中国科学技术大学
University of Science and Technology of China

USTC-IME LGAD pre-production for HGTD

Xiangxuan Zheng, Nov 30th

On behalf of the USTC HGTD Group

University of Science and Technology of China

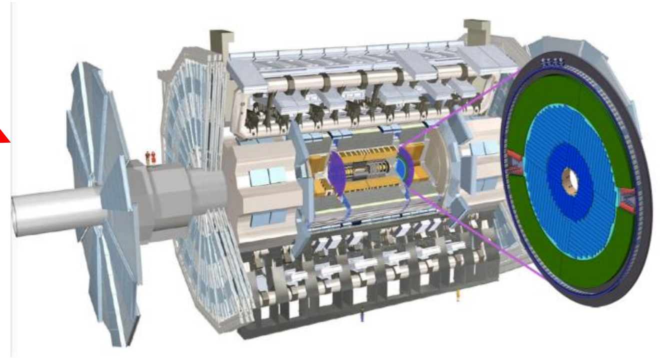
Overview

- Introduction
- Performance of USTC-IME-v2.1 W17
- Probe station testing systems
- Yield estimation
- LGAD sensors on QC-TS
- Radiation hardness evaluation
- Collected charge and timing resolution
- Other results of QC-TS at USTC
- Summary

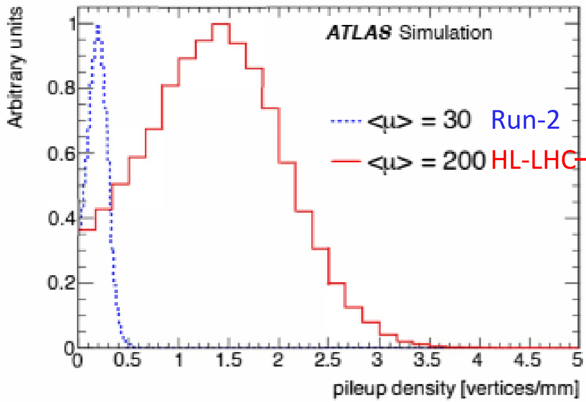
ATLAS HGTD project

- LHC (Large Hadron Collider) → HL-LHC (high-luminosity phase of LHC) in 2028 → pileup vertex densities ↑
- ATLAS (one of the 4 major experiments at the LHC at CERN) → upgrade its detectors
- The HGTD (High-Granularity Timing Detector) is chosen for the ATLAS Phase II upgrade.
- The time information be used as another dimension for identifying the hard-scattering vertex at the HL-LHC.
- HGTD should withstand the non ionizing radiation levels throughout the HL-LHC operations.
  - This determines lifetime
- Because of its good timing performance and radiation hardness, LGAD (Low Gain Avalanche Detector) has been chosen as the sensor.

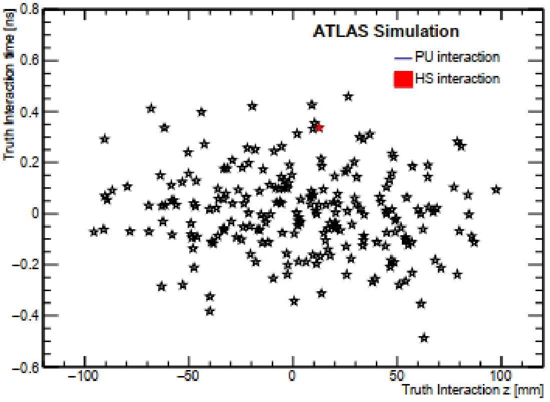
ATLAS Detector in LHC



Position of the HGTD within ATLAS

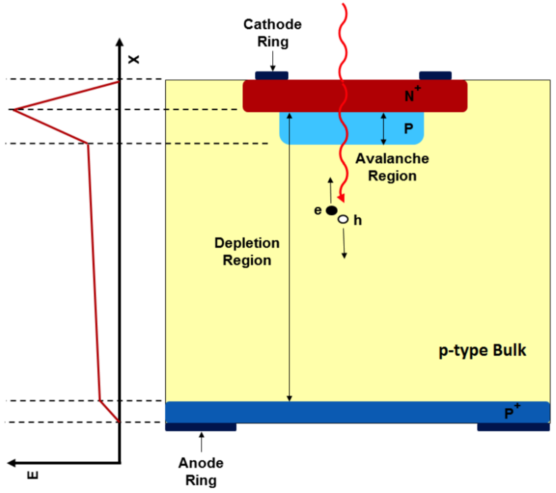


Local pileup vertex densities at generator level



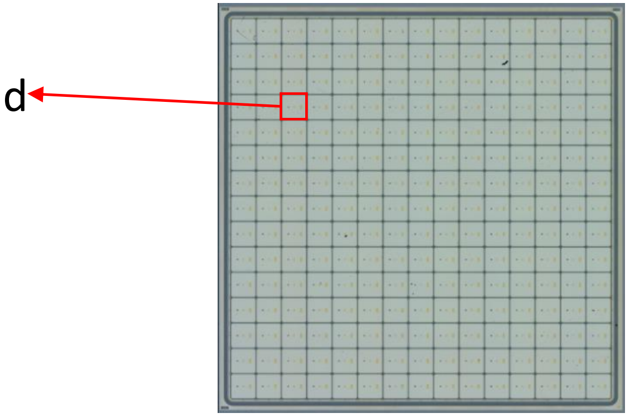
truth interactions in a single bunch crossing in the z–t plane

Low Gain Avalanche Detector



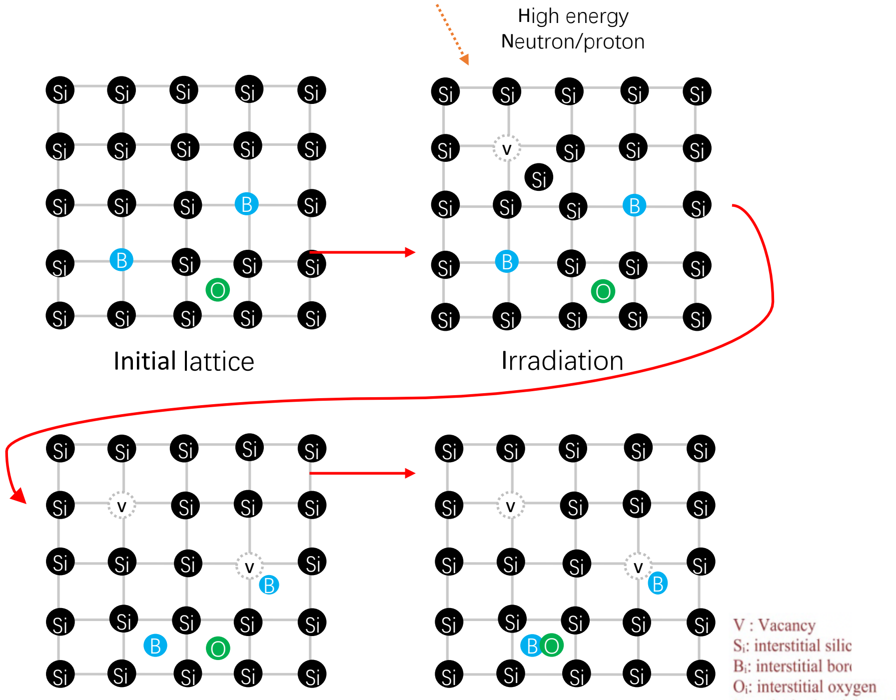
- LGADs are n-in-p silicon detectors containing an extra highly-doped p-layer (gain layer) below the n-p junction.
- The high electric field in gain layer region will accelerate the drifting electrons and generate avalanches.
- With a proper design of gain layer, the LGAD can achieve promising S/N and time resolution.
- Designed parameters:
  - Active thickness: 50 µm
  - Pad size: 1.3 x 1.3 mm^2
  - Collected charge (most probable value): > 4 fC
  - Time resolution: 40 ps (start), 70 ps (end of lifetime)
  - Hit efficiency: > 95%
  - Radiation tolerance: 2.5e15 $\mathrm{n_{eq}\ cm^{-2}}$, 1.5 MGy

1 LGAD pad



15x15 LGAD sensor

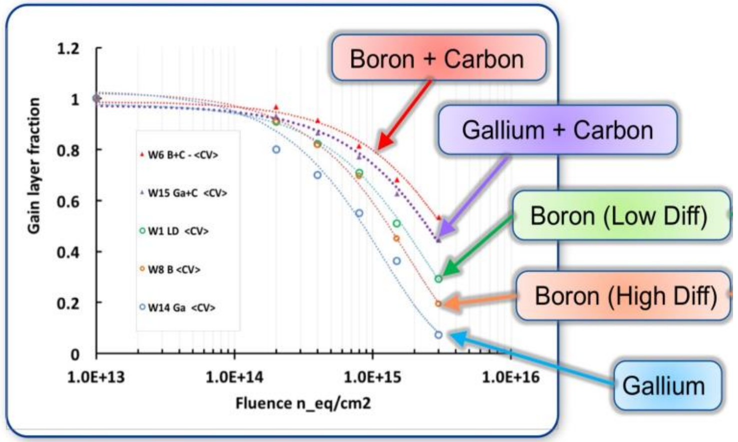
Low Gain Avalanche Detector (LGAD) R&D



$Si_i + B_s \rightarrow Si_s + B_i$ $B_i + O_i \rightarrow B_iO_i$

Acceptor (B_s) removal in the gain layer after irradiation

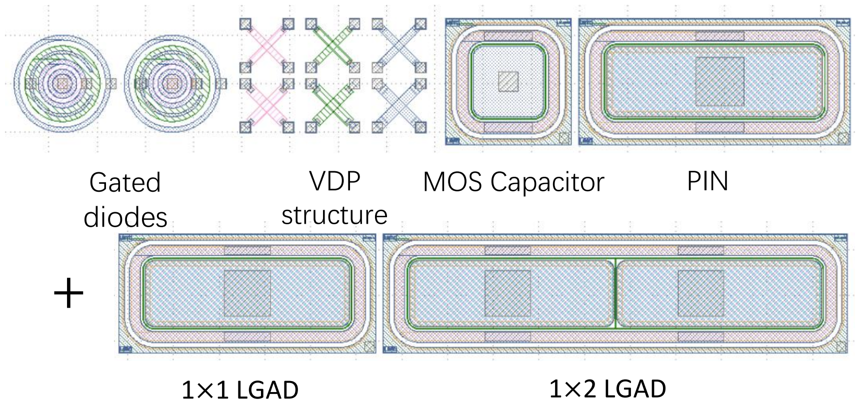
M. Moll, VERTEX2019

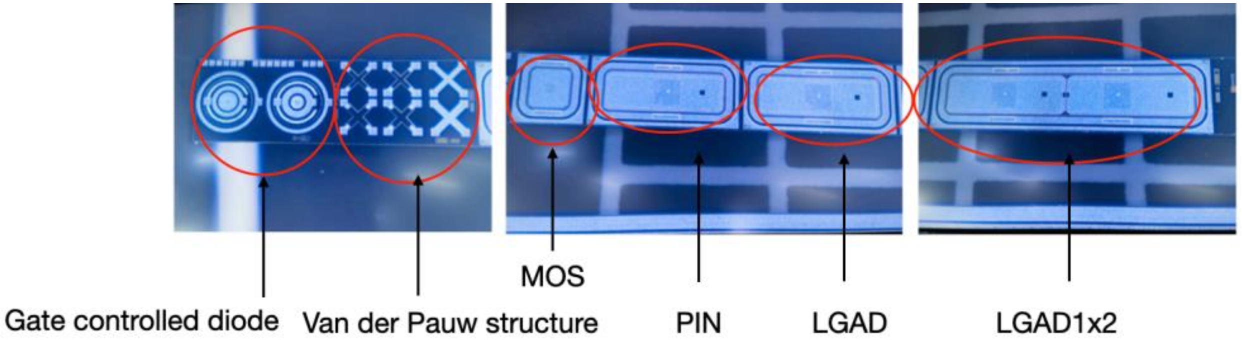


G.Paternoster, TREDI 2019

- The **reduction of effective doping** in the gain layer is caused by the "acceptor removal" process → LGADs' gain reduces
- Explored use of **different designs**, **doping materials** and **C-enriched substrates** → Boron + Carbon shows largest gain after irradiation ($C_i + O_i \rightarrow C_iO_i$ competes with $B_i + O_i \rightarrow B_iO_i$)

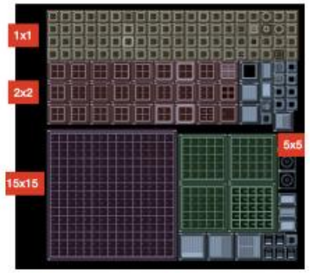
Quality Control Test Structure (QC-TS)





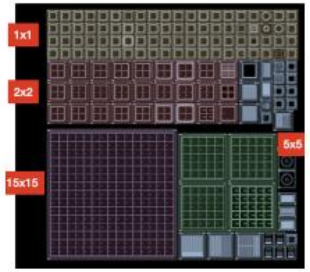
- QC-TS will be used by CERN to monitor the production process and perform quality assurance measurements on the supply for LGAD
- LGAD test sensors with the same gain layer design properties as the sensors organized as:
  - 1x1 LGAD, 1x2 LGAD
- Process control test structure that will provide diagnostic capability for the nearby main sensor. It shall be composed of:
  - PIN diode, MOS capacitor, 2 Gated diodes, 3 Van der Pauw structures

