S. Cova, M. Ghioni, A. Lotito, F. Zappa

# Evolution and Prospect of Single-Photon Avalanche Diodes and Quenching Circuits

*Politecnico di Milano, Dip. Elettronica e Informazione, Milano, Italy*

# Outline

- Introduction
- From Device Physics to Detector Performance
- Technology and Device Design
- Quenching Circuit : Role and Evolution
- Conclusions

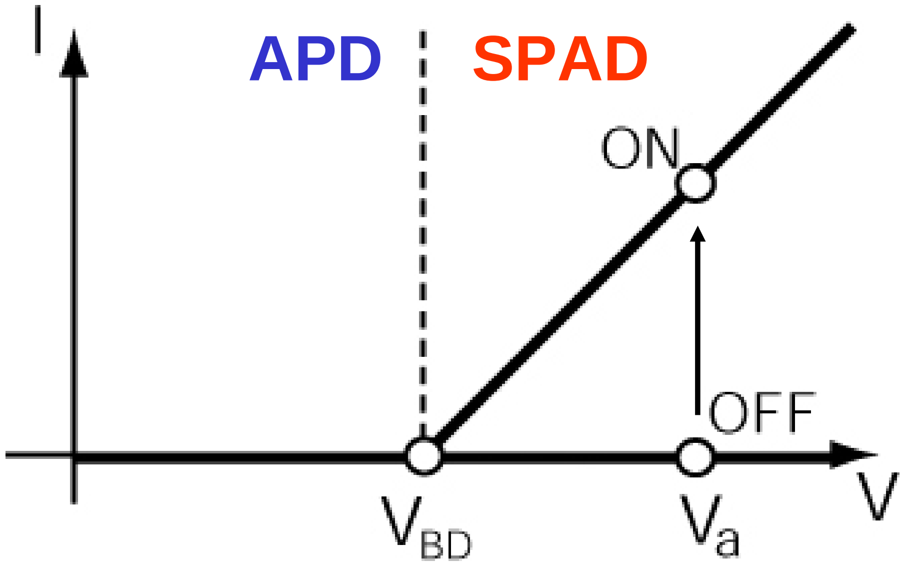
# The Origin

*@ Shockley Laboratory in early 60's :*

*Avalanche Physics Investigation*

- Basic insight
- Model of behavior above Breakdown
- Single-Photon pulses observed, but …
- application limited by device and circuit features

*R.Haitz et al, J.Appl.Phys. (1963-1965)*




**A**valance **P**hoto**D**iode

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

**S**ingle-**P**hoton **A**valanche **D**iode

- Bias: well ***ABOVE*** breakdown
- Geiger-mode: it's a ***TRIGGER*** device!!
- Gain: meaningless ... or **"***infinite***"** !!

# for SPAD operation anyway

**mandatory**

to avoid local Breakdown, i.e.

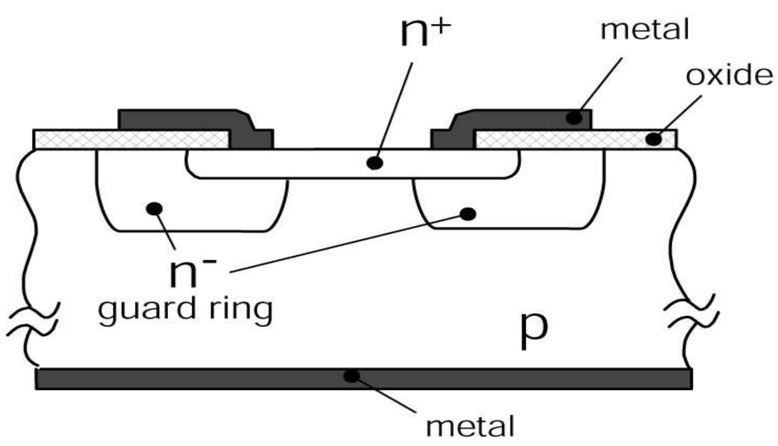
- edge breakdown → guard-ring feature
- microplasmas → uniform area, no precipitates etc.

but for good SPAD performance.....

**further** requirements!!

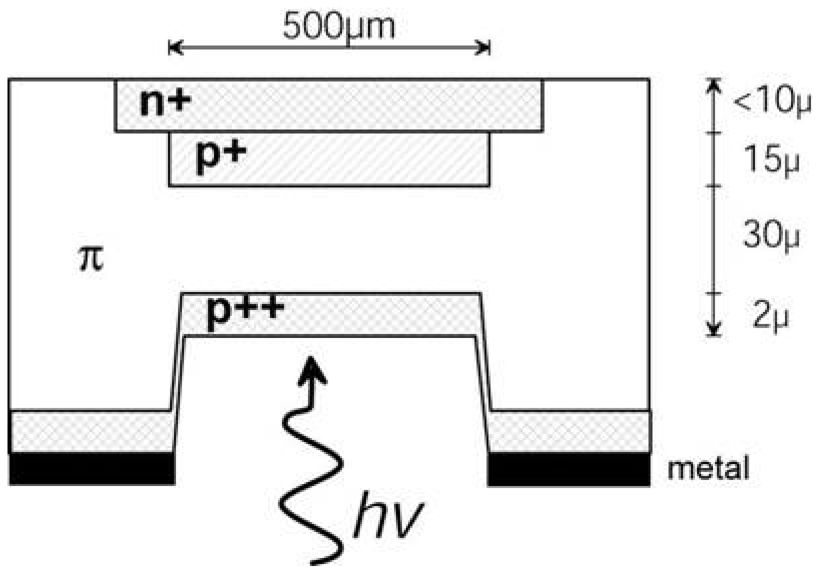
# Earlier Diode Structures

## Haitz's planar diode




"Thin" SPAD

## McIntyre's reach-through diode




"Thick" SPAD

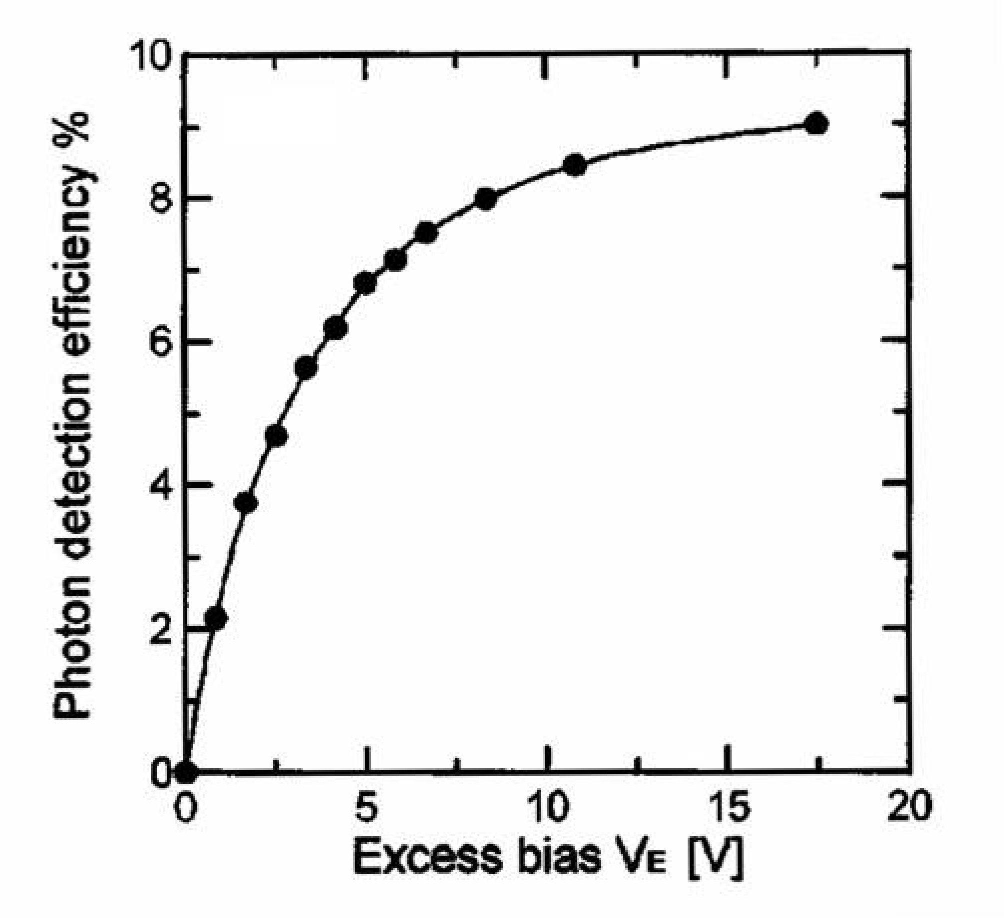
# Quantum Detection Efficiency (QE)

Carrier Photogeneration

AND

Avalanche Triggering!!

