Development of tracking and timing sensors and imagers at FBK

Gianluigi Casse
Fondazione Bruno Kessler
FBK-CMM Director
LBL, 12th February 2020
The Fondazione Bruno Kessler (FBK) in Trento (Italy) has a 25 year long activity in developing sensors and imagers for experimental physics and applications. It started with a clean room designed to produce CCD cameras for robotics on 4” wafers, and it evolved to today’s infrastructure that makes high end, niche devices for ground and space based experiments (SDD, SSD, PD, 3D column sensors). The requirements on sensors have evolved in a spectacular way with time (on granularity, speed, radiation tolerance, ecc) and FBK has been one of the actors in the fast race to improved performance.

Novel approaches have also emerged, like the progressive substitution of Photo Multipliers Tubes in a number of applications, and the use of tracking with accurate timing information (4D tracking) in particle physics. In this presentation, I will show FBK’s state-of-the-art and future perspectives in the design and development of sensors and imagers for scientific experiments and applications.
Based on **scientific excellence** we provide unique innovation capabilities to institutional and industrial partners.

<table>
<thead>
<tr>
<th>7</th>
<th>200+</th>
<th>43</th>
</tr>
</thead>
<tbody>
<tr>
<td>400+</td>
<td>500+</td>
<td>20</td>
</tr>
<tr>
<td>researchers</td>
<td>contribution in conferences (2018)</td>
<td>joint labs and co-located companies</td>
</tr>
<tr>
<td>100+</td>
<td>39</td>
<td>27</td>
</tr>
<tr>
<td>PhD students from 25 different Countries</td>
<td>patents</td>
<td>innovative startups</td>
</tr>
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</table>

More than 130 people between researchers, engineers and PhD students.
CAPABILITIES

- Wide base of complementary competences
- know-how and state of art research infrastructure
- outstanding results in both research and innovation fields.

Photonics
CMOS sensors, imagers
MEMS, Bio-Mems
Nanotechnologies
Innovative Materials and Interfaces
Micro and Nano devices
Energy and sustainable future
Quantum Technologies
CAPABILITIES

6” Microfabrication Area
Clean Room Detectors
Clean Room MEMS
Testing Area
Integration Area

Analytical facility:

- D-SIMS Dynamic Secondary Ion Mass Spectrometry
- ToF-SMS Time of Flight Secondary Ion Mass Spectrometry
- XPS X-Ray Photoelectron Spectroscopy
- SEM-EDX-EBSD Scanning Electron Microscopy
- AFM Atomic Force Microscopy
- XRD/XRF X-ray Diffraction / X ray Fluorescence
- Raman spectroscopy
Overview of sensor activities

**Detectors**
Full Custom FBK Technology

- Modeling & design
- Custom production

**Image Sensors**
Standard CMOS Technologies

- Analog and Digital IC Design
- 65nm-350nm CMOS Fab
- EO Testing
- Prototyping
CMOS Sensors and imagers

- Digital SiPM
- Pixelated HV-CMOS sensors (no bump-bonding, high resolution, rad-hard)
- Low power vision
- Multi-spectral and THz imagers
- SPAD Time resolved imaging
- TOF (3D) imaging
Custom Sensors

- Micro-strip (large area, low cost, rad-hard)
- Pixelated sensors (large area, high resolution, rad-hard)
- SDD (very high energy resolution)
- 3D column sensors (world record radiation tolerance)
- Low Gain Avalanche Detectors (radiation tolerant, world record 4D tracking)
- SiPM (best performance single photon sensors)
Silicon detectors for Particle Physics

Detector functional blocks:

- Diodes (reverse biased)
- Analogue amplifiers
- Digital readout
Silicon detectors in Physics Experiments: a spectacular success

Vertex identification, key to collider physics.

Needs for track reconstruction (late ‘80’s): high resolution, low mass (minimise multiple Coulomb scattering).


Example:
Mean decay length $B_s$ ($\tau \approx 1.5$ ps):
in $B_s$-frame: $c_\tau \approx 450 \mu m$
in lab frame $\beta c_\tau = \text{few mm}$!

$D_s$ ($\tau ~ 0.5$ ps):
in $D_s$-frame: $c_\tau \approx 150 \mu m$
in lab frame $\beta c_\tau = \text{few mm}$!
(lower mass $\Rightarrow$ more relativistic)

ASIC’s for silicon detector readout: 1988 (UA2 at the CERN/SPS): first collider experiment with silicon detectors with ASIC read-out, namely the AMPLEX, 16 channel, 3 $\mu m$ Feature Size (S) CMOS chip for read-out and signal multiplexing (E. Heijne, P. Jarron).
The sensing part can be produced in standard or custom technologies, available in mostly niche detector foundries.