USTC's roadmap on LGAD R&D with IME



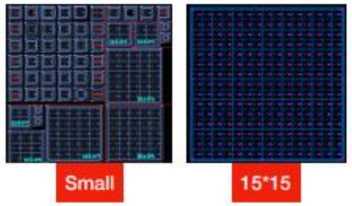
USTC-1.0

Deliver: 2020.7



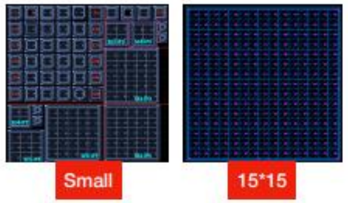
USTC-1.1

Deliver: 2020.10



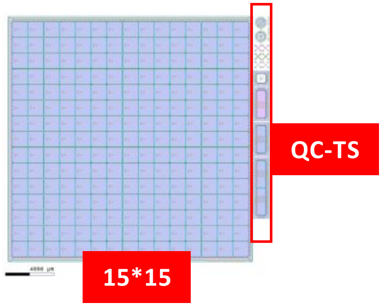
USTC-2.0

Deliver: 2021.4



USTC-2.1

Deliver: 2021.10

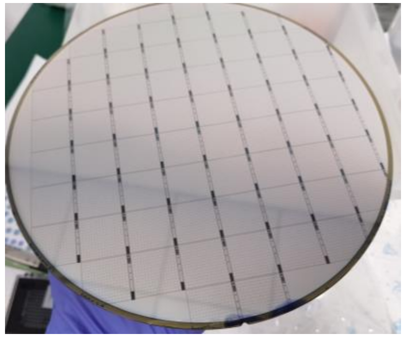


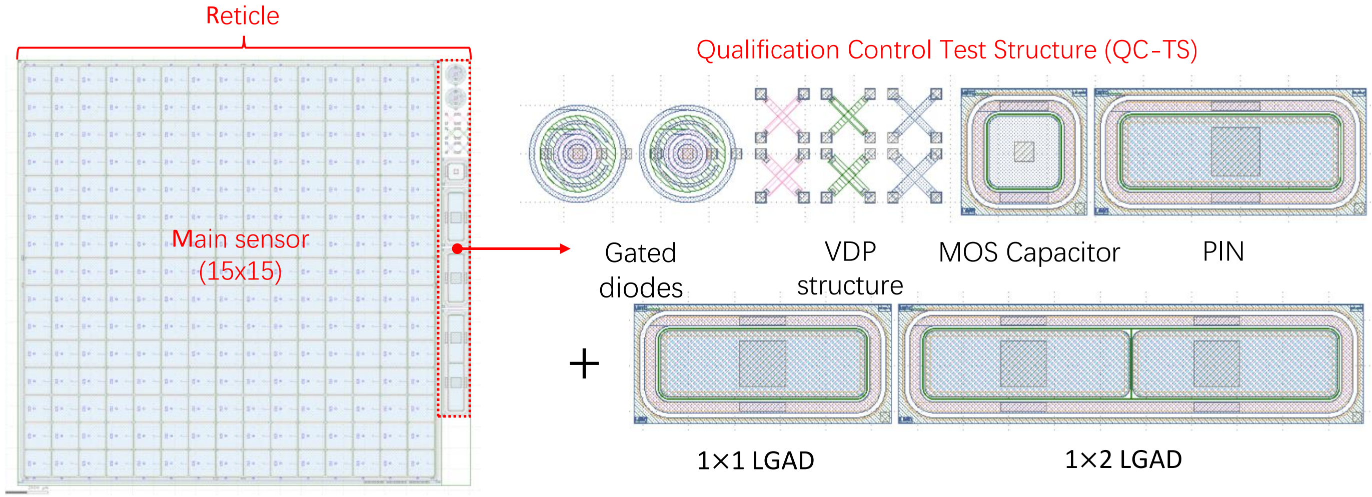
USTC-pre

Deliver: 2023.6

	USTC-1.0	USTC-1.1	USTC-2.0	USTC-2.1	USTC-pre
Propose	First attempt	Improved the process technology, same layout as 1.0	New layout, mainly for yield study and issues fix	Same layout as 2.0, fast iteration	New layout, based on USTC-2.1-W17, in-kind/tendering preproduction. (10% of total supply ~2100)
Performance	Few sensors can work (VBD ~250V, VGL 40V)	~30% can work (VBD ~300V)	> 99% small sensors and ~35% 15x15 sensors can work, GR leakage disappeared. VBD lowered (~100-170V).	>99% small sensors and ~35% 15x15 sensors can work. Better uniformity, VBDs in ideal range (~150-240V).	Under test
Problem	Almost all sensors have large current (VBD < 10V)	Almost all sensors have large GR current	Too low VBD for some wafers.		

USTC-IME Pre-production sensor for HGTD

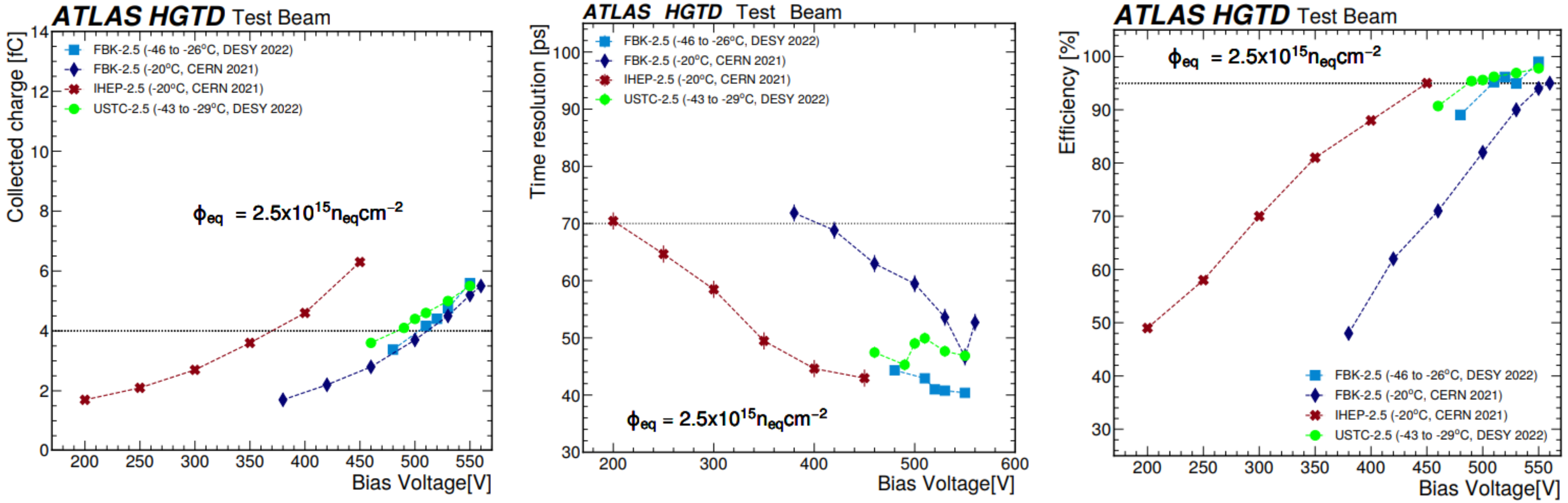




- 27 wafers have been produced without UBM, thinning and metallization on backside
  - 3 extra wafers are used for fine tuning of the carbon dose for future improvement
- The baseline wafer of USTC-IME pre-production is USTC-IME-v2.1-W17.

Performance of USTC-IME-v2.1 W17

[Paper link]



- For USTC-IME-v2.1, W17 shows the best performance after irradiation (fluences up to **2.5e15** $\mathrm{n_{eq}\ cm^{-2}}$) at safe bias (< 550V).
  - Collected charge **> 4fC**, time resolution **< 70 ps**, efficiency **> 95%.**
- USTC-IME-v2.1 W17 is chosen as the baseline wafer of USTC-IME pre-production.

Overview of USTC-IME Preproduction

Production version	Wafer No.	GL.Dose	Implantation	LGADs	VBD mean	Labelled	Thinned	Backside (Al)	UBMed	Diced	Yield	Quality
USTC-IME Pre-production	W1	Medium	**B+1C**	15x15	**~ 182.8 V**	Done					17/52 ~ 33 %	
	W2	Medium	**B+1C**	15x15	**~ 186.5 V**	Done	Done	Done		Done	2/52 ~ 4 %	
	W3	Medium	**B+1C**	15x15	**~ 193.7 V**	Done	Done	Done	Ready		**26/52 ~ 50 %**	Good
	W4	Medium	**B+1C**	15x15	**~ 190.8 V**	Done	Done	Done	Ready		**24/52 ~ 46 %**	Good
	W5	Medium	**B+1C**	15x15	**~ 191.7 V**	Done	Done	Done	Ready		**24/52 ~ 46 %**	Good
	W6	Medium	**B+1C**	15x15	**~ 188.5 V**	Done	Done	Done	Ready		**22/52 ~ 42 %**	Good
	W7	Medium	**B+1C**	15x15	**~ 184.9 V**	Done	Done	Done	Ready		**22/52 ~ 42 %**	Good
	W8	Medium	**B+1C**	15x15	**~ 186.2 V**	Done	Done	Done	Ready		**22/52 ~ 42 %**	Good
	W9	Medium	**B+1C**	15x15	**~ 195.6 V**	Done					13/52 ~ 25 %	
	W10	Medium	**B+1C**	15x15	**~ 193.6 V**	Done					16/52 ~ 31 %	
	W11	Medium	**B+1C**	15x15	**~ 192.3 V**	Done	Done	Done	Ready		**26/52 ~ 50 %**	Good
	W12	Medium	**B+1C**	15x15	**~ 193.1 V**	Done	Done	Done		Done	13/52 ~ 25 %	
	W13	Medium	**B+1C**	15x15	**~ 188.8 V**	Done	Done	Done	Ready		**21/52 ~ 40 %**	Good
	W14	Medium	**B+1C**	15x15	**~ 191.6 V**	Done	Done	Done	Ready		**18/52 ~ 35 %**	Good
	W15	Medium	**B+1C**	15x15	**~ 193.0 V**	Done					12/52 ~ 23 %	
	W16	Medium	**B+1C**	15x15	~ 152.4 V	Done					23/52 ~ 44 %	
	W17	Medium	**B+1C**	15x15	~ 150.4 V	Done					27/52 ~ 52 %	
	W18	Medium	**B+1C**	15x15	~ 137.7 V	Done					25/52 ~ 48 %	
	W19	Medium	**B+1C**	15x15	~ 146.5 V	Done					26/52 ~ 50 %	
	W20	Medium	**B+1C**	15x15	~ 138.9 V	Done					20/52 ~ 36 %	
	W21	Medium	**B+1C**	15x15	~ 127.5 V	Done					17/52 ~ 33 %	
	W22	Medium	**B+1C**	15x15	~ 143.6 V	Done					18/52 ~ 35 %	
	W23	Medium	**B+1C**	15x15	~ 130.6 V	Done					15/52 ~ 29 %	
	W24	Medium	**B+1C**	15x15	~ 151.8 V	Done	Done	Done		Done	9/52 ~ 17 %	
	W25	Medium	**B+1.3C**	15x15	~ 116.9 V	Done	Done	Done		Done	27/52 ~ 52 %	
	W26	Medium	**B+1.5C**	15x15	~ 111.8 V	Done	Done	Done		Done	12/52 ~ 23 %	
	W27	Medium	**B+0.7C**	15x15	~ 158.1 V	Done	Done	Done		Done	25/52 ~ 48 %	

Normal
VBD
in box1

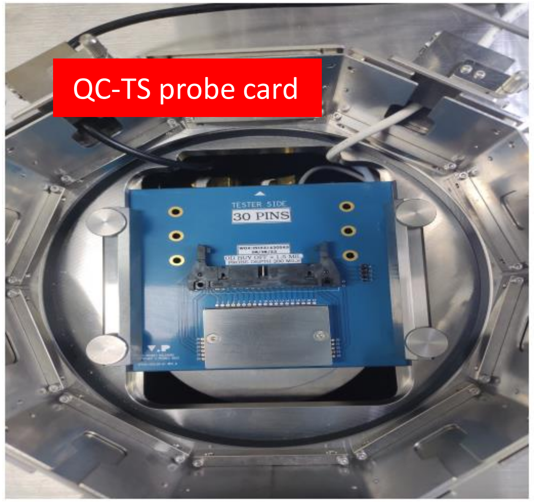
Low
VBD
in box2

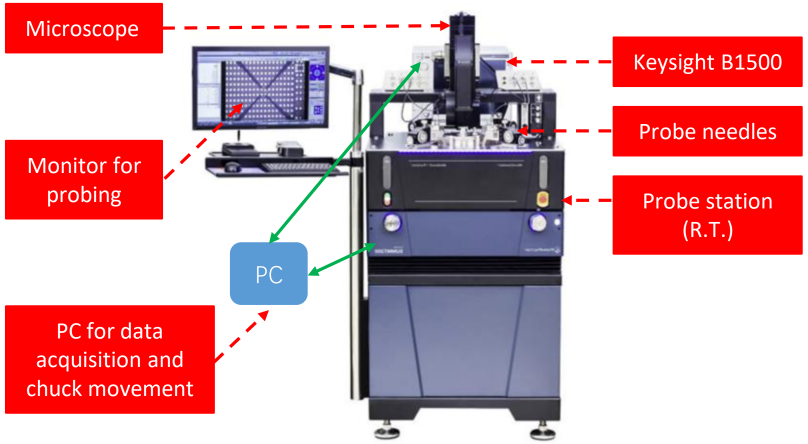
VBD: the voltage where the pad’s leakage current reaches 500 nA.

The “Good” quality means the yield is more than 18/52 (~35%)

Probe station testing systems at USTC

15x15 probe card and digital switcher


QC-TS probe card


Microscope

Monitor for probing

PC

PC for data acquisition and chuck movement

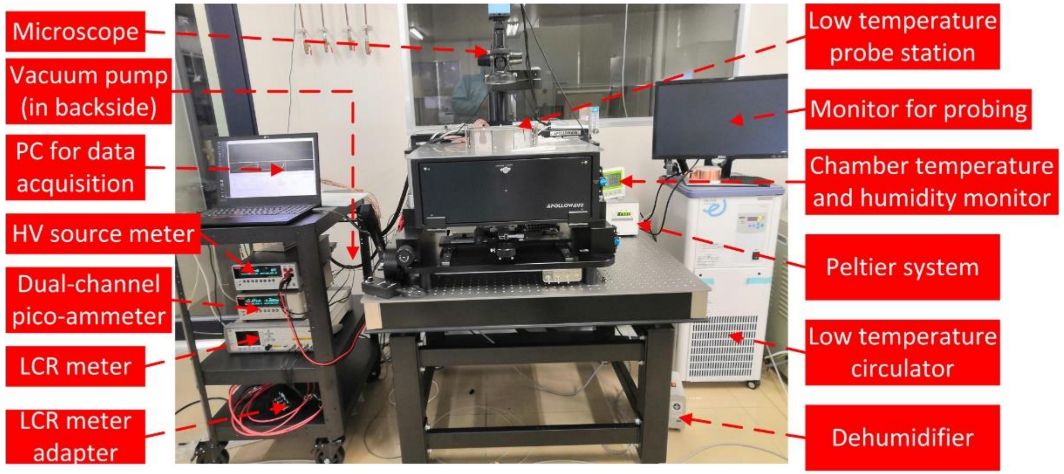
Keysight B1500

Probe needles

Probe station (R.T.)

Semi-Automatic probe station (R.T.)

