# SiPM development in India: status and test results

Two semiconductor fabrication facilities in India:

1) Semiconductor Lab. (SCL), Chandigarh

2) Bharat Electronics Ltd. (BEL), Bangalore

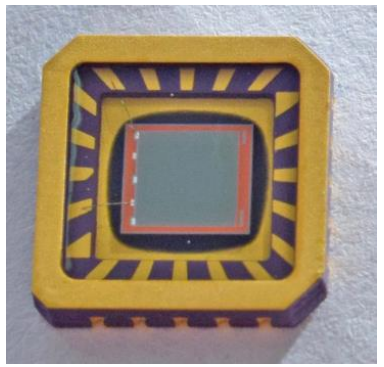
# Technical Specifications of SiPM

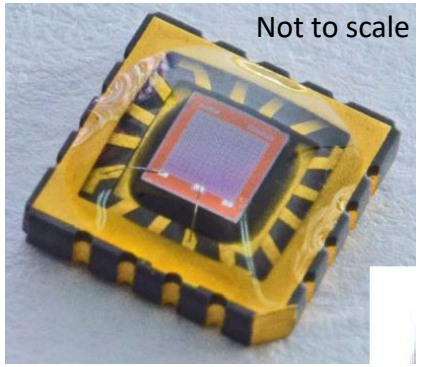


| Sr. No | Parameter (targeted by design) | Specifications | | |
|---|---|---|---|---|
| | | BARC/SCL | SCL | BEL |
| 1 | Effective active area ($mm^2$) | 1.5 x 1.5 & 3 x3 | 1.5 x 1.5 | 3.3 x 3.3 |
| 2 | Micro-cell count | 676 & 2704 | 1156 | 4836 |
| 3 | Micro-cell size | 50 x 50 $\mu m^2$ | 35 x 35 $\mu m^2$ | |
| 4 | Micro-cell fill factor | 20% & 75% | 61% | 55% |
| 5 | Capacitance (Cathode - anode) | 1000 pF | ~330 pF | ~100pF/cell and (500 pF @25.5V) |
| 6 | Recharge time constant | 120 ns – 150 ns | - | - |
| 7 | Spectral response range | 350 nm – 900 nm | - | 350 nm – 900 nm |
| 8 | Peak sensitivity wavelength | ~ 500 nm | - | 420 – 450 nm |
| 9 | Photon detection efficiency | - | - | - |
| 10 | Breakdown voltage ($V_{BD}$) | 22 V | 18 V | 23 V |
| 11 | Overvoltage range (OV) | 2 V – 3 V | 2.5 V | 2 V – 5 V |
| 12 | Dark count rate | ~ 500 kHz (@ $V_{BD}$+2.0 V and 0.5 p.e. thr. | 20 Hz/ $\mu m^2$ at 1V OV | - |
| 13 | Gain | 2 x $10^6$ @ $V_{BD}$+1V | ~ $10^6$ | ~5.2 x $10^5$ @$V_{BD}$+2V |
| 14 | $V_{BR}$ temp. coefficient | 20.0 mV/ºC | 15.0 mV/ºC | - |
| 15 | Package type | LCC* 16, 20 pin | TO-8/6 pin | On PCB |
| 16 | Package dimension | ~ 3.5 x 3.5 $mm^2$ | | |
| 17 | Dark current | < 5 nA/$cm^2$ @ 20V | < 10 nA/$cm^2$ | - |
| 18 | Quenching resistor ($R_q$) | 300-500 kΩ | 360 kΩ | $R_{eq}$ = 6.6 kΩ and $R_q$ = ~ 32 MΩ |
| 19 | Cross-talk | < 5 % @$V_{BD}$+2.0 V | - | - |

*Lead-Less Chip Carriers (LCC)

Bhabha Atomic Research Center (BARC), Mumbai

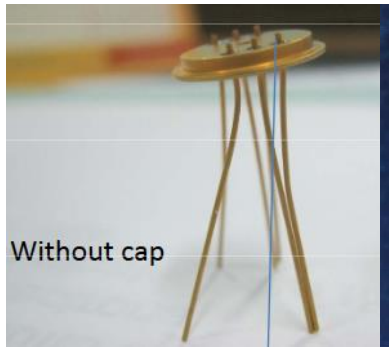




Not to scale

**BARC/SCL**
(epi., p-type)

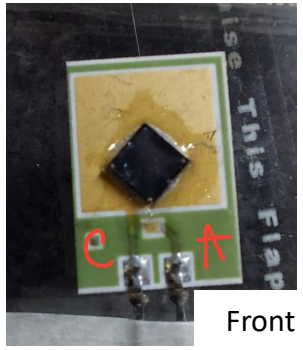
Not to scale



Without cap

**SCL sample**
(epi., p-type)

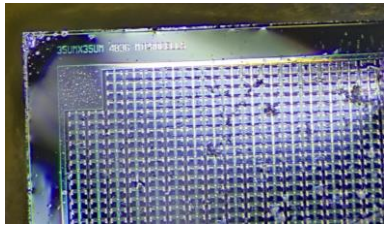
Not to scale

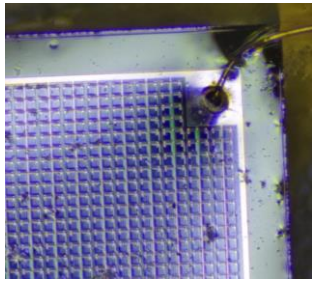


Front


Back

**BEL sample:**
(Non-epi, n-type)



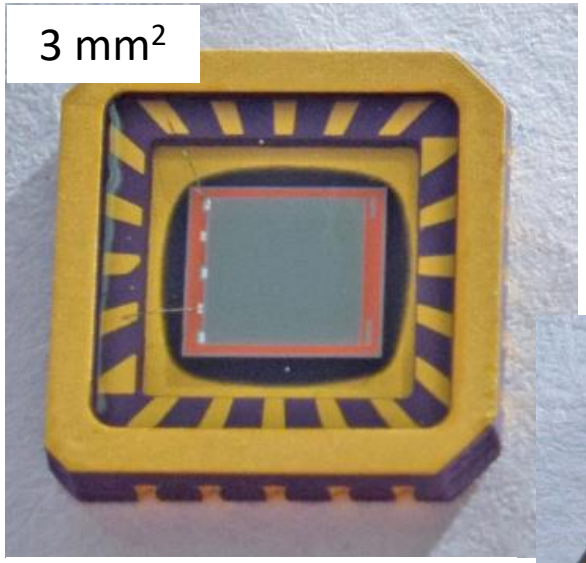


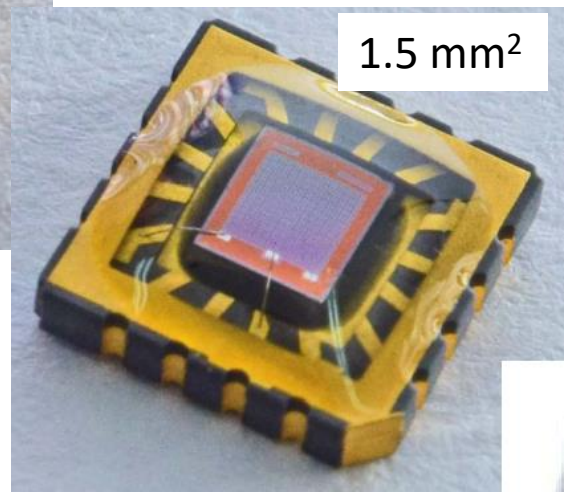
# SiPM Fabricated at SCL, Chandigarh, India



Standard low voltage **180 nm CMOS** baseline process was adopted for realizing SPADs

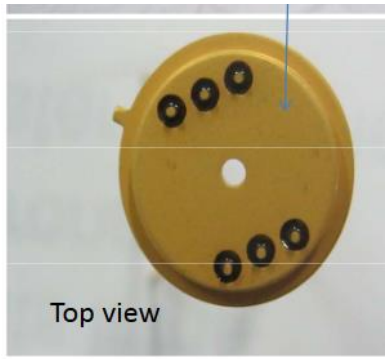
## BARC design




Size: 1.5 & 3 $mm^2$
Pixel size: 10 & 50 $\mu m^2$
No. of pixels: 2704

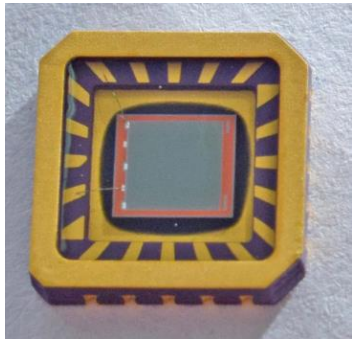
## SCL design

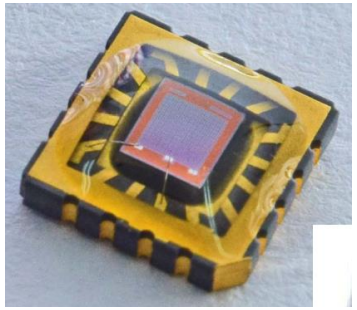

SCL:

Size: 1.5 x 1.5 $mm^2$
Pixel size: 35 x 35 $\mu m^2$
No. of pixels: 1156

Next slides on test done by SCL and BARC

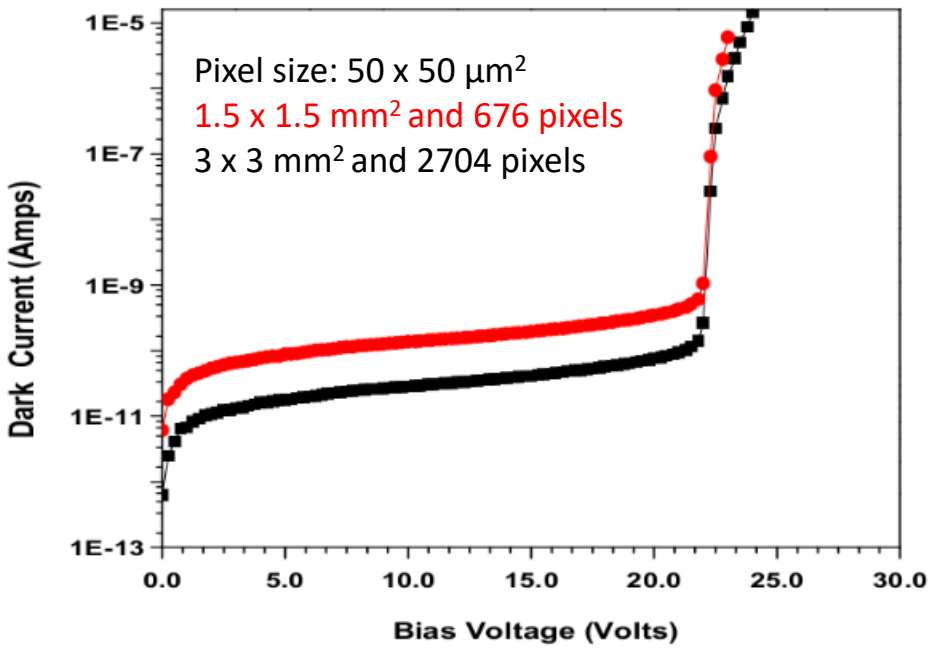


# SiPM Fabricated at SCL: Test done @ BARC





Dark current for two SiPMs



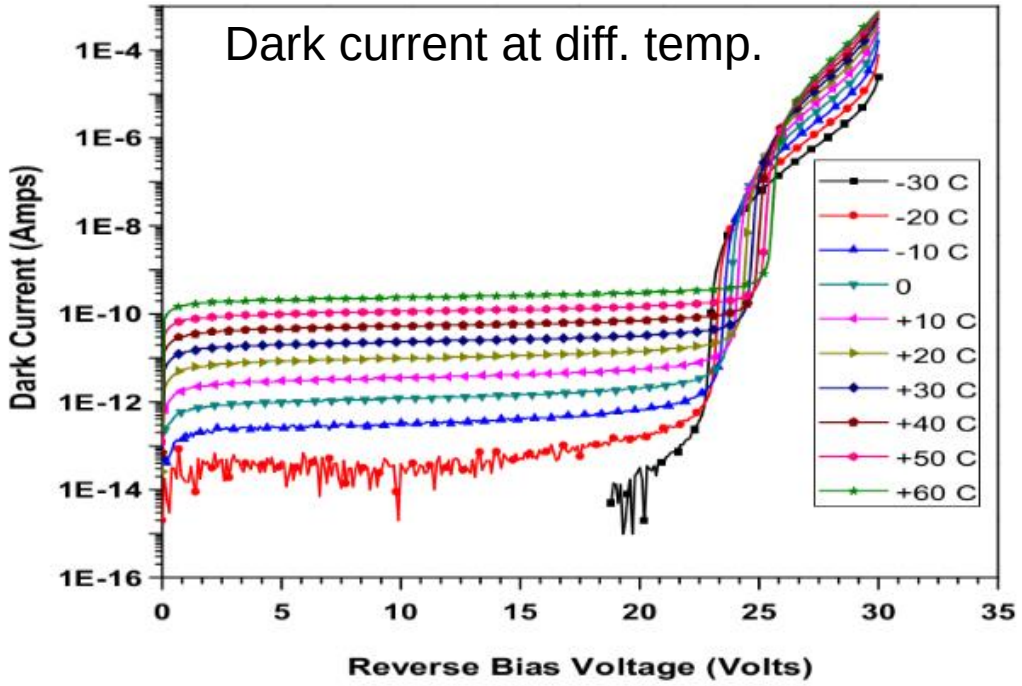
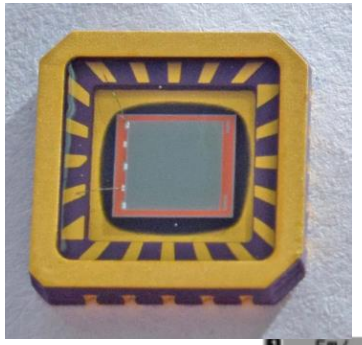



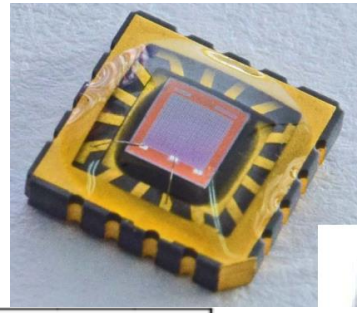

**Figure 7.** Dark current characteristics of SiPMs with STI isolation, pixel size — 50 µm × 50 µm, and active areas of 3 mm × 3 mm, 1.5 mm ×1.5 mm.

**Figure 8.** Variation of $V_{BD}$ with temperature. As expected, $V_{BD}$ decreases with temperature.

[Ref] A.Topkar et.al, (2020) JINST 15 P03032 https://iopscience.iop.org/article/10.1088/1748-0221/15/03/P03032/pdf



# SiPM Fabricated at SCL: Test done @ BARC





Dark counts

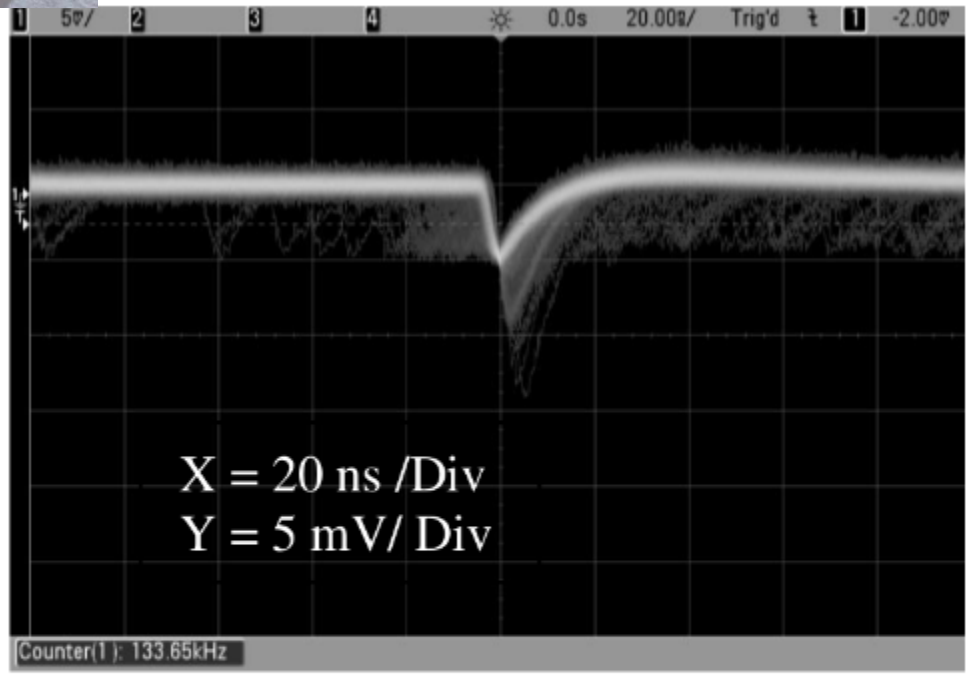



**Figure 9.** Dark counts observed on a DSO for a SiPM of active area 1.5 mm × 1.5 mm (676 pixels, pixel size of 50 μm × 50 μm). At 0.5 p. e., the dark count rate is about 133 kHz.

LED light response

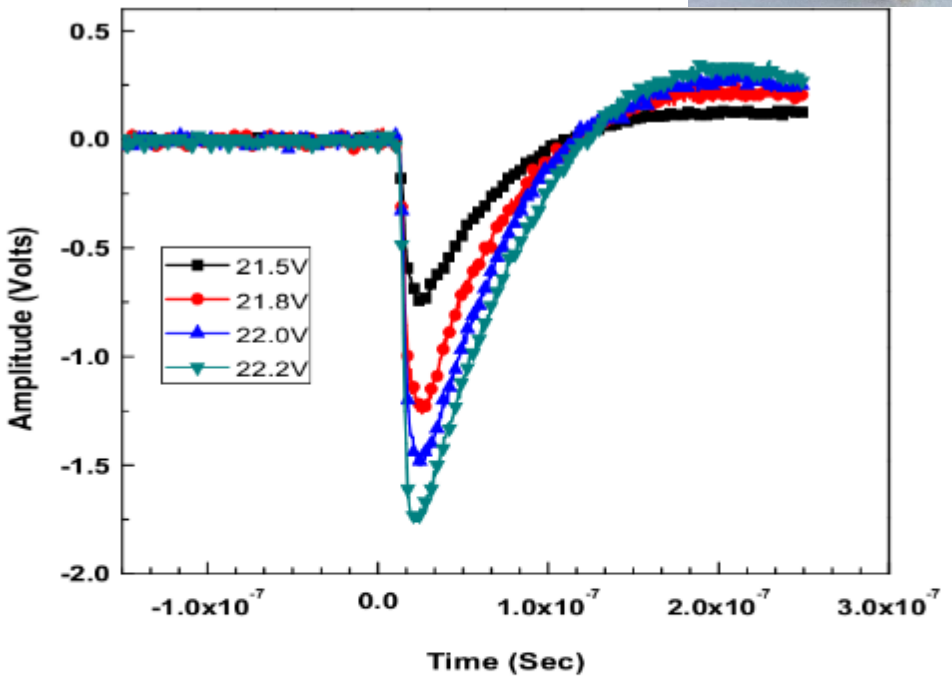
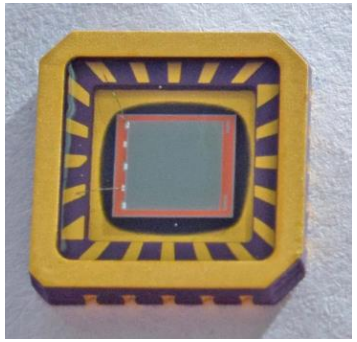
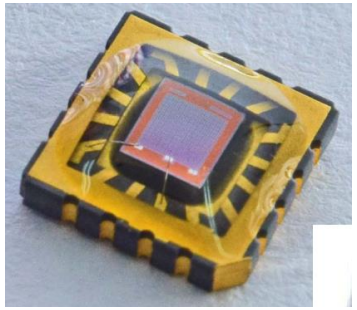



**Figure 10.** Response of a SiPM to external light photons at different bias voltages. The SiPM pulse width is about 100 ns. The amplitude of output pulse increases with bias voltage.

[Ref] A.Topkar et.al, (2020) JINST 15 P03032 https://iopscience.iop.org/article/10.1088/1748-0221/15/03/P03032/pdf



# Comparison: On-semi and BARC/SCL



| S No | Sensitive area — 3 mm × 3 mm, Pixel size — 50 µm × 50 µm | | |
|---|---|---|---|
| | | On Semiconductor C-Series 30050 | Present work |
| 1 | Breakdown voltage | 24.2 V | 22.0 V |
| 2 | No of pixels | 2668 | 2704 |
| 3 | Fill factor | 72% | 75% |
| 5 | Gain | $6 \times 10^6$ @ $V_{BD}$ +2.5 V | ~ $2 \times 10^6$ @ $V_{BD}$ +1.0 V |
| 6 | Temperature dependence of $V_{BD}$ | 21.5 mV/°C | 20.0 mV/°C |
| 7 | Capacitance (cathode - anode) | 920 pF | 1000 pF |
| 8 | Dark count rate | @ $V_{BD}$ +2.5 V Typ. 300 kHz | @ $V_{BD}$ +2.0 V Typ. 500 kHz (at 0.5 p.e.) |
| 9 | Crosstalk | @ $V_{BD}$ +2.5 V 10% | @ $V_{BD}$ +2.0 V < 5% |

[Ref] A.Topkar et.al, (2020) JINST 15 P03032 https://iopscience.iop.org/article/10.1088/1748-0221/15/03/P03032/pdf

# SiPM Fabricated at SCL: Test done @ SCL



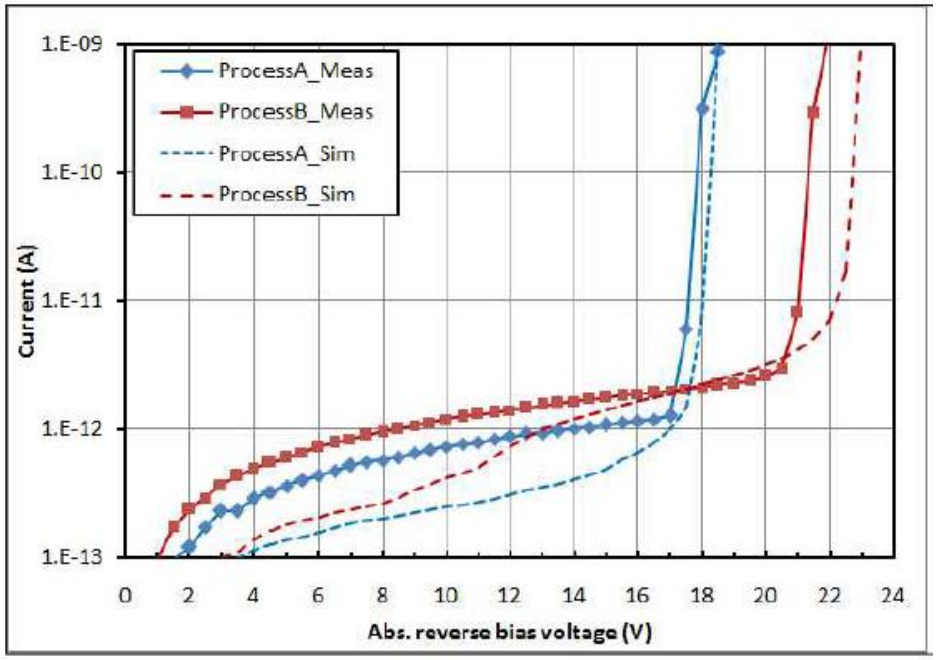



Fig. 6. Reverse I-V TCAD simulated Vs measured on silicon.

