Radiation hard SiPM development for CEPC calorimeter

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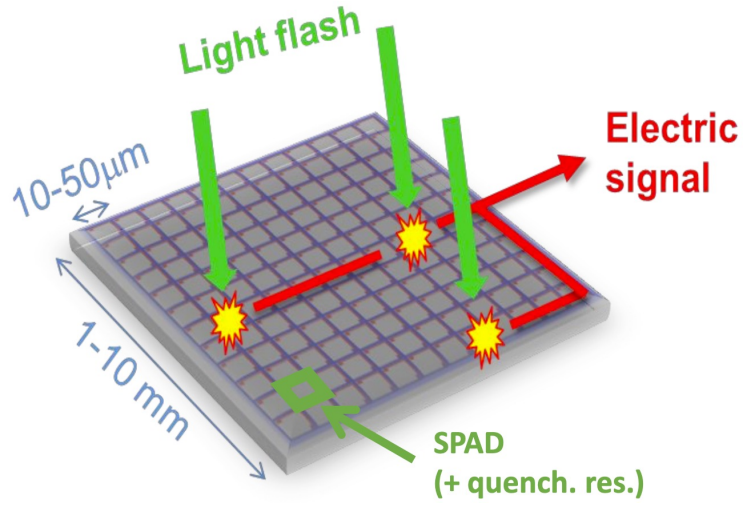
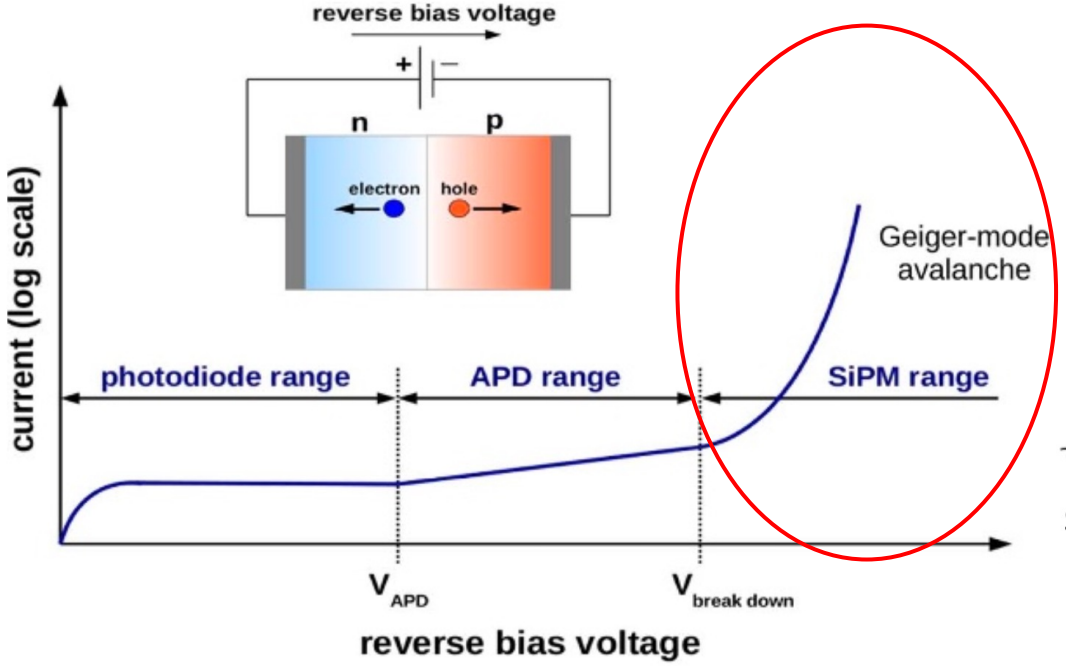
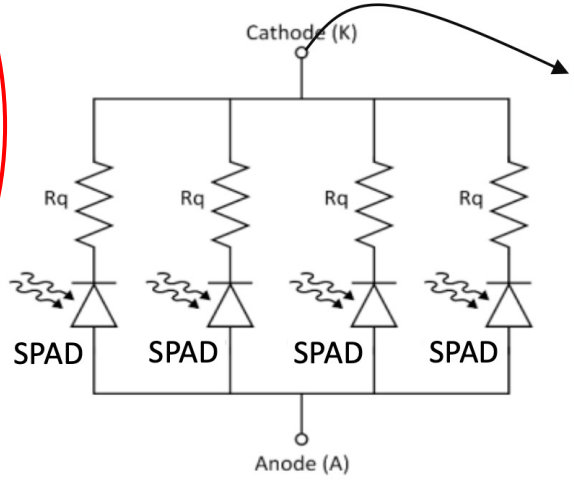
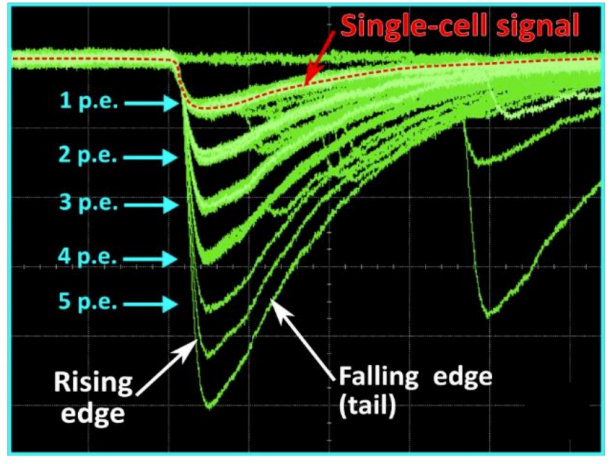
SiPM introduction

- SiPM--silicon photomultiplier: advantage:
  - High resolution
  - Single photon counting
- The goal is to develop Radiation hard SiPM





