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Recent progress in USTC-IME LGADs for the ATLAS HGTD Upgrade

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On behalf of USTC HGTD Group

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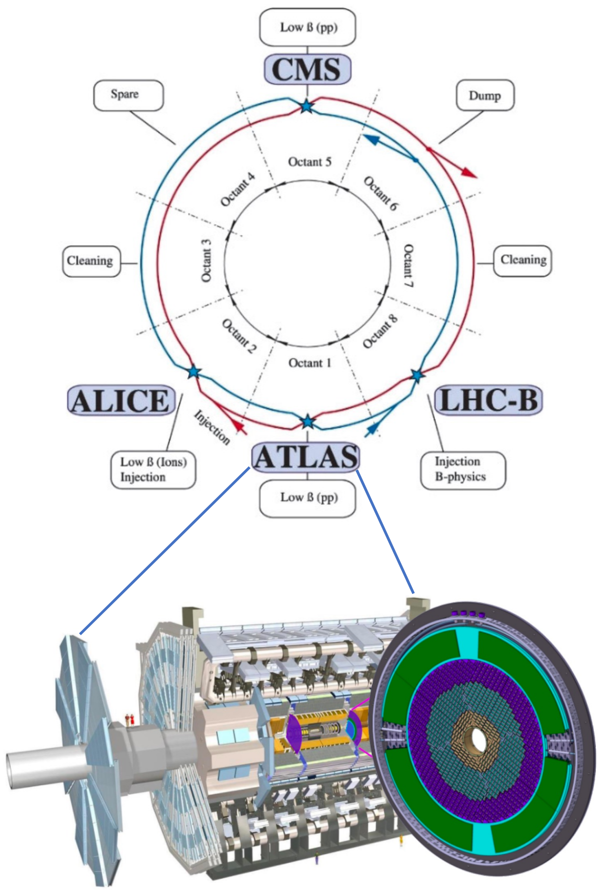
Outline

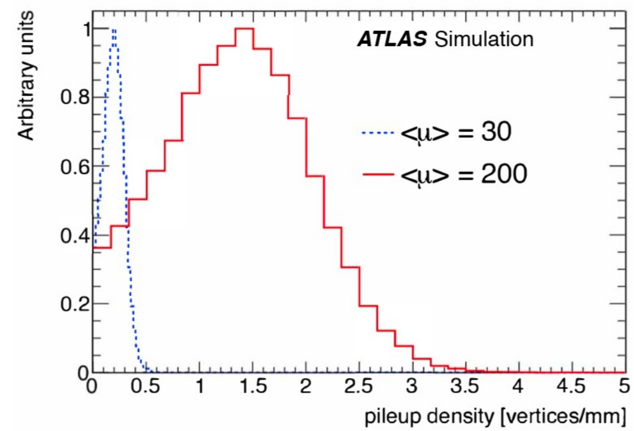
- ATLAS HGTD upgrade and LGAD technology
- Electrical characterization
- Radiation hardness evaluation
- Uniformity of large array sensors
- Inter-pad capacitance/resistance
- Charge collection and timing resolution
- Summary

A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade

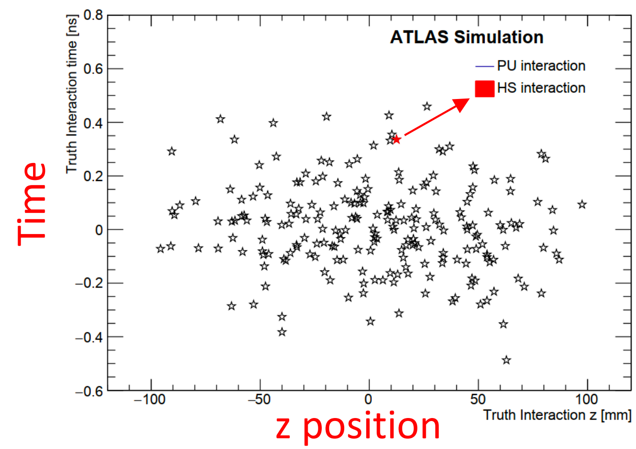
- **H**igh-**L**uminosity phase of **LHC** (**HL-LHC**): It's hard to associate track to primary vertex in high pileup environment, especially in the forward region.
- **H**igh-**G**ranularity **T**iming **D**etector (**HGTD**): measure charged-particle trajectories in time as well as space ("4D") in the forward region.



[HGTD TDR]

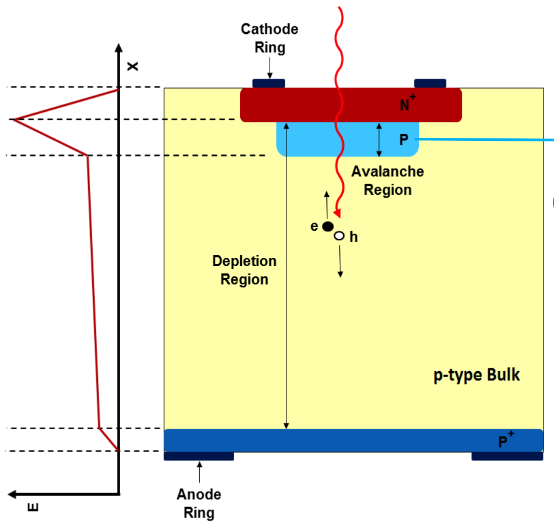


HGTD Requirements:
Collected charge > 4 fC
Timing resolution < 70 ps
after 2.5E15 n_{eq}/cm^2



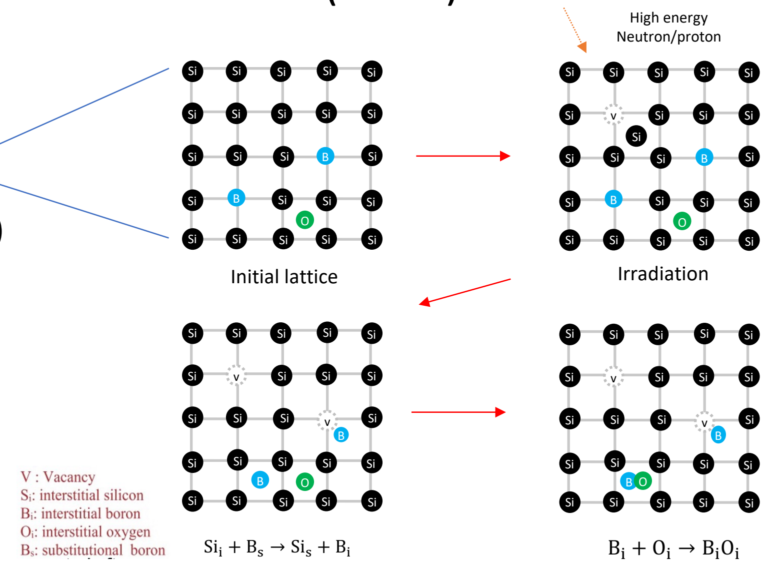
Low Gain Avalache Detector (LGAD) R&D

- A novel technology: silicon-based Low Gain Avalache Detector (LGAD)

