The MONOLITH ERC Project

• Funded by the H2020 ERC Advanced grant 884447[1], July 2020 - June 2025

• Monolithic silicon sensor able to:
  ▶ precisely measure 3D spatial position
  ▶ provide picosecond-level time resolution

• Four working packages:
  1. Optimisation of sensor geometry for timing
  2. Optimisation of gain layer, radiation hardness
  3. Fast and low-noise SiGe BiCMOS electronics
  4. Novel sensor concept: the Picosecond Avalanche Detector (PicoAD)

Our recipe for picosecond timing with silicon:

- SiGe BiCMOS
- MONOLITHIC
- PicoAD: Picosecond Avalanche Detector
# The UniGe Silicon Team

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<th>Name</th>
<th>Role</th>
<th>Responsibilities</th>
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<td>Giuseppe Iacobucci</td>
<td>Project P.I.</td>
<td>System design</td>
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<td>Thanushan Kugathasan</td>
<td>Lead chip design</td>
<td>Digital electronics</td>
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<td>Stefano Zambito</td>
<td>Laboratory tests</td>
<td>Data analysis</td>
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<td>Jordi Sabater Iglesias</td>
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<td>Antonio Picardi</td>
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<td>Rafaella Kotitsa</td>
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<td>Lorenzo Paolozzi</td>
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<td>Roberto Cardella</td>
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<td>Mateus Vicente</td>
<td>System integration</td>
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<td>Chiara Magliocca</td>
<td>Laboratory tests</td>
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<td>Théo Moretti</td>
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<td>Jihad Saidi</td>
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<td>Luca Iodice</td>
<td>Chip design</td>
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<tr>
<td>Andrea Pizarro Medina</td>
<td>Data analysis</td>
<td>Laboratory tests</td>
</tr>
</tbody>
</table>

**Main research partners:**

- Roberto Cardarelli
  - INFN Rome2 & UNIGE
- Yannick Favre
  - Board design
  - RO system
- Didier Ferrere
  - System integration
  - Laboratory tests
- Sergio Gonzalez-Sevilla
  - System integration
  - Laboratory tests
- Holger Rücker
  - IHP Mikroelektronik
- Marzio Nessi
  - CERN & UNIGE
- Matteo Elviretti
  - IHP Mikroelektronik

**Funded by:**

- Swiss National Science Foundation
- Sinergia
- Attract
- Université de Genève
- UNITEC
- European Research Council
SiGe BiCMOS Front-End Electronics

SiGe HBT = BJT with Germanium as base material.

Grading of Ge doping in base:

- charge-transport in base via drift
  - reduced charge-transit-time in base
  - high current gain $\beta$

- High doping in base is possible:
  - thinner base
  - reduced base resistance $R_b$

Leading-edge IHP SG13G2 technology, 130 nm process featuring SiGe HBT

\[
ENC_{\text{series noise}} \propto \sqrt{\frac{k_1 C_{\text{tot}}^2}{\beta} + k_2 R_b C_{\text{tot}}^2}
\]
**SiGe HBT vs. CMOS**

**Peak transition frequency vs. technology node**

A. Mai and M. Kaynak,
SiGe-BiCMOS based technology platforms for mm-wave and radar applications.
DOI: 10.1109/MIKON.2016.7492062

**Intrinsic amplifier jitter:**
common emitter (source) configuration in a 130nm technology

L. Paolozzi et al.,
Time resolution and power consumption of a monolithic silicon pixel prototype in SiGe BiCMOS technology.
Monolithic SiGe BiCMOS for timing

Monolithic prototypes with SiGe BiCMOS (without internal gain layer)

2016
- 200ps
  - 1 and 0.5 mm² pixels
  - Discriminator output

2017
- 110ps
  - 30 pixels 500x500μm²
  - 100ps TDC +I/O logic

2018
- 50ps
  - Hexagonal pixels, pitch 100μm and 200μm
  - Discriminator output

2020
- 36 ps
  - Hexagonal pixels 100μm pitch
  - 30ps TDC +I/O logic
  - Analog channels