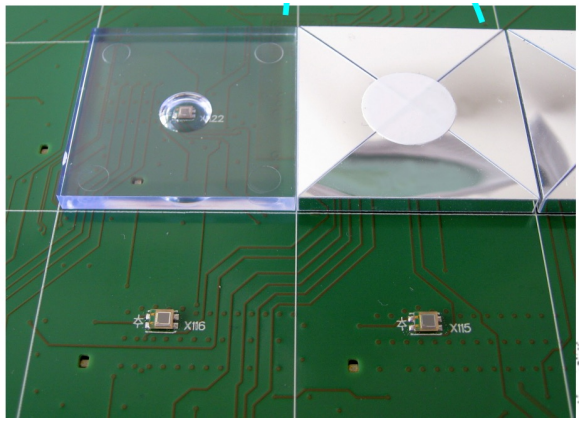




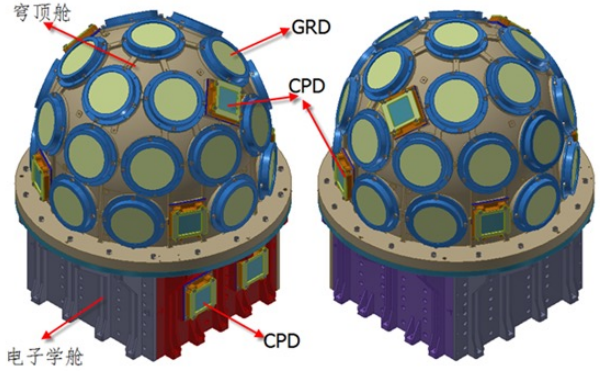
Radiation SiPM application

- Astrophysics: Space station scientific experiment (Herd …)
- Collider physics: calorimeter application
  - CMS timing layer, calorimeter
  - CEPC calorimeter and time of flight detector

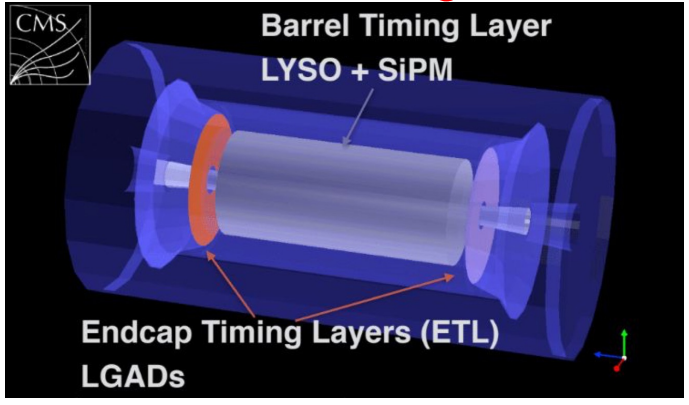
CEPC PFA calorimeter prototype



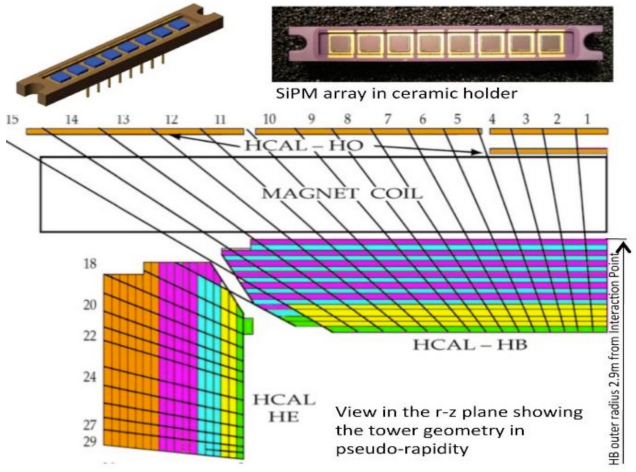
GECAM



CMS MIP timing detector



CMS Calorimeter



Example: CMS – ECAL upgrade

CEPC ECAL and HCAL: SiPM requirement

- ECAL : Small pixel size (6um*6um), large dynamic range
- HCAL: High PDE Sipm (PDE>60-70%)
- Cherenkov: high PDE for UV light

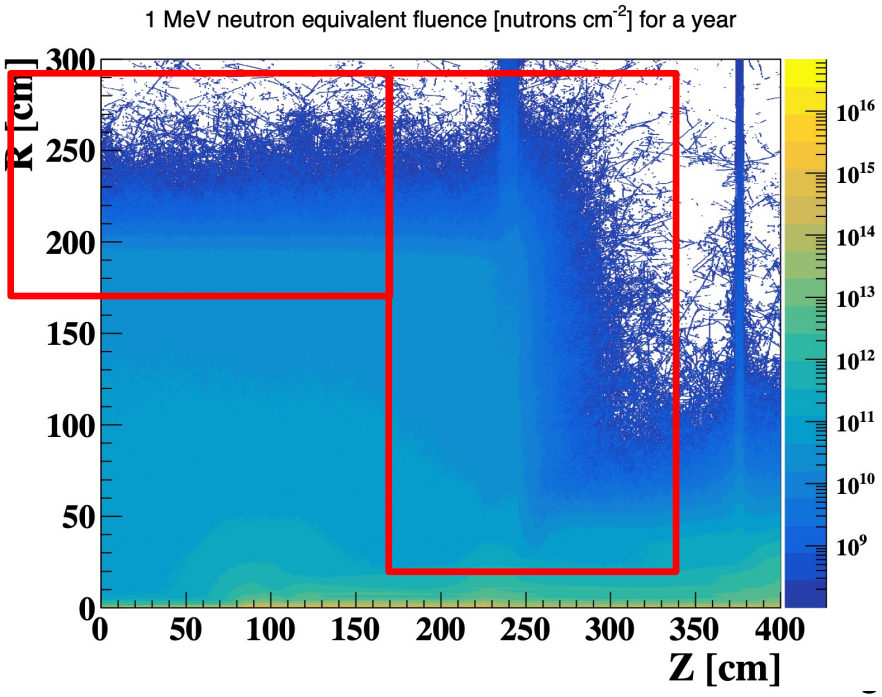
	SiPM for ECAL	SiPM for HCAL/muon	SiPM for Cherenkov
Wavelength	350 – 600 nm	350 – 600 nm	100 nm – 600 nm
Size	3 mm× 3mm	3 mm× 3mm	3 mm× 3mm (position sensitive) Or 1mm× 3mm (conventional)
Pixel size	6 μm × 6 μm	50 μm × 50 μm Or 20μm × 20 μm	50 μm × 50 μm ?
PDE	>= 30% (at 420-480nm)	>= 60% (at ~400nm)	50% at 420nm Sensitive for 200-300nm?
Number of SiPM	~1 Million	~5 Million	~0.2 Million

