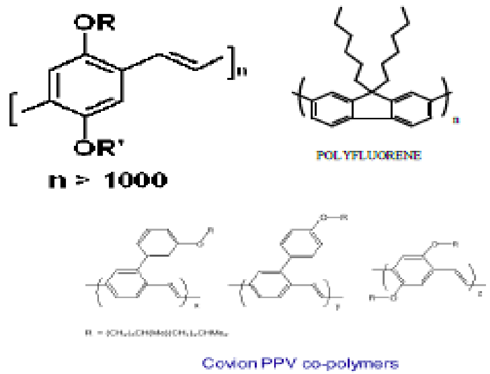
## Two types

**'Small molecules' M ~ <800**



**Vacum deposition**

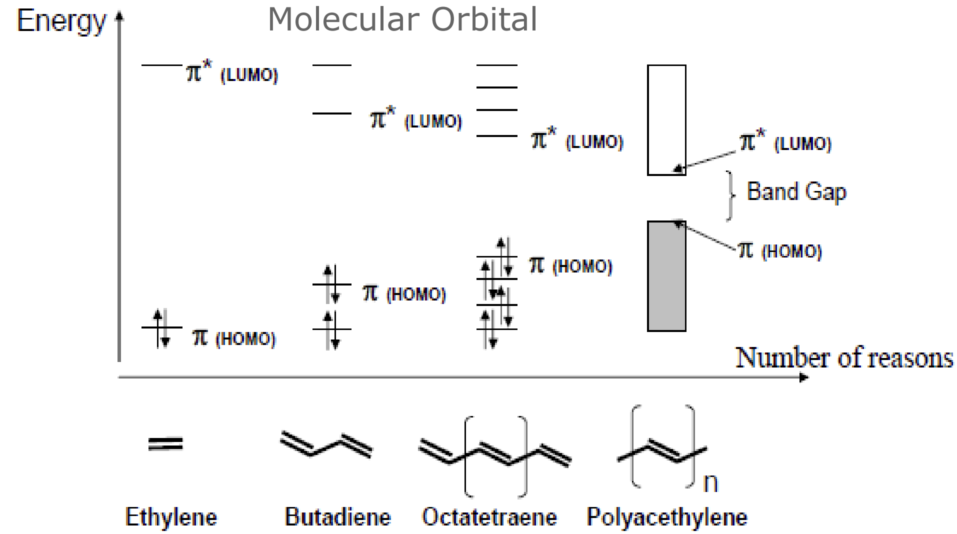
**Polymers**




**Liquid deposition**

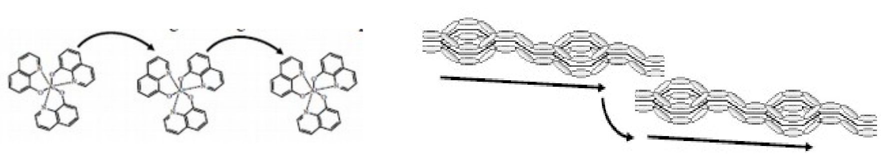
Highest Occuped    Lowest Unoccupied

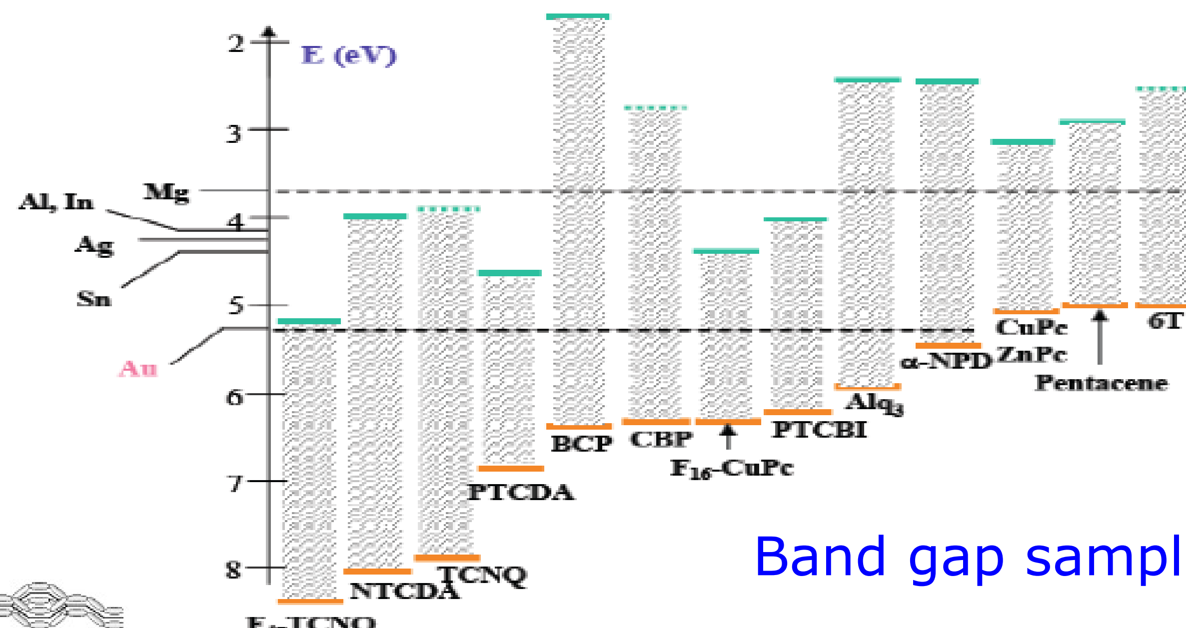
## HOMO/LUMO levels




- Conjugation
  (alternating single/double bonds)
  → electron delocalization
- σ bonds → linking molecules
- π bonds → electronic properties

- Charge Transfer:
- small molecules: hopping
- polymers: delocalisation along HOMO/LUMO bands






## Band gap samples

N. Koch et al., Appl. Surf. Sci. 2003, 82, 70

# SSPDs – Organic Semiconductors

## Carrier mobilities in organic thin films

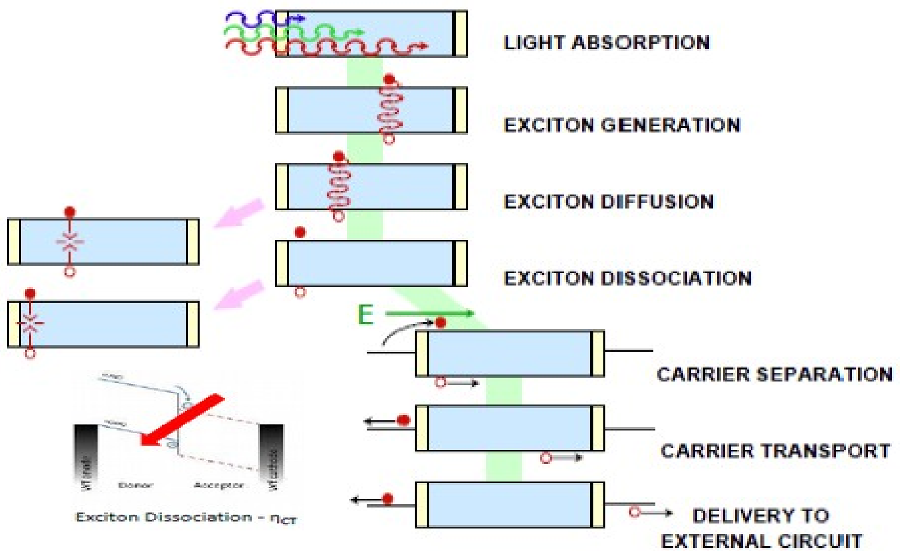
| Material | Electron (e) or hole (h) mobilities ($cm^2/(V\,s)$) | Reference |
|---|---|---|
| | Organic | |
| Polythiophene (spin-coated films) | $10^{-4} - 10^{-2}$ (h) | [21] |
| Polythiophene (aligned by drawing method) | | |
| parallel to the alignment direction | $0.9 * 10^{-4}$ (h) | [22] |
| perpendicular to the alignment direction | $7.4 * 10^{-4}$ (h) | [22] |
| Polythiophene (printed) | $0.1$ (h) | [20] |
| MDMO-PPV/PCBM (spin-coated films) | $2 * 10^{-7} - 5 * 10^{-6}$ (h),<br>$2 * 10^{-5} - 4 * 10^{-4}$ (e) | [23]<br>[23] |
| Oligothiophene | $0.1 - 0.5$ (h) | [24] |
| Pentacene (polycrystalline) | $0.3 - 1.0$ (h) | [25] |
| Pentacene (single crystal) | $2.0$ (h) | [26] |
| | Anorganic | |
| c-Si | 1400 (e), 480 (h) | [27] |
| c-GaAs | 8000 (e), 400 (h) | [28] |

*Bonnassieux - NDIP 2011*

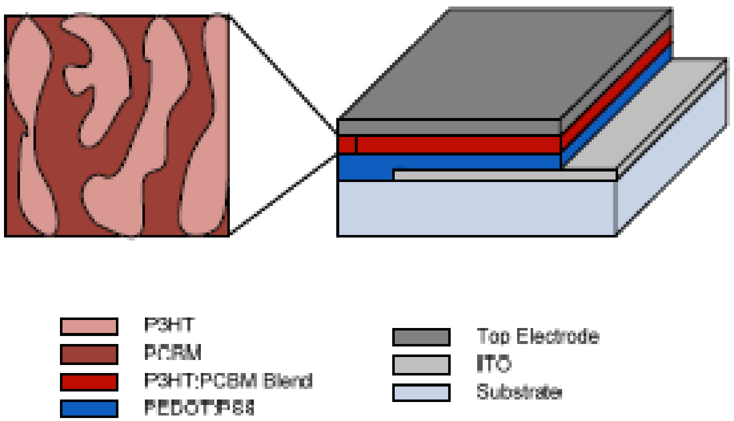
# SSPDs – Organic Semiconductors

## Photo-Detector operating principles

**photon absorption, creating excitons** Excitons = bound hole/electron pairs

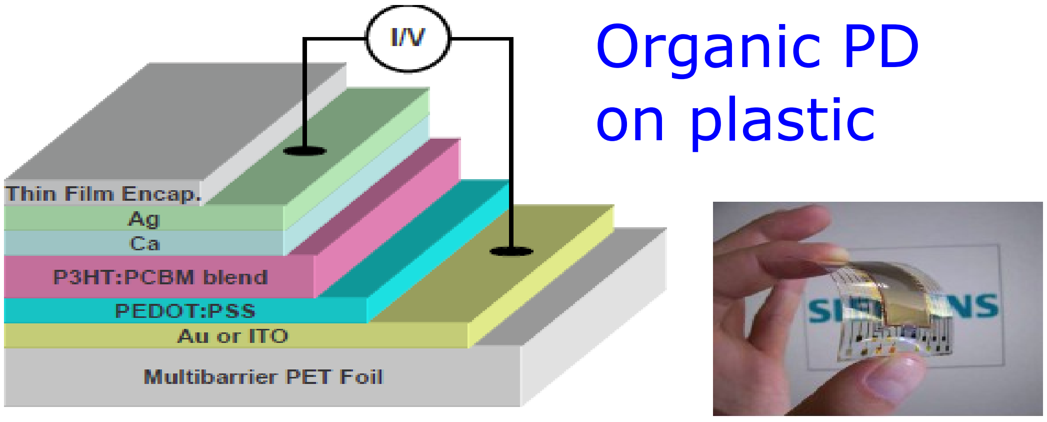



## Organic PD on glass

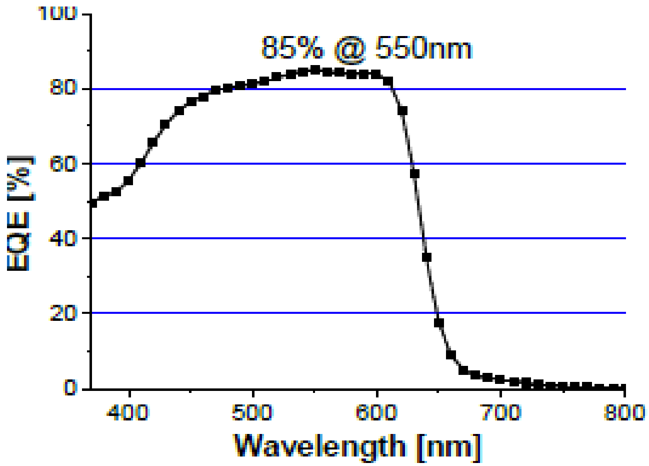



S. Tedde *et al.*, Nano Letters 9 (3), 980 (2009)

Typical exciton diffusion length in conjugated polymers: $L_d$~10nm
(Optimum domains length ~$2L_d$)

