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

Performance of the USTC first batch LGADs

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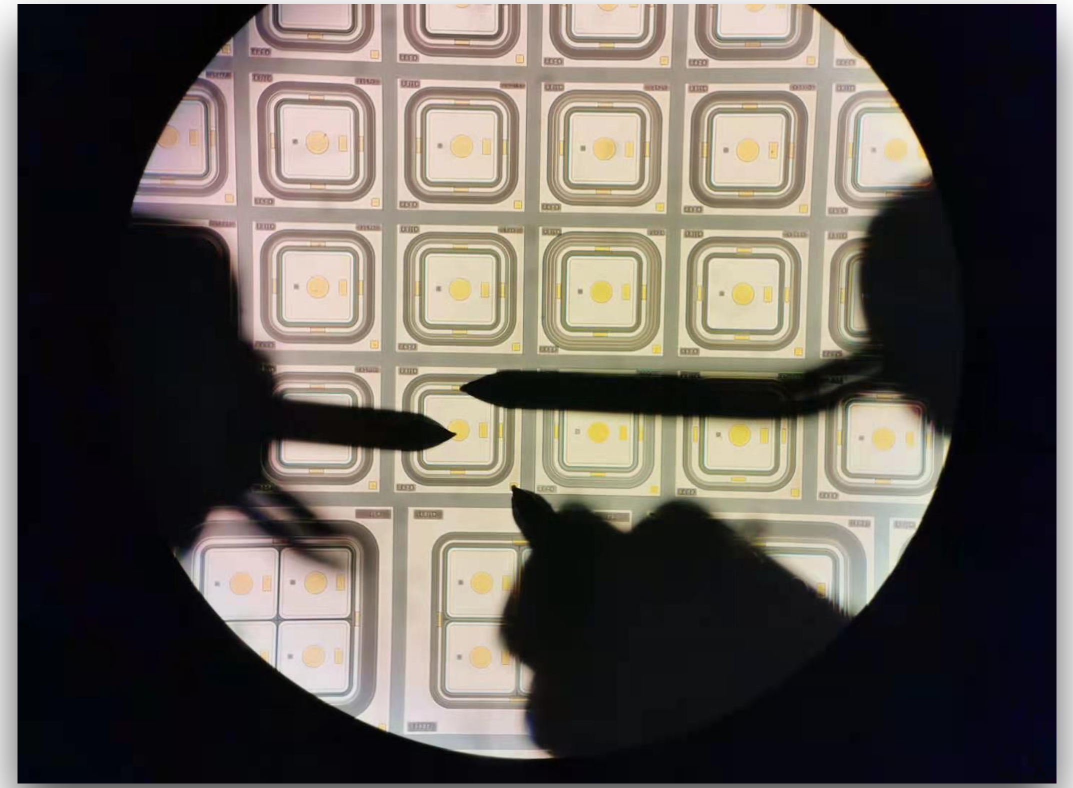
16th "Trento" Workshop on Advanced Silicon Radiation Detectors
February 18th, 2021



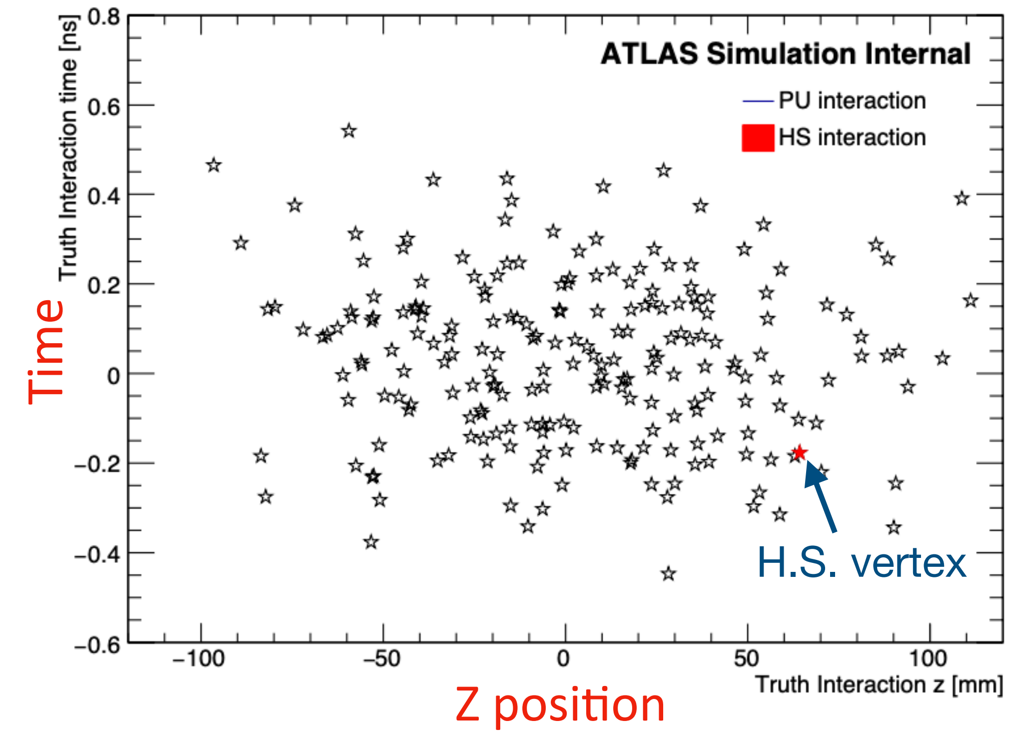
The High-Granularity Timing Detector(HGTD) for the ATLAS Phrase-II Upgrade

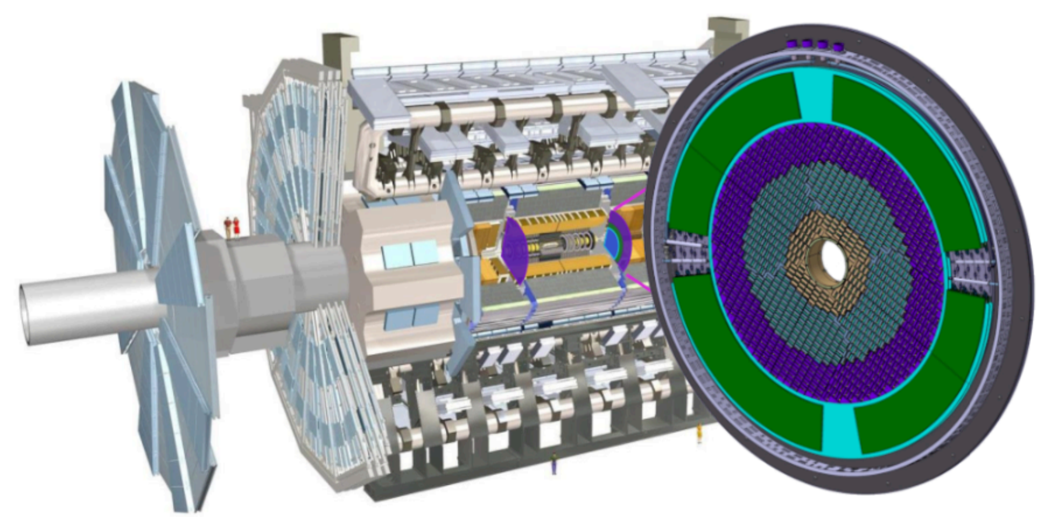
Motivation and Technique

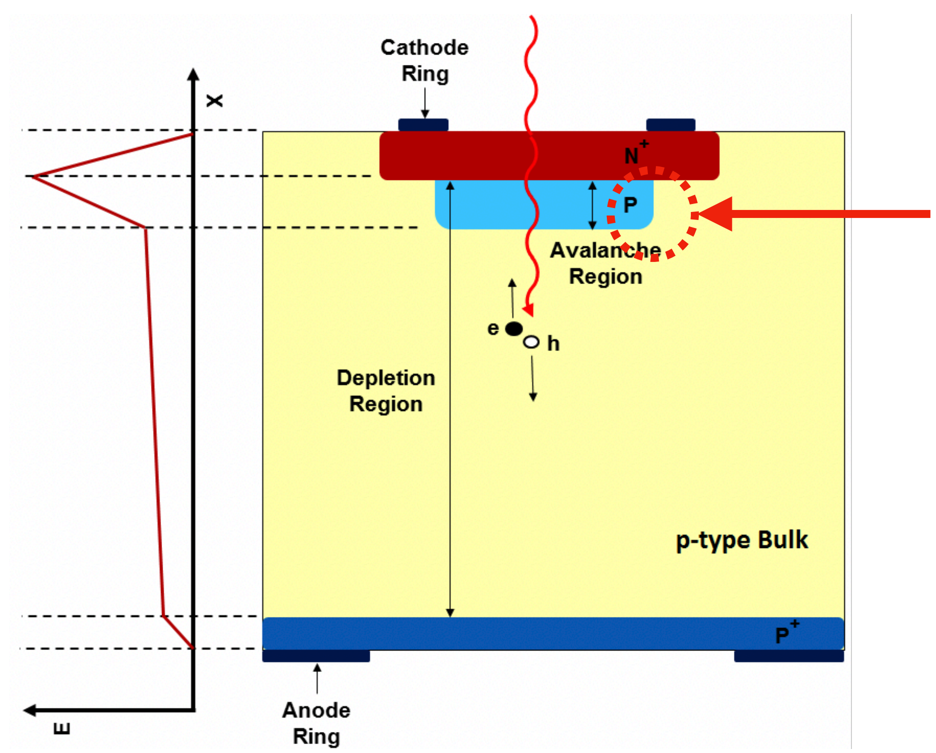
- In the HL-LHC, Pile-up density would get so high that track to vertex association would be very hard, especially in the forward region

- Having a timing detector in forward region would allow us make the matching in “4-D” space.

- A novel technology: LGAD (**Low-Gain Avalanche Detector**), which achieves promising S/N and σ_t by inducing an internal gain layer.







Gain layer

- σ_t ~30 ps per track

larger gain

↓

faster rising time and larger S/N

↓

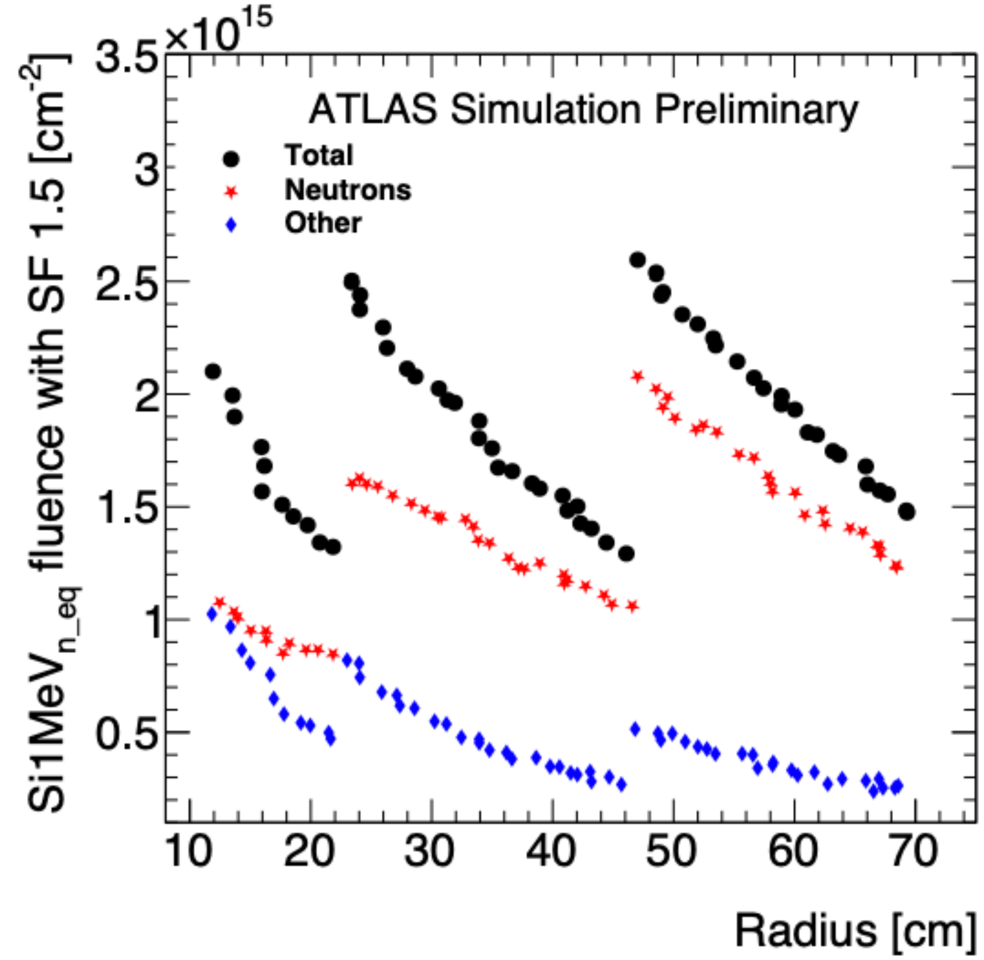
better time resolution

LGAD Sensor R&D

Challenges on LGAD Design

- **Radiation Hardness**:
  - Acceptor removal
    - **Solutions:**
      - Narrow and deep implantation of boron
      - Carbon diffusion

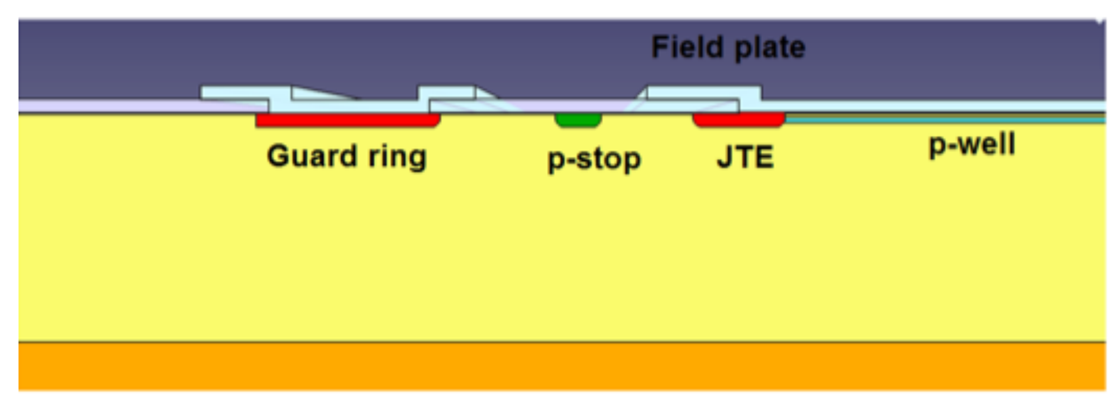
- **Premature breakdown**:
  - Optimization of the peripheral region to prevent premature breakdown (to ~800V)
  - Implementation of the structures commonly used in ***power semiconductor device***:
    Guard ring, JTE, Field plate



HGTD's requirement on the NIEL fluence

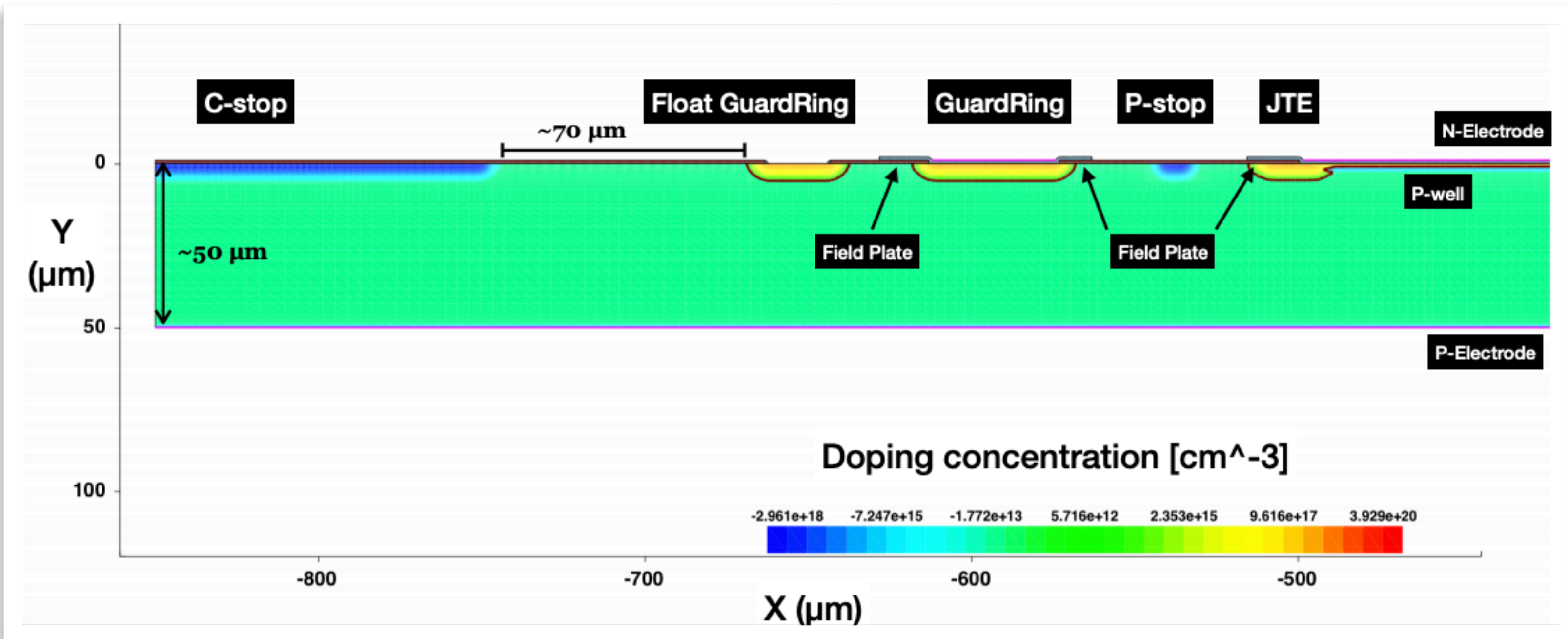
$$\rho_A(\phi) = g_{eff}\phi + \rho_A(0)e^{-c\phi}$$

