TUTORIAL

PHOTODETECTION

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www.ipnl.in2p3.fr/ebcmos

- Sources: slides from …
    - Yuri MUSIENKO (Boston / INR RAS Moscow)
    - Katsushi ARISAKA (UCLA)
    - Philippe MANGEOT (CEA/DSM/DAPNIA)
    - Thierry GYS (CERN)
    - Alain BARDOUX (CNES)
    - P. DE MOOR (IMEC)
    - And many others ….
- On the Web
    - Hamamatsu, Photonis SA, Philips, SensL, Radiation Monitoring Devices, Photonique SA, Voxtel, Zecotek Photonics, Amplification technologies, STM, Id Quantique, Micro Photon Device, Intevac, Fairchild Imaging…

- What will not be discussed in this tutorial:
    - IR Imaging devices
    - Gaseous devices
    - X ray detectors
    - ….
    - Due to personal choice and time constraint

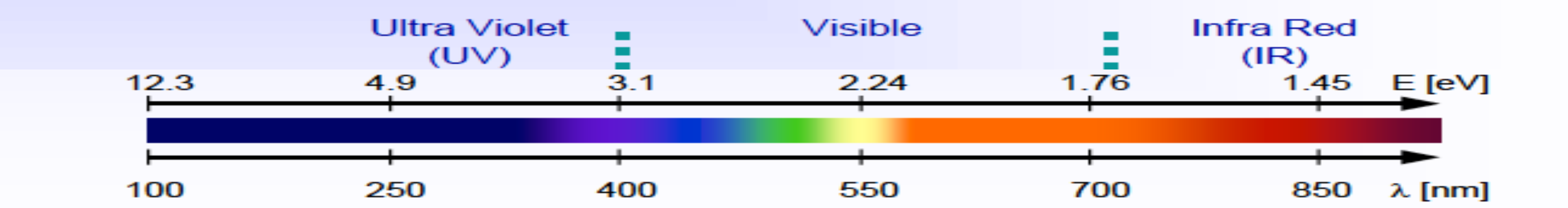
- Part I: The key parameters of the photon detection

- Part II: Photodetectors (basics & trends)
  - Vacuum devices:
    - Photomultiplier Tubes
    - MicroChannel Plate
    - Hybrid
  - Solid State devices:
    - PhotoDiode
    - Avalanche Photo Diode : APD
    - Geiger Mode APD : Arrays of SPAD: SiPM / MPPC …
    - Imaging devices: CCD and sCMOS, EMCCD

Part one : key parameters

- Photometric units
- Photoelectric effect
- The steps of the photon detection
- Quantum Efficiency and Photon Detection Efficiency
- Energy Resolution: Excess Noise Factor, Equivalent Noise Charge
- Spatial resolution & Pixels
- Temporal resolution

- We will consider only the detection of VIS photon spectrum



Some Photometric Units:

•Candela (cd): luminous intensity of a source 1 cd = 1.464 10^{-3} = 1/683 W/sr @ 555 nm (sr=steradian)

•Lumen (lm): Luminous flux through a solid angle of 1 sr by a source of 1 cd (1 lm = 1 cdx1sr) @555 nm
Rq: Lumen is related to eye sensitivity. For other wavelengths you should use the luminous efficiency.

•Luminous efficiency V(λ): relative eye sensitivity to a given wavelength with a maximum (100%) @ 555 nm

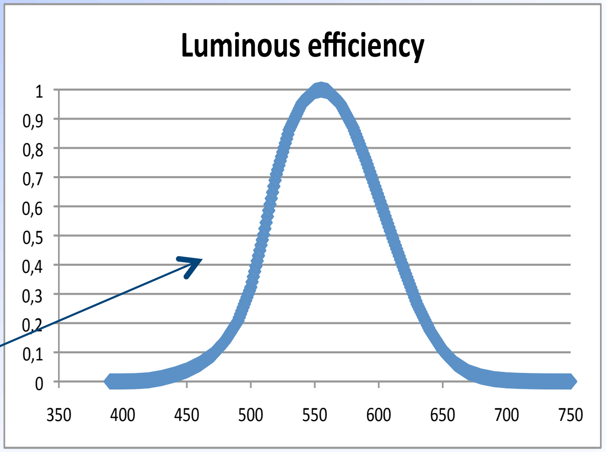
•Lux (lx): unit of illumination measurement per surface unit (1 lx = 1 lm/m^2). This unit is standard in Night Vision

Night Level	#ph/mm²/s	#ph/pixel*/ms	µLux
overcast starlight	1,30E+06	1,30E-01	1,00E+02
starlight	1,30E+07	1,30E+00	1,00E+03
quarter moon	1,30E+08	1,30E+01	1,00E+04
full moon	1,30E+09	1,30E+02	1,00E+05
deep twilight	1,30E+10	1,30E+03	1,00E+06
twilight	1,30E+11	1,30E+04	1,00E+07
very dark day	1,30E+12	1,30E+05	1,00E+08
overcast day	1,30E+13	1,30E+06	1,00E+09
daylight	1,30E+14	1,30E+07	1,00E+10
direct sunlight	1,30E+15	1,30E+08	1,00E+11

* Pixel pitch 10 microns

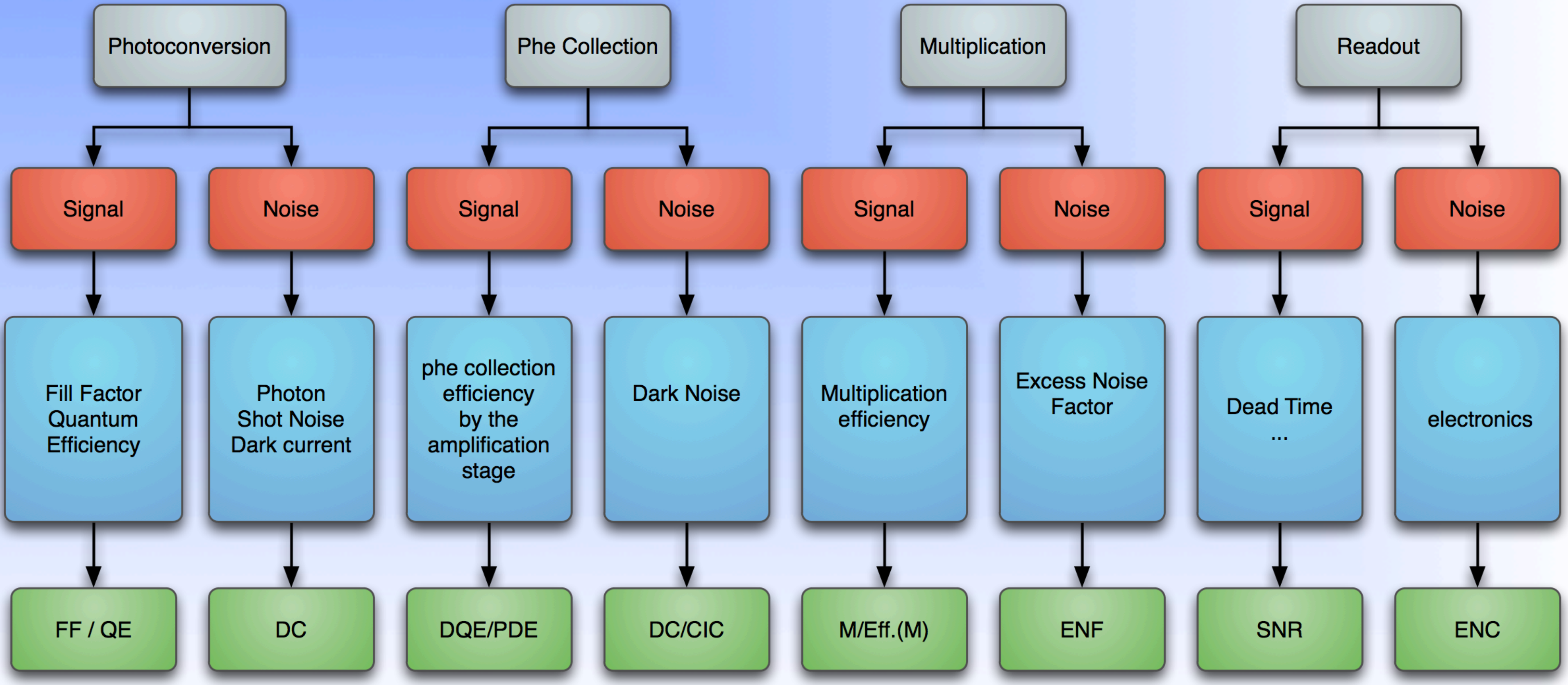
ph	λ		luminance
#/s/µm²	nm	V(λ)	lx 10⁻⁶
1,000	400	0,0004	0,1
1,000	555	1,0000	243,9
1,000	650	0,1070	22,3

•Photopic: Day Vision
•Scotopic: Night Vision



Introduction: The steps of the Photon Detection

- The 4 steps of the photo-detection process:
  1. The primary charge carrier (pe, e/h) **is produced**
  2. The primary charge carrier **is collected**
  3. The primary charge carrier **is multiplied/amplified or not** (CMOS/CCD/PD)
  4. The secondary (or primary) charges **are collected and read out**
- The measurement process is modified by noise sources and by signal collection inefficiency at each step:



- Photoconversion
  - Signal → Fill Factor Quantum Efficiency → FF / QE
  - Noise → Photon Shot Noise Dark current → DC
- Phe Collection
  - Signal → phe collection efficiency by the amplification stage → DQE/PDE
  - Noise → Dark Noise → DC/CIC
- Multiplication
  - Signal → Multiplication efficiency → M/Eff.(M)
  - Noise → Excess Noise Factor → ENF
- Readout
  - Signal → Dead Time … → SNR
  - Noise → electronics → ENC

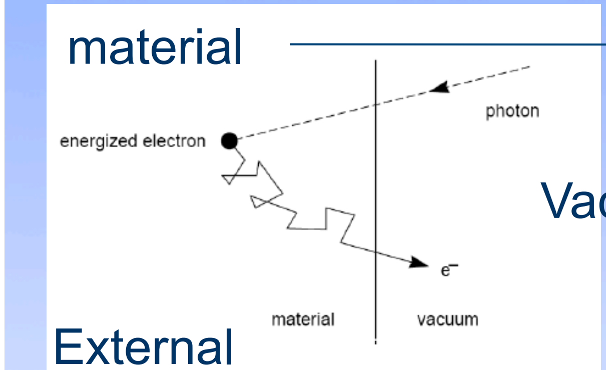
Introduction – Photoelectric effect

- The photoelectric effect is responsible for the photon detection.

We can distinguish two types:

1. **External**: the phe is emitted into the vacuum from a photocathode material.
2. **Internal**: the phe is excited and occupies the conduction band of the semiconductor material, the photoconductive effect.

Two types of photon detection



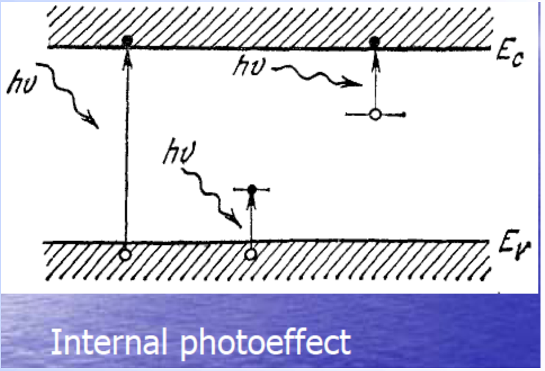
material →

Vacuum

External

pe escapes the material

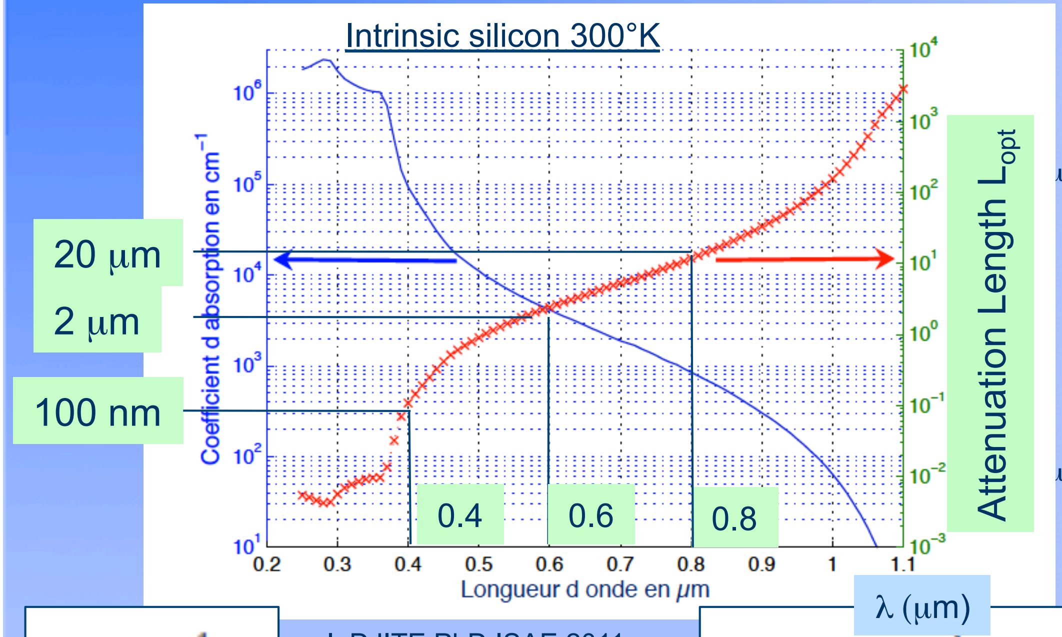
Cond. Band



pe in the Cond. band

Notation in what follows:
- ph = photon
- pe = photoelectron
- e/h = electron/hole

▪ Light absorption: depends on λ



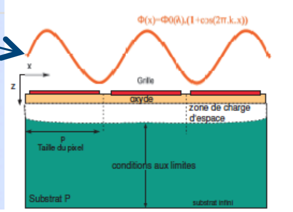
$$\alpha(\lambda) = \frac{1}{L_{opt}(\lambda)}$$

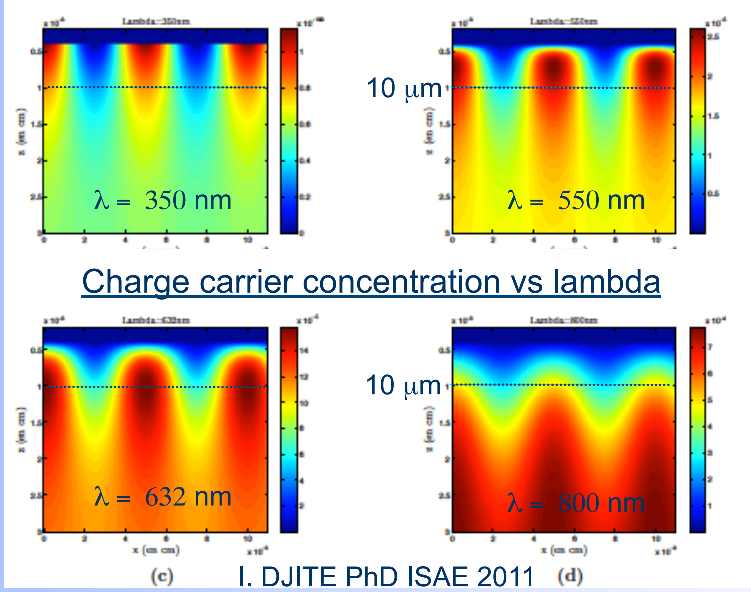
I. DJITE PhD ISAE 2011

$$L_{opt}(\lambda) = \frac{\lambda}{4 \times \pi \times \kappa}$$

input light

$$\phi(z) = \phi_0 \exp(-\alpha(\lambda) z)$$





Charge carrier concentration vs lambda

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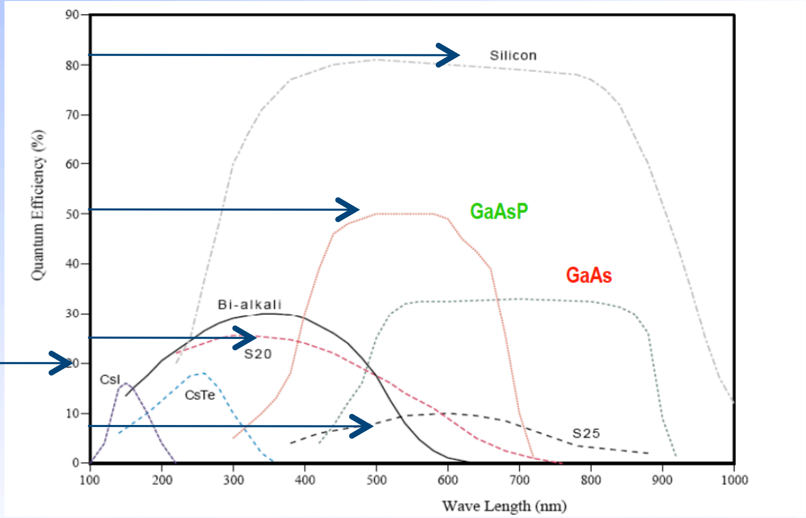
▪ Quantum efficiency:

$$QE(\%) = \frac{N_{pe}}{N_{\gamma}} \times 100$$

Silicon is at least two times better than Photocathode !!

… But … it is only the beginning of the story …



- Be careful ! each photodetector type has his proper definition of QE and PDE…

Example: QE for CCD is QExFF …

- Definitions:

1. The radiant sensitivity (S) [A/W]: is the ratio between the output current from PC and the input radiant power at a given wavelength. S is related to QE by: $QE(\%) \sim 124 \times \frac{S(mA/W)}{\lambda(nm)}$
2. The Fill Factor (FF) is the ratio between the sensitive surface and the detector surface also called geometrical efficiency (ε_{geom}).
3. Collection Efficiency (CE) is the probability to transfer the primary pe or e/h to the amplification stage or readout channel.
4. Multiplication Efficiency (ME) is the prob. that the amplification process give a detectable signal or trigger a multiplication (ε_{Geiger}).
5. Photon Detection Efficiency (PDE) is the probability that a single photon trigger a detectable output pulse also called the Detective Quantum Efficiency (DQE).

$\boxed{DQE = PDE = (FF) . (QE) . (TE) . (ME)}$ $\boxed{PDE = QE . \varepsilon_{geom} . \varepsilon_{geiger}}$ (SiPM)

Part I: key parameters – Energy resolution and ENF

- Energy = Number of collected secondary carriers

$$E = M \times PDE \times N_\gamma$$

- Energy Resolution with Readout Noise

$$\frac{1}{SNR} = \frac{\sigma}{E} = \sqrt{\frac{ENF}{PDE \times N_\gamma} + \left(\frac{ENC}{M \times PDE \times N_\gamma}\right)^2}$$

Multiplication Noise Readout Noise

- M is the Mean Multiplication coefficient
M is a stochastic variable with variance σ_M^2
- ENF is the excess noise factor. **ENF is the noise due to the multiplication process**
- ENC : Equivalent Noise Charge
(readout noise from the electronics)
- PDE is the Photon Detection Efficiency

- Excess Noise Factor for single pe: ENF_{1pe} also noted F or sometimes F^2

$$ENF_{1pe} = 1 + \frac{\sigma_M^2}{M^2}$$

Many different definitions in the literature

- Excess Noise Factor for N_{pe} input carriers: ENF_{Npe}

Experimentalist definition

$$ENF_{N_{pe}} = \frac{\sigma^2_{n_{out}}}{\sigma^2_{n_{in}}}$$

$$n_{out} = \sum_{i=1}^{n_{in}} m_i \quad \langle n_{out} \rangle = \langle m \rangle \langle n_{in} \rangle$$

$$\sigma^2_{n_{out}} = \langle m \rangle^2 \sigma^2_{n_{in}} + \langle n_{in} \rangle \sigma^2_m$$

Burgess's theorem

$$ENF_{N_{pe}} = M^2 \left[1 + \frac{\langle n_{in} \rangle}{\sigma^2_{n_{in}}} \left(ENF_{1pe} - 1 \right) \right]$$

$$ENF_{N_{pe}} = M^2 ENF_{1pe}$$ If n_{in} Poisson

- Summary:

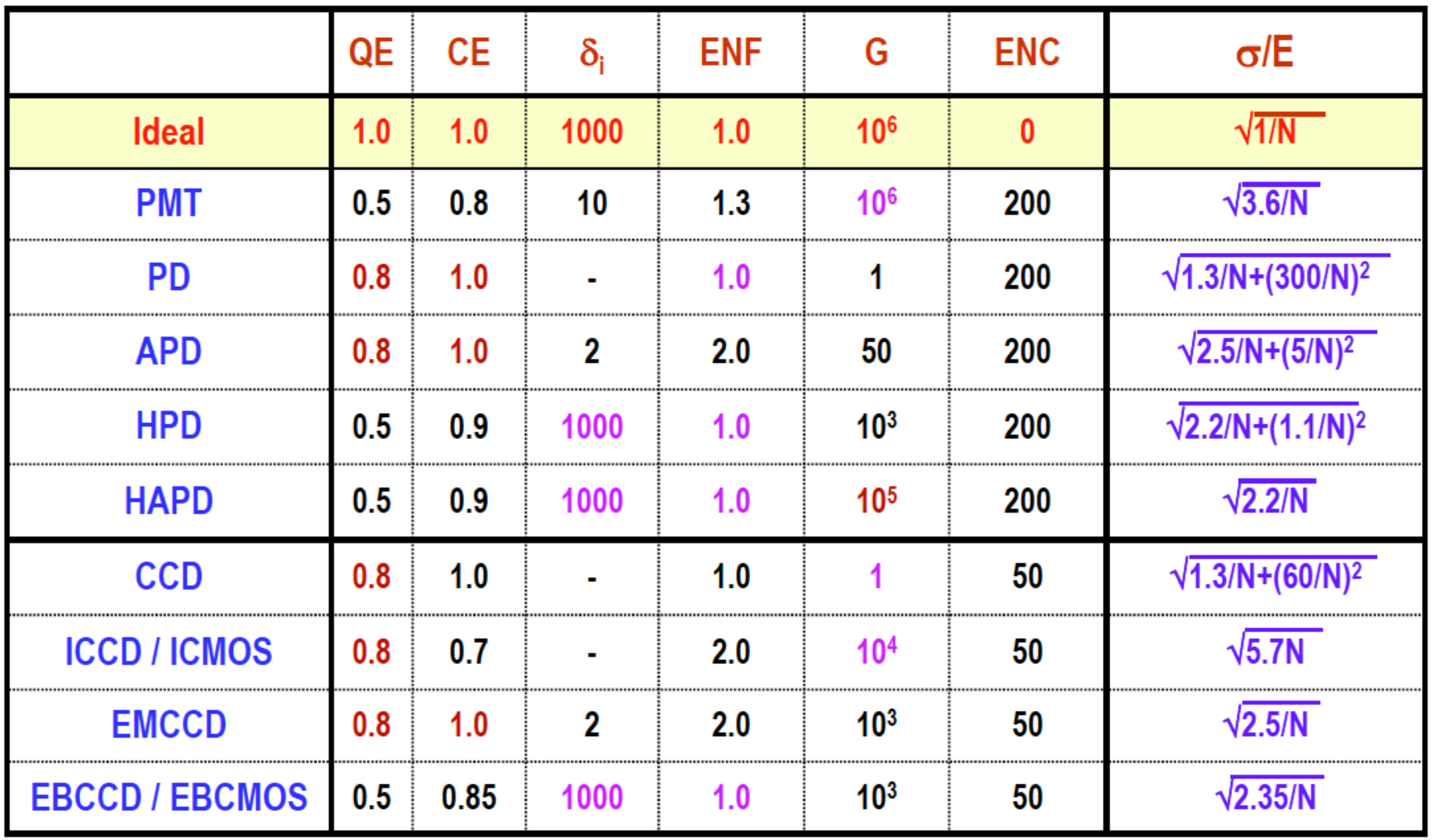
K. Arisaka, NIM A 442 (2000) 80

$$\frac{1}{SNR}=\frac{\sigma}{E}=\sqrt{\frac{1}{N_\gamma}}$$

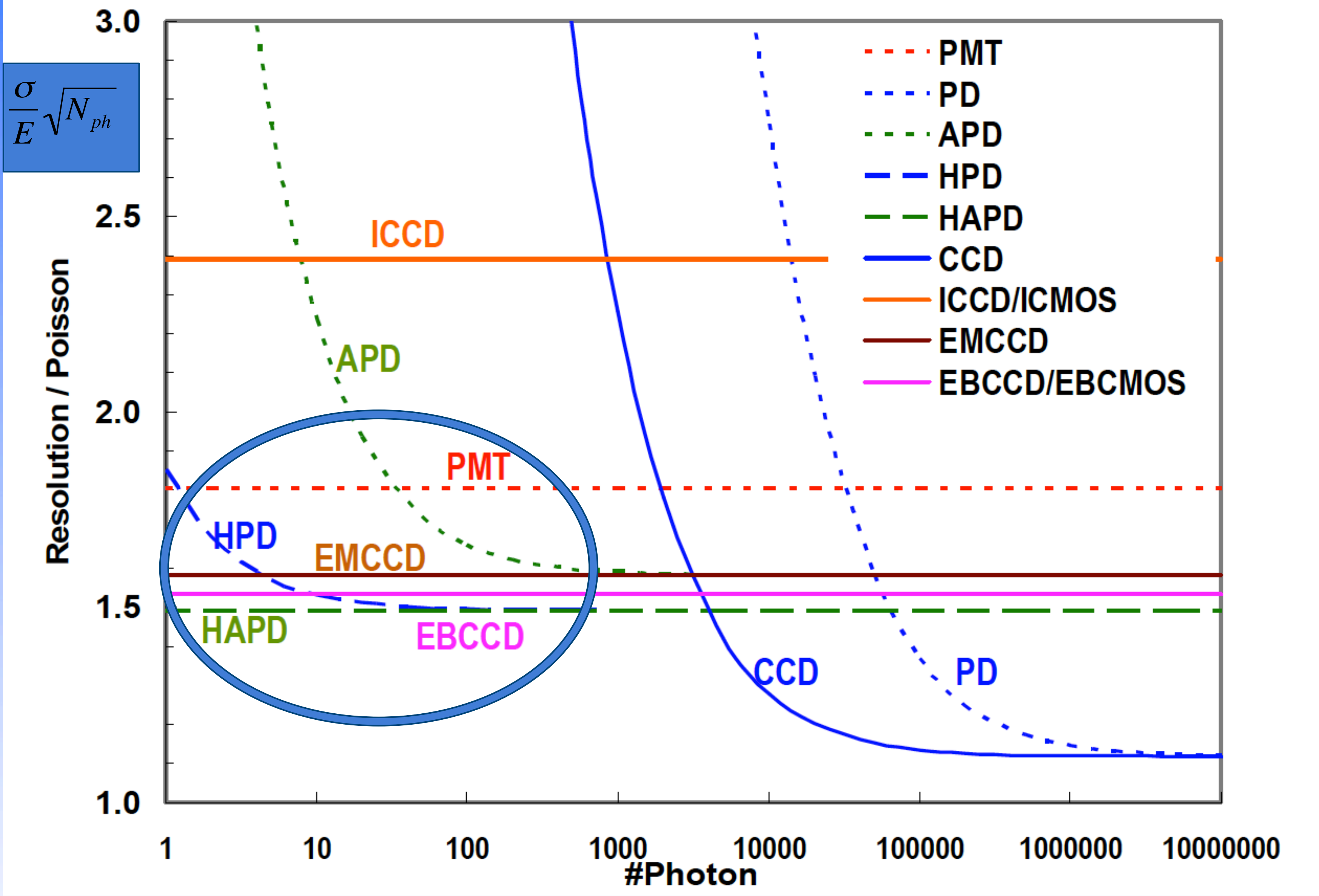
Ideal case: shot noise

$$\frac{1}{SNR}=\frac{\sigma}{E}=\sqrt{\frac{ENF}{PDE\times N_\gamma}+\left(\frac{ENC}{M\times PDE\times N_\gamma}\right)^2}$$

Slide from K. Arisaka Lecture UCLA



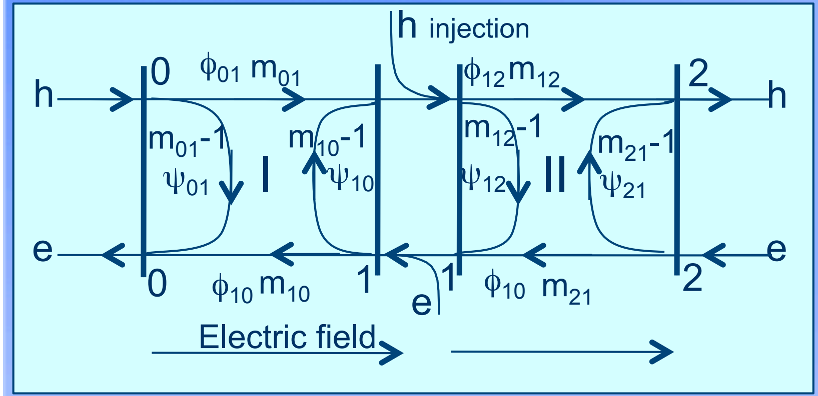
	QE	CE	δ_i	ENF	G	ENC	σ/E
Ideal	1.0	1.0	1000	1.0	10^6	0	$\sqrt{1/N}$
PMT	0.5	0.8	10	1.3	10^6	200	$\sqrt{3.6/N}$
PD	0.8	1.0	-	1.0	1	200	$\sqrt{1.3/N+(300/N)^2}$
APD	0.8	1.0	2	2.0	50	200	$\sqrt{2.5/N+(5/N)^2}$
HPD	0.5	0.9	1000	1.0	10^3	200	$\sqrt{2.2/N+(1.1/N)^2}$
HAPD	0.5	0.9	1000	1.0	10^5	200	$\sqrt{2.2/N}$
CCD	0.8	1.0	-	1.0	1	50	$\sqrt{1.3/N+(60/N)^2}$
ICCD / ICMOS	0.8	0.7	-	2.0	10^4	50	$\sqrt{5.7N}$
EMCCD	0.8	1.0	2	2.0	10^3	50	$\sqrt{2.5/N}$
EBCCD / EBCMOS	0.5	0.85	1000	1.0	10^3	50	$\sqrt{2.35/N}$


$\frac{\sigma}{E}\sqrt{N_{ph}}$
Resolution / Poisson
3.0
2.5
2.0
1.5
1.0
1
10
100
1000
10000
100000
1000000
10000000
#Photon
PMT
PD
APD
HPD
HAPD
CCD
ICCD/ICMOS
EMCCD
EBCCD/EBCMOS
ICCD
APD
PMT
HPD
EMCCD
HAPD
EBCCD
CCD
PD

Part I: T. Hollenhorst, A theory of multiplication Noise, IEEE Transactions on electron devices Vol. 37. N0. 3. MARCH 1990

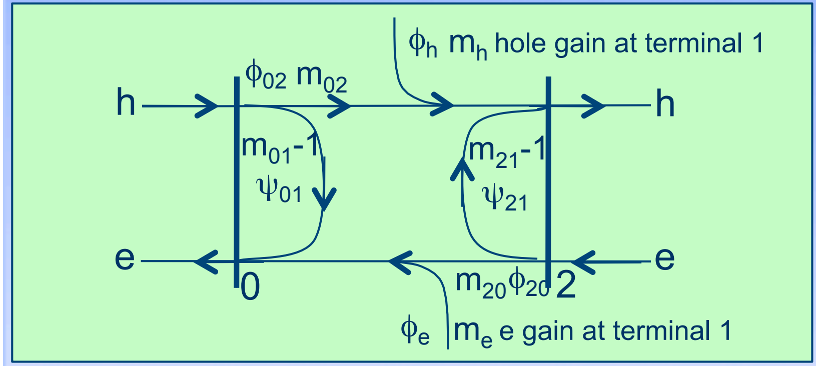
•Two stages gain: definitions and notations.