SiPM radiation hardness challenge

- After 10 year operation of CEPC, fluence is above 10^{13} n_{eq}/cm^2
- SiPM typically work below 1krad or 10^9 n_{eq}/cm^2 fluence
  - Performance drop after 1krad or 10^9 n_{eq}/cm^2
  - In great need to develop radiation hard SiPM

	Long term Satellite or Space station application	CEPC requirement
TID does	100 krad	>100 krad
Fluence	~10^{10} n_{eq}/cm^2	~10^{10} n_{eq}/cm^2 (Barrel) ~10^{13} n_{eq}/cm^2 (Endcap)

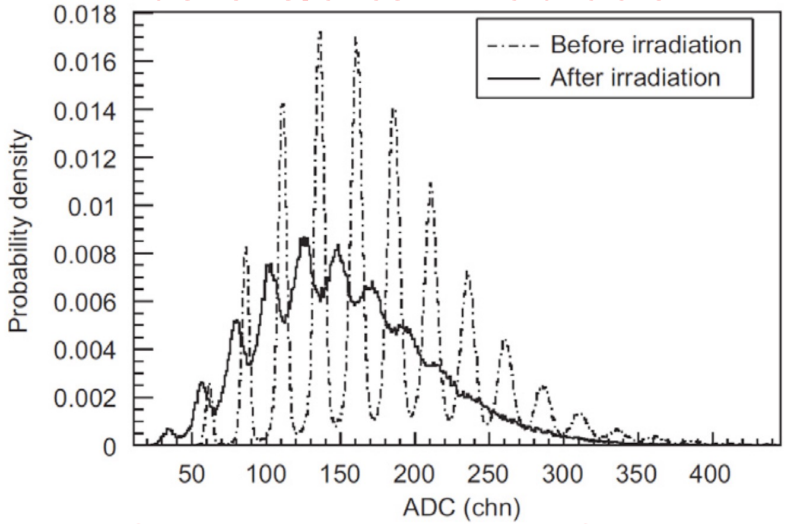
Fluence in ZH run (240GeV)



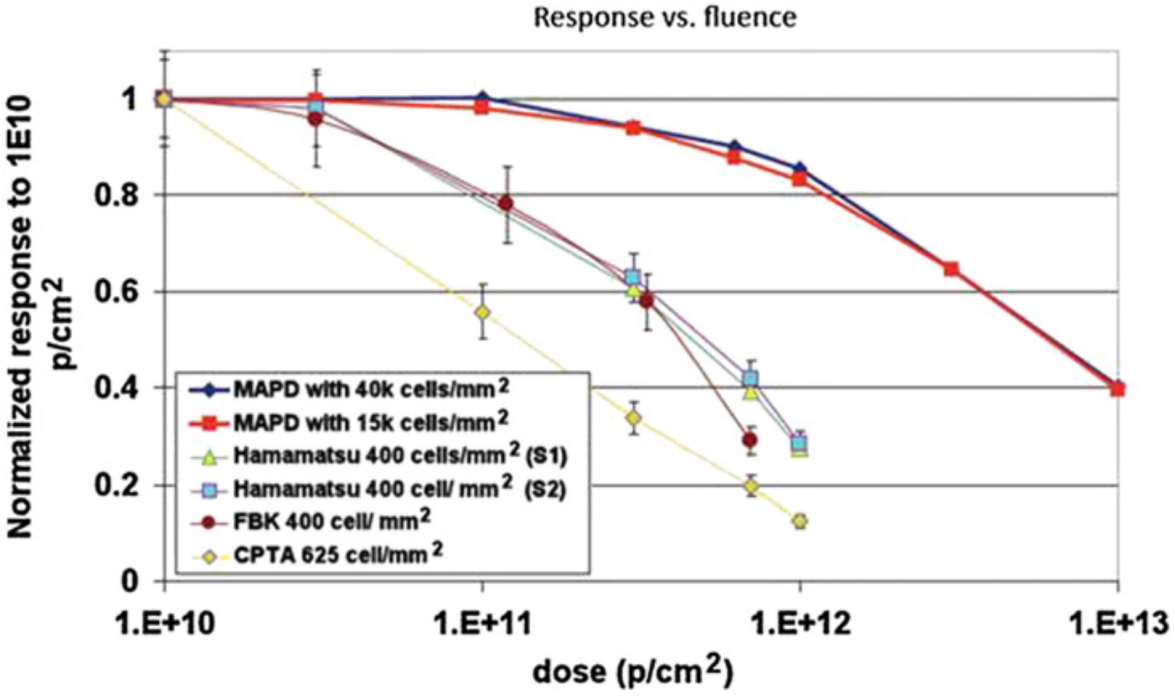
SiPM Radiation hardness

- After 10^{10} n_{eq}/cm^2 or 10Krad dose
  - Signal gain decrease
  - Energy resolution decrease
  - Dark count increase

