Development of Silicon Photomultipliers @ IRST

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Outline

- IRST and its activity on Si rad. det.
- Silicon Photomultipliers:
  - General considerations
  - Development @ IRST:
    - * technology
    - * results
    - * future developments

ITC-irst

ITC (Istituto Trentino di Cultura) is a public research institute in Trento mainly funded by the local government

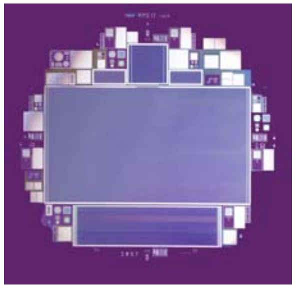
ITC

ITC-irst
Istituto per la ricerca scientifica e tecnologica

ITC-irst → **250 researchers working mainly on:**

- **microsystems & physics**
- **information technology**

Microsystems Division

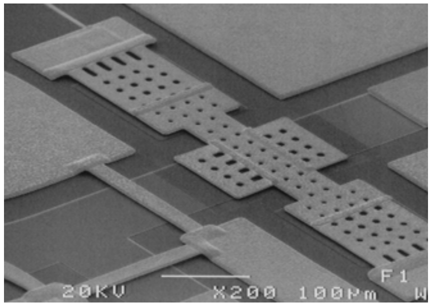


ITC

ITC-irst

Microsystems Division

research areas



MEMS
Biosensors and MEMS
(12 researchers)

SRD
Silicon Radiation Detectors
(6 researcher)

SOI
CMOS-based optical sensors
(14 researchers)

Microfabrication Laboratory

in which silicon devices are produced

Laboratories

Furnaces

MICROFABRICATION LAB.:

- Ion Implanter
- Furnaces
- Litho (Mask Aligner)
- Dry&Wet Etching
- Sputtering & Evaporator
- On line inspection
- Dicing

Automatic probe station

TEST LAB.:

- Automatic probe station
- Manual probe station
- Optical bench

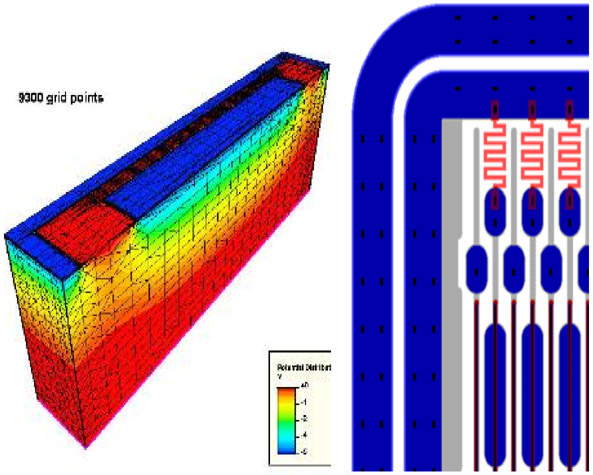
SRD group

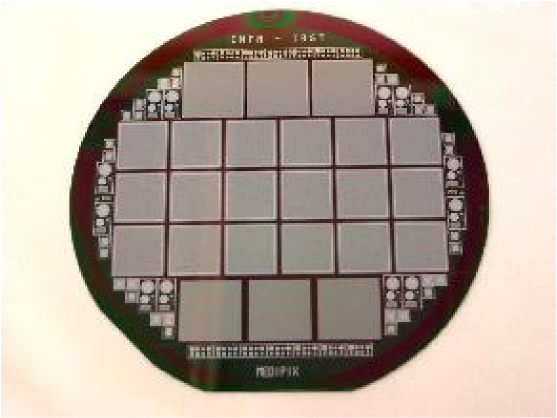
Aim: development and production of radiation detectors.

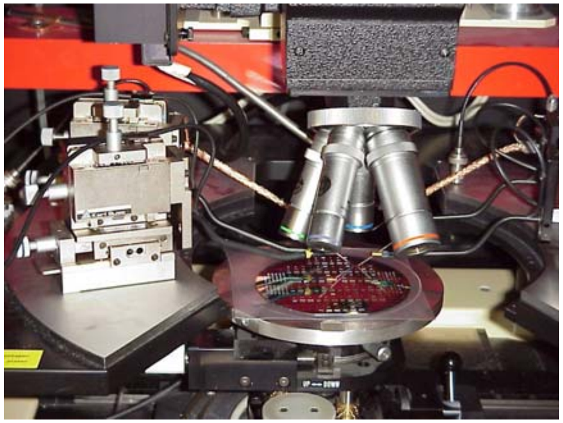
We have been working in this field since 1994.

Our expertise covers the main aspects of the development:

TCAD simulation
CAD design → Fabrication → Device testing







Main activities

“Standard” technology

From the specifications given by the “user”
we design, produce, and (electrical) test the detector.

Examples:

- **single/double-sided strip detectors**
- **p-on-n/n-on-n pixel detector**

R&D activities

Development in cooperation with the partners

Examples:

- **very thin detectors**
- **3D detectors**
- **silicon photomultipliers**
- **radiation hard silicon detectors**

Standard tech: strip detectors

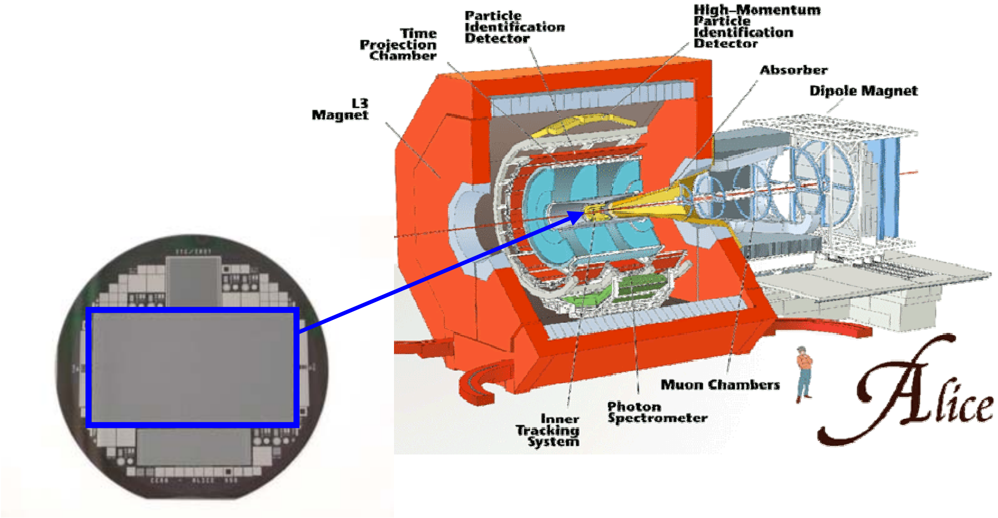
AMS experiment

Detector characteristics:

- Area: 7.2x4.2cm^2
- double-sided with orthogonal strips
- DC coupled
- spec: defective strips < 0.5% per side

700 in spec detectors were fabricated (2002-2004).

ALICE experiment



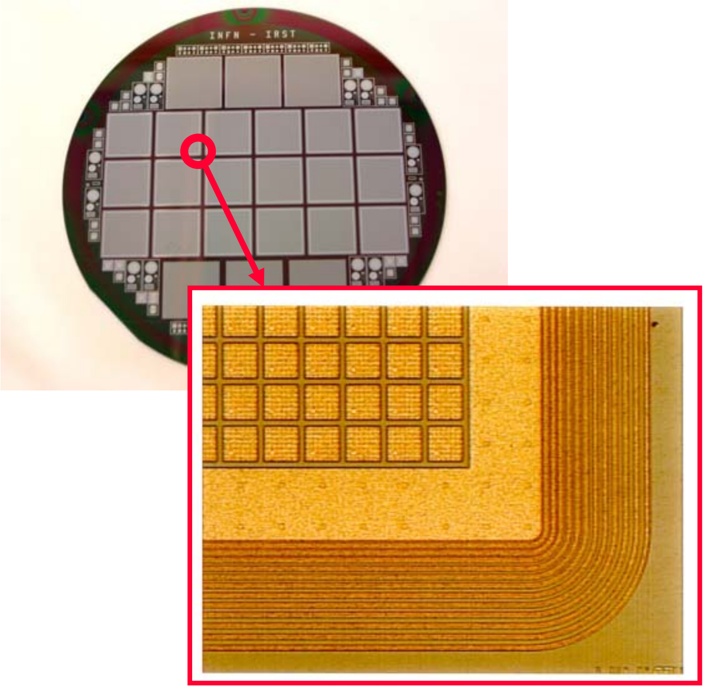
Detector characteristics:

- Area:7.5x4.2cm^2
- double-sided with strips slightly tilted
- AC coupled
- spec: defective strips <3% per detector

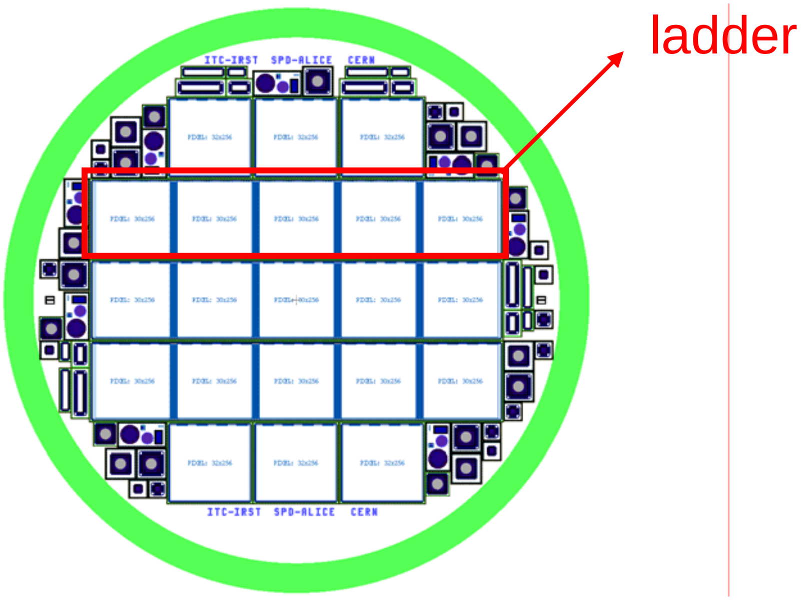
600 in spec detectors were fabricated (2003-2005).

Standard tech: pixel detectors

Medipix 1&2



NA48/ALICE experiment



- Medipix1: pixel size 170x170μm^2
- Medipix2: pixel size 55x55μm^2

- ALICE SPD layout
- pixel size 50x400μm^2

Substrate thick.: up to 1.5mm → **Substrate thickness: 200μm**

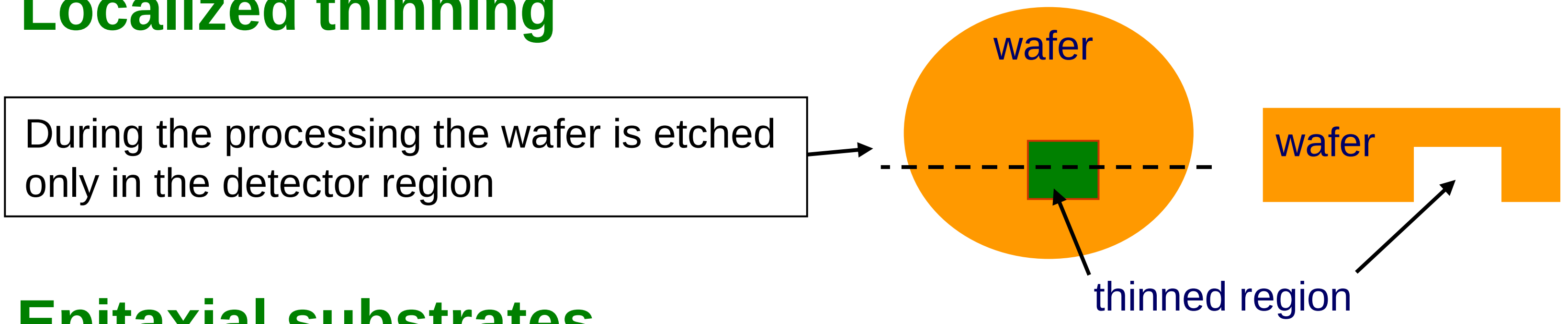
R&D 1: Thin detectors

Thin detectors:
mainly for silicon trackers requiring low material budget.