- •m_{ij} multiplication gain from i to j is described by a probability distribution function (pdf) $P_{ij}(m_{ij})$ with ij=01,10,12,21
- •m_{ij}-1 secondary carrier multiplication gain from i to j related to primary carrier gain m_{ij}
- •Φ_{ij} the generating function of the pdf of m_{ij}
- •Ψ_{ij} the generating function of the pdf of m_{ij} -1



Aim: compute the gain and the ENF of a two stage multiplication process and then to generalize to N identical stages using generating function probability theory:

-PMT
-APD
-EMCCD …



•Probability theory: generating function, moments of order l

$$\phi_{ij}(z) \equiv \sum_{m=0}^{\infty} P_{ij}(m) z^m \qquad P_{ij}(n) = \frac{1}{n!}\frac{d^n}{dz^n}\phi_{ij}(z)\Big|_{z=0}$$

$$\psi_{ij}(z) = z^{-1}\phi_{ij}(z) \qquad \langle m_{ij}{}^{l}\rangle = \sum_{m=1}^{\infty} m^l P_{ij}(m) = \left[z\frac{d}{dz}\right]^l \phi_{ij}(z)\Big|_{z=1}$$

$$\left[\begin{array}{l} \phi_{ij}(1) = 1 \\ \phi_{ij}^{'}(1) = \langle m_{ij}\rangle = M_{ij} \\ \phi_{ij}^{''}(1) = \langle m_{ij}^2\rangle - M_{ij} \end{array}\right.$$

•2 stages generating functions:

$$\phi_{02}(z) \equiv \phi_{01}\left[\phi_h(z)\right] \longleftarrow m_{02} = \sum_{k=1}^{m_{01}} m_h(k)$$

$$\phi_{20}(z) \equiv \phi_{21}\left[\phi_e(z)\right]$$

$$\phi_h(z) = z\psi_{12}\left[\phi_e(z)\right] \qquad \phi_h(z) = z\psi_{12}\left[z\psi_{10}\left[\phi_h(z)\right]\right]$$

$$\phi_e(z) = z\psi_{10}\left[\phi_h(z)\right] \qquad \phi_e(z) = z\psi_{10}\left[z\psi_{12}\left[\phi_e(z)\right]\right]$$

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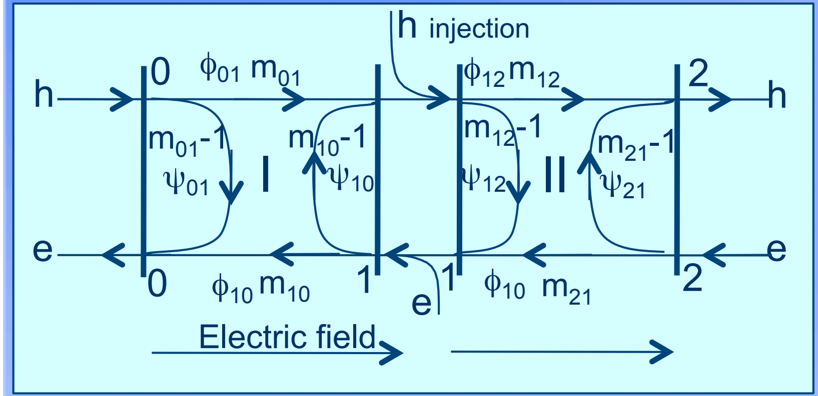
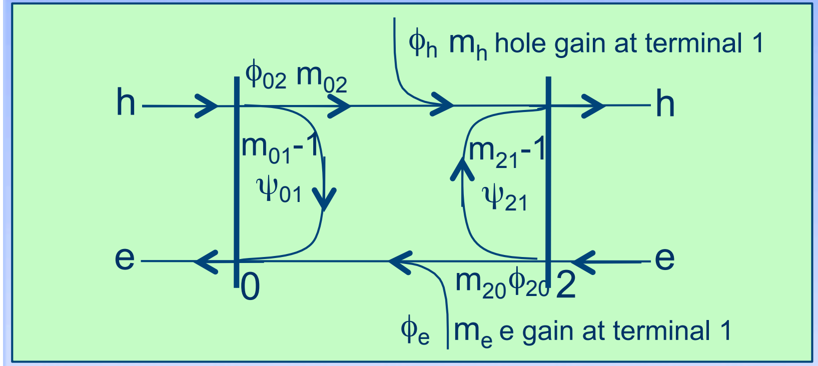
- Φ_{ij} the generating function of the pdf of m_{ij}
- Ψ_{ij} the generating function of the pdf of $m_{ij}-1$





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$$\phi_{ij}(z) \equiv \sum_{m=0}^{\infty} P_{ij}(m) z^m \qquad P_{ij}(n) = \frac{1}{n!}\frac{d^n}{dz^n}\phi_{ij}(z)\Big|_{z=0}$$

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$$\left[\begin{array}{l} \phi_{ij}(1) = 1 \\ \phi_{ij}^{'}(1) = \left\langle m_{ij}\right\rangle = M_{ij} \\ \phi_{ij}^{''}(1) = \left\langle m_{ij}^2\right\rangle - M_{ij} \end{array}\right.$$

•Excess Noise factor F and noise increment f definitions:

$$F(M) = \frac{\left\langle m^2\right\rangle}{\left\langle m\right\rangle^2} \qquad f(M) = F(M) - 1 = \frac{\left\langle m^2\right\rangle - \left\langle m\right\rangle^2}{\left\langle m\right\rangle^2} \qquad f(M) = \frac{\sigma_M^2}{M^2}$$

•After some algebra

$$F(M_{02}) = \frac{\left\langle m_{02}^2\right\rangle}{\left\langle m_{02}\right\rangle^2} \quad \left[\begin{array}{l} \phi_{02}^{'}(1) \\ \phi_{02}^{''}(1) \\ \phi_{h}^{'}(1) \\ \phi_{h}^{''}(1) \end{array}\right.$$

$$M_{02} = M_{01}M_h \qquad f_{02} = f_{01} + \frac{f_h}{M_{01}}$$

$$M_h = \frac{M_{12}}{1-(M_{12}-1)(M_{10}-1)}$$

$$f_h = f_{01}M_{10}\left(M_h - 1\right) + f_{12}M_{10}\left(1 - M_h + M_h M_{10}\right)$$

Feedback leads to breakdown if $(M_{12}-1)(M_{10}-1) = 1$

$M_h \rightarrow \infty$

•2 stages generating functions:

$$\phi_{02}(z) \equiv \phi_{01}\left[\phi_h(z)\right] \longleftarrow \quad m_{02} = \sum_{k=1}^{m_{01}} m_h(k)$$

$$\phi_{20}(z) \equiv \phi_{21}\left[\phi_e(z)\right] \qquad \phi_h(z) = z\psi_{12}\left[z\psi_{10}\left[\phi_h(z)\right]\right]$$

$$\phi_h(z) = z\psi_{12}\left[\phi_e(z)\right] \qquad \phi_e(z) = z\psi_{10}\left[z\psi_{12}\left[\phi_e(z)\right]\right]$$

$$\phi_e(z) = z\psi_{10}\left[\phi_h(z)\right]$$

•Solutions for 2 multiplication stages (e/h):

$$M_{02} = \frac{M_{01}M_{12}}{1-(M_{12}-1)(M_{10}-1)}$$

$$f(M_{02}) = f_{02} = f_{01} + \frac{M_{10}^2 M_{02}}{M_{01}^2 M_{12}}\left[f_{10}(M_{12}-1) + f_{12}\right]$$

•Single carrier Ionization:

$$M_{02} = M_{01}M_{12}$$

$$f_{02} = f_{01} + \frac{f_{12}}{M_{01}}$$

Part I: T. Hollenhorst, A theory of multiplication Noise, IEEE Transactions on electron devices Vol. 37. N0. 3. MARCH 1990

M_N, and f_N: Gain and noise increment of a of the N **identical** stage device

$\Phi_N(z)$ Generating function of the N stage device

$\phi_N(z)$ Generating function of the stage N

$$\Phi_{N+1}(z) = \Phi_N\left[\phi_{N+1}(z)\right]$$

$$\Phi_N(z) = \phi_1\left[\phi_2\left[\ldots\phi_{N-1}\left[\phi_N(z)\right]\ldots\right]\right]$$

Recursion relations for M_N and f_N:

$$M_{N+1} = \frac{M_{01}M_N}{1-(M_N-1)(M_{10}-1)}$$

$$f_{N+1} = f_{01} + \frac{M_{10}^2 M_{N+1}}{M_{01}^2 M_N}\left[f_{10}(M_N-1)+f_N\right]$$

$$M_N = \frac{(M_{01}-M_{10})M_{01}^N}{(M_{01}-1)M_{10}^N-(M_{10}-1)M_{01}^N}$$

$$f_N = A\left(M_N-1\right)+B\left(1-\frac{1}{M_N}\right)$$

$$A = \frac{f_{01}M_{01}\left(M_{10}-1\right)+f_{10}M_{10}\left(M_{01}-1\right)}{\left(M_{01}-1\right)^2\left(M_{10}+M_{01}\right)}$$

$$B = \frac{M_{01}\left[f_{01}\left(M_{01}^2-M_{10}\right)+f_{10}M_{10}\left(M_{01}-1\right)\right]}{\left(M_{01}-1\right)^2\left(M_{10}+M_{01}\right)}$$

N stages : PMT / APD / EMCCD

M_N, and f_N: PMT

$M_{01} = \delta \quad M_{10} = 1$

$$f_{01} = \frac{\sigma_{01}^2}{M_{01}} \quad f_{10} = 0$$

$$M_N = M_{01}^N$$

$$f_N = f_{01}\left(1-\frac{1}{M_{01}}\right)^{-1}\left(1-\frac{1}{M_N}\right)$$

$\sigma_{01}^2 = \delta$ (Poisson)

$$f_{01} = \frac{1}{M_{01}} = \frac{1}{\delta}$$

$$M_N = \delta^N$$

$$f_N = \frac{1}{\delta-1}\left(1-\frac{1}{\delta^N}\right)$$

M_N and f_N: APD

$M_{01} = 1+\mu \quad M_{10} = 1+\nu$

$f_{01} = \mu \quad f_{10} = \nu$

$$k \equiv \frac{\alpha}{\beta} < 1$$

$$\mu = \beta\Delta x$$

$$\nu = \alpha\Delta x$$

$$k = \frac{\nu}{\mu}$$

$$M_N = \frac{(1-k)}{\exp\left[(k-1)\mu N\right]-k}$$

$$M = M_{N\to\infty}$$

$$M = \frac{1-k}{\exp\left[(k-1)\int\beta(x)dx\right]-k}$$

$$f = k(M-1)+(1-k)\left(1-\frac{1}{M}\right)$$

M and f: EMCCD

$M_{01} = 1 \quad M_{10} = 1+\nu$

$$f_{01} = 0 \quad f_{10} = \frac{\nu(1-\nu)}{(1+\nu)^2}$$

$$\phi_{10} = (1-\nu)z+\nu z^2$$

Bernoulli trial

$$M_N = (1+\nu)^N$$

$$f_N = \frac{1-\mu}{1+\mu}\left[1-\frac{1}{M_N}\right]$$

Do it as an exercise !

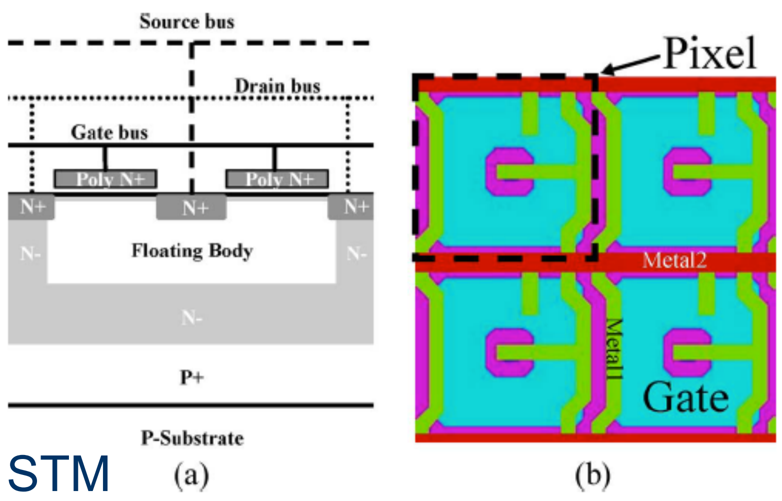
From large area detector PMT for Cherenkov detector to pixel array for highly resolved imaging

- Cherenkov detector : Large aperture devices
- PET scan … MaPMT or pixelAPD: Typical pixel size ~2x2mm^2
- Imaging camera system : MTF (lp/mm)
  - Typical pixel size (Pitch) ~5-15 μm
  - Cellular phone 2 μm
  - DTI, doping profile, SOI

G-N Lu, A. Tournier, F. Roy, B. Deschamps
Sensors ***2009, 9, 131-147; doi:10.3390/s90100131***

1.4-μm-Pitch 50% Fill-Factor 1T Charge-Modulation Pixel for CMOS Image Sensors

Arnaud Tournier, F. Roy, G.-N. Lu, and B. Deschamps



20" PMT

Vacuum Devices

Stitching

Solid State Devices

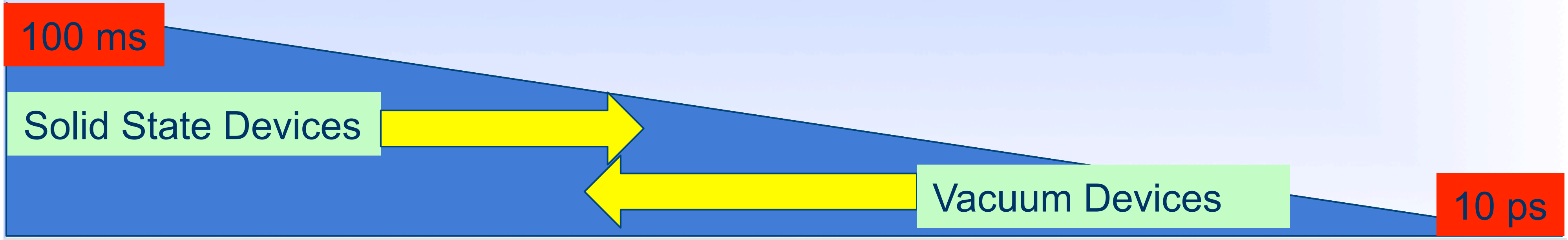
1.4 μm

Time resolution:

- Detection process – drift of the charge – jitter …
- Front-end electronics: fast shaper
    - fast and slow shapers can be used (time stamping and energy measurement) ROC ASICs

- CMOS imager CCD are extremely slow (~s-ms) compare to PMT or APD, GAPD and MCP (~ns-ps).

- MCP based devices should have the best timing resolution (10 ps)

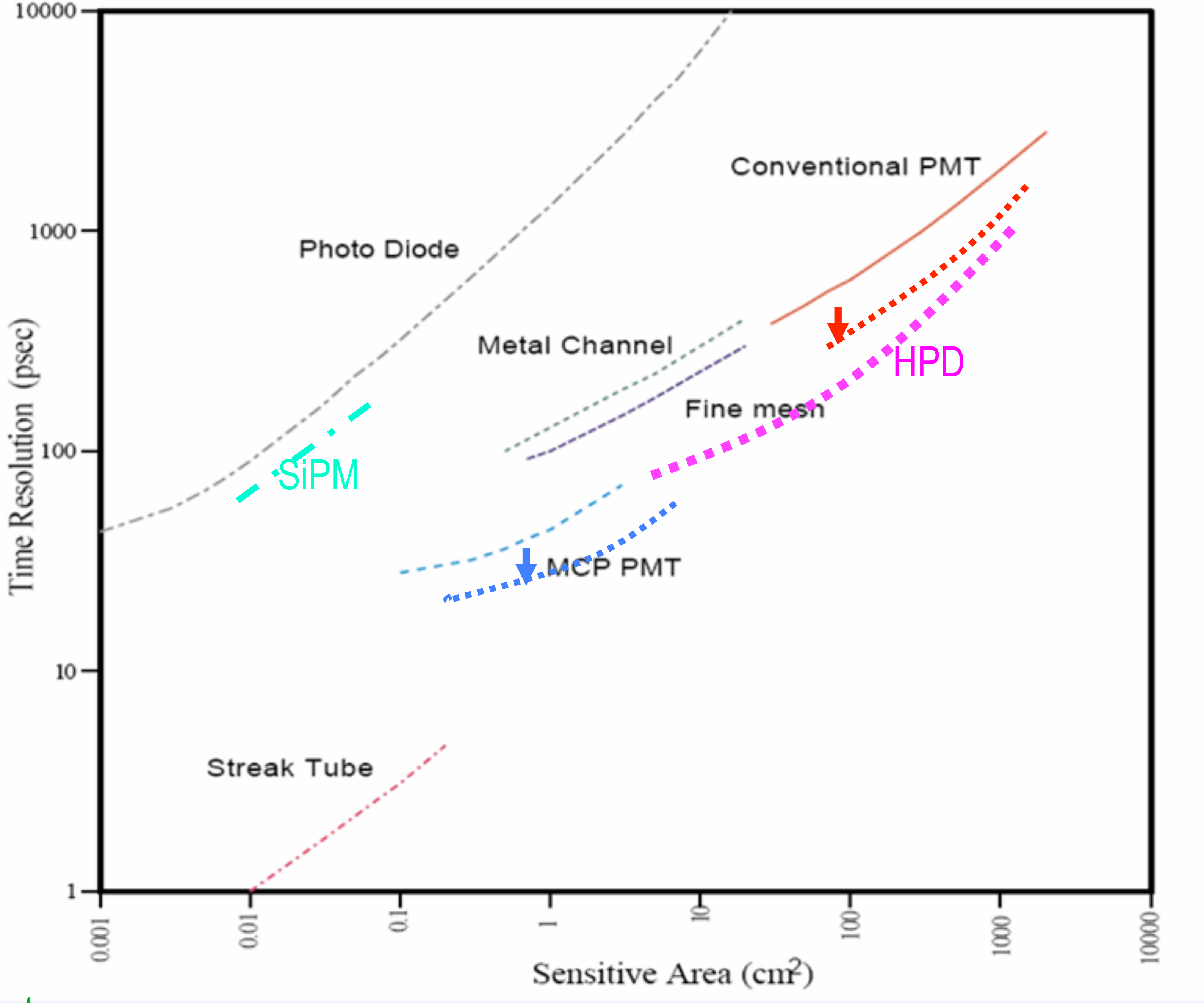


100 ms

Solid State Devices

Vacuum Devices

10 ps


10000
1000
100
10
1
Time Resolution (psec)
0.001
0.01
0.1
1
10
100
1000
10000
Sensitive Area (cm2)
Photo Diode
Conventional PMT
Metal Channel
Fine mesh
HPD
SiPM
MCP PMT
Streak Tube

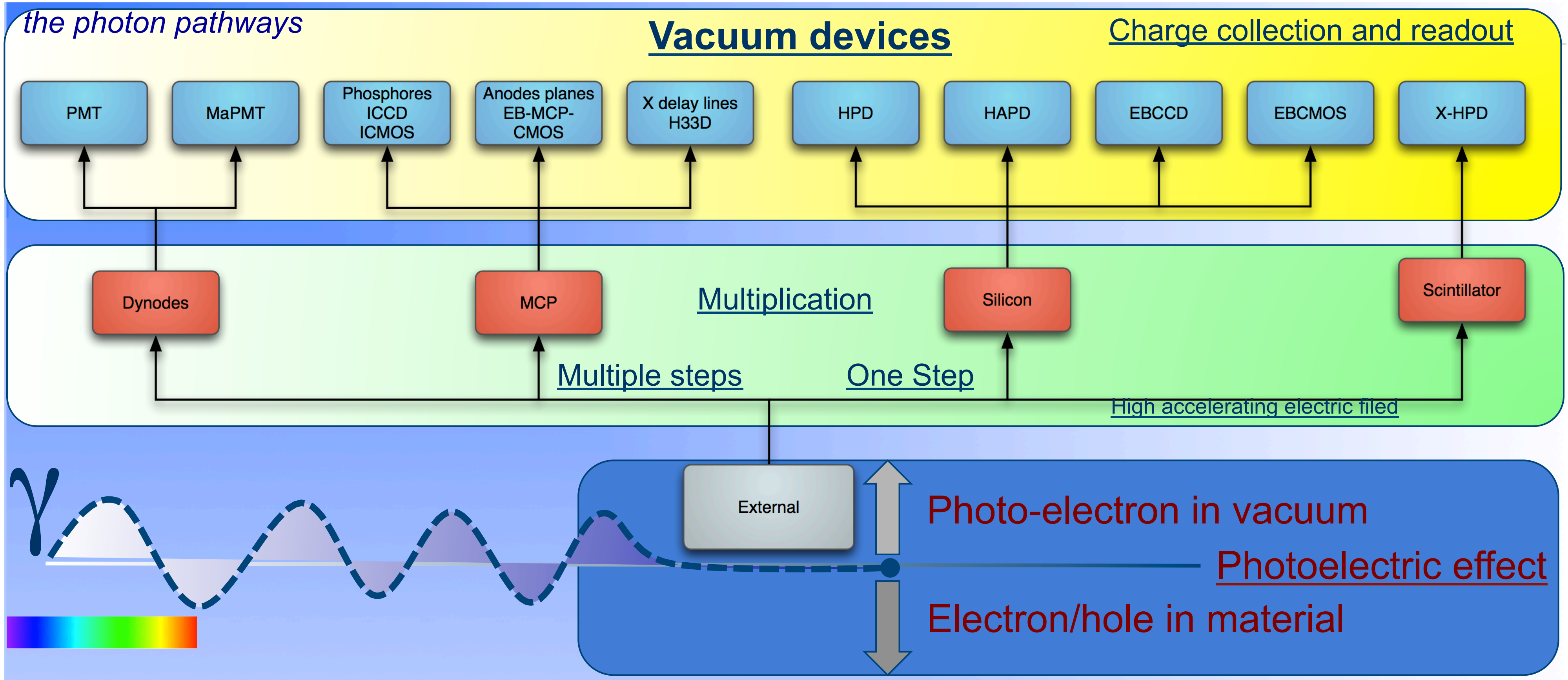
K. Arisaka

Part two : Photodetectors

- ✓Vacuum devices
- ✓Solid State devices

the photon pathways

Vacuum devices



Charge collection and readout

PMT
MaPMT
Phosphores ICCD ICMOS
Anodes planes EB-MCP-CMOS
X delay lines H33D
HPD
HAPD
EBCCD
EBCMOS
X-HPD

Multiplication

Dynodes
MCP
Silicon
Scintillator

Multiple steps

One Step

High accelerating electric filed

External

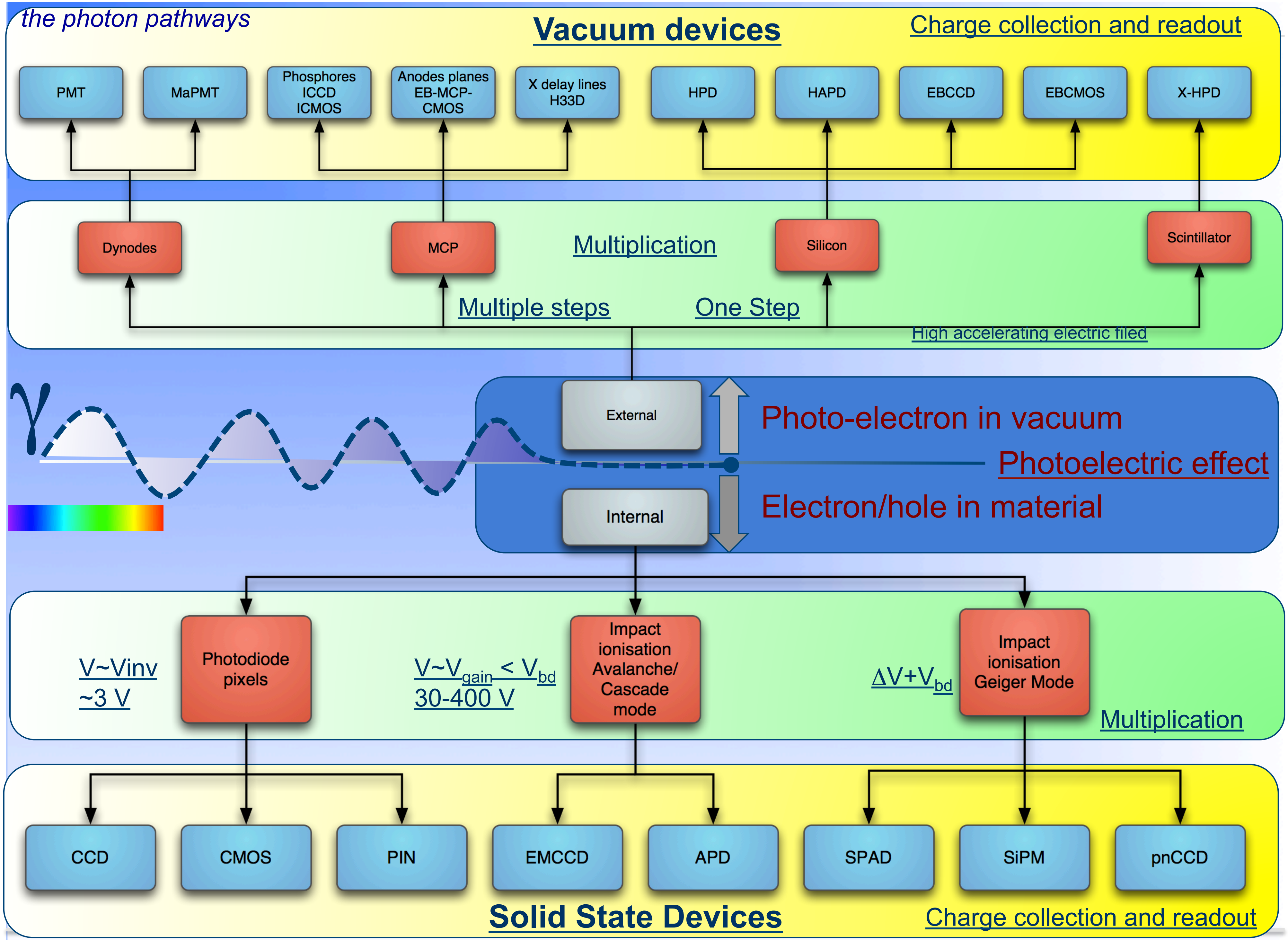
γ

Photo-electron in vacuum

Photoelectric effect

Electron/hole in material

the photon pathways



Vacuum devices

Charge collection and readout

PMT

MaPMT

Phosphores ICCD ICMOS

Anodes planes EB-MCP-CMOS

X delay lines H33D

HPD

HAPD

EBCCD

EBCMOS

X-HPD

Dynodes

MCP

Multiplication

Silicon

Scintillator

Multiple steps

One Step

High accelerating electric filed

γ

External

Photo-electron in vacuum

Photoelectric effect

Electron/hole in material

Internal

$V \sim V_{inv}$
~3 V

Photodiode pixels

$V \sim V_{gain} < V_{bd}$
30-400 V

Impact ionisation Avalanche/ Cascade mode

$\Delta V + V_{bd}$

Impact ionisation Geiger Mode

Multiplication

CCD

CMOS

PIN

EMCCD

APD

SPAD

SiPM

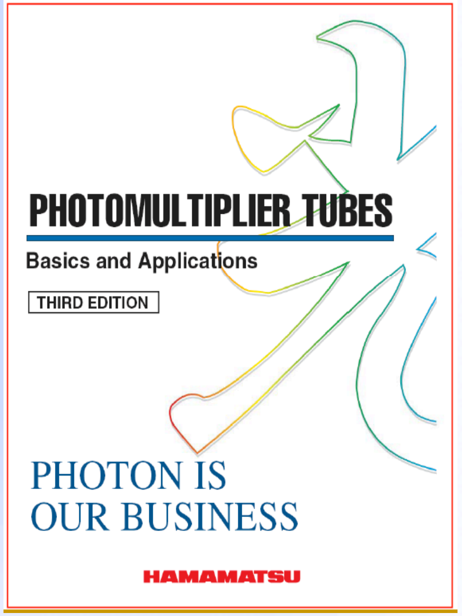
pnCCD

Solid State Devices

Charge collection and readout

Vacuum devices

- Photomultiplier Tubes: PMT
- MultiChannel Plates: MCP-PMT
- Hybrid Photon Detectors: HPD



PHOTOMULTIPLIER TUBES
Basics and Applications
THIRD EDITION
PHOTON IS
OUR BUSINESS
HAMAMATSU

Can be downloaded
on hamamatsu web page

Photomultiplier Tubes

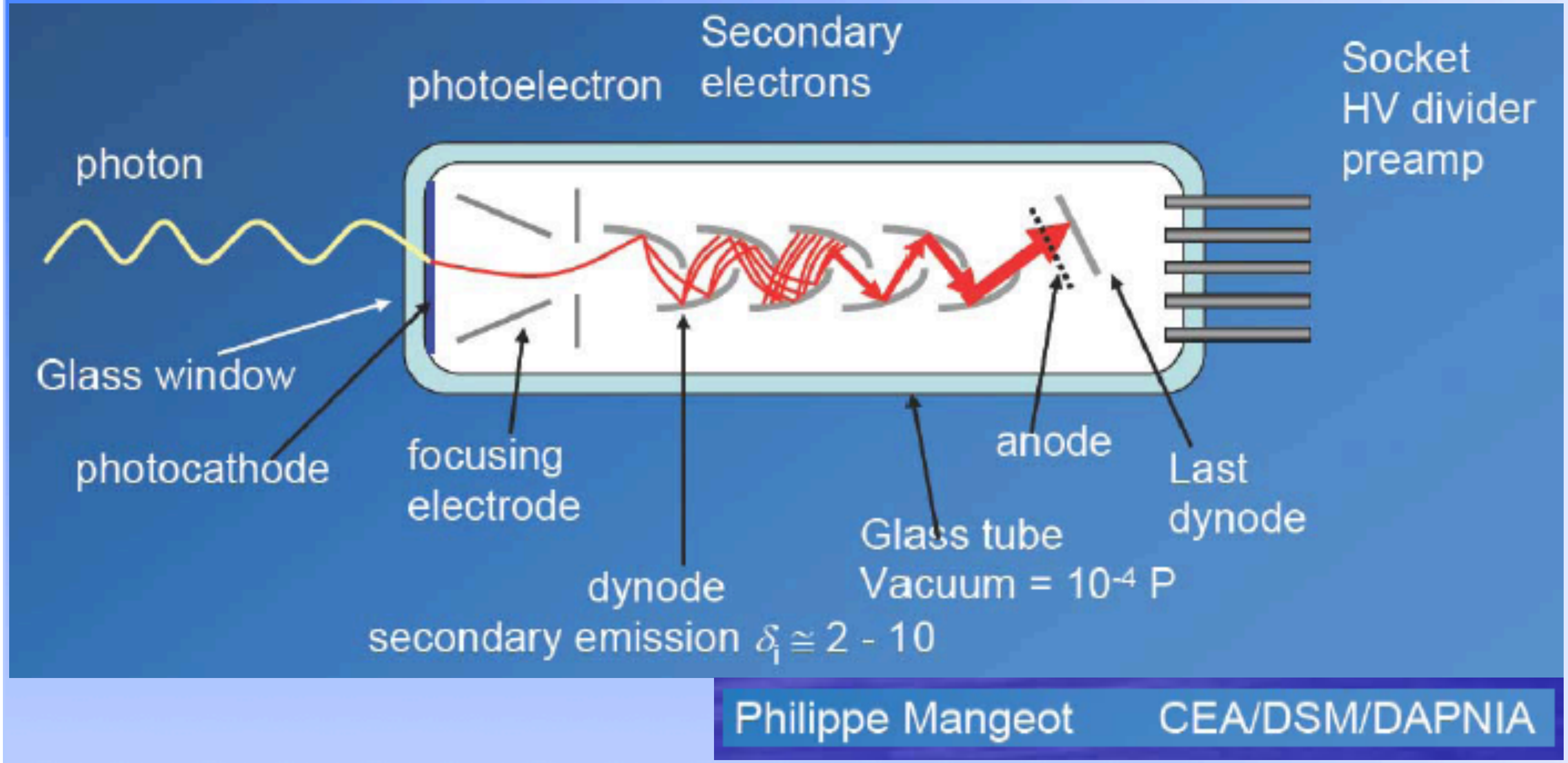
Single channel : 20 inch diam.

1740 cm^2/channel

Multianodes
8x8 – 16x16
~2x2 mm^2/channel

Hamamatsu

Different applications: medical… science …



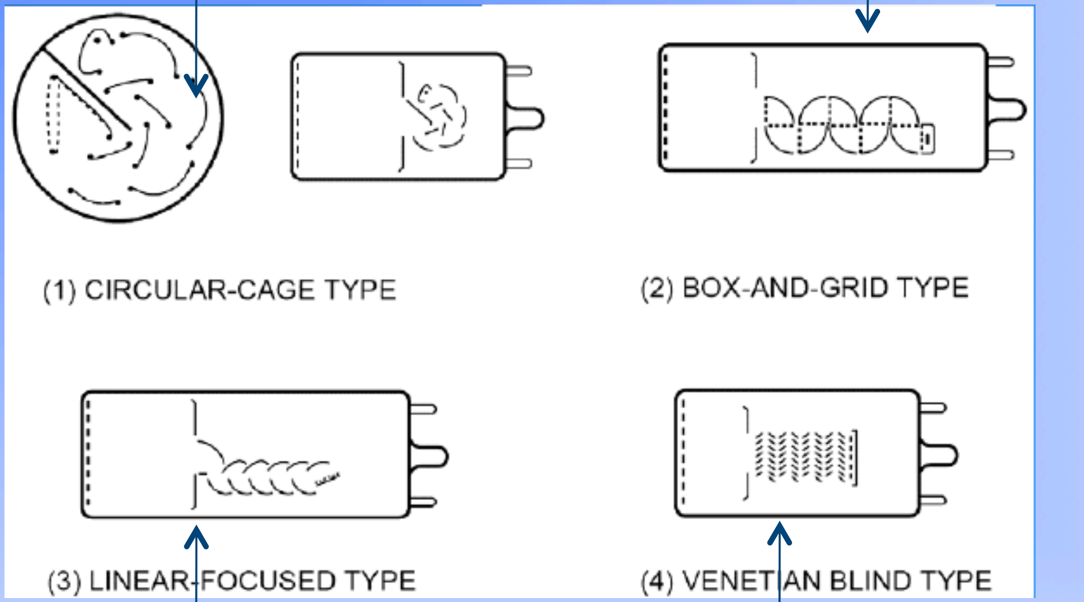
1. The photon (ph) produce a photoelectron (pe) (Quantum Eff.)
2. The pe is emitted into the vacuum (Quantum Eff.)
3. The pe is collected by the first dynode (Coll. Eff)
4. The pe is “amplified” by dynodes multiplication stages (M and ENF)
5. The secondary charges are collected by the anode
6. The anode signal is readout (Equ. Noise Charge ENC)

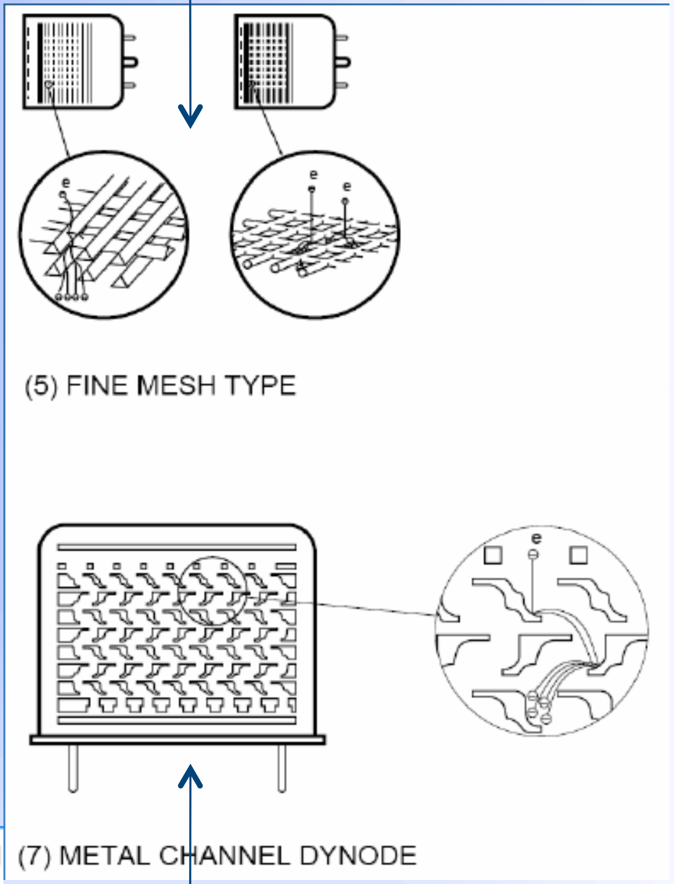
Part II: PMT – dynodes geometries

Circular-cage:
very compact

Box-and-Grid:
Good CE
Slow

Fin-mesh:
Fast, compact,
Operate @ 1Tesla
Low CE





HAMAMATSU

Linear-focused:
Small TTS, fast,
Sensitive to magnetic field

Venetian-blind:
Good CE, Gain stability,
Slow

Metal Channel: compact high CE,
operate in magnetic field 10 mT

PMT’s are sensitive to magnetic field even to earth field ➔ Magnetic Shielding required

- The Gain M is due to secondary emission.

