Innovative Back-Side Illuminated SiPMs (BSI-SiPMs): first results from the IBIS project

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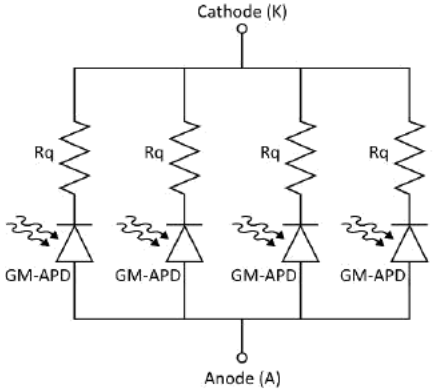
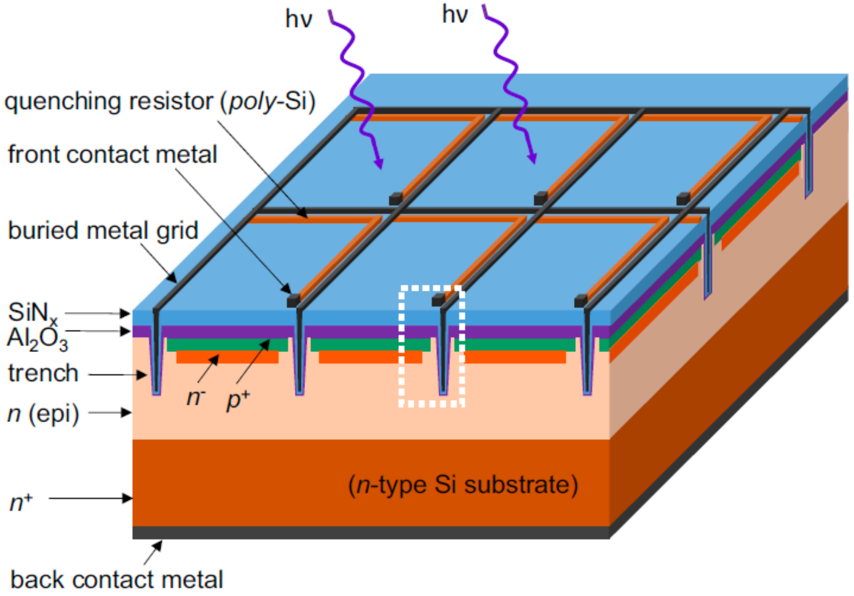
Outlook

- **Introduction on FSI and BSI SiPM**
- **The IBIS project**
- **Features of FBK NUV-BSI SiPMs**
- **RUN1 BSI front-side characterization**
  - Electrical characterization
  - Cryogenic test 77 K
  - DCR analisys
  - Timing

BackSide illuminated SiPM

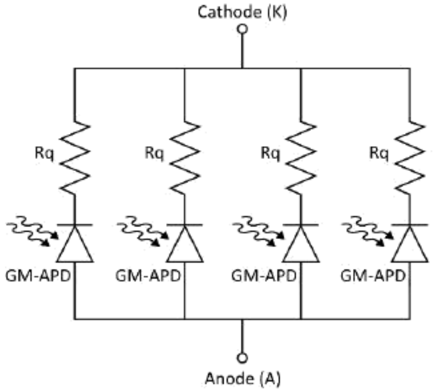


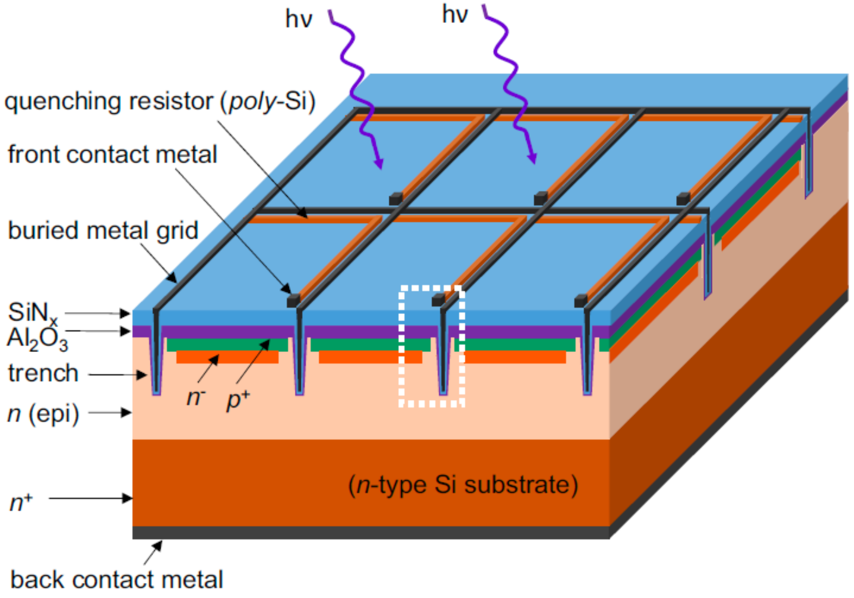


SiPMs

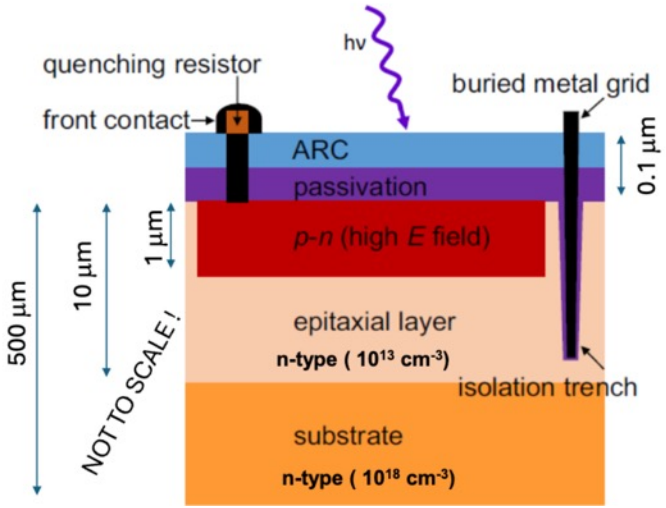
Array of Geiger-mode avalanche photodiodes (SPADs) and quenching resistors, connected in parallel metallic grid on a common Silicon substrate. SPADs are isolated with trenches often filled with metal (DTI). The two electrical contacts (anode and cathode) are naturally on the top and bottom of the device

BackSide illuminated SiPM

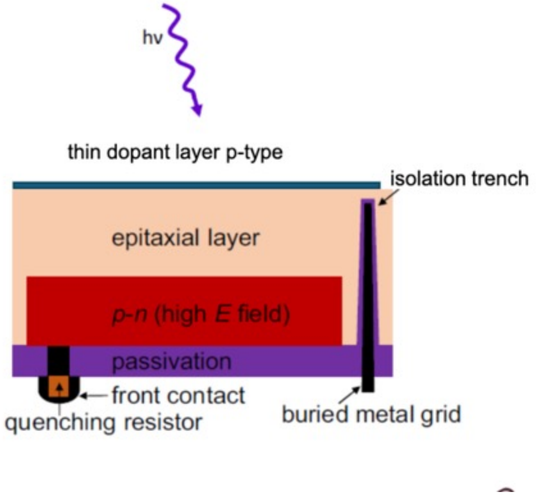




FrontSide Illuminated



BackSide Illuminated



Front-Side Illuminated (FSI) SiPM
Photons enter from the front side through passivation and metal routing layers before reaching the high-field p–n junction, resulting in partial optical shadowing and reduced effective fill factor.

Back-Side Illuminated (BSI) SiPM
Photons enter from the back side through a thin doped layer directly into the epitaxial volume, avoiding front-side metal structures and enabling higher PDE.