Problem: with standard machines it is difficult to handle wafers with thickness below 150μm.

Two approaches:

1) Localized thinning


During the processing the wafer is etched only in the detector region

2) Epitaxial substrates


At the end of the process, subst. is removed

We already produced sensors with both technologies

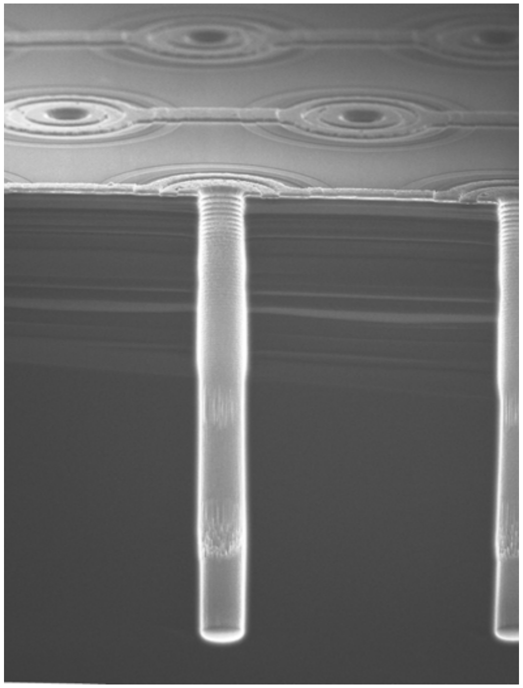
R&D 2: 3D detectors

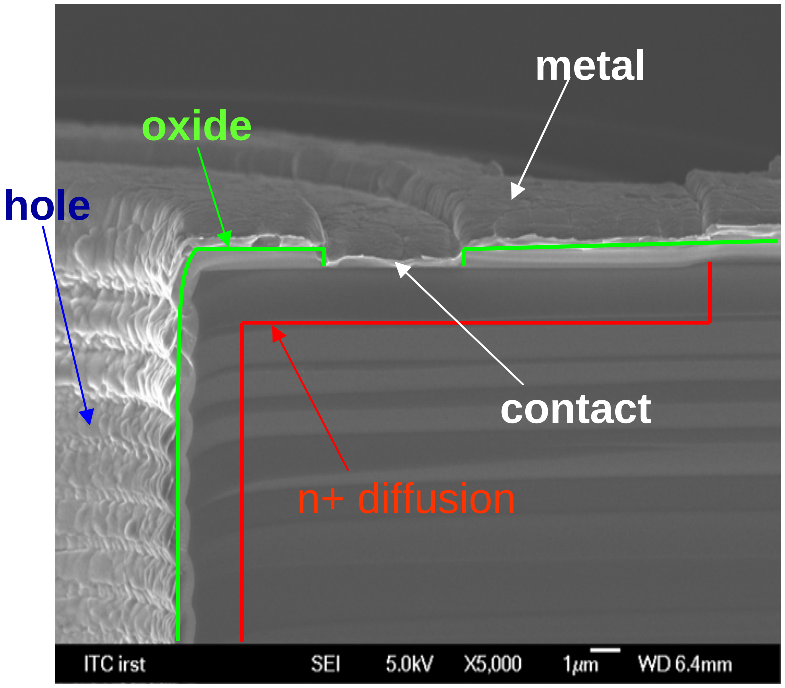
Electrodes are columns which penetrate into the bulk.

Distance between n and p electrodes can be made very short

→ **extremely radiation hard detector**

(low full depl. volt. and high CCE even at very high fluences)





SEM pictures of our devices

Col. depth 180µm
Col. width 10µm

More info on http://infn-tredi.itc.it
http://tredi.itc.it

R&D 3: Rad-hard silicon

Effects of rad. damage: 1. growth of leakage current
2. growth of depletion voltage
3. loss of charge collection efficiency

Techniques to moderate these detrimental effects:

1. apparently nothing can be done.

2. use of oxigen-rich substrates:
   - DOFZ substrates
   - Cz/MCz substrates
   - Epitaxial substrates

3. use of p-type substrates

   in order to collect electrons which have higher mobility

We have produced/are producing detectors on this non-standard silicon within the CERN RD50 collaboration

Silicon Photomultipliers

- General considerations

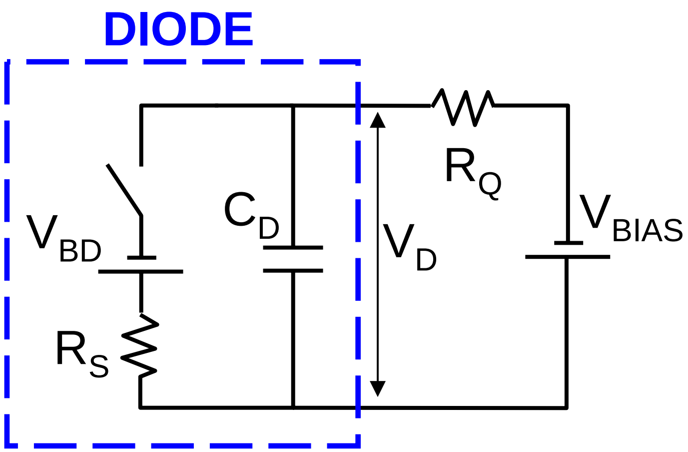
- Development @ IRST:
  - * technology
  - * results
  - * future developments

GM-APD

The building block of a SiPM is the Geiger-mode APD

First modeled in the ’60 to study micro-plasma instabilities in p-n junctions
[R.J. McIntrye, JAP vol.32, n.6 **1961**; R. Haitz, JAP vol.35, n.5 **1964**]

The GM-APD can be modeled with **an electrical circuit and two probabilities**:



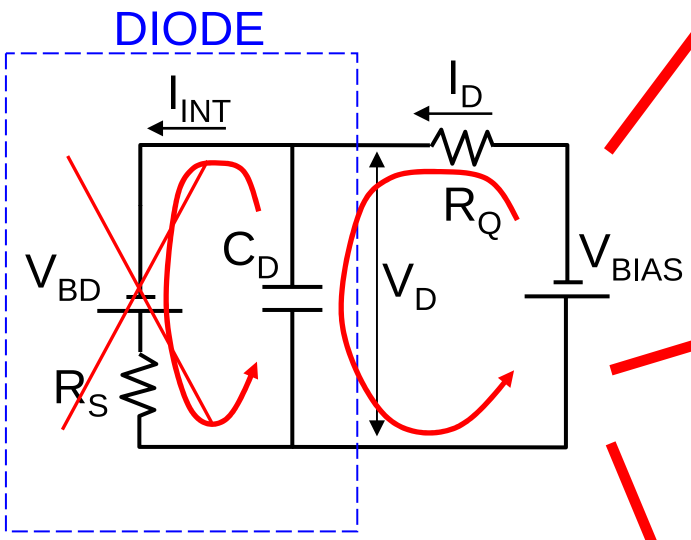
- C_D = diode capacitance
- R_s = series resistance (~1kΩ)
- V_{BD} = breakdown voltage

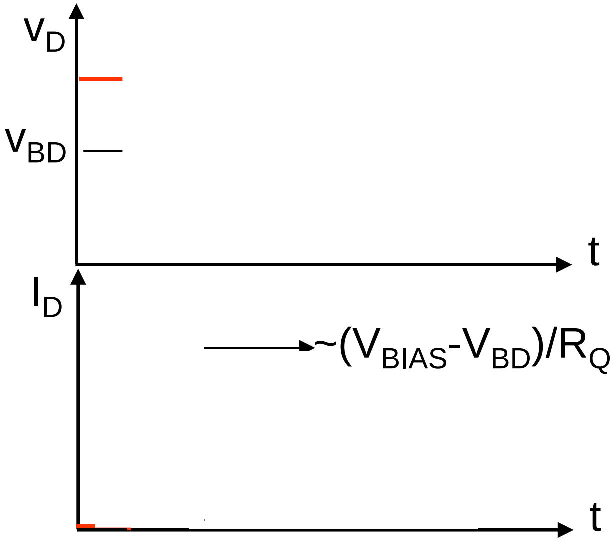
- R_Q = quenching resistance (>300kΩ)
- $V_{BIAS} > V_{BD}$

- P_{01} = Triggering probability
- P_{10} = turn-off probability

which govern the switch transition

Model of a GM-APD





OFF condition: switch open,
(capacitance charged to V_{BIAS}, no current flowing)

⬇

Avalanche triggering (P_{01})

⬇

ON condition: switch closed
⇒ C_D discharges to V_{BD} with
a time constant R_SxC_D, at the same time
the external current grows to $(V_{BIAS}-V_{BD})/R_Q$

⬇

Avalanche quenching (P_{10})

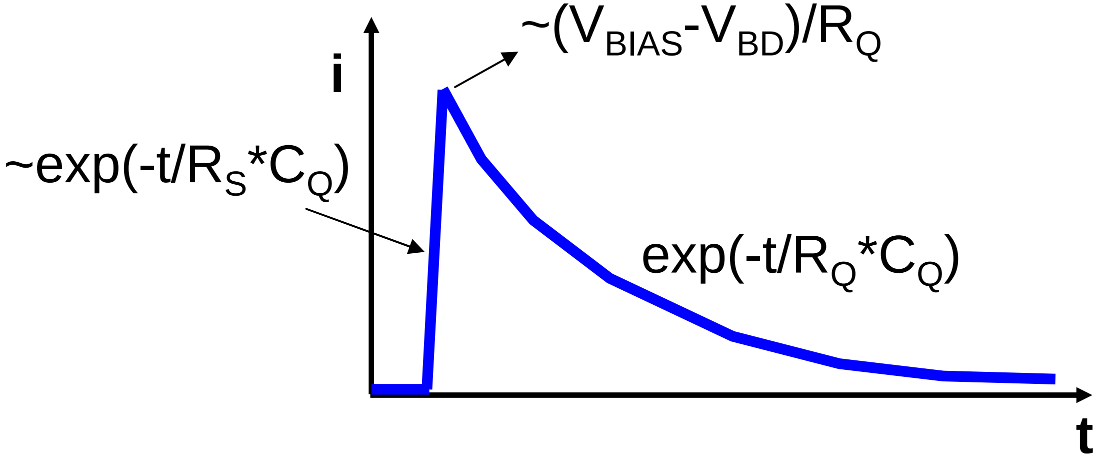
⬇

OFF condition: switch open
⇒ diode capacitance recharghes from V_{BD}
to V_{BIAS} with a time constant R_QxC_D

⬇

Ready for new detection

GAIN in GM-APD



The first part of the signal is much faster than trailing edge

- charge collected per event is the area of the exponential decay which is determined by circuital elements and bias.

- **It is possible to define a GAIN**

$$\textbf{Gain} = \frac{I_{MAX}{*}\tau_Q}{q} = \frac{(V_{BIAS}-V_{BD})}{R_Q}\frac{{*}\tau_Q}{q} = \frac{\mathbf{(V_{BIAS}-V_{BD}){*}C_D}}{\mathbf{q}}$$

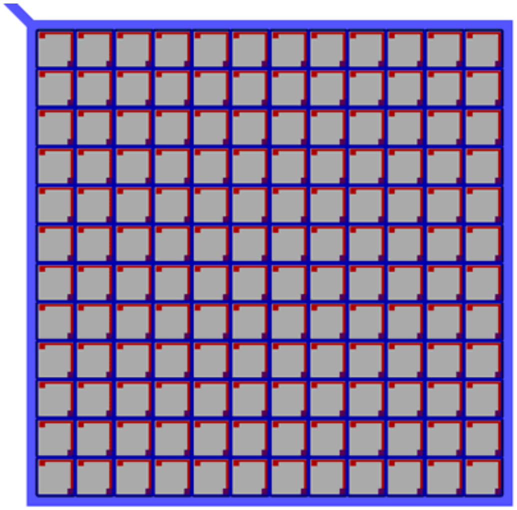
This property is exploited in a Silicon photomultiplier….

