FBK silicon radiation detectors
An overview

Nicola Zorzi

on behalf of the radiation detectors team

GASPARD-HYDE-TRACE Workshop 2015 - 25-27 March 2015

FBK Organization

Scientific and Technological Area

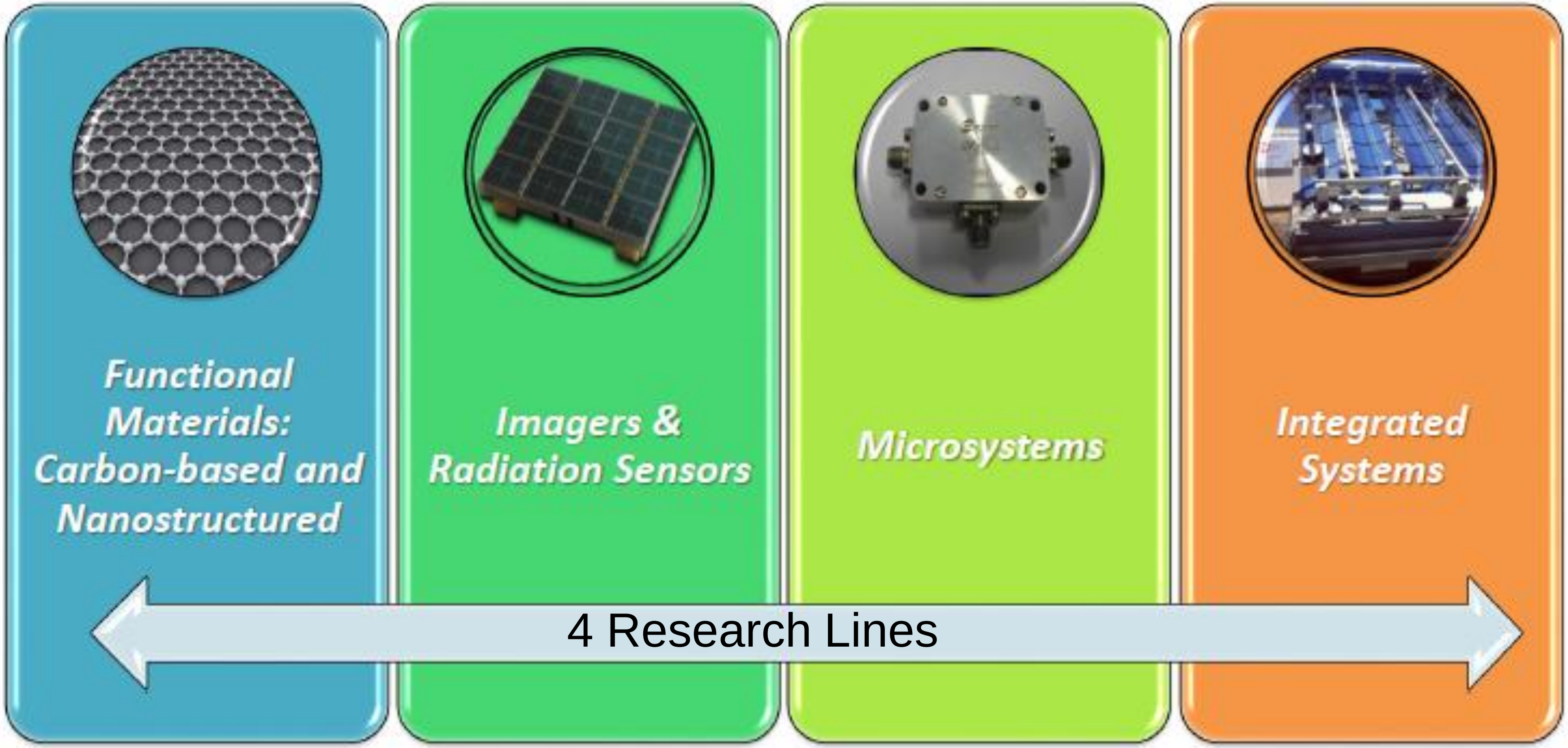
- **CMM** – Centre for Materials and Microsystem
- **ICT** – Centre for Information Technology
- **ECT*** – European Centre for Theoretical Physics
- **CIRM** – International Center for Mathematical Research

Humanities Area

- **ISIG** – Centre for Italian-German Historical Studies
- **ISR** – Centre for Religious Sciences
- **IRVAPP** – Research Institute for the Evaluation of Public Policies
- **CERPEG** – Research Center on War, Peace and International Change

FBK — CMM

Centre for Materials and Microsystems
(http://cmm.fbk.eu/)



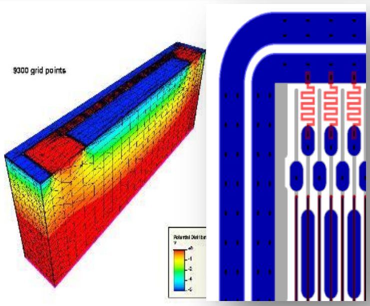
Research Units

MNF (Micro Nano Facility)
IRIS (Integrated Radiation Imagers and Sensors)

http://mnf.fbk.eu/
http://srs.fbk.eu/
http://iris.fbk.eu/

Silicon Devices Expertise

TCAD simulation CAD design



Process flow development

Fabrication

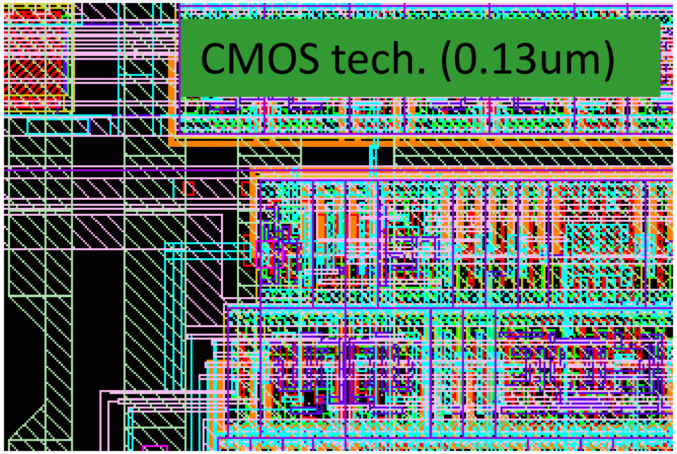
Device testing

Material Characterisation

- XPS
- SIMS
- ToF-SIMS
- TXRF
- AFM
- SEM

Custom CMOS design

Development of ROIC by exploiting state of the art CMOS tech (external services)



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FONDAZIONE BRUNO KESSLER

Micro Nano Facility

2 separate clean rooms:

- CR Detectors
  500 m^2 in class 10 and 100

- CR MEMS
  200 m^2 in Class 100 and 1000

Equipments:

- Lithography
- Diffusion
- Implantation
- Dry Etching
- Wet Etching
- Control Area

6” wafers processing capability starting by 2013

Test Laboratories

- Manual probers
- Automatic probers
- Parametric Test
- Functional Test
- Optical Test

Microsystems Integration Lab
- Microassembly
- Bonding
- Micromilling/Drilling
- Screen printing

Silicon Radiation Detectors

Sensors on high-resistivity substrates

- pixel detectors
- strip detectors
- drift detectors
- 3D detectors

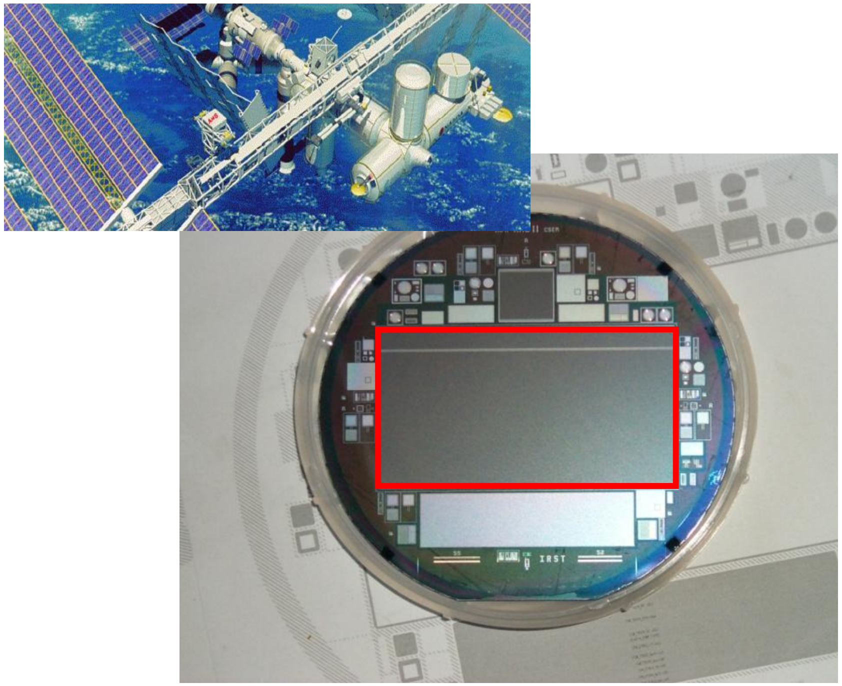
Sensors with internal gain for light detection

- Silicon Photomultipliers
- SPADs

- Custom design
- Technology development
- Device manufacturing (small/medium production capability)

Strip detectors: medium-scale productions

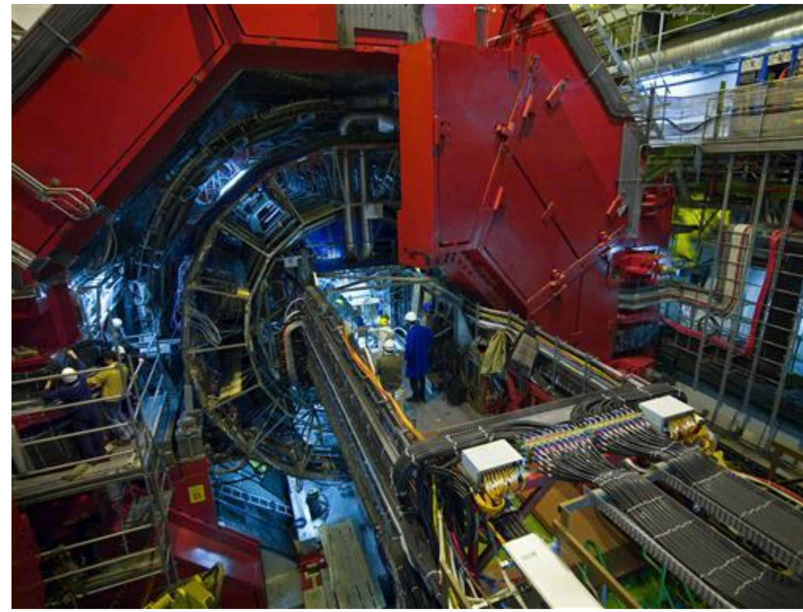
AMS experiment (@ISS)



Silicon microstrip detectors:

700 large-area double-sided in spec detectors fabricated in 2002-2004.