IBIS Project Innovative Backside Illuminated Single photon detector

IBIS is an **INFN project** started in **2020**, funded by **INFN–CSN5** and **FBK** within the **DRD4**.
Originally conceived to **maximize VUV sensitivity of SiPMs** for **track imaging in Liquid Argon detectors**, with a primary focus on **DUNE**.
Growing interest from other **HEP experiments** (**ePIC, LHCb, ALICE3**) in:

- Higher **Photon Detection Efficiency (PDE)** for **RICH detectors**
- **Enhanced radiation hardness**

Goal:

- Develop **back-side illuminated SiPM technology** optimized for next-generation particle physics detectors.
- **Characterization** of prototypes samples of BSI SiPMs
- Test **Radiation tolerance**
- Test MIPs detection capability and **timing**
- Design of a vertically integrated readout electronics (Read Out Chip bump bonded)
- Study application to novel **imaging** technique to Liquid Argon detectors

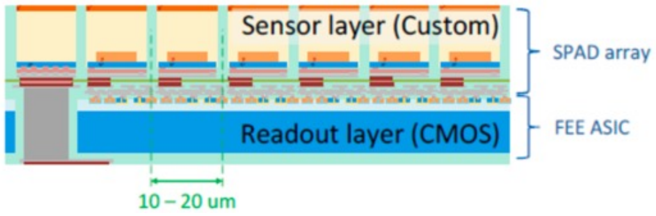
Features of FBK NUV-BSI SiPMs

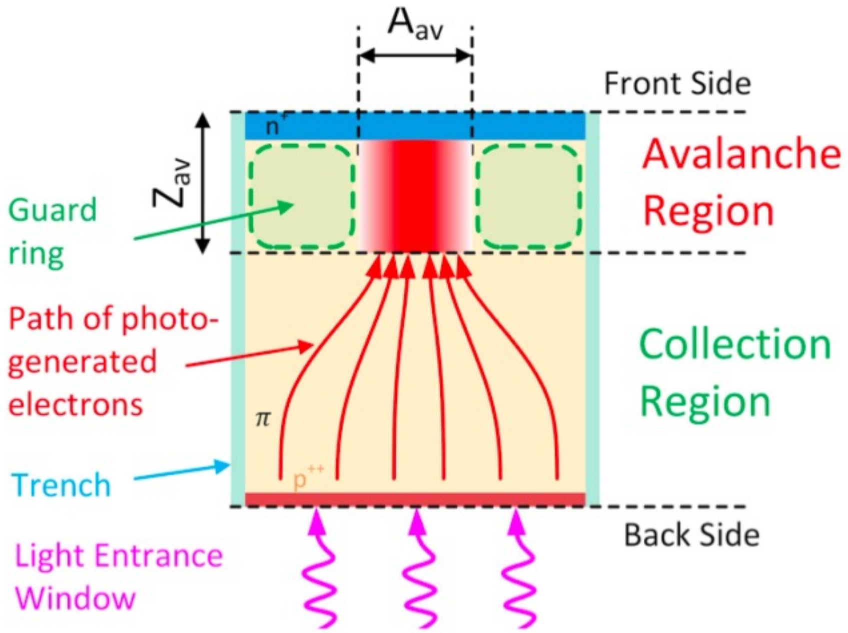
Enhanced Sensitivity:
No structures on the **entrance** window allow to reach **maximal fill factor** (~100%) even with **small cells**
Possible application of **treatments** for **enhanced** sensitivity in **VUV**
Direct Read Out Chip bonding:
Enabling **single or group SPAD access** without TSV leading towards **imaging SiPM** with local electronics for **fast timing** and **low-power**.

FBK new design with **separation between charge collection and avalcnhe regions** aloows **charge focusing** (deep implant and doped trenches)

Better Radiation Tollerance:
Under the assumption that the main source of **DCR** is **field-enhanced generation or tunnelling**, radiation induced **DCR** is lower because the **high field region** volume is **smaller**

Drowbacks:
Higher crosstalk due to not metal filled trenches
Timing performance may be **degraded** from difference in charge collection path length.
Lower gain due to smaller cell capacity

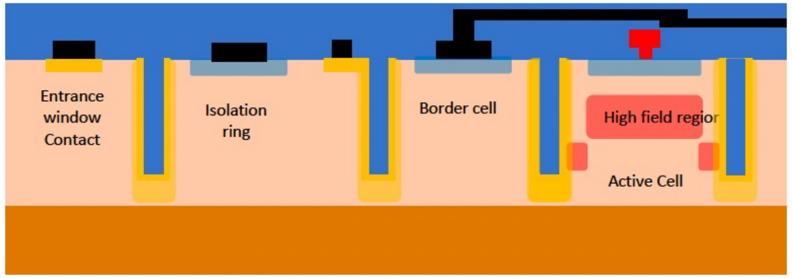




RUN1 BSI front-side characterization

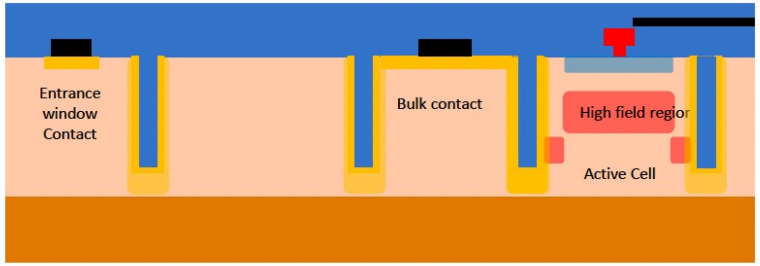
Partially processed devices (before thinning) **1x1 mm^2 SiPM** (4444 **15 um** SPADs) in 2 splits

Type B

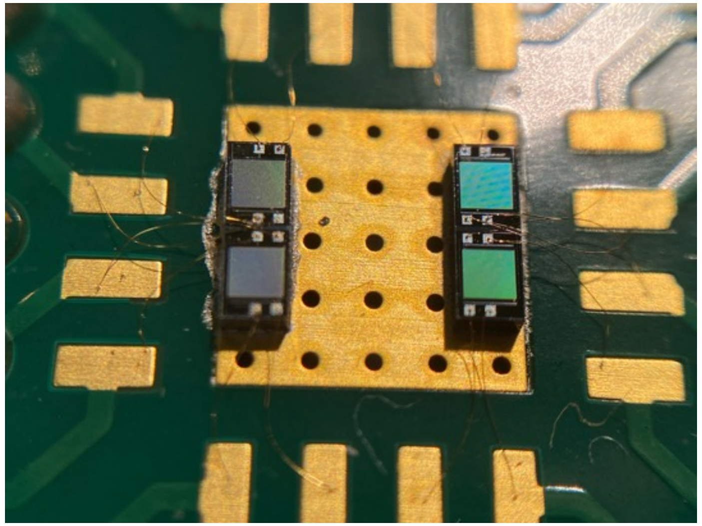


Guard cells are connected with the active cells.

Type E



No guard structures.

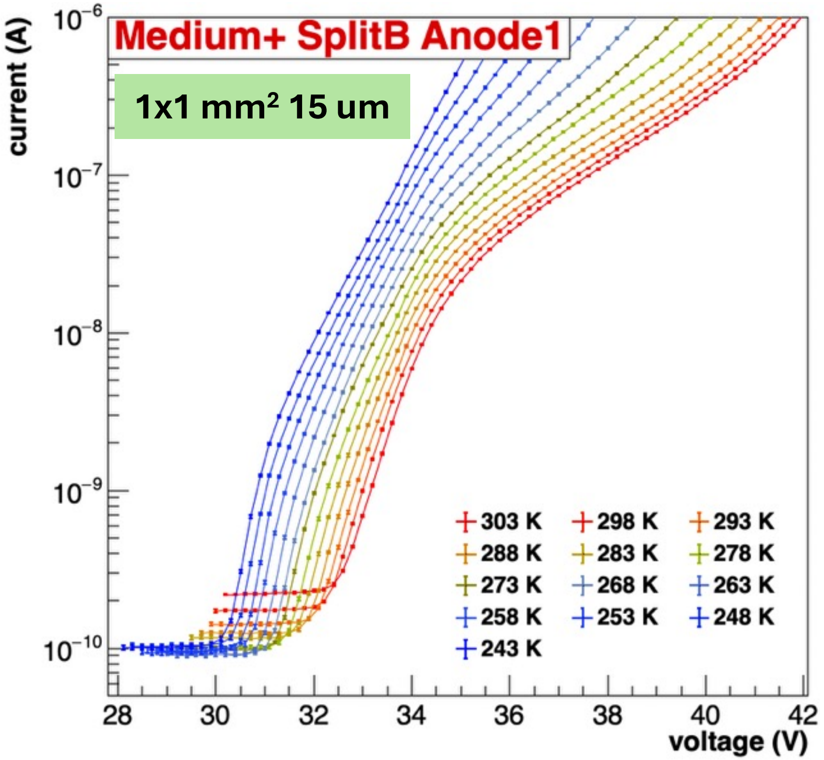


Further details on the RUN produciton can be found here: https://agenda.infn.it/event/47073/contributions/276400/