The SiPM

GM-APD gives no information on light intensity when irradiated with short (in time) bunches of photons

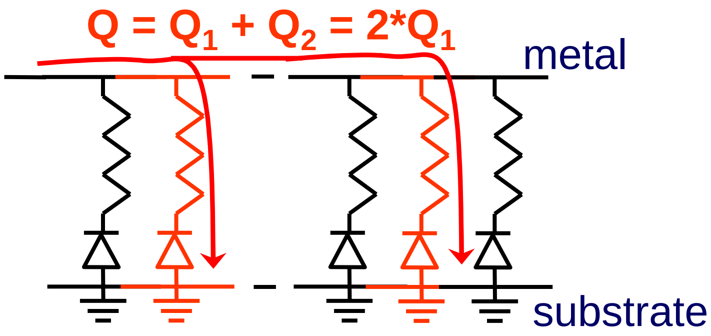
SiPM

first proposed by Golovin and Sadygov in the ’90s



A single GM-APD is segmented in tiny micro GM-APD connected in parallel.

Each element is independent and gives the same signal when fired by a photon



⇒ output charge is proportional to the number of triggered cells that, for PDE=1, is the number of photons

Important parameters of a SiPM

- **Gain** → $G=(V_{BIAS}-V_{BD})*C_D/q$

- **Noise**: primary dark count;
  after-pulse;
  optical cross-talk;
  → pulses triggered by non-photogenerated carriers

- **Photodetection efficiency** → Given by 3 factors:
  - Quantum efficiency
  - Triggering probability
  - Area efficiency

- **Dynamic range** → linked to the density of microcells

- **Time resolution** → linked to the collection process and avalanche propagation

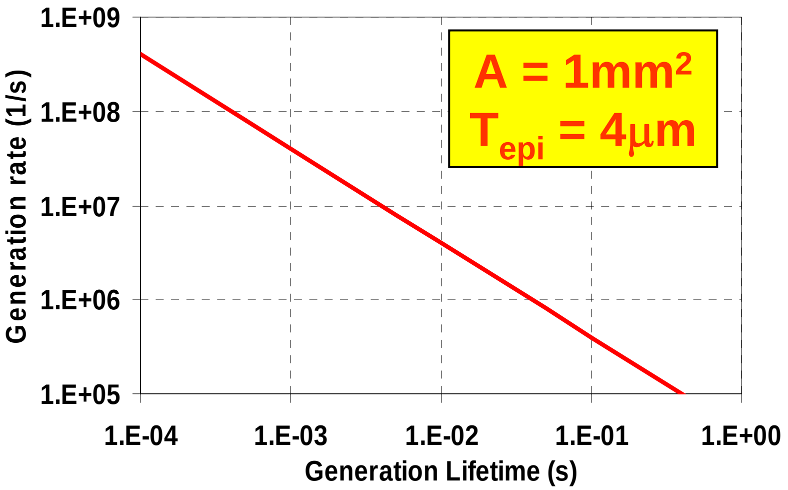
Noise (1)

1) Primary DARK COUNT

Main source of carriers: **SRH generation in the depleted region.**

- Generation rate: $G_t = \frac{n_i}{\tau_g} \quad (1/cm^3 s)$

n_i = intrinsic carrier concentration
τ_g = generation lifetime
~ **1/number of gen. centers**



A = 1mm²
T_{epi} = 4μm

Estimation of the generation rate at room temperature

[trap-assisted tunneling not considered]

$DC = P_{01} * A_e * G_t$

~ $0.5*0.5*G_t = 0.25*G_t$ p+/n junction
~ $1 \; *0.5*G_t = 0.5*G_t$ n+/p junction

τ_g=10ms -> DC = 2MHz (n+/p) (in FZ silicon we were able to obtain τ_g~500ms)

Critical points: **quality of epi silicon**; **gettering techniques.**

Noise (2)

2) Afterpulsing:

carriers are trapped during the avalanche and then released triggering an avalanche

$$\boxed{P_a(t) = P_c \cdot \frac{\exp(-t/\tau)}{\tau} dt \quad \cdot \quad P_{01}}$$

After-pulse probability at time t

P_c – trap capture probability, depends on:

- number of traps
- number of carriers flowing during an avalanche

P_{01} – triggering probability, depends on:

- bias voltage
- the recovery condition of the micro-cell

τ – trap lifetime, depends on:

- trap level position

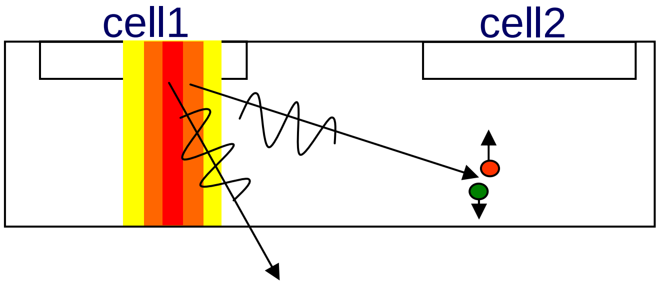
Low P_a: low number of traps, long recovery time, low gain

Noise (3)

3) Optical cross-talk

During an avalanche discharge photons are emitted mainly because of spontaneous direct carrier relaxation in the conduct. band.

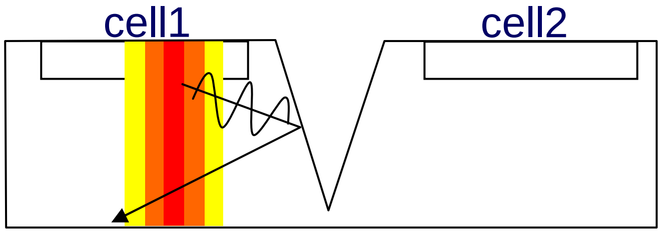
3×10^{-5} photons with energy higher than 1.14eV emitted per carrier crossing the junction. [from A. Lacaita et al., IEEE TED, vol. 40, n. 3, 1993]



Those photons can trigger the avalanche in an adjacent cell: optical cross-talk.

Depends on:
- distance between the high-field regions
- gain

<u>Definitive solution</u>:
trenches in silicon filled with opaque material

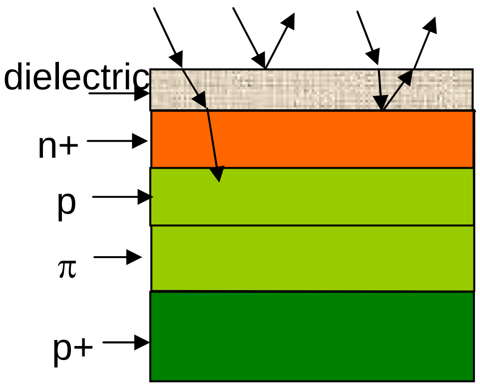


PDE (1)

$$\mathrm{PDE} = N_{\mathrm{pulses}} / N_{\mathrm{photons}} = \mathrm{QE} \times P_{01} \times \mathrm{Ae}$$

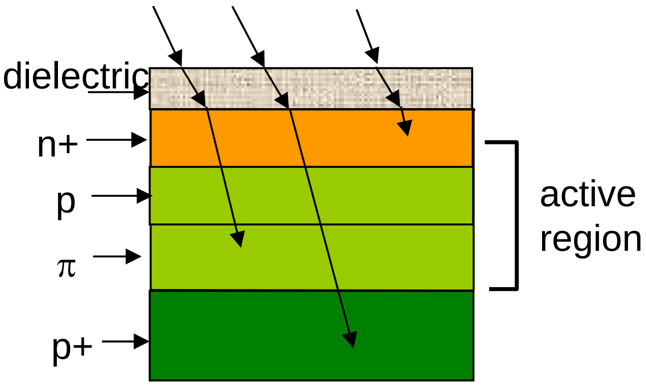
1. QE Quantum efficiency is the probability for a photon to generate a carrier that reaches the high-field region.

a. Transmission efficiency



wavelength dependent

b. Internal quantum efficiency



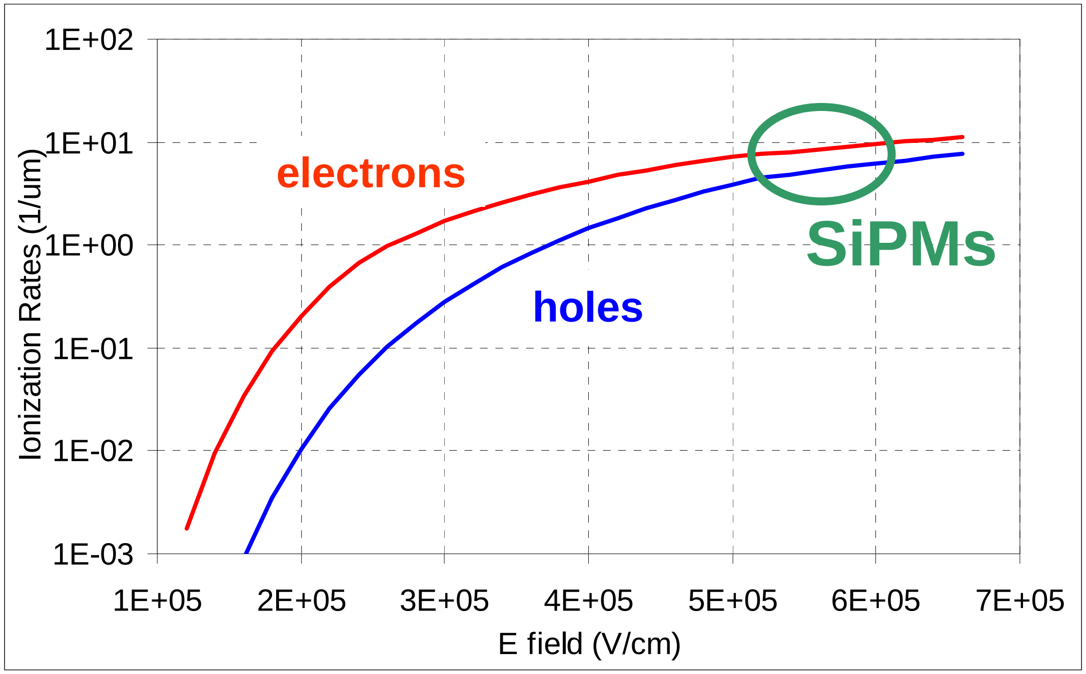
wavelength dependent

Optimization:
- Anti-reflective coating
- shallow junctions for short λ
  thick epi layer for long λ

PDE (2)

2. P_{01}. turn-on probability

probability for a carrier traversing the high-field to trigger the avalanche.