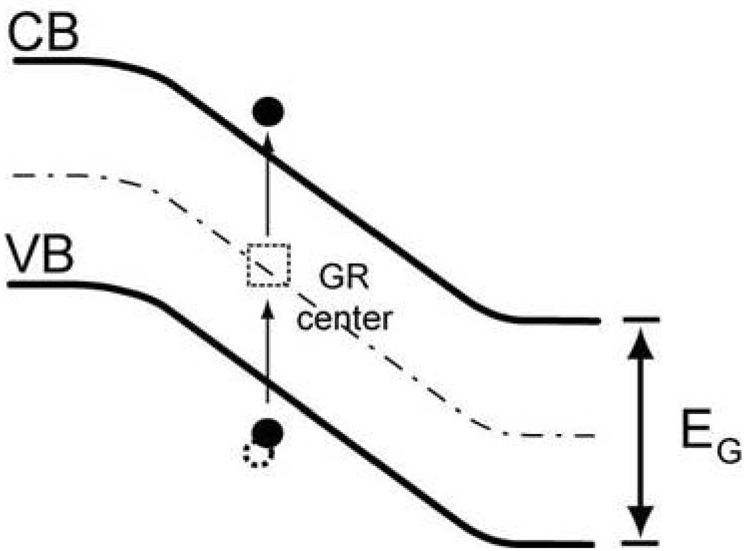
→ high excess bias voltage



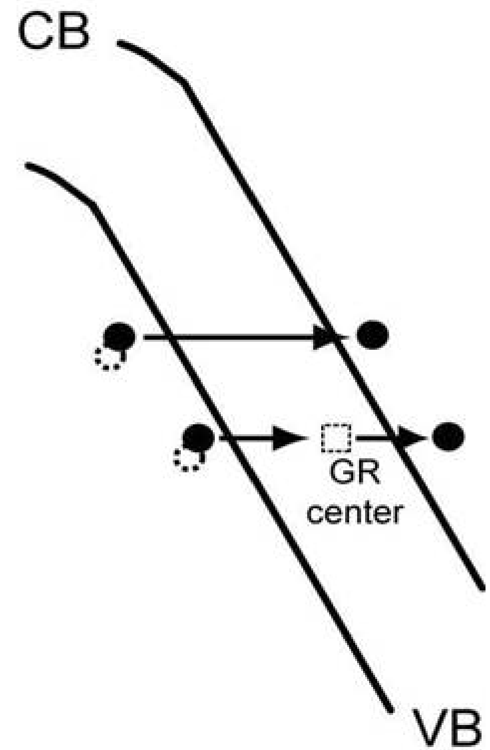

*W.Oldham, P.Samuelson, P.Antognetti, IEEE Trans. ED (1972)*

# Dark-Counting Rate (primary noise)

## Free Carrier Generation

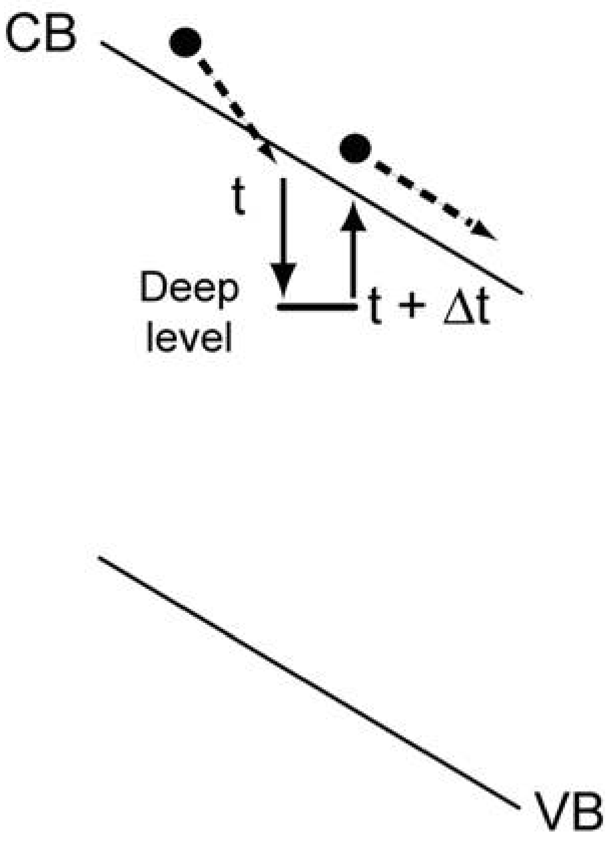


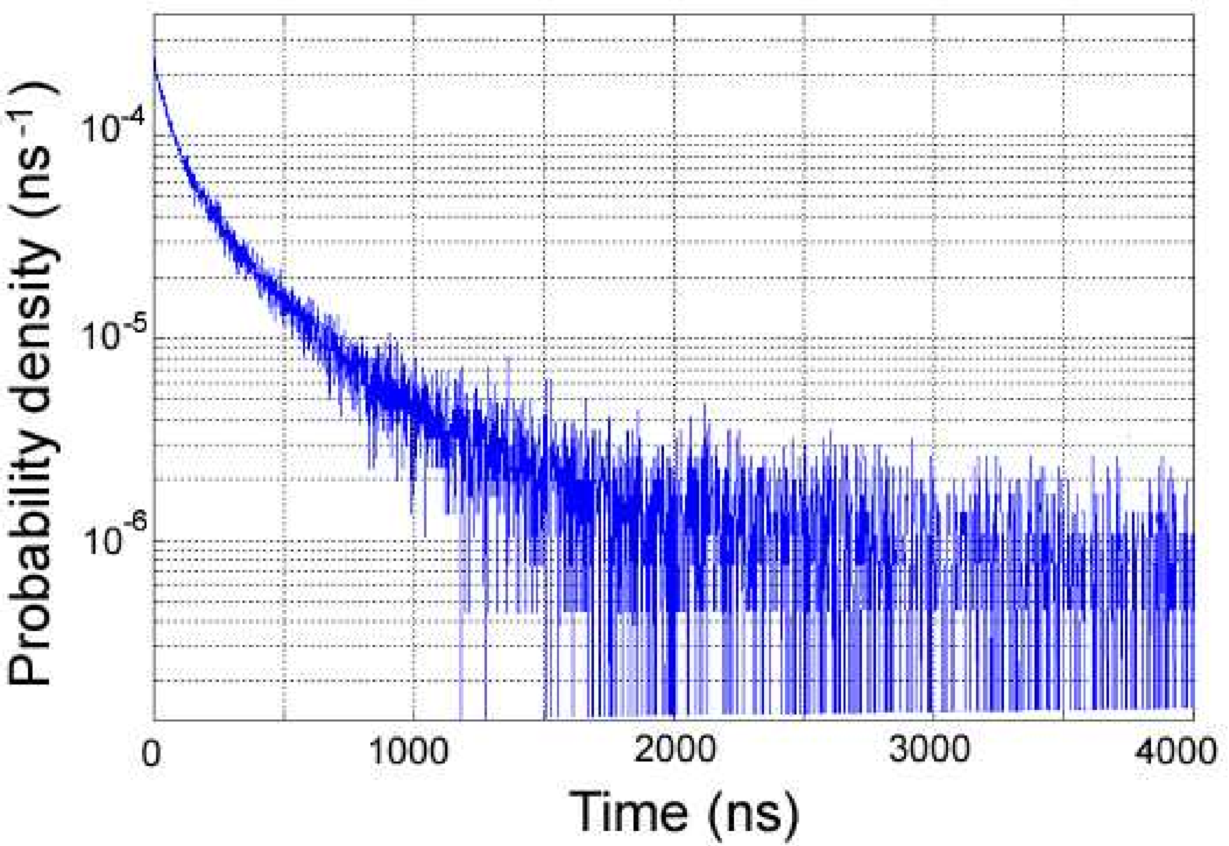

Generation - Recombination Centers



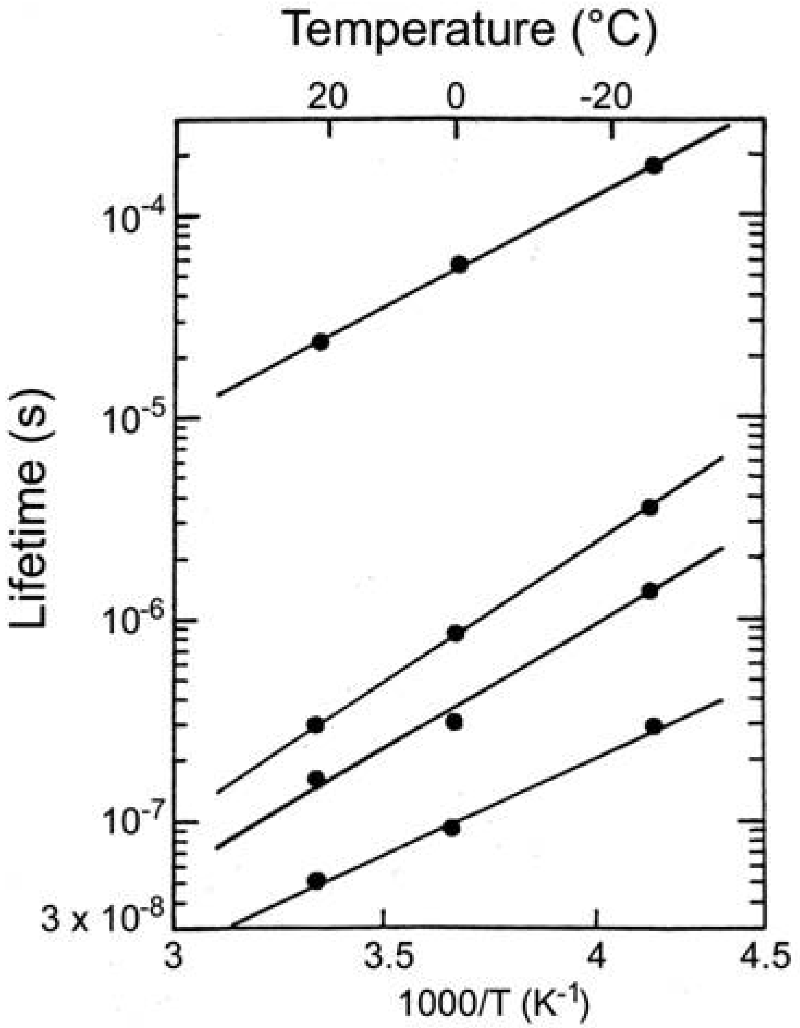

Field-Assisted Generation

# Carrier Trapping and Delayed Release → Afterpulsing



# Trapping and Afterpulsing




in operation @ low temperature

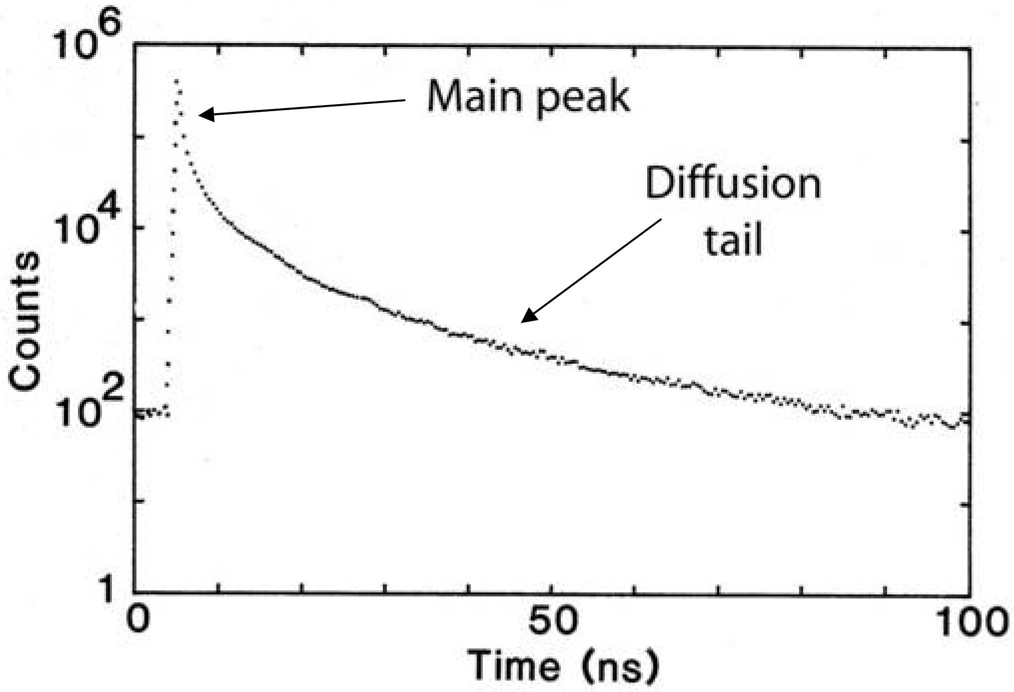
→ **slower trap release**

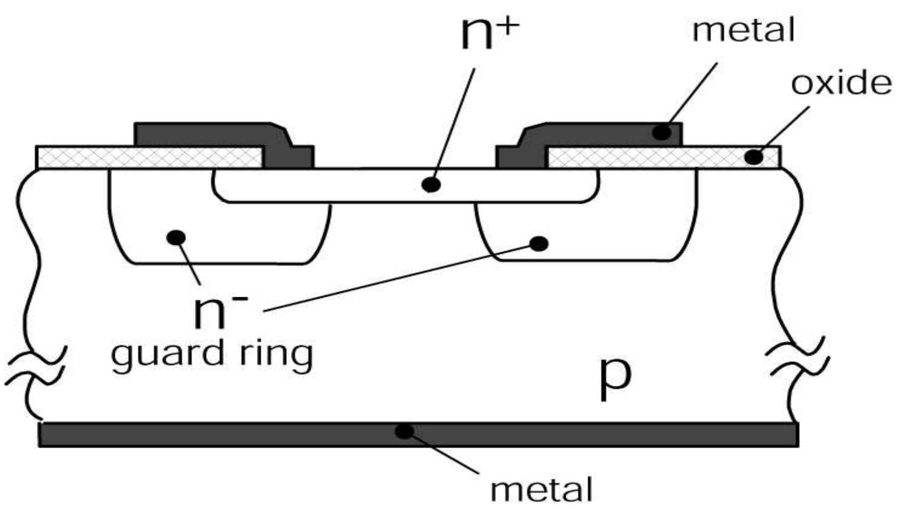
primary dark-counting rate is **reduced**