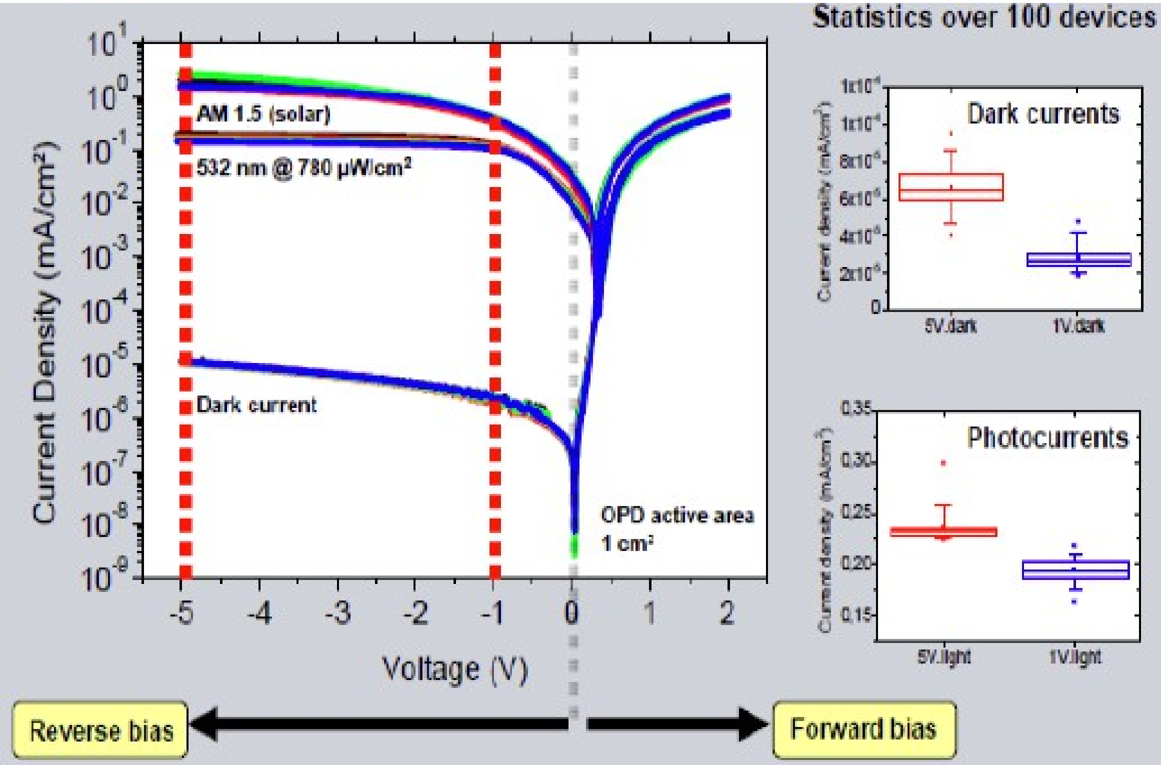



## Organic PD on plastic

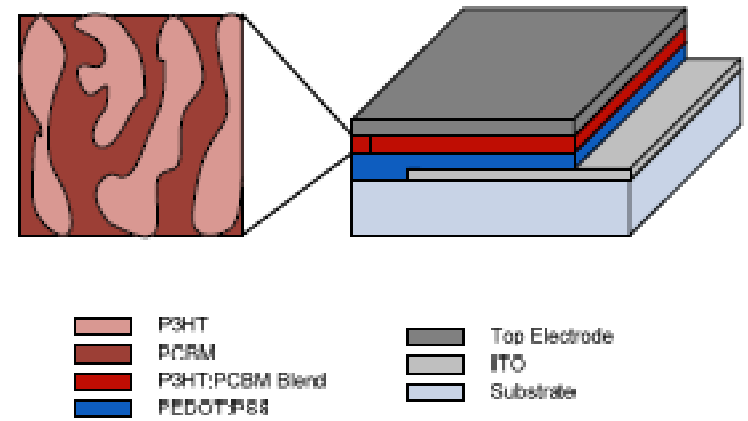


# SSPDs – Organic Semiconductors

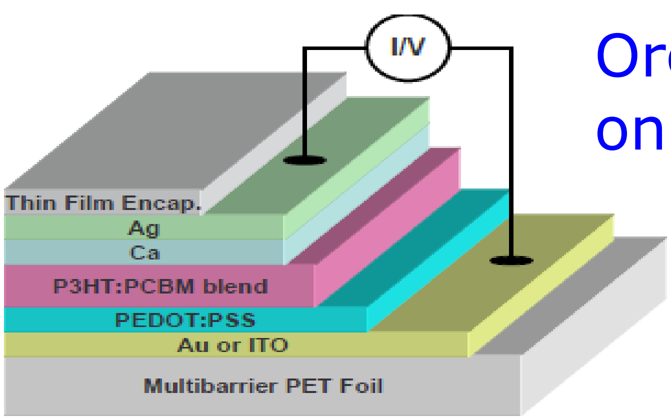
## Photo-Detector operating principles



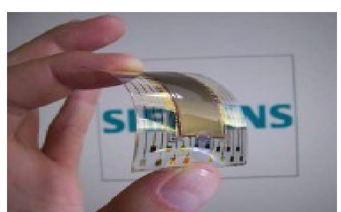

## Organic PD on glass

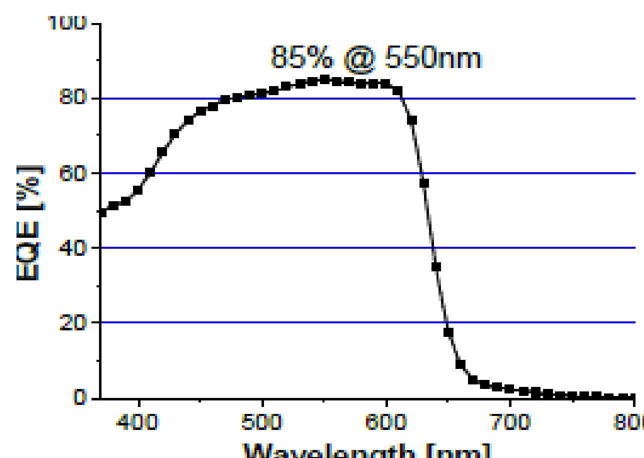



S. Tedde *et al.*, Nano Letters 9 (3), 980 (2009)



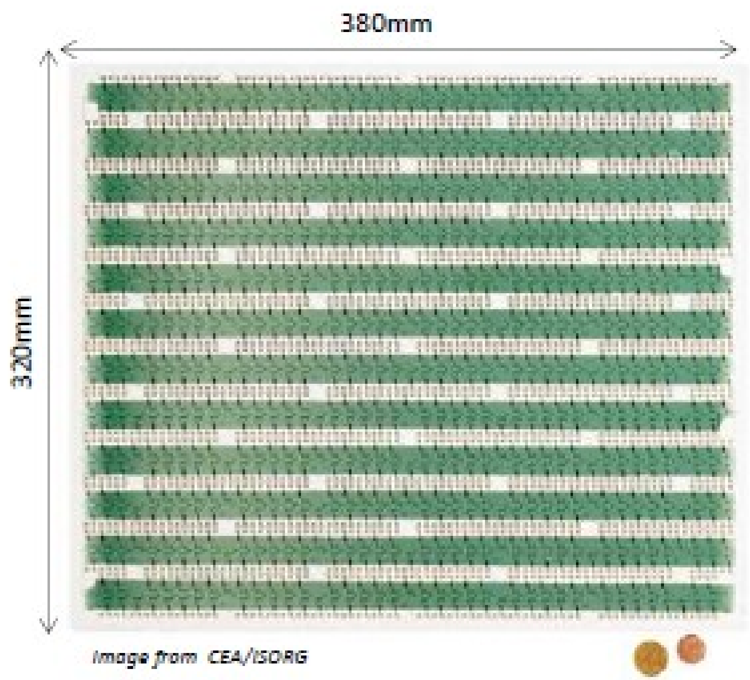

## Organic PD on plastic



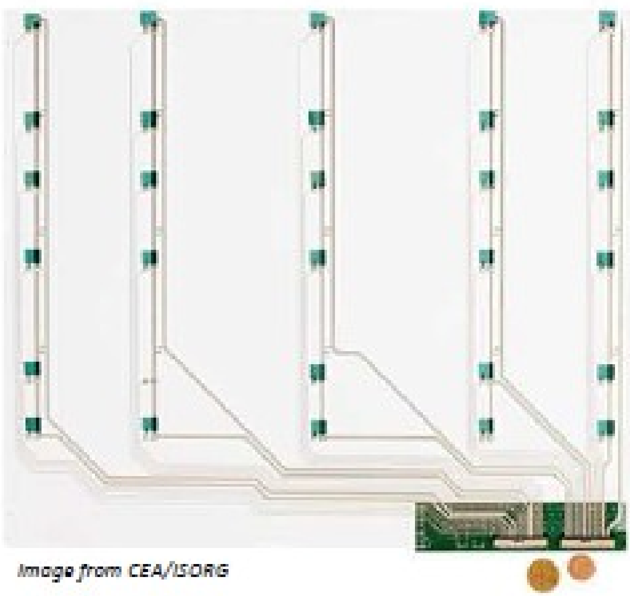


# New generation of SSPDs - OPD

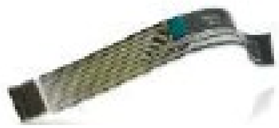
## Printed OPD devices on large area (Gen1)




Fully printed OPD devices (>1000/sheet)



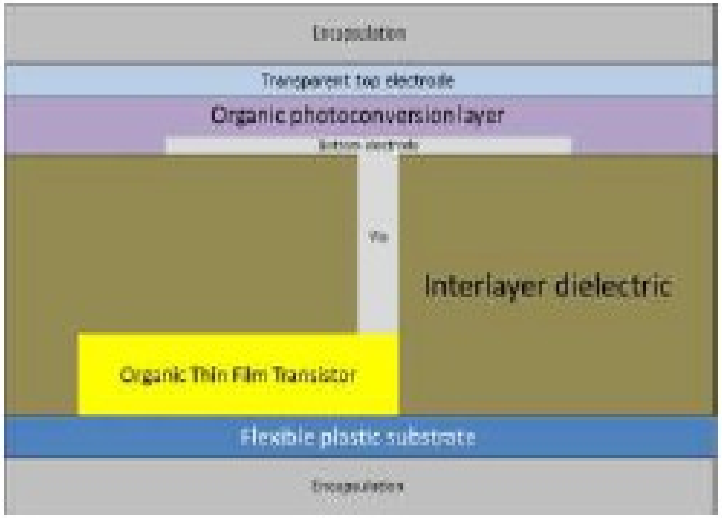

Custom printed OPD designs



*CEA and ISORG (www.isorg.fr)*

# New generation of SSPDs - OPD

- Fully solution-processed and flexible visible imager (OTFT + OPD),
- Collaboration between CEA/ISORG/plastic Logic (Flexi Award 2014),
- Demo substrate size: 50x50mm,
- 96x96 pixels,
- Pixel size = 175µm,
- Pixels spacing = 200µm (<30µm for next demo),
- Process compatible with large area.





*CEA and ISORG (www.isorg.fr)*

# SSPDs – Organic Semiconductors

## Organic advantages

- Metallic and semiconducting properties by doping
- Combination of plastic with electronic properties
- Property engineering
- Solubility in organic solvents, variable processibility
- Use of printing technologies
- No vacuum and no high temperature processes

High absorption coefficients of organic materials,

**Low-cost production**

## Disadvantages

- Low integrated devices and circuits
- Degeneration in $O_2$- and $H_2O$-atmosphere ( → need passivation)

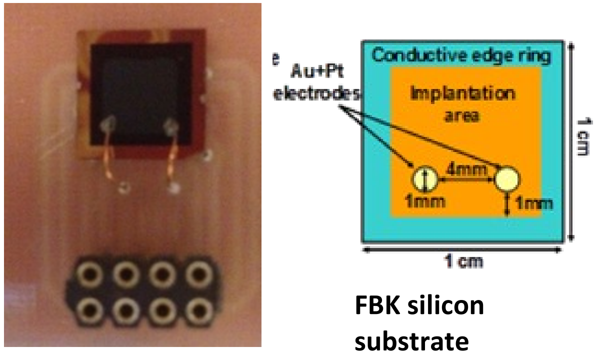
## Integration with CMOS

The combination of organic semiconductors with a CMOS-chip offers advantages compared with a conventional CMOS-sensor:

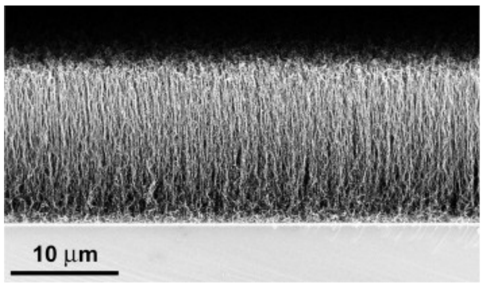
- high photosensitivity -> fill factors up to 100 %
- wavelength tunability -> sensors for infrared/ultraviolet region
- inexpensive fabrication
- subwavelength grading for optimized performance and polarization sensitivity