All ASICs produced with IHP SG13G2 technology

New ASIC matrix (“prototype2”) produced in 2022

Test beam results of 2019 prototype

CERN SPS Testbeam with 180 GeV/c pions

sensor with no gain (23 μm depletion)

JINST 17 (2022) P02019
• Same matrix configuration as previous, but
  ▶ **Substrate**: 50Ωcm → 350Ωcm epilayer, 50µm thick on low-res (1Ωcm) substrate
    ➤ smaller pixel capacitance
    ➤ depletion 23µm → 50µm
    ➤ much larger voltage plateau
    ➤ can operate sensor with $v_{\text{drift}}$ saturated everywhere
  ▶ **Preamp and driver** voltage decoupled:
    ➤ was limiting optimal amplifier operation
    ➤ cross-talk removed
  ▶ **Optimised FE layout, differential output**, high-frequency cables:
    ➤ better rise time (600ps → 300ps)
**55Fe** measurements in cleanroom:

\[ \text{ENC} \approx 100 \text{ e}^{-} \]

\[ \text{Risetime (20\%–80\%)} \approx 350 \text{ ps} \]

- **ENC**
  - Entries: 4773
  - \( \chi^2 / \text{ndf} \): 146.2 / 34
  - Constant: 323.2 \( \pm \) 6.1
  - Mean: 99.76 \( \pm \) 0.19
  - Sigma: 11.4 \( \pm \) 0.1

- **Risetime**
  - Entries: 4773
  - \( \chi^2 / \text{ndf} \): 37.61 / 22
  - Constant: 266.2 \( \pm \) 5.4
  - Mean: 346.5 \( \pm \) 1.1
  - Sigma: 56.79 \( \pm \) 1.13
Test Beam: Experimental Setup

Mid October SPS testbeam with 120 GeV/c π to measure **efficiency** and **time resolution**

UNIGE FE-I4 telescope to provide spatial information ($\sigma_{x,y} \approx 10 \mu$m)

Two MCPs ($\sigma_t \approx 5$ ps) to provide the timing reference

Lots of data taken: results in **JINST 18 (2023) P03047**
Voltage noise of the differential signal: 
\[ \sigma_V \approx 1 \text{ mV} \]

Amplitude distribution of differential signal: 
Landau with most probable value \( \approx 50 \text{ mV} \)
Efficiency at the external edges affected by the telescope resolution of 10 µm

Full efficiency (yellow is 99.8%) in the two triangles unaffected by telescope resolution
Large efficiency plateau at $\approx 99.8\%$, that allows operation at very low noise-hit rate.
8 working points \((HV, \text{ power consumption})\) taken at the testbeam:

**MONOLITH** prototype (2022) - no gain layer

- CERN SPS Testbeam: 120 GeV/c pions
- JINST 18 (2023) P03047
- \(V_{\text{th}} = 7\sigma_V\)
- \(P_{\text{density}} = 2.7 \text{ W/cm}^2\)

\[100 \quad 120 \quad 140 \quad 160 \quad 180 \quad 200 \quad 220 \quad 240 \quad 260\]

Efficiency [%]

\[99.8 \quad 99.6 \quad 99.4 \quad 99.2 \quad 99\]

High Voltage [V]

**MONOLITH** prototype (2022) - no gain layer

- CERN SPS Testbeam: 120 GeV/c pions
- JINST 18 (2023) P03047
- \(V_{\text{th}} = 7\sigma_V\)
- \(HV = 200 \text{ V}\)

\[3 \times 10^{-2} \quad 10^{-1} \quad 12 \times 10^{-1}\]

Efficiency [%]

\[99.8 \quad 99.6 \quad 99.4 \quad 99.2 \quad 99\]

\[1 \quad 2 \quad 3 \]

