Characterization on the radiation hardness of USTC-1.1 LGADs

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On behalf of USTC Group

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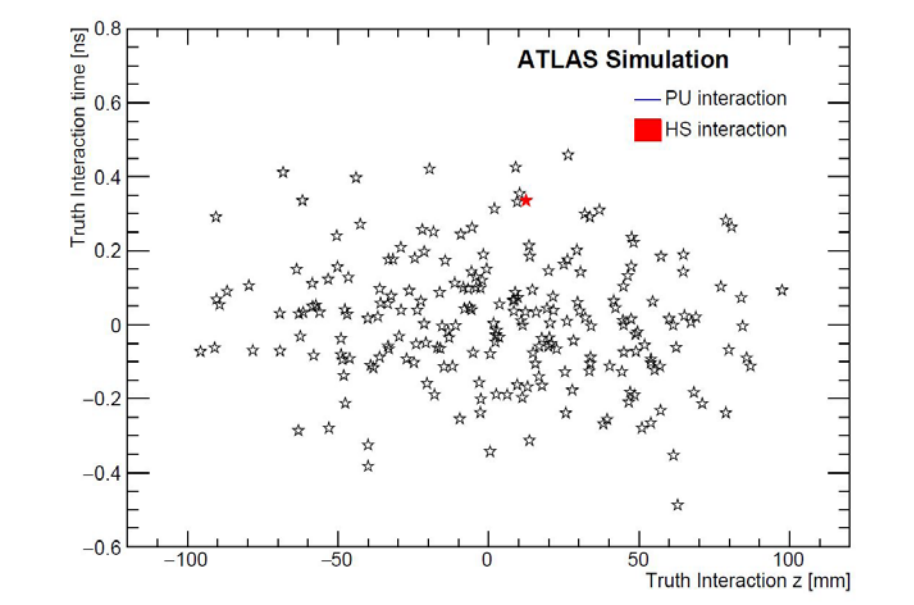
Overview

- HGTD & LGAD
- USTC-1.1 LGADs overview
- Single sensor performance before and after irradiation
  - IV/CV characterization
  - Beta scope test
- Large array performance

ATLAS HGTD project

- Pile-up is one of the main challenges at high luminosity.
- Adding time information to trackers to resolve pile up interactions.
- A High Granularity Timing Detector (HGTD), based on low gain avalanche detector (LGAD) technology, is proposed in the forward regions.

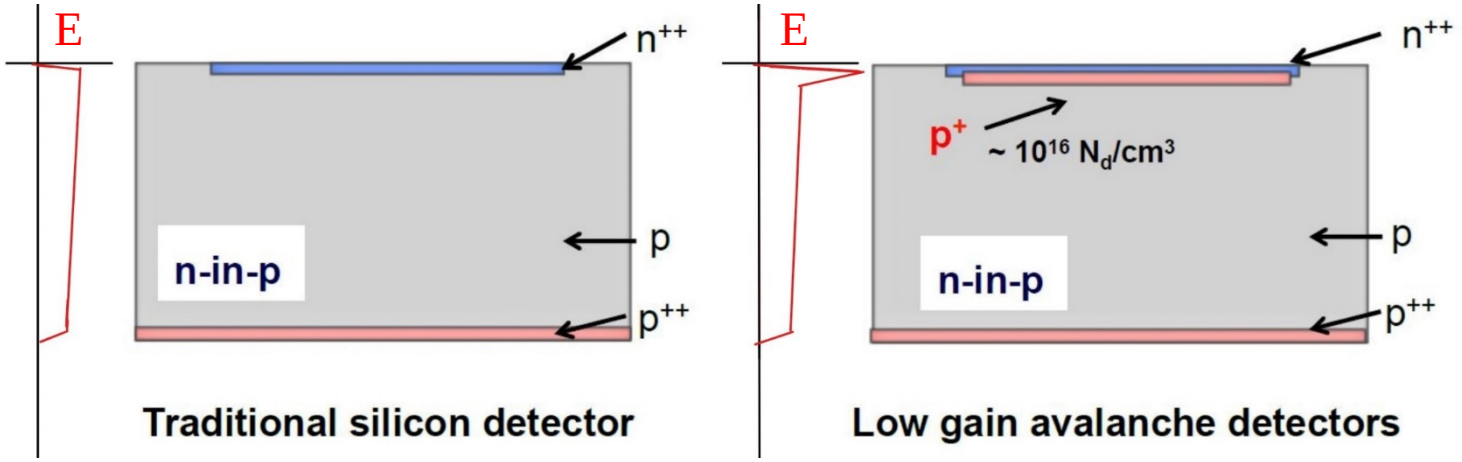


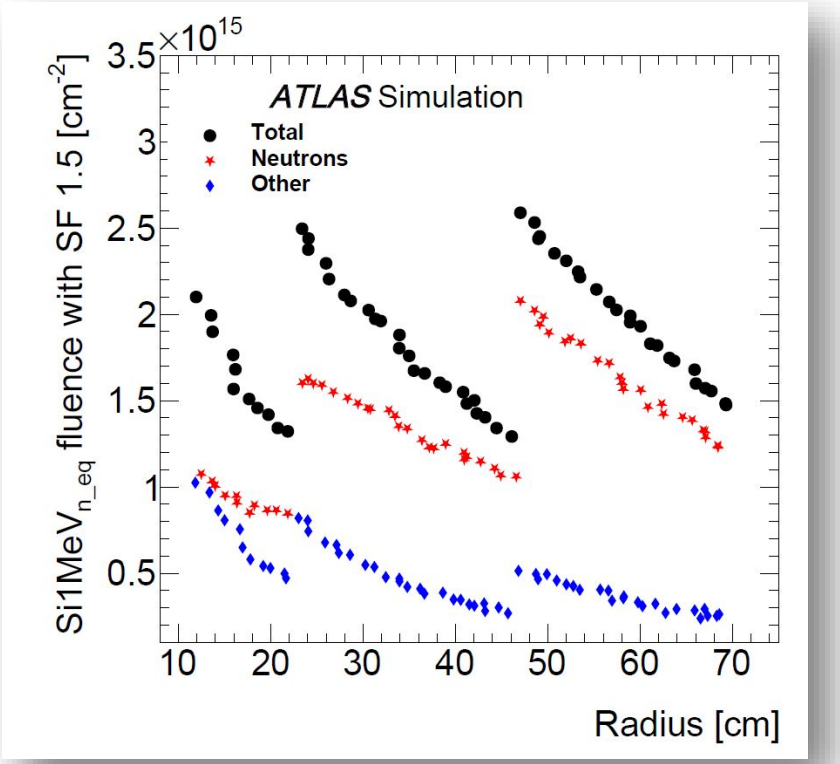
An average of 200 simultaneous *pp* interactions within the same bunch crossing interval

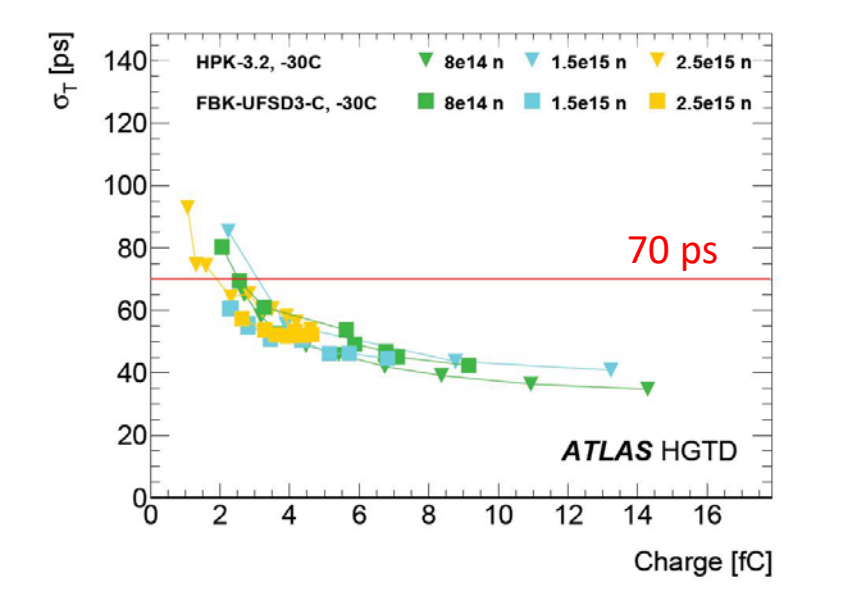
Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	±3.5 m
Weight per end-cap	350 kg
Radial extension:	
Total	110 mm $< r <$ 1000 mm
Active area	120 mm $< r <$ 640 mm
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.6 M
Active area	6.4 m^2
Module size	30 x 15 pads (4 cm × 2 cm)
Modules	8032
Collected charge per hit	> 4.0 fC
Average number of hits per track	
$2.4 < \|\eta\| < 2.7$ (640 mm $> r >$ 470 mm)	≈2.0
$2.7 < \|\eta\| < 3.5$ (470 mm $> r >$ 230 mm)	≈2.4
$3.5 < \|\eta\| < 4.0$ (230 mm $> r >$ 120 mm)	≈2.6
Average time resolution per hit (start and end of operational lifetime)	
$2.4 < \|\eta\| < 4.0$	≈ 35 ps (start), ≈ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	≈ 30 ps (start), ≈ 50 ps (end)

Table 2.1: Main parameters of the HGTD.