ALICE experiment (@LHC)



Silicon microstrip detectors:

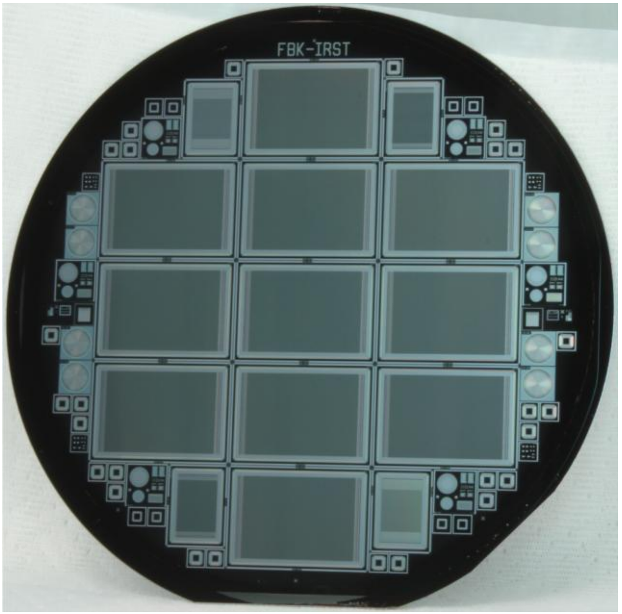
600 large-area double-sided in spec detectors fabricated in 2003-2005.

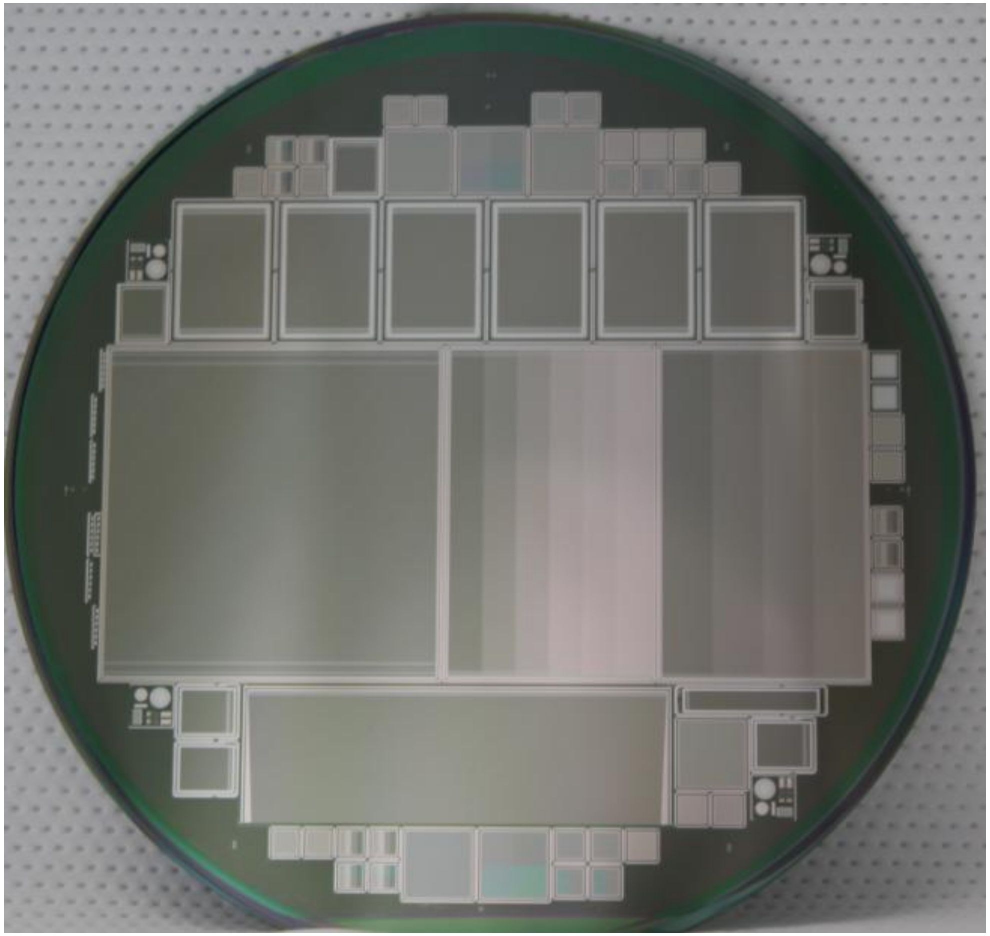
ALICE Industrial Awards in 2006

Strip detectors: custom productions

Custom development of strip detectors for private companies and research institutions:

- single/double-side,
- DC/AC coupled,
- punch-through biasing,
- very low leakage,
- high yield



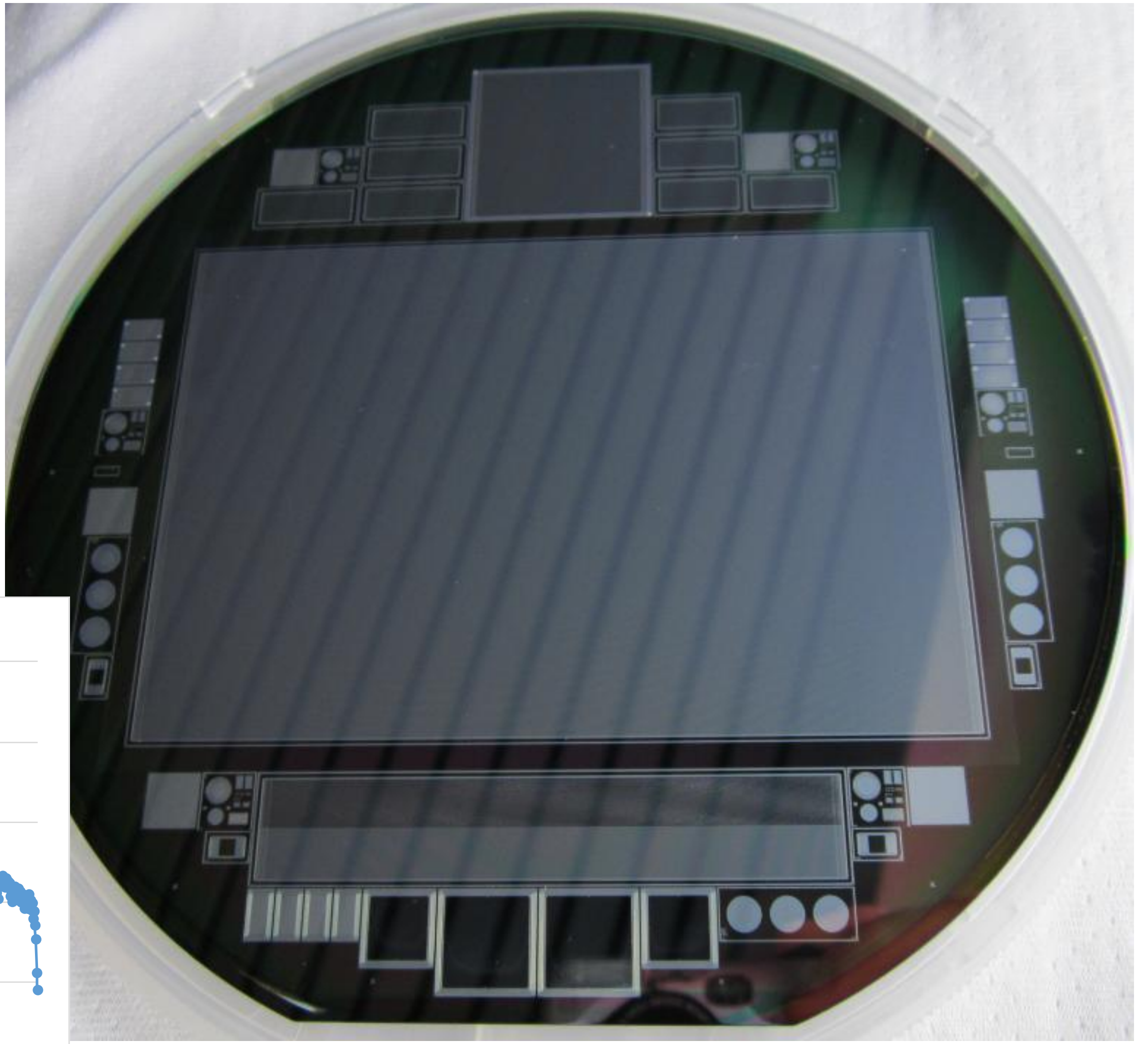


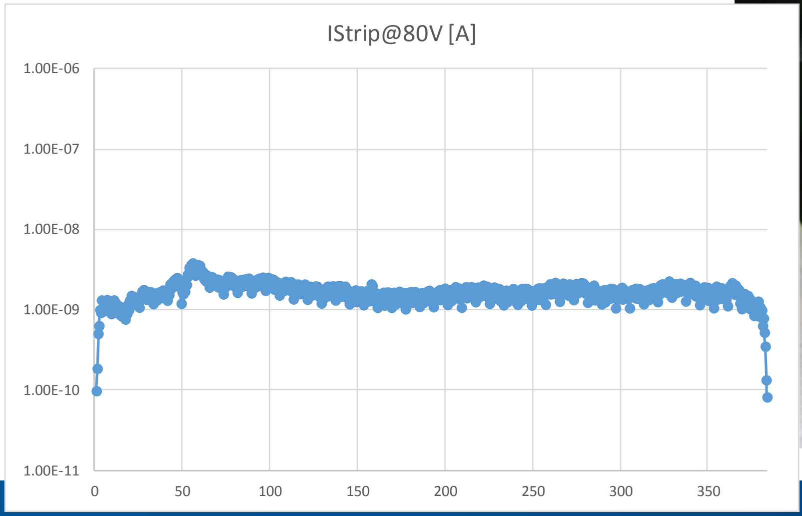
Strip detectors: large area on 6”

Development of strip detectors for CSES/Limadou project:
China **S**eismo-**E**lectromagnetic **S**atellite

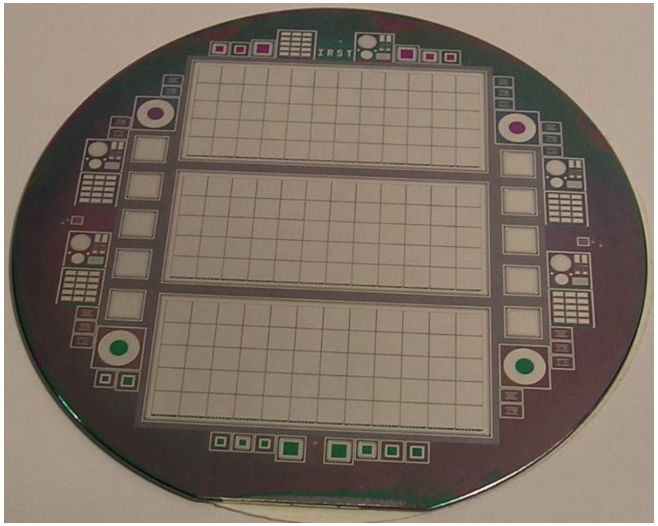
CNSA/ASI/INFN collaboration

~ 11x7.8cm2 strip detector:
- double-side,
- AC coupled,
- punch-through biasing,
- orthogonal strips