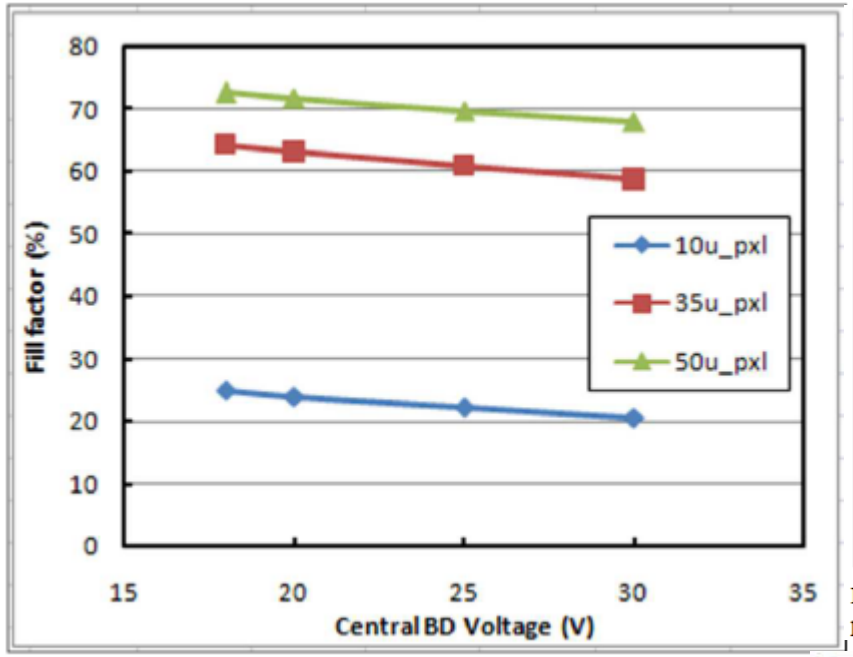



Fig. 9. Fill factor roll-off w.r.t central breakdown voltage.

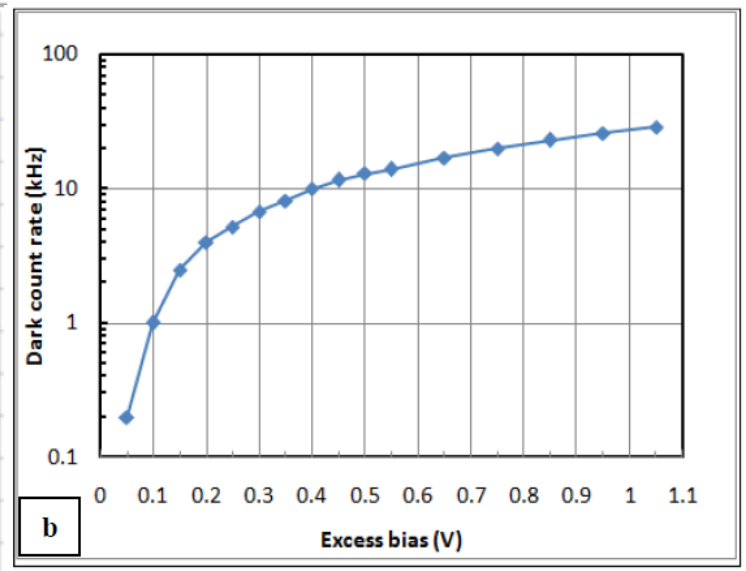


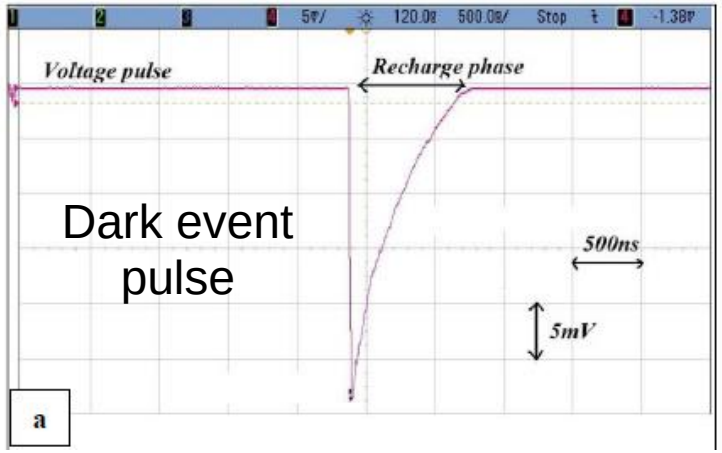

Fig. 10. (a) Dark event pulse (b) Dark count rate of SPAD (35x35 sq um pixel area) at different excess bias voltage


SCL:

Size: 1.5 x 1.5 $mm^2$

Pixel size: 35 x 35 $\mu m^2$

No. of pixels: 1156




[Ref] A. Yasser et.al, "Fabrication and Electrical Measurements of CMOS-integrated GM-APDs and Test Structures in 180nm CMOS Technology Platform," 2022 IEEE 19th India Council International Conference (INDICON), Kochi, India, 2022, pp. 1-4, doi: 10.1109/INDICON56171.2022.10040143.

# Technical Specifications of SiPM



Bhabha Atomic Research Center (BARC), Mumbai

| Sr. No | Parameter (targeted by design) | Specifications | | |
|---|---|---|---|---|
| | | BARC/SCL | SCL | BEL |
| 1 | Effective active area ($mm^2$) | 1.5 x 1.5 & 3 x3 | 1.5 x 1.5 | 3.3 x 3.3 |
| 2 | Micro-cell count | 676 & 2704 | 1156 | 4836 |
| 3 | Micro-cell size | 50 x 50 $\mu m^2$ | 35 x 35 $\mu m^2$ | |
| 4 | Micro-cell fill factor | 20% & 75% | 61% | 55% |
| 5 | Capacitance (Cathode - anode) | 1000 pF | ~330 pF | ~100pF/cell and (500 pF @25.5V) |
| 6 | Recharge time constant | 120 ns – 150 ns | - | - |
| 7 | Spectral response range | 350 nm – 900 nm | - | 350 nm – 900 nm |
| 8 | Peak sensitivity wavelength | ~ 500 nm | - | 420 – 450 nm |
| 9 | Photon detection efficiency | - | - | - |
| 10 | Breakdown voltage ($V_{BD}$) | 22 V | 18 V | 23 V |
| 11 | Overvoltage range (OV) | 2 V – 3 V | 2.5 V | 2 V – 5 V |
| 12 | Dark count rate | ~ 500 kHz (@ $V_{BD}$+2.0 V and 0.5 p.e. thr. | 20 Hz/ $\mu m^2$ at 1V OV | - |
| 13 | Gain | 2 x $10^6$ @ $V_{BD}$+1V | ~ $10^6$ | ~5.2 x $10^5$ @$V_{BD}$+2V |
| 14 | $V_{BR}$ temp. coefficient | 20.0 mV/ºC | 15.0 mV/ºC | - |
| 15 | Package type | LCC* 16, 20 pin | TO-8/6 pin | On PCB |
| 16 | Package dimension | ~ 3.5 x 3.5 $mm^2$ | | |
| 17 | Dark current | < 5 nA/$cm^2$ @ 20V | < 10 nA/$cm^2$ | - |
| 18 | Quenching resistor ($R_q$) | 300-500 kΩ | 360 kΩ | $R_{eq}$ = 6.6 kΩ and $R_q$ = ~ 32 MΩ |
| 19 | Cross-talk | < 5 % @$V_{BD}$+2.0 V | - | - |

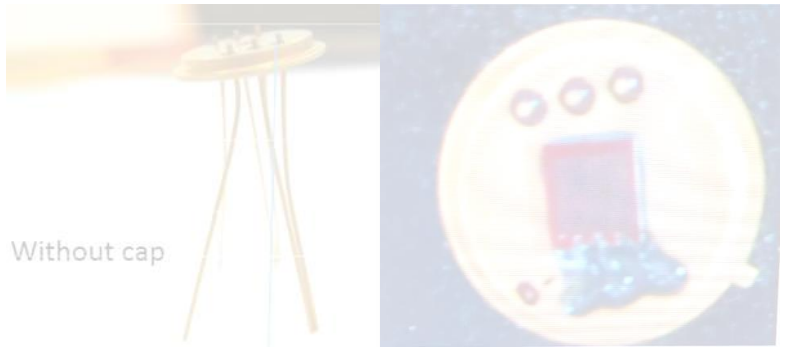
*Lead-Less Chip Carriers (LCC)

Not to scale



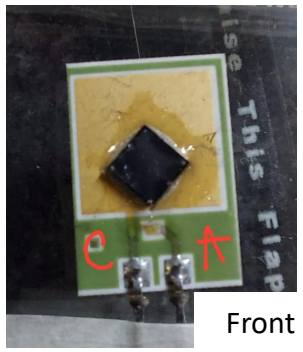
**BARC/SCL**
(epi., p-type)

Not to scale




**SCL sample**
(epi., p-type)

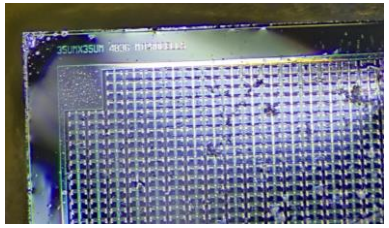
Not to scale

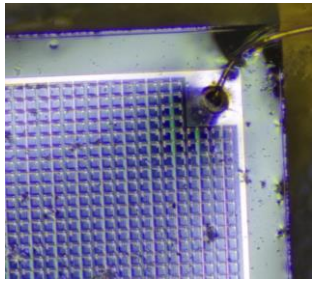


Front

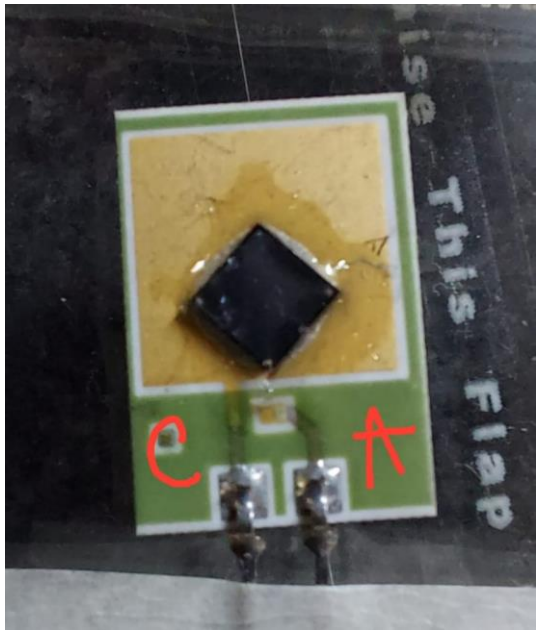

Back

**BEL sample:**
(Non-epi, n-type)





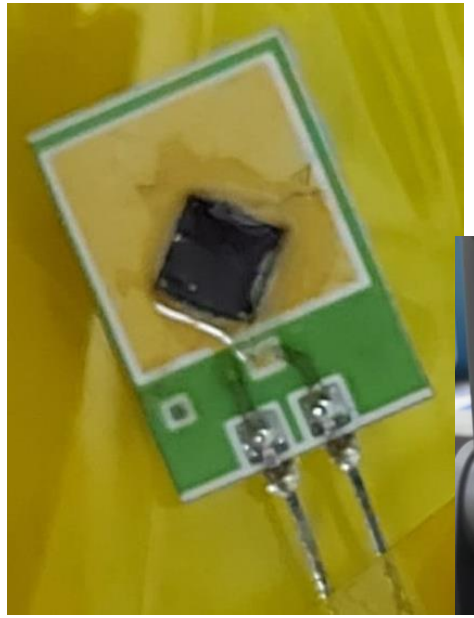
# Next slides on test done by NISER using SiPM samples received from BEL