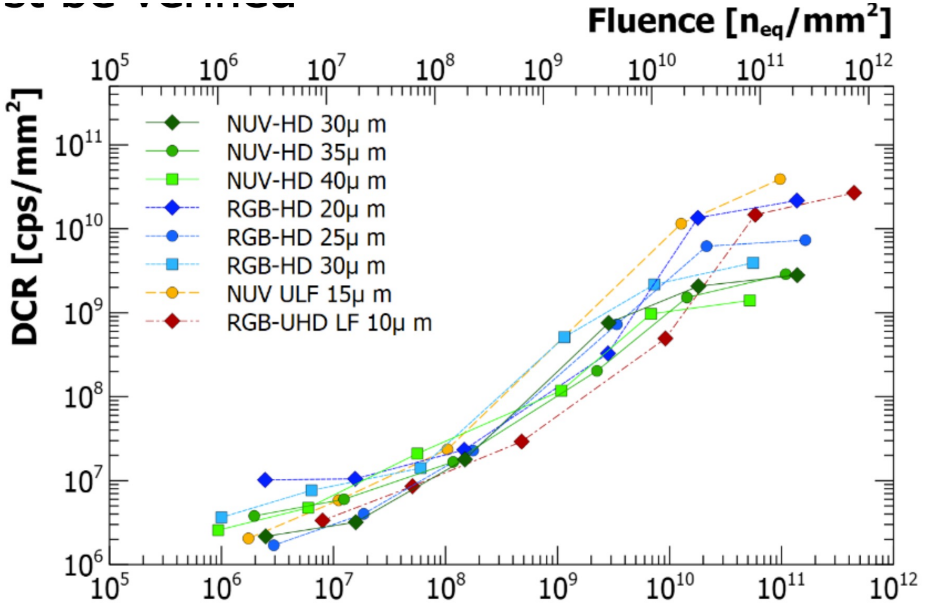
Energy resolution before/after irradiation



SiPM gain VS Dose

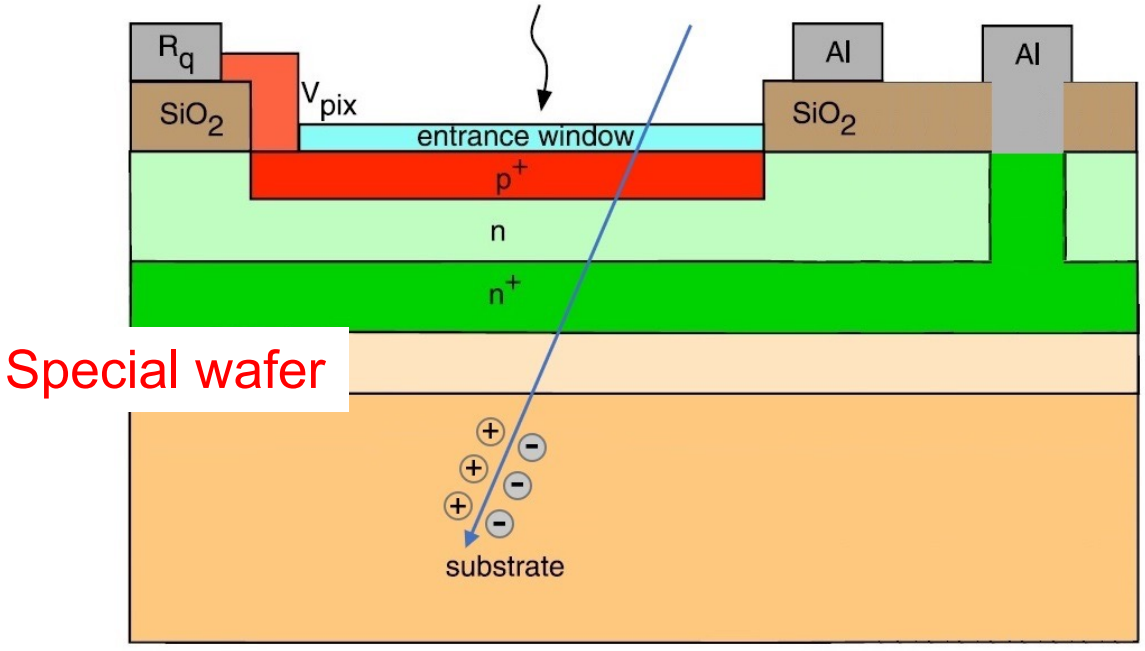


SiPM dark count VS Fluence



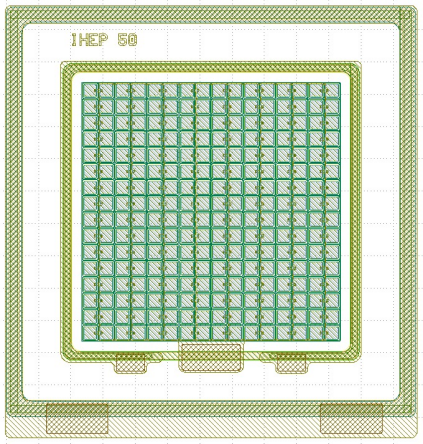
SiPM dark count after irradiation

- Bulk damage after irradiation → dark count increased
- Potential Solution:
  - Design a special wafer to isolate the dark current from bulk damage
  - Isolate the bulk damage from the device



