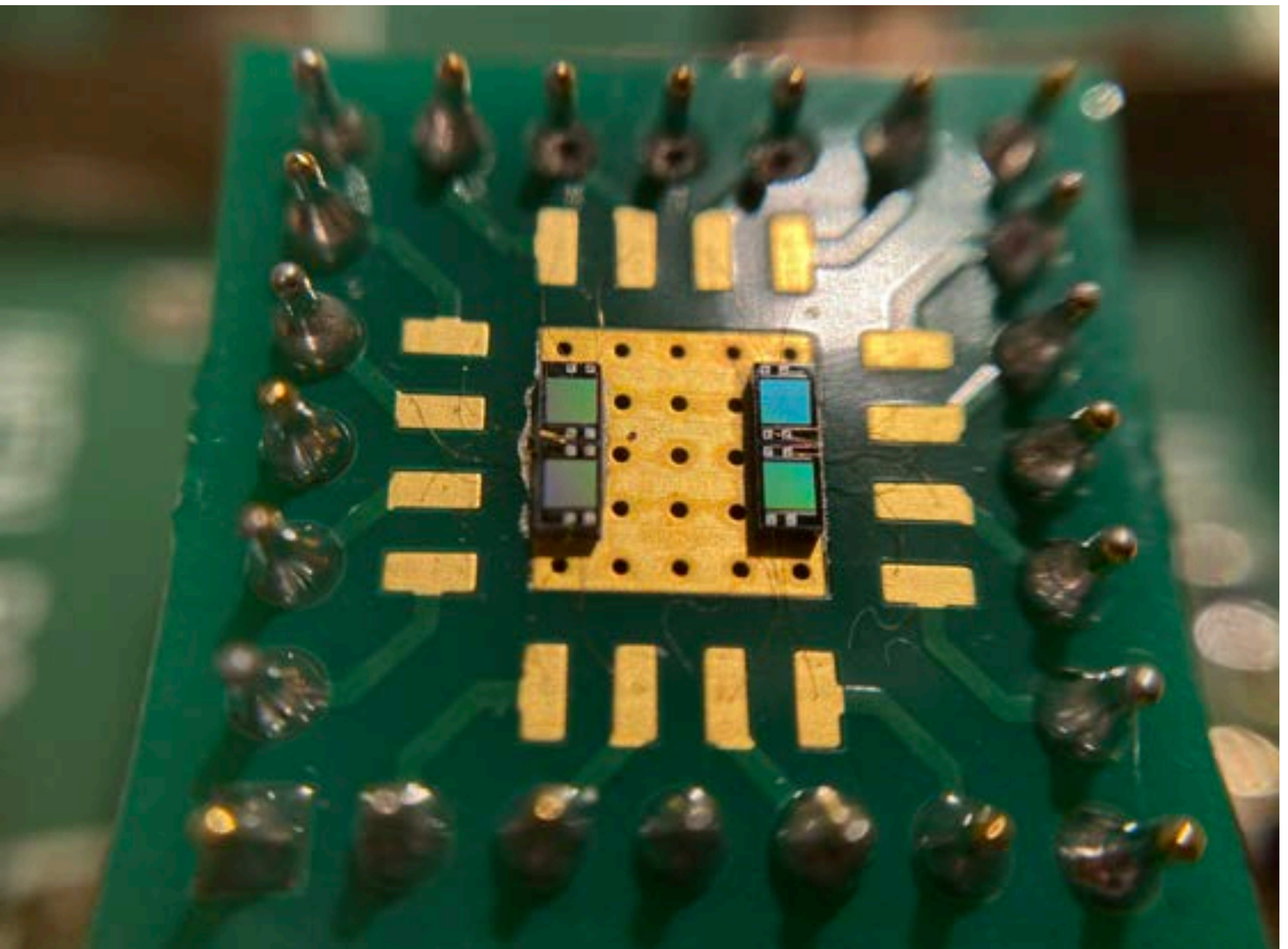
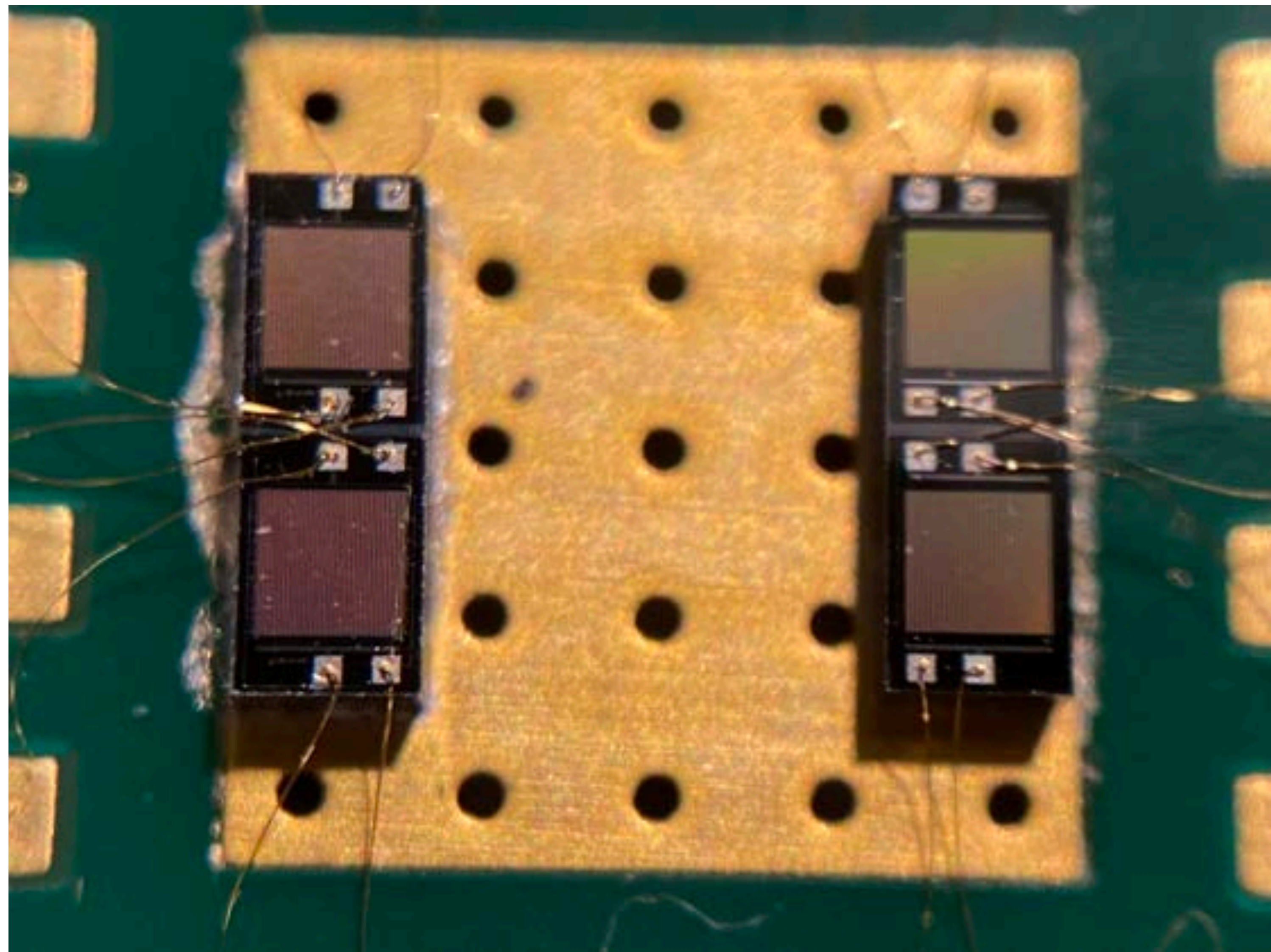
CHARACTERIZATION OF IBIS RUN 1 BACK-SIDE ILLUMINATED SIPM PROTOTYPES FOR IMAGING APPLICATION IN FUTURE EXPERIMENTS

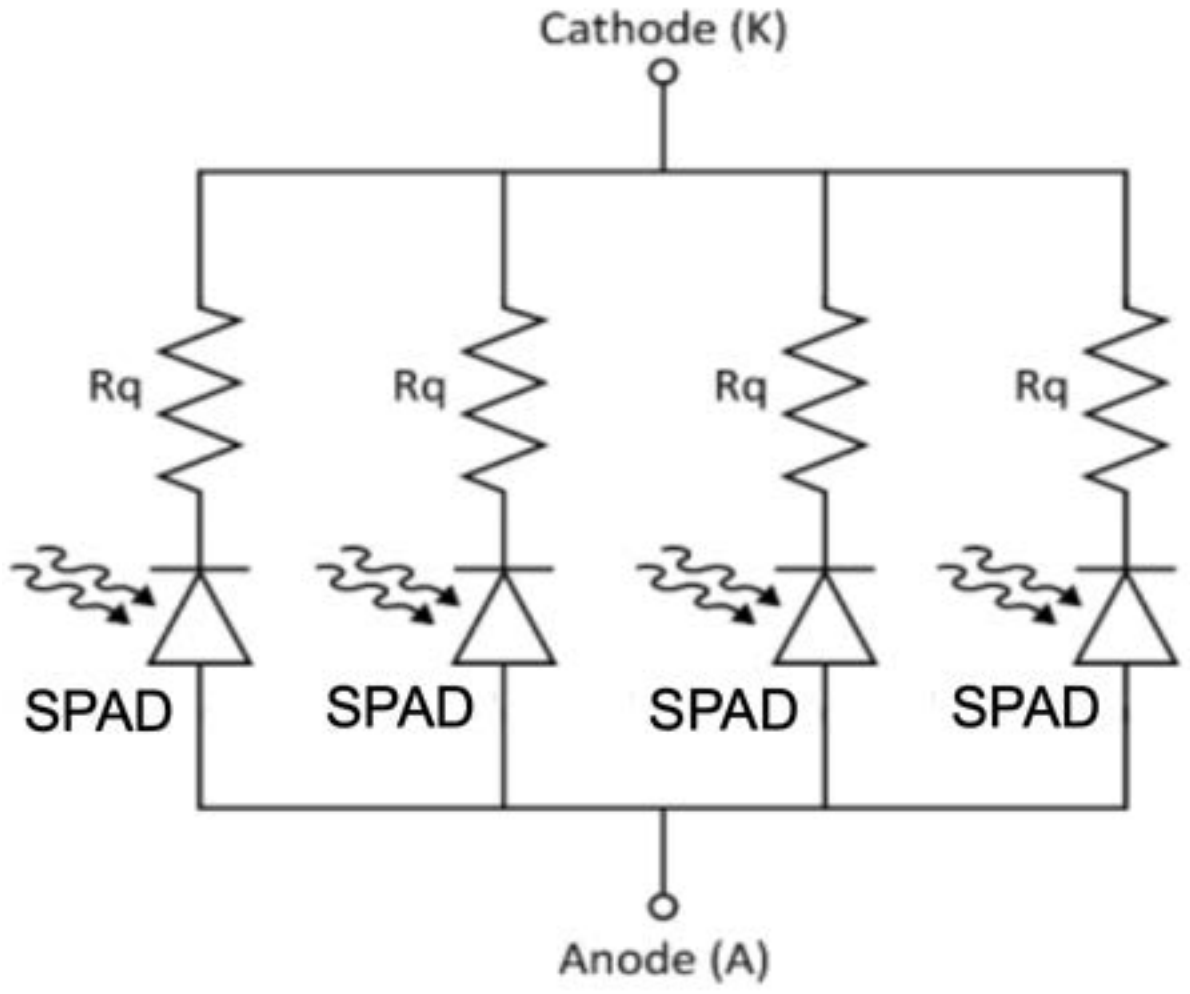


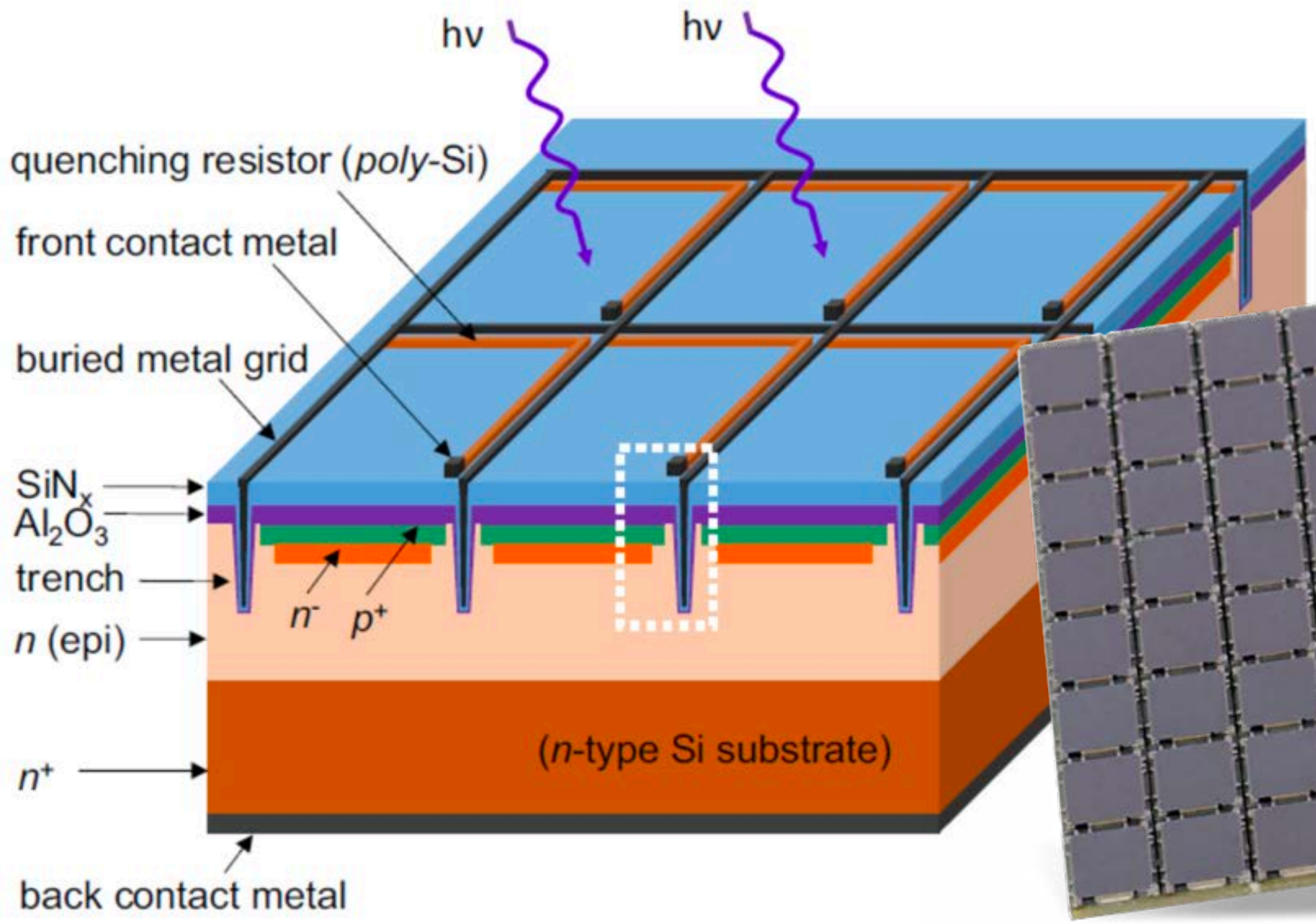
Presented by: Edoardo Rovati
(INFN & UNIBO)

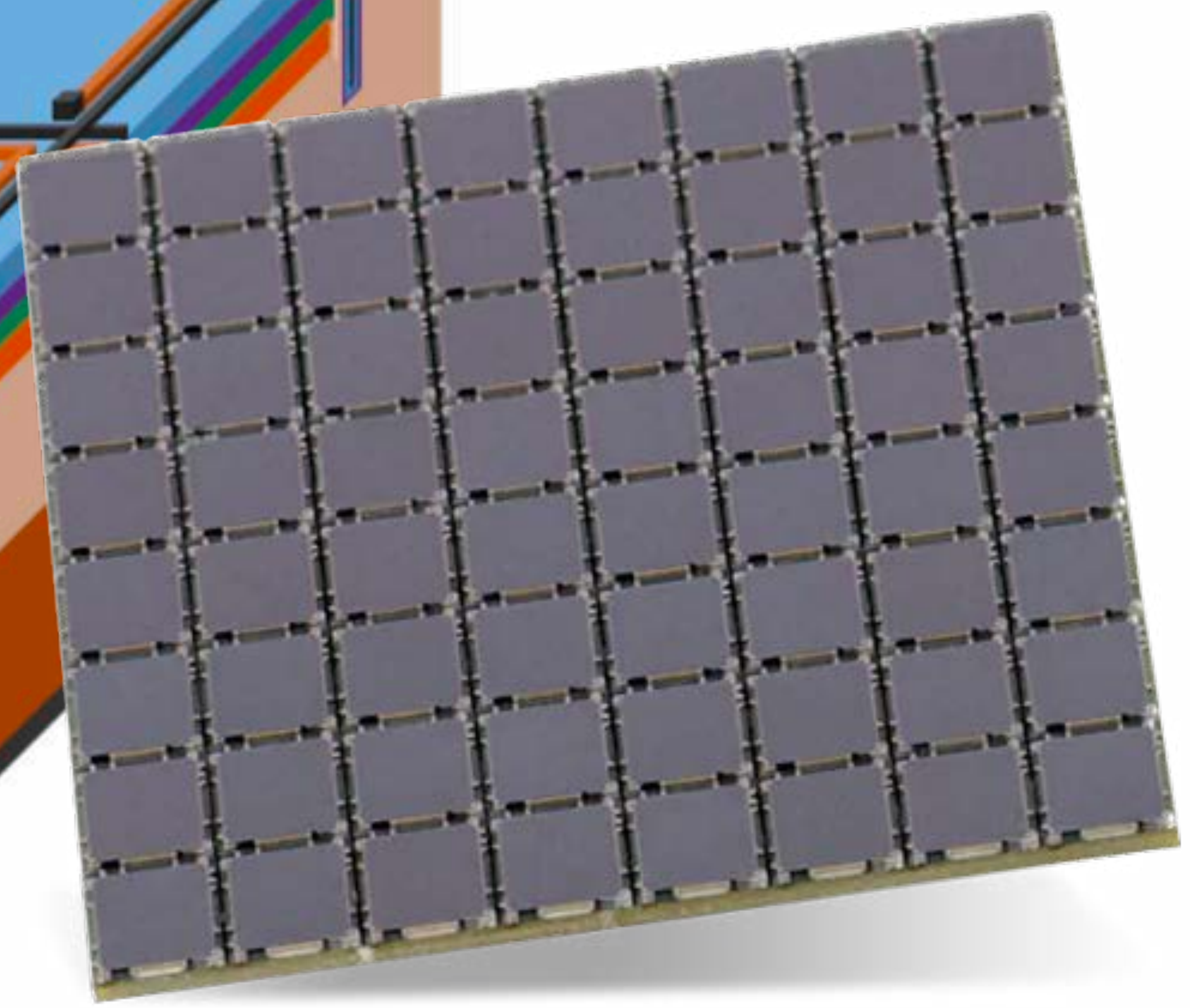
on behalf of the IBIS-NEXT

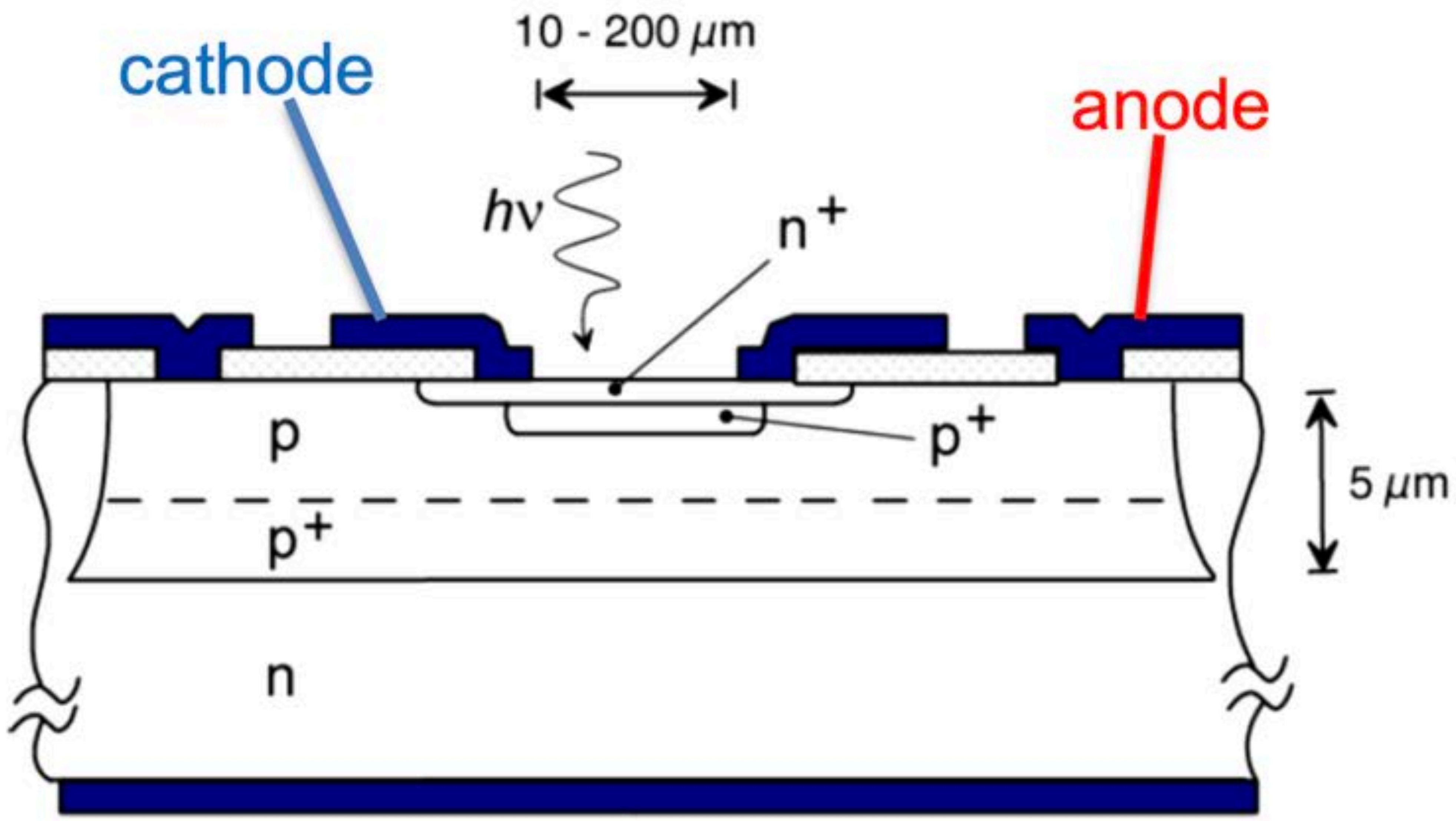


A **Silicon Photomultiplier** (SiPM) is an array of **Geiger-mode Single-Photon Avalanche Diode** (SPADs) operating above the **breakdown voltage** (V_{BD}). Each microcell includes a **passive quenching resistor** (Rq), and all cells are connected in parallel on a common substrate.





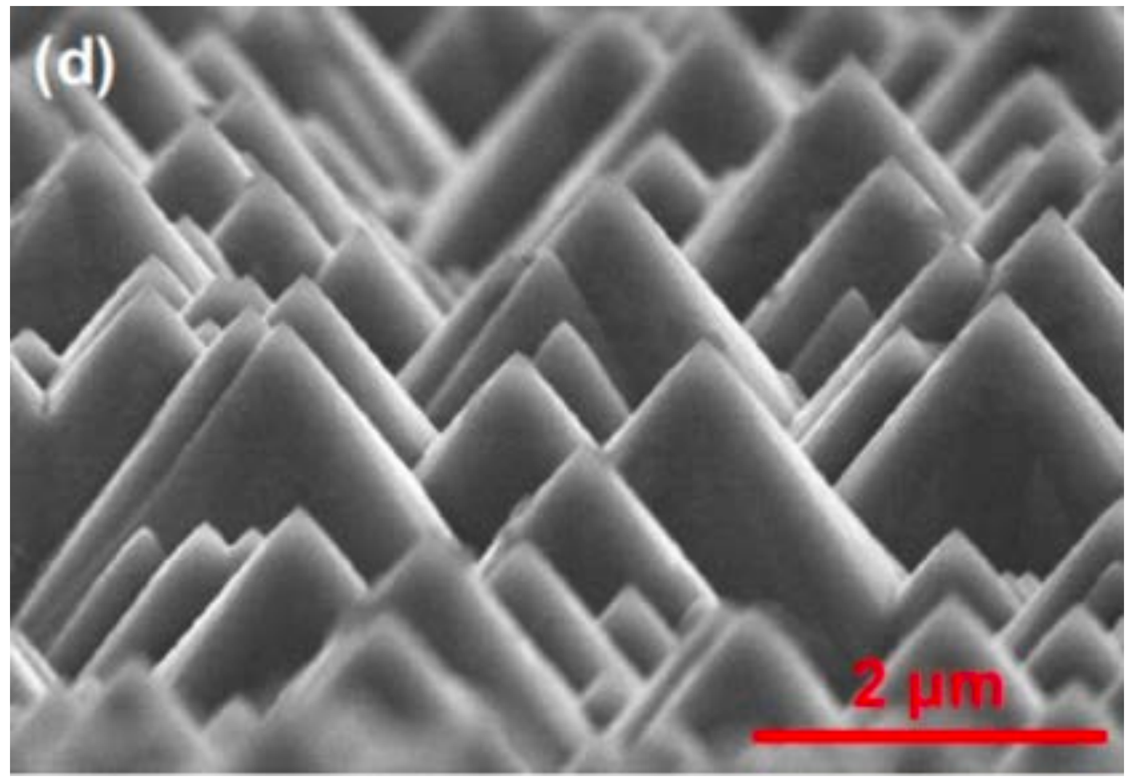




WHAT IS A BACKSIDE ILLUMINATED SIPM?