but afterpulsing is **enhanced !**

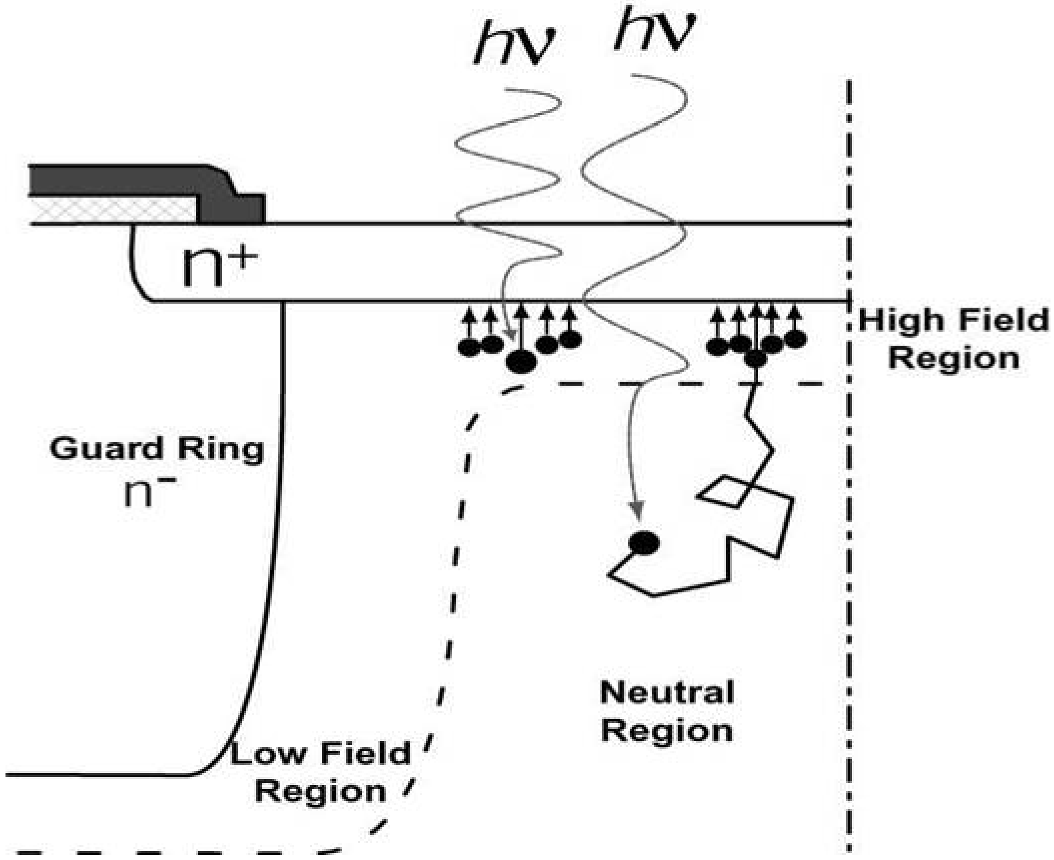
*S.Cova, A.Lacaita, G.Ripamonti, IEEE EDL (1991)*

# Photon Timing



# Photon Timing: Diffusion Tail




carrier diffusion in neutral layer

→ delay to avalanche triggering

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

# Photon Timing: main peak width

Statistical Fluctuations in the Avalanche

- Vertical Build-up (minor contribution)
- Lateral Propagation (major contribution)

- via Multiplication-assisted diffusion

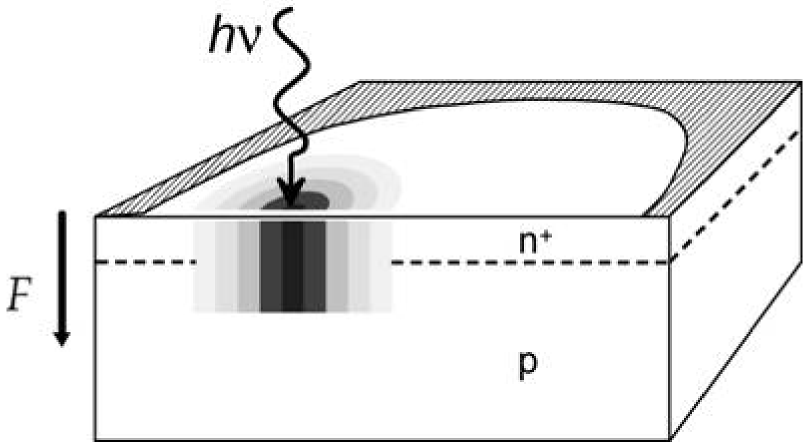
*A. Lacaita, M.Mastrapasqua et al, APL and El.Lett. (1990)*

- via Photon-assisted propagation

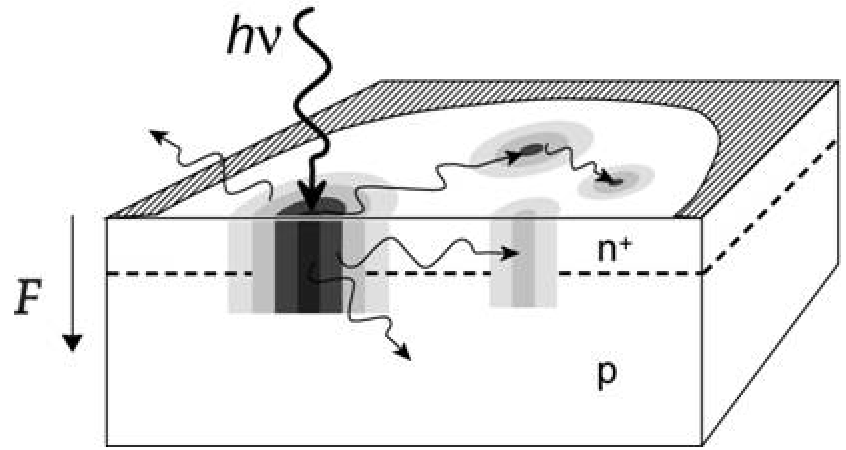
*P.P.Webb, R.J.McIntyre RCA Eng.(1982);*
*A.Lacaita et al, APL (1992)*

# Avalanche Lateral Propagation

Multiplication-assisted




Photon-assisted




higher excess bias voltage → improved time-resolution

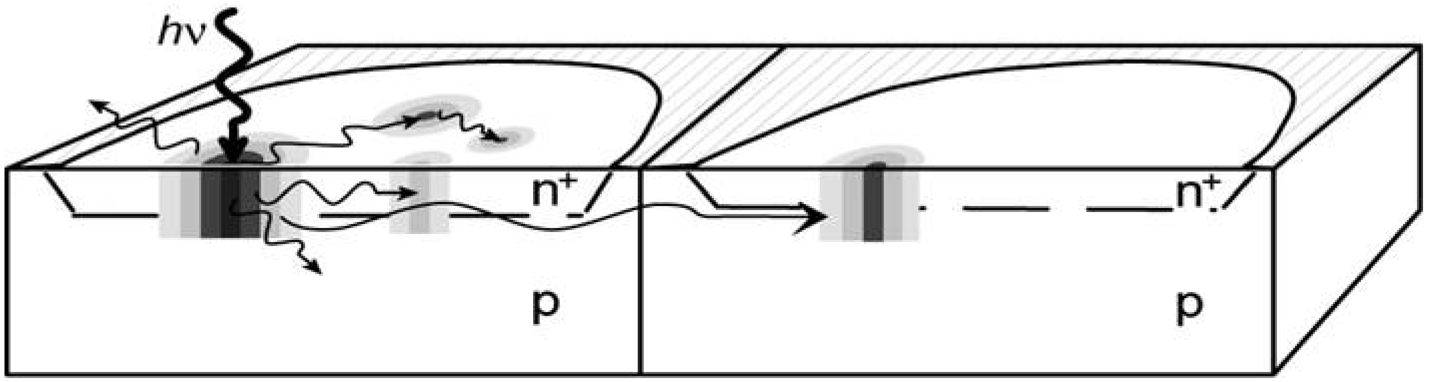
*A. Spinelli, A. Lacaita, IEEE TED (1997)*

# Arrays and optical crosstalk

Hot-Carrier Luminescence

**$10^5$** avalanche carriers → 1 emitted photon

*A. Lacaita et al, IEEE TED (1993)*




Counteract:

- Optical isolation between pixels
- Avalanche charge minimization

*F.Zappa et al, ESSDERC (1997)*

# Low Detector Noise

- For low dark-counting rate

  → Reduce GR center concentration

  → Reduce Field-assisted generation

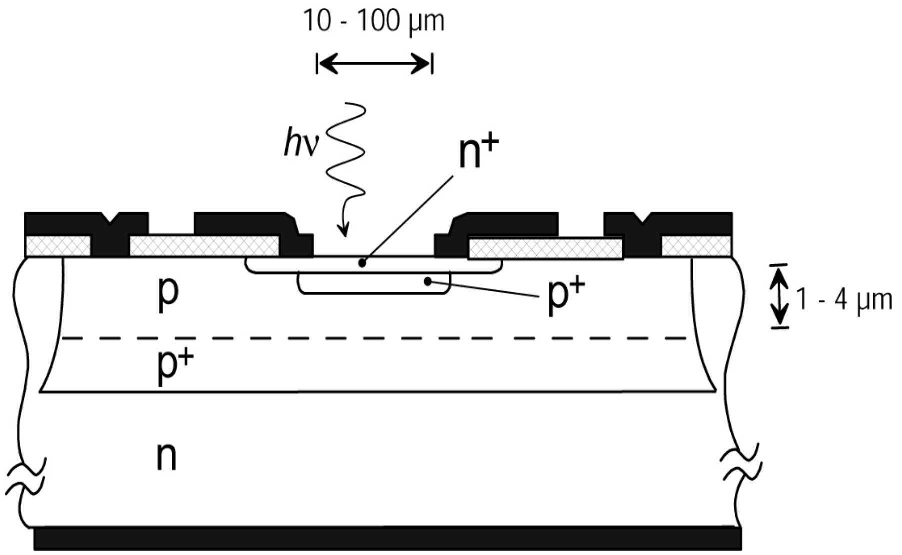
- For low afterpulsing probability

  → Reduce deep level concentration (minority carrier traps)

**Technology issue:**

**for wide sensitive area very efficient gettering is required!!**

## Thin Si SPAD



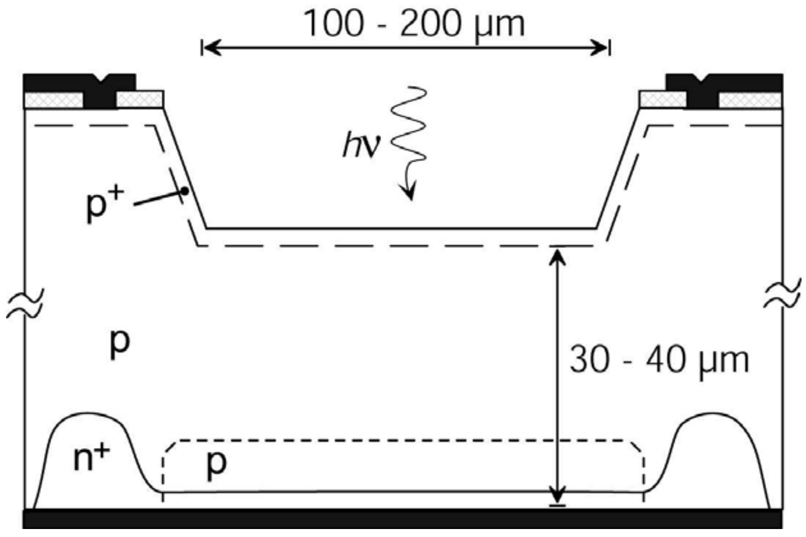

Planar structure

typical active region:

20 μm diameter

1 μm thick

## Thick Si SPAD




Reach-Trough structure

typical active region:

200 μm diameter

30 μm thick

## Thin Si SPAD's

- Good QE and low noise
- Picosecond timing

- Low voltage : 15 to 40V
- Low power : cooling not necessary

- Standard Si substrate
- Planar fabrication process
- COMPATIBLE with array detector and IC's (integrated circuits)
- Robust and rugged
- Low-cost
- NO COMMERCIAL SOURCE TODAY

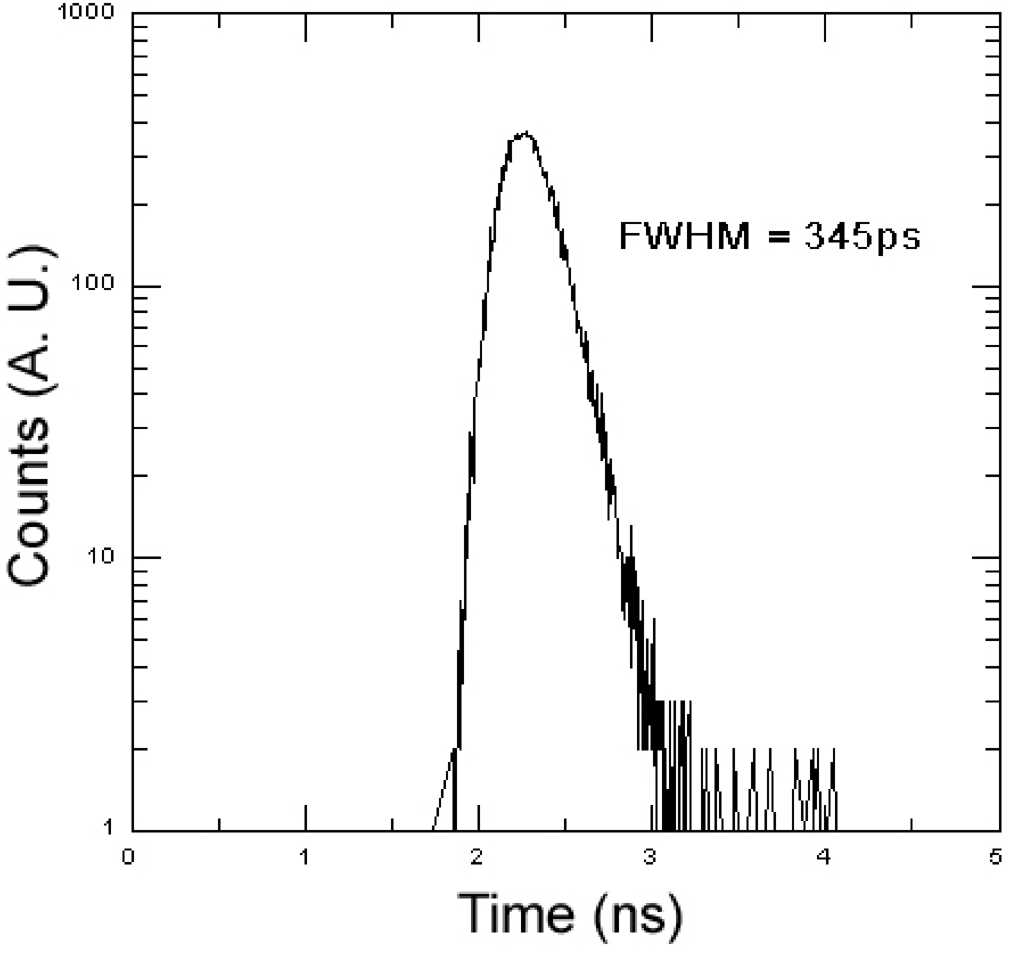
## Thick Si SPAD's

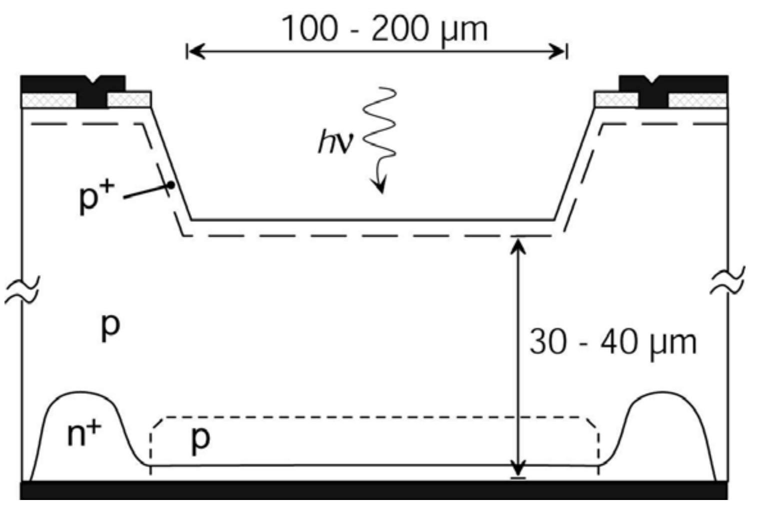
- Very good QE and low noise
- Sub-nanosecond timing

- High voltage : 300 to 400V
- High dissipation : Peltier cooler required

- Ultra-pure high-resistivity Si substrate
- Dedicated fabrication process
- NOT COMPATIBLE with array detector and IC's
- Delicate and degradable
- Very expensive
- SINGLE COMMERCIAL SOURCE

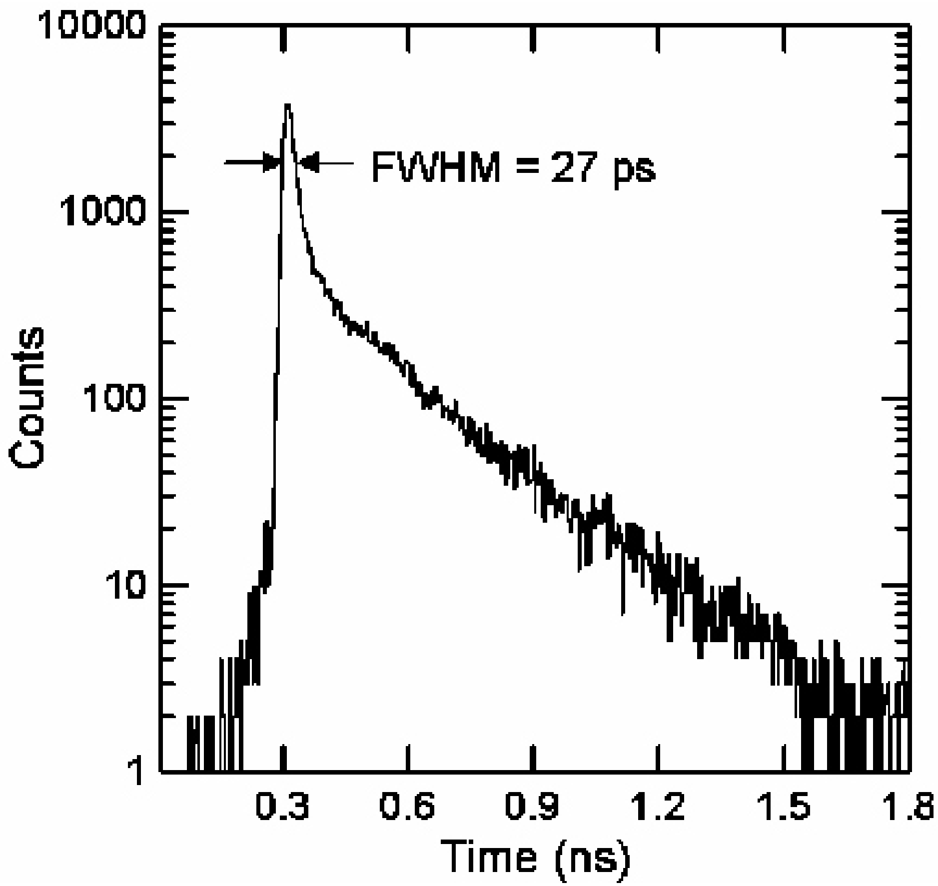
# Photon Timing: SLIK$^{TM}$ reach-trough structure