# BEL SiPM test done @NISER - Dark Current plot

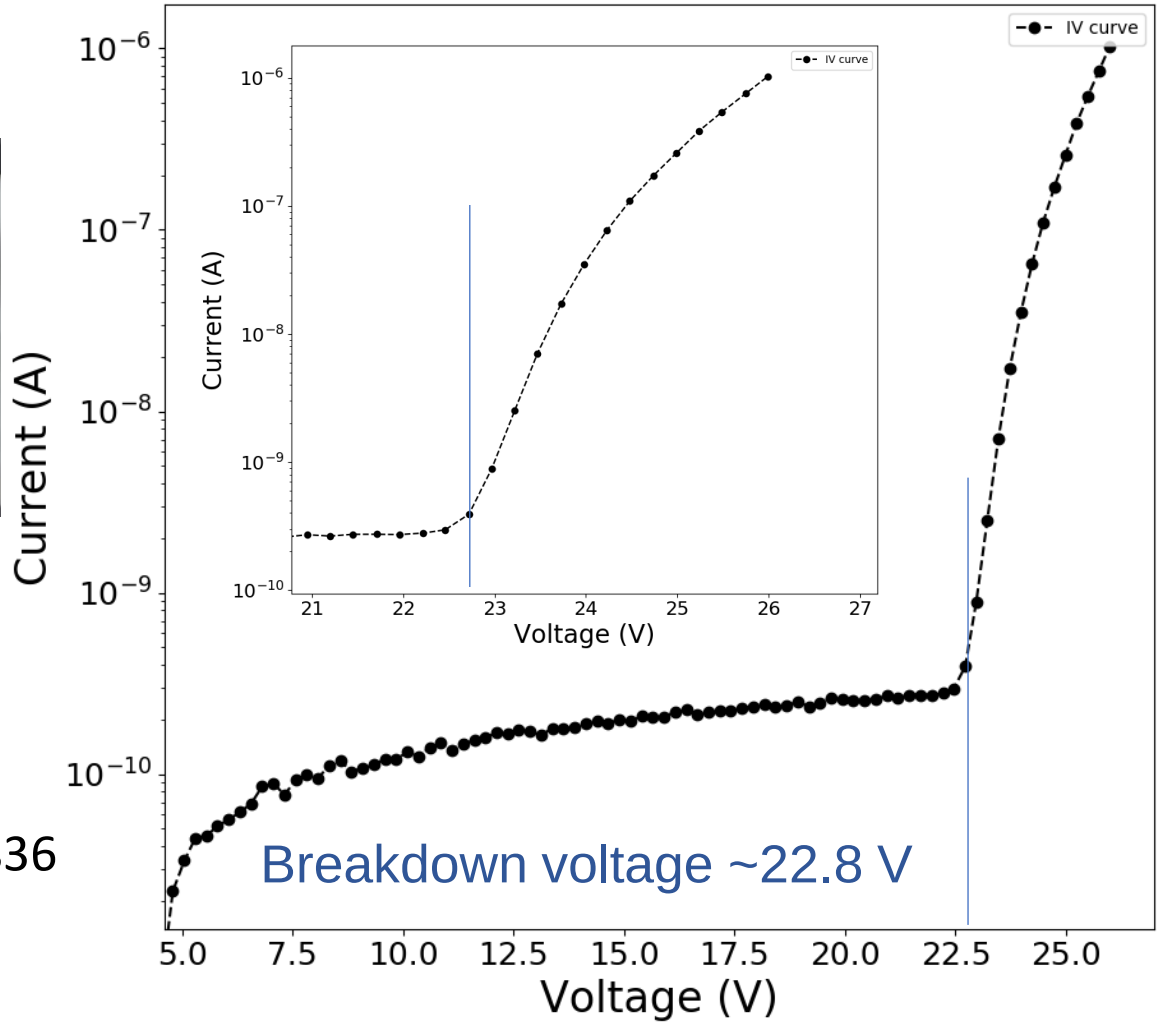


SiPM sample on PCB



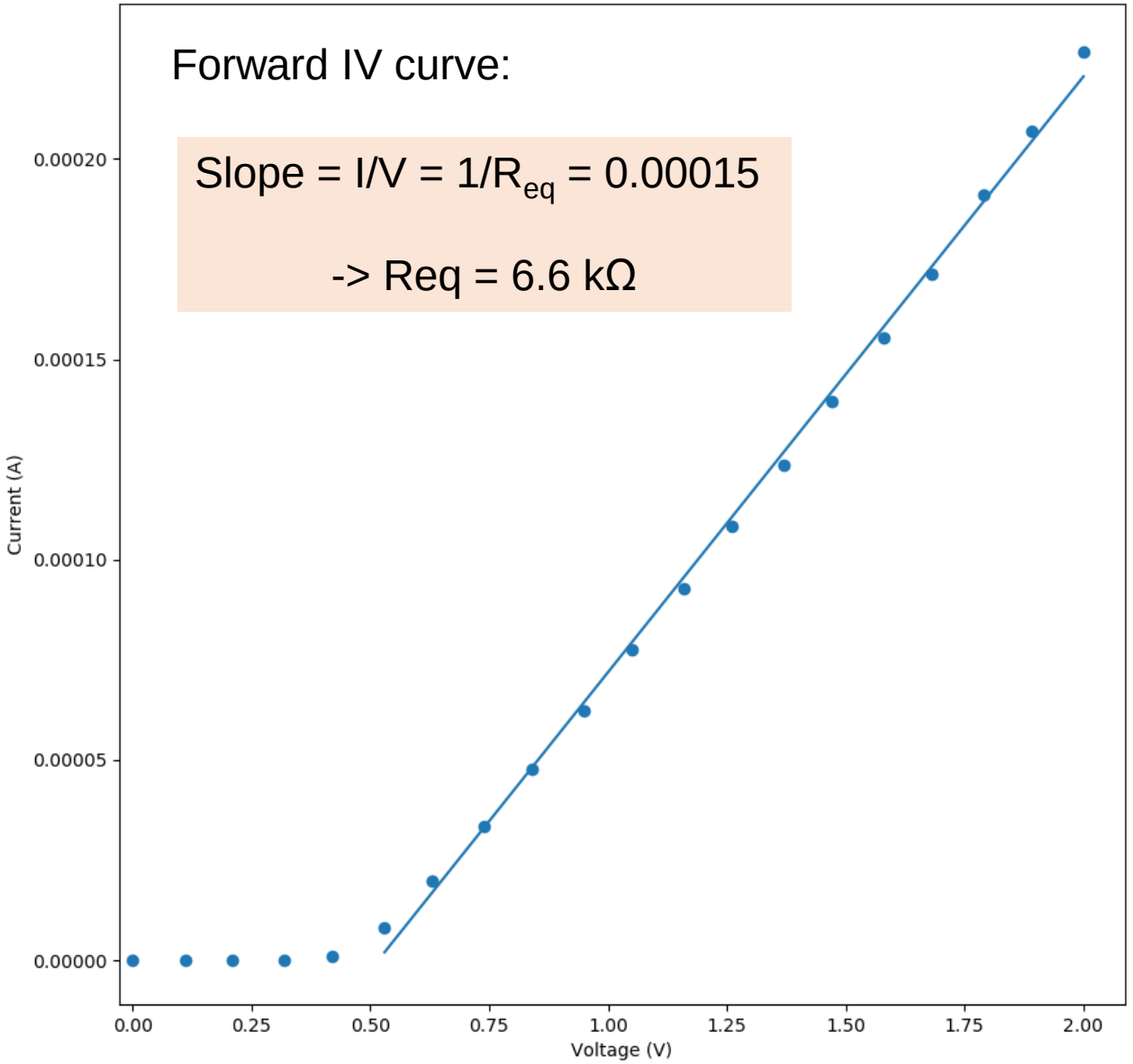
SMU screen


- Connected in Reverse bias mode
- Reverse bias voltage applied using Keithley 2470
  - sweep: 0 to 26 V (0.25 V step)



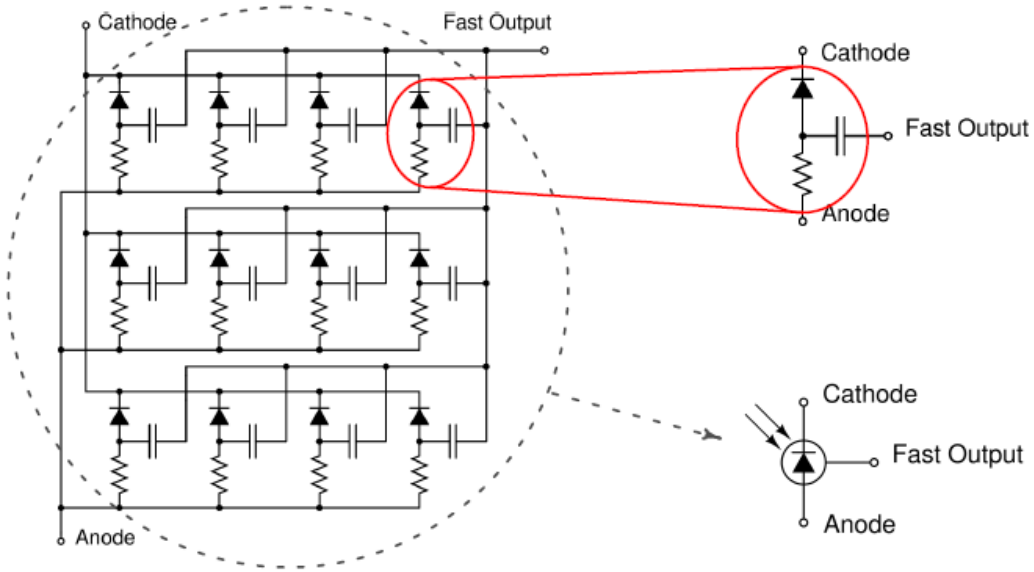

- SiPM fabricated on non-epi, n-type wafer
- SiPM was mounted on a PCB
- Pixel size: 35 x 35 µm$^2$
- Effective area: 3 x 3 mm$^2$ and No. of pixels: 4836
- Fill factor: 55%, Peak sensitivity: ~450 nm
- Breakdown volt.: ~23V

# BEL SiPM test done @ NISER: Quench resistor value




- Connected in Forward bias mode
- Bias voltage applied using Keithley 2470
  - sweep: 0 to 2 V (0.11 V step)