Advantages:

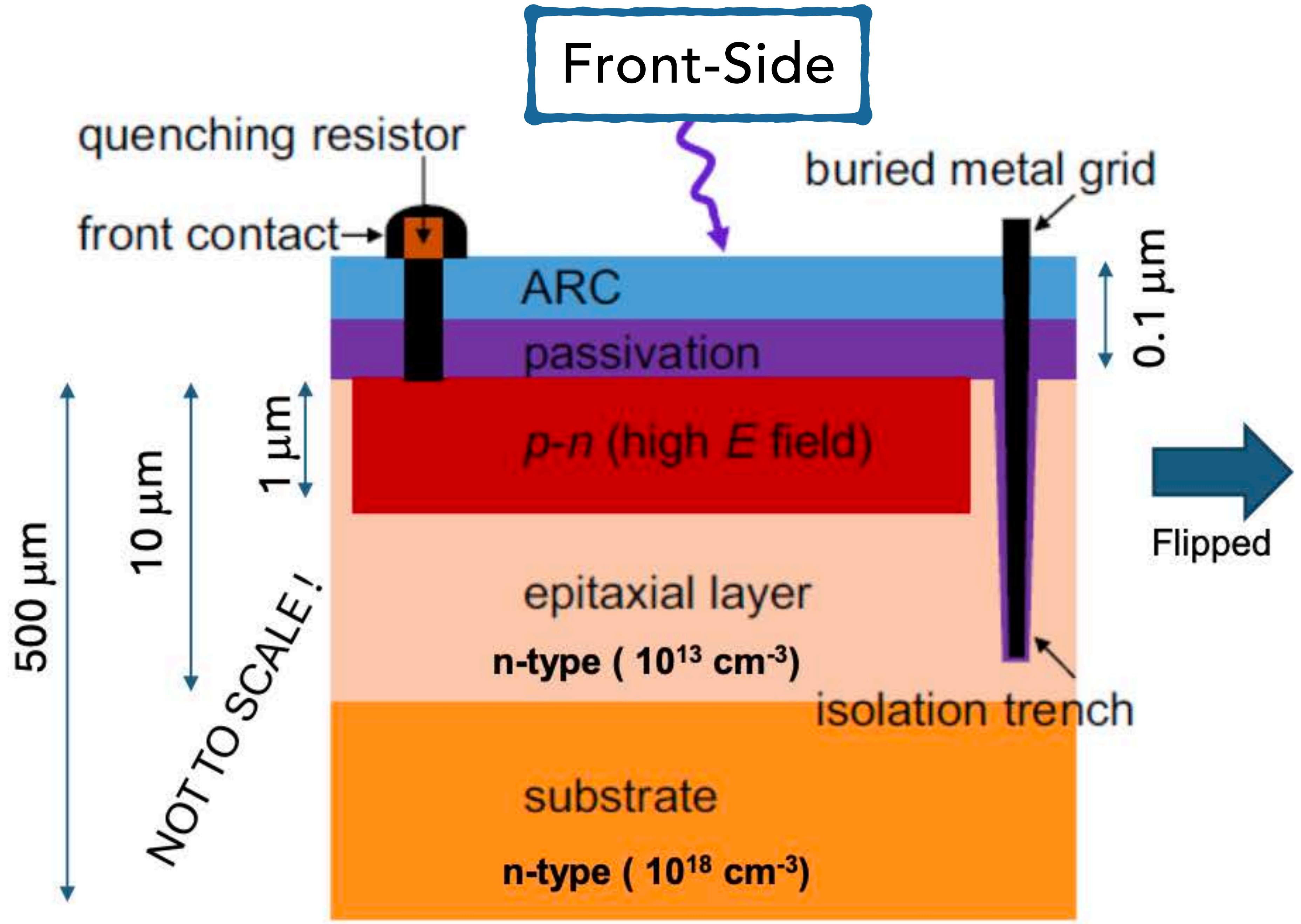
- Entrance window completely free of metal grid, quenching resistance, through silicon vias
  - ➡ enhanced fill factor **~ 100%**,
  - ➡ more advanced surface treatments to **improve optical properties** (enhanced sensitivity in VUV)
- No need for vias → smaller SPAD size
  - ➡ **High dynamic range**
  - ➡ **~ 15-35 μm**

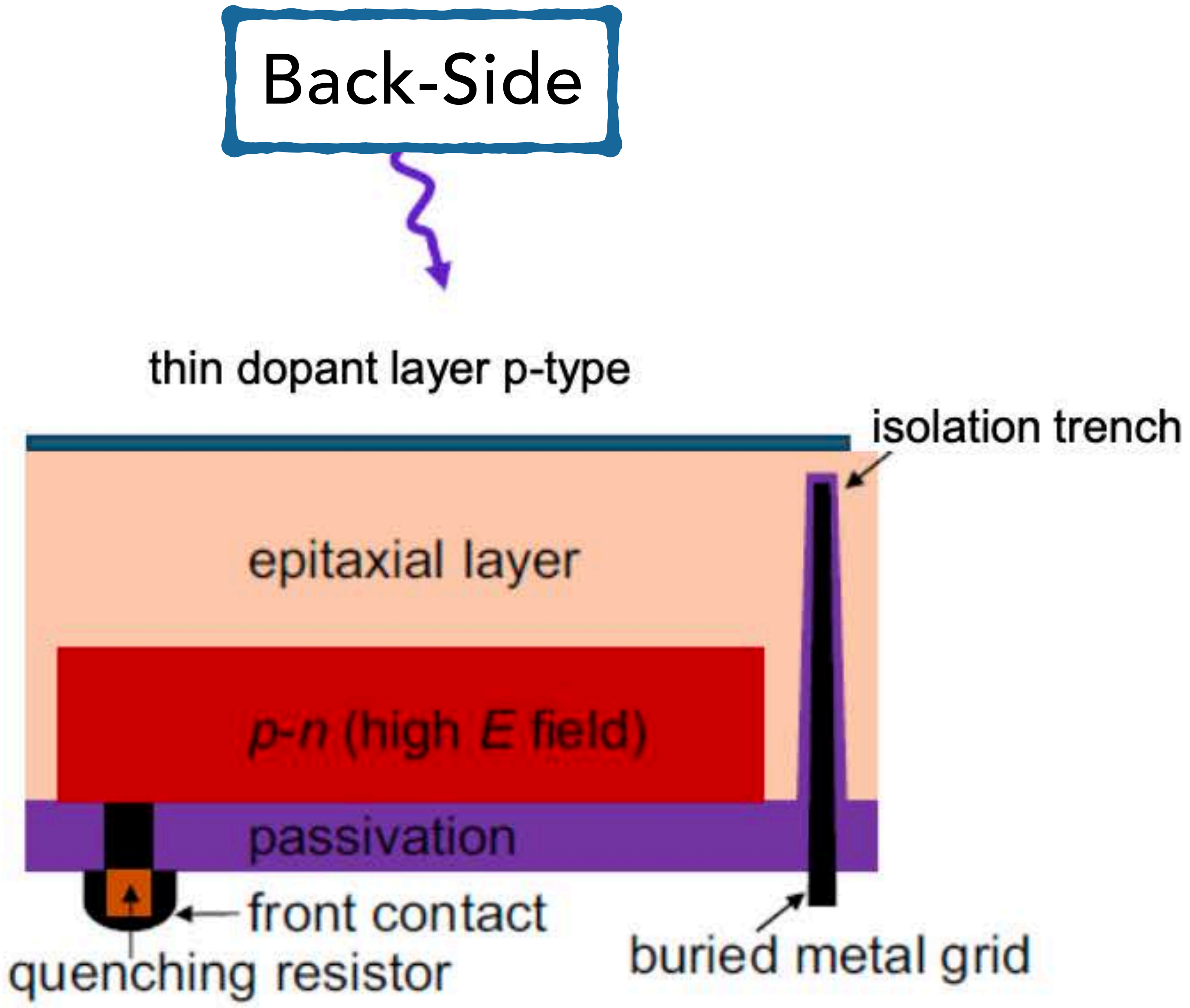


"Advanced antireflection for back-illuminated silicon photomultipliers to detect faint light", y.tao,Nature Scient. Rep.

Disadvantages:

- More difficult to control **CrossTalk and Afterpulse**

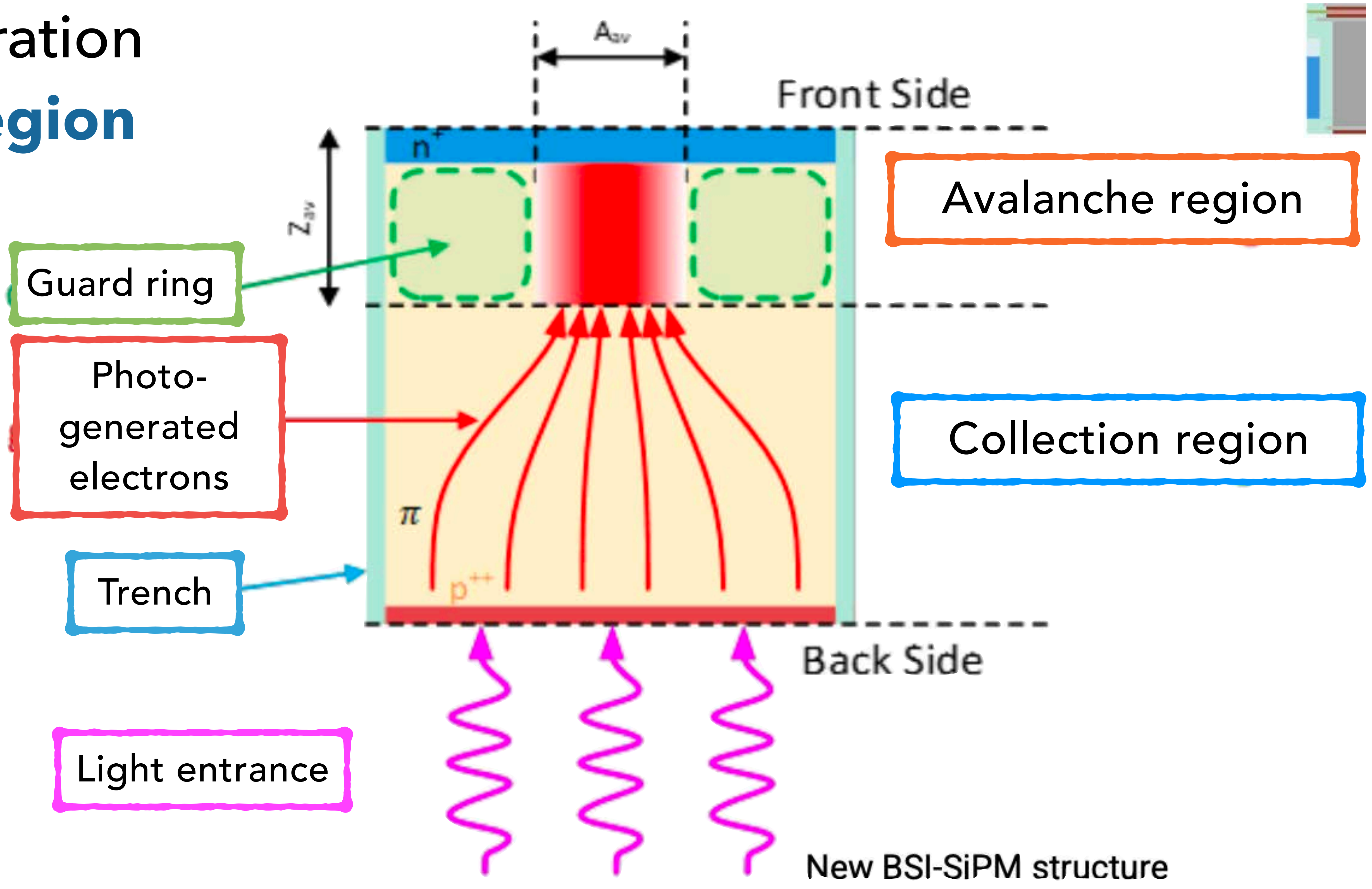




FEATURES

Significant advantage of BSI cell is the clear separation between **charge collection** and **multiplication region**

➡ **Charge focusing mechanism**



FEATURES

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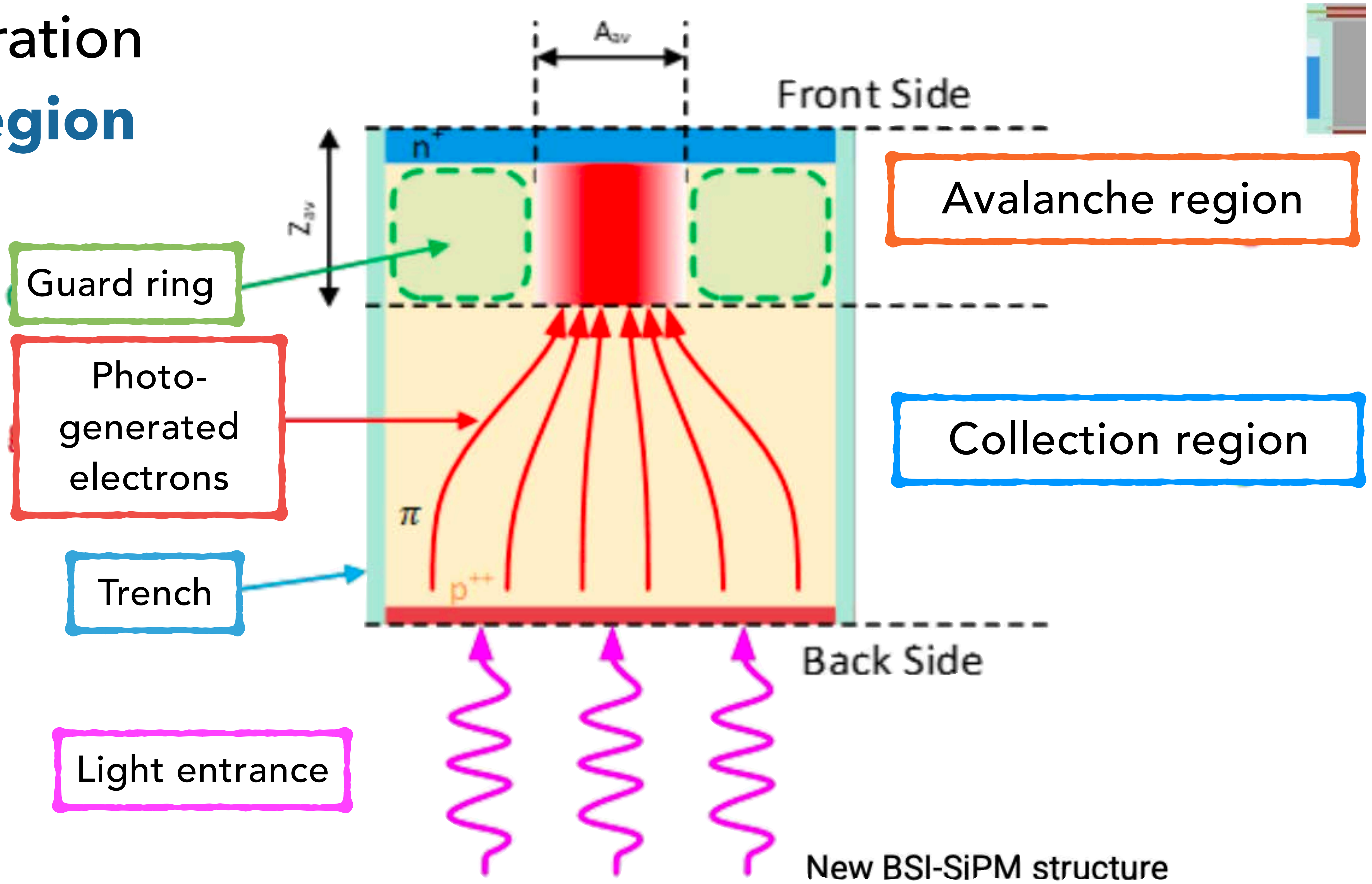


Better radiation tolerance: under the assumption that the main source of DCR is field enhanced generation or tunnelling, **radiation induced DCR is lower due to smaller high field region**

➡ area sensitive to radiation damage is smaller than the light sensitive are

Drawbacks:

- Time performance degradation from difference in charge collection path length
- Lower gain leading to worse single photon time resolution (SPTR)

FEATURES

Significant advantage of BSI cell is the clear separation between **charge collection** and **multiplication region**

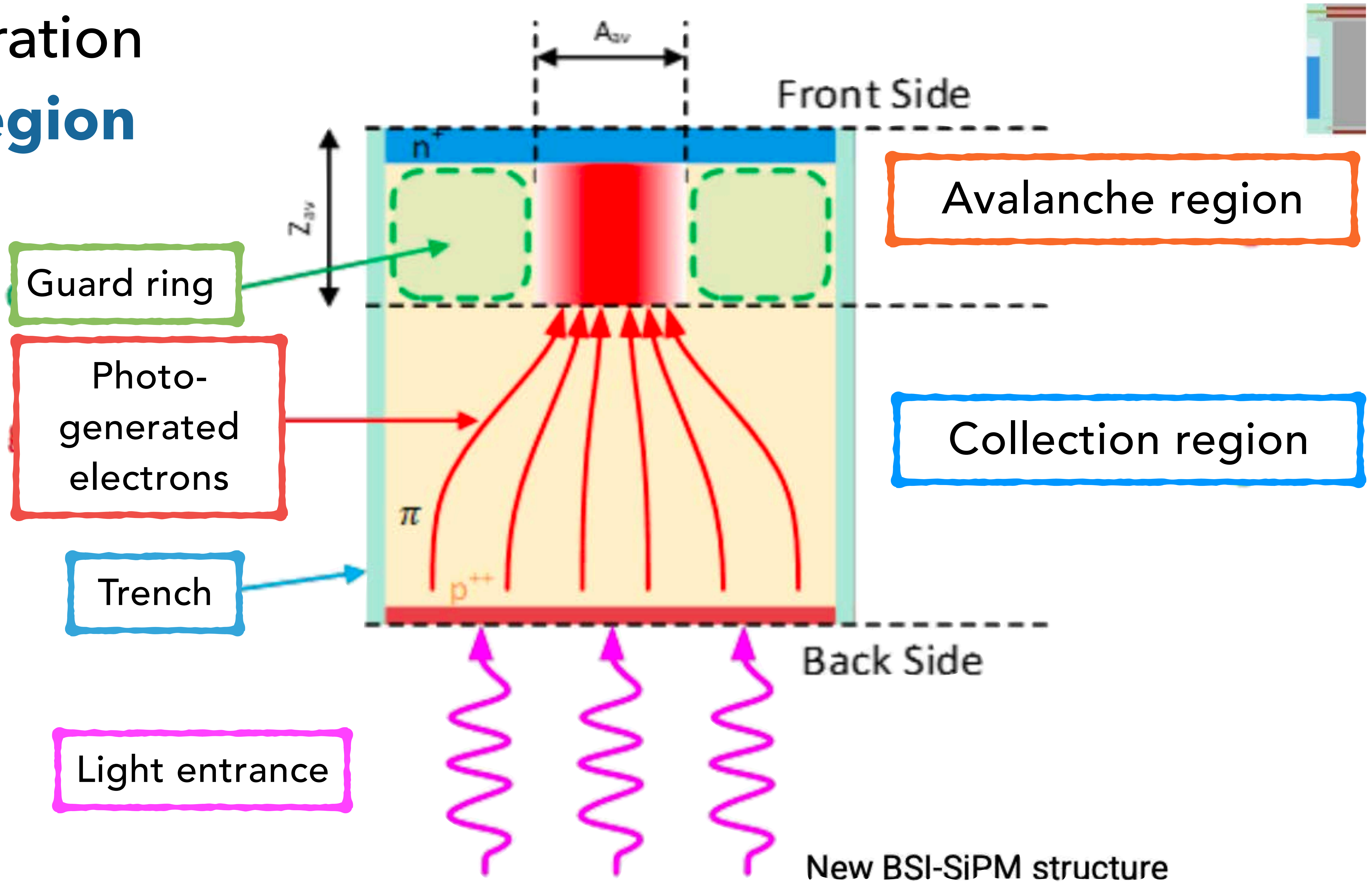
➡ **Charge focusing mechanism**

Better radiation tolerance: under the assumption that the main source of DCR is field enhanced generation or tunnelling, **radiation induced DCR is lower due to smaller high field region**

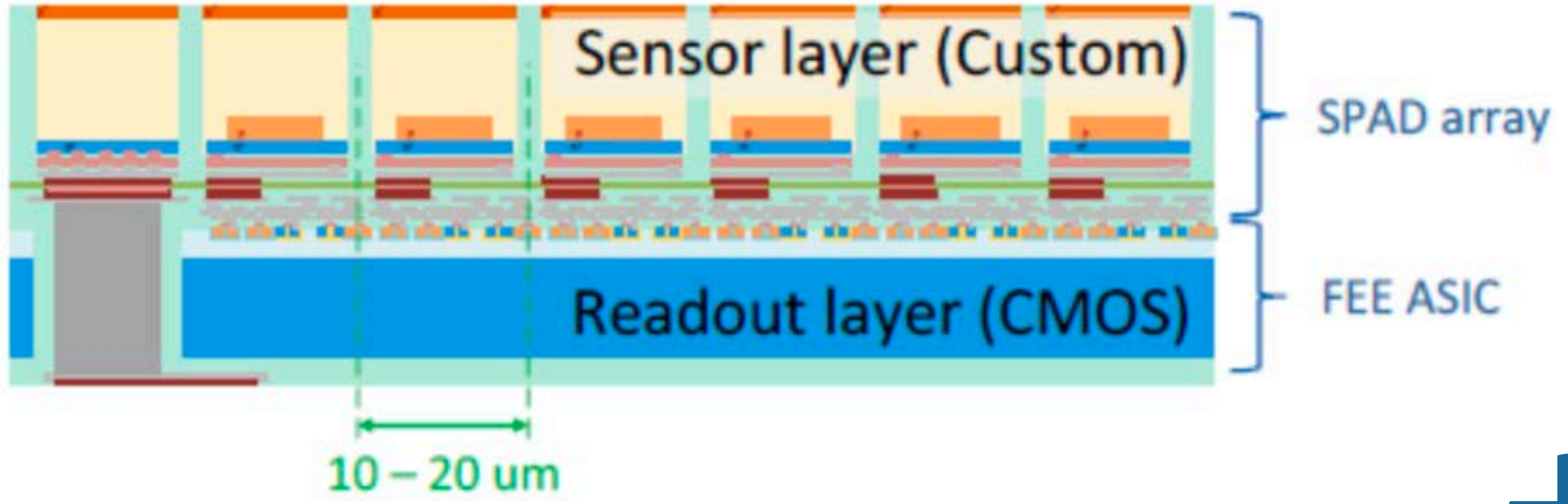
➡ area sensitive to radiation damage is smaller than the light sensitive are

Direct readout chip bonding: enabling up to single SPAD access without TSV

➡ Path towards imaging SiPM



New BSI-SiPM structure

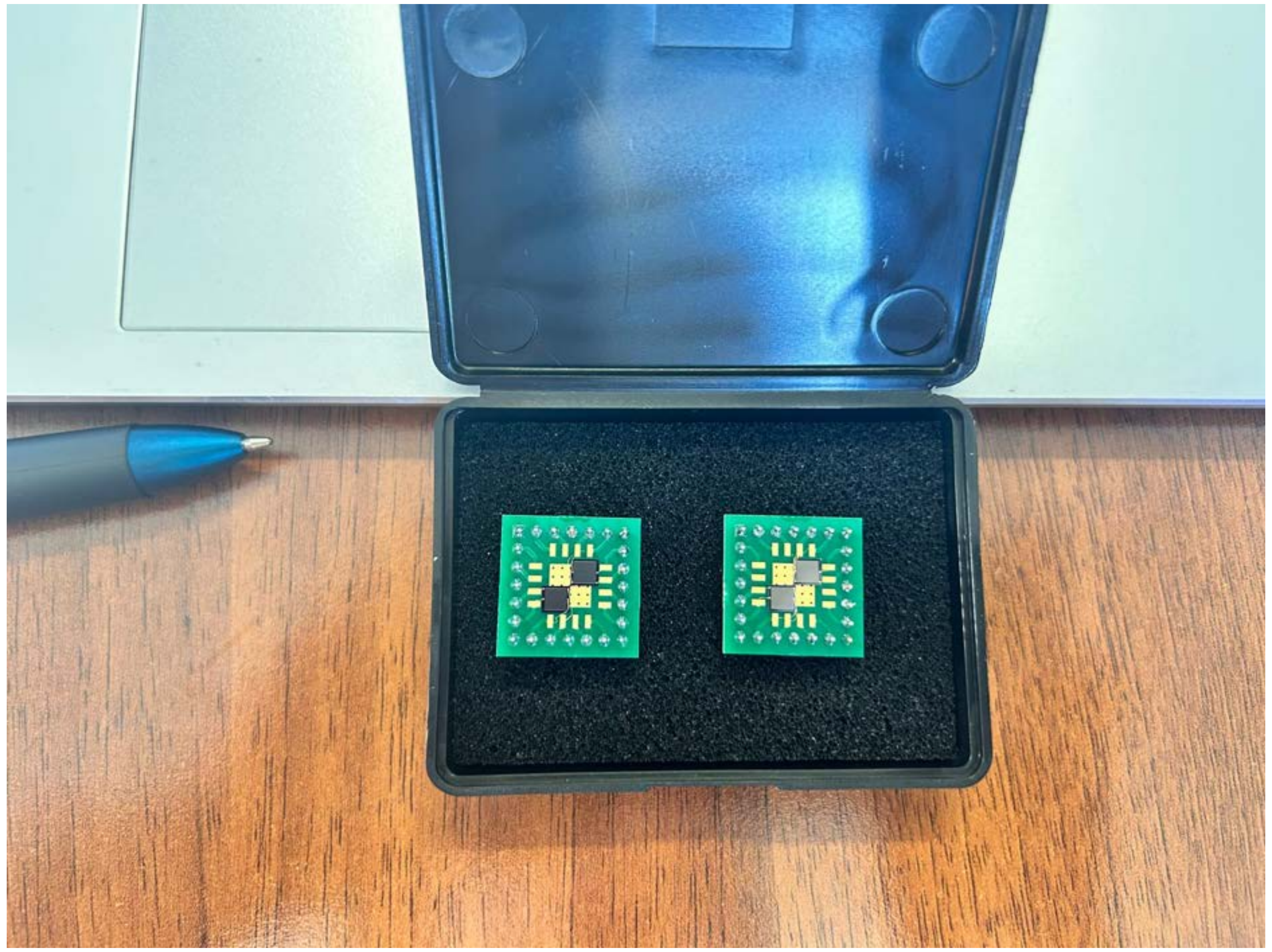


IBIS NEXT COLLABORATION

Innovative **B**ack **I**lluminated **S**ilicon PhotonMultiplier (**IBIS**) is a joint effort of several experiments (**ePIC**, **DUNE**, **ALICE3**, **LCHb**) conducted within **INFN sections** in collaboration with Fondazione Bruno Kessler (**FBK**), Trento.