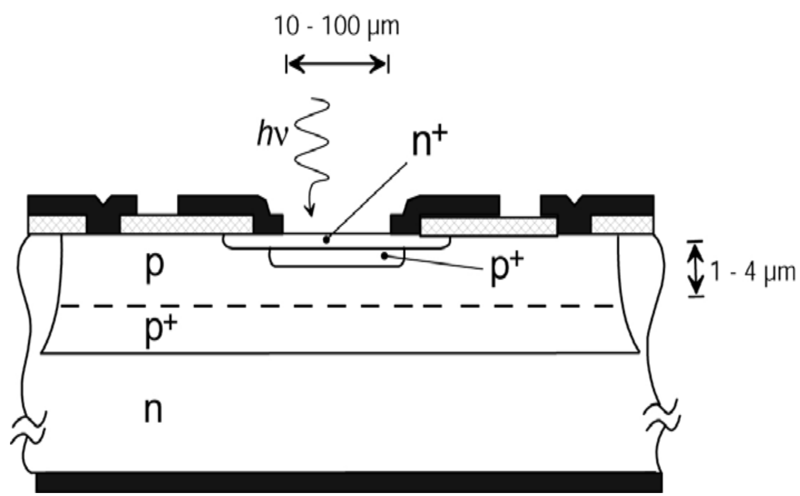

*H.Dautet et al, Appl.Opt. (1994)*

# Photon Timing: planar epitaxial structure



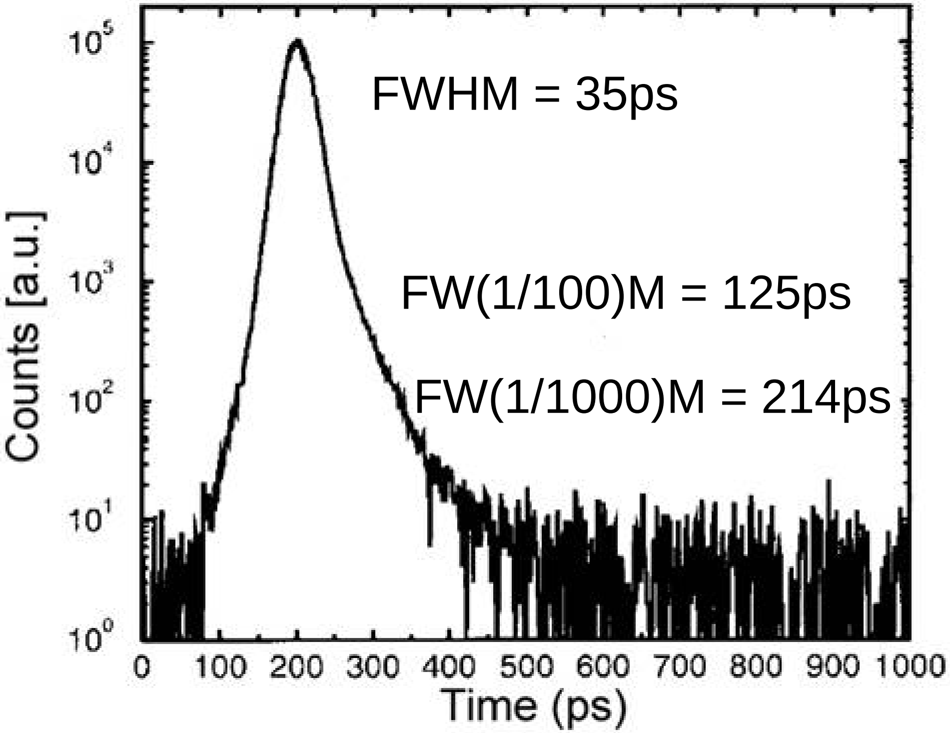

neutral p layer thickness **w**

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

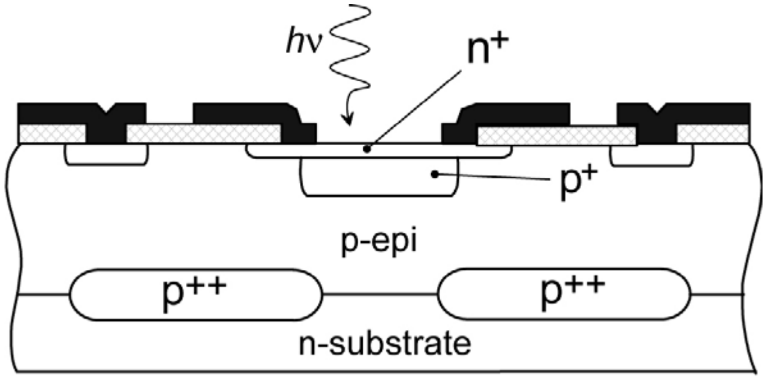



*A.Lacaita, M.Ghioni, S.Cova, Electron. Lett. (1989)*

# Photon Timing: diffusion-tail-free structure

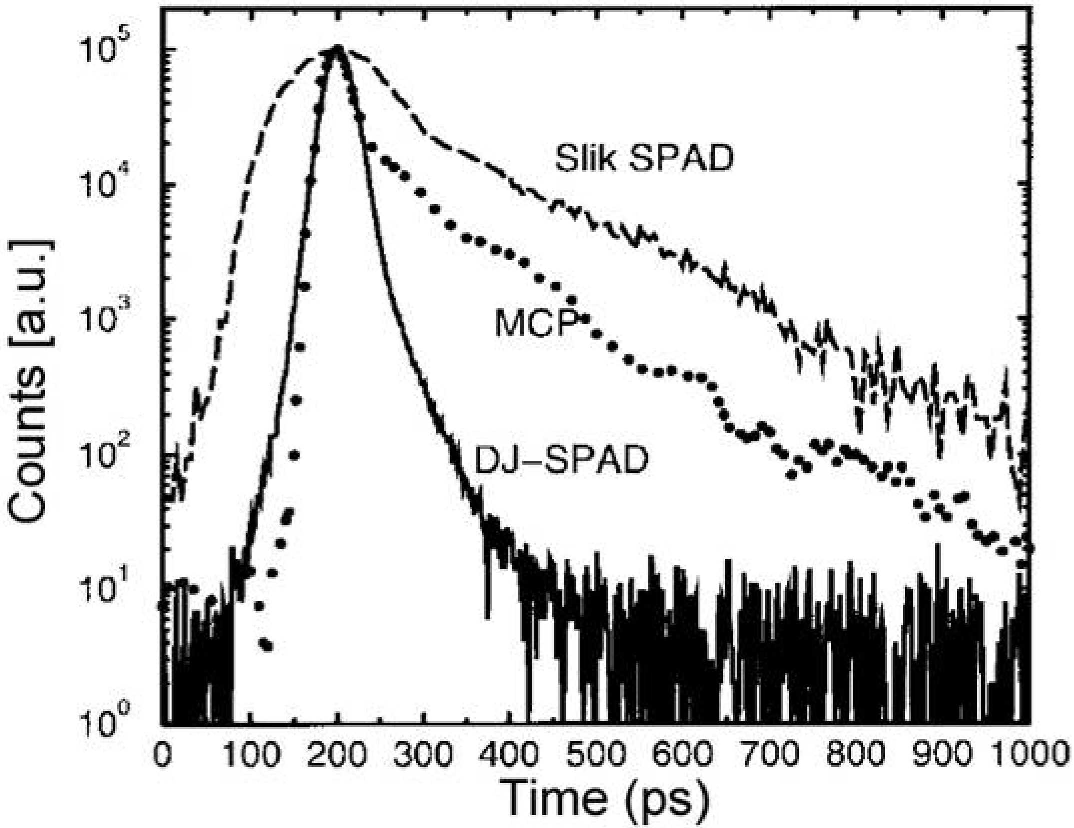



Dual-Junction epitaxial structure

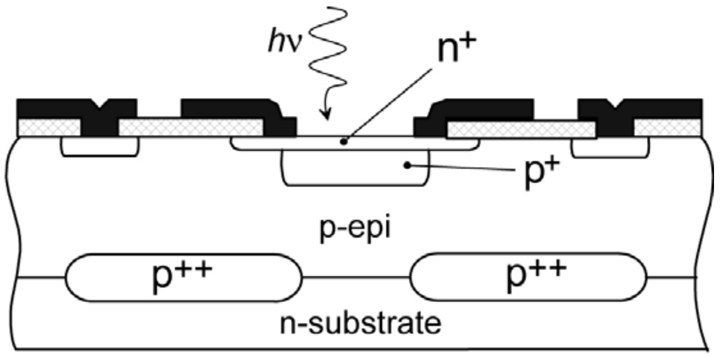



*A.Lacaita, S.Cova, M.Ghioni, F. Zappa, IEEE EDL (1993)*

# Photon Timing: diffusion-tail-free structure




Dual-Junction epitaxial structure




*A.Spinelli, M.Ghioni, S.Cova and L.M.Davis, IEEE JQE (1998)*

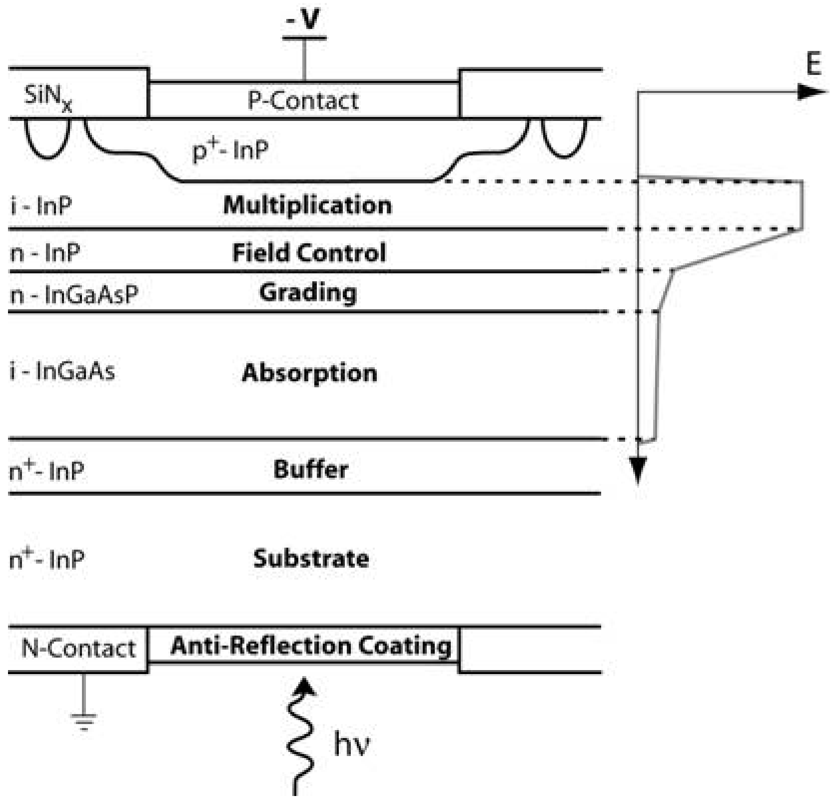
# IR spectral range : Ge devices

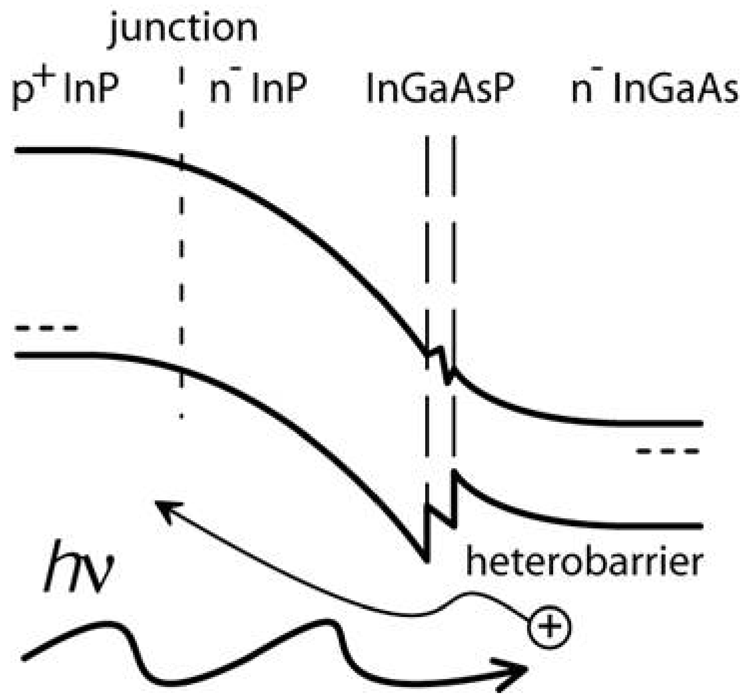
Similar to silicon devices, but

- deep cooling mandatory
- absorption edge below 1500nm @ low temperature
- very strong trapping effects
- strong field-assisted generation effects