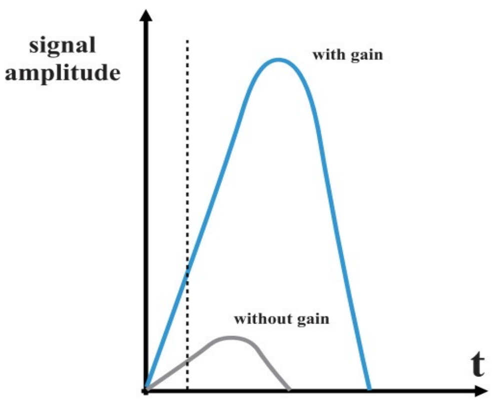


Gain layer

(Secondary ionization)



Acceptor(B_s) removal in gain layer after irradiation



LGAD's internal gain provide signal with faster rising edge, leading to a better timing performance

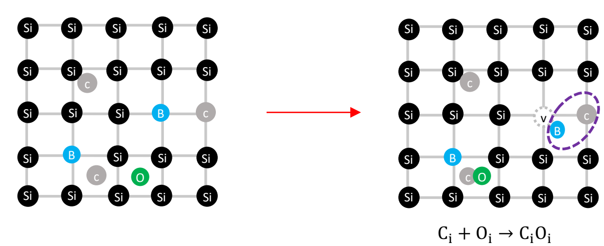
$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS}\right)^2 + \sigma_{Landau}^2$$

The effective doping concentration is reduced due to B_i and B_iO_i complexes:

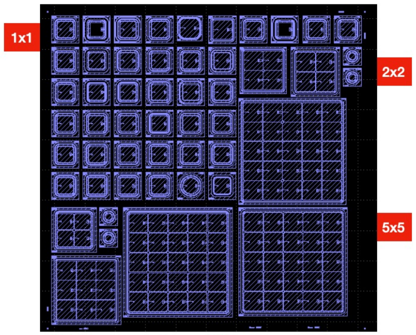
$$N_{eff}(\Phi_{eq}) = N_{eff}(0)e^{-c\cdot\Phi} + g_{eff}\Phi_{eq}$$

c is acceptor removal constant, g_{eff} is acceptor introduction rate and Φ_{eq} is the fluence (1MeV equivalent neutron).

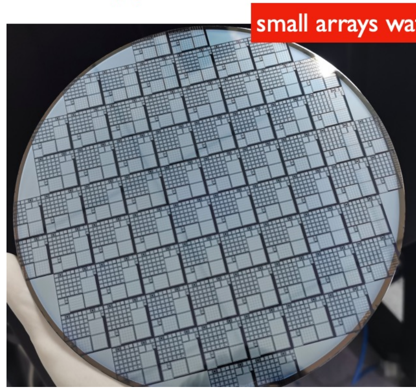
Carbon diffusion

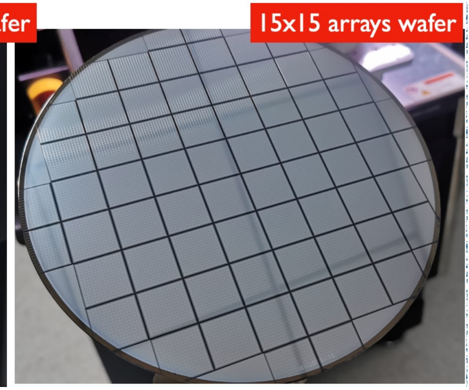


USTC-IME LGADs overview



Stepper size: 21 mm x 21 mm,





- USTC (Design) and IME, CAS (Fabrication)
- 8 inch wafer with 50 μm Epi. layer

Production version	Wafer No.	GL.Dose	Implantation	Layout arrays	UBMed	Diced
USTC-1.1	W7	Low (High energy)	B	Mixed	No	✅
	W8	Medium (Medimum energy)	B	Mixed	✅	✅
	W9	Medium (Ultra-high energy)	B	Mixed	✅	✅
	W10	Medium (High energy)	B	Mixed	✅	✅
	W11	Medium (High energy)	B+C	Mixed	✅	✅
USTC-2.0	W12	Low	B	Small	✅	✅
	W13	Low	B	15x15	✅	✅
	W14	High	B	Small	✅	✅
	W15	High	B	15x15	✅	✅
	W16	High	**B+10C**	Small	✅	✅
USTC-2.1	W17	Medimum	**B+1C**	Small	✅	✅
	W18	Medimum	B	15x15		✅
	W19	Medimum	**B+2C**	Small	✅	✅
	W20	Medium (High energy)	**B+C (W11 like)**	15x15	✅	✅
	W21	Medium (High energy)	**B+C (W11 like)**	Small	✅	✅

- The test results of wafers, which are circled, will be shown.

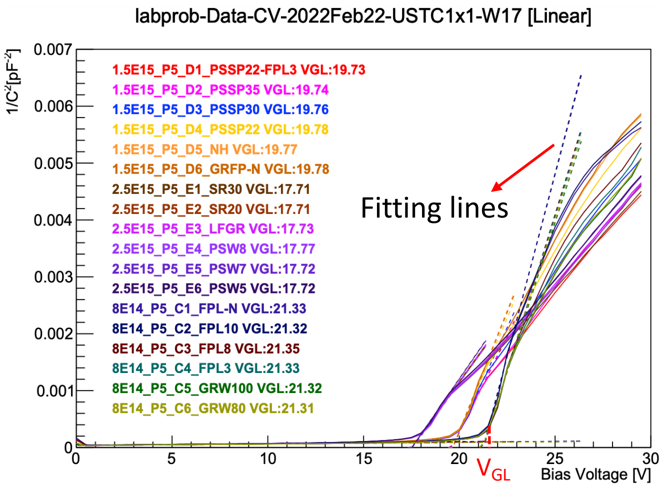
The main parameters in measurements

Experimental Techniques	Purposes	Comments
Leakage current-Voltage (IV)	Depletion voltage of gain layer ($\mathbf{V_{GL}^{I}}$)	Depletion behavior of gain layer
	Break down voltage of sensor($\mathbf{V_{BD}}$)	Safe operating voltage range (500 nA/pad @20 °C for unirradiated sensors, 5 uA/pad @-30 °C for irradiated sensors)
	Leakage current@V_x or voltage@I_x	Power consumption of circuit
	Inter pad resistance ($\mathbf{R_i}$)	Isolation between pads
Capacitance-Voltage (CV)	Depletion voltage of gain layer ($\mathbf{V_{GL}^{C}}$)	Depletion behavior of gain layer
	Full depletion voltage of the sensor ($\mathbf{V_{FD}}$)	Depletion behavior of bulk
	Electrode capacitance ($\mathbf{C_{pad}}$)	Depletion behavior of sensor
	Inter pad capacitance ($\mathbf{C_i}$)	Cross talk between pads
Beta-scope test (^{90}Sr)	Charge collection and timing resolution	appropriate operating voltage

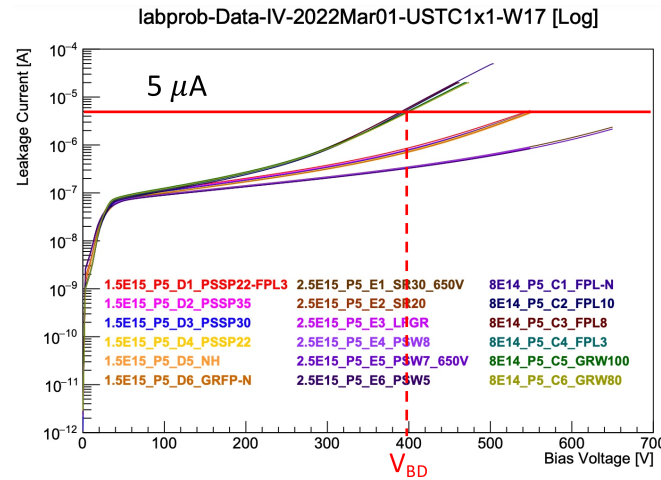
- Fitting the V_{GL} on different radiation fluences can evaluate **radiation hardness of gain layer**.
- For large array sensors, the variation of V_{GL} and V_{BD} can reflect the **uniformity**.