Ionization rates in Silicon

1. Electrons higher ionization rate. Difference decreases for higher fields, e.g. at 6e5V/cm α_n/α_p~2.

2. Ioniz. rates increase with field

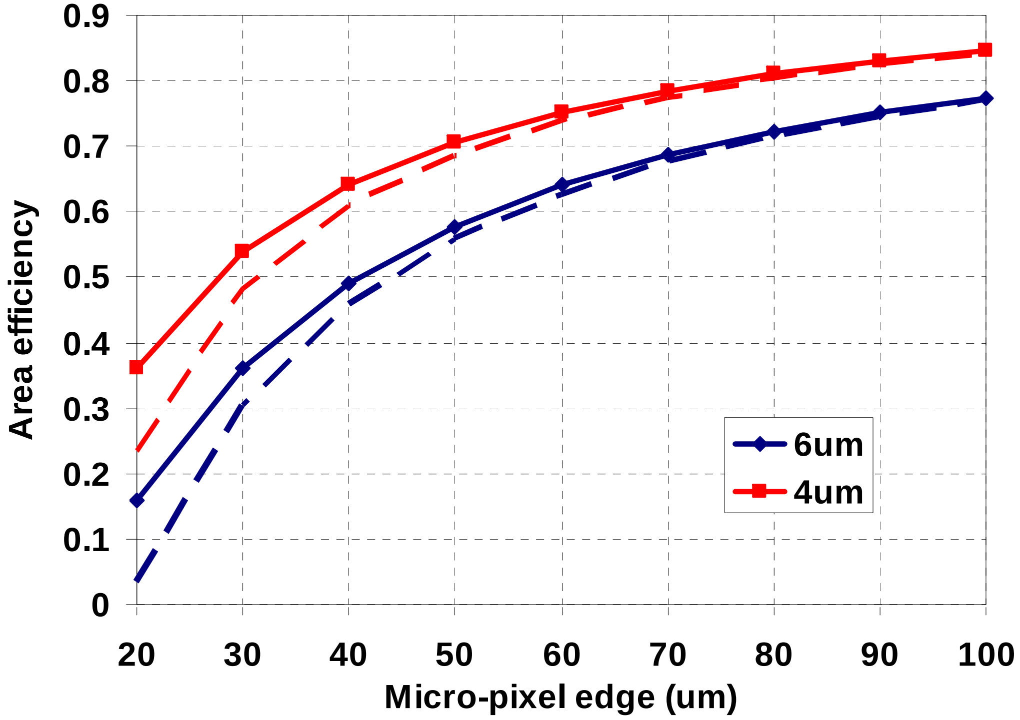
P_{01} maximization:

- high overvoltage
- photo-generation in the p-side of the junction

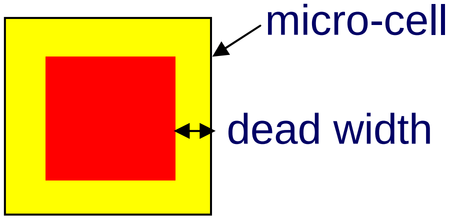
PDE (3)

3. Ae. Area efficiency

"standard" SiPMs suffer from low Ae due to the structures present between the micro-cells (guard ring, trench)



Maximum Ae for a width of the dead region of 4 and 6μm (in a front-side illuminated SiPM)



These values can be worse if the polysilicon resistor overlaps the high field region (dashed lines: 50μm^2 overlap).

Features of a SiPM

Most important features of a SiPM are:

- **capability to detect extremely low photon fluxes** giving a proportional information;
- **extremely fast response** (determined by avalanche discharge): in the order of few hundreds of ps.

Other features are:

- Low bias voltage (<100V)
- Low power consumption
- Insensitive to magnetic fields
- Compact and rugged

→ **extremely interesting alternative to PMTs**

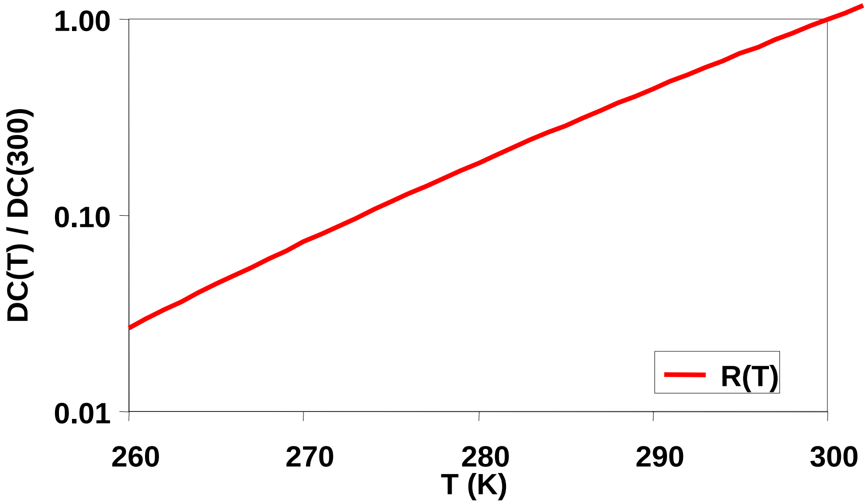
Problematics (apart from technological):

- temperature dependence of dark count and gain
- low radiation resistance (generation and trapping centers)

Temperature dependence

Change in Dark count rate

If dominated by thermal generation:



For a given overvoltage:

$$\frac{DC(T)}{DC(300)} = \frac{T^2}{300^2} \cdot \exp(-\frac{Eg}{2k_B}\left[\frac{1}{T} - \frac{1}{300}\right])$$

Change in Breakdown Voltage

Lower temperature => longer mean free path

➡ lower breakdown voltage

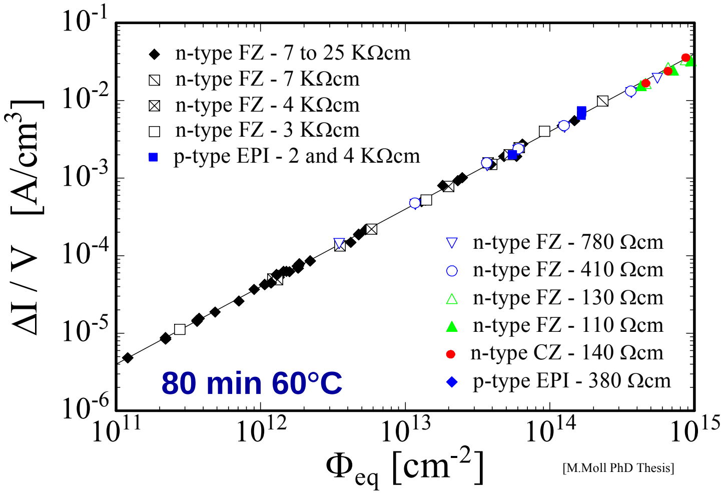
$$\boxed{C_T = \frac{1}{V_{BD}(300)} \cdot \frac{dV_{BD}}{dT} \quad \sim \quad 0.3\%/K}$$

Temperature coefficient
of the breakdown voltage

Cova et al., *Appl. Optics vol. 35 n. 12* (1996) 1956.

Radiation Damage

- **Increase of Dark count rate** because of introduction of generation centers. Same behavior of the leakage current for diodes:



[M.Moll PhD Thesis]

Leakage current on diodes

Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

- **does not depend on the substrate type**
- **depends on particle and energy (NIEL)**
- **partial anneal in time**

Considering:

α= 3e-17A/cm

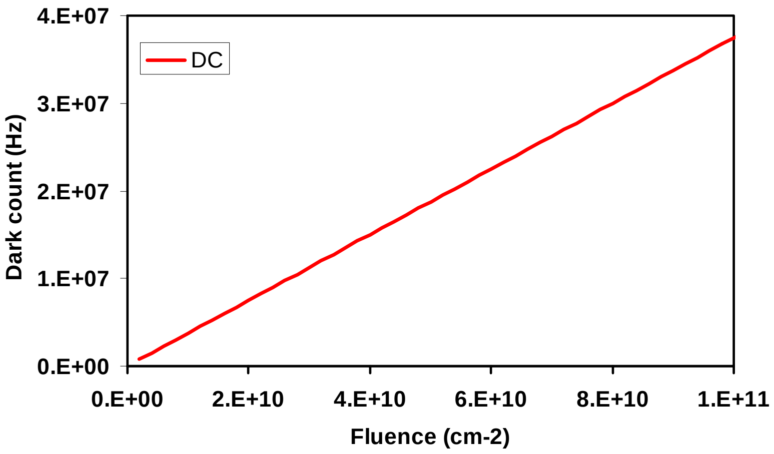
(typical for hadrons)

A_{SiPM} = 1mm^2

Epi thick = 4µm

estimation

$$DC = P_{01} * \left(\frac{\alpha * \Phi * Vol}{q}\right)$$



- **Increase of after-pulse** because of introduction of trapping centers

=> loss of single pixel resolution

SiPM state-of-the-art

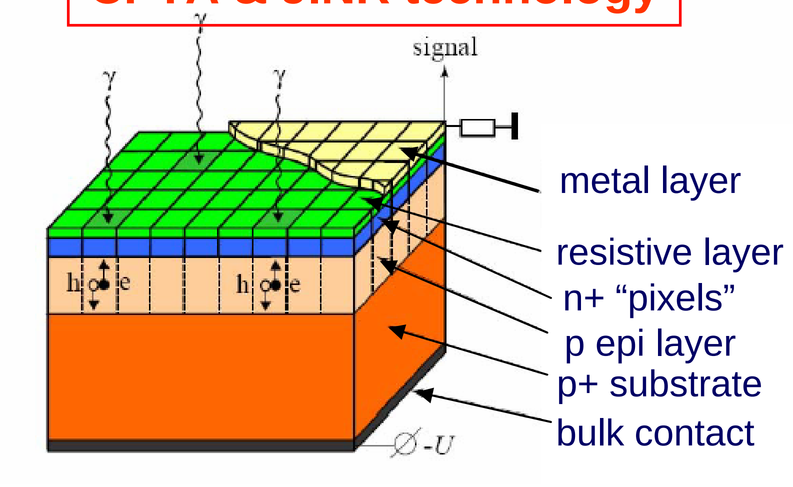
Pioneering work in the 90's by russian institutes

- JINR, Dubna
- Obninsk/CPTA, Moscow
- Mephi/PULSAR, Moscow

JINR and Obninsk/CPTA: Metal-Resistive-Semiconductor

Mephi/PULSAR → polysilicon resistor

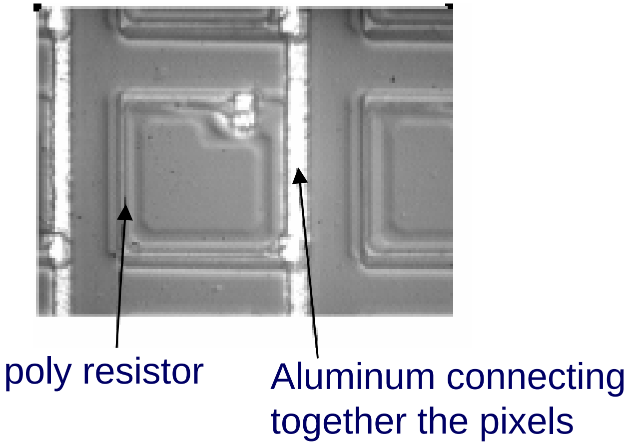
CPTA & JINR technology



- High Area efficiency
- high density of microcells

e.g., Voloshin, NIMA 539 (2005)

Mephi technology



- Low area efficiency
- Standard fabrication tech.

e.g., Dolgoshein, NIMA 563 (2006)

SiPM state-of-the-art

More institutes/companies involved in SiPM production:

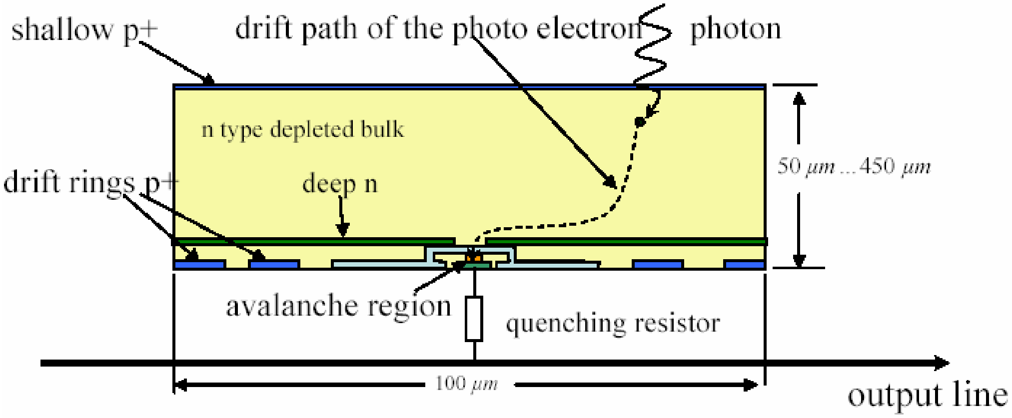
- Hamamatsu, Japan
- SensL, Ireland
- IRST, Italy
- MPI, Germany

Front-side illumination **devices available**

Back-side illumination; device ready by end 2007

MPI technology

sketch of a microcell



e.g., G. Lutz, IEEE TNS 52, n. 4, 2005

- ~100% fill factor
- Thick depleted region:
  - higher QE for wide range λ
  - possible high dark count
  - less rad-hard
  - worse timing performance
- micropixel size $>100\mu m^2$

Few considerations

1) The technology is evolving very fast, following three aims:
   - reduce dark count rate;
   - large area;
   - increase photodetection efficiency.