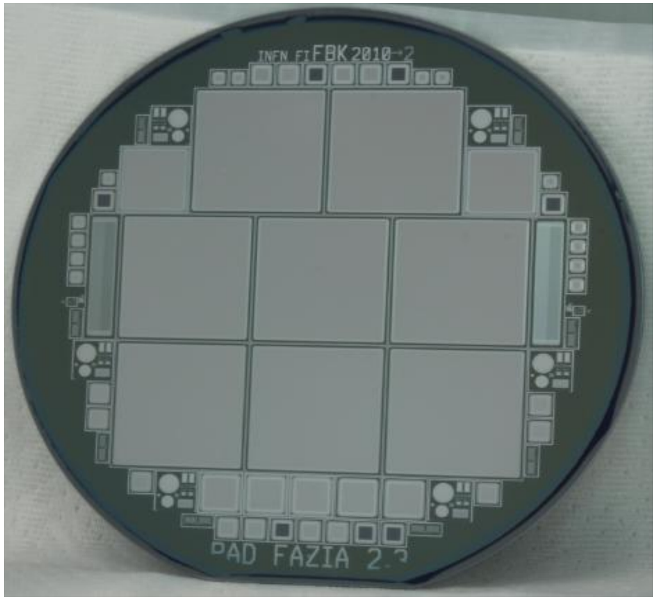
Custom Pad detectors: examples (4”)



Segmented PAD detectors for TRACE

- 12x5 array, 4mm pitch
- AC coupling, punch-through biasing
- **1.5mm** and 0.2mm thick substrates

Thick-substrates require non-standard processing and equipment-settings
Starting material quality play a key role



Large area PADs for FAZIA

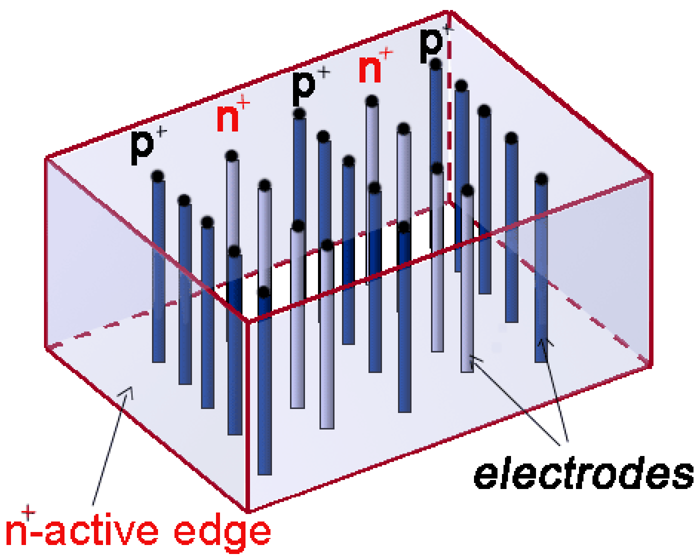
- 2x2cm^2 active area,
- NTD substrates with peculiar orientation
- 0.3mm and 0.5mm thicknesses
- double-side dedicated process
- two (thick/thin) metal layers

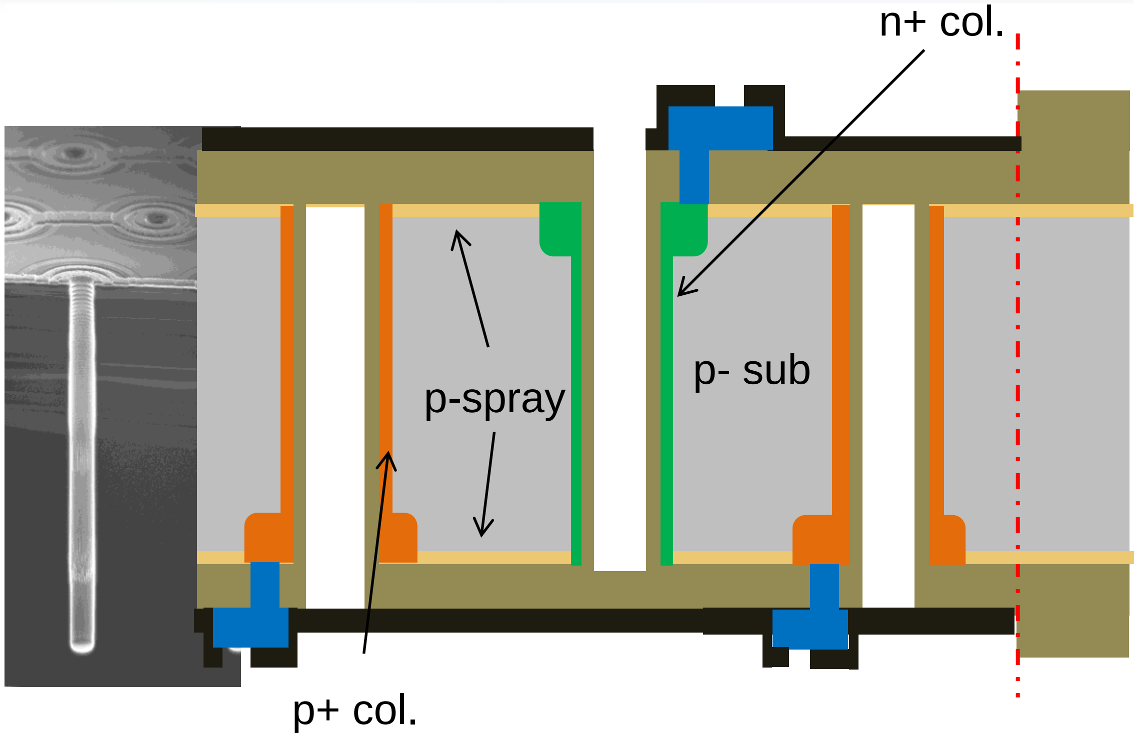
Different production cycles for the development of the proper technology

Procurement of non-standard substrates more difficult for 6”

FBK 3D technology

First proposed by S. Parker et. al.
in NIMA 395 (1997), 328





Original Double side fabrication process

- junction columns etched from front
- ohmic columns etched from back
- empty columns (~11µm diam.)
- passing-through columns (230µm)
- p-type FZ wafer with p-spray isolation

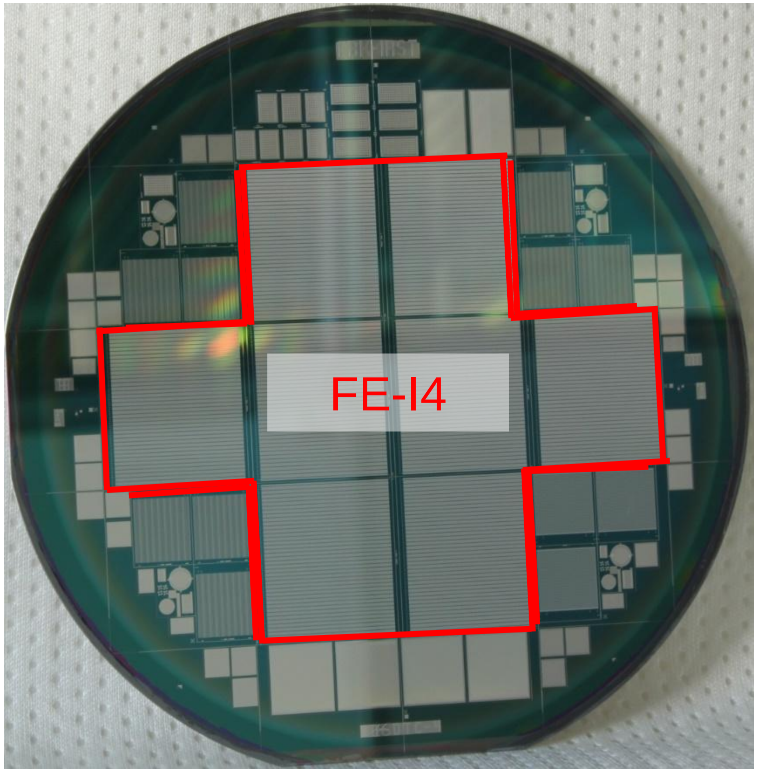
Latest Technology developments

- both column-types etched from front (single-side, thin substrates with support)
- partial column filling with poly-Si
- partial etching of junction columns
- From 4” to 6”

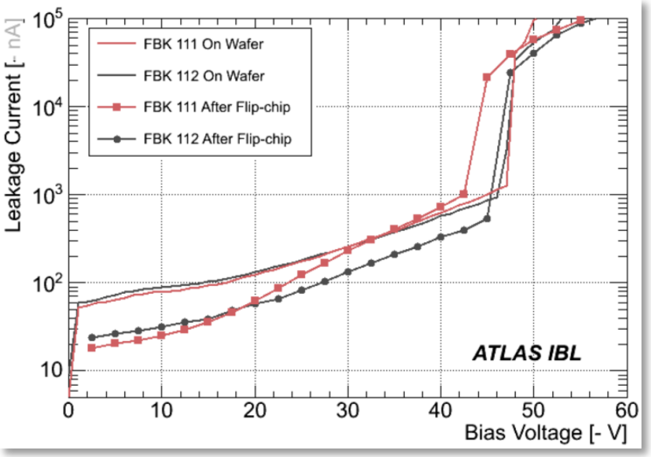
3D detectors for ATLAS-IBL up-grade

- Insertable B-Layer based on hybrid pixels/FEI4 (~2x1.8cm^2)
- IBL installed in ATLAS during current LHC shutdown
- ~25% of pixel sensors for ATLAS-IBL are 3D (from CNM & FBK)

3D sensors for the 1st time in an exp

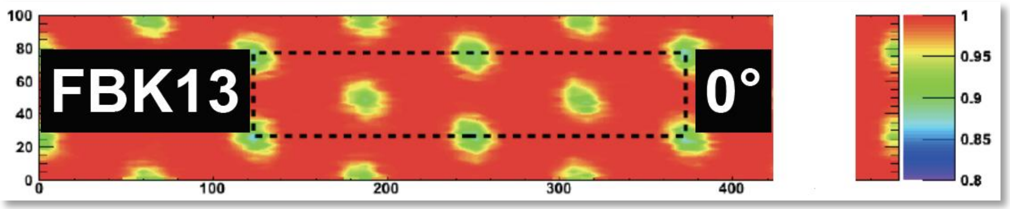


Common wafer layout of ATLAS/3D collaboration (8 FEI4 sensors, 4”)



Total leakage current measured at:

- wafer level
- after bump-bonding to FEI4 chip



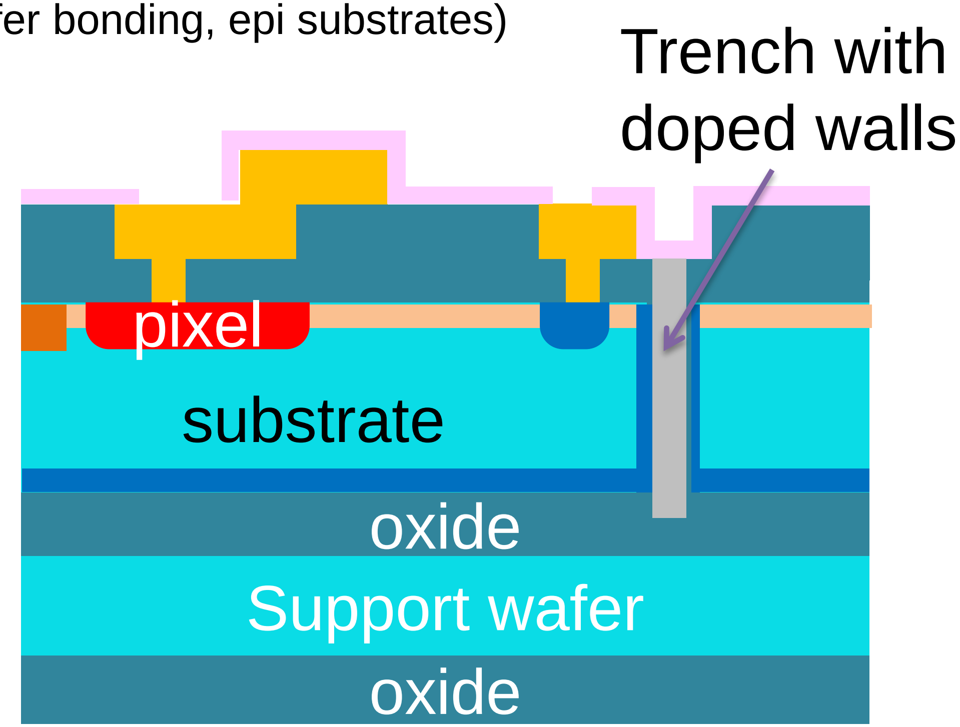
Tracking efficiency map at normal incidence for an un-irradiated detector at 20V (after bump-bonding to the FEI4 chip)

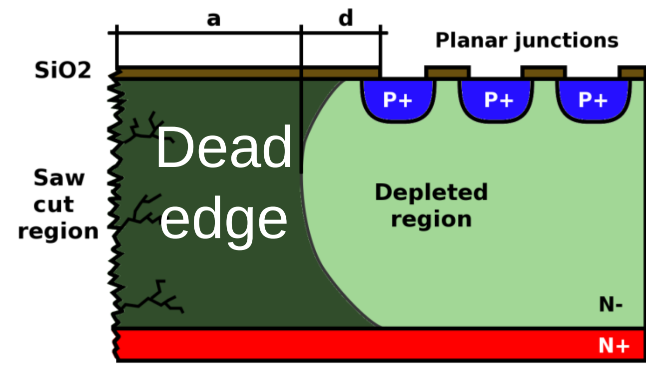
Active-Edge (Edgeless) detectors

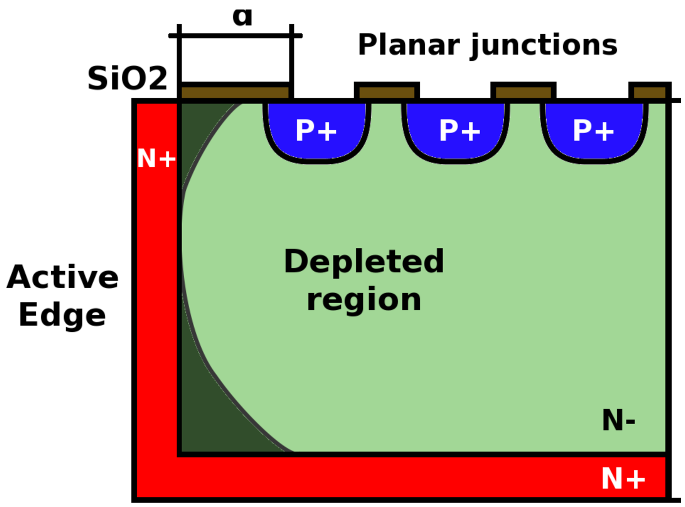
Main motivation:
minimize dead area at the borders

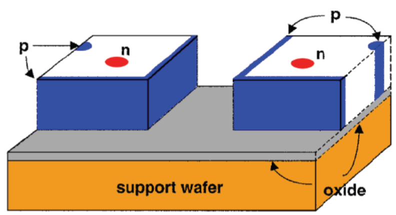
Compatible with both planar and 3D devices

Requires a support wafer
(wafer bonding, epi substrates)



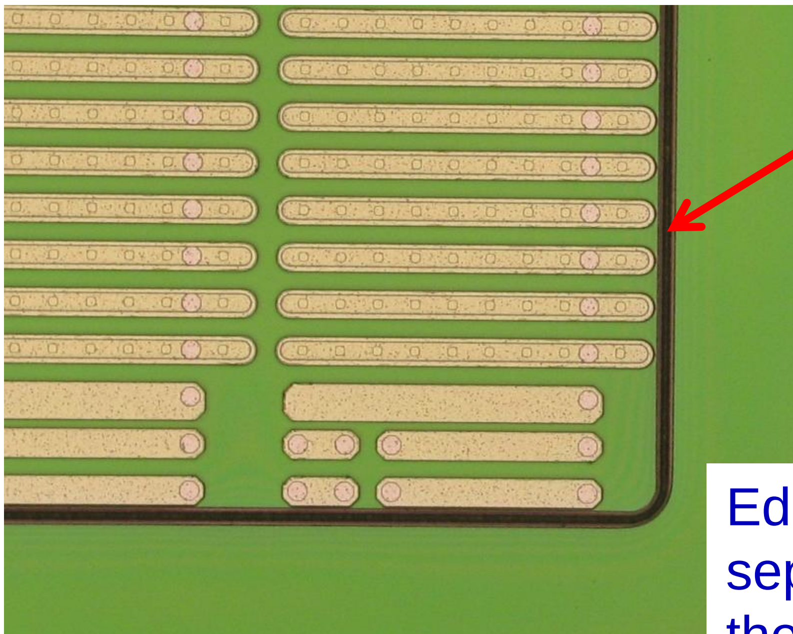


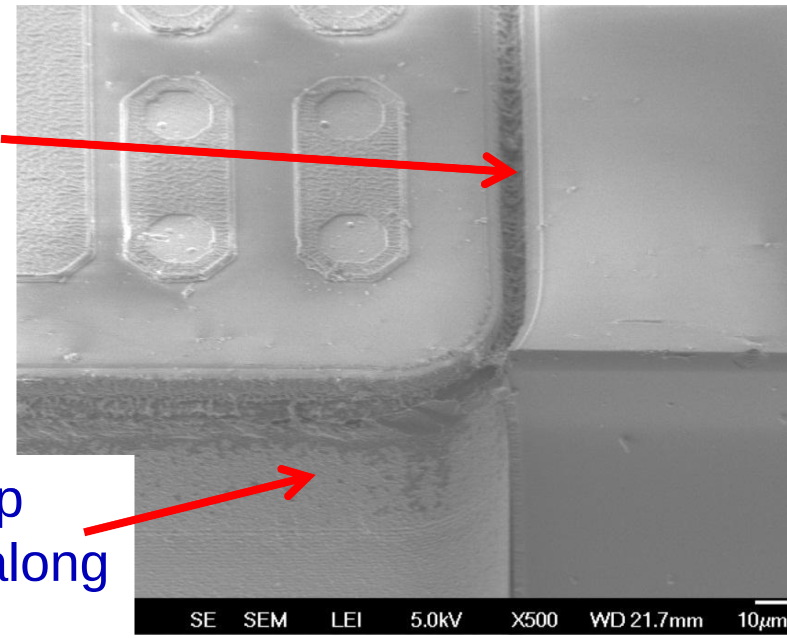




FBK Active edge: example (4”)

- ~5µm wide trench
- 100-200µm deep (depending on the depth of active substrate)
- poly-Si filled (walls doping and planarization for further process steps)





Trench

Edge of chip separated along the trench

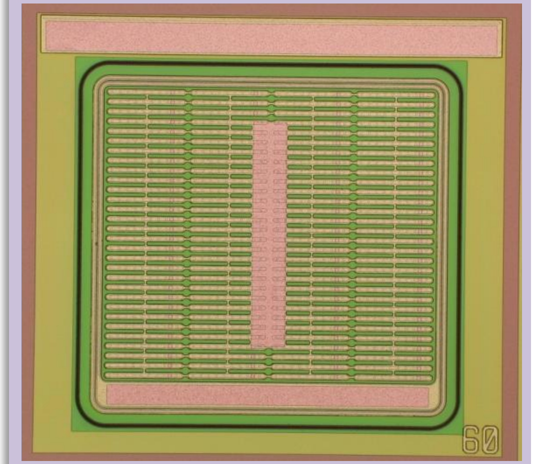
Silicon pixel sensors produced using:

- 200µm-thick FZ substrates, oxide-bonded to CZ support wafer
- 100µm-thick epi layer on thick substrates

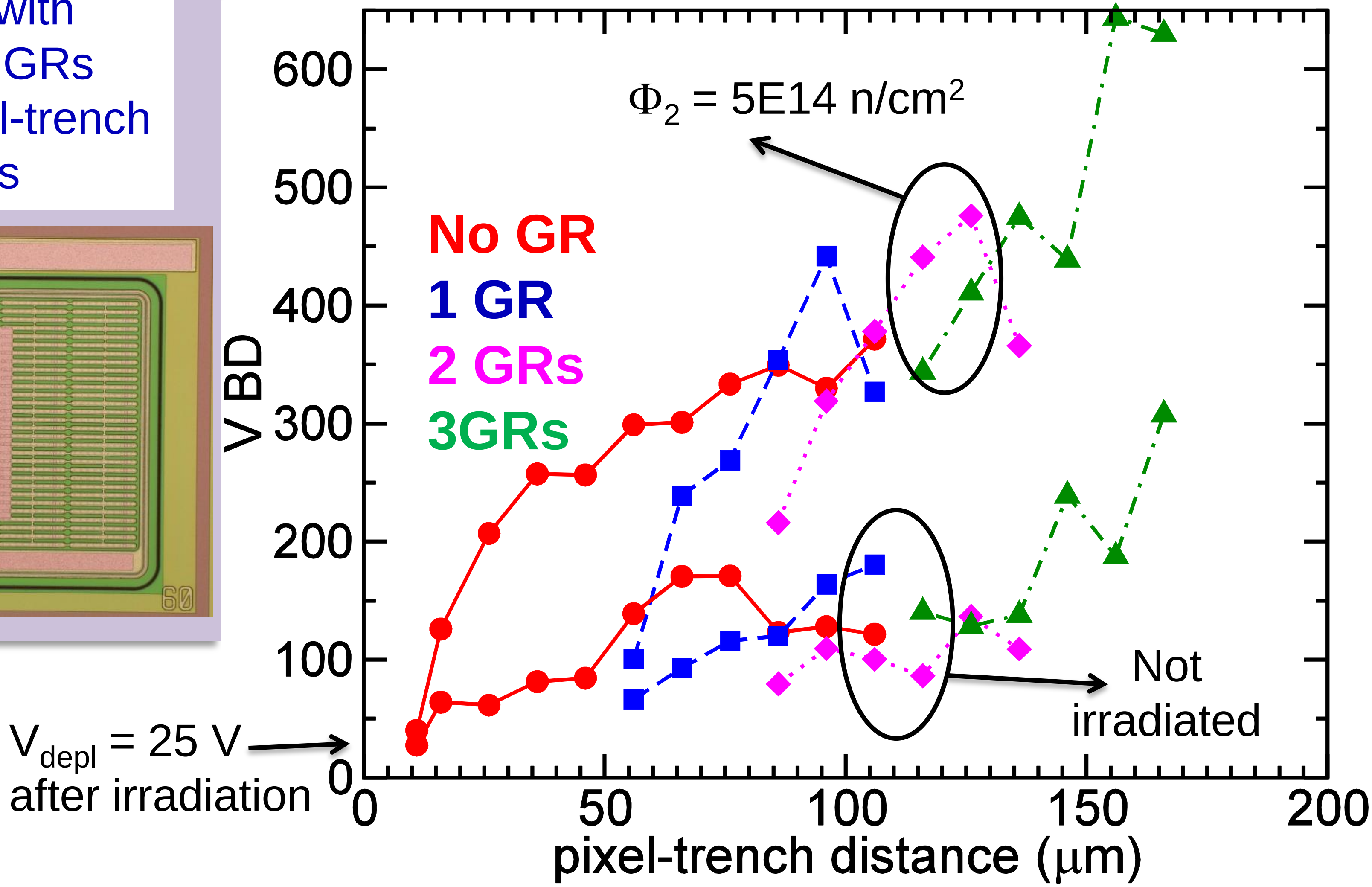
Si-Si direct bonded wafers (FZ-on-CZ) under evaluation (planar process)

