Development of SiPMs by ITC-irst

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on behalf of
ITC irst, MEMS project & DASIPM collaboration
CENTRO PER LA RICERCA SCIENTIFICA E TECNOLOGICA

for further information see
http://sipm.itc.it
or write
(piemonte@itc.it)

Outline:

1) Background : who, where, why and when
2) Development of SiPMs: design and objectives
3) first batch : results
4) summary

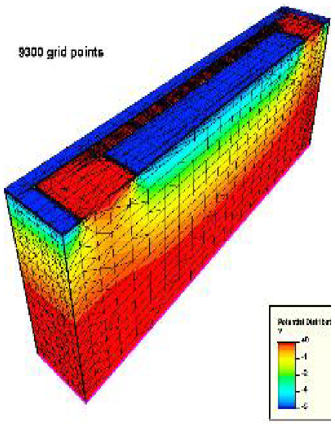
SRD Group @ ITC-irst

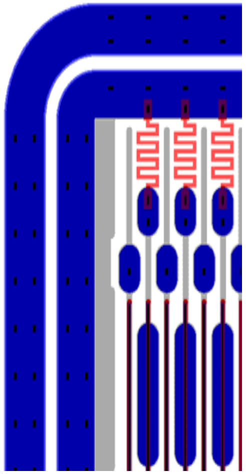
ITC-irst: research center in Trento, Italy

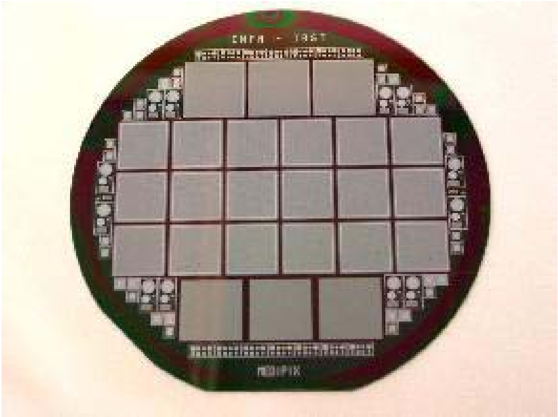
SRD group: development and production of radiation detectors.

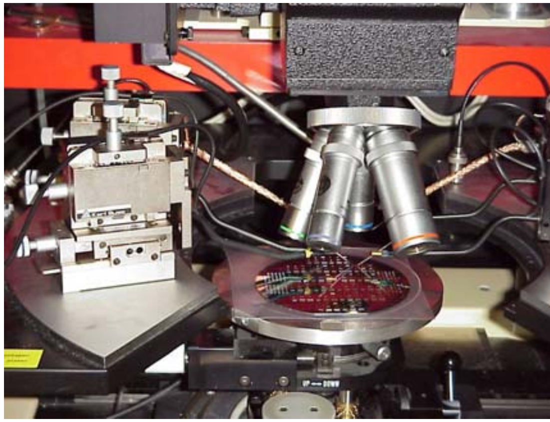
In this field since 1994.

TCAD simulation
CAD design → Fabrication → Device testing









Main Activities

"Standard" technology

From the specifications given by the "user"
they design, produce, and (electrically) test the detector.

Examples:

- **single/double-sided strip detectors (e.g. ALICE and AMS)**
- **p-on-n/n-on-n pixel detector (e.g. MEDIPIX and NA48)**

R&D activities

Development in cooperation with the partners

Examples:

- **very thin detectors**
- **3D detectors**
- **silicon photomultipliers**
- **detectors made on radiation hard silicon substrates**

Development of Silicon Photomultipliers at ITC-irst

Development of systems SiPMs was initiated with support from the INFN and the region of Trento and formalized in an agreement

On the basis of this agreement*:

- **the role of ITC-irst and INFN Trento is:**
to develop the technology for the production of **matrixes of SiPMs** with detection efficiency optimized in the **short-wavelength** region (blue).

- **and the role of INFN is:**
to develop applications of SiPMs and
to develop readout systems.

The application which originally motivated the development of SiPMs was PET (INFN project DaSiPM). Other applications quickly followed (Space applications, calorimetry and tracking).

*for details of SiPM project see: http://sipm.itc.it

SiPM Technology Evolution

ITC irst — CENTRO PER LA RICERCA SCIENTIFICA E TECNOLOGICA

Project started at the beginning of 2005.

January – April: process/device simulations to define fabrication parameters;

April – May: layout design;

September 2005	May 2005	September 2006
First batch →	**Second batch** →	**Third batch**
Aims: 1) Verify the functionality of the device; 2) Study the problem of the photo detection efficiency.	Aims: 1)Verify reproducibility of the first batch 2)Implement structure for reduction of optical cross-talk	Aim: Reduce dark count rate via technological actions

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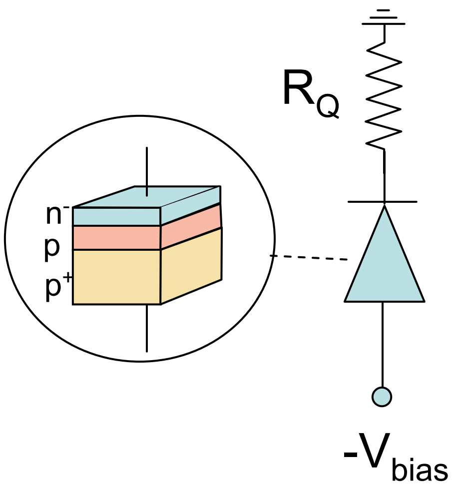
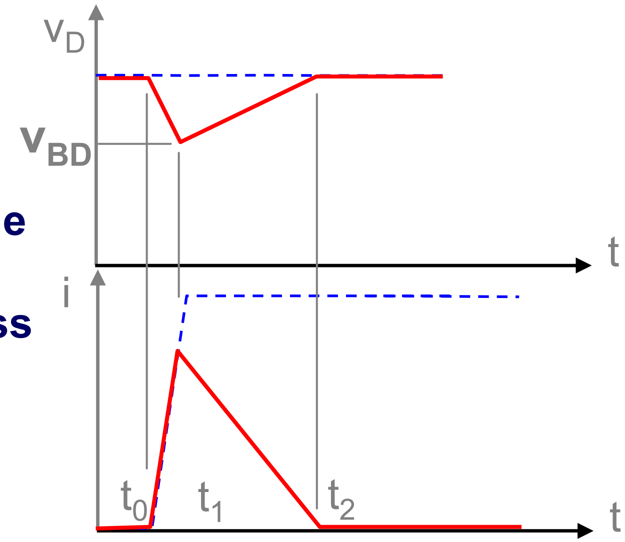
SiPMs: principle and functional parameters