- Vender testing


Microscope

Vacuum pump (in backside)

PC for data acquisition

HV source meter

Dual-channel pico-ammeter

LCR meter

LCR meter adapter

Low temperature probe station

Monitor for probing

Chamber temperature and humidity monitor

Peltier system

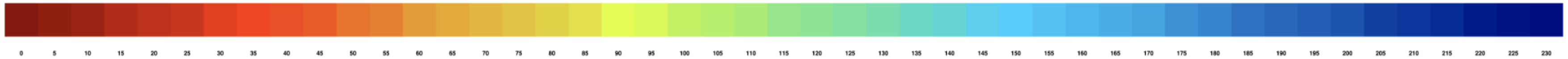
Low temperature circulator

Dehumidifier

Manual probe station (Generally, chuck at 20 ℃)

- Cross-check vender testing results
- Test the sensors by probe card and compare results with three probe needles

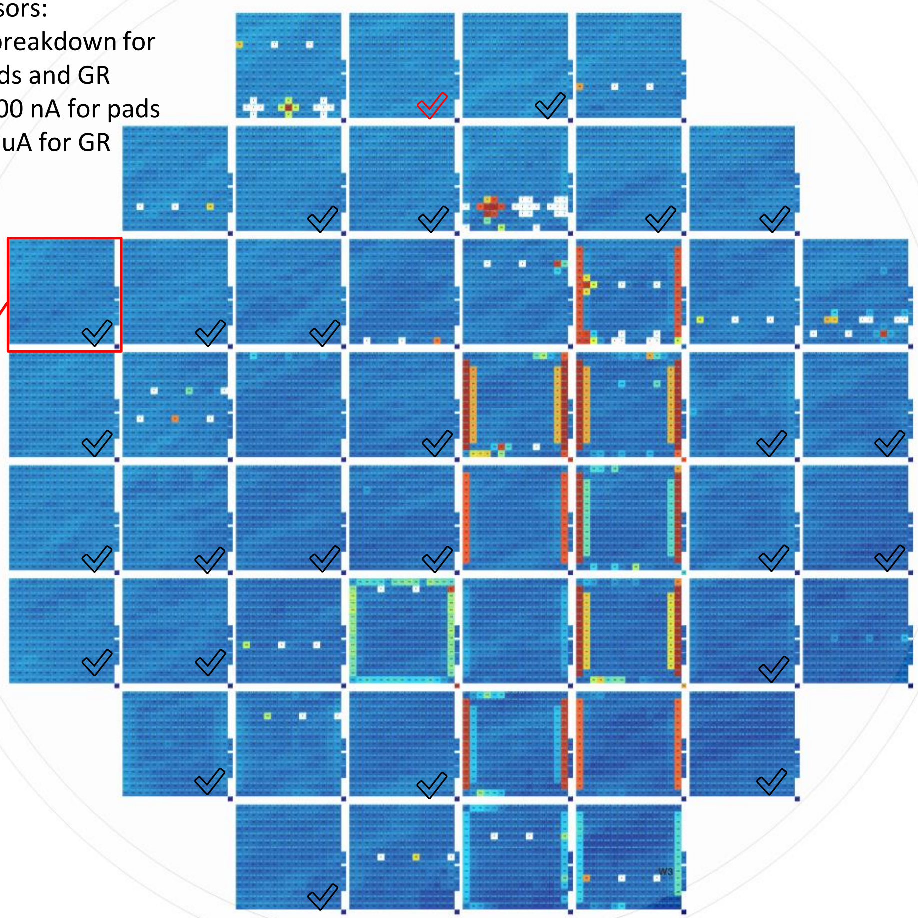
VBD Histogram (USTC-IME-pre W3)

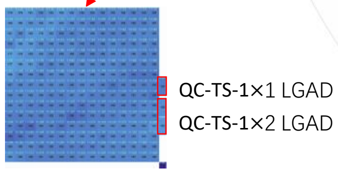


0 • VBD = VMAX (VMAX < 150 V) due to the limit of compliance

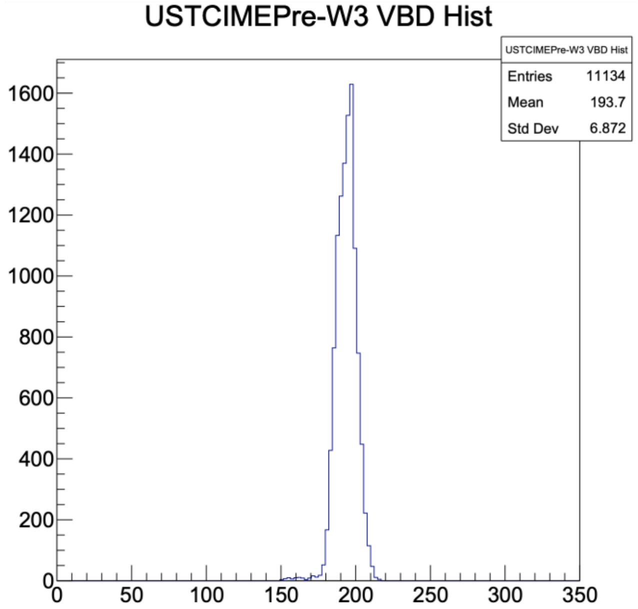
Good sensors:
No early breakdown for all 225 pads and GR

- Ith = 500 nA for pads
- Ith = 1 uA for GR



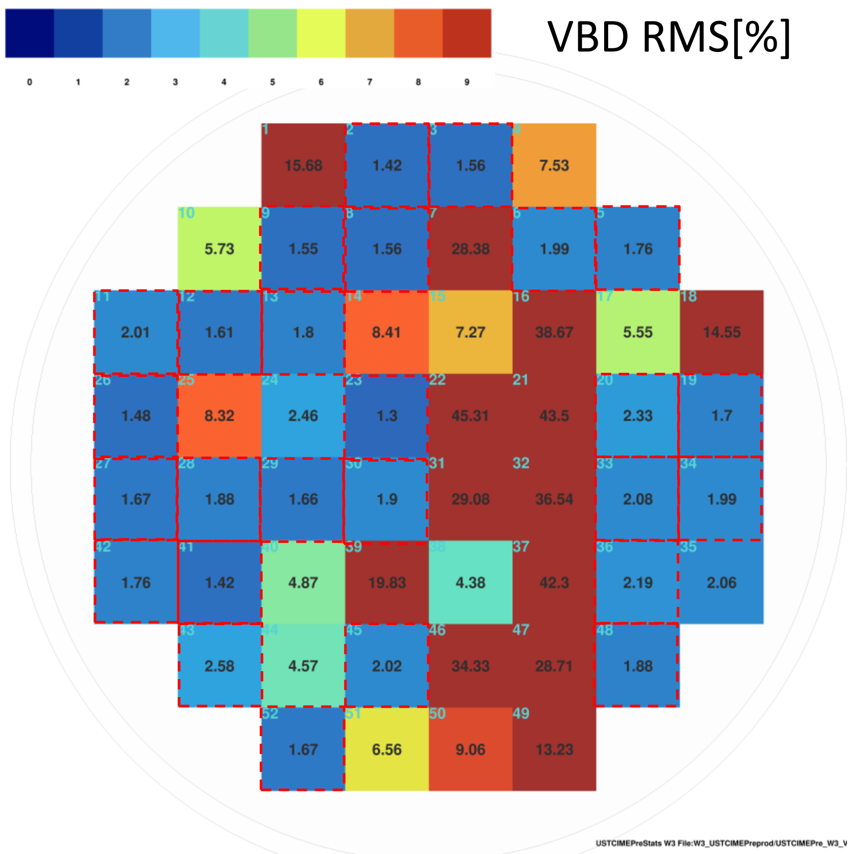


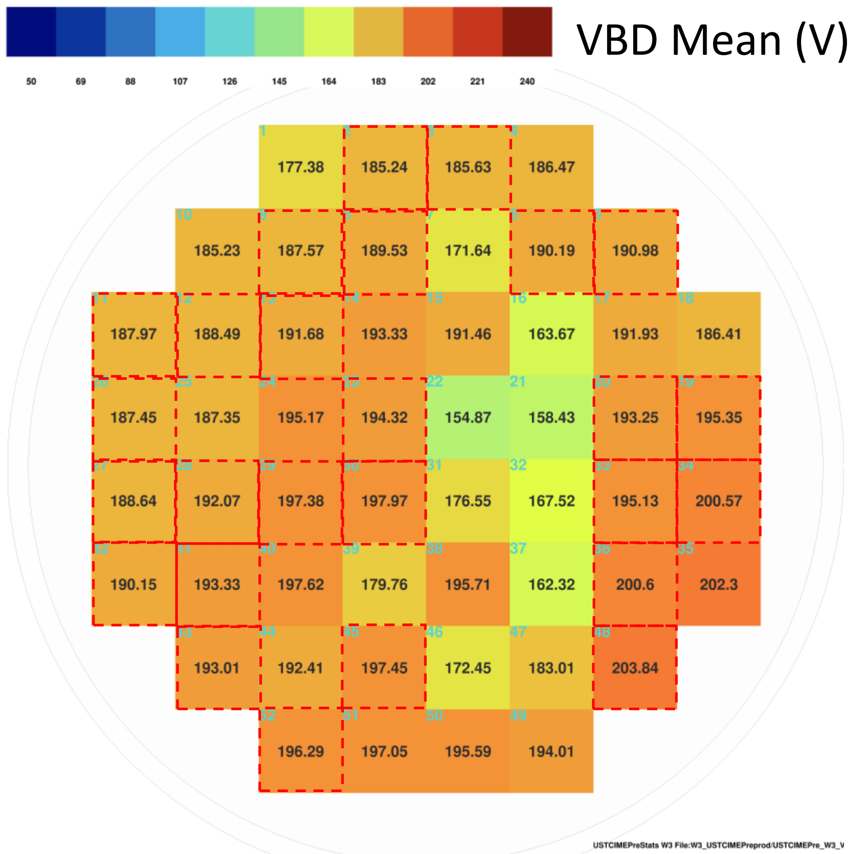
Main (15×15) LGAD



Vth > 150 V to cut early breakdown pads, for calculation of mean per wafer.

Yield estimation (USTC-IME-pre W3)





With limits both on RMS and average breakdown voltage, combined results:
yield ~ 50 %

$V_{bd,pad}$ spread over the Sensor*,$^{\square}$	RMS($V_{bd,pad}$)/<$V_{bd,pad}$> <0.05

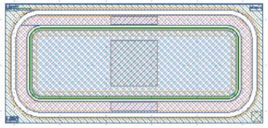
Good/Total: 26/52 ~ 50 %

Variation of the V_{bd} between different sensors	±8% from the average V_{bd}

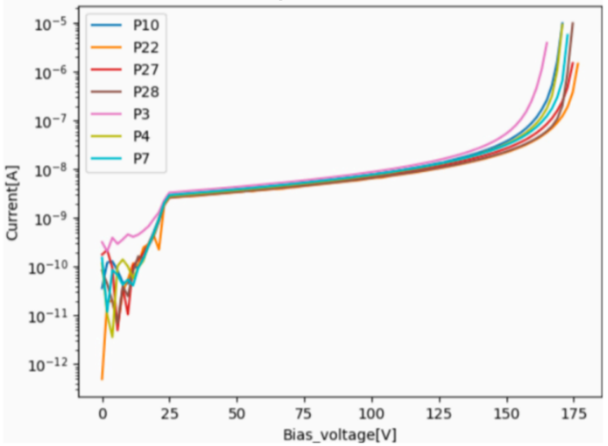
[178.20, 209.20] (V)

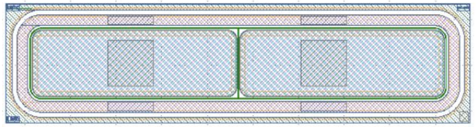
Good/Total: 26/52 ~ 50 %

LGAD sensors on QC-TS

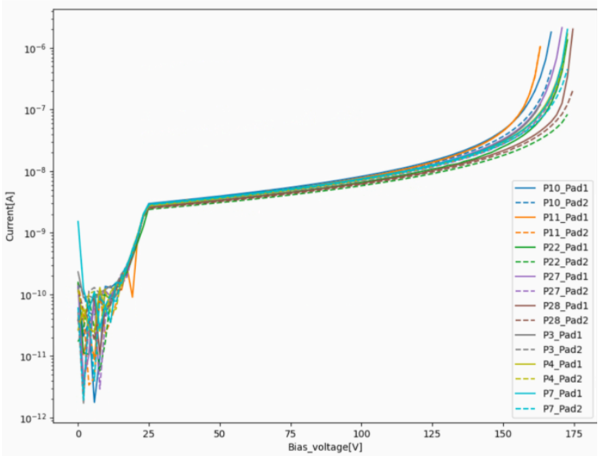


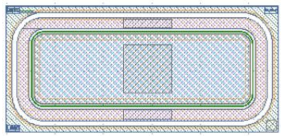
W2 single LGAD IV



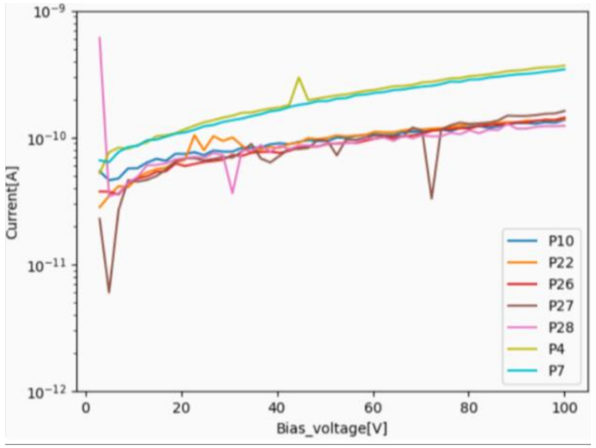


W2 1x2 LGAD IV





W2 PIN IV

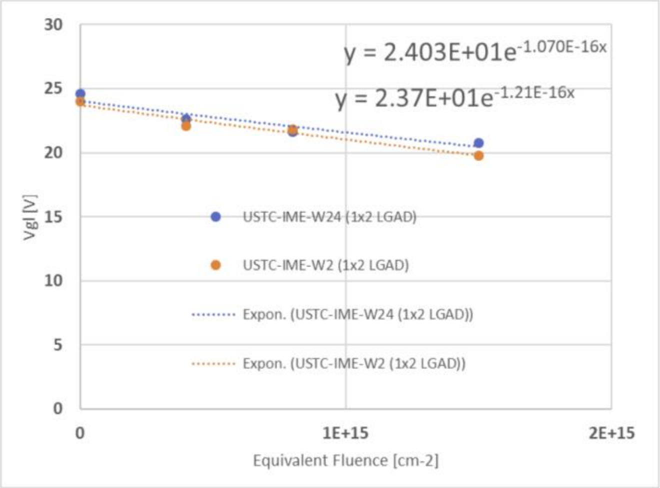


- The pads of PIN, 1x1 LGAD and 1x2 LGAD have the same area with pads of main sensor.
- The 1x1 LGAD and 1x2 LGAD have the same doping with the main sensor.
- The parameters extracted from the test structure can be used to estimate the nearby 15x15 main sensor.
  - Acceptor removal constant, collected charge, time resolution, efficiency etc.