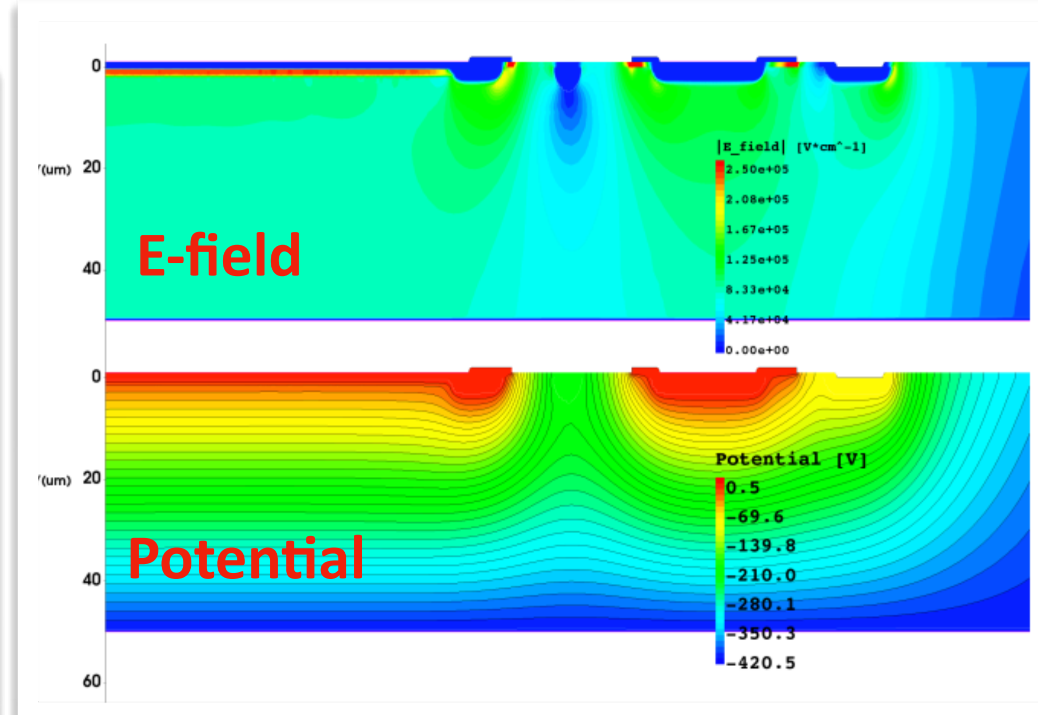
Acceptor density with NIEL fluence



Structures to avoid premature breakdown

USTC-LGAD Design with TCAD



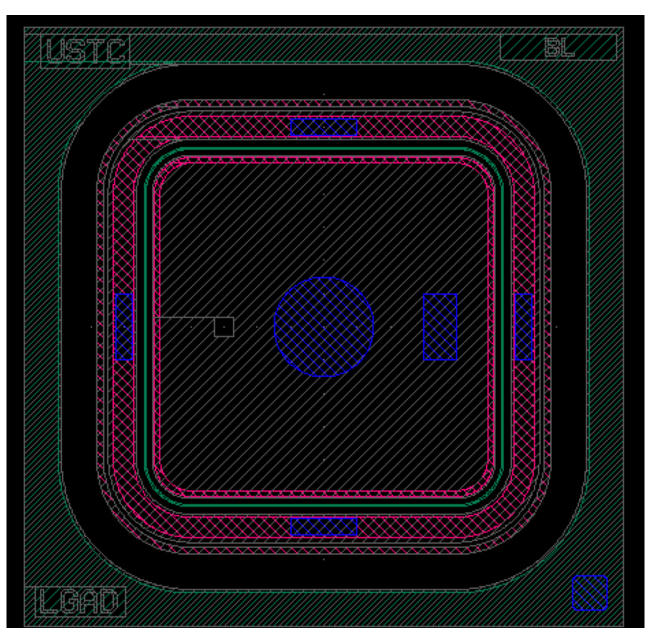


- TCAD structure based on process simulation
- The geometry and process are thoroughly optimized
- Major radiation damage model included

➡**Recommendation:**

- High resist. substrate: > 1kOhm*cm
- High energy boron implantation: at least ~1MeV
- Carbon diffusion on one wafer

Simulation → • **Layout Mask** • **Fab. Process** → **Functional USTC LGADs**



Designed mask

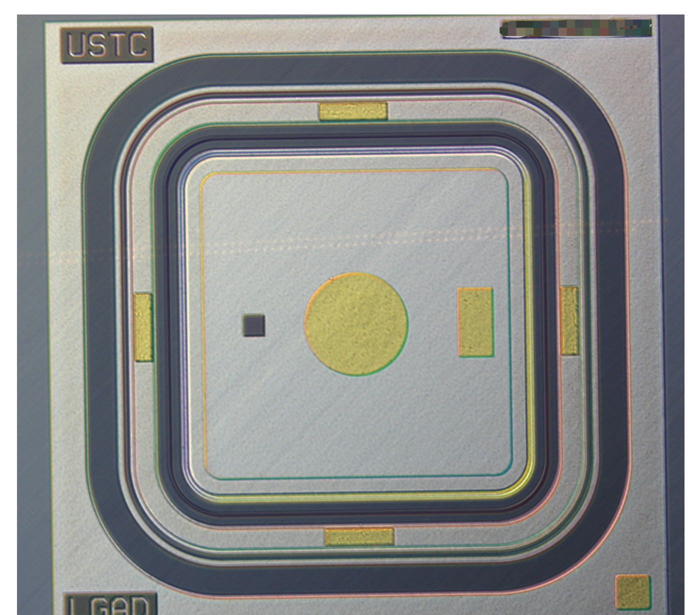
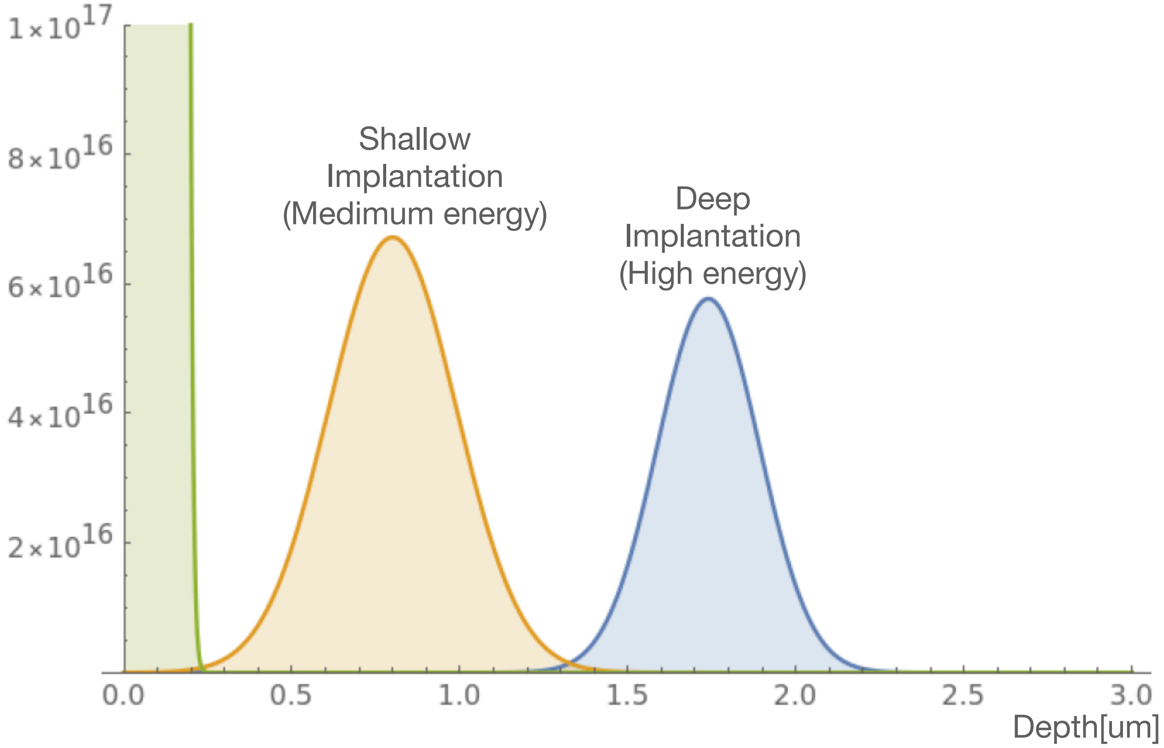
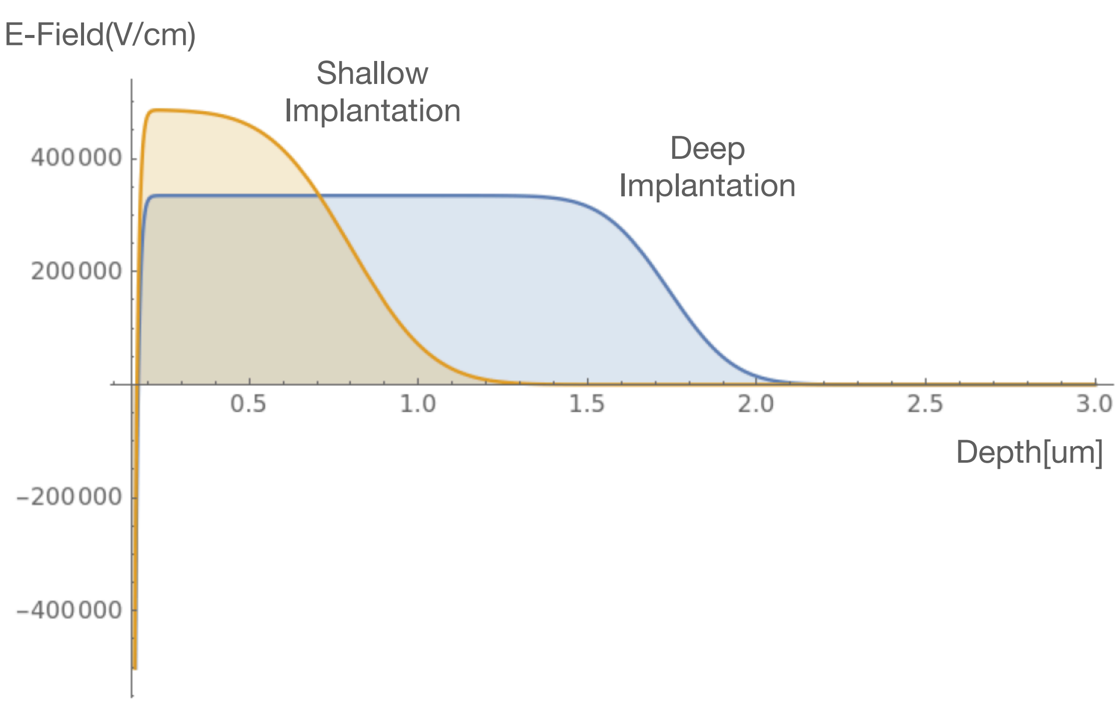
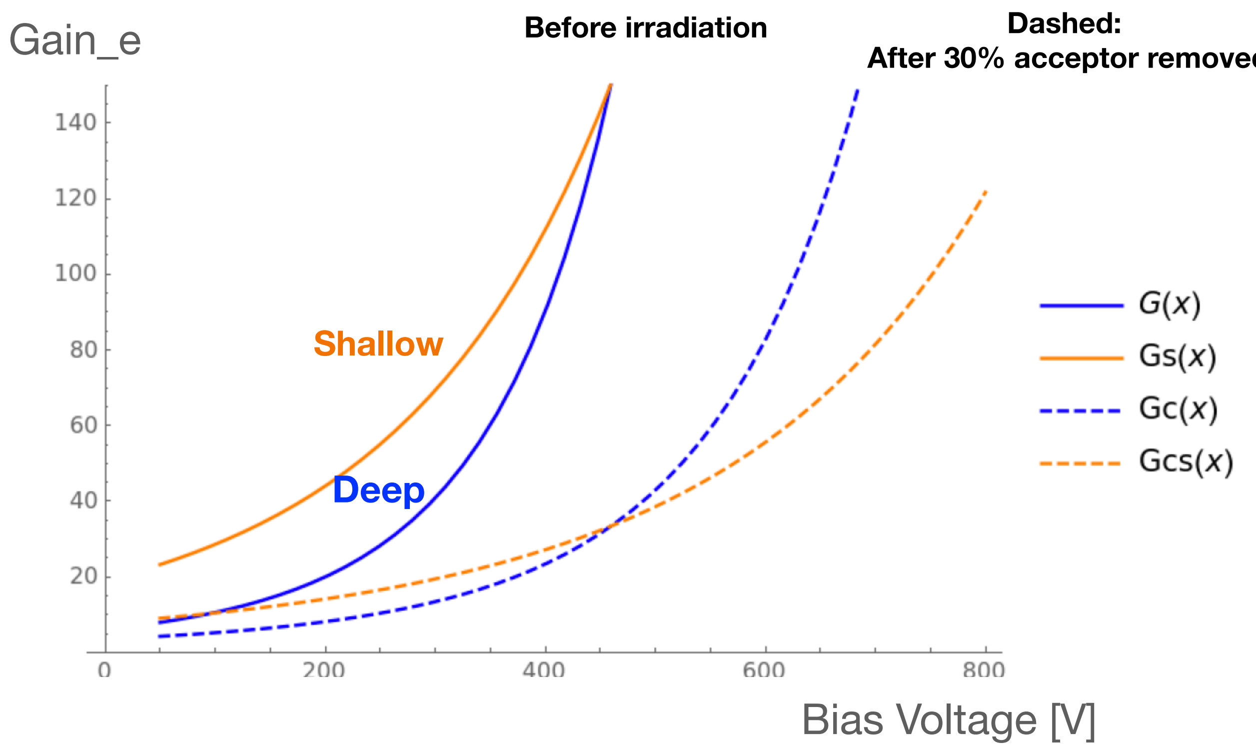


Photo of the device produced

Deep vs Shallow Gain Layer Calculation based on the Massey Model





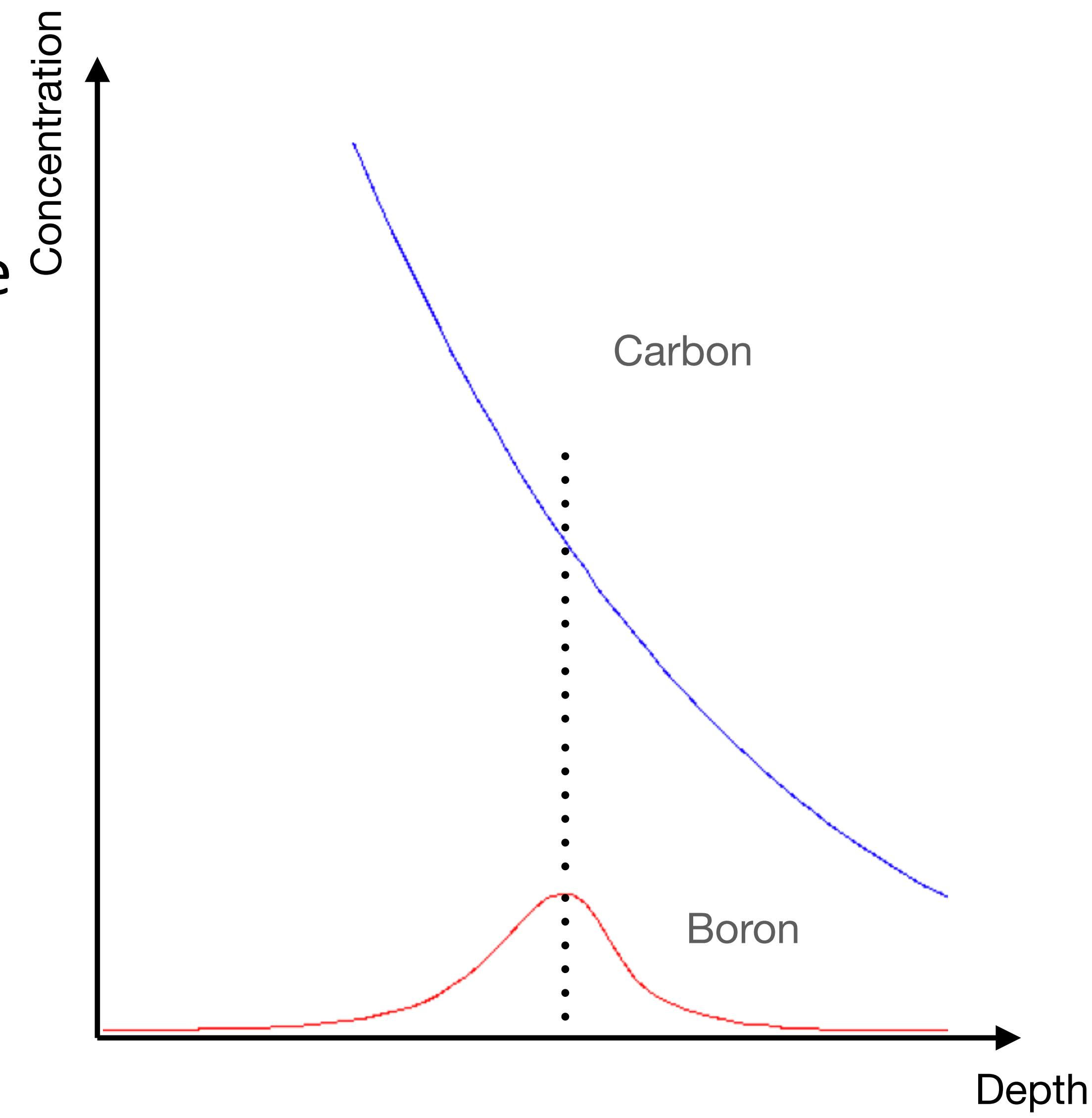


- Deep gain layer provides better recovery capability, with a fixed fraction of acceptor removed