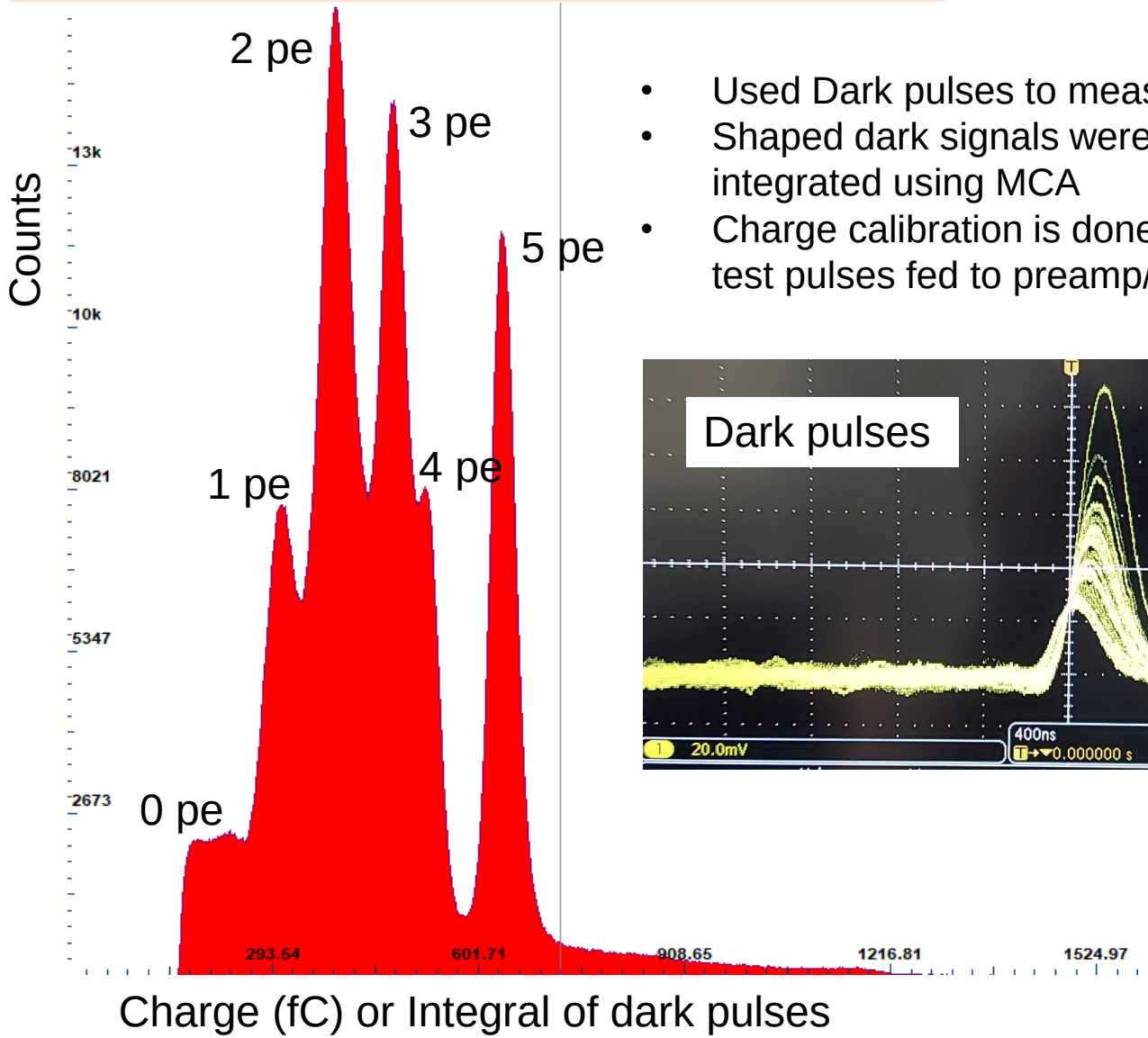
$R_q$ = $R_{eq}$ x No. of pixels
= 6.6 k Ω x 4836
$R_q$ = ~32 M Ω



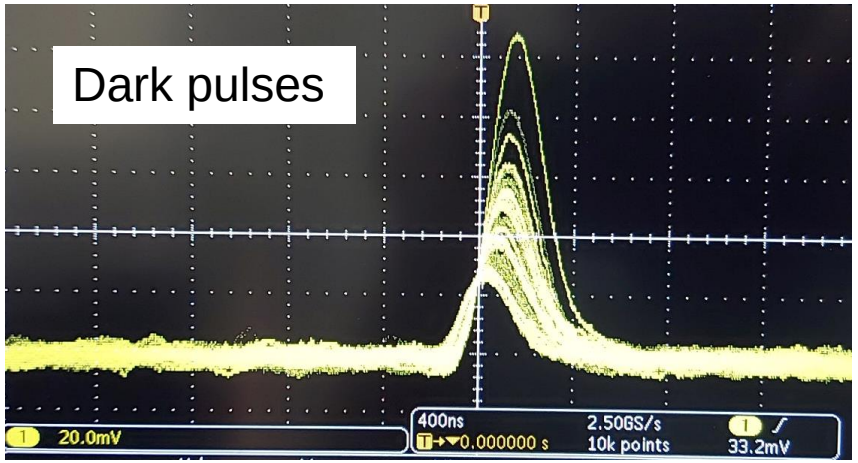
# BEL SiPM test done @ NISER: Gain



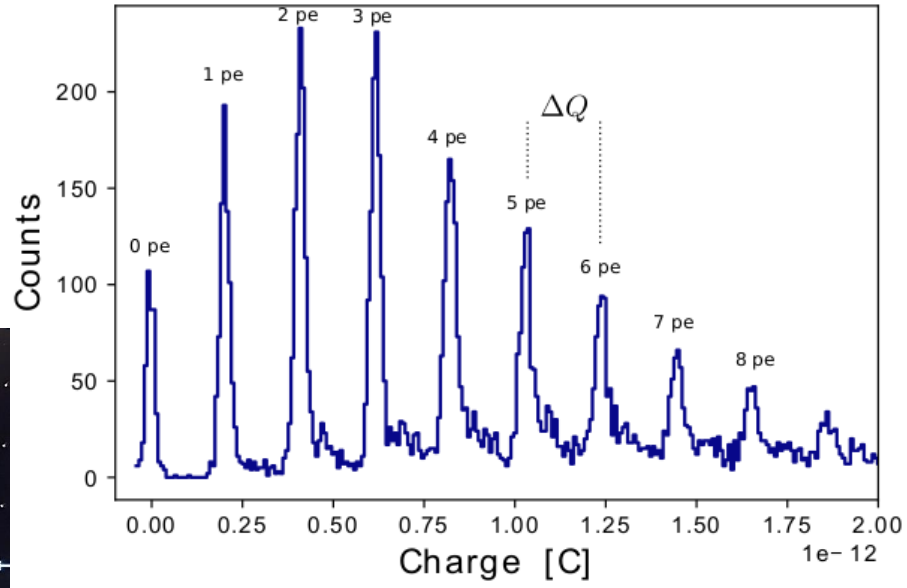
Measured charge spectrum using Dark pulses




- Used Dark pulses to measure gain
- Shaped dark signals were integrated using MCA
- Charge calibration is done using test pulses fed to preamp/shaper




Ideal charge spectrum using fast LED light [Ref.]




Gain = ΔQ/e-

$= C_d \cdot (V_{Bias} - V_{BD})/e^-$

ΔQ = (3 pe mean – 2 pe mean)