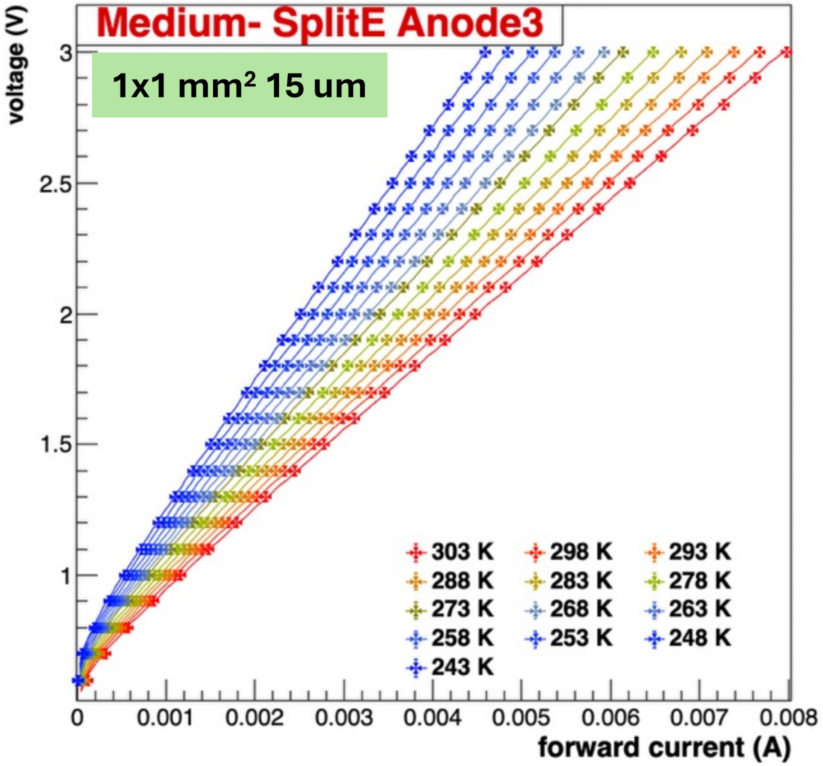
SPAD cell characterization:

- **Dark current/count rate**
- **Crosstalk**
- **Timing**

RUN1 BSI TEST Electrical characterization in climatic chamber [-30;30]°C

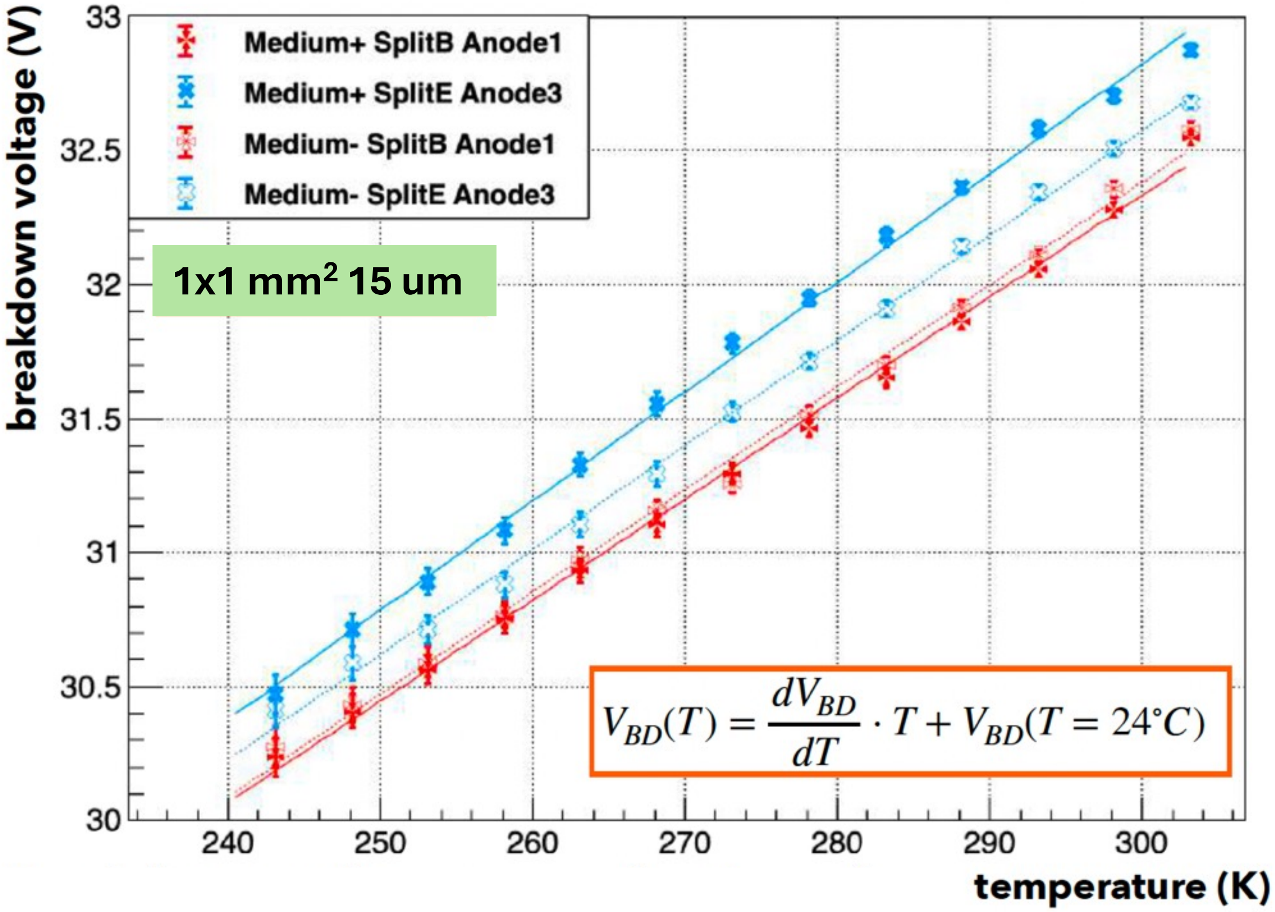


Reverse current IV
(with 560 nm light)



Direct current IV

RUN1 BSI TEST Electrical characterization in climatic chamber [-30;30]°C



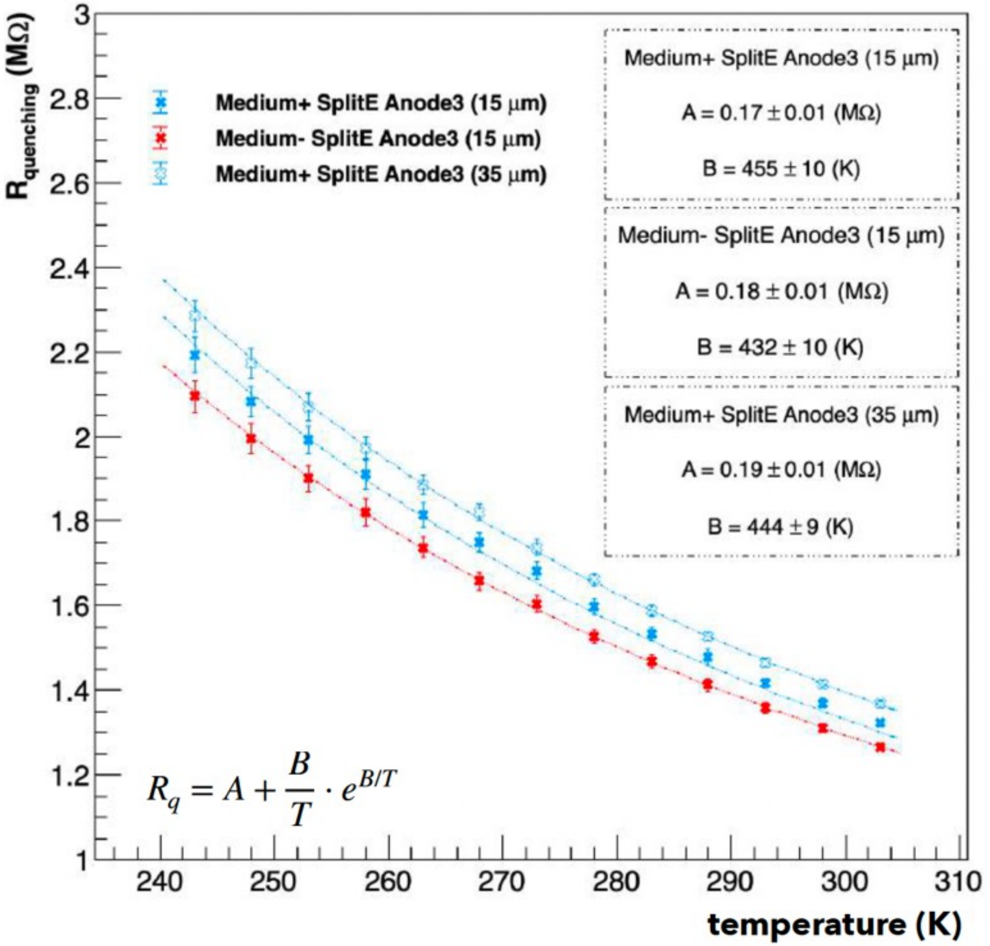
$$V_{BD}(T) = \frac{dV_{BD}}{dT} \cdot T + V_{BD}(T = 24^{\circ}C)$$

Breakdown voltage as a function of temperature

All devices exhibit a well-defined **breakdown voltage** of approximately **32.3 ± 0.3 V** at room temperature. The small spread of **0.3 V** is, consistent with variations in wafer among the samples.