CV & IV results of irradiated single sensors (W17)

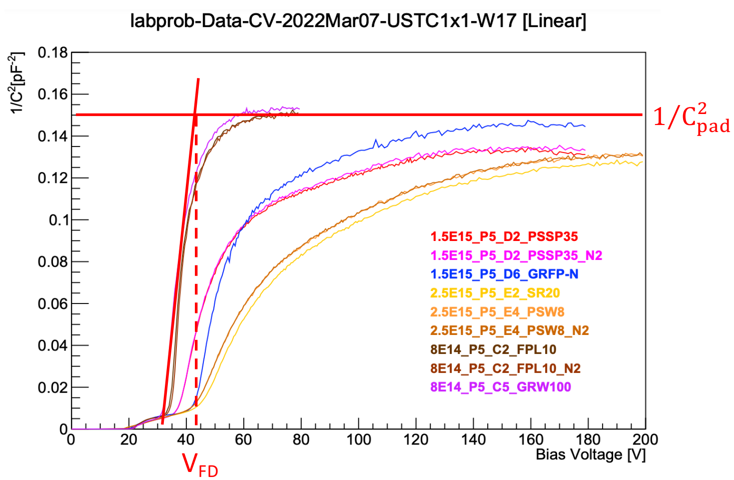
- Irradiate to 3 fluences at Jožef Stefan Institute (JSI) with **reactor neutrons.**
- Anneal for 80 minutes @60 °C and keep in the fridge (-30 °C).



Temperature: 20 $\pm$ 0.01 °C, **Frequency:** 1 kHz, **VAC:** 0.51 V, **Voltage range:** 0 – 80/180/200 V, **Voltage Step:** 0.5 V



Temperature: -30 $\pm$ 0.01 °C, **Voltage range:** 0 – 550/650 V, **Voltage step:** 3/1 V, **Compliance:** 20 μA



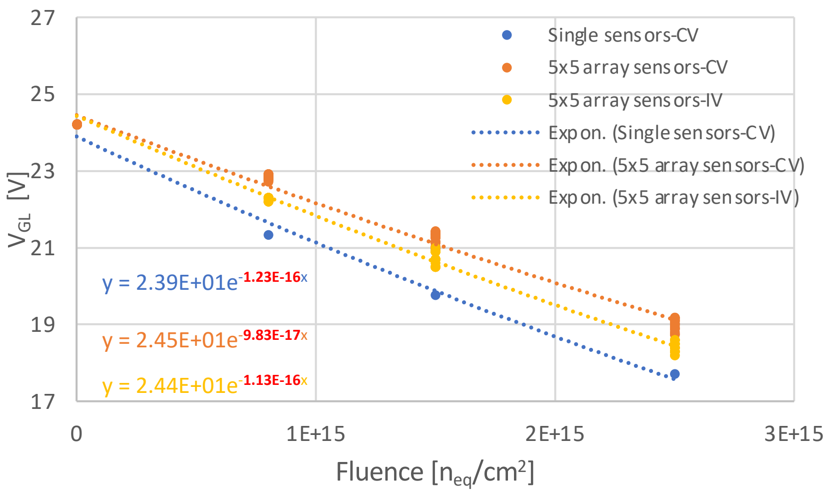
Fluence [n_{eq}/cm^2]	$\langle V_{BD} \rangle \pm$ RMS [V]	$\langle V_{GL} \rangle \pm$ RMS [V]	$\langle V_{FD} \rangle \pm$ RMS [V]	$C_{pad} \pm$ RMS [pF]
8E14	397.00 $\pm$ 3.63	21.32 $\pm$ 0.02	41.48 $\pm$ 0.29	2.57 $\pm$ 0.01
1.5E15	>550	19.76 $\pm$ 0.02	57.67 $\pm$ 2.86	2.69 $\pm$ 0.08
2.5E15	>550	17.72 $\pm$ 0.01	81.93 $\pm$ 1.71	2.79 $\pm$ 0.04

With the increase of irradiation fluence,

- V_{GL} decreases due to acceptor removal in the gain layer.
- V_{FD} increases due to acceptor creation in the bulk.

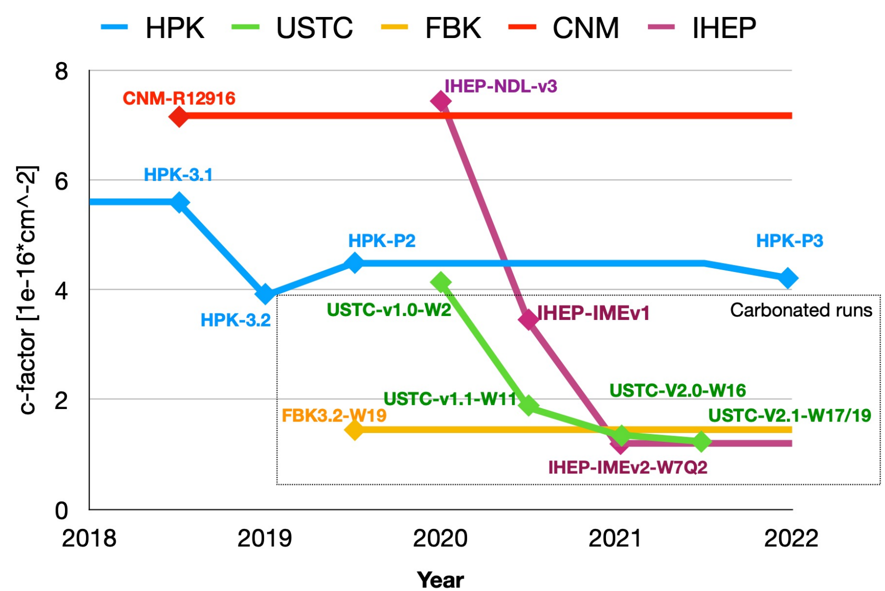
Radiation hardness evaluation

$$\frac{V_{GL}(\Phi_{eq})}{V_{GL}(0)} = \frac{N(\Phi_{eq})}{N(0)} = e^{-c\cdot\Phi_{eq}}$$



Wafer	Acceptor removal constant (c-factor) [$\times 10^{-16}$ cm^2]		
	Single sensors	5x5 array sensors	
	CV method	CV method	IV method
W17	1.23	0.98	1.13

c, acceptor removal constant (c-factor)



- c-factors are extracted from single sensors using CV method.
- Single sensors are from the most promising wafer for each vender's run.

