POLITECNICO
DI MILANO

Dip. Elettronica e Informazione - DEI

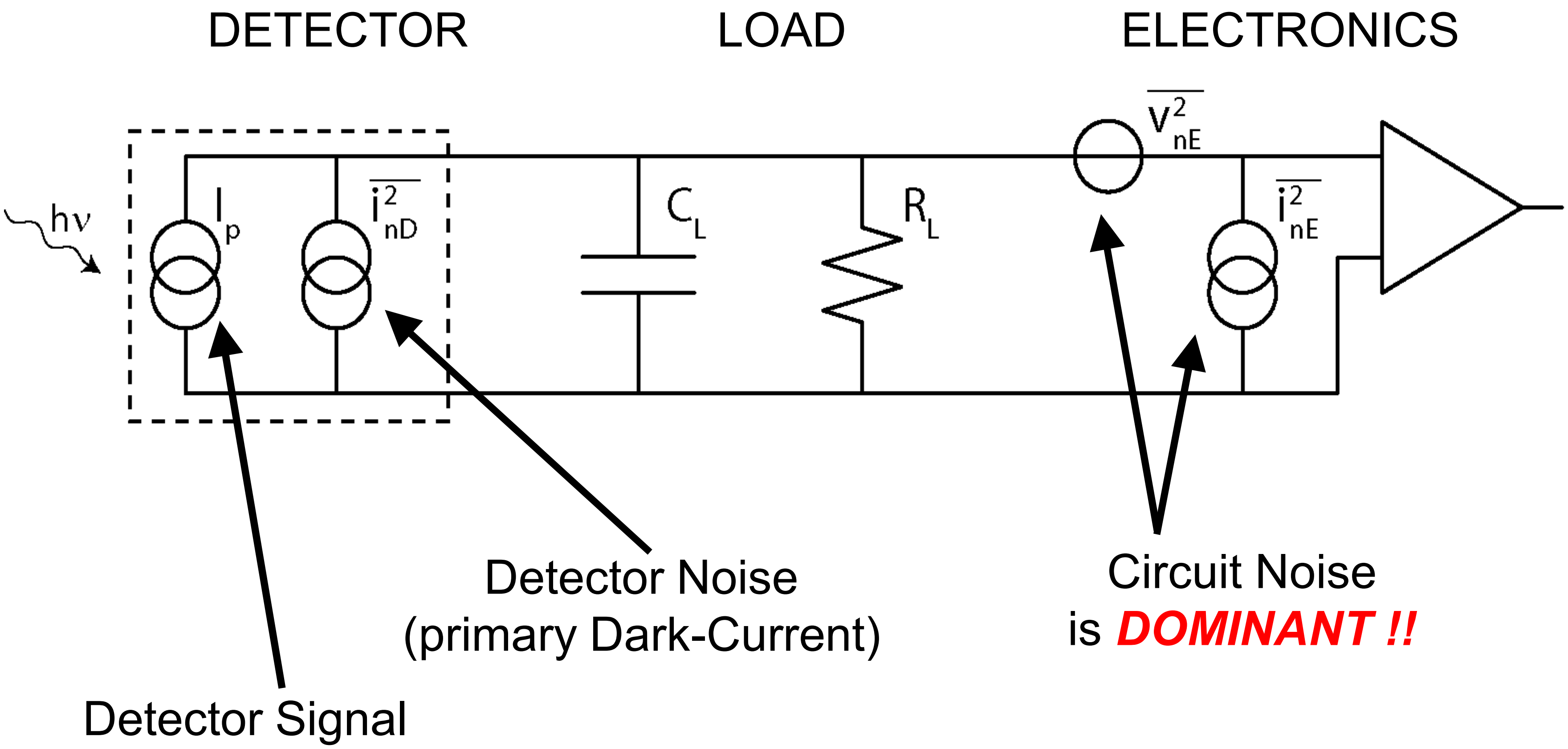
MPD
MICRO PHOTON DEVICES

Single Photon Avalanche Diode Laboratory
SPADLab

Outline

- Photon Counting: how and why
- Vacuum tube and silicon detectors
- Single-Photon Avalanche Diodes SPAD
- Challenges for SPAD development: technology and design
- SPAD for the InfraRed spectral range
- SPAD applications
- SPADLab

Circuit Noise impairs sensitivity of Analog Detectors



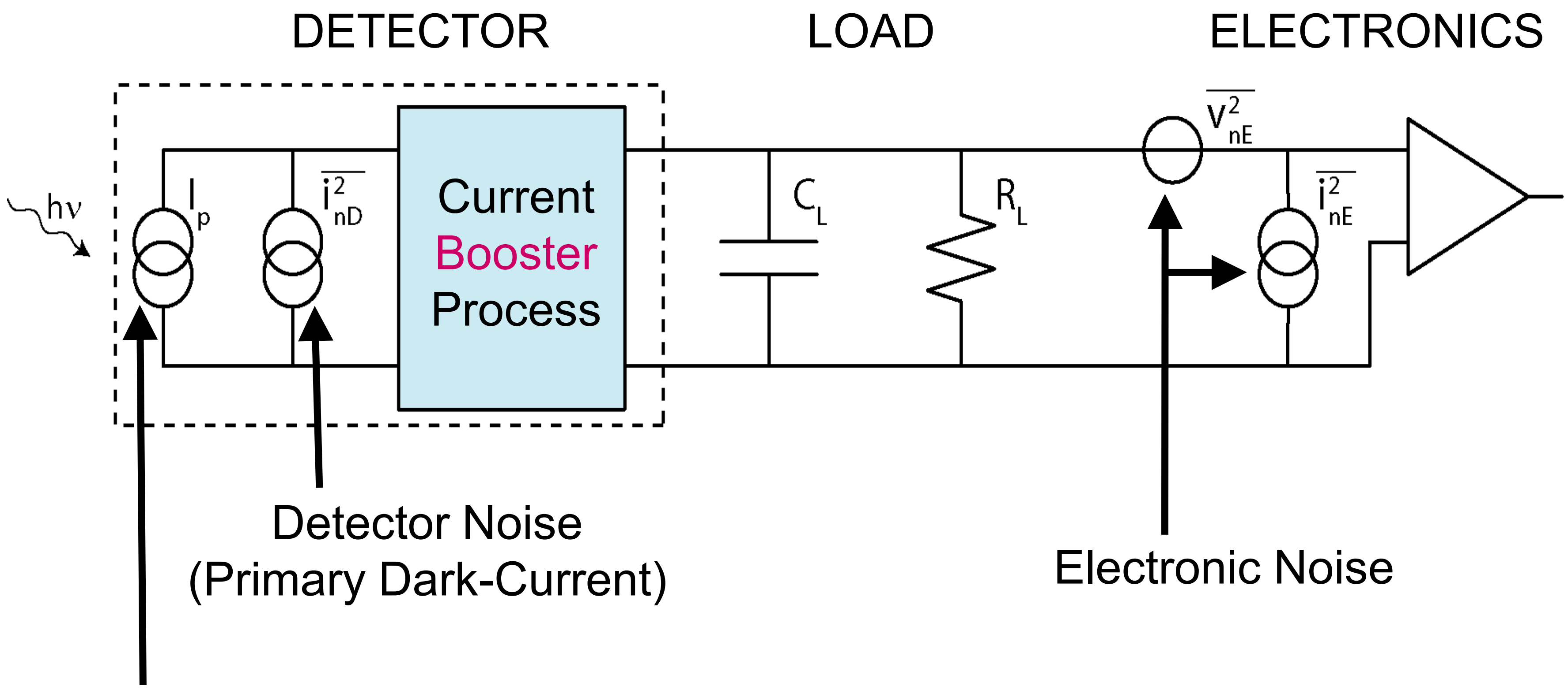
Detector Noise
(primary Dark-Current)

Circuit Noise
is ***DOMINANT !!***

Detector Signal

1 Photon $\xrightarrow{PDE}$ **1 Electron**

Single-Photon Detectors bypass the Electronic Noise Limit



Detector Noise
(Primary Dark-Current)

Electronic Noise

Detector Signal

1 Photon → 1 Electron
PDE

Single Photon Counting

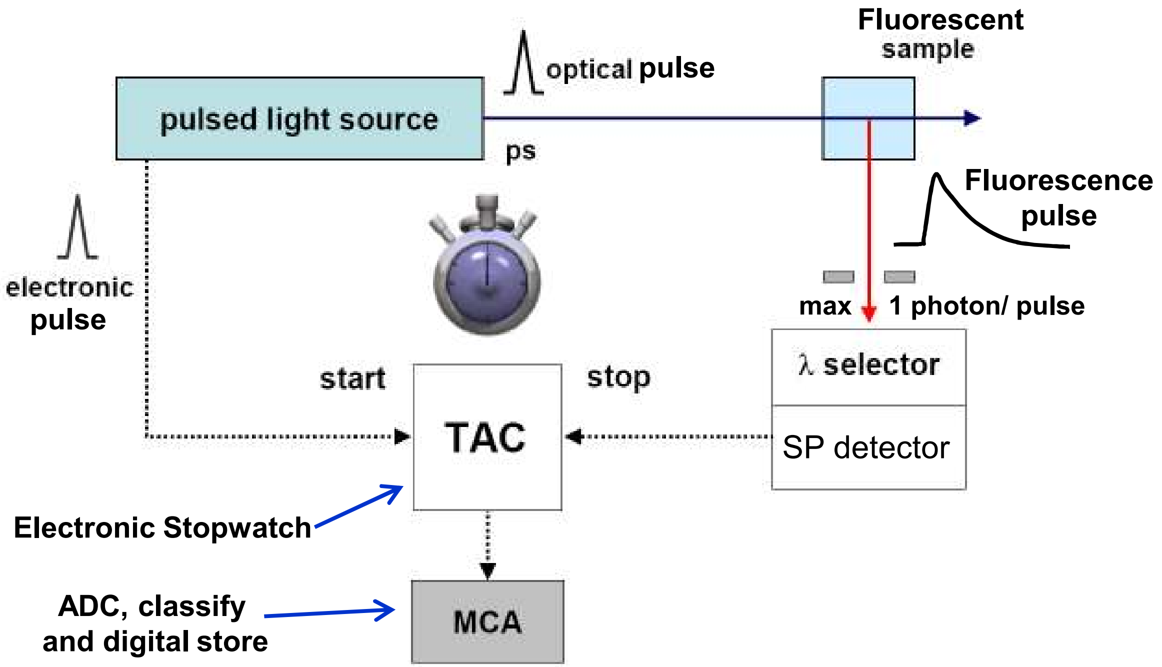
- Direct digital detection
- Overcomes the limit of analog photodetectors, i.e. circuit noise
- Noise only from the statistics of dark-counts and photons
- Measurement of light intensity with ultra-high sensitivity

and with precise **photon-timing**

Time-Correlated Single Photon Counting (TCSPC)

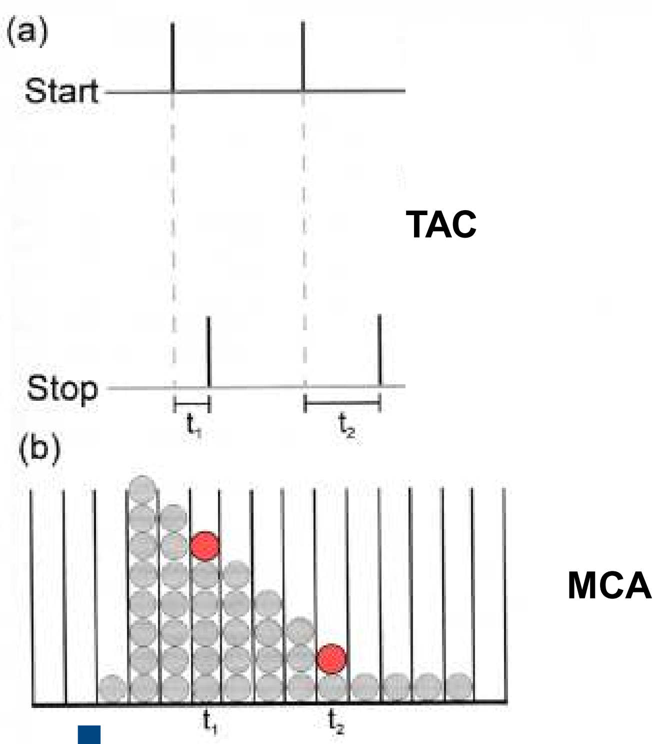
→ measurement of ultrafast waveforms with ultra-high sensitivity

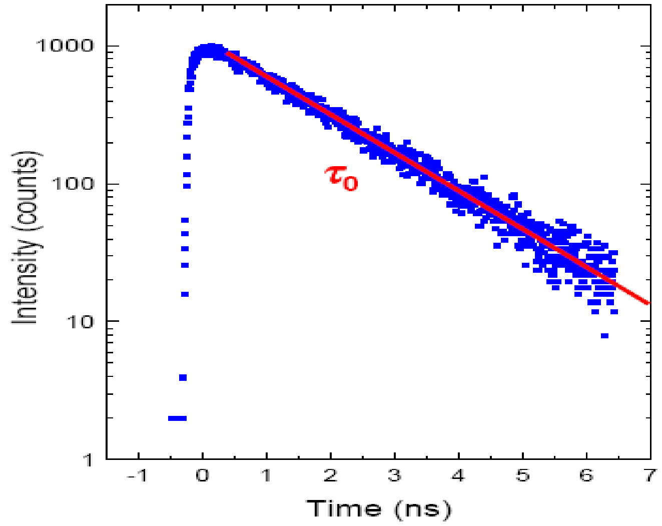
Time Correlated Single Photon Counting



Electronic Stopwatch

ADC, classify and digital store





Hystogram of many trials

≡

fluorescence decay curve

Single Photon Counting and Timing

Semiconductor detectors vs PMT - Photomultiplier Tubes

- **microelectronic advantages**

  miniaturized, low voltage, etc.

- **improved performance**

  higher Photon Detection Efficiency

  better photon timing

  comparable or lower noise (dark counting rate)

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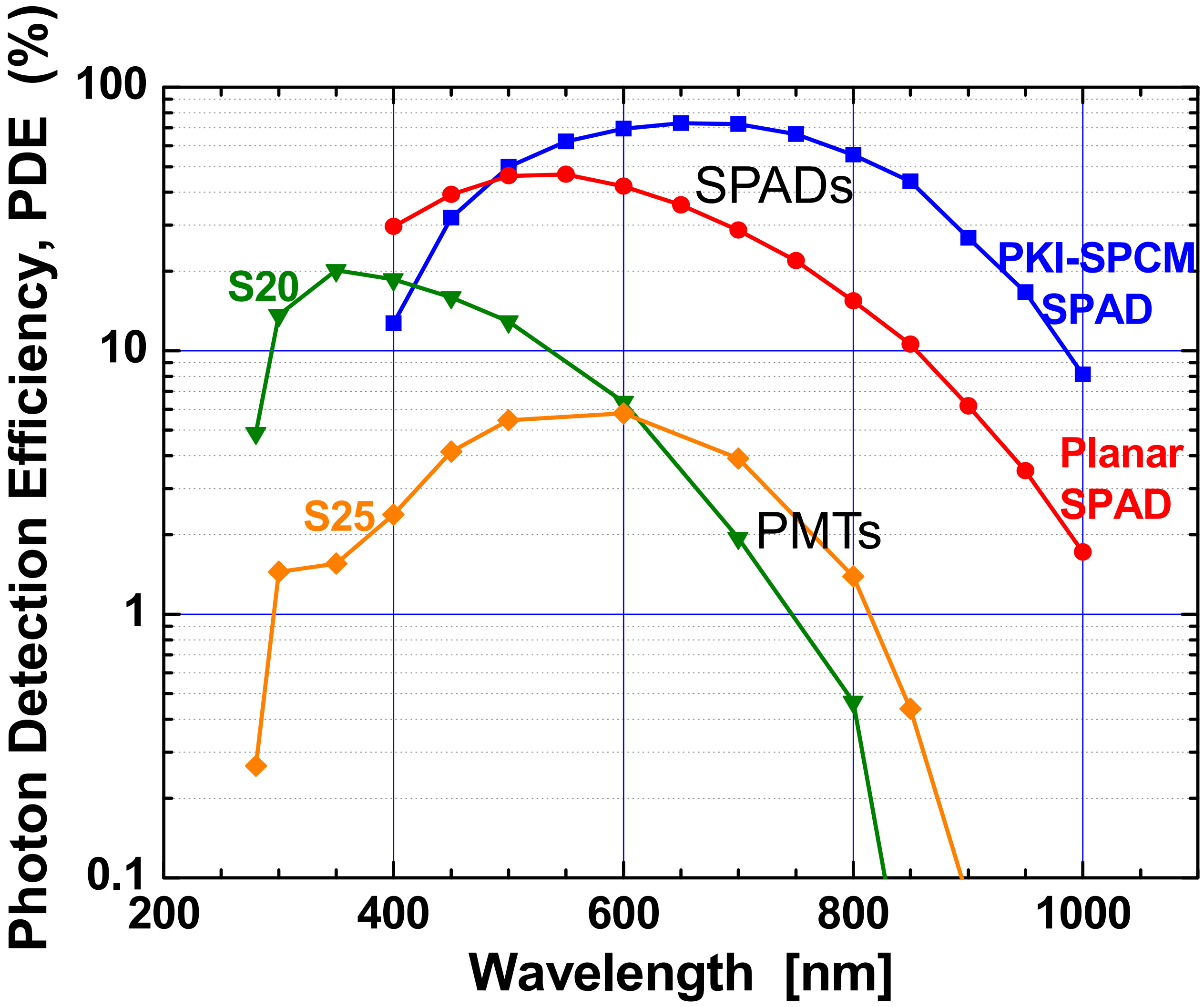
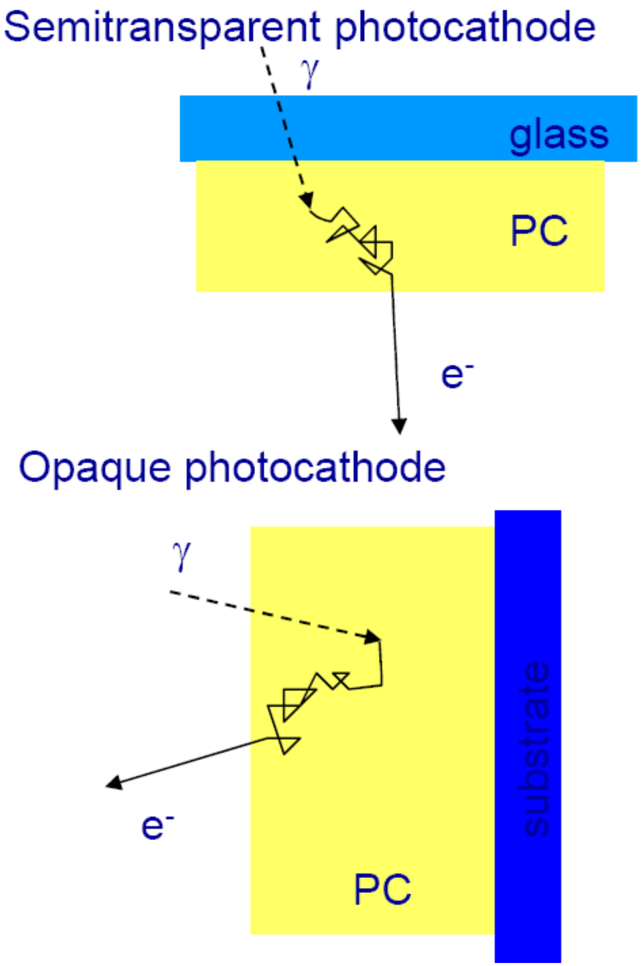
Silicon vs PMT: Photon Detection Efficiency



Emission in vacuum from PMT photocathode



3-step process

1. free electron generation
2. electron propagation through cathode
3. **escape of electron into the vacuum**

CONCLUSION

only a **THIN** layer at surface contributes by absorption to emission

(few 10nm << optical absorption length)

→ **intrinsic limitation to PDE**

Silicon vs PMT : Dark Count Rate (DCR)

- **PMT** - active **Ø 2.5 cm**
  cathode Dark Current < **1000 electron s^{-1} (at RT)**

  density **< 200 el / cm^2 s**

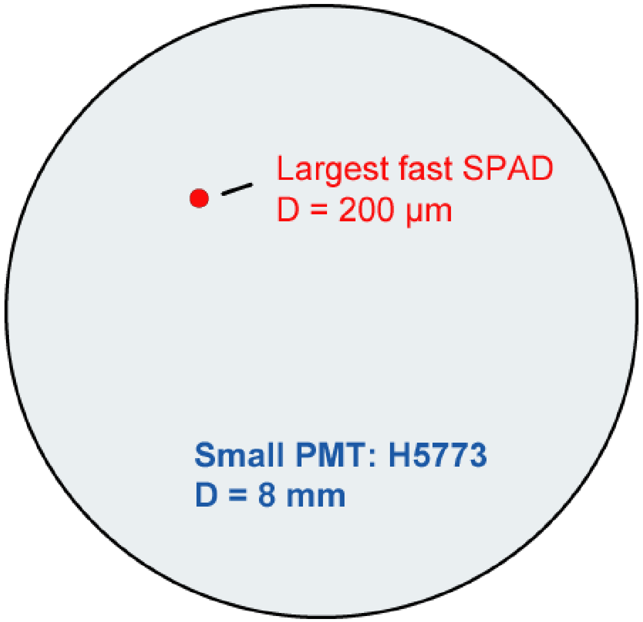
- **SPAD** Single-Photon Avalanche Diode - active **Ø 200 μm**
  primary Dark Current < **1000 electron s^{-1} (at RT)**

  density **< $4 \cdot 10^6$ el / cm^2 s**

DCR density of SPADs is **$2 \cdot 10^4$** higher than **PMT**

→ limitation to the **active area size**

Required active area



Small detector size is OK in applications were light can be focused

USERS CONSIDER THAT

→ ***detector diameter ~100 µm is OK for most applications***

AND

→ ***detector diameter ~ 50 µm is acceptable*** though it requires tighter focusing and alignment and in some cases may achieve lower coupling efficiency

Semiconductor detectors: when and why Photon-Counting types are advantageous vs analog detectors (CCDs, etc.) ?

- When the **measurement time is very short** (currently < 0.5 s).

  For instance: high frame-rate imaging, fluorescence correlation spectroscopy (FCS), fast optical pulses, etc.

- Because of the electronic **readout noise** of analog detectors.