The **temperature dependence** of the breakdown voltage is measured to be **38 ± 2 mV/K**

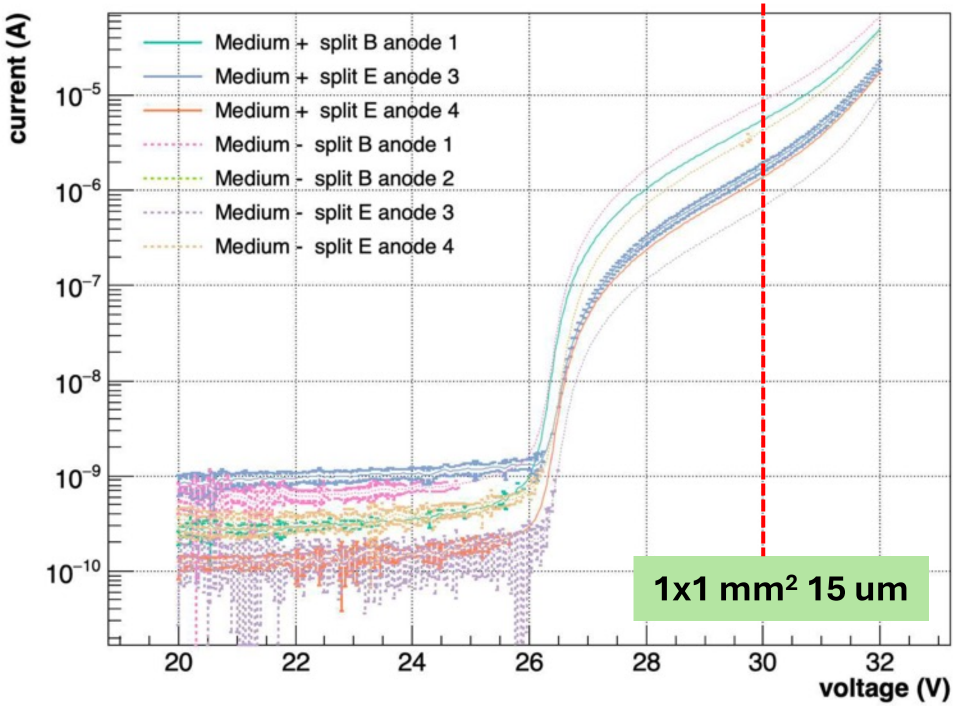
RUN1 BSI TEST Electrical characterization in climatic chamber [-30;30]°C



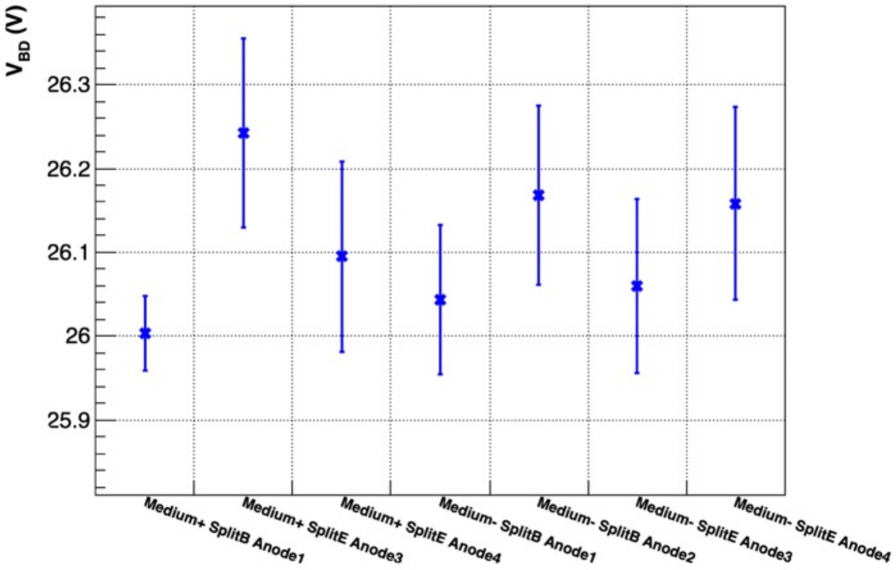
Quenching resistor value as a function of temperature

The value of the quenching resistor is exctracted from the **Shockley** formula.
1.37 MΩ at RT and a temperature dependance typical of **poly-crystalline silicon resistors**.
This value was set very **high** by **design** to allow **high OV operation**

RUN1 BSI TEST Cryogenic test 77 K



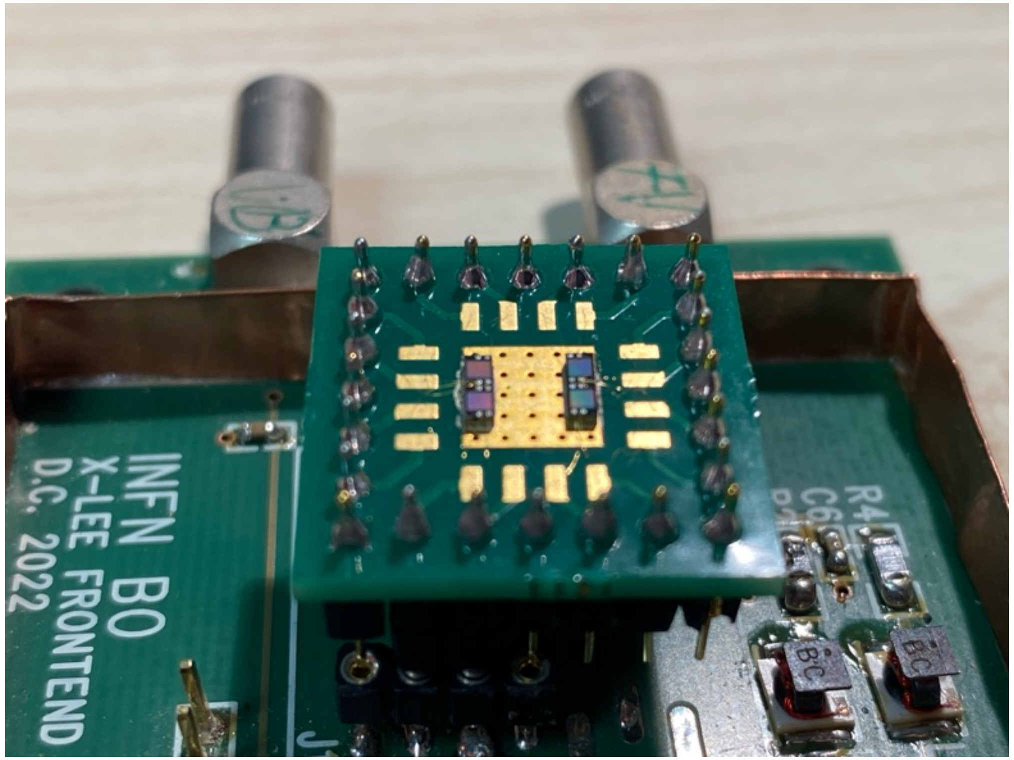
1x1 mm^2 15 um

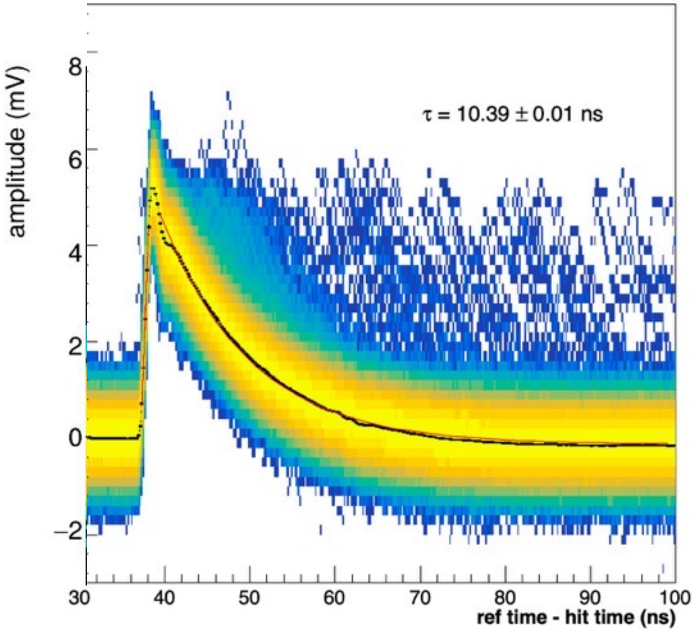


Good consistence in the breackdown value at **77 K** of **26 V** for all the samples. Start of the **second divergence at 4 VoV**.