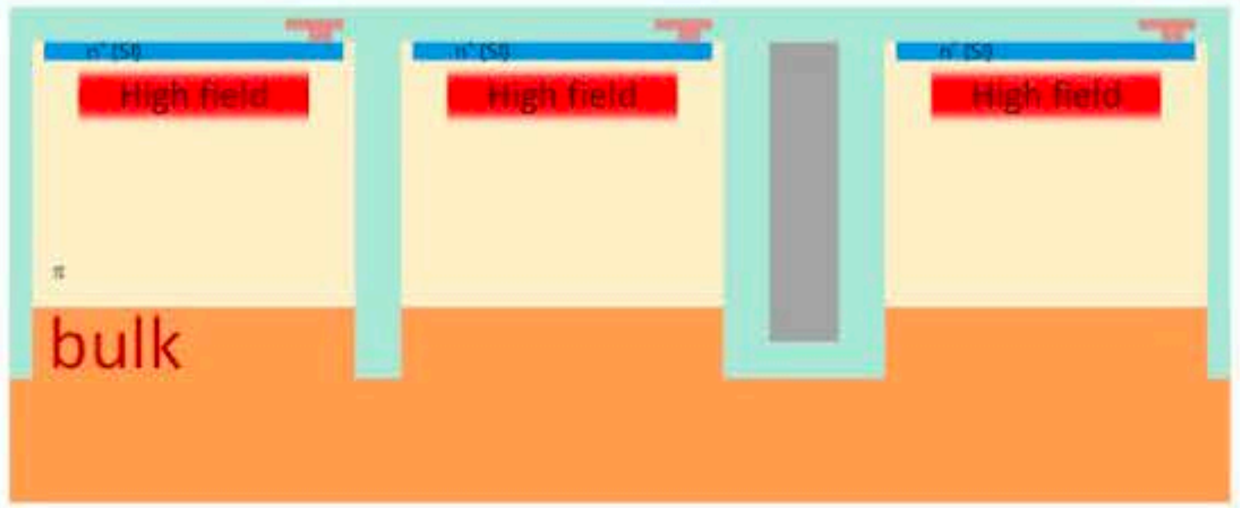
The goal of IBIS project production of several devices for several applications:

- radiation hardness
- MIP detection capability and timing
- cherenkov application
- Application to novel imaging technique to liquid argon detector



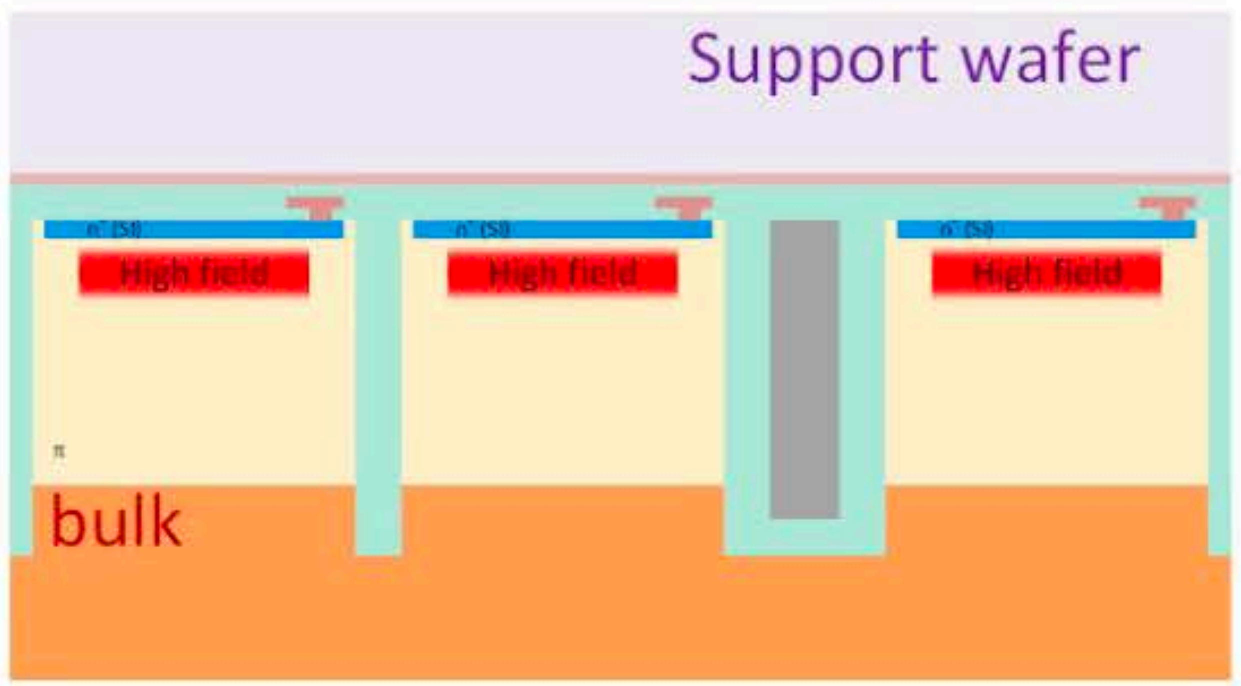
ALICE DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT ePIC FONDAZIONE BRUNO KESSLER

(a)



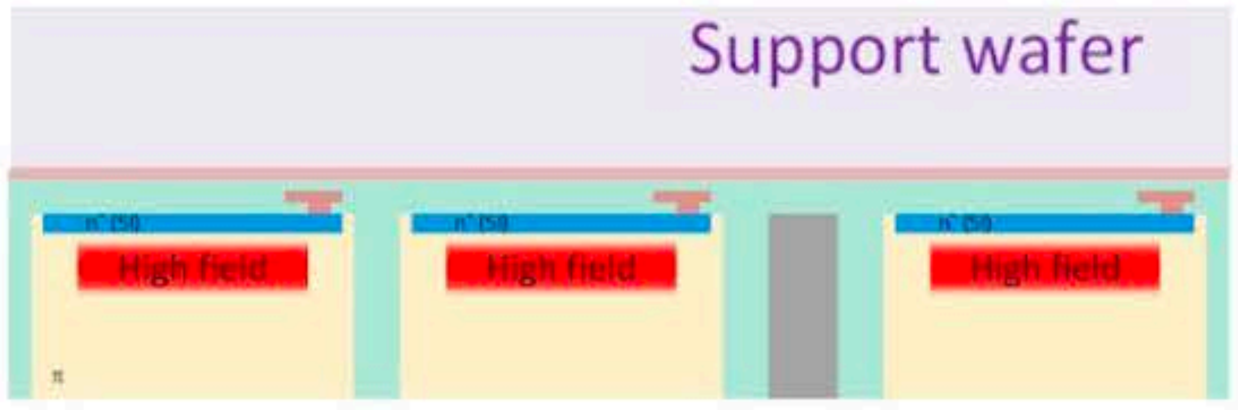
build new cell ~ 500-700 μm

(b)



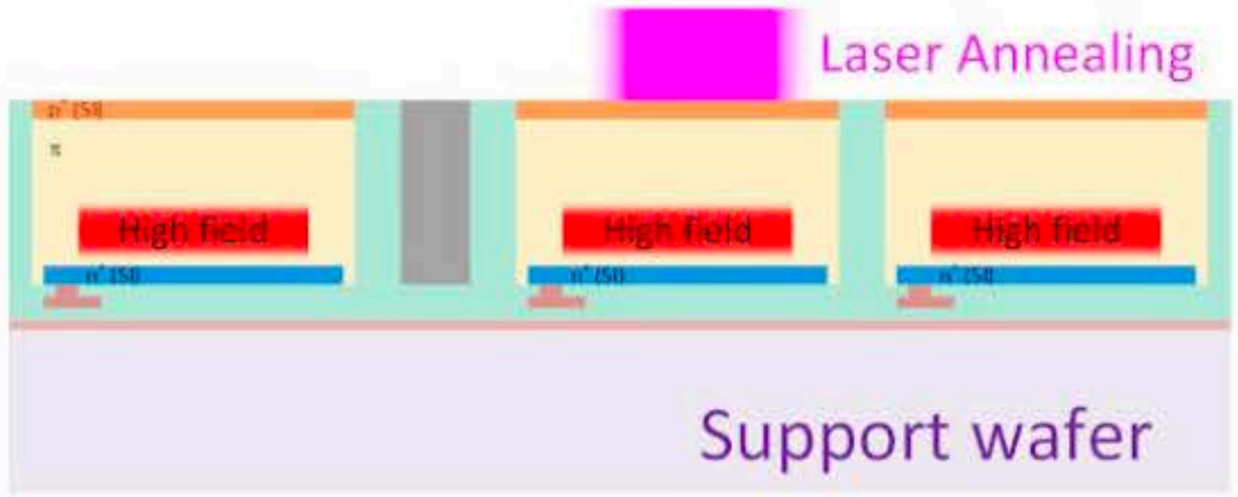
attach support wafer ~ 1 mm

(c)



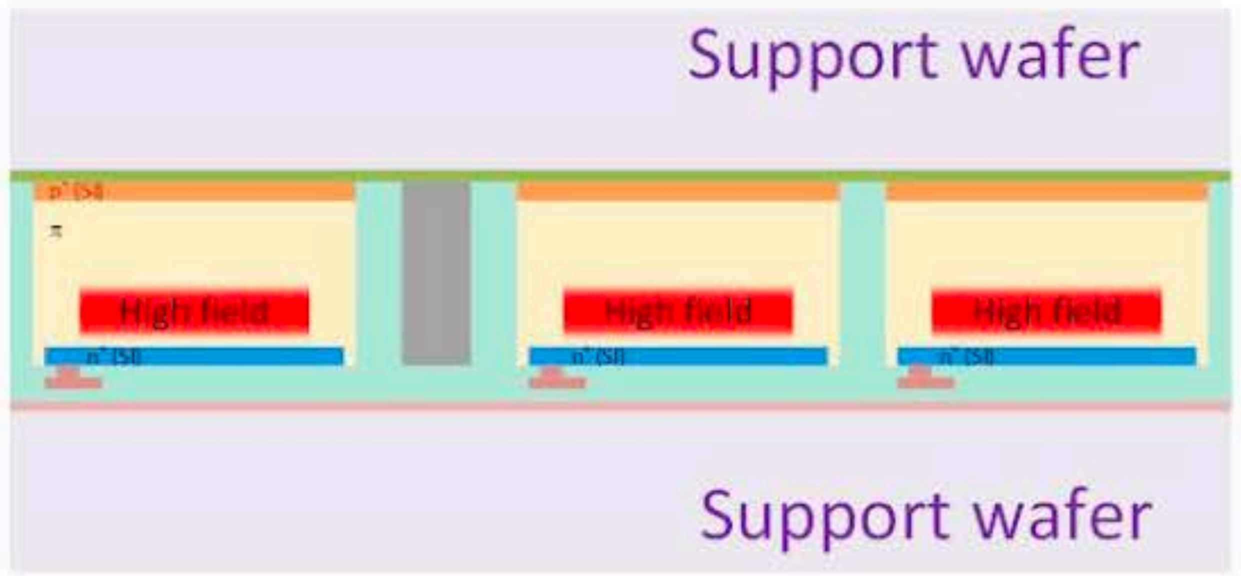
removing the bulk + plasma doping on back side

(d)



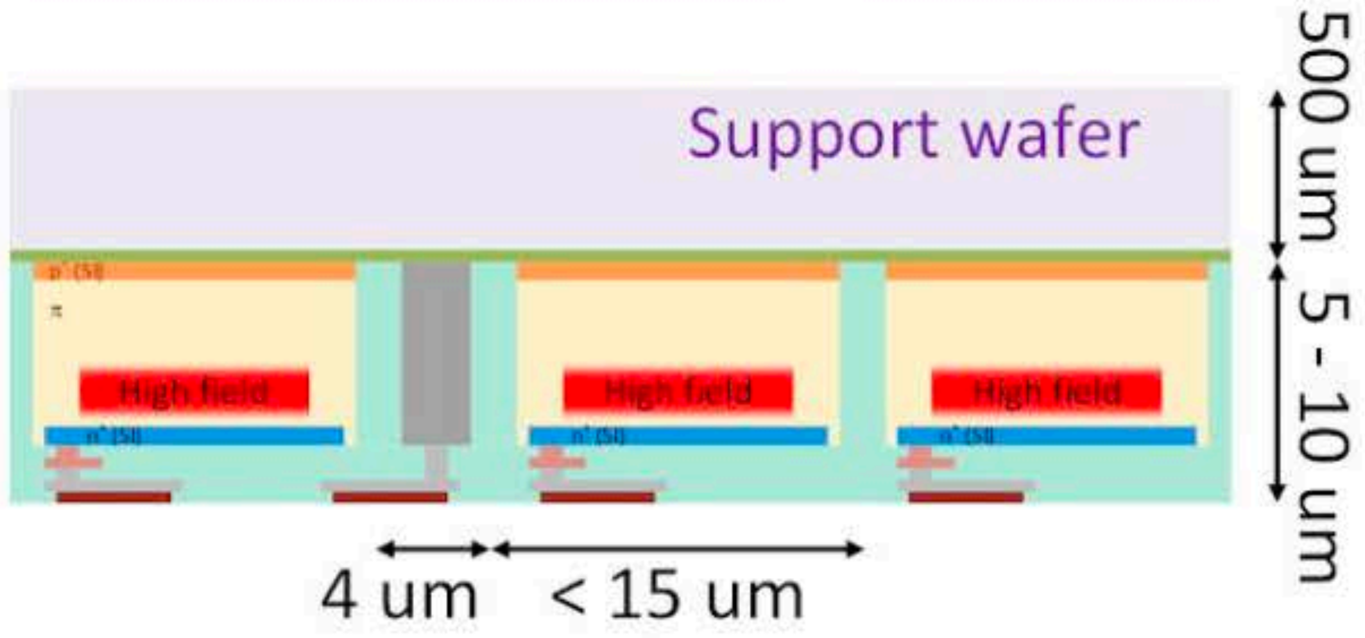
laser annealing on backside thin dopant

(e)



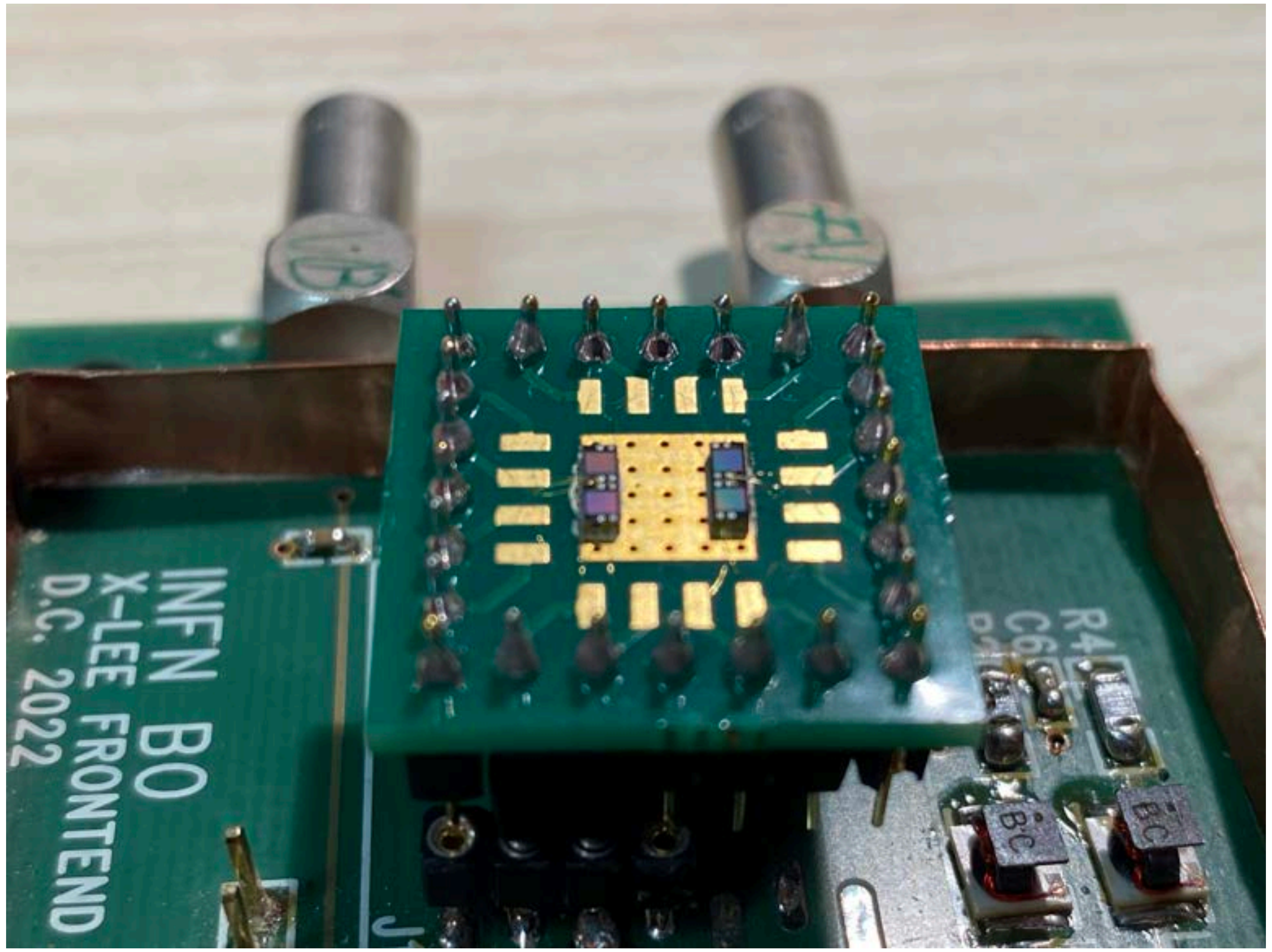
attach support wafer on back side

(f)



remove support wafer from back side from contacts

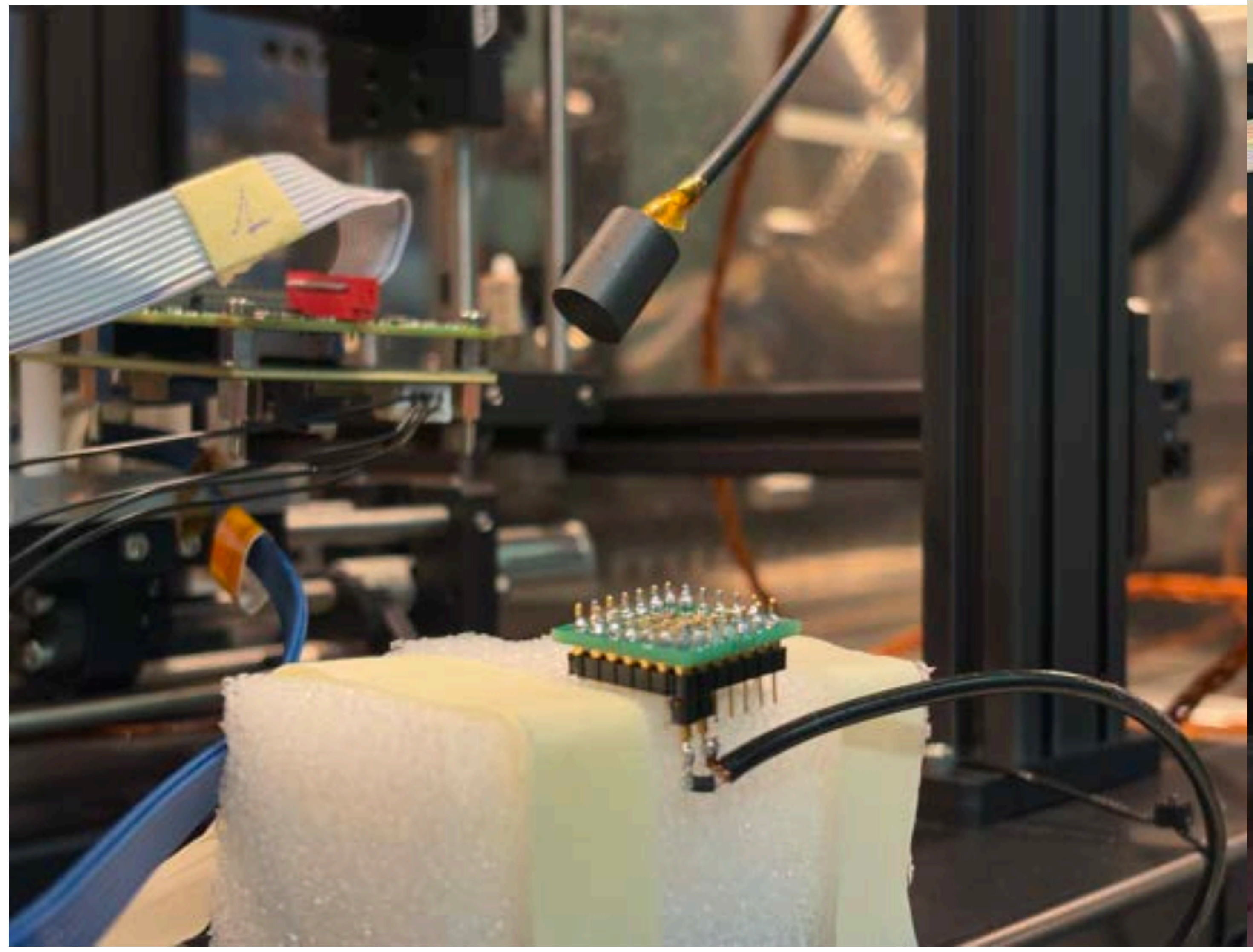
FIRST SAMPLES BSI FROM RUN1

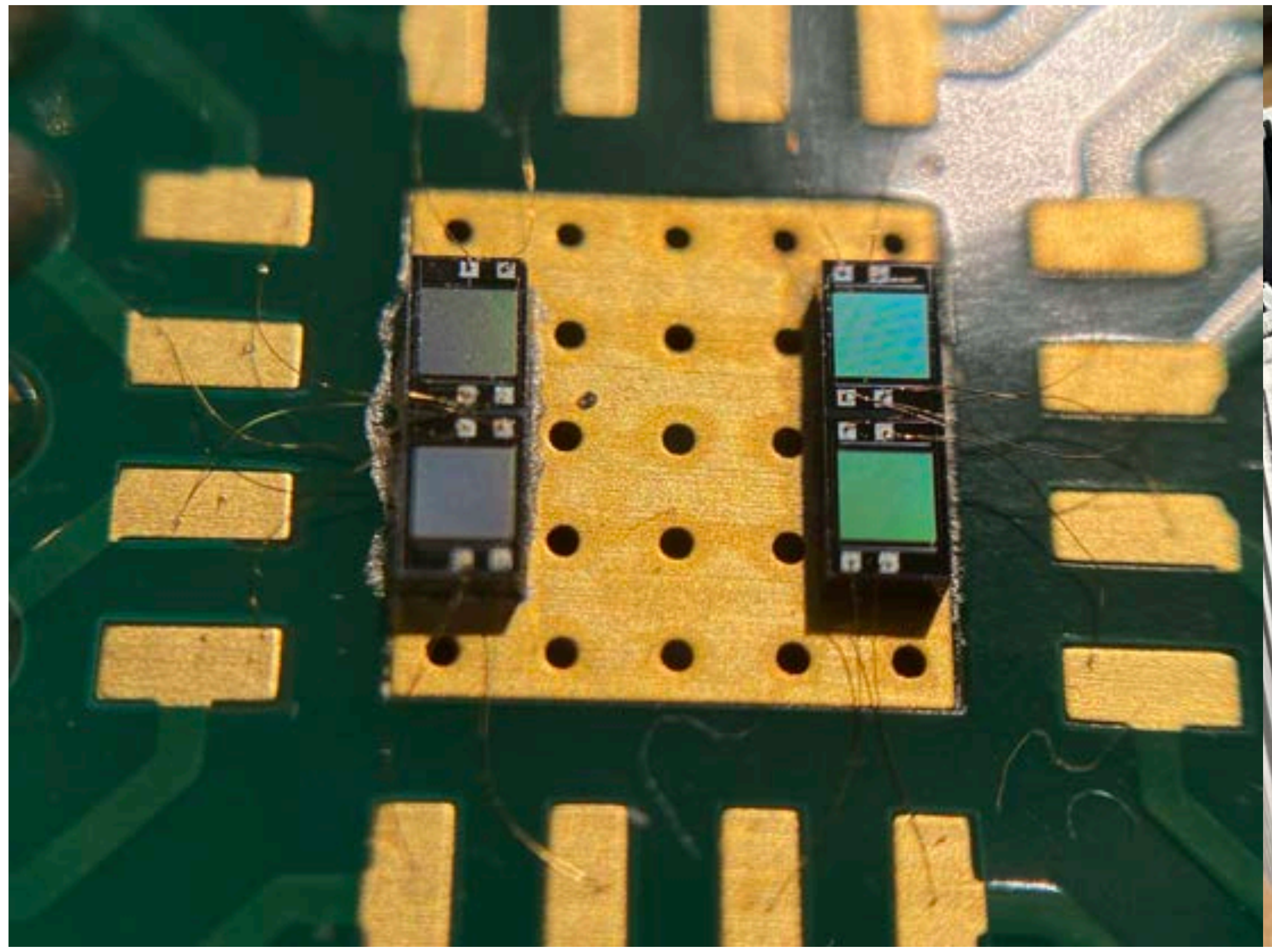


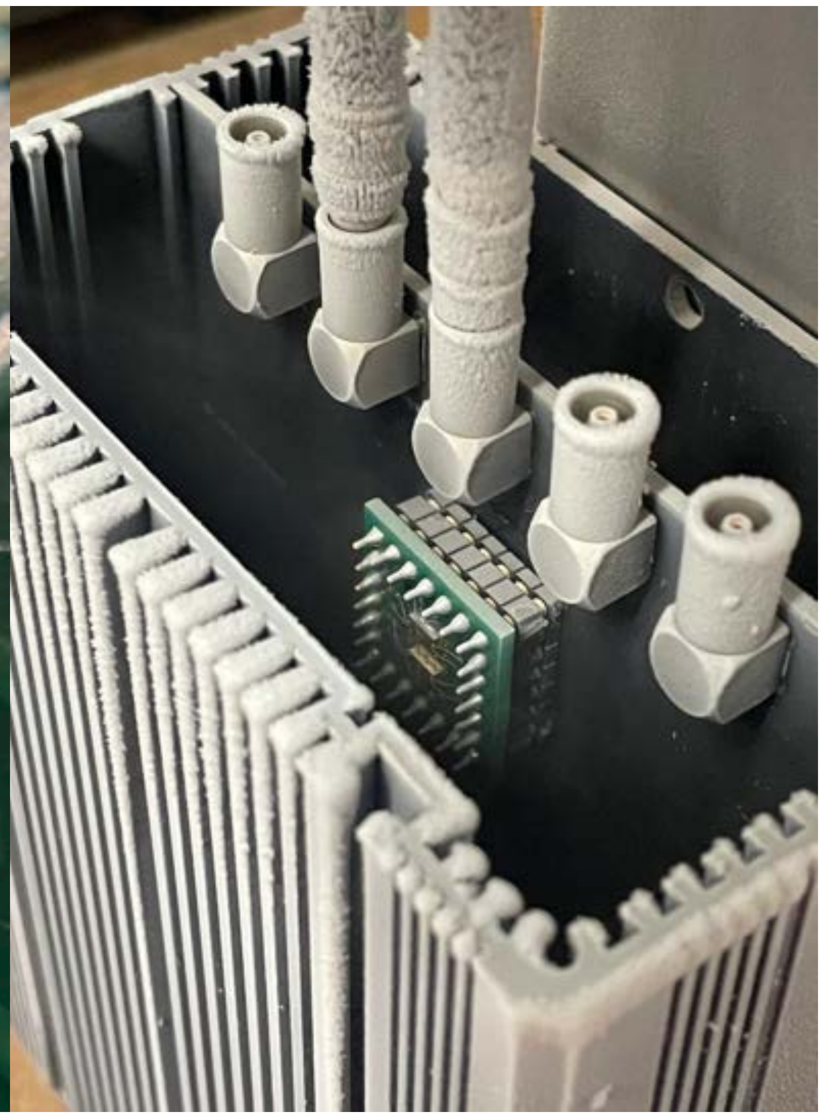
partially processed:

new cell!

but not thinned yet!