  For short measurement time with CCDs the readout noise is dominant over the dark-current noise and sets the sensitivity limit

- In photon-counting detectors the readout noise simply **does not exist**

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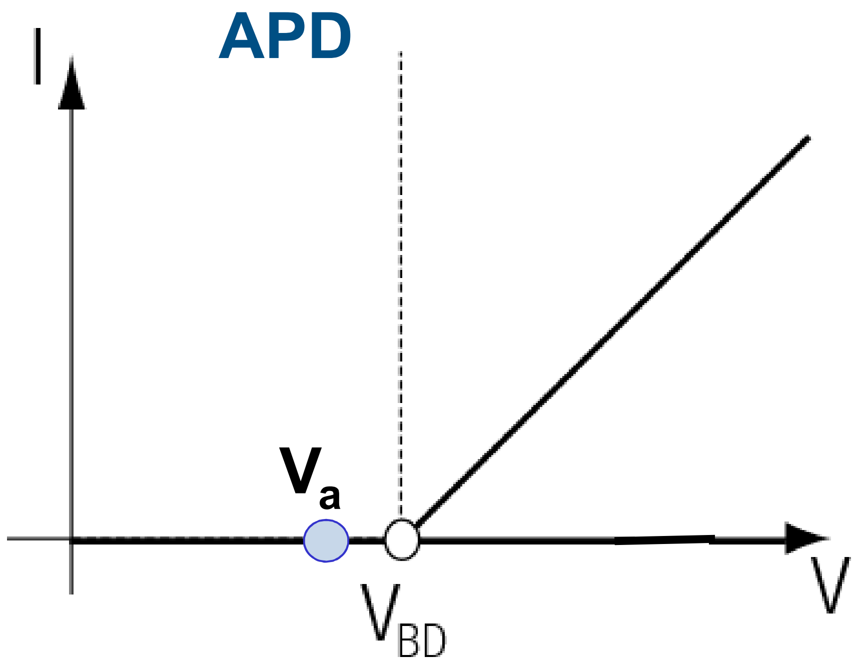
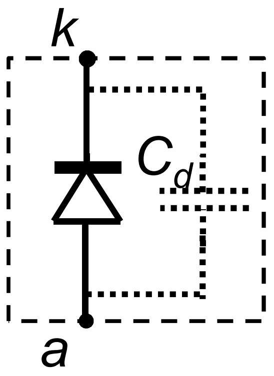
Avalanche Photo-Diode APD



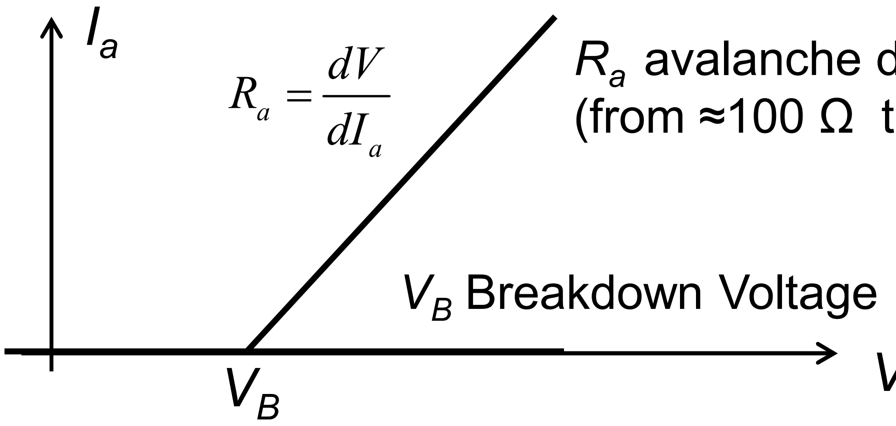
- Bias voltage **V_a** : slightly ***BELOW*** breakdown voltage **V_{BD}**
- Linear-mode avalanche diode = detector with “***AMPLIFIER inside***”
- Gain with ***low mean value*** < 1000 and ***high statistical fluctuations***

Avalanche Diode above Breakdown

AVALANCHE DIODE



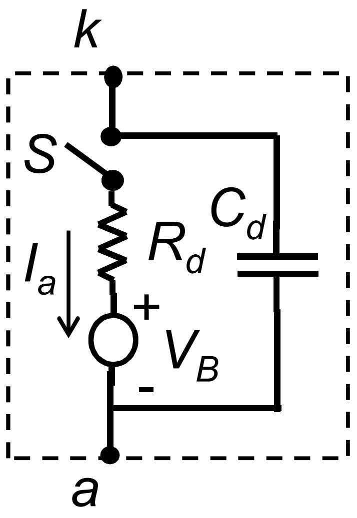
Reverse bias I-V characteristics



R_a avalanche diode resistance (from ≈100 Ω to some kΩ)

$V = V_k - V_a$

DIODE EQUIVALENT CIRCUIT



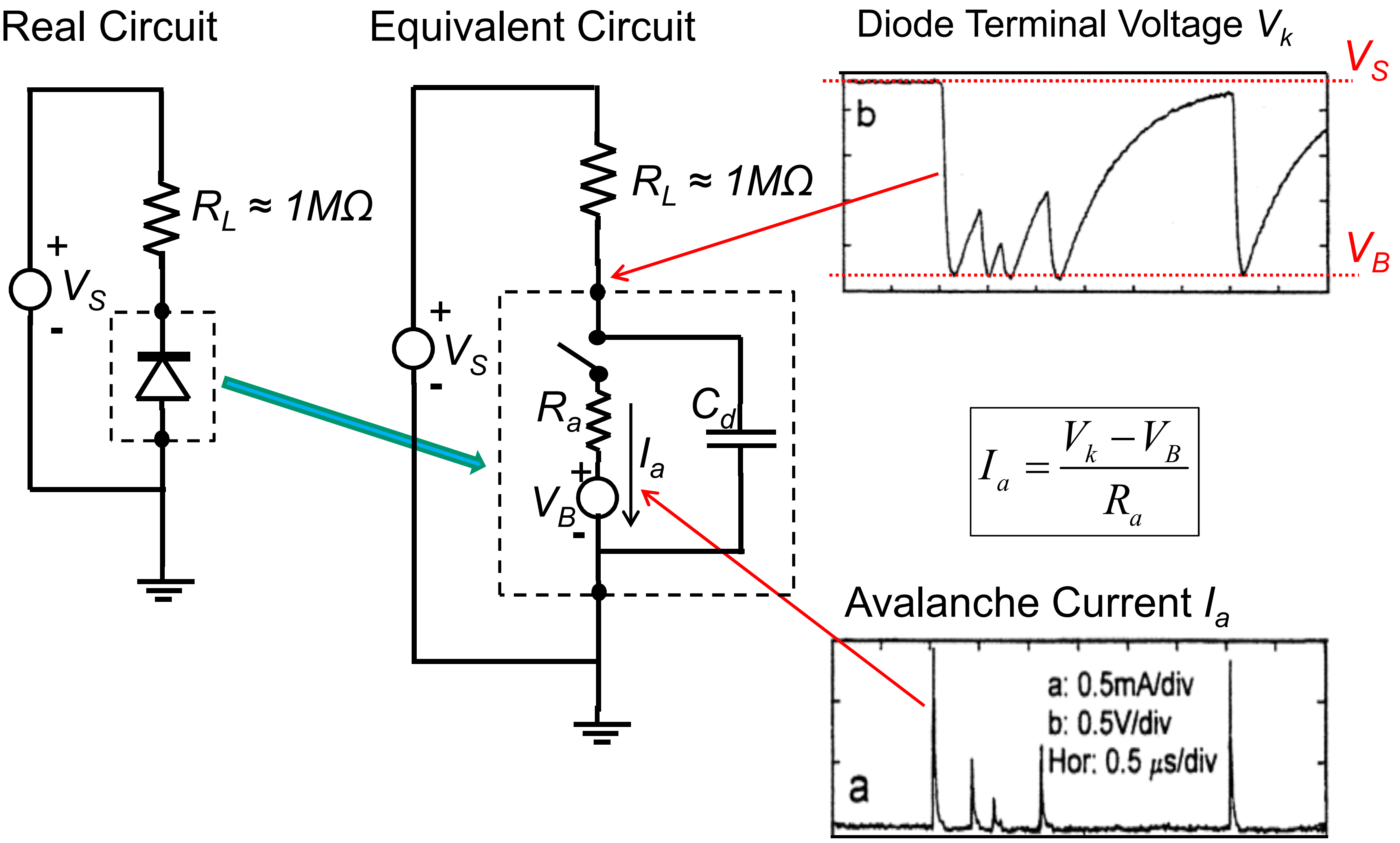
Switch S models the avalanche triggering:

- with V ≤V_B switch S is always open
- with V >V_B switch is closed by a photon detection

with S closed, avalanche current flows

$$\boxed{I_a = \frac{V_k - V_B}{R_a}}$$

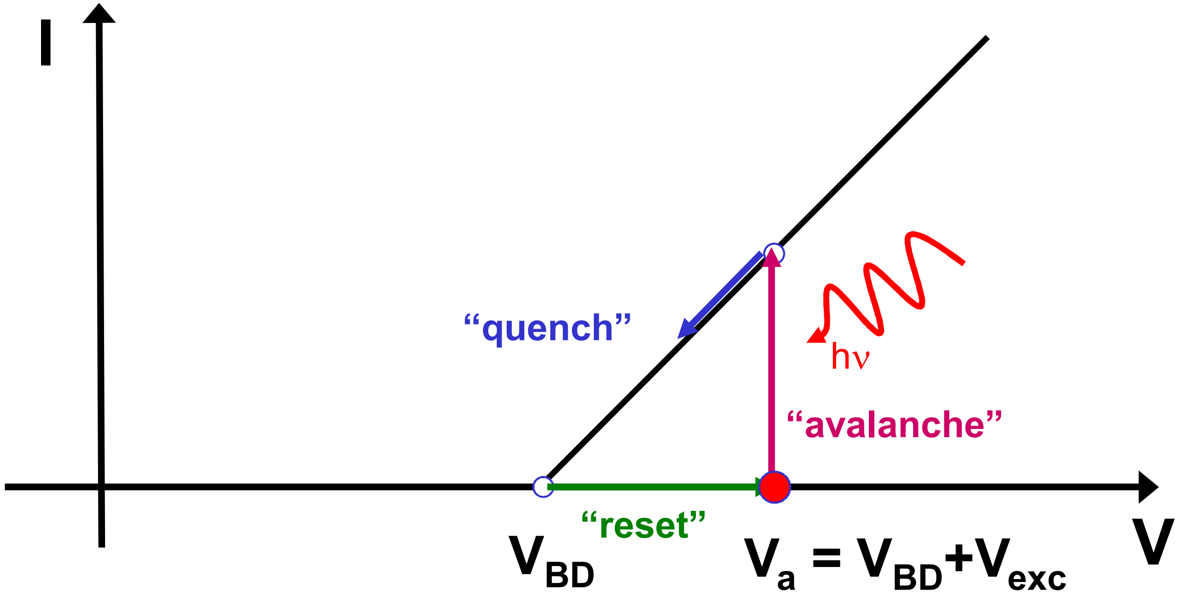
Passive Quenching Circuit



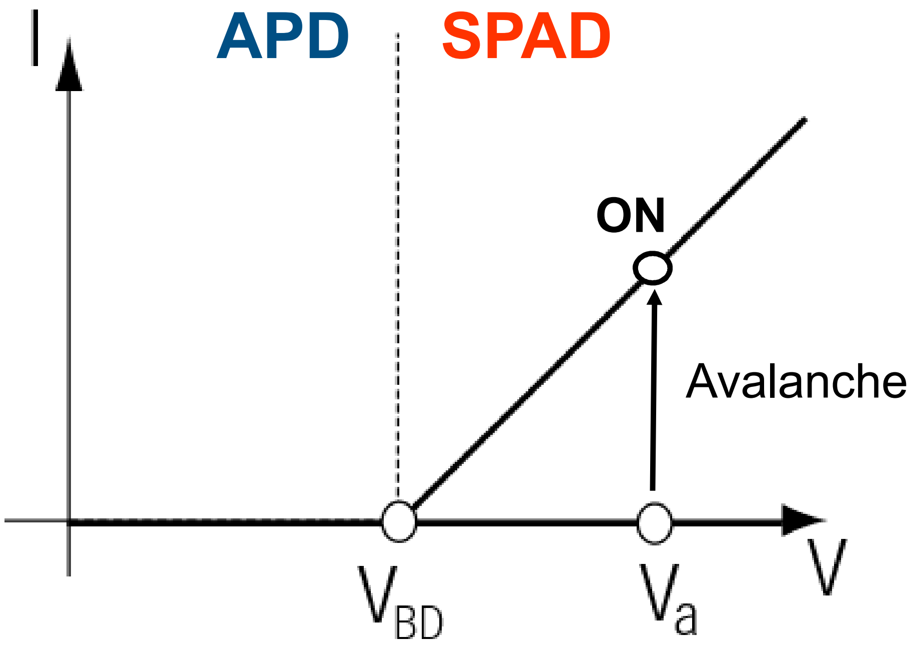
$$I_a = \frac{V_k - V_B}{R_a}$$

Geiger mode operation

- Bias voltage $\mathbf{V_a}$: ***ABOVE*** breakdown $\mathbf{V_{BD}}$ (with excess bias $\mathbf{V_{exc}}$)
  no current in quiescent state
- Single photon switches on avalanche → macroscopic current
- Triggered-mode avalanche: detector with "***BISTABLE inside***"
- Avalanche quenched by pulling V bias < $\mathbf{V_{BD}}$
- V bias reset to $\mathbf{V_a}$



SPADs are different from APDs



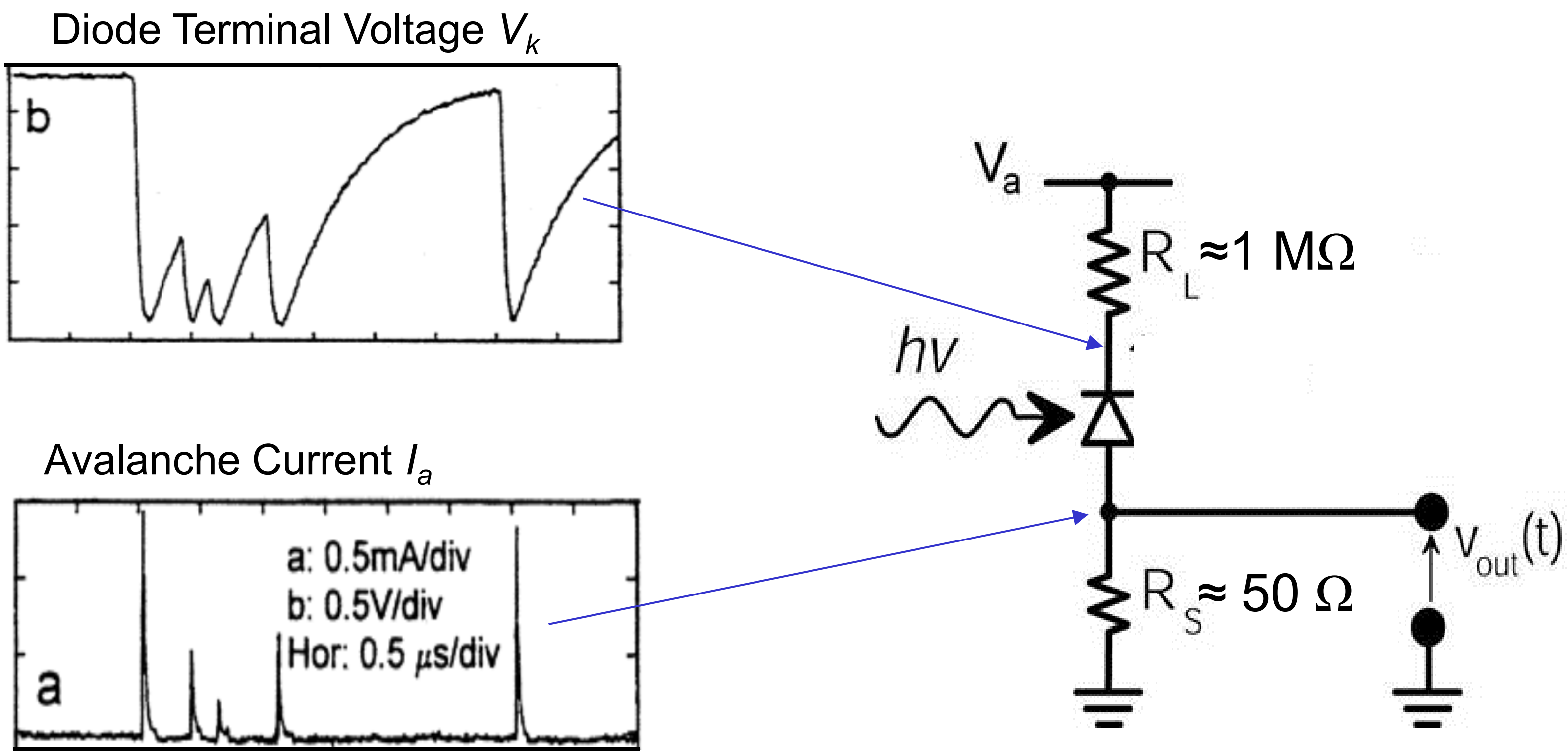
Avalanche **P**hoto**D**iode

- Bias: slightly ***BELOW*** breakdown
- Linear-mode: it's an ***AMPLIFIER***
- ***Analogue*** output
- Gain: ***limited*** < 1000

Single-**P**hoton **A**valanche **D**iode

- Bias: well ***ABOVE*** breakdown
- Geiger-mode: it's a ***BISTABLE !!***
- ***Digital*** output
- Gain: ***meaningless !!***

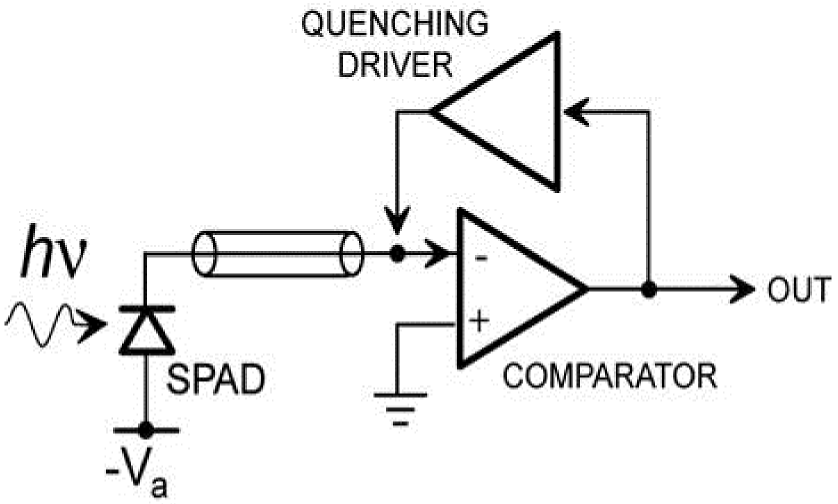
Passive quenching is simple...

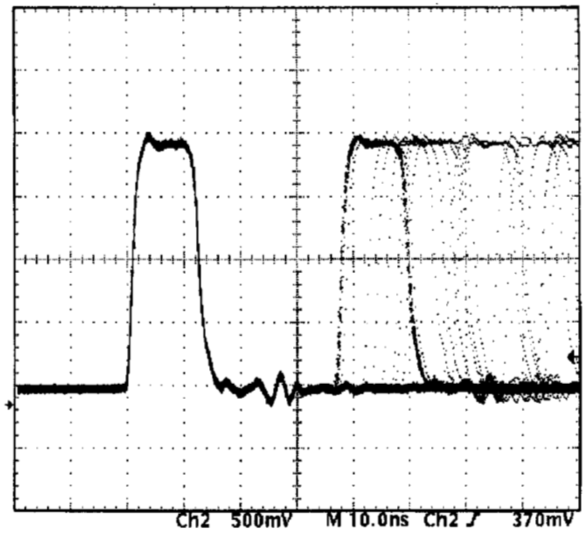


… but suffers from

- ➢ long, not well defined deadtime
- ➢ low max counting rate < 100kc/s
- ➢ photon timing spread
- ➢ et al

Active Quenching





Output Pulses

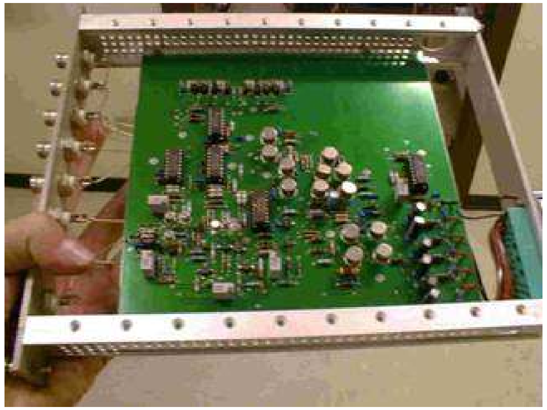
by providing

- short, well-defined deadtime
- high counting rate > 1 Mc/s
- good photon timing
- standard output

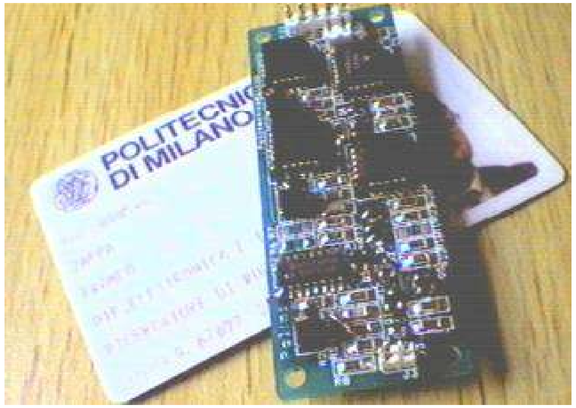
opened the way to SPAD applications

Active Quenching Evolution

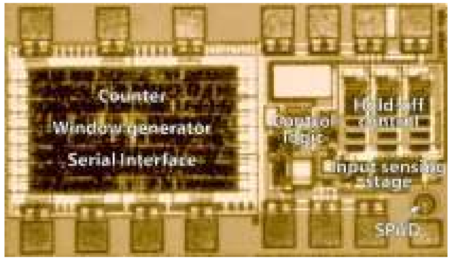
Earlier modules
in the 80's



Compact modules
in the 90's



Integrated AQC
in early 2000's



Today
Monolithic chips for
Single Photon
Counting and Timing

Technical Readiness

Results of decades of research made widely available by

Micro-Photon-Devices

a spin-off company of Politecnico di Milano

www.micro-photon-devices.com

Via Stradivari 4, Bolzano, 39100 Italy

Established in 2004 - Profitable since year 2006

96% of the production is exported to US, Europe and Asia

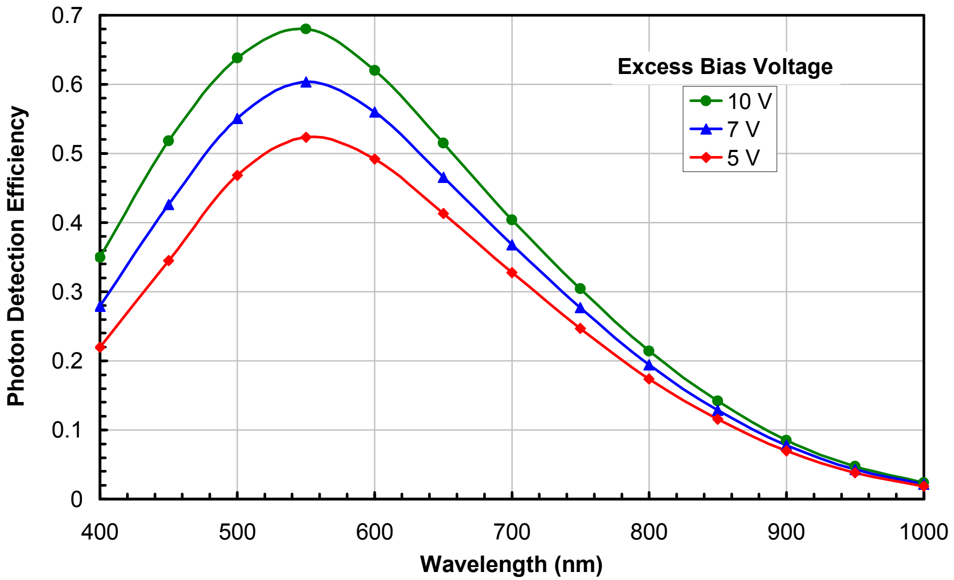
Photon Detection Efficiency (PDE)

Probability of

Carrier Photogeneration

AND

Avalanche Triggering !!