# SSPDs – CNT-Si heterojunction

## CNT-Si PIN photodiode

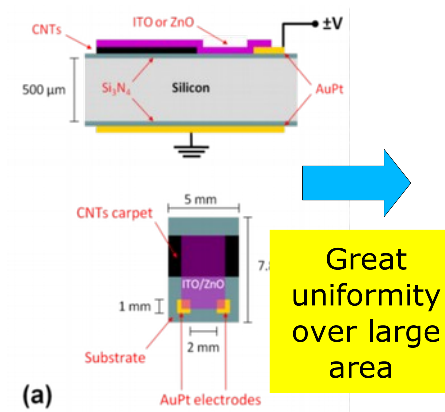


FBK silicon substrate

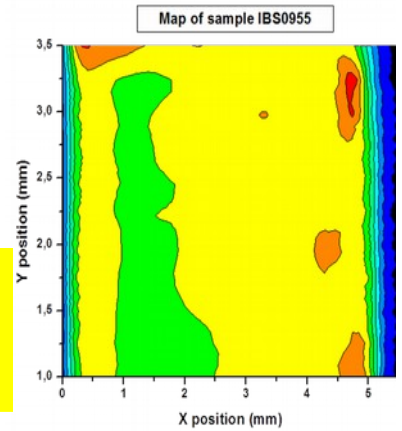


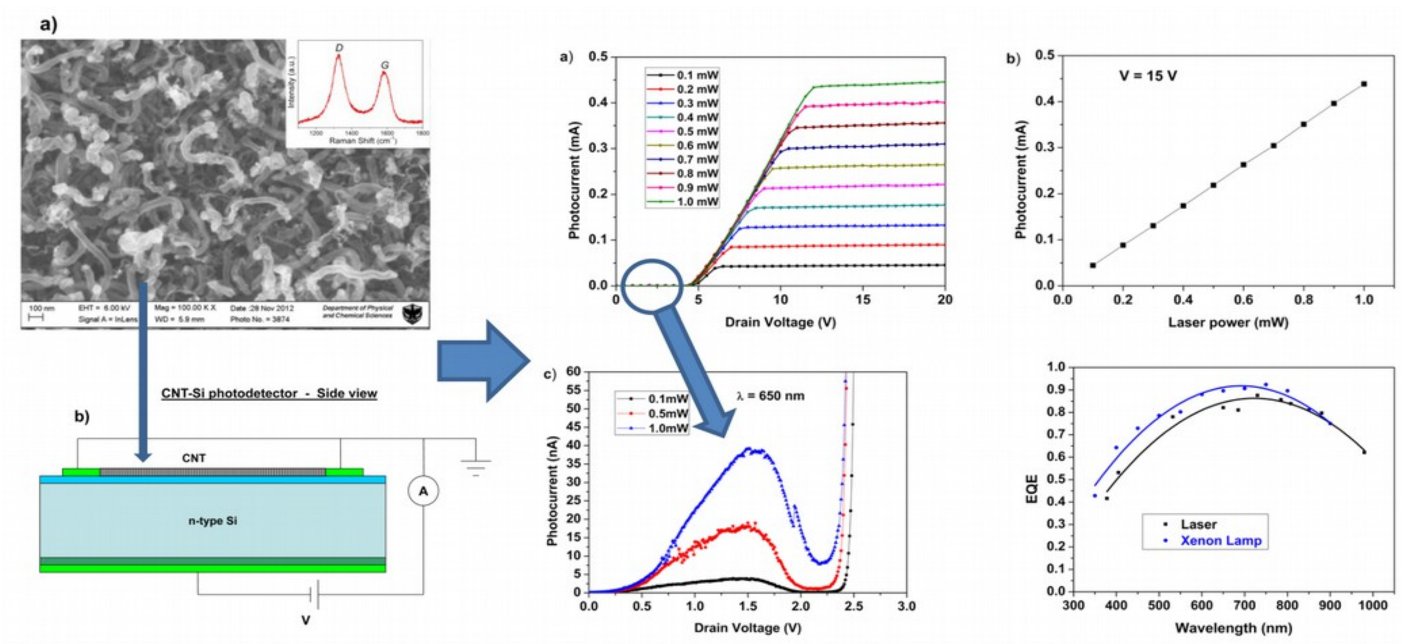
A significant **resonant tunneling effect** below the 2.4V junction threshold has been observed in a **large area** carbon nanotube - silicon (CNT-Si) **heterojunction** obtained by growing a continuous multiwall carbon nanotubes layer on an *n*-doped silicon substrate insulated w/ $Si_3N_4$

Coating



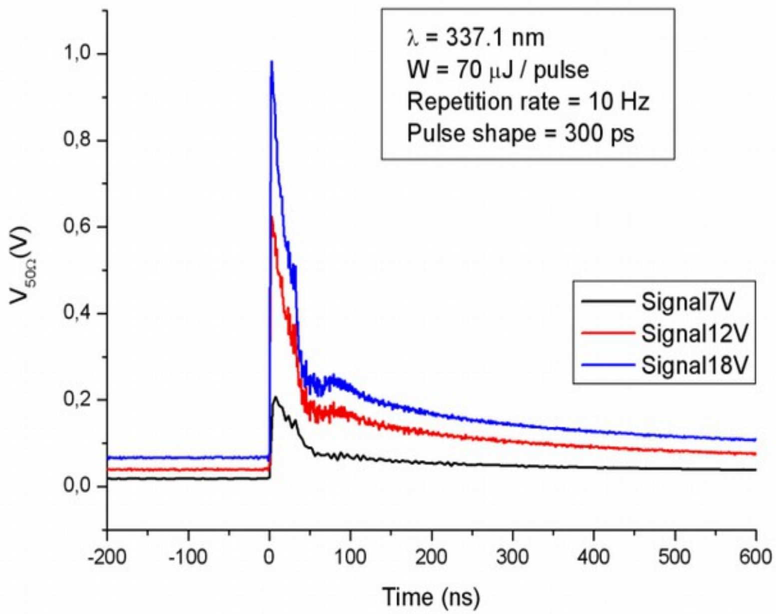
Great uniformity over large area



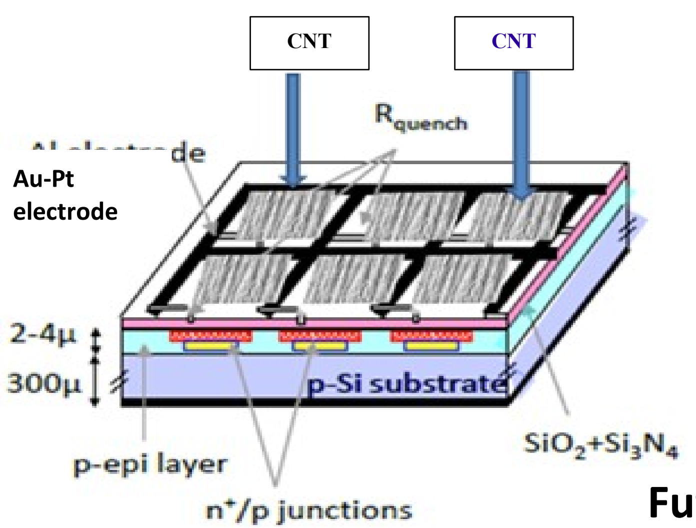


The junction presents **rectifying properties** with a 2.4 V threshold to the flow of reverse current, a strong **photosensitivity** to light radiation with a wavelength between 378 and 980 nm, a very broad plateau extended over a large range of drain voltage and good photoresponsivity **linearity** versus light intensity.

# New generation of SSPDs - Si-CNT

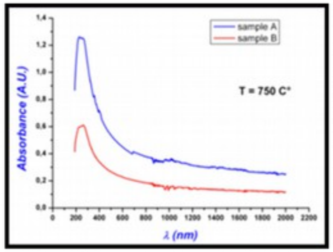



**Signals generated by pulsed light**

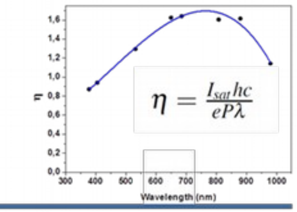



**Future**

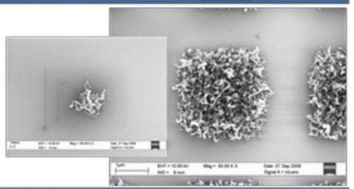
## Main Scientific Challenges



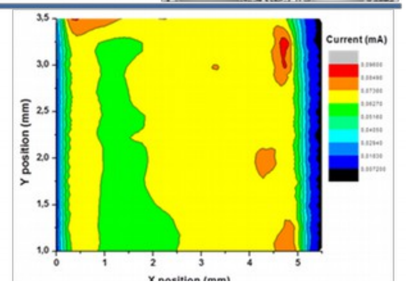

- ✓ **Increase quantum efficiency > 50%** due to the photoresponsivity enhancement from MWCNT absorbance, in the wavelength range 200-400 nm.




- ✓ **Decrease dark noise** thanks to the internal amplification due to hetero-junction MWCNT/Si → increase the device area ($cm^2$ or more VS $mm^2$ SiPM).



- ✓ **MWCNT bottom-up technology** → cells (pad or strip) hundreds of nm up to mm VS 15 μm up to 100 μm for SiPM.




- ✓ **Maximizes the sensitive area for photo-conversion and its uniformity** → Electric field applied via a conductive coating.

### CNT-SiPM

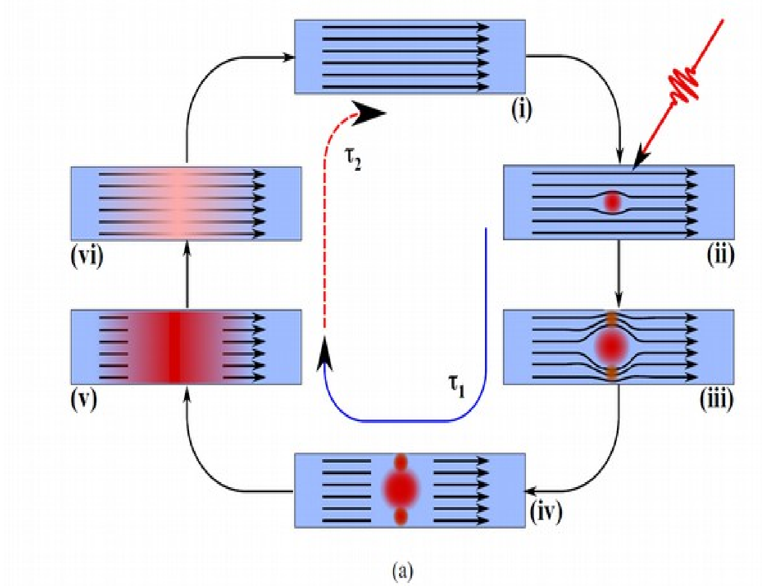
- **New SiPM structure** for high temperature tolerance
- **The CNT grown** directly on the device surface
- **Sensitive surface for every pixel** (MWCNT-Si hetero-junction)
- **Graphene vs CNT**

**Tinti A. et al. NIM 2011, *A629*.**
**Ambrosio, A.; Aramo, C et al:. *JINST* 2012, 7, P08013.**
**Aramo C. et al: *Beilstein J. Nanotech.* 2015, *6*, 704–710.**

# Superconducting Single Photon Detectors

# New generation of SSPDs – "SSPD"

## Superconducting Nanowire Single Photon Detectors



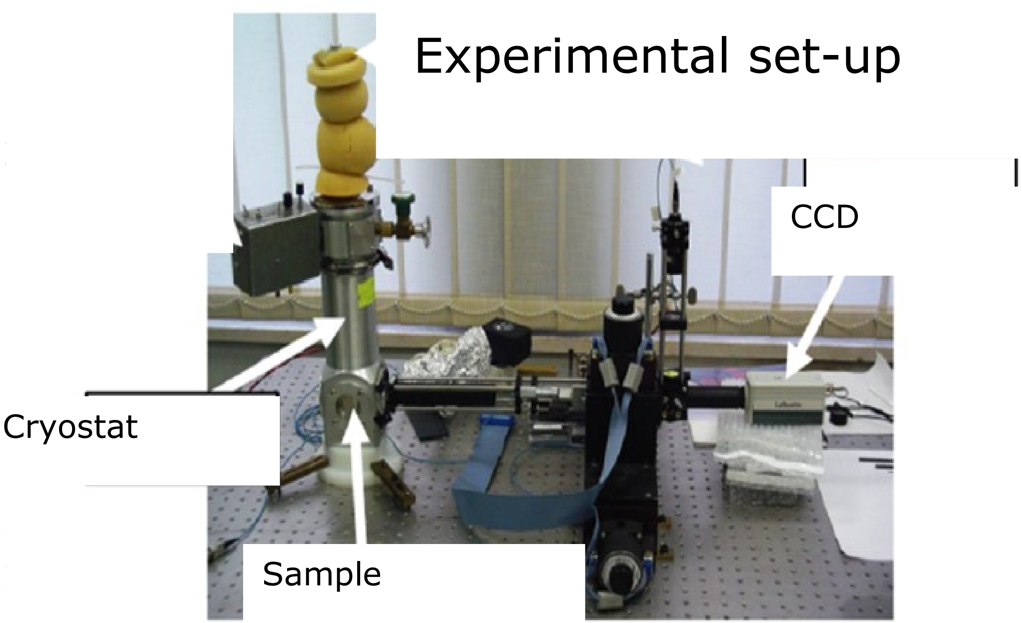

Evolution in time of the normal region (in red) generated by a photon absorption in a current biased super-conduting nano-wire

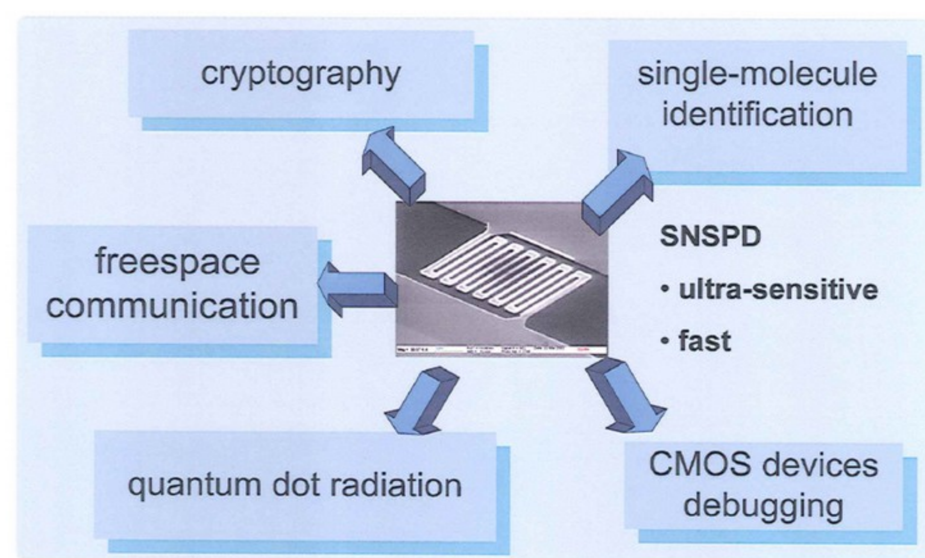
Black arrows indicate the current

When the entire cross section is normal the nano-wire temporarily switch to resistive state

*G.P.Pepe et al – SPIN-CNR Napoli*

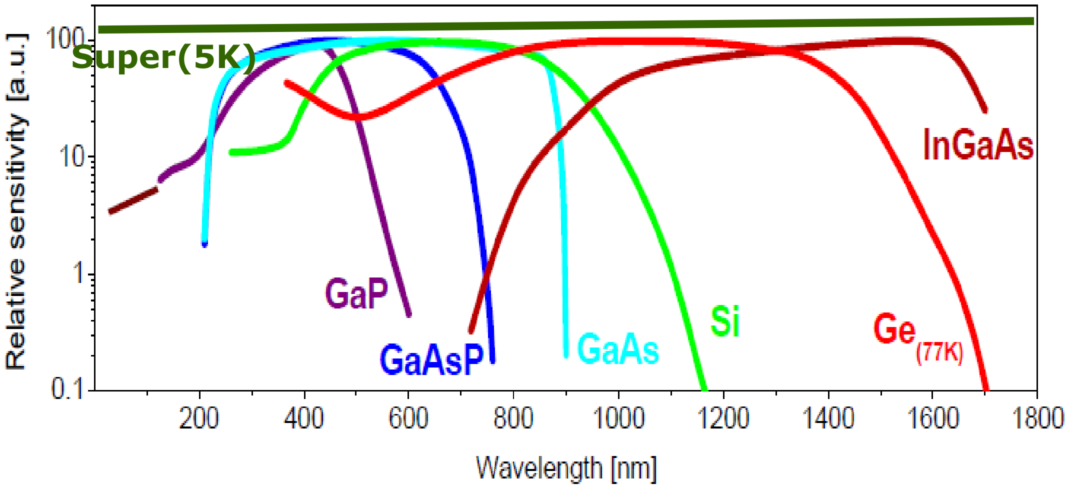
Experimental set-up



# New generation of SSPDs – SNSPD

**SNSPD**s working principle: exploit the fast and temporary phase **transition** from the superconducting to the normal state produced by any type of radiation (photons, ions, neutral particles, electrons….)