$e^- = 1.6 \times 10^{-19}$ C

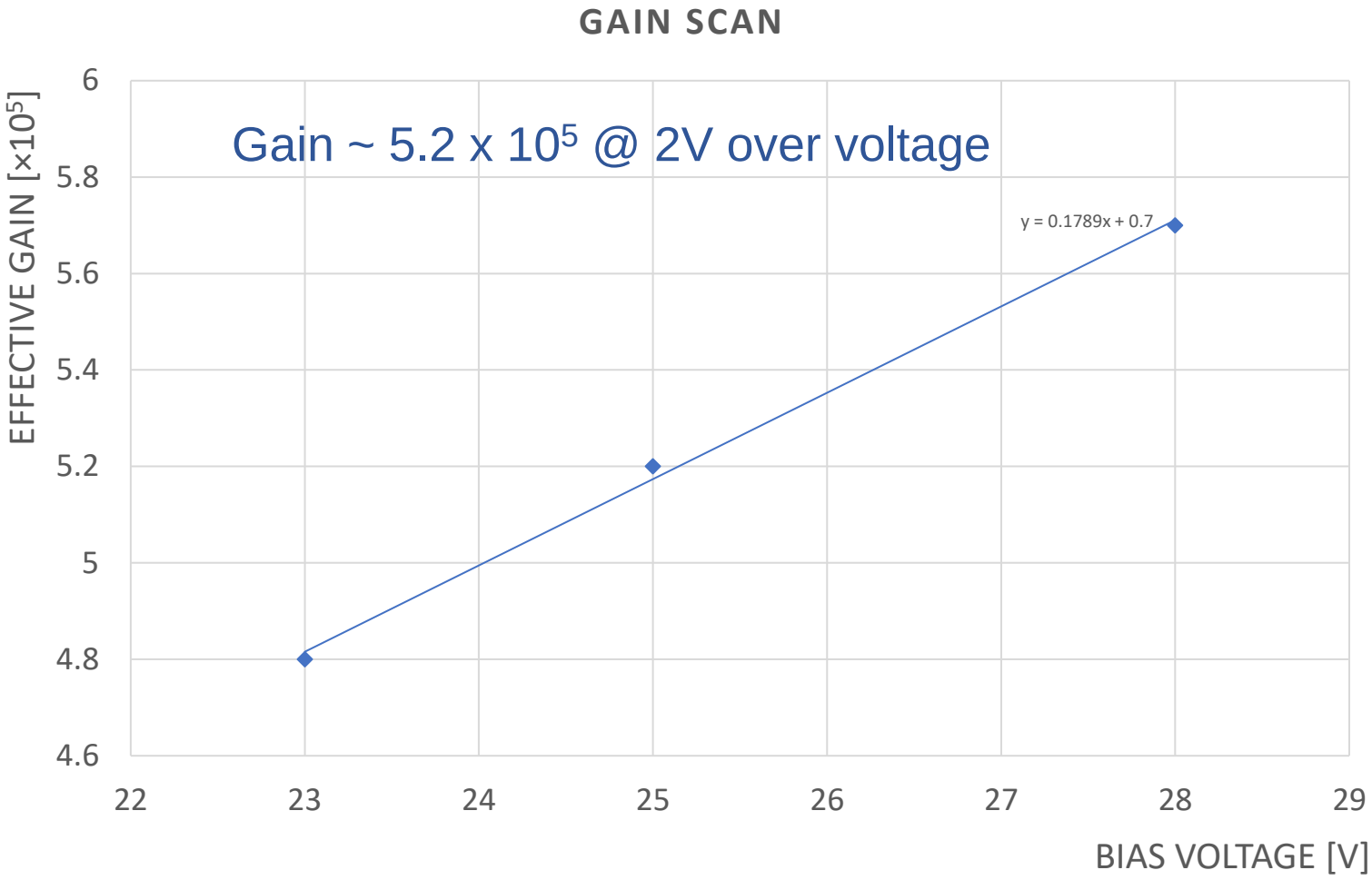
$C_d$= detector capacitance

$V_{Bias}$ = applied bias voltage

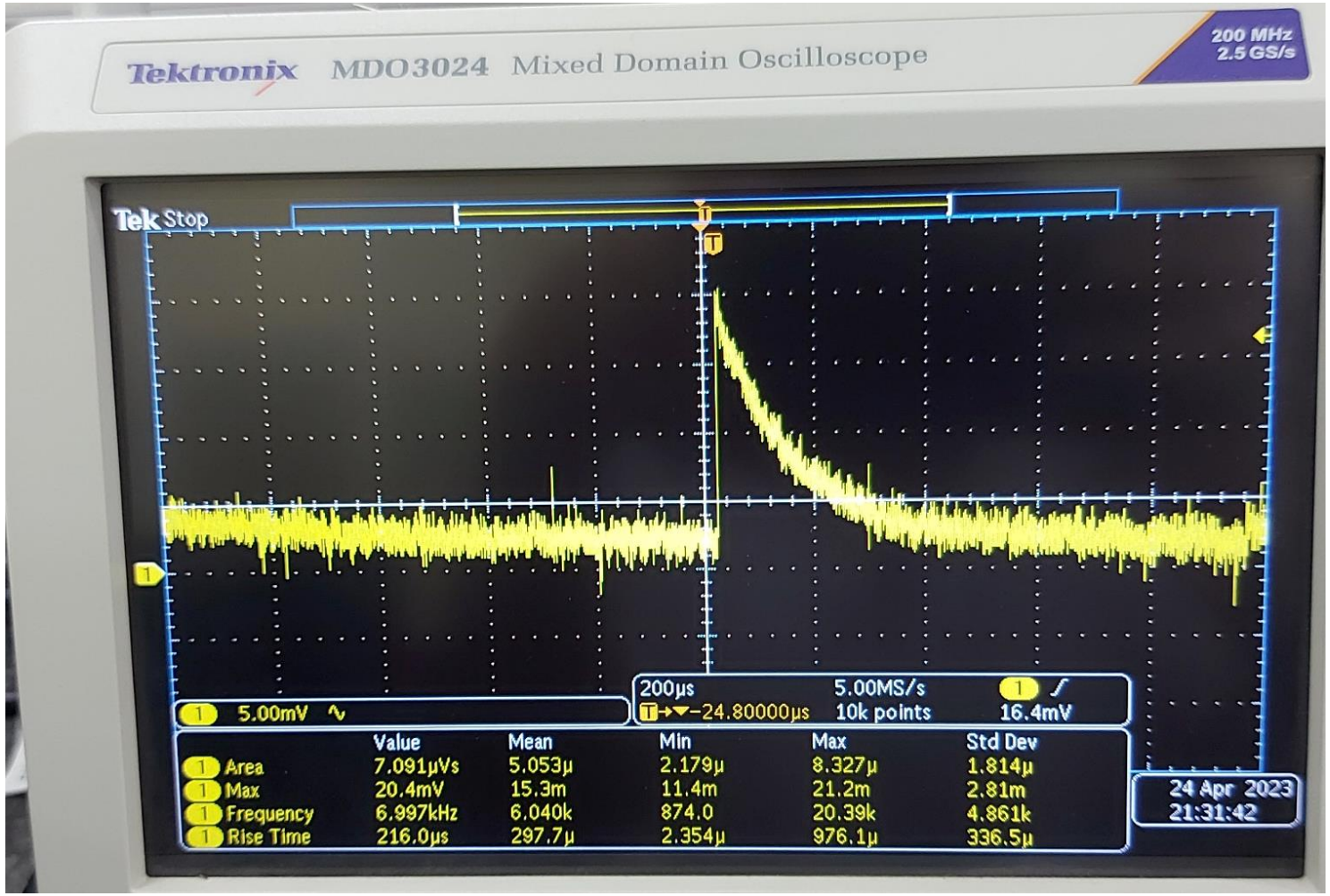
$V_{BD}$ = breakdown voltage

[Ref] J. P-Rodrigues et.al, (2022) Instruments 2023, 7, 7. https://doi.org/10.3390/instruments7010007

# BEL SiPM test done @ NISER: Gain



# BEL SiPM test done @ NISER: Dark count rate




Dark count rate ~ 7 kHz at 22.5 V bias

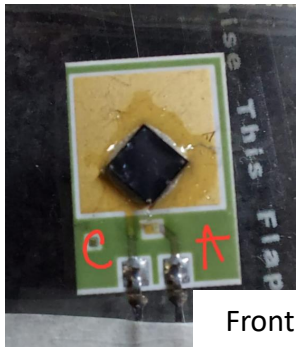
Rate increase with bias voltage

# BEL SiPM: Specifications comparison

| Sr. No | Parameter (targeted by design) | Specifications | | |
|---|---|---|---|---|
| | | BARC/SCL | SCL | BEL |
| 1 | Effective active area | 1.5 & 3 $mm^2$ | 1.5 $mm^2$ | 3.3 $mm^2$ |
| 2 | Micro-cell count | 676 & 2704 | 1156 | 4836 |
| 3 | Micro-cell size | 50 $\mu m^2$ | 35 $\mu m^2$ | |
| 4 | Micro-cell fill factor | 20% & 75% | 61% | 55% |
| 5 | Capacitance (Cathode - anode) | 1000 pF | - | ~100pF/cell and (500 pF @25.5V) |
| 6 | Recharge time constant | 120 ns – 150 ns | | - |
| 7 | Spectral response range | 350 nm – 900 nm | | |
| 8 | Peak sensitivity wavelength | ~ 500 nm | ~ 510 nm | 420 – 450 nm |
| 9 | Photon detection efficiency | - | - | - |
| 10 | Breakdown voltage ($V_{BD}$) | 22 V | 15 V - 21 V | 23 V |
| 11 | Overvoltage range (OV) | 2 V – 3 V | 3 V | 2 V – 5 V |
| 12 | Dark count rate | ~ 500 kHz (@ $V_{BD}$+2.0 V and 0.5 p.e. thr. | 20 Hz/ $\mu m^2$ at 1V OV | - |
| 13 | Gain | 2 x $10^6$ @ $V_{BD}$+1V | ~$10^5$ - $10^6$ | ~5.2 x $10^5$ @$V_{BD}$+2V |
| 14 | $V_{BR}$ temp. coefficient | 20.0 mV/°C | 15.0 mV/°C | - |
| 15 | Package type | LCC* 16, 20 pin | TO-8/6 pin | On PCB |
| 16 | Package dimension | ~ 3.5 $mm^2$ | | |
| 17 | Dark current | < 5 nA/$cm^2$ @ 20V | < 10 nA/$cm^2$ | - |
| 18 | Quenching resistor ($R_q$) | 300-500 kΩ | 2 kΩ | $R_{eq}$ = 6.6 kΩ and $R_q$ = ~ 32 MΩ |
| 19 | Cross-talk | < 5 % @$V_{BD}$+2.0 V | - | - |

*Lead-Less Chip Carriers (LCC)

Not to scale





**BEL sample:**
(Non-epi, n-type)

## Test result comparison with design

| parameter | BEL | Test results NISER |
|---|---|---|
| Breakdown voltage ($V_{BD}$) | 23V | ~22.8V |
| Quenching/ series resistor($R_q$) | - | $R_q$ ~ 32 MΩ (Req=6.6kΩ) |
| Gain | $10^5$ | 5.2x$10^5$ |
| Dark Count Rate | - | ~ 7 kHz@ 22.5V |

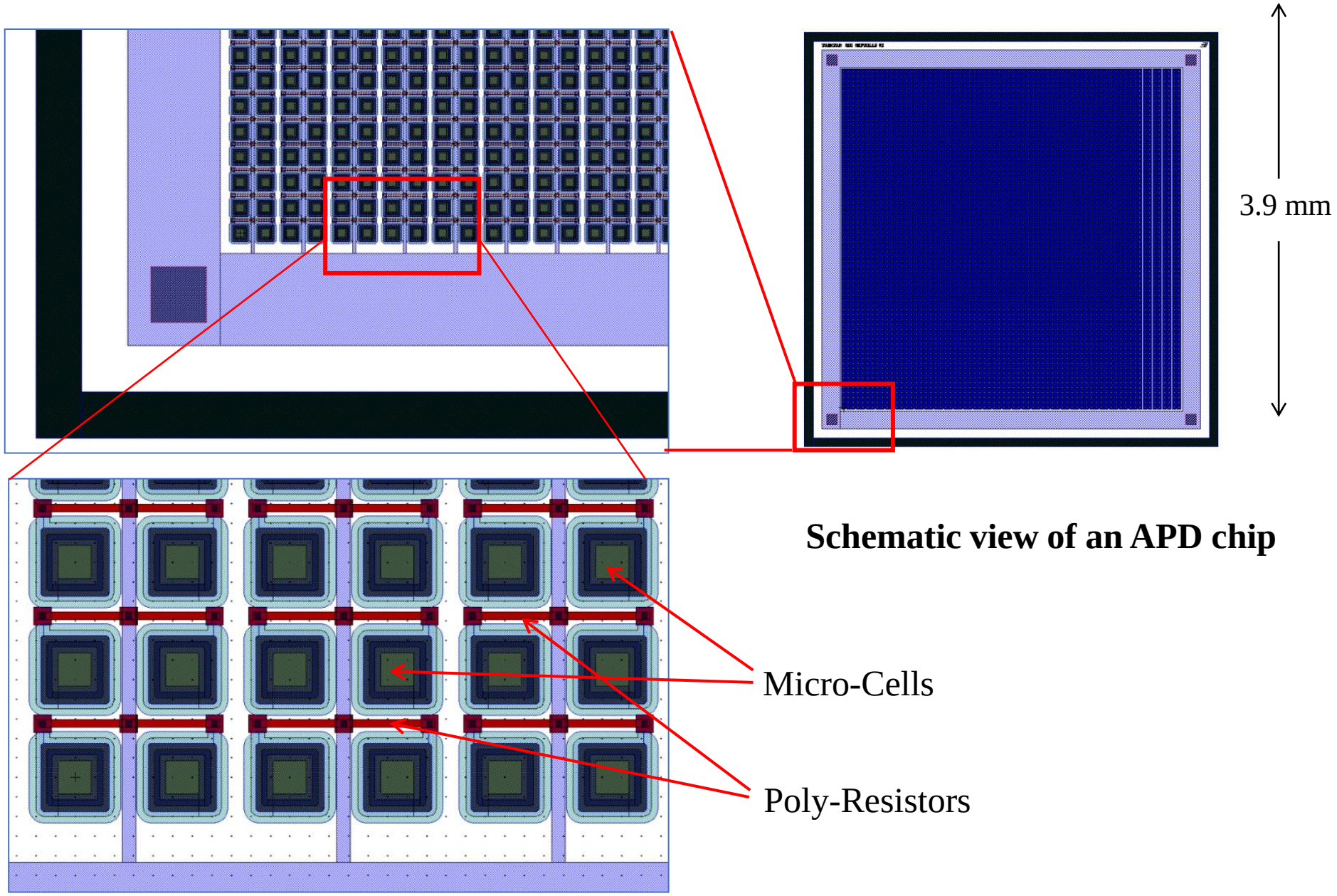
# New SiPM development at BEL

## BEL: working on the design and fabrication of SiPM

Targeted Technical Specification for Internal proactive development of SiPMs:

| Sl. No. | Parameter | Value |
|---|---|---|
| 1 | Number of Pixels | 4 x4 |
| 2 | Pixel Active area | 3 mm x 3 mm |
| 3 | Number of microcells | 4774 |
| 4 | Size of microcell | 35 micron x 35 micron |
| 5 | Typical Quench Resistor Value | 200 kΩ to 300 kΩ |
| 6 | Typical Breakdown Voltage (VBR) | 25 Volt |
| 7 | Typical Operating/Bias Voltage Range | (VBR + 1 Volt) to (VBR + 5 Volt) |
| 8 | Typical microcell Gain | $3 \times 10^6$ @ VBR+2.5 Volt @ RT |
| 9 | Device Light Sensitivity Range | 300 nm to 800 nm, with peak sensitivity @ 400nm. |
| 10 | Rise time | ~ 1 ns @ VBR + 2.5 Volt |
| 11 | Capacitance (anode to cathode) | 850 pF @ VBR + 2.5 |