Evaluation of radiation hardness

Sensor ID	V_{BD} (V), unirradiated		Fluence (n_{eq}/cm^2)
	1x2 Left_pad	1x2 Right pad	
W2_P39	190	190	0
W2_P29	194	194	4E14
W2_P24	184	184	8E14
W2_P37	194	196	1.5E15
W24_P39	146	148	0
W24_P29	152	152	4E14
W24_P41	150	150	8E14
W24_P23	146	148	1.5E15

Measured by JSI

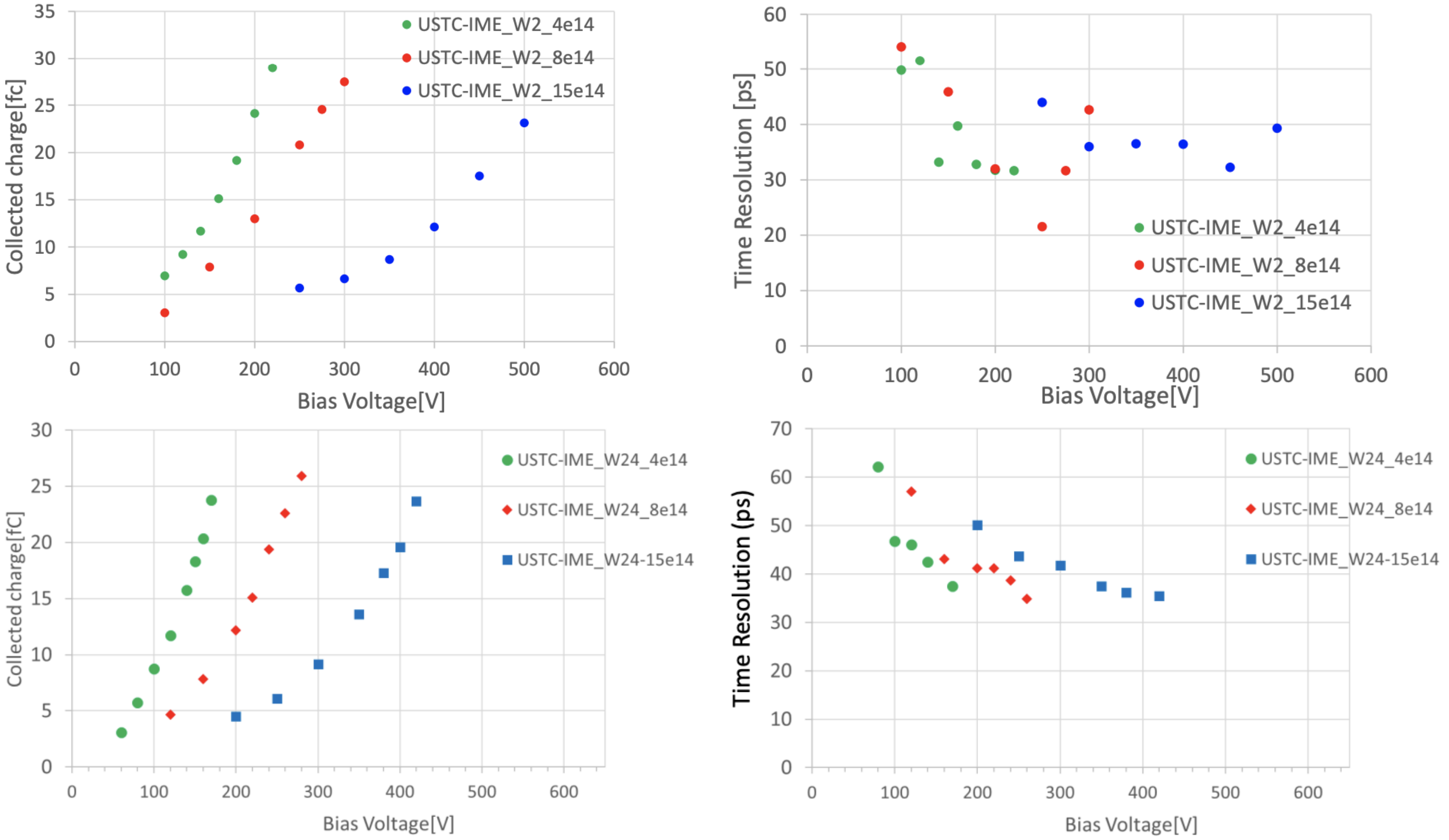


- Sensors were exposed to fluence up to 4e14, 8e14, 1.5e15 $\mathrm{n_{eq}\ cm^{-2}}$ at the TRIGA reactor in Ljubljana, Slovenia with neutrons
- Acceptor removal constant (c-factor) is extracted from the gain layer depletion voltages obtained from CV curves: $\frac{V_{GL}(\Phi_{eq})}{V_{GL}(0)} = e^{-c\cdot\Phi_{eq}}$
- The c-factor of USTC-IME Preproduction W2-LGADs (**1.21e-16** $\mathrm{cm^2}$) is similar to USTC-IME v2.1 W17-LGADs (1.23e-16 $\mathrm{cm^2}$) , which means the gain layer is radiation tolerant.

Collected charge and timing resolution – irradiated

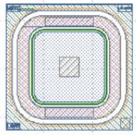
Beta-scope (^{90}Sr) @ -30 ^{o}C

Measured by JSI

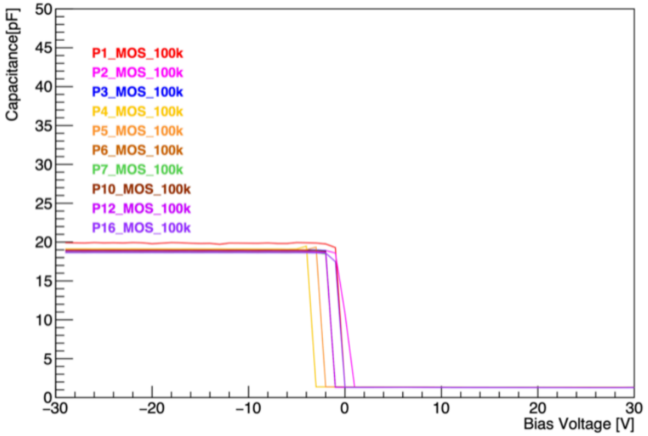


The collected charge can be **> 4 fC** and timing resolution can be **< 70 ps** after irradiation (fluences up to 1.5e15 $\mathrm{n_{eq}}\ \mathrm{cm^{-2}}$) at safe bias (<550V)

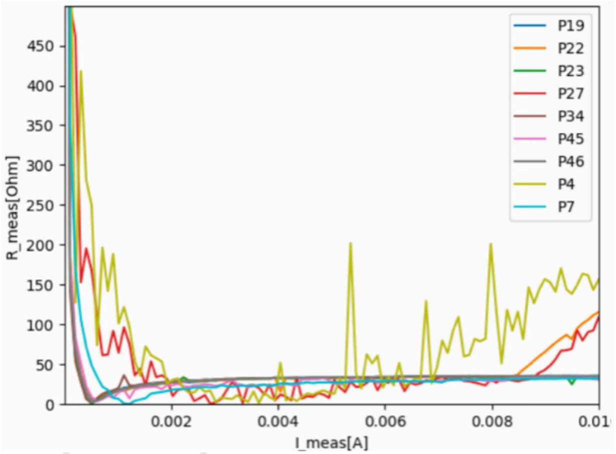
Other Results of QC-TS at USTC (by needle)



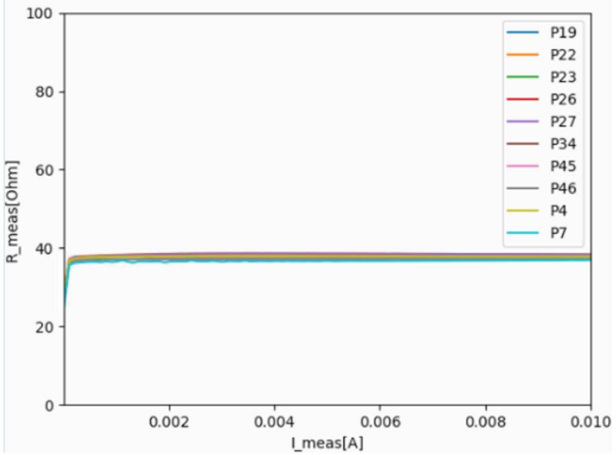
W2 CV result for MOS



P-stop VDP



N+ VDP



- Max depleted capacitance from CV of MOS capacitor can be used to get thickness of oxide. (0.91 – 0.96 μm)
- From VDP structure, resistance of different structures in LGAD can be extracted.
  - For N+ layer, ~38 Ω
  - For P-stop, ~34 Ω

Summary

- The USTC-IME preproduction sensors have been produced based on USTC-IME-v2.1 W17.
- The vender testing results shows that very good yield of around 40-50% is reached and 9 wafers with at least 18 good sensors are selected.
- The acceptor removal constant of W2 is **1.21e-16 cm^2**, which means the gain layer is radiation tolerant.
- The charge collection can **> 4 fC** and timing resolution can be **< 70 ps** after irradiation (fluences up to 1.5e15 $\mathrm{n_{eq}\ cm^{-2}}$) at safe bias (< 550V).
- QC-TS will provide diagnostic capability to production process and perform quality assurance measurements for LGAD.
  - By now, most of the test results are in our expected range but some result still needs to be understood

Thank you RD50!

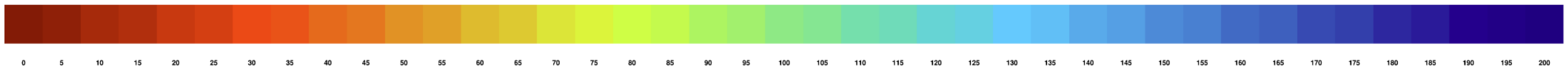
The USTC team acknowledges the strong support from the RD50 collaboration during the entire course of the LGAD RD!

Report	Meeting
Preliminary USTC-1 LGAD Results and Large Array Characterization for HGTD	37th RD50 Workshop
Characterization on the radiation hardness of USTC-1.1 LGADs	38th RD50 Workshop
Recent results of the carbonated USTC-IME LGADs and fabrication of the AC-LGADs at USTC NRFC	40th RD50 Workshop
USTC-IME LGAD pre-production for HGTD	43rd RD50 Workshop

Thank you for your attention!!

Back up

W19 – V_{BD} Histogram

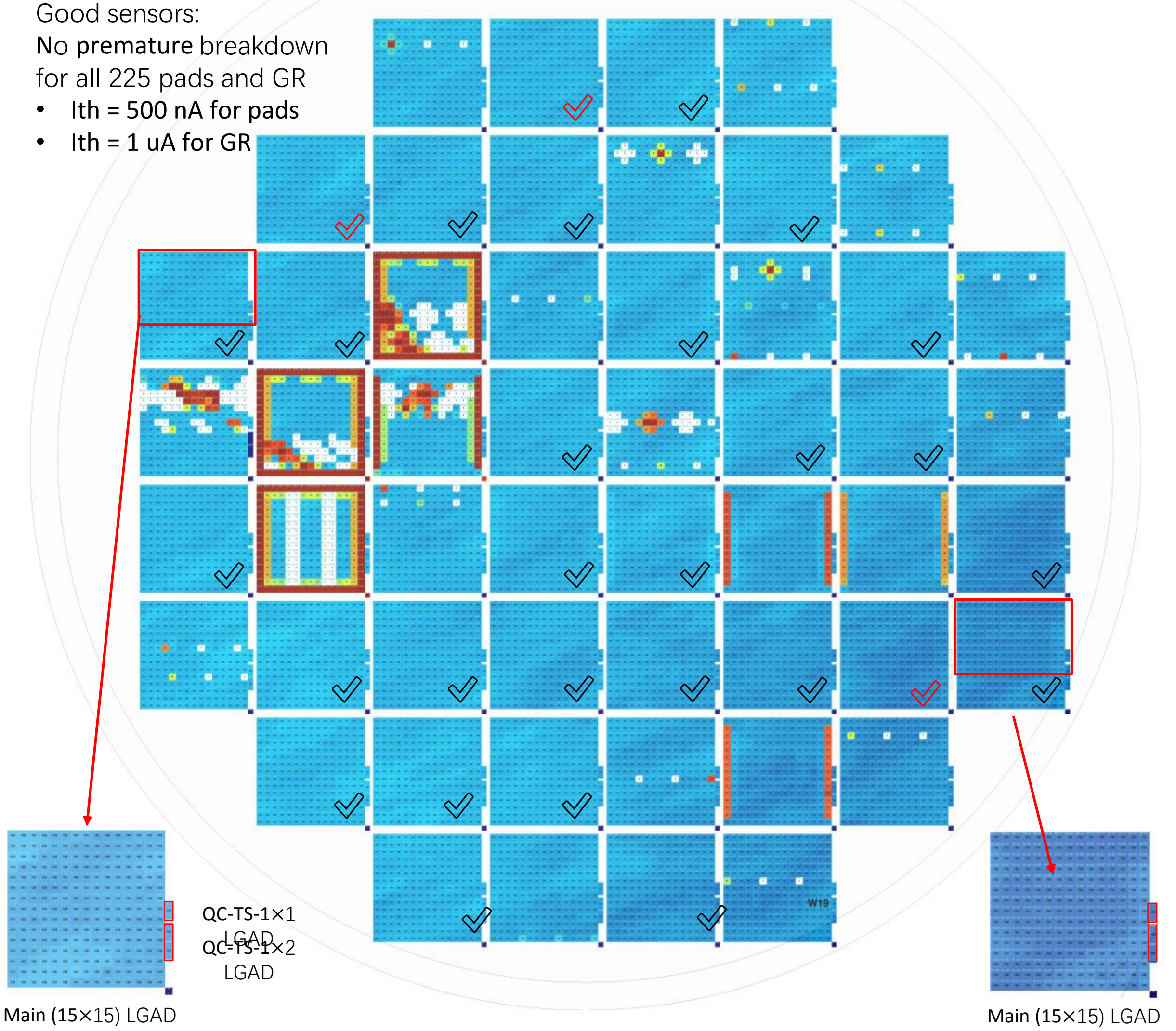


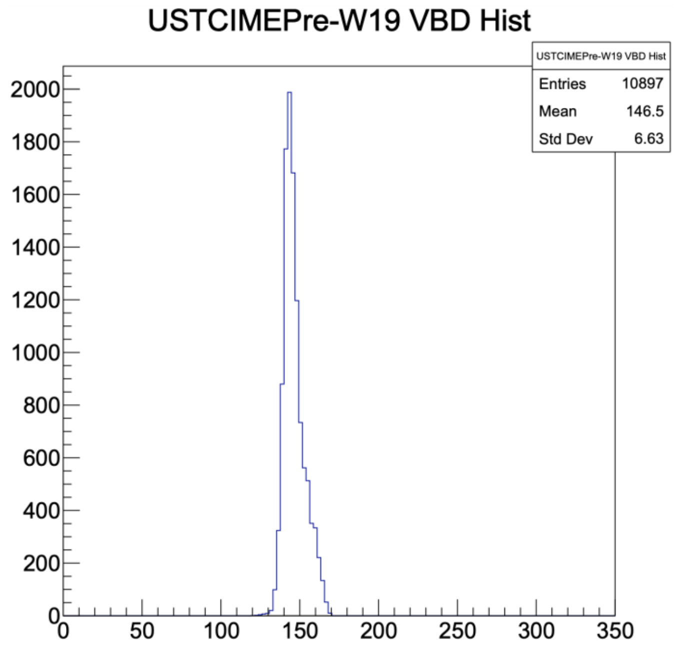
0

- VBD = VMAX (VMAX < 120 V) due to limit of compliance

Good sensors:
No **premature** breakdown
for all 225 pads and GR

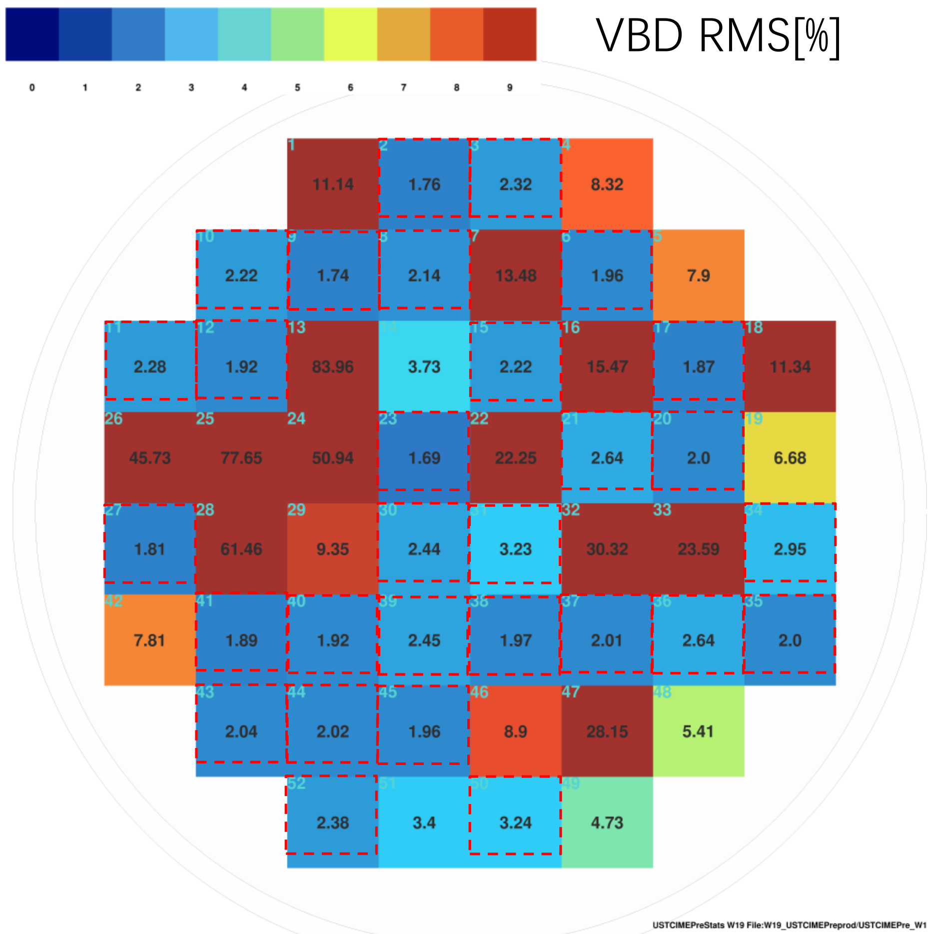
- Ith = 500 nA for pads
- Ith = 1 uA for GR