δ_i is the secondary emission coefficient of dynode i,

$$M = \delta_1 \delta_2 \delta_3 \ldots \delta_n = \prod_{i=1}^{n} \delta_i$$

$$ENF_{1pe} = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \delta_2} + \frac{1}{\delta_1 \delta_2 \delta_3} + \ldots + \frac{1}{\delta_1 \delta_2 \delta_3 \ldots \delta_n}$$

$$\delta_i = a \times V_\delta^k$$

$$a = cste$$

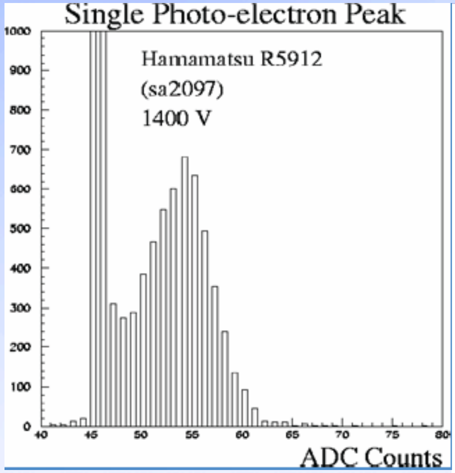
$$k = 0.7 - 0.8$$

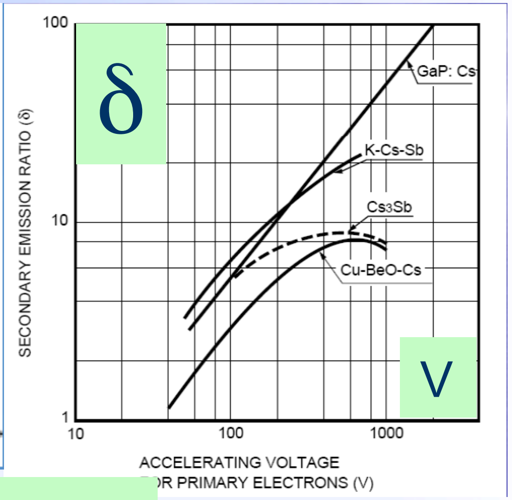
$$M = (a \times V_\delta^k)^n = a^n \times \left(\frac{V}{n+1}\right)^{k.n} = A \times V^{k.n}$$

$$ENF \approx \frac{\delta}{\delta - 1}$$

The first dynode dominates the ENF
Increase δ_1 reduce ENF and increase
single photon sensitivity and
Peak to Valley Ratio

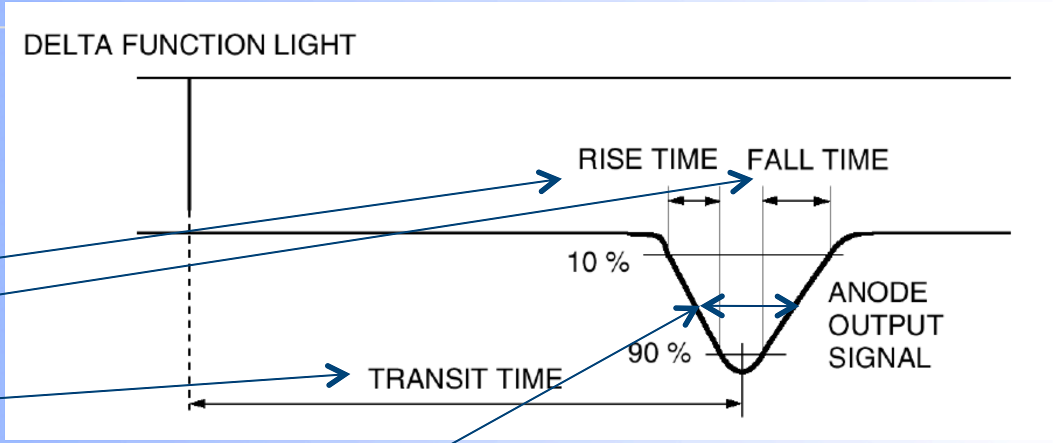
$$\left(\frac{\sigma}{E}\right)_{1pe} = \sqrt{ENF_{pe} - 1}$$





M 10^6 to 10^8 / ENF ~1.3

Part II: PMT – Time resolution



Definitions:

- Rise Time (10% to 90%)
- Fall Time
- Electron Transit Time
- Transit Time Spread : FWHM of the distrib. of the TT (TTS) or Transit Time jitter

~0.3-1 ns

Unit : ns

Dynode Type	Rise Time	Fall Time	Pulse Width (FWHM)	Electron Transit Time	TTS
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50	0.37 to 1.1
Circular-cage	3.4	10	7	31	3.6
Box-and-grid	to 7	25	13 to 20	57 to 70	Less than 10
Venetian blind	to 7	25	25	60	Less than 10
Fine mesh	2.5 to 2.7	4 to 6	5	15	Less than 0.45
Metal channel	0.65 to 1.5	1 to 3	1.5 to 3	4.7 to 8.8	0.4

Table 4-3: Typical time characteristics (2-inch dia. photomultiplier tubes)

- Different photocathode sensitivities
  - GEN II alkali metals (Sb K Rb Cs)
  - GEN III III-V compound semiconductors (GaAsP GaAs InGaAs)

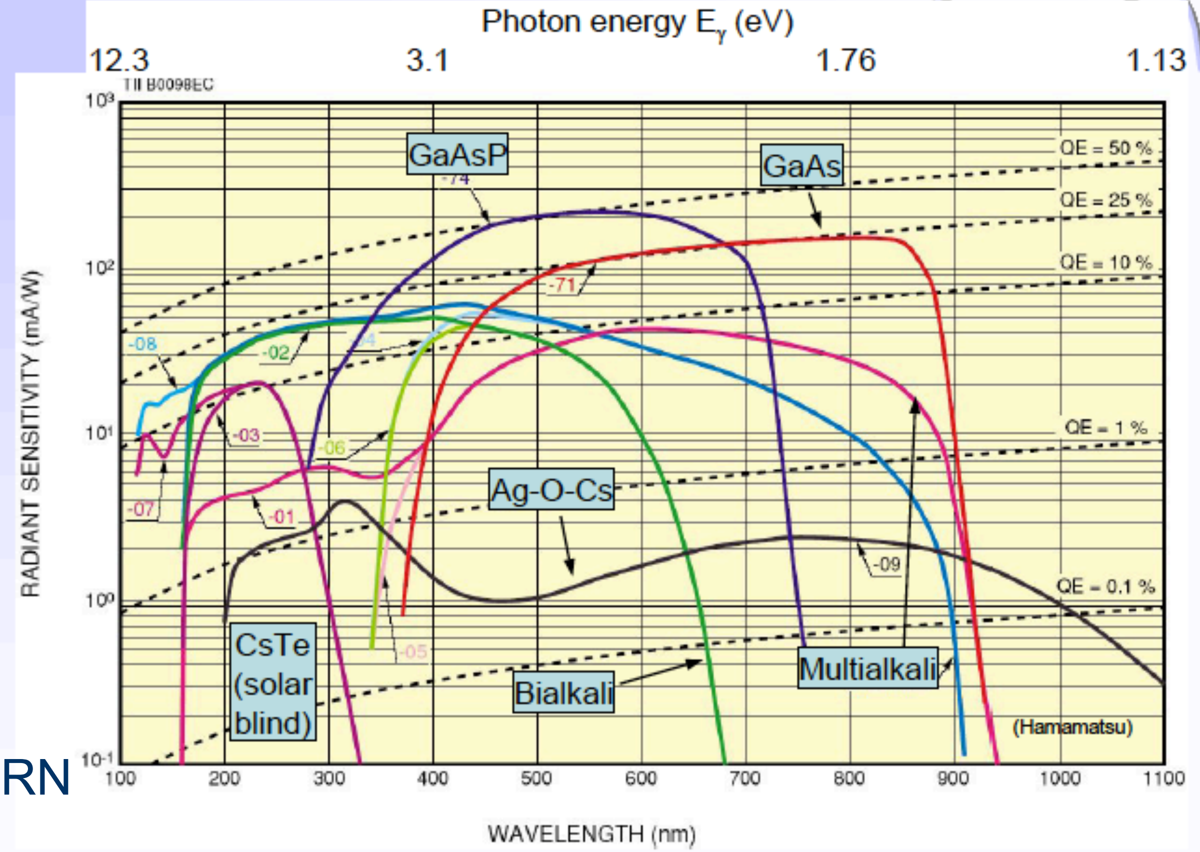
QE 20 to 30% @ 400 nm
CE 70 to 90 %

Q : Why QE is limited?
(~40%)

A: Competing two factors:
✓Absorption of ph
✓Emission of pe

3b Photo-detection

QE's of typical photo-cathodes



Bialkali: SbKCs, SbRbCs Multialkali: $SbNa_2KCs$ (alkali metals have low work function)

T Gys CERN

Part I : PMT - photocathode and quantum efficiency

- Definitions:

$$QE = (1-R) \times \frac{P_\nu}{\mu} \times \frac{P_e}{1+ {}^{1}\!/_{\mu L}}$$

•material

R: reflection coefficient
P_ν : pe Prob. to be above E_0
μ: full absorption coefficient

•Cristal quality
•Electron Affinity

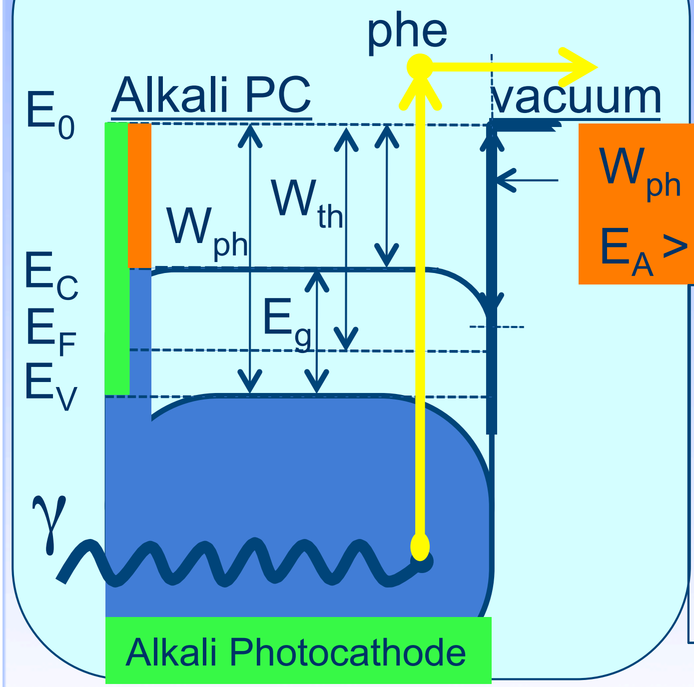
L: pe mean escape length
P_e : Prob. to escape

PC band Model

- E_F Fermi level
- E_V valence band
- E_0 vacuum level
- E_C conduction band

- W_{th} thermionic Work Function: $W_{th} = E_0 - E_F$
- E_A electron affinity: $E_A = E_0 - E_C$

Positive Electron Affinity



$W_{ph} > W_{th}$
$E_A > 0$

•W_{ph} photoemission threshold
$W_{ph} = E_0 - E_V = E_g + E_A$

$W_{ph} = E_g$
$NE_A < 0$

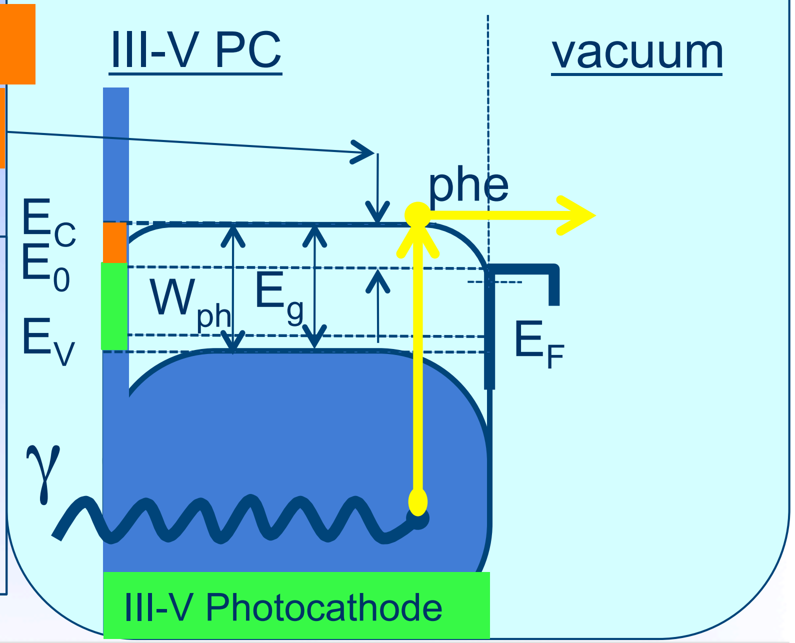
Schottky effect:
An external electric field at the PC surface has an effect on the photoemission efficiency: the potential barrier is reduced by an amount ΔW_{th}

$$\Delta W_{th} = \sqrt{\frac{eE}{4\pi\varepsilon_0}}$$

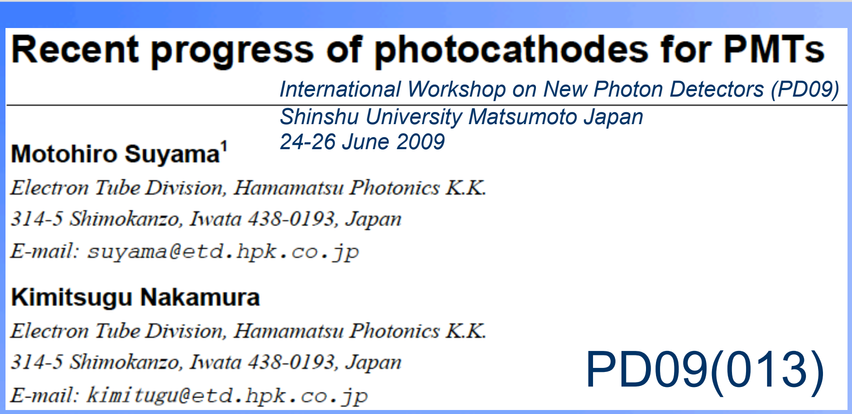
E accelerating field

Negative Electron Affinity

CsO_2 is applied -> NEA



Part I - PMT – Photocathode improvements



Recent progress of photocathodes for PMTs

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

Motohiro Suyama[1]
Electron Tube Division, Hamamatsu Photonics K.K.
314-5 Shimokanzo, Iwata 438-0193, Japan
E-mail: `suyama@etd.hpk.co.jp`

Kimitsugu Nakamura
Electron Tube Division, Hamamatsu Photonics K.K.
314-5 Shimokanzo, Iwata 438-0193, Japan
E-mail: `kimitugu@etd.hpk.co.jp`

PD09(013)

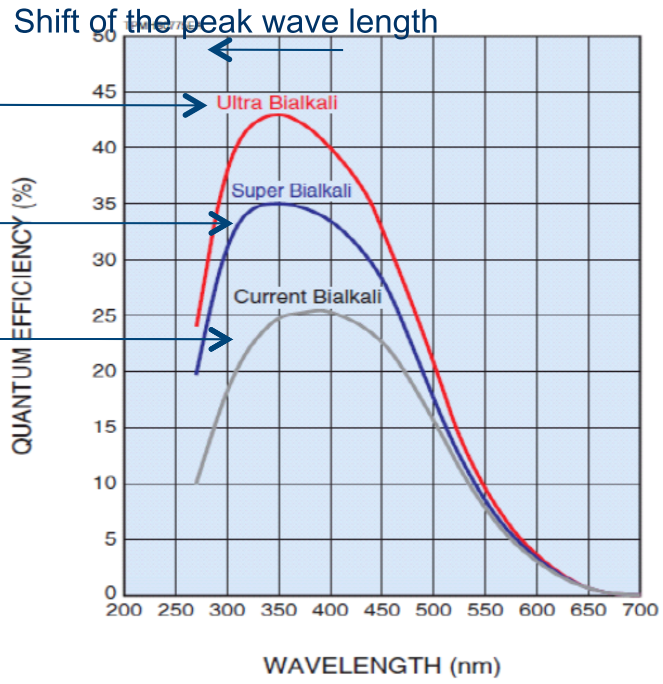
43% @ 350 nm

35% @ 350 nm

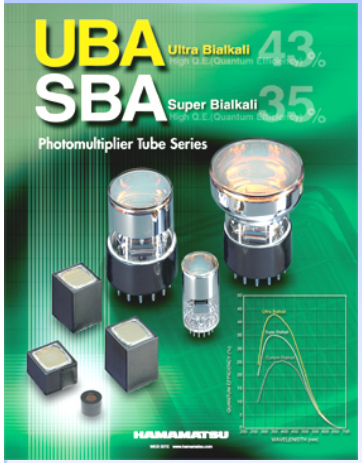
25% @ 350 nm

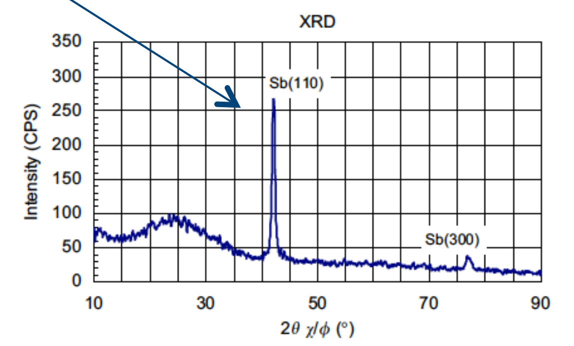
hamamatsu

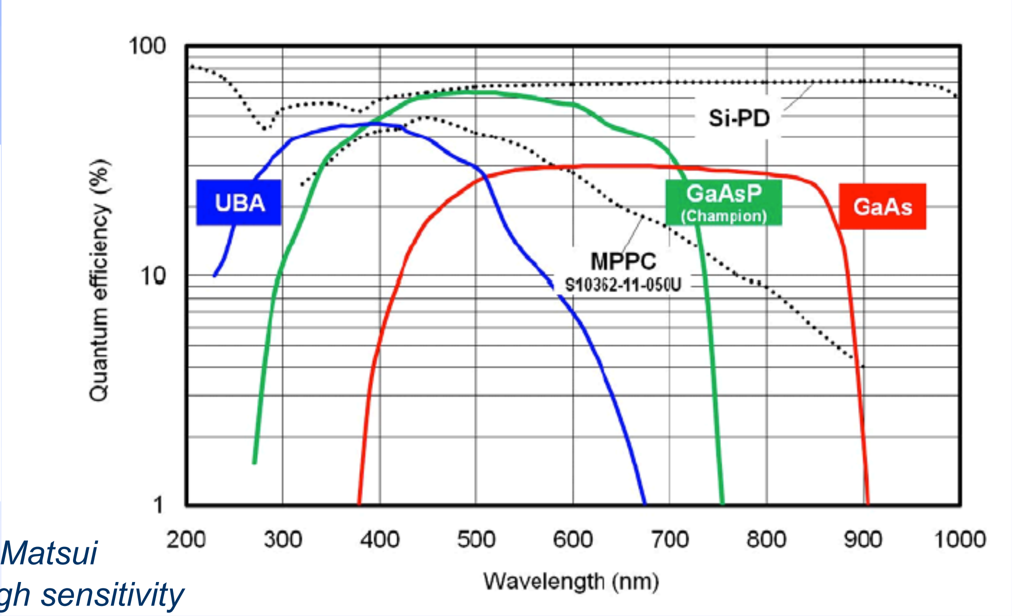
Shift of the peak wave length



PC Bialkali : K-Sb-Cs
Sb thin film deposited with an improvement of the crystalline structure (the mean escape length L is increase)
X-ray diffraction analysis







REF:
K. Nakamura, Y Hamana, Y Ishigami, T. Matsui
Latest bialkali photocathode with ultra high sensitivity
NIM A 623 (2010) 276

INCREASE FILL FACTOR

Flat Panel H9500 Hamamatsu

- 16x16 (256) anodes
- Pixel size 2.8x2.8 mm^2
- Pitch : 3.04 mm
- Effective area = 49x49 mm square
- FF = 89%
- G = 1.5 10^6
- 12 Dynodes
- PC: Bialkali 24% @ 420 nm
- Transit Time 6 ns
- Transit Time Spread = 0.4 ns
- Rise Time = 0.8 ns
- Xtalk = 5%
- Anode Uniformity 1:4

Flat Panel is MaPMT

Planacon is MCP-PMT
(see later)

Planacon XP85012 Photonis

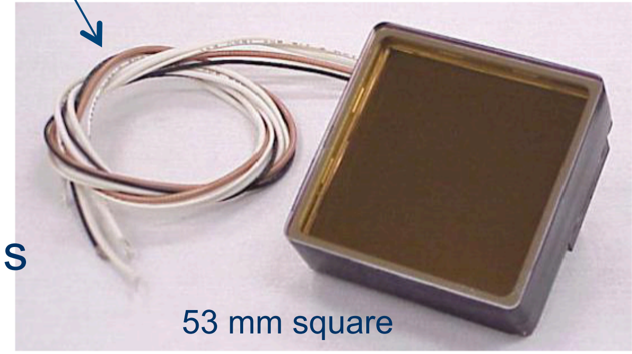
- 8x8 (64) anodes
- Pixel size 5.9x5.9 mm^2
- Pitch : 6.05 mm
- Effective area = 49x49 mm square
- FF = 80%
- G = 6. 10^6
- 2 MCP chevron 25 micron pore 40:1 L:D ratio
- PC: Bialkali 24% @ 420 nm
- Pulse Width = 1.8 ns
- Rise Time = 0.6 ns

H9500
52 mm Square

Medical applications

XP85012

PLANACON



53 mm square

Multichannel plates MCP-PMT

Image Intensifier: Night Vision

Input Window
- Quartz
- Glass
- Fiber Optic
- MgF2

Photocathode
- Solar blind
- S20 (UV)
- S20
- Broadband
- Hot S20
- Supergen
- (=Super S25)

Active Ø (mm)
- 18
- 25
- 40

MCP	**L:D**
None	
Single	50:1
Double	2x50:1
Double+	50:1+90:1

Gating Sublayer
- None
- Slow
- Fast
- Ultra

Phosphor
- P22
- P24
- P43
- P46
- P47

Output Window
- Straight fiber optic
- Twisted fiber optic
- Glass

Power Supply
- Standard fixed gain
- EGAC (ext gain contr)
- Autogating
- Autogating EGAC + ext sync
- EGAC with gate-unit

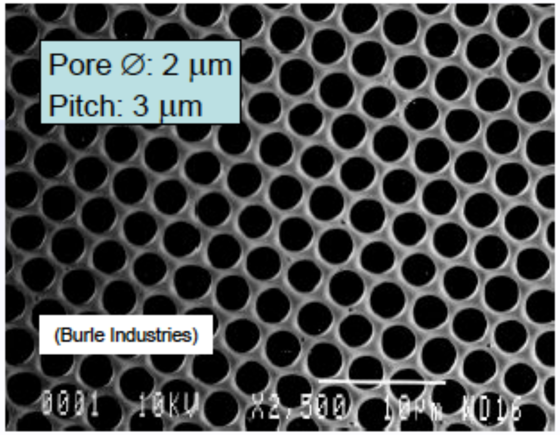
PHOTONIS
INDUSTRY & SCIENCE

With USB connector

ICU
ICMOS
Photonis

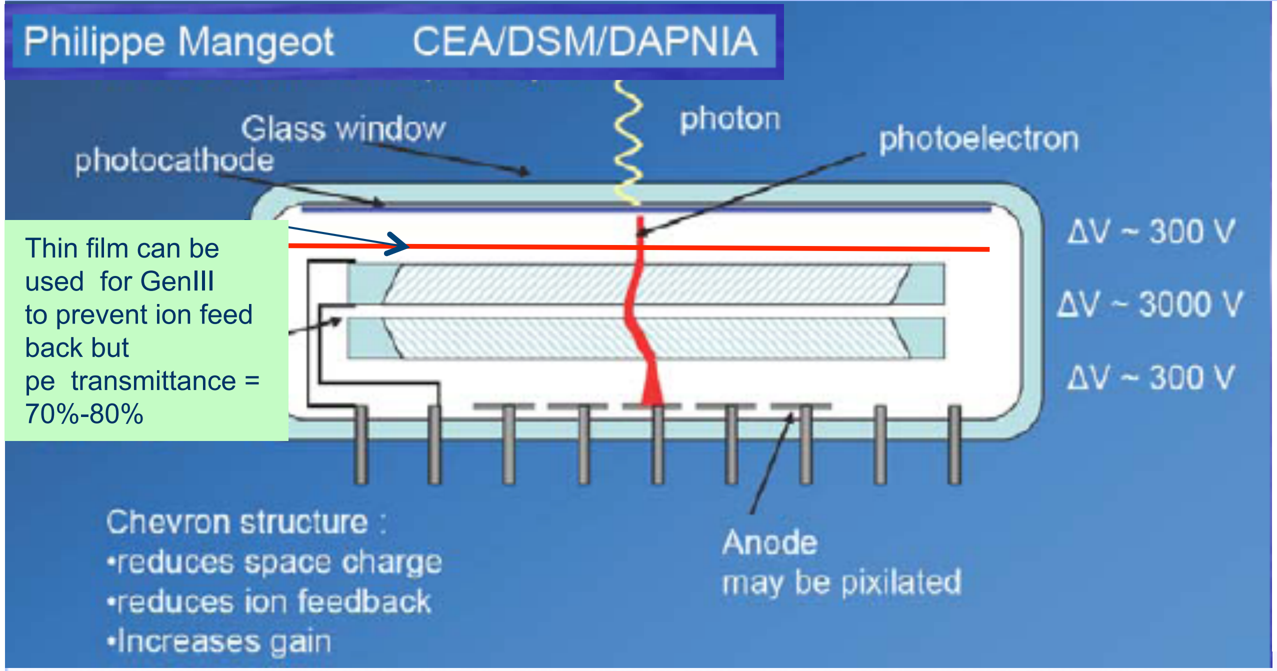
Part II: PMT - MCP - Basic

1. The pe is emitted and accelerated to the MCP V~300V
2. MCP multiplies the pe (V~3000V – G ~ 10^4) →
3. Readout of the secondary electrons
   - Phosphor + eye
   - Phosphor + CCD = ICCD
   - Phosphor + CMOS = ICMOS
   - Multi Anodes + ROC = ebMCP-CMOS
   - X Delay Line or X strip = H33D



FF~<80%

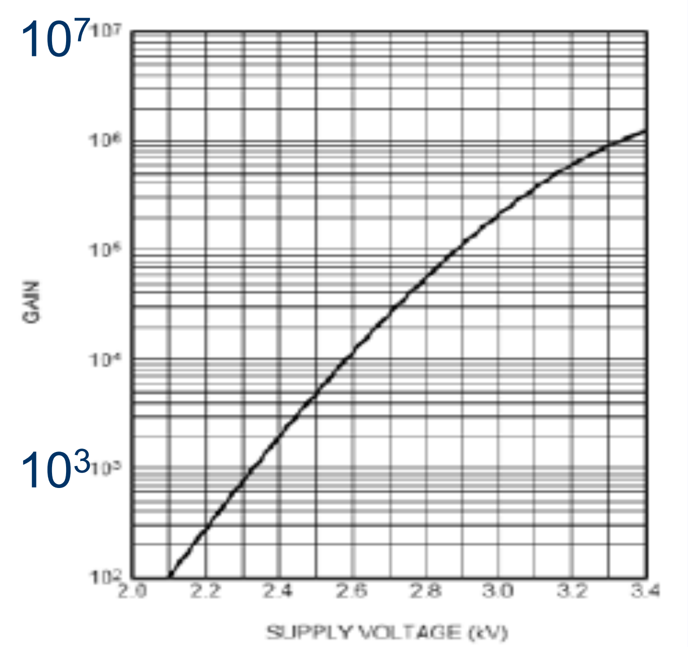
Picture of the MCP's pores



Thin film can be used for GenIII to prevent ion feed back but pe transmittance = 70%-80%

Chevron structure :
- reduces space charge
- reduces ion feedback
- Increases gain

GAIN vs V



Gain:

- Single stage: G ~10^3 to 10^4
- Dual MCP: G ~10^6 to 10^7

$$M = \exp(K \times \alpha)$$

$$\alpha = \frac{Length}{Diameter}$$

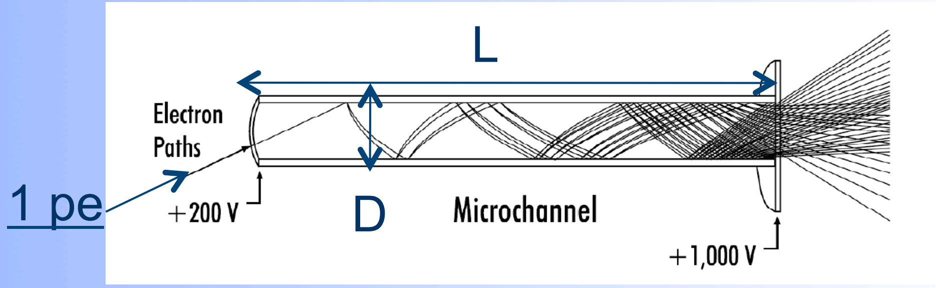
K secondary emission characteristics

Very Good Temporal resolution:

ultra-fast devices

- Low Transient Time ~1 ns
- Transient Time Spread ~ 50 ps
- Sub-ns rise and fall time
- Ex: 30 ps resolution (Hamamatsu R3809)
- Gating capability (Mesh 250 ps – 10 ns D=18mm)

One pore



Diameter pore ~ 2 to ~12 μm

Photocathodes:

- Bialkali
- Multi alkali (Photonis/Photek/Hamamatsu)
- GaAsP or GaAs (Hamamatsu …)
- Cs-Te for UV

Phosphor screen:

P24, P46, P47 (fast μs) ;P43 (slow 1ms);

Sensitive to single photon

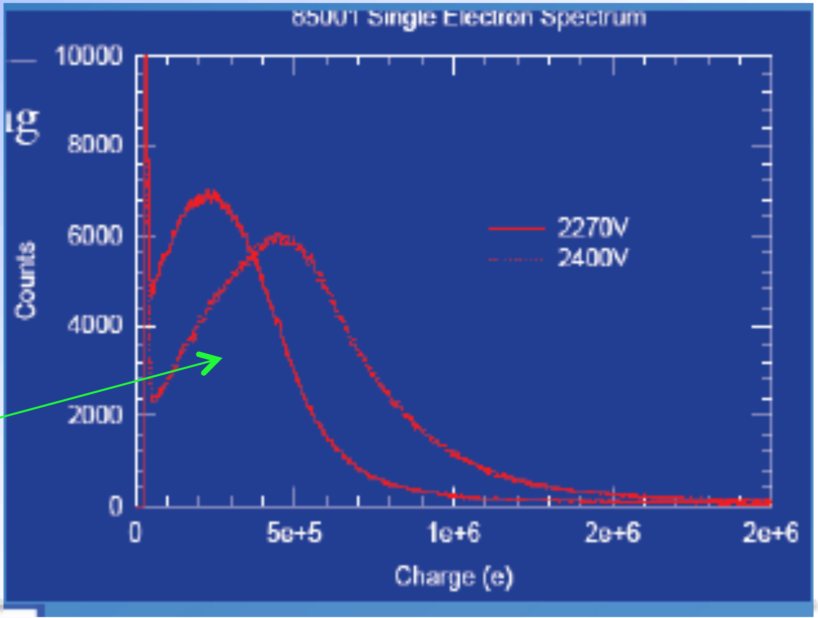


Image Intensifiers:

- Improve PDE
- Improve readout with CMOS: ICCD➔ICMOS
- Power consumption, functionalities, integration for night vision …
- Aging – compactness
- Fast Gating

ebMCP-CMOS

Improve time resolution !

Time of Flight System: 10 ps Fermi Lab & Photek (see below).

FLIM system: 25 ps CERN Nino chip & Photek

J.S. Lapington, T. Conneely, Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2010.11.175

10 ps

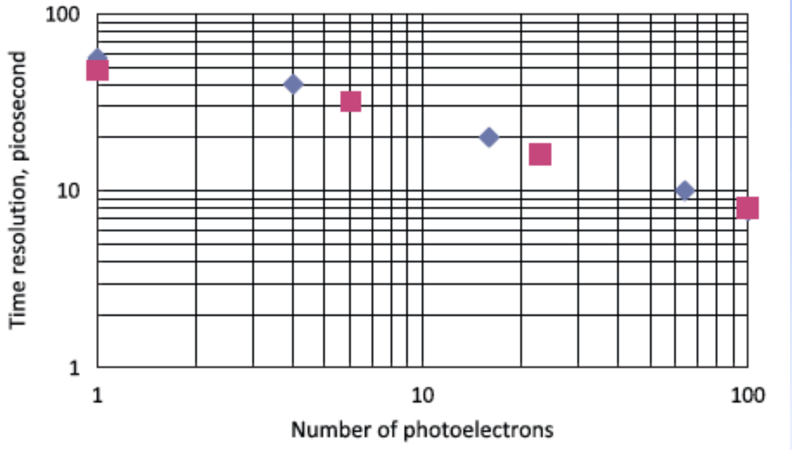
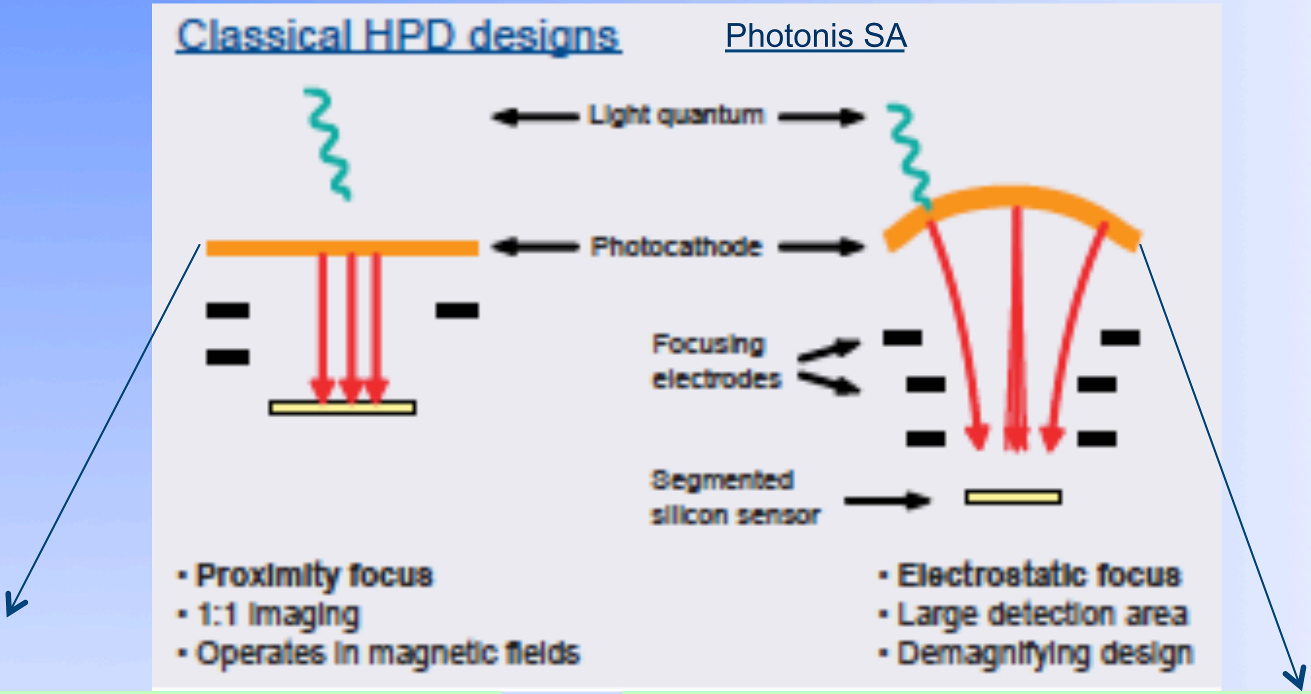


Fig. 7. Time resolution (σ) of the Photek 240 as a function of the number of photoelectrons. The data are from the test bench.