Geiger-mode APD (binary device)

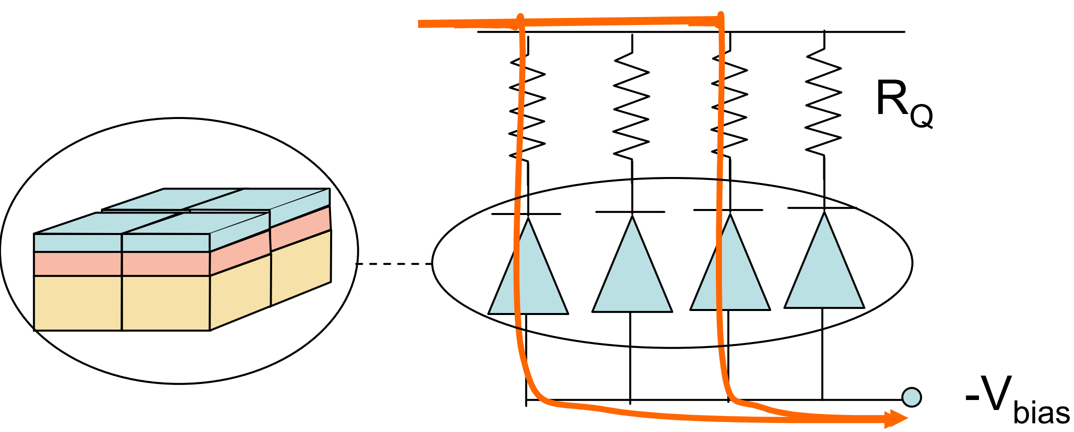


- $t < t_0$ — i=0 (if no free carriers in the depletion region)
- $t = t_0$ — carrier initiates the avalanche
- $t_0 < t < t_1$ — avalanche spreading
- $t > t_1$ — self-sustaining current unless quenched
- $t_1 < t < t_2$ — large resistance → passive quenching

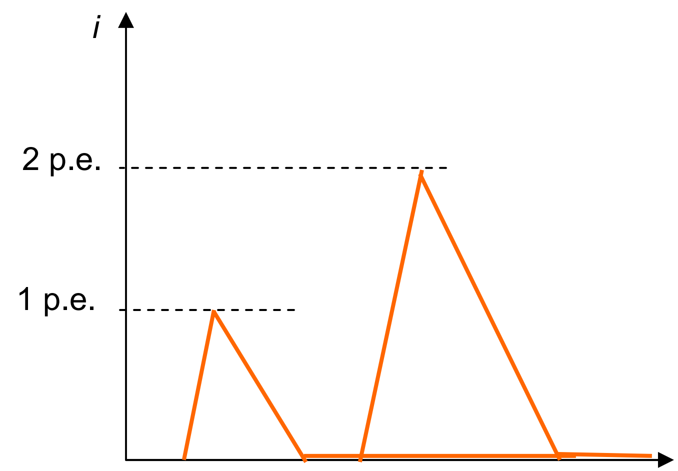


SiPM (signal amplitude ~ # of triggered cells)

(first proposed by Golovin and Sadyov in mid-90s



Signal ~ # of triggered cells



Features of the SiPM

Most important features of a SiPM are:

- sensitivity to low photon fluxes (1 to few hundred)
- proportional reponse
- single photon sensitivity
- speed : signal risetime ~ few hundreds of ps

(determined by avalanche formation):

Other features are:

- Low bias voltage (20-60V)
- Low power consumption
- Insensitive to magnetic fields
- Compact and rugged

Drawbacks:

- large dark current (~MHz) because of single photon sensitivity
- properties change with temperature (dark count, gain)
- low radiation resistance (generation, trapping centers)

Important Properties & Parameters

Important properties:

- Gain = $C \times (V_{BIAS}-V_{BD})/q$
- Photodetection efficiency $PDE = QE * P_t * Ae$
- Noise count
- Recovery time constant = R_Q*C
- Uniformity
- Cross-talk

Paramenters governing the signal response:

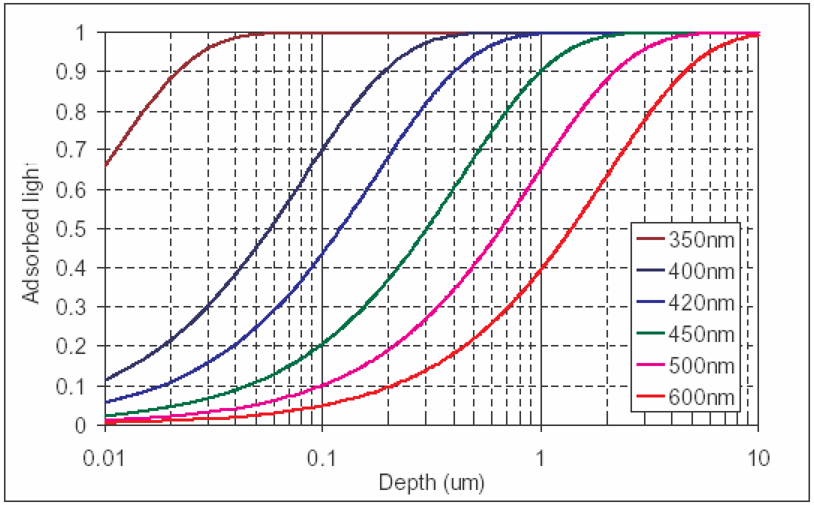
- Diode capacitance C
- Quenching resistance R_Q
- Triggering probability P_t
- Turn-off probability P_0
- Over-voltage $\mathbf{(V_{BIAS}-V_{BD})}$

Max PDE ?