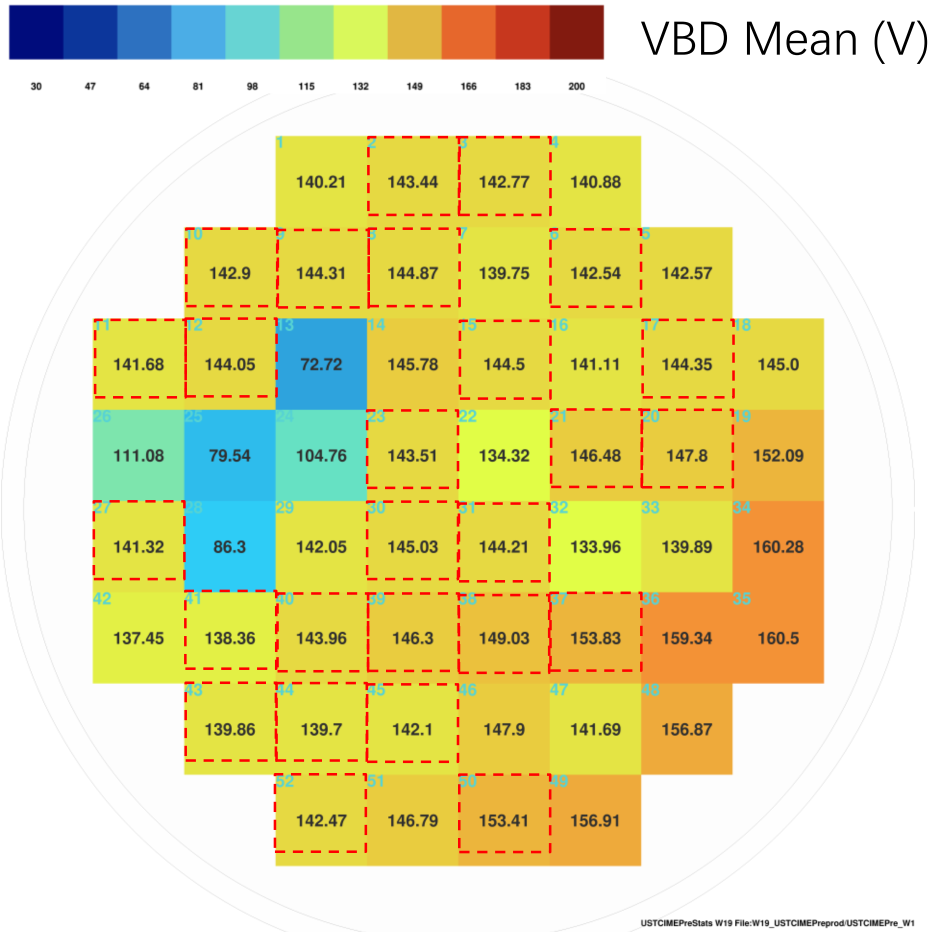




- Vth > 120 V to cut early breakdown pads

W19 – V_{BD} RMS and Mean





[134.78, 158.22] (V)

$V_{bd,pad}$ spread over the Sensor*,¤	$RMS(V_{bd,pad})/<V_{bd,pad}> <0.05$

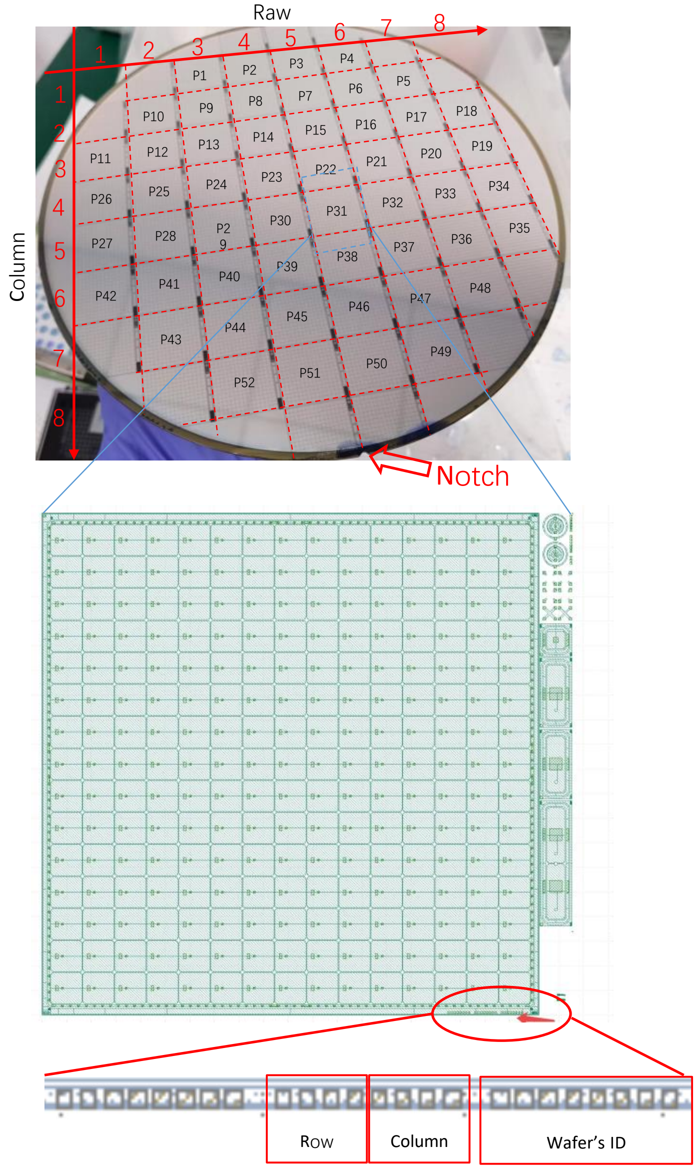
Variation of the V_{bd} between different sensors	±8% from the average V_{bd}

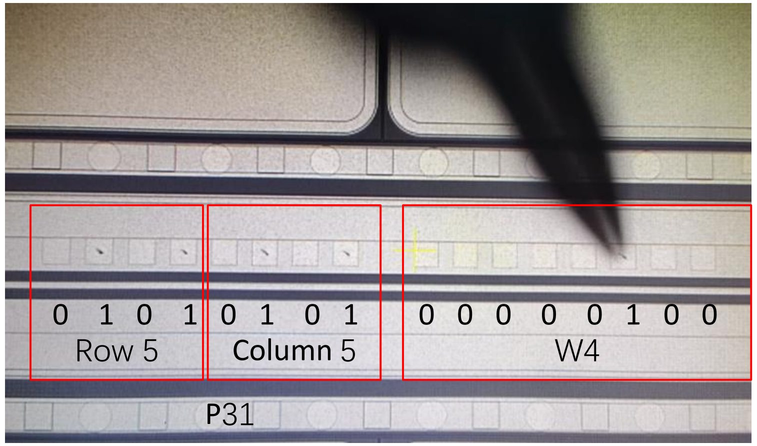
Good/Total: 29/52 ~ 56 %

Good/Total: 26/52 ~ 52 %

- Combined results: yield ~ 52 %

Label of sensors

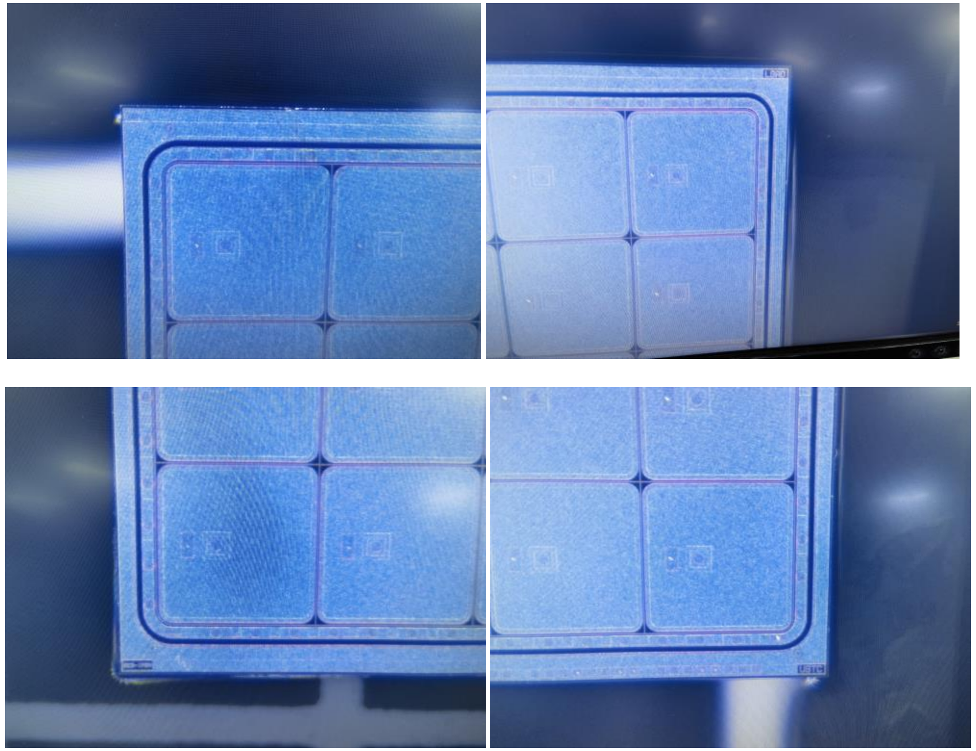




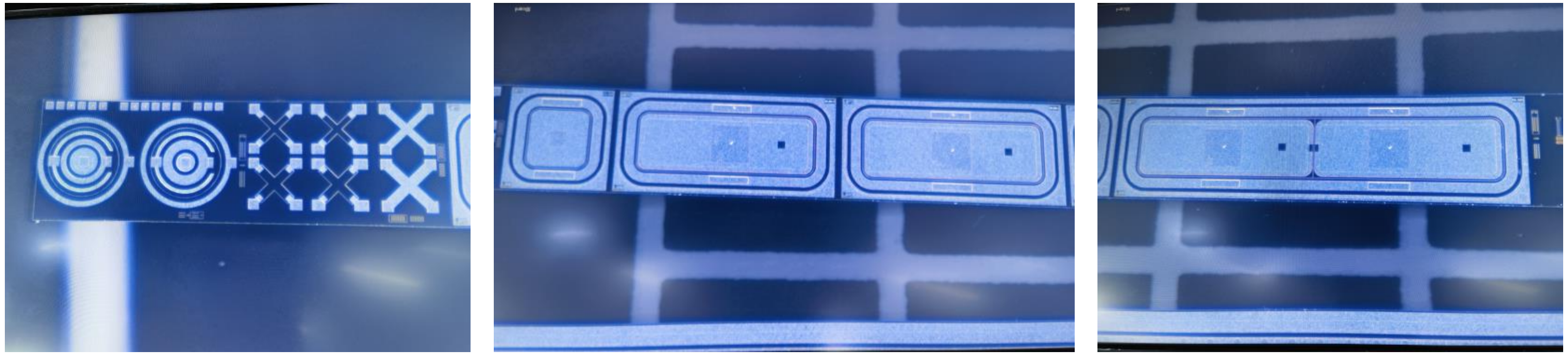
- The label is done by **a unique binary-coded**.
- The value of scratched pad is “1”
- The value of non-scratched pad is “0”.

Checking of cutting edge

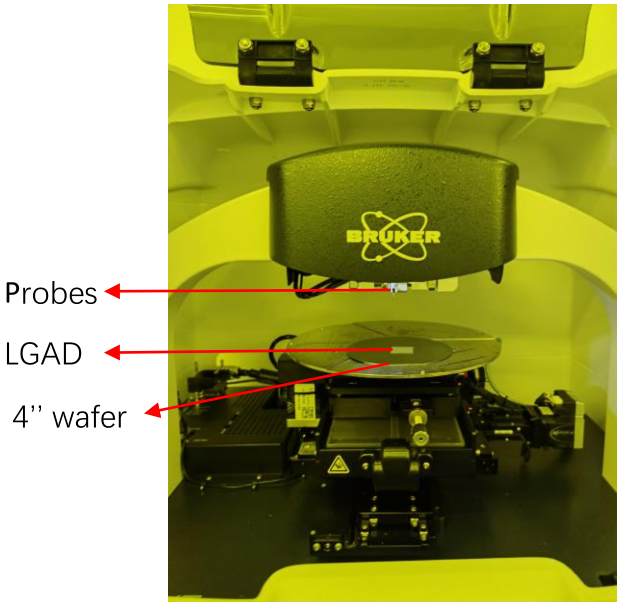
Sensor's corner:

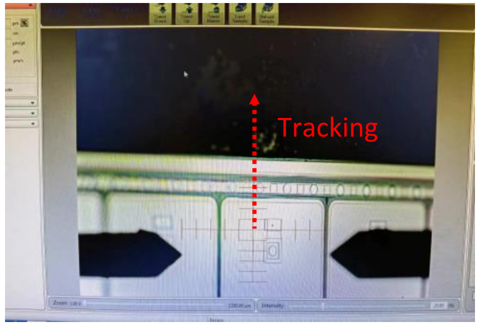


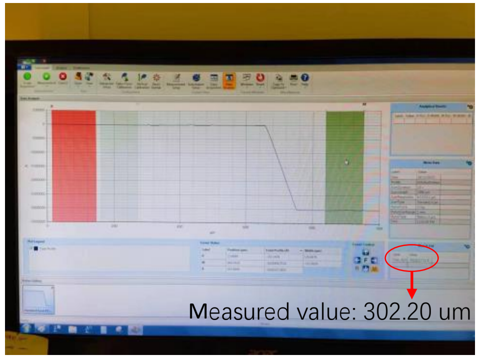
QC-TS:

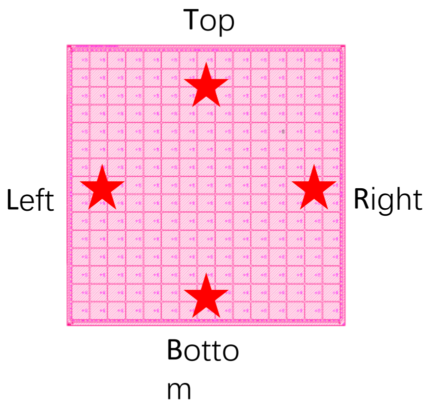


Measurements of sensors' thickness (Profiler)