# New SiPM development at BEL: Mask Layout of SiPMs die




**Schematic view of an APD chip**

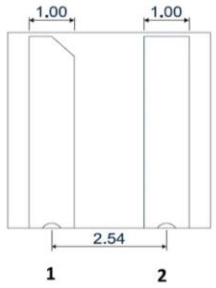
# Imported SiPM packaged at BEL

**Technical Specification of Silicon Photo Multiplier:**

| Sl. No. | Parameter | Specifications |
|---|---|---|
| 1 | Effective active area | 3 mm × 3 mm |
| 2 | Micro-Cell count | 5520 |
| 3 | Micro-Cell size | 40 um x 40 um |
| 4 | Micro-Cell fill-factor | 60 - 65 % |
| 5 | Micro-Cell capacitance | 90 fF |
| 6 | Recharge time constant | 70 ns |
| 7 | Spectral response range | 350- 900 nm |
| 8 | Peak sensitivity wavelength | 420 nm |
| 9 | Photon detection efficiency | > 40 % |
| 10 | Breakdown voltage (BV) | 26 V ± 2 V |
| 11 | Recommended Overvoltage range (OV) | 2 – 6 V |
| 12 | Dark count rate | < 100 kHz/mm2 @ 5V OV |
| 13 | Gain | $3 – 4 \times 10^6$ |
| 14 | Breakdown voltage temperature coefficient | ~ 25 mV/°C |
| 15 | Encapsulant Type | Clear transfer molding compound (Epoxy) |
| 16 | Refractive index of encapsulating epoxy resin | 1.5115 @ 589 nm |
| 17 | Packaging Type | Nickel free Chip Scale Package (CSP) / surface mount (SMT) package |
| 18 | Package Dimension | 3.5 mm x 3.9 mm |

Packaged at BEL, made in Germany:

**Electrical Connections:**

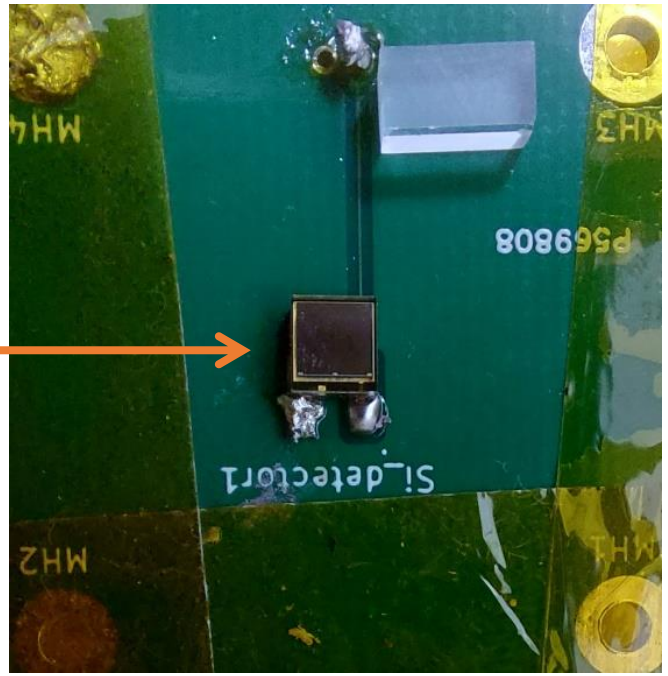



| Pin | Name | Function |
|---|---|---|
| 1 | K | Cathode |
| 2 | A | Anode |

# Imported SiPM – Dark current

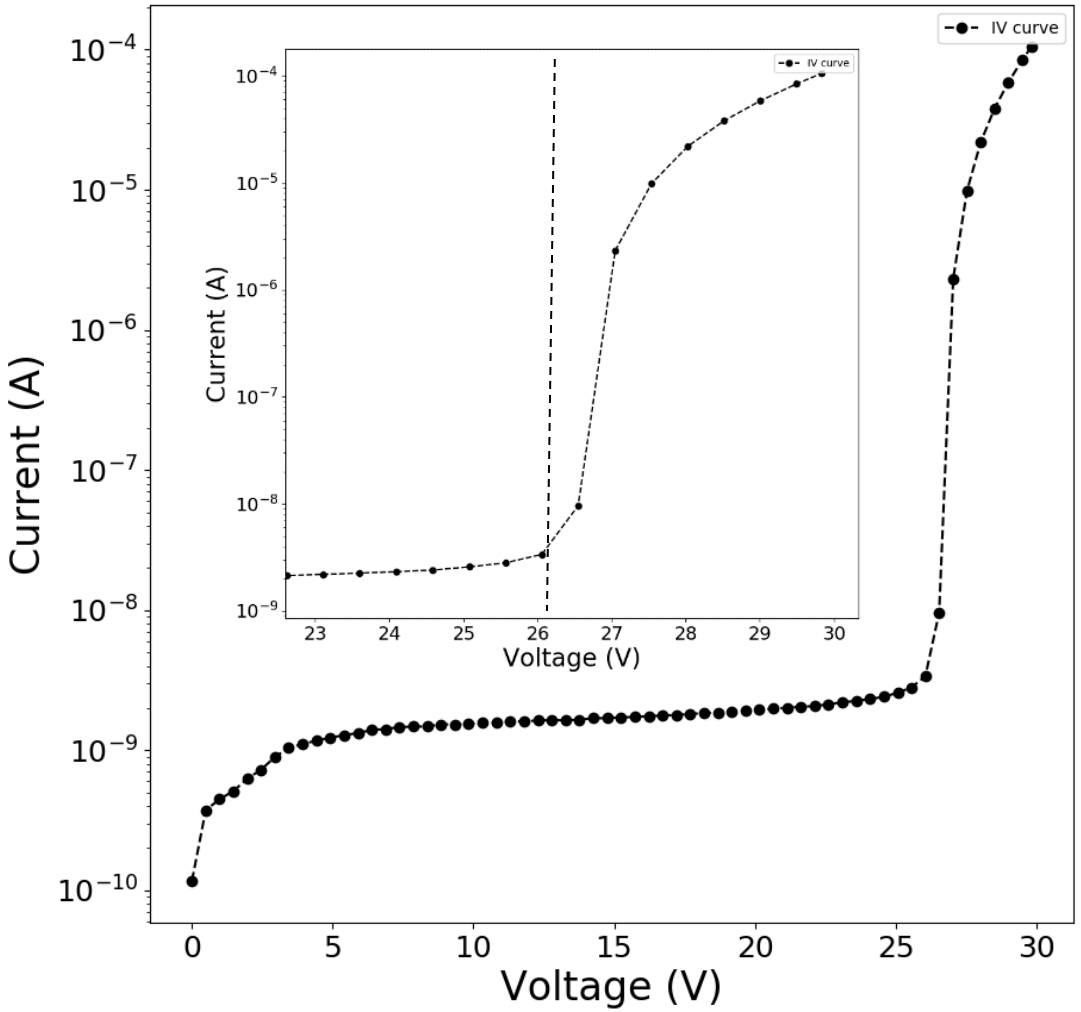
- SiPM was mounted on a PCB
- Connected in Reverse bias mode
- Reverse bias voltage applied using Keithley 2470
  - ➢ sweep: 0 to 28 V (0.5 V step)

SiPM
3x3 mm²



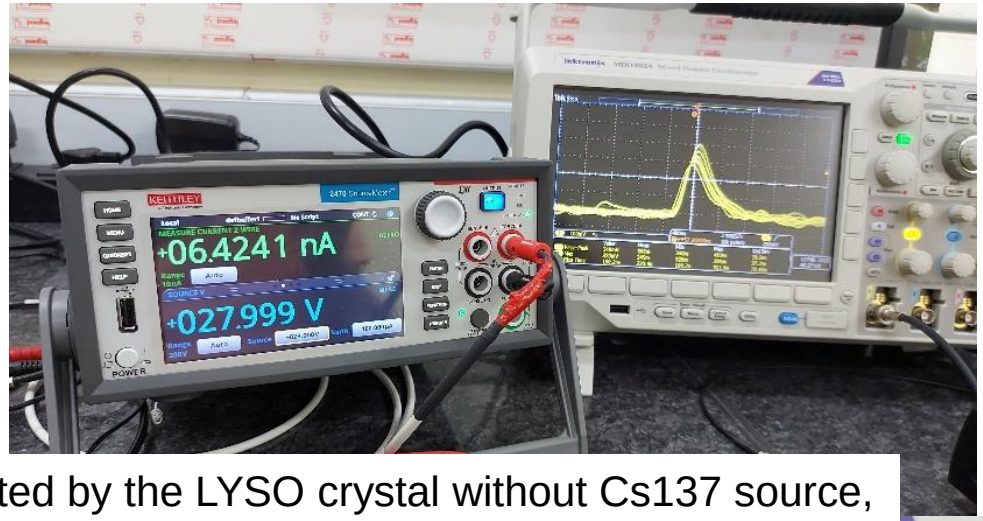

Packaged at BEL, made in Germany. BEL could sell this to Indian institutes (partly made in India product!)