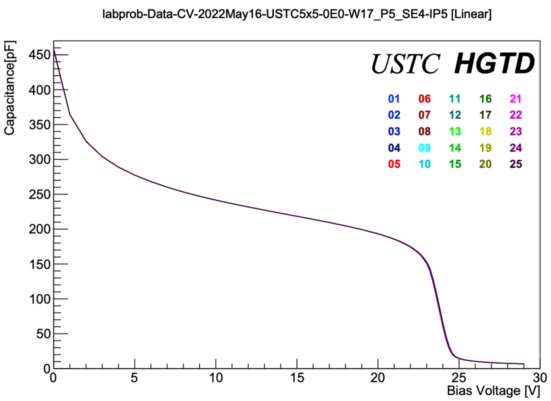
- In our previous analysis, the relative error of c-factor is within 10% (Details are in backup).
- For irradiated 5x5 array sensors, pad's (under test) capacitance can be effected by other pads' configuration → the V_{GL} from CV can be shift by about 1V which can causes the c-factor smaller.
- The small c-factor (~1.2e-16 cm^2) indicates that the carbon works well.

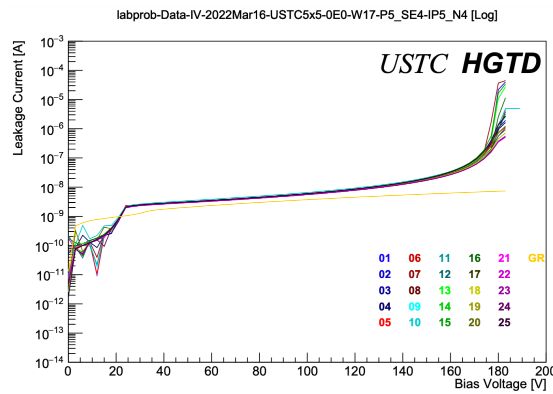
Uniformity of large array sensors

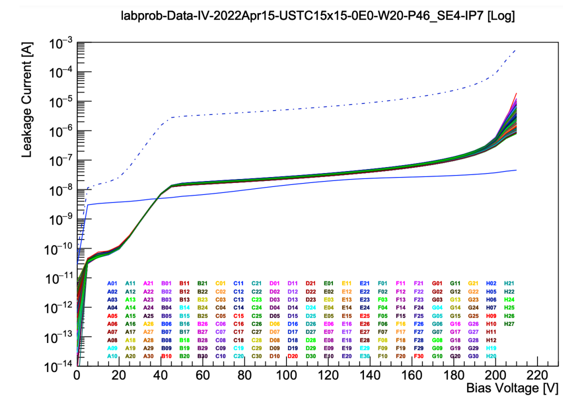
- **Tested by probe card, all pads and GR GND.**