Nicolò Cartiglia, Progresses in UFSD radiation hardness

Carbon diffusion design

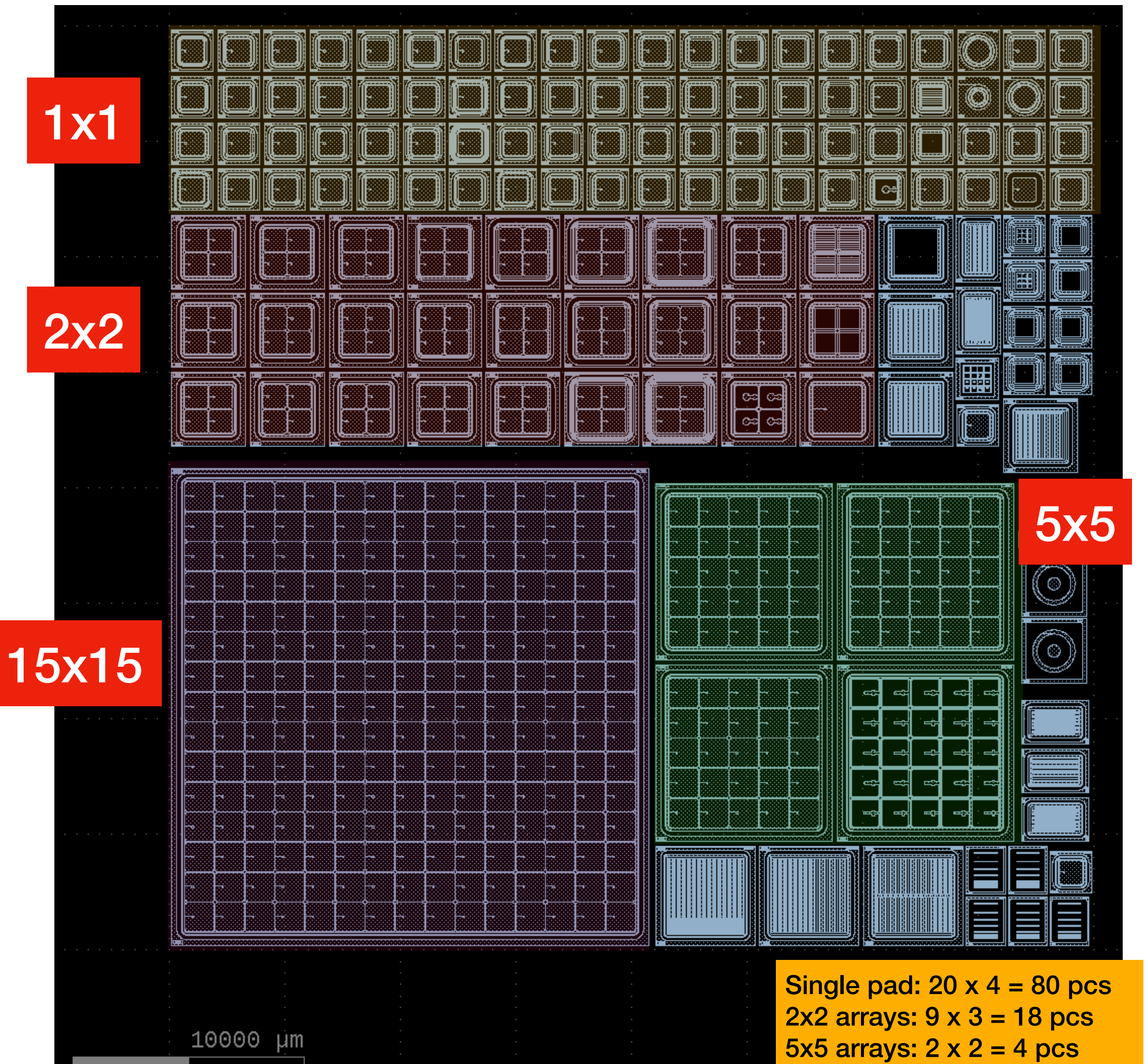
- The Carbon diffusion profile is designed to have 3-4 times concentration of the Boron's
- Make sure the Carbon works and prevent over-dope of the Carbon that might deactivate the Boron by B+C cluster formation.
- Future optimization work will be carefully done at the next batch (including scan of Carbon dose and diffusion depth)
- The irradiation campaigns are being completed at JSI, and the irradiated samples will be studied to optimize the design for the next iteration.



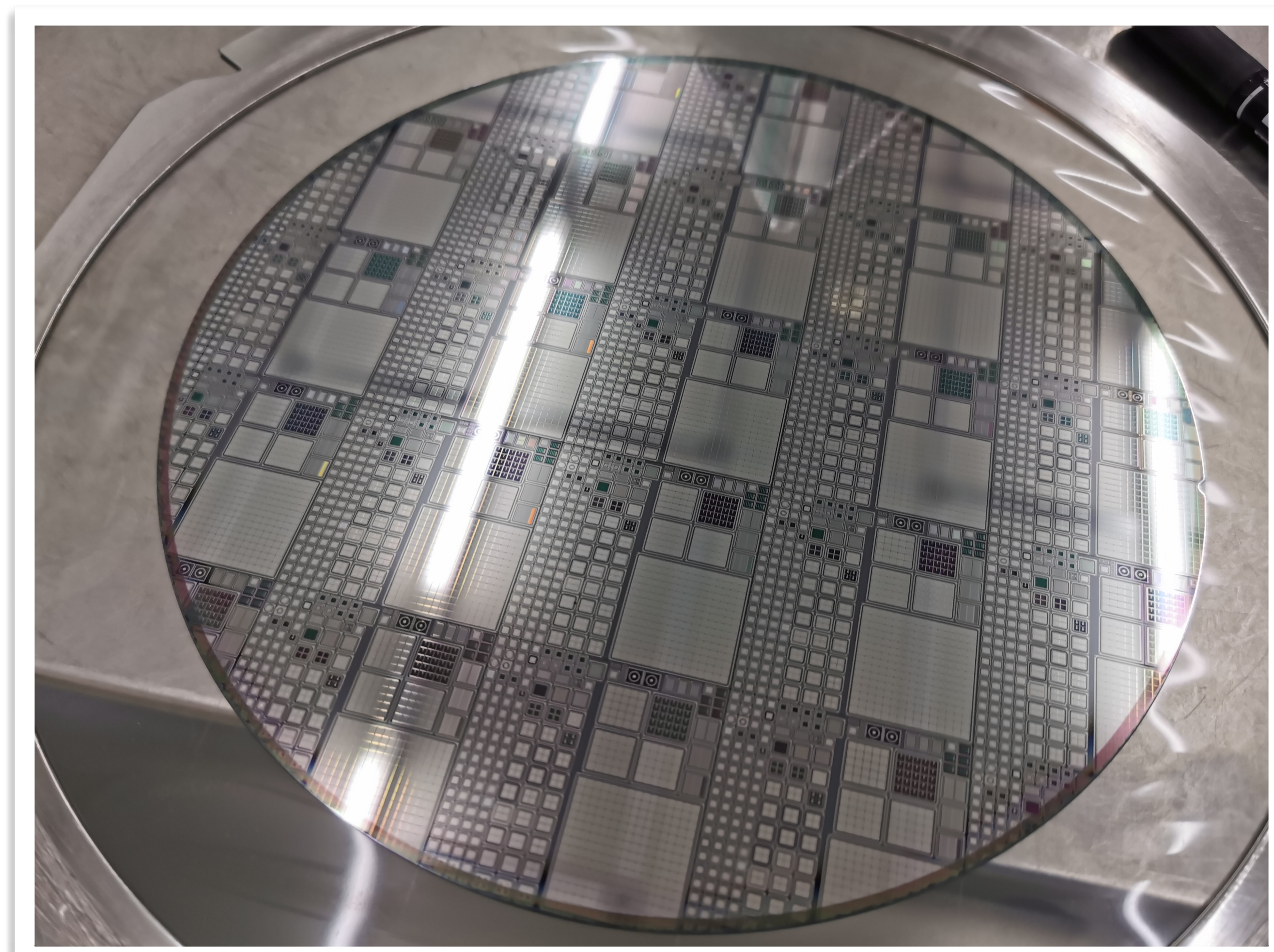
USTC first batch LGAD Wafers

- Joint force: **USTC(Design) + <u>IME,CAS</u> (Fab.)**
- Deep gain layer
- Carbon diffusion

8 inch wafer, with **50 µm** Epi. layer.
Stepper size: 40 mm x 40 mm,

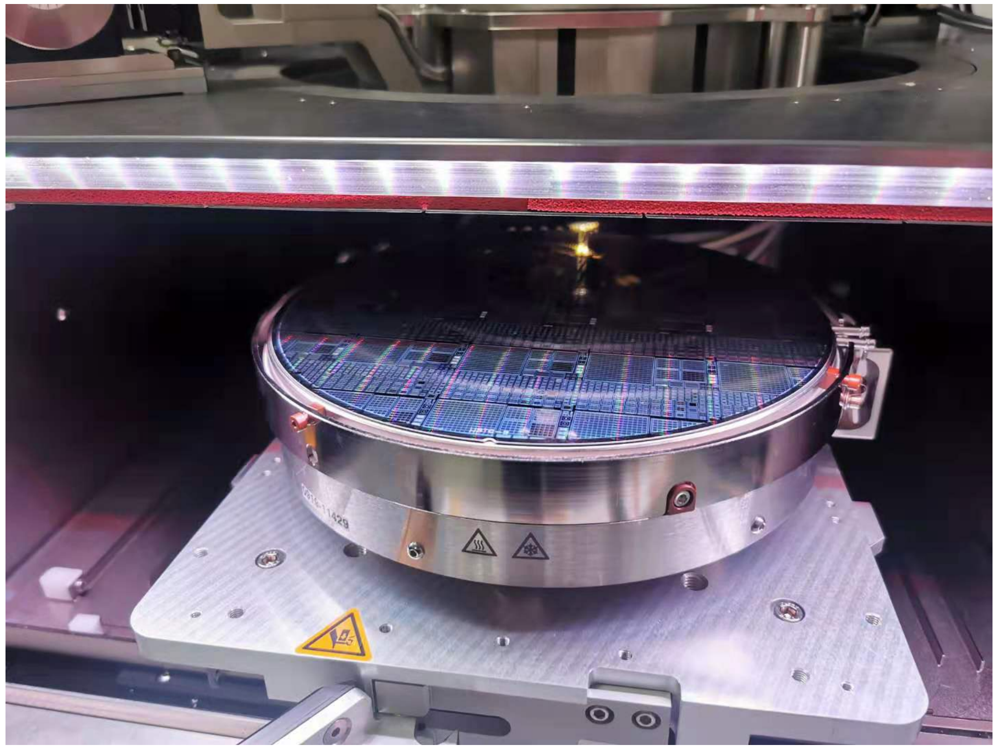


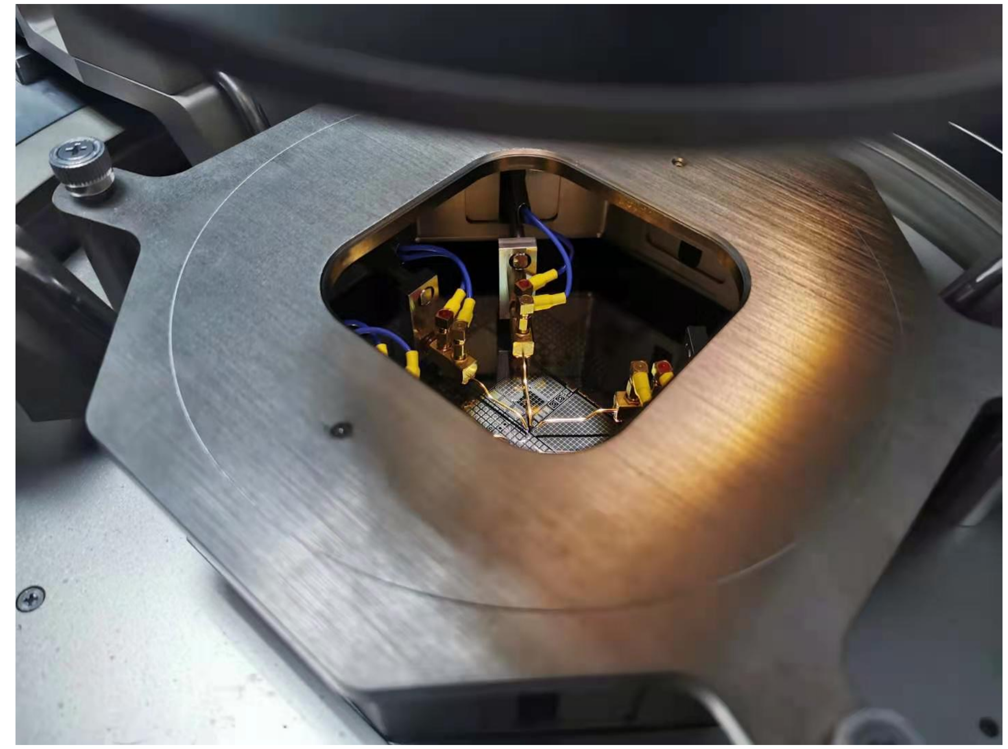
Single pad: 20 x 4 = 80 pcs
2x2 arrays: 9 x 3 = 18 pcs
5x5 arrays: 2 x 2 = 4 pcs
15x15 arrays: 1

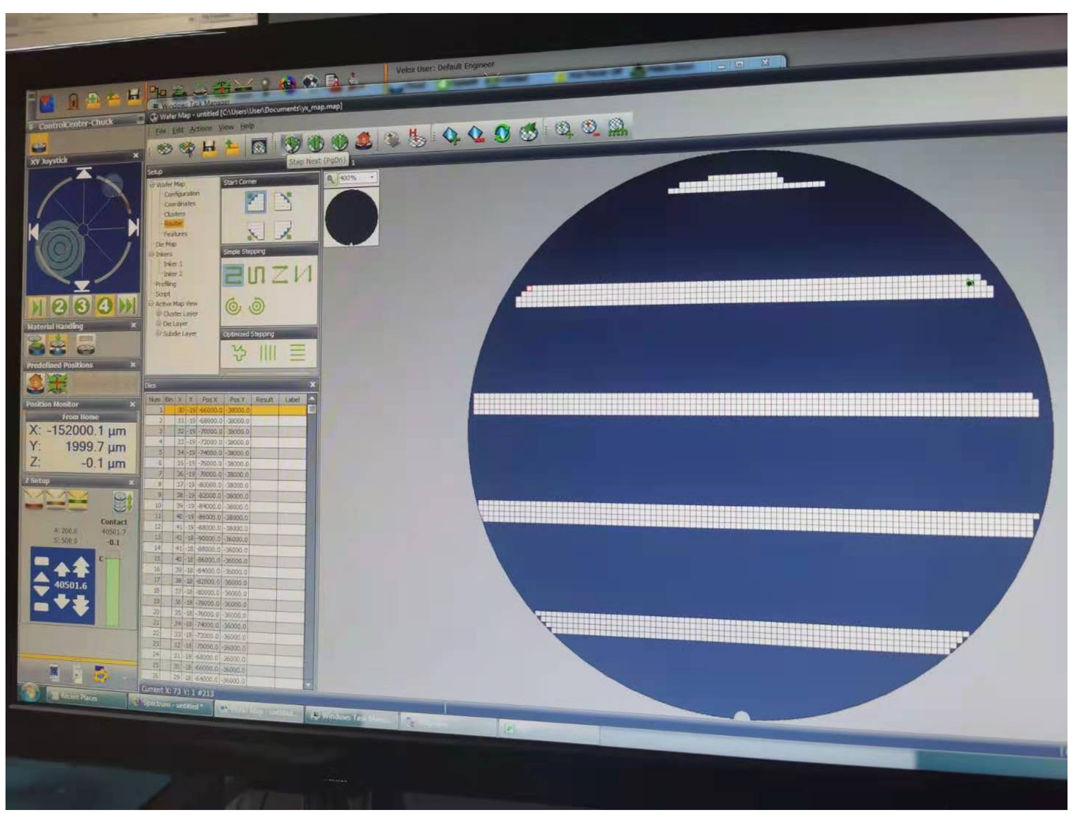


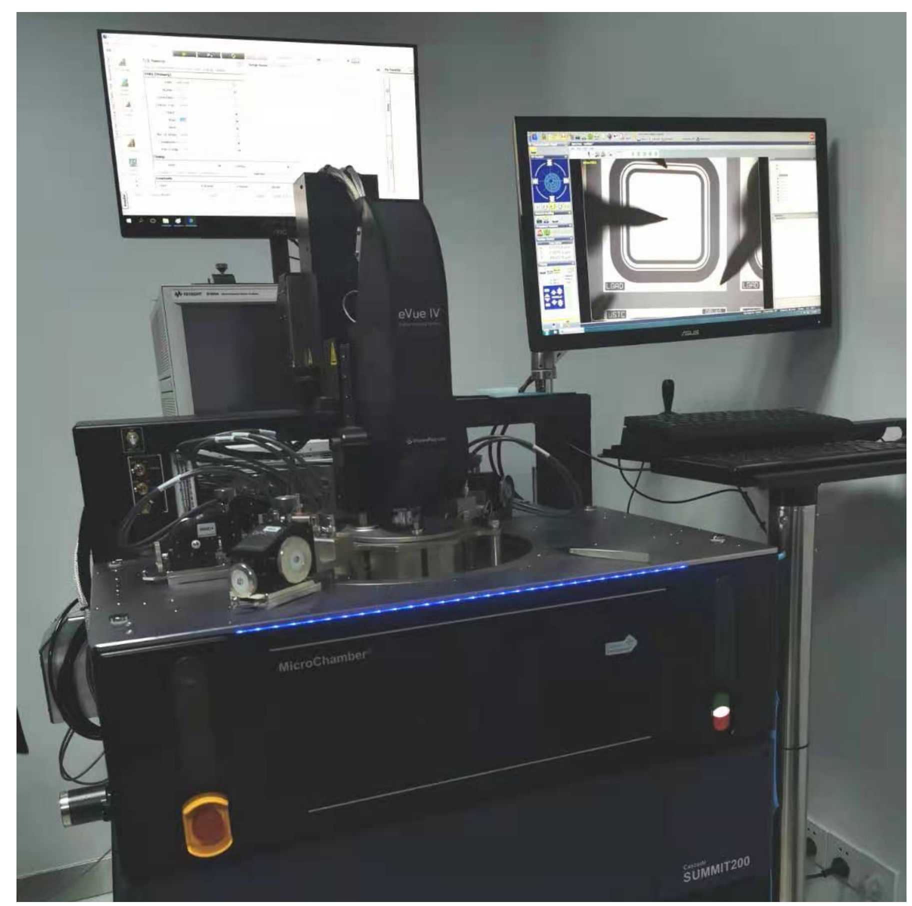
On-wafer probe with the automagical probe station