LGAD sensor R&D







- The internal gain depends on the doping profile of the multiplication layer.
- Better S/N and time resolution are achieved from higher gain (10 ~50).
- Gain loss due to radiation damage
  - Acceptor removal: $\rho_A(\phi) = g_{\text{eff}}\phi + \rho_A(0)e^{-c\phi}$

USTC-1.1 LGADs overview

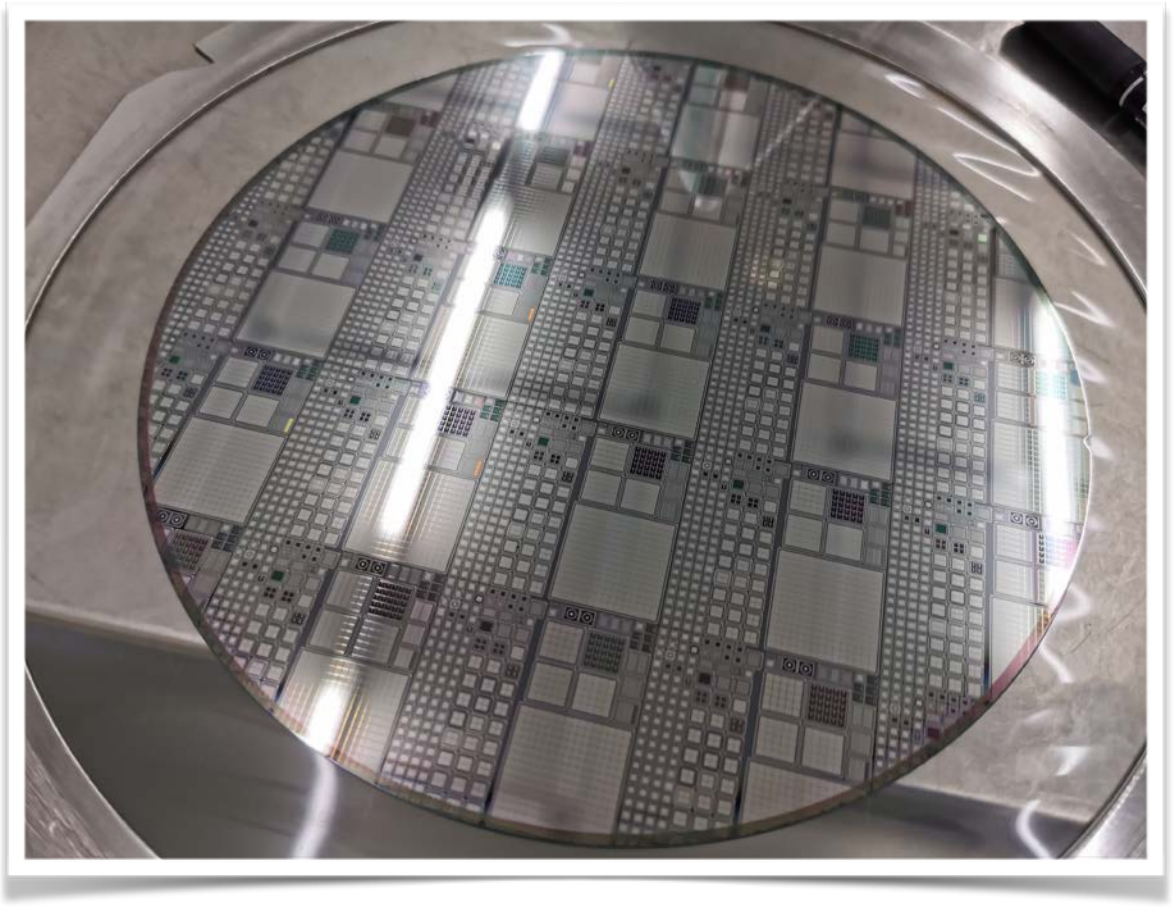
- The USTC Group is focusing on the improvement of radiation hardness of LGAD sensors.
- Deep gain layer implantation and carbon diffusion are included in the present design.

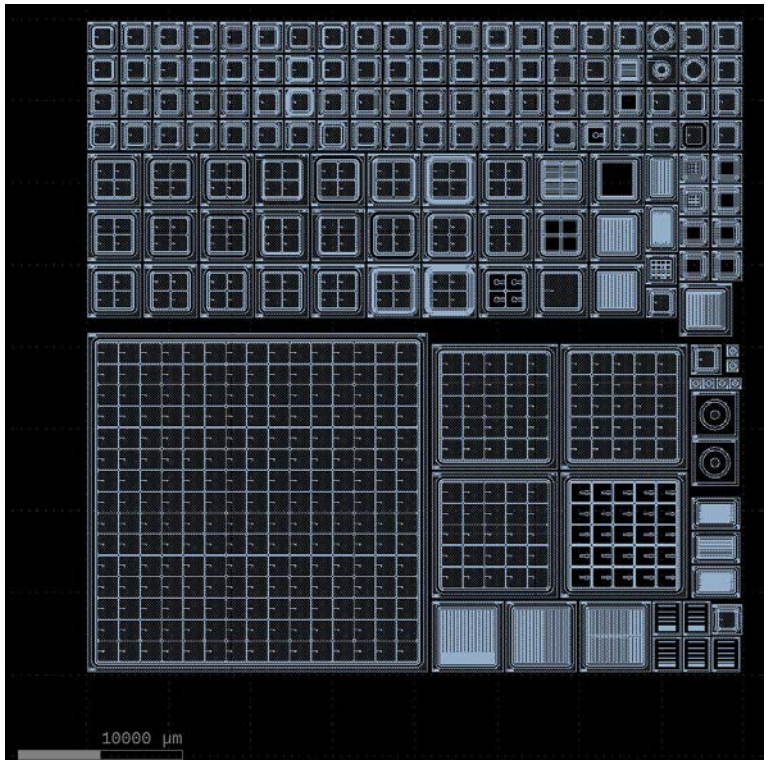
	Designed VBD [V]	GL.Energy	GL.Dose	Implantation	Radiation fluence [$\mathrm{neq/cm^2}$]	Annealing
W7	270	Medium	Low	B	8E14, 1.5E15, 2.5E15, 6E15	80 min@60 ℃
W8	195	Low	High	B		
W9	200	High	Low	B		
W10	200	Medium	Medium	B		
W11	200	Medium	Medium	B+C		

Thanks to colleagues at JSI for irradiating our samples!

On-wafer USTC-1.1 LGADs

Designed by USTC
Fabricated by IME, CAS

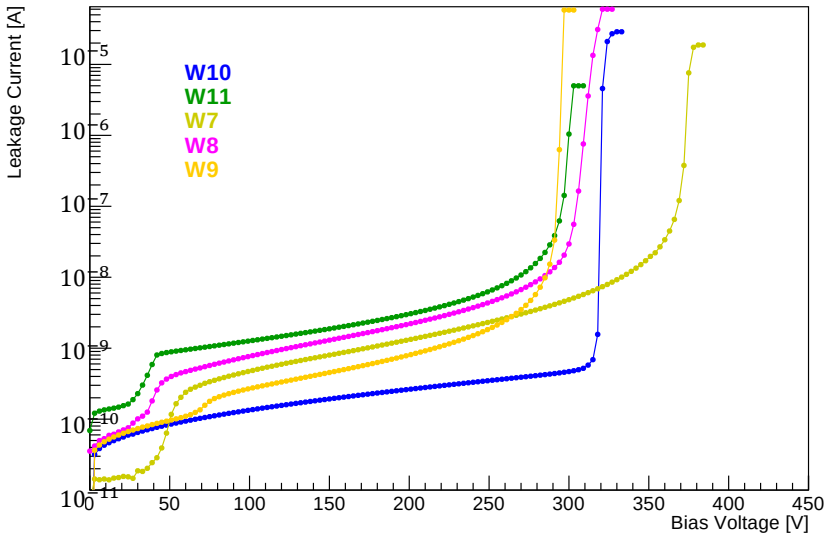


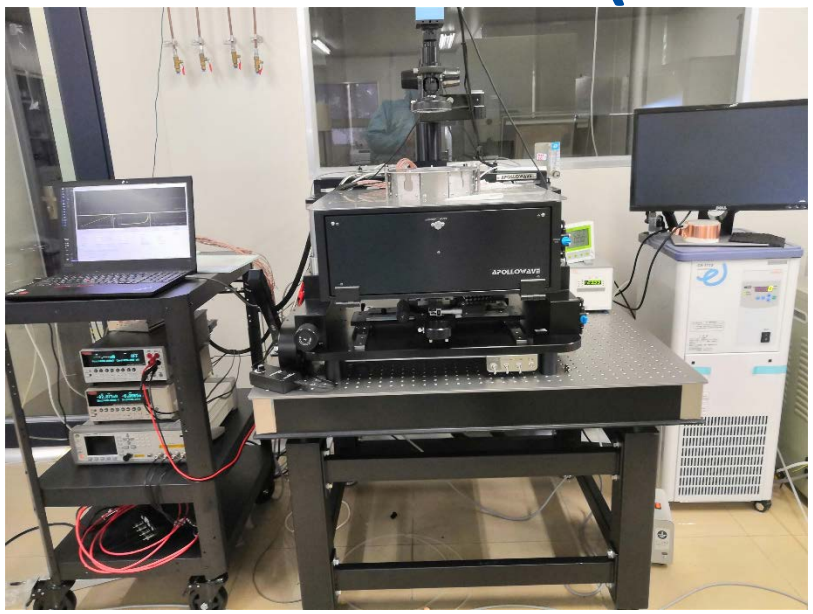


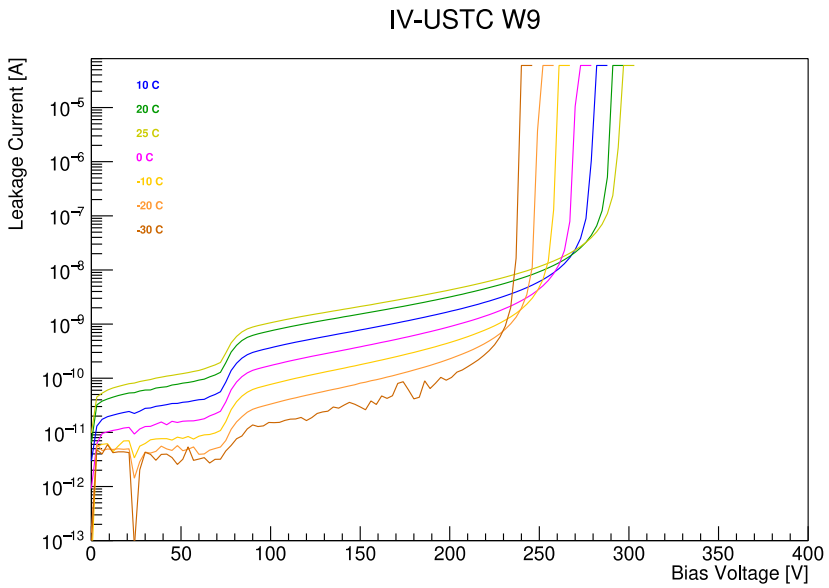
8 inch wafer, with 50 µm Epi. layer.
Stepper size: 40 mm × 40 mm