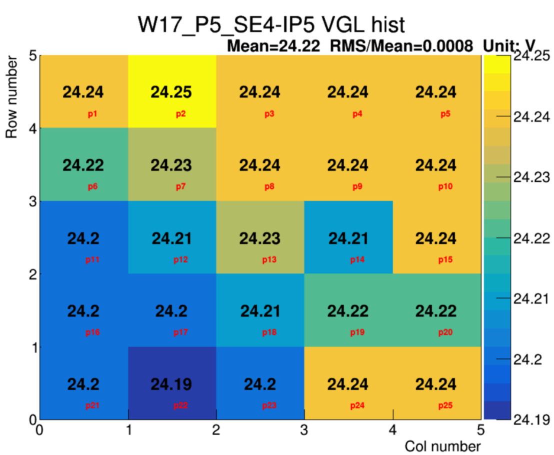
5x5 array sensor

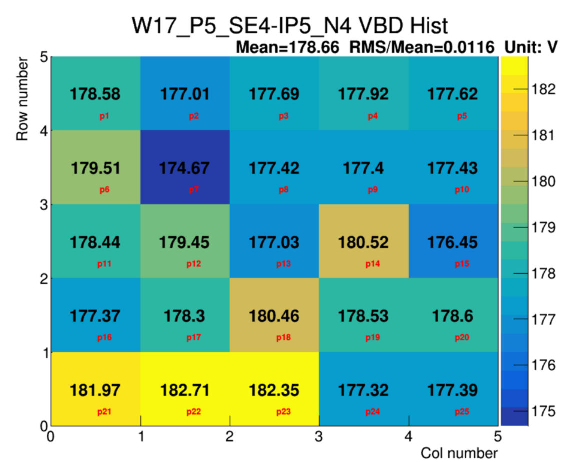
15x15 array sensor

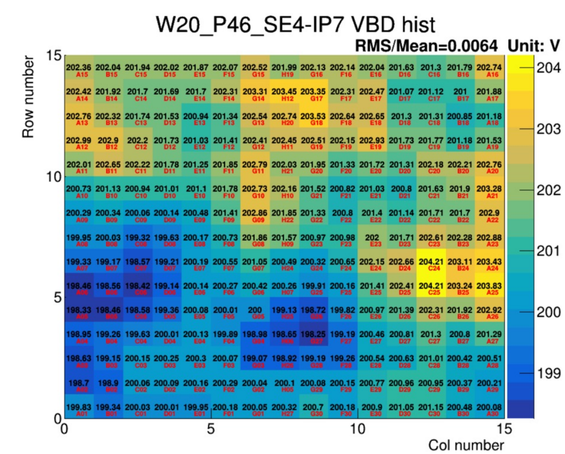








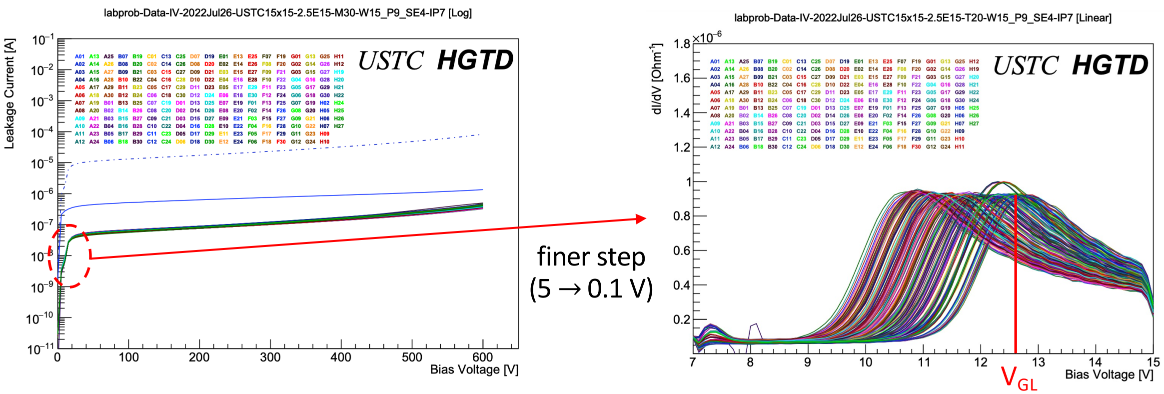


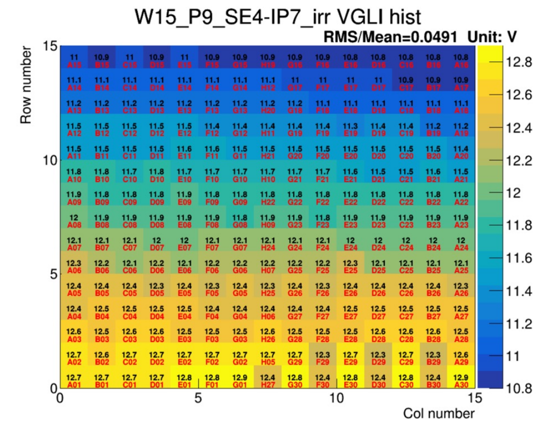


- The variation of V_{GL} and V_{BD} is smaller than 0.1% and 2%. (HGTD specification: 0.5% for V_{GL} and 5% for V_{BD}).
- The uniformity of large array sensors is very good.

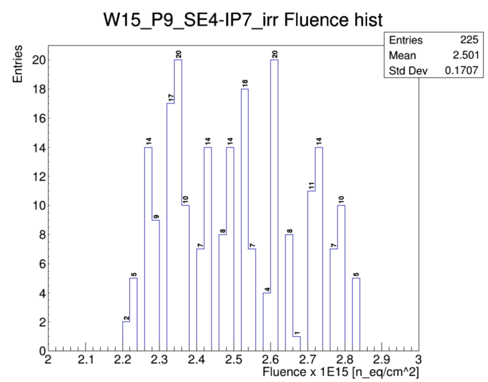
The uncertainty of irradiation fluence

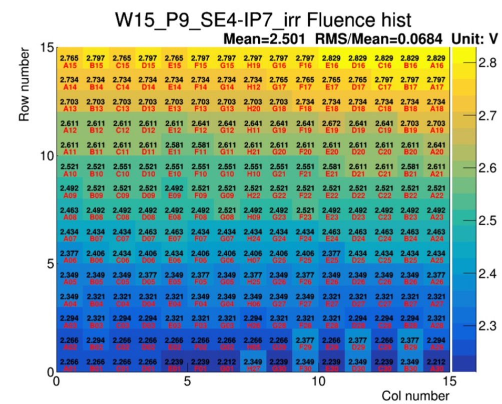
- **Tested by probe card, all pads and GR GND.**
- **Irradiation fluence (neutron):** 2.5E15 n_{eq}/cm^2, **Design**: SE4-IP7





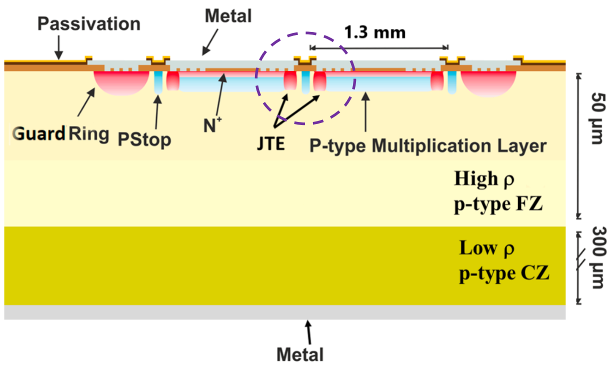
$$\frac{V_{GL}(\Phi_{eq})}{V_{GL}(0)} = e^{-c\cdot\Phi_{eq}}$$



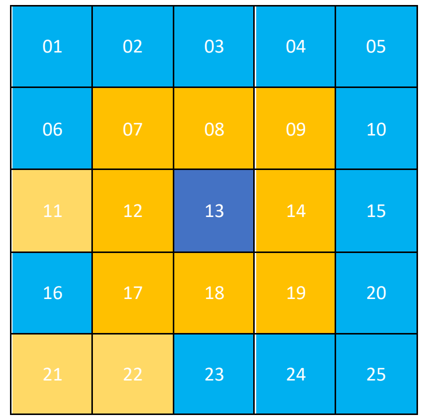


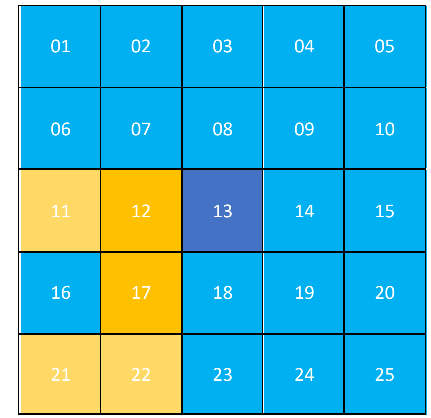
- Get the fitting function from single sensors and calculate the fluence after getting V_{GL} of each pad.
- The variation of V_{GL} become worse after irradiation probably due to the non-uniformity of irradiation fluence across the large array sensors. The relative error of fluence is about 6.8% for this sensor.

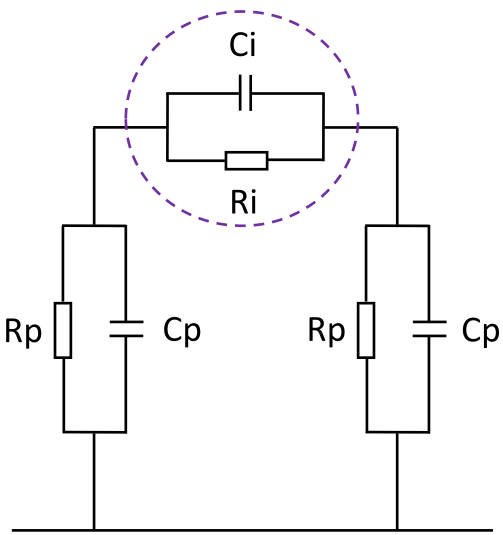
Inter-pad capacitance/resistance setup



HGTD TDR (a) Cross section of a 2 × 2 array.







- Estimate the crosstalk and isolation between pads

- ➢ **Configuration (Inter-pad capacitance):**
- **Temperature:** 20/10 °C, **Frequency:** 10/1 kHz, **VAC:** 0.51 V, **Step:** 3.0 V**,** GR and other pads GND**.**
- Applied negative high voltage to sensors' backside.
- Measured the inter-pad capacitance between the central pad (13) and the **neighboring pads** (07, 08, 09, 12, 14, 17, 18, 19).
- Also, measured the inter-pad capacitance between the central pad (13) and **next to neighboring pads** (11, 21, 22).

- ➢ **Configuration (Inter-pad resistance):**
- **Temperature:** 20 °C, **Step:** 1.0 V
- Apply negative high voltage to sensor's backside
- Apply **0 or 1 V** to pad 13's probe, GR and other pads GND.