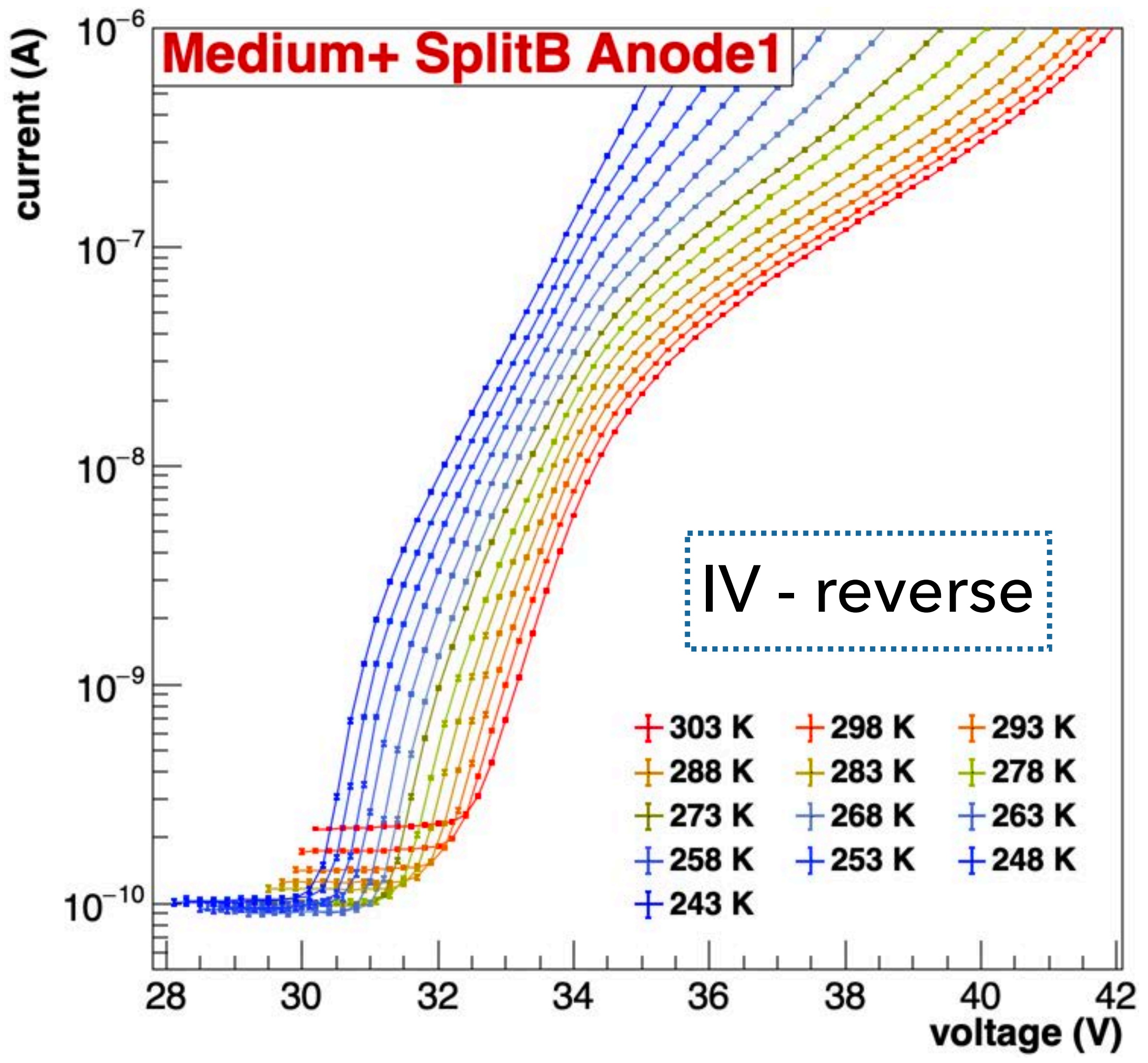


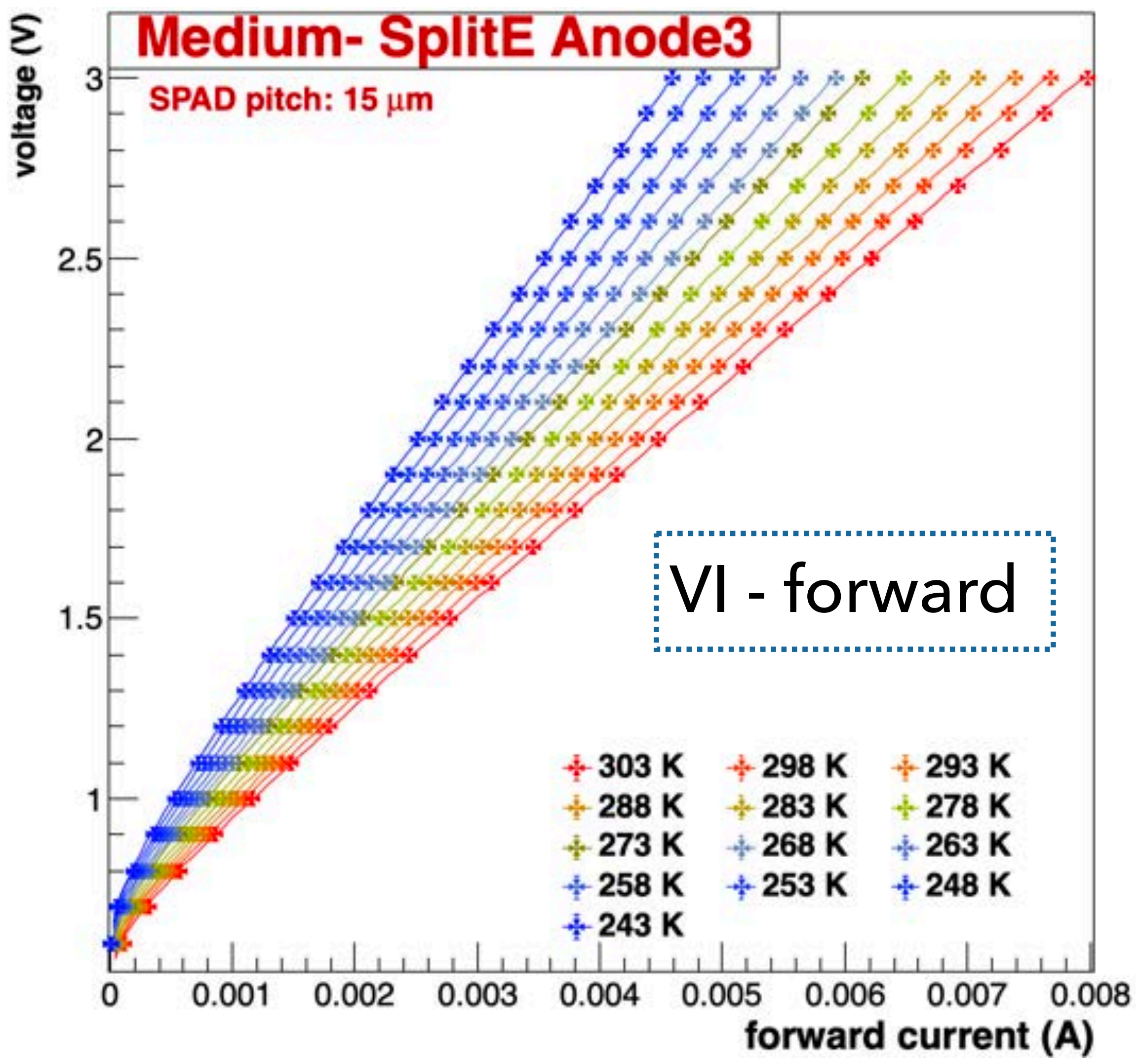


TEST SETUPS FOR I–V CHARACTERISTICS

Setup used for the I-V measurements:

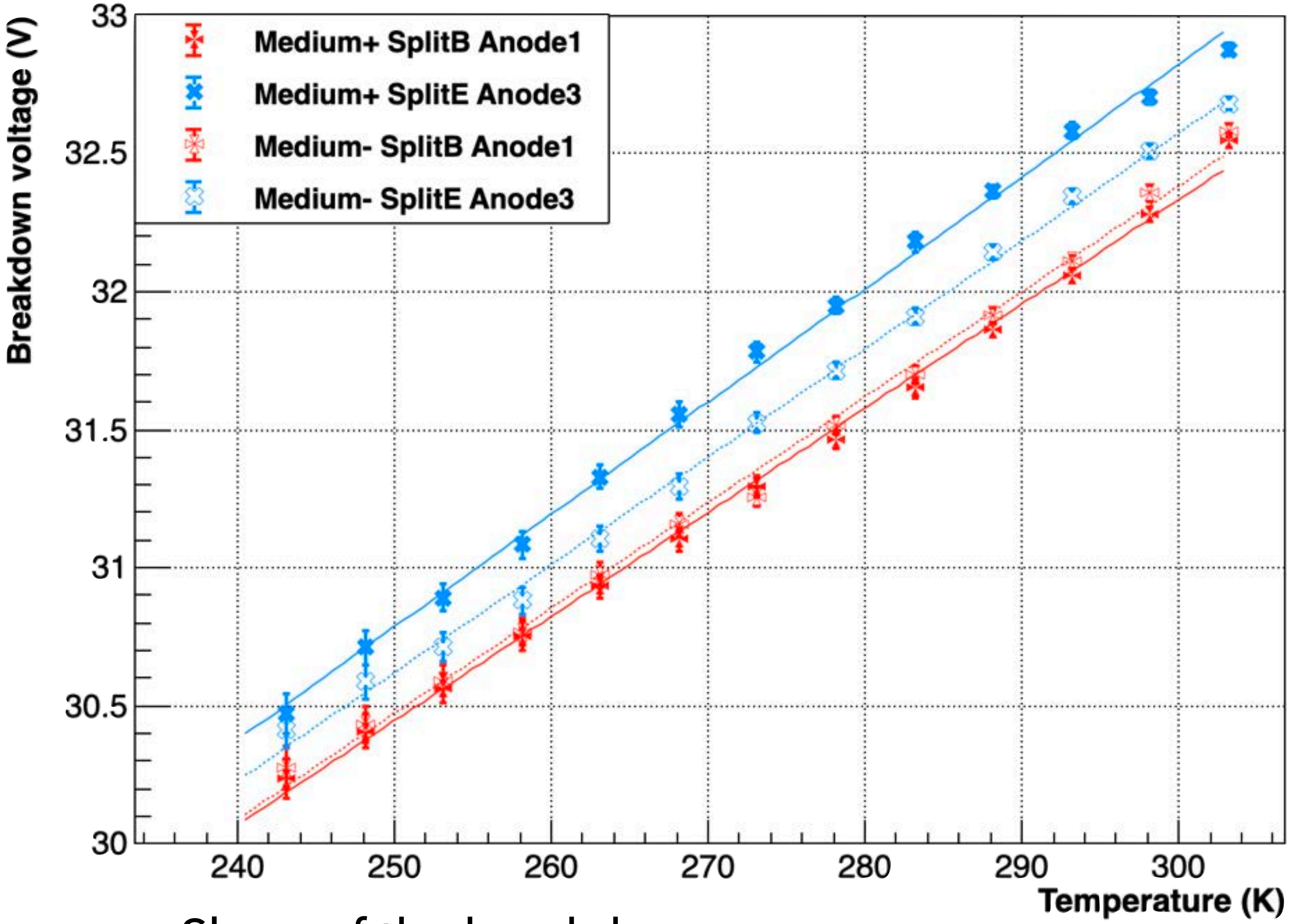
- Source Measure Unit to bias the SiPM
- **Yellow LED** for a precise determination of V_{BD}
- Climatic chamber to do a scan in temperature from **30°C → -30 °C by a step of 5°C**
- Forward and reverse IV taken to measure V_{bd} and R_q





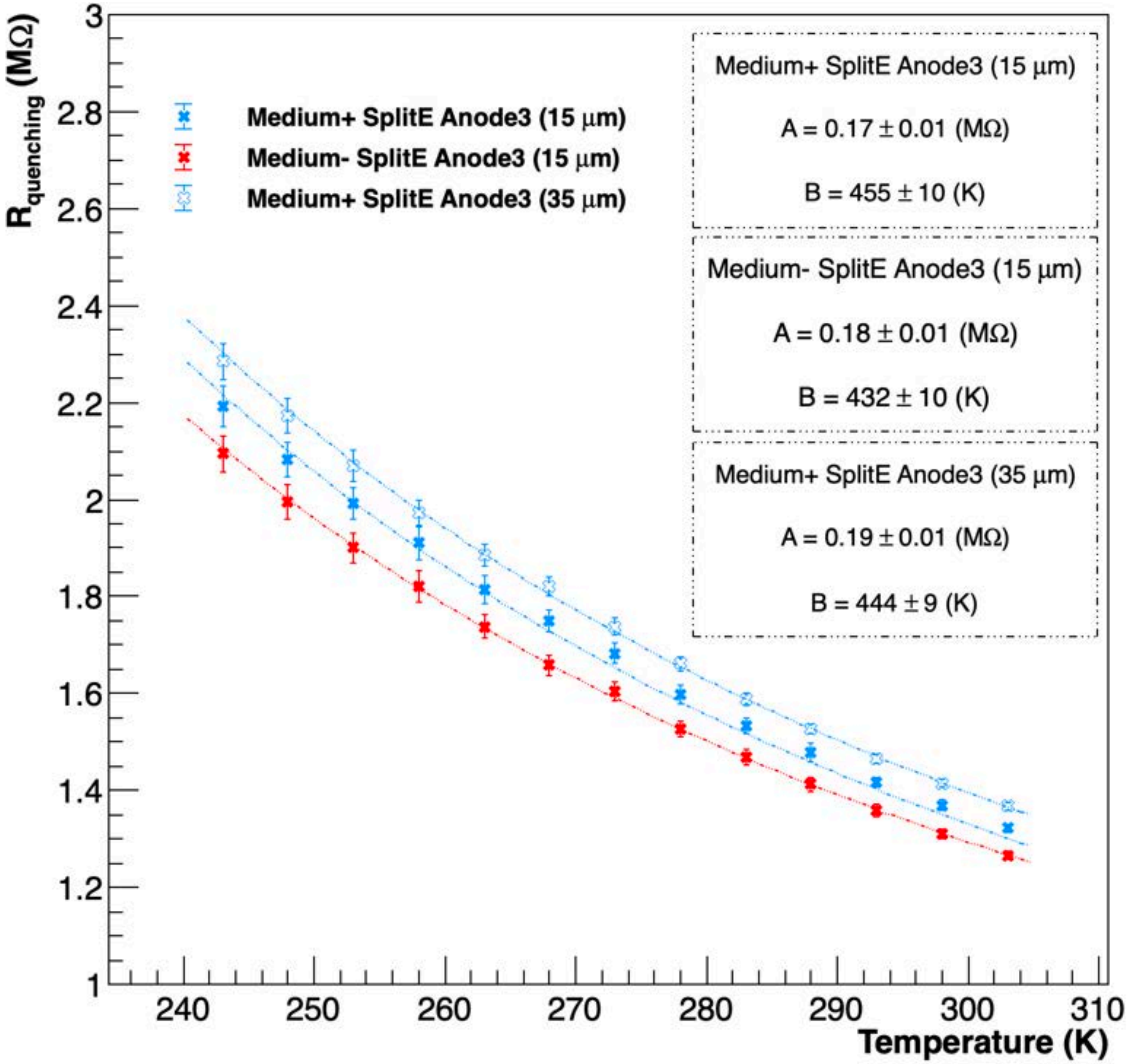
RESULTS FROM I-V CHARACTERISTICS

V_{BD} vs temperature



Slope of the breakdown as a function of temperature

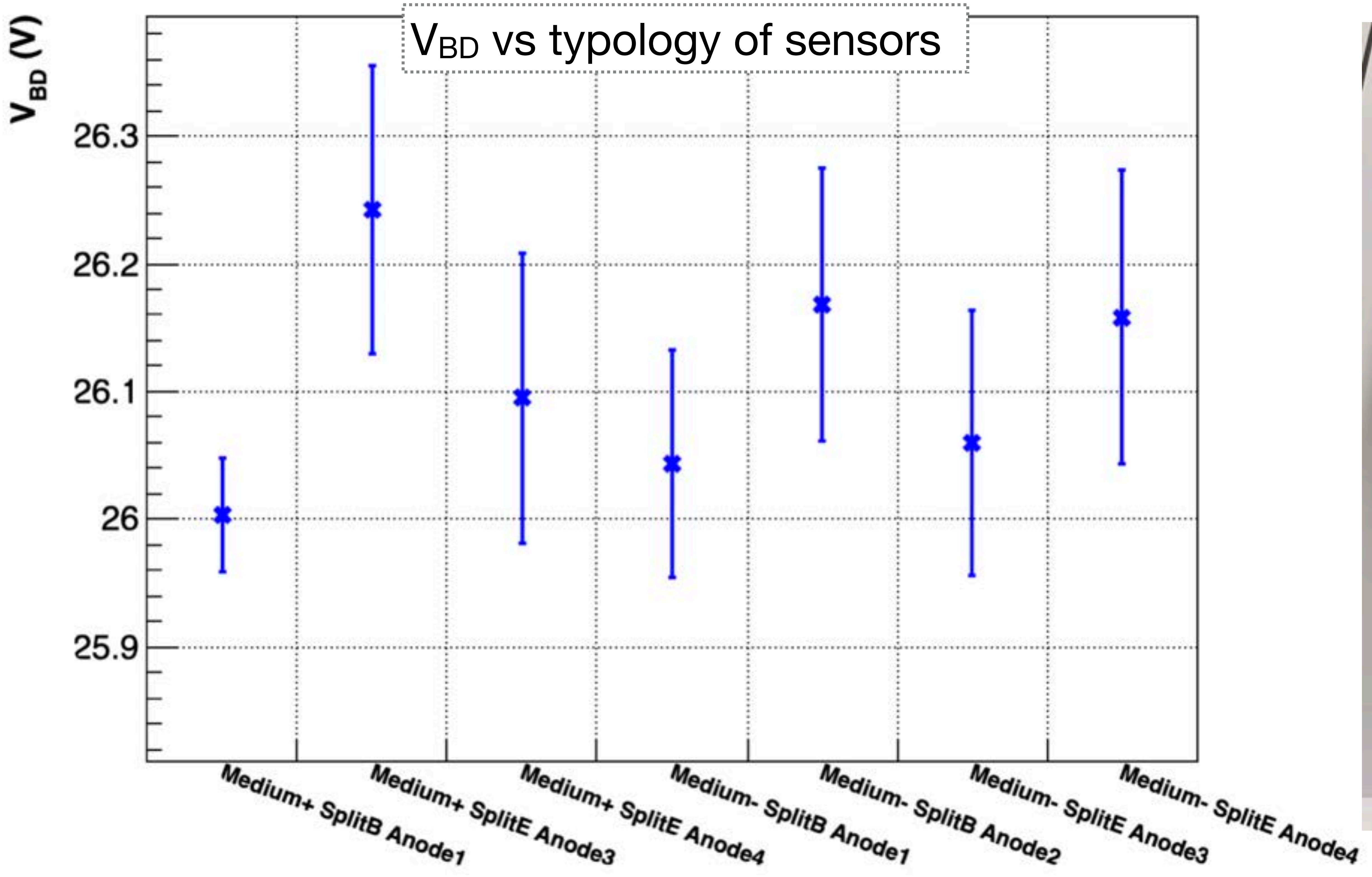
$R_{quenching}$ vs temperature

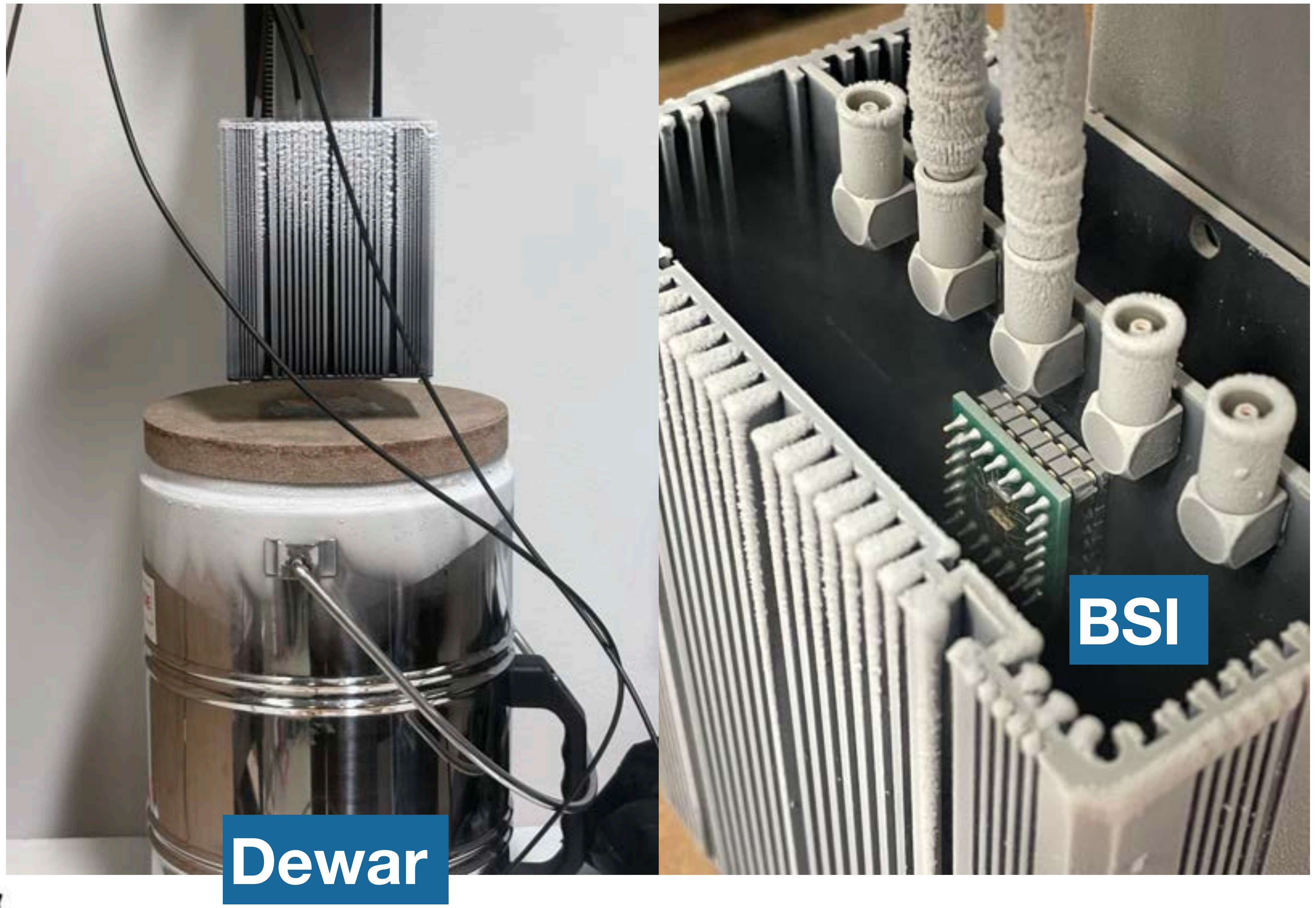


TEST ALSO IN CRYOGENICS

First test of these samples in a cryogenic environment:

- 6 lt dewar for **Liquid Nitrogen** (77 K) measurements
- Determine breakdown voltage (V_{BD}) at cryogenic temperature (**77 K**)

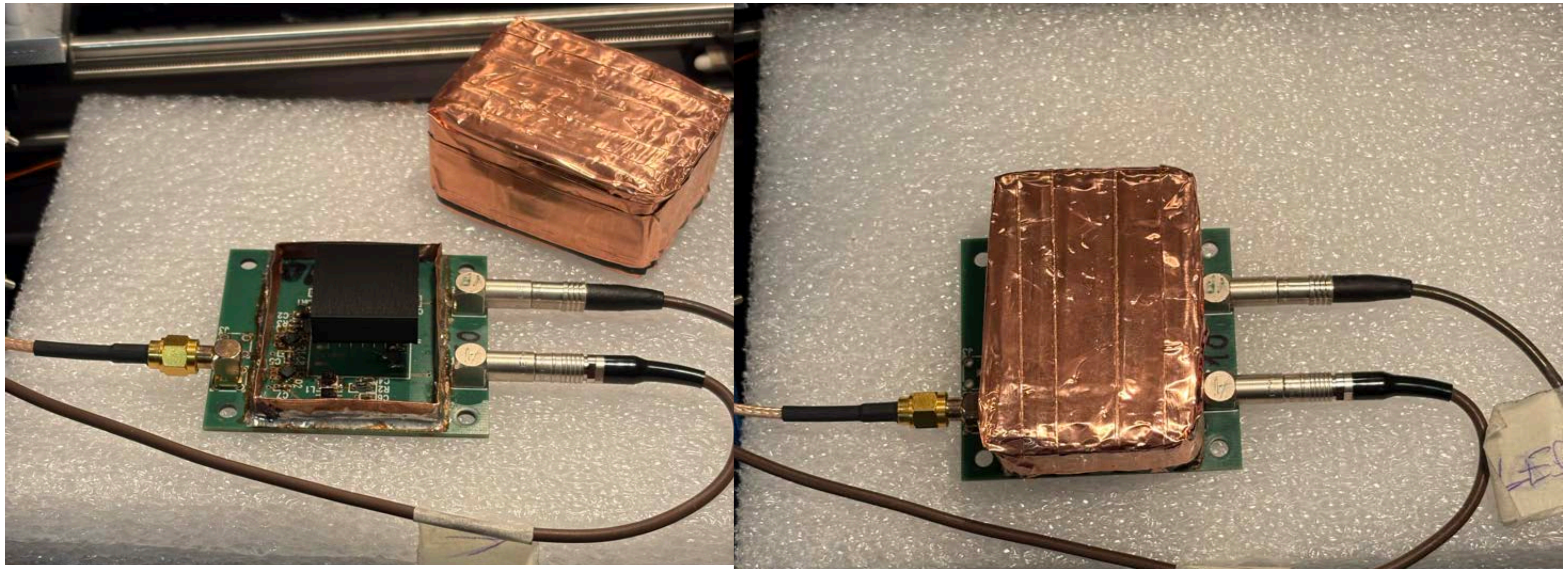


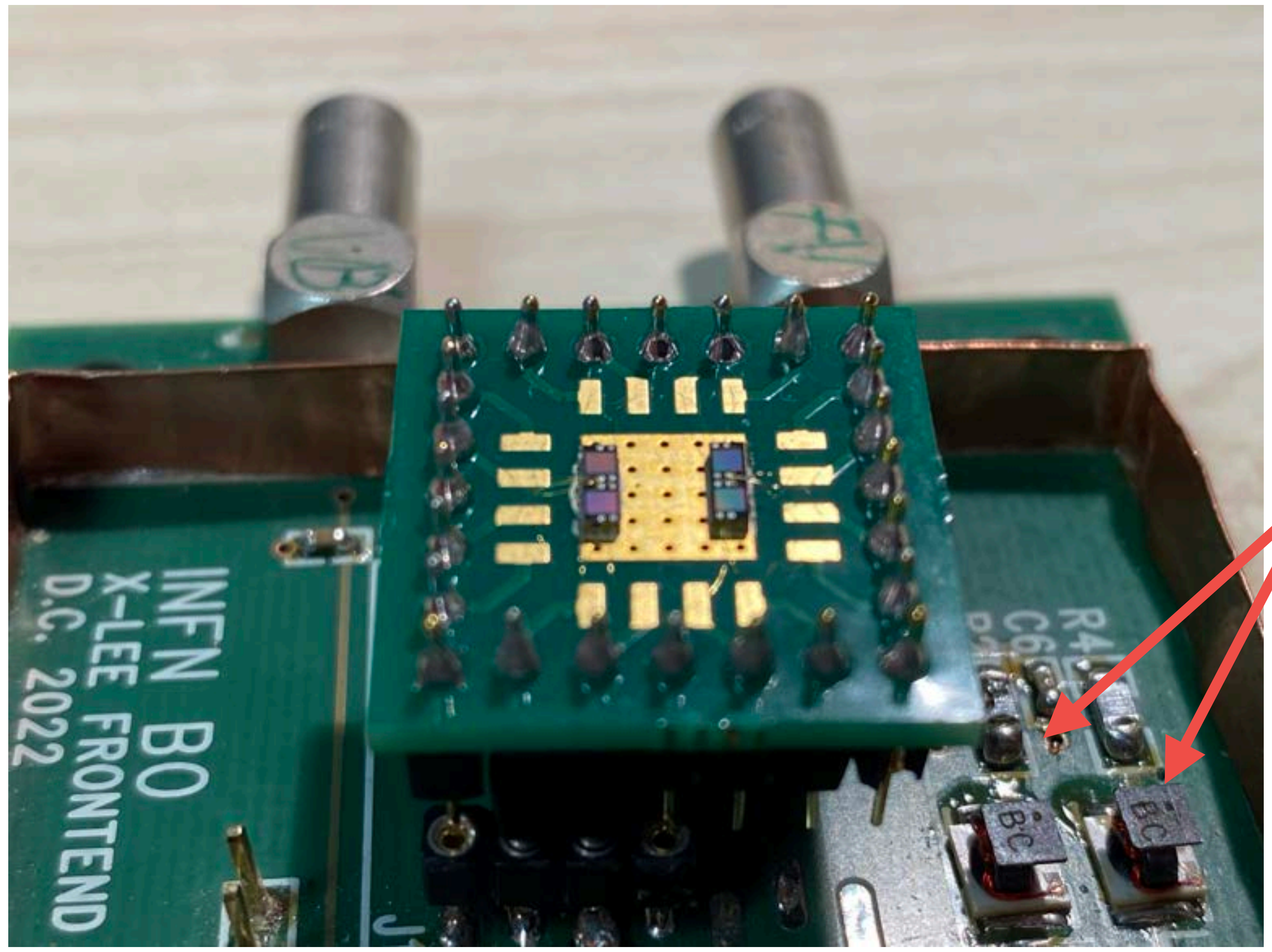


DARK COUNTS CHARACTERISATION

Measurements procedure:

- Waveform taken at oscilloscope 100 μs time window
- Processing offline → lowpass filter + **thr scan procedure**
- Temperature scan **20°C → -20°C** (step 5°C) + a measurements at -30°C done in climatic chamber



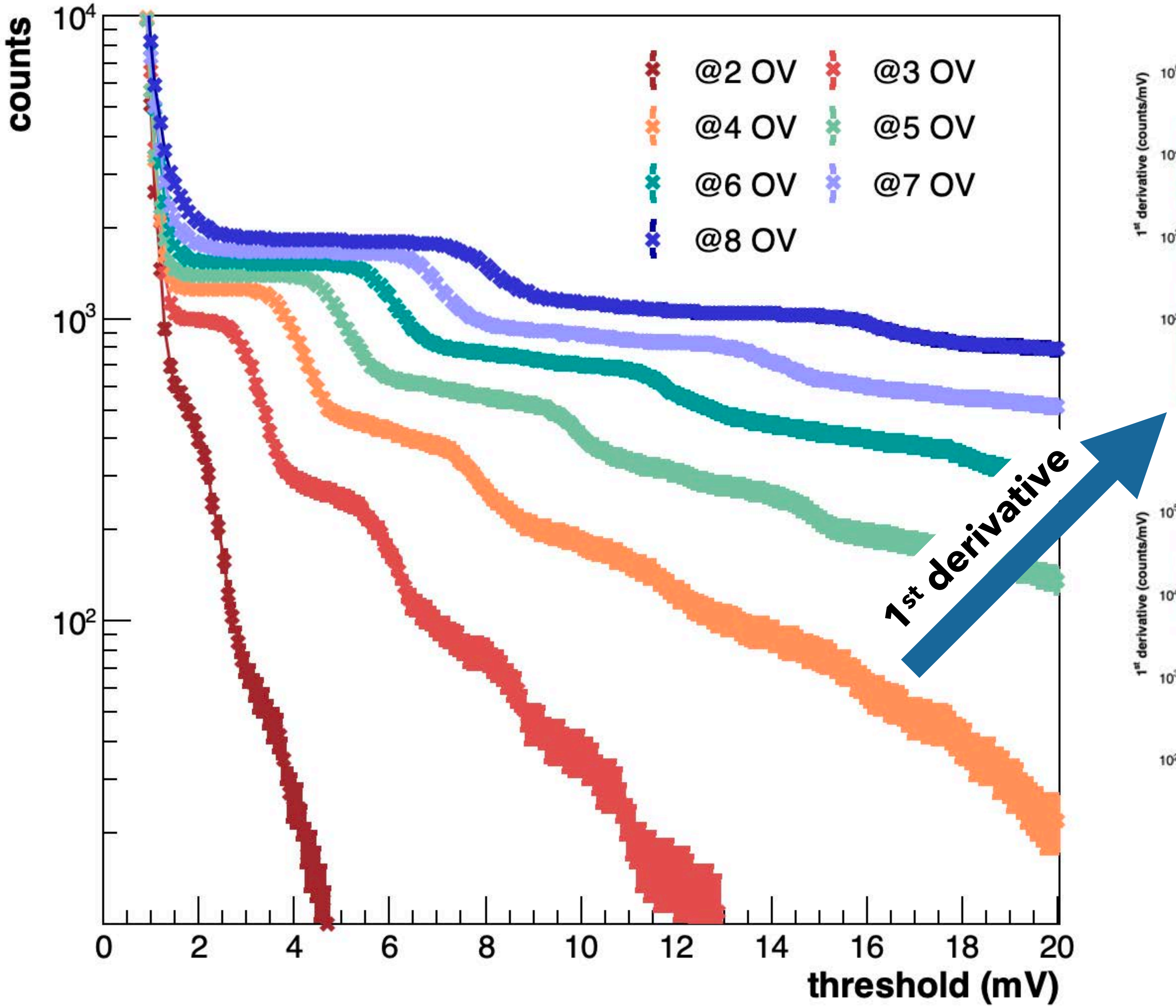


The amplification is based on two X-LEE39s connected in series, providing a total gain of 45 dB.