PDE = QE * Pt * Ae

Geometrical efficiency

1) Internal quantum efficiency



2) Transmission efficiency of the coating

Electrons should trigger the avalanche because of the higher ionization rate

In any case, the higher the overvoltage is the higher Pt is.

The first design approaches simulated were aimed at maximizing PDE at short wavelength

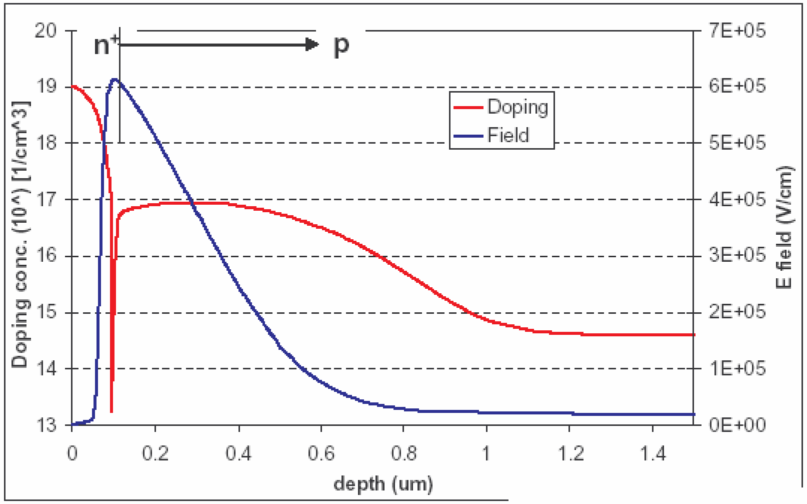
Simulation

ITC

ITC-irst approaches

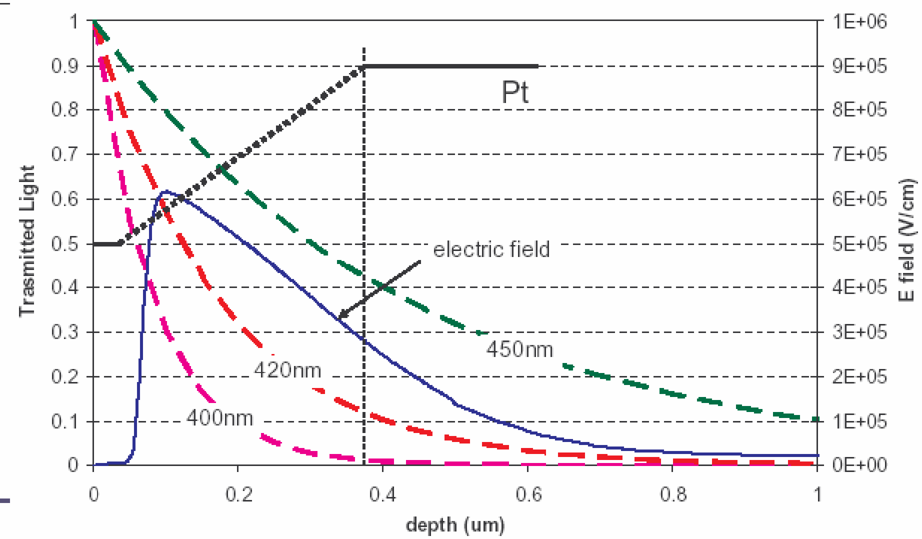
First approach: Shallow-junction SiPM

very shallow junction to improve quantum efficiency at short wavelengths



…. but…

Pt is not maximized @ short wavelengths



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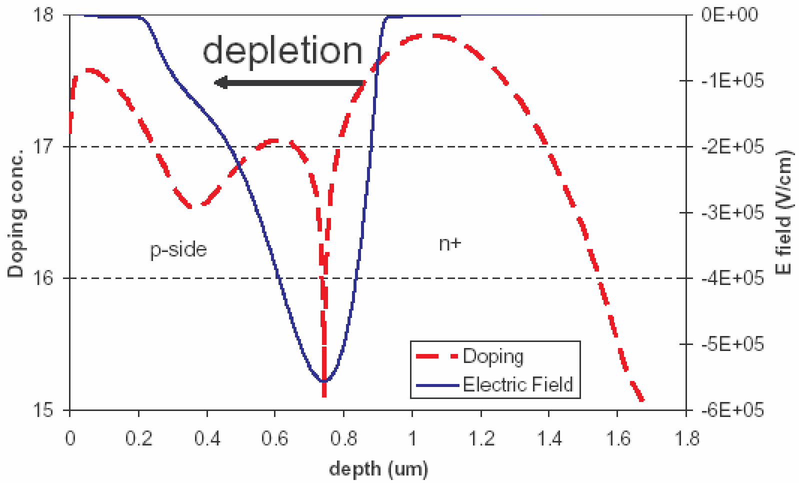
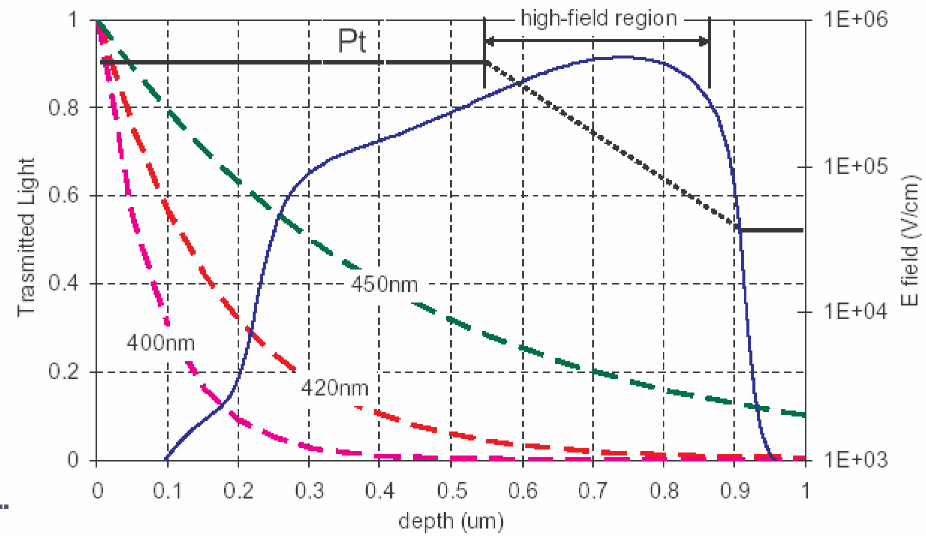
ITC-irst approaches