Photek 240

Ronzhin et al. NIM A623 (2010) 931: Development of a 10 ps level time of flight system in the Fermilab Test Beam Facility

Hybrid Photon Detector



Imaging with single photon sensitivity and spatial resolution

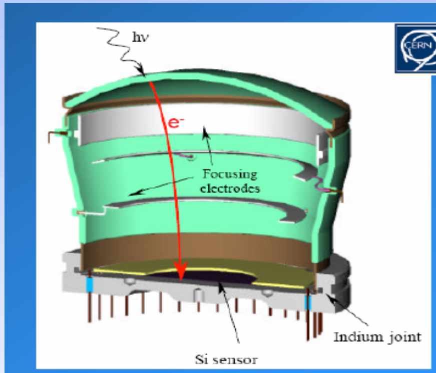
Large aperture & single photon sensitive
Fast : Cherenkov detectors …

Part II: HPD - Basic

1. Photocathode (Alkali / GaAs)
2. High Electric field (HV 2 to 20 kV)
3. Gain in one step by energy dissipation of keV pe's in solid-state detector; ENF ~1
4. Secondary carriers for multiplication are produced and directly readout by
    - Si-Anode+ROC = HPD / ISPA Tube …
    - APD = HAPD
    - Back thinned CCD = EBCCD
    - Back thinned CMOS = EBCMOS

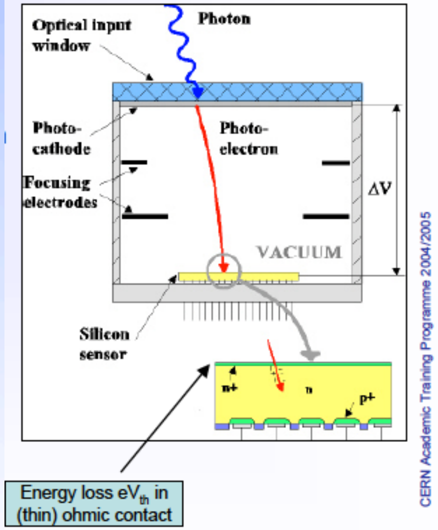
Large Area HPD / Small number of pixels

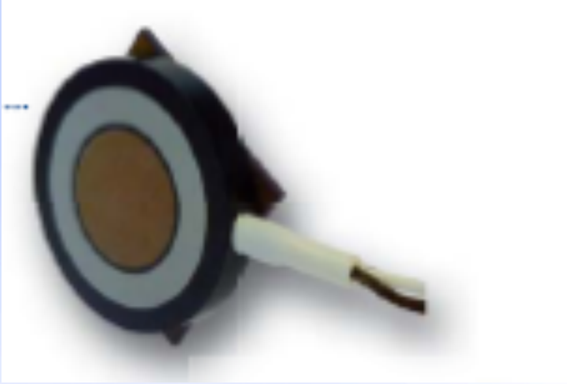
LHCb CERN



5" HPD
Bialkali KCsSb UV extend
Si 2048 ch 1x1mm²
HV = 20 kV
C.Joram Beaune 2002

Imaging / Megapixel device



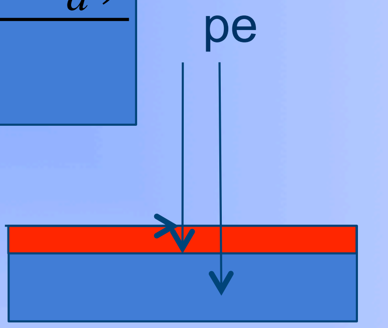


PHOTONIS

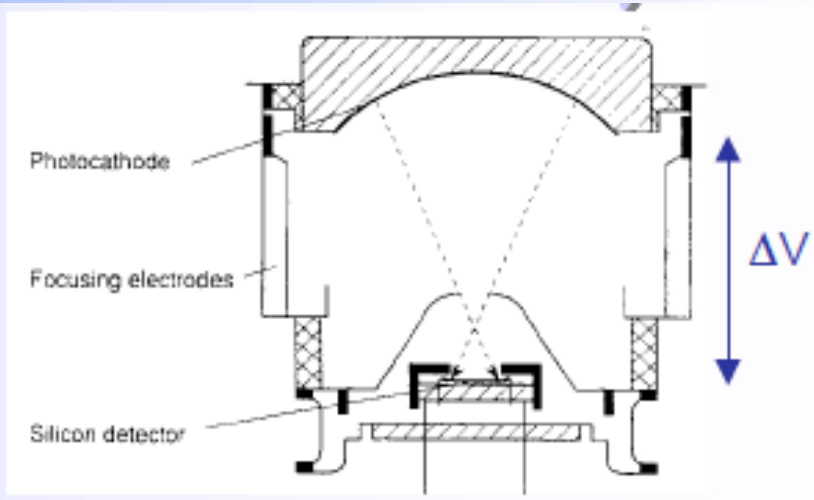
Part II: Photodetectors – HPD - principle

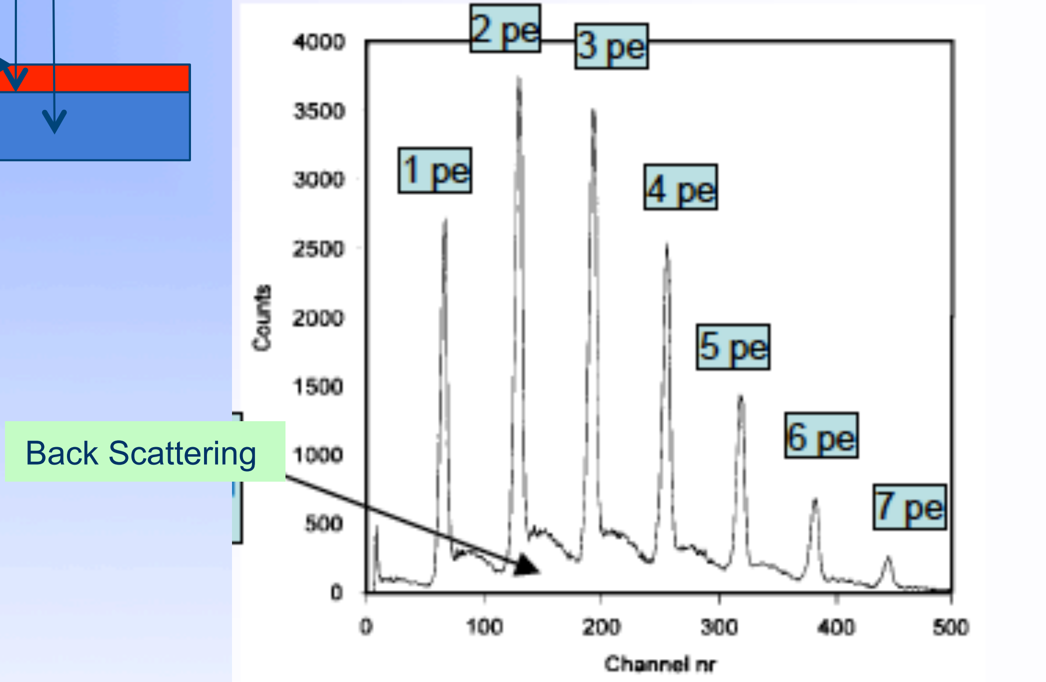
- Gain: Energy dissipation through ionization and phonons ➔ e-h
- To generate 1 e-h pair in Si: W_{si}=3.6 eV
- Gain

$$M = \frac{e \times (\Delta V - V_d)}{W_{Si}}$$



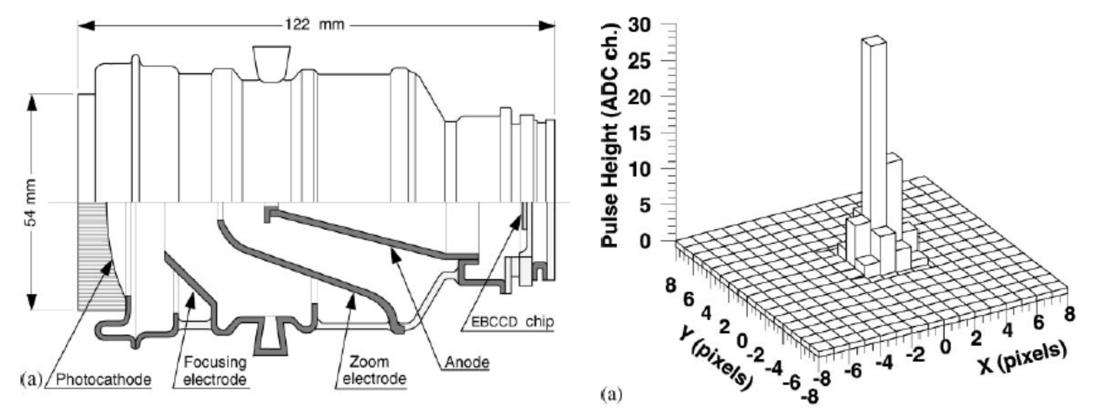
- V_d is the threshold voltage (entrance dead layer !!!!)
- ΔV = 2 to 20 kV depends on
  - dead layer thickness
  - readout noise
  - electron charge collection efficiency
  - DC required
  - cathode gap length
- Single-photon sensitive device
- Time resolution depends on:
  - Charge collection
  - Readout sequence of the chip
  - Number of channels to readout 64 to 10^6





(C.P. Datema et al., NIM A 387(1997) 100)

Megapixel ebCCD single photon sensitive



L. Benussi et al. NIMA 442 (2000) 154

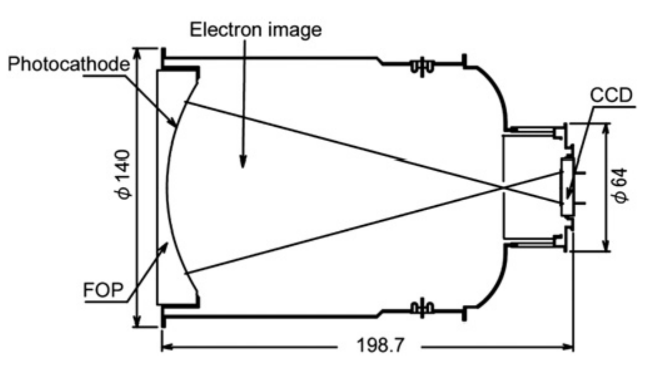
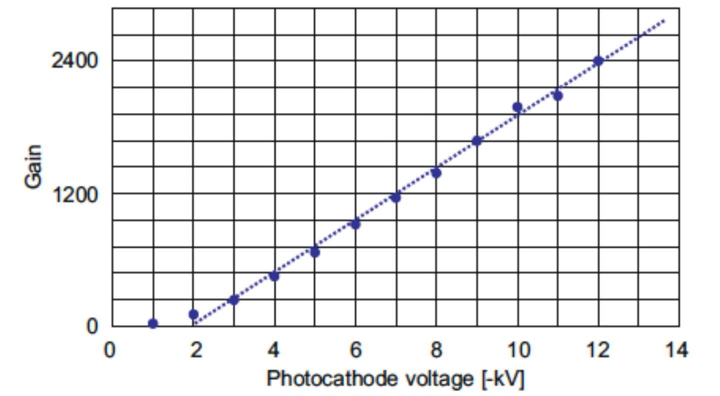
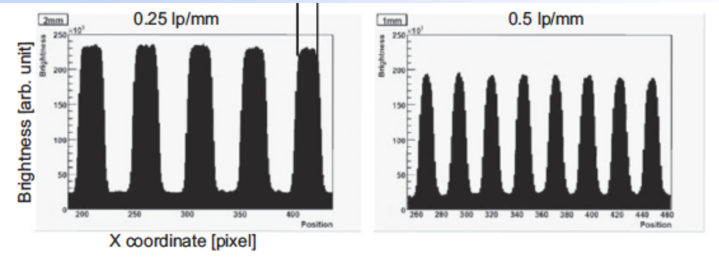


Fig. 1. Structure of the EBCCD.





Novel large aperture ebCCD (Hamamatsu)

Table 1
Device specifications.

Parameters		Description/value	Unit
Spectral response		300–650	nm
Photocathode	Material	Bi-alkali	–
	Effective area	46 × 36	mm
Window material		Fiber optic plate (FOP)	–
Magnification		1/5	–
Target	Type	FT-CCD	–
	Effective area	9.0 (H) × 6.7 (V)	mm
	Number of pixels	640 (H) × 480 (V)	–
	Pixel size	14 × 14	µm
Frame rate		30	Hz

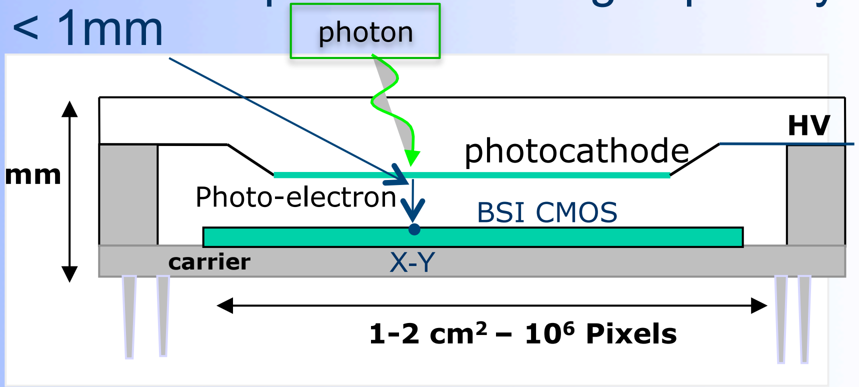
A. Suzuki et al. NIMA 628 (2011) 260

Part II: HPD - EBCMOS

- Intevac Night Vision EBAPS(TM)
- Photonis SA: EBMI5/LUSIPHER

-photon counting capability

GAP < 1mm



27 fps / 10^6 Pixels

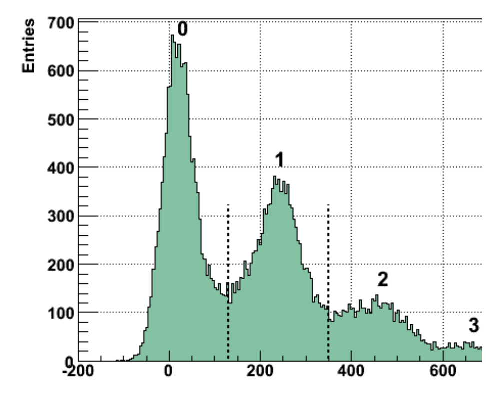
EBMIMOSA5

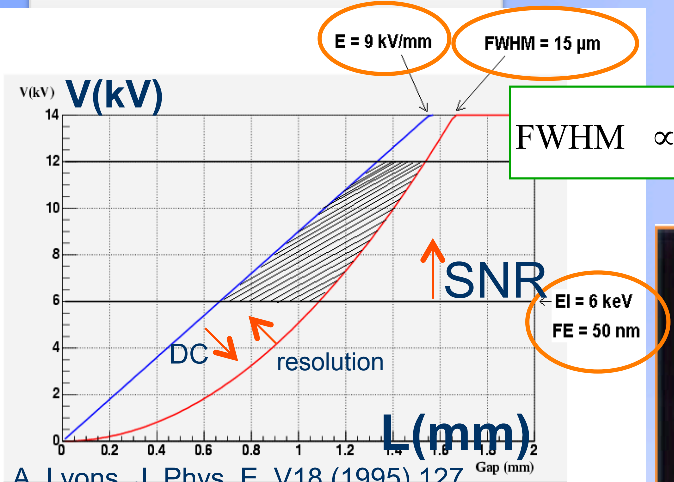
500 fps / 10^5 Pixels

LUSIPHER

PHOTONIS

R. Barbier, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.04.018

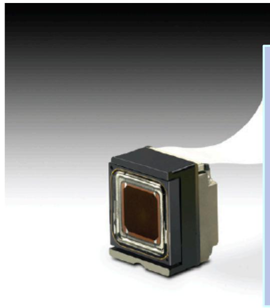




$$\mathrm{FWHM} \propto L\sqrt{\frac{V_{0r}}{V}}$$

A. Lyons J. Phys. E. V18 (1995) 127

Digital Image Intensifier (DI²)



1280x1024 (SXGA)
10.8 micron pitch
GaAs Cathode
45 lp/mm
< 400 mW
10-bit parallel

E3010M Digital Image Intensifier (DI²)

FIGURE 3.2 GaAs EBAPS®: NightVista, ISIE6, and ISIE10

4. EBAPS Performance

Standard Halo

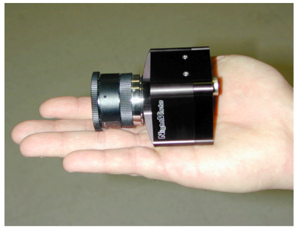


FIGURE 5.1 NightVista camera

Halo due to Back Scattering

INTEVAC

Halo suppression

Zero Halo

▪Large aperture HAPD for next generation Cherenkov detector

Status and Perspectives of vacuum-based photon detectors
T. Iijima NIM A 639 (2011) 137

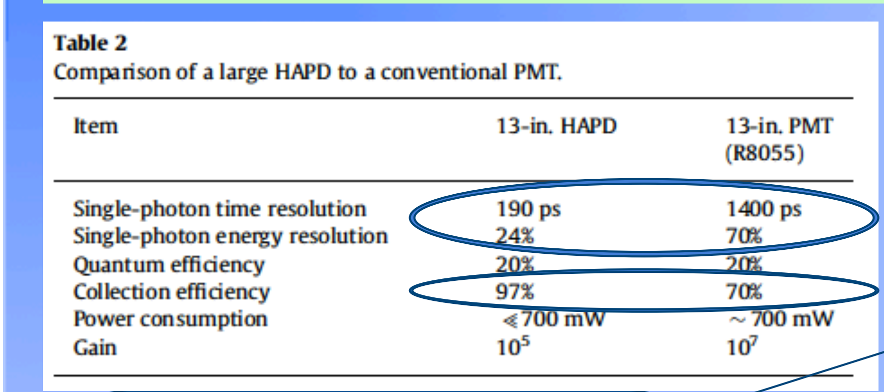


Table 2
Comparison of a large HAPD to a conventional PMT.

Item	13-in. HAPD	13-in. PMT (R8055)
Single-photon time resolution	190 ps	1400 ps
Single-photon energy resolution	24%	70%
Quantum efficiency	20%	20%
Collection efficiency	97%	70%
Power consumption	⩽700 mW	~ 700 mW
Gain	10^5	10^7

Single APD

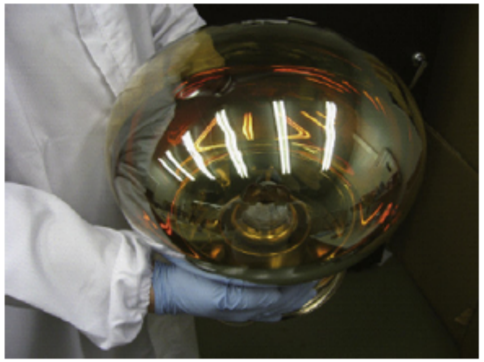


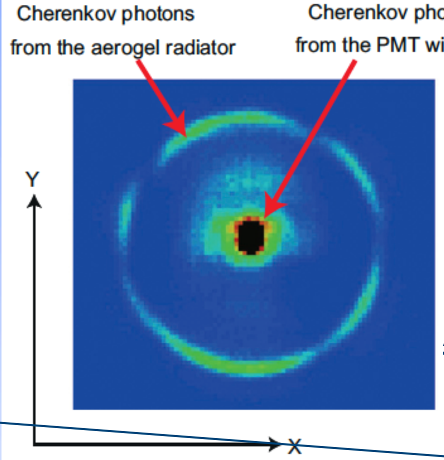
Fig. 8. Large aperture HAPD under development by the collaboration of Tokyo, KEK and Hamamatsu.

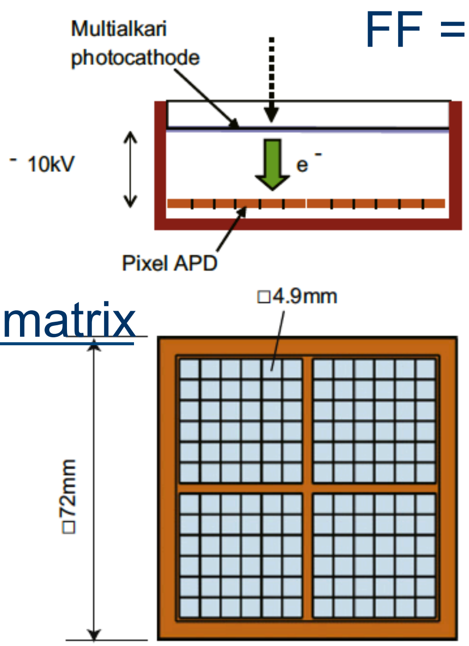
Electrostatic focussing

HAPD

Proximity focussing

FF = 65%





APD matrix

Fig. 5. Schematic drawing of the 144-ch HAPD.

HV = 8.5 kV
ebGain = 1600
V_{APD}=350 V M=10-20
Total Gain 2. 10^4

Hamamatsu
Under development

4 x (6x6) APD arrays

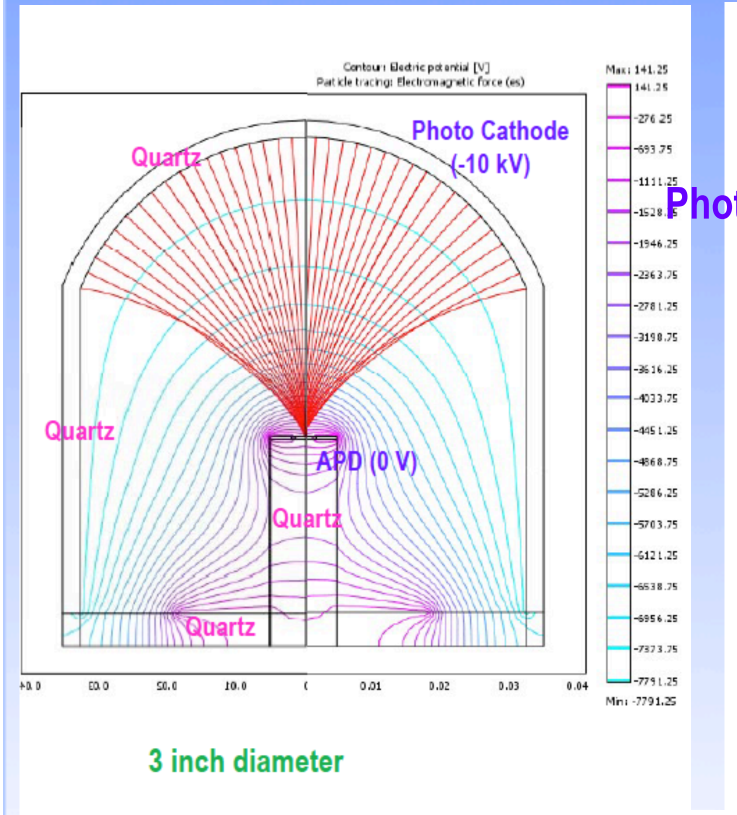
▪Proximity focussing HPD for Belle II RICH

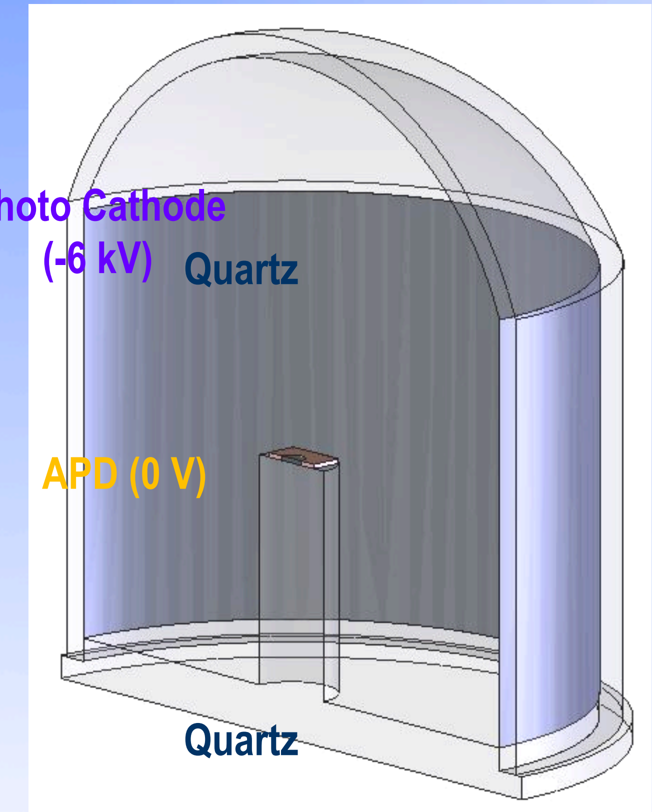
Low DC HAPD under low temperature:

A. Fukasawa et al. NIM A623 (2010) 270

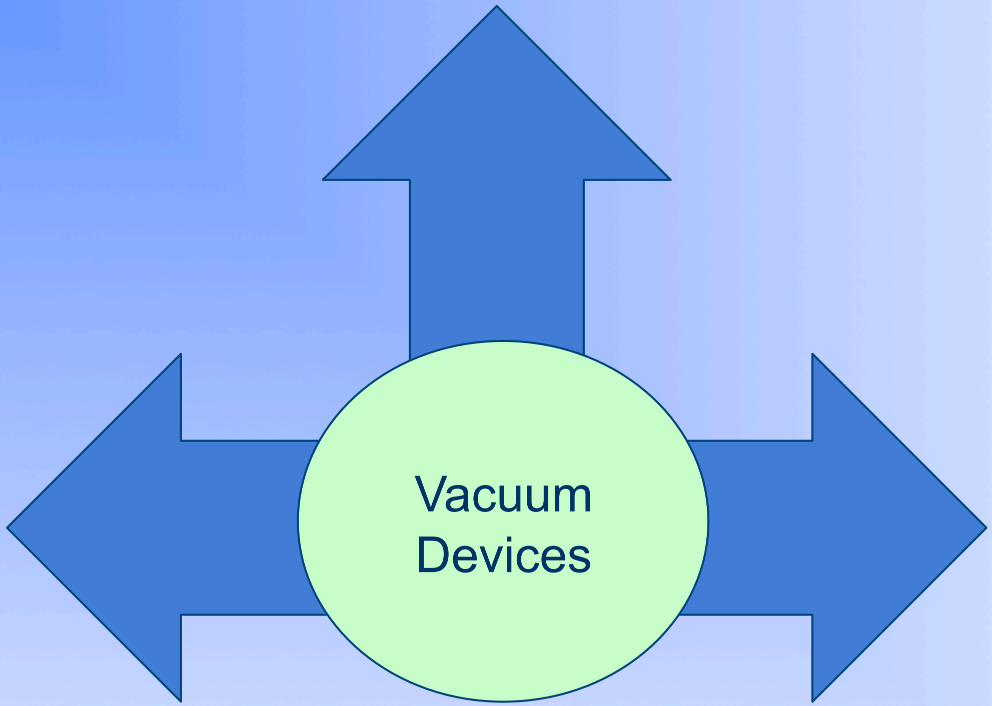
- Dark matter search and double beta decay.
- Special bialkali photocathode under extremely low temperature (Xenon -108°C)
- ebGain = 1000
- APD Gain ~100
- low radioactive materials : Quartz < 1 mBq
- Single photon sensitivity

Arisaka group UCLA





QUPID (Quartz Photon Intensifying Detector)



LARGE APERTURE
HAPD, PMT

ULTRA FAST
MCP-PMT

Vacuum
Devices

FAST & PIXELS
NIGHT VISION
EBCMOS

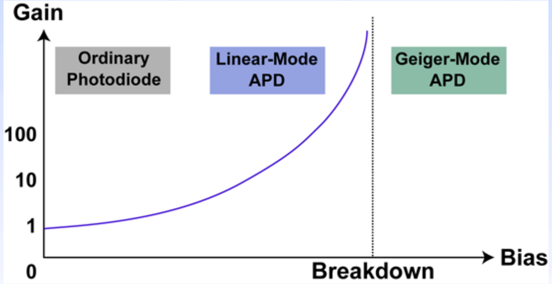
Solid State Devices

~mm

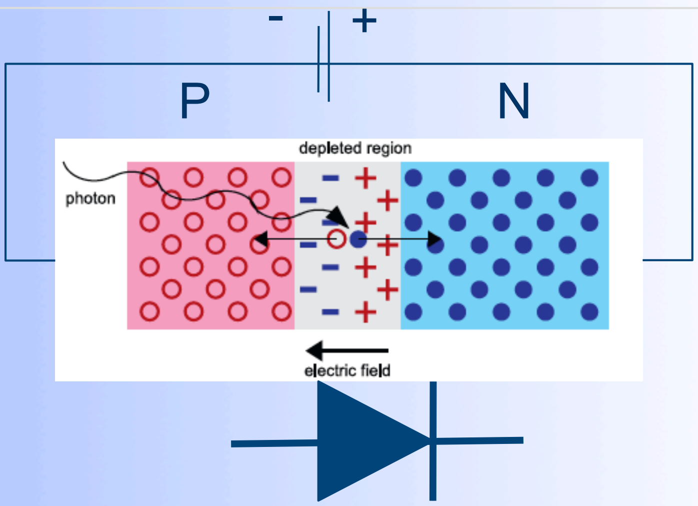
~µm

<u>Single or multichannel photon detectors</u>
- Photo Diode
- APD
- SPAD
- SiPM
- …

<u>Imaging devices / Megapixels</u>
- CCD
- CMOS sCMOS
- EMCCD
- pnCCD
- …



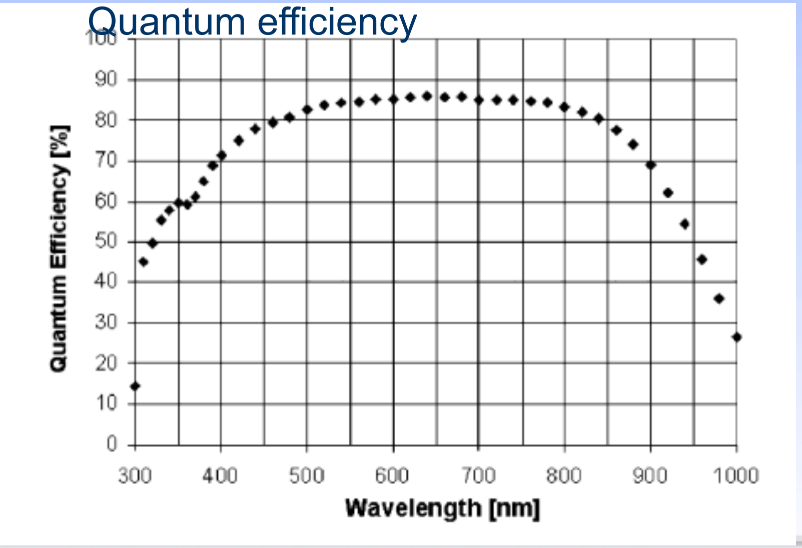
Part II: Solid State devices : PD basic

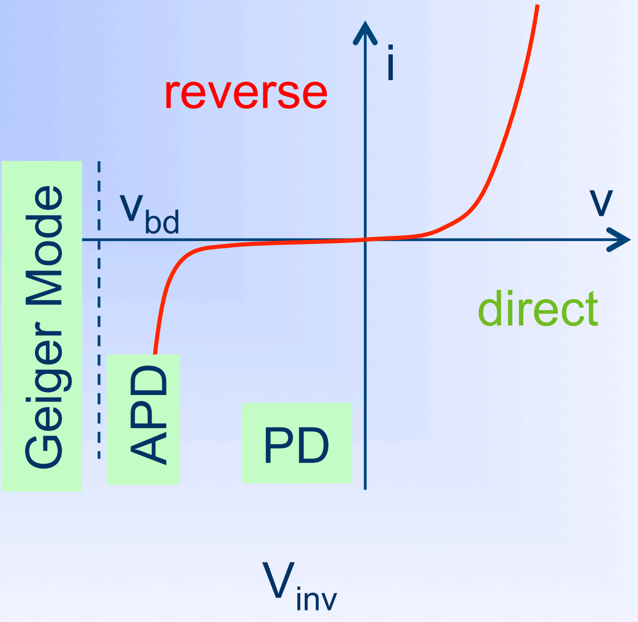


- <u>the PN junction with reverse bias: PhotoDiode</u>
  - ✓ Si bulk => N layer (Phosphor doped);
  - ✓ P layer on top (Boron doped)
  - ✓ Depleted zone (increased by V_{inv})
  - ✓ If e/h created in the depleted zone
    - ✓ e- ➔ in conduction Band and drift to N layer
    - ✓ h ➔ in valence Band drift to P layer
  - ✓ The current is read out with no internal gain.
- <u>The PIN Diode:</u>

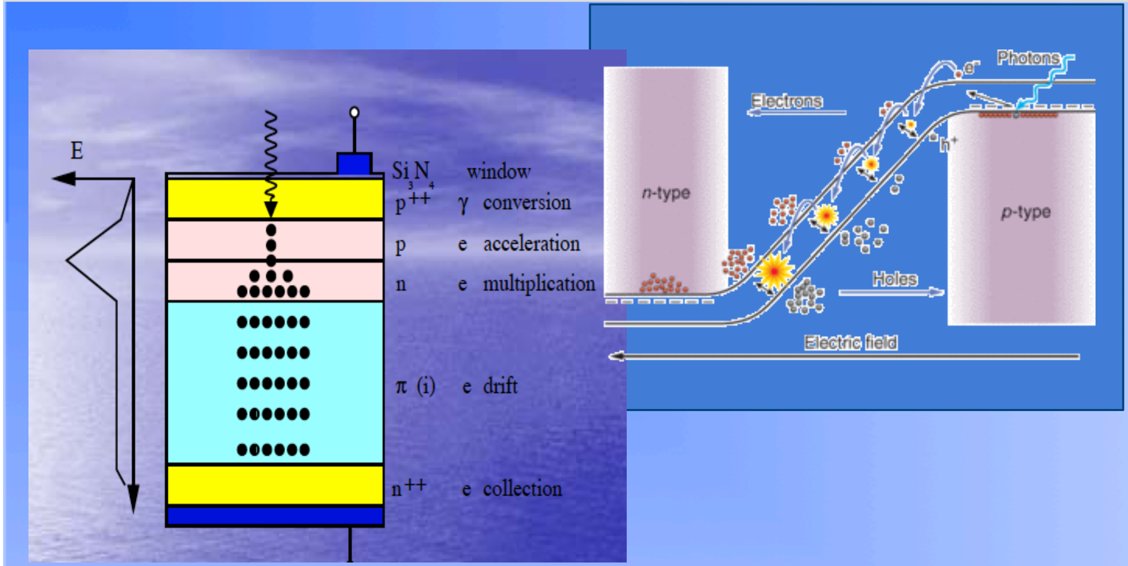
300 μm of intrinsic (high-purity) layer sandwiched between n+ (P) and p+ (B)

This reduces capacitance (reduce noise) sensitive to red





Part II: Solid State Devices – Avalanche Photo Diode - Basic



Basic:

- High electric Field : 10^5 V/cm
- Electrons and holes are accelerated
- Multiplication by Impact ionisation for e- and holes !
- α ionisation coefficient for electrons
- β ionisation coefficient for holes

ENF minimized if $\alpha > \beta$ or $\alpha < \beta$ ie

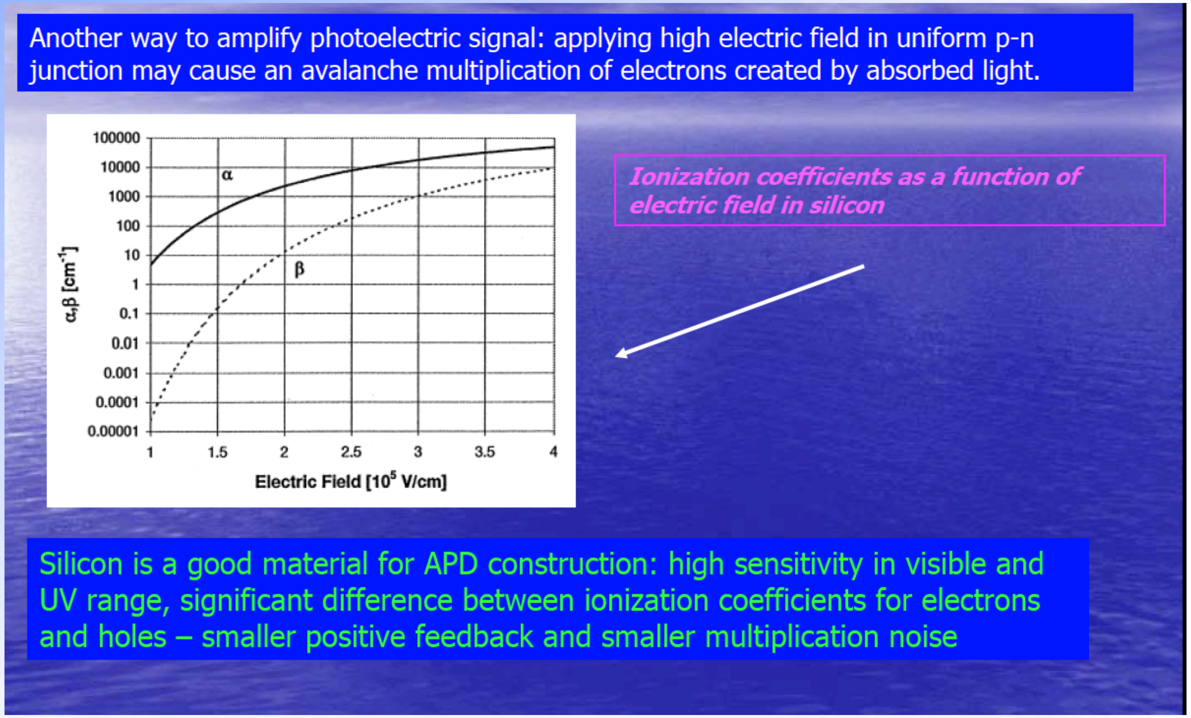
k-factor = $\beta/\alpha \ll 1$

Features:

- Gain = 50 to 200
- QE=80%
- Operating Voltage >300 V
- Faster than PD ~ns
- ENF = 2
- Sensitivity of the Gain to
  - Voltage
  - Temperature

hamamatsu

Musienko Tutorial NDIP08



Another way to amplify photoelectric signal: applying high electric field in uniform p-n junction may cause an avalanche multiplication of electrons created by absorbed light.