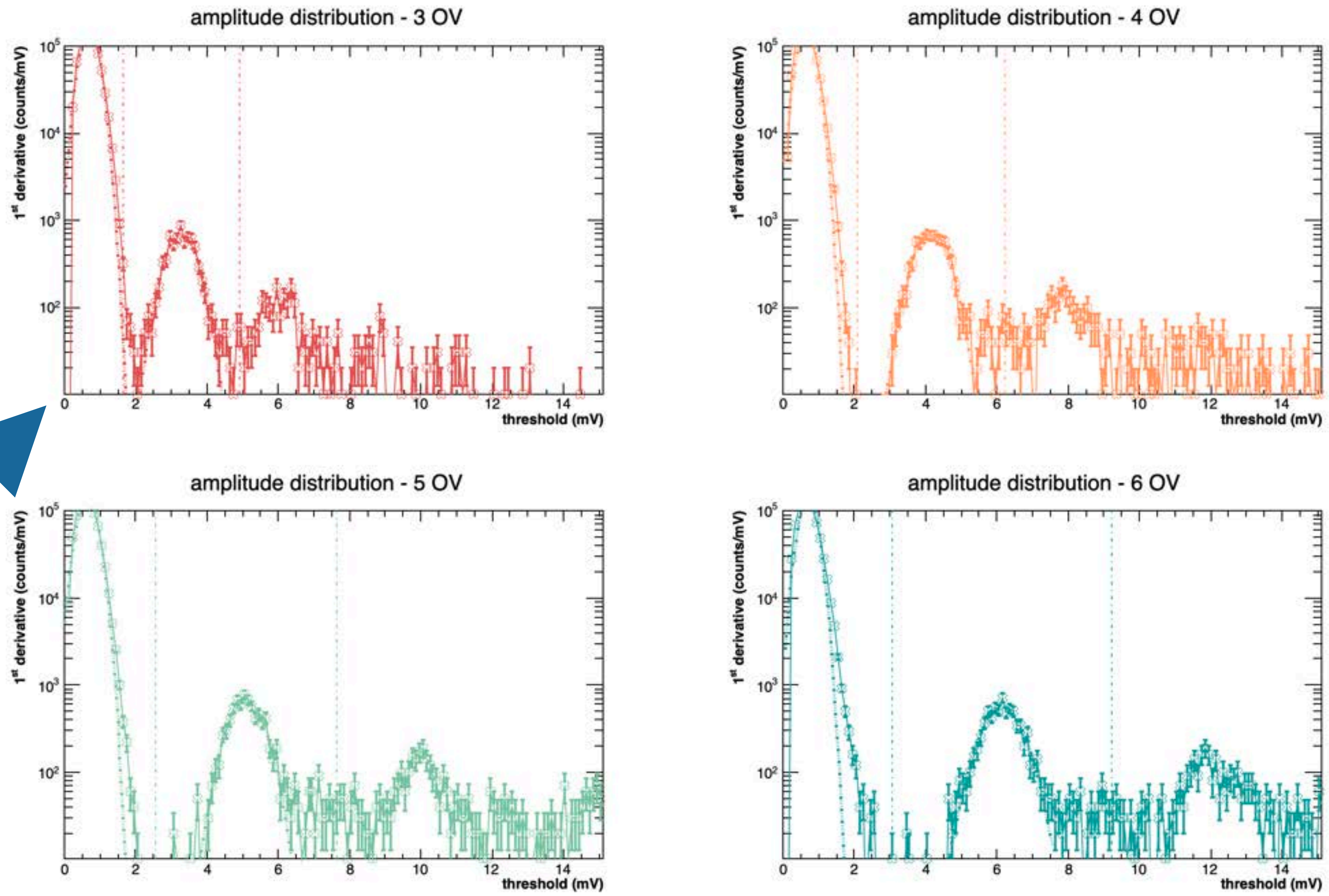
the signal goes outside the climatic chamber into directly the oscilloscope

THRESHOLD SCAN PROCEDURE

Threshold scan: counts vs a variable thr

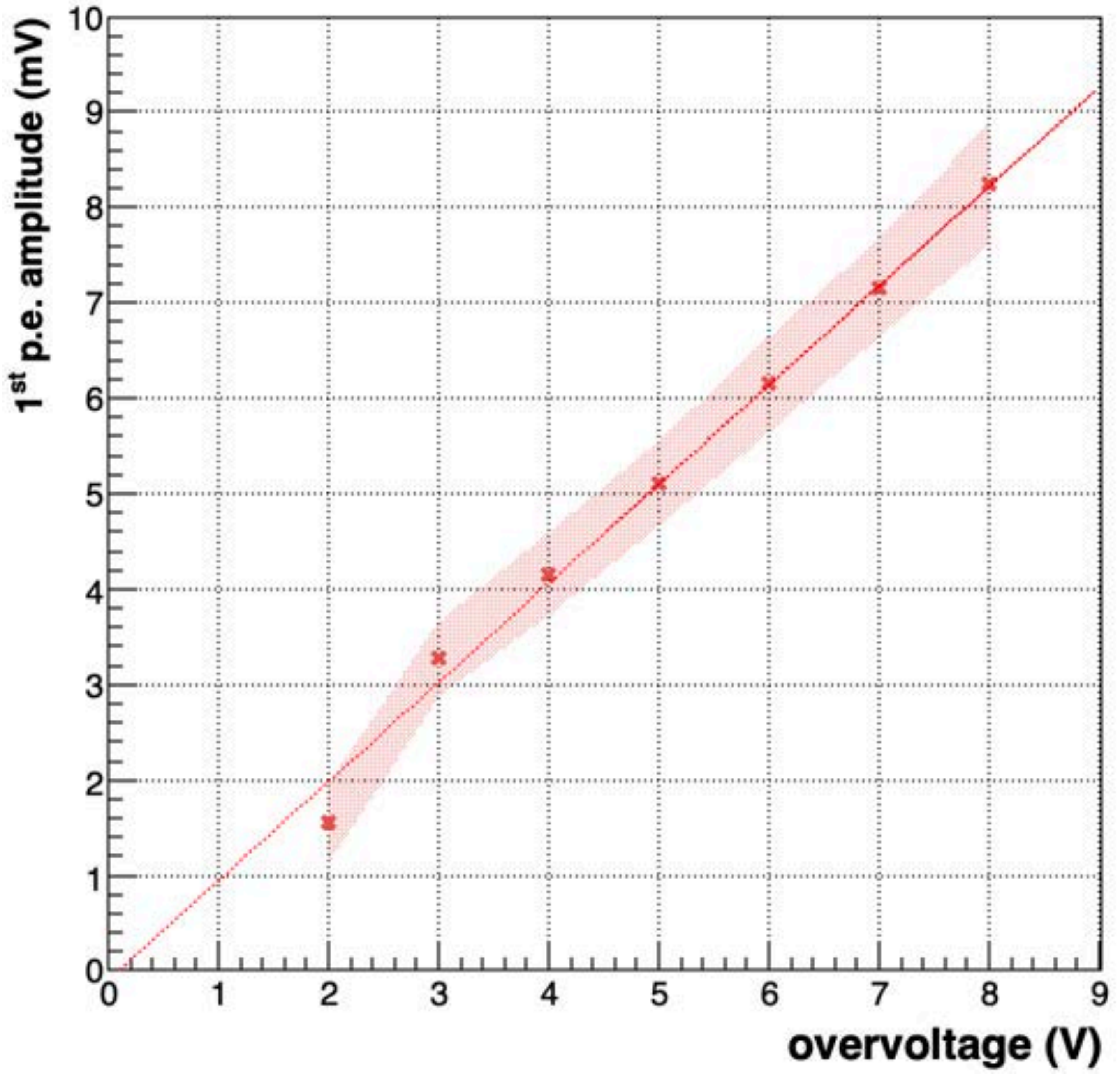


Amplitude distribution

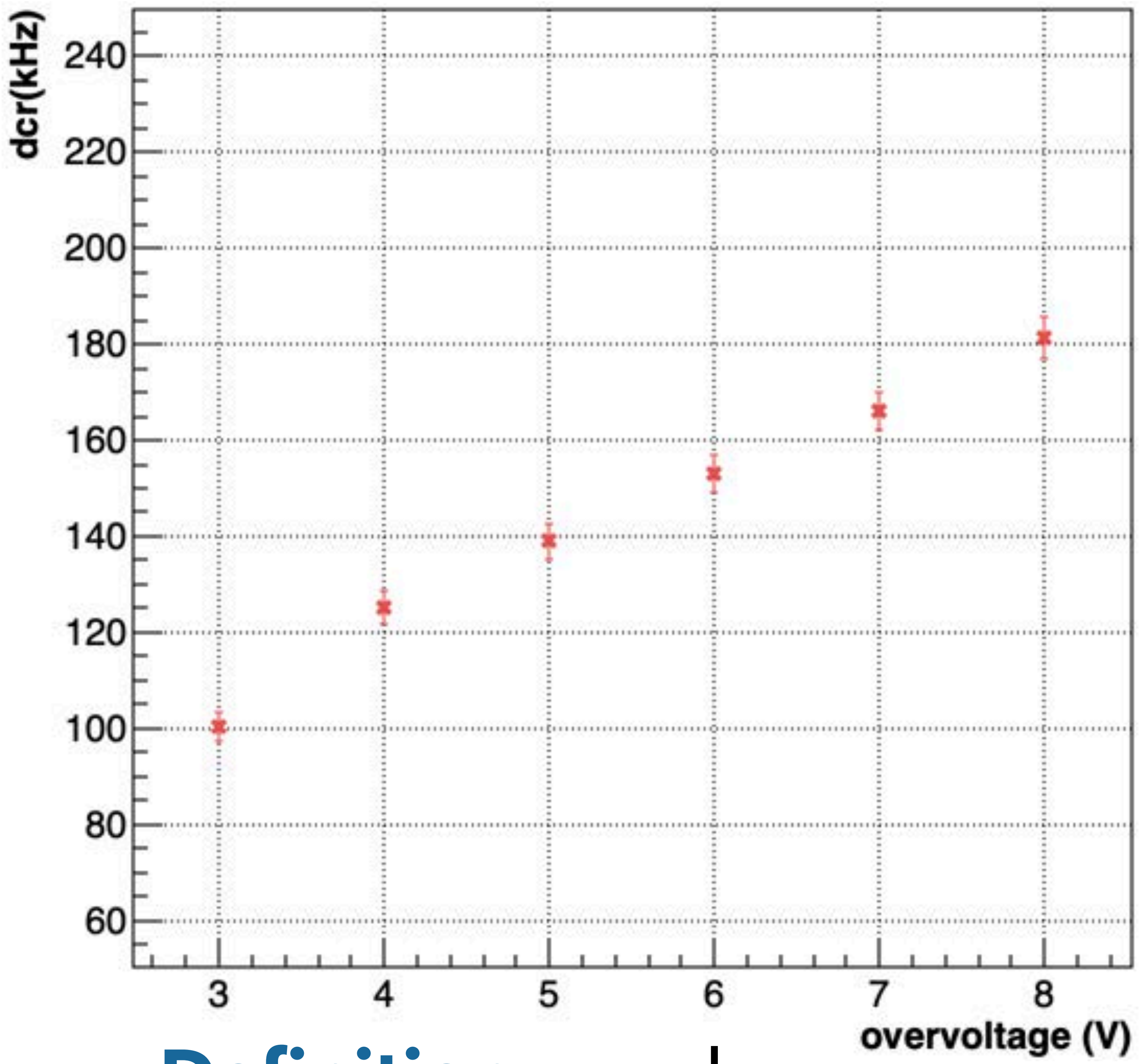


RESULTS @20°C

distribution of 1st p.e.

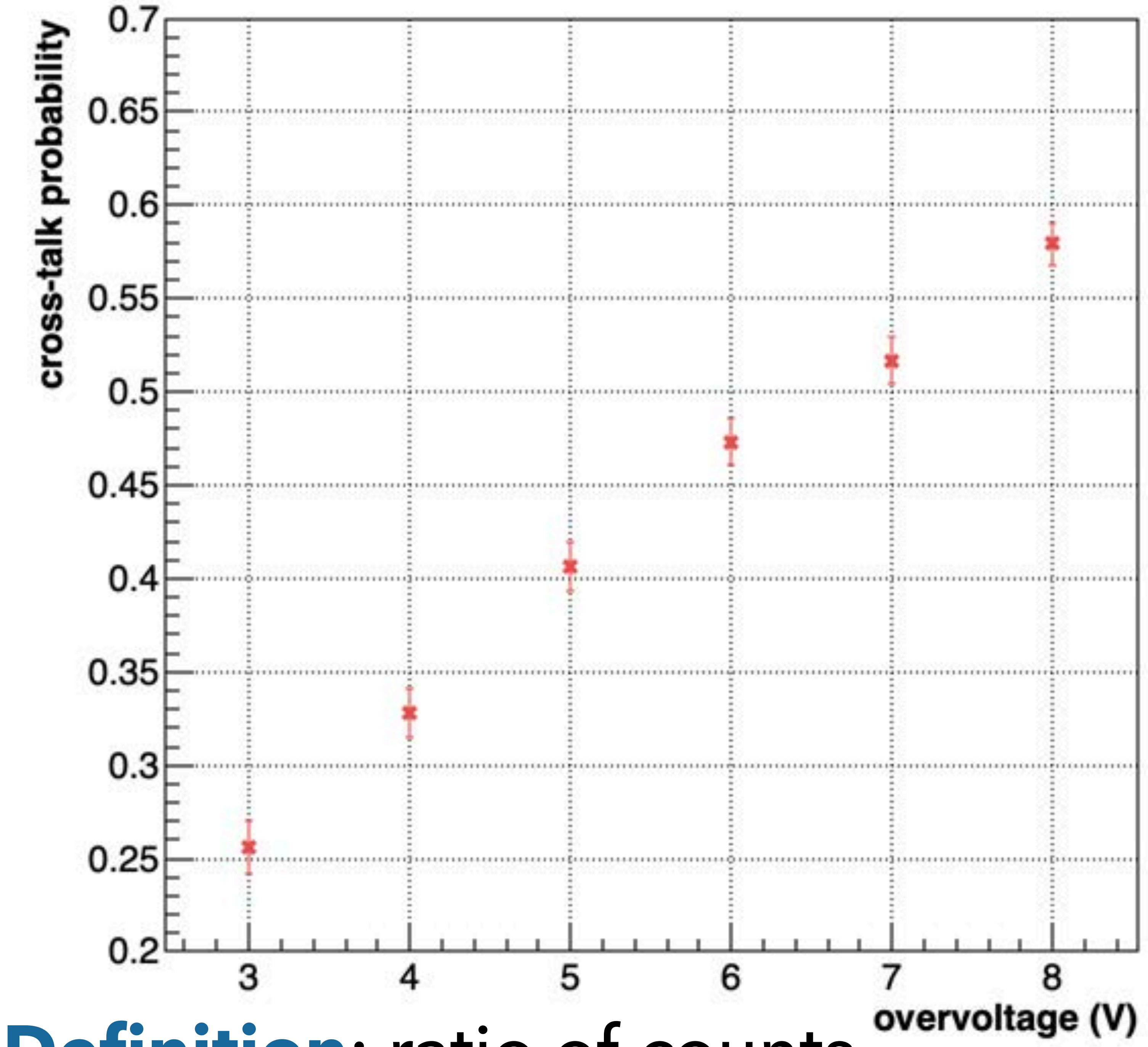


distribution of dark count rate



Definition: number of counts at 0.5 p.e.

distribution of cross-talk

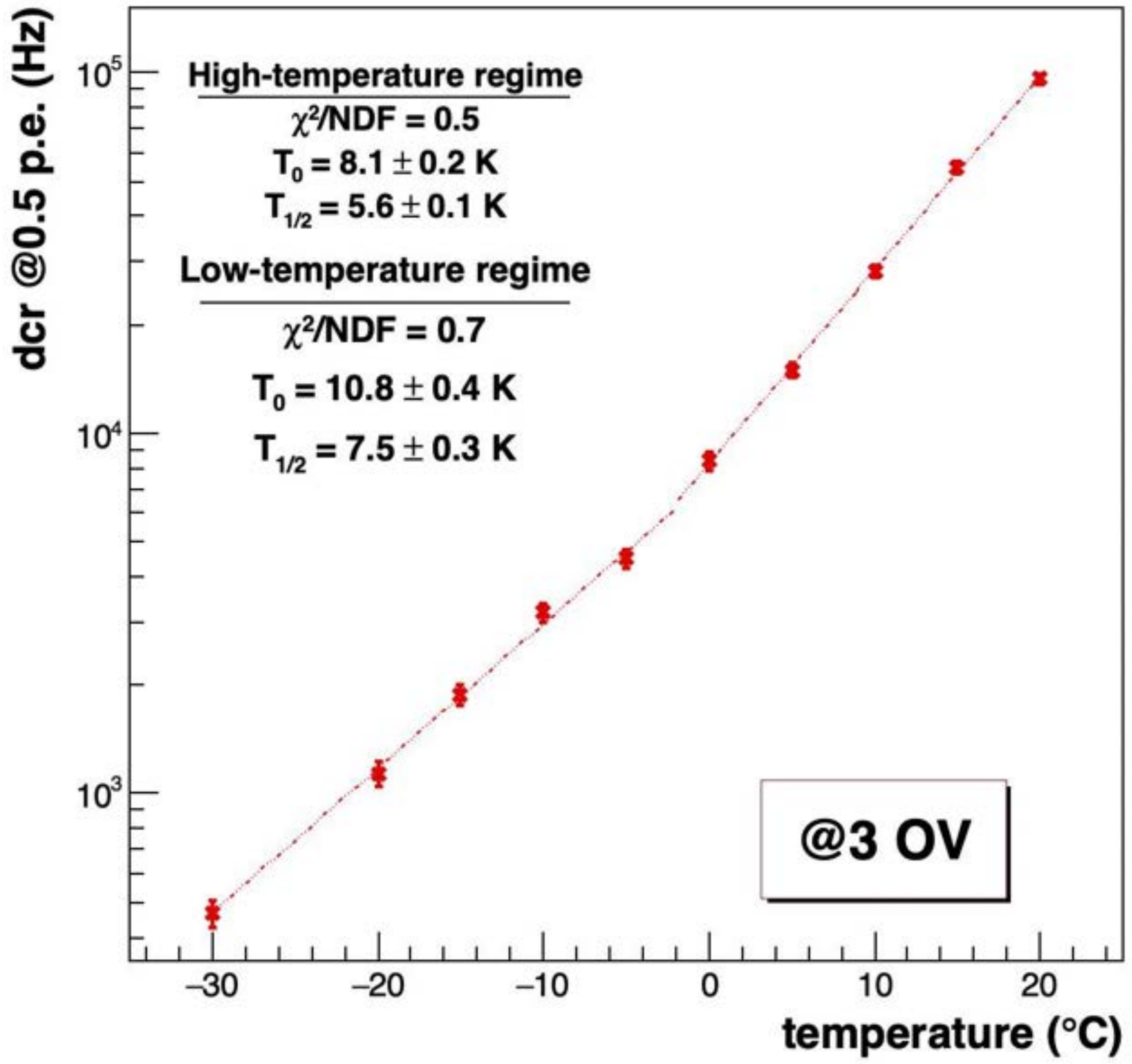


Definition: ratio of counts at 1.5 p.e. over 0.5 p.e.

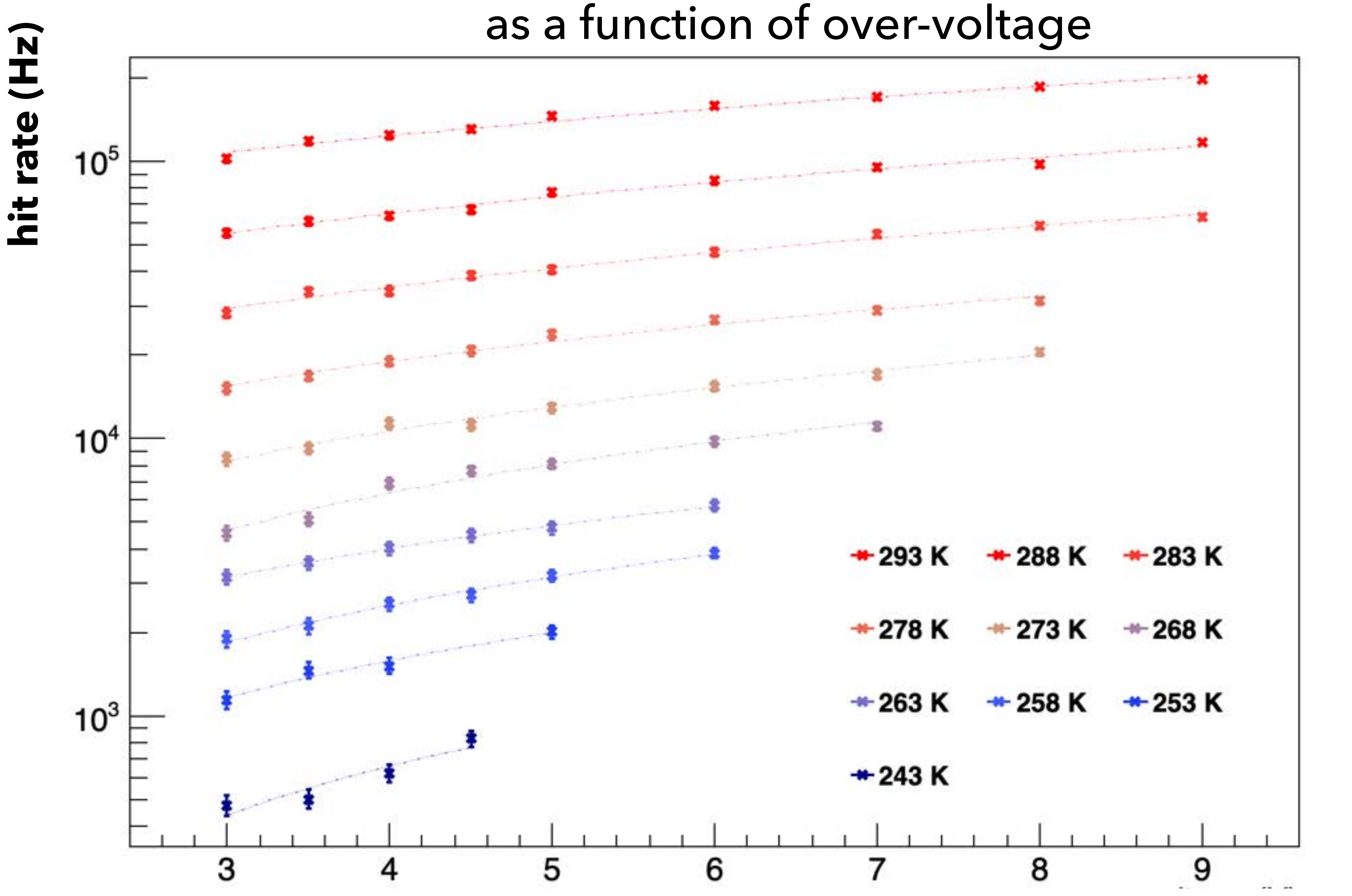
Results taken at 20°C in climatic chamber

DARK COUNTS CHARACTERISATION

dark count rate results are very encouraging since they ranges from hundreds of kHz (@20°C) and reach **800 Hz** values **@-30°C**



dark count rate at various temperature as a function of over-voltage



Definition: number of counts at 0.5 p.e.

dark count is measured to get halved very rapidly with temperature

Results taken at 20°C in climatic chamber

CONCLUSION

- First sensors **BSI from Run 1** arrived at INFN BO and a set of measurements done on partially processed BSI

  ✓ **New cell is working**

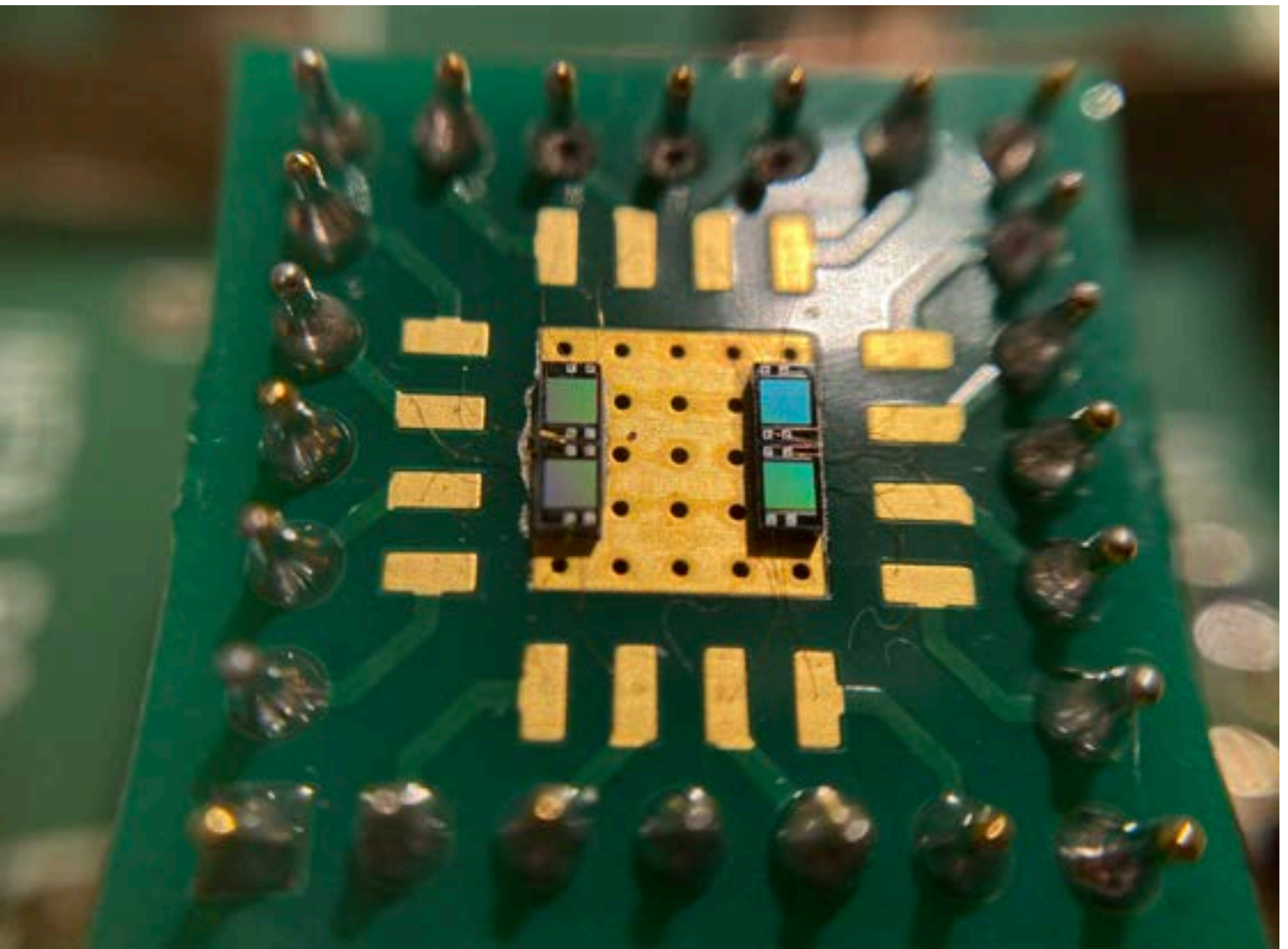
  ✓ Preliminary IV (also in cryogenics) and Dark counts

  ✓ In future runs some strategy to reduce CT will be investigated

- A **new run** is co-funded by IBIS project and scheduled for end **2025**/ begin **2026** it will profit from experience gained since today

- So far interest from DUNE for VUV, EIC, LCHb and ALICE3 for radiation hardness and timing

THANK YOU FOR YOUR ATTENTION!