Active edge results (epi substrate)

Pixel-like test devices with different GRs and pixel-trench distances

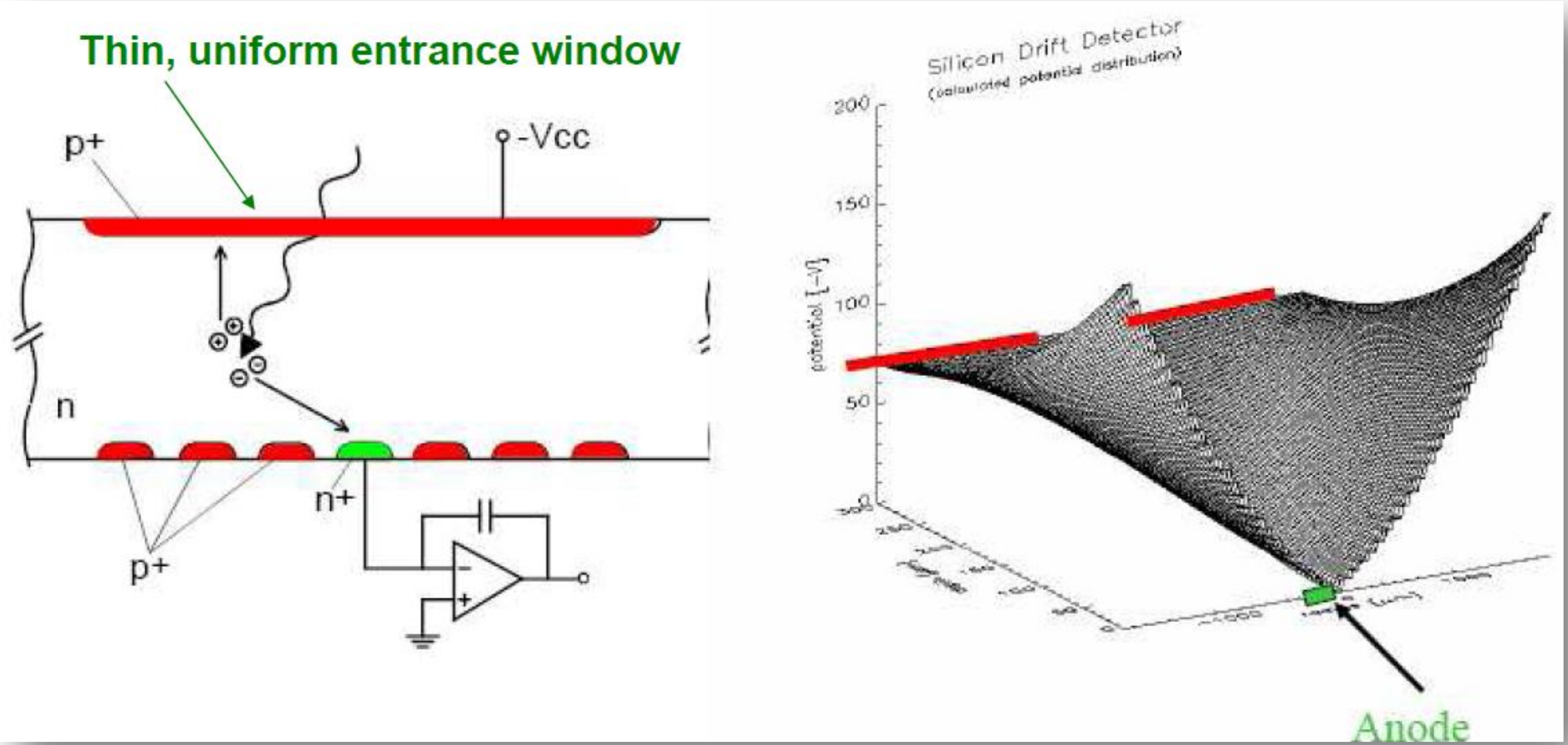


Samples irradiated with reactor neutrons in Ljubljana



Lateral dead layer can be kept at few 10µm

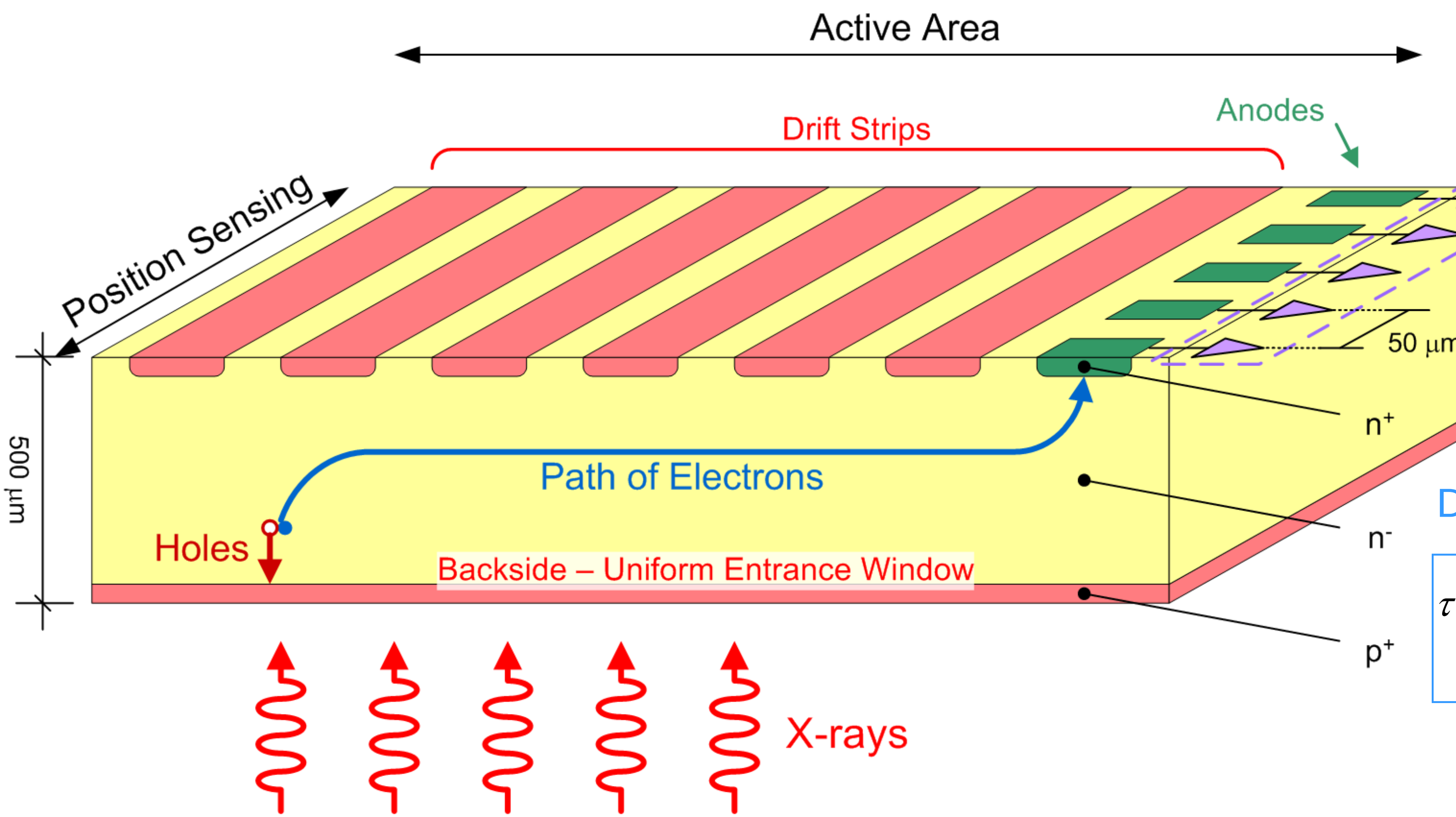
Silicon Drift Detectors (SDDs)



- Very tiny collecting electrode → low capacitance (low noise)
- ~10-100mm^2 active area (single central anode, “circular” symmetry)

Applications: • γ- and X-ray spectroscopy (with or w/o scintillator)

Multi-anodes Linear SDDs



$$\tau_d = \frac{x_S - x_A}{\mu_e \dfrac{\Delta V}{L}}$$

- array of collecting electrodes (anodes) → 1D spatial information
- ~100cm^2 active area
- for large devices an effective drift field requires patterning of both sides
- drift time gives additional 1D spatial information

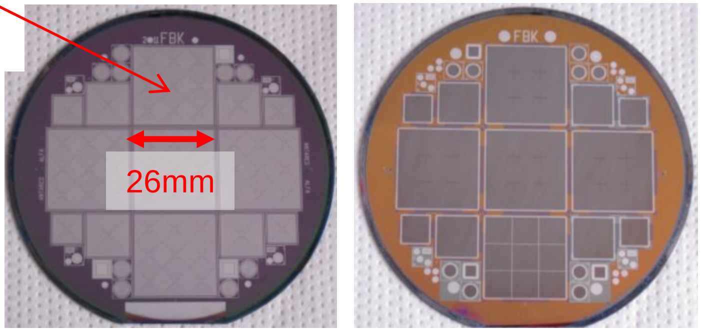
Applications:
- 2D position sensitive detectors (use of drift time)
- tracking, X -ray spectroscopy