**The wide energy range covered by superconductors**

! normalized to peak sensitivity

**SNSPD features:**

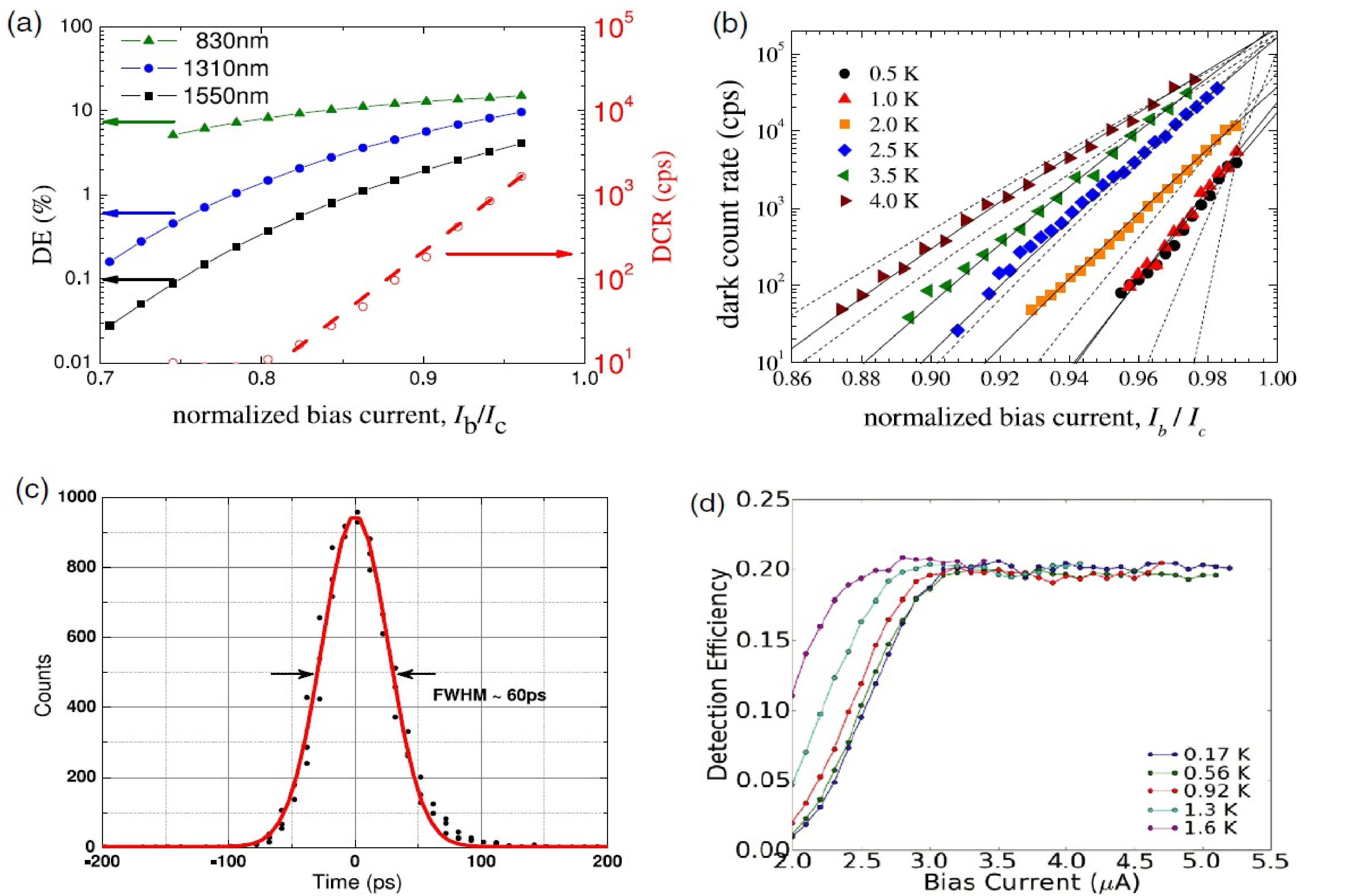
- free-running (no gate)
- few ns dead-time
- no after-pulsing
- photon counting

| Efficiency @ 1550 nm | Jitter (ps) | Dark counts | Max count rate | Operation temperature |
|---|---|---|---|---|
| WSi: 90%<br>NbN: 57% | 150<br>30 | 1 kHz<br>10 kHz | 200 MHz<br>1 GHz | ≤ 3 K<br>≤ 5 K |

*G.P.Pepe et al – SPIN-CNR Napoli*

# New generation of SSPDs – SNSPD

ercond. Sci. Technol. **25** (2012) 063001 Topical Re



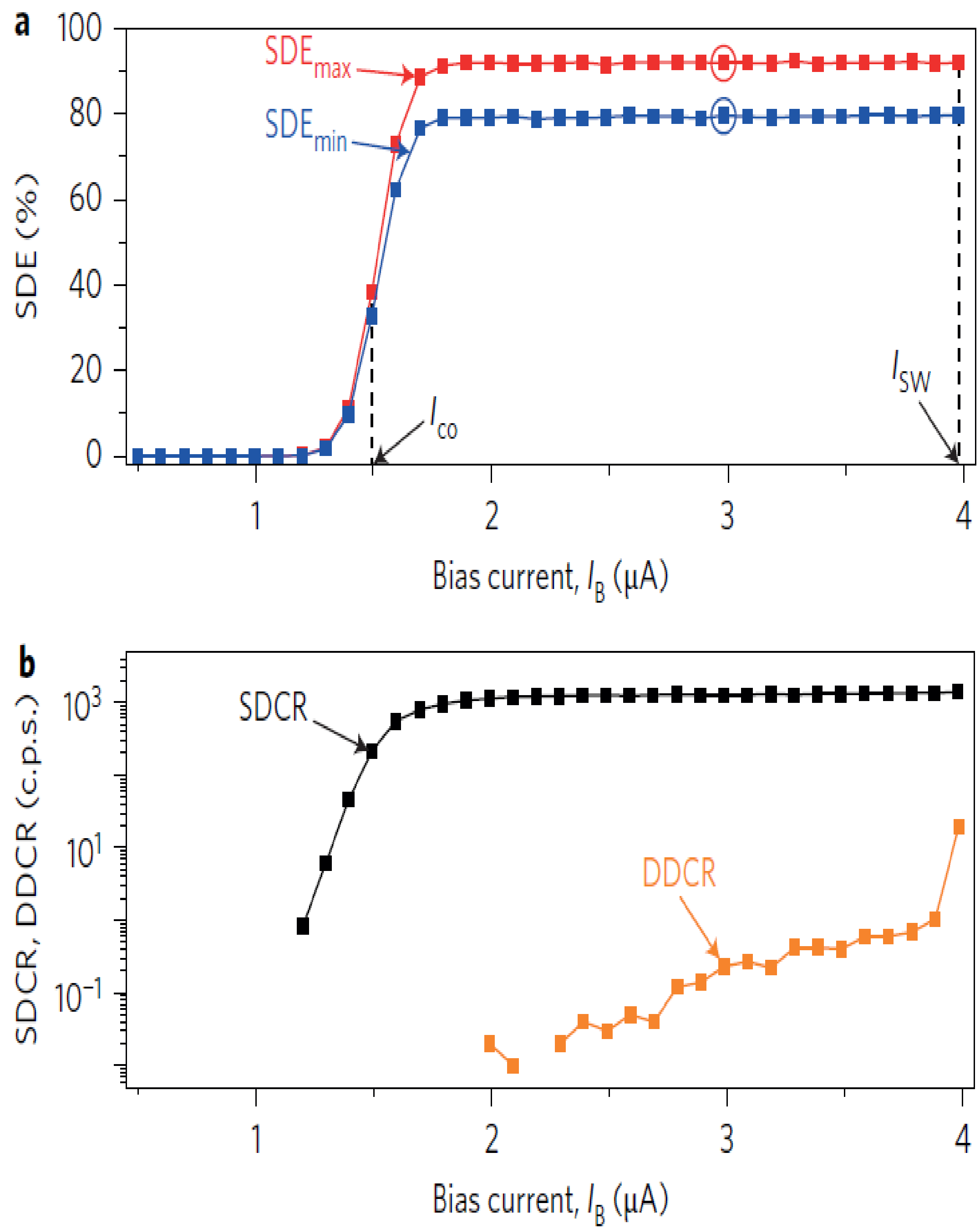

*G.P.Pepe et al – SPIN-CNR Napoli*

# New generation of SSPDs – SNSPD

Best results for WSi SNSPD sample

- System detection efficiency **(>90%),**
- Low dark count rate **(<1 c.p.s.),**
- Low timing jitter **(<100 ps)**
- Short reset time **(<100 ns)**

*G.P.Pepe et al – Nature Photonics 2013*



# Conclusions

Solid state PDs, lively field, trends in many directions

→ Silicon continuous improvements (ruthless)

→ Compound Semicond. no show-stopper but cost

→ Organic Semicond. not easy bet as it may seem

Vacuum PDs are not dead at all

→ new photo-cathodes

→ more and more hybrids

Gaseous PD focused on RICH

→ still promising (single UV photon over large area)

→ hybrids and new structures

→ Visible light more critical than UV

# Additional material

# Photo-detection and Main Parameters

## multi-step process

- Photo Conversion

  Emission in vacuum:
  → low detection efficiency
  → low dark count rate

- Primary Charge carrier Collection and Transport

- Charge Multiplication

  Internal charge multiplication:
  → better Signal/Noise ratio
  → intrinsic fluctuations in amplitude and timing

- Primary/Secondary Charge Collection

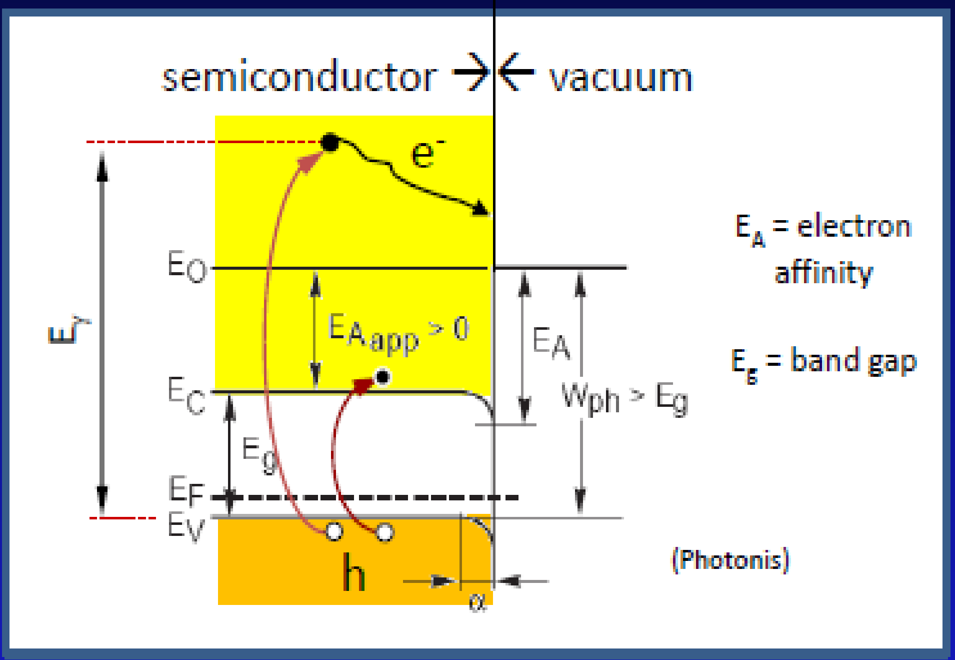
- Photo-detection efficiency (PDE)
- Sensitivity spectrum
  - Active area / Fill factor
  - QE (internal/external)
  - primary carrier transport eff.
  - multiplication efficiency
- Signal resolution
  - gain → amplitude fluctuations (single photon sensitivity)
  - timing fluctuations
  - spatial resolution
- Noise
  - intrinsic: dark charge generation
  - multiplication noise
  - correlated: after-pulsing, cross talk
  - external: electronics ENC
- Rate capability
  - dead time, double pulse resolution
  - gain → photon/ion feedback
  - gain → space charge effects
  - gain → sparks
- Ageing
  - Photo-cathode degradation
  - rad. tolerance
- Environmental
  - Operation in B field
  - Operation in vacuum
  - Low Temperature

# Photo-extraction

## Solid materials (usually semiconductors)

### Multi-step process:

1. absorbed γ's impart energy to electrons (e) in the material; If $E_\gamma > E_g$, electrons are lifted to conductance band.
   → In a Si-photodiode, these electrons can create a photocurrent. → Photon detected by Internal Photoeffect.