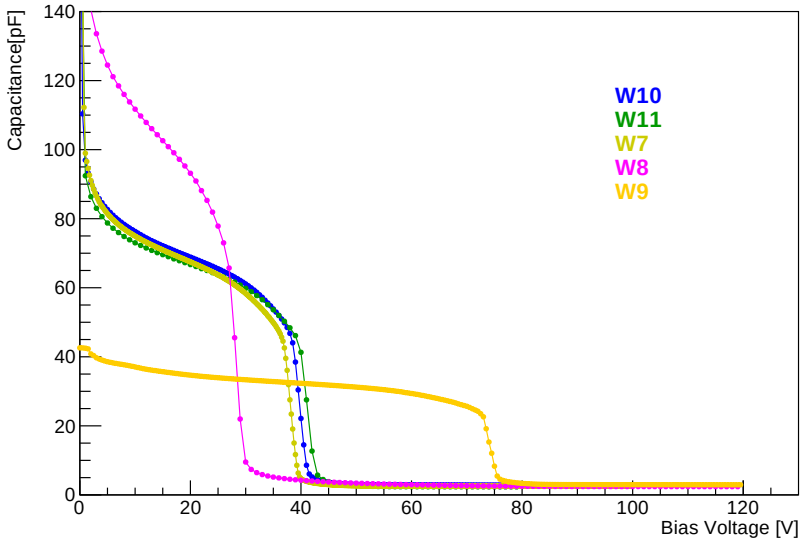
Size	Single	2×2	5×5	15×15
Num. per stepper	80	18	4	1

IV/CV characterization (Pre-irradiation)





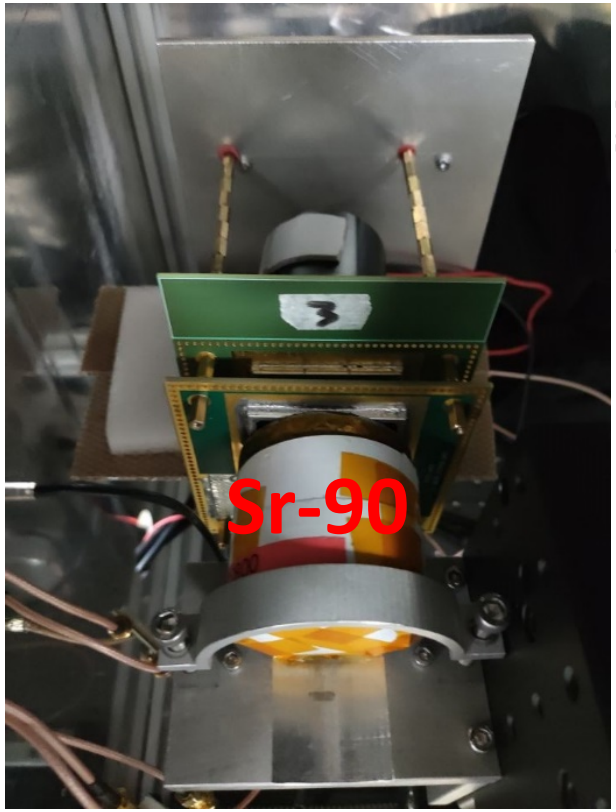


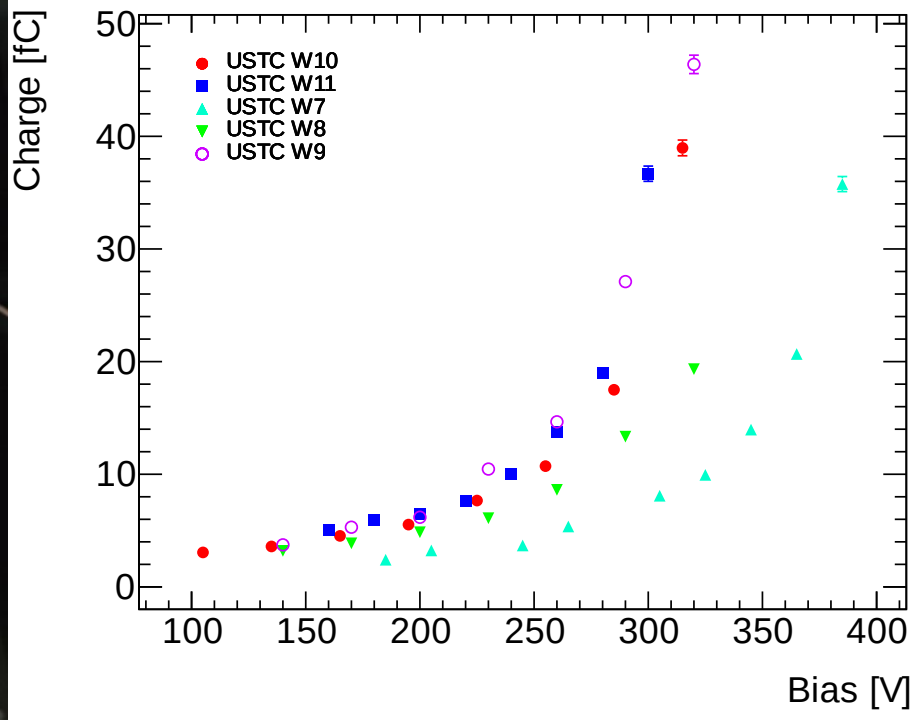


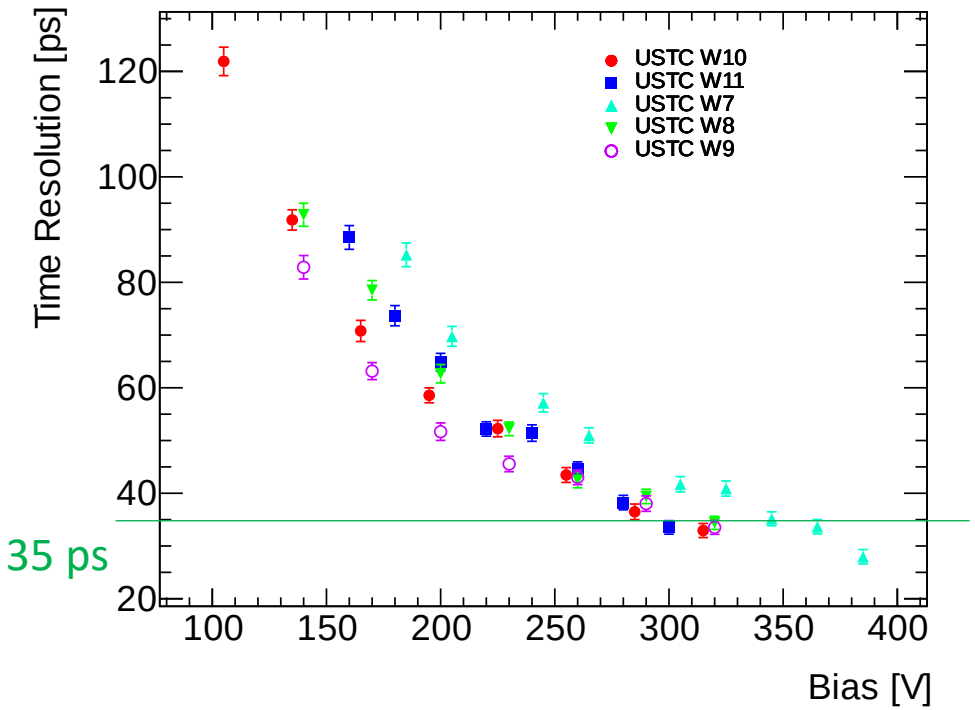
	VBD [V] (un-irradiated, Room T.)	VGL [V] (un-irradiated, Room T.)
W7	370	38
W8	295	29
W9	295	70
W10	320	40
W11	300	41

Gain layers of all sensors can be depleted at V <VBD at low temperatures (-30°C)

Beta scope test (Pre-irradiation)