SDD: ESA project

ESA/PoliMI/INFN-MI

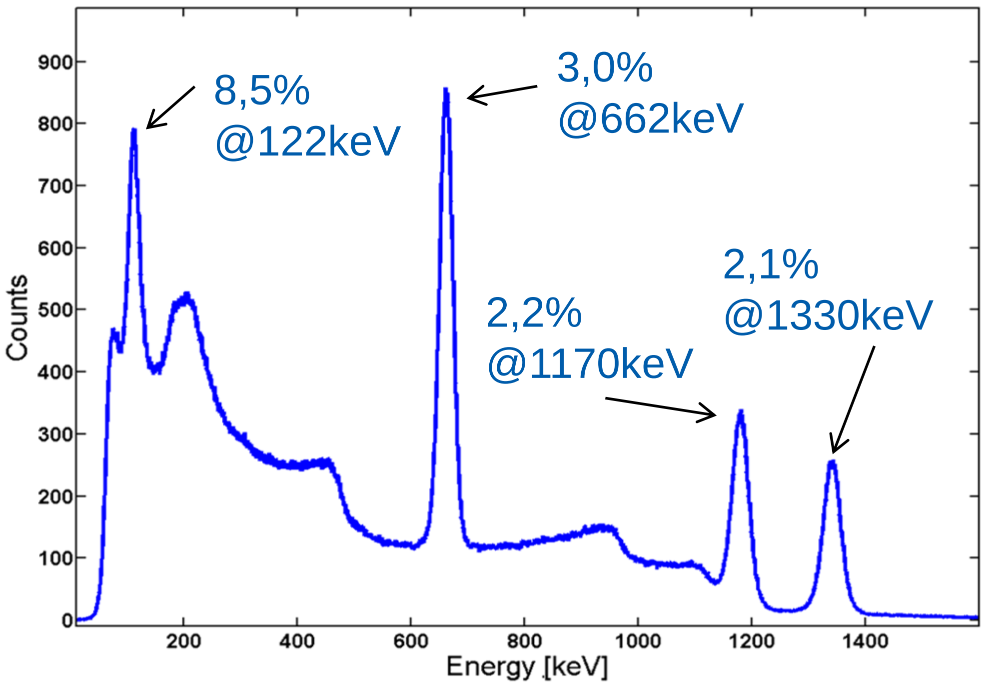
4” wafers

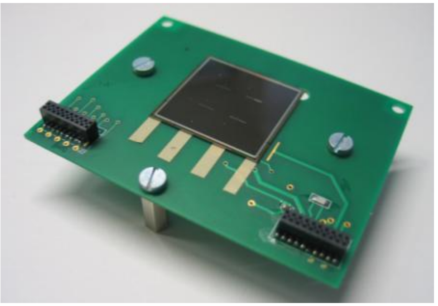
3X3 SDD matrices



- γ-ray detector
- $LaBr_3$:Ce scintillator (1” to 3” Ø)
- optical entrance window for ~370nm light

^{57}Co, ^{137}Cs, ^{60}Co spectra measured with the SDD array coupled to a 1’’ $LaBr_3$ crystal





(Energy resolution @662keV measured with a PMT = 3.2%)
(courtesy F.Quarati)

presented at IEEE NSS-MIC 2012

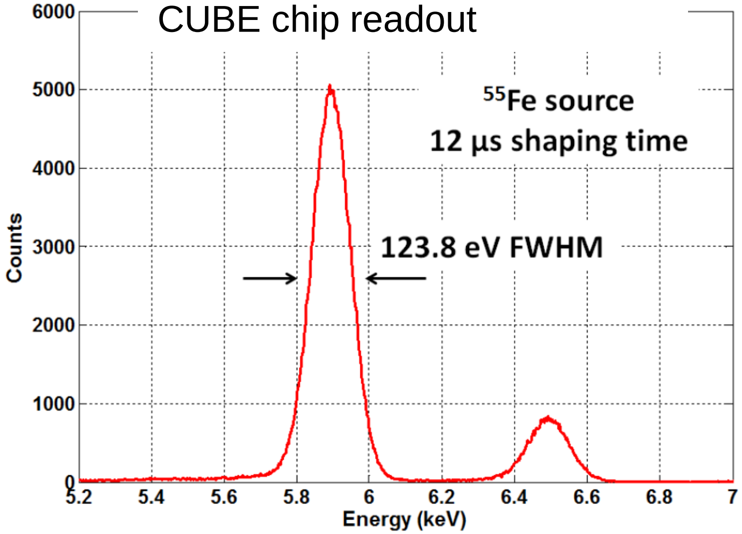
T=: -20°C
peaking time: 6 μs

SDD: SIDDHARTA INFN-Frascati/PoliMI

(Silicon Drift Detector for Hadronic Atom Research by Timing Application)

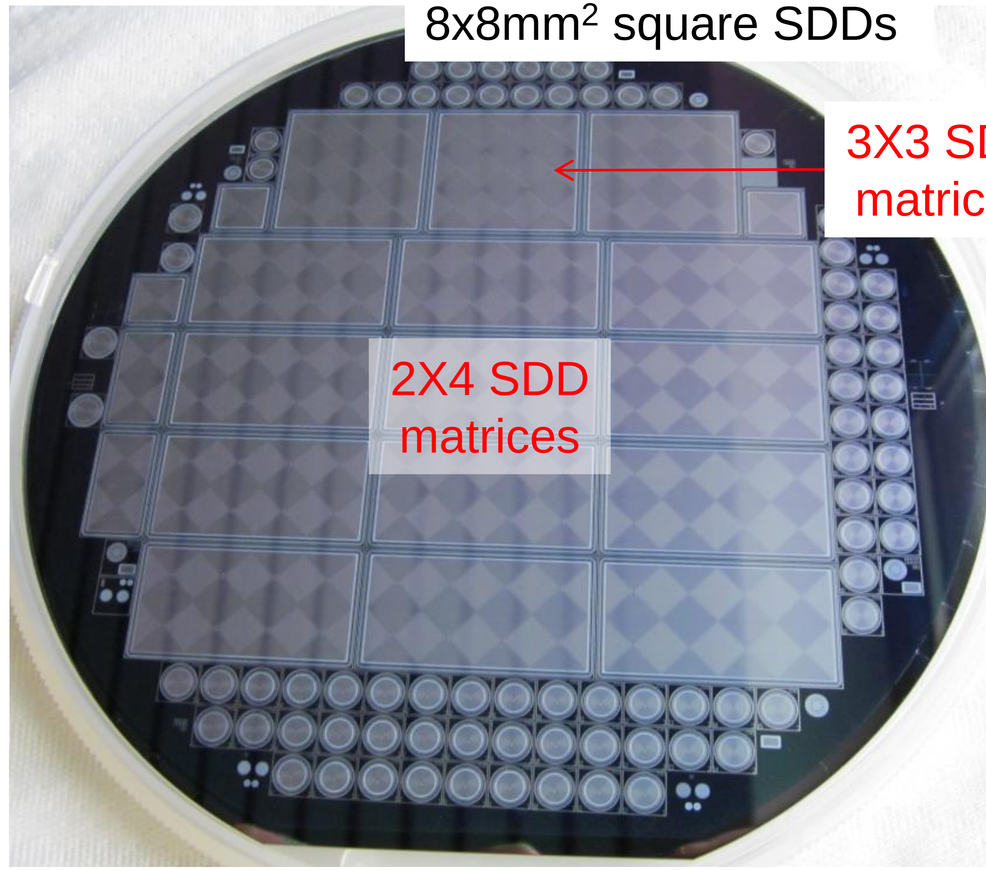
Almost same technology as of ESA, but 6”

64mm^2 SDDs from 4” wafers
4” production
T=160K
CUBE chip readout



From: R. Quaglia et al.,
JINST 10 C03001, 2015

Matrix elements:
8x8mm^2 square SDDs



First 6” production recently finished

SDD: ReDSoX/LOFT project

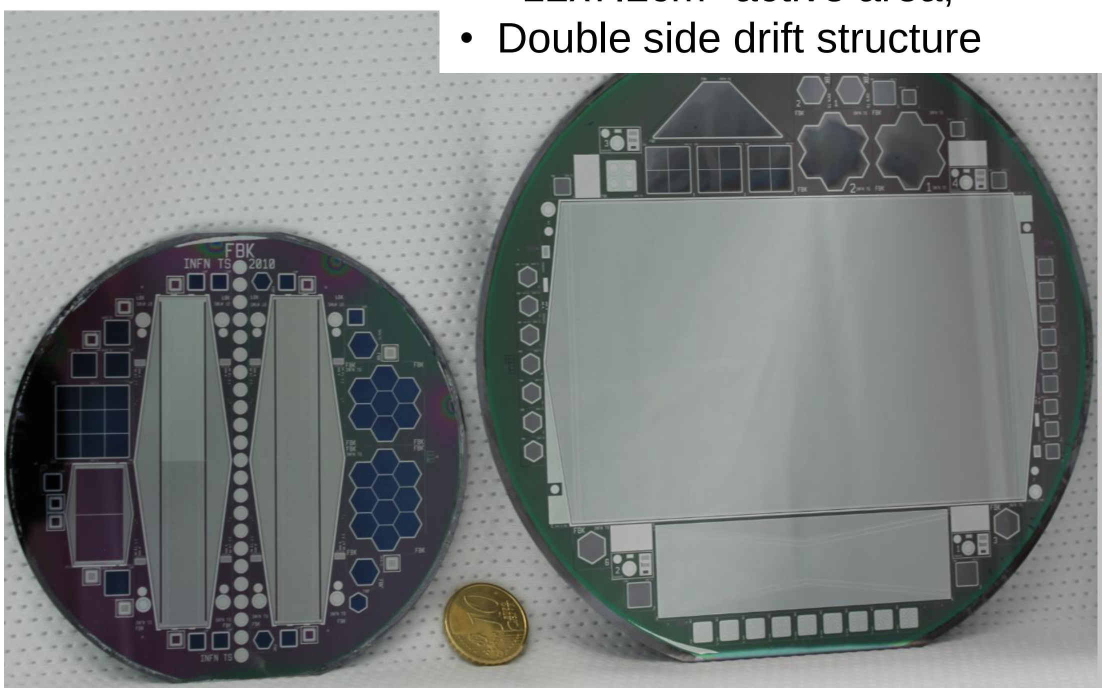
Research Drift for Soft X-rays

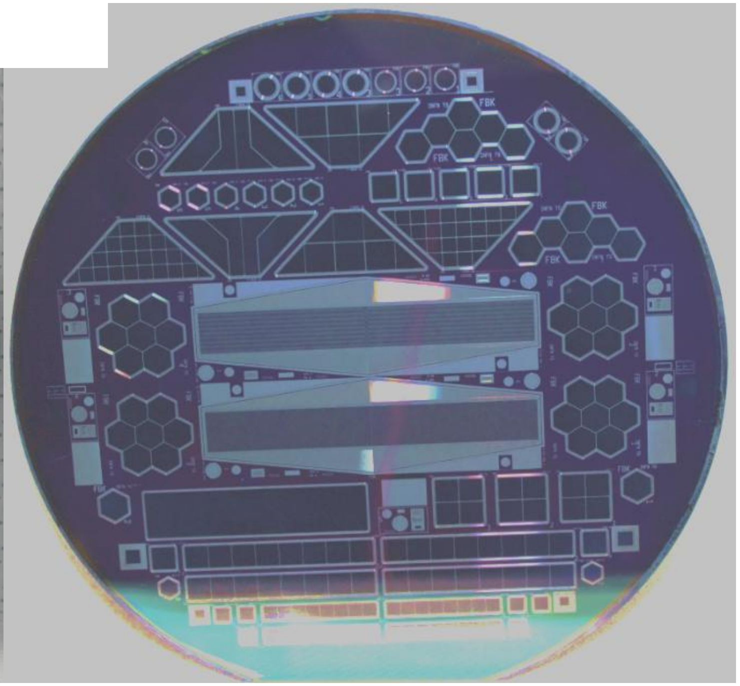
INFN/INAF

- development of large area Silicon Drift Detectors for X-ray astrophysics
- development of high energy resolution detectors for soft X-rays
- development of detectors for Advanced Light Sources
- improvement of the SDD technology