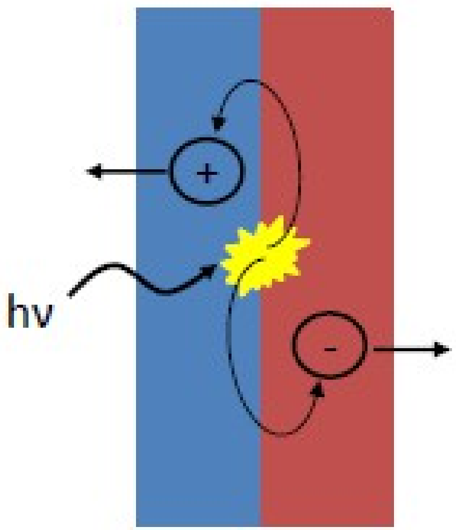



However, if the detection method requires extraction of the electron, 2 more steps must be accomplished:

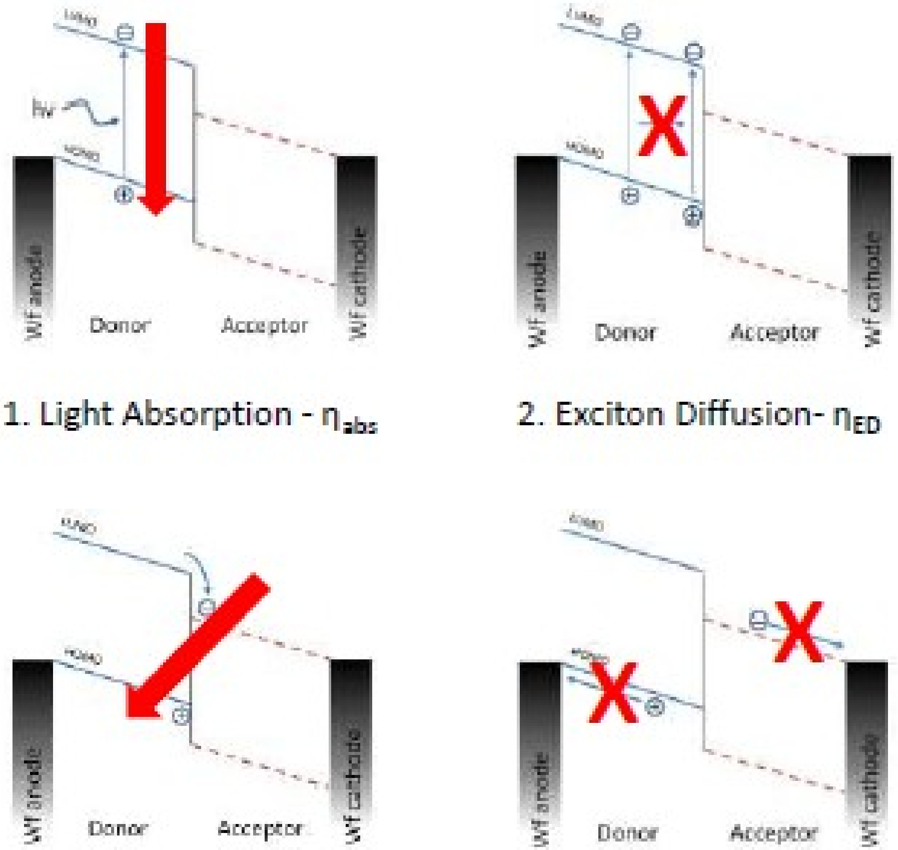
2. energized e's diffuse through the material, losing part of their energy (~random walk) due to electron-phonon scattering. ΔE ~ 0.05 eV per collision. Free path between 2 collisions $\lambda_f$ ~ 2.5 - 5 nm → escape depth $\lambda_e$ ~ some tens of nm.
3. only e's reaching the surface with sufficient excess energy escape from it
   → External Photoeffect

$$E_\gamma = h\nu > W_{ph} = E_G + E_A$$

Combination of Donor and Acceptor material




C.W. Tang, Appl. Phys. Lett. 1985, 48, 183




1. Light Absorption - $\eta_{abs}$

2. Exciton Diffusion- $\eta_{ED}$

3. Exciton Dissociation - $\eta_{CT}$

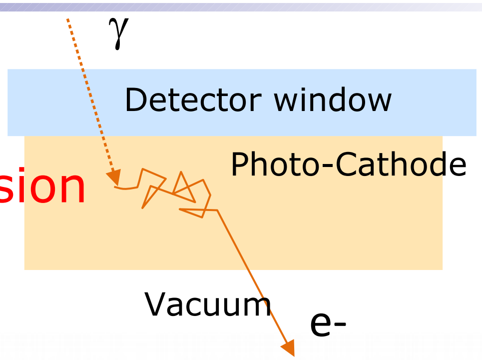
4. Charge Collection- $\eta_{CC}$

$$\eta_{EQE} = \eta_{abs}\,\eta_{ED}\,\eta_{CT}\,\eta_{CC}$$

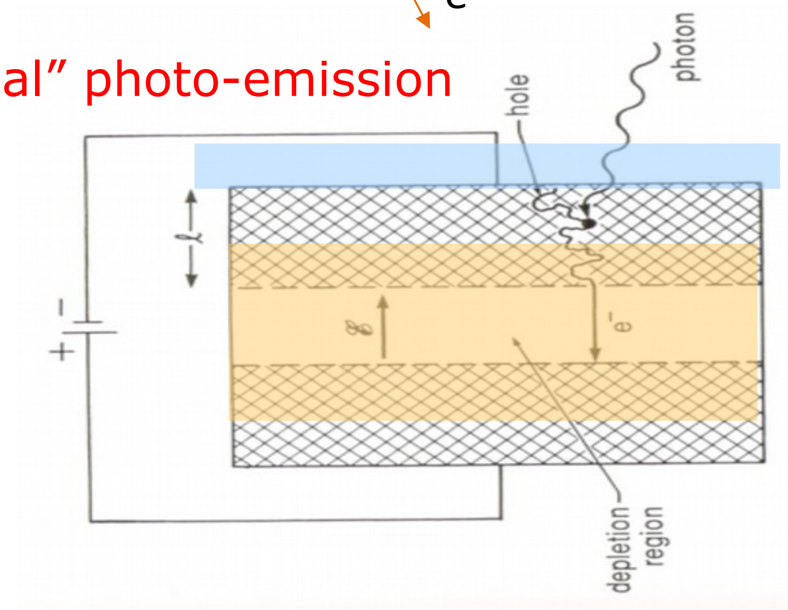
# Photo-detection steps

**1.** Photo-electric conversion with or without emission in vacuum

"external" photo-emission




"internal" photo-emission




Emission in vacuum implies

→ low detection efficiency

→ low dark count rate

...source of differences between vacuum and solid state devices including multiplication mechanisms...

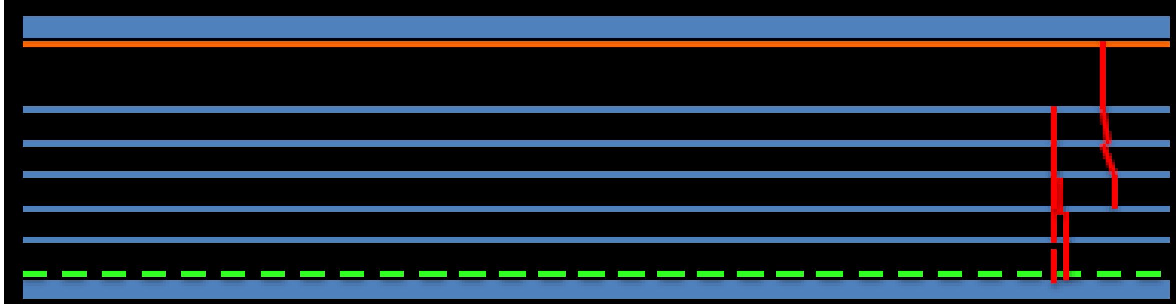
**2.** Internal charge multiplication

Charge multiplication within the device implies

→ better Signal/Noise ratio (wrt external amplification)

→ intrinsic fluctuations in amplitude and timing (depending on the multiplication mechanism)

# Tipsy




- Thin (~10 nm), planar dynodes, spaced ~ 30 μm
- CMOS pixel chip, square pitch ~ 55 μm
- Electron crossing time ~ 5 ps: straight short path due to homogeneous E-field
- With gain of ~ 30 k: digital (1 V) signal on pixel input pad (small source cap)
- Very strong electric field between dynodes, but far away from Fowler-Nordheim limit
- B-field has little influence since Lorentz force is small wrt. electrostatic force
- Signal development on pixel chip defined by crossing of the last gap (~ 2 ps)
- No ion feedback (not even a little bit)
- Noise-free electron multiplier
- No bias current: no bias current noise or bias current dissipation
- radiation hard

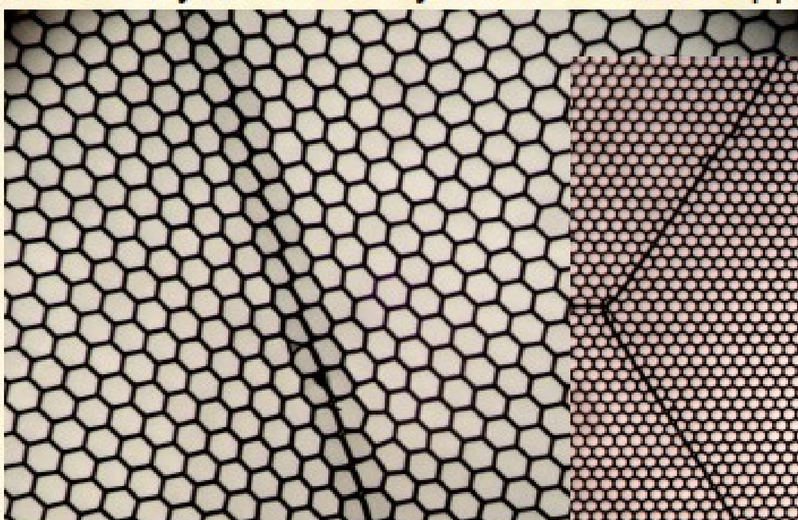
"the best electron is a free electron"

# New generation of Charge Multipliers

## MCP PMT – Hybrids w/ APD – w/ SiPM (Vacuum-SiPM)

### Borosilicate Substrate Atomic Layer Deposited Microchannel Plates

Micro-capillary arrays (Incom) with 10µm, 20 µm or 40µm pores (8° bias) – borosilicate glass. l/d typically 60:1, but can be much larger. Open area ratios from 60% to 83%. Fabricated with using hollow tubes (no etching). Separate resistive and secondary emissive layers are applied (ANL, Arradiance) using atomic layer deposition to allow these to function as MCPs. ALD secondary emissive layers can also be applied to “standard” MCPs to improve yield.



40µm pore borosilicate micro-capillary MCP with 83% open area.

Pore distortions at multifiber boundaries, otherwise very uniform.

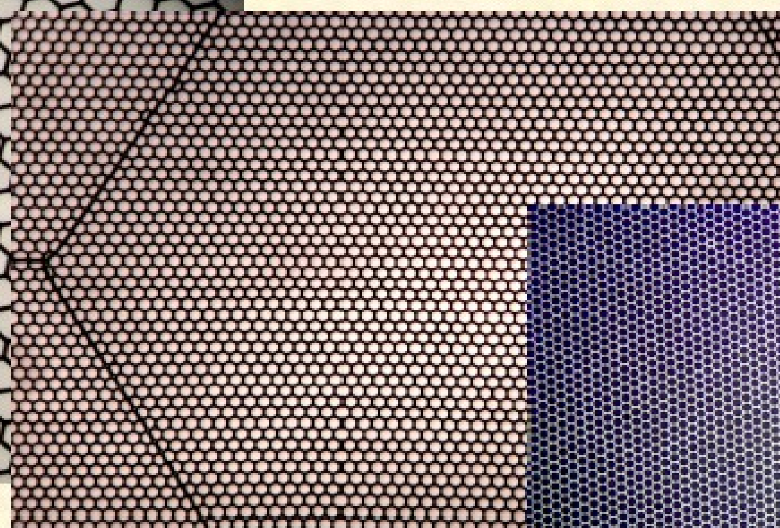


Photo of a 20 µm pore, 65% open area borosilicate micro-capillary ALD MCP (20cm).

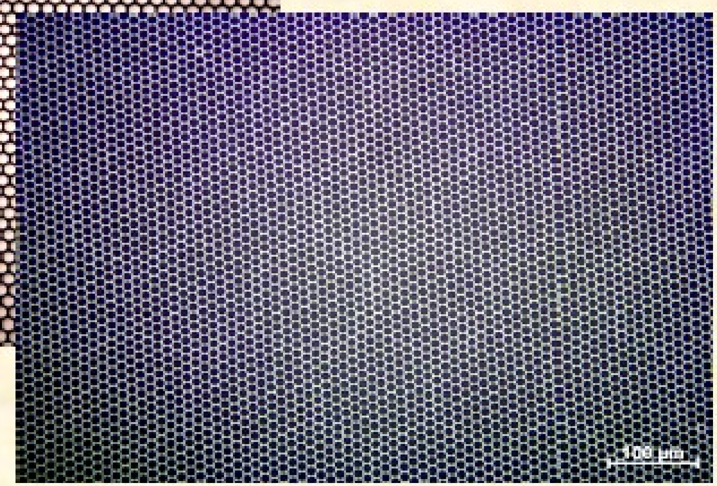
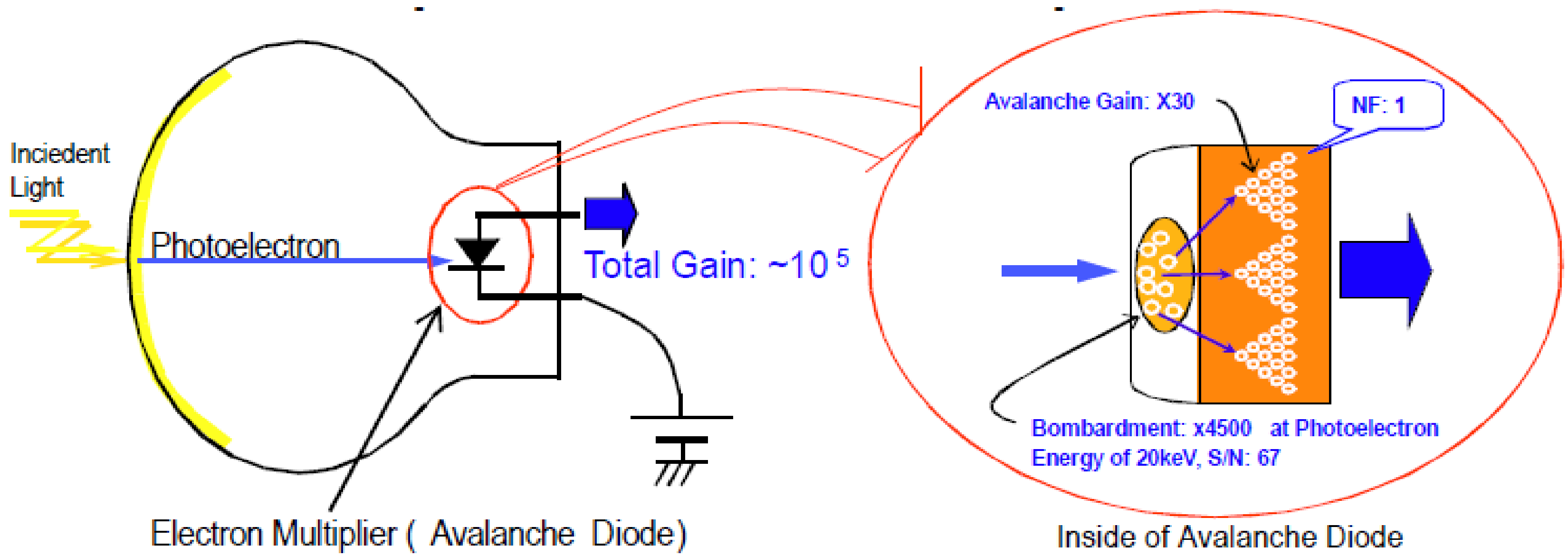


Photo of a 10 µm pore, 60% open area borosilicate micro-capillary ALD MCP.