I-V curve: Breakdown voltage ~26 V

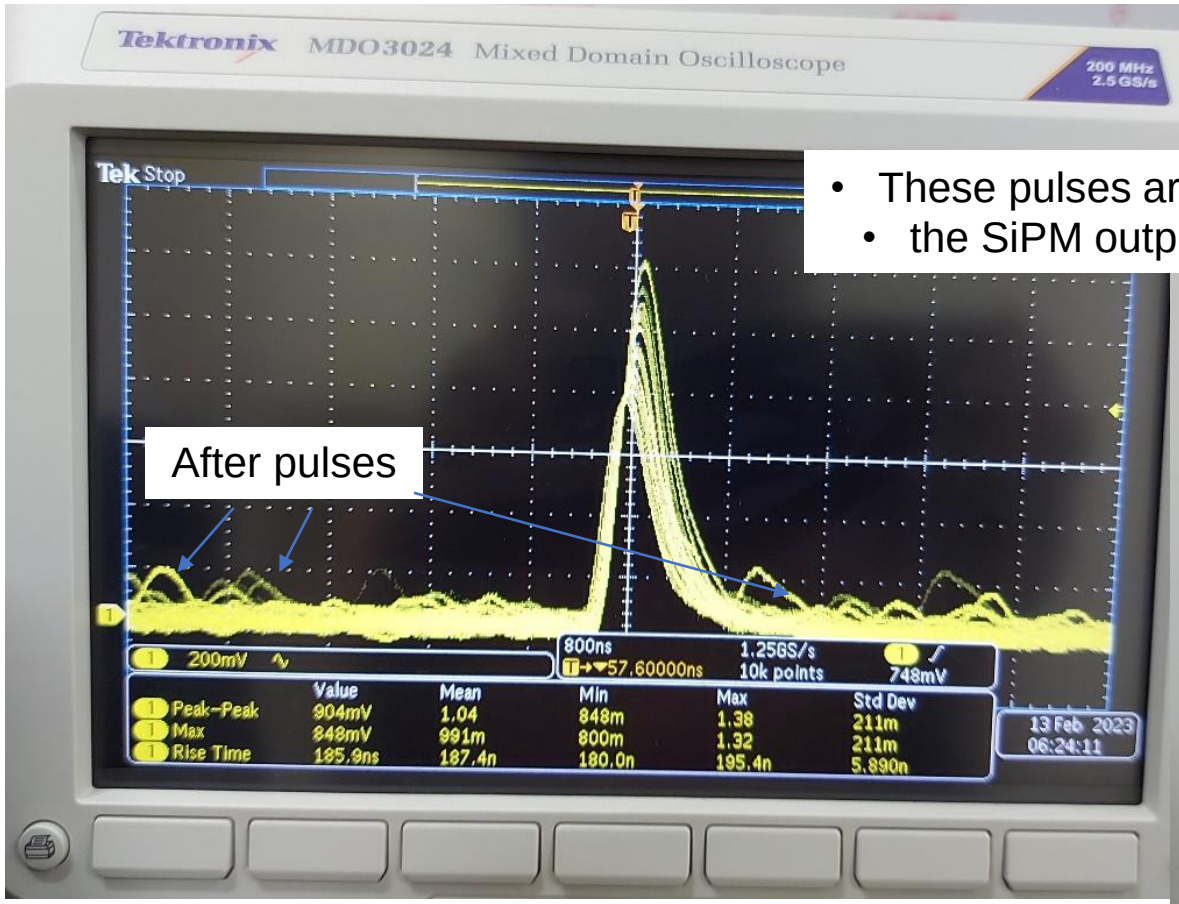


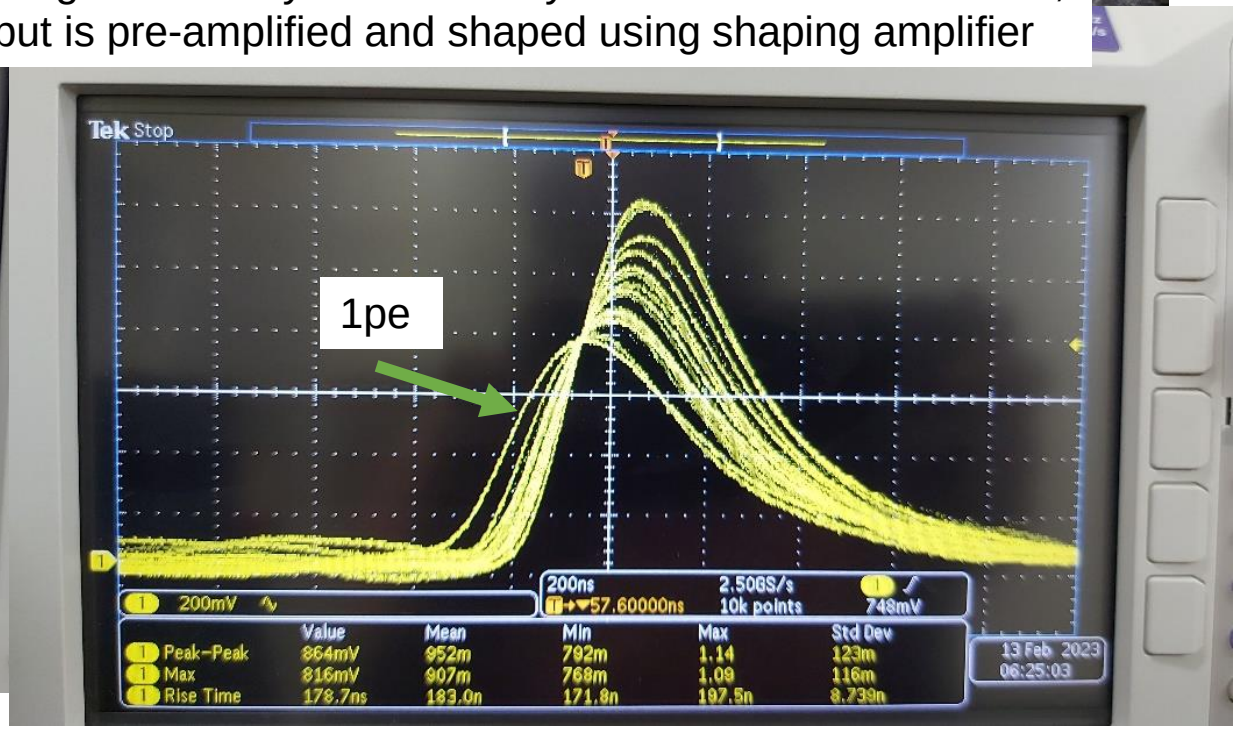
# Imported SiPM – Signals

- SiPM was coupled to LYSO crystal
- Setup operated at 28 V reverse bias



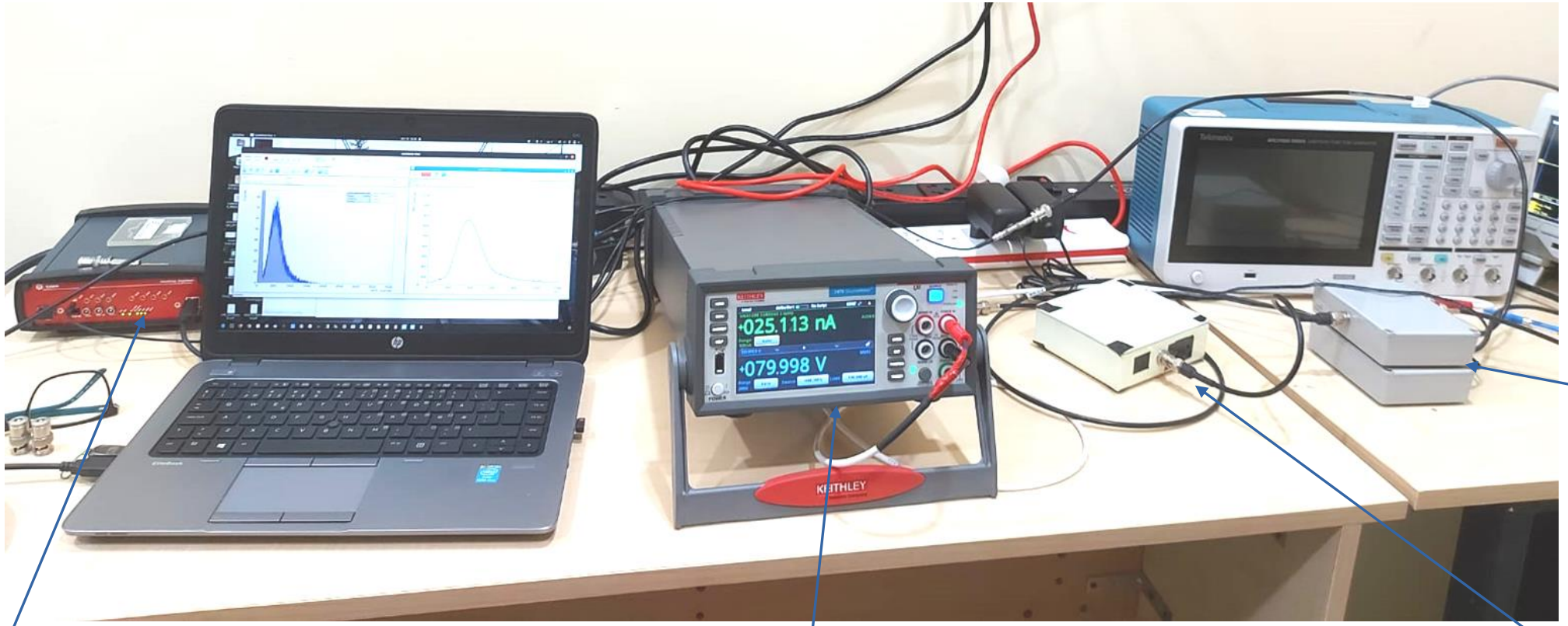

- These pulses are generated by the LYSO crystal without Cs137 source,
- the SiPM output is pre-amplified and shaped using shaping amplifier




Single photo e- pulses and after-pulses are visible

# Test setup @ NISER: Few channels




Preamp
(cremat 110) and
Shaping amplifier
(cremat 200)

CAEN Digitizer (DT5730) 8 ch, 14 bit resolution, 500 MS/s sampling rate, 2Vpp dynamic range

With DPP firmware

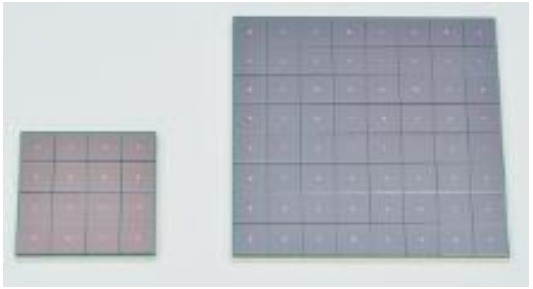
Detector bias supply
(Keithley 2470 SMU)

SiPM inside
the detector box

# SiPM large array readout option @ NISER

- We have purchased the electronics to readout RPCs, originally designed for SiPM arrays
- 4 chips (32 channels each): could readout 128 SiPMs

MPCC array Hamamatsu
S13361-3050 series



- Complete readout system based on Weeroc ASICs and with programmable FPGA.
- PETIROC ASIC:

  Input channels: 32 voltage inputs
  Signal polarity: positive or negative
  Dynamic range: 0-480 pC
  32 trigger outputs
  40 ps bin TDC

- FPGA:

  Xilinx XC7K160T open FPGA

# Preparation of SiPM test station @ NISER

- LED driver ordered, arriving soon

## SP5601

**LED Driver**

Request a quote

Manual | Downloads

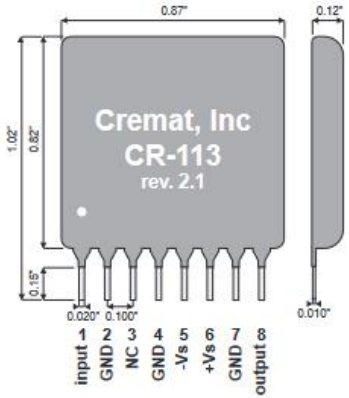

### Features

- Pulse width: 8 ns
- LED color: violet (400 nm) 1500 mcd
- Pulse generator: internal/external
- Optical output connectors: FC
- Optical fiber included
- Dimension: 79 x 42 x 102 $mm^3$ (WxHxD

- Cremat fast preamp order in process


**Detector coupling**

The CR-113-R2.1 can be used either in a direct coupled (DC) mode or an AC coupled mode. If the detector current exceeds




cremat

+1(617) 527-6590
http://cremat.com

## Specifications

Assume temp =20 °C, $V_s$ = ±6V, unloaded output

| | CR-113-R2.1 | units |
|---|---|---|
| Preamplification channels | 1 | |
| Equivalent noise charge (ENC)* | | |
| ENC RMS | 18,000 | electrons |
| | 3 | femtoCoul. |
| ENC slope | 30 | elect. RMS /pF |
| Gain | 1.3 | mV / picoCoul. |
| Rise time ** | 1 | ns |
| Decay time constant | 50 | µs |
| Unsaturated output swing | -3 to +3 | volts |
| Maximum charge detectable per event | 1.3 x$10^{10}$ | electrons |
| | 2.1 | nanoCoul. |
| Power supply voltage ($V_s$) | | |
| maximum | $V_s$ = ±13 | volts |
| minimum | $V_s$ = ±6 | volts |
| Power supply current (pos) | 5 | mA |
| (neg) | 5 | mA |
| Power dissipation with no load | 70 | mW |
| Operating temperature | -40 to +85 | °C |
| Output offset | +0.2 to -0.2 | volts |
| Output impedance | 50 | ohms |

# Summary

- There are two fabs which are involved in the development of SiPMs - initial results look promising, there is capability to fabricate SiPM using CMOS technology.
- Initial discussion with Fab engineers, they have show keen interest in collaborating with us and they are willing to help us for further development.
- Once the requirements are clear, the research work can be initiated focused to the EPIC activities.
- Work in progress to set up SiPM test station at NISER.

Thanks!