Large area linear drift detector for LOFT (Large Observatory For X-ray Timing)

- ~$12 \times 7.2 cm^2$ active area;
- Double side drift structure



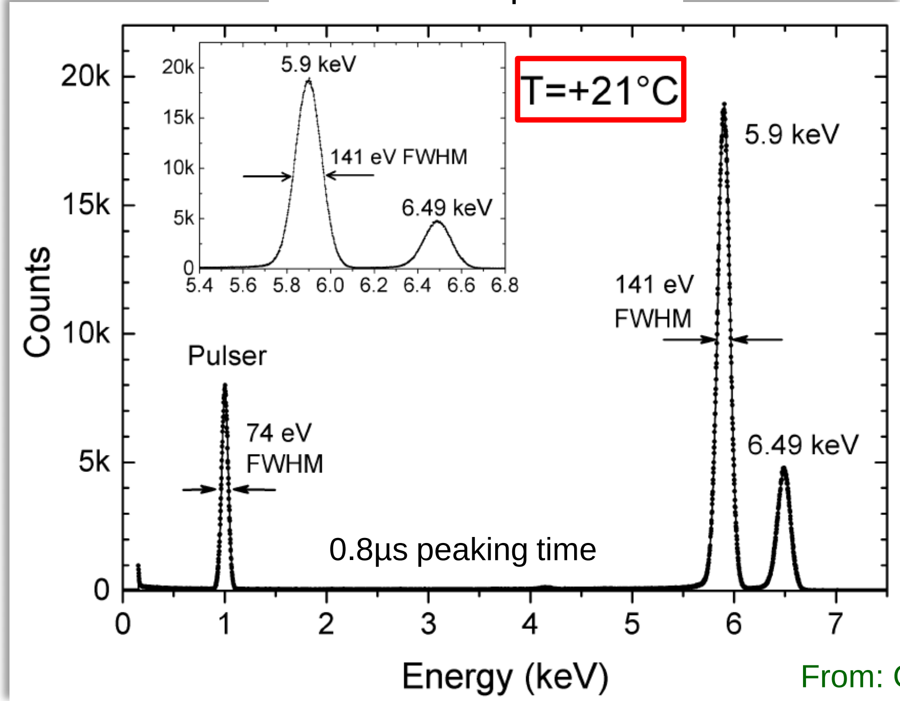


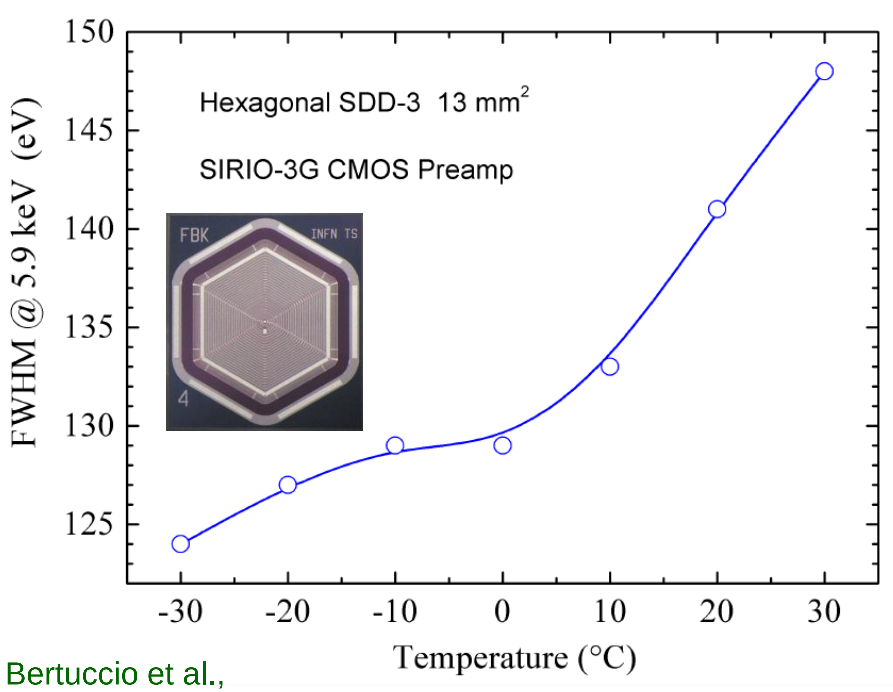
SDD: ReDSoX project

- development of large area Silicon Drift Detectors for X-ray astrophysics
- development of high energy resolution detectors for soft X-rays
- development of detectors for Advanced Light Sources
- improvement of the SDD technology

Gettering technique allows to obtain J_{leak} ~ 25pA/cm^2 at ~20C → Room-temperature High-resolution X-ray spectroscopy feasible with Si detectors

^{55}Fe source spectrum





From: G. Bertuccio et al., JINST 10 P01002, 2015

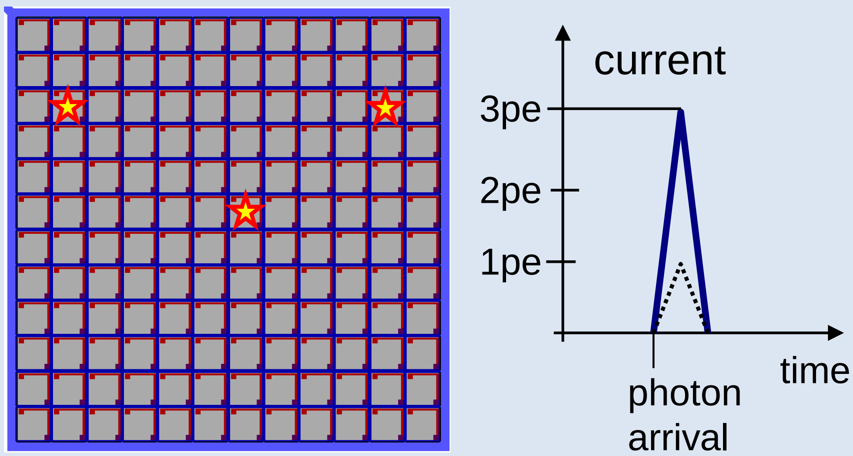
Silicon PhotoMultiplier (SiPM)

Avalanche Geiger-mode photodiodes

Each photon triggers a discharge which is shortly quenched

- Gain ~10^6
- Timing ~ 100ps /1ph.e.
- Bias voltage <100V
- Sensitivity ~1 ph. e.
- QE ~ medium

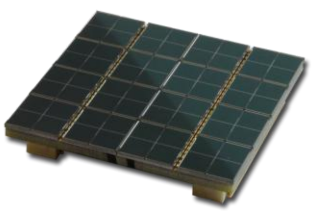
Array of tiny GM APDs: proportionality



SiPM:

Silicon Photo-Mulitplier

From vacuum…



…to solid-state

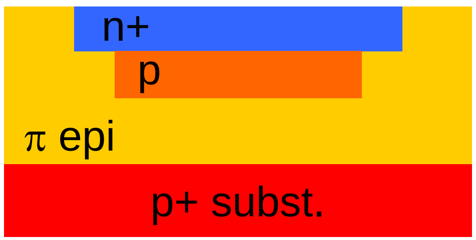
.. compact, robust, insensitive to magnetic fields

Standard SiPM technology at FBK

RGB Technology

N-on-P structure

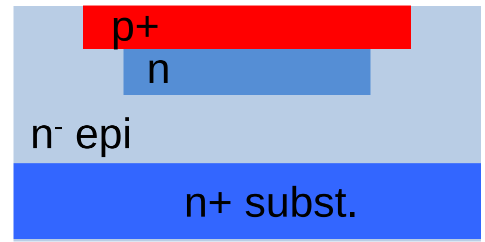
Peak sensitivity: Red-Green-Blue



NUV Technology

P-on-N structure

Peak Sensitivity: Near Ultra Violet



Parameter	RGB	NUV
Breakdown voltage	28.5 V	26.5 V
Cell Size (Fill Factor)	40 µm (60%)	40 µm (60%)
DCR (20C)	<400 kHz/mm^2	100 kHz/mm^2
DiCT	20%	<10%
DeCT+AP	15%	40%
Max PDE band	480-600 nm	300-400 nm
Peak PDE	35%	35%

Standard SiPM Technology limits

Performance limit	Possible solution
• Limited Fill Factor • Limited PDE	• Increase cell size • Reduce dead cell border
• Correlated noise (CrossTalk & AfterPulse)	• Decrease gain (reduce cell size) • Add optical isolation at cell border

Technology improvement: HD-SiPM

(High Density)

Performance limit

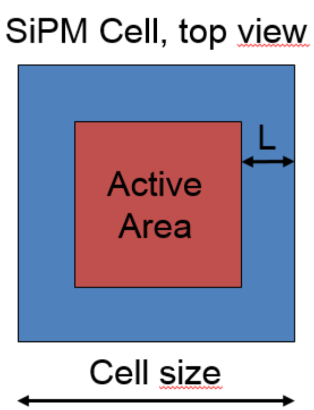
- Limited Fill Factor
- Limited PDE

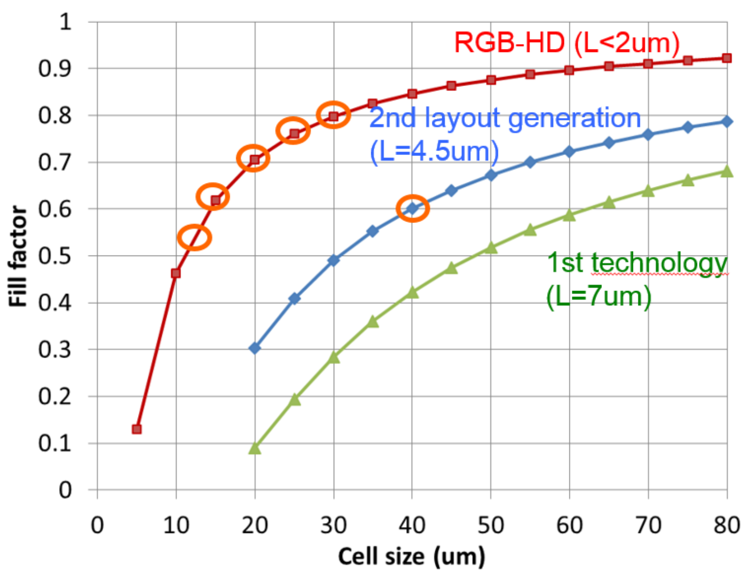
- Correlated noise (CrossTalk & AfterPulse)