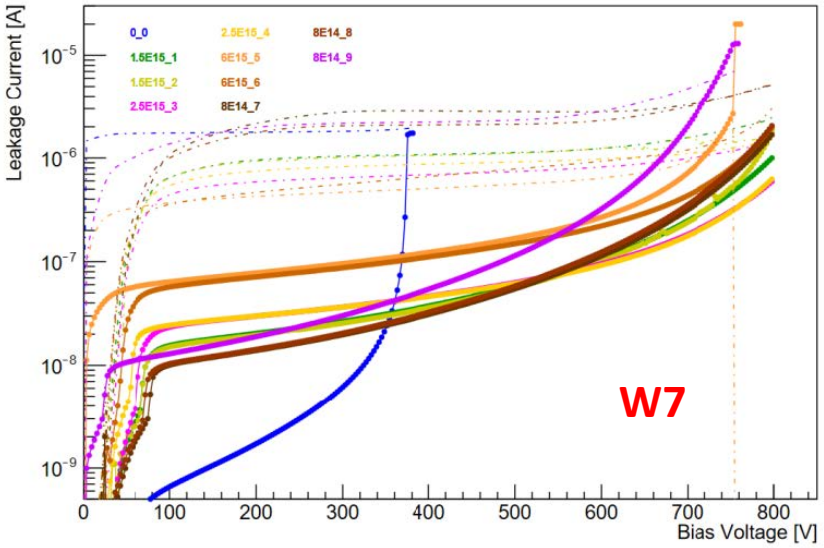


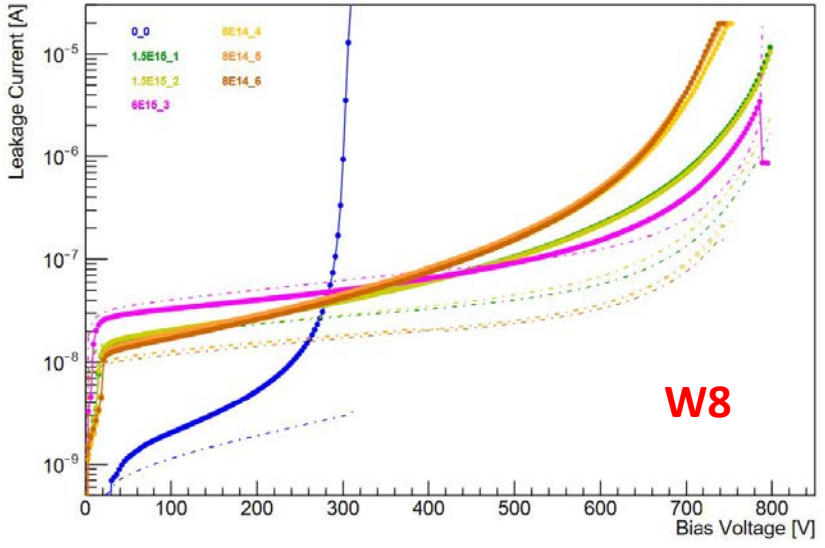


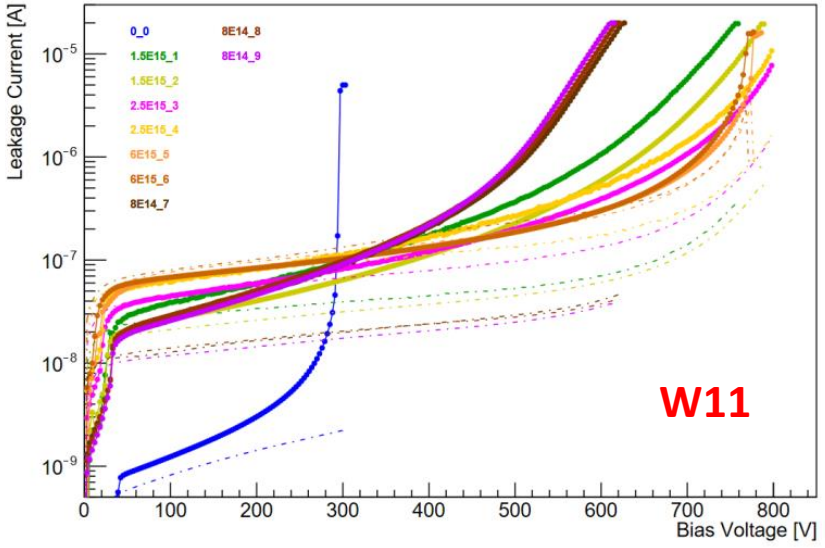


- Sensors with deep implantation(W9) and carbon diffusion(W11) can work normally before irradiation.
- All the 5 wafers can have time resolution of ~35 ps before irradiation.

Cold IV measurement



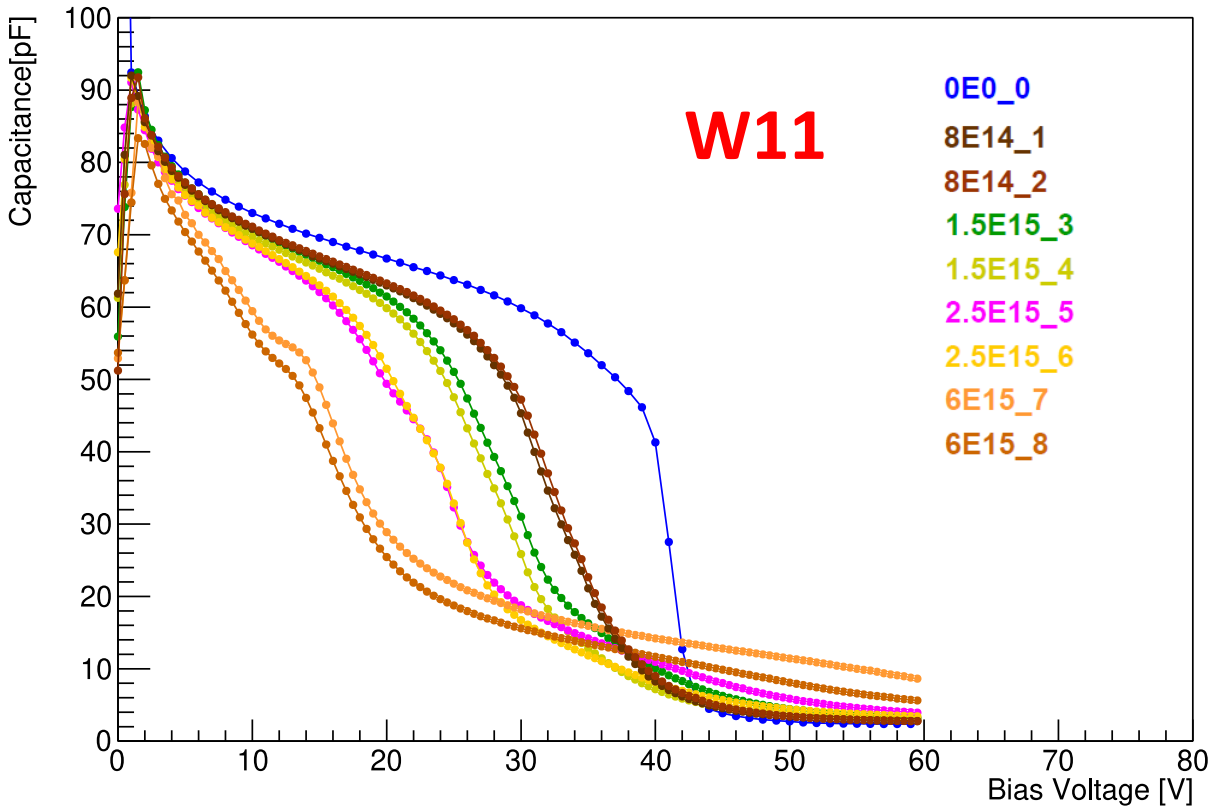




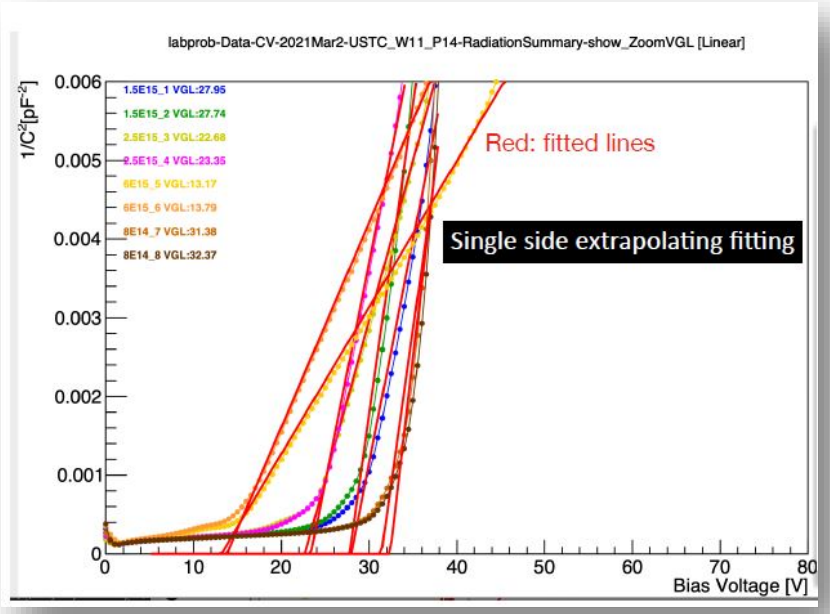
- Setup
  - Temperature: -30℃ (For irradiated sensors)
  - Bias range: 0 ~800 V
  - GR grounded
- W7 shows poor radiation hardness with too high VBD. W8 can work within 800 V with fluence of 1.5E15
- W11 shows the promising radiation hardness.

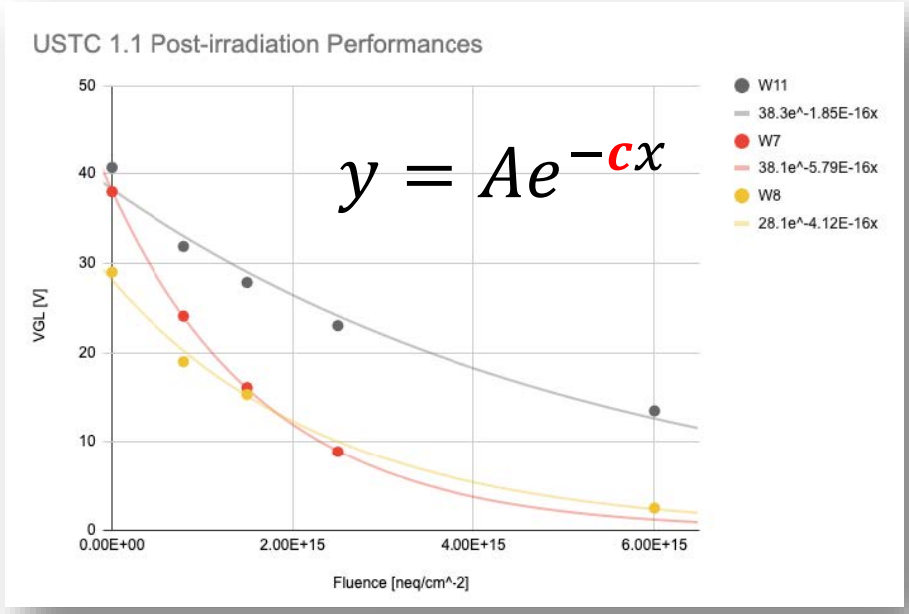
Room T. CV measurement

- Setup
  - Temperature: 20℃
  - AC amplitude: 1 V
  - Frequency: 1 kHz
  - Bias range: 0 ~60 V
- Sensors from W11 are measured at different fluence points. Most devices get normal performance.