Central role of these niche silicon fabs in the success of silicon sensors in physics experiments.
Silicon detectors in Physics Experiments: a spectacular success

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Central role of these niche silicon fabs in the success of silicon sensors in physics experiments.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor thickness (µm)</td>
<td>50/300</td>
</tr>
<tr>
<td>Spatial resolution (µm)</td>
<td>3/100</td>
</tr>
<tr>
<td>Cell Dimension (µm²)</td>
<td>28 × 28</td>
</tr>
<tr>
<td>Power density (mW cm⁻²)</td>
<td>300/1000</td>
</tr>
<tr>
<td>Time resolution (ns)</td>
<td>0.06</td>
</tr>
<tr>
<td>Detection efficiency (%)</td>
<td>&gt; 99</td>
</tr>
<tr>
<td>Fake hit rate</td>
<td>10⁻⁵</td>
</tr>
<tr>
<td>TID radiation hardness (Grad)</td>
<td>1</td>
</tr>
<tr>
<td>NIEL radiation 1 MeV n₉EQ cm⁻²</td>
<td>2.5 × 10¹⁶</td>
</tr>
<tr>
<td>TID radiation 1 MeV n₉EQ cm⁻²</td>
<td>2.5 × 10¹⁶</td>
</tr>
</tbody>
</table>

FE-I3 CMOS 250 nm
FE-I4 CMOS 130 nm
RD-53 CMOS 65 nm
A bit of history:

Si CCD @ FBK-CMM
(our 1st technology)
1990 -1991 Linear 4 µm CCD technology
(project ISS)
1991-1992 4µm CMOS technology
1992-1993 4 µm CCD-CMOS technology

Planar technology (strip, pixels)
4” wafers: 1998
for AMS project ISS
ALICE (CERN-LHC)
On 150 mm wafers: 2014
2016 DS-Microstrip for
CSES (China Seismo-Electromagnetic Satellite)

Silicon Drift Detectors: 2009
Large area: 90 cm² SDD for Xray detection in Space (and
Synchrotron applications)
A bit of history:

3D – A proposed new architecture for solid-state radiation detectors¹

S.I. Parker,*, C.J. Kenney*, J. Segal†

* University of Hawaii, Honolulu, USA
† Integrated Circuits Laboratory, Stanford University, Stanford, USA

3D column technology (strip, pixels)
6" wafers: 2006, now in ATLAS IBL
Final R&D for ATLAS and CMS upgrade inner layers

Strong reduction in pixel size (from 50 x 250 µm² to 25 x 100 µm²)
New concept for HL-LHC

4D silicon sensors developed before the expression of interest of experiments (within CERN RD50). Example of virtuous synergy between sensor R&D and physics needs.

Simulated and reconstructed vertices in a 200 pileup event with a MIP timing detector.

Rate of tracks from pileup vertices incorrectly associated with the primary vertex.

To exploit the High Luminosity capability of the future accelerator, a 4D tracker is required!
LGAD Developments In FBK

• Since 2015 FBK, INFN Torino and University of Trento have been developing LGADs for fast timing and 4D-tracking application in HEP experiments (Ultra Fast Silicon Detectors – UFSD)

In 2015 FBK started to develop UFSD detectors, i.e. LGADs optimized for timing in HEP, in collaboration with INFN Torino, University of Trento and University of Turin

Possible applications:
• ATLAS → High granularity timing detector
• CMS → Endcap timing layer
• ..........

Requirements:
• Fast timing → Time resolutions < 30-40 ps
• Radiation Hard. → Fluences > $10^{15}$ n$_{eq}$/cm$^2$
• ............
LGAD Technology Roadmap at FBK

A collaboration: FBK, INFN, University of Torino, University of Trento

- **2015**
  - LGAD first Batch on thick sub.
- **2016**
  - UFSD2 thin Sub. + C
  - Parallel developments to:
    - Reduce inter-pixel dead region
    - Develop LGADs strips and pixel with small pitch
  - Final goal:
    - 4D high-resolution tracking detectors for HEP
    - General purpose fine-pitch pixel/strip detectors
- **2017**
  - UFSD3 thin Sub. + C
- **2018**
  - Today
  - RSD
- **2019**
  - UFSD4 Next...
A “gain layer” is included in the structure (local doping enrichment with $E > 2\times10^5$ to activate the impact ionization). Termination structure JTE for stability.