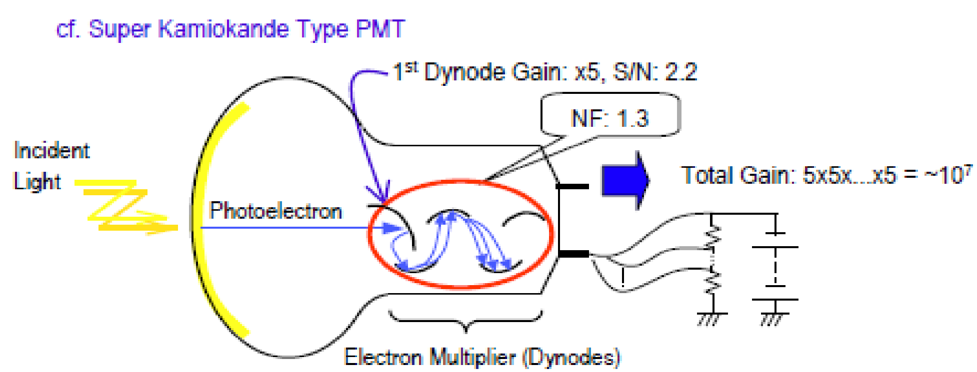
*O.Siegmund – Application of AL-Deposited MCP to imaging PD with High Time Resolutoin - NDIP 2014*

# Large Area Photo-Detectors → H-APD

## moderate “Bombardment” gain + low avalanche gain



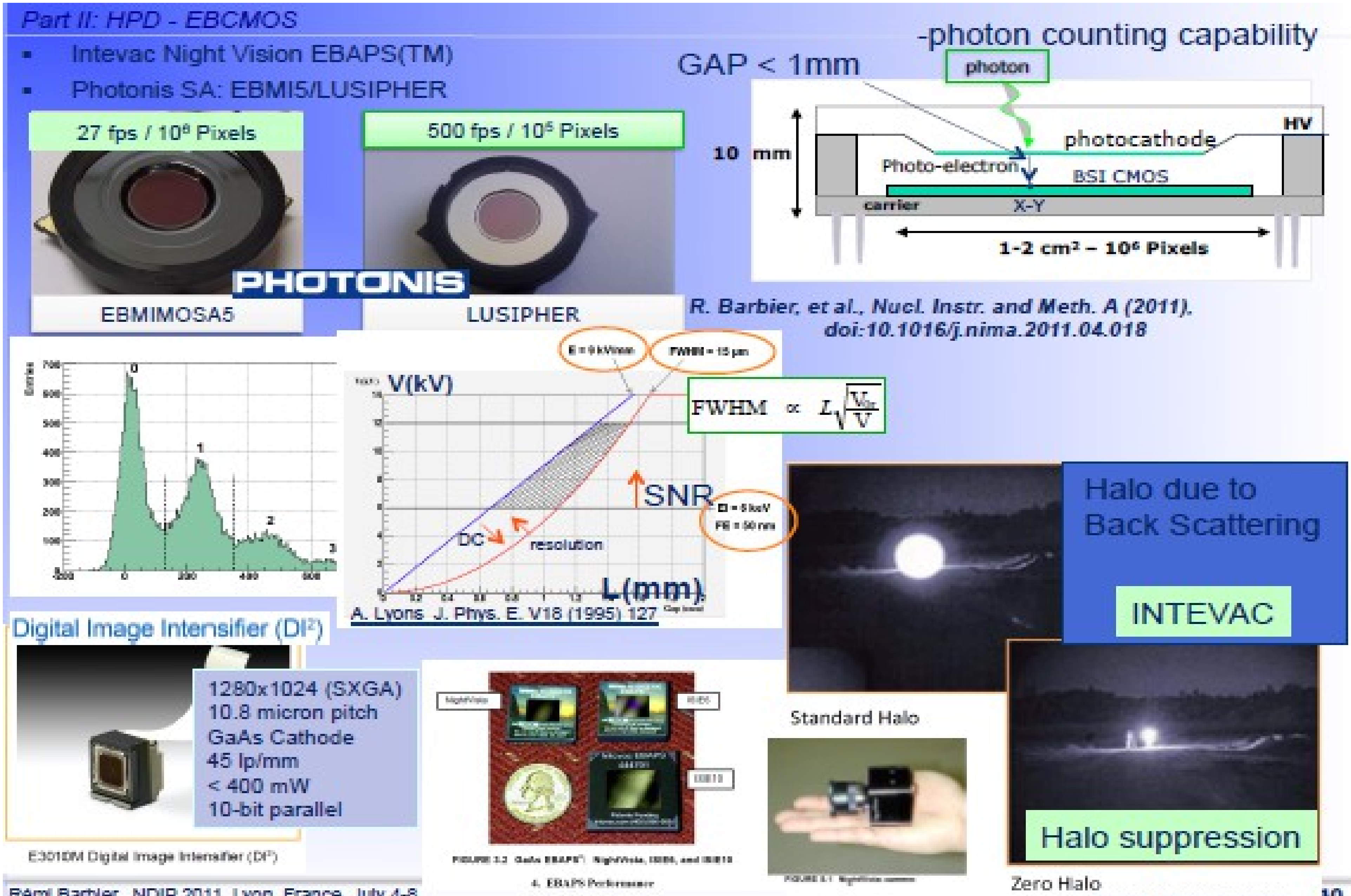

HPD
- ✓ has a simpler structure
- ✓ is expected to save production costs
- ✓ have better S/N but lower gain.



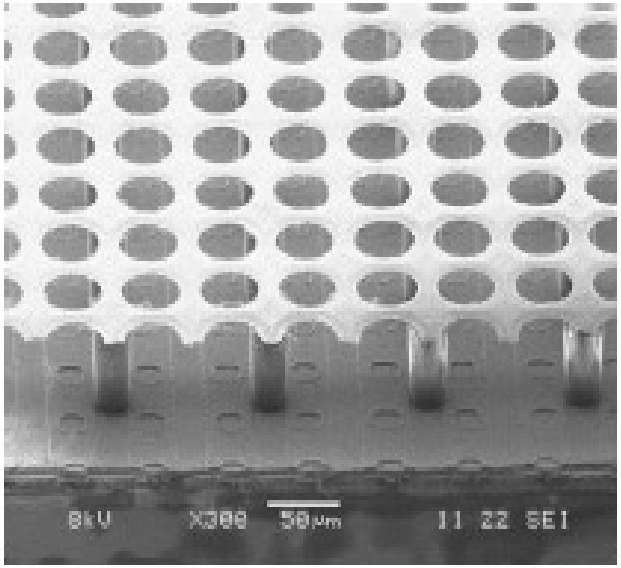

Developements (Hamamatsu) for various Cherenkov based detectors
→ Belle II ARICH (baseline) *S.Nishida at RICH 2013*
→ Hyper-Kamiokande (option) *S.Hirota at RICH 2013*

# New generation of Charge Multipliers

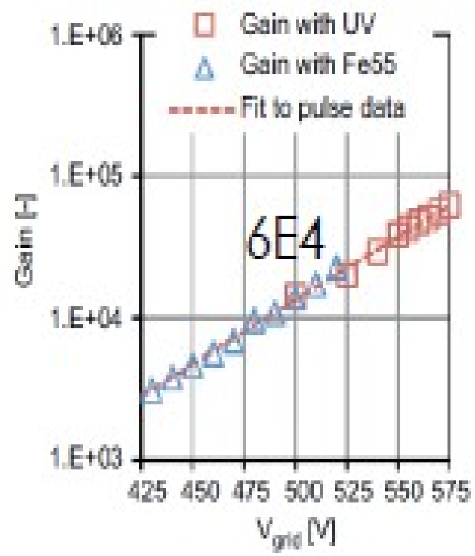
## MCP PMT – Hybrids → Megapixels

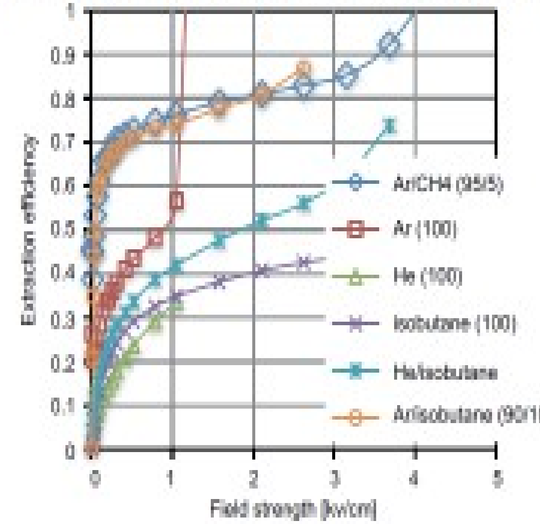


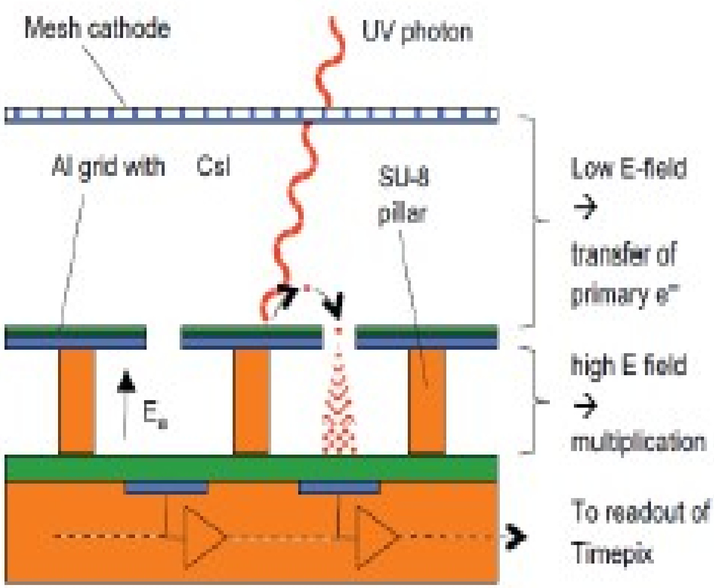
# New generation of GPDs → Hybrids

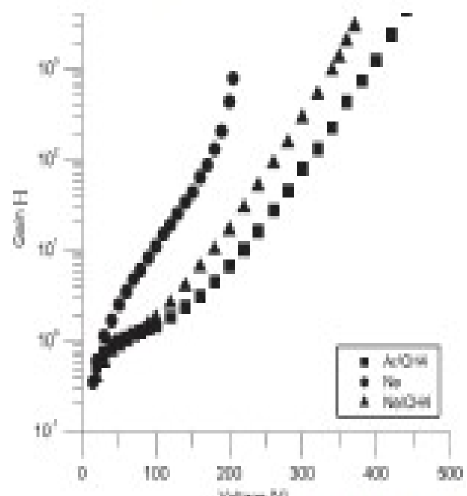


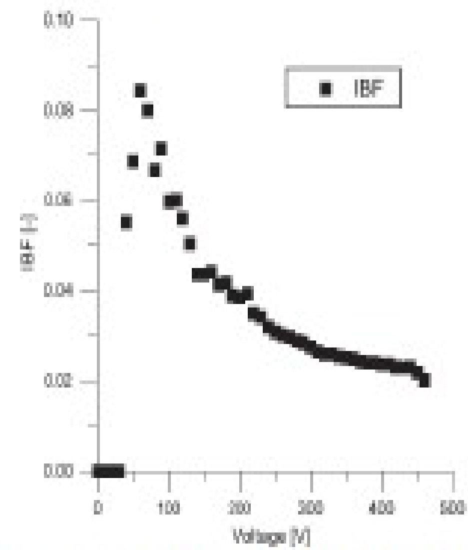

Best gain in He/i-$C_4H_{10}$, not optimal for extraction ~50%





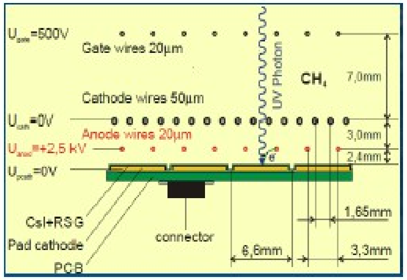

J. Melai et al.: NIM A628 (2011) 133, NIM A633 (2011) S194

R&D ongoing on gas mixture and IBF, possible application in visible GPD (UHV materials)