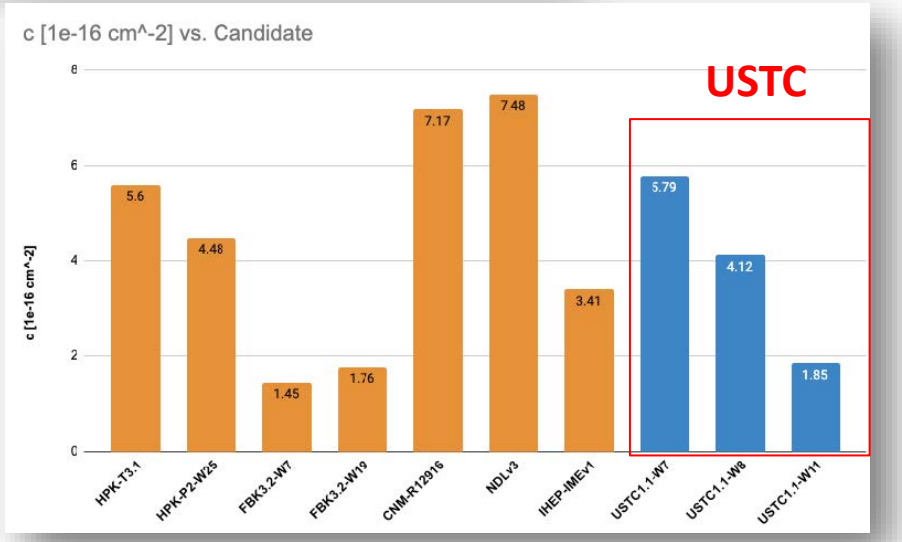
C-factor extraction





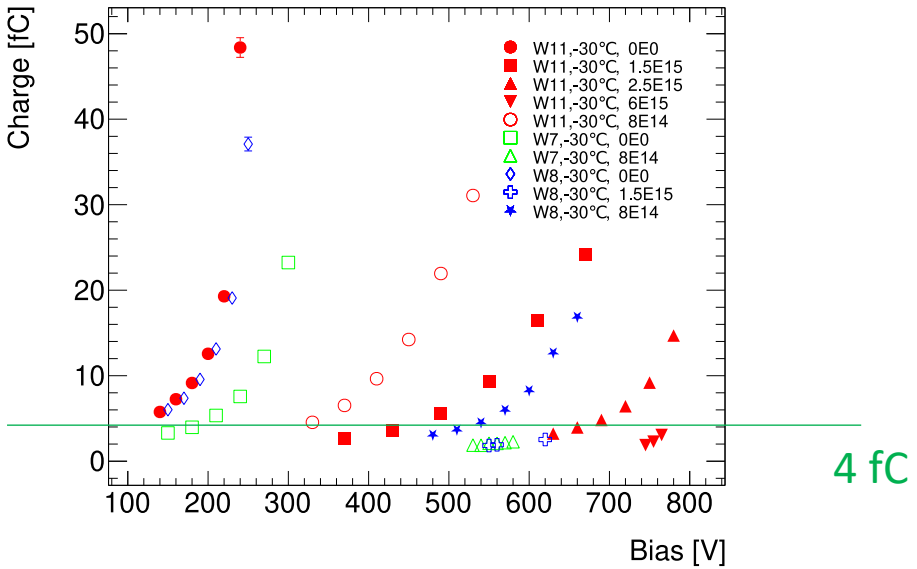
VGL [V] & c-factor

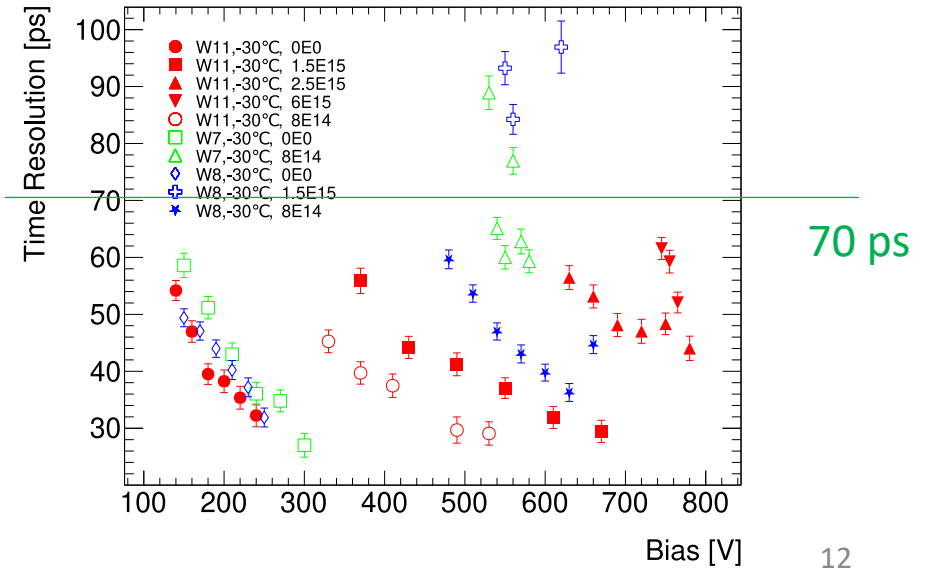
Wafer	Fluence [$\mathrm{neq/cm^2}$]					c-factor [10^{-16} $\mathrm{cm^2}$]
	0E0	8E14	1.5E15	2.5E15	6E15	
W7	38.04	24.08	16.08	8.875	-	5.79
W8	29.19	18.98	15.31	19.27	2.48	4.12
W11	41.69	31.88	27.85	23.02	13.48	1.85



Performance on irradiated sensors

- Setup
  - Temperature: -30°C
  - UCSC pre-amplifier board & 2nd stage amplifier used
  - Reference: HPK Type 1.1, un-irradiated
- $\sigma_{\mathrm{DUT}} = \sqrt{\sigma^2_{\mathrm{total}} - \sigma^2_{\mathrm{Ref}}}\ (\sigma_{\mathrm{Ref}} = 30\ \mathrm{ps})$
- W7 and W8 stop before the maximum radiation fluence on HGTD (2.5E15). W11 performs well after irradiation.
- For W11, the time resolution can be better than 70 ps at fluence of 2.5E15 with the collected charge large than 4 fC.





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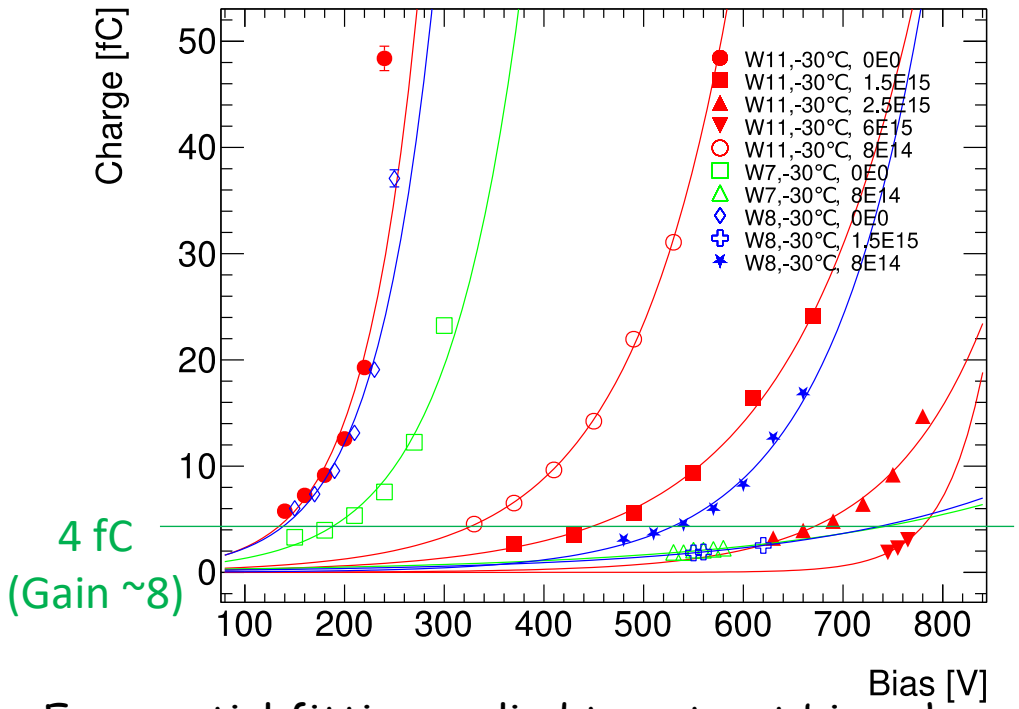
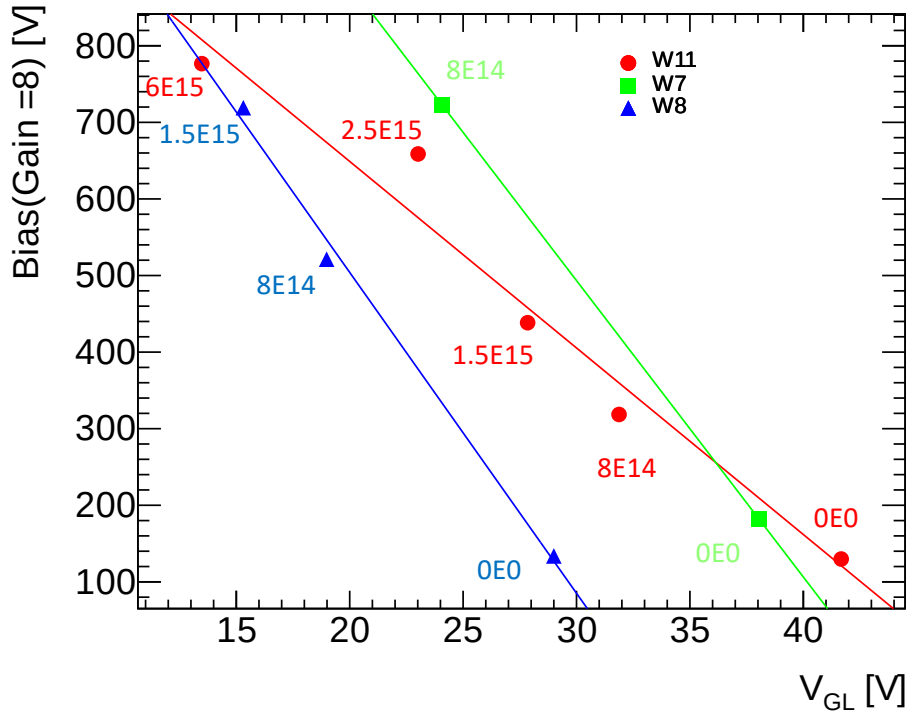