RUN1 BSI TEST DCR setup

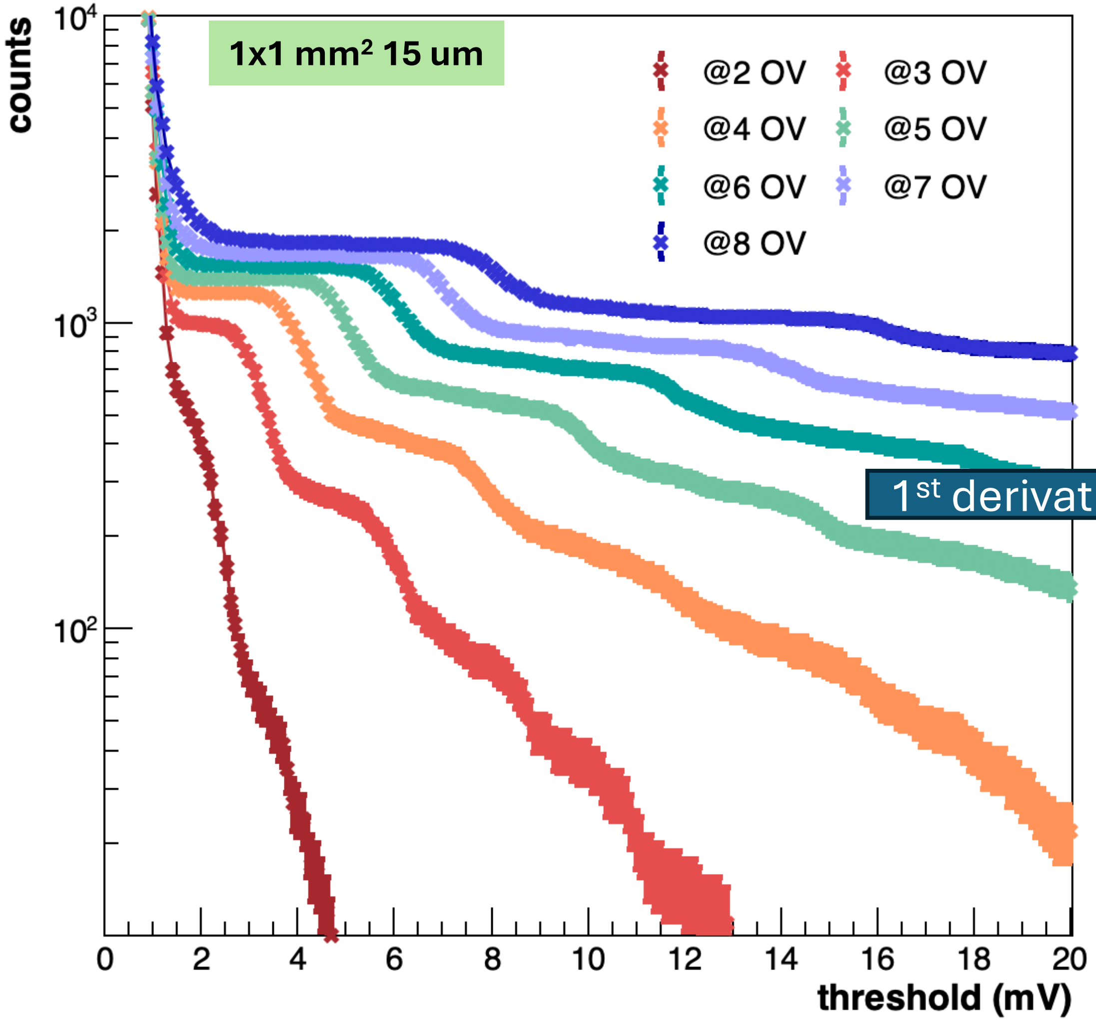
Sensor connected to a **custom FE** board hosting 2 **X-LEE39** monolithic linear amplifier from **MiniCircuit** connected in a 2 stages **amplification** circuit. The **gain** is set to **45 dB** with a flat response up to **1 GHz**. Sensors are placed inside an **RF shielding** and the amplified signals are acquired by a LeCroy WaveRunner 9000 oscilloscope with 4 GHz BW and 40 Gs/s.