\(P_{\text{density}} [\text{W/cm}^2]\)

\(36 \text{ mW/cm}^2\)
Efficiency $\approx 99.8\%$ even in the inter-pixel region, for all working points.
Simultaneous fit to extract time resolutions of the DUT, MCP0, MCP1:

- MCPP0: \( \sigma_T = (3.6 \pm 1.5) \) ps
- MCP1: \( \sigma_T = (5.0 \pm 1.1) \) ps
- (MCP0-MCP1) \( \Delta T_{OA} = 21.0 \) ps
- (DUT-MCP0) \( \Delta T_{OA} = 21.3 \) ps
- (DUT-MCP1) \( \Delta T_{OA} = 6.1 \) ps

non-Gaussian tails \( \approx 3\% \)
Plateau of 100V with time resolution of \( \approx 20\ \text{ps} \) obtained with simple analysis and simple signal processing.
Remark:
20.7 ps with very simple analysis:

- **Linear interpolation** of oscilloscope samplings (25ps)
- Time Of Arrival (ToA): time at $V_{\text{threshold}} = 7\sigma_{V}$
- $\Delta_{\text{ToA}}$ distributions are **time-walk corrected**

More complex analysis (spline interpolation, filtering, ...) reaches **17.7 ps**
**2022 prototype2 — no gain layer**

**MONOLITH prototype (2022) - no gain layer**

**CERN SPS Testbeam: 120 GeV/c pions**

\[ V_{th} = 7 \sigma_v \text{ ; } HV = 200 \text{ V} \]

**calculation:** \[ \sigma_t = \frac{\sigma_v}{dV/dt} \]

**Table:**

<table>
<thead>
<tr>
<th>( P_{\text{density}} ) [W/cm²]</th>
<th>Amplitude MPV [mV]</th>
<th>Time Resolution [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>48.6 ± 0.5</td>
<td>20.7 ± 0.3</td>
</tr>
<tr>
<td>0.9</td>
<td>35.8 ± 0.5</td>
<td>23.8 ± 0.3</td>
</tr>
<tr>
<td>0.36</td>
<td>22.6 ± 0.4</td>
<td>30.1 ± 0.4</td>
</tr>
<tr>
<td>0.13</td>
<td>14.2 ± 0.3</td>
<td>47.2 ± 0.7</td>
</tr>
<tr>
<td>0.04</td>
<td>16.2 ± 0.3</td>
<td>77.1 ± 0.9</td>
</tr>
</tbody>
</table>

**20 ps at 2.7 W/cm²**

**50 ps at 100 mW/cm²**

**without gain layer**
For HV $\geq 160$V, time resolution ranges from $\approx 19$ ps at the center to $\approx 23$ ps at the edge of the pixel.

Still something to improve with the weighting field far from pixel center.

For HV = 120 V:  $\approx$ 3 ps worse.
Laser measurements

with the 2022 prototype2 without gain
Preliminary measurement with a laser with a jitter of **100 fs**
(repetition frequency = **80 MHz**)

Time coincidence between two of our samples:

- "Reference" receiving always large laser pulse producing 17k electrons ($\sigma_t = 2.5$ ps)
- "DUT" receiving variable laser power, to study the performance vs. amplitude

Many thanks to L. Bonacina’s lab of GAP UNIGE
Our prototype "Reference":

Time resolution = 2.5 ps

with 17k e⁻ (5—6 mips)

\[
\sigma_t = \frac{3.6}{\sqrt{2}} = 2.5 \text{ ps}
\]
Laser Measurement (preliminary)

**MONOLITH** prototype (2022) - no gain layer

- Laser Measurements
- CERN SPS Testbeam
- Laser Measurement (preliminary)
- Estimate of the charge-collection ("Landau") noise

- $P_{\text{density}} = 2.7 \text{ W/cm}^2$
- $HV = 200 \text{ V}$
Radiation hardness studies

with the 2022 prototype2 without gain
Radiation tolerance studies started in collaboration with KEK and IHP colleagues. 8 samples of prototype2 ASIC were irradiated in Japan up to $1 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$. The 8 boards were irradiated in Japan with protons by Koji Nakamura and Manabu Togawa.
Radiation hardness of SiGe HBTs

Radiation tolerance studies started in collaboration with KEK and IHP colleagues. 8 samples of prototype2 ASIC were irradiated in Japan up to $1 \times 10^{16}$ n$_{eq}$/cm$^2$.