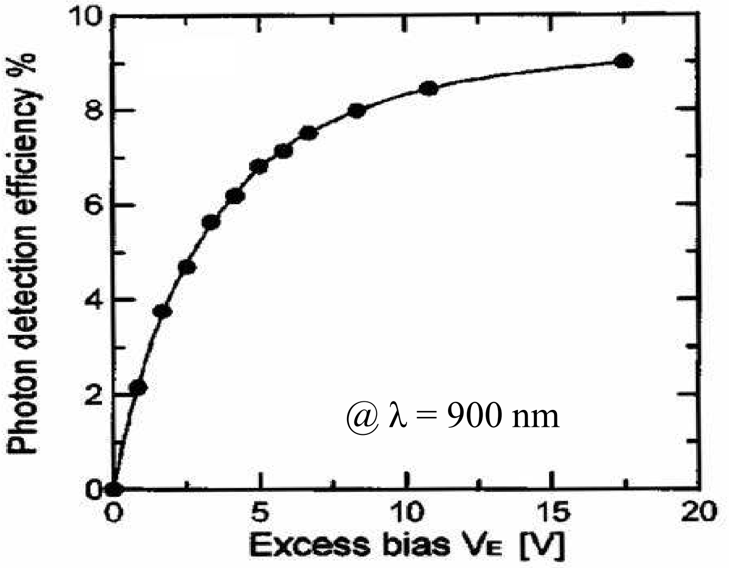


hence

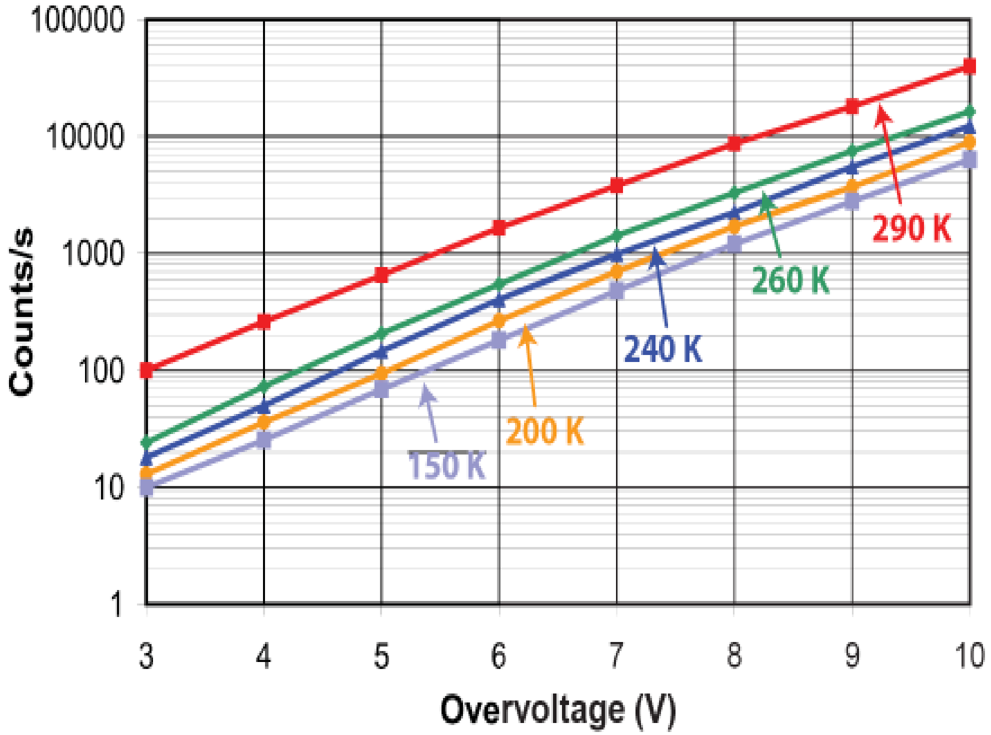
higher excess voltage V_{exc} above V_{BD}

→ higher electric field

→ higher PDE



Dark Count Rate (DCR)



higher excess voltage **V**$_{exc}$ above **V**$_{BD}$

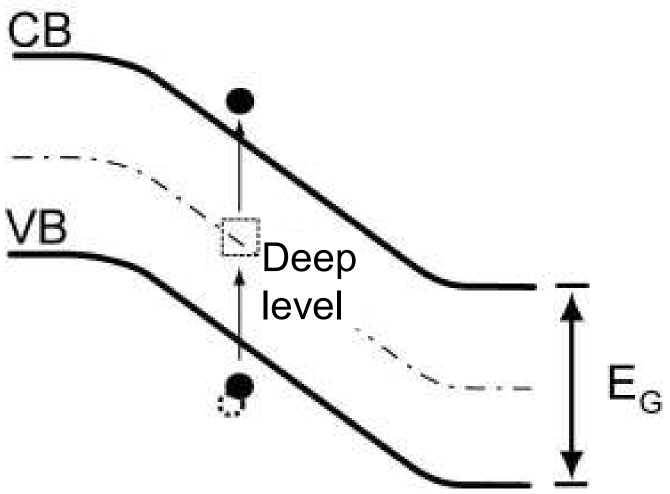
→ higher electric field

→ higher dark count

DCR rise is steeper than PDE

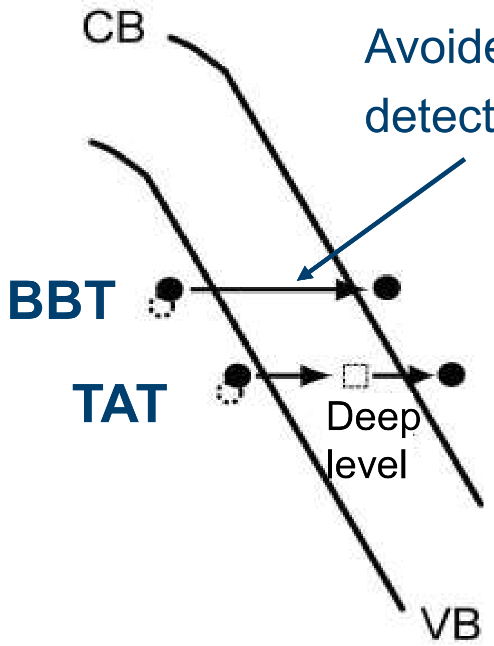
Dark Count Rate

- Thermal generation and tunneling of carriers in the depletion region



Thermal generation via deep levels
(@ low field F < 10^5 V/cm)

Avoided by suitable detector design !

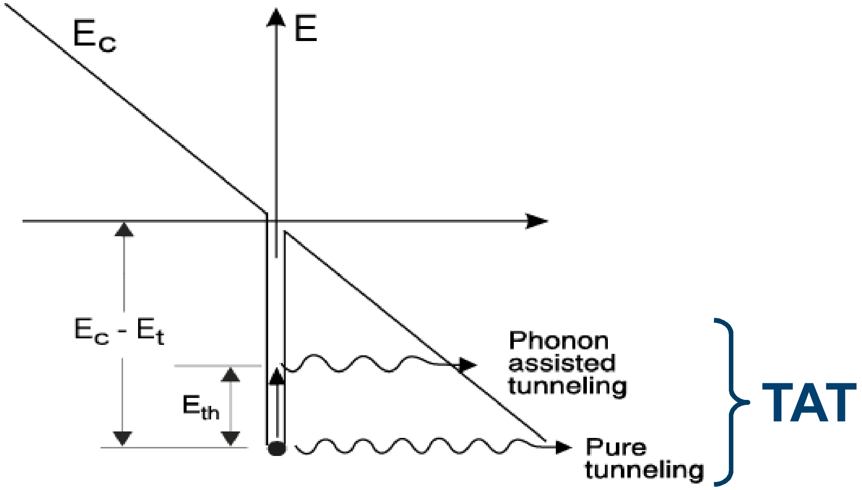


Field-enhanced generation

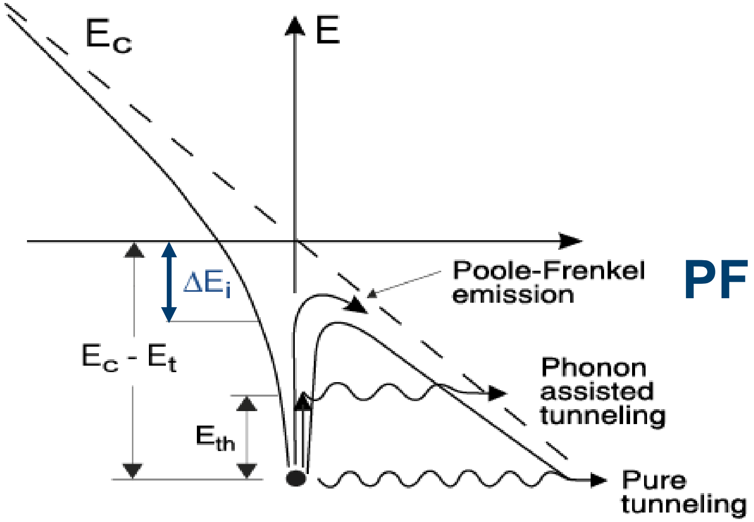
- ➢ Deep levels (traps) mainly due to transition metal impurities
- ➢ Fe, Cu, Ti or Ni are usually found in silicon in concentrations of **~10^{11} - 10^{12}cm^{-3}** (unintentional contaminants)

Field-enhanced generation

Dirac well



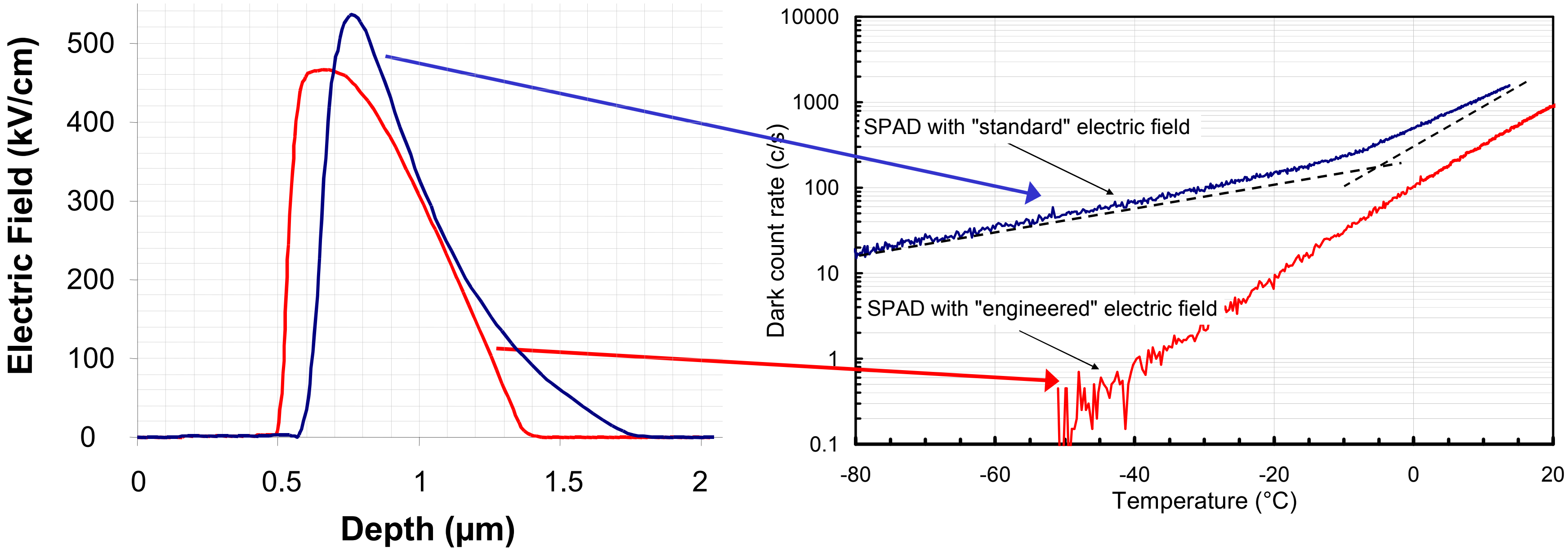
Coulombic well



- Phonon-assisted tunneling
  - barrier width decreased

- Poole-frenkel effect
  - barrier height lowered

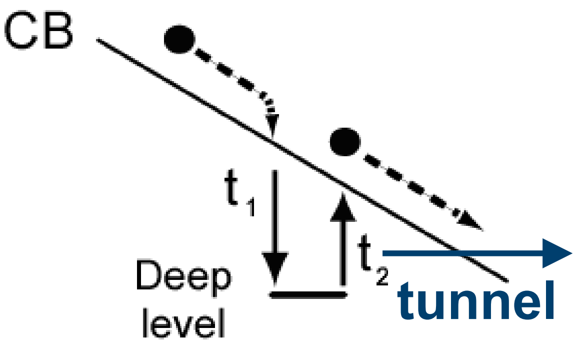
Electric field engineering

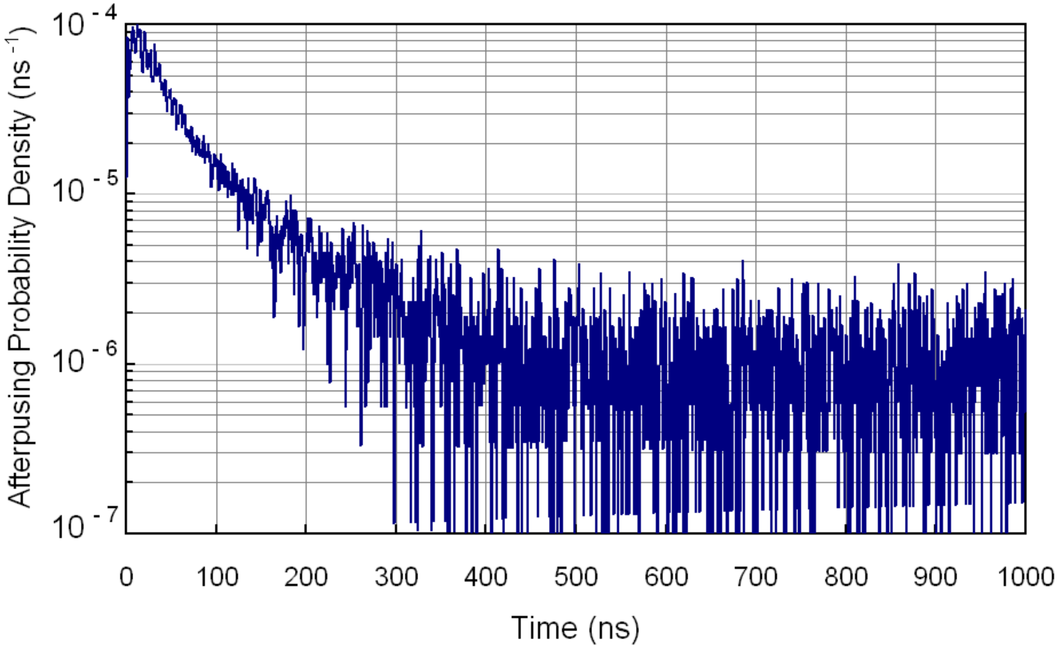


Electric field engineered to avoid band-to band tunneling

- Field-enhanced generation less intense
- DCR strongly reduces with temperature

Afterpulsing





Afterpulsing Effect

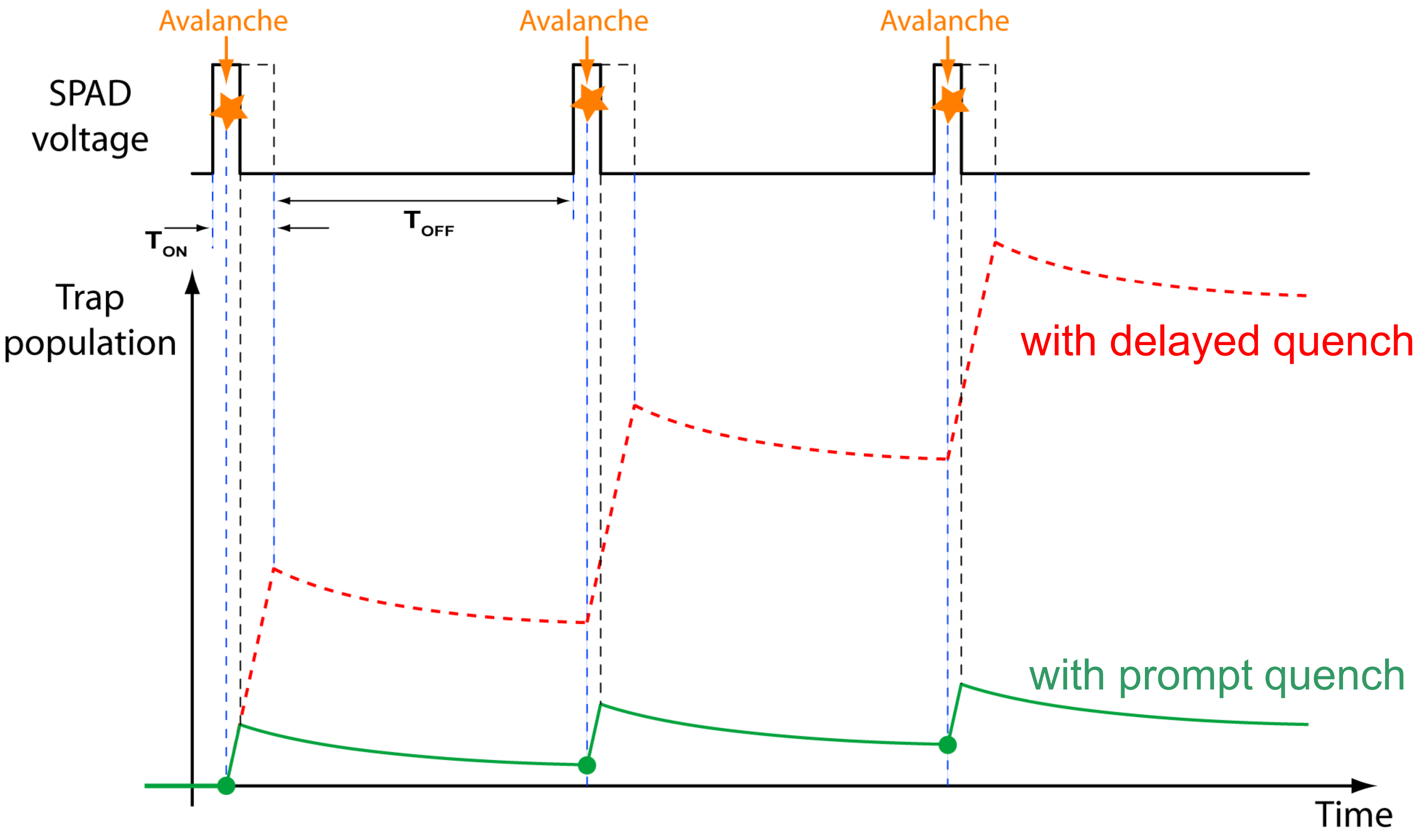
- Carriers trapped during avalanche
- Carriers released later trigger the avalanche

Characterization of afterpulsing

- 100 μm detector
- 80ns deadtime
- Time Correlated Carrier Counting (TCCC) method
- Afterpulsing negligible after 1 μs
- **Total afterpulsing probability:**

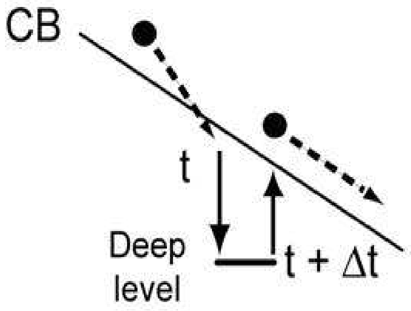
< 1% @ RT

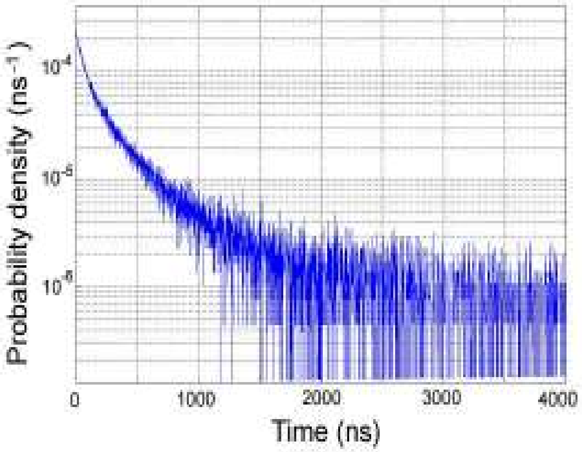
Afterpulsing effect build-up

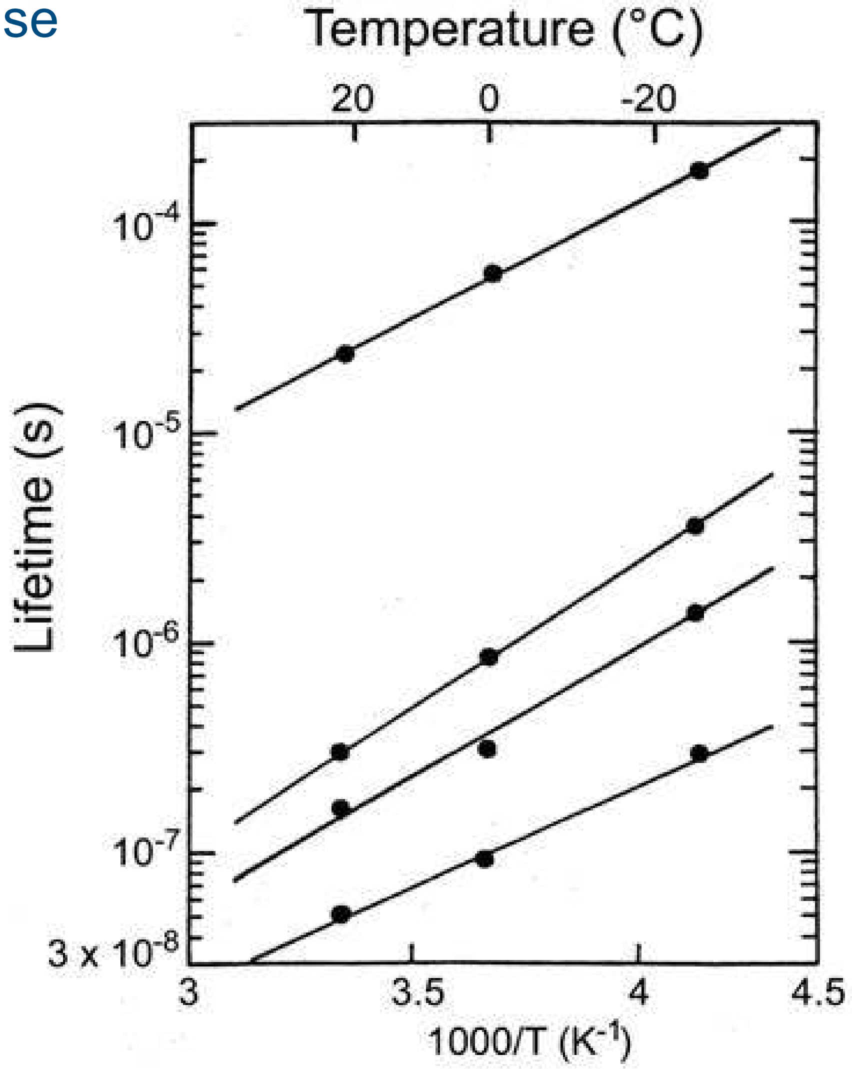


Effect of temperature on the afterpulsing

Carrier Trapping and Delayed Release







Challenges in SPAD development

Microelectronic Technology

- **Strict control** of transition metal contamination
  - ultra-clean fabrication process (defect concentration **< 10^9 cm^{-3}**)
  - suitable gettering processes **compatible** with device structure

Device design

- **Electric field engineering**

  avoids BB tunneling and reduces field-enhanced generation, with impact on:
  - → dark count rate
  - → dark count decrease with temperature
  - → photon detection efficiency
  - → photon timing jitter

Timing electronics

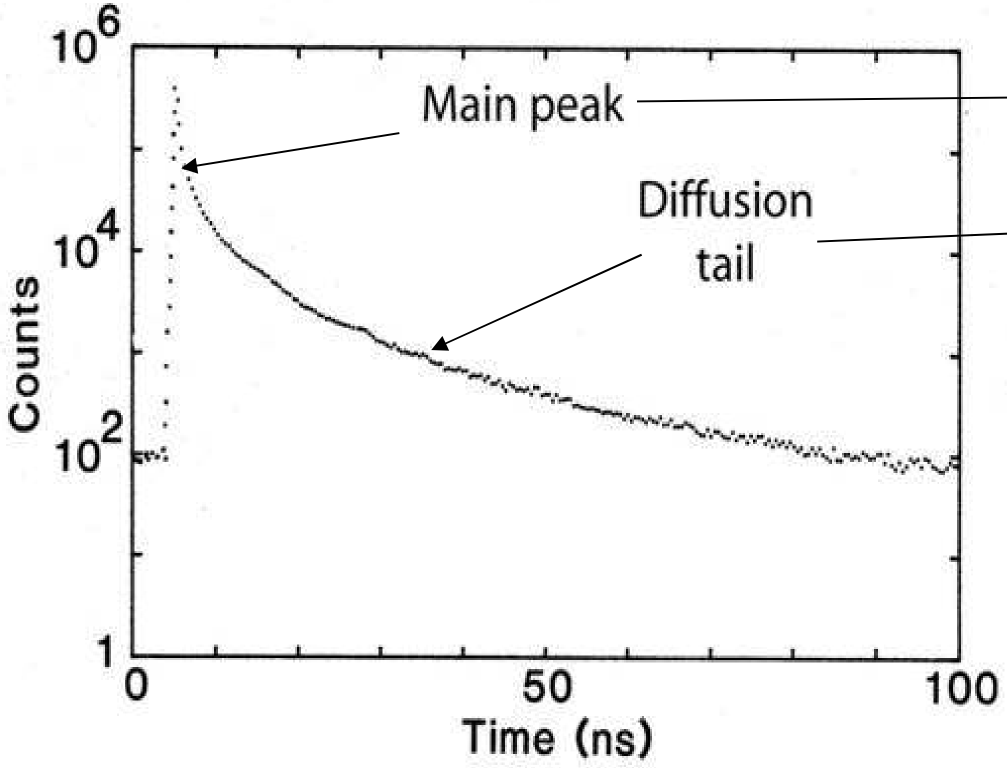
- **Low-level sensing of the avalanche current →** avoids or reduces trade-off

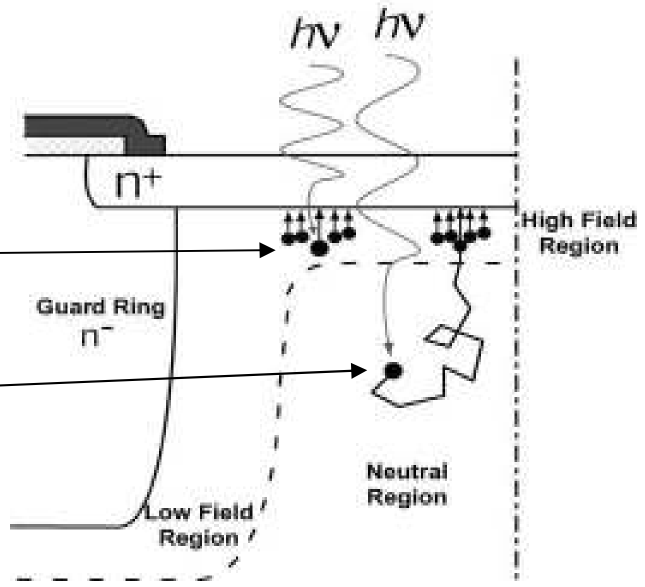
  between timing jitter and active area diameter