*A.Lacaita, P.A.Francese, F.Zappa, S.Cova, Appl.Opt. (1994)*

# IR spectral range : InGaAs-InP devices

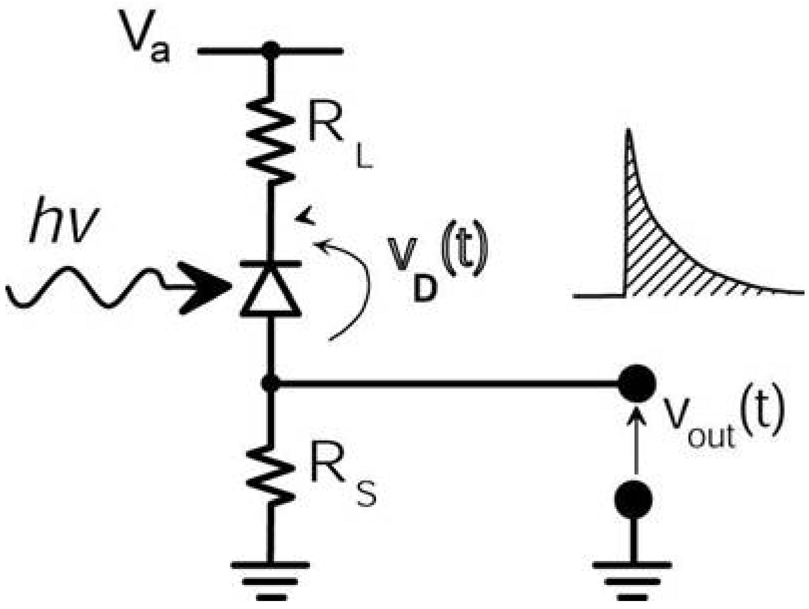


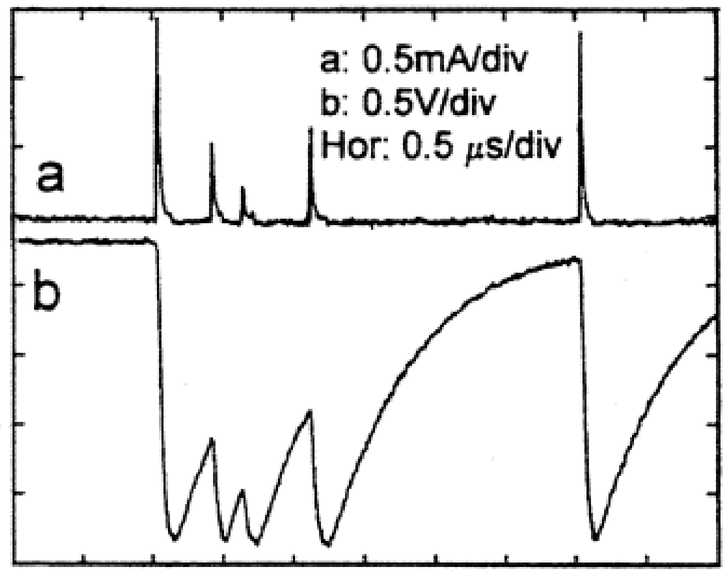




- very strong trapping
- fast-gated operation only!

*A.Lacaita, F.Zappa, S.Cova, P.Lovati, Appl.Opt. (1996)*

# Passive quenching is simple...



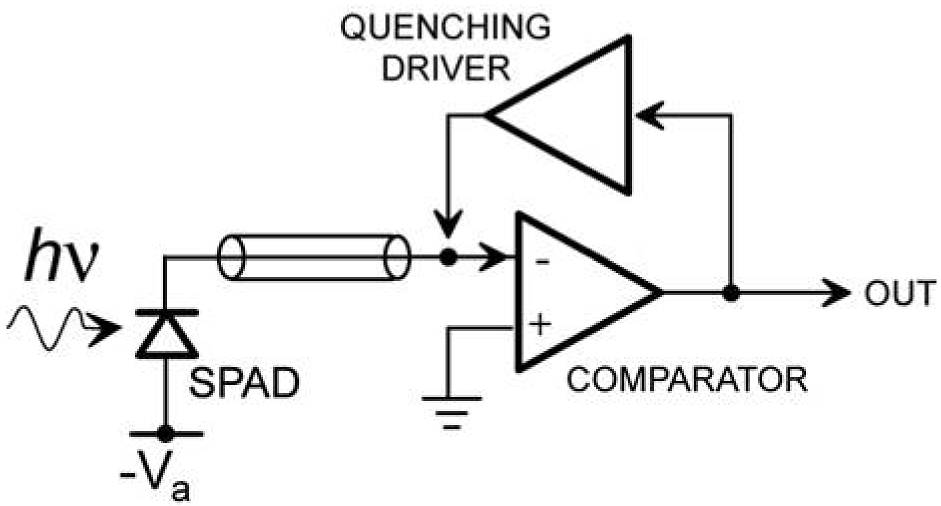

Current Pulses

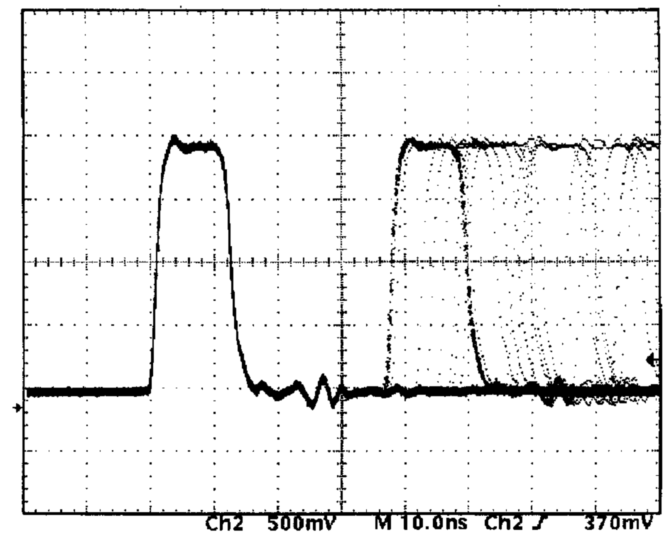
Diode Voltage

# … but suffers from

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

# Active quenching….




Output Pulses

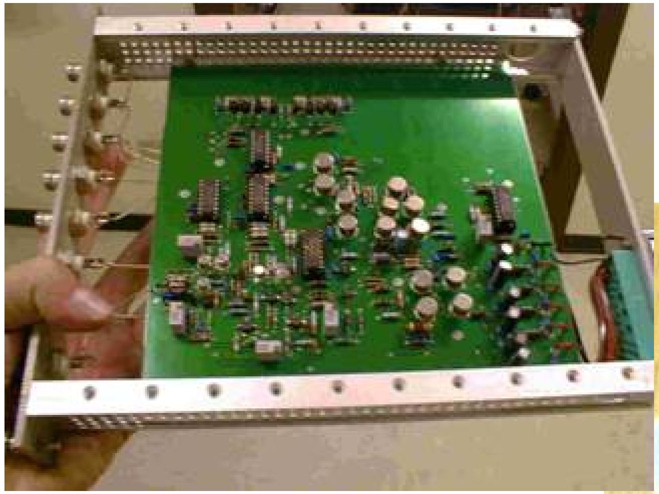
## ...provides:

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

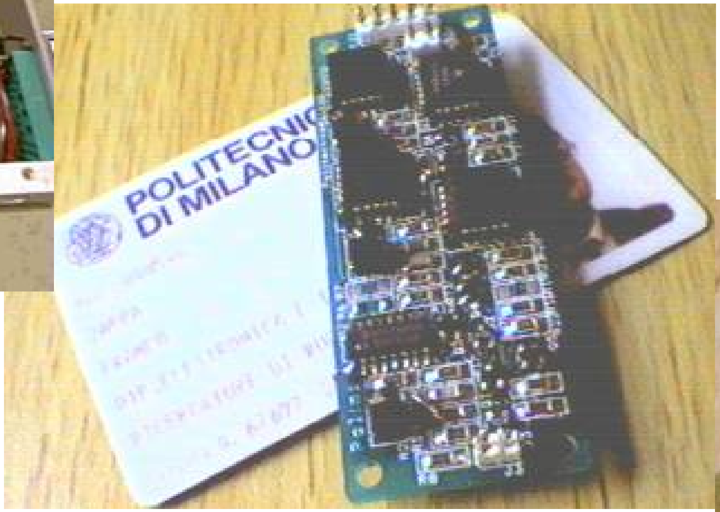
*P.Antognetti, S.Cova, A.Longoni*
*IEEE Ispra Nucl.El.Symp. (1975)*
*Euratom Publ. EUR 537e*

# AQC evolution

Earlier modules
in the 80's



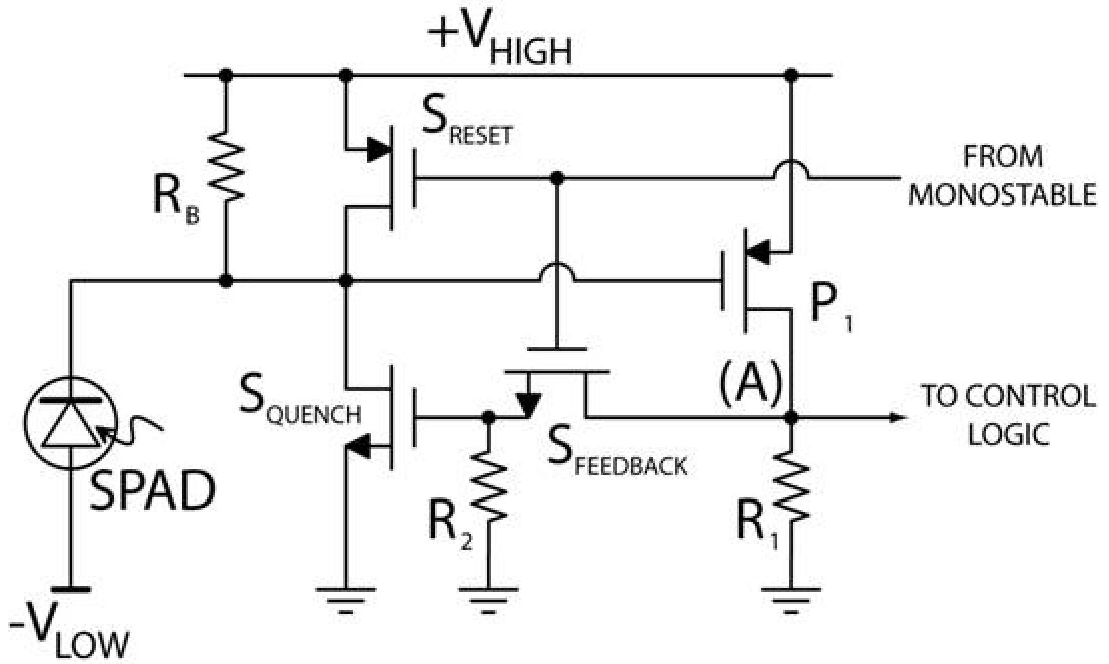
Compact modules
in the 90's




Integrated AQC
today

# iAQC - Integrated Active Quenching Circuit

Input sensing and quenching stage



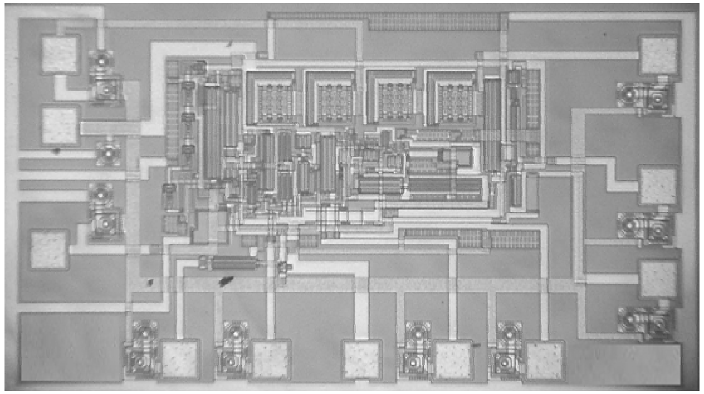

- *F.Zappa, S.Cova, M.Ghioni, US patent appl. March 5, 2001,*
  *(allowance notice Nov. 6, 2002, priority date March 9, 2000)*
- *F. Zappa et al, ESSCIRC 2002*