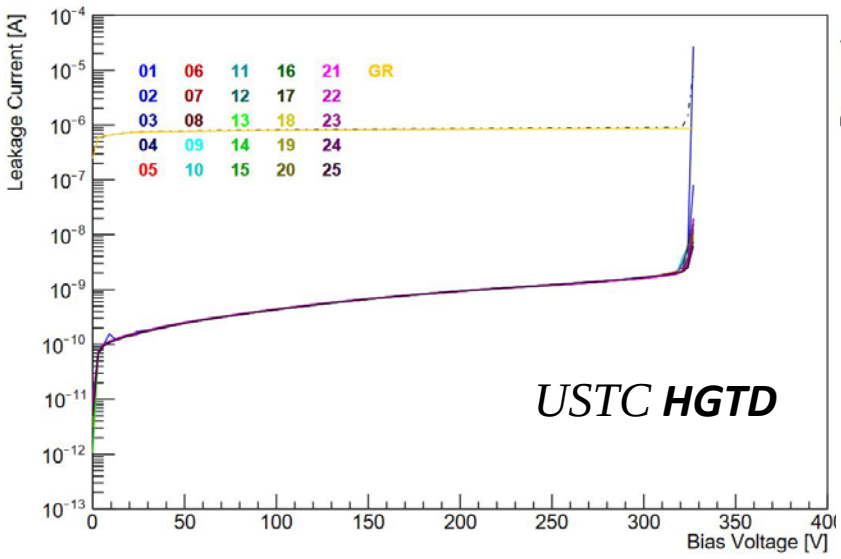


Exponential fitting applied to extract bias where gain ~8

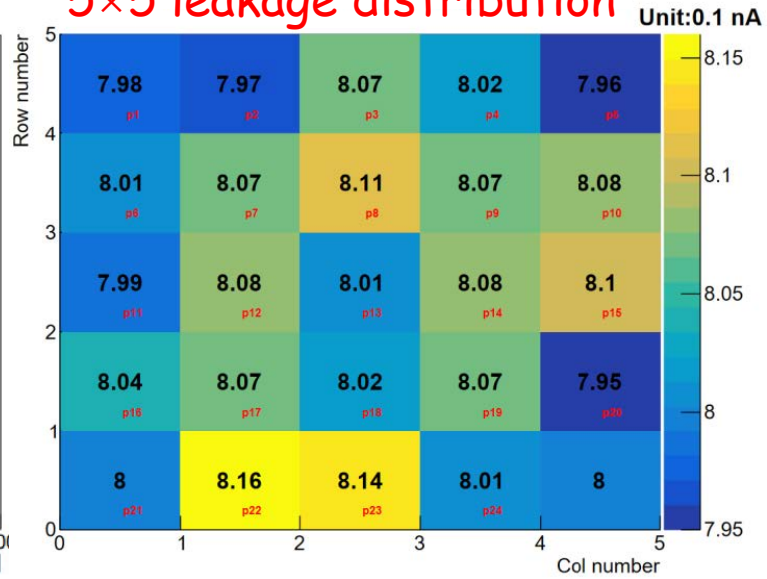
- The internal gain depends on the E field E_{GL} in gain layer.
  - E_{GL} is proportional to the doping concentration and bias voltage
- Good consistency between results from CV characterization and beta scope test

Large array performance (Pre-irradiation)

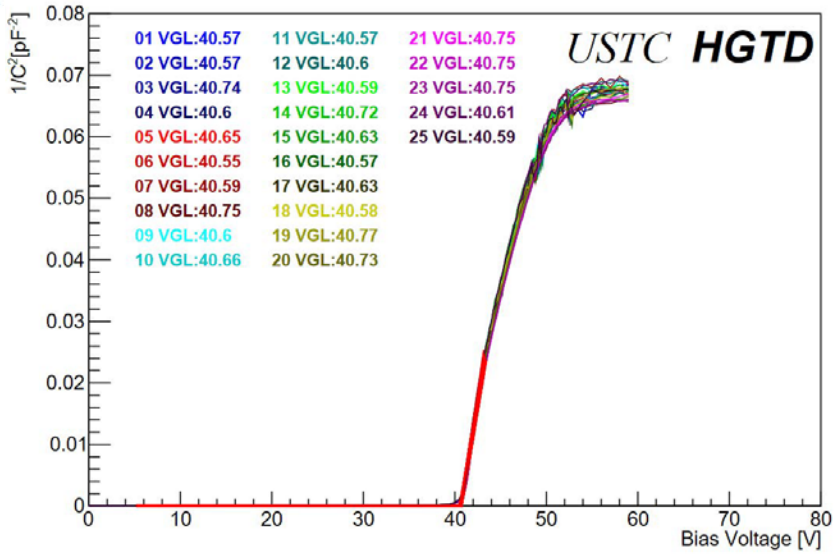
5×5 IV



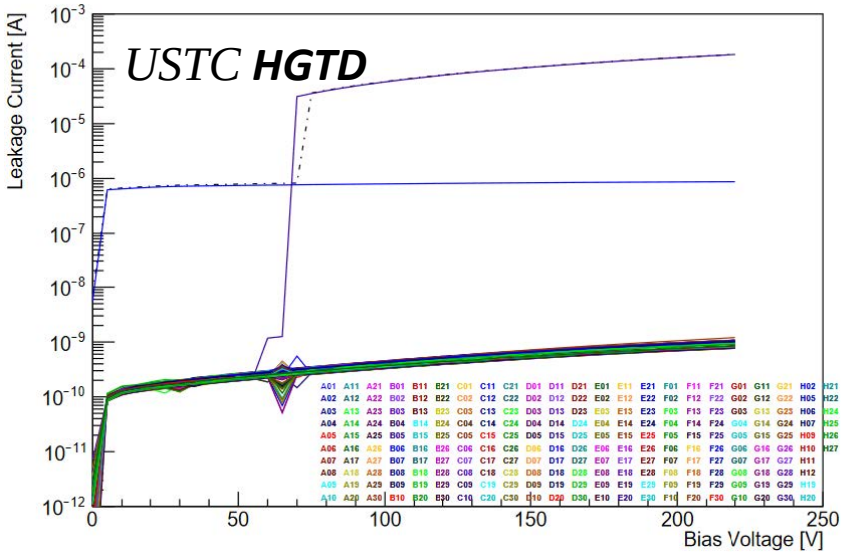
5×5 leakage distribution



5×5 CV



15×15 IV



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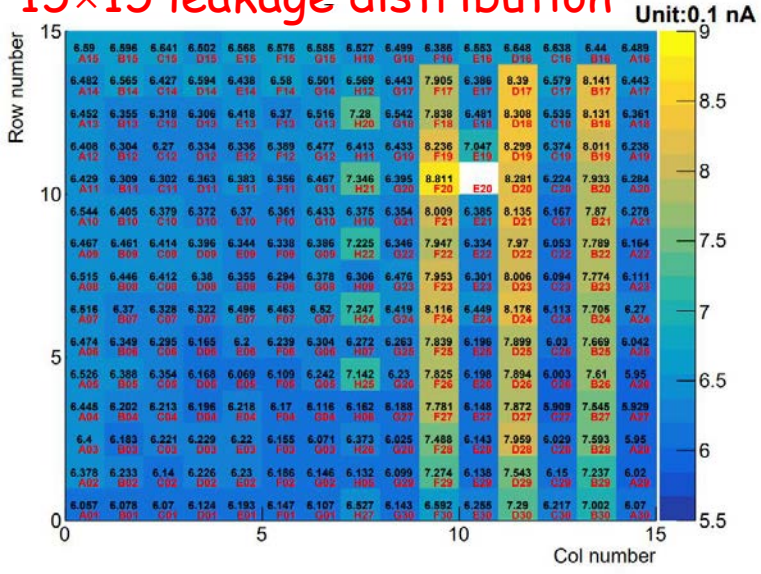


Summary

- The USTC group is involved in ATLAS HGTD project and has been developing the LGAD sensor technology.
- Different designs, like deep gain layer implantation and carbon diffusion, are applied to improve the radiation hardness of LGAD sensor.
- The radiation hardness of USTC-1.1 LGAD sensors can potentially satisfy the specification of HGTD.
- Measurements performed on the large arrays show results with good uniformity.

Further plans:

- Optimization on design and fabrication process
  - Detailed study on the radiation hardness
  - Improve the yields of the large array

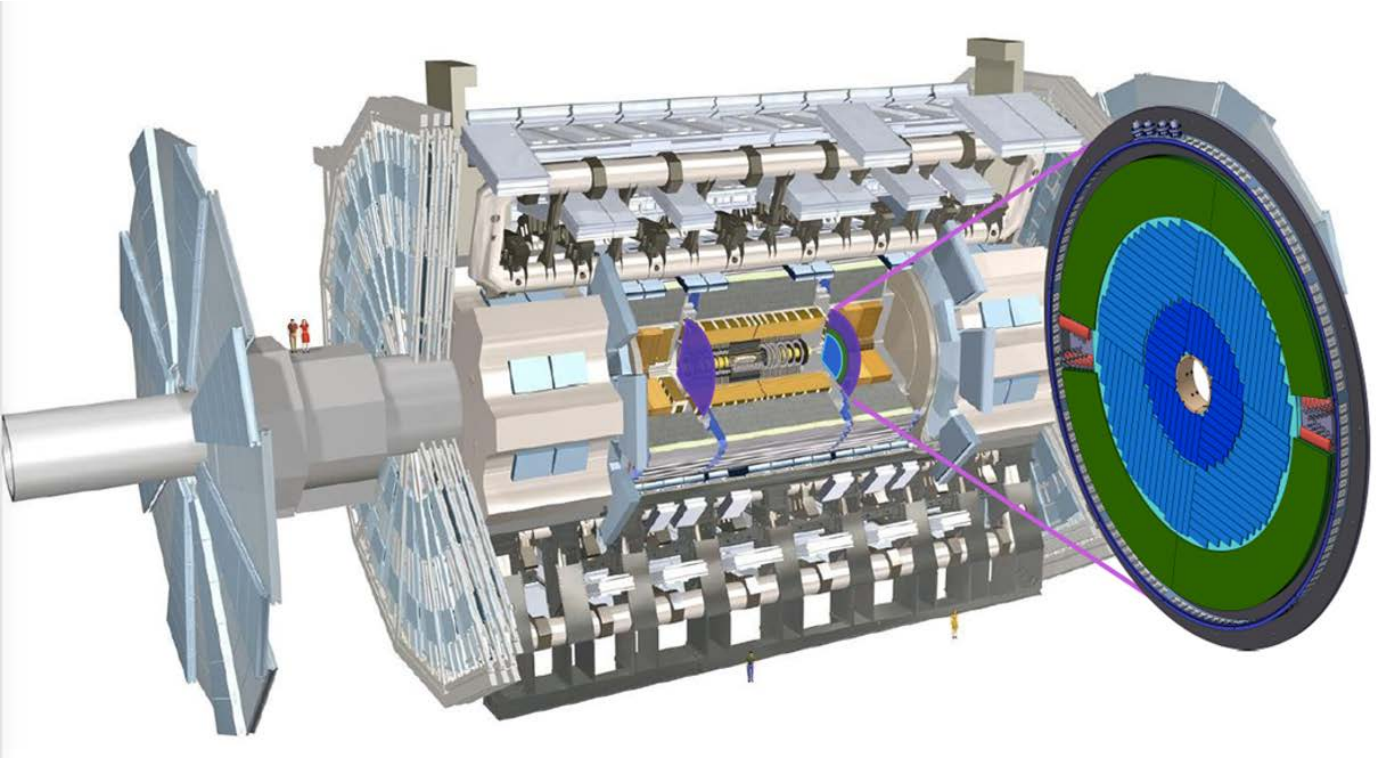
Thanks for your attention!