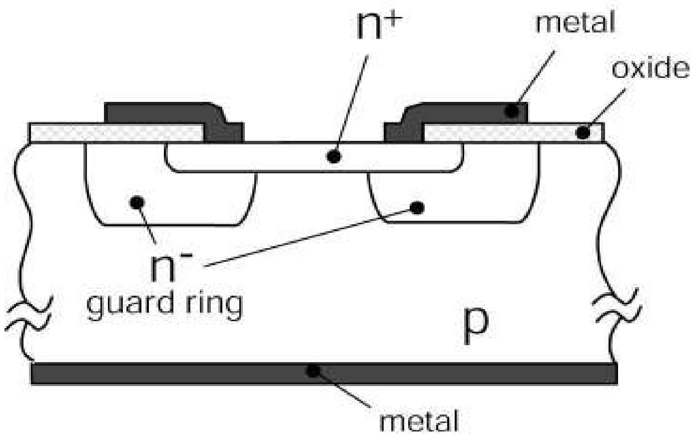
Milestones in SPAD development at Polimi

1975	Invention of the Active Quenching Circuit (AQC)
1980-82	Picosecond photon timing with planar SPADs
1987	Epitaxial silicon SPADs for improved timing
1992-95	Single-photon technique extension to IR range with Germanium and InGaAs/InP devices
1995	First monolithic integrated AQC
1990-96	Gaining insight in the physical processes that control the SPAD performance
2004	Wide area SPADs (diameter up to 200 µm) with excellent timing performance
2005	SPAD array detectors in monolithic chip
2008	Resonant-Cavity-Enhanced SPADs

Photon Timing jitter: diffusion tail

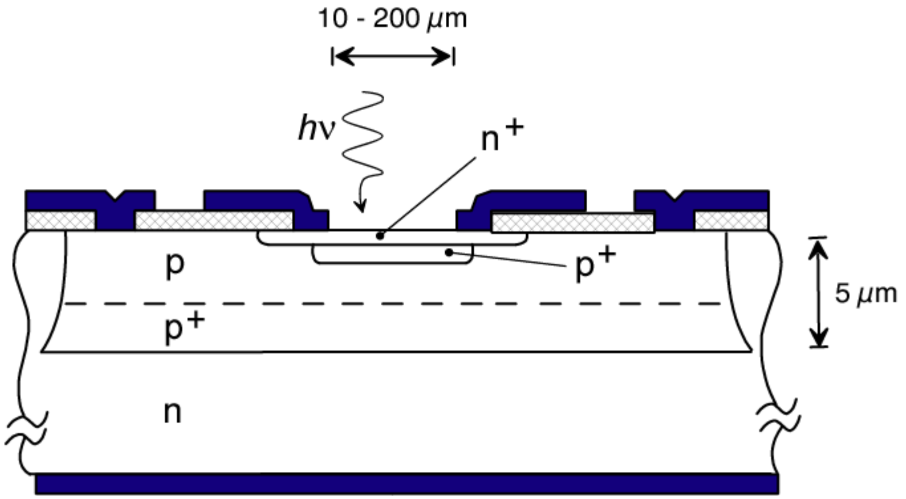


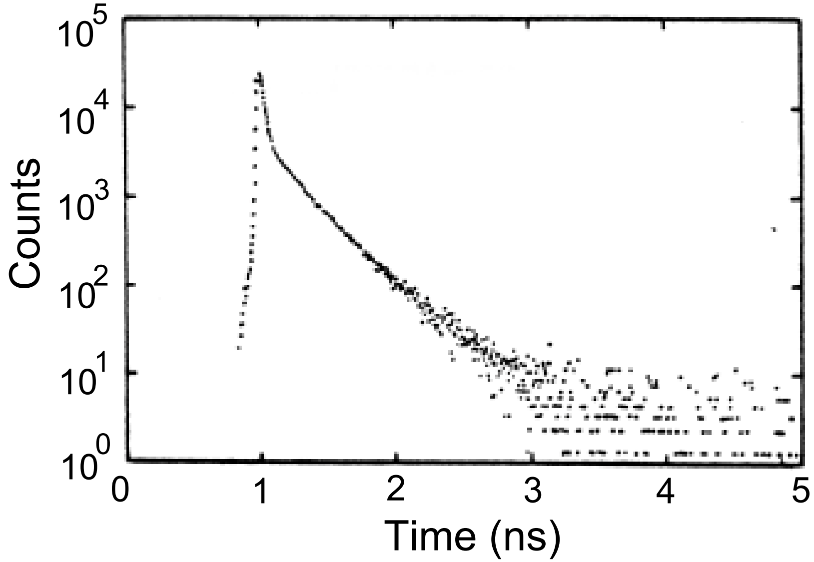




simple planar SPAD structure
with deep diffused guard ring
on bulk p-substrate (no epitaxy)

p-p$^+$-n Double-Epitaxial SPAD structure





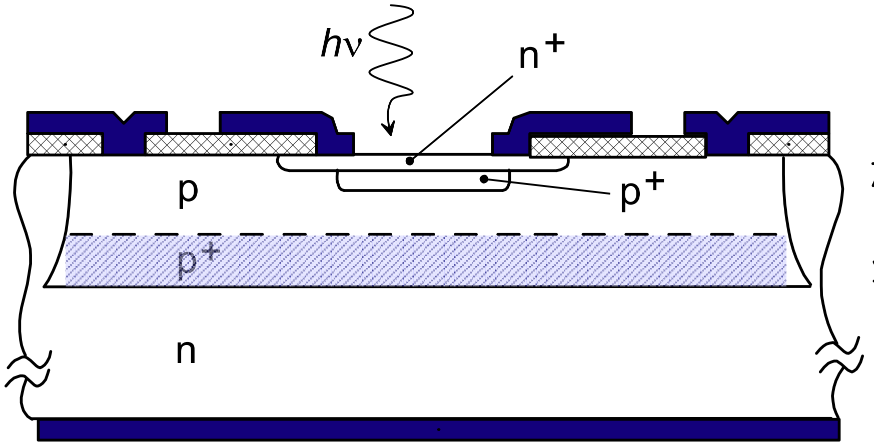
- Short diffusion tail with clean exponential shape
- Active area defined by p+ implantation
- No guard-ring (uniform QE)
- Adjustable V_{BD} and E-field
- **SUITABLE** for array fabrication

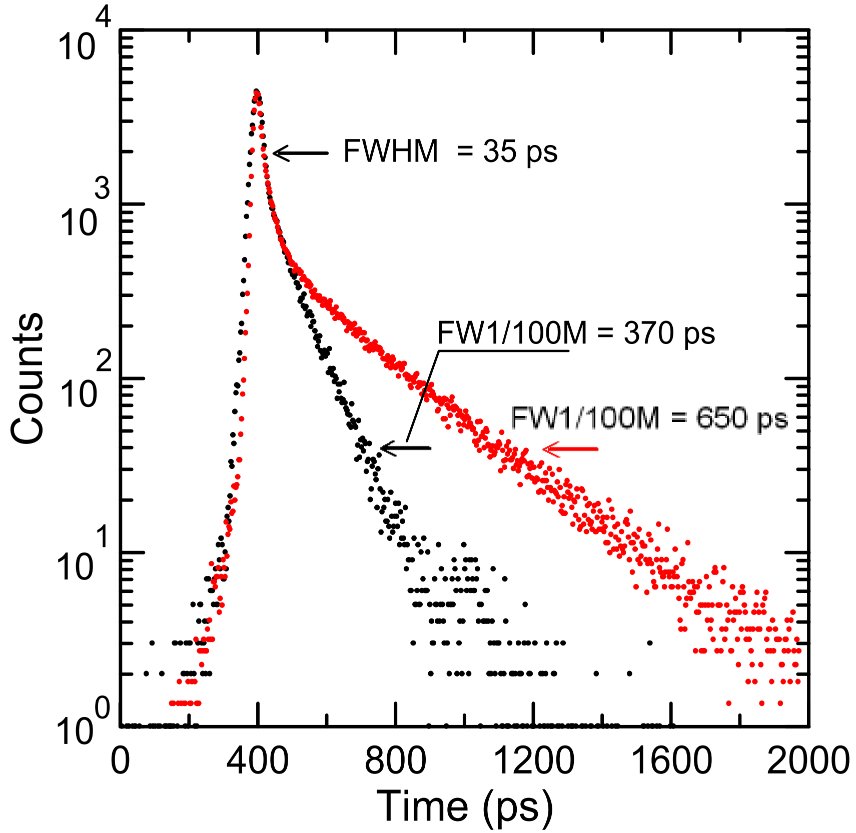
neutral p layer thickness w

tail lifetime $\tau = w^2 / \pi^2 D_n$

A.Lacaita, M.Ghioni, S.Cova, Electron.Lett. 25, 841 (1989)

Custom SPAD technology





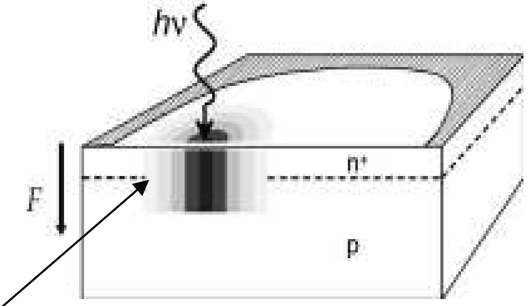
→ Bottom epi-layer thickess can be adjusted for achieving shorter diffusion tail

Photon-timing jitter: main peak width

is set by **fluctuations** in:

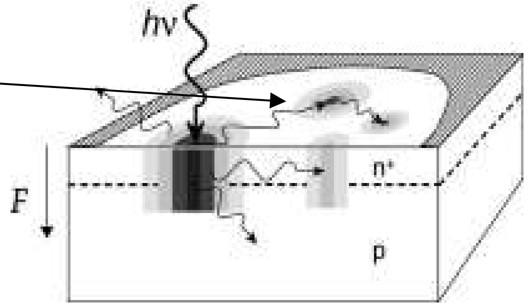
Avalanche local build-up

strongly dependent on field intensity F



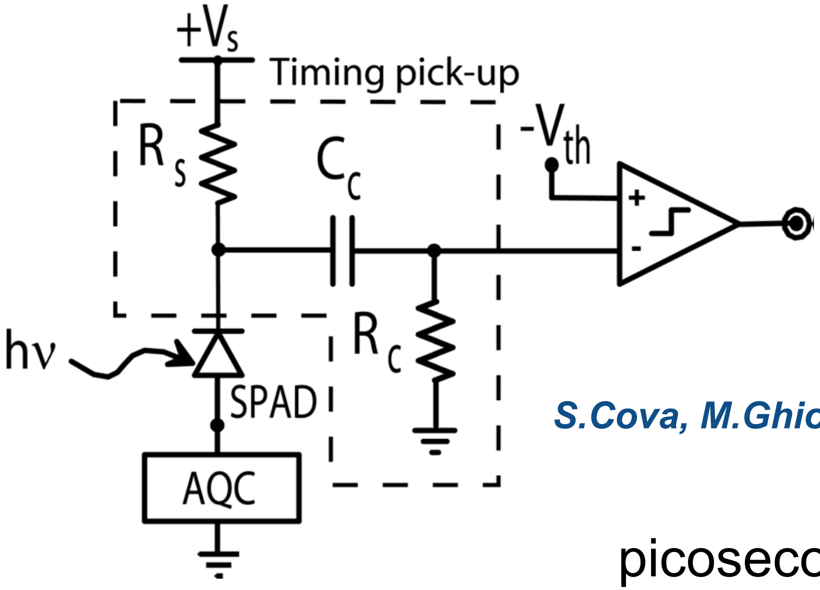
Avalanche transverse propagation

- by multiplication-assisted diffusion
- by photon-assisted propagation

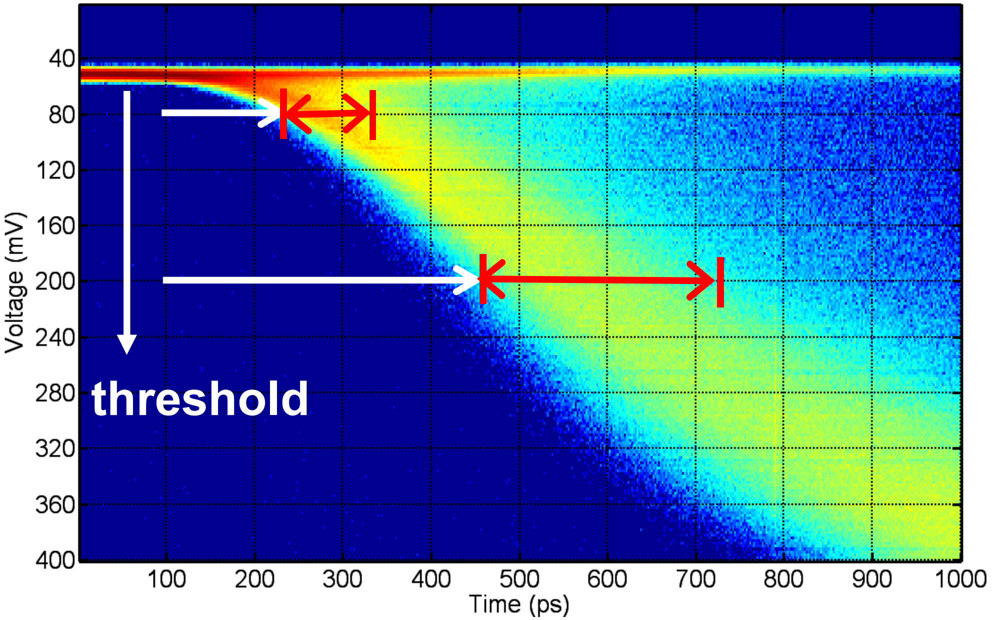


Large area SPADs: timing jitter

current pick-up circuit
sensing the avalanche current
at very low level (< 100 μA)



Avalanche current leading edge

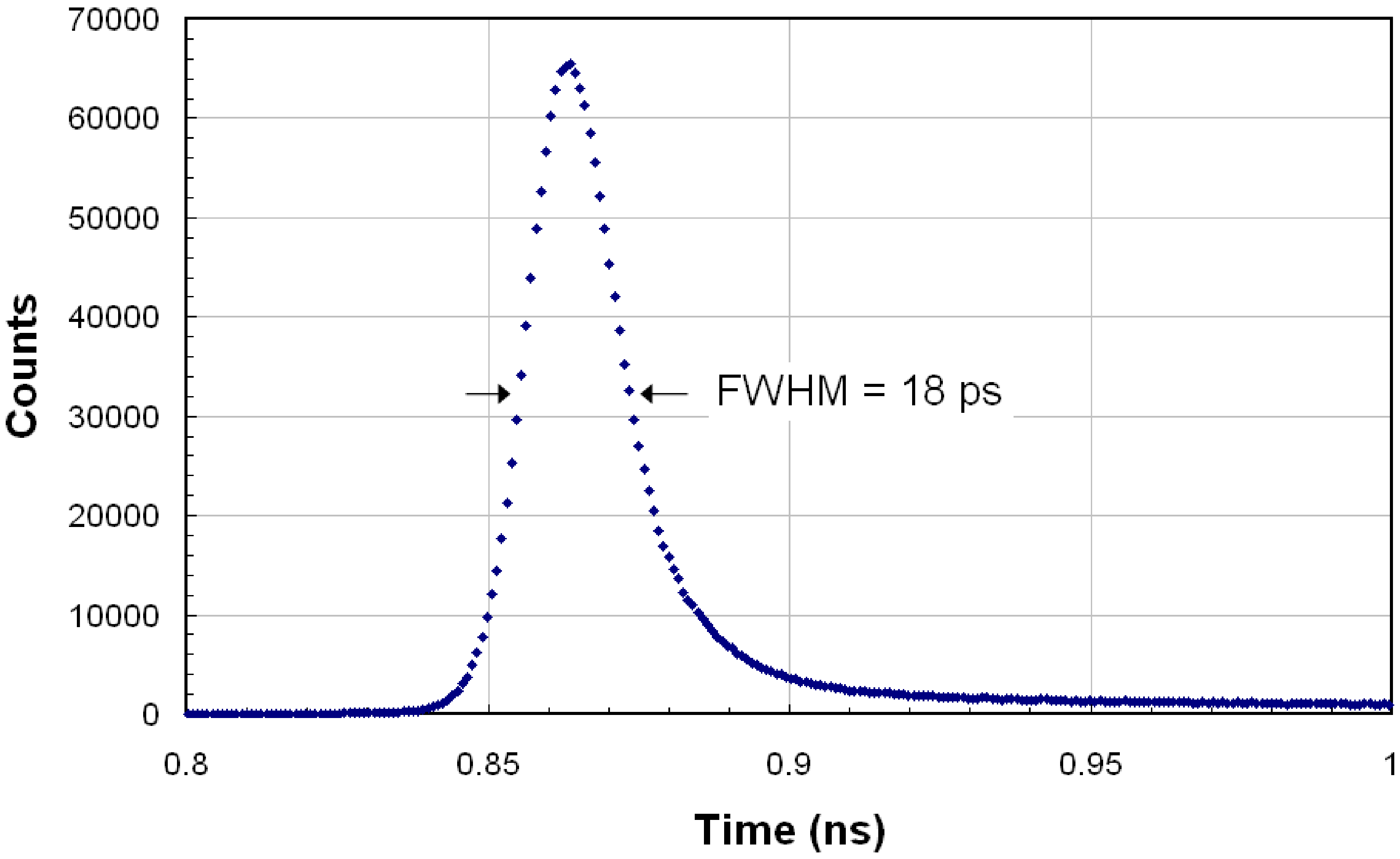


S.Cova, M.Ghioni, F.Zappa, US Pat. N. 6,384,663 B2, 2002

picosecond timing jitter is achieved
also with wide detectors

35ps FWHM checked for **200 μm device** at room temperature

Planar SPADs with high F: timing jitter



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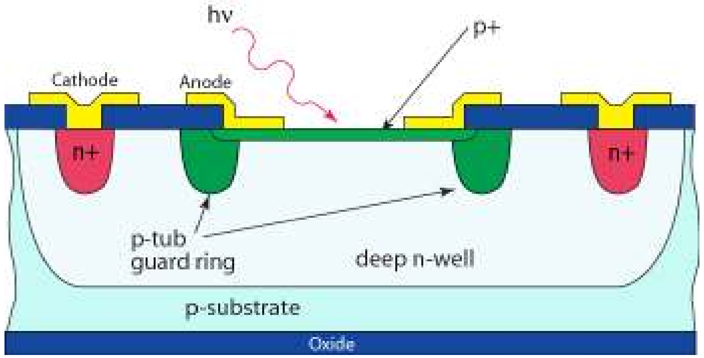
Timing electronics

- **Low-level sensing of the avalanche current →** avoids or reduces trade-off

  between timing jitter and active area diameter

Standard CMOS technology and SPADs

good SPADs can nowadays be produced by industrial High-Voltage CMOS technologies



some limitations are met

- p$^+$n junction → hole-initiated avalanche → lower PDE
- Guard ring necessary
- no flexibility, device designers cannot modify the process
- technology evolution driven by circuit requirements (not by detectors!)

but it becomes possible to integrate SPADs with circuit systems !!

SPAD arrays

Two approaches in applications

- **Dense** arrays: **high** pixel number and/or **smart** pixels for
  - High frame-rate, low-level imaging
  - 3D imaging

- **High performance** arrays: **low** pixel number (< 100) and **hi-Q** pixels for
  - **Photon Counting in**
    - Adaptive Optics in astronomy
    - Parallel Fluorescence Correlation Spectroscopy
    - Multiphoton Multifocal Microscopy
    - Chemiluminescent assay analysis
  - **Photon Timing in**
    - Spectrally-resolved Fluorescence Lifetime Imaging (SFLIM)

Basic requests → ***- increase throughput***

- miniaturization and lower system-cost

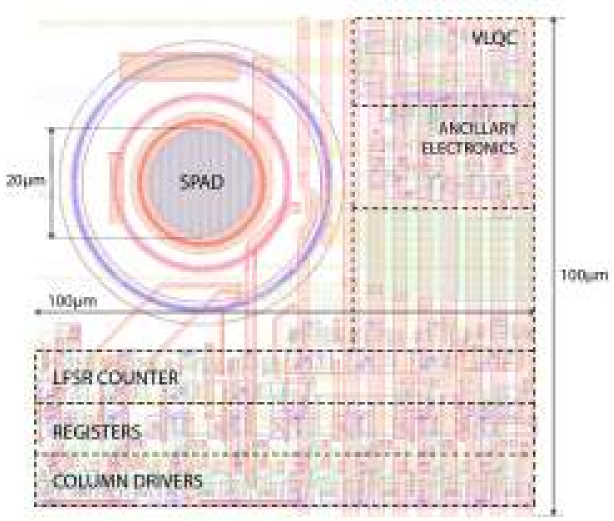
SPAD arrays

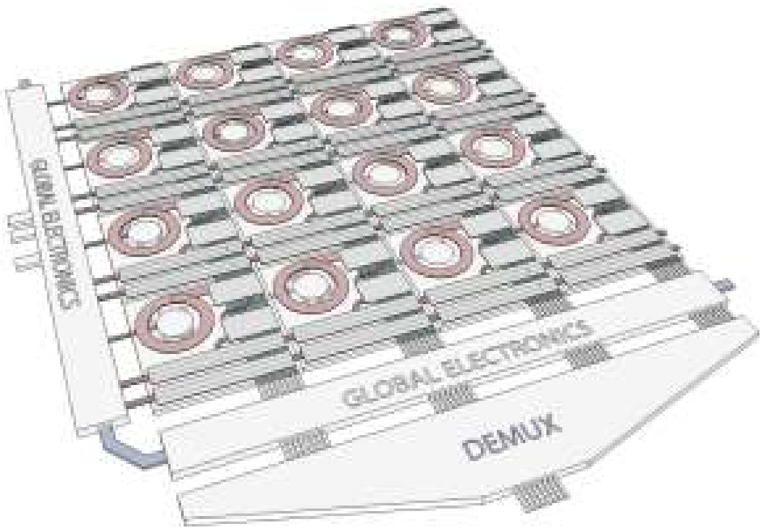
Two approaches in detector technology

- **Dense** arrays → **standard CMOS** technology
  - small pixel diameter (< 50µm, due to higher dark count rate)
  - large number of pixels
  - **smart pixels** (with in-pixel electronics !!)