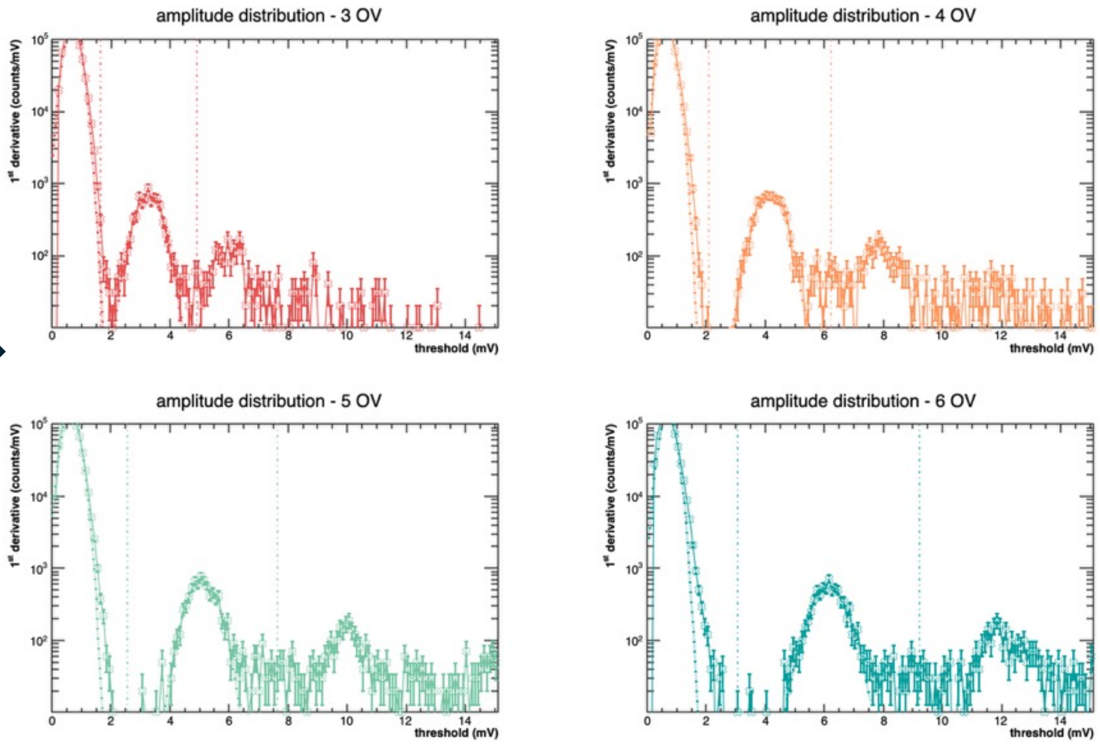
RUN1 BSI TEST DCR analysis

Threshold scan: counts vs a variable thr



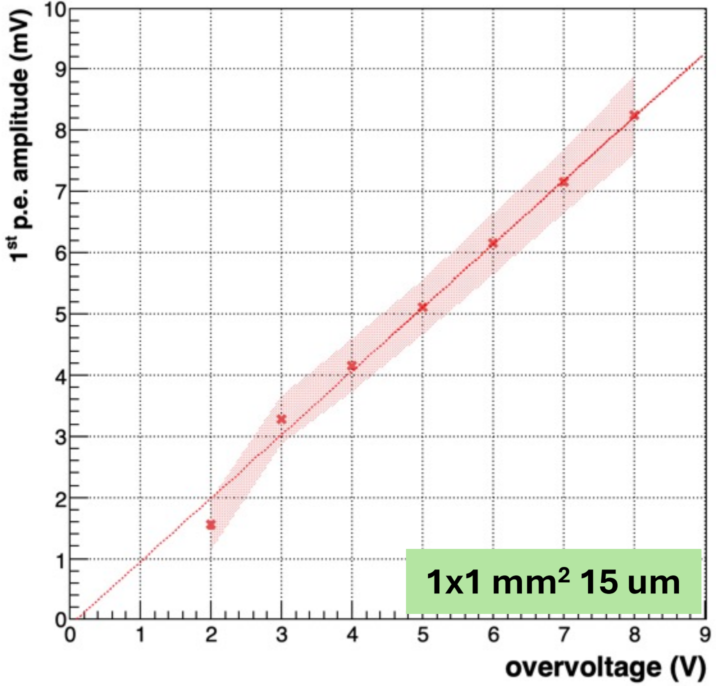
1st derivative

Amplitude distribution



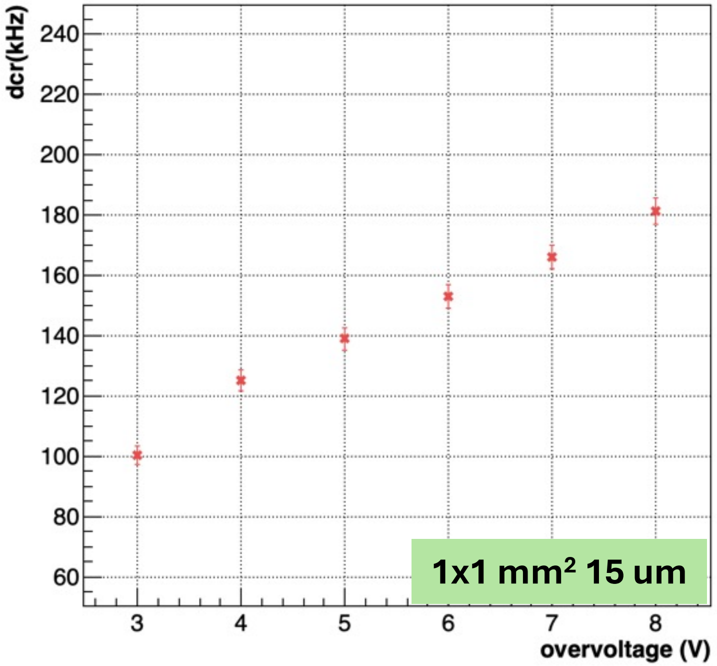
RUN1 BSI TEST DCR results

1st PE amplitude



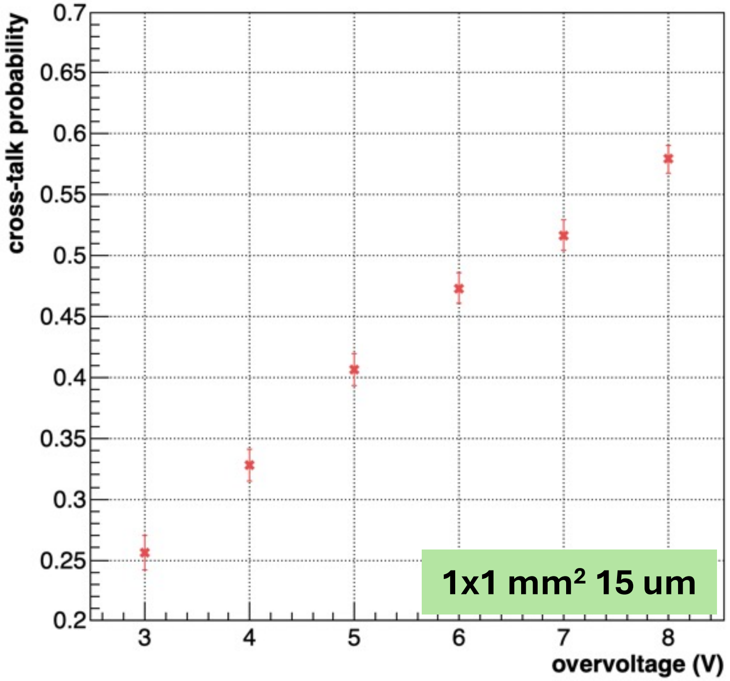
Good gain linearity with OV

DCR



Good performance in terms of **DCR** that follows linearly the OV

Crosstalk

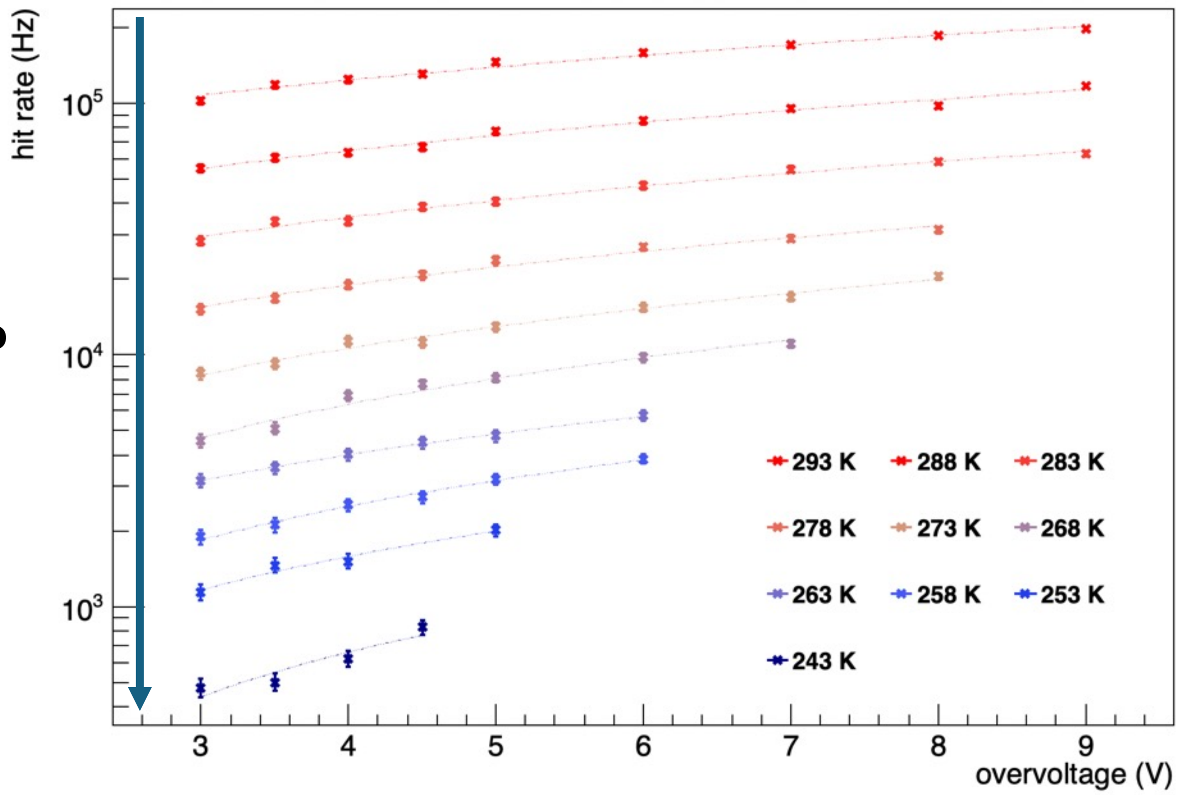


CT is **higher** than in traditional SiPM.