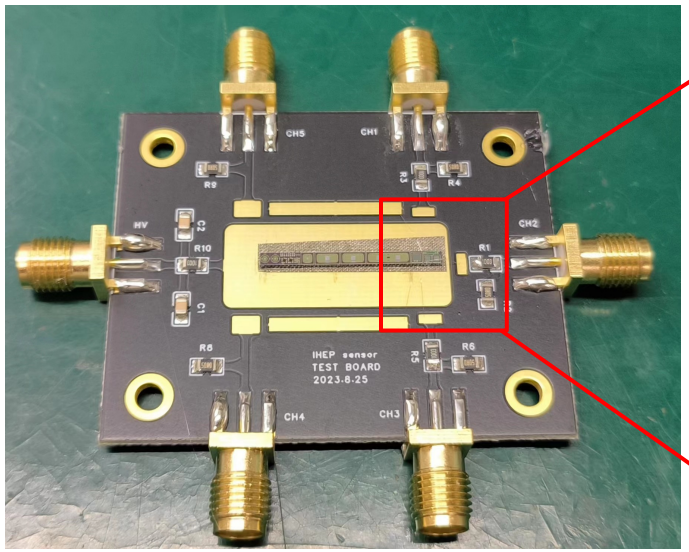
SiPM sample from 1st trial MPW run

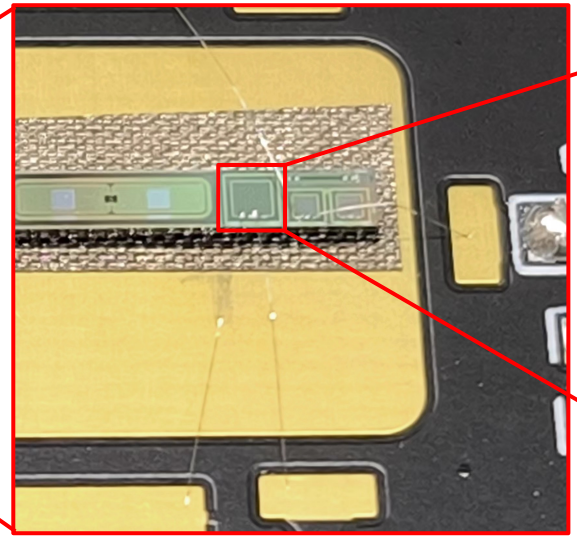
- We prototyped a small SiPM design

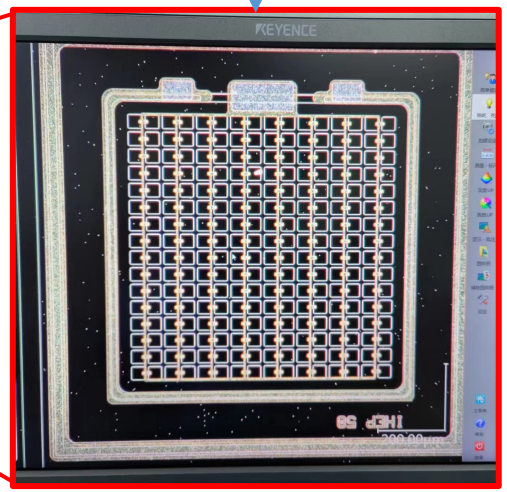


- **Pixel size： 50μm**
- **16 x 16 pixels**

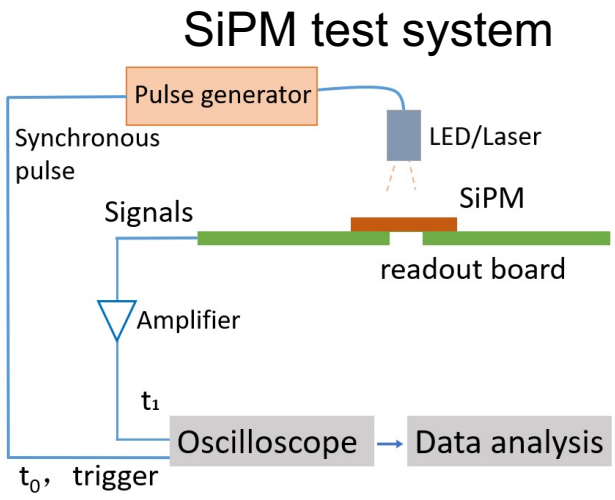
Small SiPM

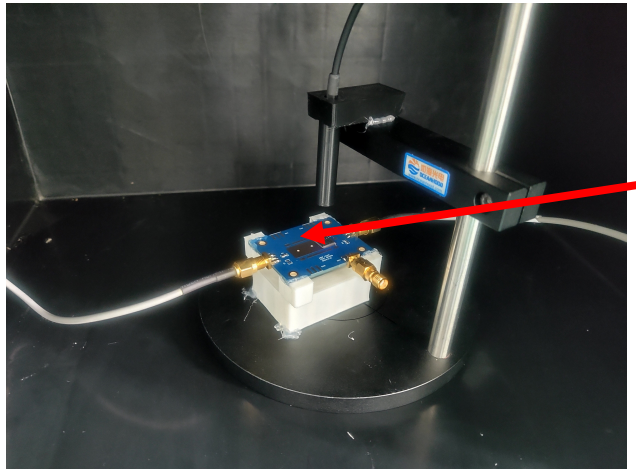


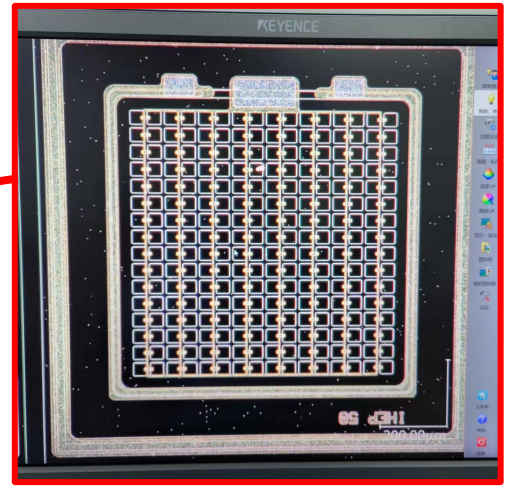


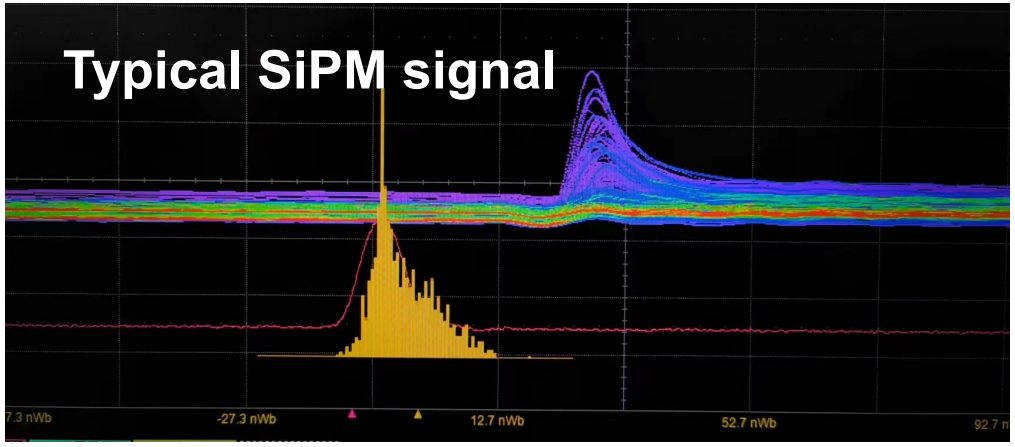


SiPM sample from 1st trial MPW run

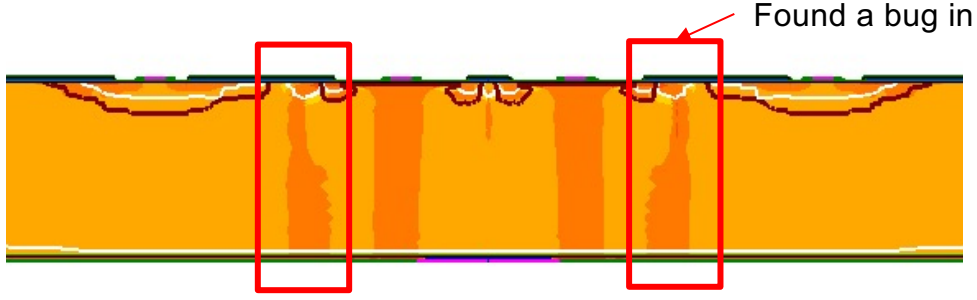








SiPM layout and process has been validated



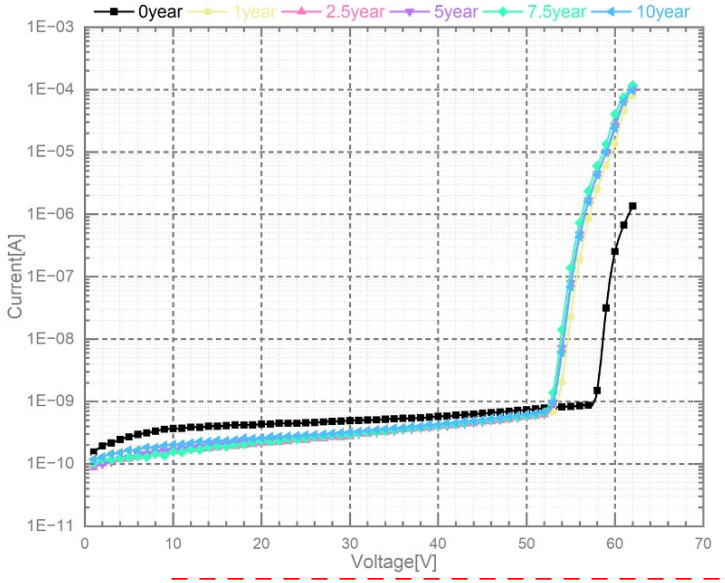
SiPM Leakage current is a bit high in 1st trial run

- **Pstop and GR design has some issue**