Second approach: Buried-junction SiPM

[C. Piemonte, presented @ Xth European Symposium on solid state detectors, Wildbad Kreuth, June 2005]

It maximizes Pt @ short wavelengths



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Characteristics of first prototypes

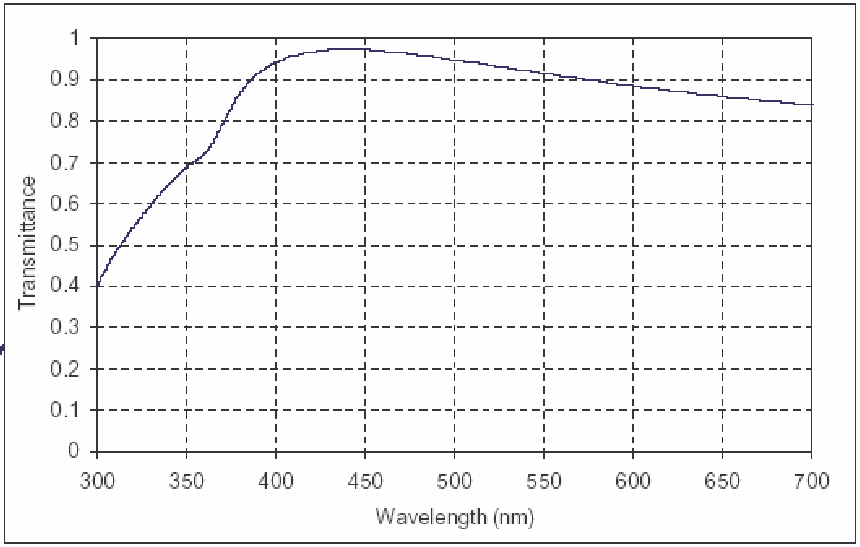
Experimental data shown here refer to the shallow-junction approach!

Main characteristics:

1) Substrate:
   p-type epitaxial

2) Quenching resistance made of doped polysilicon

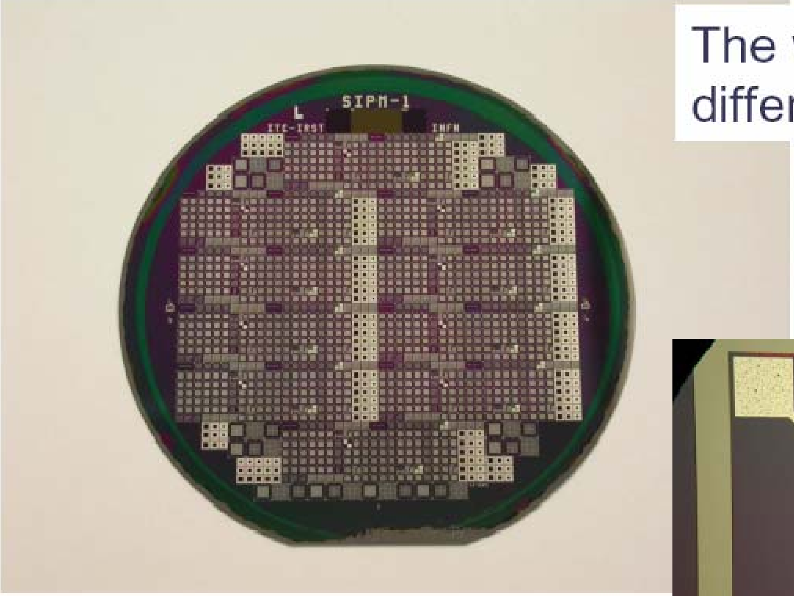
3) Anti-reflective coating optimized for λ~450nm