The equipment from the department of micro-electrons, USTC



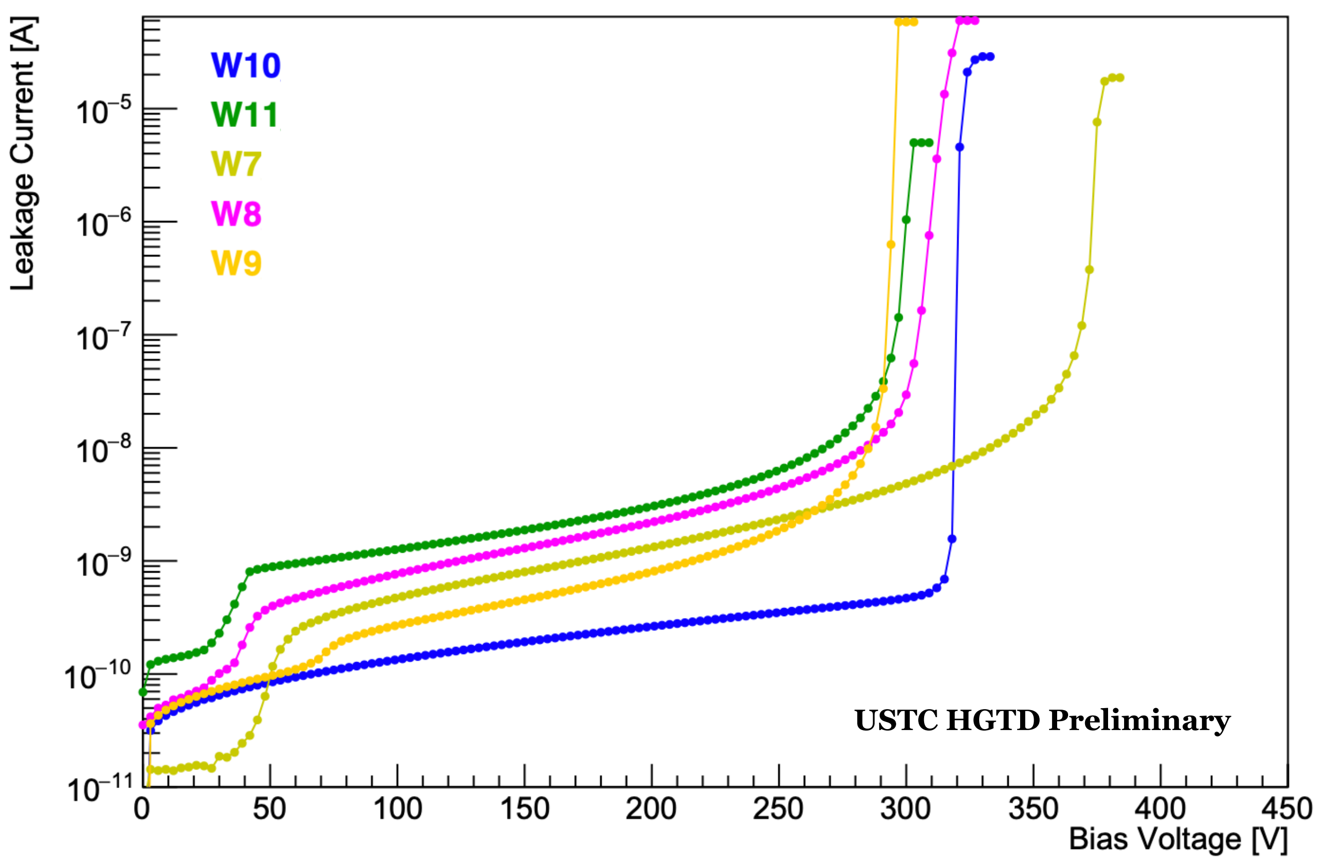


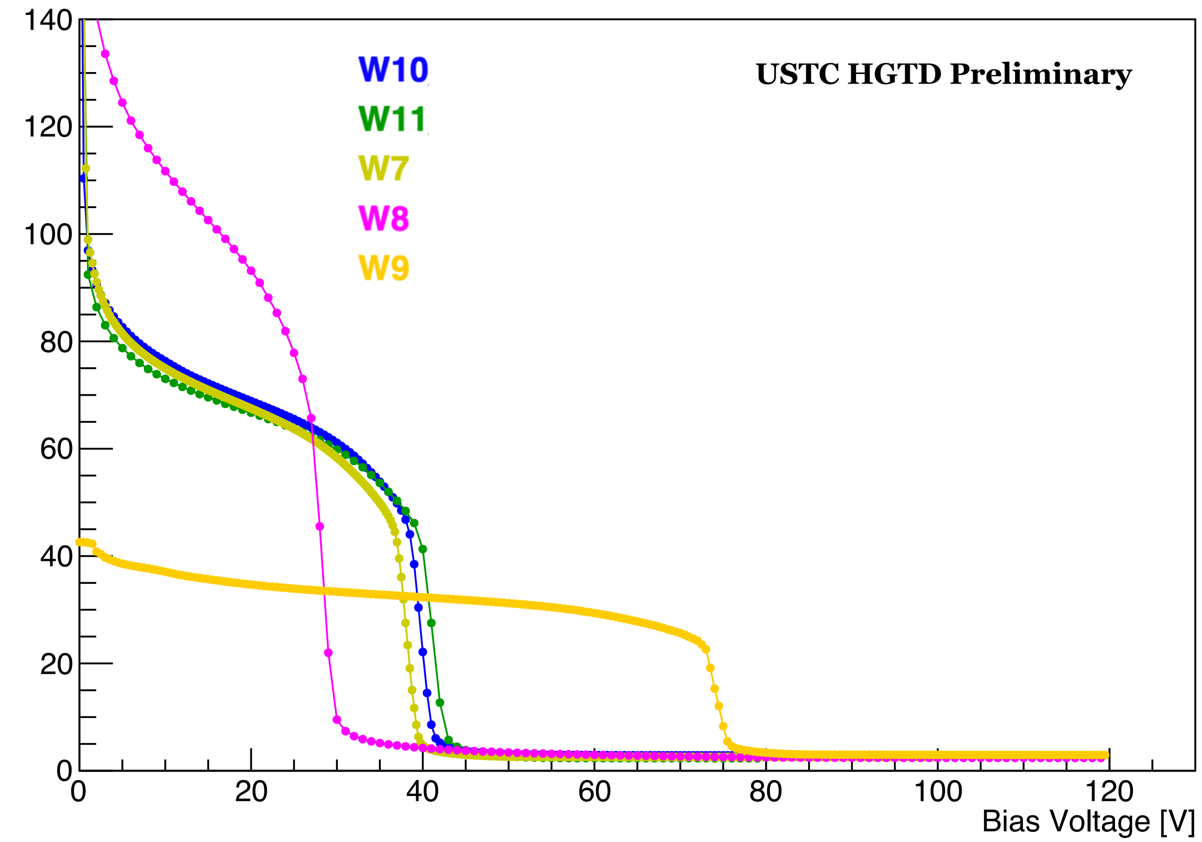




Perform quick on-wafer I-V test for thousands of single sensors' in the range of 0-200V

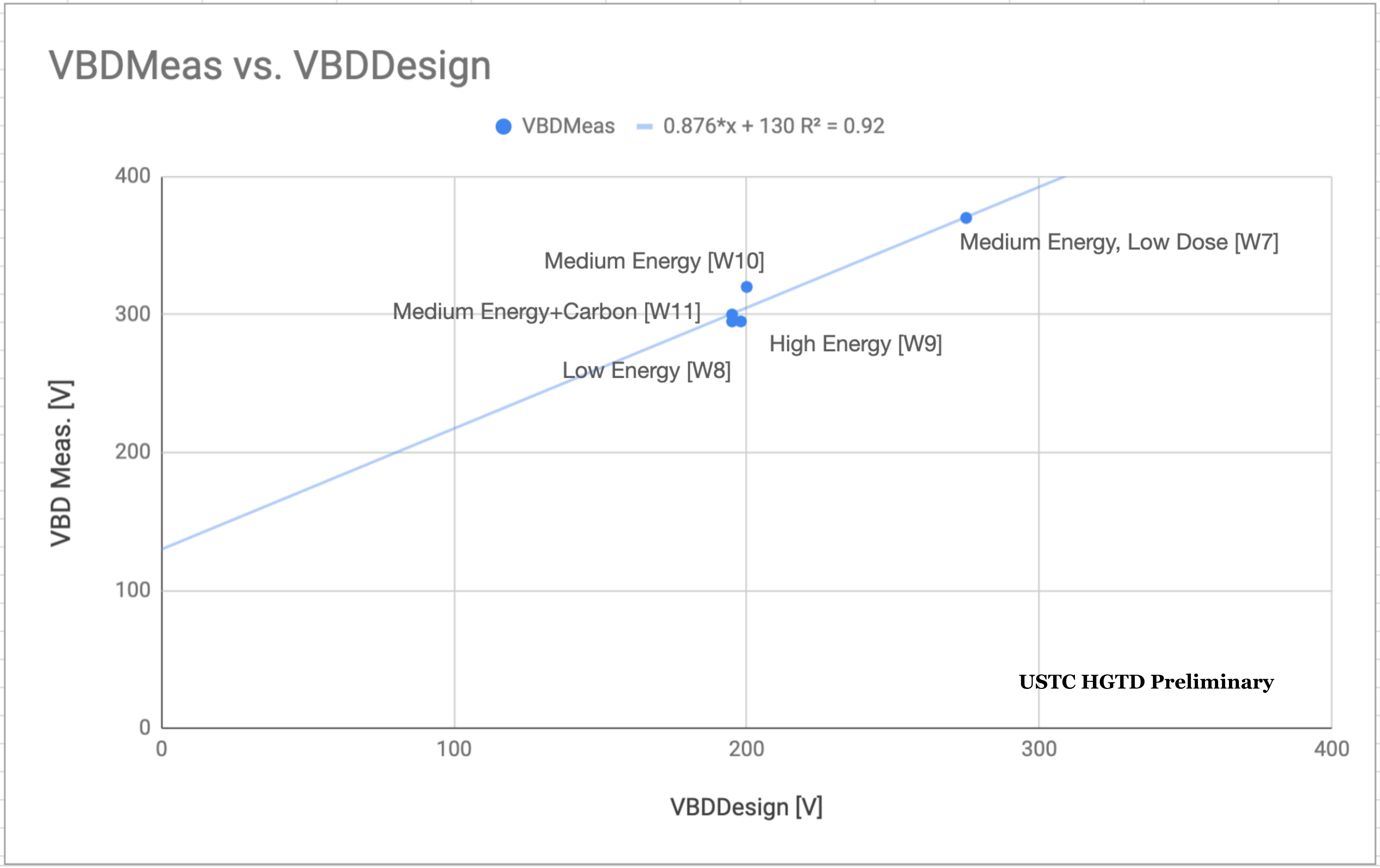
USTC First Batch LGADs Summary





Production Batch	Wafer No.	Target VBD [V]	GL.Energy	GL.Dose	Implantation	VBD [V]	VGL [V]	VFD [V]	Status
USTC-1	W1	165	Medium	Medium	B	154	45	65	Pre-production
	W2	165	Medium	Medium	B	150	46	54	
	W3	150	Low	High	B	110	34	>70	
	W4	180	High	Low	B	148	75	100	
	W5	265	Medium	Low	B	264	45	80	
	W6	165	Medium	Medium	B+C	84	48	>65	
USTC-1.1	W7	270	Medium	Low	B	370	38	55	Stable version
	W8	195	Low	High	B	295	29	40	
	W9	200	High	Low	B	295	70	85	
	W10	200	Medium	Medium	B	320	40	50	
	W11	200	Medium	Medium	B+C	300	41	52	