**LGAD Technology**

- Silicon detectors that look like a normal pixel or strip sensor, but with a **much larger signal** (internal Gain in the range $\sim 10 – 20$)
- High signals also with thin silicon substrates
- **Better timing performance**
- Easy to be segmented
- Low gain -> **low excess noise**

Two major challenges:
- Radiation tolerance
- Fill factor

![Diagram of LGAD Technology](image-url)
Radiation level changes the doping concentration of the gain layer, so it changes the way the device works.
Radiation tolerance

\[ \frac{N_A(\Phi)}{N_A(0)} = e^{\frac{1}{2}c(NA(0))\Phi/\Phi_0} \]

Small c, improved tolerance

Addition of carbon improves by a factor ~2 the radiation tolerance.

Idea: Carbon co-implantation

Materials Science in Semiconductor Processing
Volume 3, Issue 4, 1 August 2000, Pages 257-261
Radiation effects in silicon detectors processed on carbon and oxygen-rich substrates
A. Ruzin, G. Casse, M. Glaser, F. Lemeilleur, J. Matheson, S. Watts, A. Zanet
Timing resolution depends on the gain value and on the holes drift velocity ($\propto V_{bias}$)

Legend:
- Wafer number
- Fluence (1 MeV n$_{eq}$/cm$^2$)

Timing resolution down to 30 ps for MIP detection
Other applications of LGAD

Low Energy X-ray Detection

Photon counting strip detectors, fluorescence X-rays

Planar sensor

LGAD sensor

Zoomed x-axis

E < 3.3 keV visible

E > 8 keV visible

A. Bergamaschi, TREDI 2019
Other applications of LGAD

LGAD Segmentation: Fill Factor

Focused 20 keV X-ray beam

Inter-strip border

Nominal Gain region

Nominal FF: 55%
Effective FF (Sim): 45%
Measured FF (50% signal amplitude) ≈ 40%

Signal vs position for 3 strips

New Segmentation Strategies under development at FBK

**iLGAD: P-side segmentation**
- Uniform gain layer
- The p-layer is segmented

**First trials CNM Barcelona.**

**Trench-Isolated LGADs (TI-LGAD)**
- Metal Pads AC-coupled to the resistive n+ via dielectric coupling layer
- Not-segmented PGAIN -> virtually 100% FF
- JTE and p-stop are replaced by a single trench.
- Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.
- The trenches are a few microns deep and < 1um wide.
- Filled with Silicon Oxide
- The fabrication process of trenches is compatible with the standard LGAD process flow.

New LGAD technology proposed by FBK:
TI-LGAD inter-pad Characterization
(TCT laser Setup)

Measurements performed in Torino Silicon Lab (University of Torino - INFN)
F. Siviero – 35th RD50 Workshop, November 2019
SiPM, increasing use in science and technology

FBK SiPM technology roadmap

Original technology 2005

Electric field engineering

RGB
NUV

New cell border (trenches)

RGB-HD
NUV-HD

NUV-HD-Cryo
VUV-HD
RGB-UHD
NIR

Ongoing Developments
SiPM @ FBK: NUV-HD

35 µm cell pitch

Photon detection efficiency

Timing performance of NUV-HD

Single Photon Time Resolution (SPTR)

1) Worse charge collection at SPAD edges
2) Signal pick-up is also very important

Covering the SPAD edges with metal reduces the SPTR to 20 ps

<table>
<thead>
<tr>
<th>ACTIVE AREA LAYOUT</th>
<th>Diameter / side (µm)</th>
<th>Metallization</th>
</tr>
</thead>
<tbody>
<tr>
<td>circular</td>
<td>20</td>
<td>Covered edges (A) with metal</td>
</tr>
<tr>
<td>circular</td>
<td>20</td>
<td>uncovered edges (B)</td>
</tr>
<tr>
<td>square</td>
<td>50</td>
<td>uncovered edges</td>
</tr>
</tbody>
</table>

$\Delta t = \Delta \lambda/c/n$
Excellent SPTR also with large-area SiPMs, employing improved electronics.