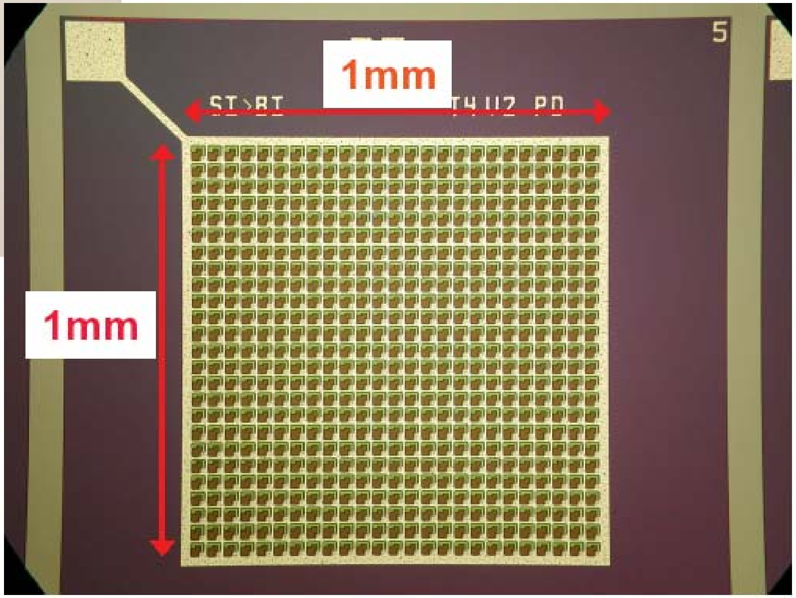
4) No structure for optical isolation

5) Geometry NOT optimized for maximum PDE

First prototypes



The wafer includes many structure differing in geometrical details



The basic SiPM geometry is composed by 25x25 cells

Cell size: 40x40μm^2

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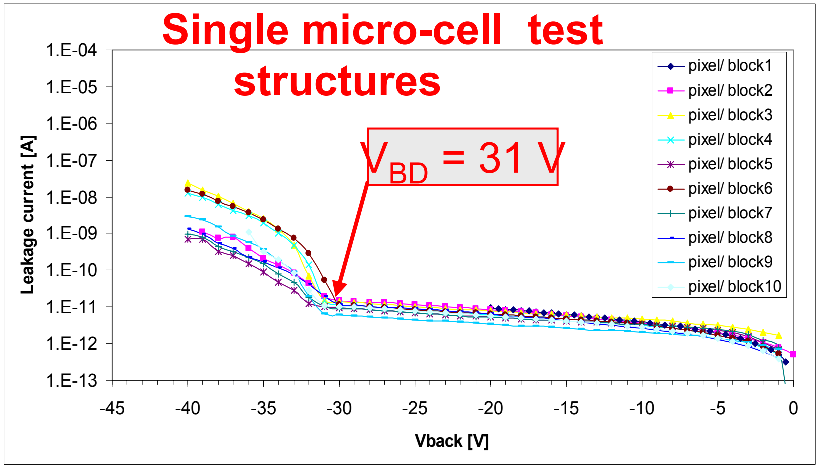
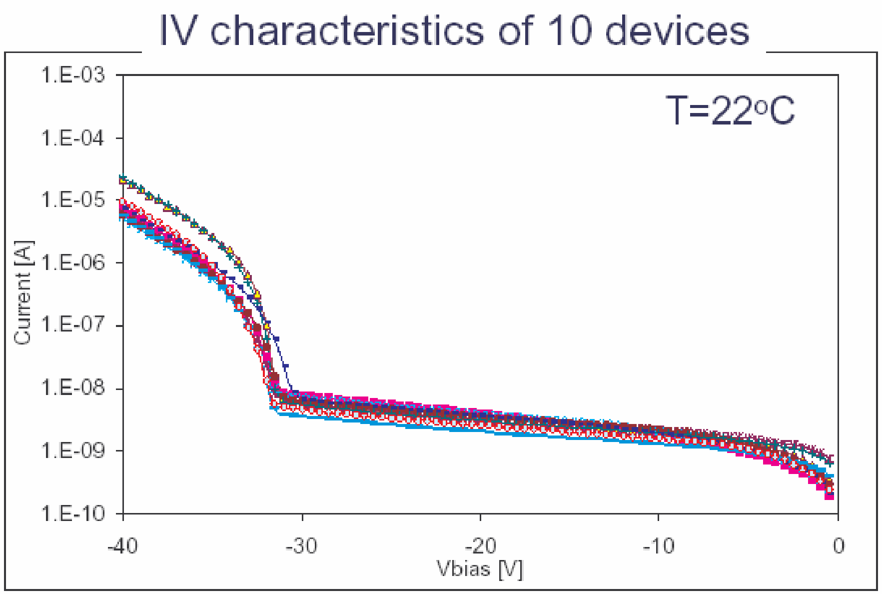
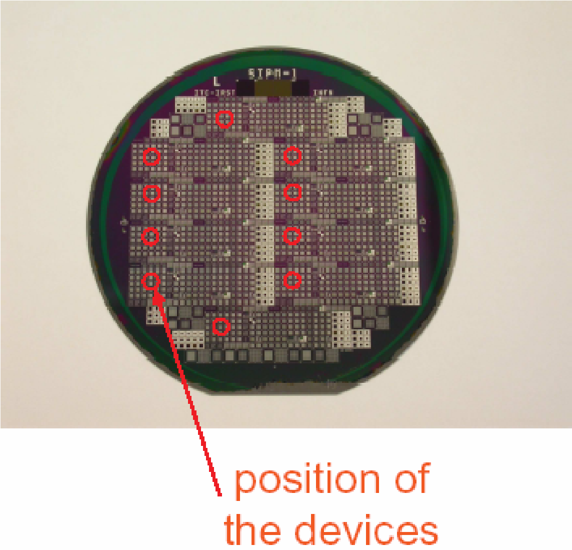
Electrical characterization