<table>
<thead>
<tr>
<th>Board Name</th>
<th>Fluence [1 MeV n$_{eq}$/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M23</td>
<td>$2 \cdot 10^{13}$</td>
</tr>
<tr>
<td>M22</td>
<td>$9 \cdot 10^{13}$</td>
</tr>
<tr>
<td>M21</td>
<td>$6 \cdot 10^{14}$</td>
</tr>
<tr>
<td>M19</td>
<td>$6 \cdot 10^{14}$</td>
</tr>
<tr>
<td>M18</td>
<td>$3 \cdot 10^{15}$</td>
</tr>
<tr>
<td>M17</td>
<td>$3 \cdot 10^{15}$</td>
</tr>
<tr>
<td>M16</td>
<td>$1 \cdot 10^{16}$</td>
</tr>
<tr>
<td>M15</td>
<td>$1 \cdot 10^{16}$</td>
</tr>
<tr>
<td>M06</td>
<td>not irradiated – for comparison</td>
</tr>
</tbody>
</table>

Boards with damaged voltage regulators: bypassed with wire bonds

Not configurable – not used

Same chip as CERN testbeam (results published in JINST 18 (2023) P03047)
Very good news:
even after $10^{16} \, n_{eq}/cm^2$ the ASICs work !!!
Radiation hardness of SiGe HBTs

Characterisation with $^{90}\text{Sr}$ source of boards irradiated up to $10^{16} \text{n}_{\text{eq}}/\text{cm}^2$

Average of the 4 analog pixels (HV = 200 V, T=-35°, 0.9 W/cm²)

Average Amplitude [mV]

Average Voltage noise [V]

Average Signal/Noise Ratio

Average Time over Threshold [ns]

Average Signal slope @ thresh. [mV/\mu s]
Excellent news from radiation tolerance studies:

The time jitter with $^{90}\text{Sr}$ increases from 22 ps (unirradiated) to 50 ps (at $10^{16}\text{n}_{\text{eq}}/\text{cm}^2$) at HV = 200 V and 0.9 W/cm$^2$. 

Average Time Jitter [ps] vs. Fluence [$\text{n}_{\text{eq}}/\text{cm}^2$] for $^{90}\text{Sr}$ data, T = -35 °C:

- HV = 200 V
- $P_{\text{density}} = 0.90 \text{ W/cm}^2$

Chip M06 not irradiated

$\sigma_{\text{jitter}} = (21.6 \pm 0.9) \text{ ps}$

$\sigma_t = \frac{\sigma_V}{dV/dt}$
At 0.9 W/cm² the time jitter with $^{90}\text{Sr}$ at $\Phi = 10^{16}$ n$_{eq}$/cm$^2$ decreases from ~50ps at HV = 200 V to ~40ps at HV = 325 V.

Working point for sensor and electronics still being optimised.