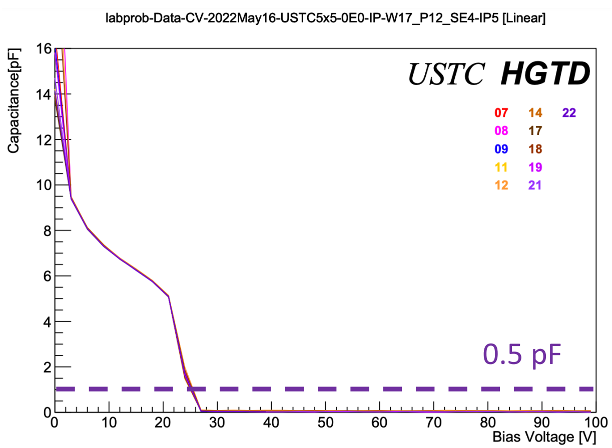
$$R_i = \frac{U_1 - U_0}{I_1 - I_0}$$

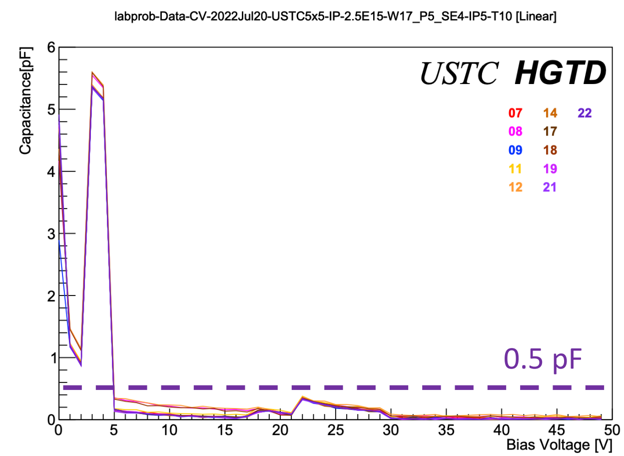
- Measured the inter-pad resistance between the central pad (13) and the **neighboring pads** (12, 17).
- Also, measured the inter-pad capacitance between the central pad (13) and **next to neighboring pads** (11, 21, 22).

Results of inter-pad capacitance/resistance (W17)

Unirradiated | **Irrradiated @2.5E15 n_{eq}/cm^2**

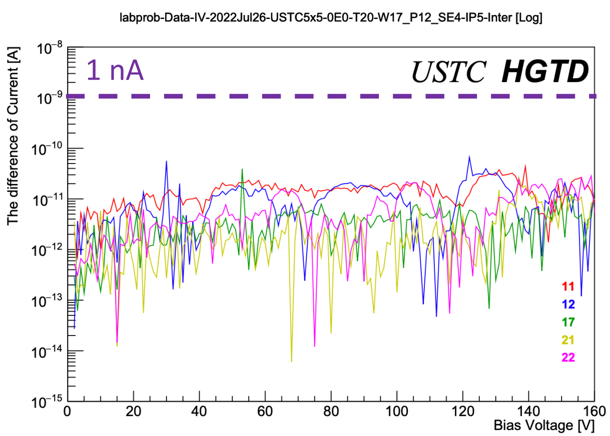
Capacitance

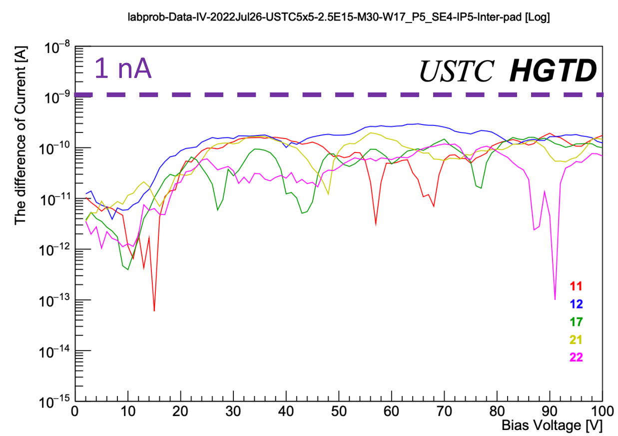




The difference of current

$$R_i = \frac{U_1 - U_0}{I_1 - I_0}$$

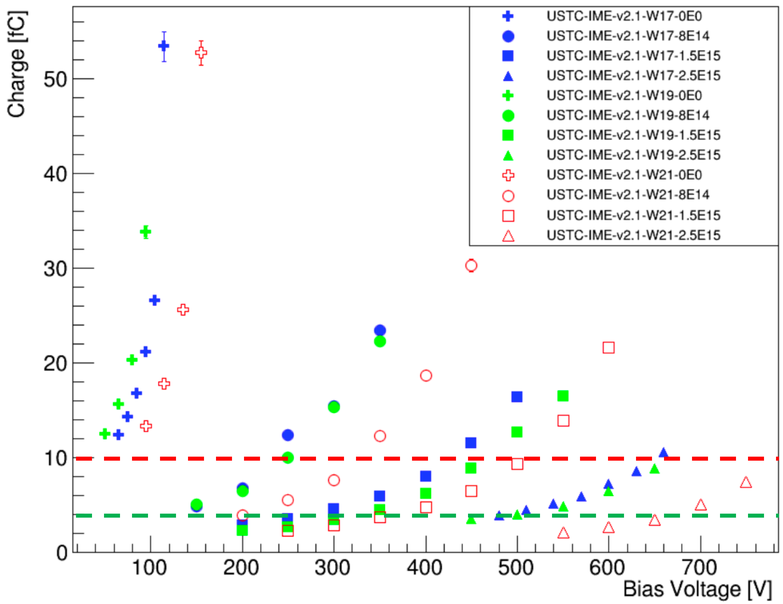


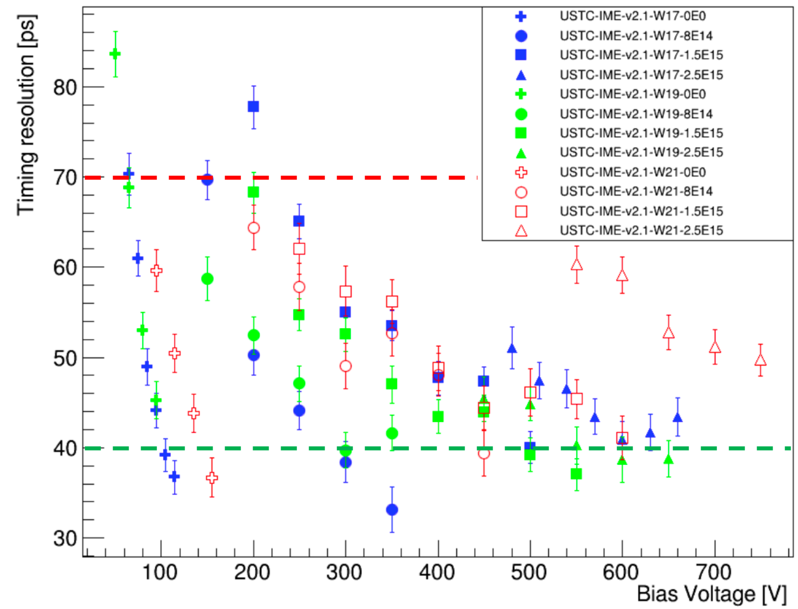


- The inter-pad capaticance can be **smaller than 0.5 pF** at appropriate bias voltage.
- The difference of current is lower than 1 nA which means that the resistance is **larger than 1 GΩ**.
- The crosstalk can be neglected and the isolation between pads is good before and after irradiation.