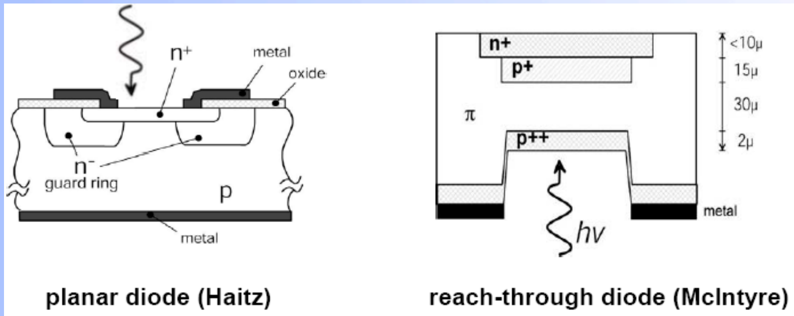
Ionization coefficients as a function of electric field in silicon

Silicon is a good material for APD construction: high sensitivity in visible and UV range, significant difference between ionization coefficients for electrons and holes – smaller positive feedback and smaller multiplication noise

Basic works :Haitz/McIntyre (1966)
Pioneers are Russian groups: Sadygov, Golovin

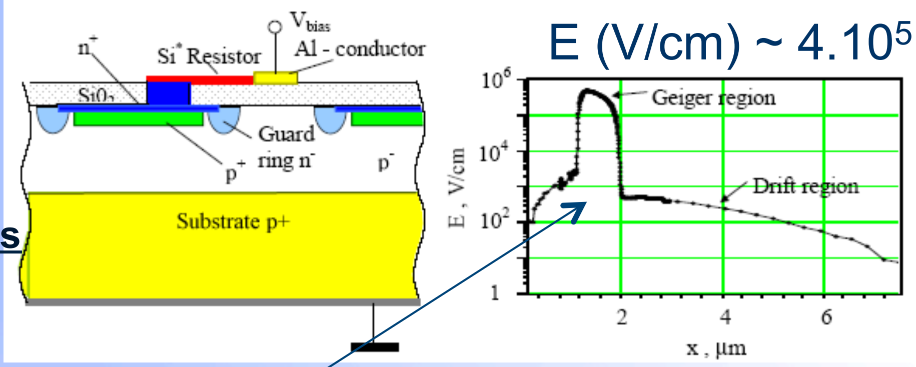
SPAD	Single Photon Avalanche Diode
SiPM	Silicon PhotoMultiplier
MRS	Metallic Resistive Semiconductor
MPGM APD	Multipixel Geiger-mode Avalanche PhotoDiode
AMPD	Avalanche Micro-pixel PhotoDiode
SSPM	Solid State PhotoMultiplier
GAPD	Geiger-mode Avalanche PhotoDiode
GMPD	Geiger-Mode PhotoDiode
DPPD	Digital Pixel PhotoDiode
MCPC	MicroCell Photon Counter
MAD	Multicell Avalanche Diode
….	

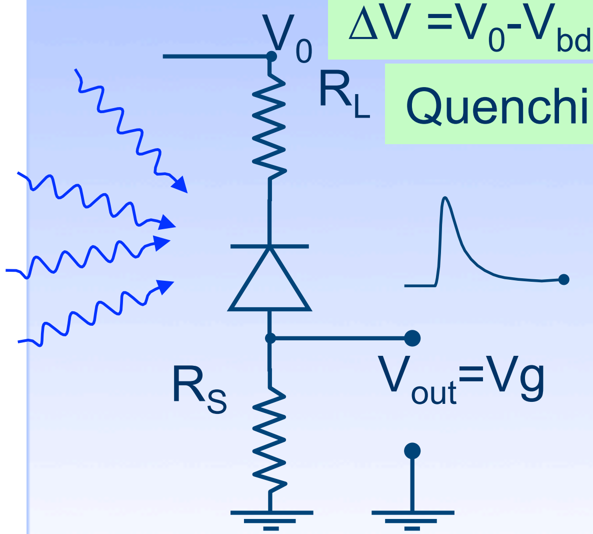
- **Same concept – different technological implementations**



planar diode (Haitz) **reach-through diode (McIntyre)**

P. Buzhan, B. Dolgoshein *et al* ICFA 2001



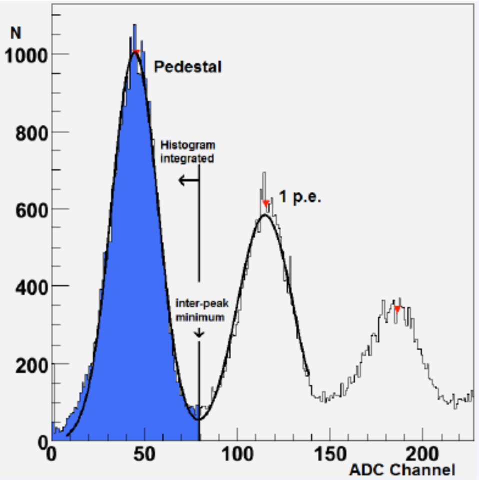


$\Delta V = V_0 - V_{bd}$ « overvoltage»

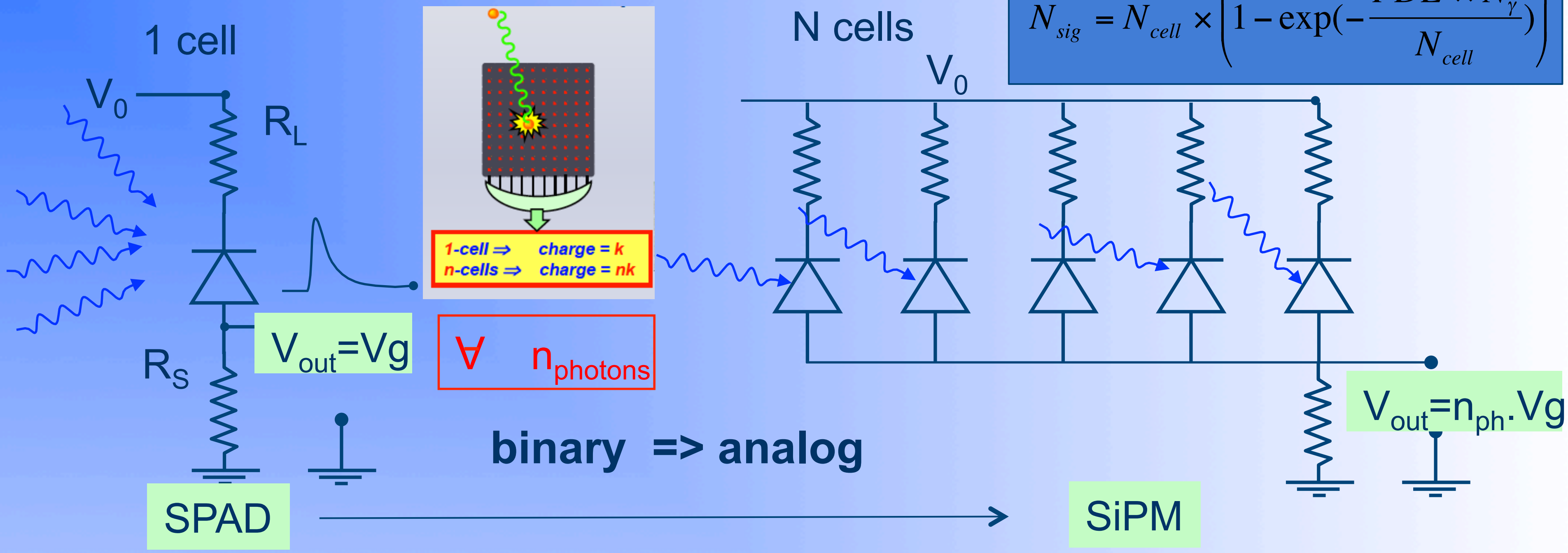
Quenching Resistor: passive quenching

$\Delta V \sim 4V$ ➔ Geiger Mode

IBINARY MODE



$$N_{sig} = N_{cell} \times \left(1 - \exp(-\frac{PDE \times N_{\gamma}}{N_{cell}})\right)$$



binary => analog

- Size: ~1mm square up to 1 cm square (RMD SSPM)
- # of cells: 100 to thousands

- PDE is reduced due to Quenching resistor

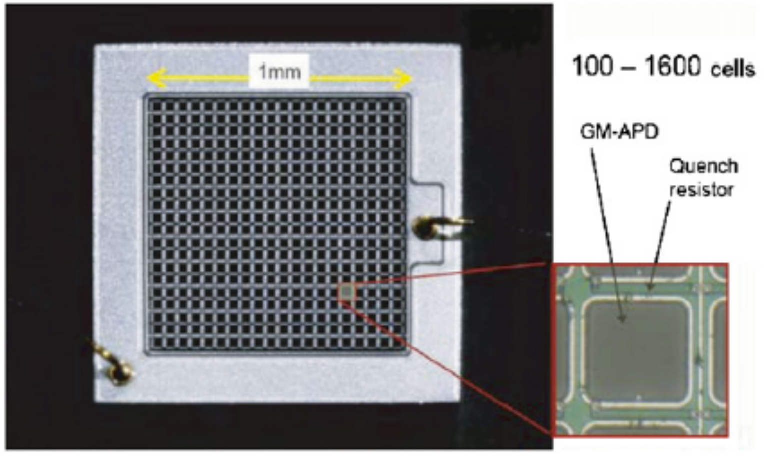


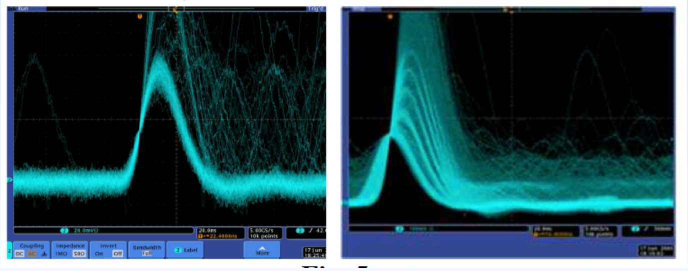
Fig. 6. Silicon photomultiplier (Hamamatsu MPPC) with a close-up of one of the cells.

Hamamatsu MPPC

PD09-019

- Photon counting

M. Dziewiecki et al. PD09-016

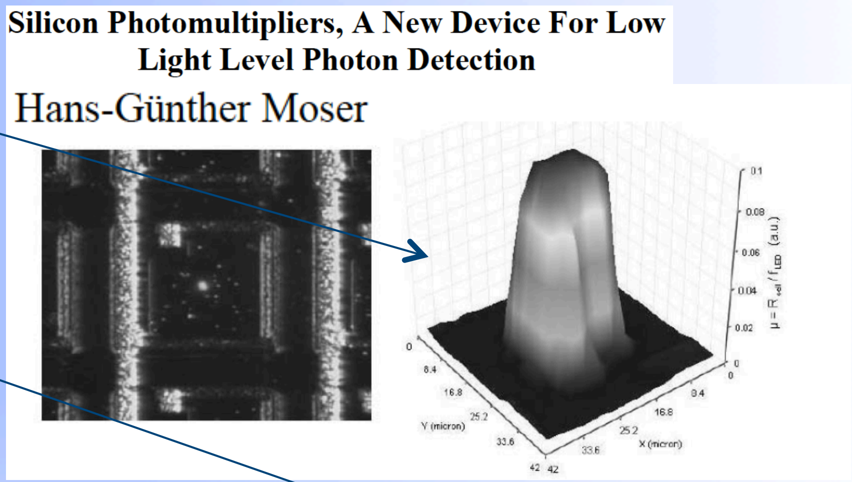


- **Gain**
  - $Q_{pixel} = \Delta V.\ C_{pixel}$ $\Delta V = V_0 - V_{bd}$ « overvoltage»
    - C_{pixel} ~50 fF / ΔV~ 6 V (~ 10% of V_0) and Q_{pixel}~300 fC = $2*10^6\ e^-$

$G \sim 2.10^6$ @ $\Delta V \sim 6$ V

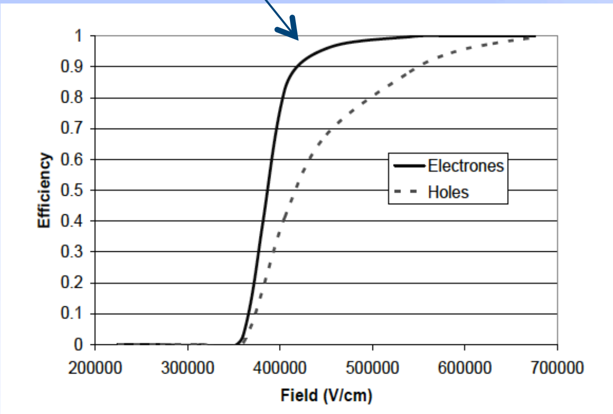
- **Photon Detection Efficiency**
  - PDE = QE .FF .GE
  - GE = Geiger efficiency
  - FF = Geometrical efficiency

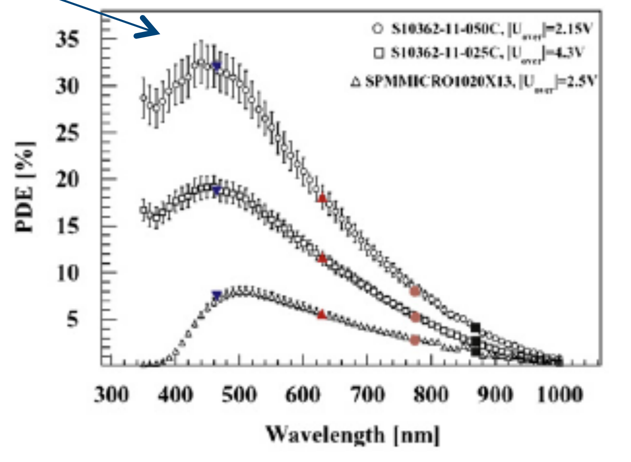
PDE ~ 20%



Silicon Photomultipliers, A New Device For Low Light Level Photon Detection

Hans-Günther Moser





S. Korpar NIMA 639 (2011) 88

Part II: Solid State Device - SiPM – main features

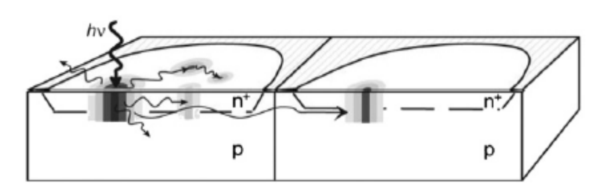
- Photon counting
- Optical Cross talk; False counting
- Dynamic range is limited by the # of cells:

Geiger mode gives counting error if > 1 ph/cell !

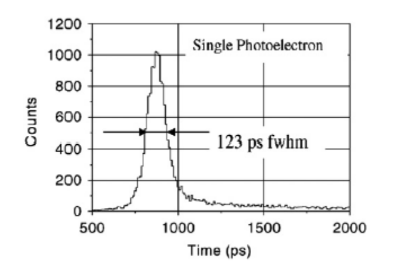
- Dark count rate 0.1 to 1MHz/mm² @ 25°C
- Radiation hardness issue
- Timing resolution 100 ps

S. Korpar NIMA 639 (2011) 88

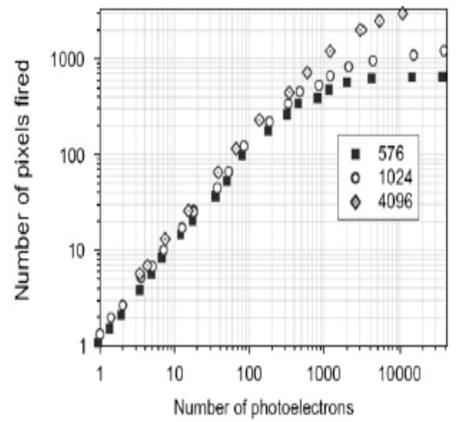
•Cross Talk



•Timing



•Dynamic Range



•Radiation Hardness

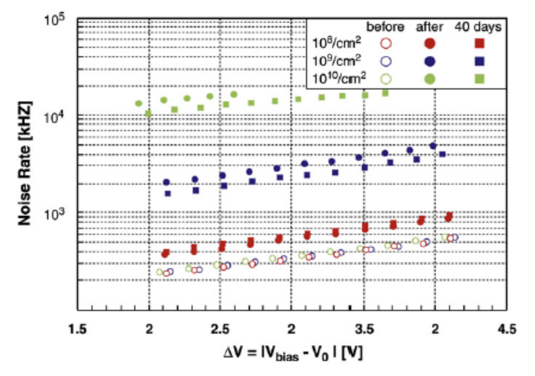
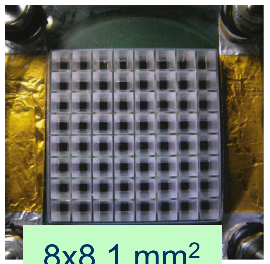
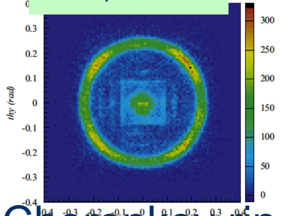


Fig. 15. The noise rate of a SiPM as a function of over-voltage before irradiation with neutrons and after 10^8, 10^9 and 10^{10} neutrons/cm² (at 25 °C)[17].

Hamamatsu MPPC
Pitch 2,54mm



8x8,1 mm²



Cherenkov ring

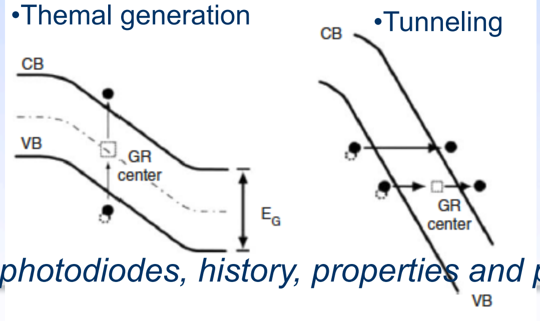
•Dark Rate

$$\frac{I(T)}{I(T_0)} = I\frac{T^2}{T_0^2}\exp\left(-\frac{E_g}{2kT}\left(1-\frac{T}{T_0}\right)\right)$$

Leakage current increase from T_0 to T

DC Temperature dependency
- factor 2 every 8°C

•DC sources



D. Renker** Geiger-mode avalanche photodiodes, history, properties and problems **NIMA 567 (2006) 84

- **CMOS (HV) technology** – active quenching, TDC, logic
  - STM
  - MPD
  - RMD
  - Charbon
  - **Philips**
  - …

SPAD array

Pros: logic
Cons: PDE

2D : 64x64 pixels
Résolution profondeur :1.3mm
σ_t = 50 ps FWHM
Distance : 3.75m

E. Grigoriev et al. / Nuclear Instruments and Methods in Physics Research A 571 (2007) 130–133

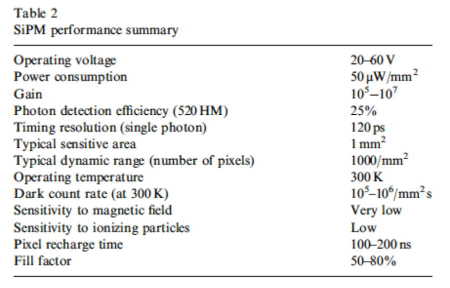


Table 2
SiPM performance summary

Operating voltage	20–60 V
Power consumption	50 μW/mm^2
Gain	10^5–10^7
Photon detection efficiency (520 HM)	25%
Timing resolution (single photon)	120 ps
Typical sensitive area	1 mm^2
Typical dynamic range (number of pixels)	1000/mm^2
Operating temperature	300 K
Dark count rate (at 300 K)	10^5–10^6/mm^2 s
Sensitivity to magnetic field	Very low
Sensitivity to ionizing particles	Low
Pixel recharge time	100–200 ns
Fill factor	50–80%

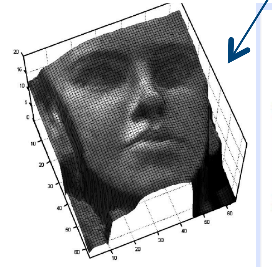
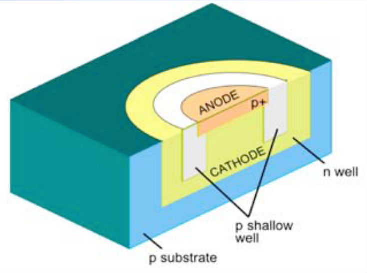
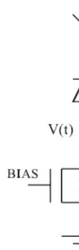
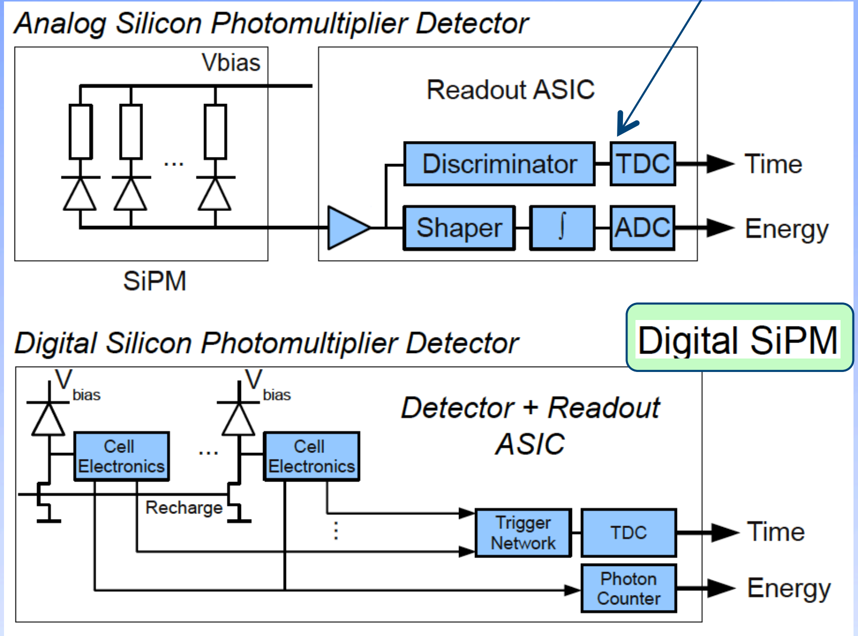


Fig. 3. Depth map obtained with SPAD array.



E. Charbon 2007

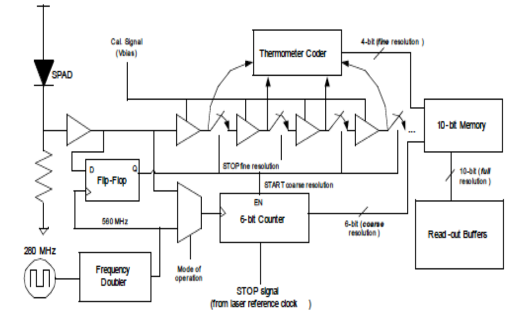




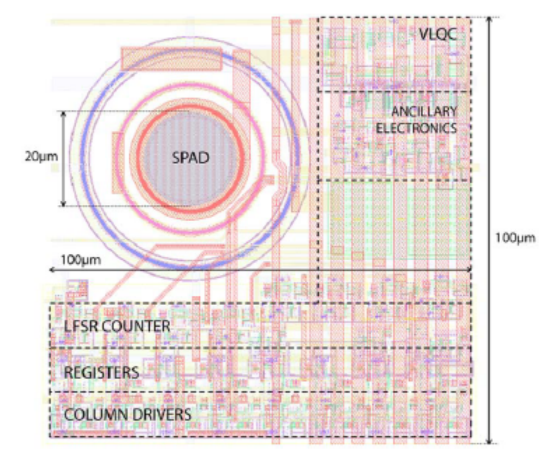
Digital SiPM

IEEE NSS/MIC 2010

Thomas Frach, Gordian Prescher, Carsten Degenhardt, Andreas Thon, Ben Zwaans



A SPAD Architecture



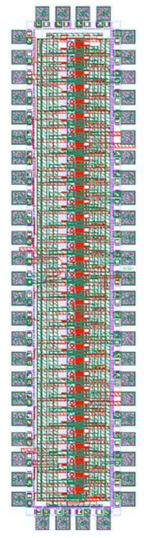


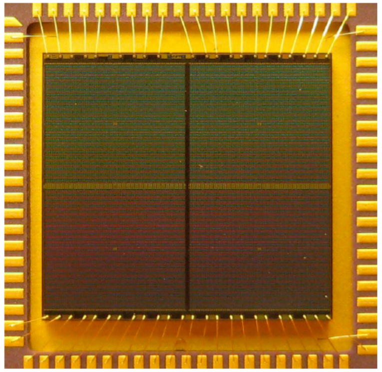
Fig. 6. Layout of the prototype 32 × 1 pixels column-like array with overall dimensions (including pads) of 3.5 mm × 0.5 mm.

32 SPADs pixel Milano S. Tisa, F. Guerrieri, F. Zappa NIM A610 (2009) 24

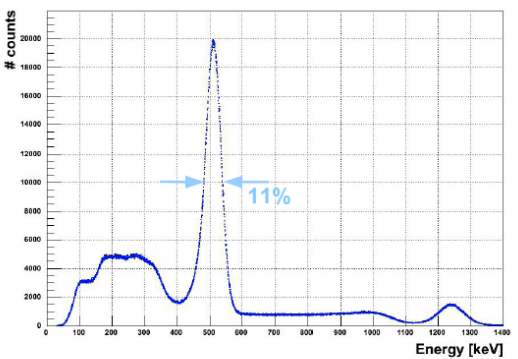
From passive quenching to active quenching and SPAD array in CMOS technology

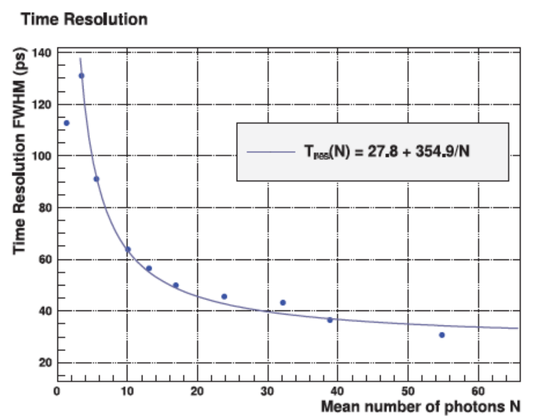
PHILIPS

DLS-6400-22 DSiPM Prototype:

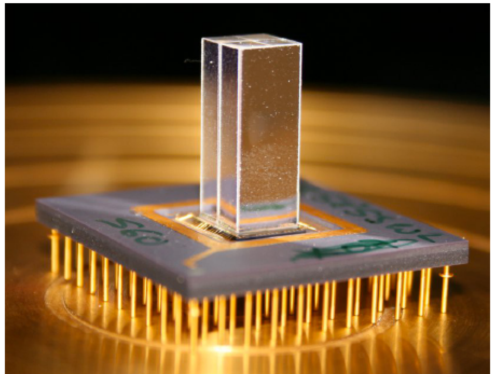


- *25600 Geiger-mode cells*
- *Two complementary TDCs*
- *Integrated acquisition controller*
- *JTAG for configuration & test*
- *Two serial data outputs*
- *48 bond wires*



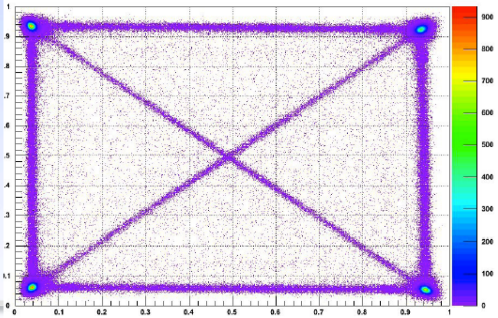


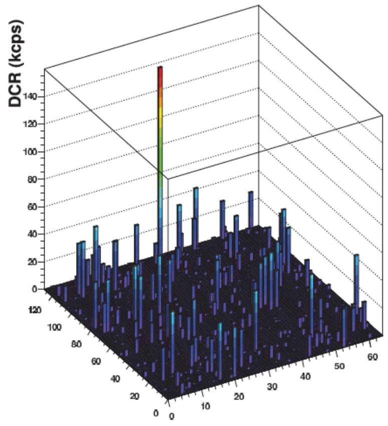
Thomas Frach, *Member, IEEE,* Gordian Prescher, Carsten Degenhardt, Rik de Gruyter, Anja Schmitz, and Rob Ballizany

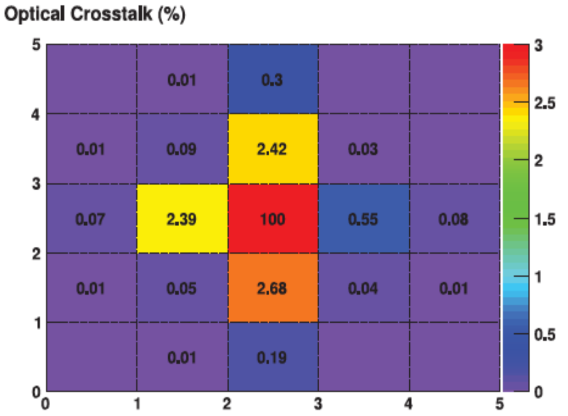


PET applications

- *2x2 Array of 3x3x15mm³ LYSO*
- *1:1 coupling using MeltMount*
- *Illuminated by* ^{22}*Na source*
- *Corrected only for saturation*
- *dE/E = 11% (combined)*







Optical Crosstalk (%)

	0–1	1–2	2–3	3–4	4–5
4–5		0.01	0.3		
3–4	0.01	0.09	2.42	0.03	
2–3	0.07	2.39	100	0.55	0.08
1–2	0.01	0.05	2.68	0.04	0.01
0–1		0.01	0.19		

Thomas Frach, Gordian Prescher, Carsten Degenhardt, Andreas Thon, Ben Zwaans

MPI Munich developments on SiPM with Bulk integrated quench resistors:

J. Ninkovic NIMA 628 (2011) 407

SOI wafer n-doped sensor wafer 70 micron

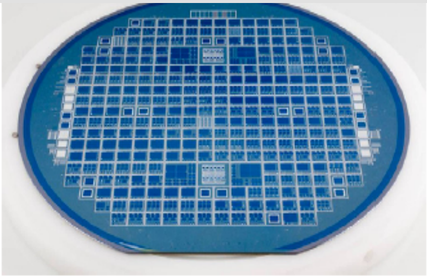


Fig. 2. Photograph of one of the produced 6 in. wafers.

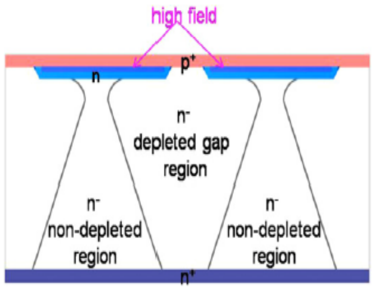
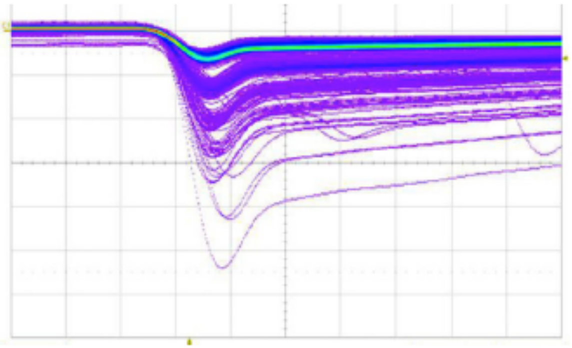


Fig. 1. Schematic cross-section of two neighboring cells.



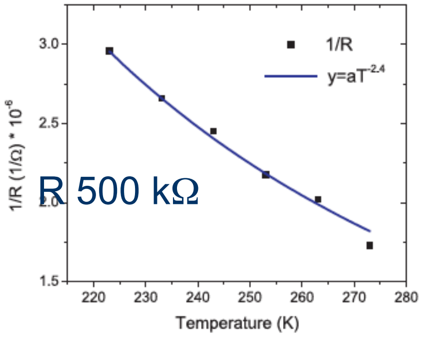
Pros:

- **Low Cost**
- **Rad. Hard. No Si-SiO$_2$ depl.**
- **PDE is increase (no Poly)**

Cons:

- **Longer Recovery time 1.5 µs**
- **Cooling mandatory for this prototype**

DC 10 MH/mm^2 V=4V @ T=20°C



R 500 kΩ

Bulk Doping Concentration
mean=2.8 10^{+12} cm

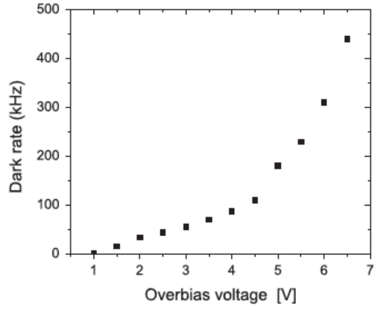


Fig. 8. Dark rate behavior as a function of applied overbias measured at −45 °C for the array of 100 cells of a 135 µm pitch and a 13 µm gap size.