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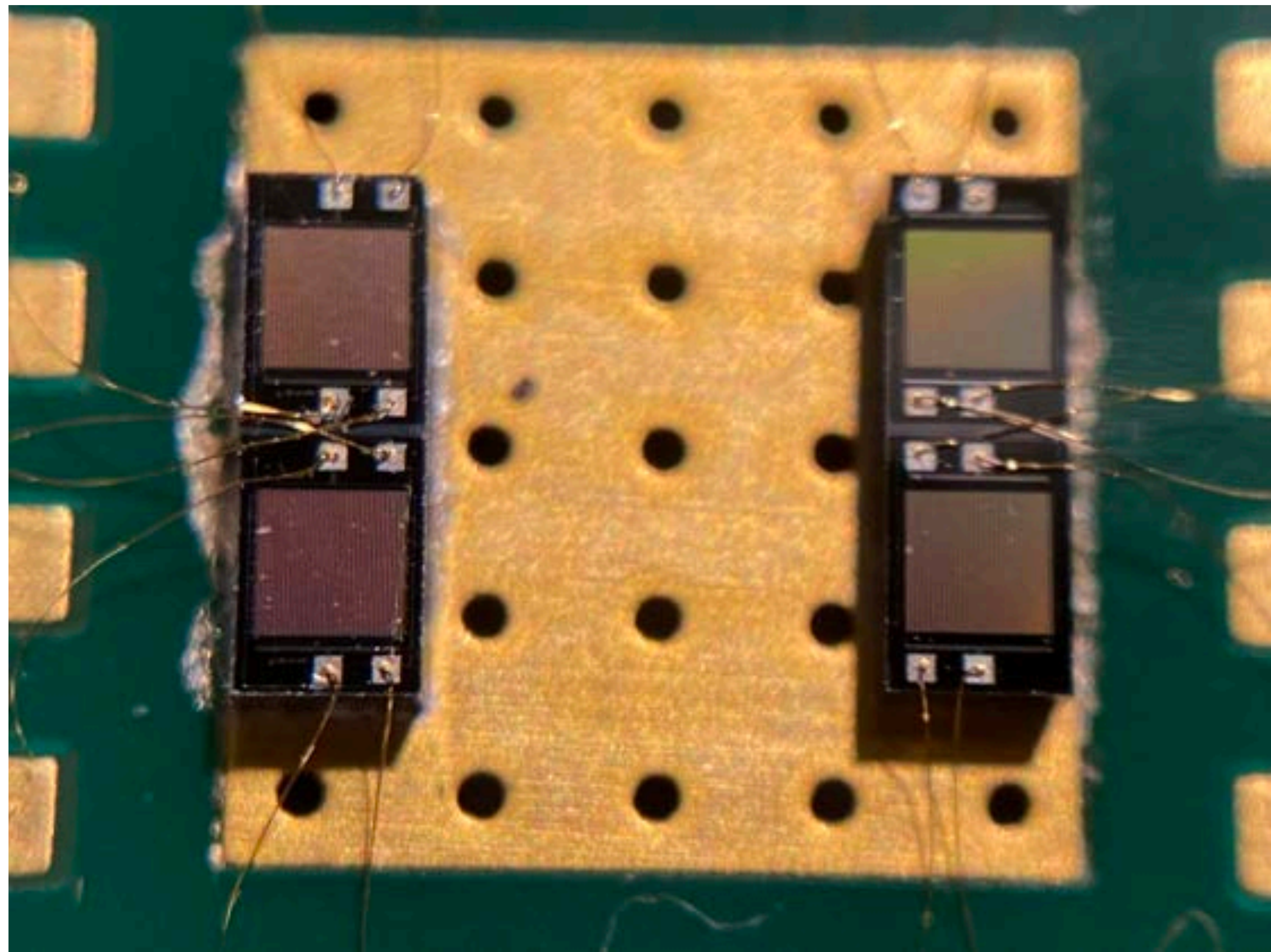
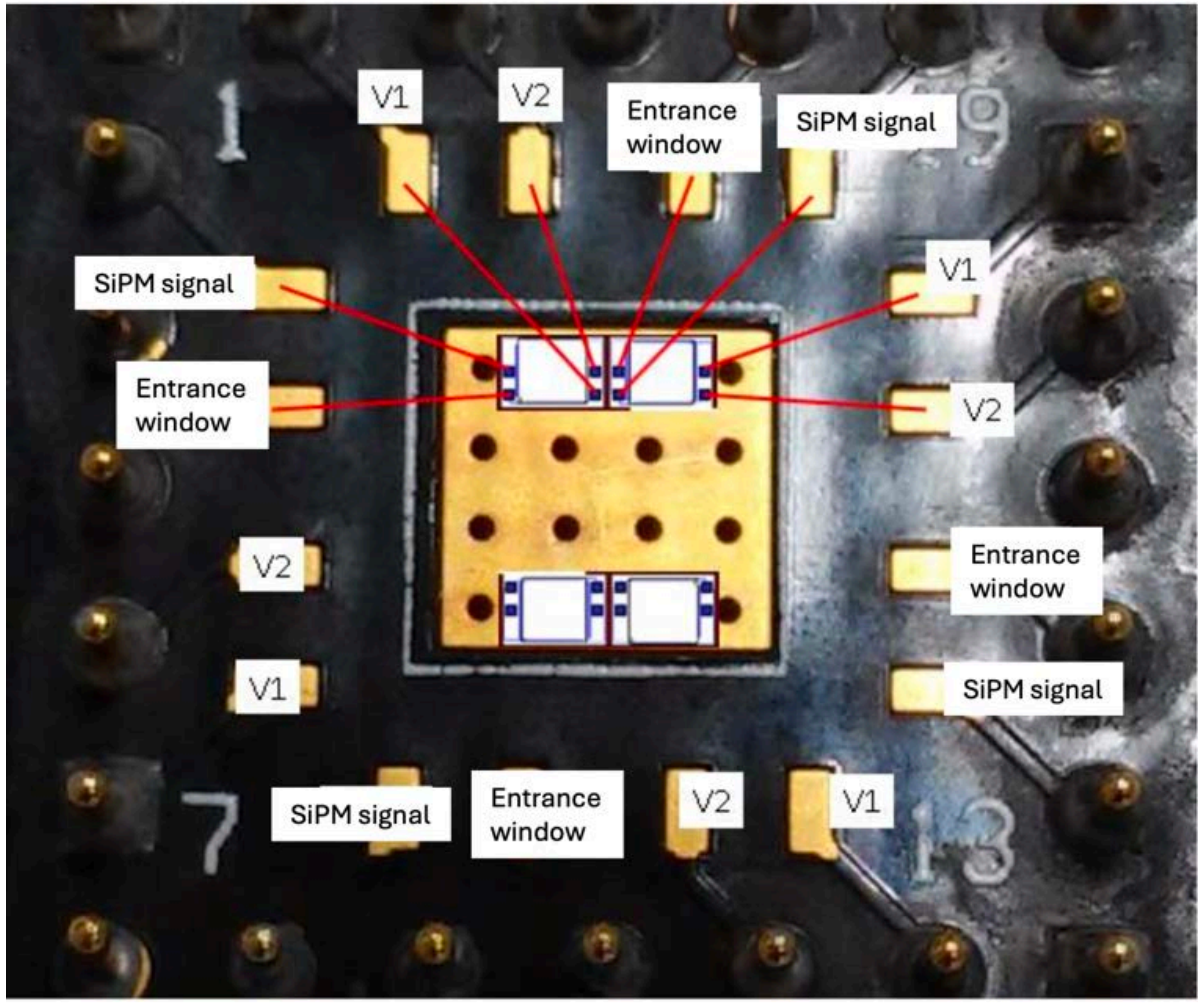
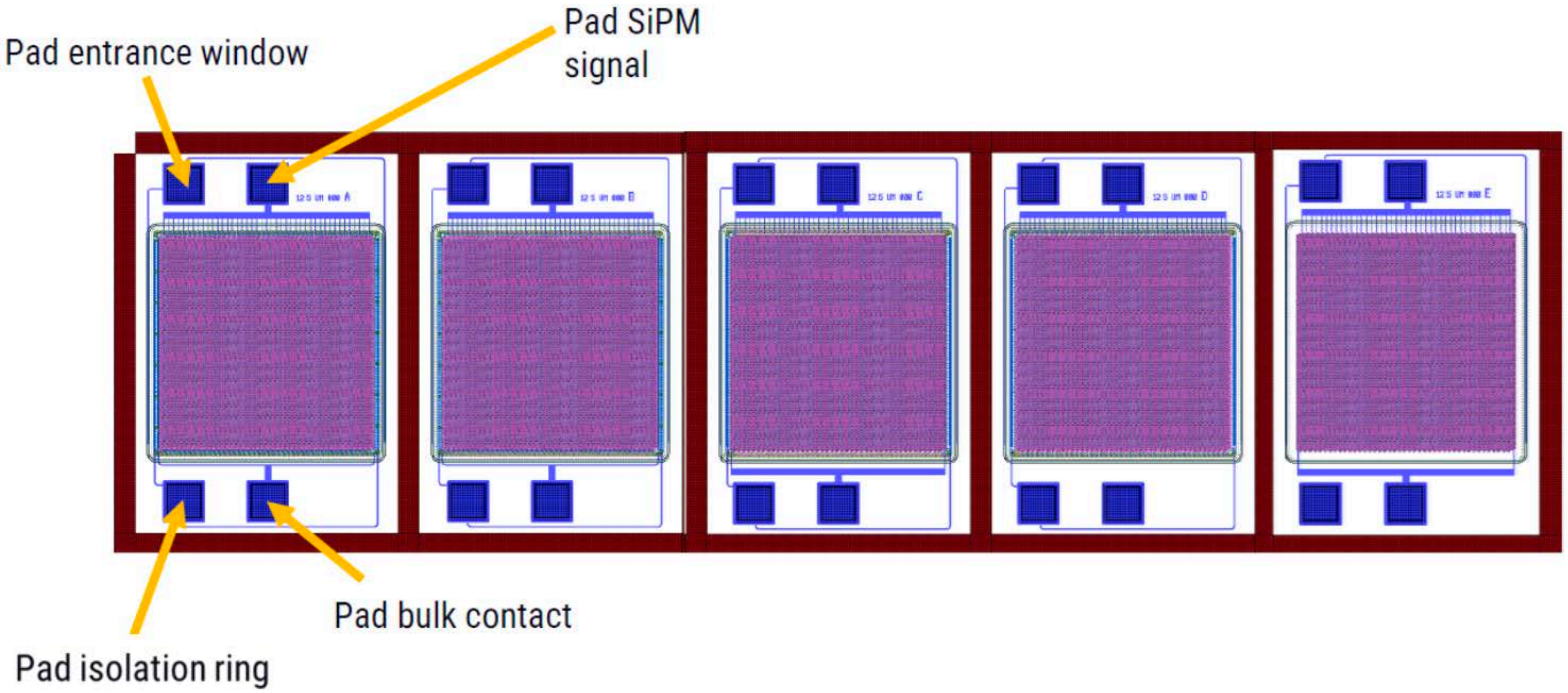
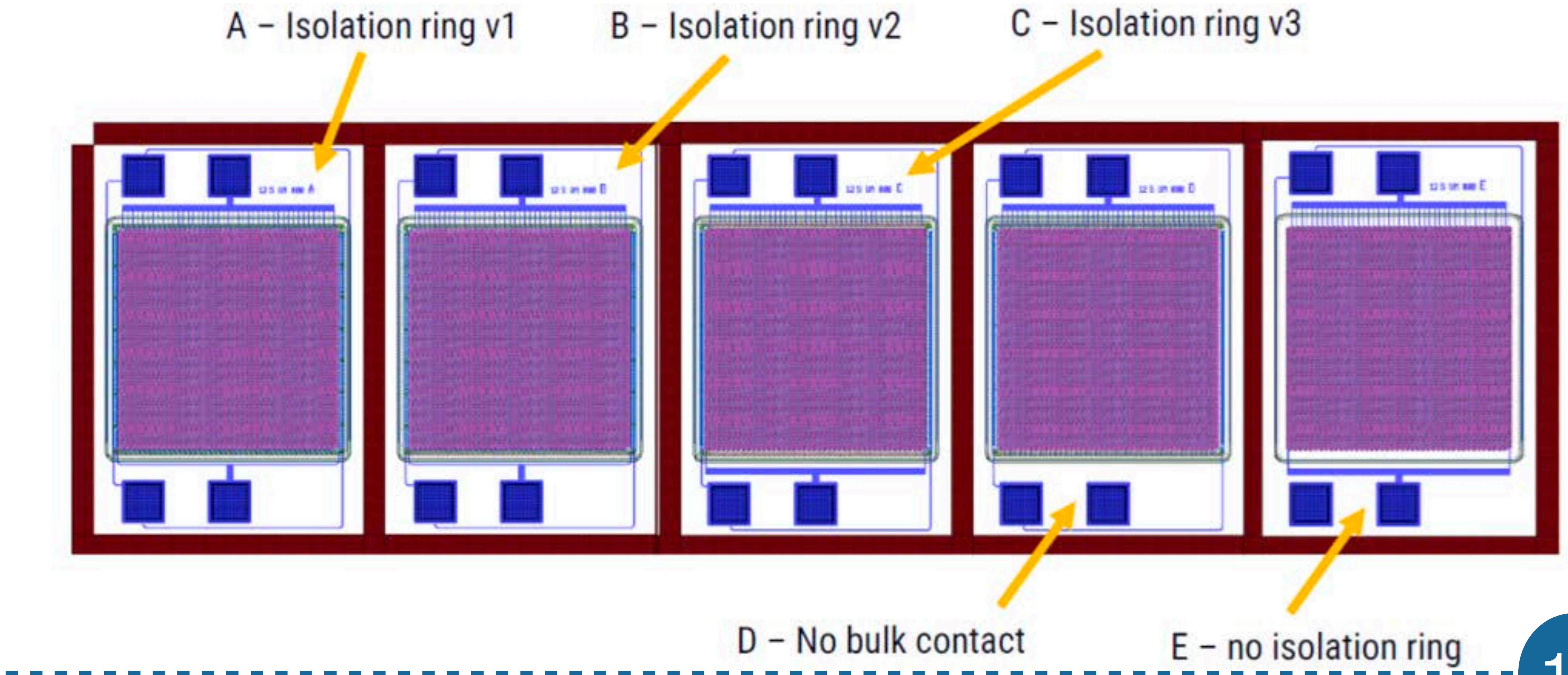


SAMPLE TESTED

n-on-p structure in SiPM



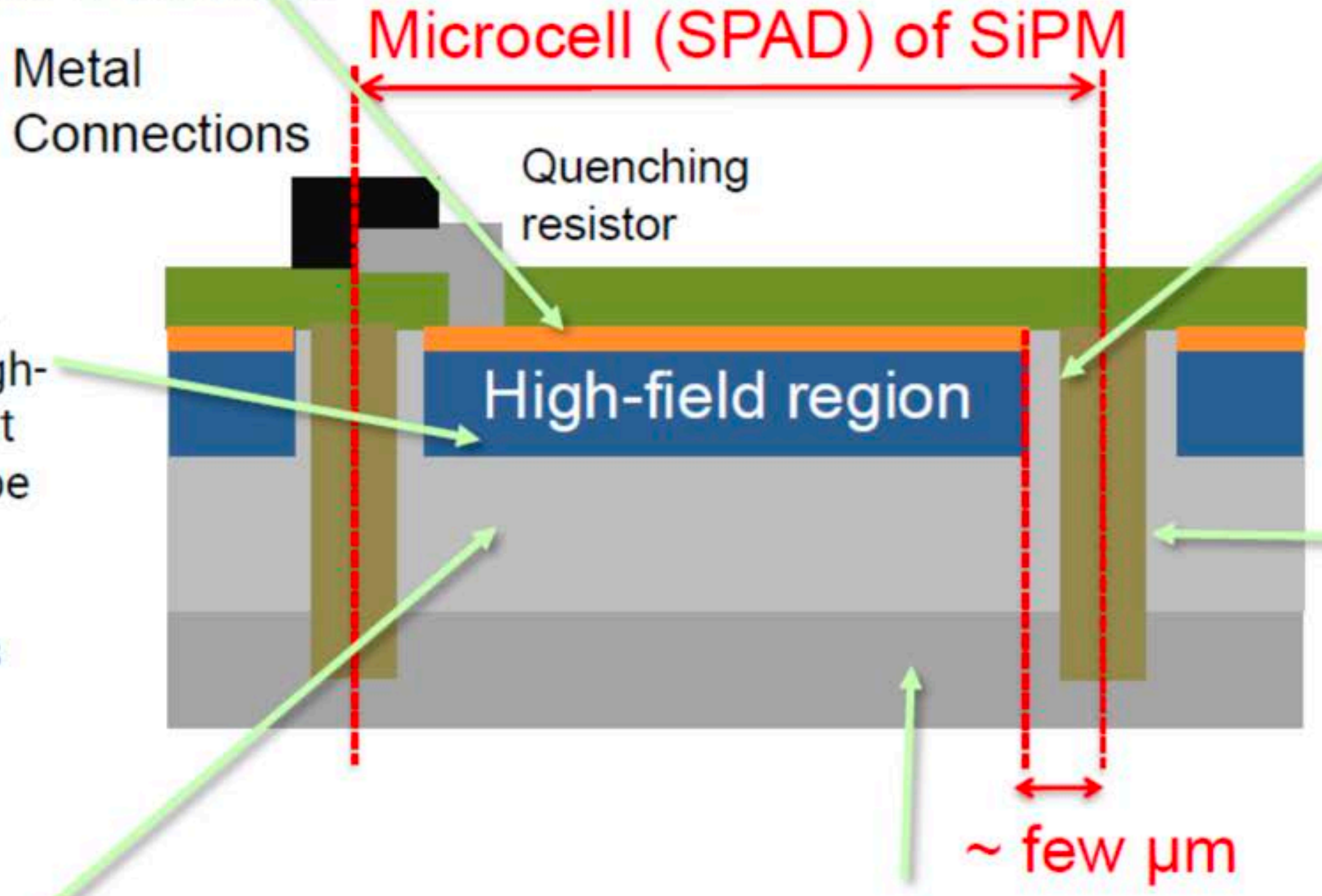




SIPM STRUCTURE

Superficial implant (SI):
Very thin, constitutes the entrance window for the light into the SPAD. High-dose, opposite dopant polarity compared to the epitaxial layer, partially undepleted. Constitutes one half of the diode.

High-field region:
is defined with a high-energy deep implant **(DI)** of the same type as the epi layer. Avalanche multiplication takes place here.

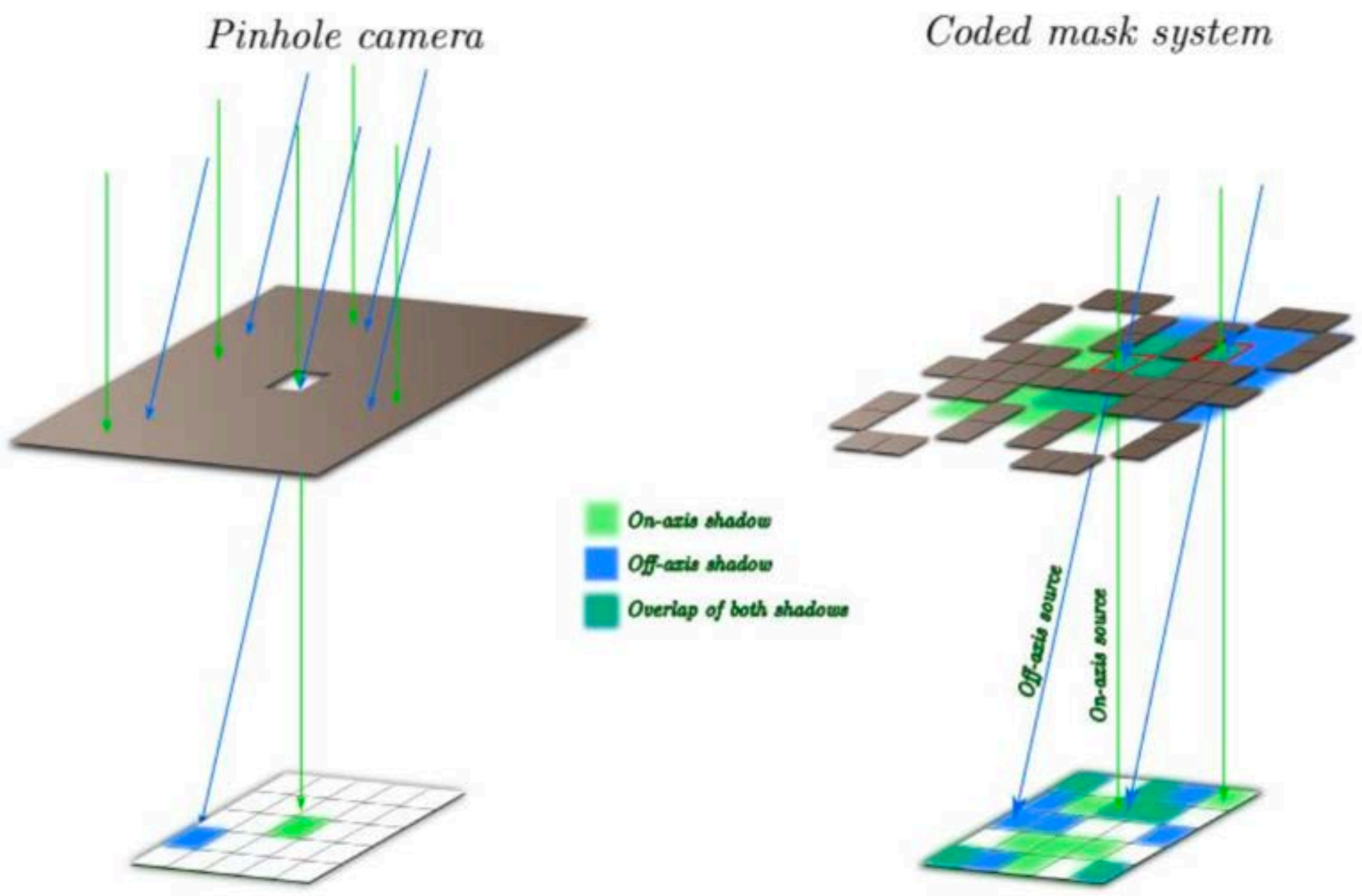


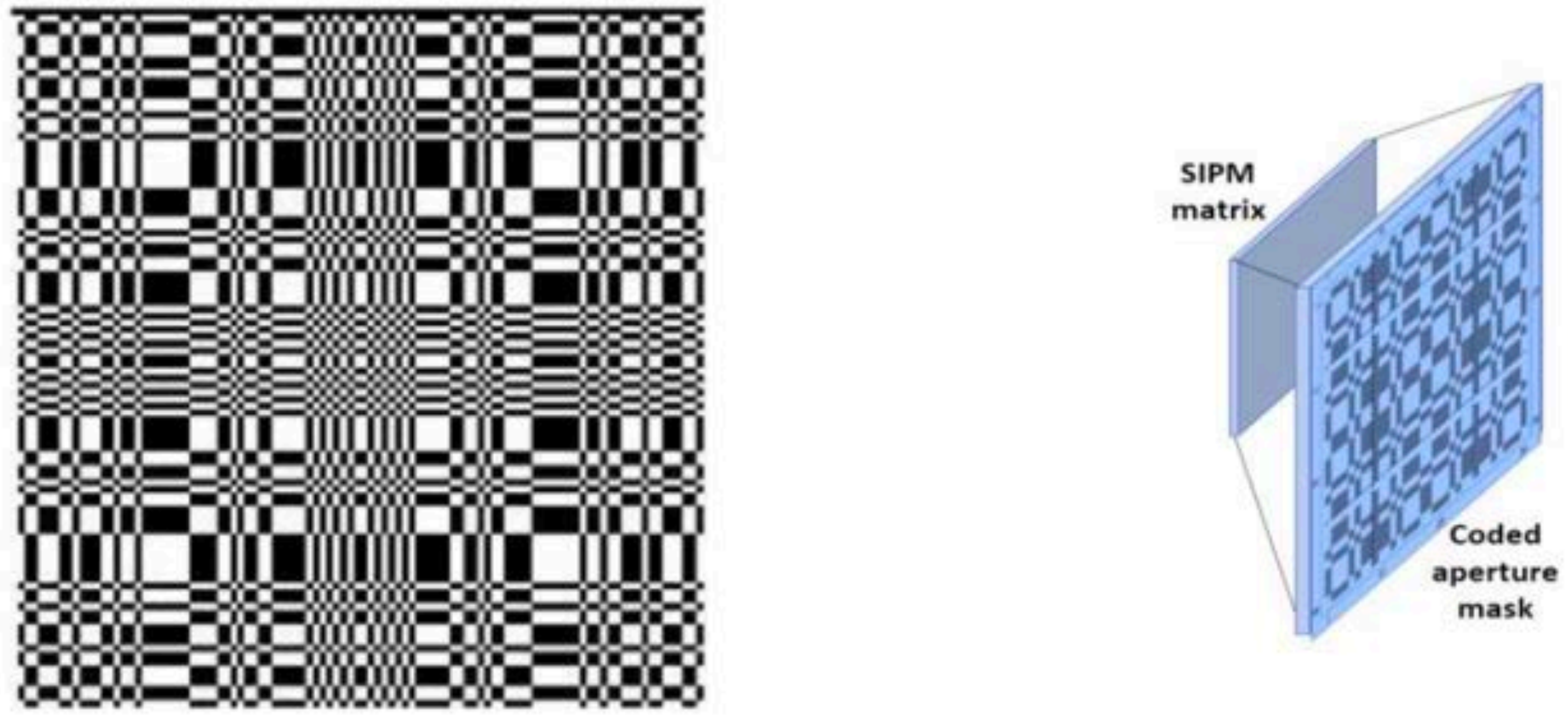
Virtual Guard Ring:
Dead border around the high-field region, necessary to prevent edge breakdown.