- **Optimized the design for engineering runs**

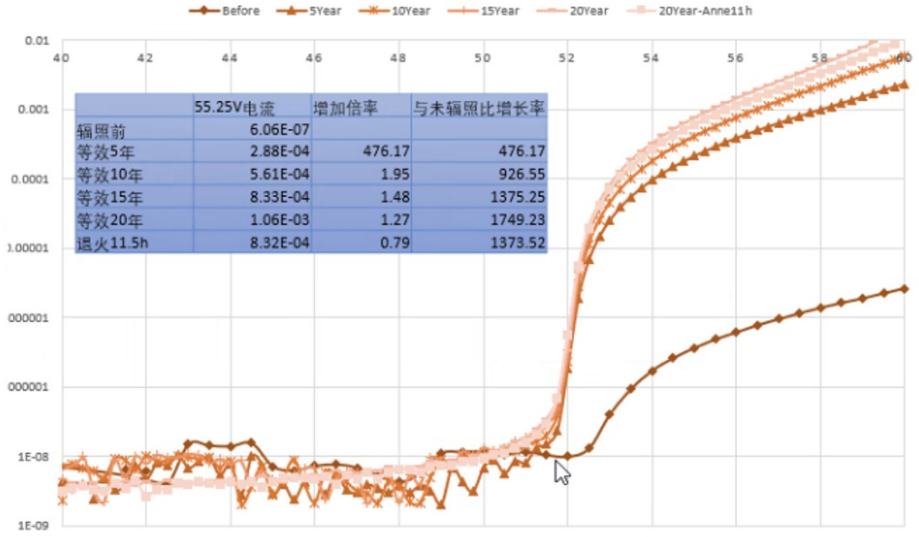
Leakage current of Sipm after irradiation

- First trial of this special wafer idea in LGAD development
- Indication that IHEP Sipm has potential to be irradiation hard
  - After 2E10 n_{eq}/cm2, IHEP SiPM leakage current increased by ~10
  - After 2E10 n_{eq}/cm2, HKP sipm increase by 2-3 order of magnitude

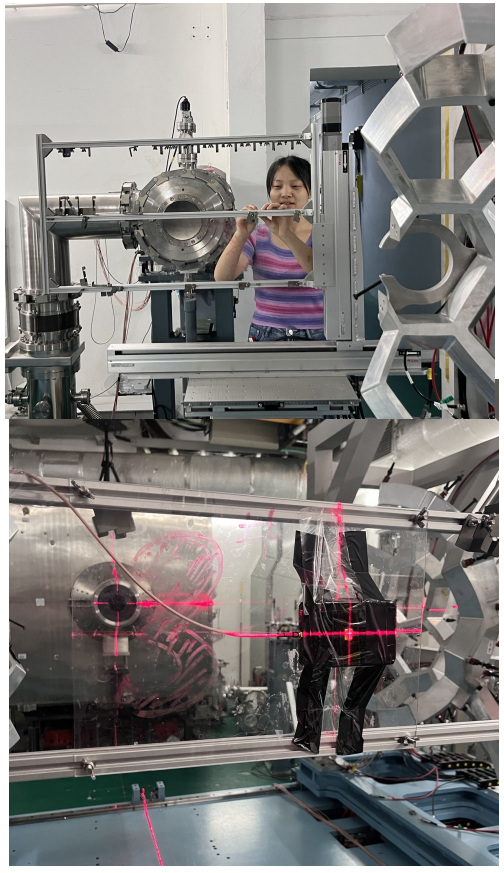
IHEP-SiPM



Hamamatsu -SiPM



	55.25V电流	增加倍率	与未辐照比增长率
辐照前	6.06E-07		
等效5年	2.88E-04	476.17	476.17
等效10年	5.61E-04	1.95	926.55
等效15年	8.33E-04	1.48	1375.25
等效20年	1.06E-03	1.27	1749.23
退火11.5h	8.32E-04	0.79	1373.52