DC -45°C

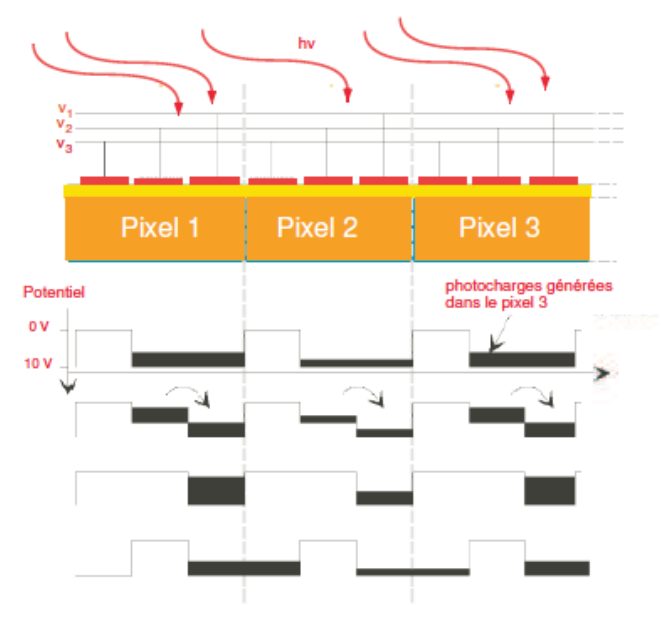
A new name ☺
SiPMI
Silicon Multipixel light detector

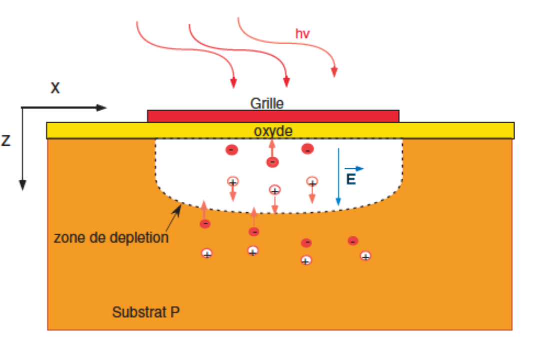
Still there is a significant room for further improvements:

- ✓ HIGHER PHOTON DETECTION EFFICIENCY
- ✓ RADIATION TOLERANCE (HEP)
- ✓ REDUCE COST FOR LARGE DETECTION SURFACE EXPERIMENT
- ✓ DARK COUNT RATE
- ✓ …

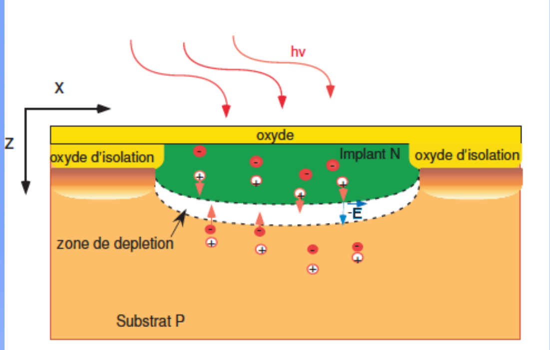
- **Basic:** CCD: Charge-Coupled Device

3 phases: R1 R2 R3





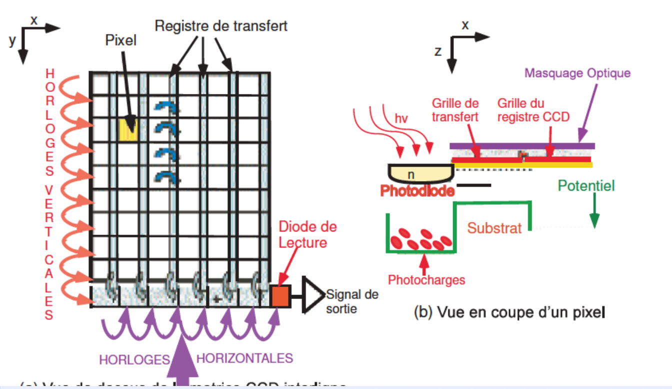
MOS capacitance



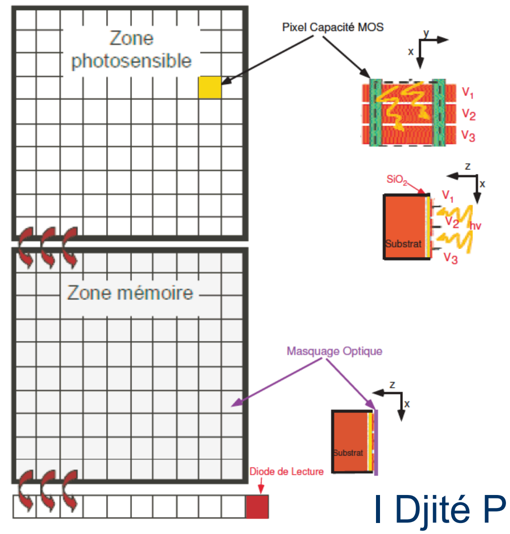
Photodiode P/N junction

Different readout strategies

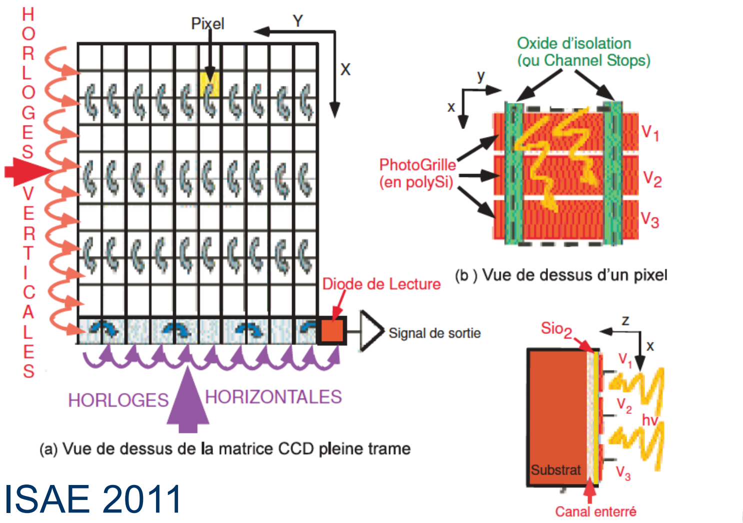
Interline CCD



Frame Transfer CCD

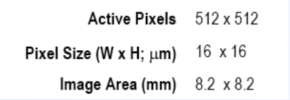


Full Frame CCD



I Djité PhD ISAE 2011

Electron Multiplying CCD L3V E2V is senstive to 1 photon



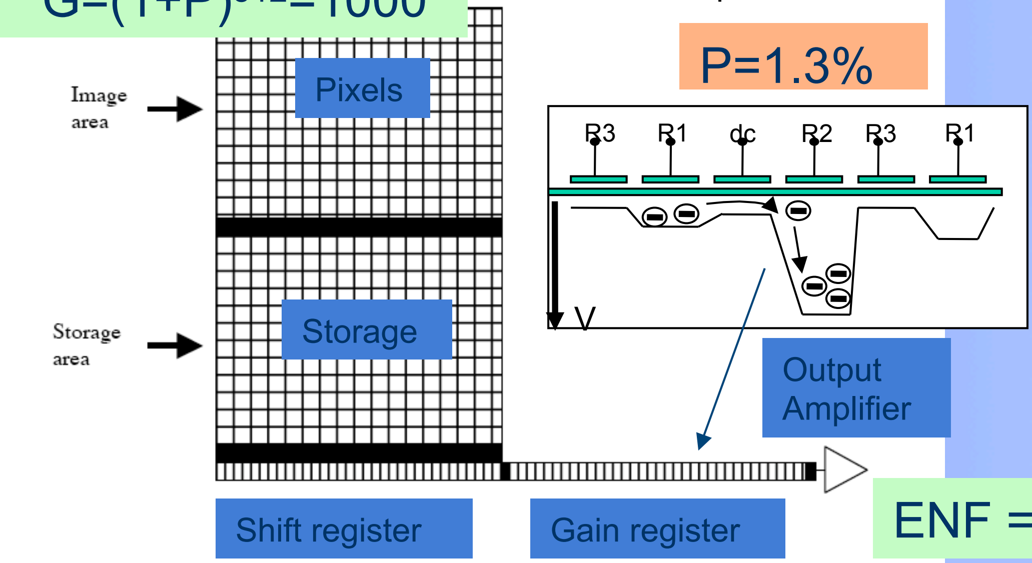
Active Pixels	512 x 512
Pixel Size (W x H; µm)	16 x 16
Image Area (mm)	8.2 x 8.2

ANDOR Tech.

$G=(1+P)^{512}=1000$

Impact ionisation

P=1.3%



ENF = 2

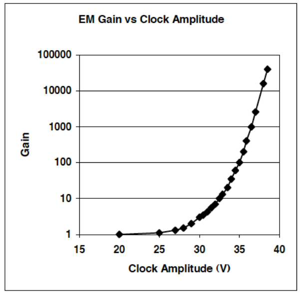
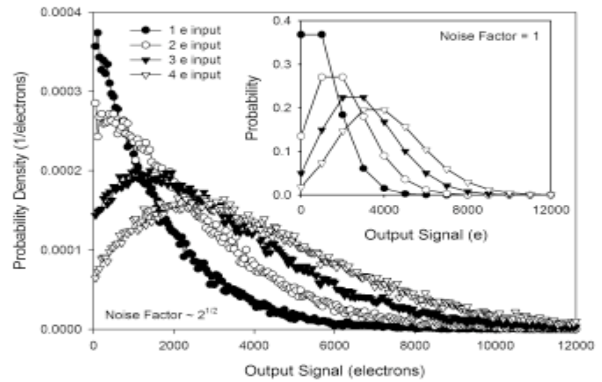


Figure 3. Clock ampli
de electrod



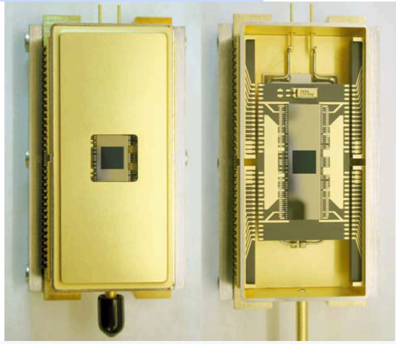
Statistical fluctuation due to multiplication in the gain register !!

G = 1 to 1000 (V_EM_Gain = 35-45 V)
Readout Noise ~40 e- @ 10 MHz
Effective Readout noise
40/400~ 0.1 e
PDE ~40 % in Photon counting mode

Clock Induced Charge (CIC) effect: Spurious Noise = 6 x DC(EBCMOS)

G=x1000 @ T=-85°C
Clock Induced Charge = 0.5 % events/pix/frame
For 30 ms integration time -> fake rate = 647 Hz/mm²

The L3Vision CCD220 with its OCam test camera for AO applications in Europe



EMCCD OCAM for adaptive optics
CCD 220 e2V
BI CCD 240x240 pixels
1.5 kHz frame rate
LAM CNRS J. Gach

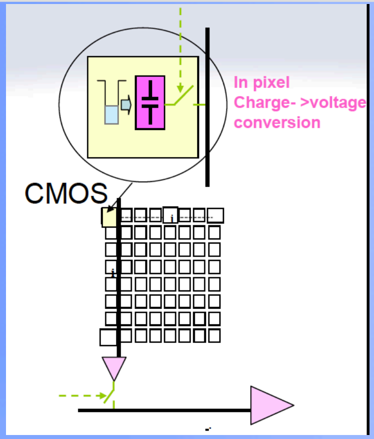
- Basic:

Pixel architecture

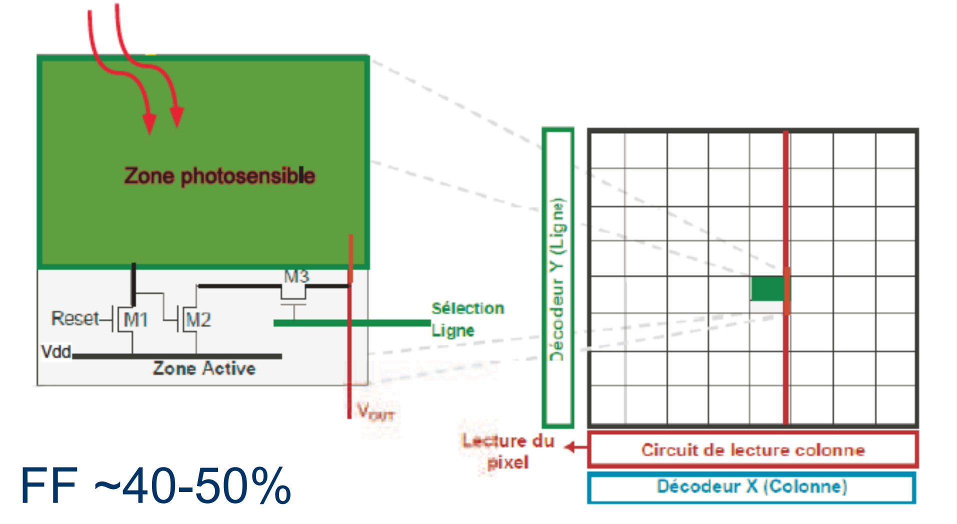
APS :

Active Pixel Sensor

3T 4T ….

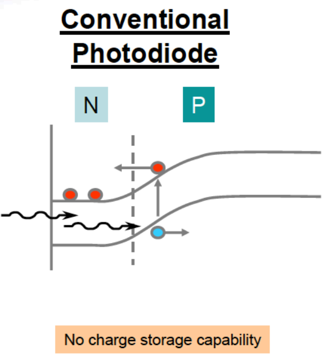


CMOS principle

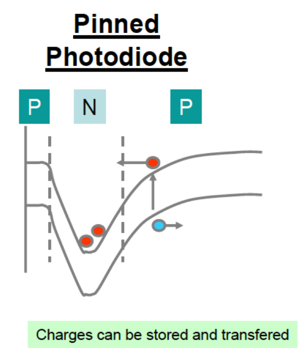


FF ~40-50%

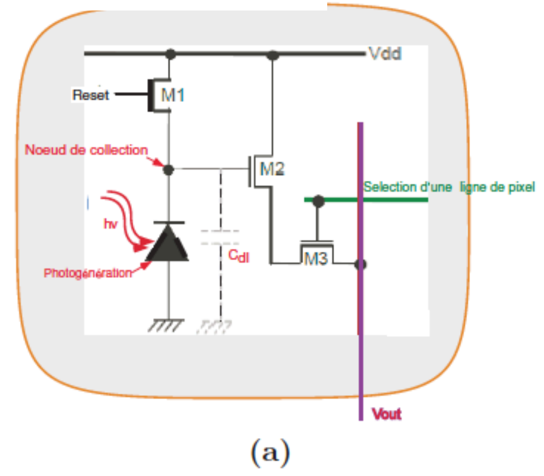
Microlens array can be used



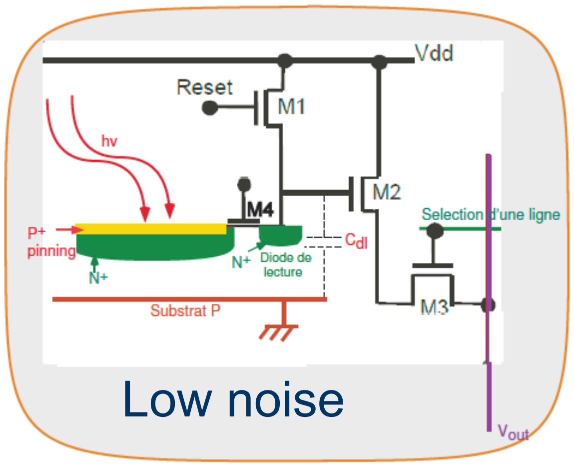
No charge storage capability



Charges can be stored and transfered

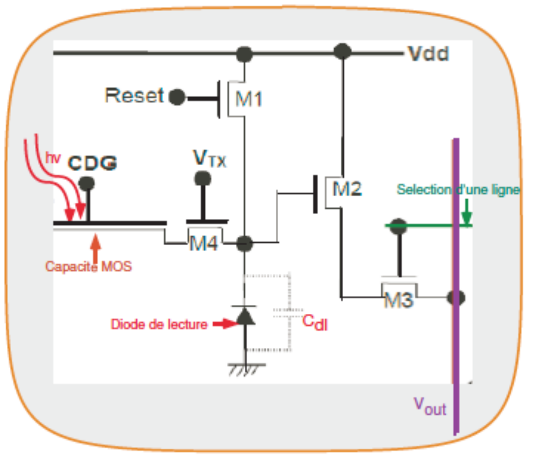


3T Pixel Photodiode



Low noise

Pinned photodiode

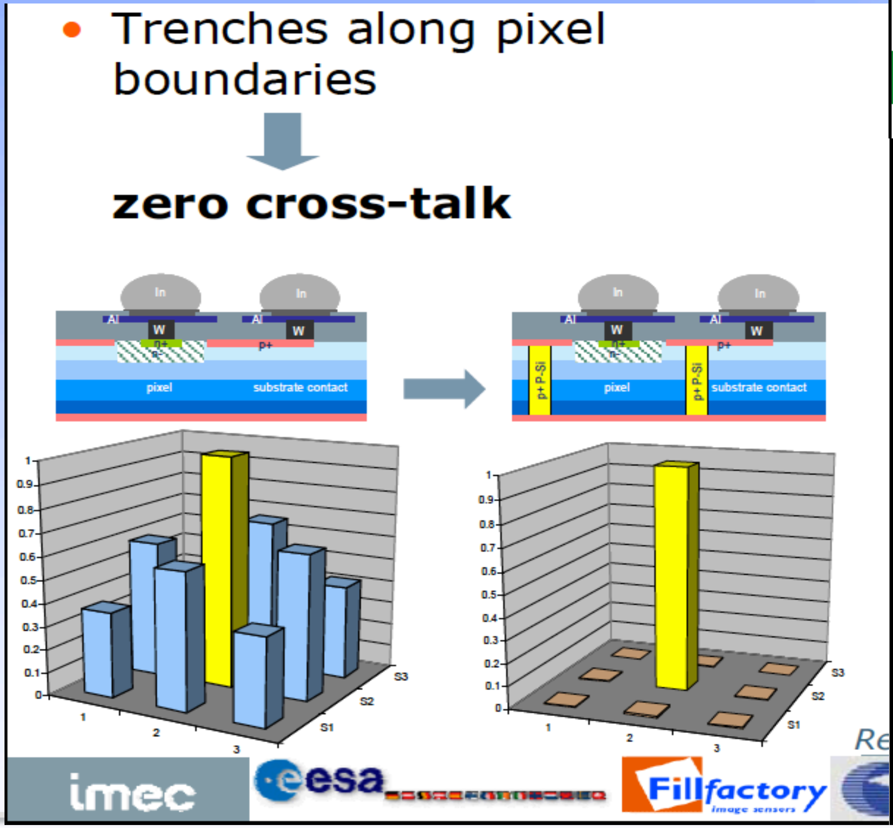


photoMOS

CMOS pixels array with 100% FF

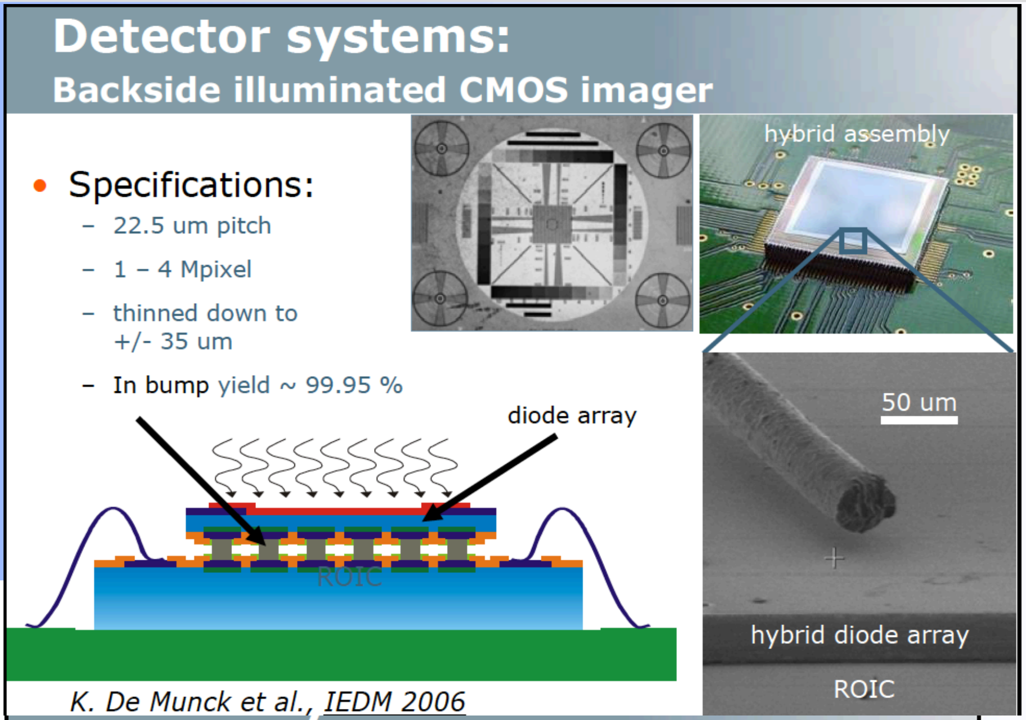
- Backside thinning
- post processing Boron implant
- Laser annealing
- < 100 nm dead layer

P. De Moor IMEC



- Trenches along pixel boundaries

zero cross-talk

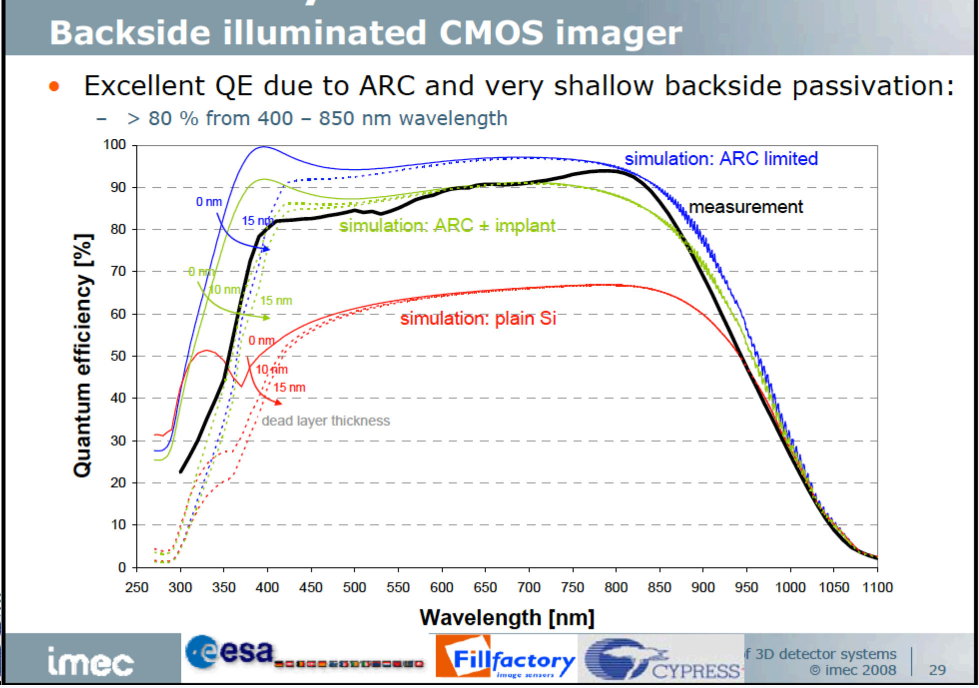


Detector systems:

Backside illuminated CMOS imager

- Specifications:
  - 22.5 um pitch
  - 1 – 4 Mpixel
  - thinned down to +/- 35 um
  - In bump yield ~ 99.95 %

K. De Munck et al., IEDM 2006



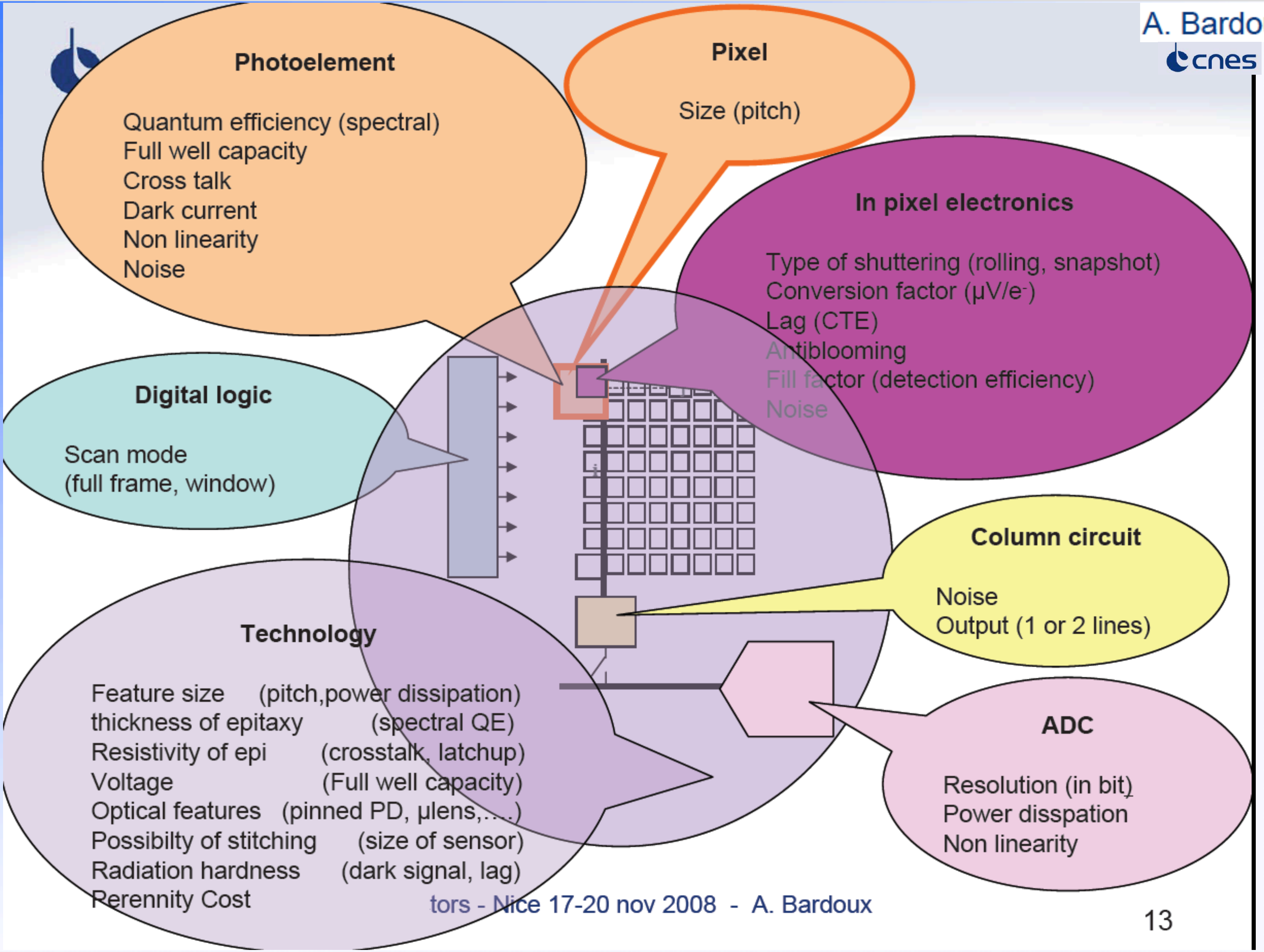
Backside illuminated CMOS imager

- Excellent QE due to ARC and very shallow backside passivation:
  - > 80 % from 400 – 850 nm wavelength

f 3D detector systems
© imec 2008
29

Part II: Solid State Devices – CMOS – A DAQ system on chip

A. Bardoux
cnes



Photoelement

- Quantum efficiency (spectral)
- Full well capacity
- Cross talk
- Dark current
- Non linearity
- Noise

Pixel

- Size (pitch)

In pixel electronics

- Type of shuttering (rolling, snapshot)
- Conversion factor (µV/e-)
- Lag (CTE)
- Antiblooming
- Fill factor (detection efficiency)
- Noise

Digital logic

- Scan mode (full frame, window)

Column circuit

- Noise
- Output (1 or 2 lines)

Technology

Feature size	(pitch,power dissipation)
thickness of epitaxy	(spectral QE)
Resistivity of epi	(crosstalk, latchup)
Voltage	(Full well capacity)
Optical features	(pinned PD, µlens,….)
Possibilty of stitching	(size of sensor)
Radiation hardness	(dark signal, lag)
Perennity Cost	

ADC

- Resolution (in bit)
- Power disspation
- Non linearity

A NEW device for Night Vision

Scientific CMOS

- Chip: Fairchild Imaging
- **< 2e RMS Readout Noise**
- Camera: Neo ANDOR Tech.

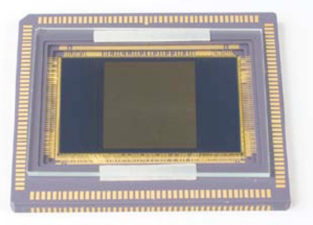
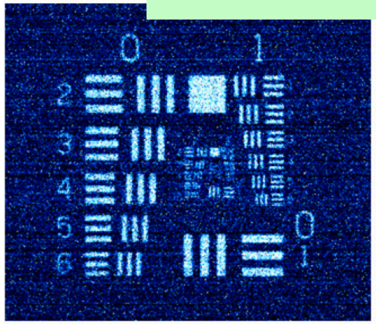
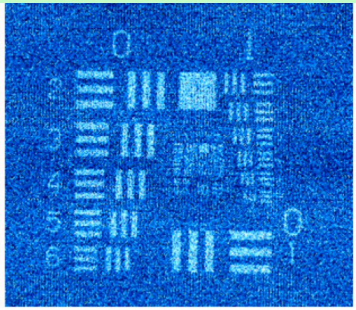


Figure 4: The 5.5 Megapixel sCMOS sensor

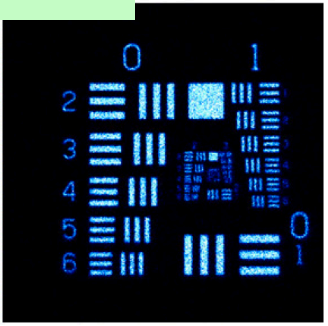
1300x1024
220 fps



sCMOS (*1.5 e⁻ noise*)



Interline CCD (*5 e⁻ noise*)



Back-illuminated EMCCD (*<1 e⁻ noise*)

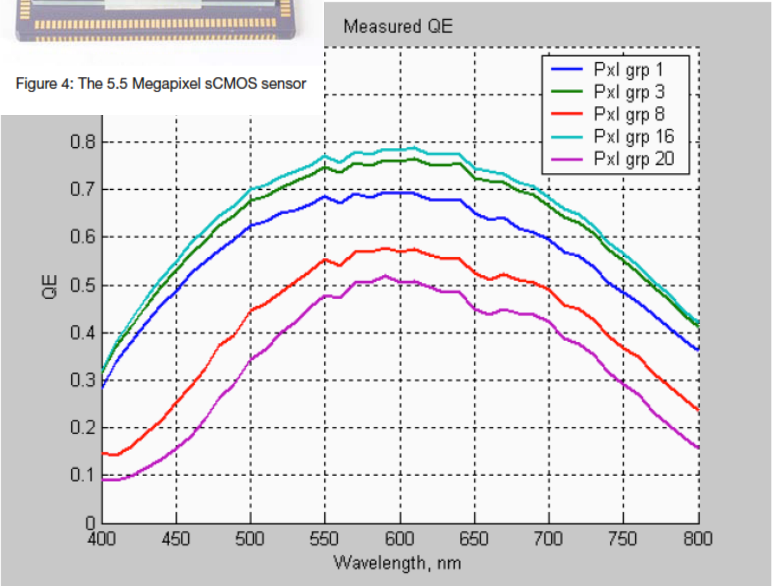


Figure 12. Measured quantum efficiency of 5 pixel groups (with microlens)

Paul Vu, Boyd Fowler, Chiao Liu, Janusz Balicki, Steve Mims, Hung Do, and Dan Laxson
Fairchild Imaging
1801 McCarthy Blvd., Milpitas, CA 95035, USA

2.3. Pixel design

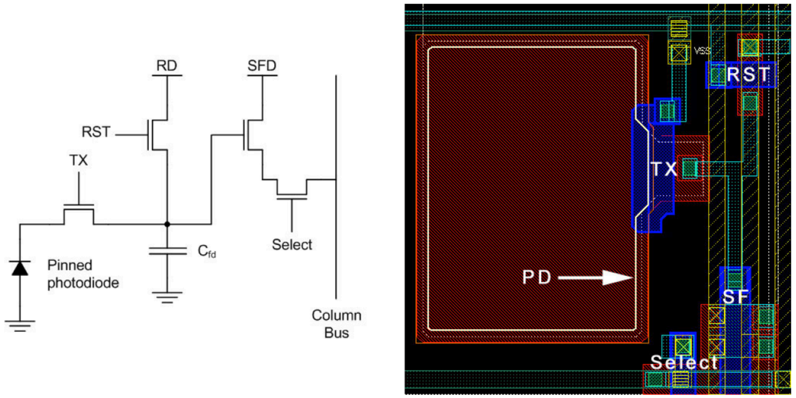
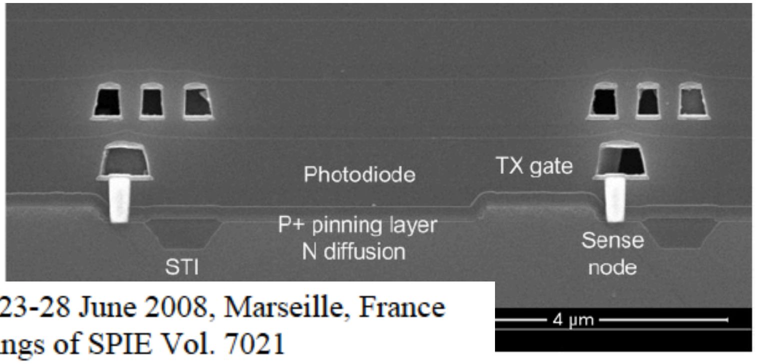


Figure 5. Simplified schematic of a 4T pixel and a sample pixel layout



PRE-PRINT: SPIE Astronomical Telescopes and Instrumentation, 23-28 June 2008, Marseille, France
Paper #7021-2 to be published in Proceedings of SPIE Vol. 7021

Figure 6. SEM cross-section of Fairchild Imaging 6.5 μm 4T pixel

3D electronics: Through Silicon Via, Wafer Level Package

Wafer stacks with TSV open a new area for photon detectors:

- Increase FF
- Large area
- Fast (1 TDC/pixel)
- Resolution (pixel)
- Smart Trigger per pixel
- Dynamic (buffer memory)
- Compact
- Embedded
- Sparsification
- Data rate 100 Gbit.s in //
- …

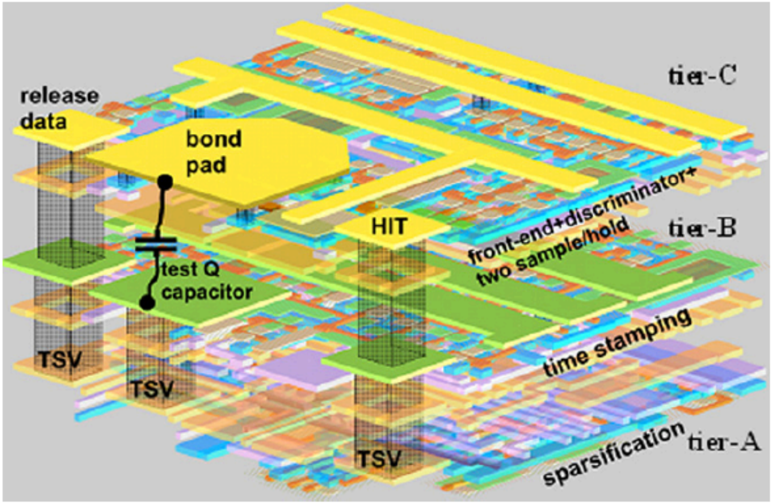
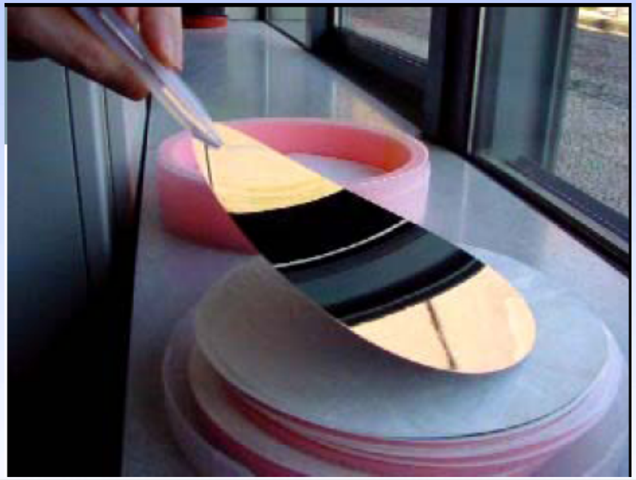
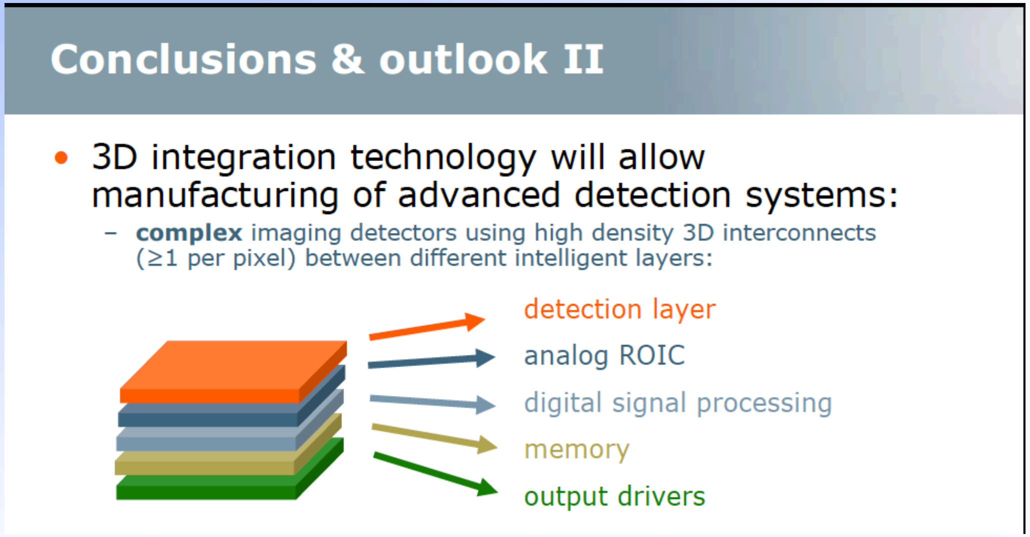


Fig. 11. 3D circuit diagram and 3D layout of pixel cell.