2) Different applications require very different device characteristics. (in terms of dynamic range, PDE *vs* light wavelength, noise requirements…)

3) A direct comparison among the devices is extremely difficult because the geometry, operational conditions and experimental methods must be uniform and clearly specified;

4) Finally, the performance reproducibility of a technology is an issue (in the breakdown voltage, noise rate, PDE…)

Silicon Photomultipliers

- General considerations

- Development @ IRST:

*** technology**

*** results**

*** future developments**

Our activity

Development and application of SiPMs is a project involving IRST and INFN.

- **IRST:**
  to develop the technology for the production of **SiPMs** (large area devices/matrices) + functional tests

- **INFN:**
  to develop systems, with optimized read-out, based on SiPMs for applications such as:
  - **tracking with scintillating fibers**;
  - **PET**;
  - **TOF**;
  - **calorimetry**

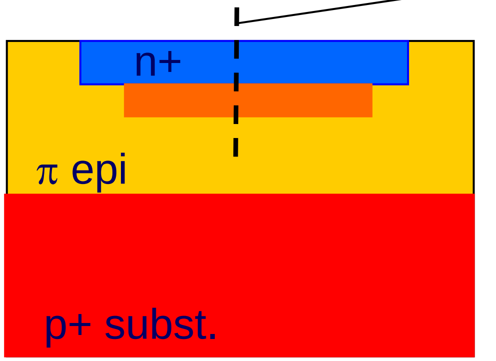
IRST technolgy

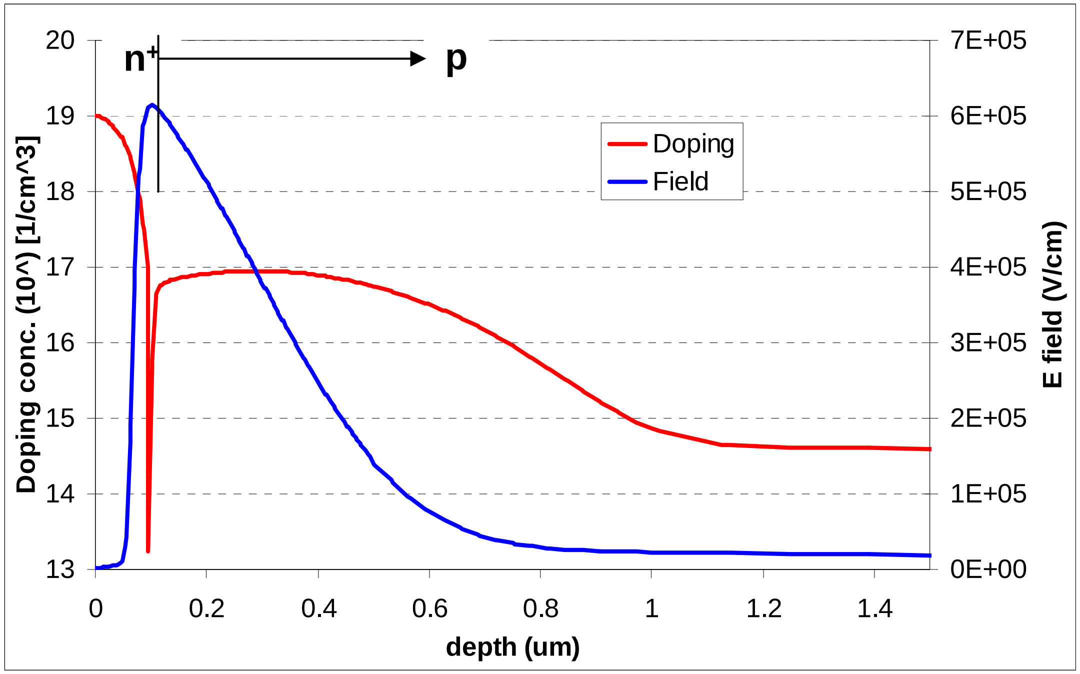
We developed 2 technologies. In this talk only one is reported.

(the first production of the second technology is in its final stages)

[C. Piemonte "A new Silicon Photomultiplier structure for blue light detection" in press on NIMA (see ScienceDirect)]

Shallow-Junction SiPM





1) Substrate: p-type epitaxial
2) Very thin n+ layer
3) Quenching resistance made of doped polysilicon
4) Anti-reflective coating optimized for λ~420nm

SiPM Technology Evolution

Project started at the beginning of 2005.

January – May: process/device simulations to define fabrication parameters; layout design.

September 2005

First batch

Aims:

1) Verify the functionality of the device;

2) Study the problem of the photo-detection efficiency.

May 2006

Second batch

Aims:

1)Verify reproducibility of the first batch

2)Implement structure for reduction of optical cross-talk

October 2006

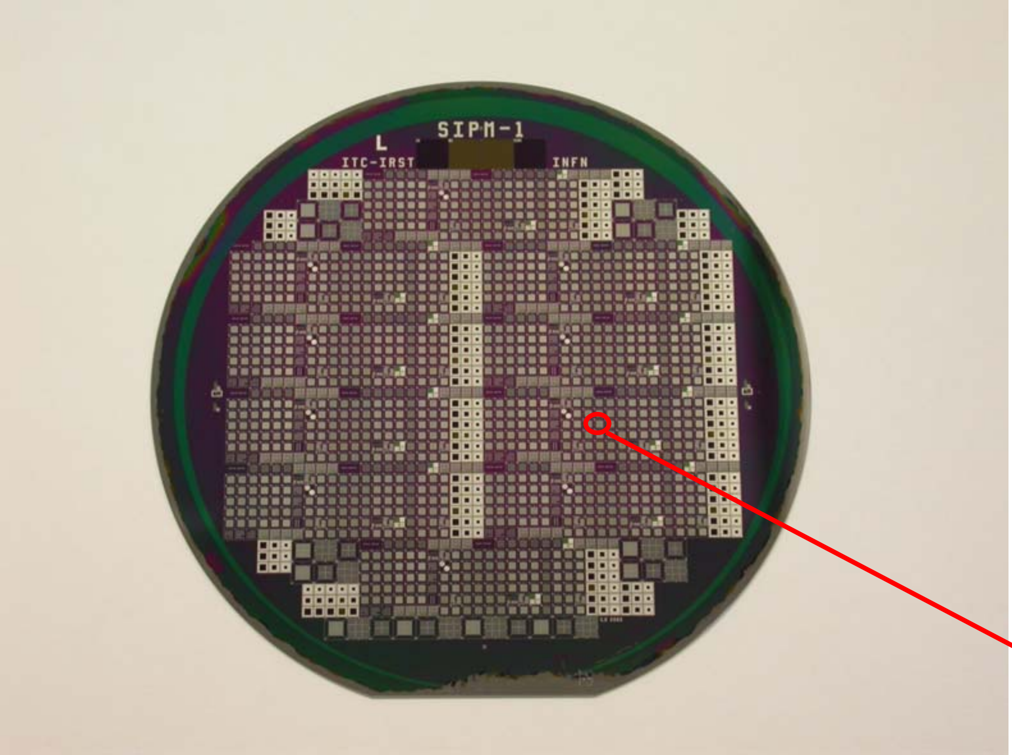
Third batch

Aim:

Reduce dark count rate via technological actions

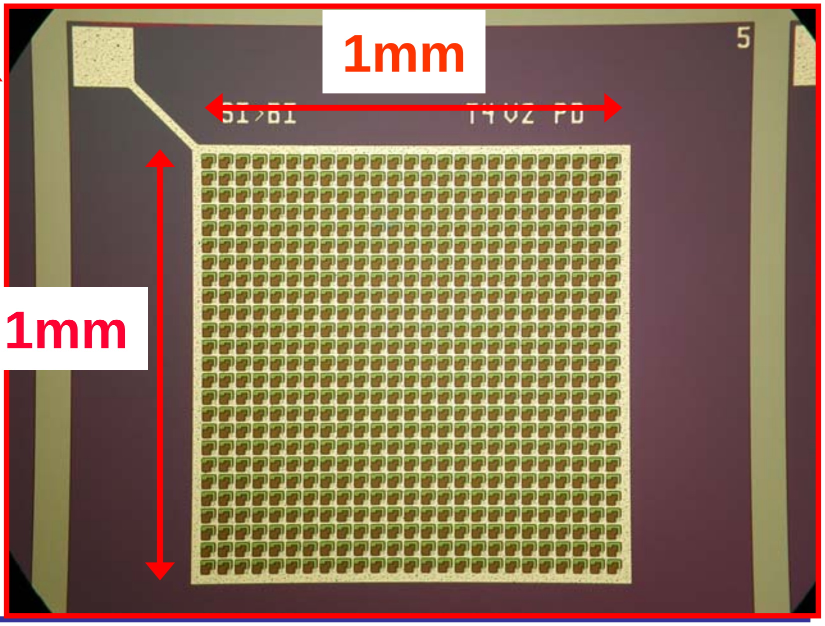
Same layout for 3 batches.
Geometry NOT optimized for maximum PDE (Ae=20-30%)

Wafer layout



The wafer layout includes many structures:

- SiPMs;
- GM-APDs;
- “large-area” diodes;
- several test structures



Basic SiPM geometry:
- 25x25 cells
- cell size: 40x40μm^2

Test performed so far

- **Static IV measurement**
  extremely important fast test to verify the functionality of the device (breakdown voltage, dark count rate level).