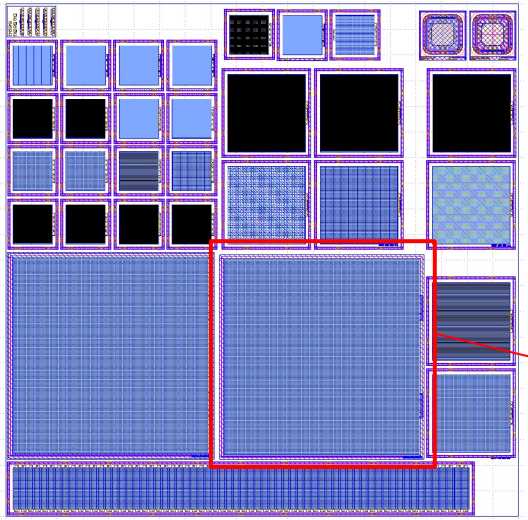
by Tianyuan Zhang.

Tested together with HERD team in CSNS.

1E10 n_{eq}/cm2 is the fluence received by HERD in 10 years operation

Dedicated SiPM engineering run

- Dedicated radiation hard SiPM run will be submitted next month
  - Various SiPM size: 1*1mm, 3*3mm, 5*5mm
  - Various Pixel size: 10um ,20um, 50um

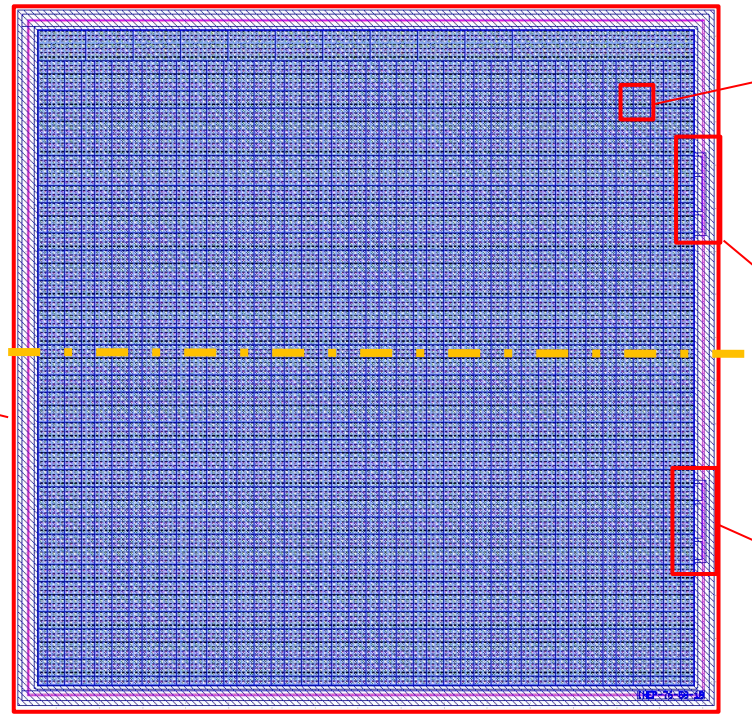


IHEP SiPM layout

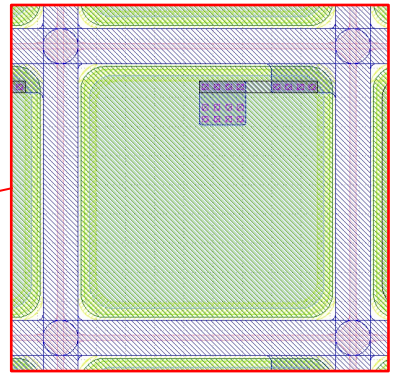
SiPM for LACT :

- **7.6 mm X 7.6 mm**
- **152 x 152 pixels**
- **Pixel size： 50um**
- **Fill factor 64%**