# iAQC - Integrated Active Quenching Circuit

$+V_{HIGH}$

+5V

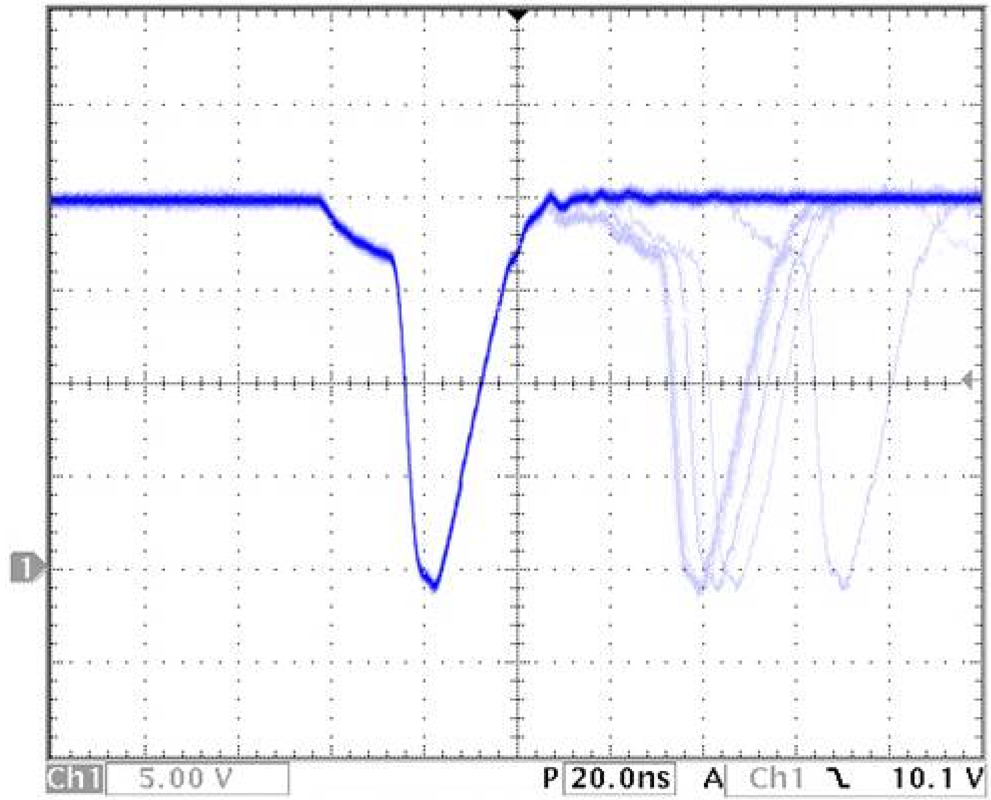
IN



OUT

GATE GND WIDTH

CMOS design



# iAQC - Integrated Active Quenching Circuit

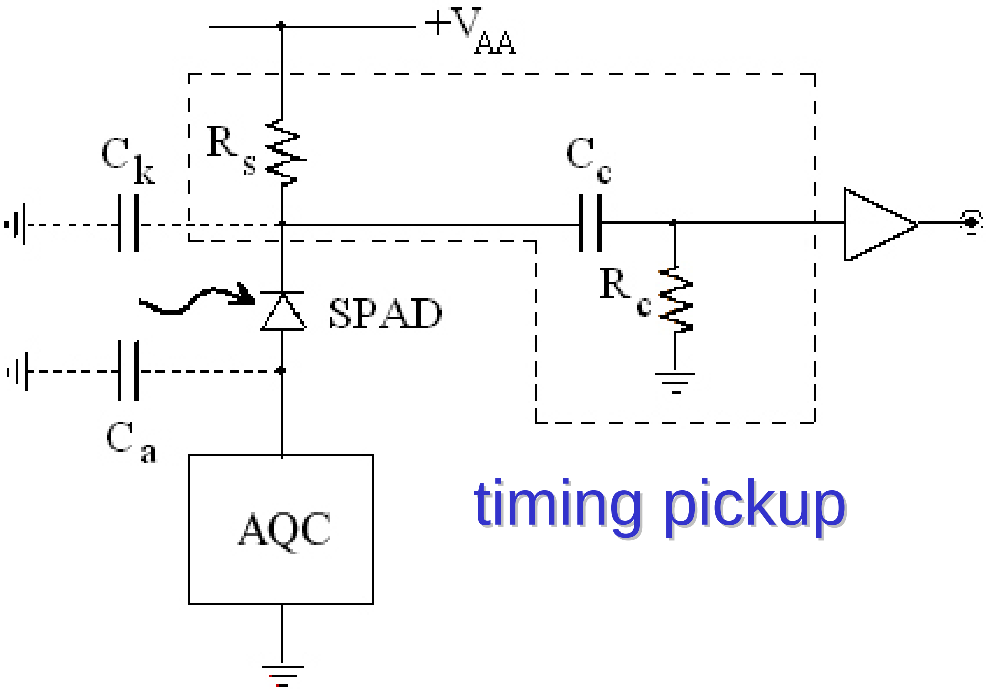
## Practical advantages

- Miniaturization → mini-module detectors
- Low-Power Consumption → portable modules
- Ruggedness and Reliability

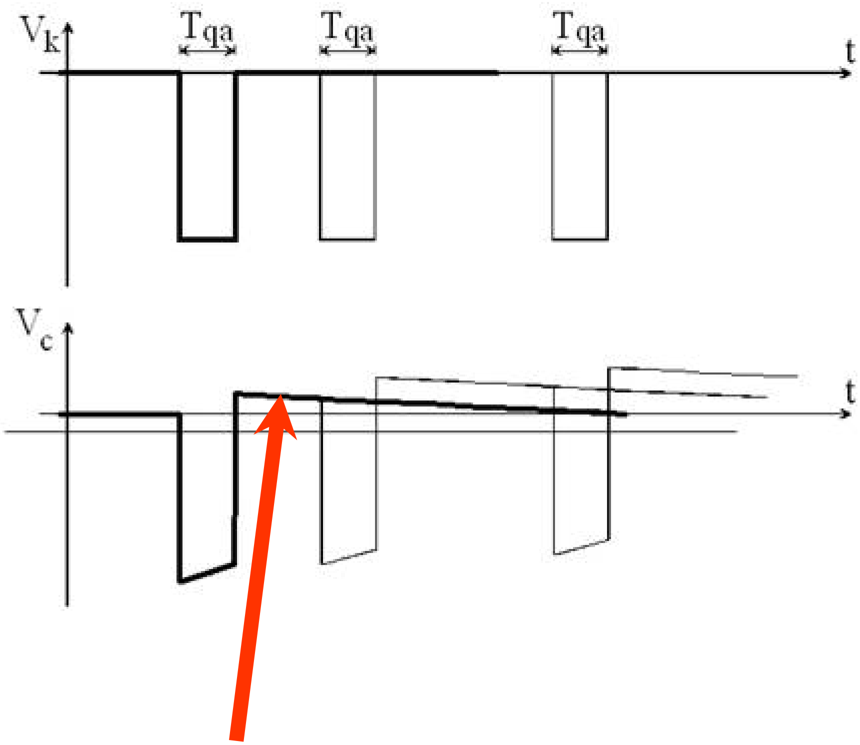
## Plus improved performance

- Reduced Capacitance
- Improved Photon Timing
- Reduced Avalanche charge
- Reduced Afterpulsing
- Reduced Photoemission → reduced crosstalk in arrays