Charge collection and timing resolution

Beta-scope (^{90}Sr)





- Within safe bias voltage (<550 V), before (after) irradiation:
  - The charge collection of W17/W19 can be greater than 10 (4) fC.
  - The timing resolution of W17/W19 can be better than 40 (70 ps).

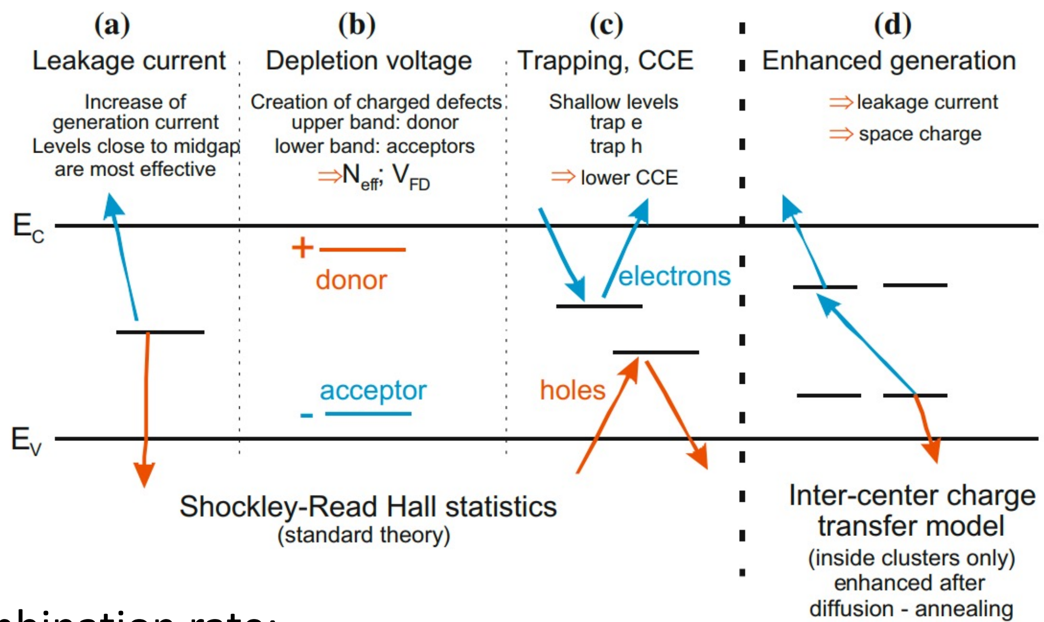
Summary

- The gain layer of W17 is **irradiation tolerant** (c-factor is 1.23e-16 cm^2, in the first class).
- The uniformity (**V_{GL} variation < 0.1%** and **V_{BD} varaition < 2%**) of large array sensors is very good (HGTD specification, 0.5% for V_{GL} and 5% for V_{BD}).
- The uniformity become worse after irradiation probably due to the non-uniformity of irradiation fluence across the large array sensors.
- The inter-pad capacitance can be **smaller than 0.5 pF** and the inter-pad resistance is **larger than 1 GΩ**.
- Beta-scope test results of W17,
  - charge collection **>10 fC** and timing resolution **< 40 ps @pre-irradiated**
  - charge collection **>4 fC** and timing resolution **< 70 ps @2.5E15 n_{eq}/cm^2**.
- These parameters of W17 all meet the HGTD specification.

Thanks for your attention!

Back up

Principle: effect of radiation



Recombination rate:

$$U = \frac{N_t r(np - n_i^2)}{n + p + 2n_i ch(\frac{E_t - E_i}{k_0 T})}$$

Current density:

$$J_g = qWU$$

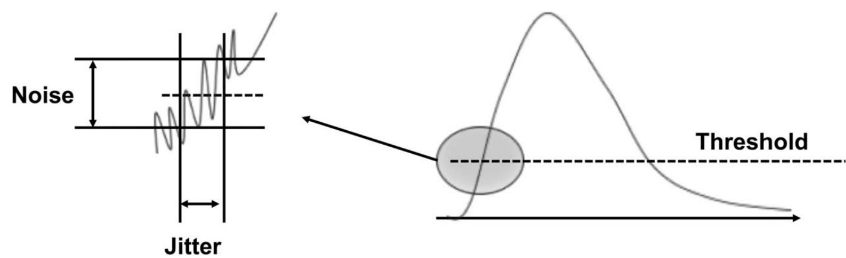
N_t: the concentration of the recombination center in the recombination energy level, n/p: number of e/hole in conductive/valence band, N_t: recombination energy, N_i: fermi energy,

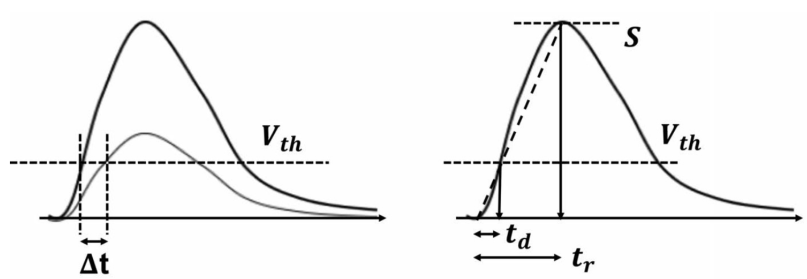
Principle: time resolution

$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Ionization}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2. \quad (2.12)$$

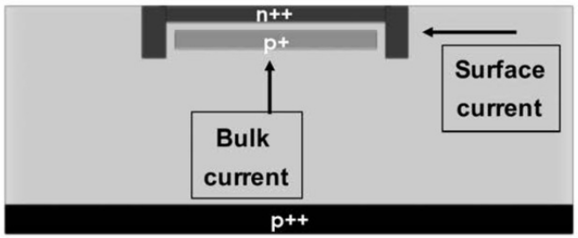
Each of these four terms influences when the signal crosses the discriminator threshold V_{th}. The underlying reason for each of them is:

1. σ_{Jitter}: electronic noise;
2. $\sigma_{\text{Ionization}}$: irregularity in the signal shape due to non-uniform energy deposition by the impinging particle. This effect is called Landau noise;
3. $\sigma_{\text{Distortion}}$: signal distortion due to non-saturated drift velocity of charge carriers and non-uniform weighting field;
4. σ_{TDC}: the uncertainty due to the finite size of the TDC bin.