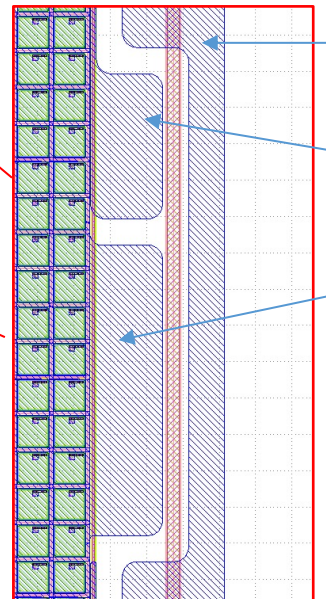
SiPM designed for LACT



Designer: MengZhao Li, Mei Zhao

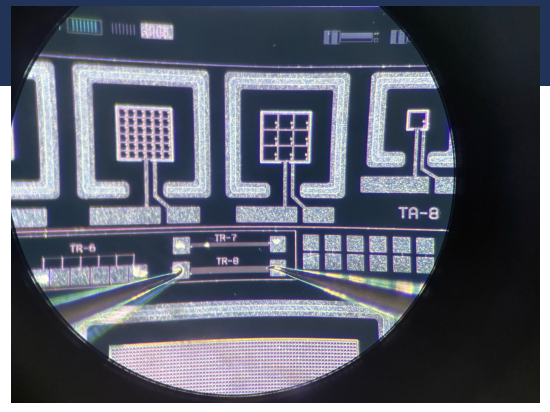


- Pixel size 50um
- Quenching resistance 200KΩ



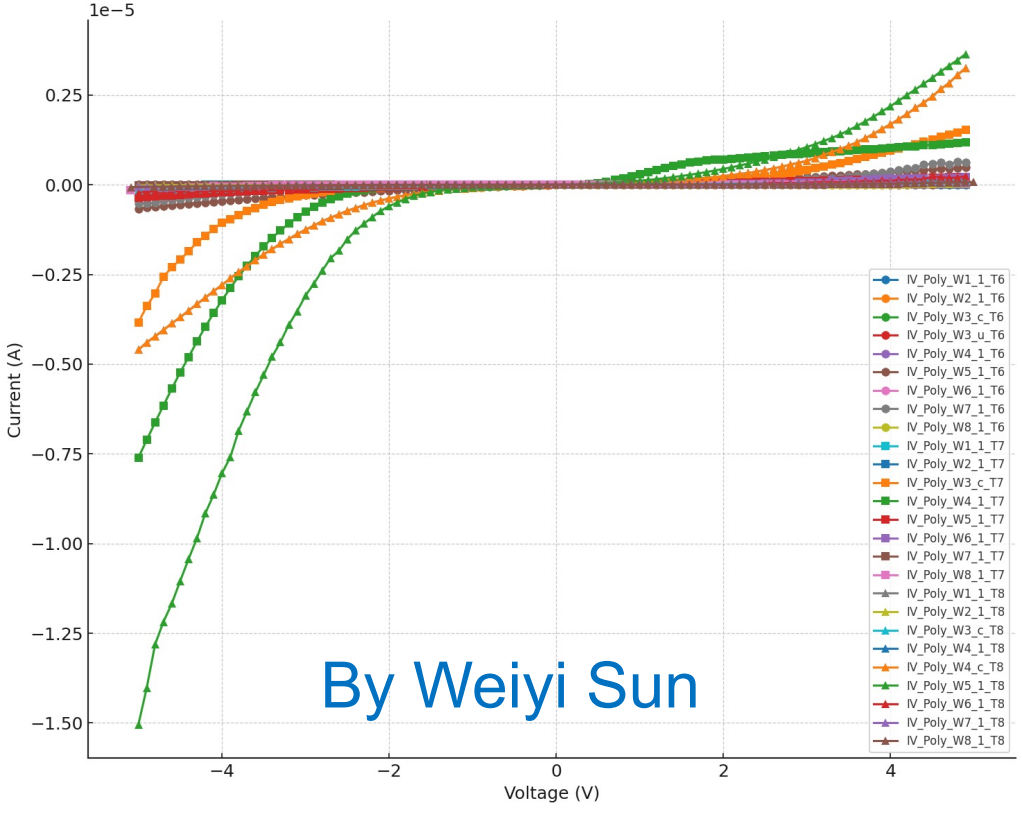
Dedicated SiPM engineering run

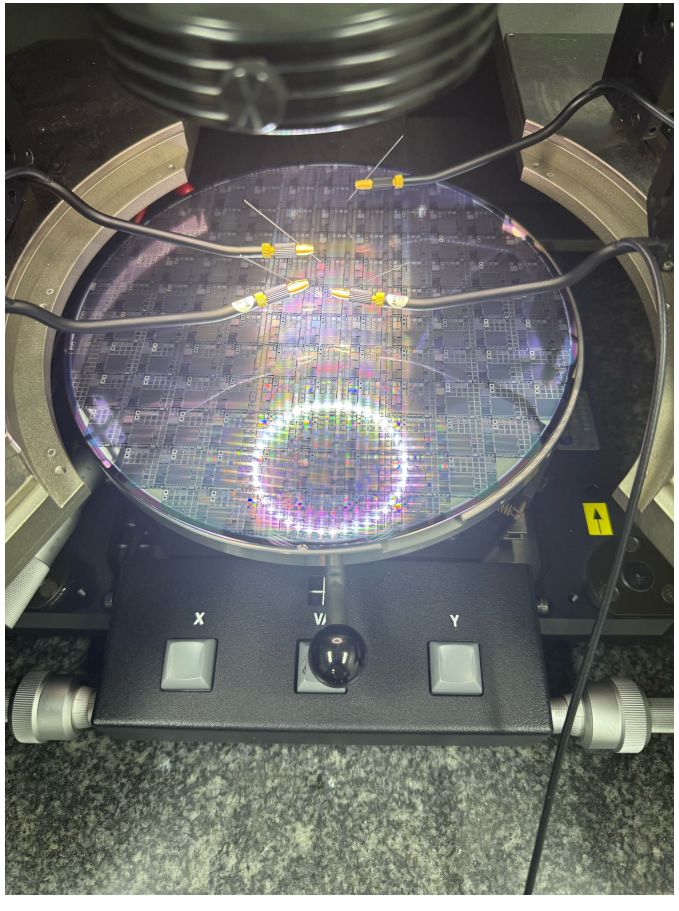
- First trial run wafers received at the end of 2025.
  - Validate the doping for poly-silicon quenching resistors
  - Validate the mask design



Engineering run wafers

Validating quenching resistors: I-V curve





Time line for radiation hard SiPM

- 2026 :SiPM irradiation hard design engineering run
  - 1st full engineering run ready in June:
    - Two type of radiation hard Sipm
      - Normal wafers and Special wafers with bulk damage isolation.
- 2027: 2nd engineering run (More dedicated optimization for CEPC)
  - Integration with ECAL/HCAL/ Cherenkov prototype

Summary

- Development for radiation hard SiPM
  - Aim for CEPC and Astrophysics application
- Key technology has been validated in ATLAS HGTD detector
  - Radiation hard LGAD sensor developed by IHEP team
- Status of Radiation SiPM R & D project
  - 1st MPW small prototype was fabricated and tested.
    - Showed good potential to be radiation hard in the tests
  - Full engineering run designed
    - Received trial run wafers at the end of 2025.
    - Expect to get full wafers by middle of 2026.
  - Plan to integrate into ECAL and HCAL prototyping in the coming years.

Some thought about the Cost

- One 8 inch cost in production : 16k RMB
- Number of 3*3mm SiPM in one wafer (assuming 90% yield): ~3000
- Raw Cost of SiPM: ~5 RMB
- Assuming packaging of SiPM will double the price
- Final cost per Sipm ~10 RMB