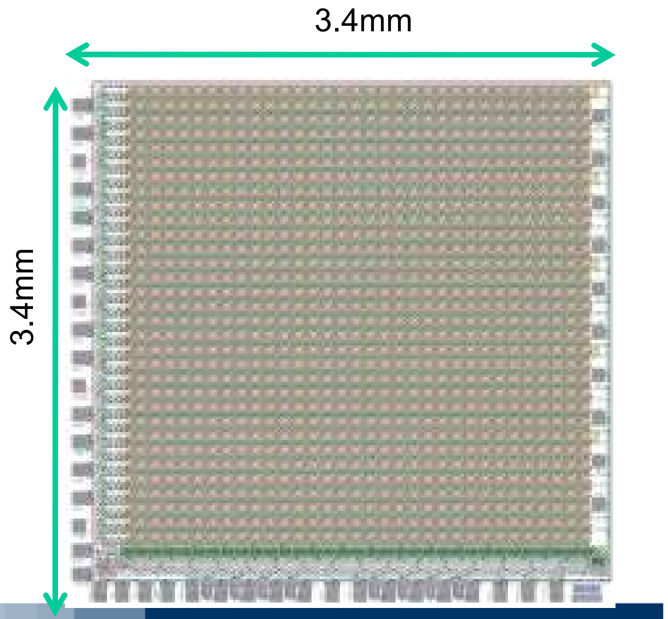
- **High-Quality-pixel** arrays → **Custom** technology
  - large diameter of pixel (> 100µm)
  - low or moderate number of pixels (< 100 pixel)
  - limitations due to off-chip electronics

SPAD Arrays in HV-CMOS technology



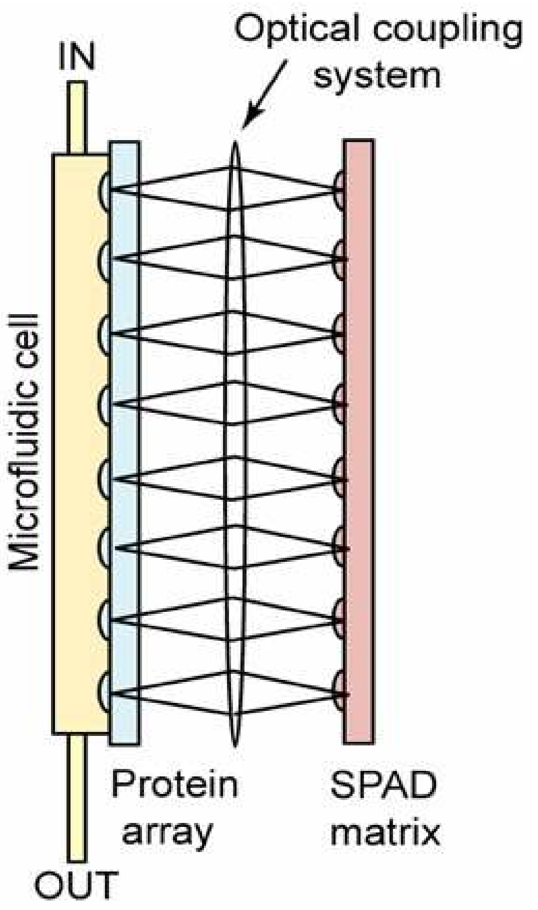


- Smart-pixel
  - ✓SPAD + AQC + counting electronics + register
- Fully parallel operation
  - ✓1024 pixel Single-Photon Imager
    - High frame rate single photon imaging
  - ✓can also act as a “Single pixel” large area detector
    - Low dead time, high count rate and photon number resolution
- Up to 100kframe/s for a 32x32 array
- No dead time between frames

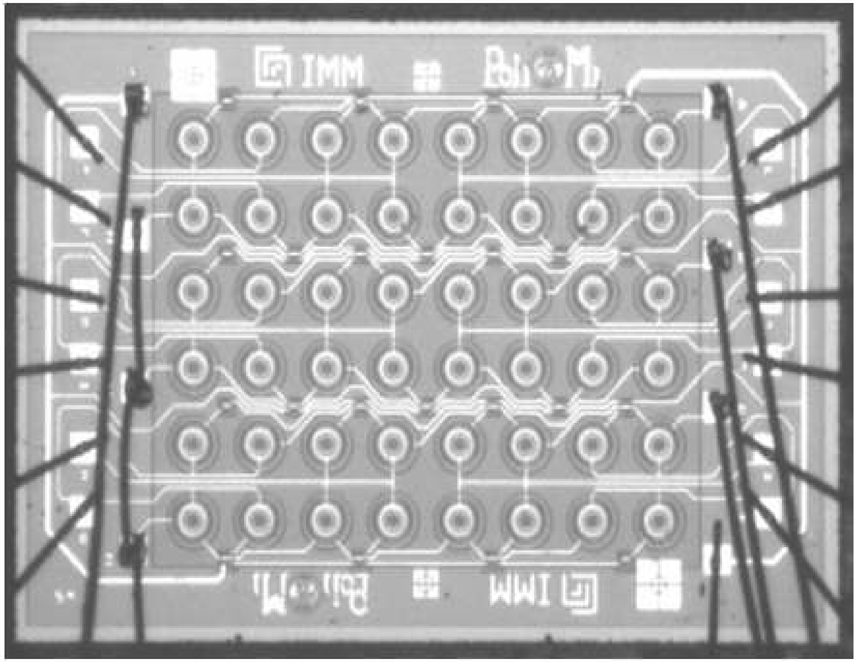


SPAD arrays in custom technology

Matrix detector for analysis of protein microarray (allergy diagnostics)

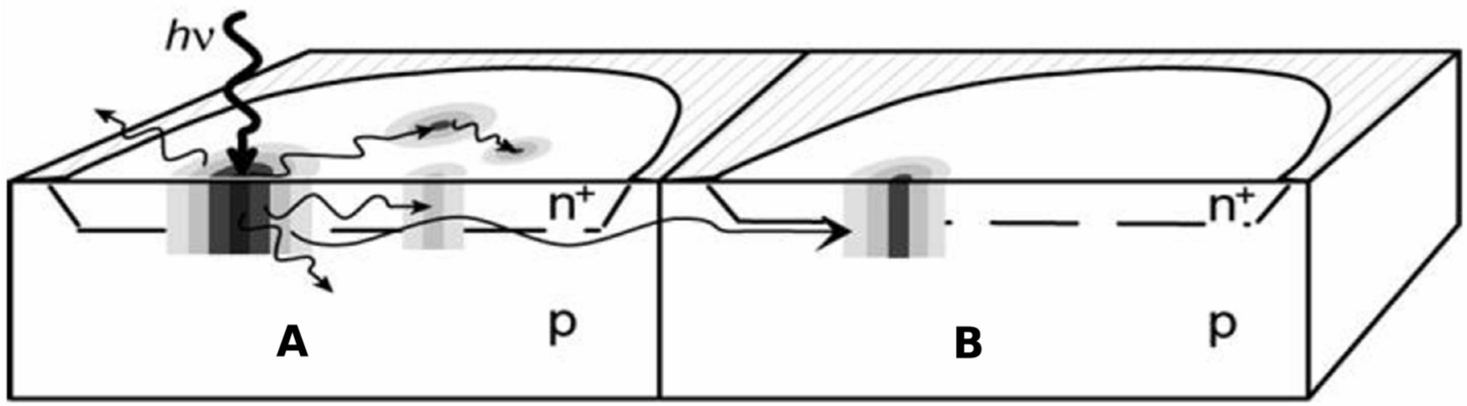


50 µm pixel diameter



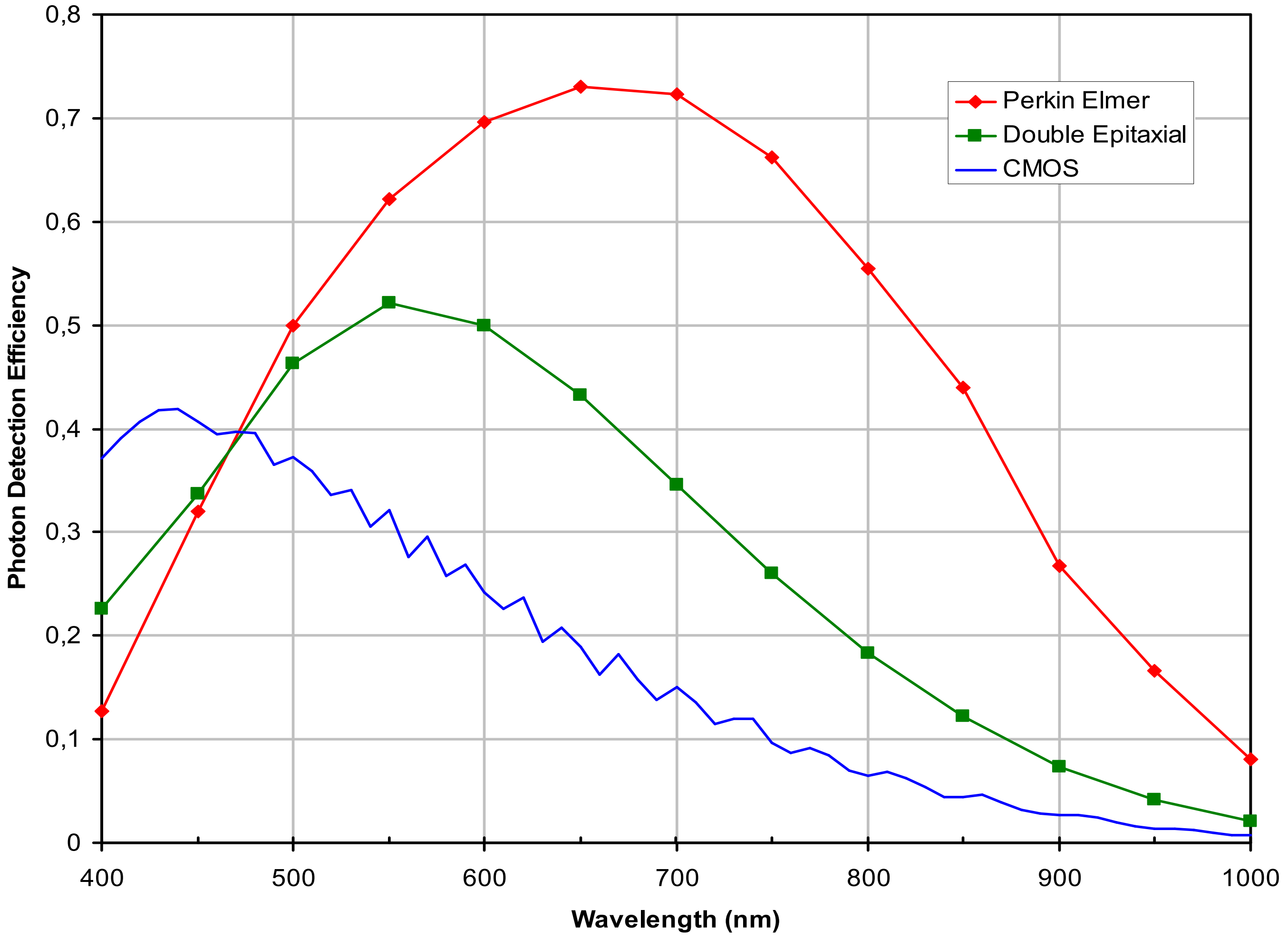
6x8 pixels, 240 µm pitch

Optical Crosstalk in Arrays

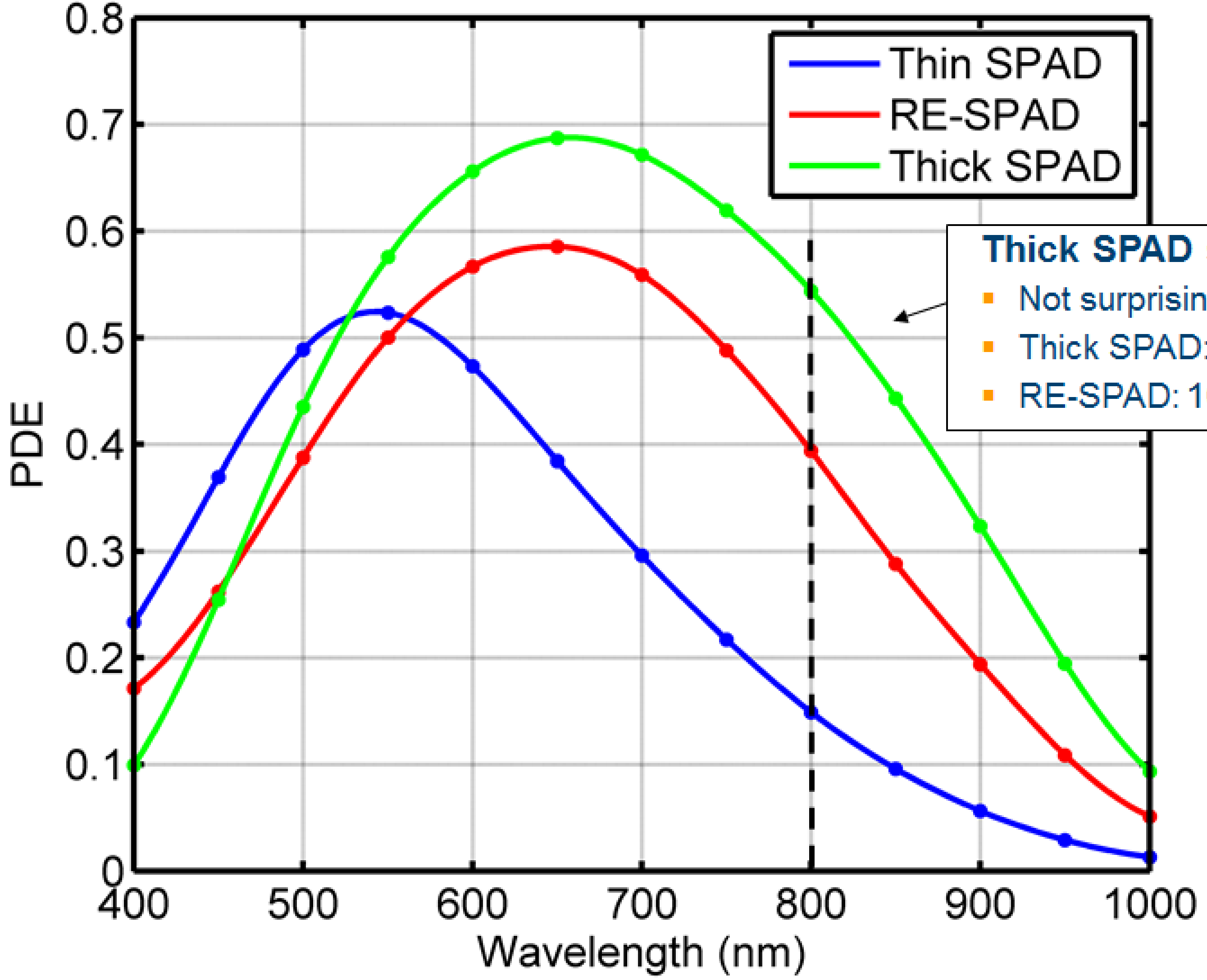


- An impinging **photon triggers a primary avalanche** in a pixel (A)
- **Secondary photons** are emitted by the hot electrons of the avalanche current
- These photons propagate through the bulk silicon and can **trigger a secondary avalanche** in another pixel (B)

PDE Photon Detection Efficiency



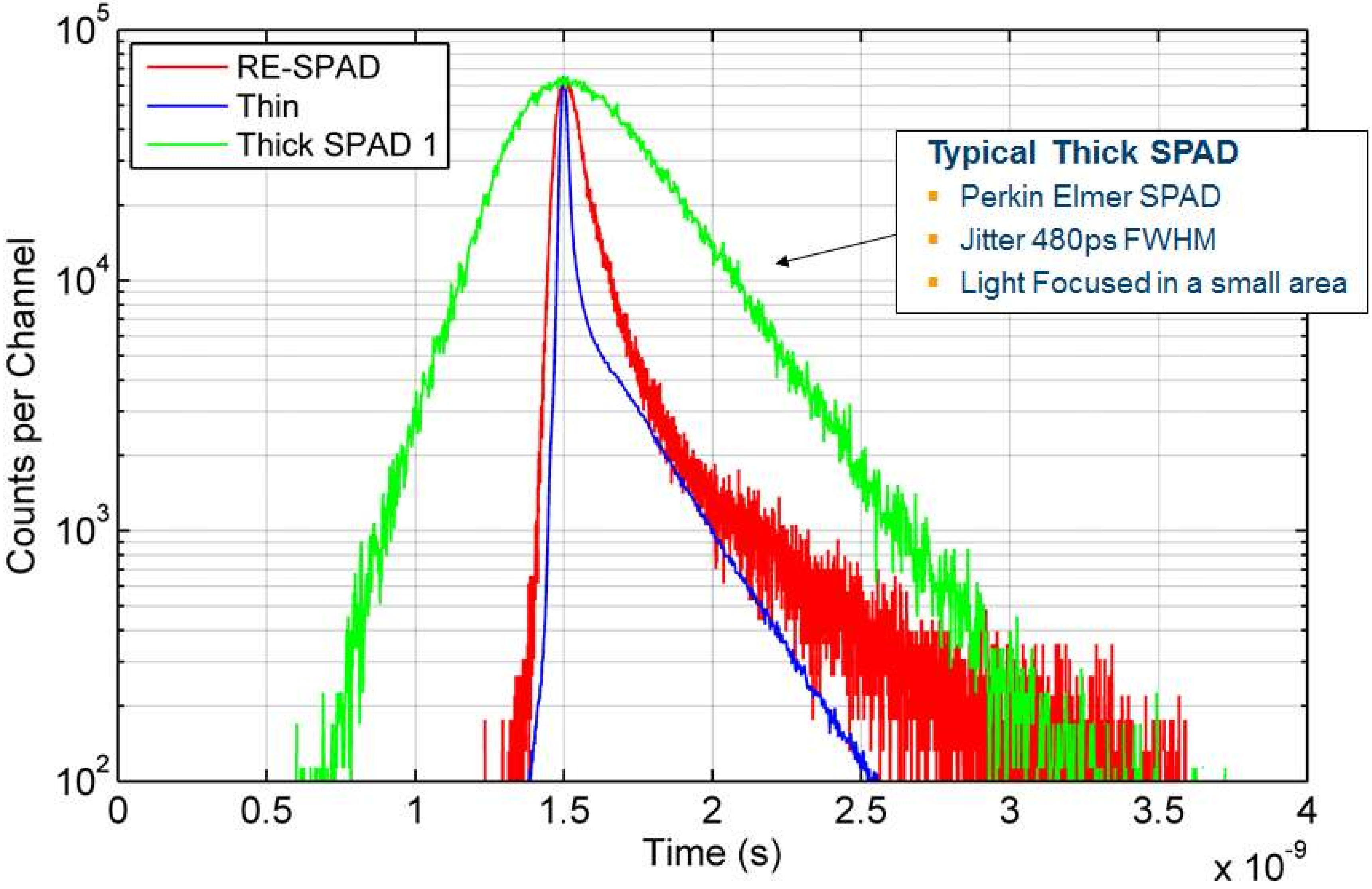
Photon Detection Efficiency



Thick SPAD still has higher PDE

- Not surprising
- Thick SPAD: 30μm – thick
- RE-SPAD: 10μm – thick

Photon Timing



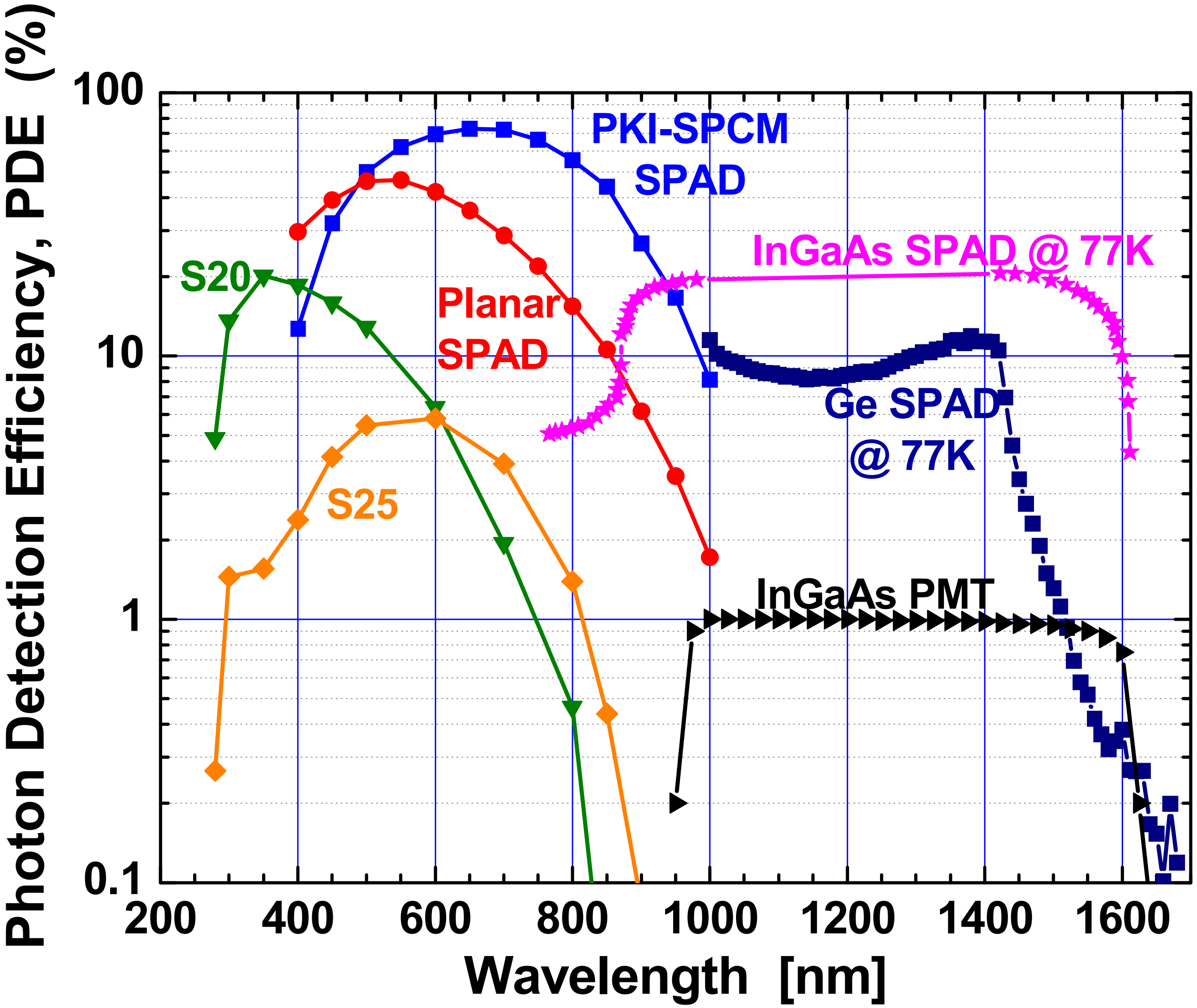
Typical Thick SPAD

- Perkin Elmer SPAD
- Jitter 480ps FWHM
- Light Focused in a small area

Outline

- Photon Counting: how and why
- Vacuum tube and silicon detectors
- Single-Photon Avalanche Diodes SPAD
- Challenges for SPAD development: technology and design
- SPAD for the InfraRed spectral range
- SPAD applications
- Working in SPADLab

Single Photon Detectors: PDE



SPAD for the Near InfraRed (NIR)

Silicon absorbs up to λ = ***1.1μm***

⬇

Smaller bandgap required for working at longer λ

⬇

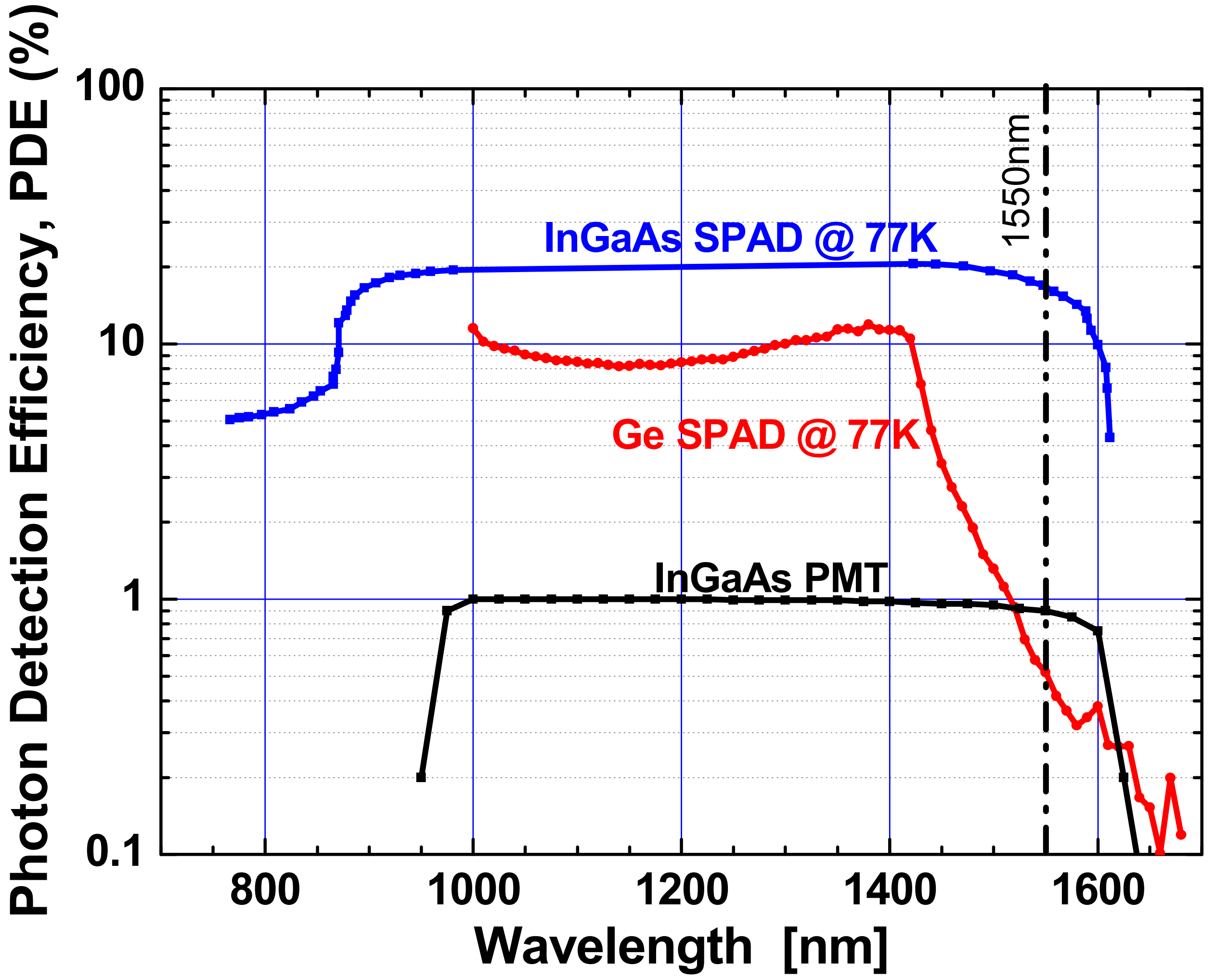
Mandatory:

- ***Deep cooling (< 220 K)***
  for limiting thermal carrier generation

&

- ***Limitation to electric field***
  for avoiding tunnel-assisted generation

Photon Detection Efficiency: long λ detectors



SPAD for the Near InfraRed (NIR)

$In_{0.53}Ga_{0.47}As$ works up to $\lambda \sim 1.7\mu m$ because $E_g \sim 0.75$ eV

but

it must be cooled

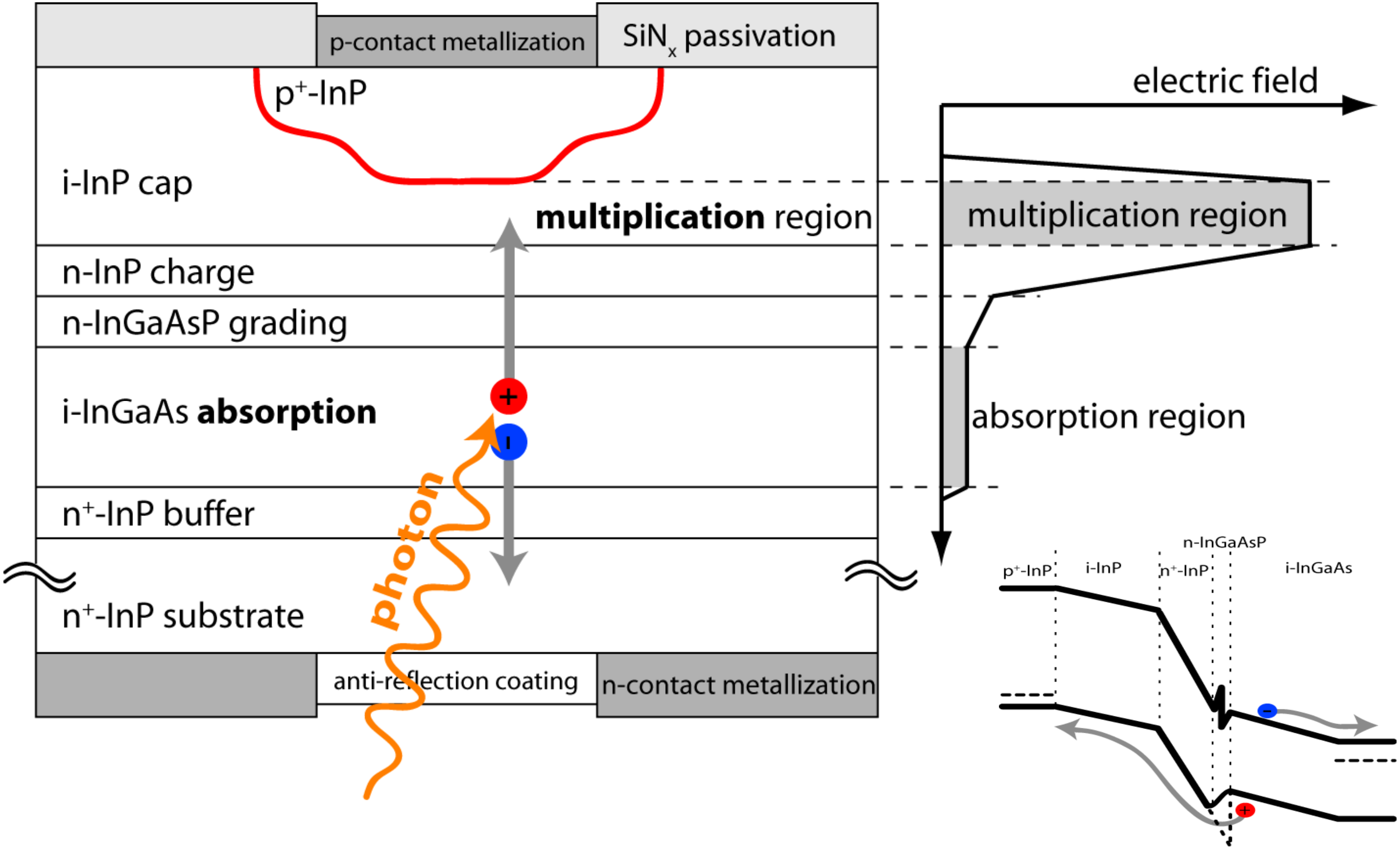
it is unsuitable for avalanche

↓

Separate Absorption and Multiplication (SAM)

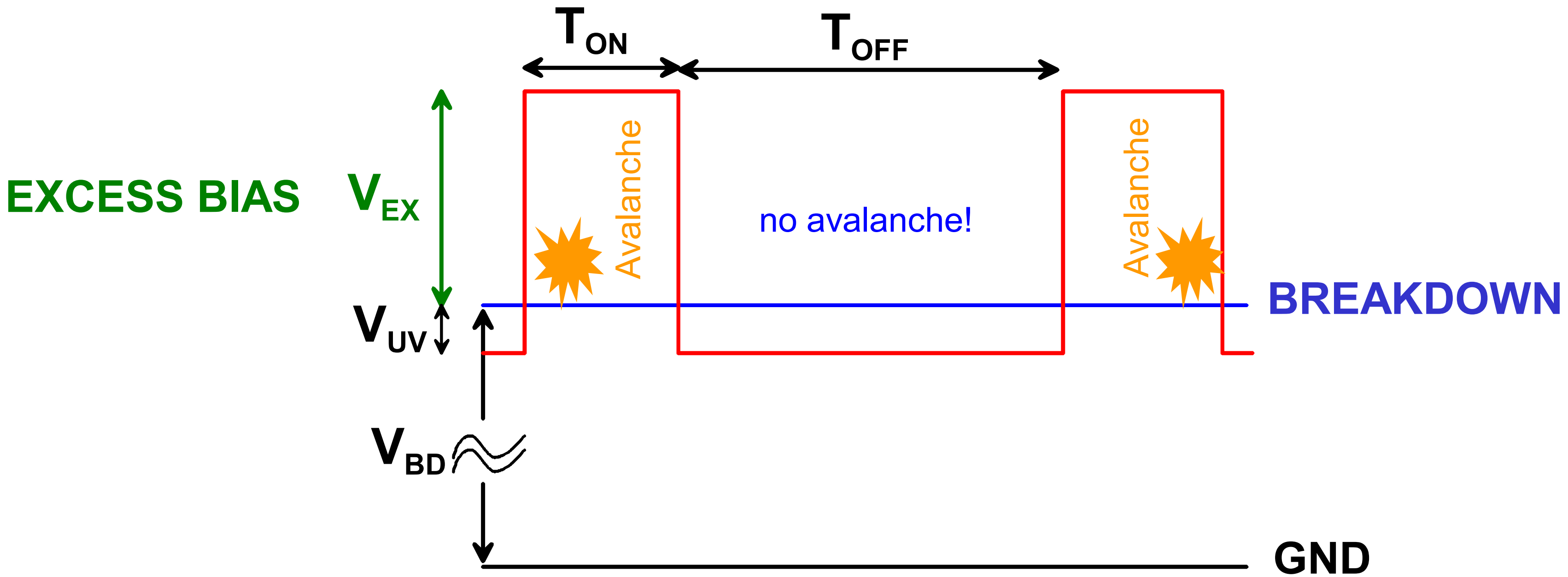
heterostructure device

Photon absorption and carrier collection



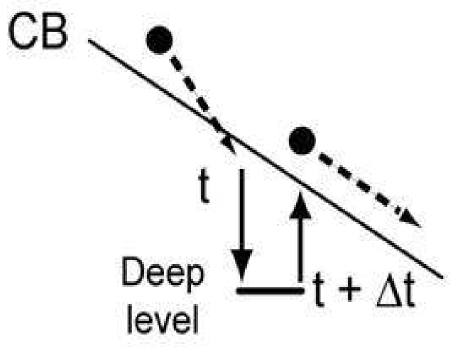
$In_{0.53}Ga_{0.47}As$ absorption layer → E_g ~ 0.75 eV → Cut-off 1.7µm

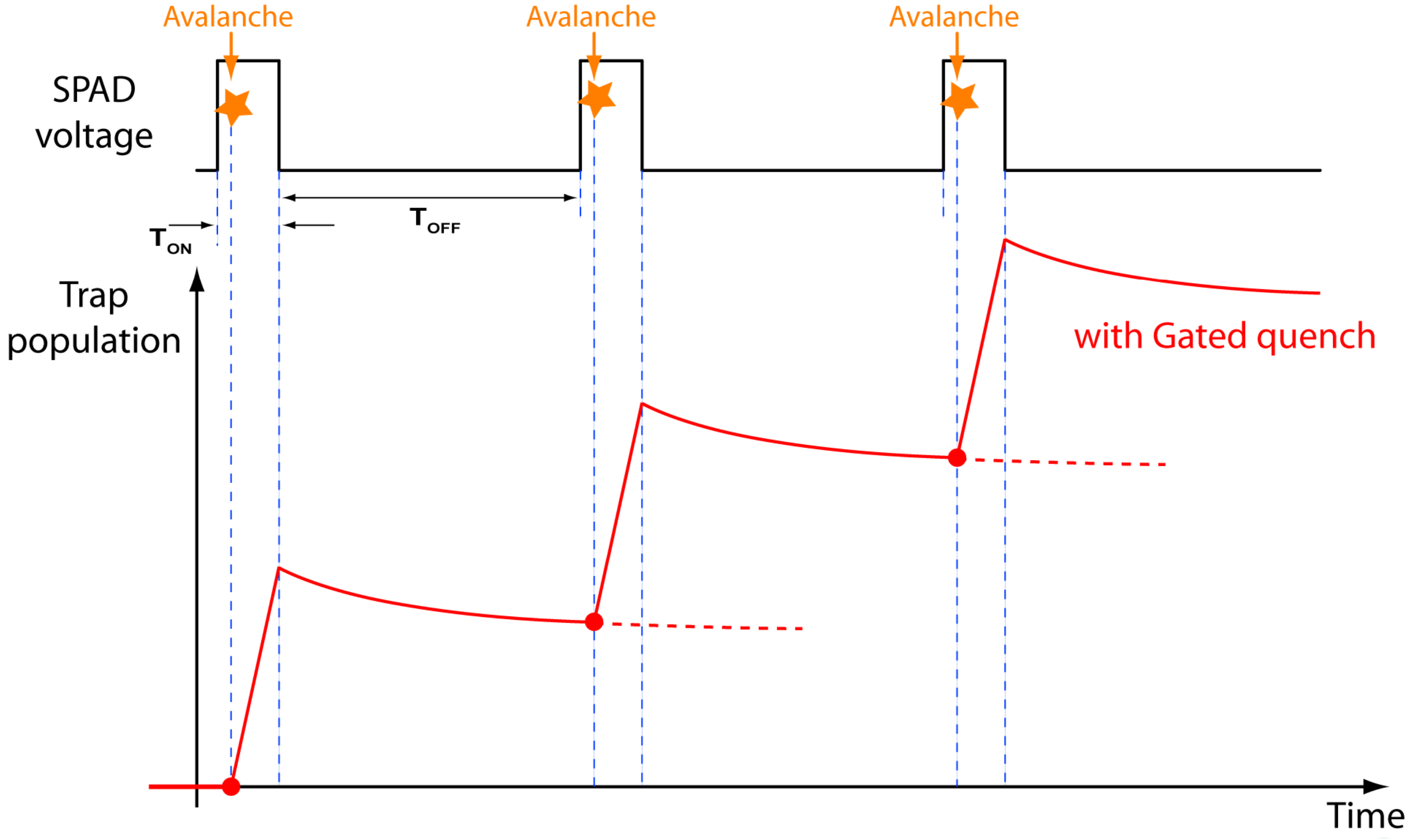
Gated-mode operation



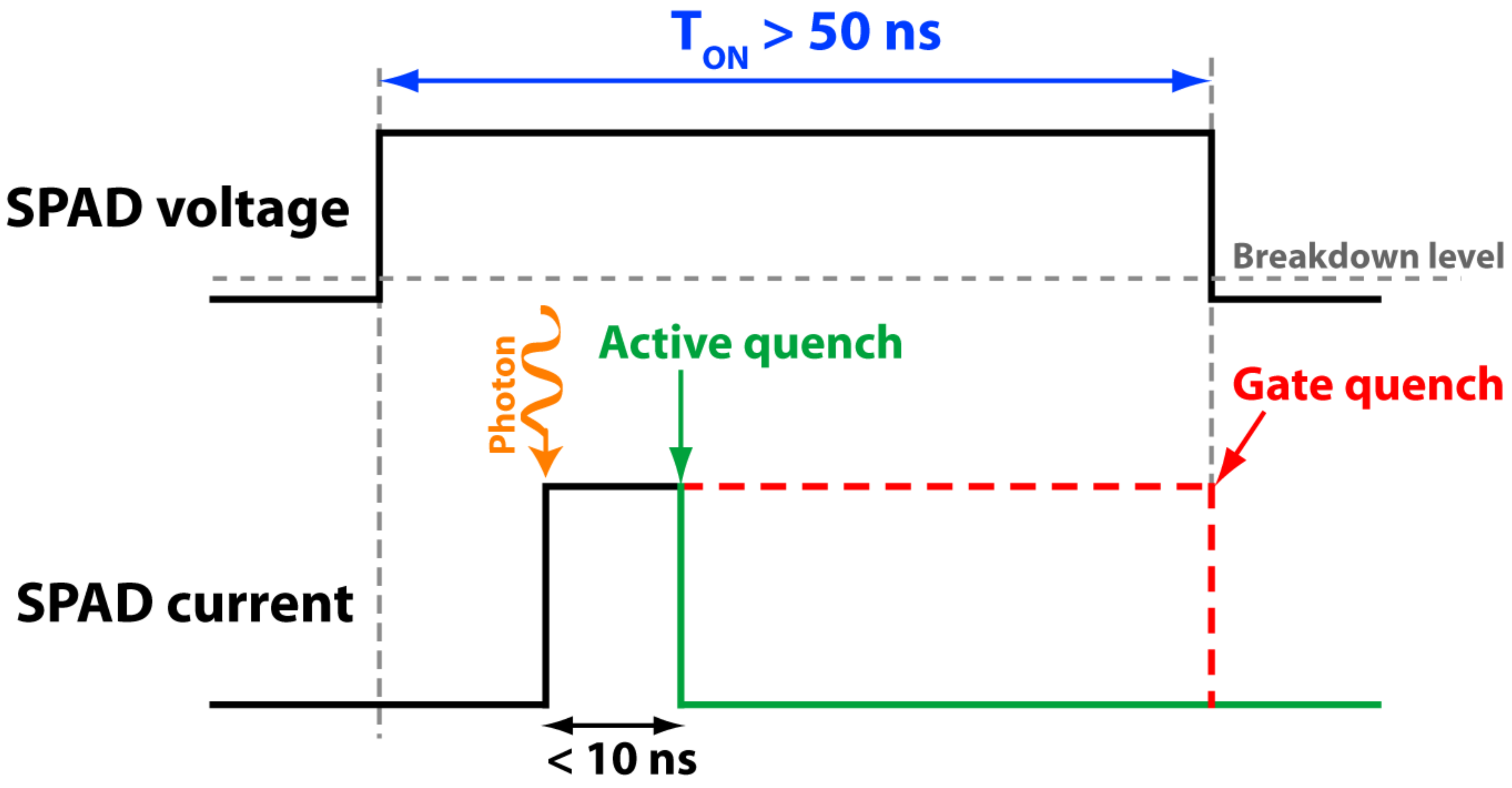
Afterpulsing

Carrier Trapping and Delayed Release





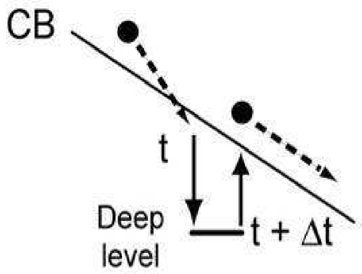
Gated Active Quenching (AQC)

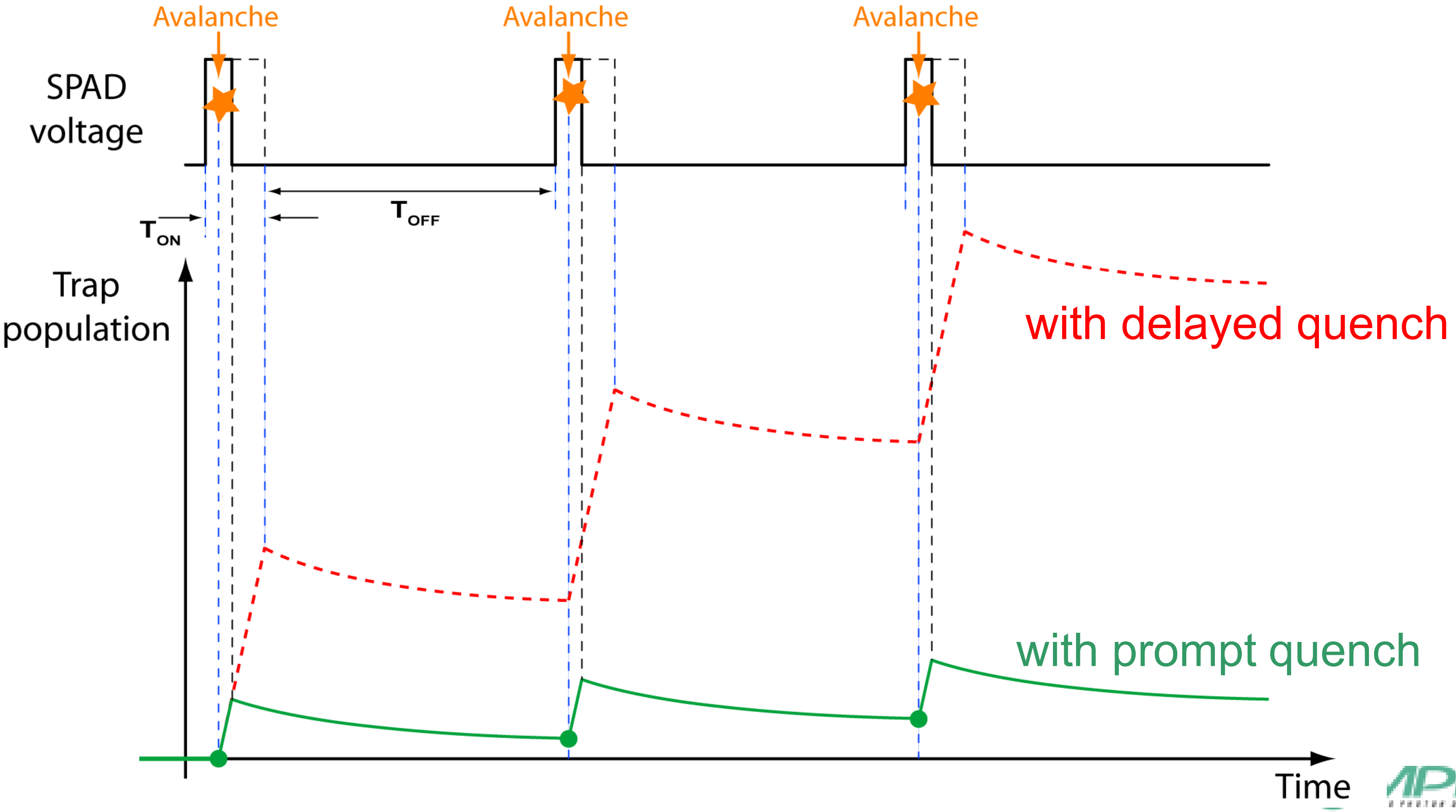


- < *10 ns* avalanche duration
- Lower charge → lower afterpulsing
- Longer gate duration with low afterpulsing

Afterpulsing

Carrier Trapping and Delayed Release

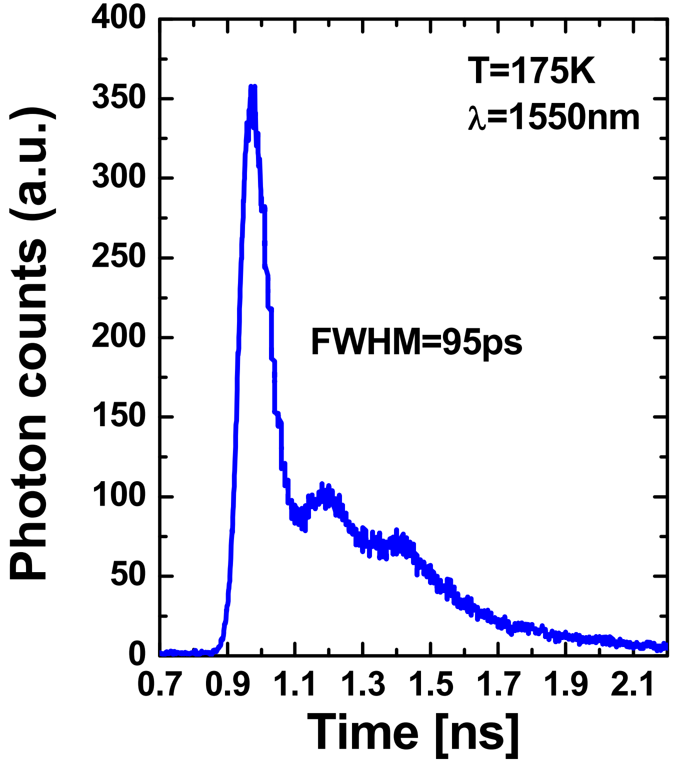




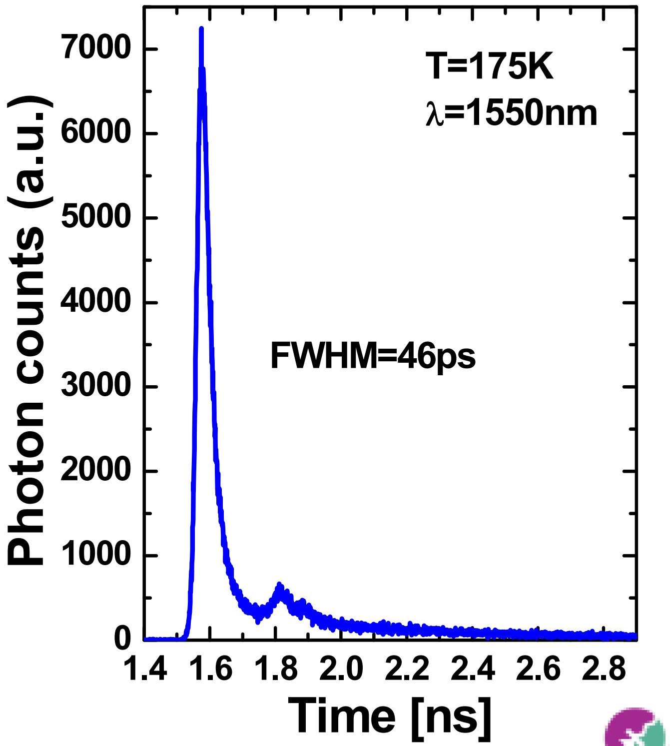
Feedthrough - Compensated signal pick-up

by feed-through in the diode capacitance,
the rising and falling-edge of the gate signal inject disturbing spikes
in the timing electronics
Remedy:
accurate capacitive compensation

no compensation



with compensation



Outline

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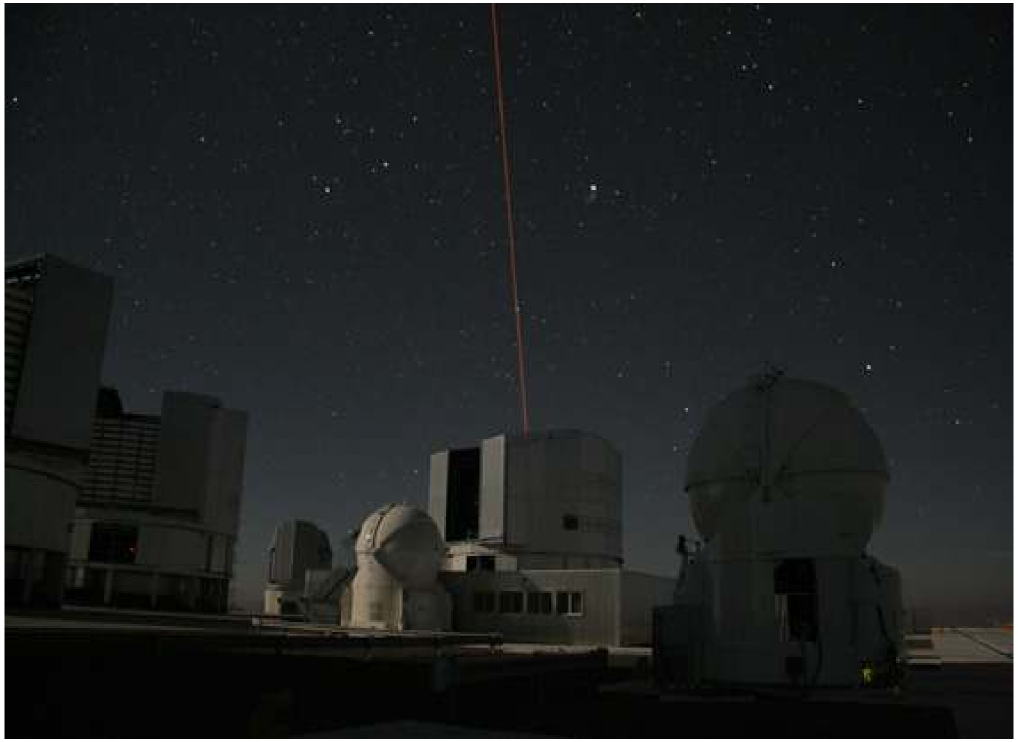
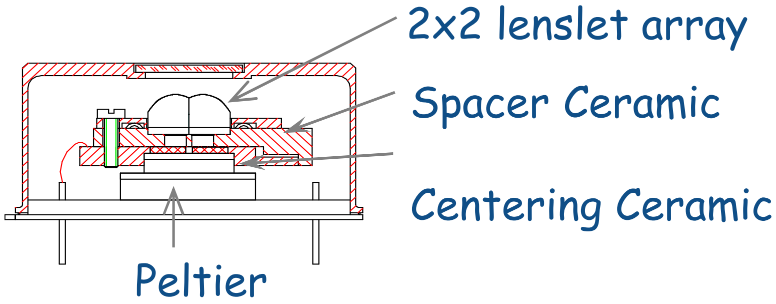
Four quadrant SPAD detector for Adaptive Optics