This summer:
- Efficiency & time resolution with mips at CERN testbeam
- Study also large digital matrices
Radiation hardness of SiGe HBTs

\[ \beta_{\text{max}} = 900 \]

IHP SG13G2 process

\[ \beta = 20 \]

Our working point


From: J.D. Cressler, IEEE transactions on nuclear science, vol. 60, n. 3 (2013)
Monolithic SiGe BiCMOS for timing

Monolithic prototypes with SiGe BiCMOS (without internal gain layer)

- 2016
  - 200ps
  - 1 mm² pixel
  - Discriminator

- 2017
  - 110ps
  - 30 pixels 500x500μm²
  - 100ps TDC +I/O logic

- 2018
  - 50ps
  - Hexagonal pixels 100μm and 200μm pitch
  - Discriminator output

- 2020
  - 36 ps
  - Hexagonal pixels 100μm pitch
  - 30ps TDC +I/O logic
  - Analog channels

- 2022
  - 20 ps
  - Hexagonal pixels 100μm pitch
  - improved electronics
  - 50μm epitaxial layer (350Ωcm)

- May 2023
  - < 20 ps?
  - Hexagonal pixels 50μm pitch
  - improved electronics (4 times less power consumption)

BJT radiation hardness up to $10^{16}$ demonstrated

Next step of our R&D without internal gain layer
Third MONOLITH prototype: 50µm pitch

- New prototype: pixels with **50µm pitch**
  - smaller capacitance

- **improved FE electronics**
  - same timing performance with **4-times less power**
  - 3 different configurations:
    - analog output with FE in pixel
    - analog output with FE off pixel
    - discriminated output with FE and discriminator in pixel
  - reduced inter-pixel distance from 10µm to 6µm to maintain time resolution at pixel edges

- Back from foundry mid June; testbeam at CERN SPS this summer.
The MONOLITHIC Project

SiGe BiCMOS

MONOLITHIC

PicoAD: Picosecond Avalanche Detector

Production of PicoAD sensors
Monolithic prototypes with SiGe BiCMOS (without internal gain layer)

<table>
<thead>
<tr>
<th>Year</th>
<th>Features</th>
</tr>
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<tbody>
<tr>
<td>2016</td>
<td>200ps</td>
</tr>
<tr>
<td></td>
<td>• 1 mm² pixel</td>
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<td></td>
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</table>

In 2022: **proof-of-concept monolithic prototype with internal gain layer**

(using 2020 masks)

**PicoAD**

special wafers produced internally by IHP (not optimised yet)

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Giuseppe Iacobucci — Université de Genève

iWoRiD 2023, Oslo — June 28, 2023
**PicoAD:**

**Multi-Junction Picosecond-Avalanche Detector©**

with continuous and deep gain layer:

- **De-correlation from implant size/geometry**
  ➔ **high pixel granularity and full fill factor**
  (high spatial resolution and efficiency)

- **Only small fraction of charge gets amplified**
  ➔ **reduced charge-collection noise**
  (enhance timing resolution)

---

**Wafer-production procedure:**

1. Step 1
2. Step 2
3. Step 3
4. Step 4
5. Step 5
6. Step 6
Gain Measurement with $^{55}$Fe source

X-rays from $^{55}$Fe radioactive source:
- mainly $\sim 5.9$ keV photons
- point-like charge deposition

Characteristic double-peak spectrum
- photon absorbed in drift region
  - holes drift through gain layer & multiplied
  - first peak in the spectrum
- photon absorbed in absorption region
  - electrons through gain layer & multiplied
  - second peak in the spectrum

JINST 17 (2022) 10, P10032

$^{55}$Fe X-ray Source

PicoAD
A gain up to $\approx 20$ for $^{55}$Fe X-rays obtained at HV = 120 V and T = -20 °C

We estimated that $^{55}$Fe gain of $\approx 23$ corresponds to gain 60–70 for a MIP
CERN SPS Testbeam with 180 GeV/c pions to measure **efficiency** and **time resolution**

- **UNIGE FE-I4 telescope** to provide spatial information \((\sigma_{x,y} \approx 10 \, \mu m)\)
- **Two LGADs** \((\sigma_t \approx 35 \, \text{ps})\) to provide the timing reference (and **two SPADs** with \(\sigma_t \approx 20 \, \text{ps}\))
Testbeam results: Detection Efficiency