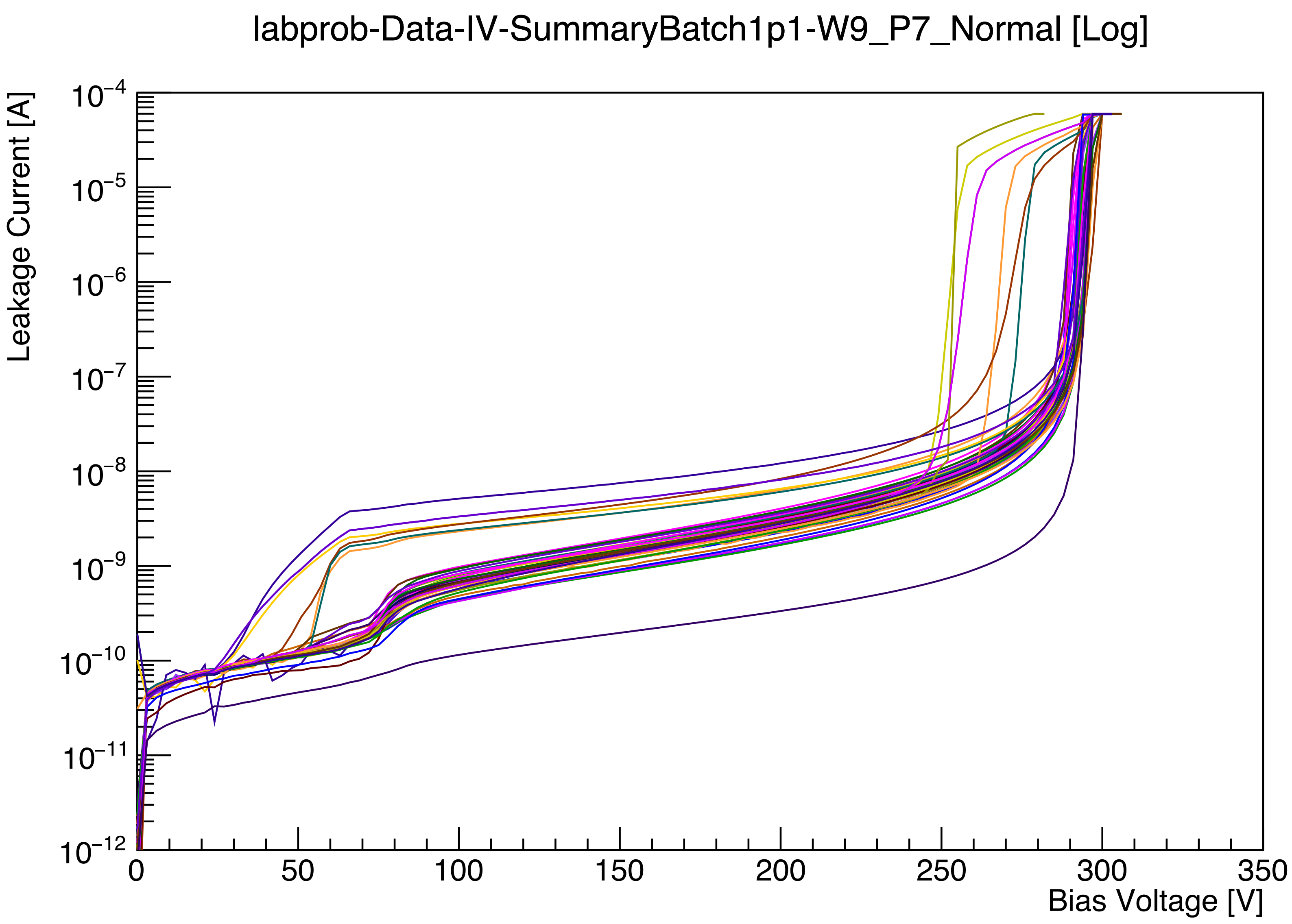
Comparison of designed and measured VBD

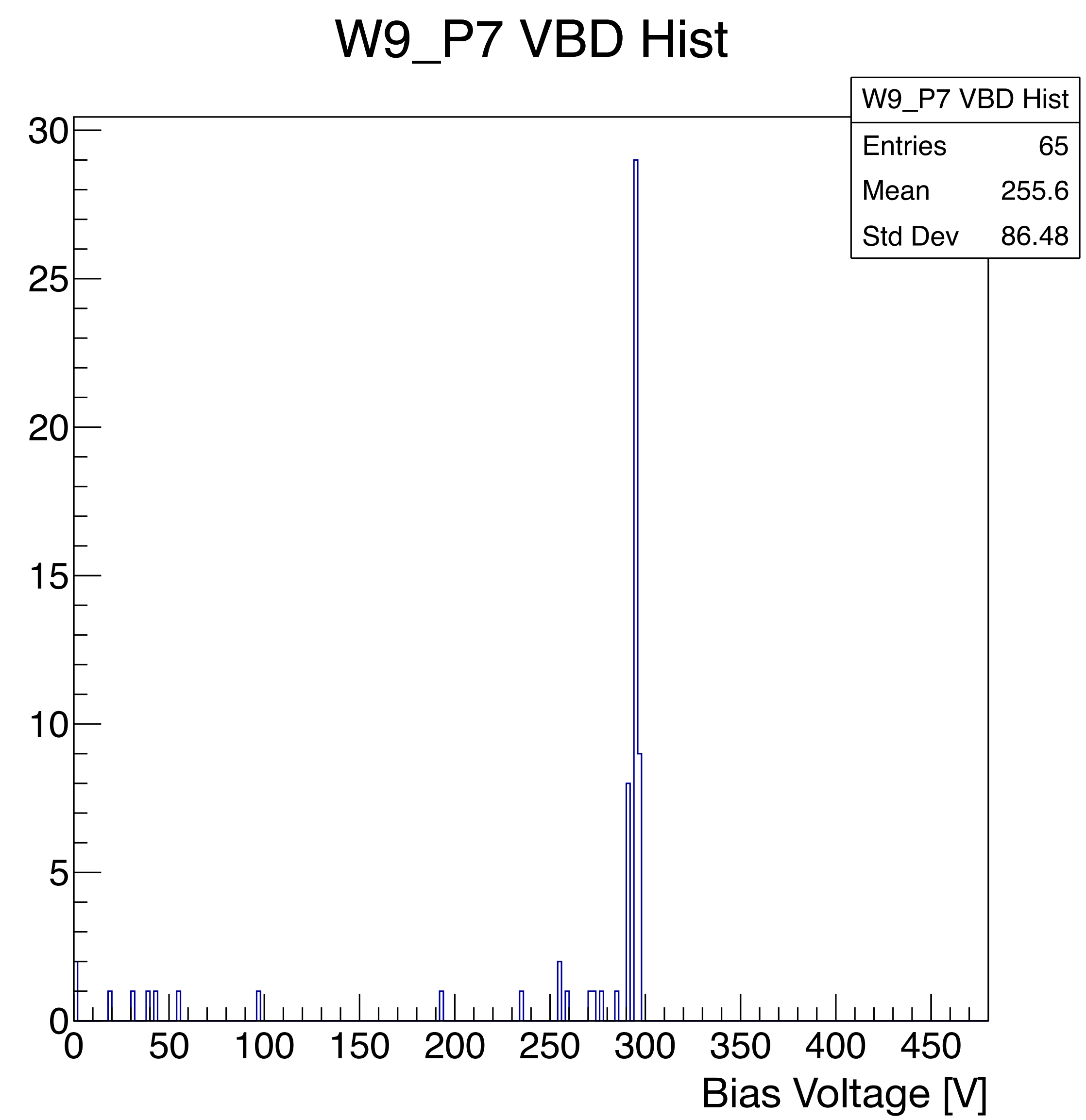


- The detectors with close target VBD show similar measured VBD
- The VBD is ~ 100V higher than the expectations, further investigation with CV and TCT result is in progress

W9: Ultra-deep gain layer

IV and VBD Distribution

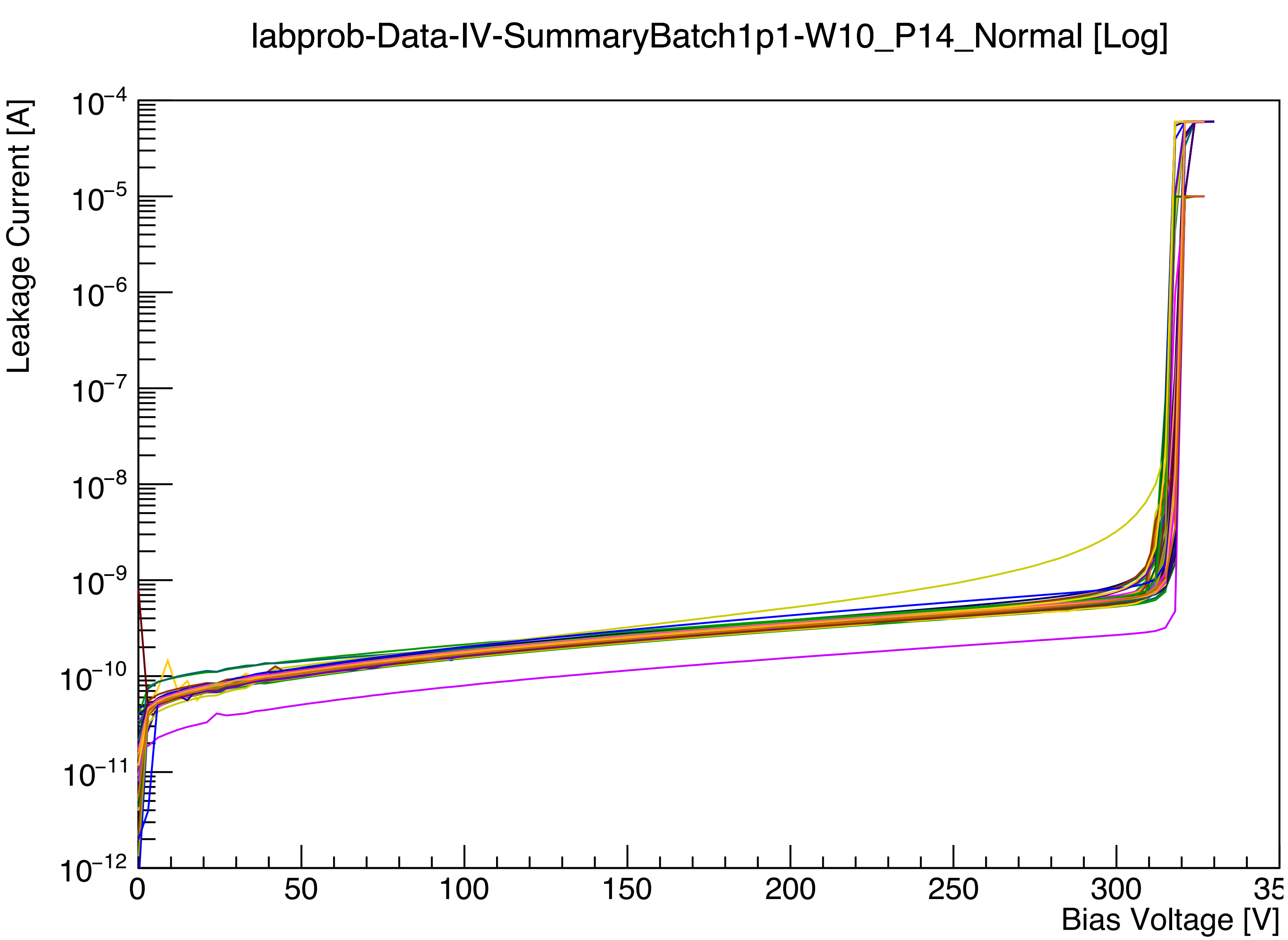


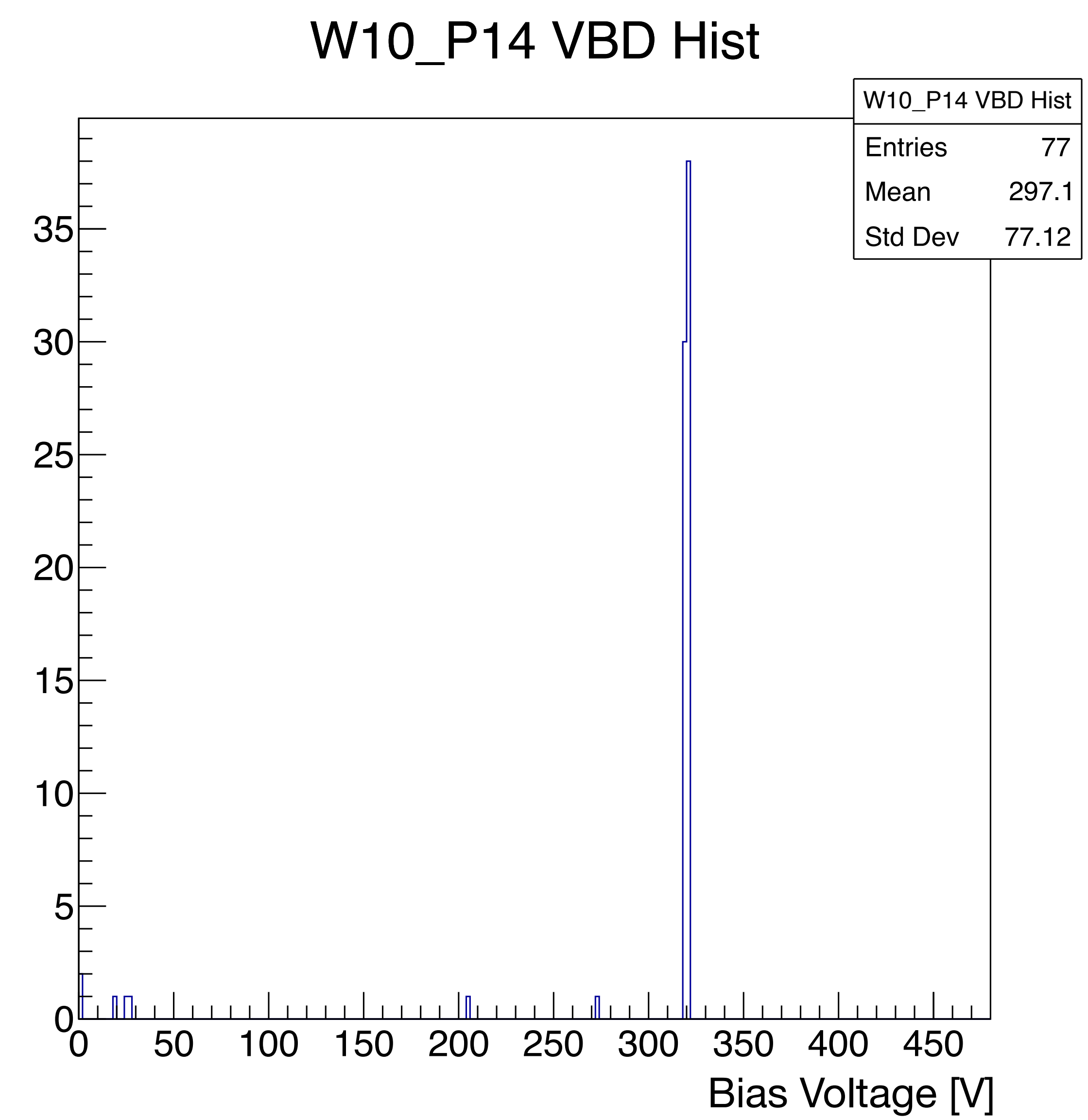


Non-uniform leakage current and VBD for some LGADs, further investigation ongoing.

W10: Baseline gain layer (Mid. Energy&Dose)

IV and VBD Distribution

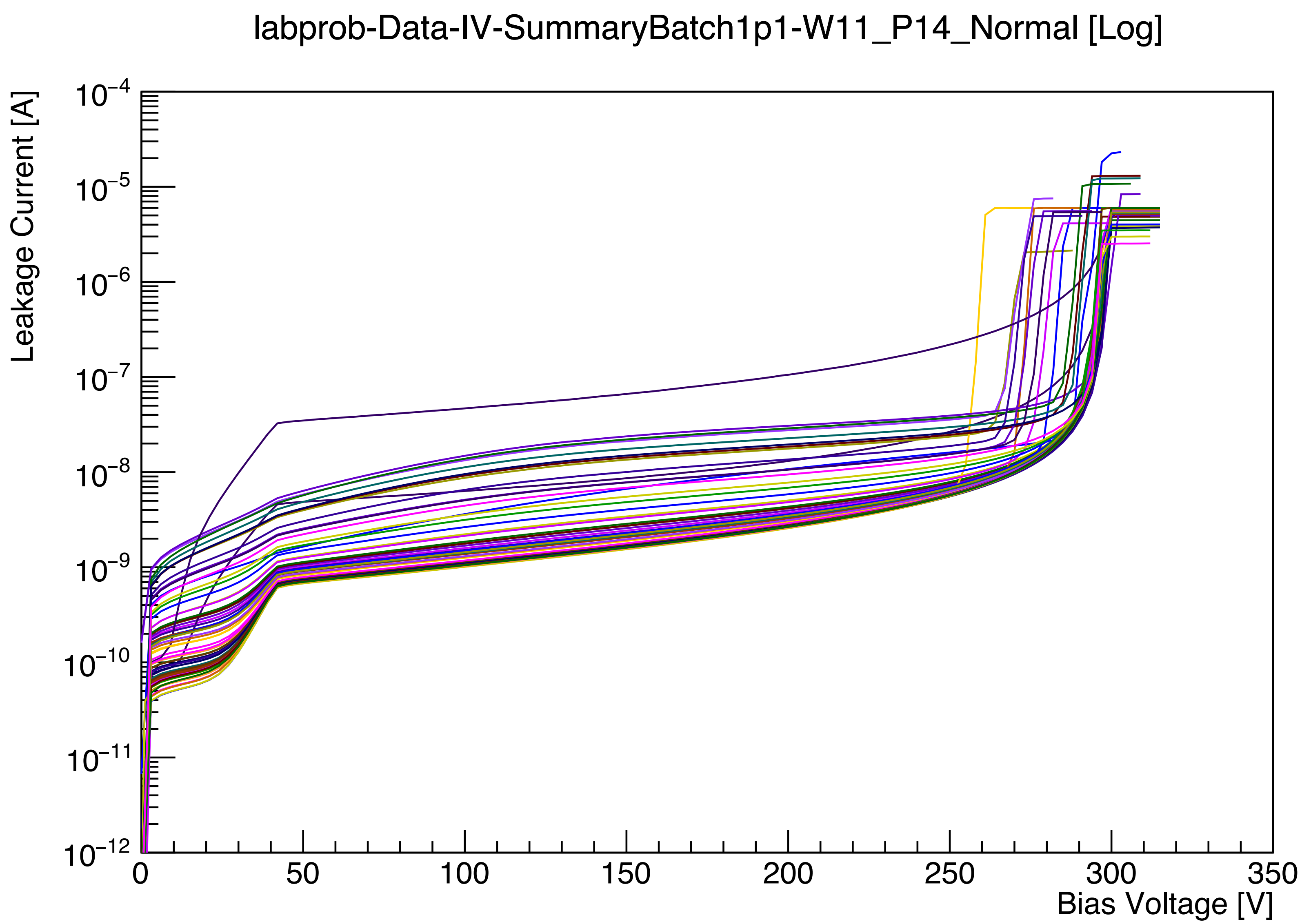


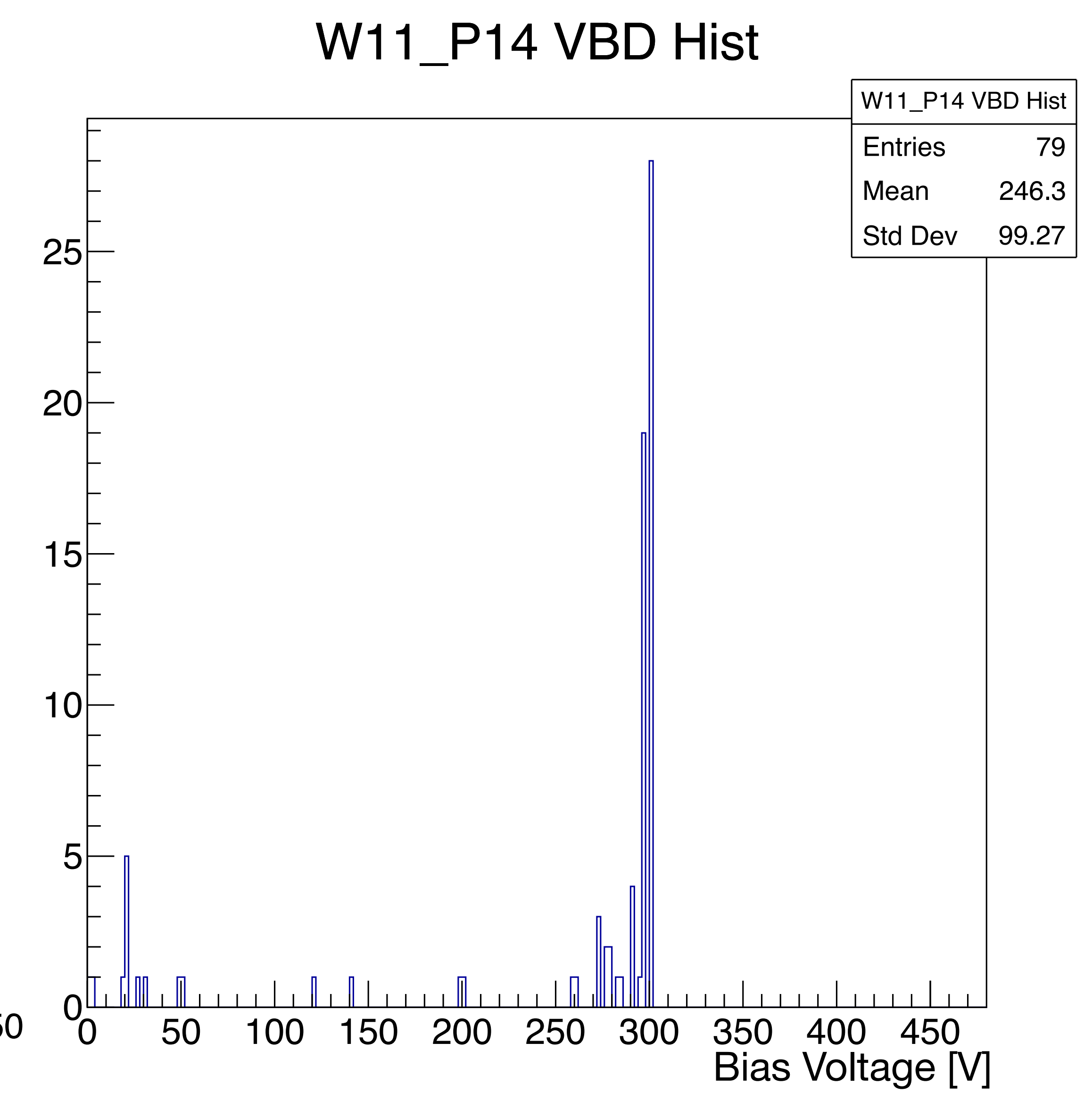


Good uniformity on both leakage current and VBD obtained.