V_{BD} uniform over microcells

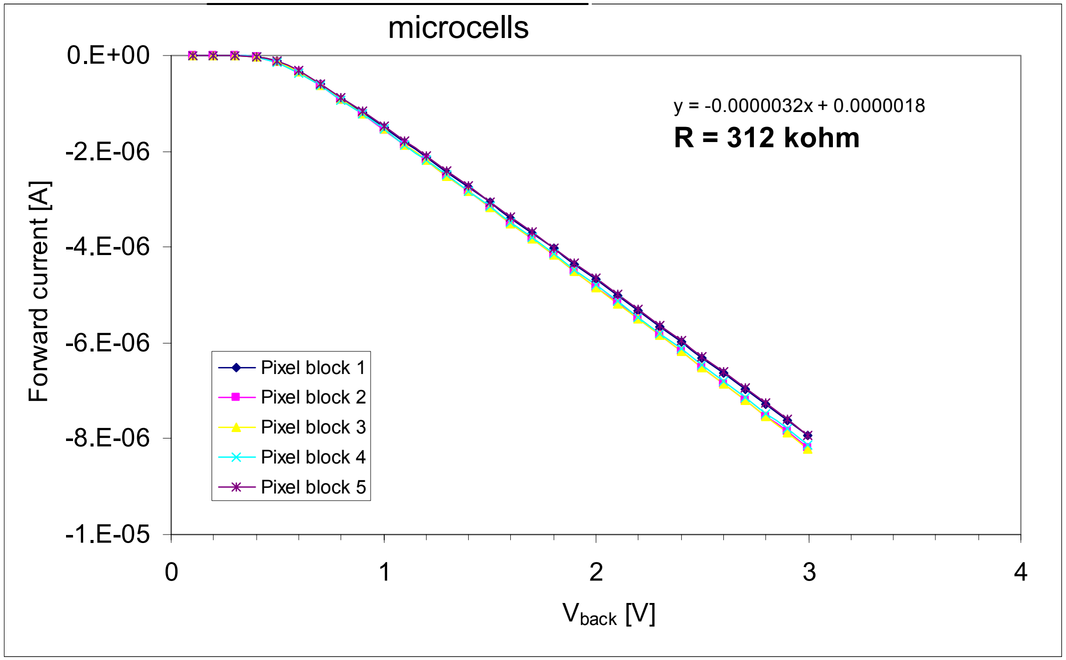
……and over different SiPMs



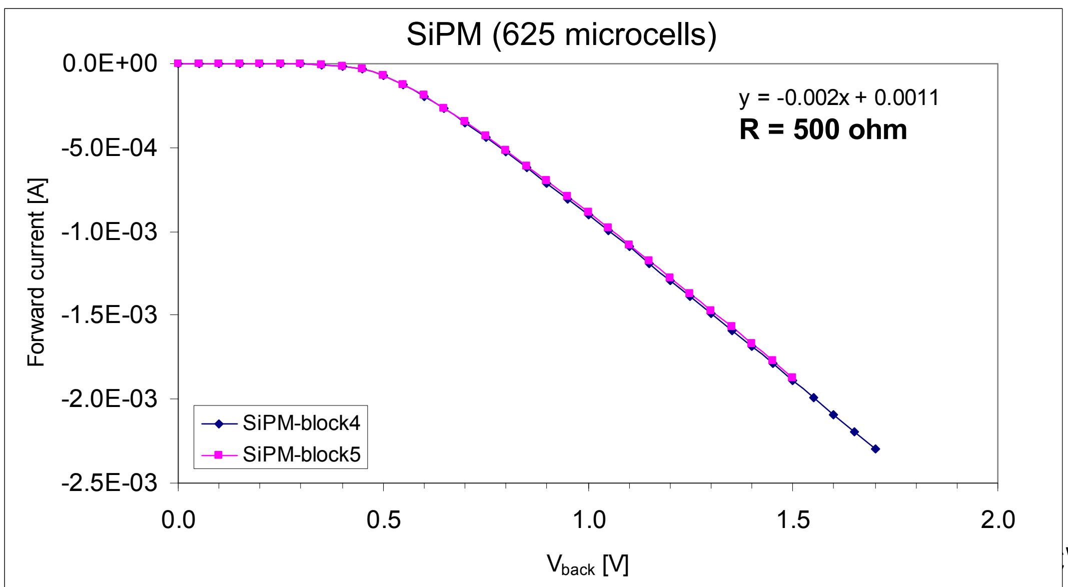


Post –breakdown currrent very uniform (measured over 90 devices) – 20% show anomalous behaviour