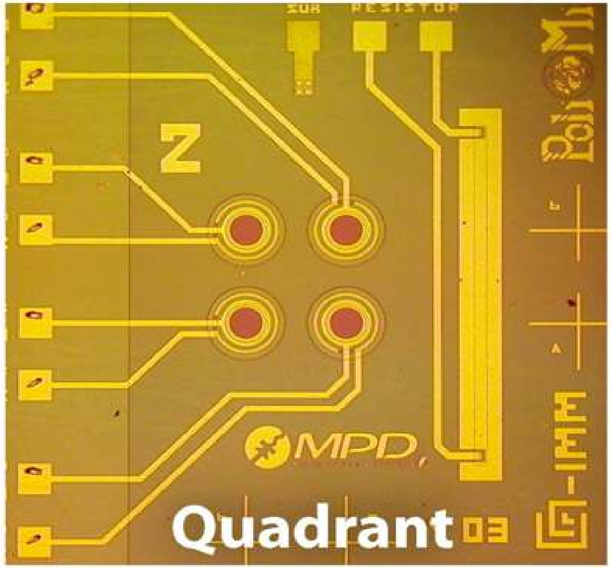
STRAP system for Tip tilt correction



VLT Very Large Telescope (Chile)

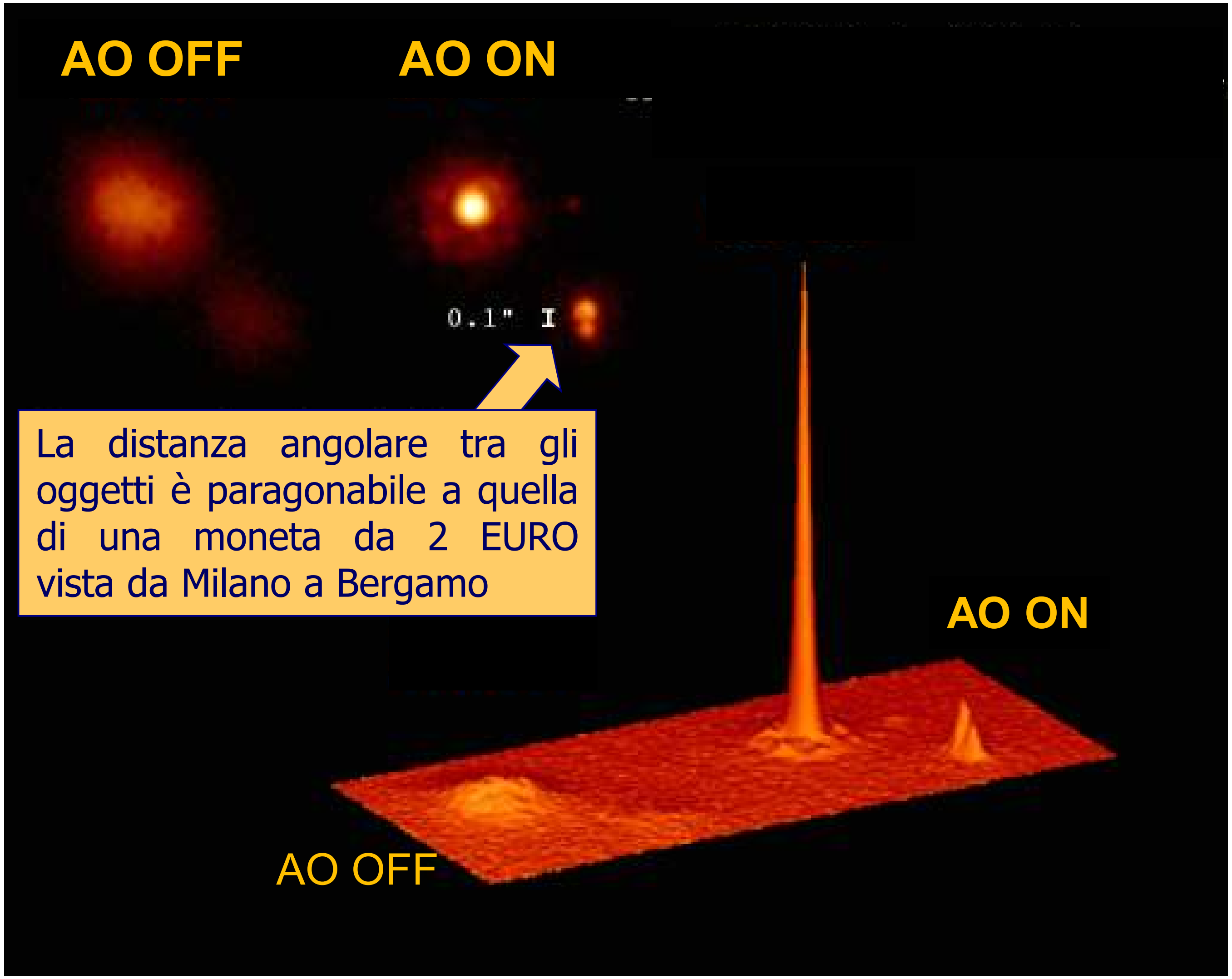
www.eso.org





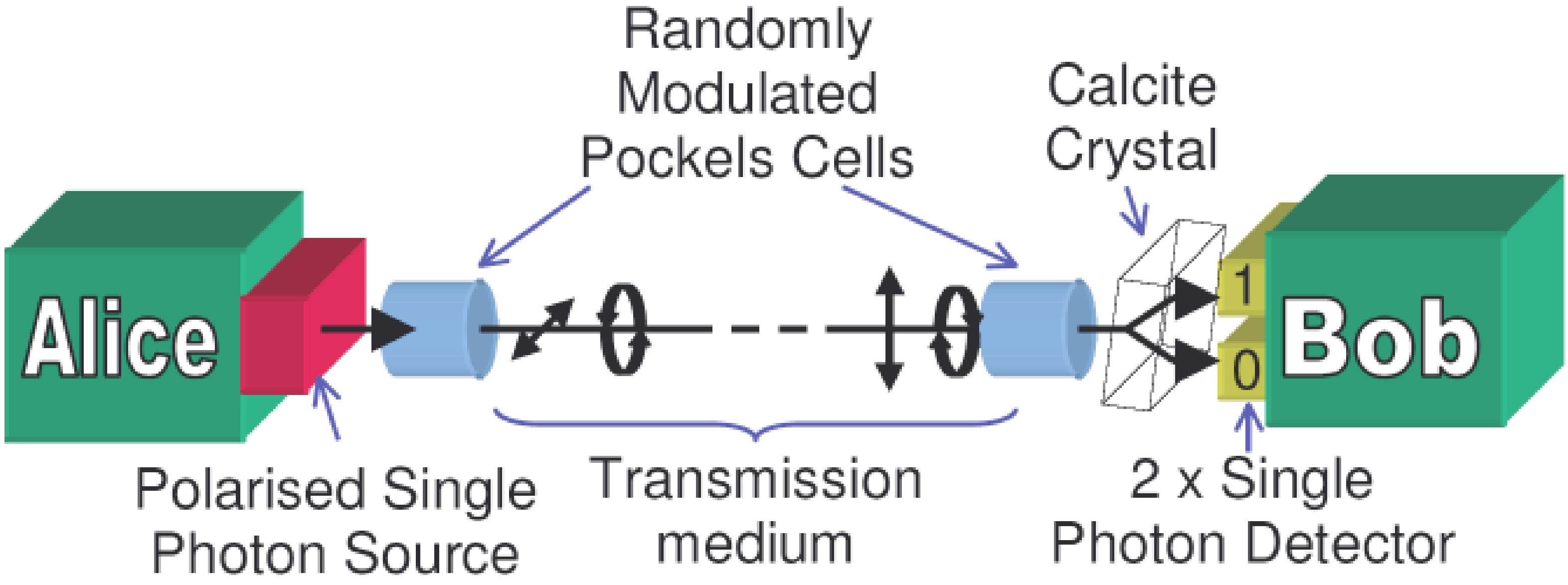
pixel diameter up to 100μm

Example of AO correction: image taken by the MMT telescope

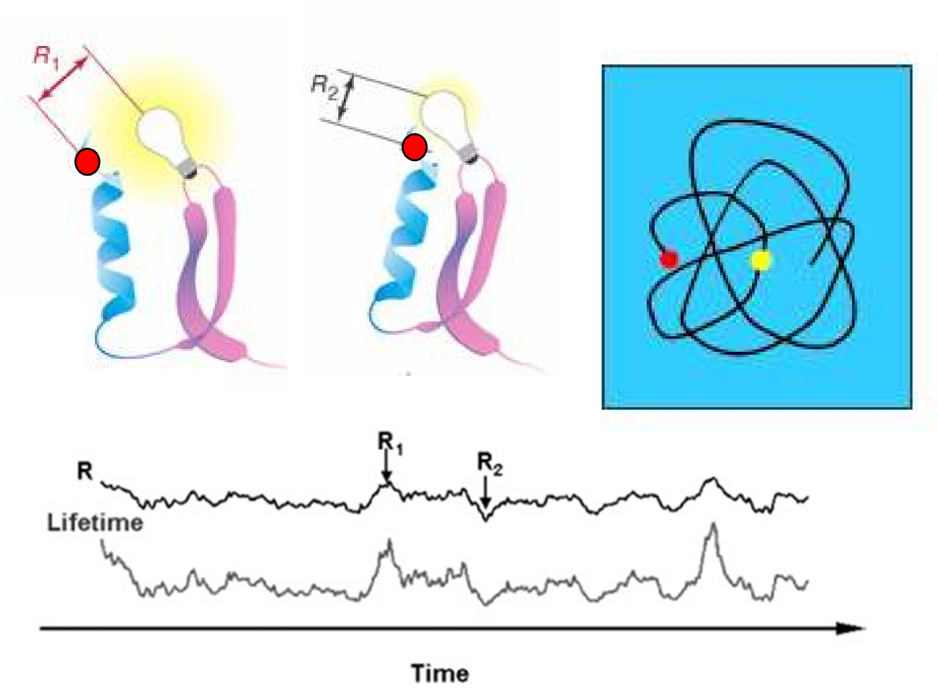


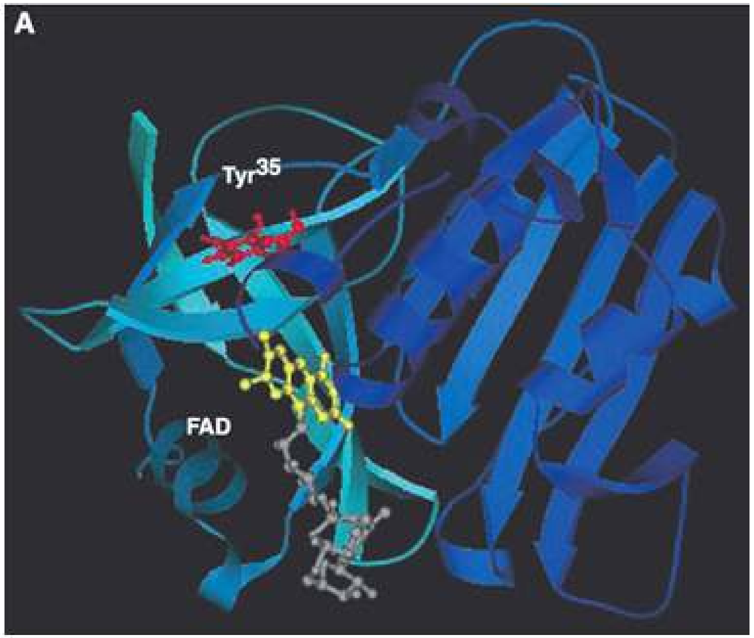
La distanza angolare tra gli oggetti è paragonabile a quella di una moneta da 2 EURO vista da Milano a Bergamo

Quantum Key Distribution (QKD) principle



Single molecule spectroscopy





Fre-FAD complex

(Flavin reductase - Flavin Adenine Dinucleotide)

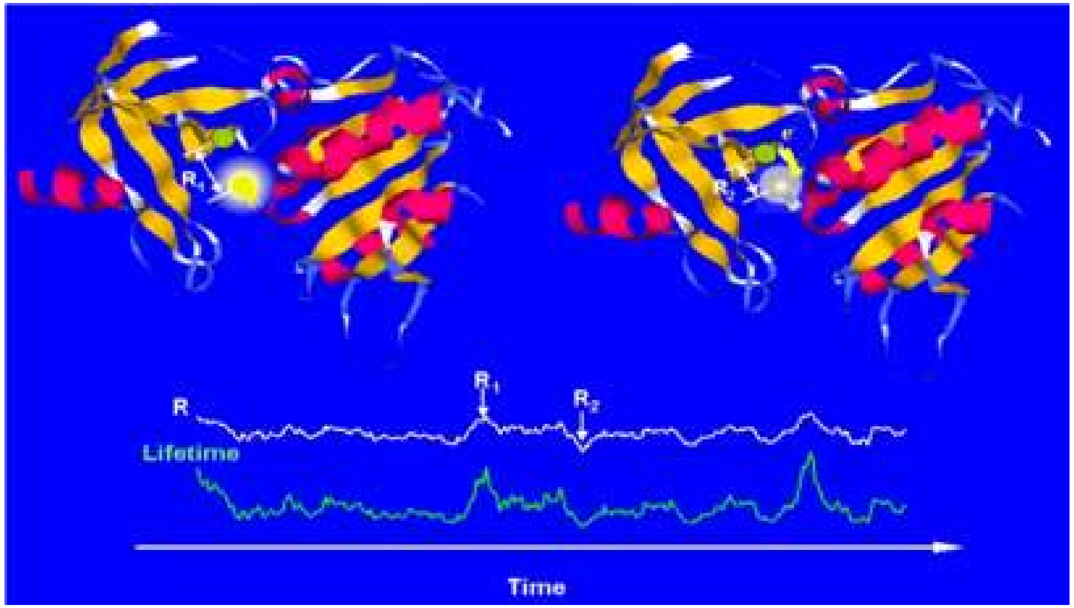
- Conformational dynamics of biomolecules is crucial to their biological functions
- Electron transfer used as a probe for angstrom-scale structural changes
- Measure fluorescence lifetimes down to < 100ps to gauge conformational dynamics

H. Yang, G. Luo, P. Karnchanaphanurach, T.M. Louie, I. Rech, S.Cova, L. Xun, X. Sunney Xie, Science vol.302, 262-266 (2003)

Single Molecule Conformational Dynamics

at **Harvard University the principle** was proposed:
probing on nanometer scale the protein dynamics (Fre–FAD complex)
by laser excitation and ***correlation*** analysis of ***fluctuations in real time***
of the fluorescent ***photon picosecond delay***

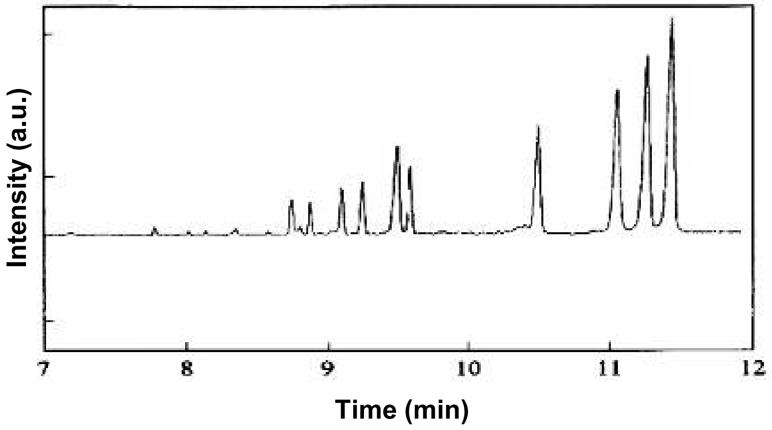
at **Politecnico di Milano the essential tool** was developed:
the Picosecond-Timing Single-Photon Detector



H. Yang G.Luo, P.Karnchanaphanurach, T.M.Louie, I.Rech, S.Cova, L.Xun, X.S.Xie,
“Protein Conformational Dynamics Probed by Single-Molecule Electron Transfer”
Science, vol.302, 262-266 (2003) - Citations: 217 at May 2009, IF 29.8

DNA analysis by Capillary Electrophoresis (CE)

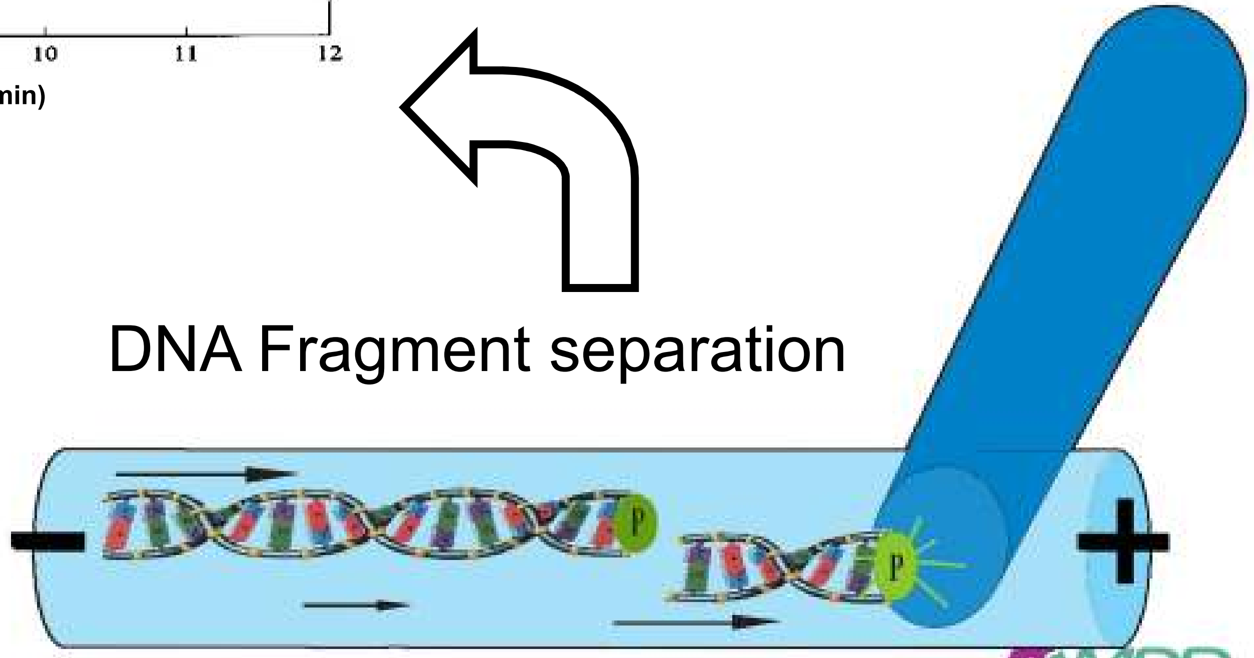
Electropherogram



Reduction of analysis time and cost by:

- **integrated** series of steps
- **small** quantities analyzed
- **reduced** reagent consumption

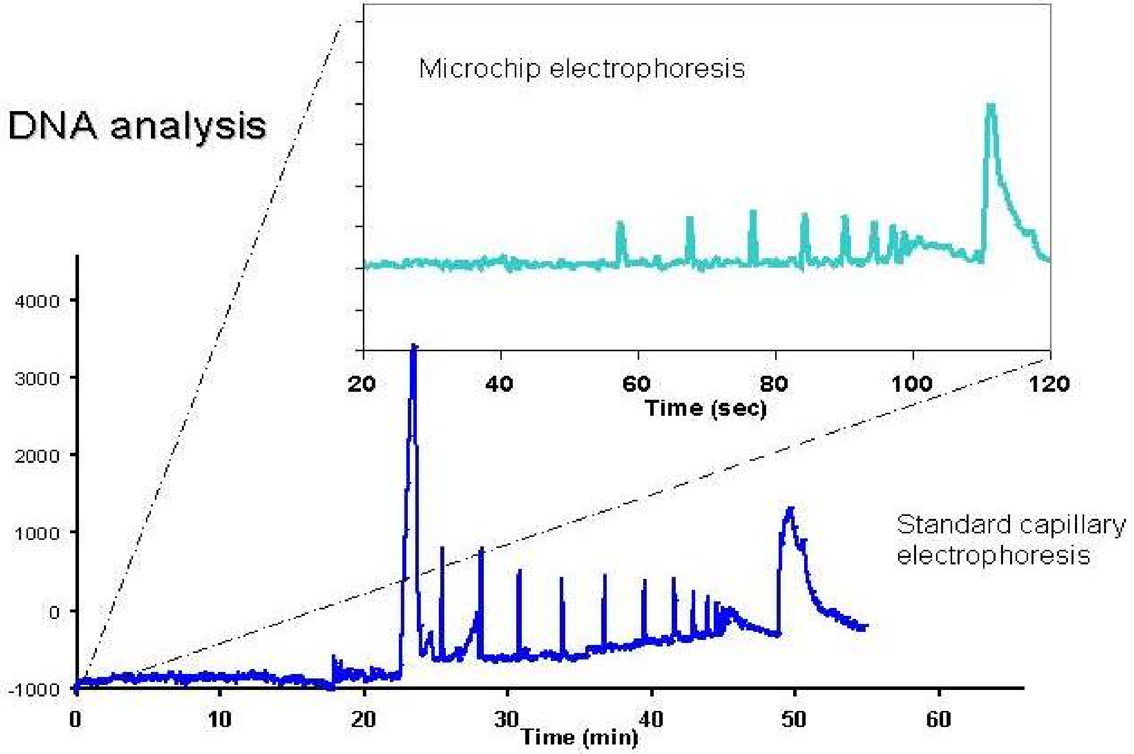
→ **high sensitivity required**



DNA Fragment separation

DNA fragment separation in microchip

- Reducing analysis time and cost in genetic tests:
  small samples, low reagent consumption,
  integrated series of analytical steps, rapid analysis