Version	Sensors	Size	Ground	Top	Bottom	Left	Right
USTS-IME Preproduction	W2_P4	15x15	Wafer level	302.32 um	304.39 um	307.01 um	306.40 um
	W24_P4	15x15		305.56 um	305.40 um	305.39 um	305.68 um
	W12_P1	15x15		301.83 um	301.60 um	304.44 um	302.16 um
	W12_P49	15x15		303.14 um	302.74 um	302.09 um	302.20 um
	W25_P1	15x15		301.18 um	300.80 um	303.43 um	302.45 um

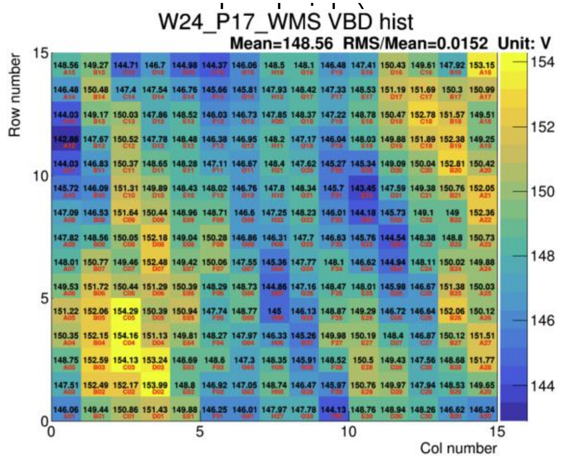
Check the effect of thinning, metallization on backside and dicing

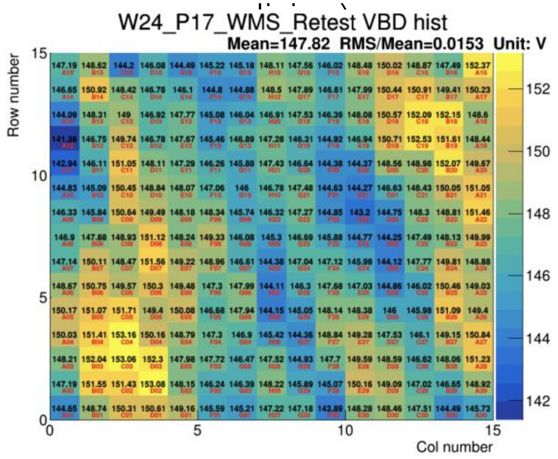
W24_P17

(Wafer level, no metallization on

(After thinning, metallization on backside and

VBD distribution

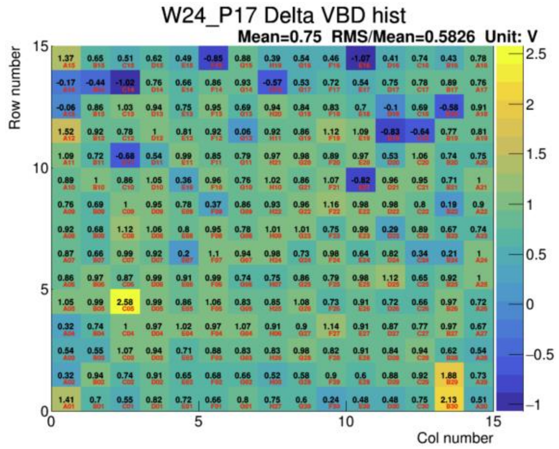


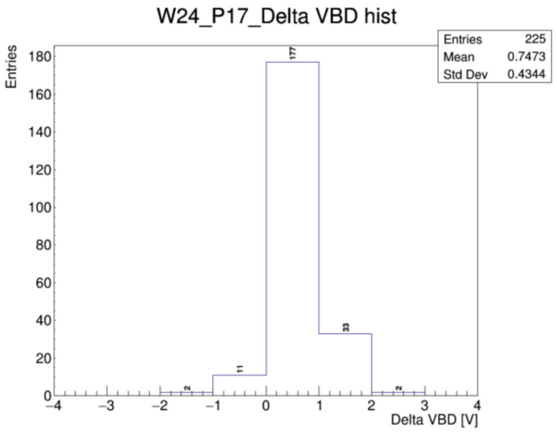


2D distribution

1D distribution

The difference of VBD (Delta VBD)



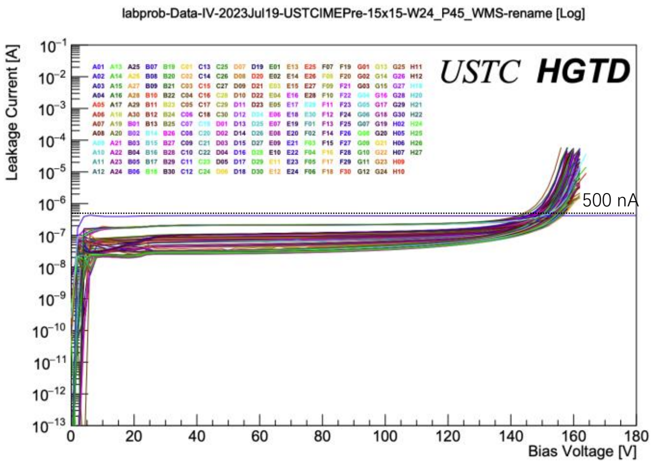


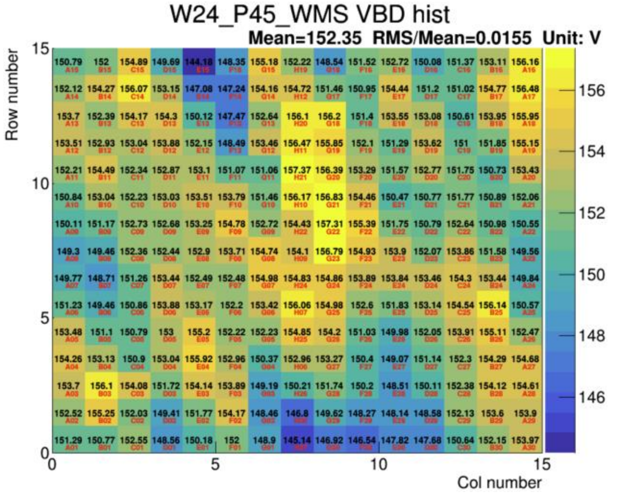
- $\text{Delta VBD tested by probe needles} = (\text{VBD } \textbf{on wafer level} - \text{VBD } \textbf{after thinning, dicing} \ldots)\ (\text{V})$
- The uniformity of 15×15 sensor is consistent and the difference of VBD (Delta VBD) is within ± 2 V, which means the processes (thinning, metallization on backside and dicing) are reliable.

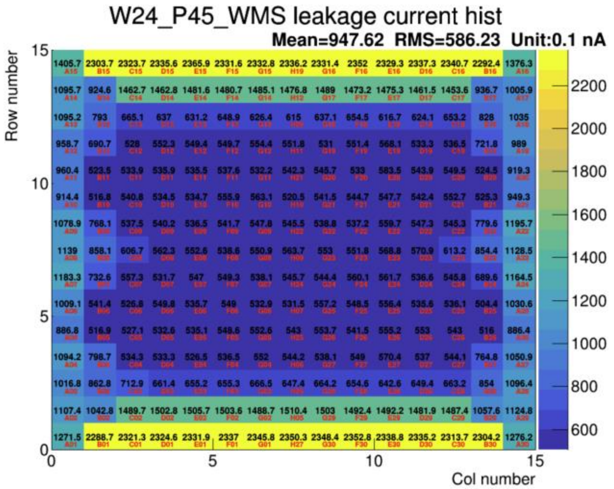
Cross-check of 15×15 sensors by 15×15 probe card

W24_P45

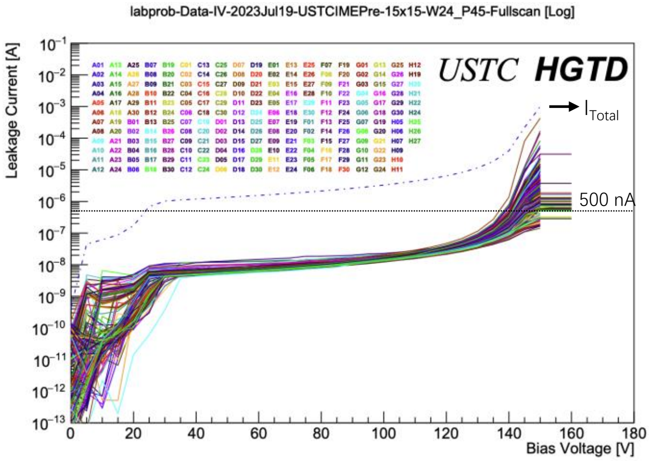
- Tested by **probe needles** while other pads and GR are floating, **R.T.**

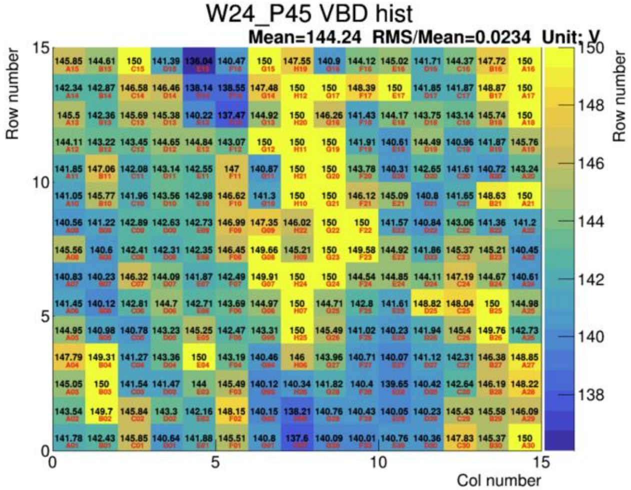


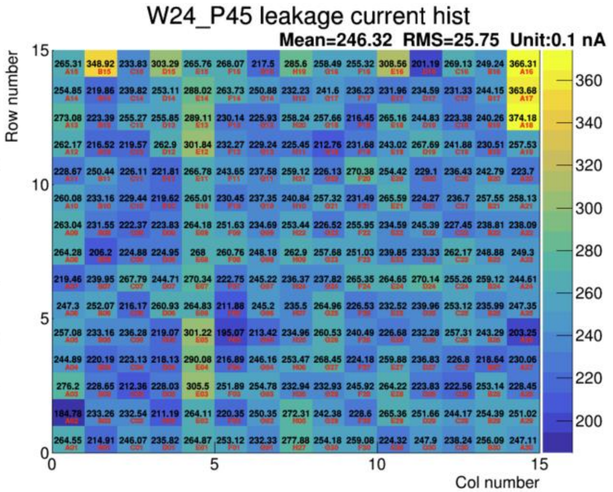




- Tested by **probe card** while other pads are grounded and GR is floating, **chuck at 20 °C**



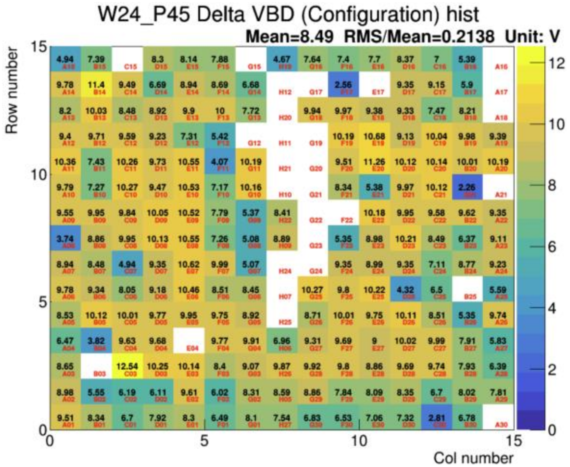


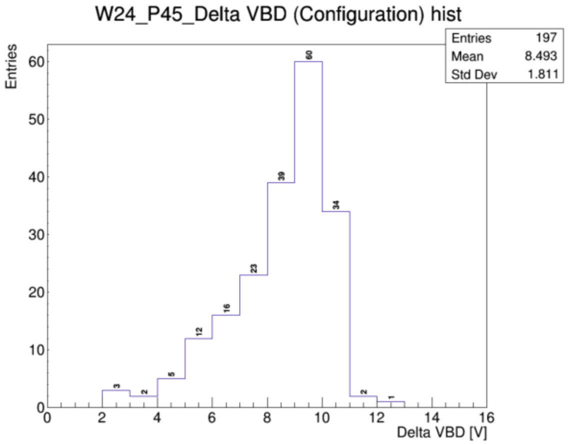


Max/Min($I@0.8V_{BD}$) = 2.03 (<3)

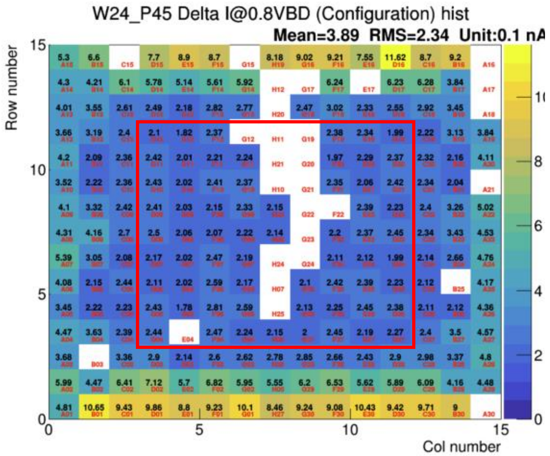
The 1D and 2D distribution of ΔVBD and ratio of I@0.8VBD

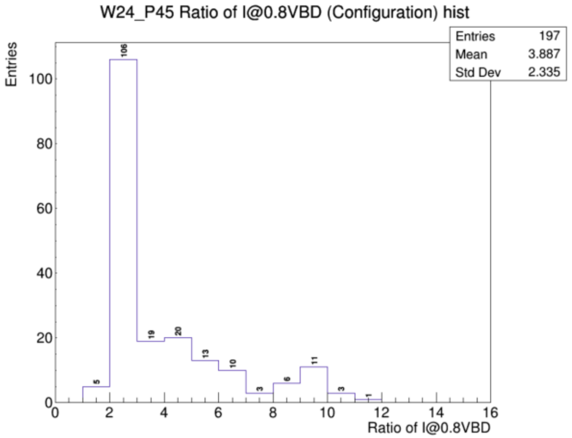
- $\Delta\mathbf{VBD} = (\text{VBD tested on wafer level by } \mathbf{probe\ needles} - \text{VBD test by } \mathbf{probe\ card} \text{ after thinning, dicing} \ldots)\ (\text{V})$





- $$\mathbf{Ratio\ of\ I@0.8VBD} = \frac{\mathbf{I@0.8VBD} \text{ tested on wafer level by } \mathbf{probe\ needles}, \mathbf{R.T.}}{\mathbf{I@0.8VBD} \text{ test by } \mathbf{probe\ card} \text{ after thinning,dicing} \cdots, \mathbf{chuck@20}\ ^{\circ}\mathrm{C}}$$





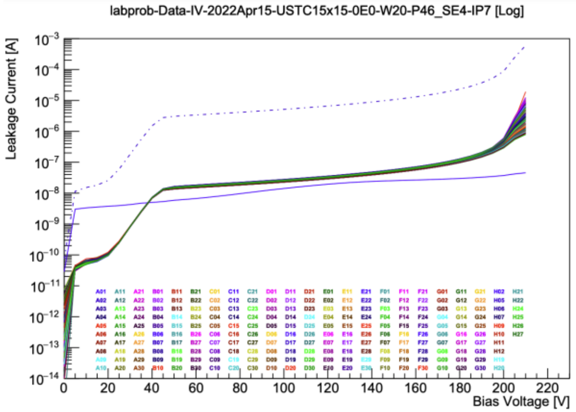
- The difference of VBD (ΔVBD) is in order of 10 V and the Ratio of I@0.8VBD for inner pads is in the range of 1.7-2.6, which is mainly related to the temperature of the chuck.