Collaborations with:
- CERN (P. Lecoq, S. Gundacker)
- Stanford (Craig Levin, Joshua Cates)

SPTR and CRT with LSO – 4x4 mm$^2$ SiPMs

Coincidence Resolving Time (CRT) with 511 keV gamma photons

FBK NUV-HD, 4x4mm², 40μm @ 38V

$P(x) \Delta t_n c t x \Delta t = \Delta nc$
Improvement of SPTR is, possibly, even more important for BGO readout:

- Timing is improved with Cherenkov light detection

SPTR and CRT with BGO – 4x4 mm$^2$ SiPMs

NINO ASIC

HF-AMP

FBK NUV-HD, 4x4 mm$^2$, 40 μm @ 38 V

CRT with BGO

CTR$_{\text{min}}=158\pm3$ ps FWHM

511 keV gamma photons
NUV-HD SiPMs for big science

> 3-year long collaboration between FBK and DarkSide to optimize performance of the NUV-HD technology for the specifications of the project.

- **DarkSide-20k Experiment**

- **~ 23t of UAr**

- **TPB WLS:** emission at 400 – 450 nm

2 light readout planes: 20 m² (+ veto)

SiPM tiles
Satisfying DS specs

Primary DCR reduction

Thermal generation

0.3 counts per day per cell at 77 K!

A 10x10 cm² SiPM array would have a total DCR < 100 cps!

> 7 orders of magnitude!

> 20x
DS-20k – Photo-detector module

Good gain uniformity of ~ 3M SPADs at 77 K

- 24x 12x8 mm² SiPMs (~ 1 cm²)
- Front-end cryogenic pre-amplifier with differential output
- Sensitivity from single photon to few thousands photons

PDM Specifications:
- 5x5 cm² active surface
- PDE @ 420 nm > 40%
- DCR < 0.08 cps/mm²
- Baseline hit rate ≤ DCR ↔ SNR > 8
- Timing resolution ~ 10 ns

Integration window of 6 µs
- 20.7 m² • 6 µs • DCR = 10 pe

Measurements from LNGS

30 µm cells, 7 V over-voltage ~500 ns recharge time

DS motherboard with 25 PDMs, power distribution and signal transmitter.
R&D carried out for nEXO to develop SiPMs capable of direct detection of photons at 178 nm and operation at -100°C

- TPC Filled with LXe
- 4-5 m² SiPM
- Single VUV photon sensitive (178 nm)
  - > 15% efficiency
  - < 20% correlated noise
  - < 50 mHz/mm² DCR
- Very low radioactivity
  - Silicon is generally very radio pure

**0νββ with LXe**

**VUV–HD**

**PDE vs OV (~190 nm)**

- Best result reported in literature
- $\lambda = 175$ nm
- $T = -104^\circ$C (LXe)

**nEXO experiment at Stanford**

- SiPMs
- SiPMs Support
- Charge Tiles
- Charge Tiles Support
- Field Shaping Rings
- Sapphire Rods and Spacers

arXiv:1904.05977
State of the art performance for silicon, single-photon detectors!

NIR-HD PDE

With new cell termination structures, PDE is significantly improved in almost all the spectrum.

Preliminary results

New NIR-HS developments
Application of NIR-SiPMs
Quantum Technologies

The pillars of the Quantum Flagship

Suitable novel devices will be in high demand for development in all of these fields!
Quantum microscopy: SUPERTWIN

SUPERTWIN concept

N^{th} entanglement \times N \text{ resolution} 

:N \text{ diffraction}
Quantum Optics and Photonics on Chip

QIP (quantum information processing) – photons as ideal candidates (long coherence @ room temperatures)

Miniaturisation – Photonic Integrated Circuits (CMOS-compatibility)

- Silicon-on-Insulator SOI (waveguiding layer c-Si, 250-500nm, $\lambda > 1\mu m$)
- Silicon Nitride ($\lambda > 0.3\mu m$, from VIS to MIR)
- Hybrid-integrated III-V on Si (light source, GaAs, InP and their ternary alloys)
- ASIC (application-specific integrated circuits)
  - SiN/SiO2 multilayered waveguides (optical nonlinearities and VIS-MIR transparency)
  - Si-nanocrystals in SiO2 host (VIS-NIR light emission)

<table>
<thead>
<tr>
<th>Area</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10,\text{m}^2$</td>
<td>$10,\text{m}^3$</td>
</tr>
<tr>
<td>$100,\text{mm}^2$</td>
<td>$0.01,\text{mm}^3$</td>
</tr>
</tbody>
</table>
Quantum Random Number Generator

Important in
- secure communications
- stochastic simulations
- gaming

QRNGs are a subset of hardware RNGs, in which randomness is obtained using quantum phenomena.