Deep trench Isolation:
are used to isolate adjacent microcells electrically. Optical isolation depends on filling material.

Epitaxial layer:
The high-resistivity region in which the SiPM cells are built. Few um thick. Almost fully depleted at breakdown. Close to the interface with the bulk, part of it is undepleted. Constitutes one half of the diode.

Bulk:
(Very) highly doped region upon which the epitaxial layer is built. Never depleted.

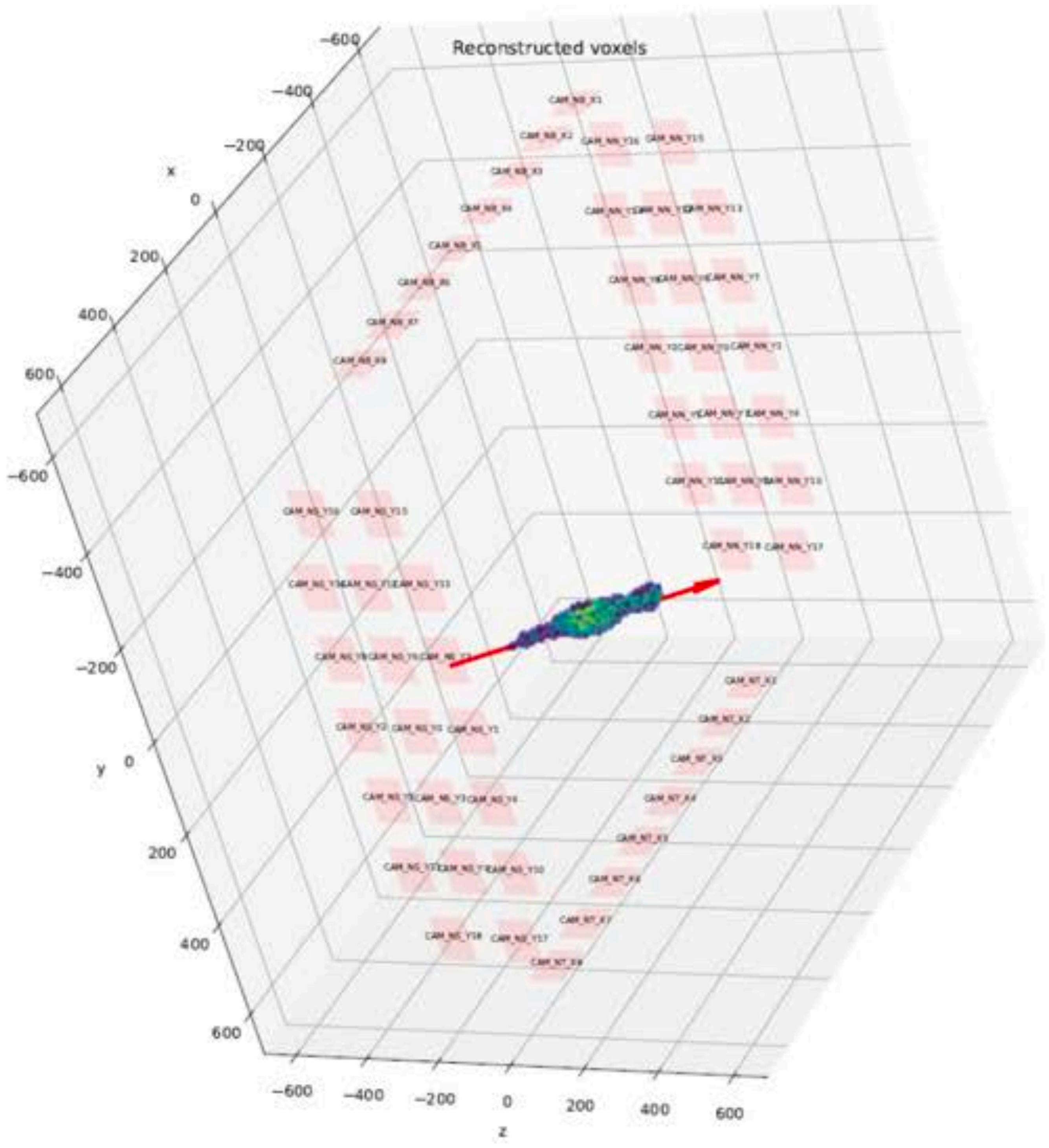




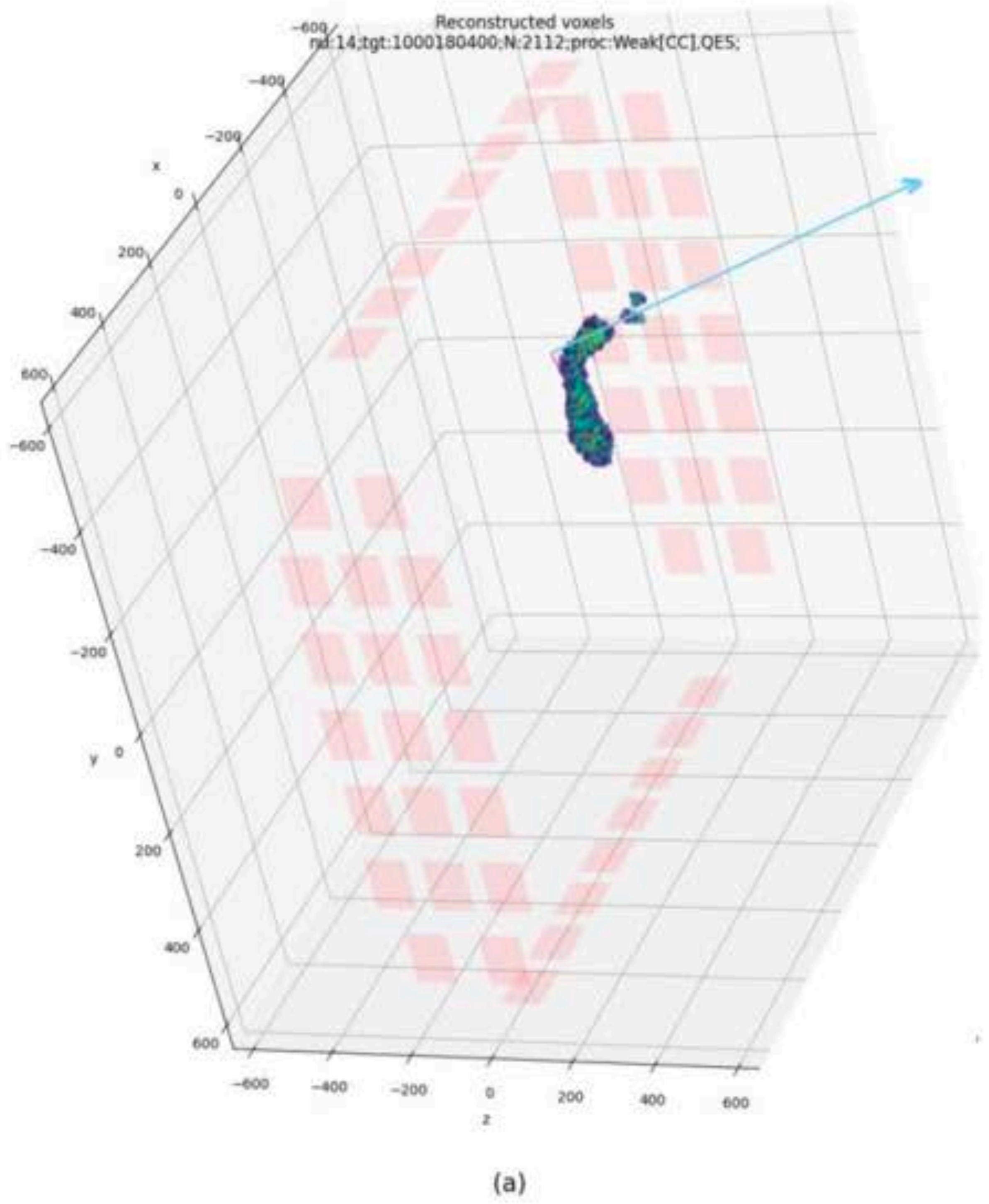
- **Coded Aperture**: mask technique were developed as the evolution of a single pinhole camera
  - Matrix of multiple pinholes to improve light collection and reduce exposure time
- Image formed on sensor is the superimposition of multiple pinhole images
- Advantages:
  - Good light transmission (50%)
  - Good depth of field
  - Small required volumed

SIMULATION ON LAR: EXAMPLE

- **Simulations of Coded Aperture masks with 3D reconstruction algorithm in LAr:**



Cosmic Muon

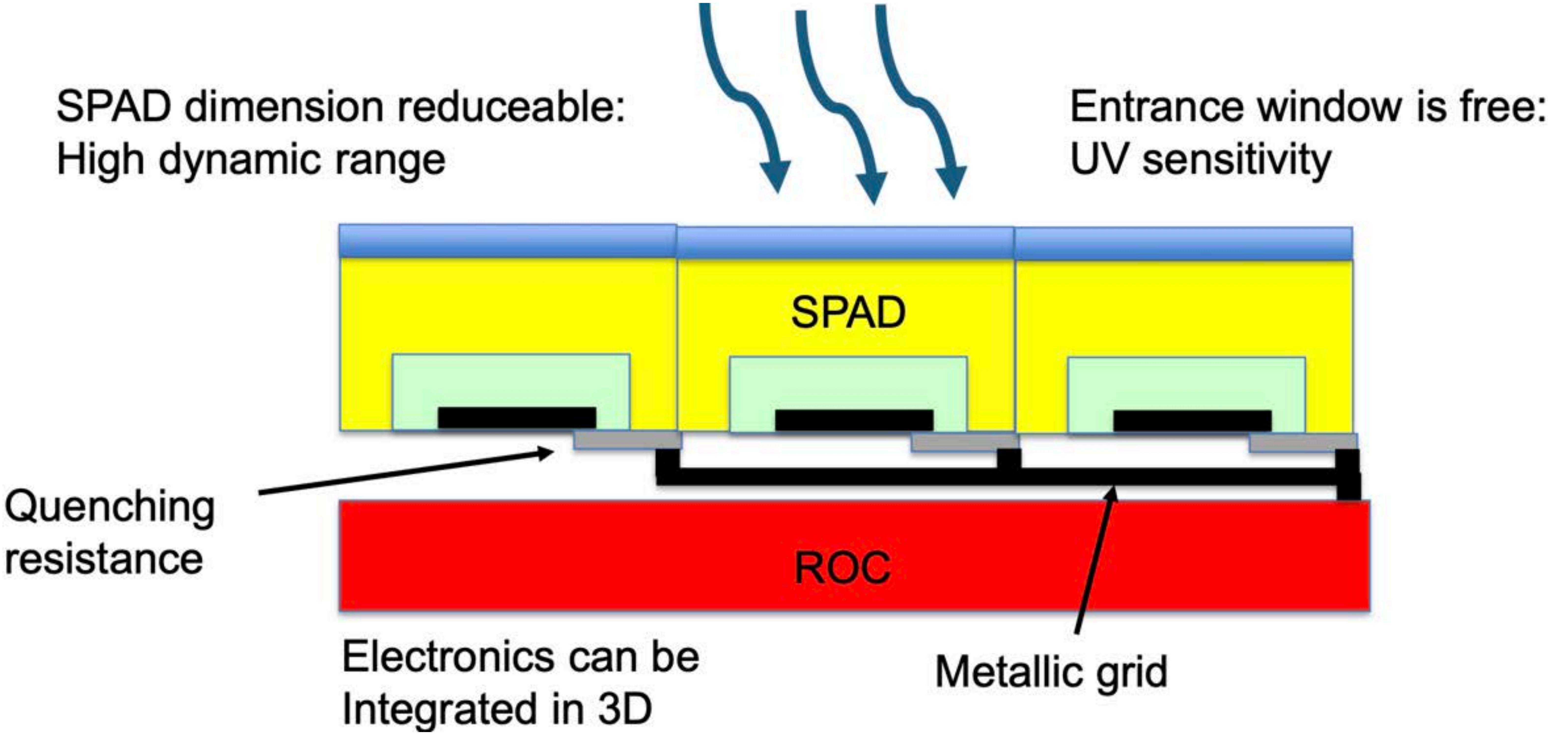


Neutrino Interaction (proton + muon)

ELECTRONICS

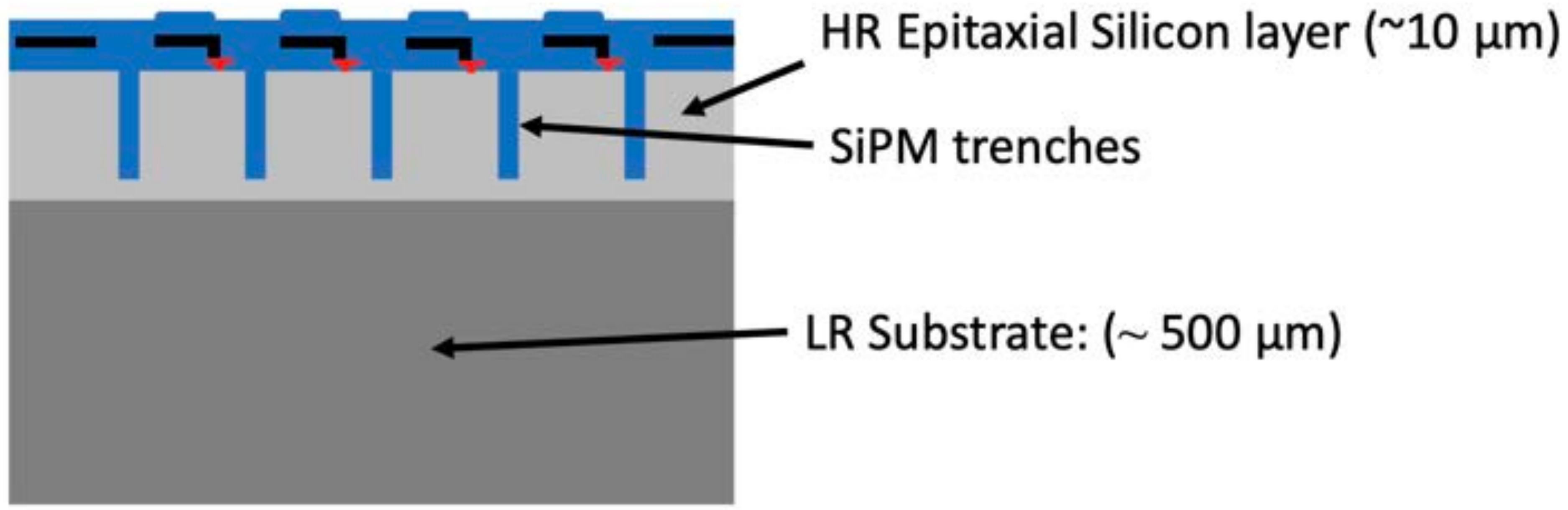
As a first step of 3D integration, the design of INFN-Torino foresee a readout chip (ROC) based on “Alcor” ASIC:

- One channel in 440x440 μm^2
- mini-SiPM by grouping SPADs so that the size correspond to one channel
- Chip bonding

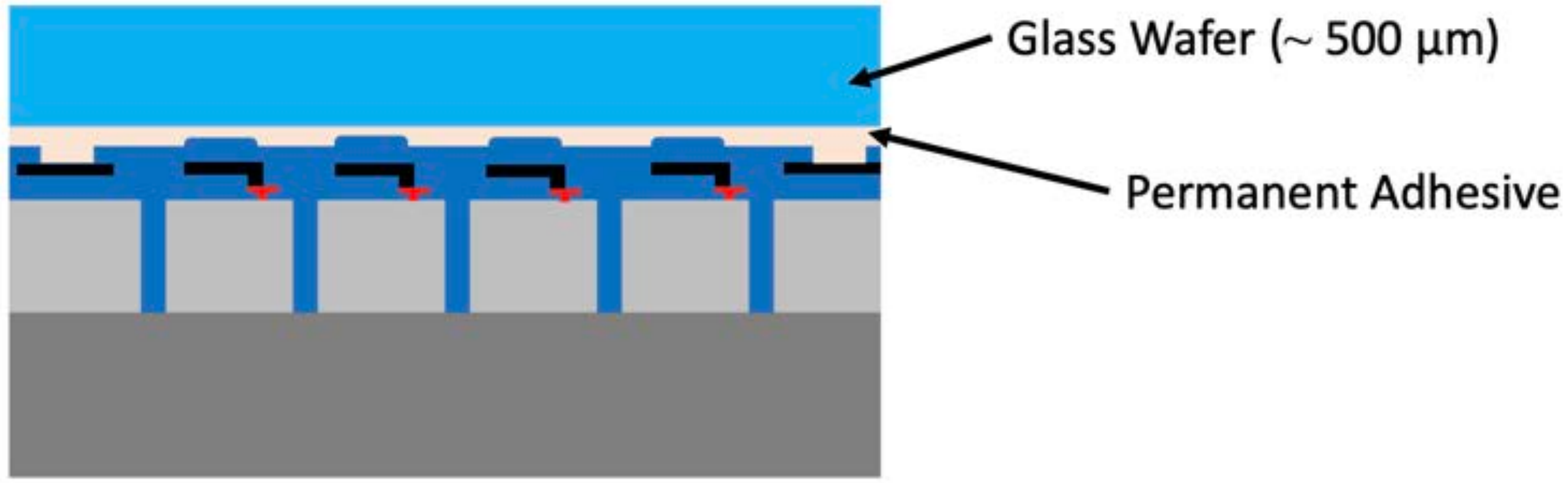


PRODUCTION PROCEDURES [1/2]

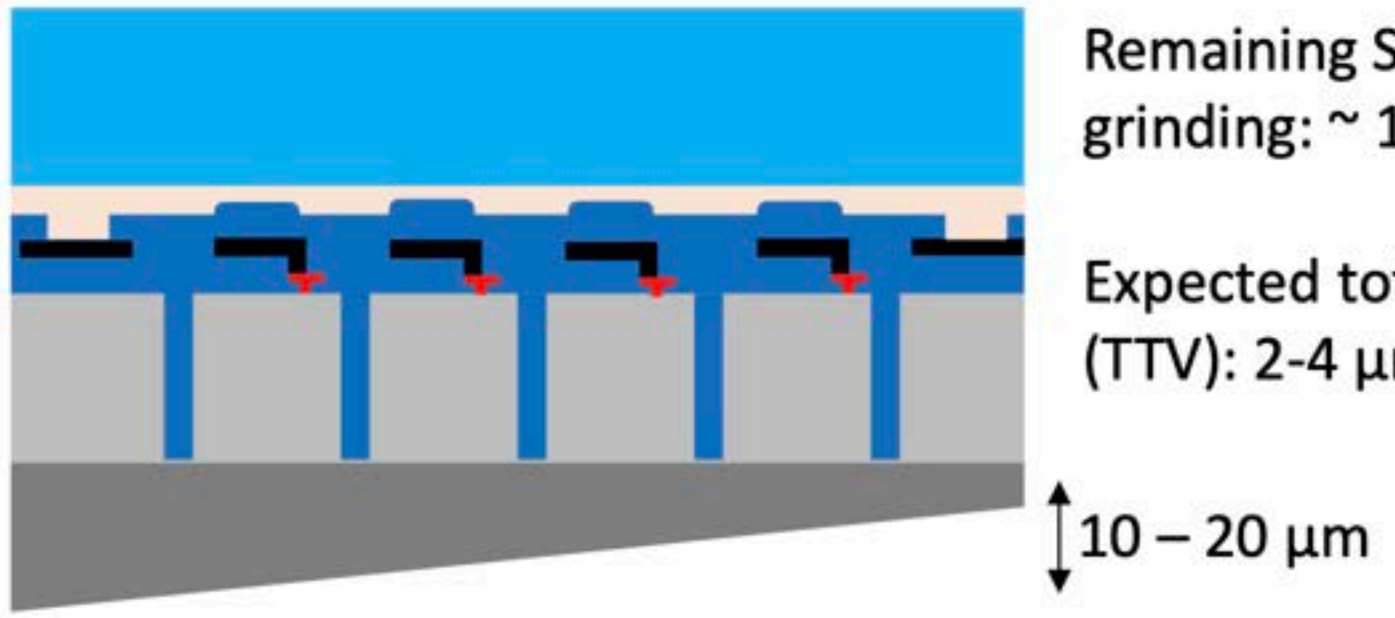
1. Starting Wafer (6”)



2. Adhesive Permanent Bonding to Glass Wafer



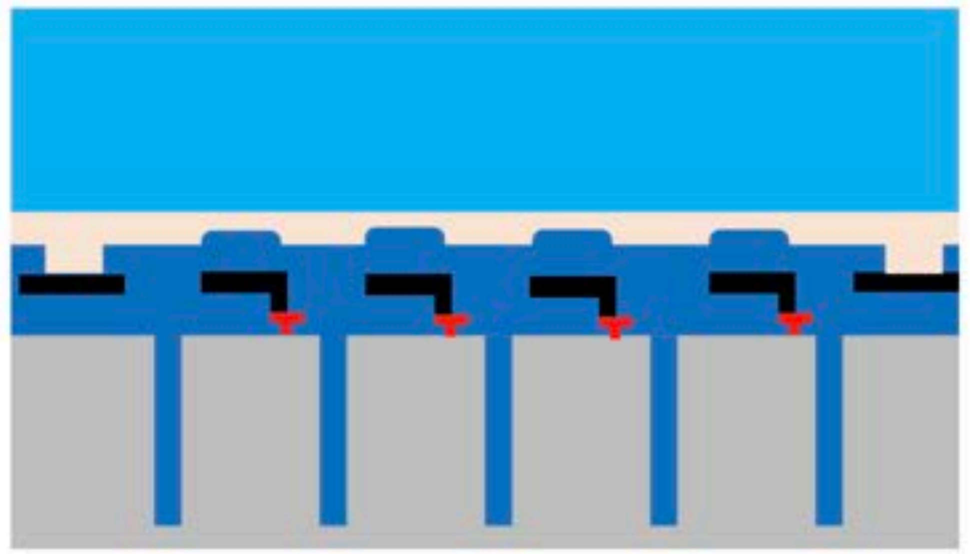
3. Wafer thinning (Substrate Removal)



Remaining Substrate buffer after grinding: ~ 10 µm

Expected total thickness variation (TTV): 2-4 µm

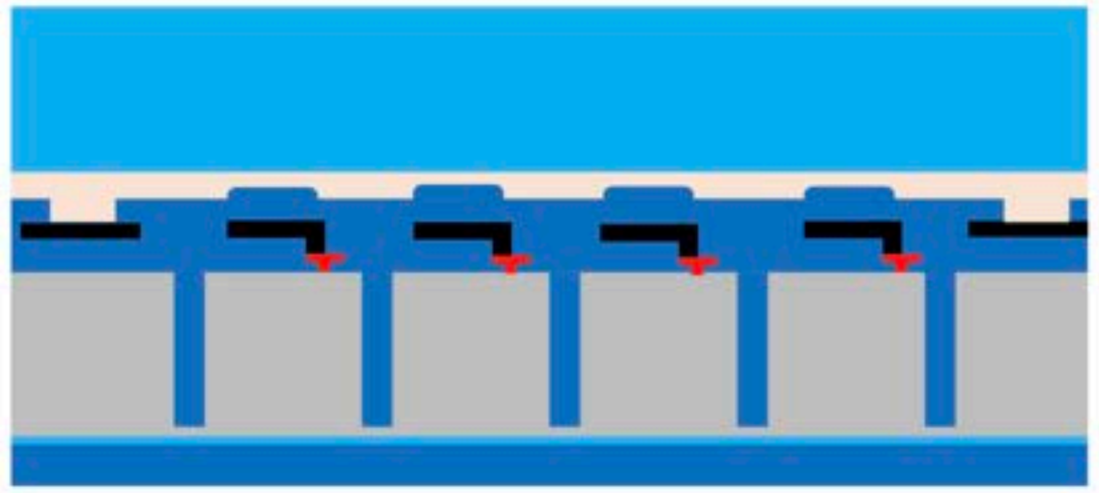
4. Etching of highly doped Silicon substrate using doping selective etching



Doping Selective WET etching is used to complete the substrate removal and to reach the epi/sub interface by reducing the final TTV

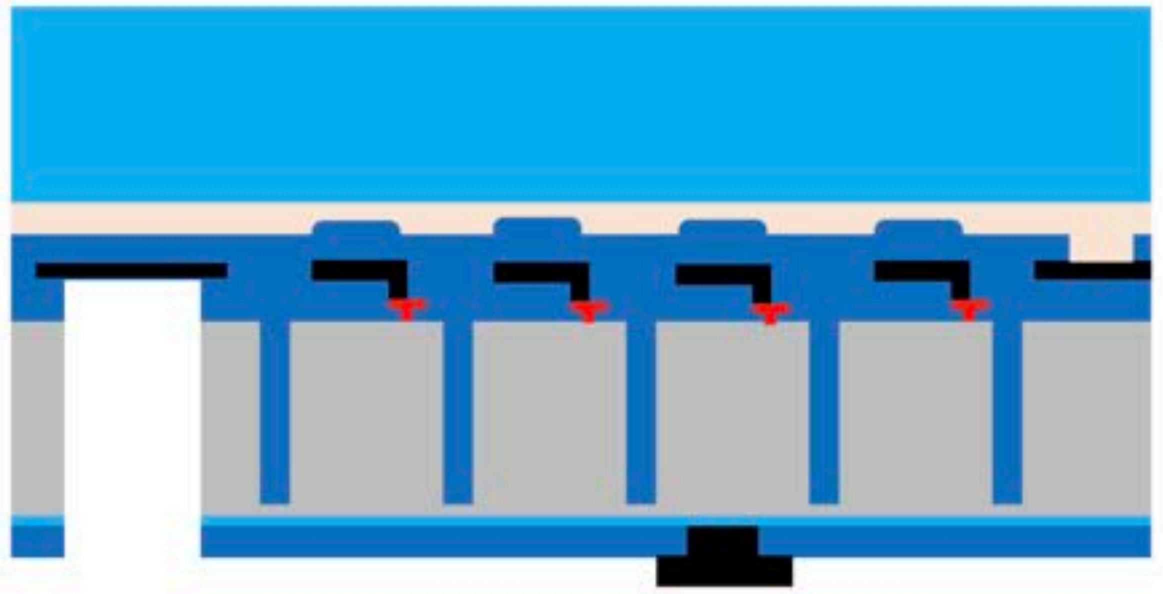
PRODUCTION PROCEDURES [2/2]