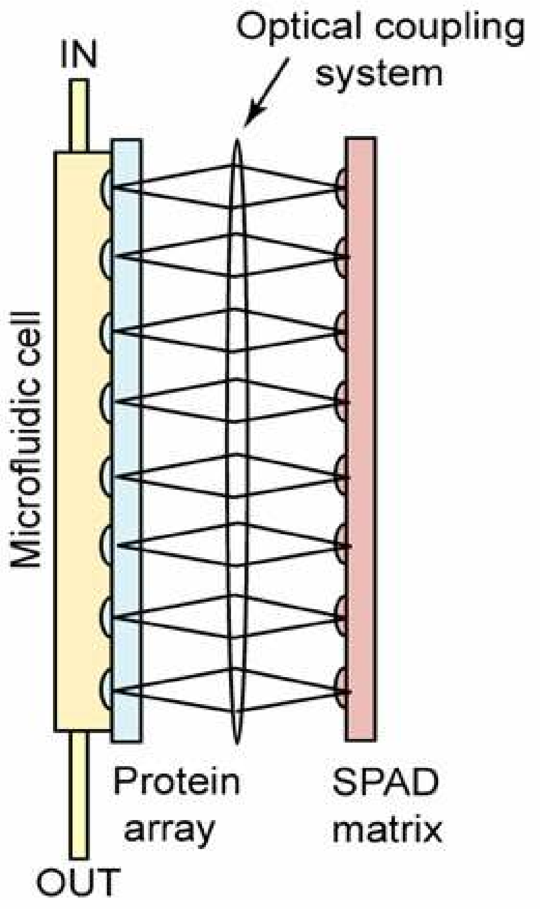
Sensitivity limit: 1pM

that is

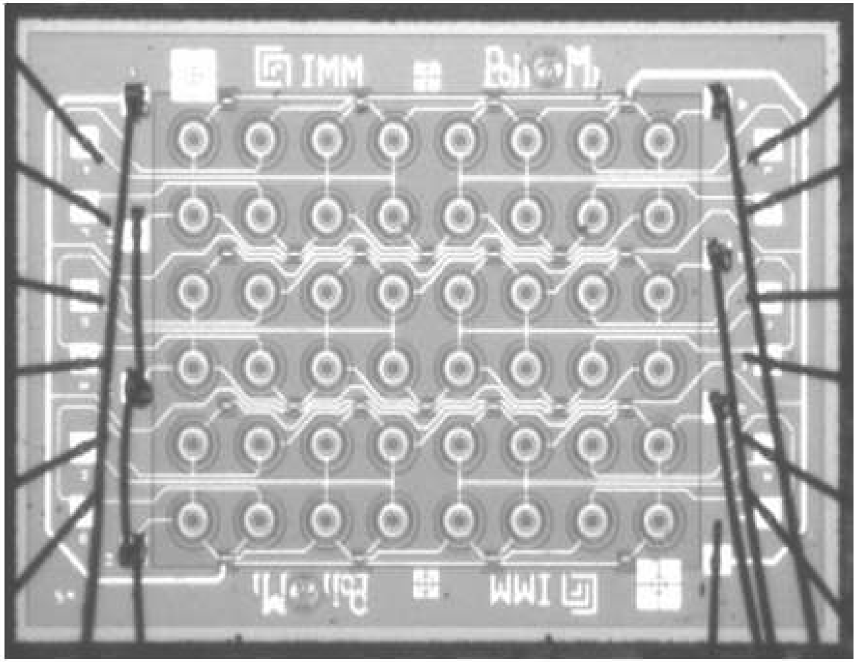
< 30 molecules in 50pL

SPAD arrays in custom technology

Matrix detector for analysis of protein microarray (allergy diagnostics)



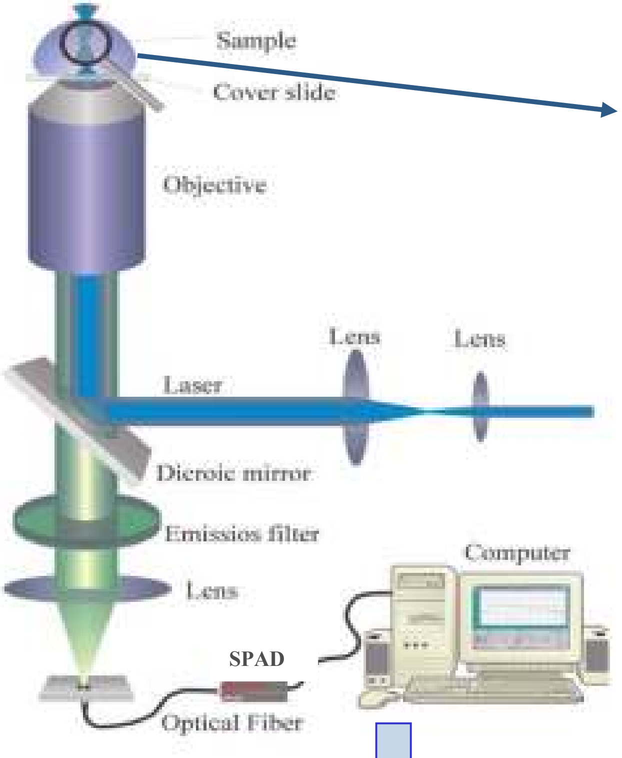
50 µm pixel diameter

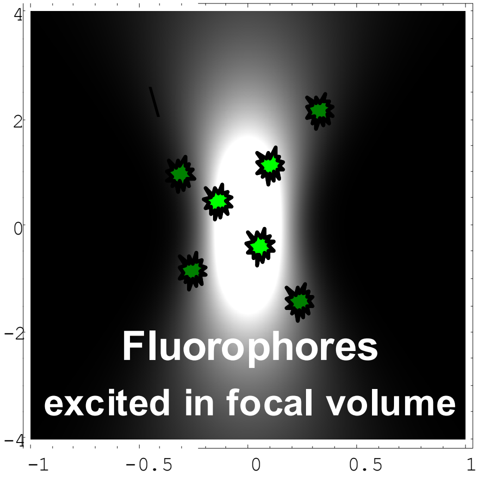


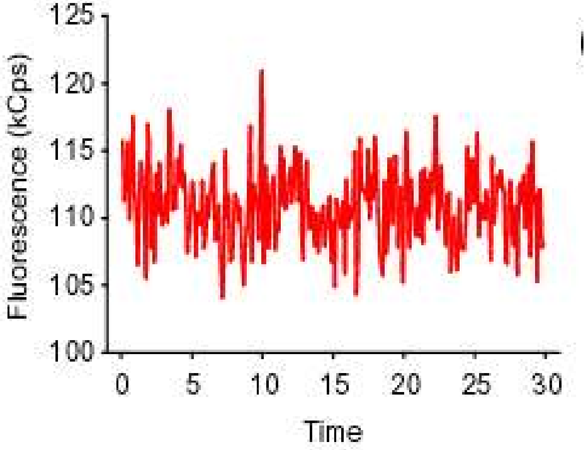
6x8 pixels, 240 µm pitch

Fluorescence Correlation Spectroscopy (FCS)

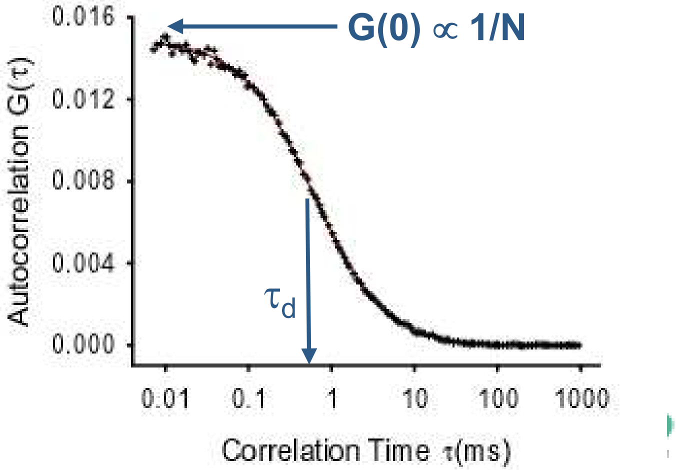
- **Principle:** Excited molecules in the focal volume give rise to a fluorescent signal
- The fluorescence signal fluctuates in time → F(t)
- Fluctuations quantified by calculating the normalized autocorrelation function $G(\tau)$







$$G(\tau) = \frac{\langle \delta F(t) \delta F(t+\tau) \rangle}{\langle F(t) \rangle^2}$$



Fluorescence Correlation Spectroscopy (FCS)

FCS read out parameter

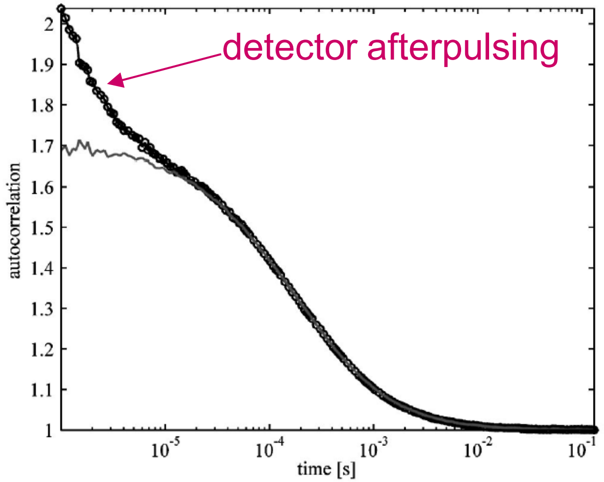
- Mean Number of Molecules => Concentration
- Diffusion times => Molecule size, Viscosity
- Fraction of components => Bound/free ratio
  => Kinetic parameters of or chemical reactions
- Triplet and other dark states => Inherent properties of molecules
  => Environmental parameters (pH, …)

FCS applications

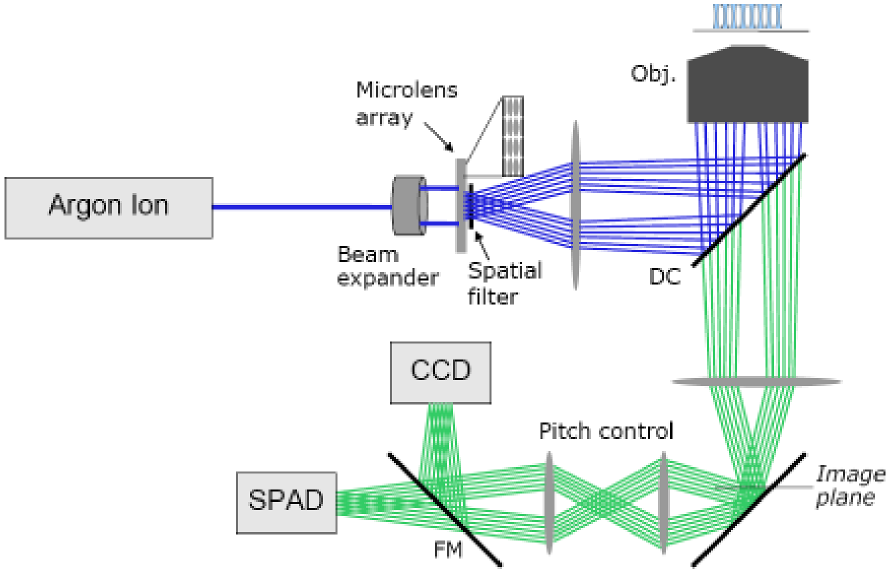
- Measurement of absolute concentrations at well-defined positions
- Transport/diffusion
- Binding studies: reaction kinetics, equilibrium constants
- Aggregation
- …..

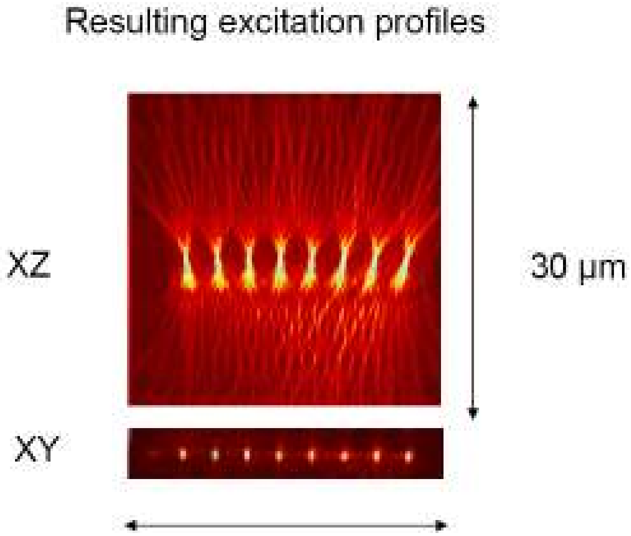
Required SPAD performance

- Low afterpulsing
- High count rate → Short dead-time

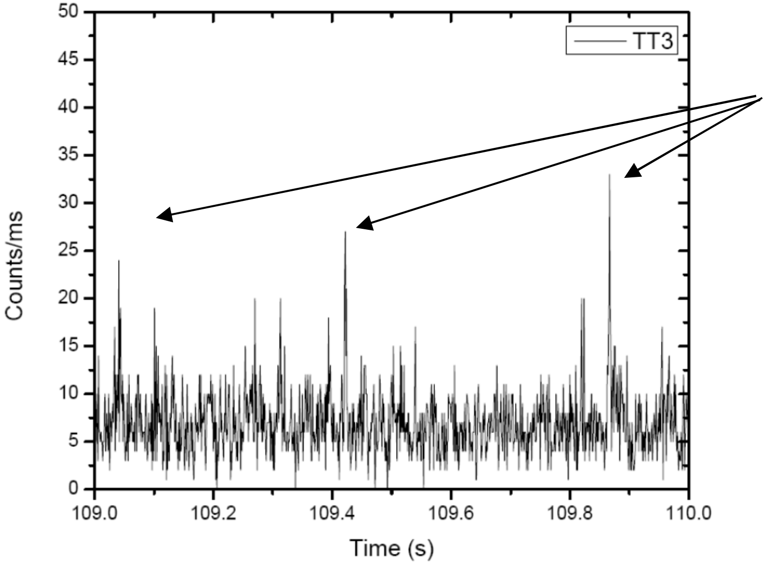


8-channel parallel FCS





Cy3B-DNA sample (Exc@ 532 nm)



Single molecule bursts

Collab. POLIMI - UCLA Chem&Biochem. Dept.

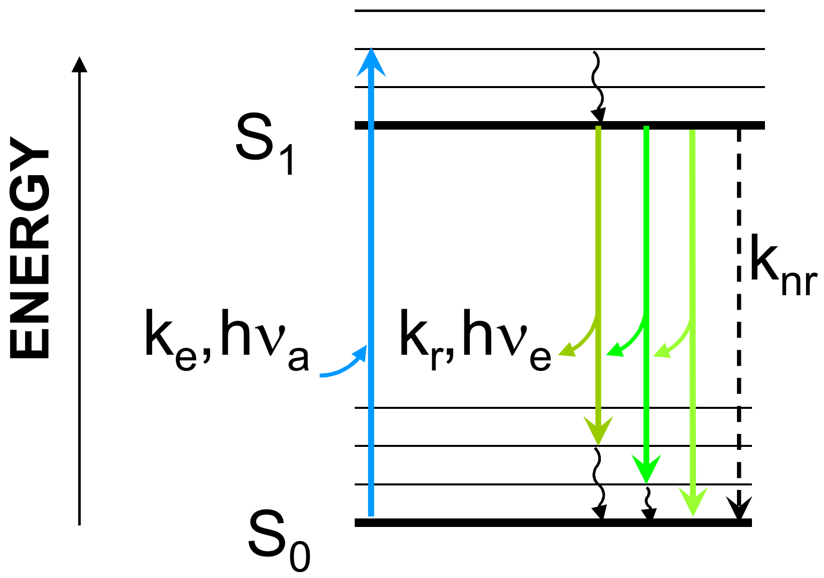
X. Michalet, R. A. Colyer, G. Scalia, T. Kim, M. Levi, D. B. Aharoni, A.M. Cheng, K.Arisaka, J. E. Millaud, I. Rech, S. Marangoni, M. Ghioni, S. Cova, S. Weiss

"High-throughput single-molecule fluorescence spectroscopy using parallel detection "

Photonics West, San Francisco, January 2010

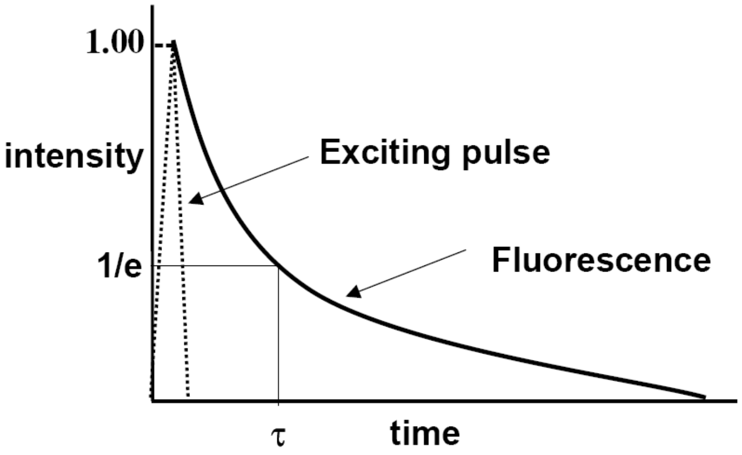
Fluorescence lifetime

Jablonski diagram



Deactivation of an electronically excited molecule: the molecule relaxes from the lowest vibrational energy level of the excited state to a vibrational energy level of the ground state.

k_r, k_{nr} : radiative and non-radiative transition rates



Fluorescence lifetime

$$\tau = \frac{1}{k_r + k_{nr}}$$

Fluorescence lifetime: average time a molecule spends in the excited state S_1 before returning to ground state S_o (sub-nanoseconds to a few nanoseconds).

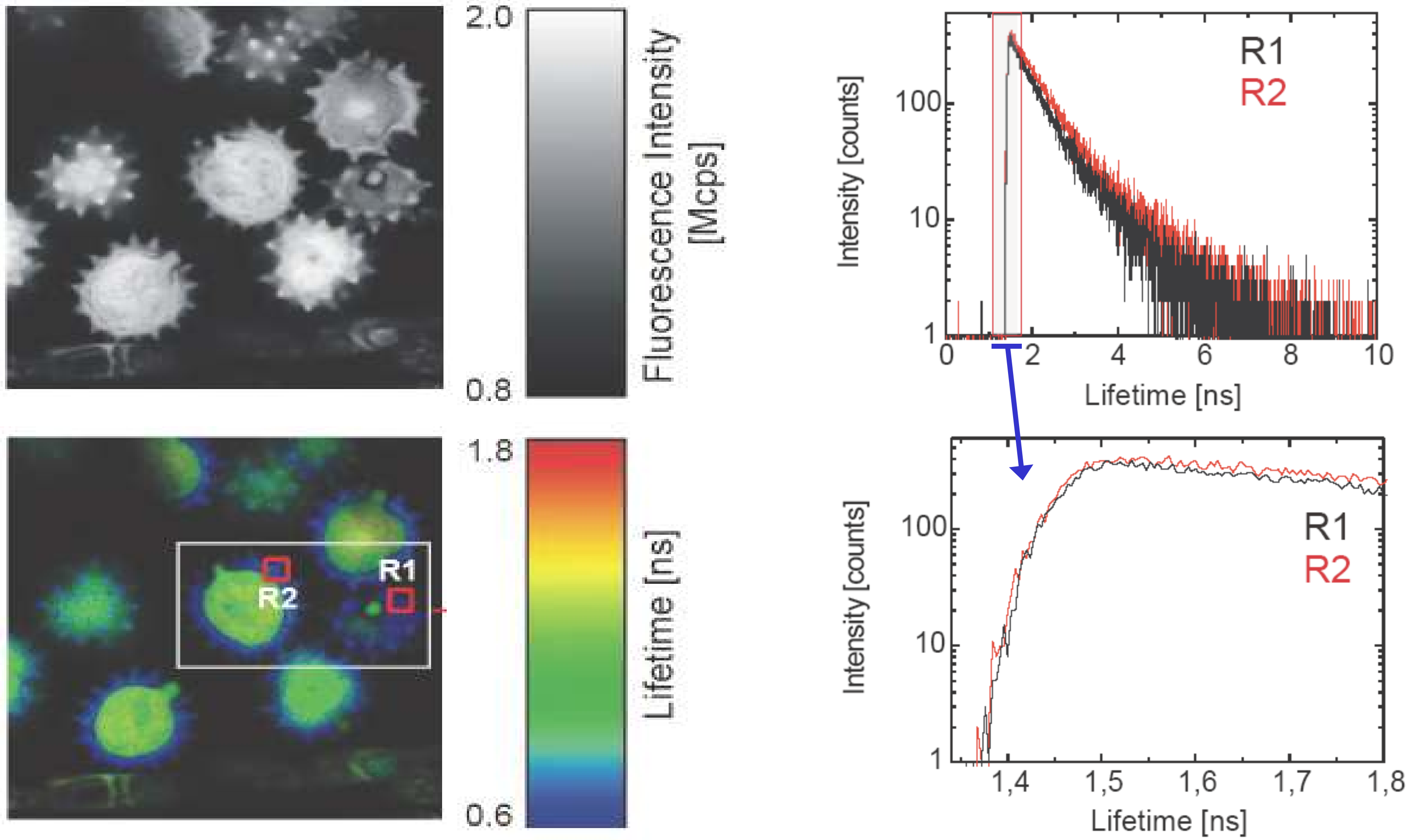
Why fluorescence lifetime spectroscopy ?

- Lifetimes are minimally affected by the variation of excitation intensity or other factors that affect the fluorescence intensity.
  - *sources of light loss (endogenous absorbers, photobleaching, optical misalignments), fluorophores concentration, excitation collection geometry.*

- Lifetimes can provide effective means of discrimination among fluorophores.
  - *fluorophores with overlapping emission spectra but with different fluorescence decay times can be discriminated.*

- Lifetimes are sensitive to important parameters of the biological microenvironment:
  - *pH, ion concentration (e.g. Ca^{2+}, Mg^{2+}, Na^{+}),O_2 concentration, binding, enzymatic activity, temperature.*

Fluorescence Lifetime Imaging (FLIM)



FLIM image of the autofluorescence of daisy pollen grains

- 64 μm x 64 μm area (256 pixels/axis)
- 0.6 ms/pixel acquisition time → 2 min total measurement time

Courtesy of Picoquant GmbH, Germany

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SPADLab

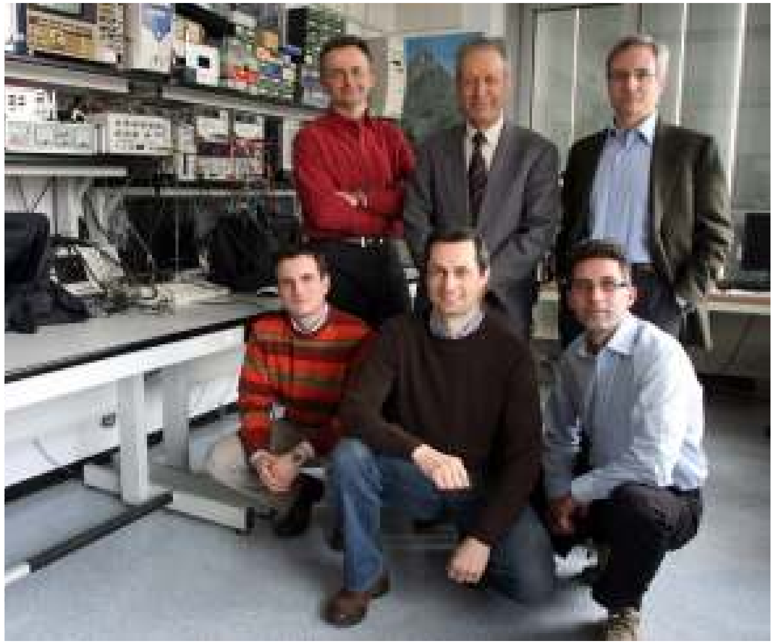
6 permanent staff

3 research associates

> 10 PhD students

stream of students in graduation thesis ("Tesi di Laurea")

SPADlab Staff



COVA, S.	Emeritus Professor
GHIONI, M.	Full Professor
ZAPPA, F.	Full Professor
RECH, I.	Assistant Professor
TOSI, A.	Assistant Professor
GULINATTI, A.	Assistant Professor

SPADlab people

CNR-IMM Bologna Silicon Foundry

Permanent Staff:	**49**
Short Term Staff:	**5**
Associated Researchers:	**30**

- Class 100 clean area (250 square meters)
- Pilot line for fabrication of devices and IC's in 4" silicon wafer
  - Technological processes with high flexibility
  - Consolidated know-how in Si device technology
  - Si-micromachining and Si anodization

Results of decades of research now available:

Micro-Photon-Devices

since 2005 a spin-off company of Politecnico di Milano

Technical Staff 2013

BIASI R. PhD, (CEO)
GIUDICE A. PhD (CTO)
TISA S. PhD
MAGNI, L (CCO)
SIMMERLE, G.
PICCIN, F.

MPD MICRO PHOTON DEVICES

www.micro-photon-devices.com

PDM Photon Detector Modules
Window input

PDF Photon Detector Modules
Fibre input

PDC Photon Detector Carrier
Window input