D. Bortoletto Solid state detectors NIMA 623 (2010) 35



P. De Moor IMEC



Conclusions & outlook II

- 3D integration technology will allow manufacturing of advanced detection systems:
  - **complex** imaging detectors using high density 3D interconnects (≥1 per pixel) between different intelligent layers:

Thank you for your attention

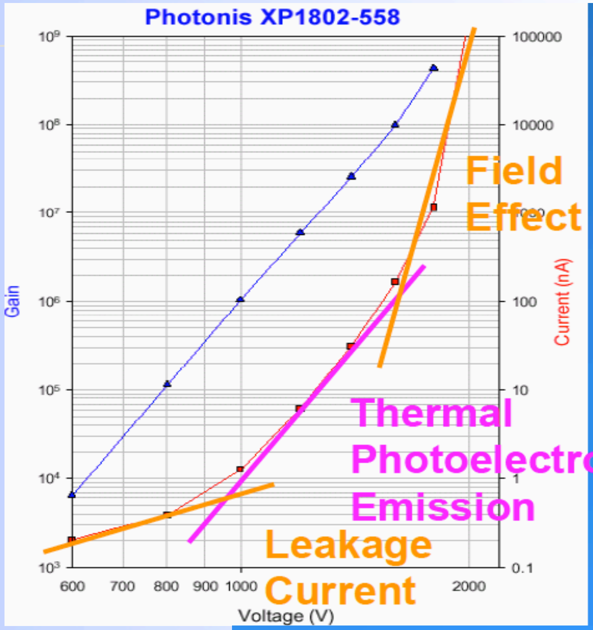
BACKUP SLIDES

- Photocathode Dark Noise
  - Dark current (nA)
  - Dark count (Hz/mm^2) (photon counting)

Main effects:

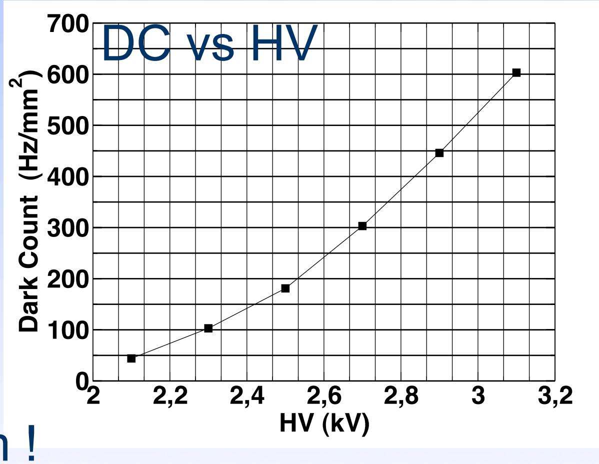
- Leakage current
- Thermionic pe emission (cooling)
- Field effect (HPD)
- Ion feedback: ionization current from residual gases

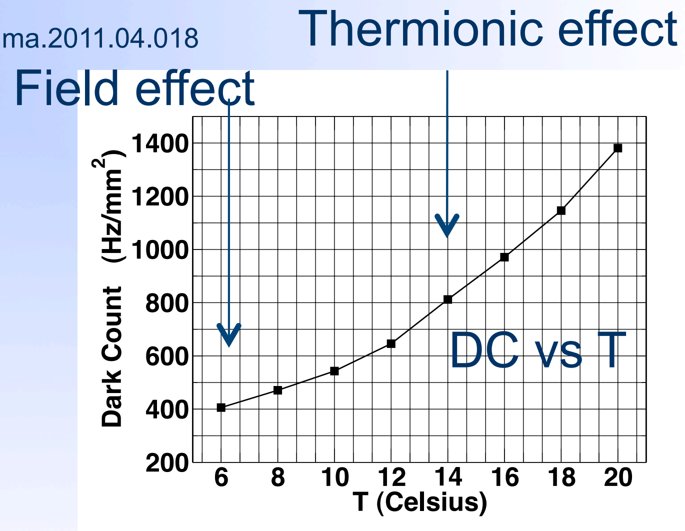
  An atom is ionized and accelerated : photocathode bombardment
  - aging issue (thin film protection can be used for AsGa Intensifier)



Katsushi Arisaka (UCLA)

R. Barbier, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.04.018





ebCMOS

Cathode S20

E ~ 3 kV/mm !

Single-Photon Imaging Devices

EBCMOS

EMCCD

Part II: PMT - The Pros and Cons

- Pros:
  - High sensitivity : single photo-electron resolution, ENF~1.3
  - High counting capability
  - Larger sensitive surface than Solid State Devices: Cherenkov detectors
  - Good time resolution < 1ns

- Cons:
  - Sensitivity to magnetic field (HEP experiments)
  - Low granularity
  - “Low” QE
  - Need of High Voltage

- Pros:
  - Sensitive to Single Photon
  - Very Fast (Time Of Flight)
  - Gating is possible on the MCP (or modulation 300V)
  - Good spatial resolution in case of ICCD
- Cons:
  - Limited life time – ion feedback
  - Limited rate capability
  - HV

- Detect Single Photon with low Dark Count Rate
- Localize the Photon on the sensor
- Localize the Photon Source
- Quantify the Source intensity, count photons
- Track the photon source
- Track all photon sources at less than 1 ms over Megapixels array

Single-photon sensitive fast ebCMOS camera system for multiple-target tracking of single fluorophores : application to nano-biophotonics.

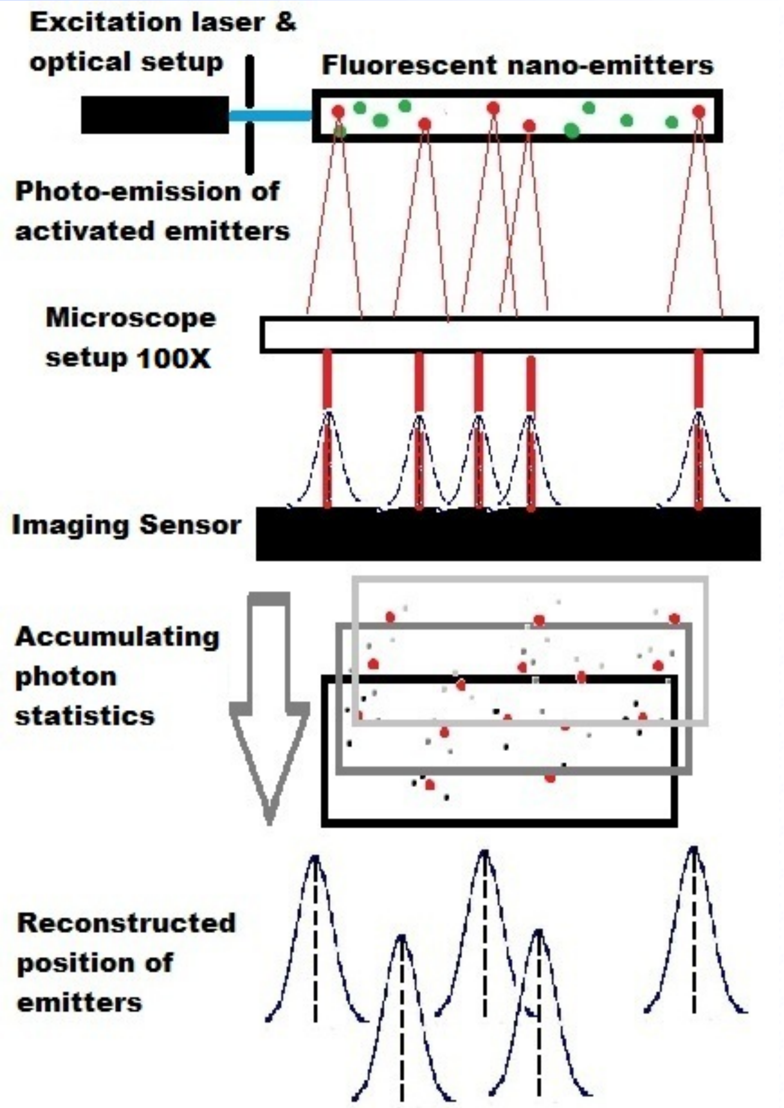
Thomas Cajgfinger, Eric Chabanat, Agnes Dominjon,
Quang T. Doan, Cyrille Guerin, Julien Houles, Remi Barbier.

IPNL, Université de Lyon, Université Lyon 1, CNRS/IN2P3,
4 rue E. Fermi – 69622 Villeurbanne cedex, France
www.ipnl.in2p3.fr/ebcmos/

27/01/2011

Thomas Cajgfinger IS&T/SPIE 2011 San Francisco Paper 7875-24

- Fluorescence microscopy : 2D imaging system
  - Population of nanometer scale single emitters:
    - Static or dynamic fluorescent beads (protein, Quantum Dots…)
    - Phototoxicity->low signal(~photons/ms)
  - Below objective diffraction limit resolution
- Wish List of imaging sensors:
  - 10 nm resolution on position of targets (=µm on sensor)
  - Fast frame rate ~ kHz
  - Photon counting ~ 1 - 10
  - Multi target tracking ~ 1000



Does that type of camera exist ?

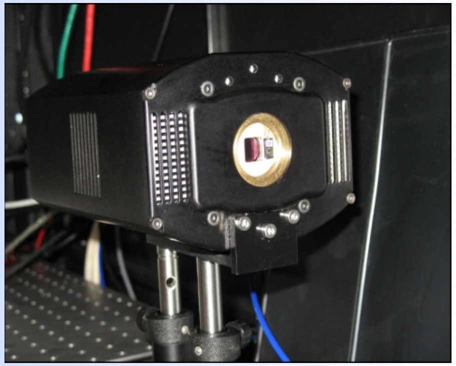
27/01/2011 Thomas Cajgfinger IS&T/SPIE 2011 San Francisco Paper 7875-24

What is an ebCMOS camera ?

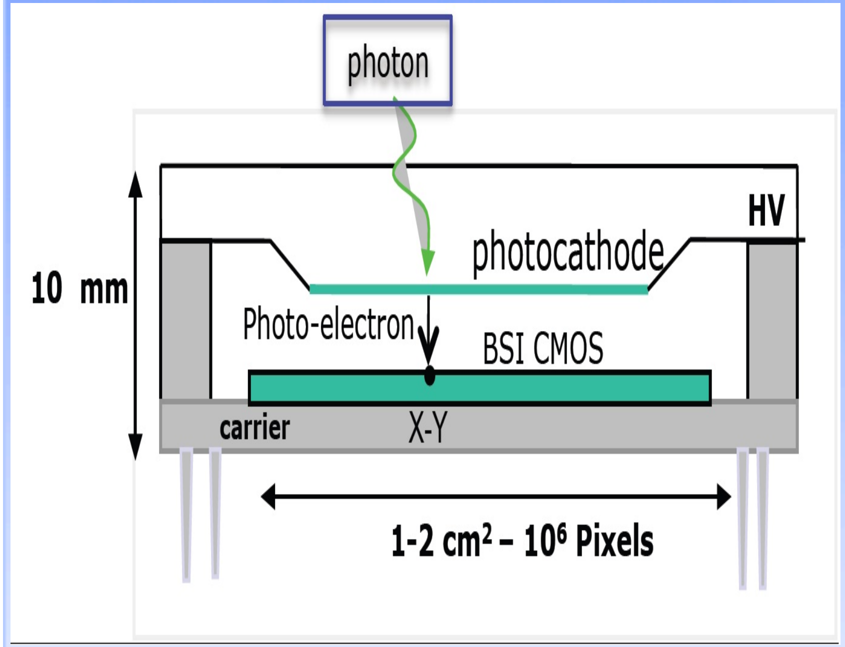
Single photon sensitive detector:

- Hybrid detector : electro bombarded CMOS
  - CMOS + photocathode + vacuum tube
- Gain = accelerated e- by electric field in vacuum tube
- Point spread function(psf) :
  - Tube: radial velocity of emitted e-
  - CMOS : thermal diffusion

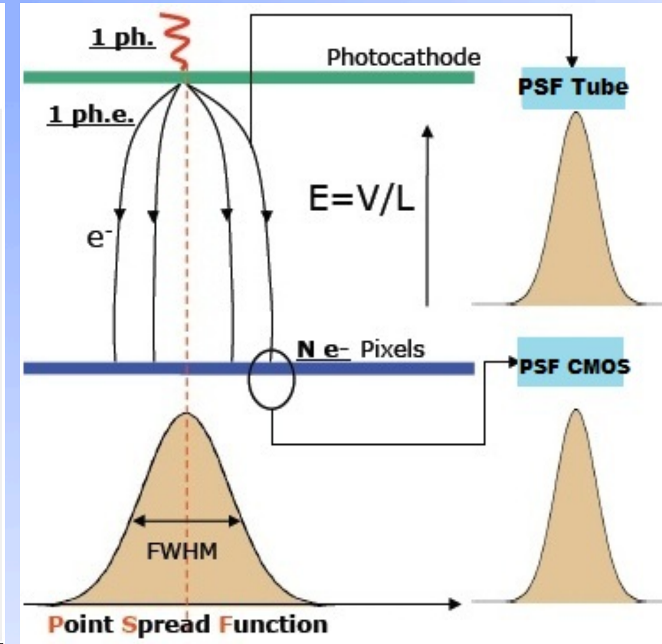
ebCMOS detector



ebCMOS Camera



ebCMOS Principle



ebCMOS PSF

ebCMOS DAQ

27/01/2011 Thomas Cajgfinger IS&T/SPIE 2011 San Francisco Paper 7875-24

Quick overview of the ebCMOS camera system prototype

CMOS

- Back side bombarded
- Back thinned
- Passivation (dead layer) <80nm
- 400x400 pixels X2
- simple 3T pixel 10 µm pitch
- 40 MHz clock

Fast frame rate

Photo Cathode

- Gain at 2.5 kV : 300e-
- Quantum Efficiency (530nm) : 25% max
- Cathode S20 : dark count : 15Hz/mm^2 ($6.25\ 10^{-6}$ evt/pix/frame)
- Cathode S25: dark count : 400Hz/mm^2 ($1.66\ 10^{-4}$ evt/pix/frame)

Single photon sensitivity

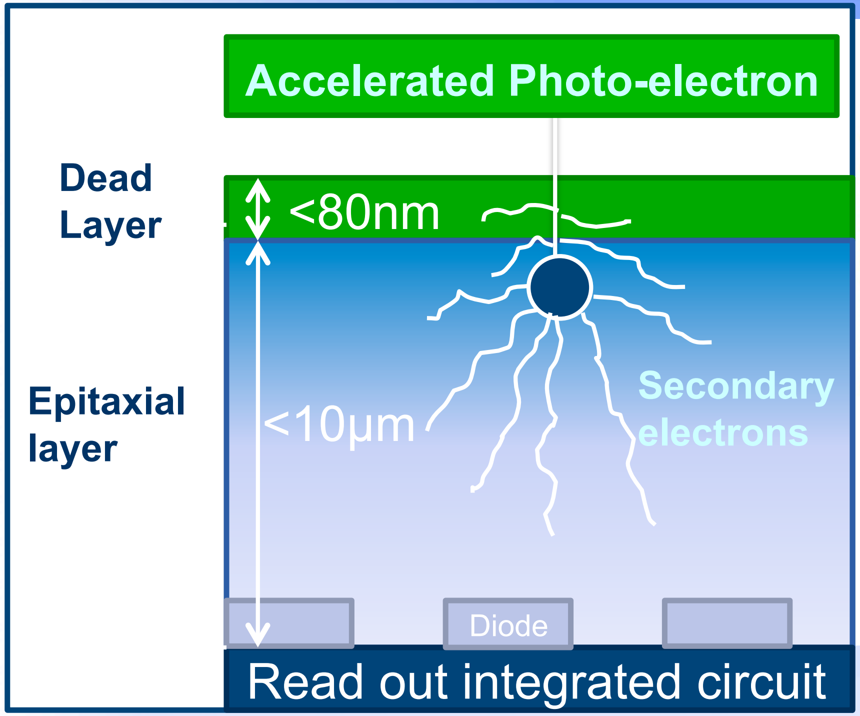
Home made DAQ

- Continuous acquisition
- Frame rates: 125, 250 & 500 fps
- FPGA DDR custom board
- Ethernet 1 Gb/s
  - Next 10 Gb/s

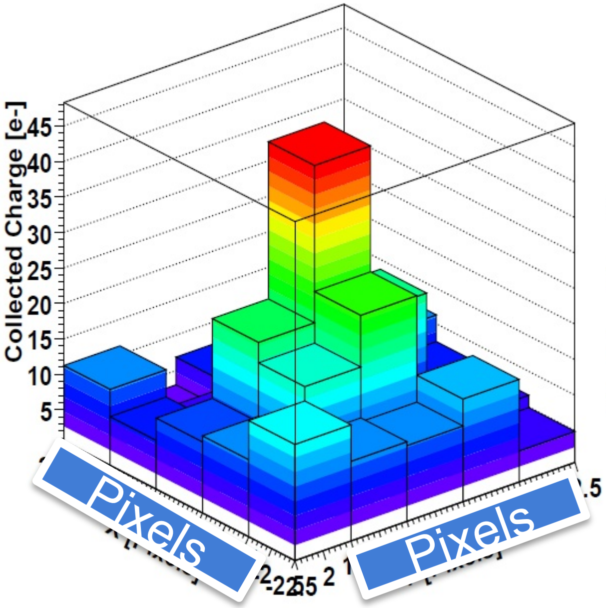
High data throughput

Building blocks of nano-emitter tracking

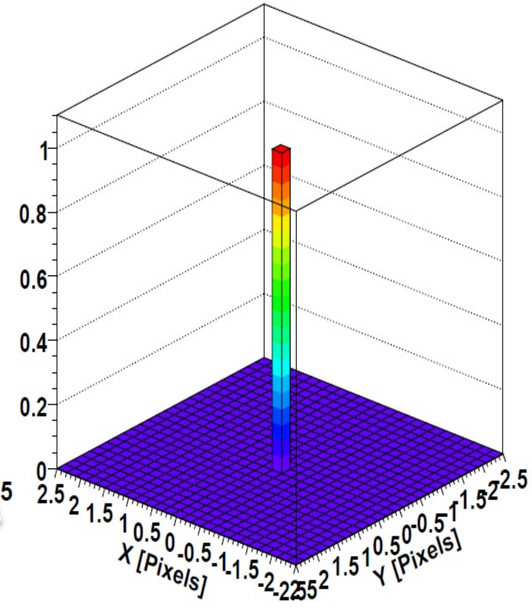
- Secondary e- diffusion & charge sharing
    - Impact pattern
        - Photo-electron reconstruction by clustering
- Computation of centre of gravity (COG) -> intra pixel localization
- Natural CMOS noise filtering
- Counting possibilities with gain linearity



Diffusion of secondary e- in the CMOS



Photoelectron Event



COG reconstruction
Resolution ~ 2 µm

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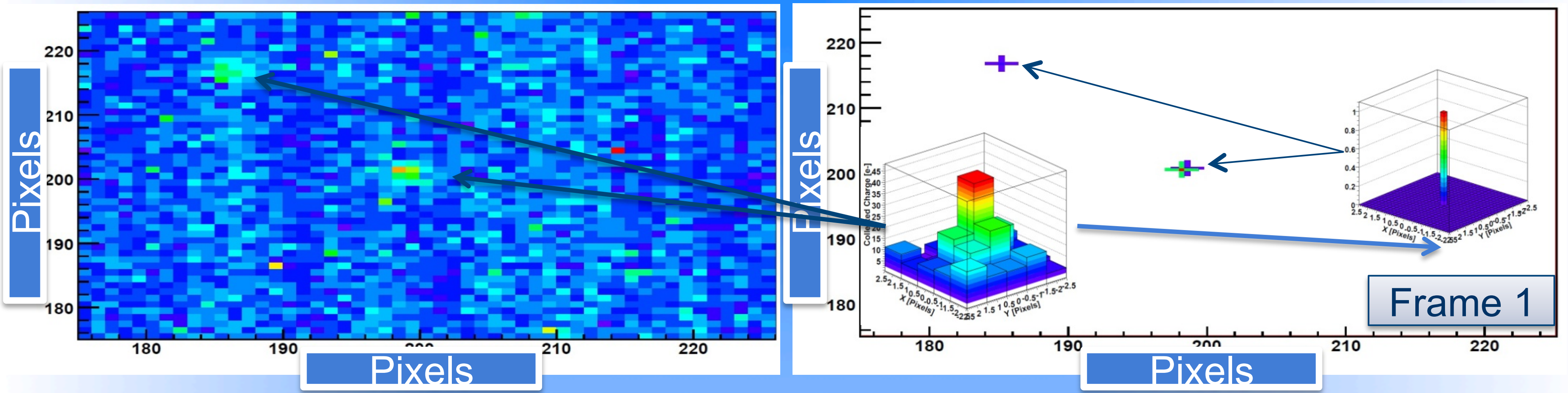
Using building blocks to follow a target



Zoom in a raw frame

Zoom in a reconstructed frame

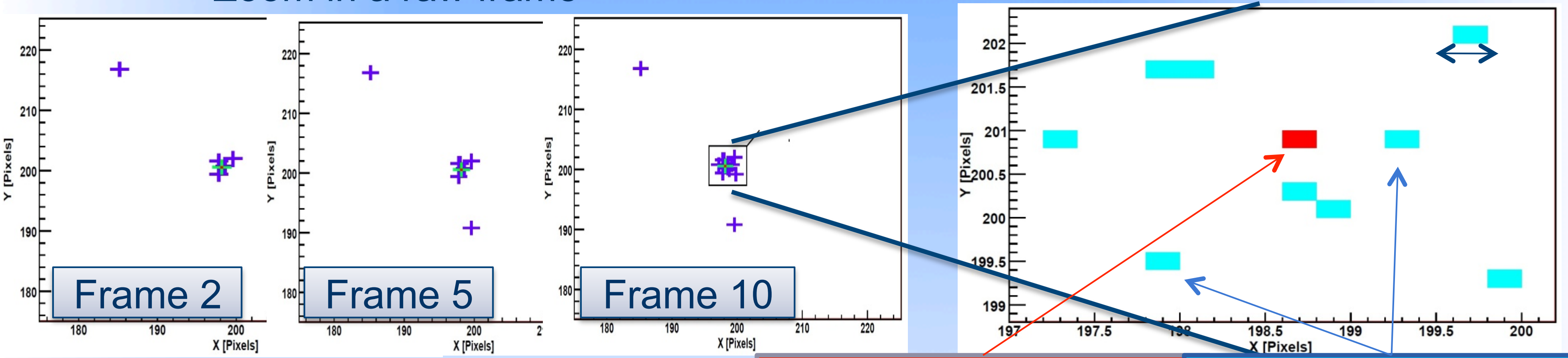


Image stack & **Kalman filtering**

Reconstructed Target State vector

Photoelectron Measurement vector

Zoom (~4x4pixels)

What resolution can be achieved with this method ?

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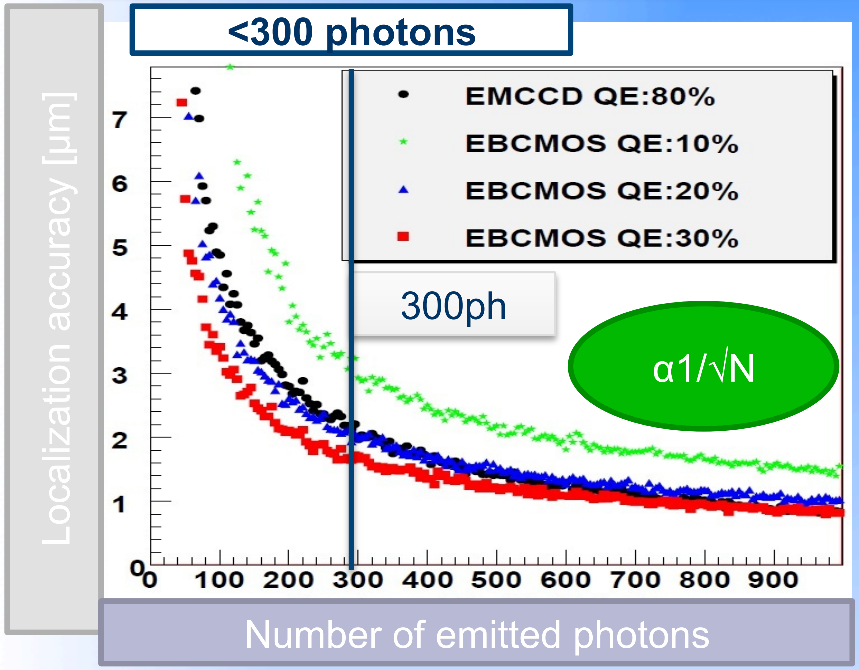
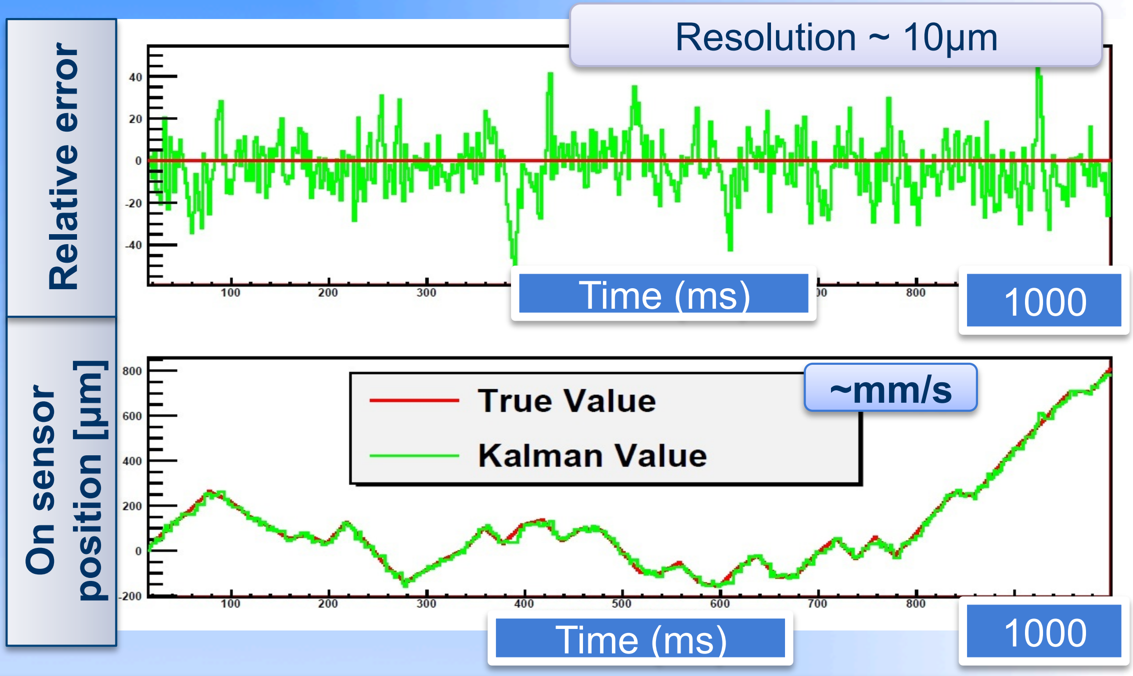
Key factor: emitter localization accuracy

Monte Carlo Simulation:
- ➢Localization accuracy of a spot
- ➢Given conditions
- ➢Static case

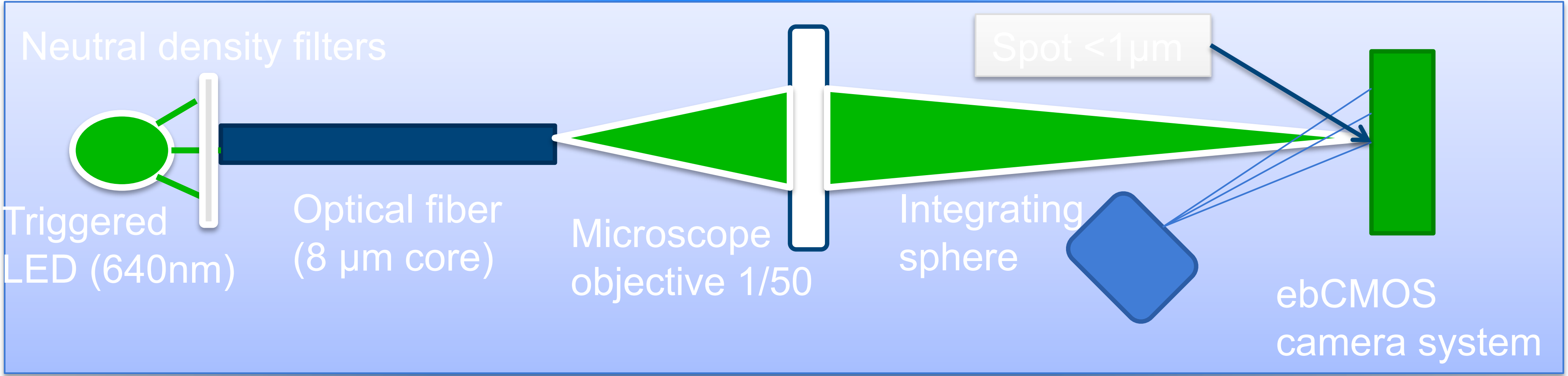
- ➢Tracking of a single emitter
- ➢Mean signal : 5 photons/2ms
- ➢Velocity on sensor
  - ➢Up to 5 mm/s (10 pixels/20ms)





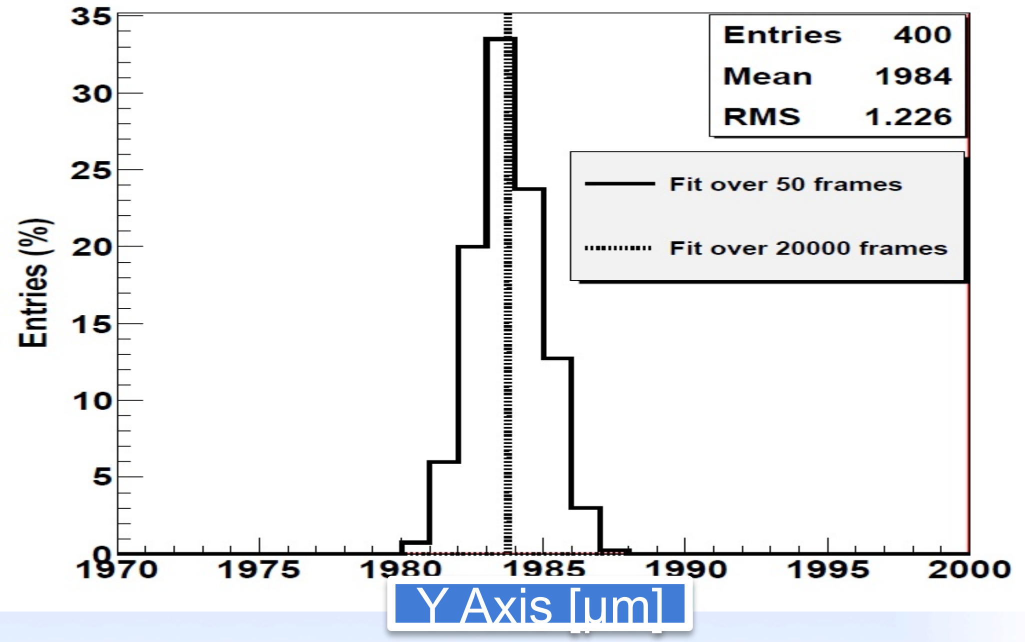
- ✓Comparable resolution EMCCD/ebCMOS QE 20% with faster frame rate
- ✓Adaptive tool (signal, background, motion…)
- ✓Promising results