W11: Carbon diffused gain layer

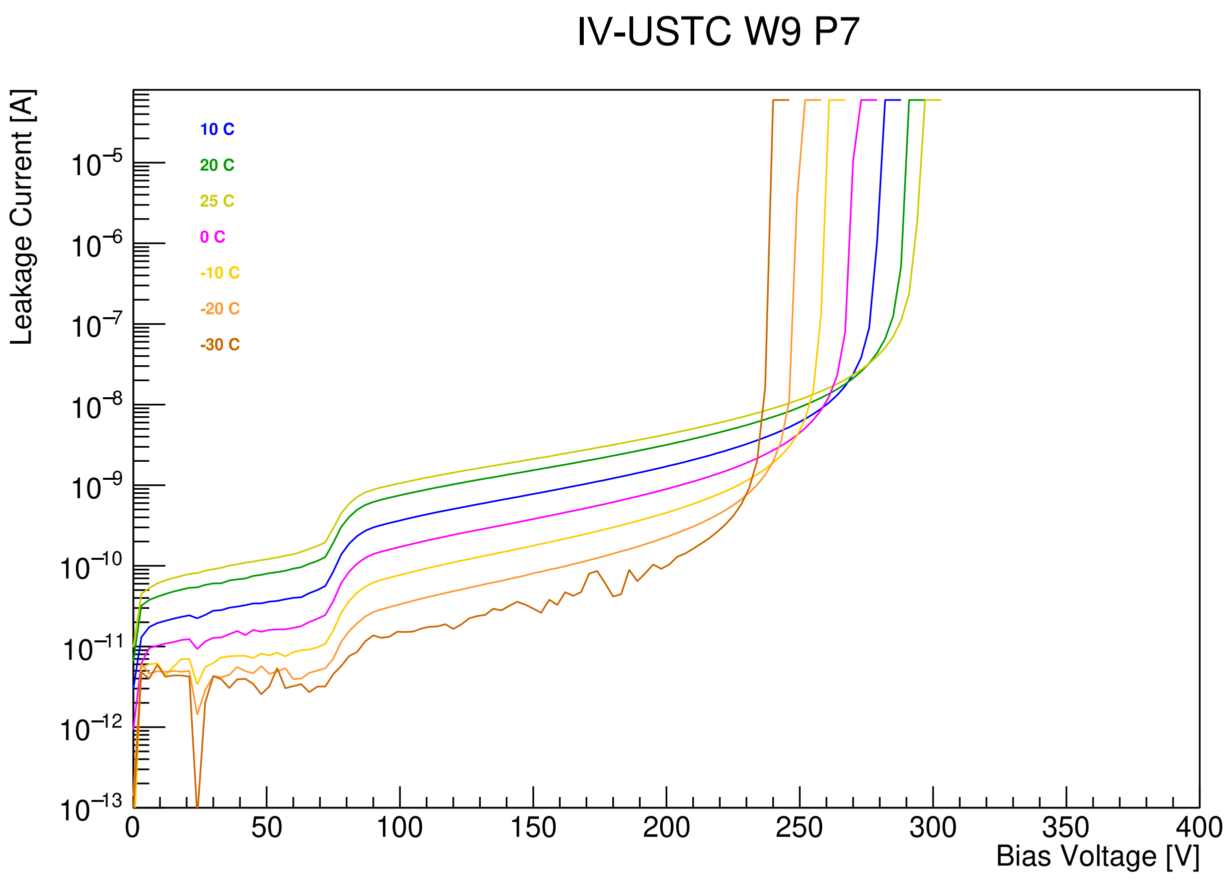
IV and VBD Distribution

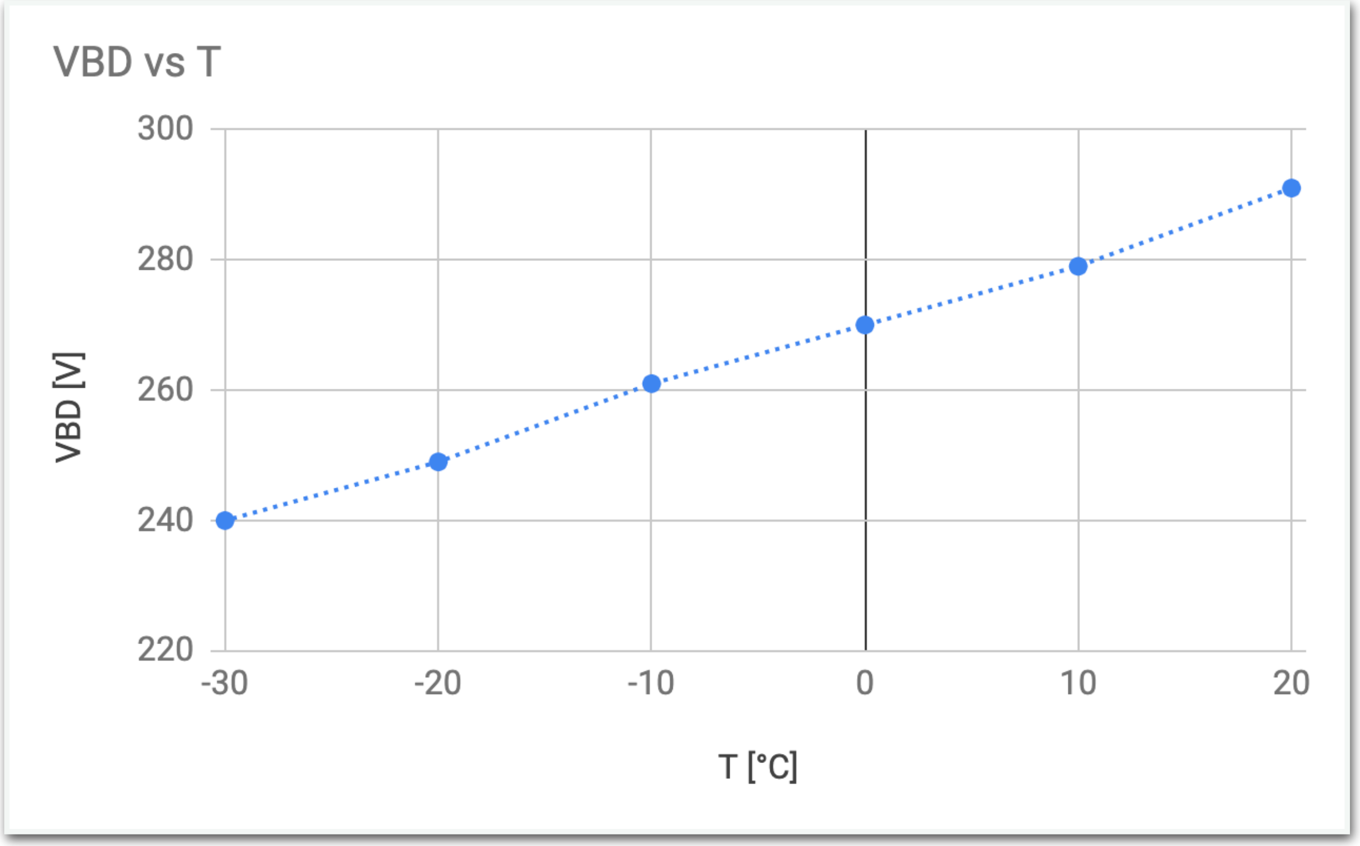




Non-uniform leakage current and VBD for some LGADs, further investigation ongoing.

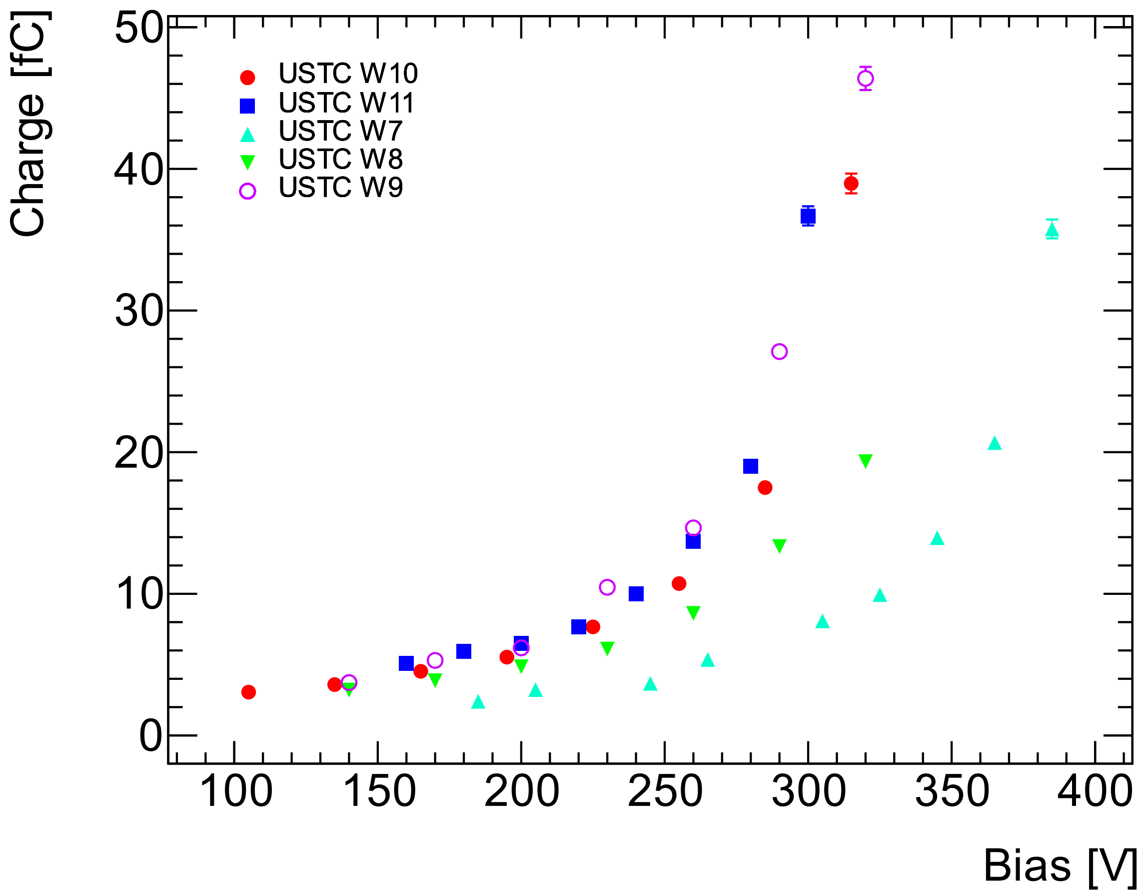
Temperature dependency of the I-V curve

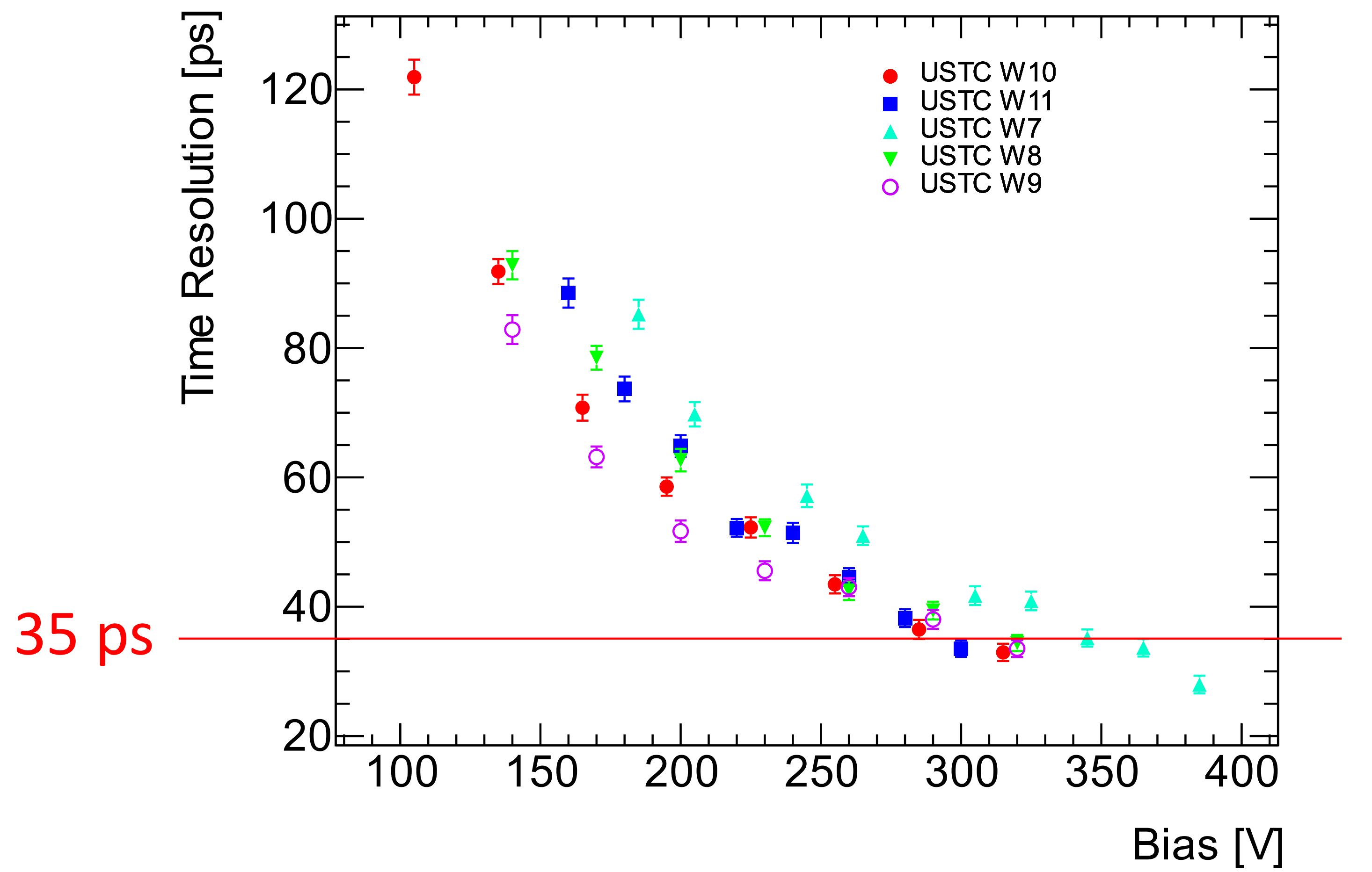




- Sufficient bias after full-depletion (~170V) to saturate the drift velocity at -30 °C
- Target VBD will be reduced by ~ 70V in next batch.