99.9% for all power consumptions

**PicoAD** proof-of-concept prototype (2022)

Drops to 99% for HV=105 V

**PicoAD** proof-of-concept prototype (2022)

CERN SPS Testbeam: 180 GeV/c pions

$V_{th} = 4$ mV; HV = 125 V

$V_{th} = 4$ mV; Power = 2.7 W/cm$^2$
Testbeam results: Time Resolution

Best performance: \((17.3 \pm 0.4)\) ps for HV=125 V and Power = \(2.7 \text{ W/cm}^2\)

Timing resolution of 30 ps even at power consumption of 0.4 W/cm\(^2\)

![Graph 1](image1.png)

![Graph 2](image2.png)
Signal MPV amplitude

**PicoAD** proof-of-concept prototype (2022)

- CERN SPS Testbeam: 180 GeV/c pions
- Power = 2.7 W/cm²; HV = 125 V; $V_{th} = 4$ mV

![Graph showing signal MPV amplitude](image)

**JINST 17 (2022) P10040**

Efficiency

**PicoAD** proof-of-concept prototype (2022)

- CERN SPS Testbeam: 180 GeV/c pions
- Power = 2.7 W/cm²; HV = 125 V; $V_{th} = 4$ mV

![Graph showing efficiency](image)

**JINST 17 (2022) P10040**

Time resolution

**PicoAD** proof-of-concept prototype (2022)

- CERN SPS Testbeam: 180 GeV/c pions
- Power = 2.7 W/cm²; HV = 125 V; $V_{th} = 4$ mV

![Graph showing time resolution](image)

**JINST 17 (2022) P10040**

**PicoAD** proof-of-concept: factor of two better time resolution than ASIC without gain

- Prototype 1, PicoAD: (JINST 17 (2022) P10040)
- Prototype 1, no gain: (JINST 18 (2023) P03047)
- Prototype 2, no gain: (JINST 17 (2022) P02019)

13 ps at the pixel center
25 ps at the pixel edge
### Monolithic prototypes with SiGe BiCMOS (without internal gain layer)

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<td>2020</td>
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<tr>
<td>2022</td>
<td>20ps • Hexagonal pixels 100μm pitch • Improved electronics • 50μm epitaxial layer (350Ωcm)</td>
</tr>
</tbody>
</table>

#### What's next?

- **2016**: 200ps
- **2017**: 110ps
- **2018**: 50ps
- **2020**: 36ps
- **2022**: < 20 ps?

**Monolithic prototypes with internal gain layer:**

- **PicoAD version (proof-of-concept)**: 17 ps
- **PicoAD version in production** (back: Sept. 2023)
- **PicoAD version expected in Early 2024**
We are developing a sub-picosecond TDC based on a novel design (our patent© & more):


It was integrated in MONOLITH 2022 prototype ASIC.
The PicoAD® sensor works. Testbeam of the monolithic proof-of-concept ASIC provided:

- Efficiency = 99.9 % including inter-pixel regions
- Time resolution $\sigma_t = (17.3 \pm 0.4) \text{ ps}$: 13 ps at center and 25 ps at pixel edge (although sensor not yet optimized for timing)

Testbeam of second prototype ASIC, without gain layer, provided:

- Efficiency = 99.8% and $\sigma_t = (20.7 \pm 0.3) \text{ ps}$
- Laser measurement: down to 2.5 ps. Contributions from Landau noise studied
- Irradiation with protons (together with KEK) shows radiation $20 \rightarrow 40 \text{ ps for } \Phi = 10^{16} \text{ n_{eq}/cm}^2$
- PicoAD sensor based on this prototype to be delivered in September 2023, optimised for timing with TCAD to achieve $\approx 10 \text{ ps}$ (thicker drift layer; improved inter-pixel region)
- Low power picosecond TDC development for fully monolithic chip ongoing

Deliverable of MONOLITH ERC project:

- Full-reticle monolithic ASIC in Summer 2025 with 50µm pitch and sub-10ps timing