Back up

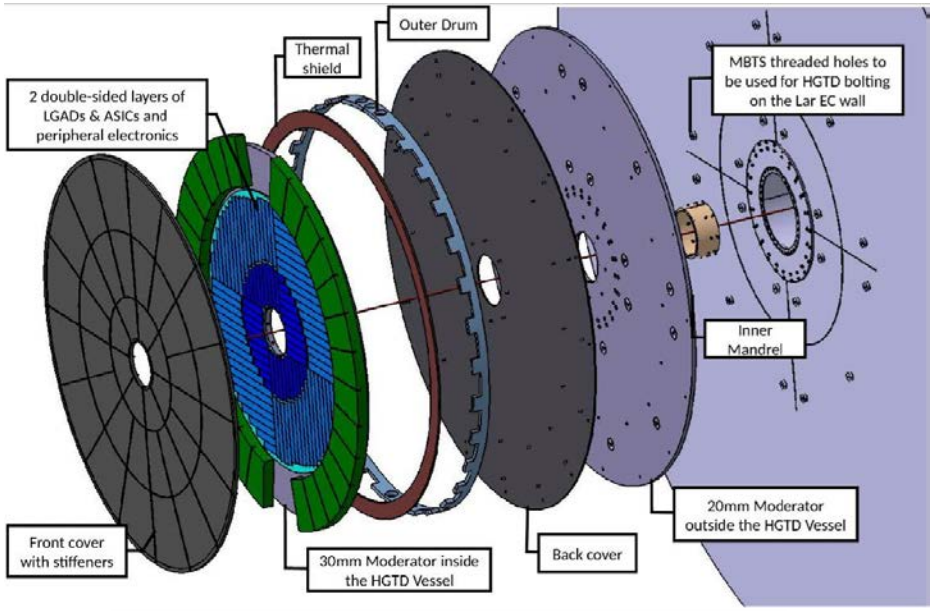
Acknowledgement

- Cooperation:
  - IME (sensor fabrication)
  - USTC nano center (dicing and partial tests)
  - JSI (neutron irradiation)
- Support:
  - “the Fundamental Research Funds for the Central Universities” of China (grant WK2030040100)
  - the National Natural Science Foundation of China (No. 11961141014)
  - the Chinese Academy of Sciences (Grant NO. : GJJSTD20200008), etc.

ATLAS HGTD project



High Granularity Timing Detector



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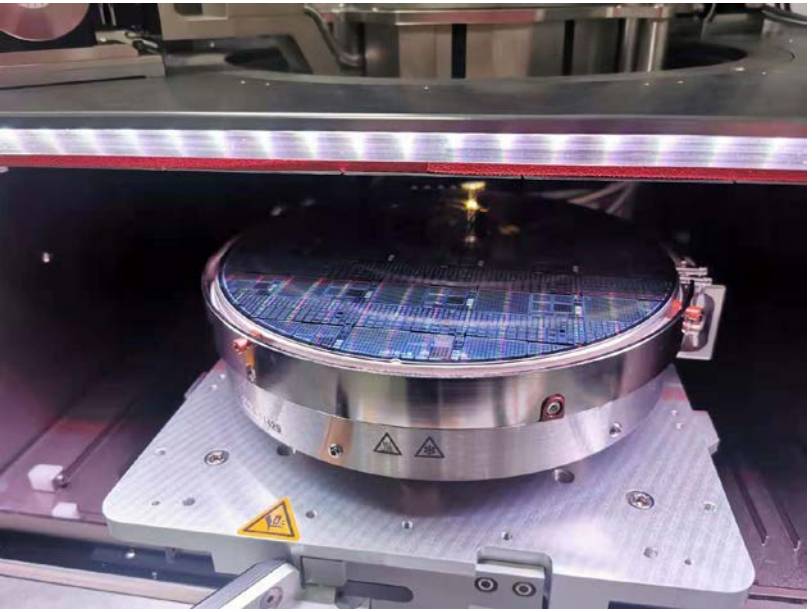
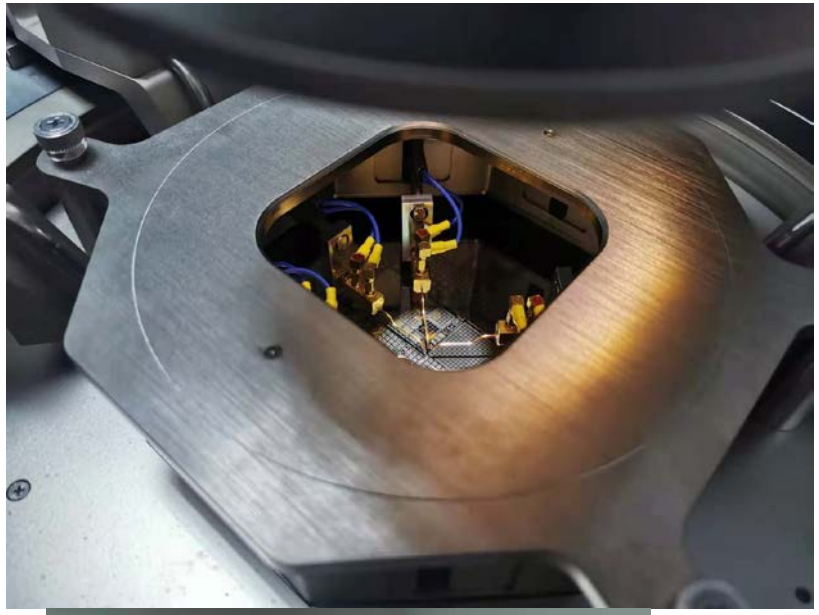
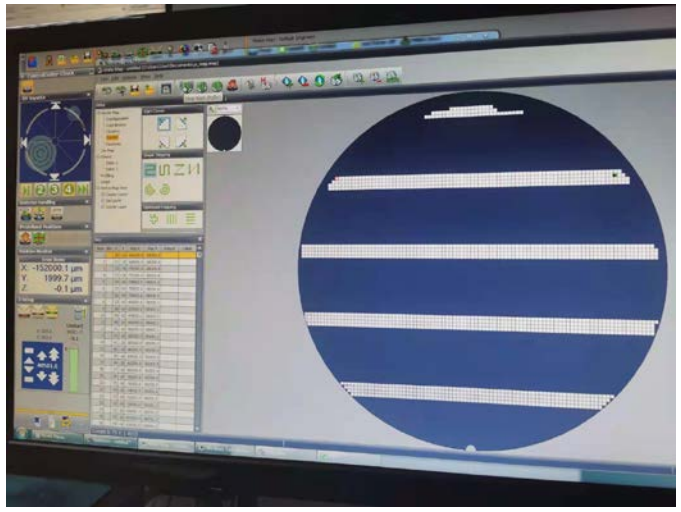
Automatic probe station