Test bed : spot <1µm
Localization accuracy measurement



Sketch : focusing a spot (Ø< 1µm) with various background noise conditions

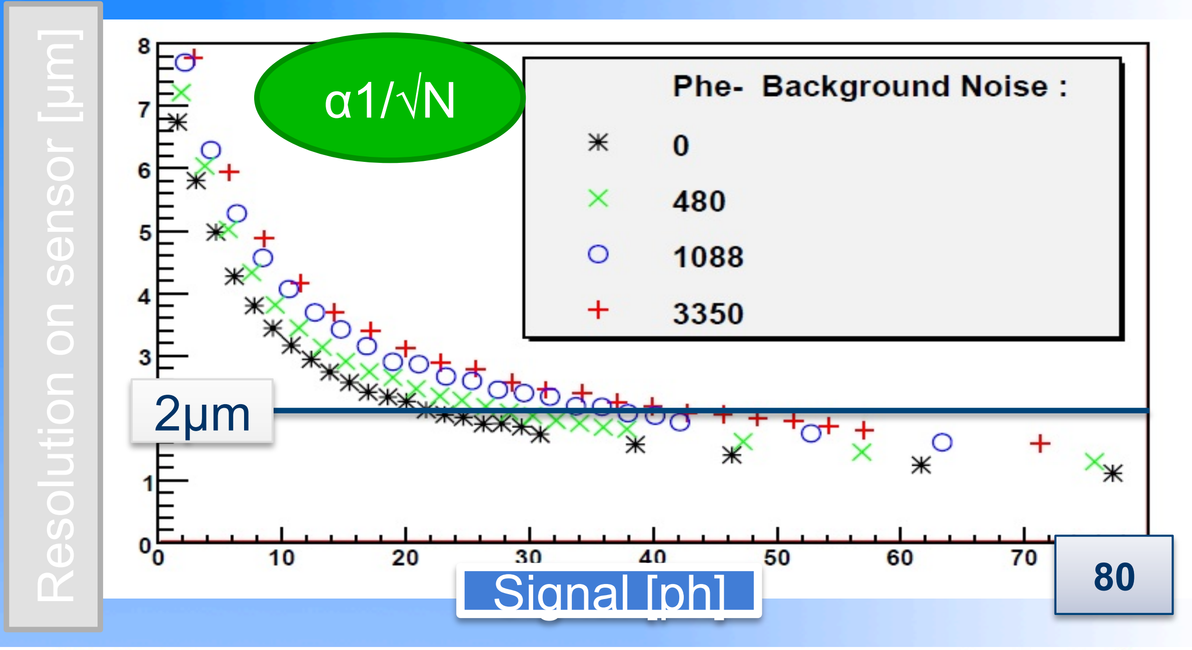
- **1.56 photon/2ms** mean received signal
- Example :
  - 50 frames period
  - 400 measured positions
  - Compared to statistical true position (20 000 frames)
  - ~78 photons resolution:**1.2µm**



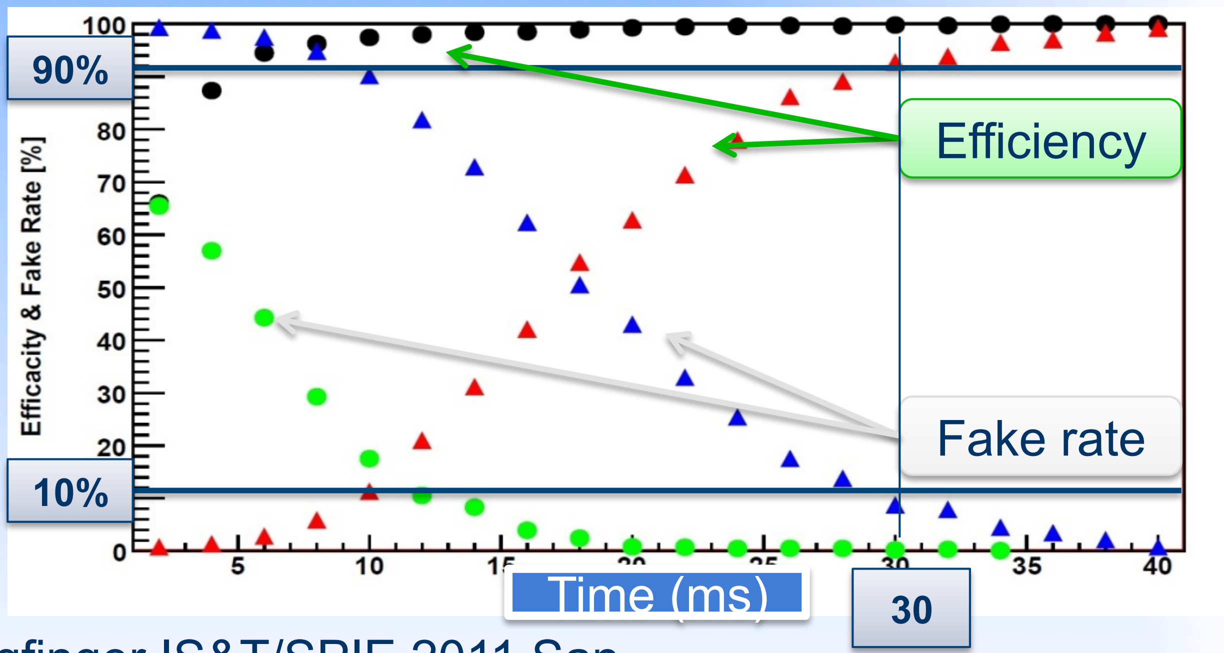
ebCMOS resolution in the noise free case

Finding & locating targets

- ➢Resolution vs. signal for 4 settings
- ➢Spot ~<u>1.56 ph/2ms</u>

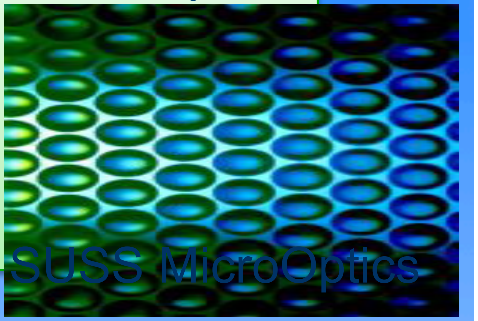


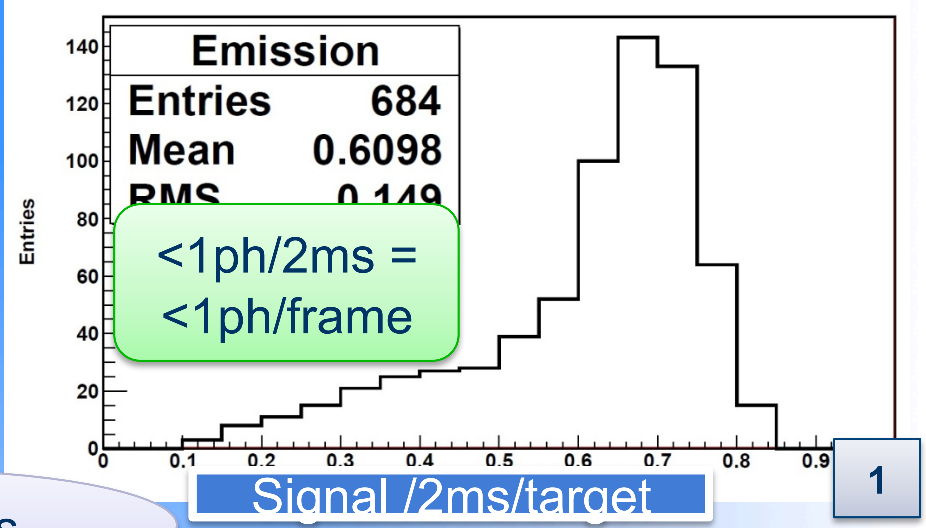
- ✓**<u>Localization accuracy:</u>**
  - ✓<u><3µm</u> after **30 photons**
  - ✓<u><2µm</u> in noise free case
- ✓**<u>Finding targets:</u>**
  - ✓Fake rate <10% & efficiency>90% after <u>30ms</u>



Multi target tracking :
684 microlenses spots

- ➢Microlenses array illuminated by collimated optical fiber
- ➢**150 µm pitch**
- ➢Detected signal :
  - ➢0.1 - 0.8 ph/2ms

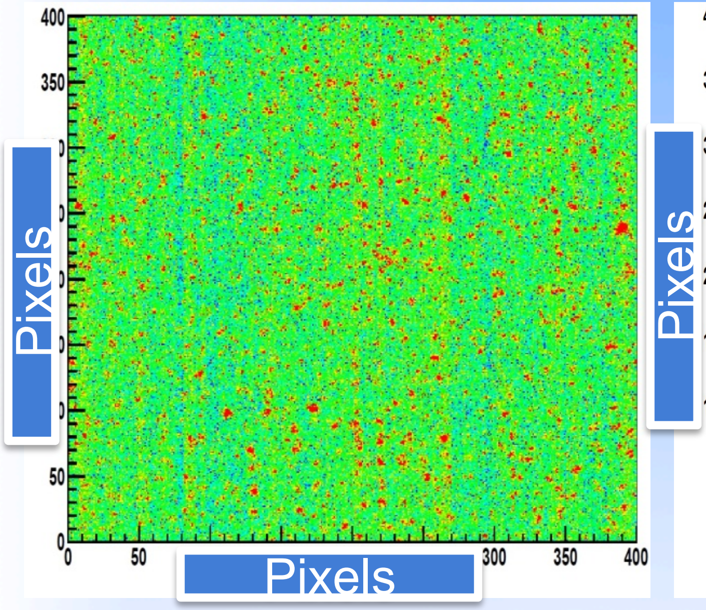




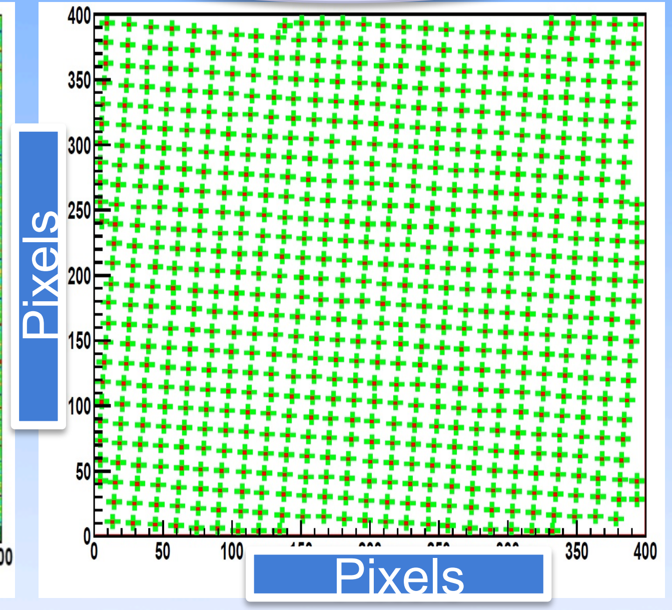
<1ph/2ms =
<1ph/frame

684 spots

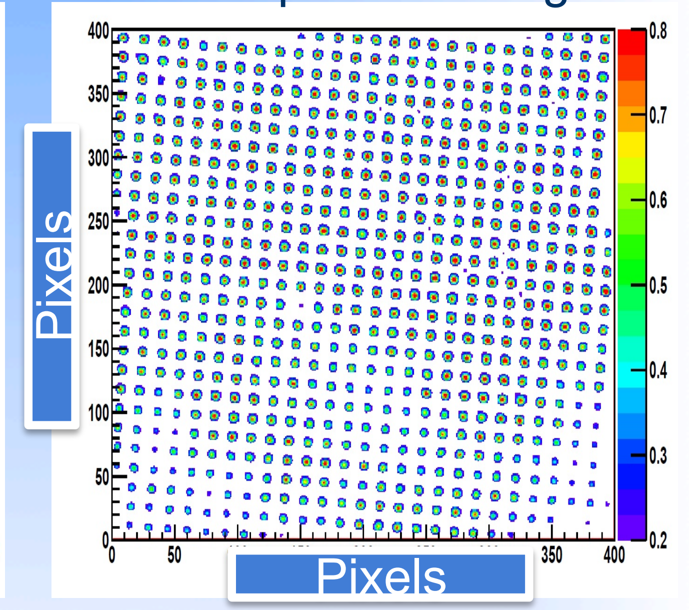
Mcrolenses Spot Mean Signal



One raw frame



Targets after ~ 20 frames

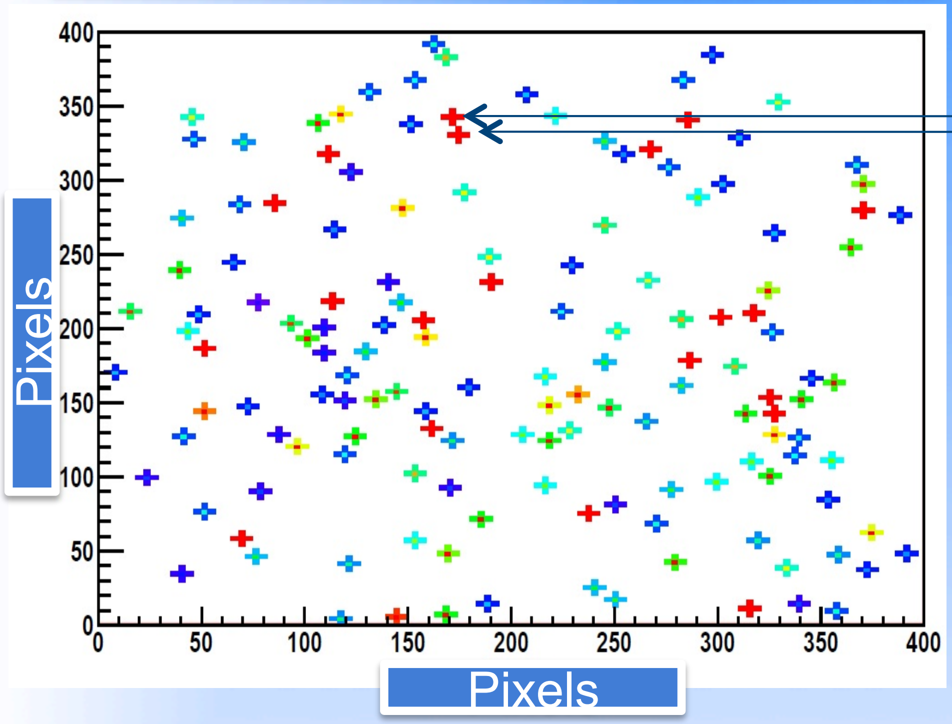


Average signal (3500 frames)

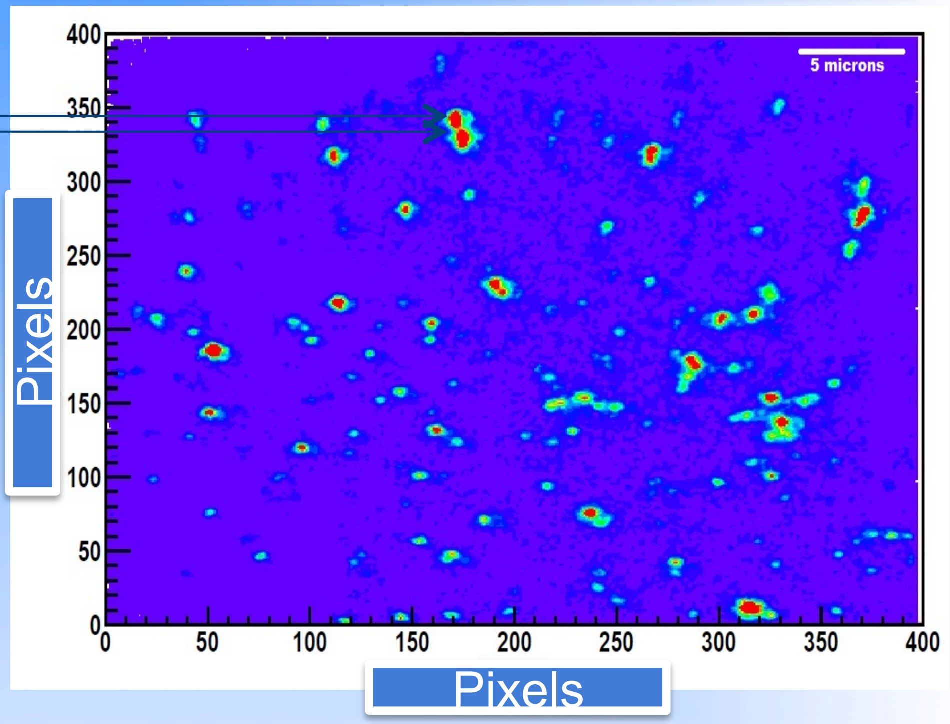
Imaging in situ data: Quantum Dots

- Setup at Nanoptec Center in Lyon:
  - Spin-coated QDs
  - Wide field microscopy setup
  - Magnification: 100X

- Quantum Dots ID:
  - Emission wavelength: 605 nm (Invitrogen)
  - Excitation wavelength: 473 nm
  - QD size: 10-20 nm



Detected targets after ~ 20 frames



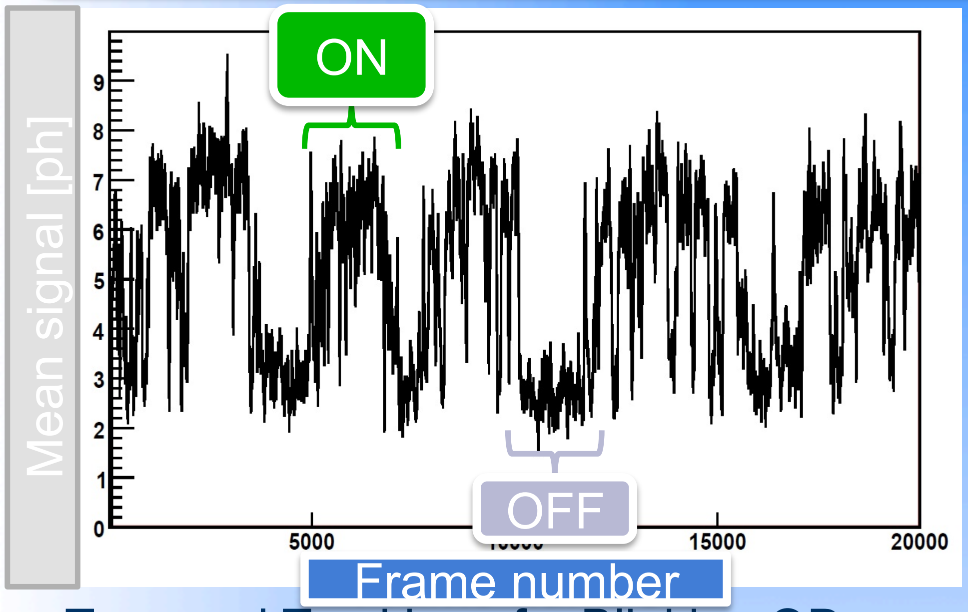
Average image (20 000 frames)

Parallel processing and data extraction

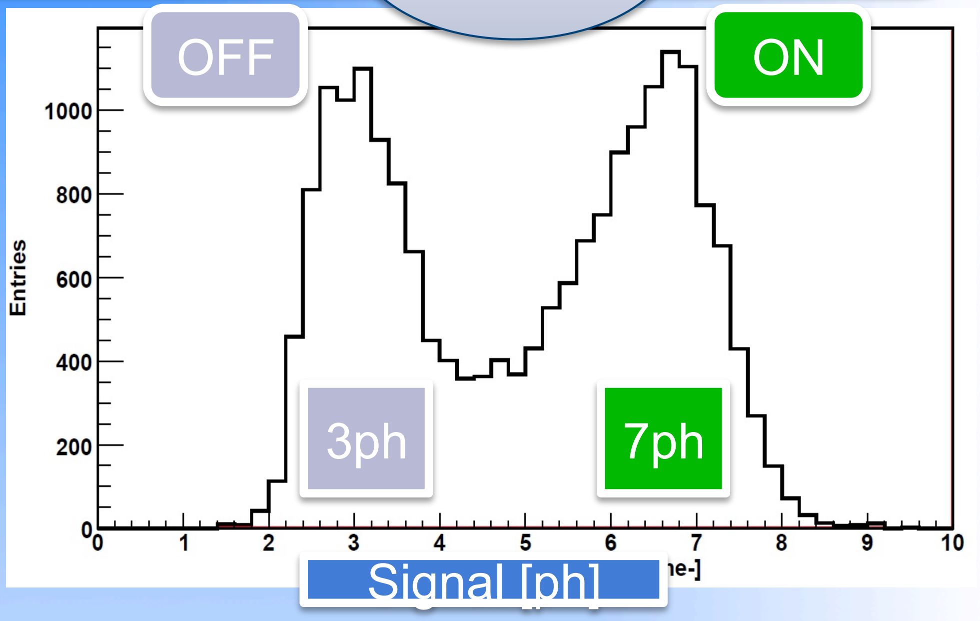
Photon counting & temporal tracking

- Temporal signal tracking:
  - 30 frame average signal
  - Blinking Quantum Dots: ON and OFF states

Blinking



Temporal Tracking of a Blinking QD



Signal Distribution of a Blinking QD

- ✓Parallel tracking of 300 nano-photo-emitters :
  - ✓Position (localization accuracy ~ µm on sensor)
  - ✓Signal (photon counting)
  - ✓High data throughput
  - ✓No time limit

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Conclusion and prospects

Proof of concept and in situ testing of the tracking of a large number of nanoscale photo-emitters on a large field of view with micrometric resolution and single photon sensitivity at millisecond time scale using an ebCMOS camera and home made DAQ & HCI system.

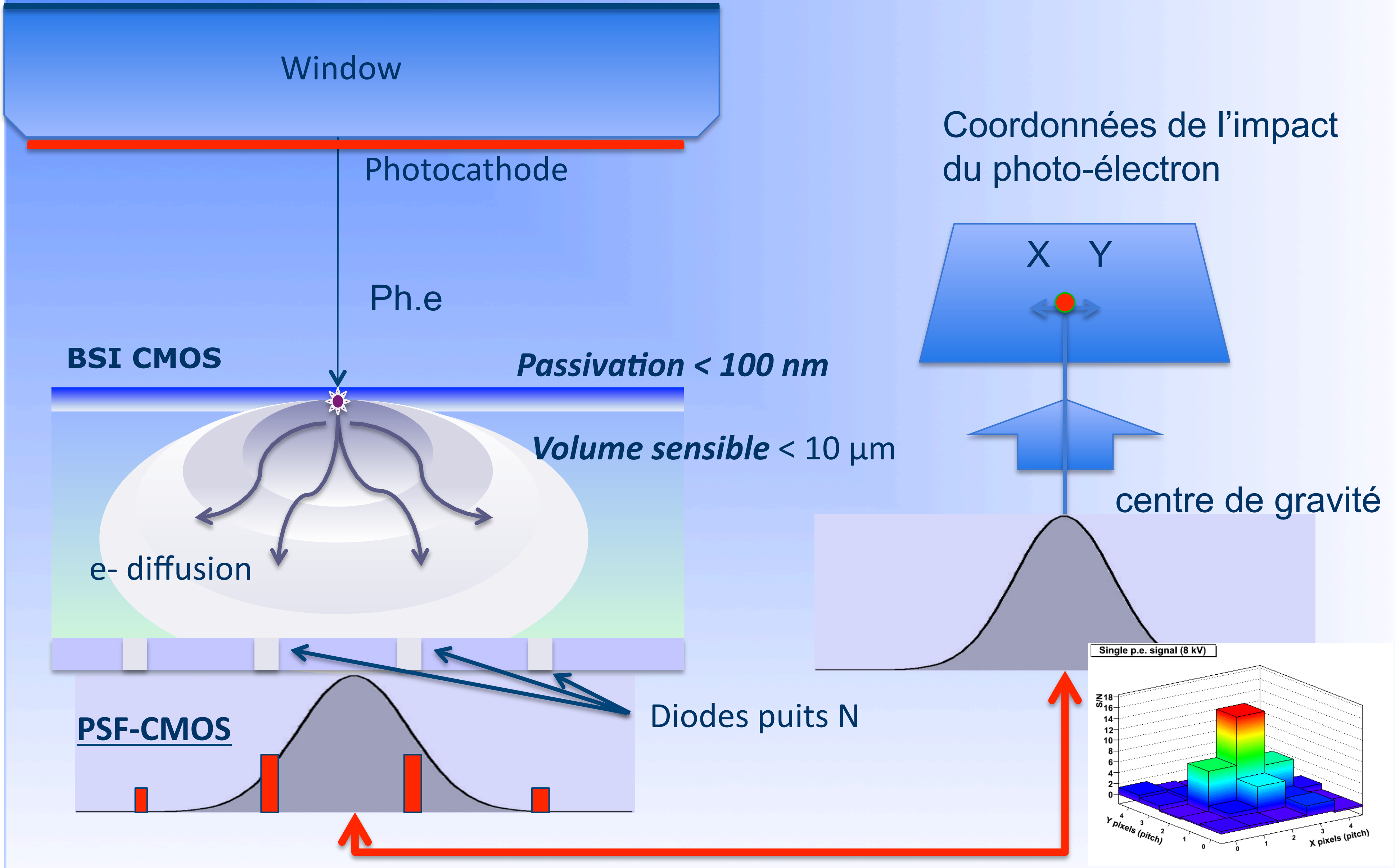
Camera system improvements:

✓Larger and faster CMOS
✓Target tracking with parallel processing : FPGA & GPU computing
✓Real time implementation

Applications:

➢Physical properties of nano-objects: mean square displacement, viscosity…
➢Photo Activated Localization Microscopy (PALM)

- Localisation accuracy on spot position



Window

Photocathode

Ph.e

BSI CMOS

Passivation < 100 nm

Volume sensible < 10 µm

e- diffusion

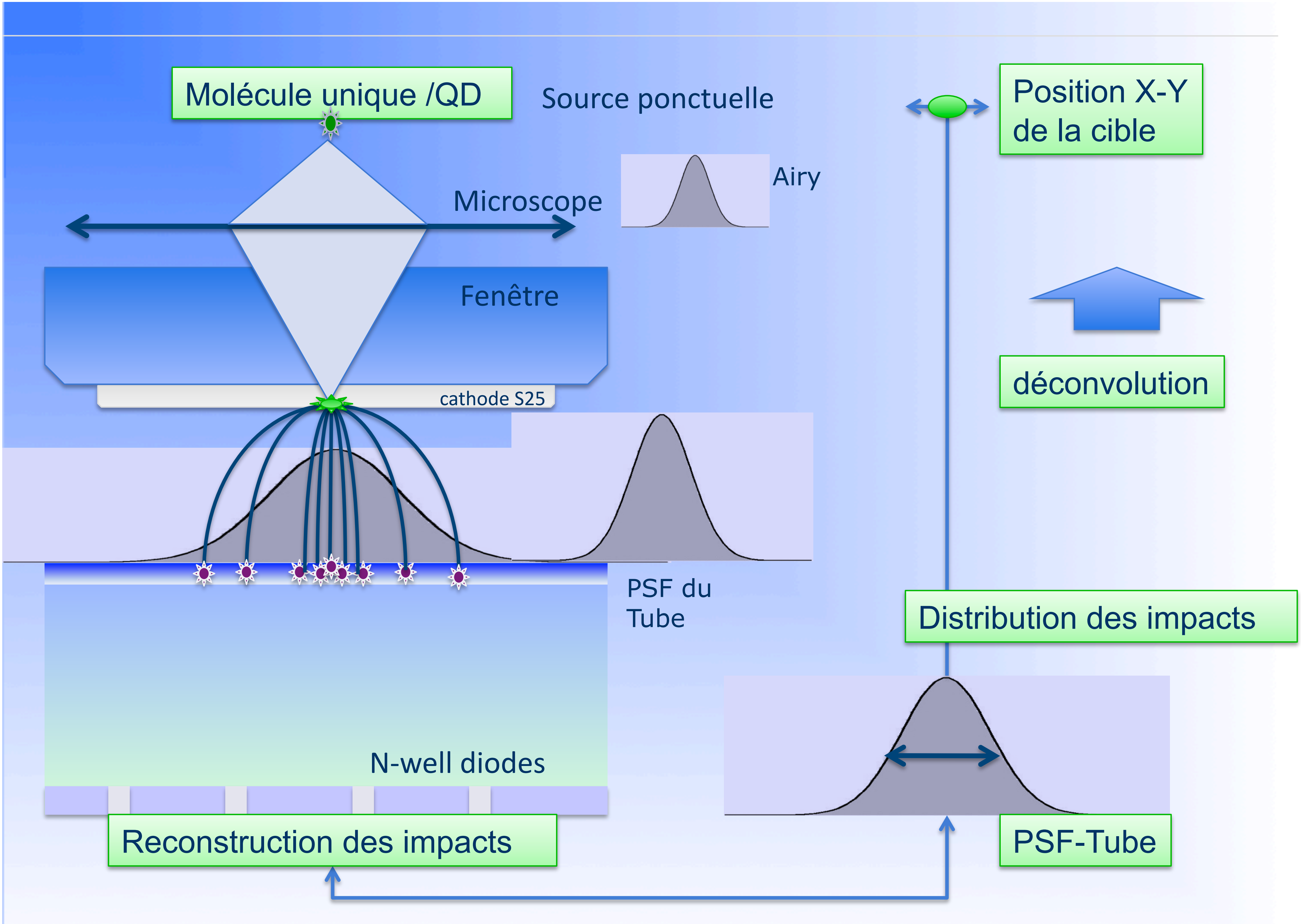
PSF-CMOS

Diodes puits N

Coordonnées de l'impact du photo-électron

X Y

centre de gravité



Molécule unique /QD

Source ponctuelle

Position X-Y de la cible

Airy

Microscope

Fenêtre

cathode S25

déconvolution

PSF du Tube

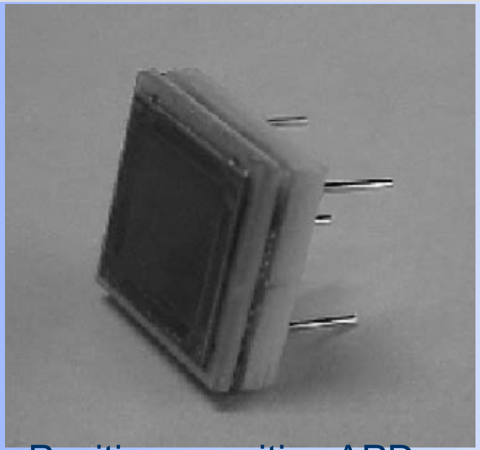
Distribution des impacts

N-well diodes

Reconstruction des impacts

PSF-Tube

- ✓ Many Sizes are available
- ✓ Many wavelength sensitivity
- ✓ APD Arrays
- ✓ APD in vacuum tubes: HAPD
- ✓ Compactness for full design of PET system (PET…)
- ✓ Need ASICs – temperature regulation



Position sensitive APD
8x8mm^2

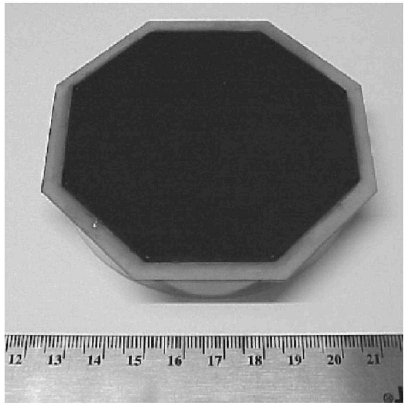
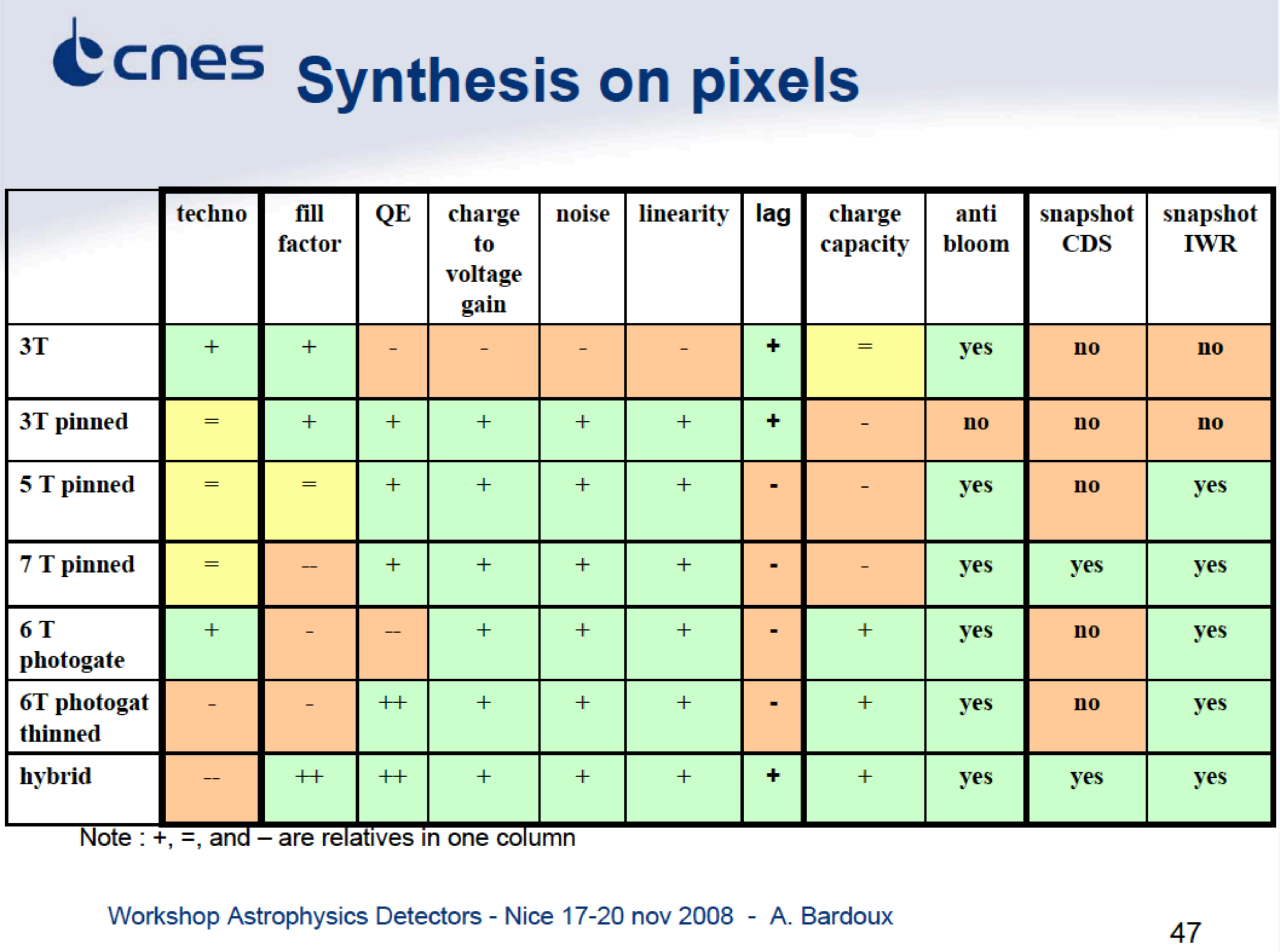


Fig. 2. A photograph of a 45 cm^2 APD.

Large APD
45 cm^2

M. McClish et al. NIM A567 (2006) 36



cnes

Synthesis on pixels

	techno	fill factor	QE	charge to voltage gain	noise	linearity	lag	charge capacity	anti bloom	snapshot CDS	snapshot IWR
3T	+	+	-	-	-	-	**+**	=	yes	no	no
3T pinned	=	+	+	+	+	+	**+**	-	no	no	no
5 T pinned	=	=	+	+	+	+	**-**	-	yes	no	yes
7 T pinned	=	--	+	+	+	+	**-**	-	yes	yes	yes
6 T photogate	+	-	--	+	+	+	**-**	+	yes	no	yes
6T photogat thinned	-	-	++	+	+	+	**-**	+	yes	no	yes
hybrid	--	++	++	+	+	+	**+**	+	yes	yes	yes

Note : +, =, and – are relatives in one column

Workshop Astrophysics Detectors - Nice 17-20 nov 2008 - A. Bardoux

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- The performances of a photodetector should be systematically discussed with the background question: what did I want to see ?
- First: fill your checklist and choose your hierarchy of priorities:
  - Counting ? Linearity ? Single Photon sensitivity ?
  - Localize ? Imaging ? Large Field of View ? Detection surface ?
  - dynamic range ?
  - time stamping ? dead time ?
  - …
- This is why presenting a tutorial on many different photodetector performances is in some sense bizarre… but … not completely stupid …
- Sometimes different possibilities of detectors are offered and chose the “best” for the application is not obvious.
- The detection technologies (Semiconductor mainly) evolve rapidly. It could happen that two technologies merge to open new application fields.