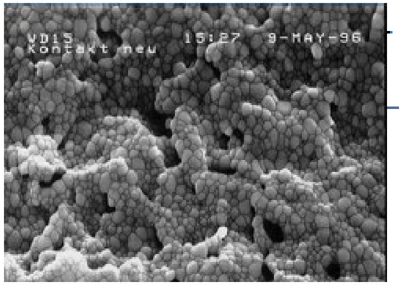
*A. Di Mauro– Status and perspectives of GPD – RICH 2013*

# Gaseous Photo-detectors (UV)

| Experiment | RICH configuration/ Cherenkov radiator | PID | Trigger rates | Photodetector type/ area |
|---|---|---|---|---|
| **HADES @ GSI** | Mirror focusing/ $C_4F_{10}$ gas | e+/e- 0.1-1.5 GeV/c | ~ $10^5$ Hz | MWPC/ 1.5 $m^2$ |
| **COMPASS @ CERN/SPS** | Mirror focusing/ $C_4F_{10}$ gas | π/K 3-55 GeV/c | ~ $5\times10^4$ Hz (beam rate 40 MHz) | MWPC/ 5.5 $m^2$ |
| **HALL-A @ JLAB** | Proximity focusing/ $C_6F_{14}$ liquid | π/K 0.8-2.4 GeV/c | $10^5$ Hz | MWPC/ 1.2 $m^2$ |
| **ALICE @ LHC** | Proximity focusing/ $C_6F_{14}$ liquid | π/K 1.5-3 GeV/c<br>K/p 2-5 GeV/c | $10^4$ Hz | MWPC/ 10.5 $m^2$ |

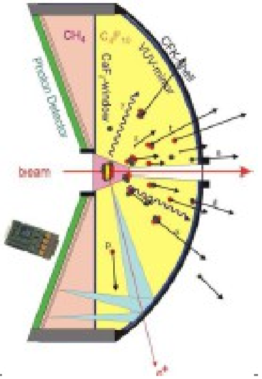


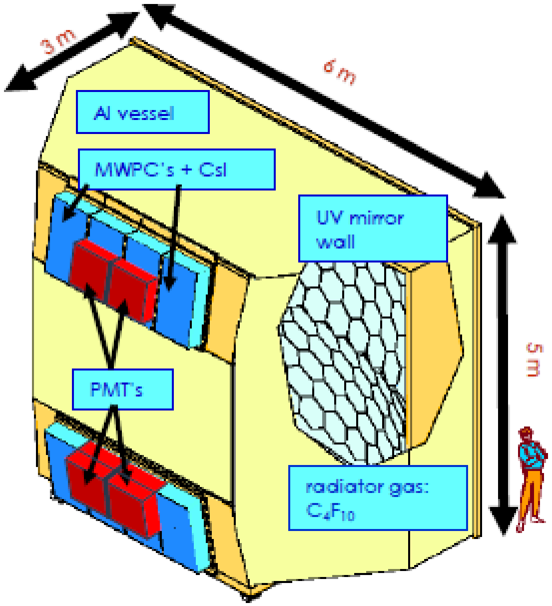

K. Zeitelach et al., NIM-A 433 (1999), 201

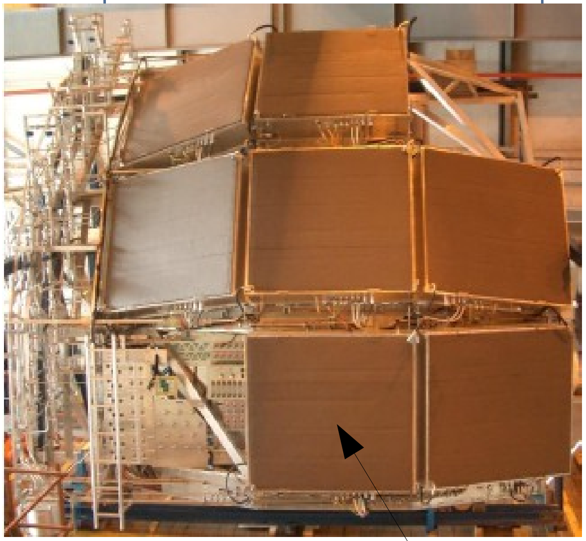



J. Friese et al., NIM-A 438 (1999), 86

PC substrate: SS+ RSG graphite spray





HMPID RICH

One the few relevant Photo-detector developments pushed by LHC

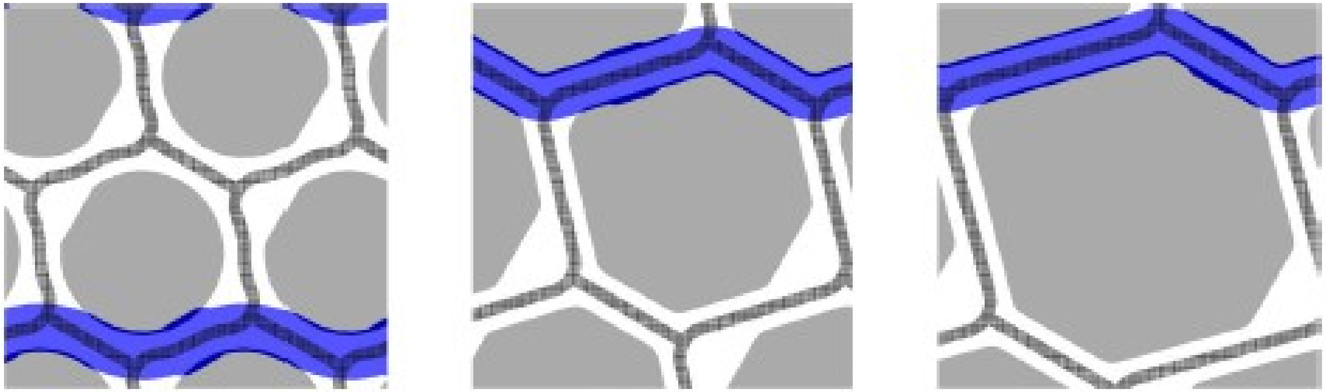
# UDH SiPM FBK

FONDAZIONE BRUNO KESSLER

## Summary of layouts

| Cell size (um) | Equivalent square cell (um) | Cell density (cells/mm$^2$) | Fill Factor (L = 0.75 um) | Fill Factor (L = 1.25 um) |
|---|---|---|---|---|
| 7.5 | 7 | 20530 | 57.1% | 40.3% |
| 10 | 9.3 | 11550 | 68.1% | 54% |
| 12.5 | 11.6 | 7400 | 74.5% | 62.1% |

L = 0.75 um



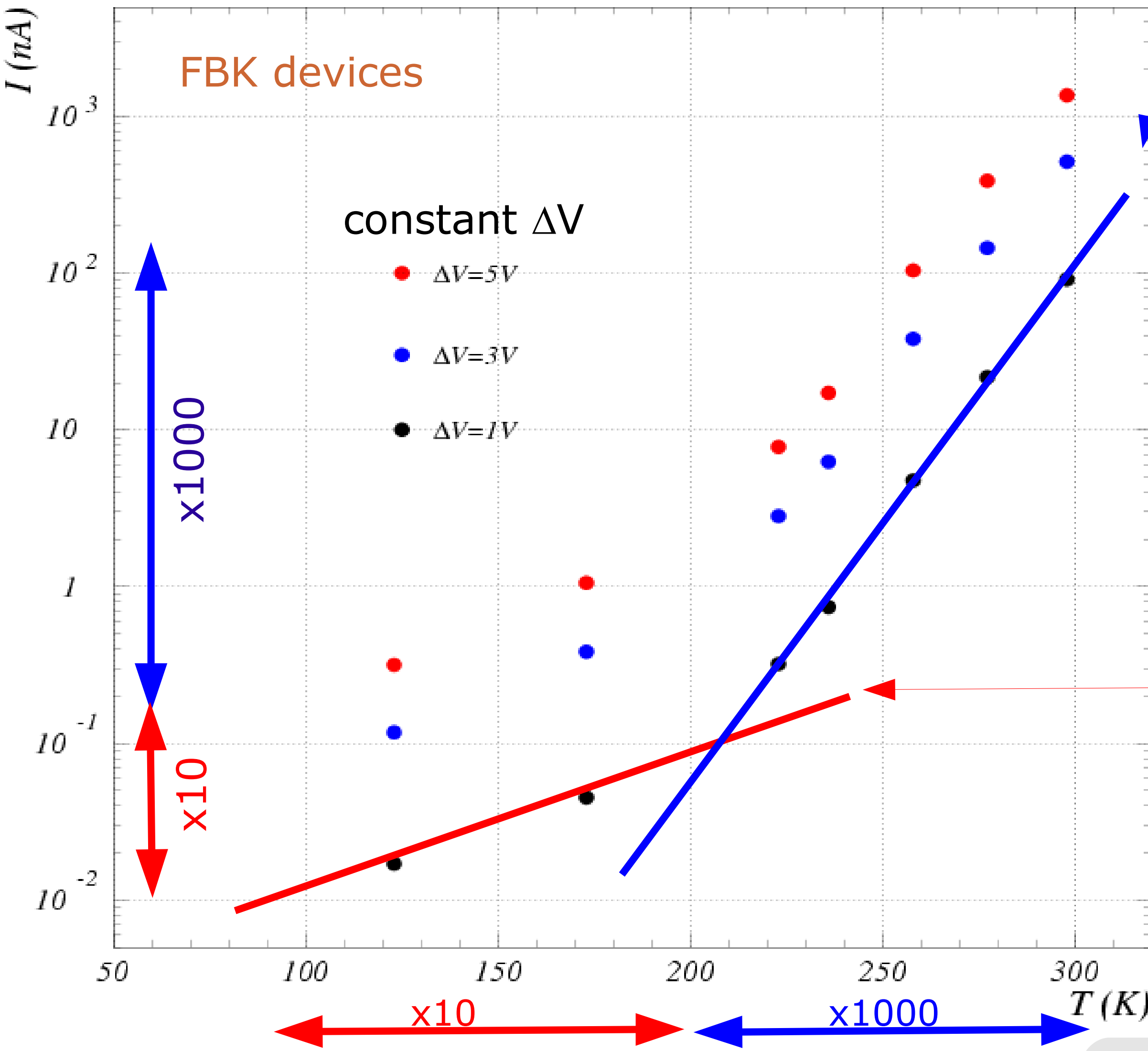
7.5 um 10 um 12.5 um

Layout of different microcells.

# Dark current vs T

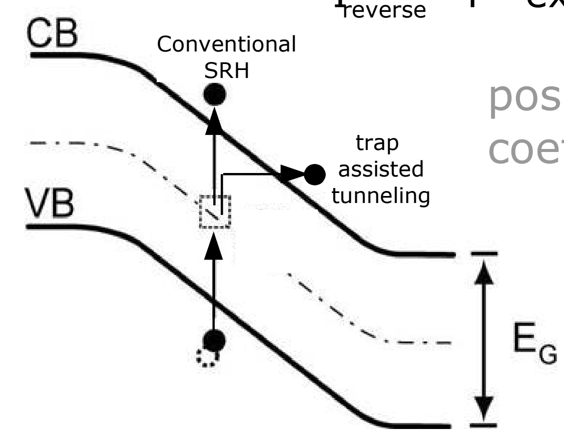
- Two sources (SHR-TAT, BBT)
- Affecting mainly the high field region

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




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

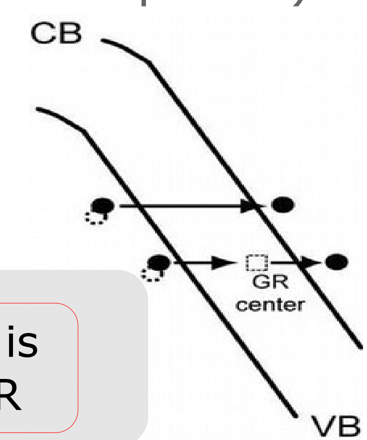
$$I_{reverse} \sim T^{1.5} \exp \frac{-E_{act}}{K_B T}$$




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

# Optimizing signal shape for timing

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

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

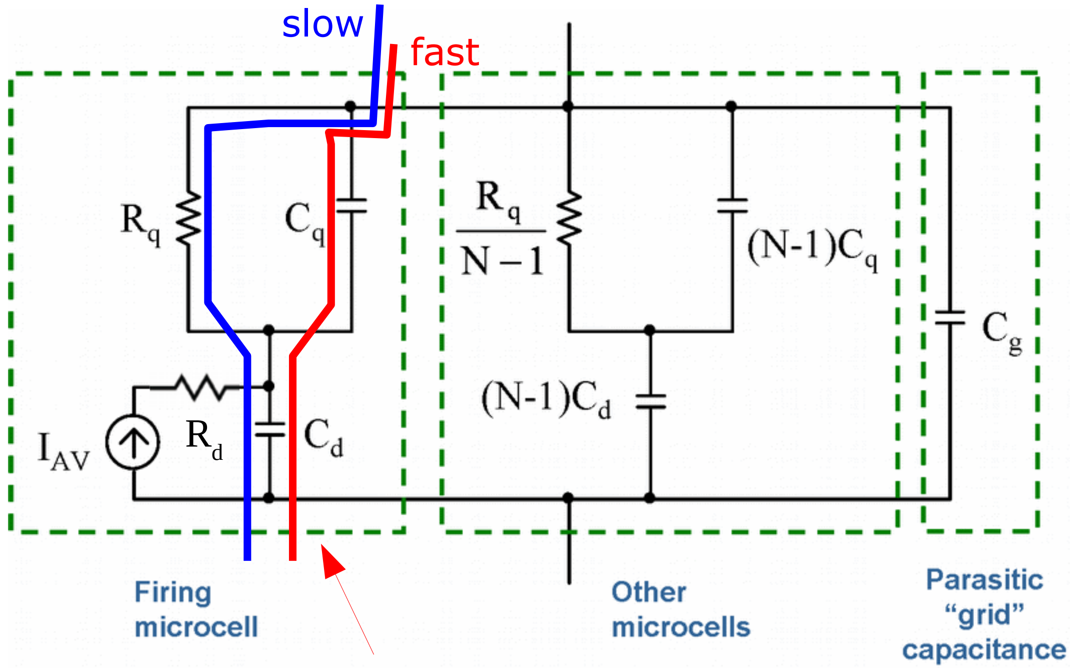
Signal = slow pulse ($\tau_{d\ (rise)}, \tau_{slow\ (fall)}$) +