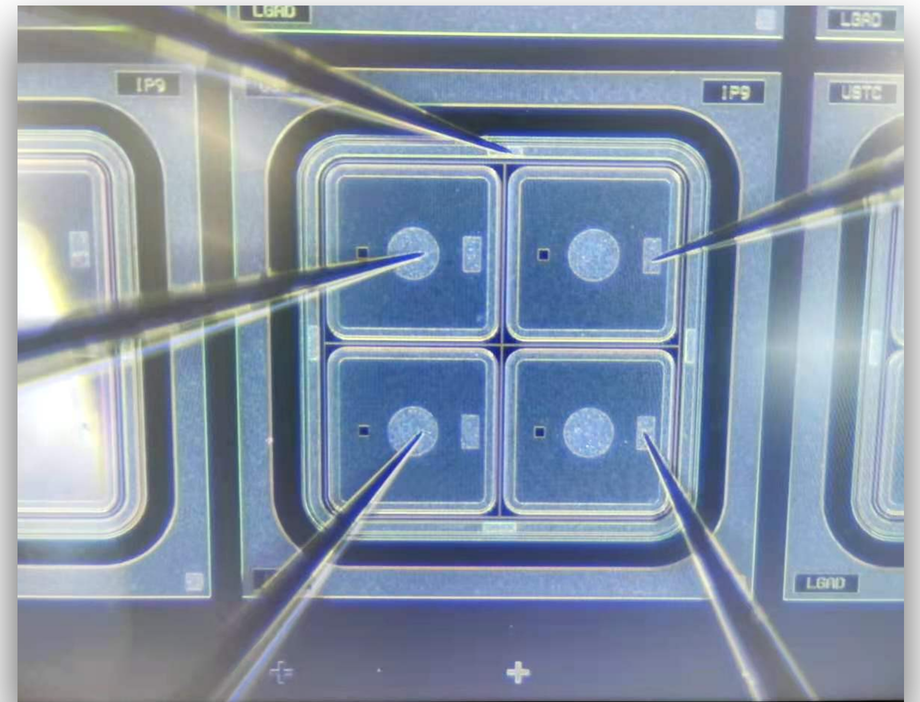
Pre-irradation TCT performance of USTC-1.1

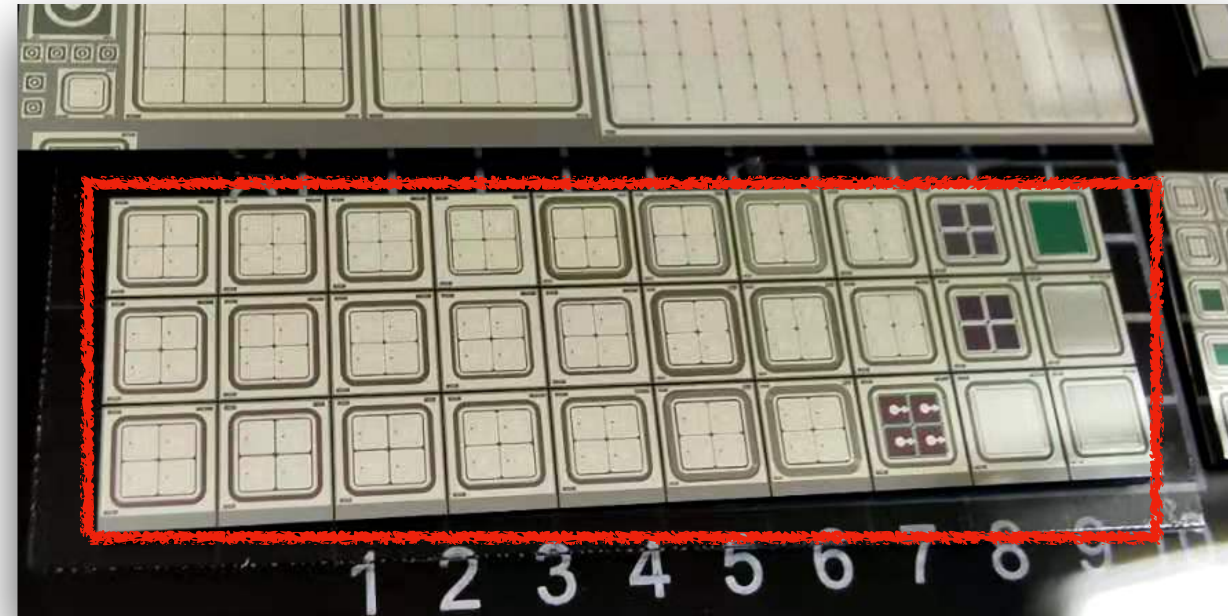


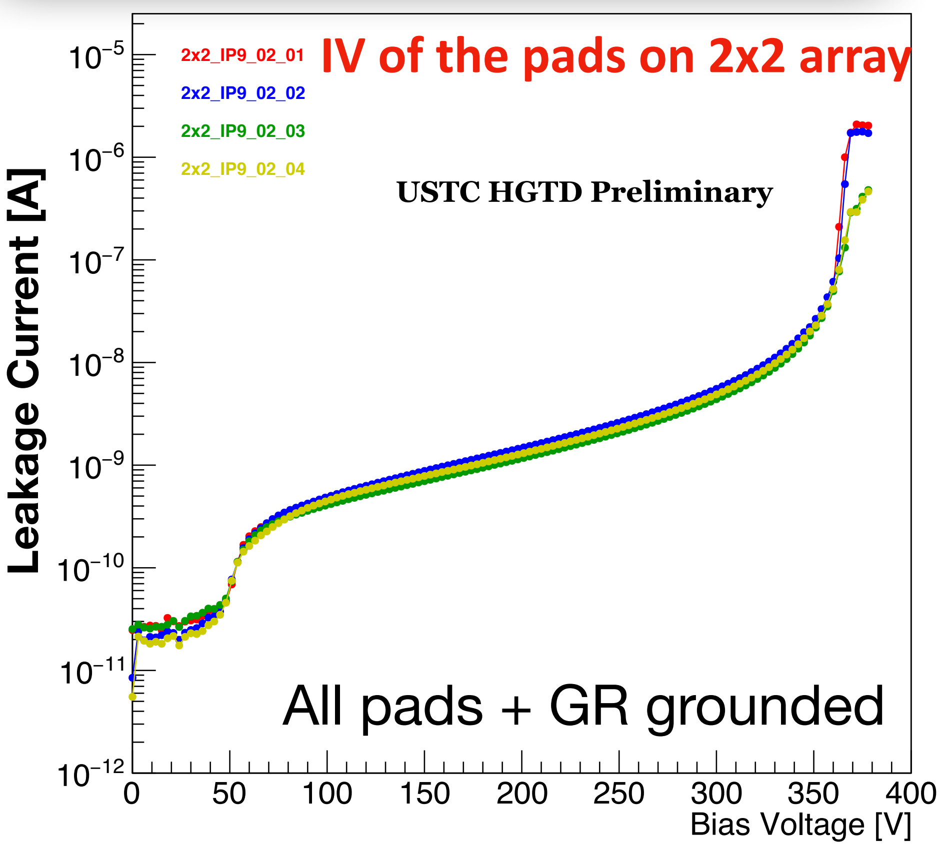


- All the 5 wafers can have time resolution of ~35 ps.
- Sensors with deep implantation(W9) and carbon diffusion(W11) can work normally as W10 before irradiation.