Cross-check of 15×15 sensors by 15×15 probe card

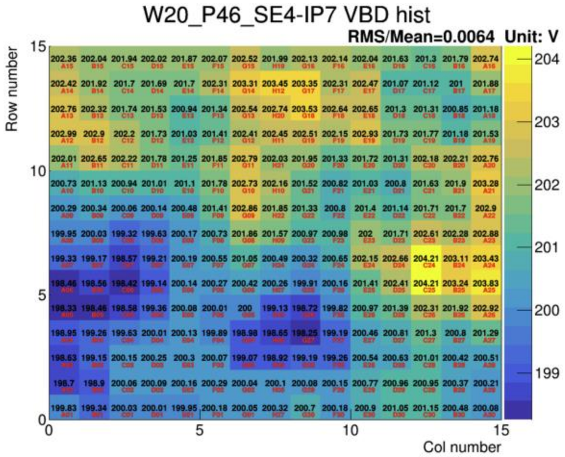
USTC-IME-v2.1-W20_P46

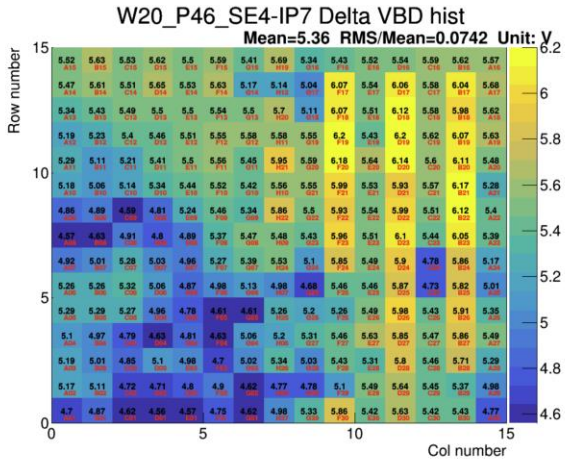
- Tested by **one probe needle** while other pads and GR are floating, **R.T.**

IV results

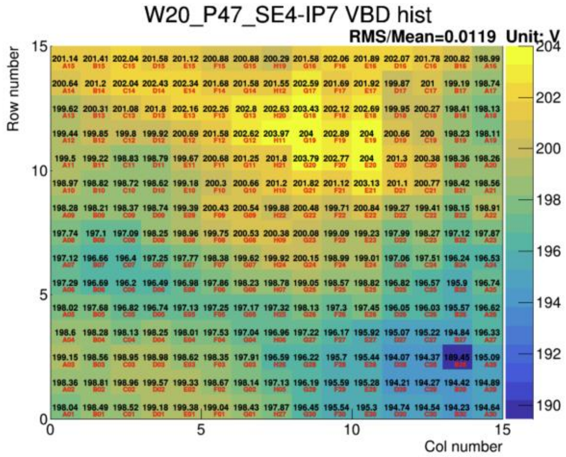


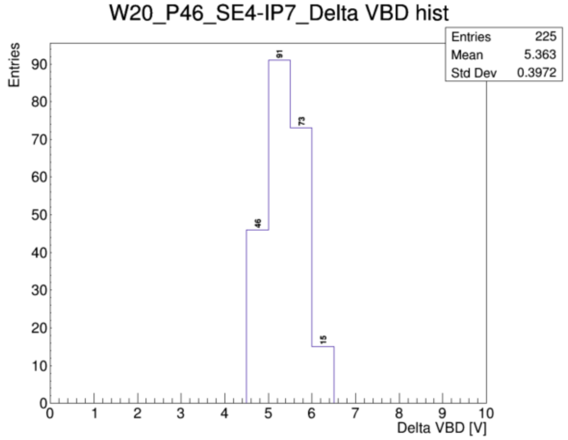
V_{BD}





- Tested by **probe card** while other pads and GR are grounded, **chuck at 20 °C**

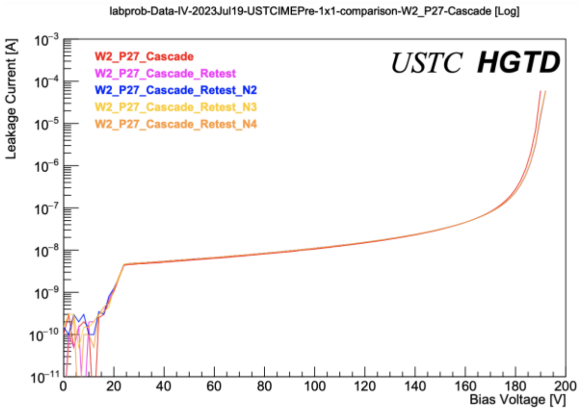


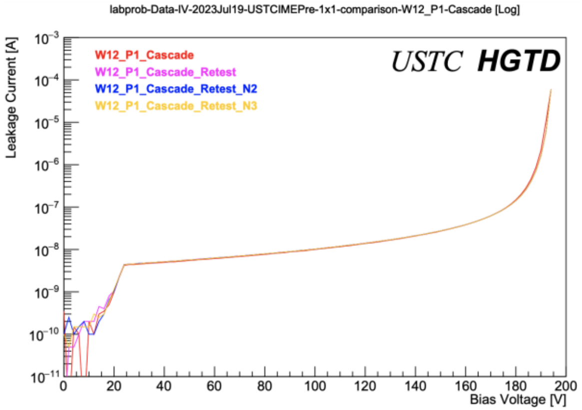


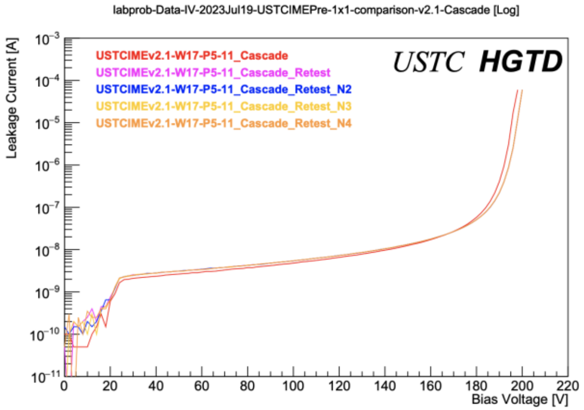
- **The difference of VBD (**ΔVBD) is also in order of 10 for **USTC-IME-v2.1 sensors**

Comparison of single LGADs (IV)

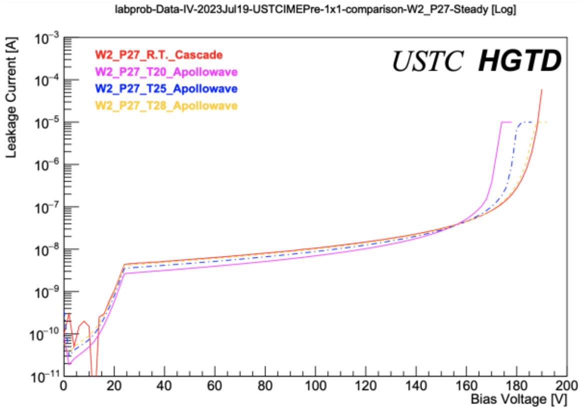
- Repeated testing on Cascade probe station at **R.T.** (vender test)



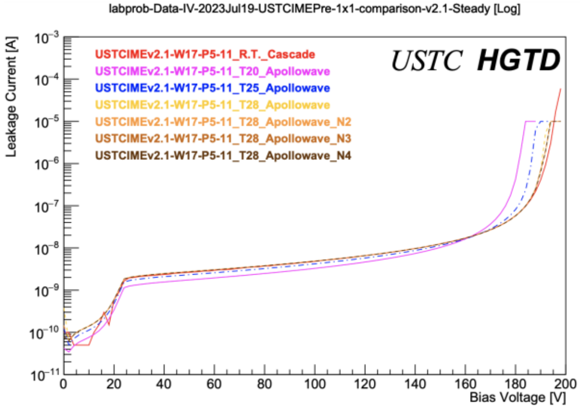




- Testing on Apollowave probe station **at different temperature of chuck** (cross-check)



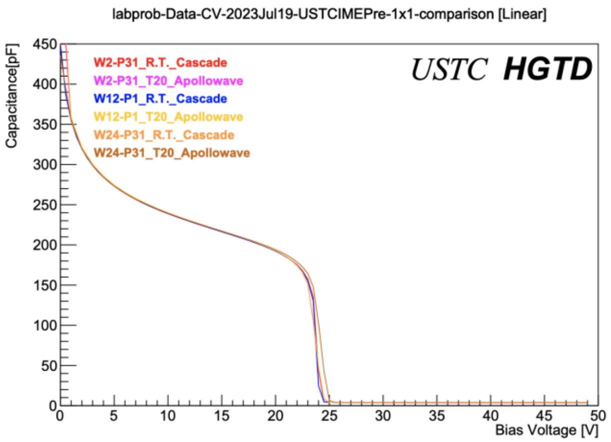
-·-· Chuck @25 °C
--- Chuck @28 °C

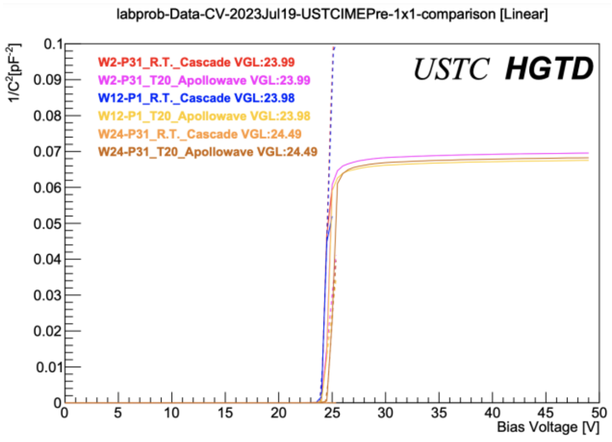


-·-· Chuck @25 °C
--- Chuck @28 °C

- The repeated vender test and cross check results is steady, respectively
- The difference of VBD is also in order of 10 V, which is **related to the temperature of the chuck**
- The ratio of I@0.8VBD is about 1.73

Comparison of single LGADs (CV)



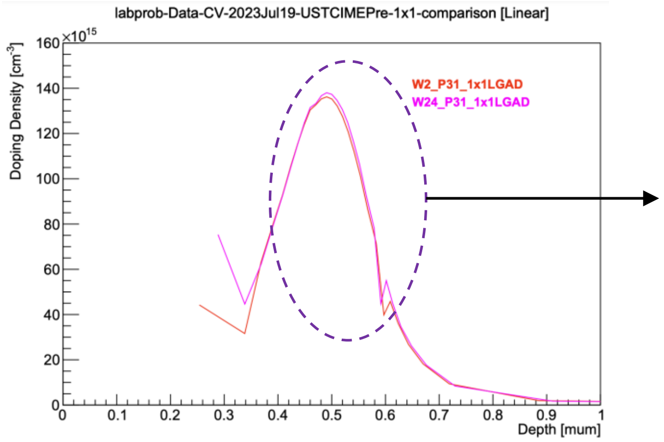


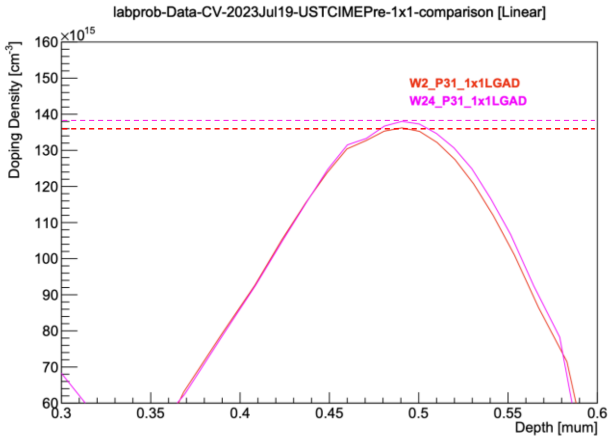
$$N(w) = \frac{2}{e \cdot \varepsilon \cdot A^2}\left[\frac{d(C^{-2})}{dV}\right]^{-1}$$

$$w = A \cdot \varepsilon \cdot \frac{1}{C}$$

N: effective doping concentration
w: depth
A: active area $(0.221946 \times 0.0704\ \mathrm{cm}^2)$

$$\varepsilon = \varepsilon_{r_{Si}}\varepsilon_0 = 11.9 \times 8.854 \times 10^{-14}\ \mathrm{F/cm}$$
$$e = 1.602 \times 10^{-19}\ \mathrm{C}$$





$$\Delta\mathrm{Conc.\,(Peak)} = 2 \times 10^{15}\ \mathrm{cm}^{-3}$$

- The depletion voltage of gain layer is consistent
- ~ 1.5% variation on gain layer dose → ~ 22.5 V variation the V_{BD}
- The true V_{BD} difference between W2 and W24 is about 36 V, maybe the difference between wafers isn’t only caused by the dose variation

Timing resolution - calibration

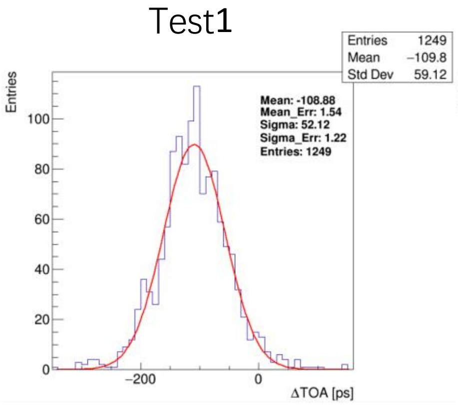
Beta-scope (^{90}Sr)

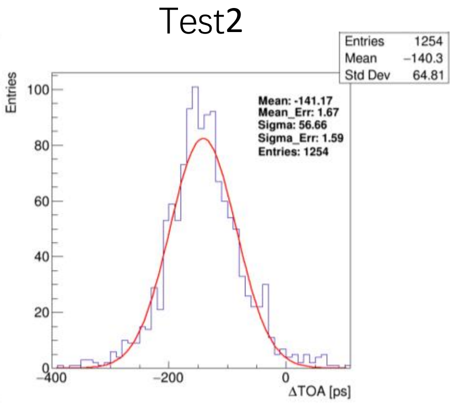
Three HPK Type 1.1 sensors @180V, 20°C

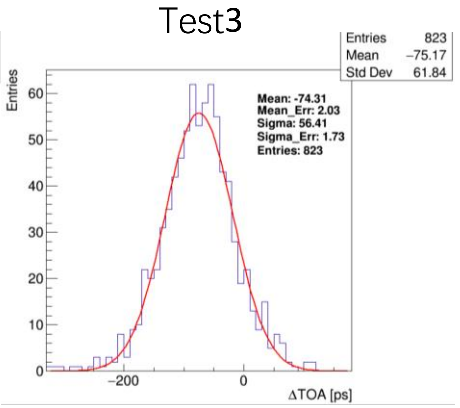
Test1
- DUT(1): **Sensor1**
- Trigger(2): **Sensor2**