# Can Photon-Timing be improved for existing AQCs?

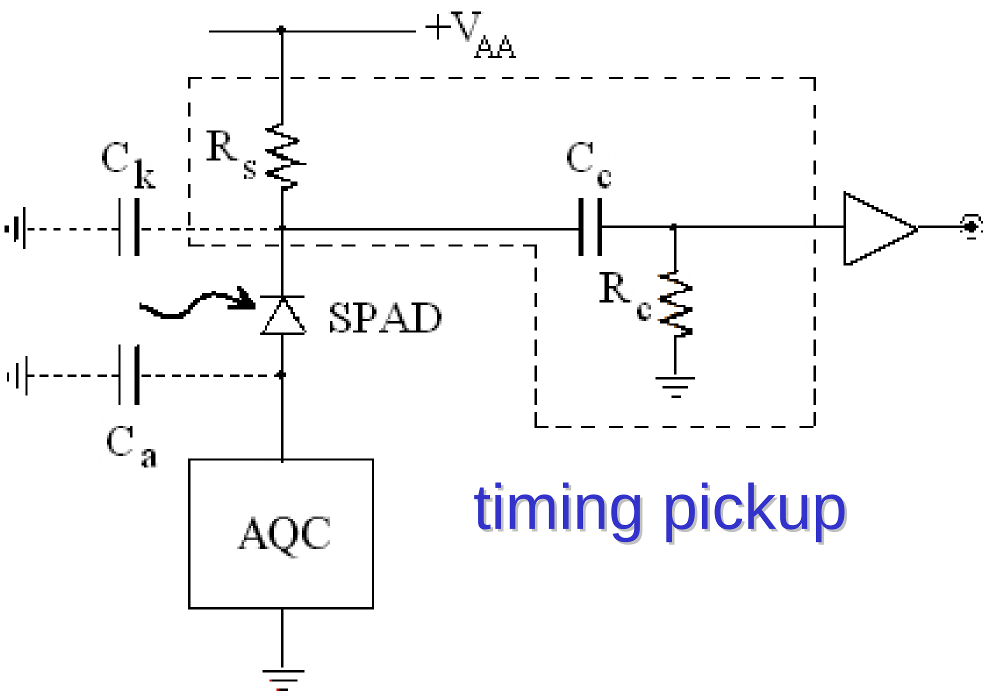



timing pickup

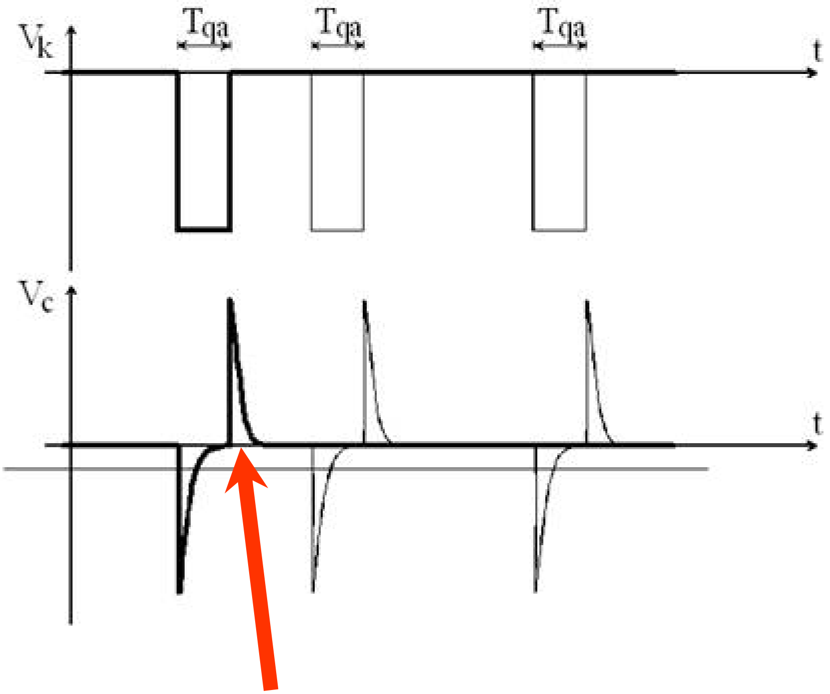



…in this way
it does not work properly

# Can Photon-Timing be improved for existing AQCs?




timing pickup

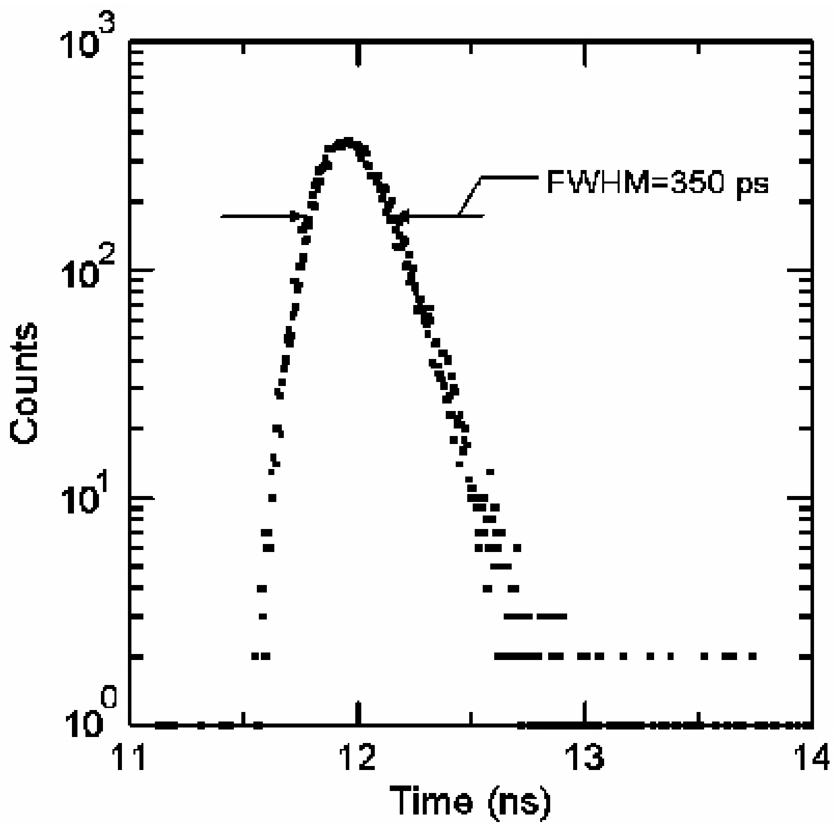



….in this way it does!!

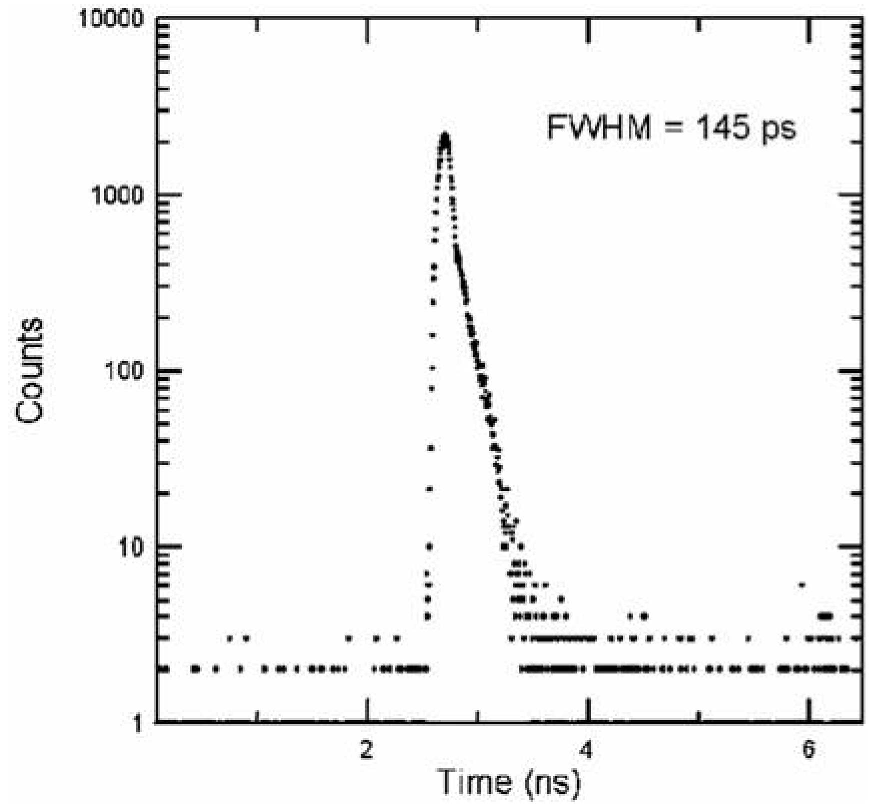
*S.Cova, M.Ghioni, F.Zappa, US patent No. 6,384,663 B2, date May 7, 2002 (priority date Mar 9, 2000)*

# Photon-Timing with PerkinElmer SLIK™ diode

with discrete-component AQC alone…



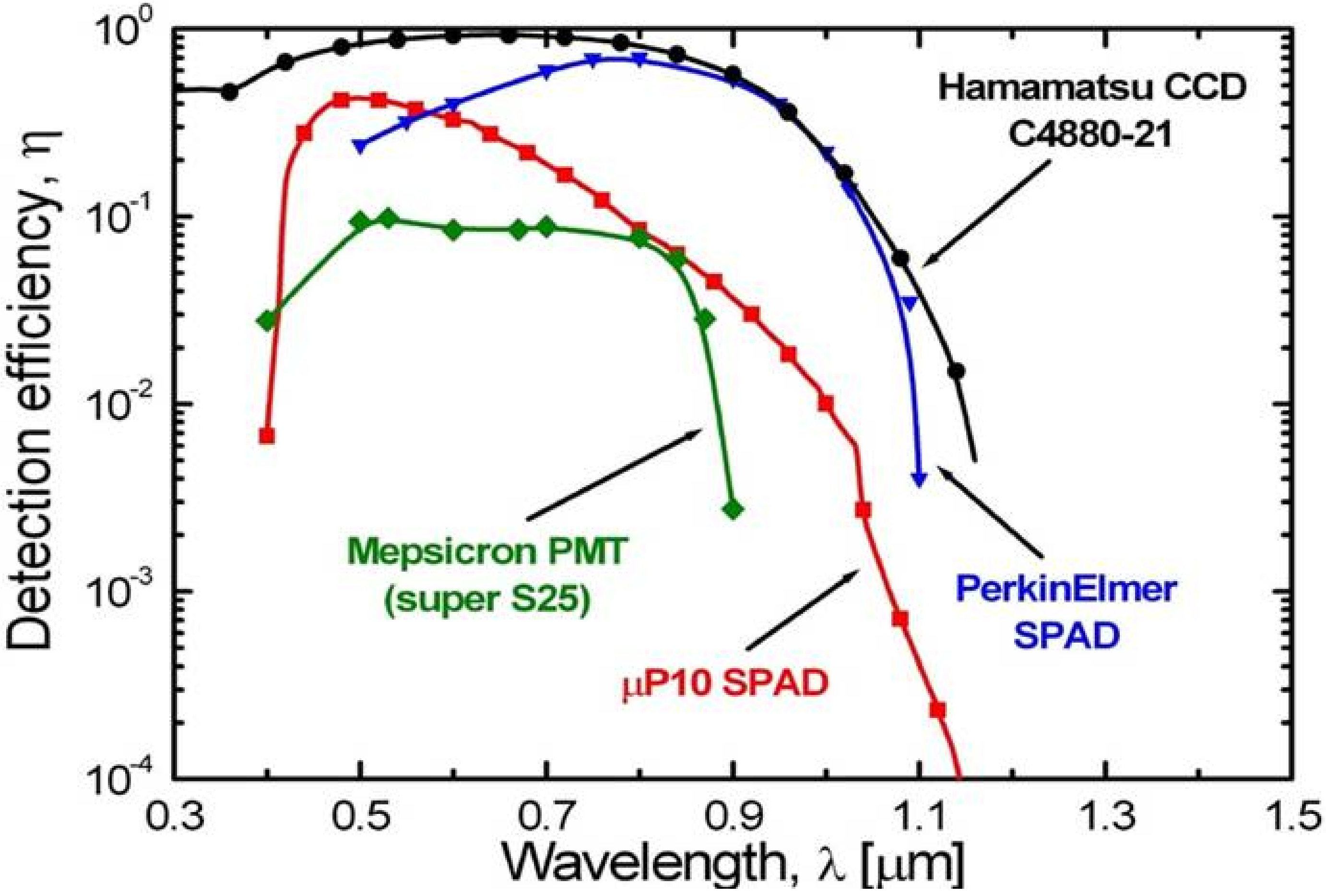

…and with additional timing circuit



# Conclusions and Outlook

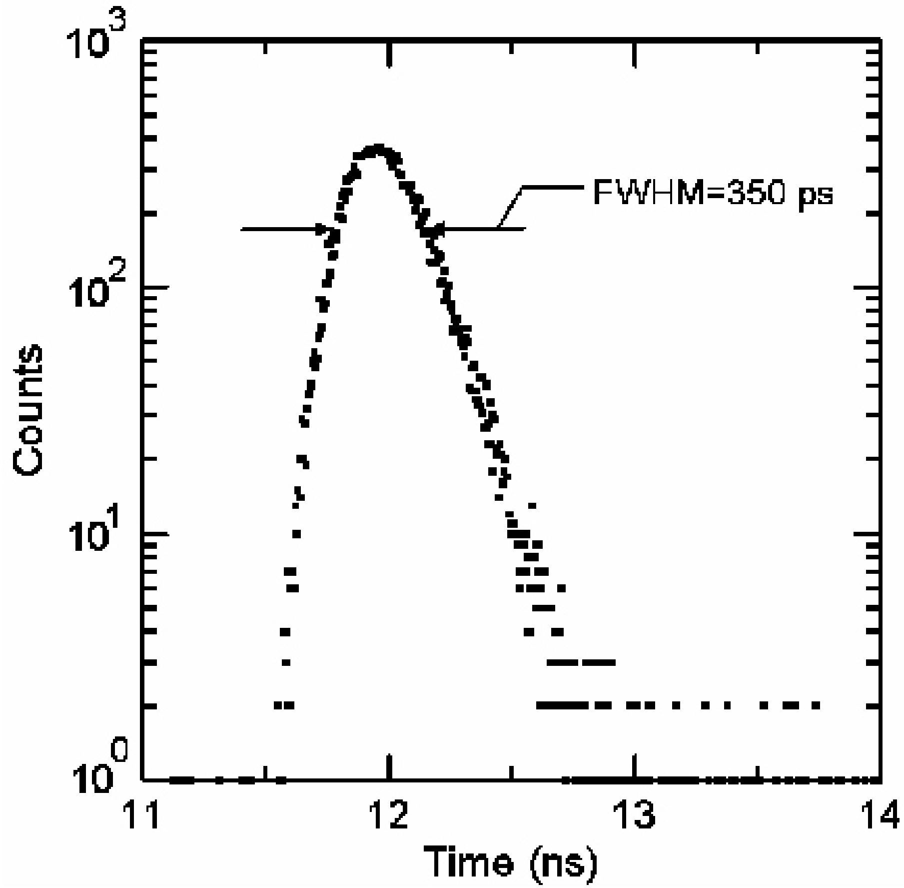
- Silicon SPAD technology
  is fairly advanced and can be further improved
- Low-cost highly efficient Si-SPADs
  appear now to be feasible
- Monolithic iAQCs
  make possible miniaturized (and even monolithic) detector modules
- SPAD Array detectors
  are a realistic prospect
- Ge, III-V and II-VI SPAD detector technologies
  require further progress, but may open remarkable new perspectives

# QE comparison



# Photon Timing comparison

PerkinElmer SPCM (SLIK™ diode)




Planar thin Si-SPAD