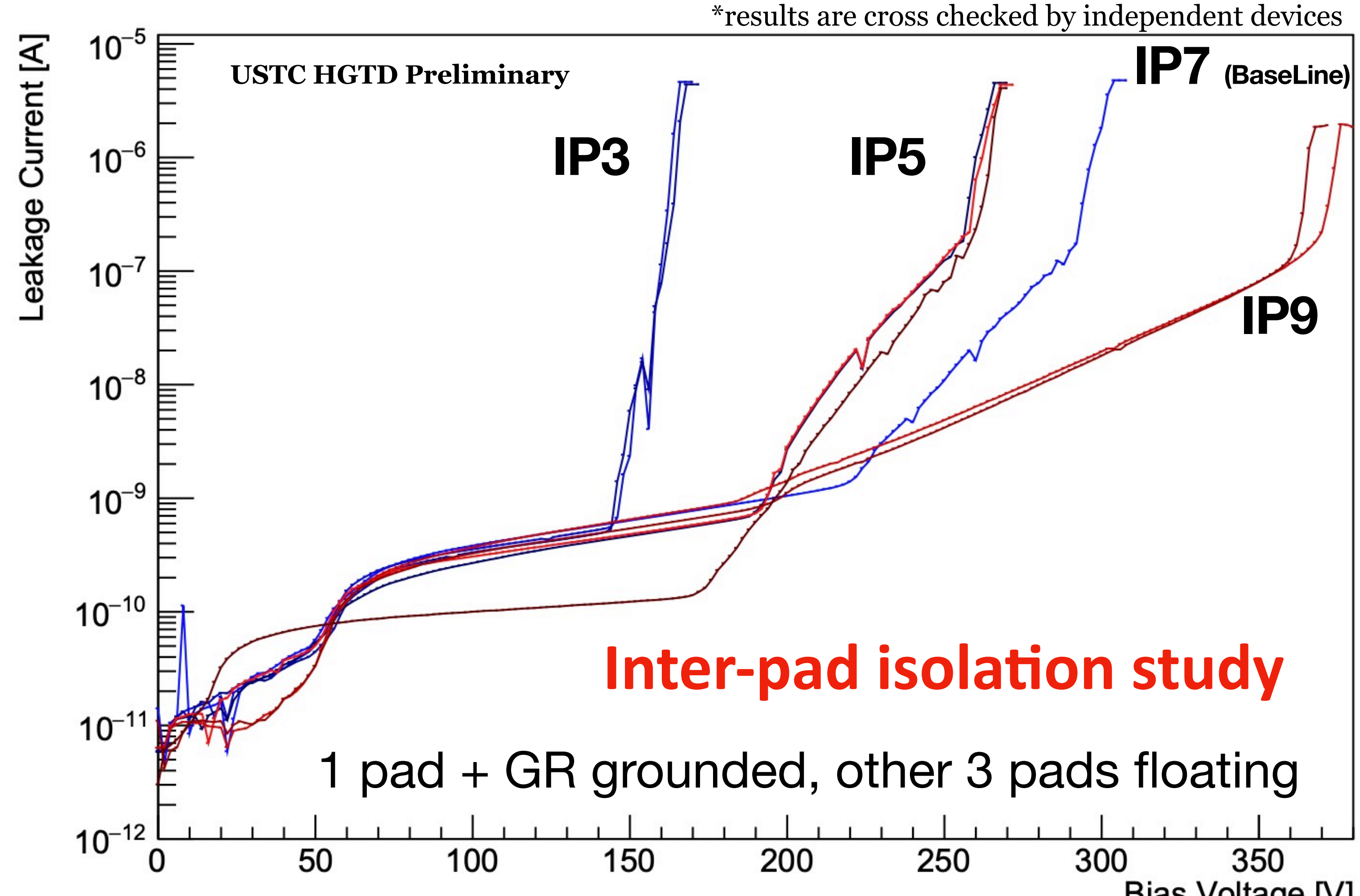
2x2 array test of USTC-1.1



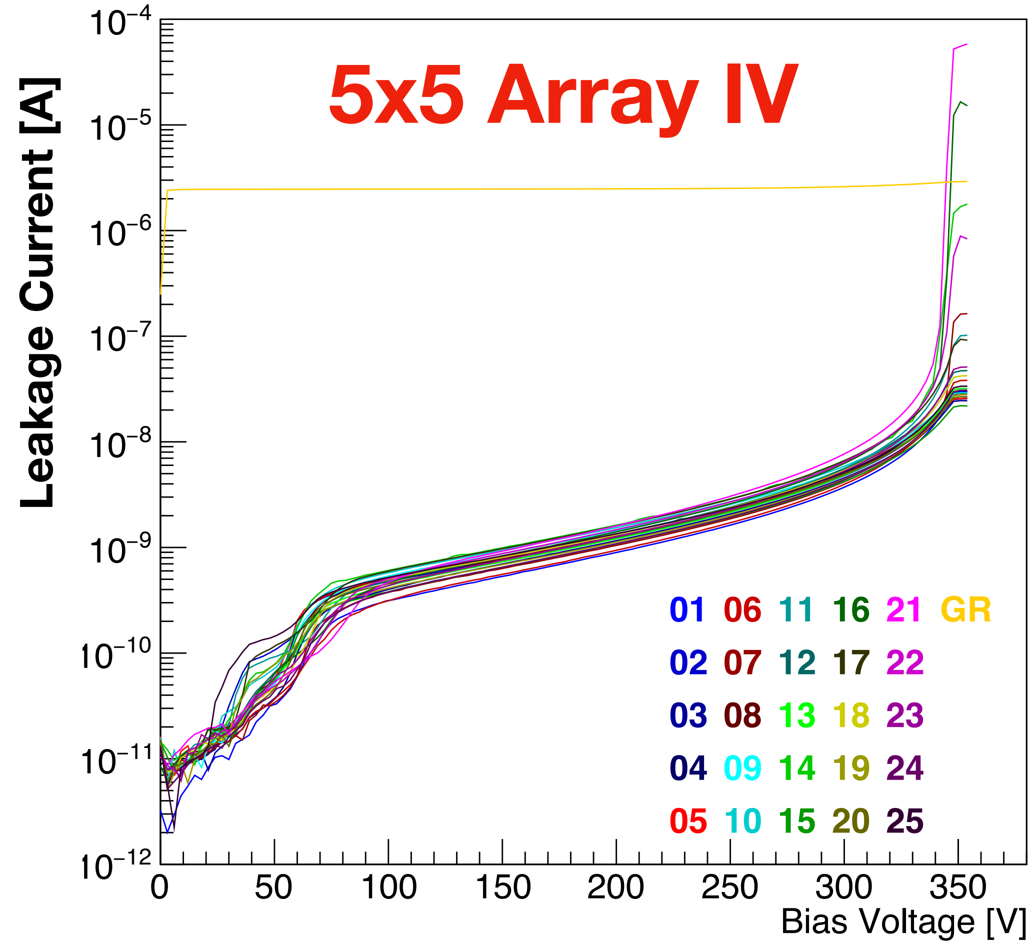


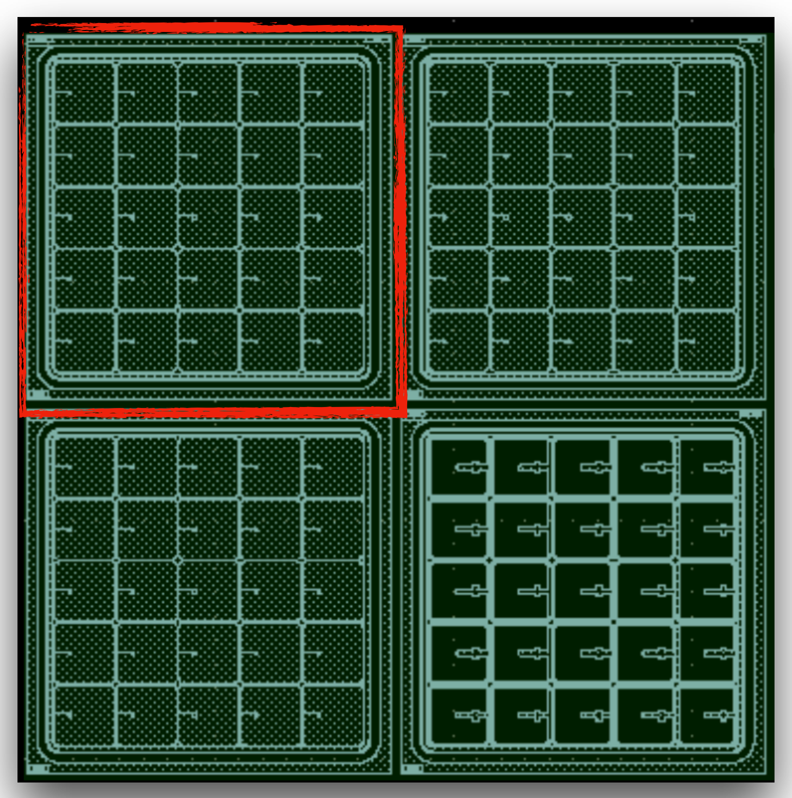


*results are cross checked by independent devices

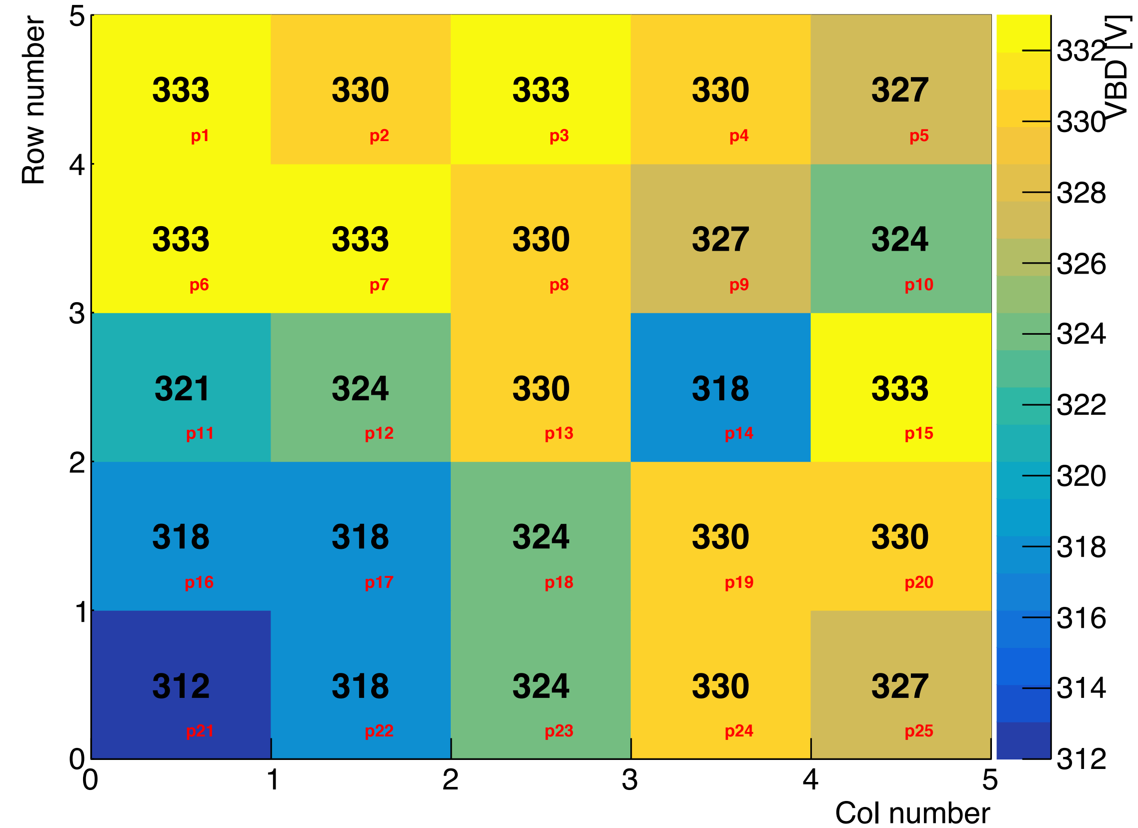


5x5 array test of USTC-1.1

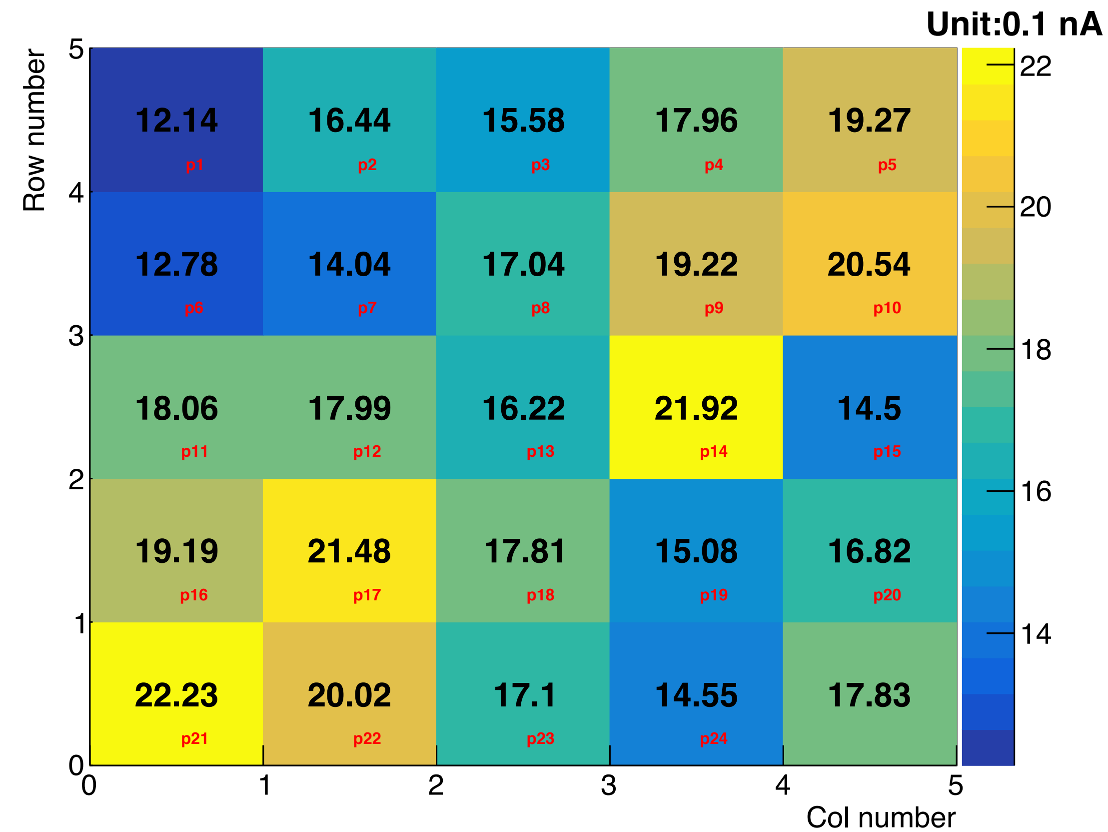




5x5 VBD distribution



5x5 Leakage Current distribution



Summary and plan for the futures

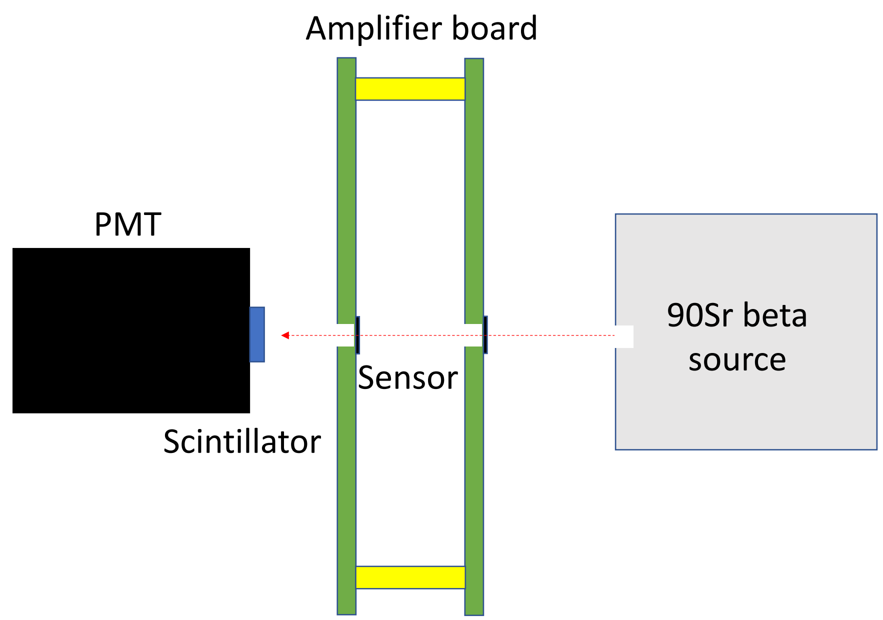
- For USTC-1.1 LGAD, all the 5 wafers have been diced and the sensors are measured to check IV, CV, collected charge and time resolution.
- The single pad LGADs meet the HGTD specifications before irradiation. The 2x2 and 5x5 LGAD arrays I-V curves looks well.
- The sensors with deep gain layer and Carbon diffusion work well. Expect to have good radiation hardness.
- Plans:
  - Investigation on the non-uniformity observed in leakage current and VBD.
  - Test on the JSI irradiated sensors for post-rad performance validation.
  - Focus on the fabrication process optimization to improve the yield of the large arrays.

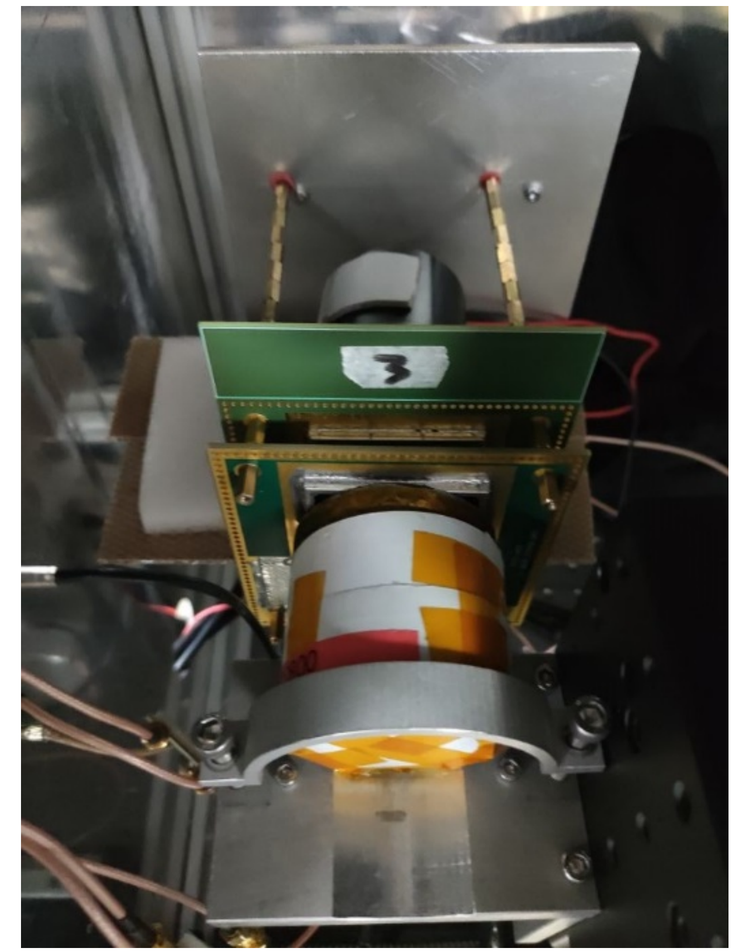
Thanks for your attention!

Backup

Setup of the USTC beta-TCT system

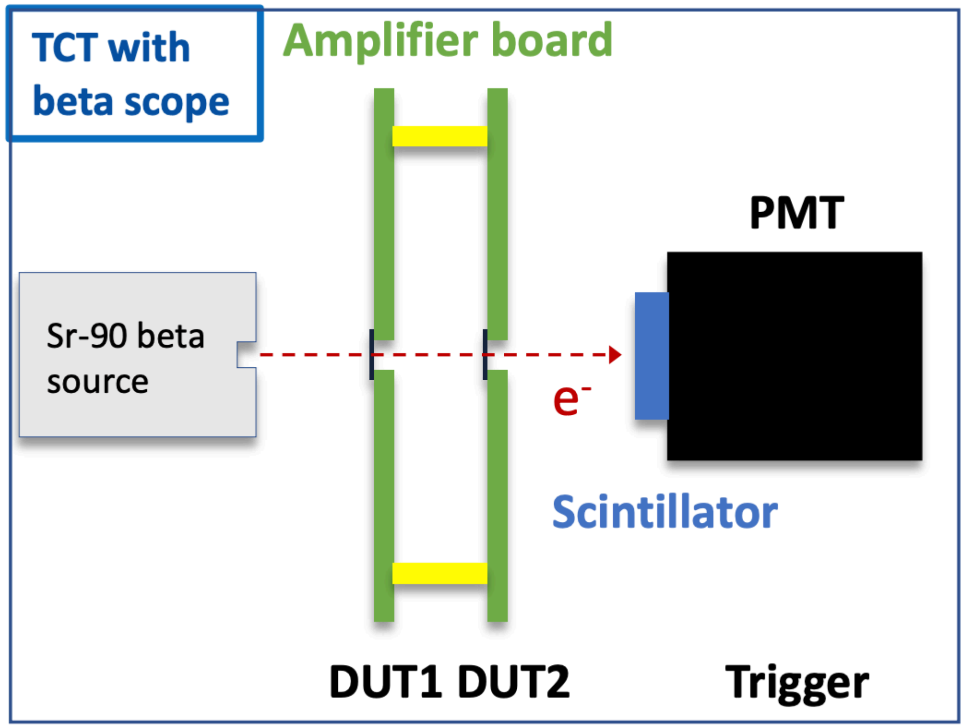
- Room temperature
- Reference
  - UCSC pre-amplifier & HPK Type 1.1 single, un-irradiated
  - With the 2nd stage amplifier
  - Bias: -210V
- DUT
  - UCSC pre-amplifier & USTC-1.1 single, un-irradiated
  - With the 2nd stage amplifier
- Trigger (Coincidence with reference)
  - R5924 PMT & EJ 232 Scintillator
  - With the attenuator
  - HV: +2000V
  - Threshold: 350 mV
- Oscilloscope
  - Sampling rate: 20 Gs/s
  - Bandwidth: 1 GHz

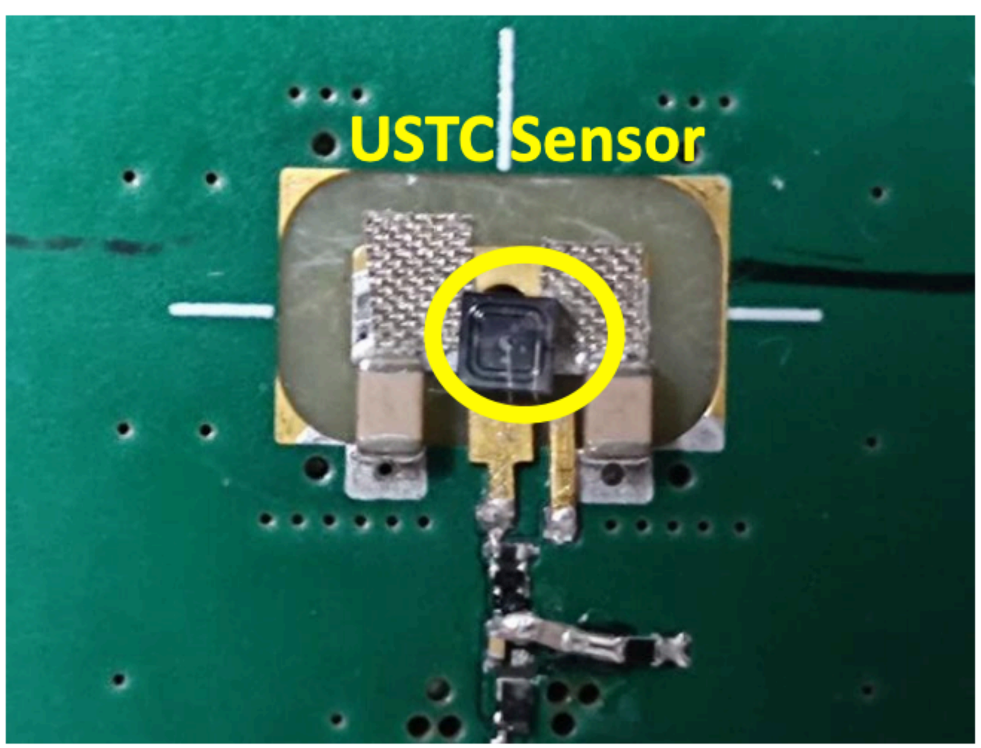




Performance from TCT

TCT System at USTC

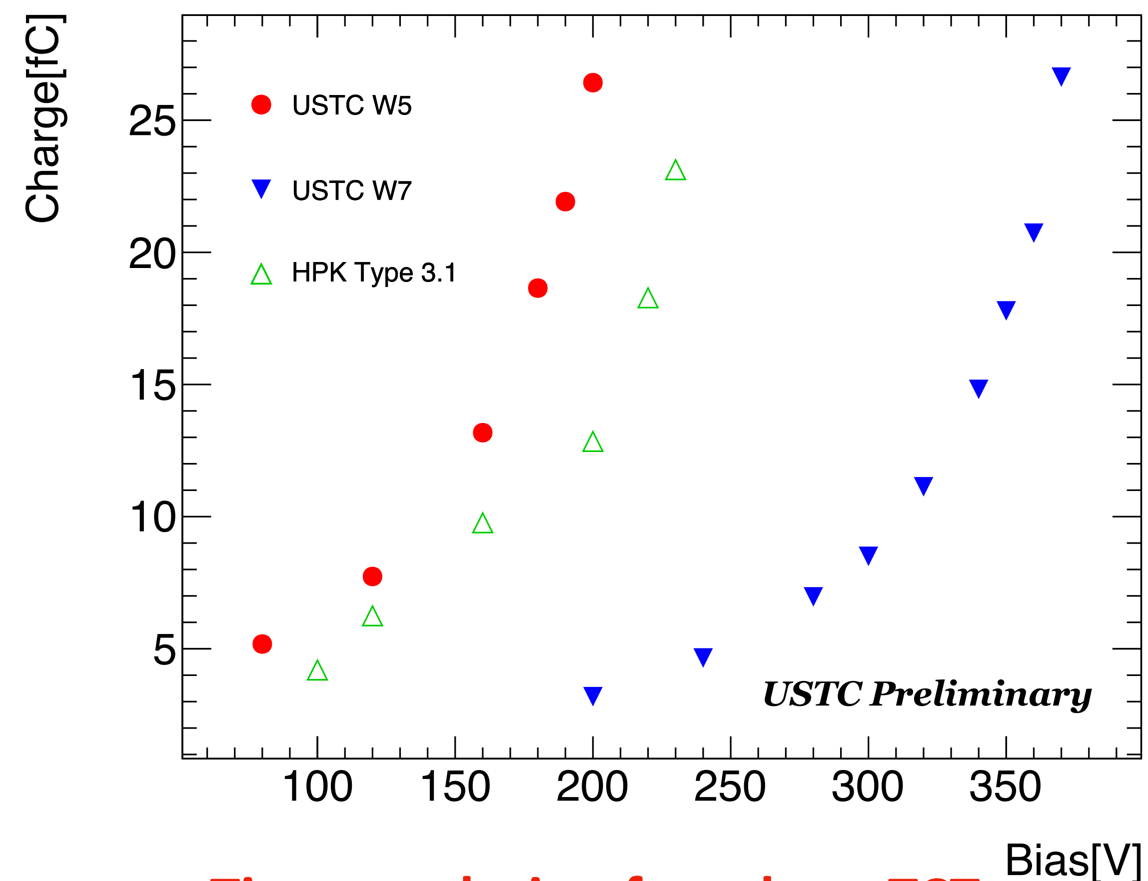




Pre-amplifier board from UCSC

by Chihao Li

Collected Charge from beta TCT



Time resolution from beta TCT