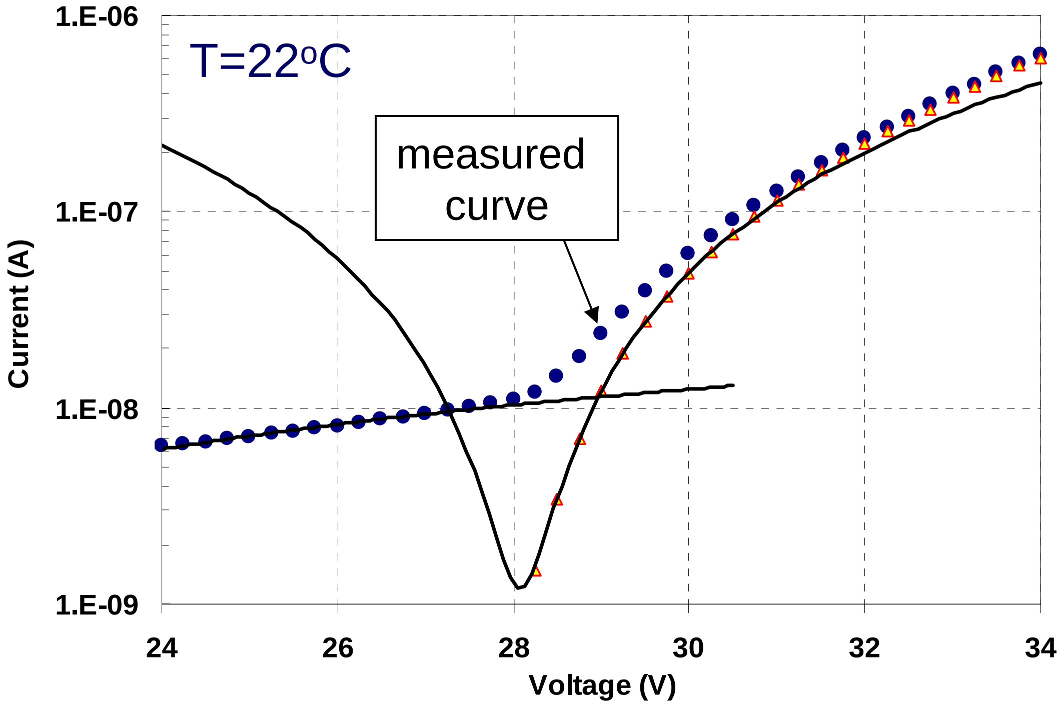
- **Dynamic characterization in dark**
  it allows a complete characterization of the output signal and noise properties (Gain, Signal shape, Dark count, optical cross-talk, after-pulse)
  [C. Piemonte et al. "Characterization of the first prototypes of SiPM fabricated at ITC-irst" to appear on TNS]

- **Photodetection efficiency**

- **Timing performance** **(INFN Pisa)**

- **Energy resolution of SiPM coupled with LSO** **(INFN Pisa)**

SiPM – static characteristic



Reverse Current around the breakdown voltage

Pre breakdown: current mainly due to generation in the surface region around the diode (linear fit)

Post breakdown: current determined by dark events

$$I_{postBD} = Gain \cdot q \cdot DC \Longrightarrow$$

parabola with Vbias

linear growth with Vbias

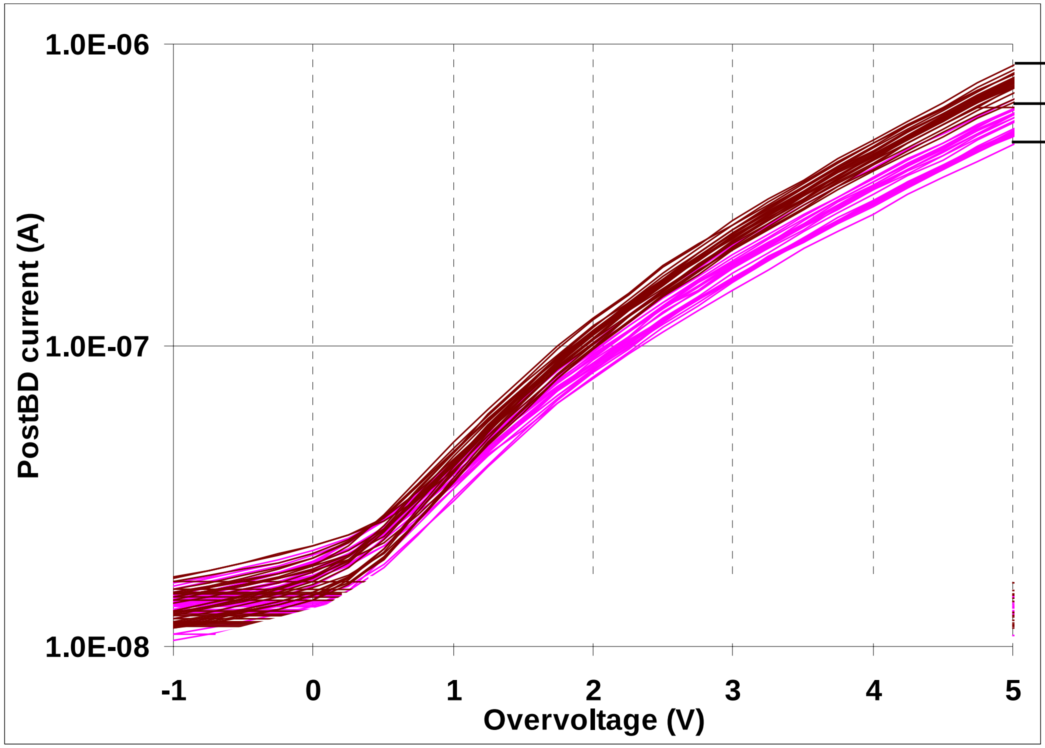
linear growth with Vbias

SiPM – static characteristic (2)

Static measurement gives information on:

1. Breakdown voltage
2. Dark count rate

Example: one wafer from the last production



Active area 1: 25 out of 27 devices

Active area 2: 32 out of 36 devices

Acive area 1 > Active area 2

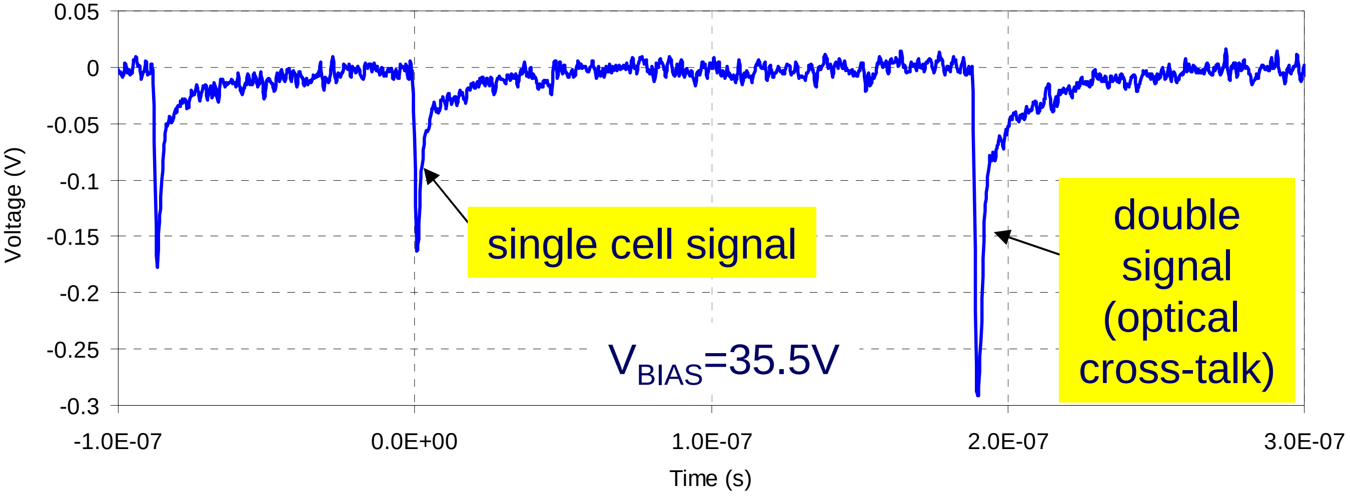
⇨ DC1 > DC2

Uniform Dark count rate!

Extracted BD voltage: V_{BD} =28.3V σ=0.4V

SiPM - Signal characteristics

SiPM read-out by means of a trans-resistance amplifier on a scope



single cell signal

double signal (optical cross-talk)

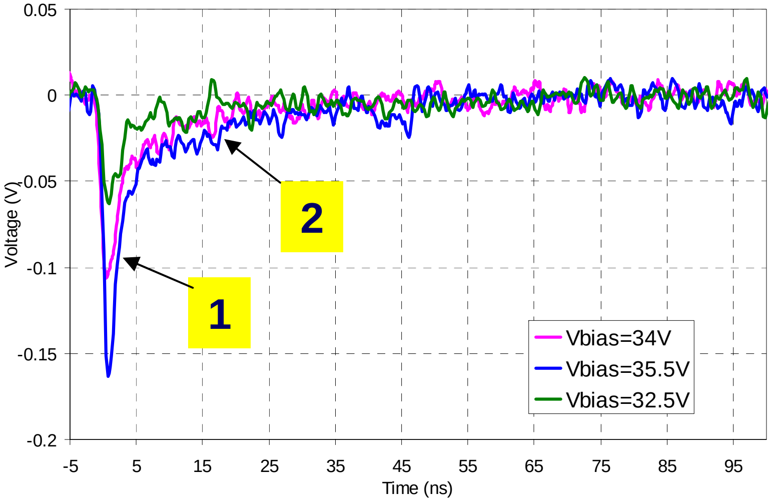
V_{BIAS}=35.5V

Dark signal

T=22^{o}C

The signal presents 2 components:

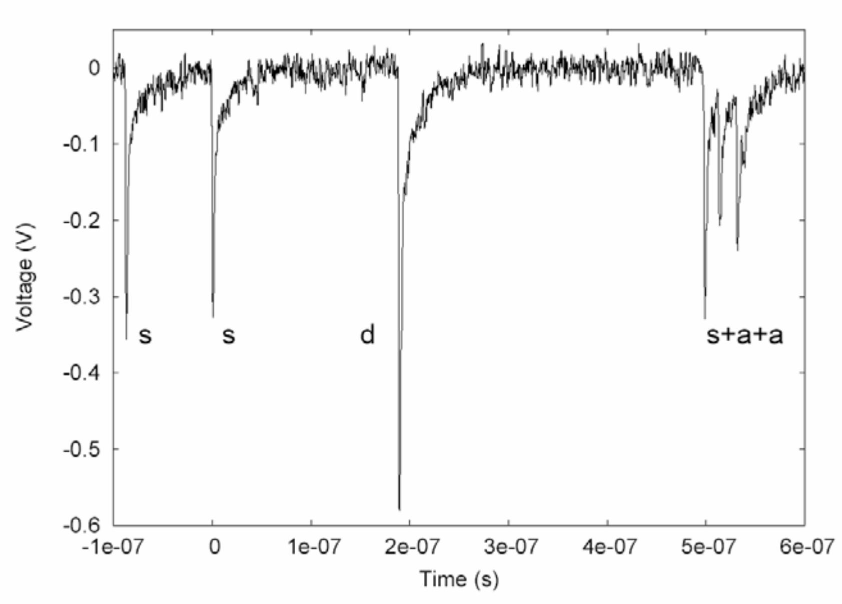
1. Avalanche current reproduced at the output by parasitic capacitor
2. slow component due to the recharge of the diode capacitance (Recovery time ~70ns)