5. Back junction Formation



- Final Polishing (tbd)
- Plasma Ion Implantation and laser annealing
- ARC deposition

7. Contact formation

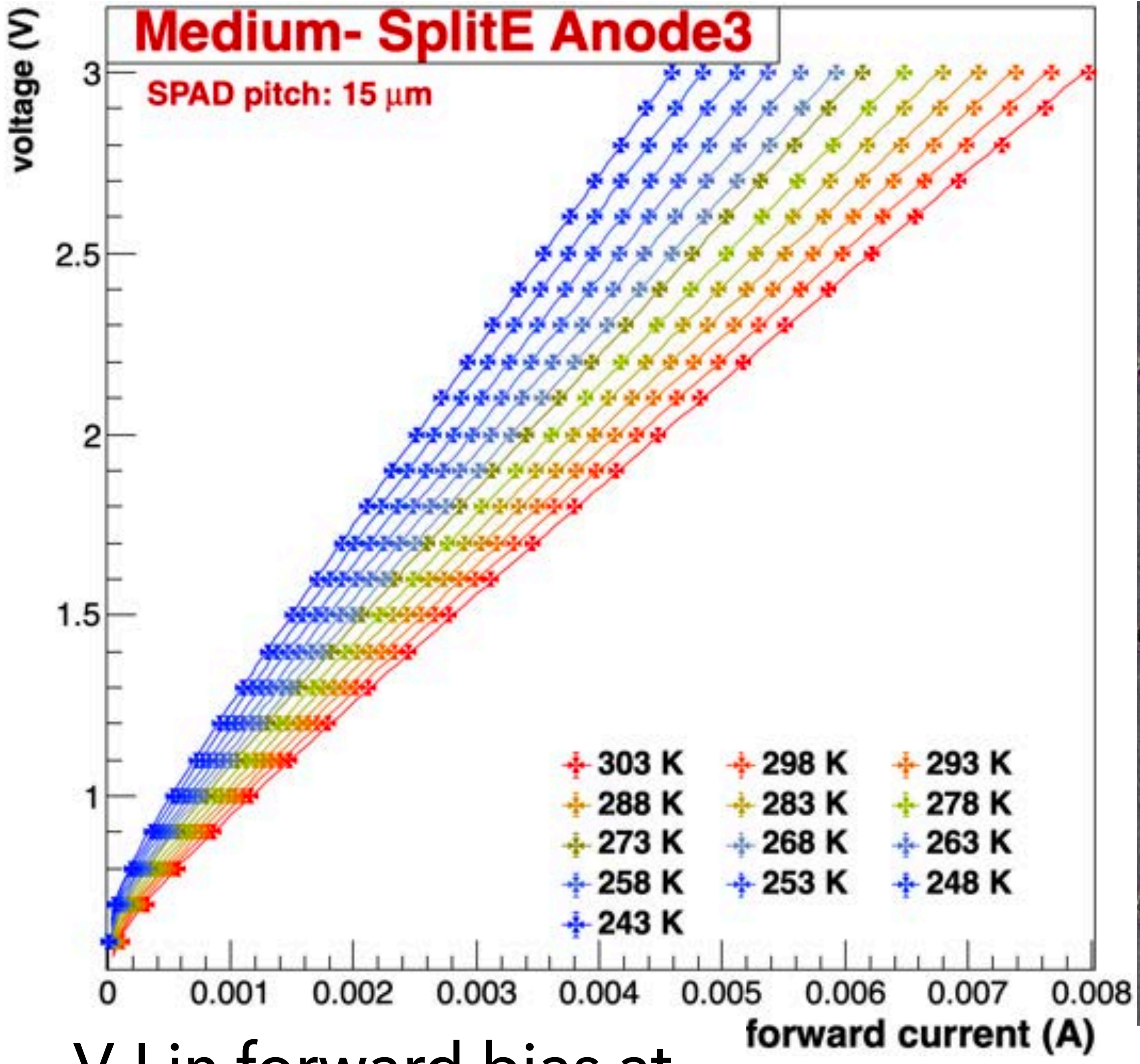


Anode and cathode contacts form the backside

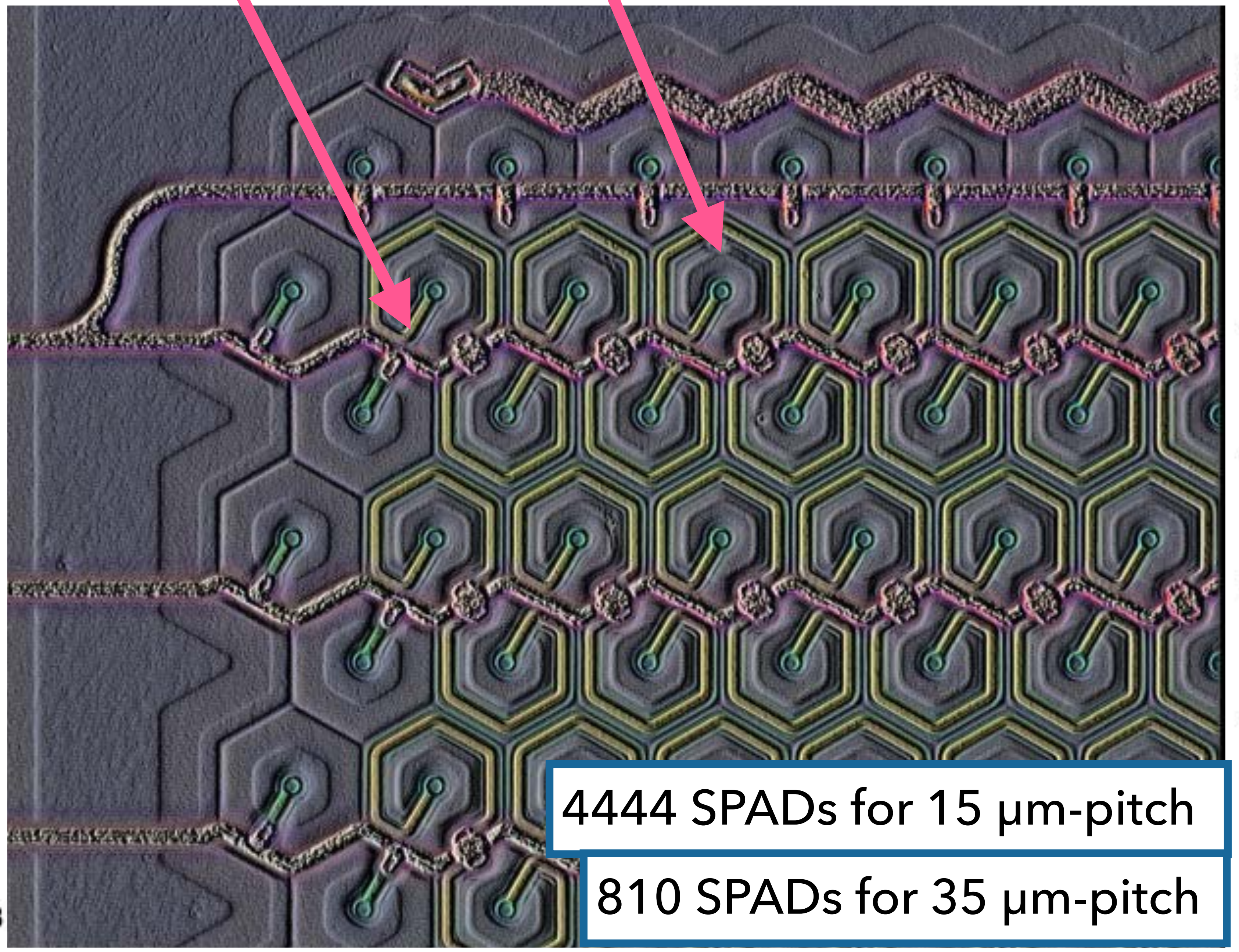
FORWARD IV – QUENCHING RESISTANCE

Quenching resistance is estimated starting from the **V-I** plot in **forward bias at various temperature** and then fitted with the **Shockley formula**.

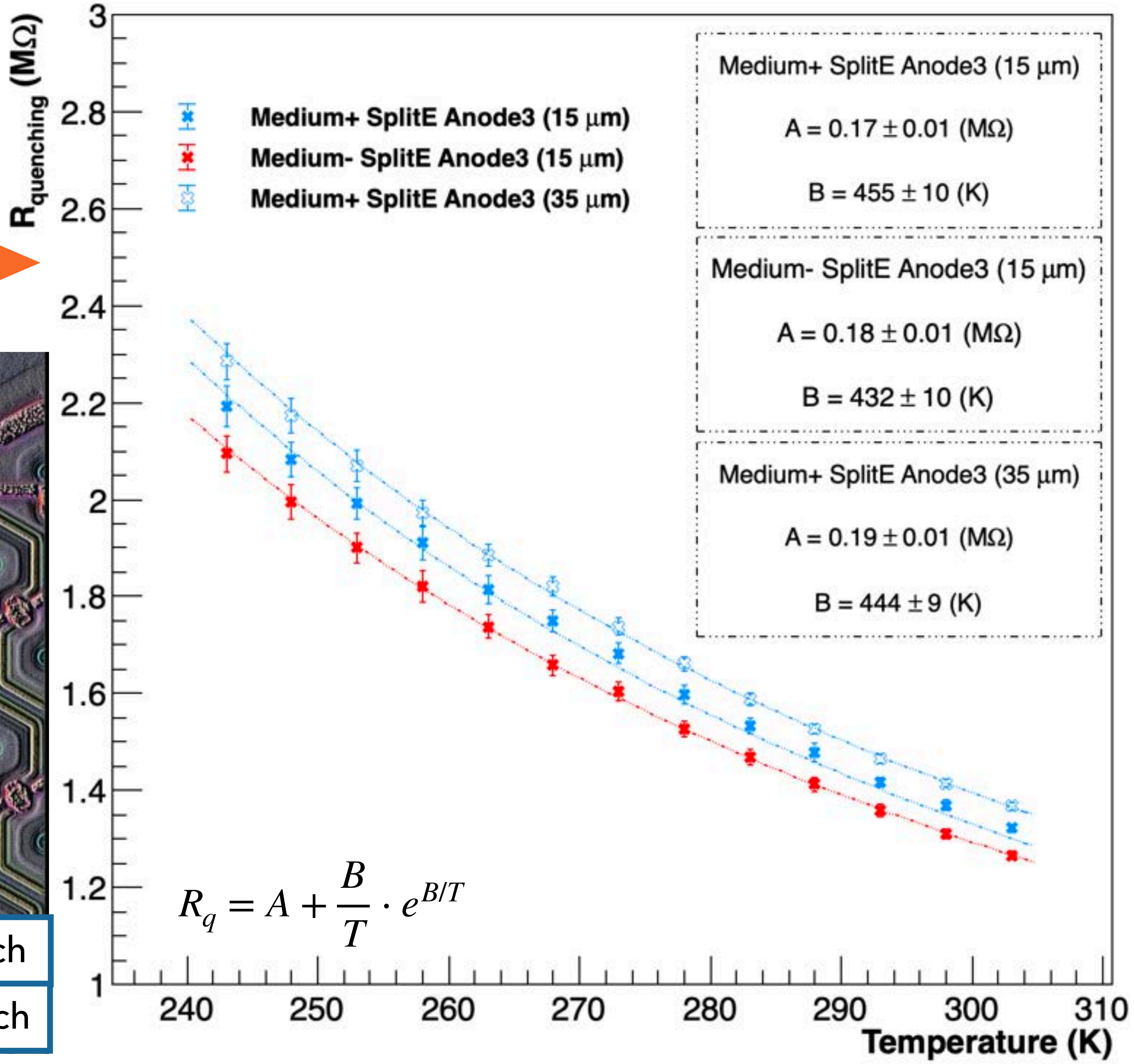
$$V = I \cdot R_{SiPM} + nV_T ln(1 + \frac{I}{I_s}) \oplus R_q = R_{SiPM} \cdot N_{SPADs}$$



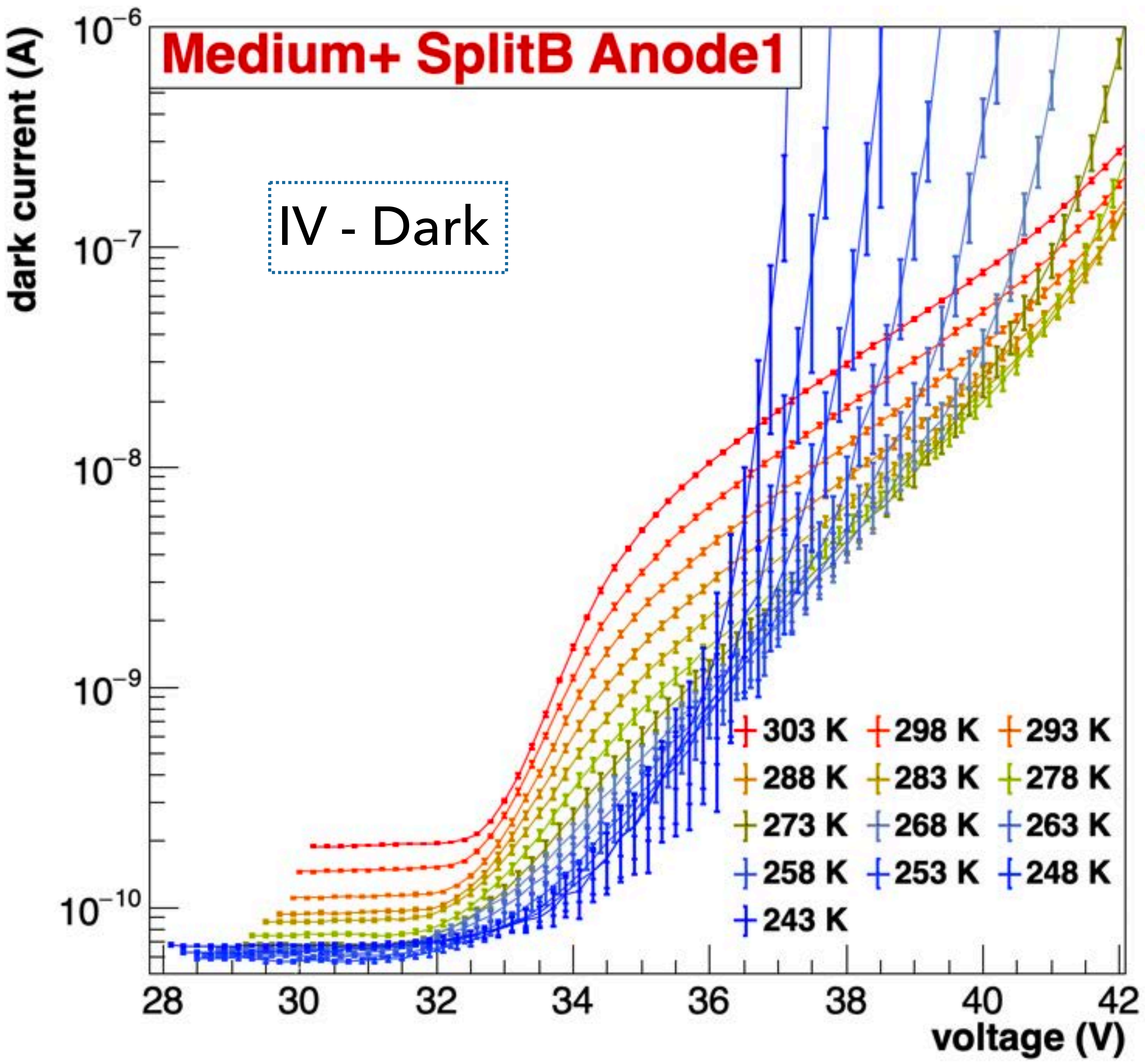
V-I in forward bias at various temperature

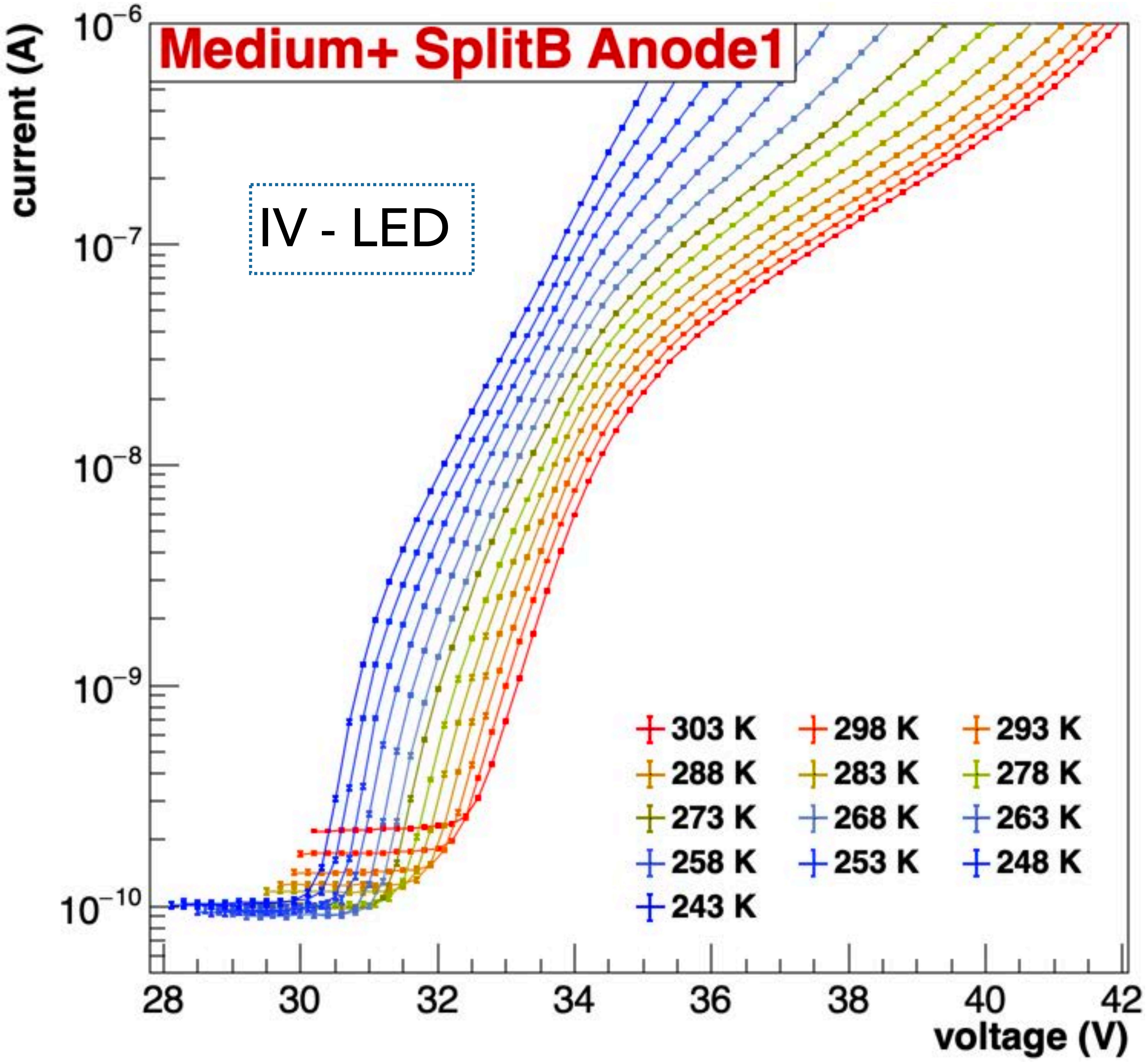


Picture taken at the electronic microscope where SIPM structure is very clear



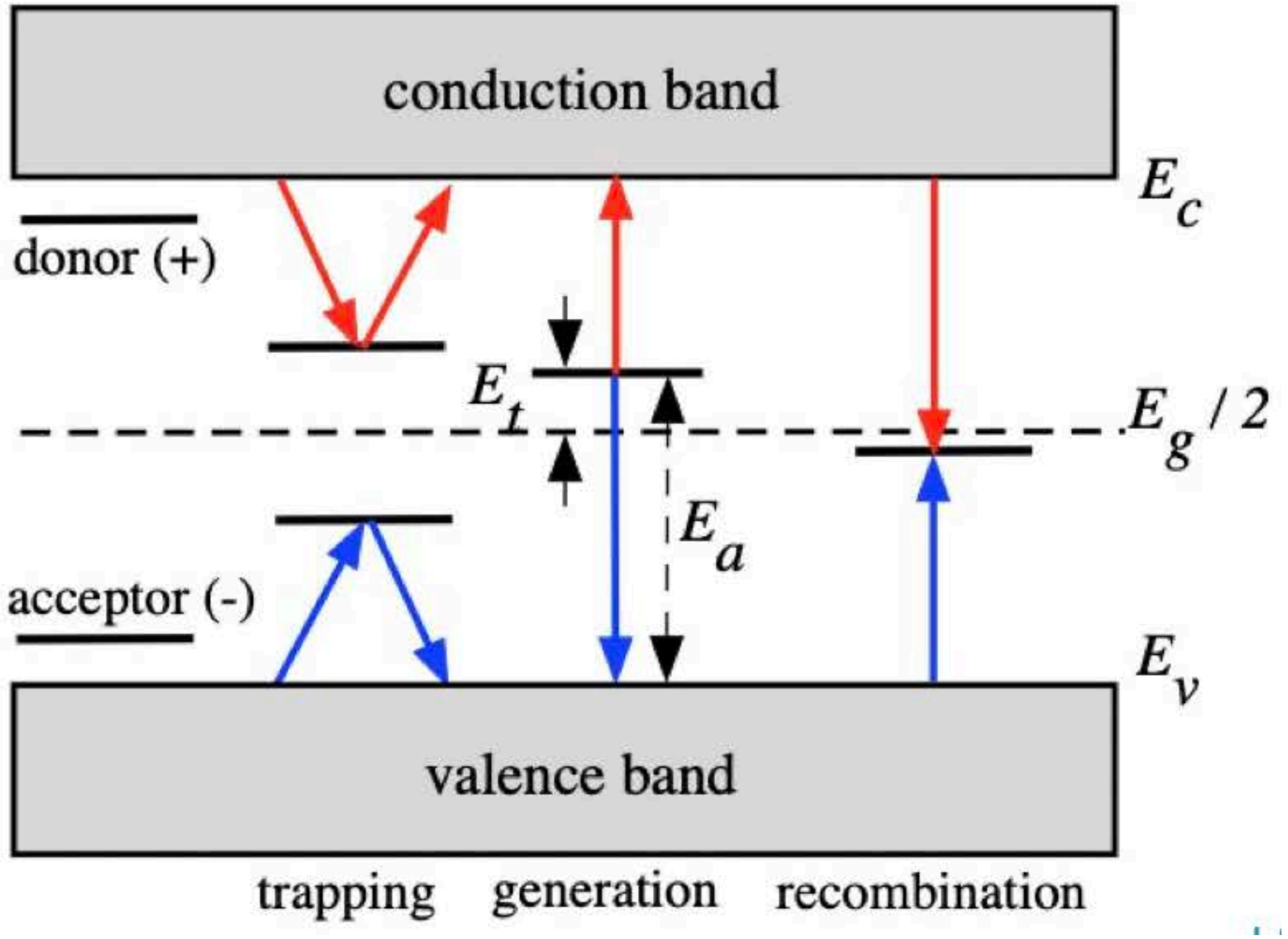
LED VS DARK IV

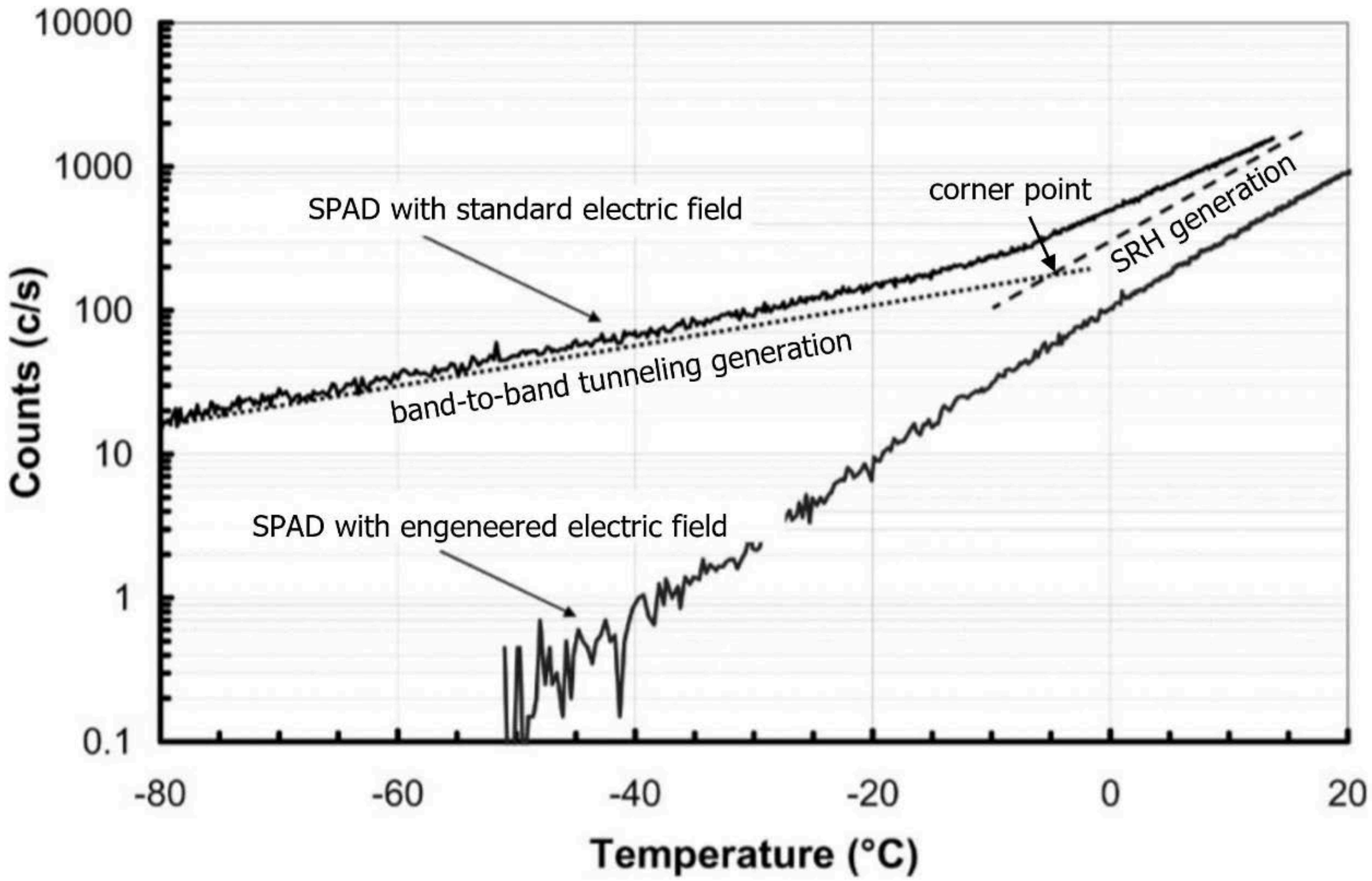




DARK CURRENT & DARK COUNTS

In silicon there are 3 main sources of primary dark events: **SRH thermal generation** in thermal region, **diffusion of minority carriers** in depletion region and **trap assisted tunnelling** in multiplication region





SRH generation dominates → **room temperature and below**, as it has a lower activation energy than the diffusion component, namely $E_g/2$

TAT due to its weaker dependence on temperature shows an activation energy lower than $E_g/2$ → is dominant only at **low temperatures**.