Test2
- DUT(1): **Sensor3**
- Trigger(2): **Sensor2**

Test3
- DUT(1): **Sensor1**
- Trigger(2): **Sensor3**







Test	Collected charge (MPV, fC)	ΔTOA (ps)
1	Sensor1: 9.63 Sensor2: 9.92	52.99
2	Sensor3: 9.52 Sensor2: 9.93	56.66
3	Sensor1: 9.30 Sensor3: 9.39	56.41

$$\sigma_3 = \sqrt{(\sigma^2_{\Delta\mathrm{TOA}(1,3)} + \sigma^2_{\Delta\mathrm{TOA}(2,3)} - \sigma^2_{\Delta\mathrm{TOA}(1,2)})/2} \approx 42.33\ \mathrm{ps}$$

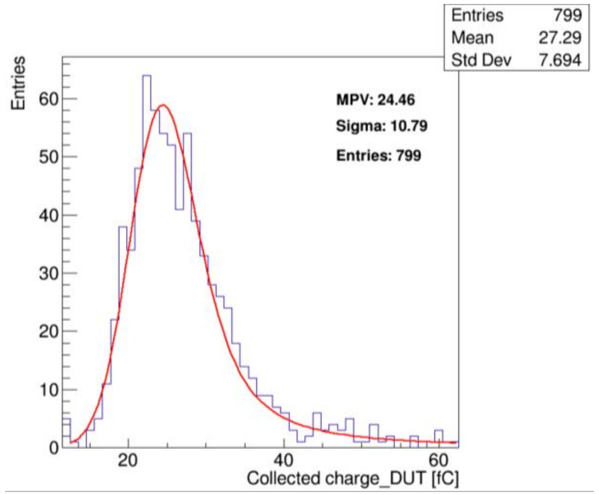
$$\sigma_2 = \sqrt{(\sigma^2_{\Delta\mathrm{TOA}(1,2)} + \sigma^2_{\Delta\mathrm{TOA}(2,3)} - \sigma^2_{\Delta\mathrm{TOA}(1,3)})/2} \approx 37.28\mathrm{ps}$$

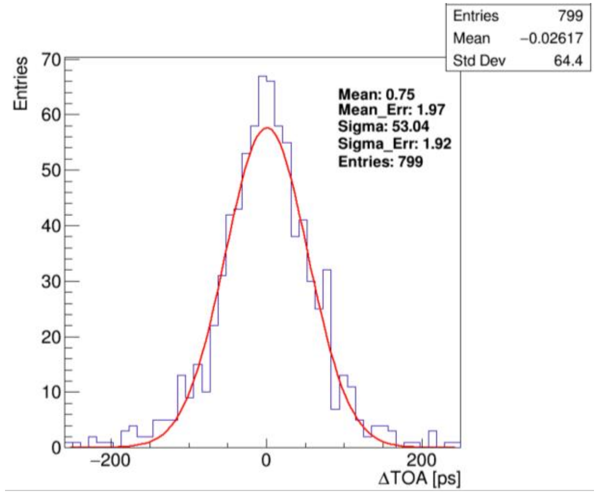
$$\sigma_1 = \sqrt{(\sigma^2_{\Delta\mathrm{TOA}(1,2)} + \sigma^2_{\Delta\mathrm{TOA}(1,3)} - \sigma^2_{\Delta\mathrm{TOA}(2,3)})/2} \approx 37.66\ \mathrm{ps}$$

Collected charge and timing resolution – W2

Beta-scope (^{90}Sr), preliminary results

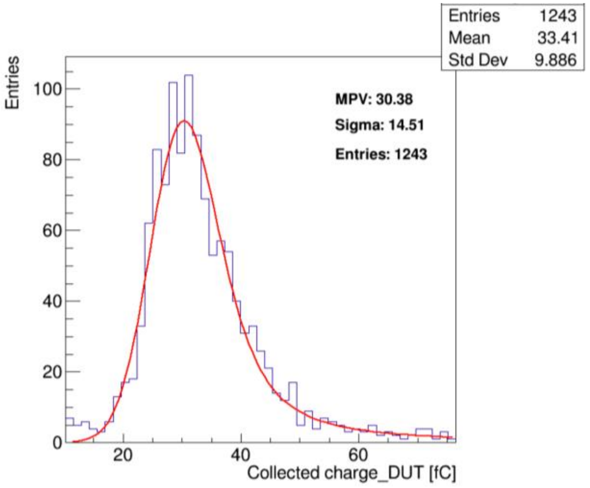
W2_P36,
@185V, 20^{o}C
(VBD: 194 V)

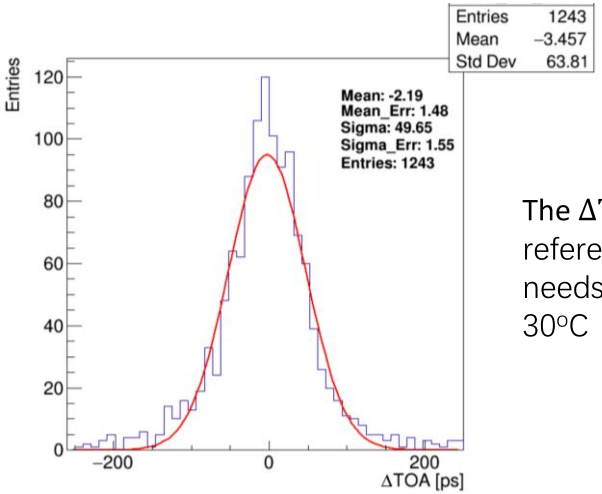




$$\sigma_{\mathrm{DUT}} = \sqrt{\Delta\mathrm{TOA}^2 - \sigma_2} \approx 37.73\ \mathrm{ps}$$

W2_P36,
@125V, -30^{o}C
(VBD: 134 V)



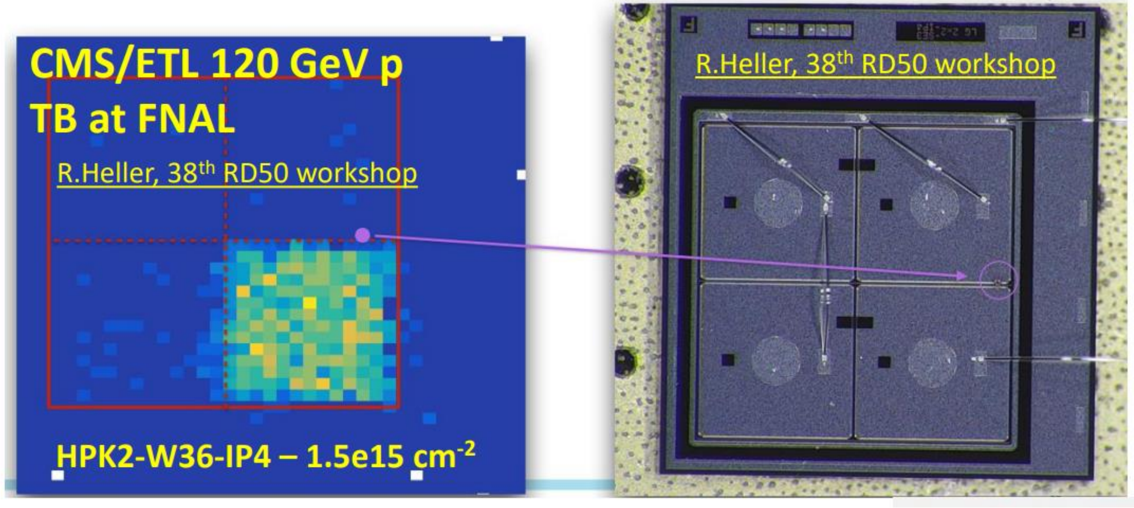


The ΔTOA decreases and the reference's timing resolution needs to be calibrated at -30^{o}C

Studied by RD50, CMS and ATLAS

Safe zone of bias voltage - Single Event Burnout (SEB)


burn mark in the CNM sensor after ATLAS TB in 2018 after the test beam – dimensions are few tens µm (crater photo taken by CNM)

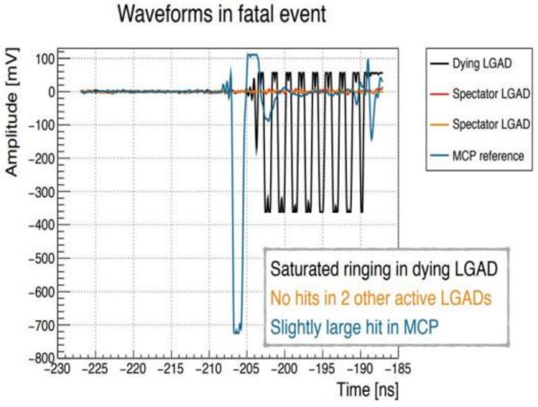

CMS/ETL 120 GeV p TB at FNAL

R.Heller, 38th RD50 workshop

HPK2-W36-IP4 – 1.5e15 cm^{-2}

R.Heller, 38th RD50 workshop

- During the test beam, some sensor died at high bias voltage with the “star shaped crater”.
- The fatality was caused by the high energy deposition of one single beam particle.
- Some signals from the event in which sensor died were recorded and the tracking information point to the place of the crater.
- This means bias voltage should not be too high, to ensure sensor won’t be damaged.



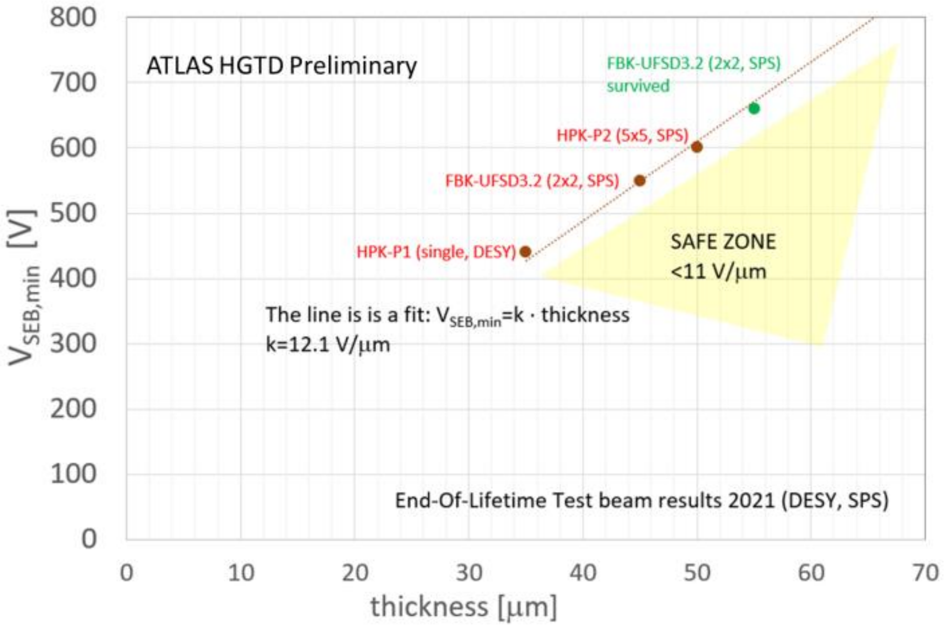
Saturated ringing in dying LGAD

No hits in 2 other active LGADs

Slightly large hit in MCP

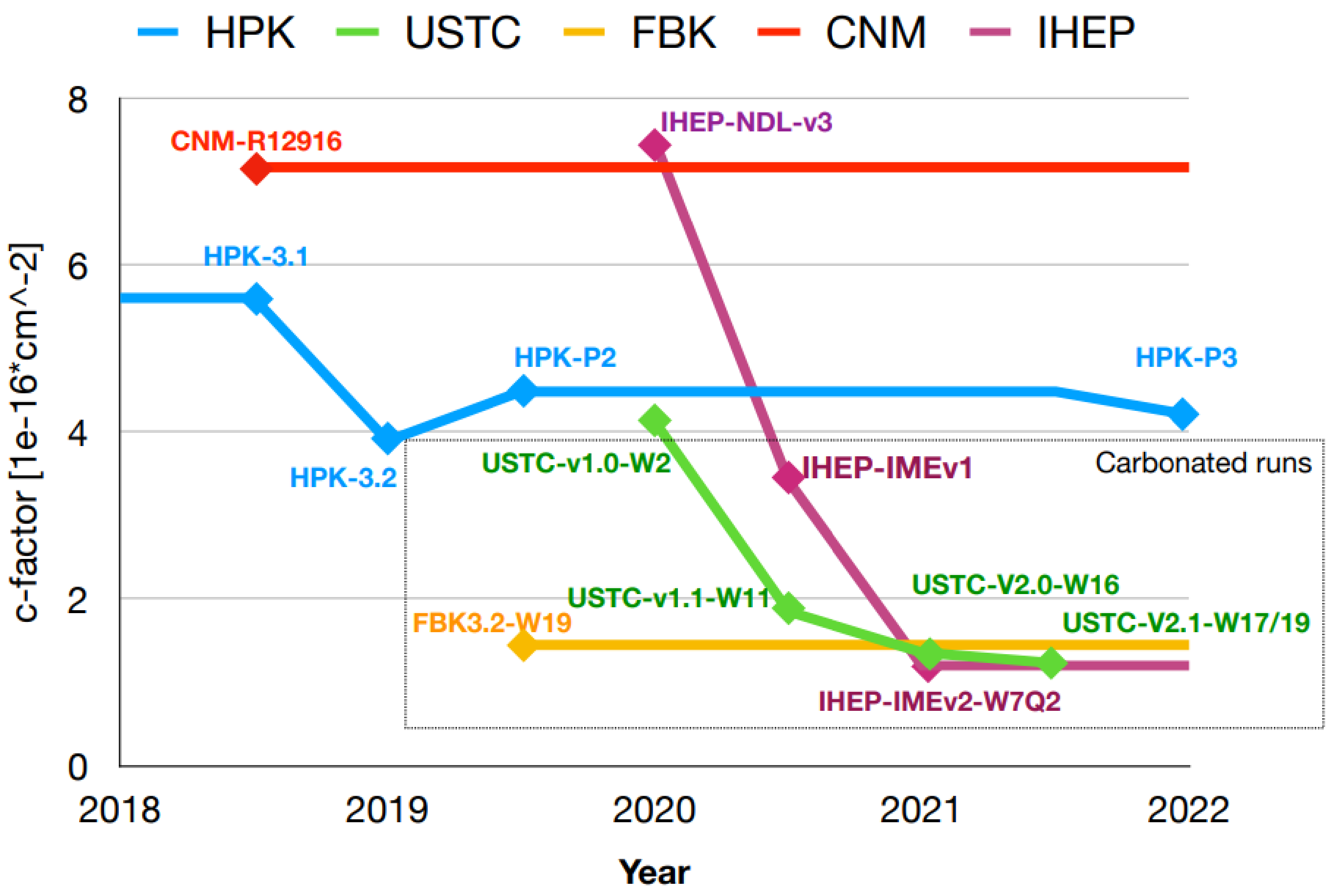
Death within 1 ns of proton arrival.

Safe zone of bias voltage



- The minimum of V_{SEB} is thickness dependent.
- The test result shows the electric field should be limited to < 11 V/µm.
- For 50 µm sensors with adequate performance, the bias voltage should < 550 V.

Evolution of the c-factor from different vendors



- c-factor measured with CV method on the most promising wafer (rad. hard) for each vendors' run.
- With the carbon in the gain layer, the USTC LGAD prototypes show promising radiation hardness compared to other vendors.