Electrical characterization



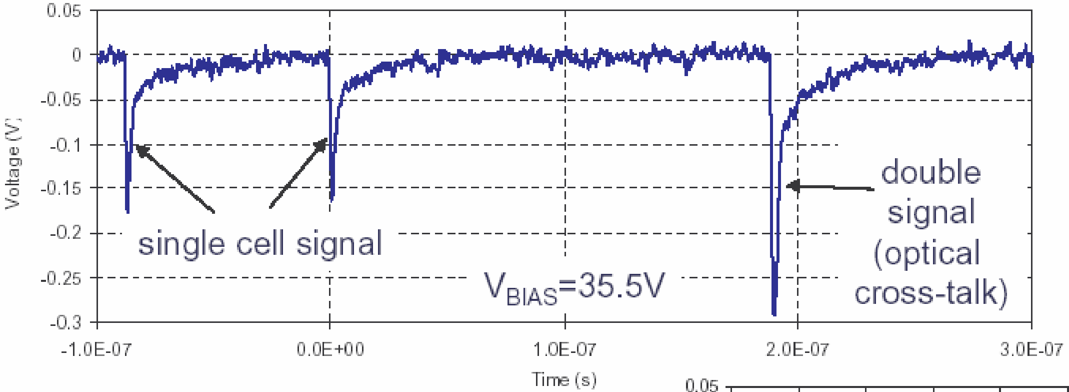
R_Q uniform over microcells



500Ω x 625 = 312 kΩ

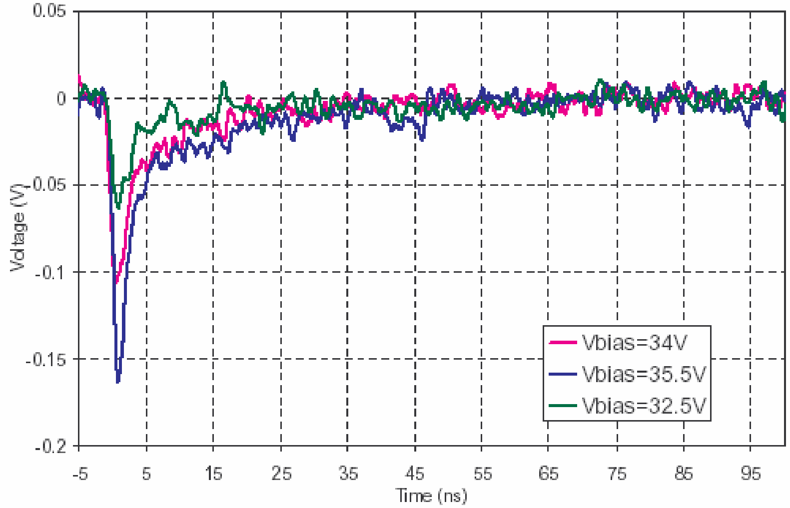
Signal characteristics

SiPM read-out by means of a wide-band voltage amplifier on a scope



Dark signal

T=22°C



Rise time < 1 ns (DAQ bandwidth)
Recovery time ~ 70 ns

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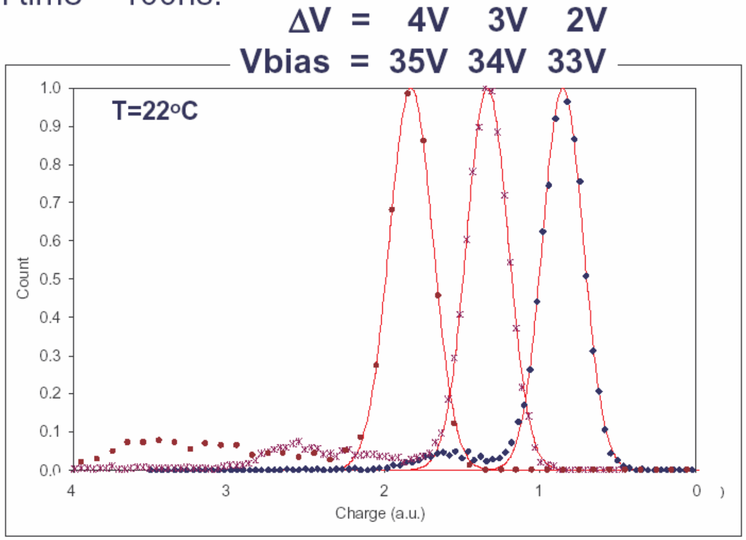
Integrated charge spectra for single p.e.

Integration time = 100ns.

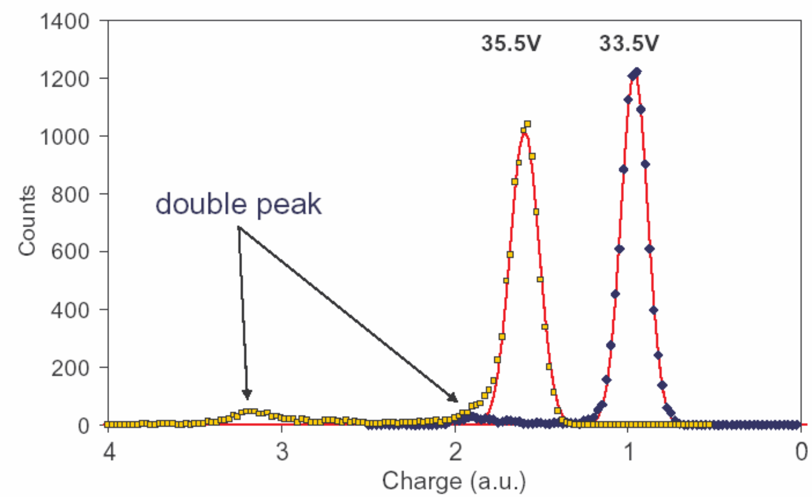
DARK



Tails due to optical cross-talk + afterpulsing

Integration time = 10ns.

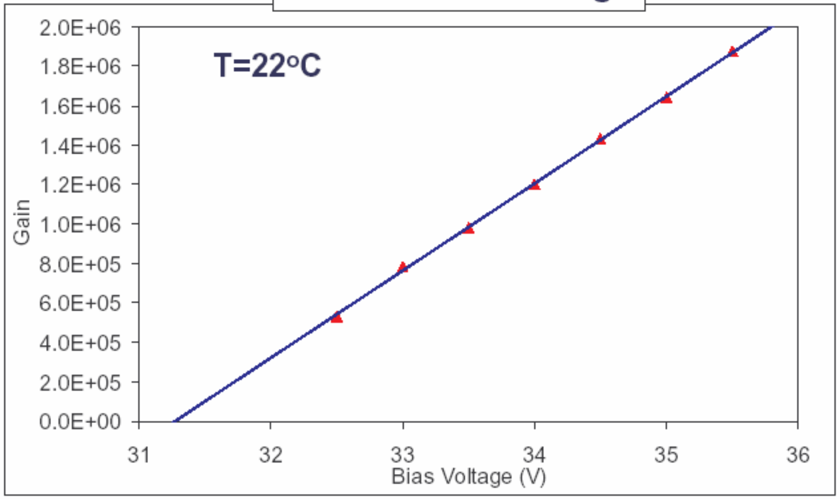
DARK



With short integration times
→info. on optical cross-talk

Gain and Noise

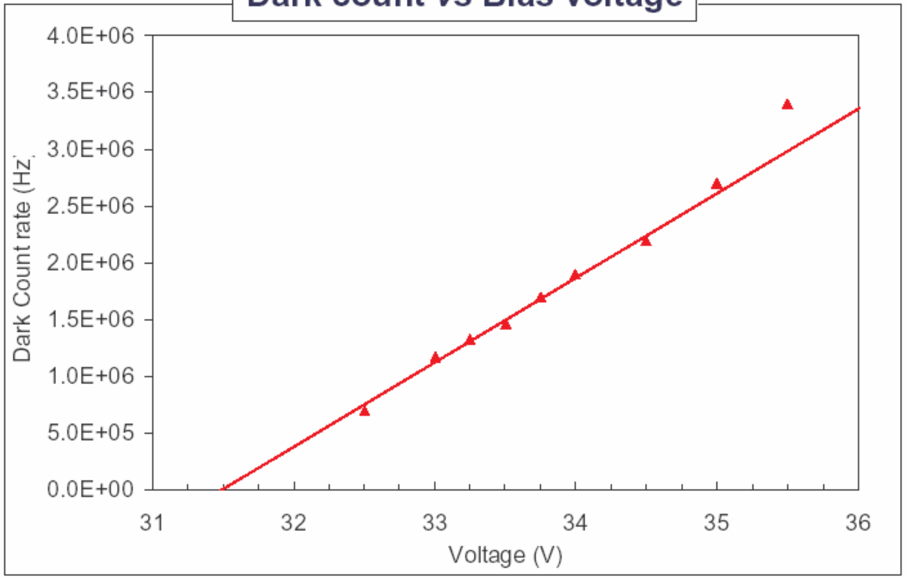
Gain *vs* Bias voltage **(measured for dark current)**