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

- $\tau_{d\ (rise)} \sim R_d(C_q+C_d)$ [intrinsic]
- $\tau_{fast\ (fall)} = R_{load}\ C_{tot}$ (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*

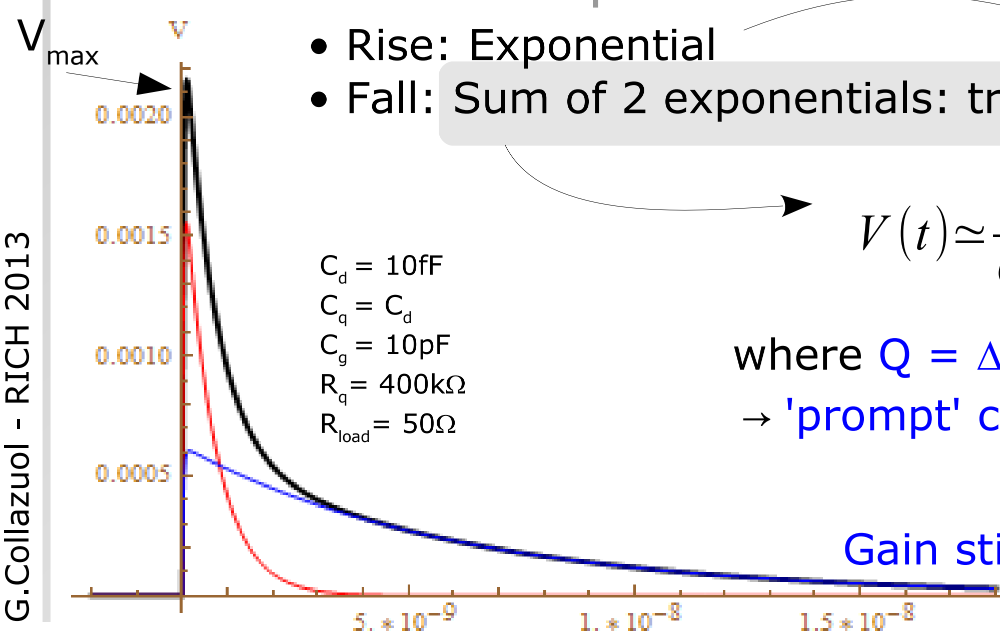



**Cq → fast current supply path in the beginning of avalanche**

## Pulse shape

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

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




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

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 parameters

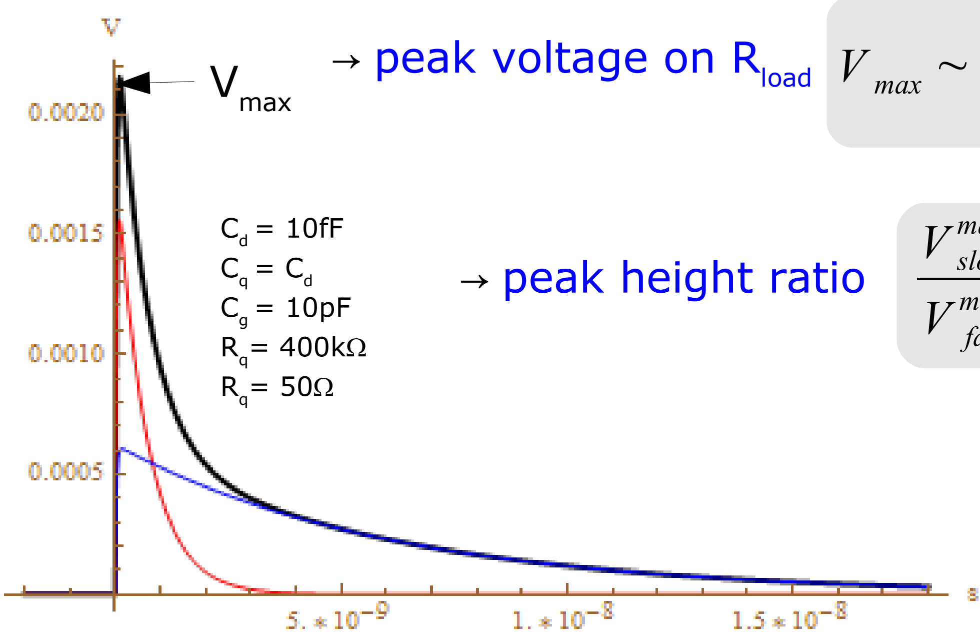
$$V(t) \simeq \frac{Q}{C_q + C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{fast}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q + C_d} e^{\frac{-t}{\tau_{slow}}}\right) = \frac{Q\, R_{load}}{C_q + C_d}\left(\frac{C_q}{\tau_{fast}} e^{\frac{-t}{\tau_{fast}}} + \frac{C_d}{\tau_{slow}} e^{\frac{-t}{\tau_{slow}}}\right)$$

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

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

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

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




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

→ peak height ratio $\boxed{\frac{V_{slow}^{max}}{V_{fast}^{max}} \sim \frac{C_d C_{tot} R_{load}}{C_q^2 R_q}}$ increasing with $C_d$ and $1/R_q$

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

G.Collazuol - RICH 2013

# SSPDs – Organic Semiconductors

## Organic advantages

- Metallic and semiconducting properties by doping
- Combination of plastic with electronic properties
- Property engineering
- Solubility in organic solvents, variable processibility
- Use of printing technologies
- No vacuum and no high temperature processes

High absorption coefficients of organic materials,

**Low-cost production**

## Disadvantages

- Low integrated devices and circuits
- Degeneration in $O_2$- and $H_2O$-atmosphere

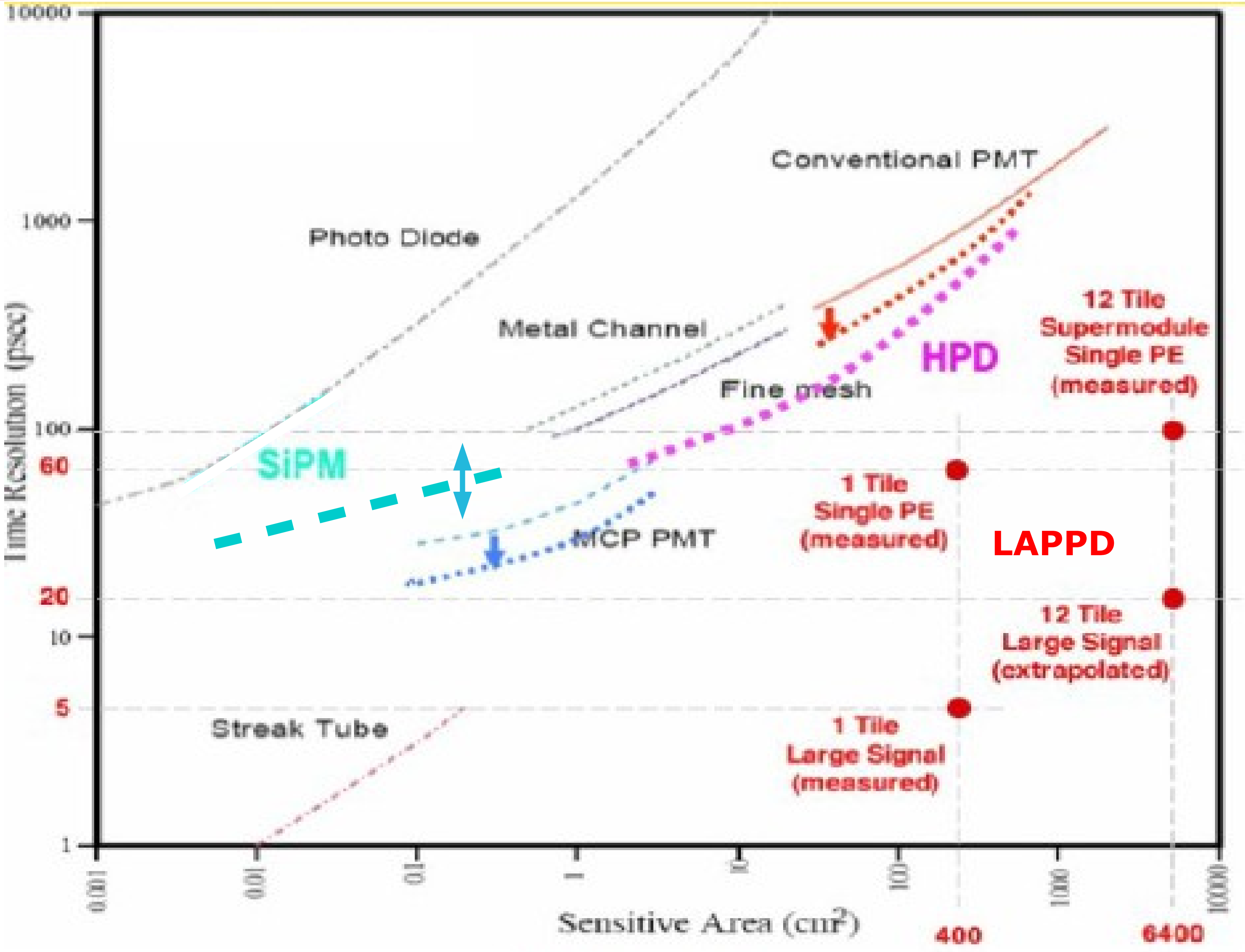
**Long-term stability is still a critical point**

## Integration with CMOS

The combination of organic semiconductors with a CMOS-chip offers advantages compared with a conventional CMOS-sensor:

- high photosensitivity -> fill factors up to 100 %
- wavelength tunability -> sensors for infrared/ultraviolet region
- inexpensive fabrication
- subwavelength grading for optimized performance and polarization sensitivity

# Timing (single photon) vs Area

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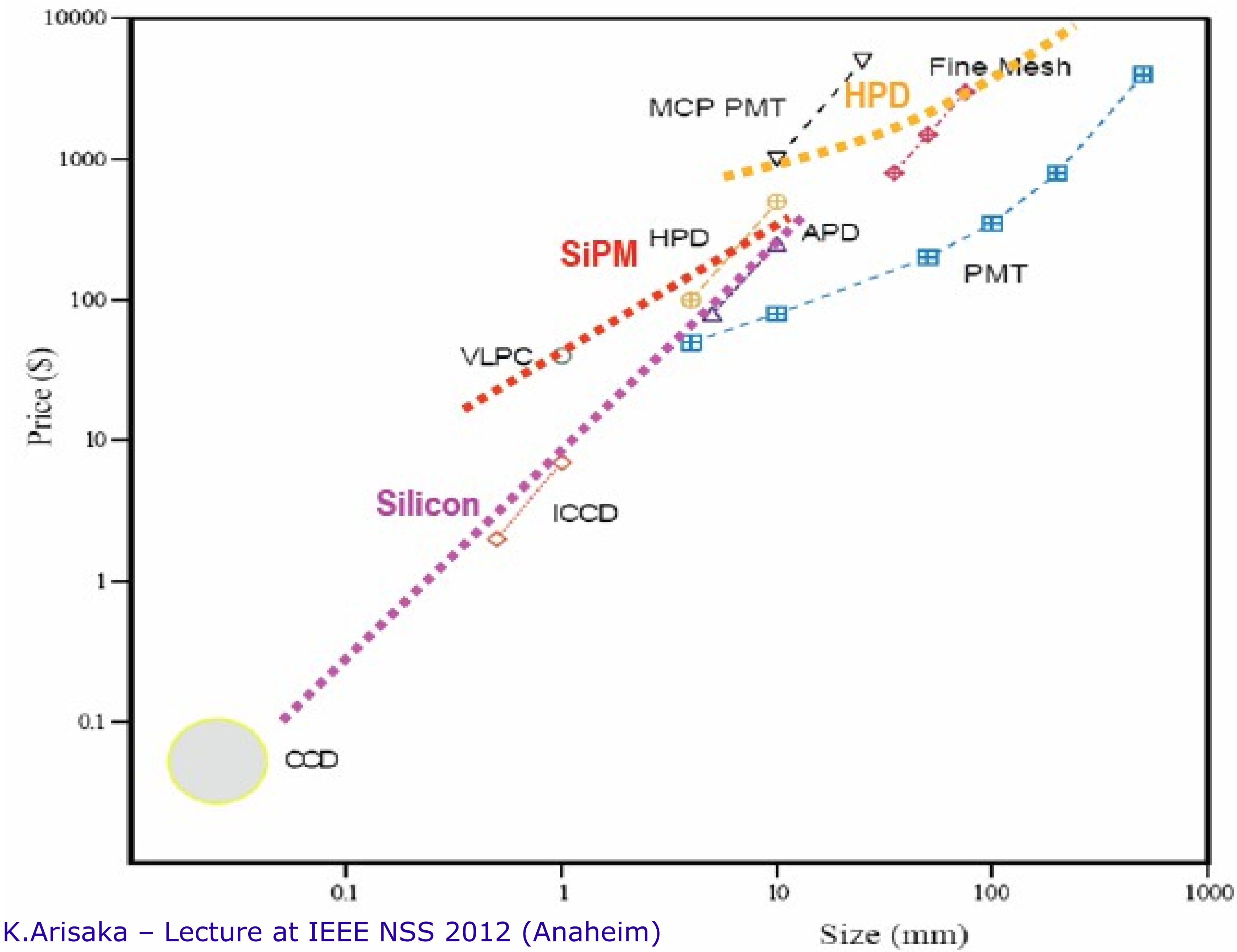
# Market price




K.Arisaka – Lecture at IEEE NSS 2012 (Anaheim)