SiPM – Charge spectra

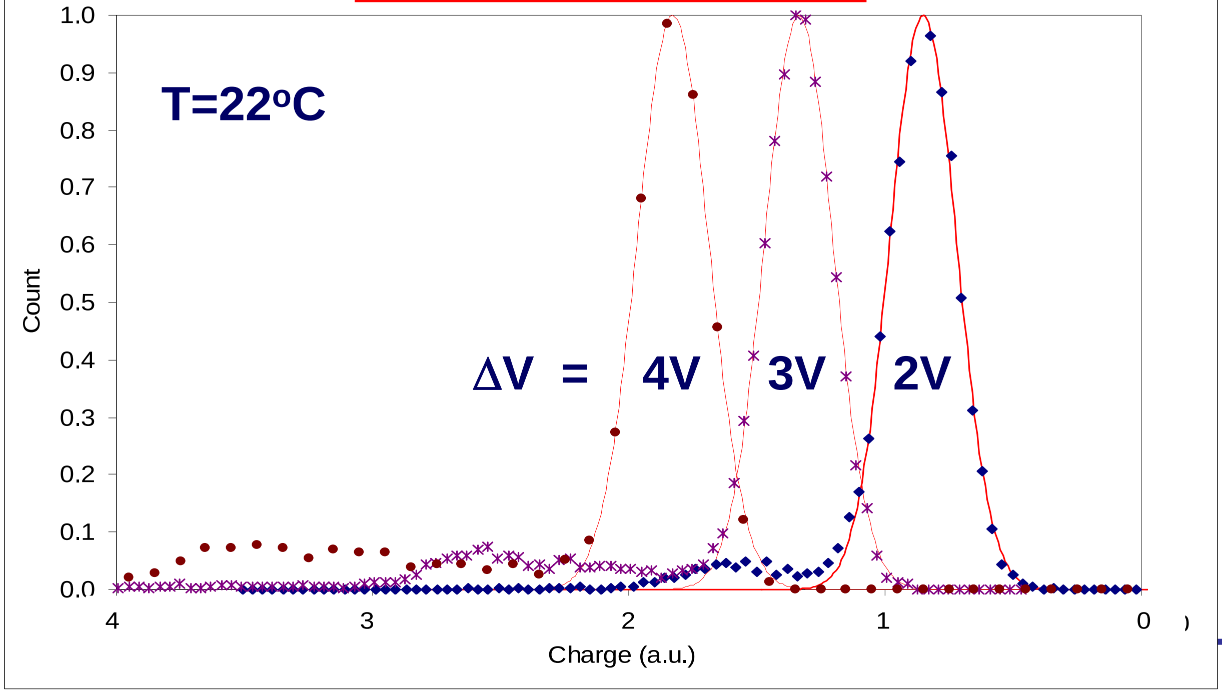
Pulses visible on the scope

DARK



s = single
d = optical cross-talk
a = after-pulse

Charge spectra

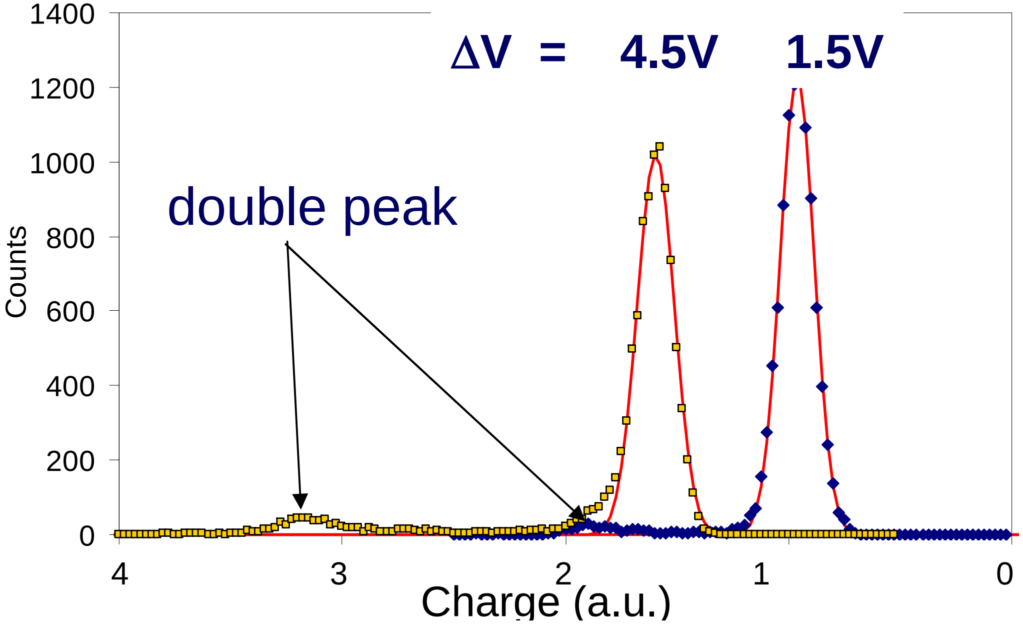


Integration time = 100ns
=> whole signal is included.

Well defined peak fitted by a gaussian distribution
⇒ uniform gain within the microcell and between microcells

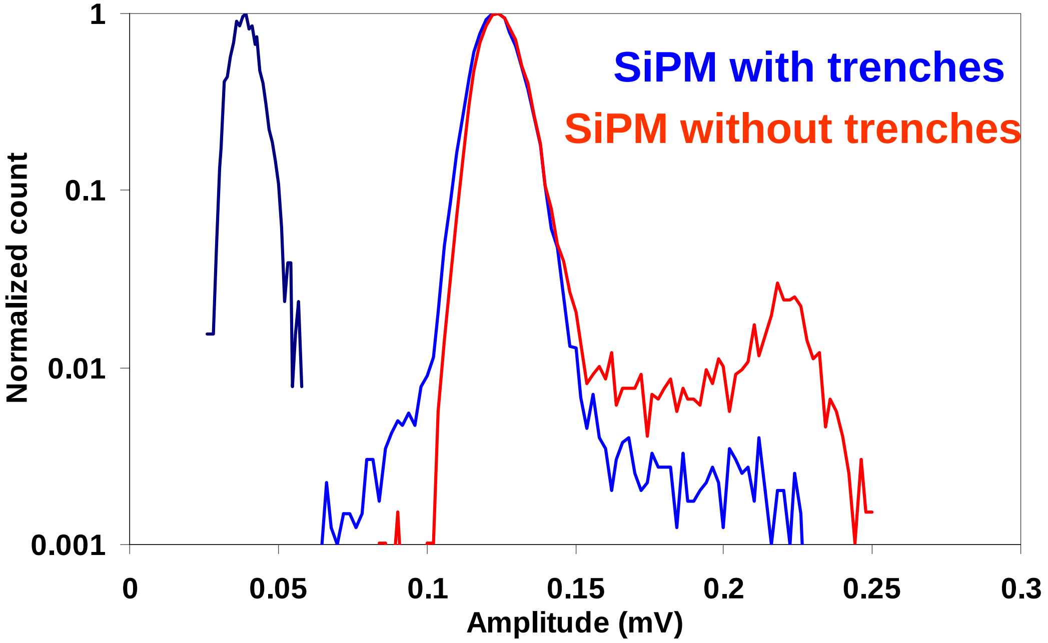
Tails due to optical cross-talk + afterpulse

SiPM – Optical cross-talk



Short integration time
⇒ only single/double/….pulses are counted

Number of events with optical cross-talk increases with voltage



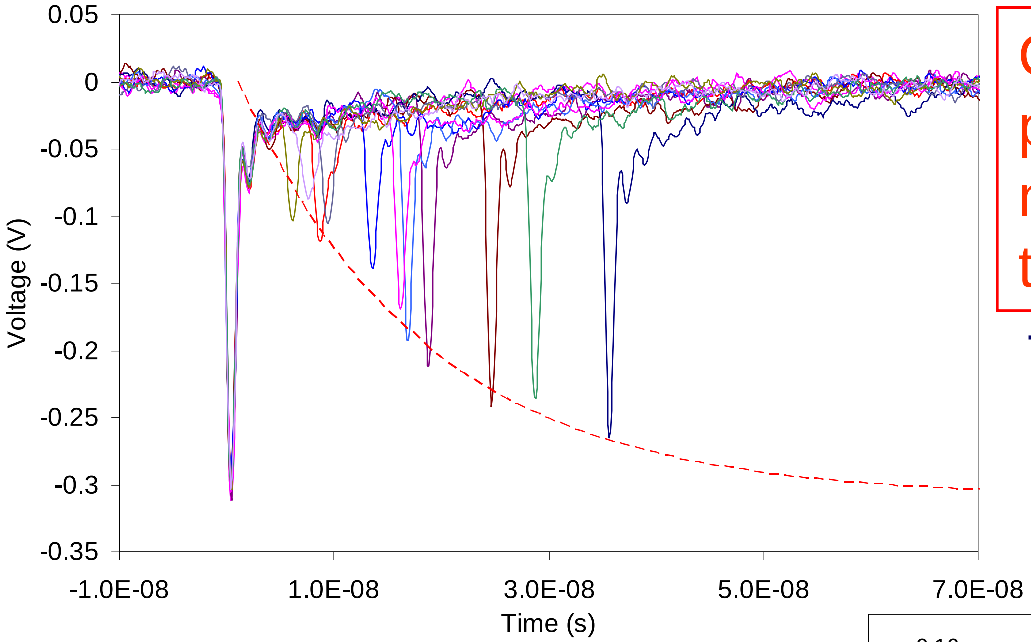
Devices with trenches have a much lower cross-talk

but

higher Dark count rate (~twice)
(process improvement needed)

DARK

GM-APD – After-pulse



Collection of 11 events presenting an after-pulse measured on a single microcell test structure

The amplitude of the after-pulse increases as the cell recovers to its opertional condition

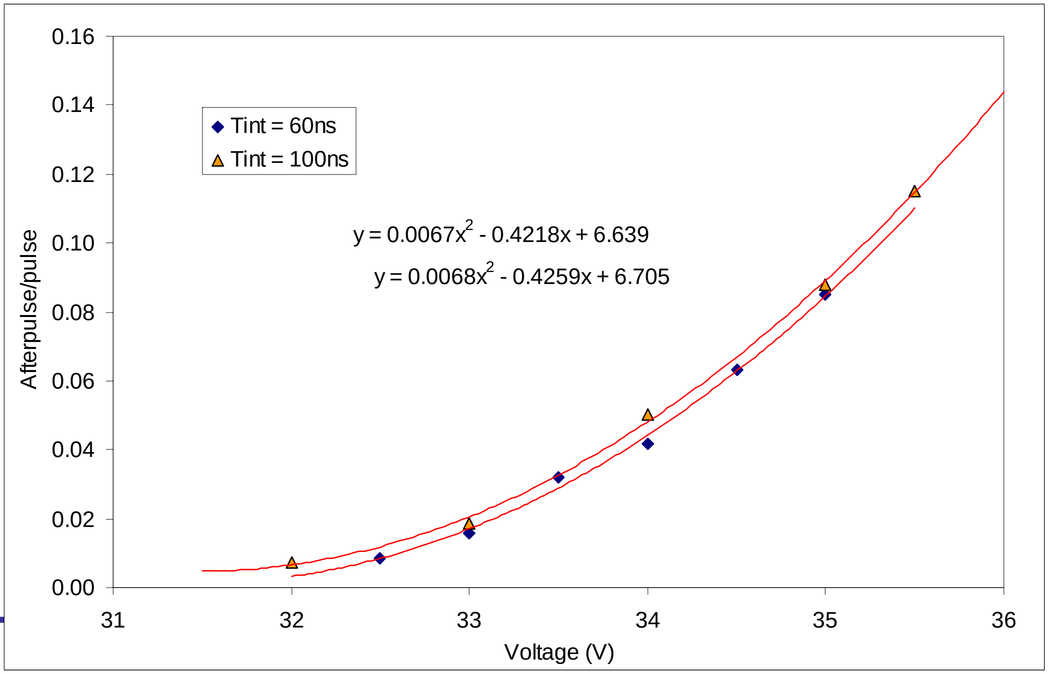
After-pulse probability *vs* bias

It increases following a parabolic law:

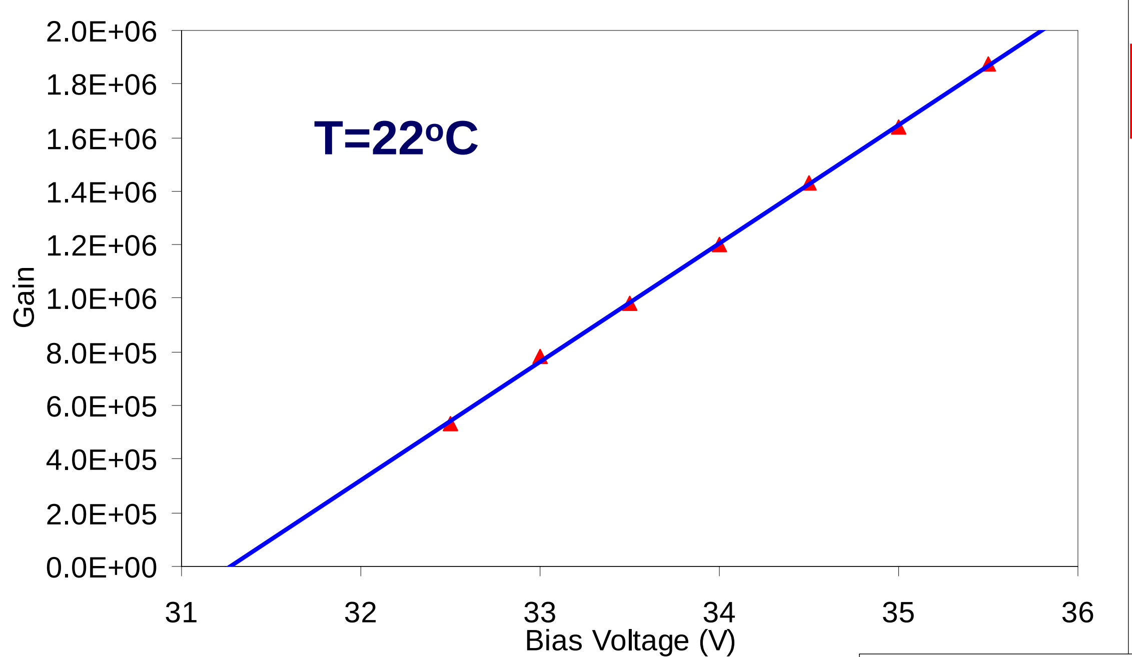
$$P_a = P_c \cdot P_{01}$$

linear with Vbias

linear with Vbias



SiPM - Gain



Gain *vs* Bias voltage

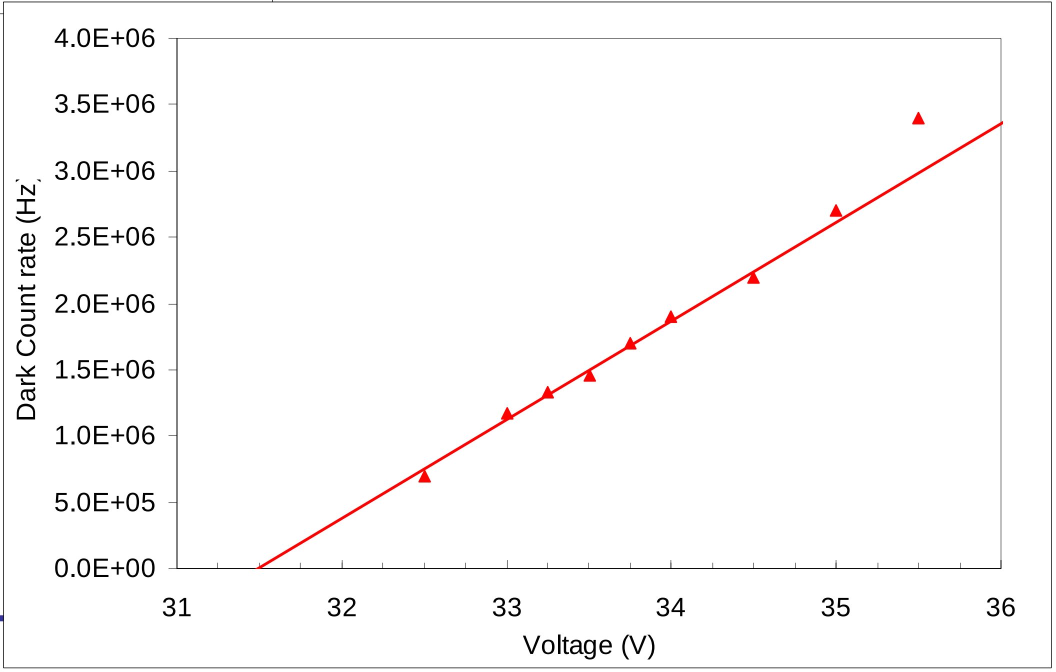
$Q=C_{microcell}*(V_{bias}-V_{breakdown})$

$\Rightarrow C = 80\text{-}90fF$

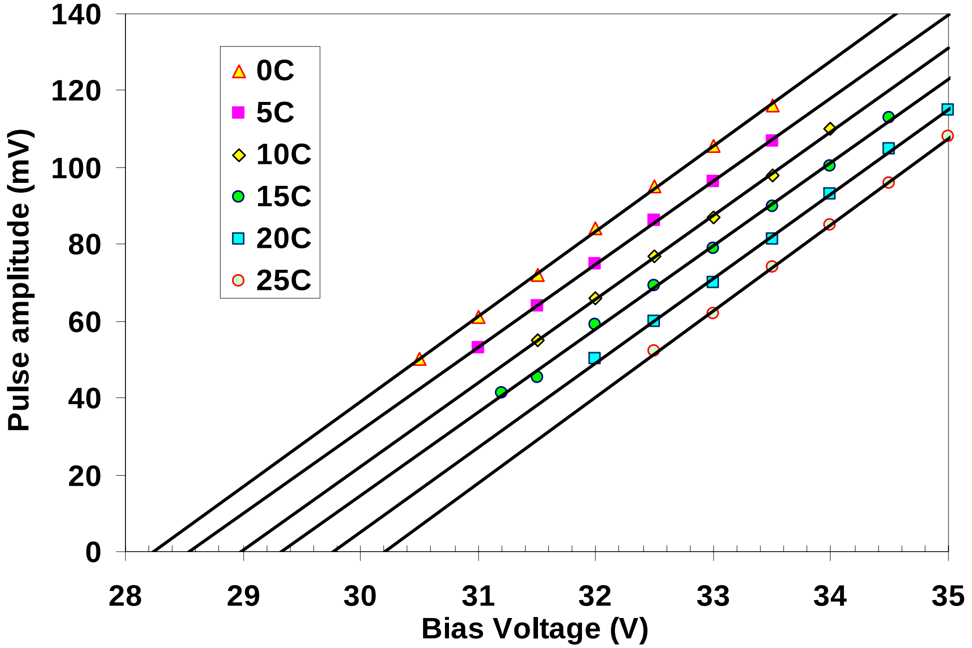
Very uniform from device to device

Dark count *vs* Bias voltage

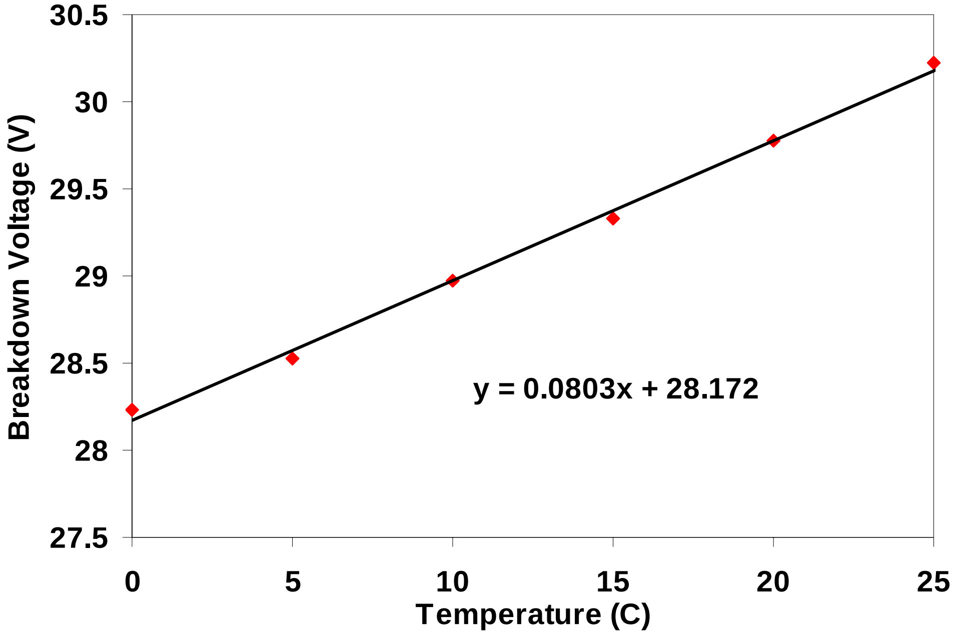
It increases linearly because the triggering probability grows linearly with bias



V_{BD} Temperature dependence



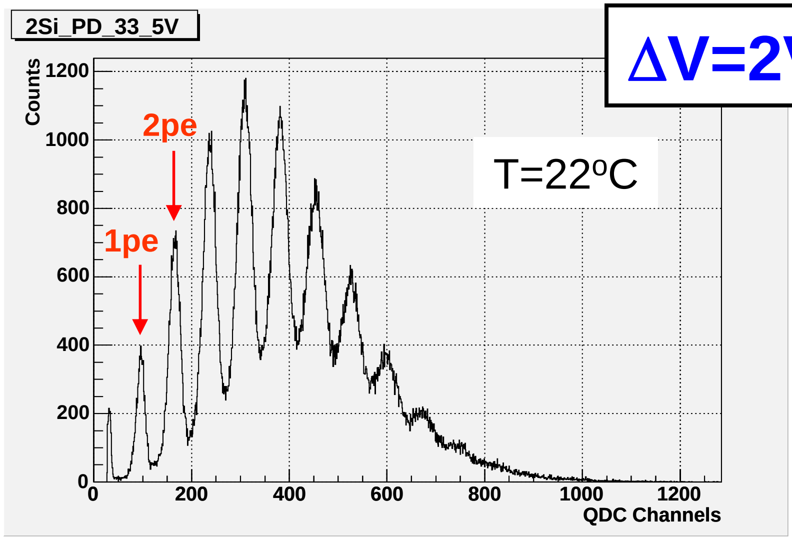
Pulse amplitude *vs* Bias voltage at 6 temperatures



Breakdown voltage *vs* Temp.

80mV/K ~ 0.27%/K

SiPM - Response to light



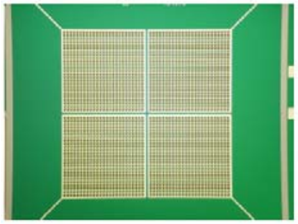
$\Delta V=2V$

Pulse charge spectrum from low-intensity light flashes (blue LED)

Very good uniformity response from the micro-cells

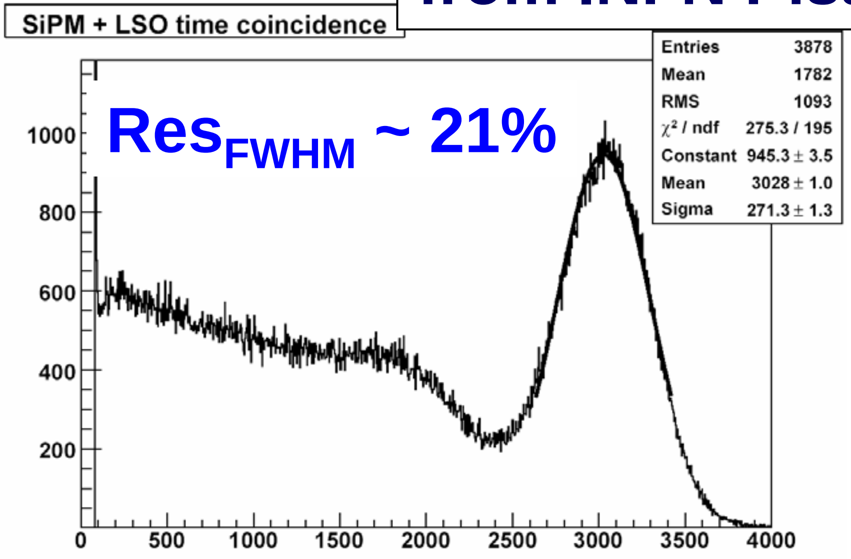
Energy resolution with scintillator

- 1x1x10mm LSO scintillator (λ_{peak}=420nm) placed directly on the SiPM
- coincidence with a second SiPM
- ^{22}Na source emitting γ 511keV



New test on 2x2 matrices in progress

from INFN Pisa



Res_{FWHM} ~ 21%

Next steps

New layout ready with:

- **increased fill factor**: 40x40μm => 44%
50x50μm => 50%
100x100μm => 76%;
- **devices with larger area**.

New production will start by the beginning of December.

On the **technological side**:
- dark count reduction;
- Buried-junction SiPM;

Conclusion

General

- SiPM can really replace PMT in many applications bringing a lot of advantages
- Technology is rapidly developing with improved features and new ideas

On IRST SiPMs

- Extremely good results from the first three productions
  - devices working well
  - very good reproducibility of the performances
  - good yield
  - extremely good understanding of the device
- Next steps: - SiPMs with lower dark count
  - Characterization of buried-junction SiPMs
  - Optimized geometry