Linear as expected

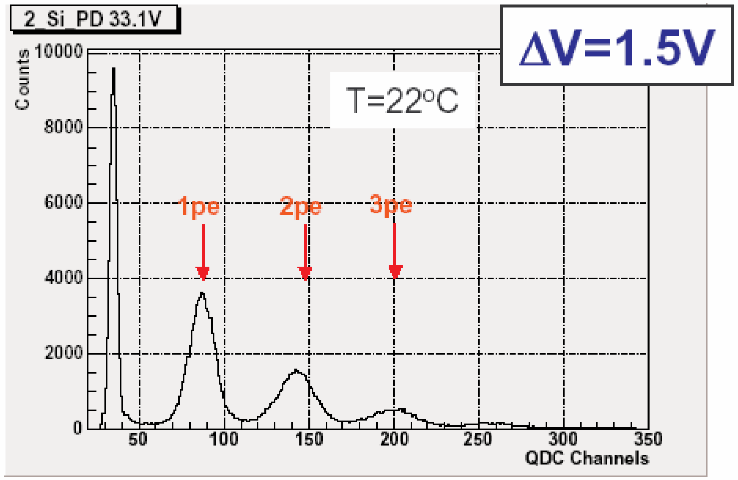
$$Q = C \times (V_{bias} - V_{BD}) \quad with \quad C = 80 - 90\, fF$$

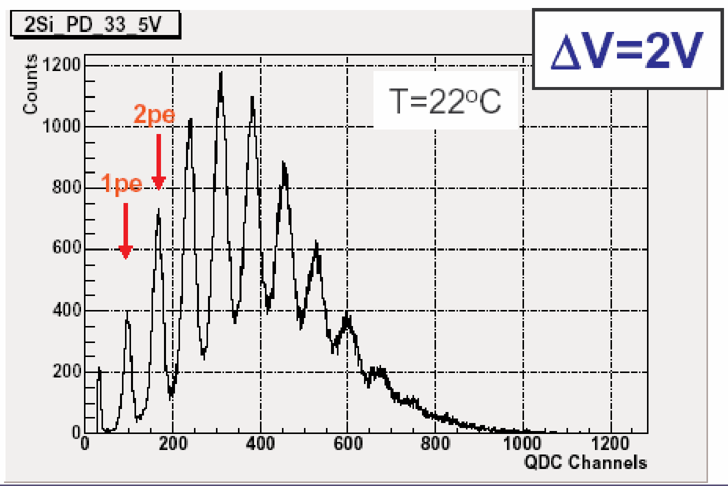
Dark count *vs* Bias voltage



Dark count increases linearly with voltage.
PDE should do the same

Response to light





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

Each peak corresponds to a different number of fired cells

Very good uniformity response from the micro-cells

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June 20th 2006

Energy resolution

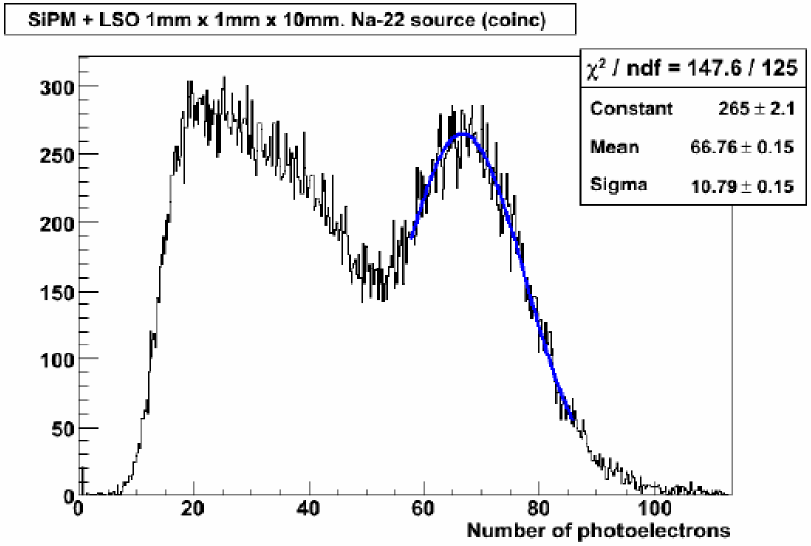
VERY PRELIMINARY from Pisa (A. Del Guerra)

Very first measurement on one single device

- 1mmx1mmx10mm **LSO crystal coupled to a SiPM**
- Data taken in coincidence with a 10mm diam, 5mm thick YAP crystal coupled to a PMT.
- ^{22}Na source.
- 2.5V overvoltage
- **37% energy resolution**

1) Optimizing the set-up and the working conditions this value can be improved

2) Area efficiency has to be optimized yet!



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Summary

- SiPMs have been designed and produced at ITC-irst
- the first production run has yielded functional devices
  - Gain ~ 10^6
  - Dark count ~MHz
  - Recovery time ~ 70 ns
  - Good uniformity over microcells and SiPMs
  - PDE measurement in progress: first results encouraging
  - high (80%) production yield

- the second production run just completed
  - isolation trenches implemented for cross-talk reduction
  - high (80%) production yield as before
  - characterization in progress
  - tests in fnal test beam planned

- next production :
  - lower dark count
  - complete fabrication of buried-junction SiPMs
  - arrays