Project develops QRNG based on FBK’s SPAD technology and LEDs in silicon developed by UniTN and FBK.

Collaboration: UniTN: Nanosciencelab, Cryptolab, FBK-CMM and Telsy;
Cancer markers Quantum sensing with DIAmond DEfect MAgnetometry: Q-Diadema (Q@TN)

NV centres to detect the individual position of nuclear spins to reconstruct the structure of a protein accommodated on a bulk diamond sensor. In this domain, the frequency resolution of NMR instruments is too low. NV polarization leakage due to entanglements to specific nuclear spins under magnetic field gradients allows for the reconstruction of nuclear spin positions with unprecedented resolution.
SupercOnductive Circuits for Casimir Effect: SOCCER

High sensitivity sensing: Josephson junctions and SQUID’s

Fabrication of coplanar superconducting waveguides and resonators closed by a SQUID device to create a tunable mirror for quantum optics experiments to observe the Dynamical Casimir Effect (DCE) and related zero-point quantum fluctuation effects in the microwave spectral domain.
Hetero-integrated solid-state laser for optical traps LESSO

- Italian project funded by ASI
- Aim: development of a prototype of a 698nm miniaturized CW optical pumped laser, FWHM in the kHz regime,
- Vision: Application in the Sr+ optical clock

A high transparent silicon-oxynitride circuit is used which couples evanescently to the LiYF-crystal doped with praseodymium (P3+), CAD of array of microring cavities with input-and output coupler.

Lasing in the Red, Pr\(^{3+}\) doped YLiF-crystal, UniPisa

Testing of the laser-crystals on optical bench.

Development of low loss optical circuits in the blue and red spectral region

![Graph showing laser performance](image)
8M€ for Nano-tech

Nanotechnology capabilities enabling QT R&D through submicron and deep submicron (350 nm - 50 nm) structure definition with state of the art E-beam and focused ion beam lithography and surface functionalization.

Press Release

November X, 2019

Raith delivers its new FIB-SEM VELION to Fondazione Bruno Kessler (FBK)

Dortmund/Trento, August 2019

Raith, the world leading manufacturer of nanofabrication instrumentation, delivers its VELION to the Center for Materials and Microsystems of FBK - Fondazione Bruno Kessler in Trento, Italy, a Research Institute that aims for results of excellence in science and technology with particular emphasis on interdisciplinary approaches and their applicative dimension.

The VELION is a Focused Ion Beam (FIB) centric FIB/SEM system for sophisticated nanofabrication applications on a lithography platform. Its FIB column is vertically mounted in order to keep the FIB always on target of the Laser Interferometer Stage. Thus, highest precision for demanding nanofabrication tasks is ensured. The high resolution FE-SEM is side mounted to serve in-situ process control, sample preparation and inspection as well as complementary Electron Beam Lithography (EBL).

"The VELION is a key instrument for the strategic investment that FBK is undertaking to significantly enhance its capabilities and strengthen its role as national reference point for Key Enabling Technologies (KET). This FIB system will enable us to implement advanced and novel integration of nanotechnological solutions on our traditional platforms (CMOS, MEMS) to boost our offer for frontier research activities as well as for innovative industrial products. Besides this, thanks to its characteristics, we will intensively use VELION for our research in the strategic field of quantum technology," says Prof Gianluigi Case, Director of the Center for Materials and Microsystems in FBK.

"The VELION is the perfect instrument for both, Focused Ion Beam (FIB) experts and nanofabrication professionals. It has been recognized in the community as the most accurate and versatile system for challenging FIB nanofabrication applications across large areas. We are proud to deliver a fully equipped VELION to FBK that provides many techniques for FIB and EBL and supports numerous applications in the field of nanofabrication in one system. We are already looking forward to first results," says Torsten Richter, Product Manager.

All information around the VELION is available to the public at: www.raith.com/velion

Inquiries or questions of any kind can be sent to: sales@raith.com
FBK only full Italian partner. Investments in the Clean-Rooms to improve vertical integration capabilities of silicon wafers and chips with different functionalities (e.g. stack of sensor, analogue, digital, photonic layers) significantly enhancing the abilities for heterogeneous integration of various technologies/chips. Heterogeneous integration already is a strength of FBK. This investment complements the one on nano-technologies (FESR) to enable a large potential for future challenges (e.g. Quantum Technologies).
Examples: Big Science and space

Beyond State of the art sensors and devices developed for Science, transferred to Industry.