RUN1 BSI TEST DCR results

3 orders of magnitude reduction from 20 C to -30 C

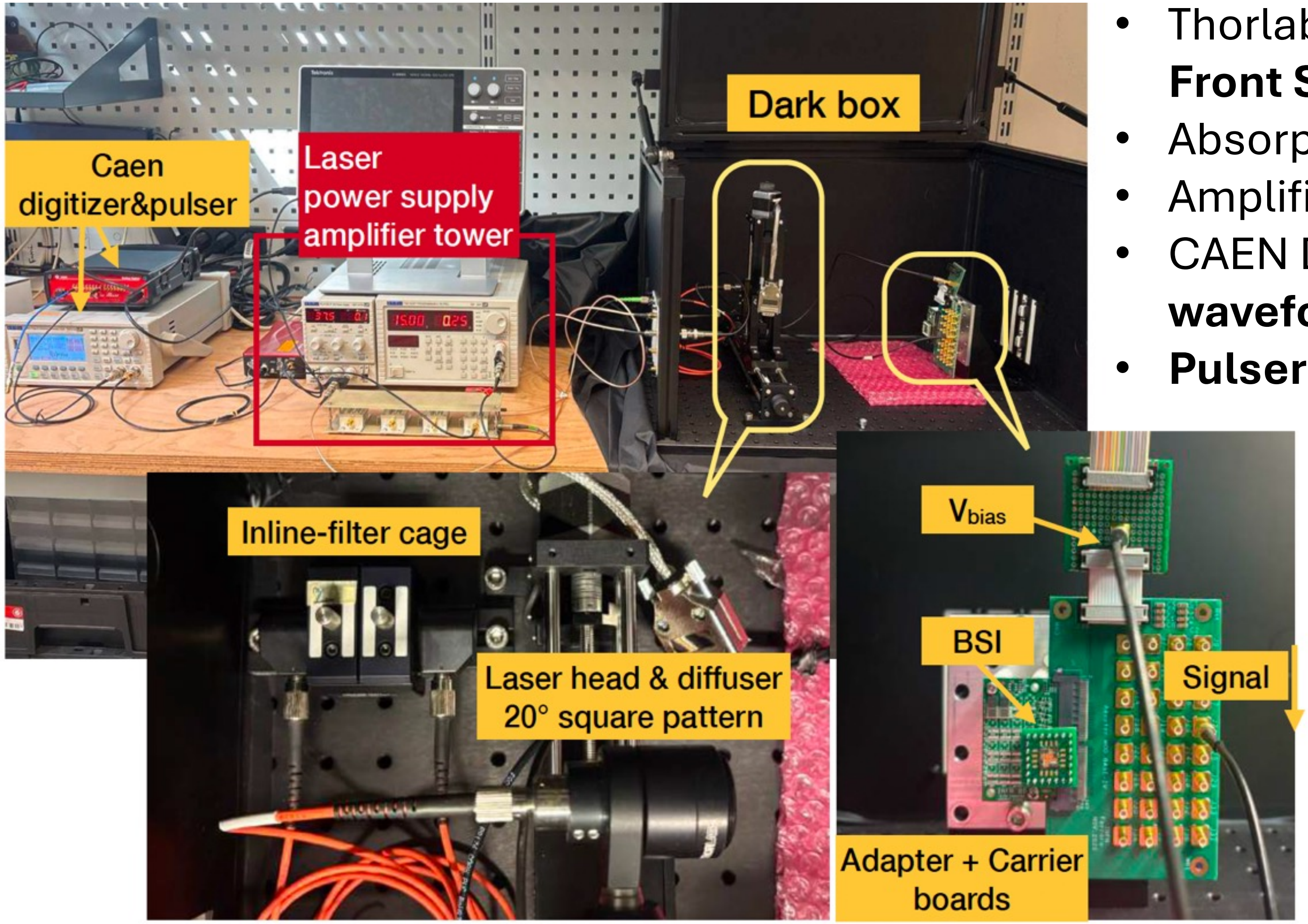
DCR as a function of OV and Temperature



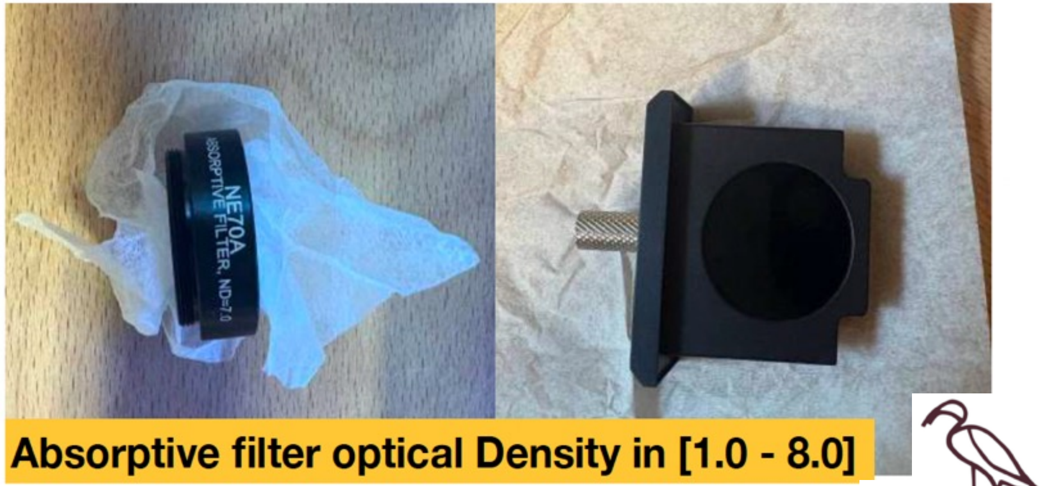
DCR below 1 kHz at -30° C

Early second divergence at low temperatures hinders high **OV measurements**

RUN1 BSI TEST Laser timing setup



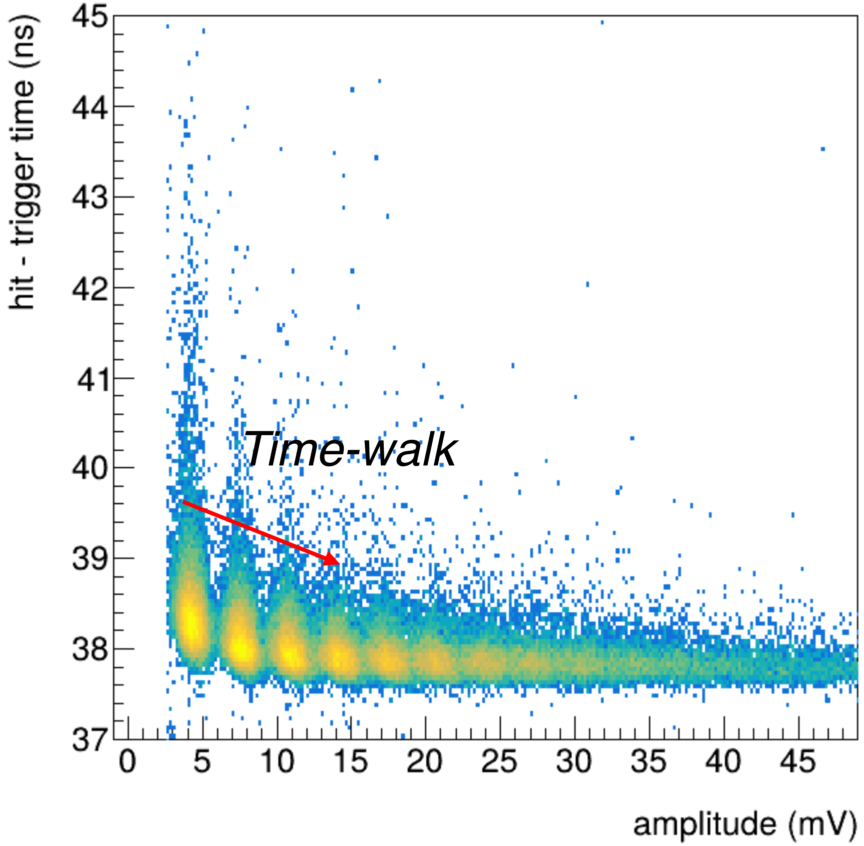
- Thorlabs **laser** (class B), **450 nm** illuminating the **Front Side**
- Absorptive **ND filters** and diffuser
- Amplification MiniCircuit ZFL - 1000LN+ **20dB 1 GHz**
- CAEN DT5742, 16-channel 12-bit, up to **5 GS/s waveform digitizer** for fast **signal acquisition**
- **Pulser** TGP3152, for **syncronization**