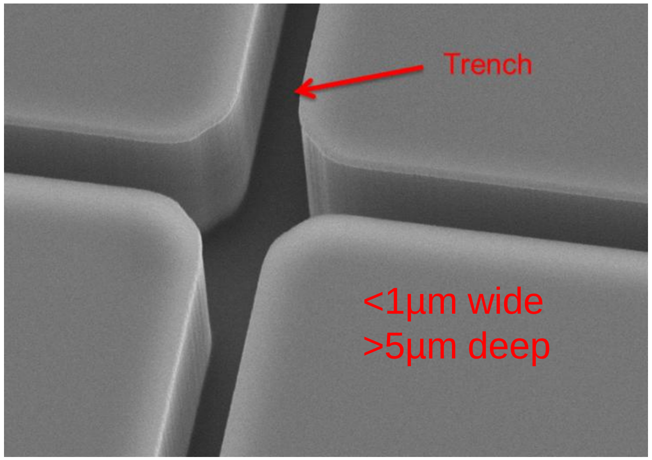
Adopted solution

- ~~Increase cell size~~
- Reduce dead cell border

- Decrease gain (reduce cell size)
- Add optical isolation at cell border

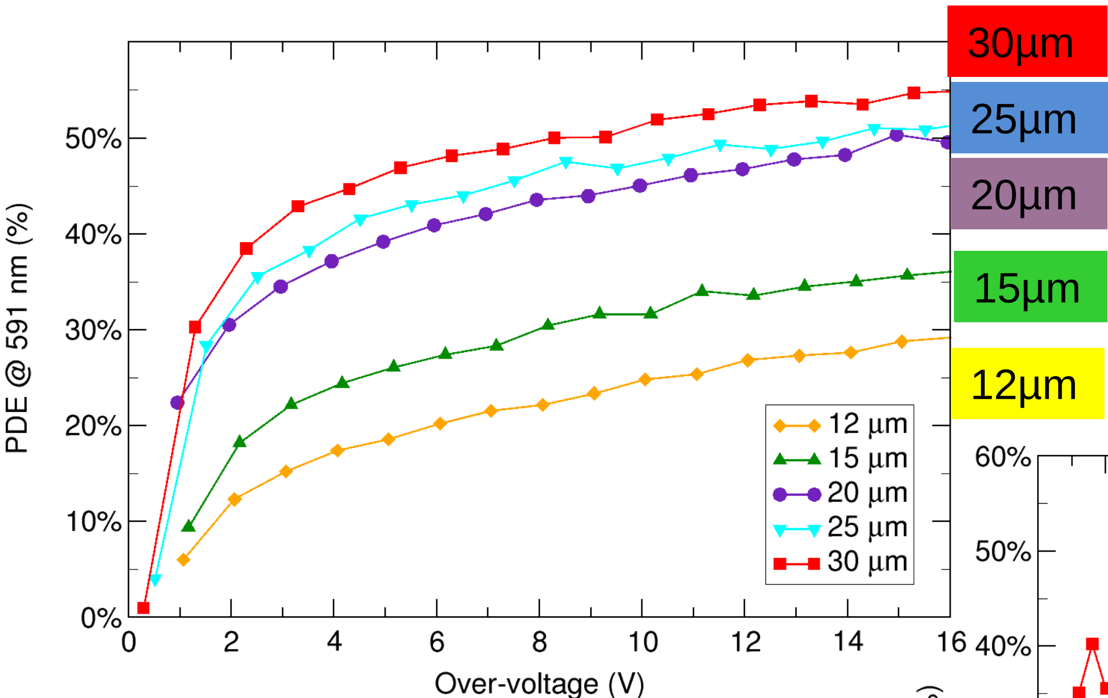






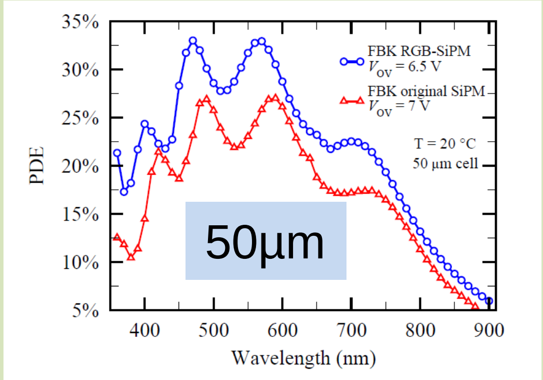
SiPM Photo Detection Efficiency (PDE)

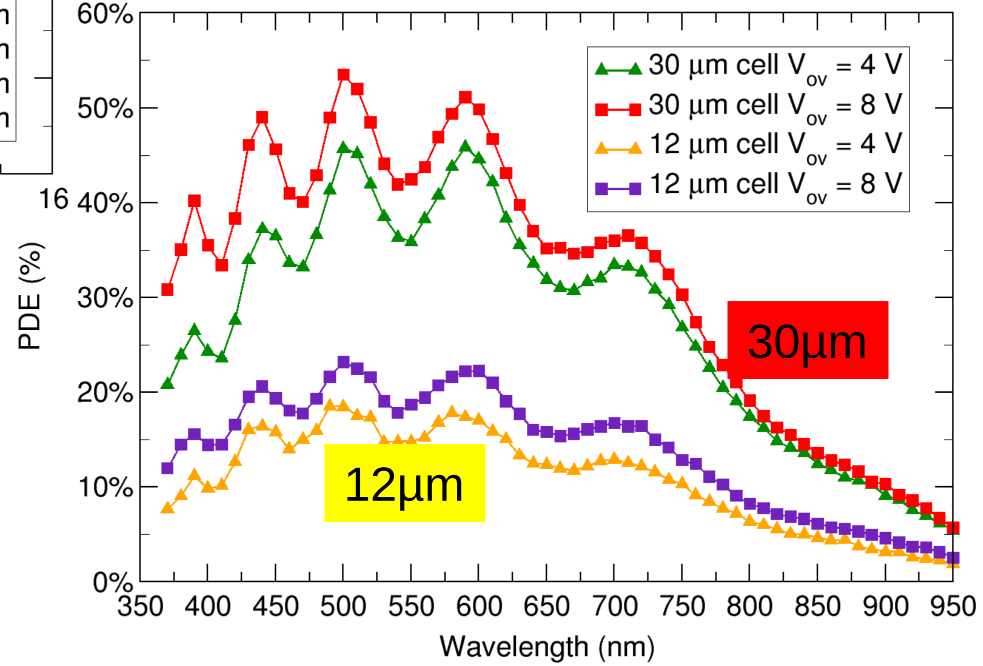
RGB-HD Technology



λ = 590 nm

Standard RGB Technology



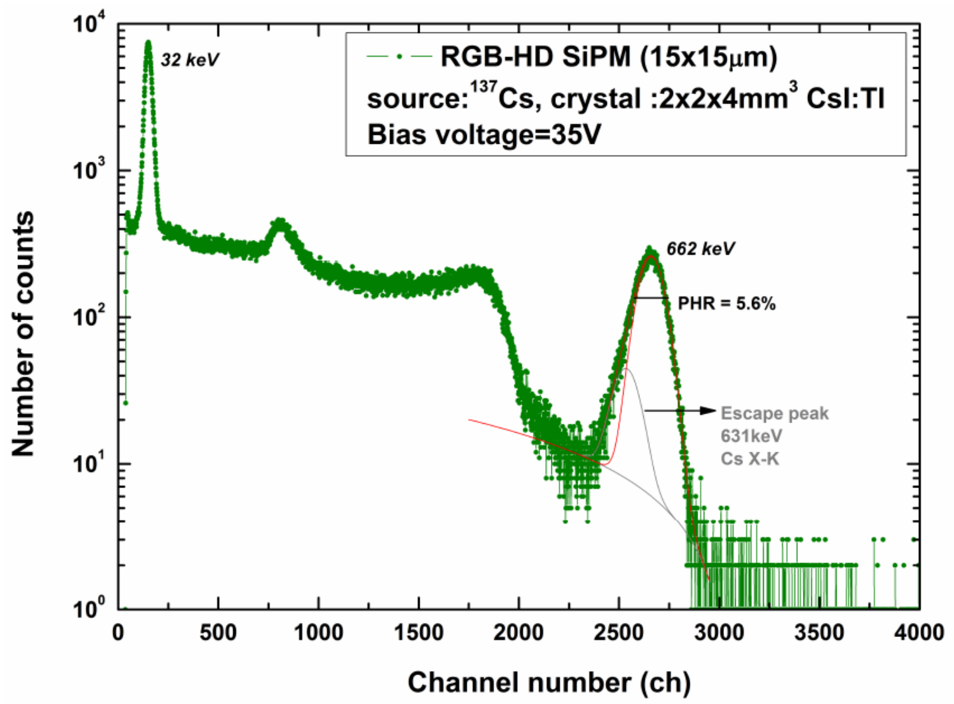


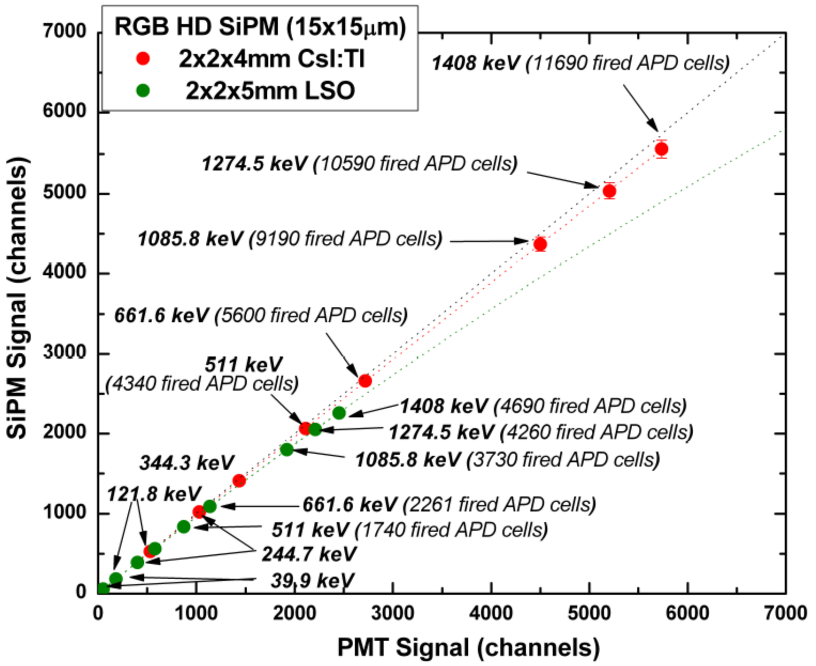
SiPM linearity

Small cells ➔ higher number of cells / unit area

Extended dynamic range, better linearity

• γ-ray spectroscopy with scintillators





From: M. Grodzicka et al., JINST 9 P08004, 2014

Other past and current activities

- Rad-hard studies on different Si sub types (FZ, Cz, epi, p-type, …)
- JFET based active elements integrated on the detector substrate
- BJT-based detectors for radon detection
- Diode array for dosimetry applications
- Supports for CNT: surface preparation and electrode definition
- Thin detectors (thinned substrates; multi-layer substrates)
- Neutron detectors (3D holes filled with scintillators)

Substrates

FBK experience in the transition from 4” to 6”

- thin epitaxial used for SiPMs: more choice, better quality
- Limited FZ types from our previous supplier; good/better quality
- Other FZ substrates from brokers:
  reasonable quality, but no guarantee (unknown producers)
- NTD substrates: High MOQ, high costs
- Thin/Thick substrates; thick epi: difficult to find and/or high costs

Summary and outlook

- 6” transition advantages
  - increase of max device area;
  - increase of # of devices/wafer;
  - access to some substrates of better quality;
  - furnaces assure a better oxide quality

- FBK technologies are evolving

- A new FBK/INFN “MEMS” agreement is under negotation