The equipment from the department of micro-electrons, USTC

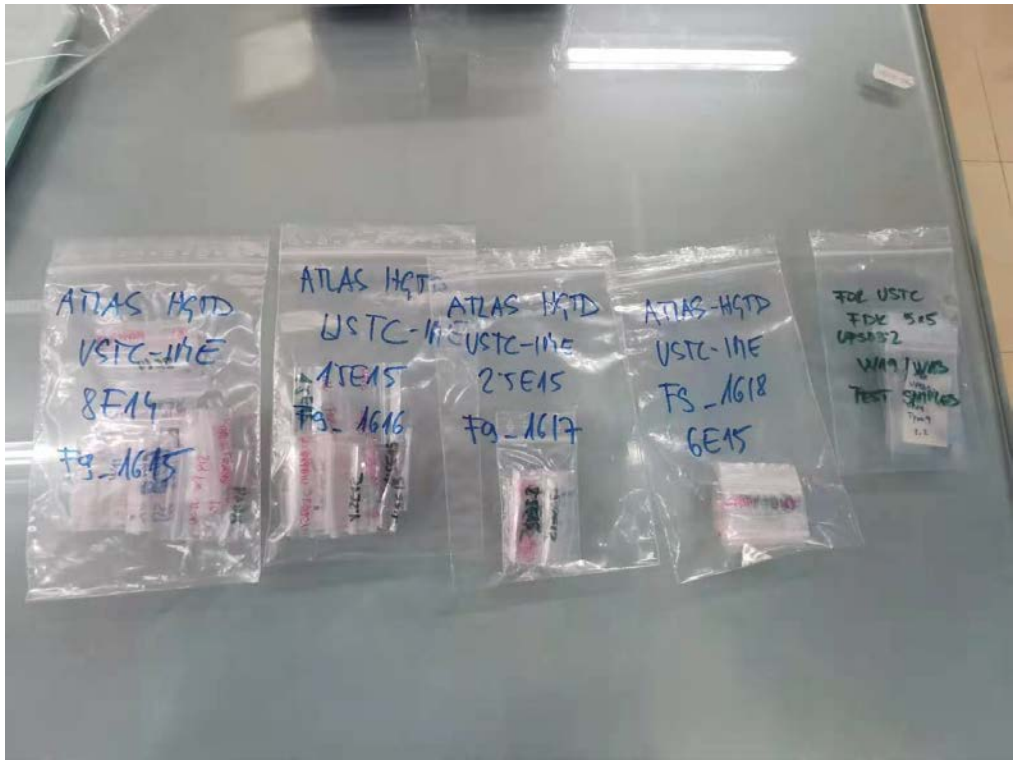


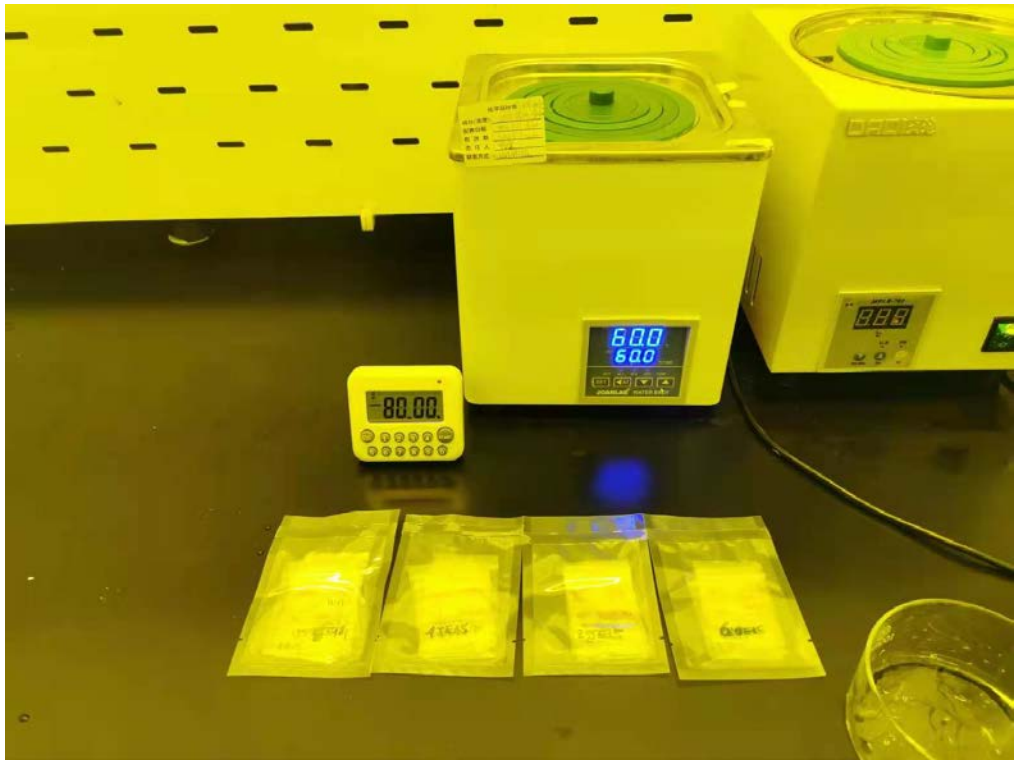




- On-wafer test for hundreds of single sensors with the automatic probe station
- Maximum HV to 200 V now, quick check for the whole wafer

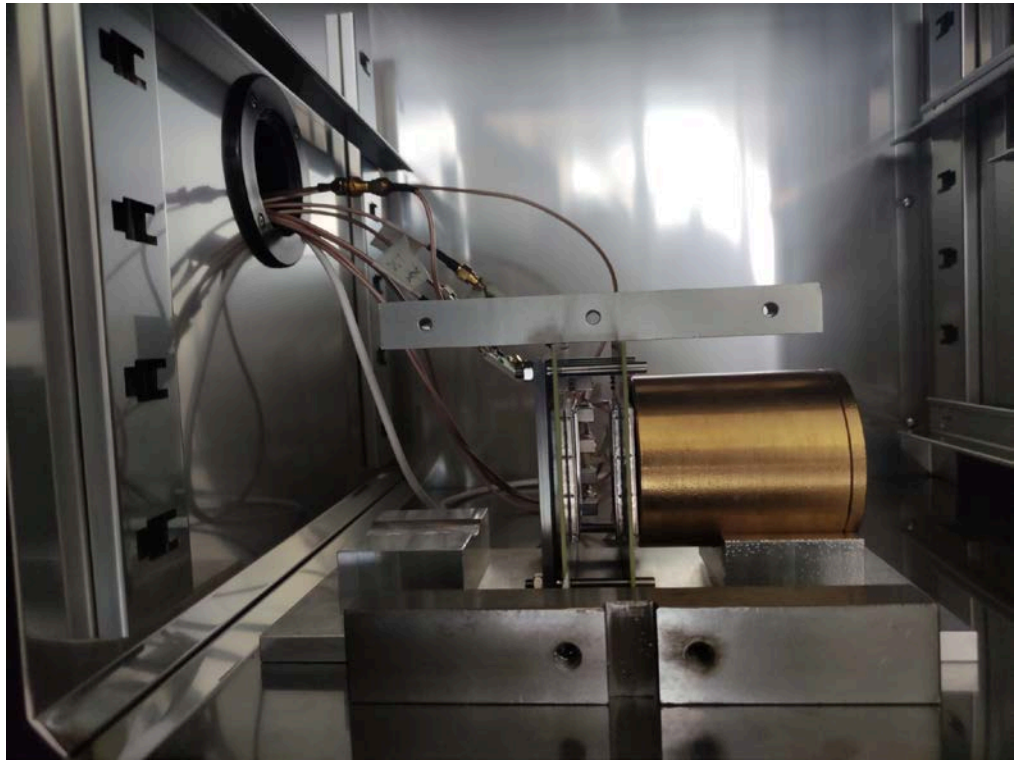
Sensor irradiation and annealing



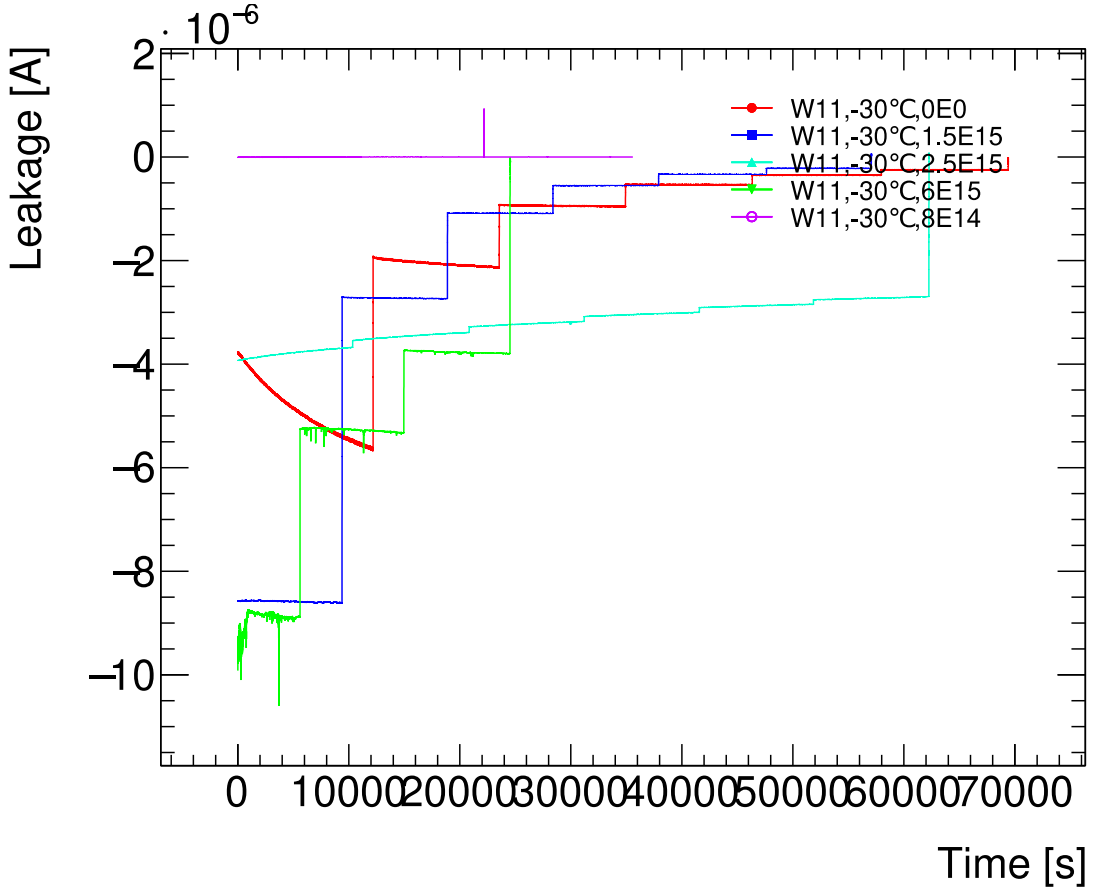


Cold beta scope setup

- Detectors and beta source set in the environmental chamber, which is flushed with N_2 before cooling
- Reference
  - UCSC pre-amplifier & HPK Type 1.1 single, un-irradiated
  - With the 2nd stage amplifier
- DUT
  - UCSC pre-amplifier & USTC v1.1 W8/W11 single, irradiated
  - With the 2nd stage amplifier
- Trigger
  - Same with the reference
  - Bias: -205 V@20 ℃/-165 V@ -30 ℃
  - $\sigma_{\mathrm{ref}} = 30\ \mathrm{ps}$
  - Threshold: 50 mV
- Oscilloscope
  - Sampling rate: 20 Gs/s
  - Bandwidth: 1 GHz



Leakage current on W11



- Each step represents leakage current variation with different bias.
- Leakage current on W11 single sensor could be always lower than 10 uA.

Large array test