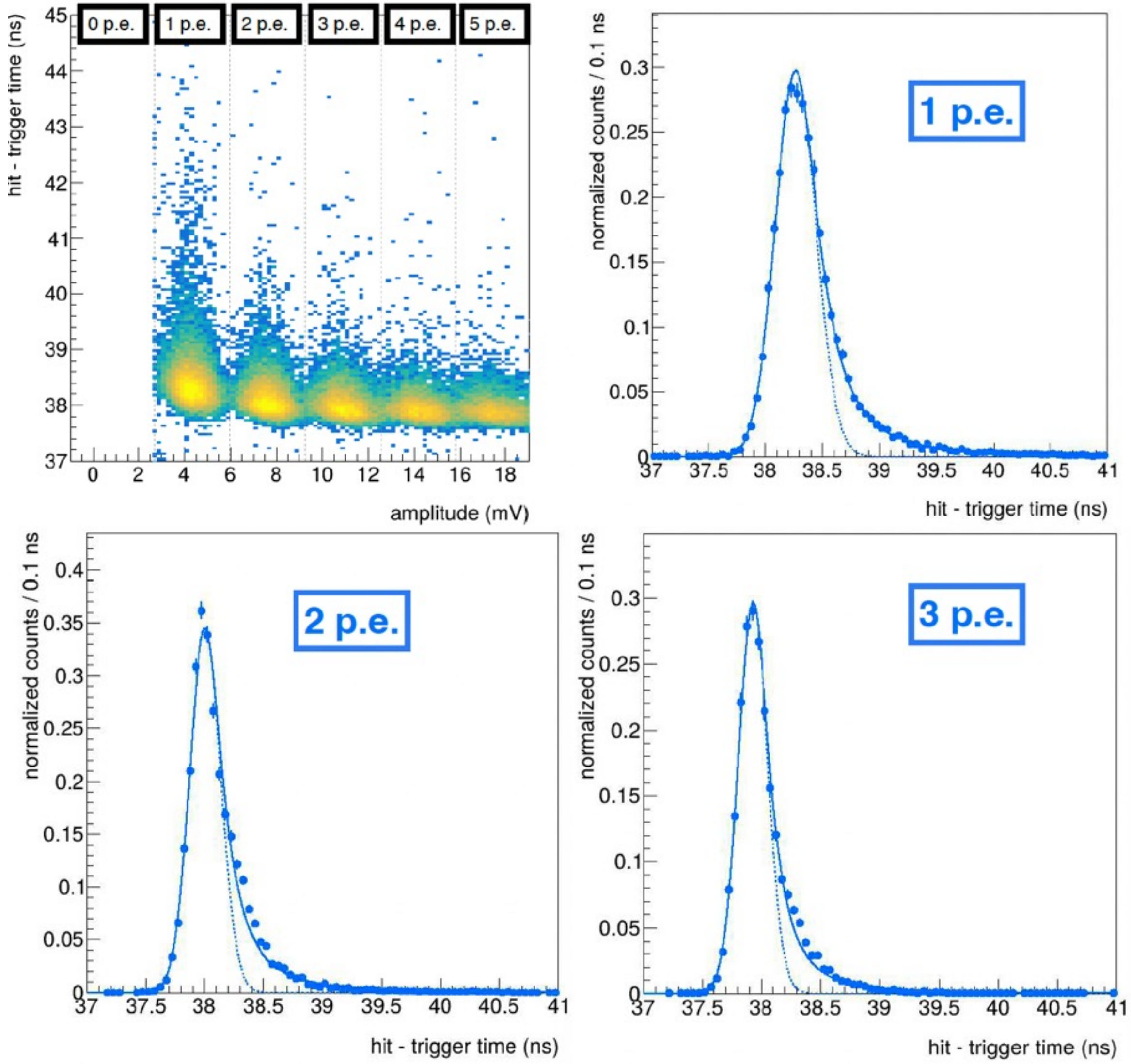


Absorptive filter optical Density in [1.0 - 8.0]

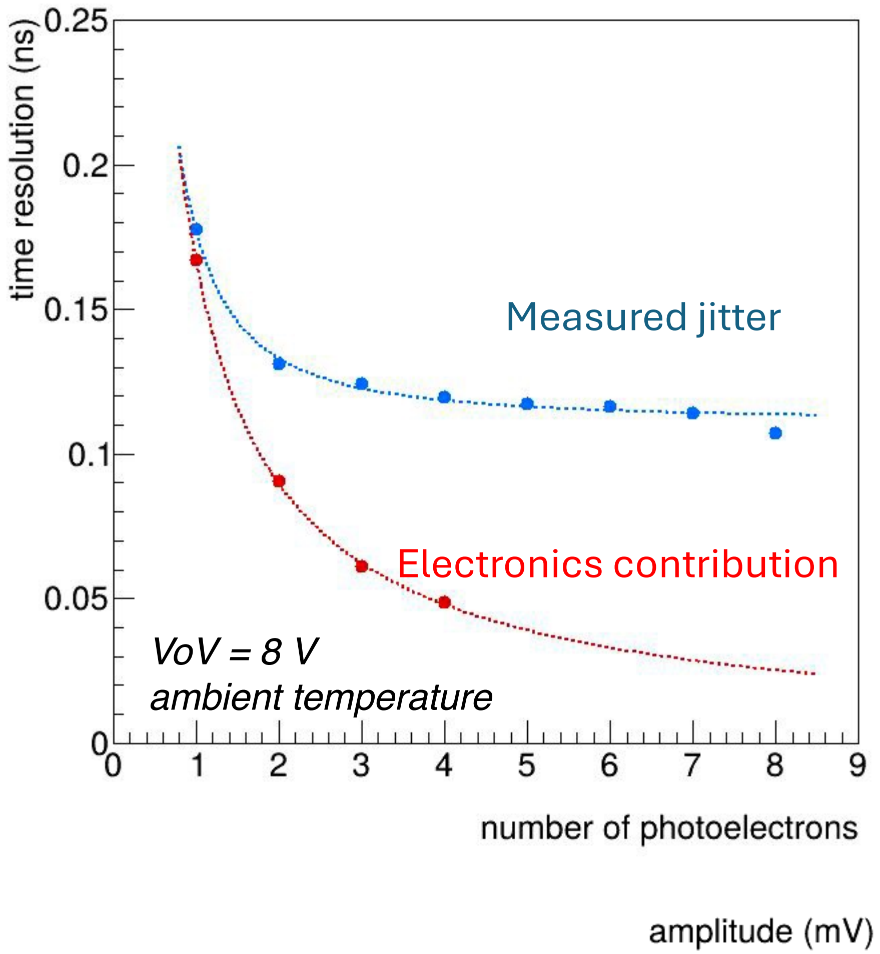
RUN1 BSI TEST Timing measuremens

Time coincidences with time taken at **@0.5 p.e. fixed threshold** as a function of **signal amplitude**





Timing measurements



Measured jitter includes all contributions.

Start at **180 ps** for **SPTR** and approaches **110 ps** for high **Npes**.

High electronic noise for **small signals**.

Still this value is **not** totally **representative** of the **real SPTR** of the **fully processed BSI sensor**.

Conclusions

The **first** iteration of **partially processed FBK NUV-BSI SiPMs** within the IBIS project has been characterized.

While the development is ongoing in a **high risk/high reward** approach, the first **results** of the characterization are **promising**.

The structure of the **SPAD** is working as expected and the **SiPM** is able to detect **single photons** while keeping the **DCR under control**.

Still some **effort** must be put into the increase of the **SNR** and **mitigation** of **crosstalk** that represents the main limitation in BSI.

Next steps

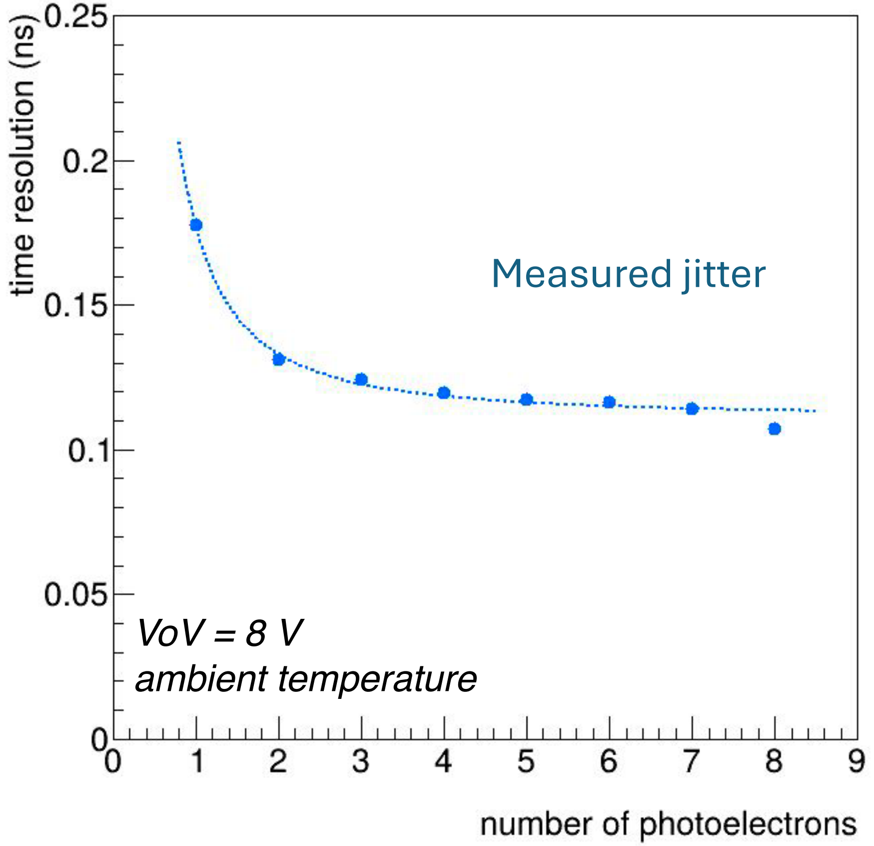
Irradiation test

Fully processed devices characterization

Integration with electronics

Thank you

Timing measurement



Gaussian core sigma as a function of the signal Npe amplitude.
Start at **180 ps** for **SPTR** and approaches **110 ps** for high **Npes**.
This includes:

- electronics jitter
- laser pulse width
- synchronisation
- Digitizer time resolution

Small signals are likely strongly affected by the electronics jitter

Timing measurements

Electronic jitter

The contribution to the time resolution from the **electronics jitter** can be estimated from the **noise RMS** and the signal **slew rate** using the following formula.

$\boldsymbol{\sigma_{jitter} = \sigma_{noise} / slewrate}$

For 1pe:

σ_{noise} = 0.662 mV

slewrate = 3.96 mV/ns

σ_{jitter} = **167 ps !**