Principle: noise



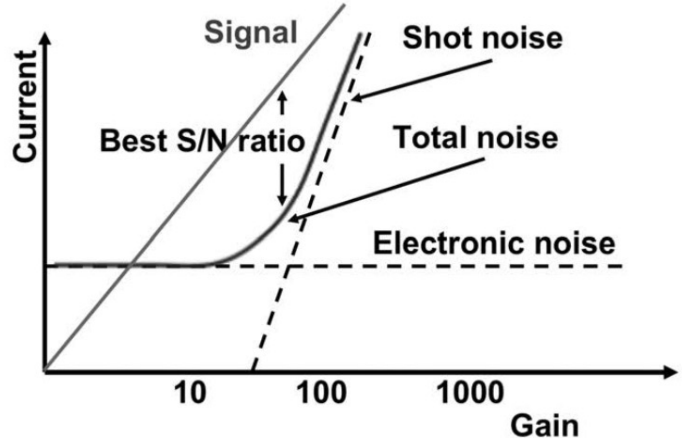


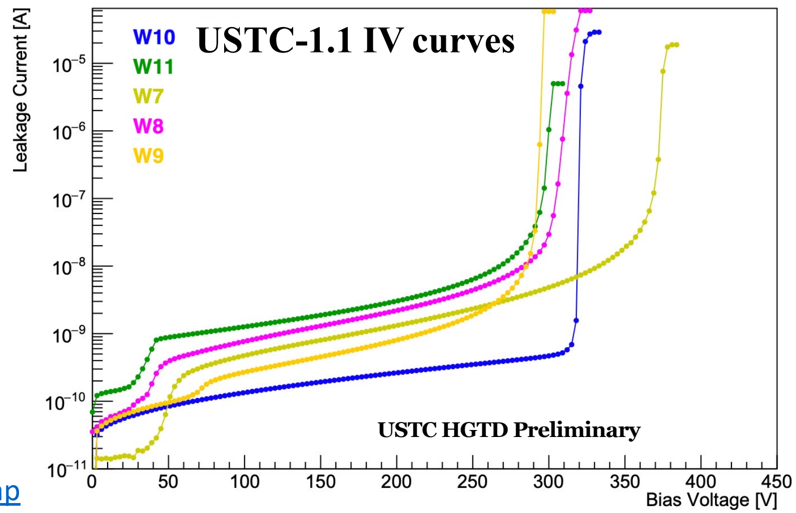
Figure 2.8 *Left*: schematic representation of a UFSD, with the localization of the bulk and of the surface leakage currents. *Right*: signal and shot noise growth as a function of the sensor internal gain.

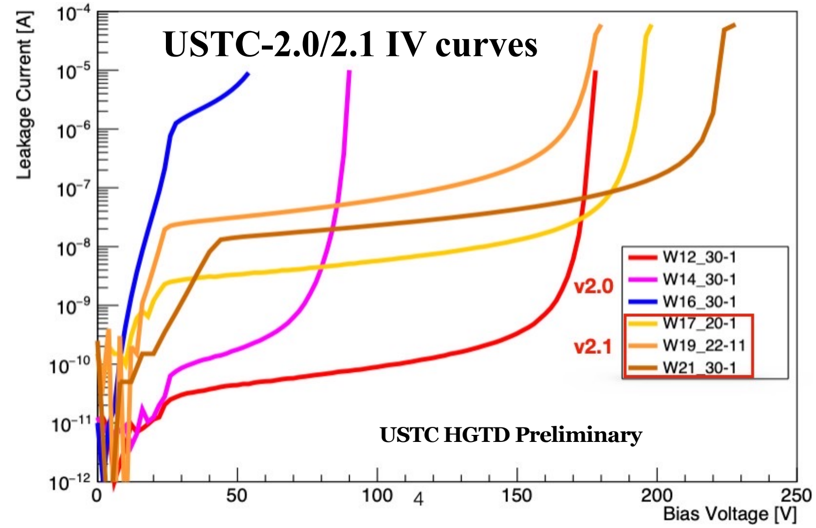
$$\mathrm{SNR} = \frac{IG}{\sqrt{2q(I_{\mathrm{surface}} + I_{\mathrm{bulk}} G^2 F)\Delta f}} \propto \frac{1}{\sqrt{F}}.$$

Experimental techniques for LGADs

Experimental Techniques	Purposes	Comments
Leakage current-Voltage (IV)	Gain layer depletion voltage ($\mathbf{V_{GL}^{I}}$)	Doping information of gain layer
	Device break down voltage ($\mathbf{V_{BD}}$)	Safe operating voltage range
	Leakage current@V_x or voltage@I_x	Power consumption of circuit
	Inter pad resistance	Isolation between pads
Capacitance-Voltage (CV)	Gain layer depletion voltage ($\mathbf{V_{GL}^{C}}$)	Depletion behavior of gain layer
	Full depletion voltage of the device ($\mathbf{V_{FD}}$)	Depletion behavior of bulk
	Electrode capacitance ($\mathbf{C_{pad}}$)	Depletion behavior of sensor
	Inter pad capacitance	Cross talk between pads
Beta-scope test (^{90}Sr)	Voltage required to collect 15 fC (**V15fC**)	Voltage required to collect 15 fC at -30°C
	Minimum operation voltage ($\mathbf{V_{op,min}}$)	S/N>10, V>4fC, noise < 1.2 noise at low bias, no ghosts, I<500nA/5μA
	Maximum operation voltage ($\mathbf{V_{op,max}}$)	The above conditions can be met
	Time resolution at 4fC (**τ4fC**)	Time resolution at $V_{op,min}$
Transient Current Technology (TCT, laser)	The no-gain distance between two adjacent pads (**Effective IP width**)	No-gain area where collected charge is less than 50%*Max (collected charge)
Test Beam (TB, proton or electron or ···)		
	Hit efficiency	
	Charge collection and timing resolution	

USTC-IME LGADs overview

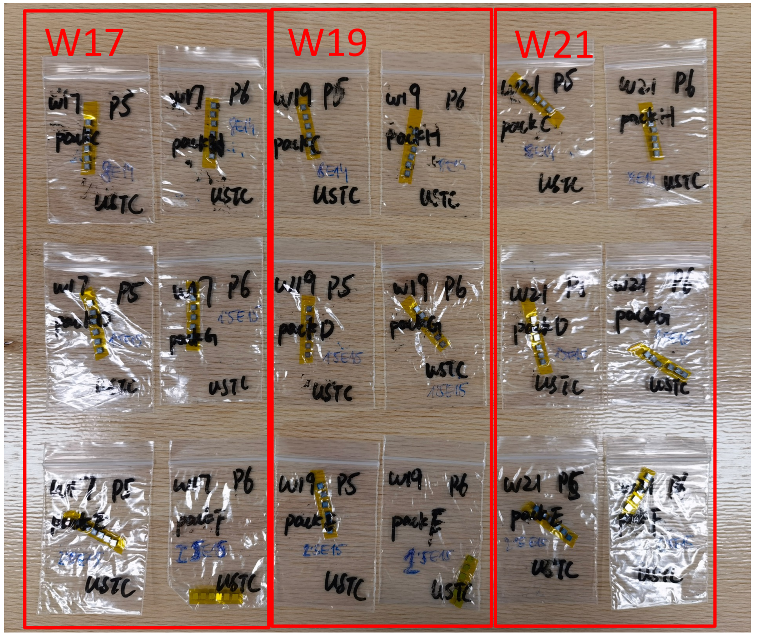


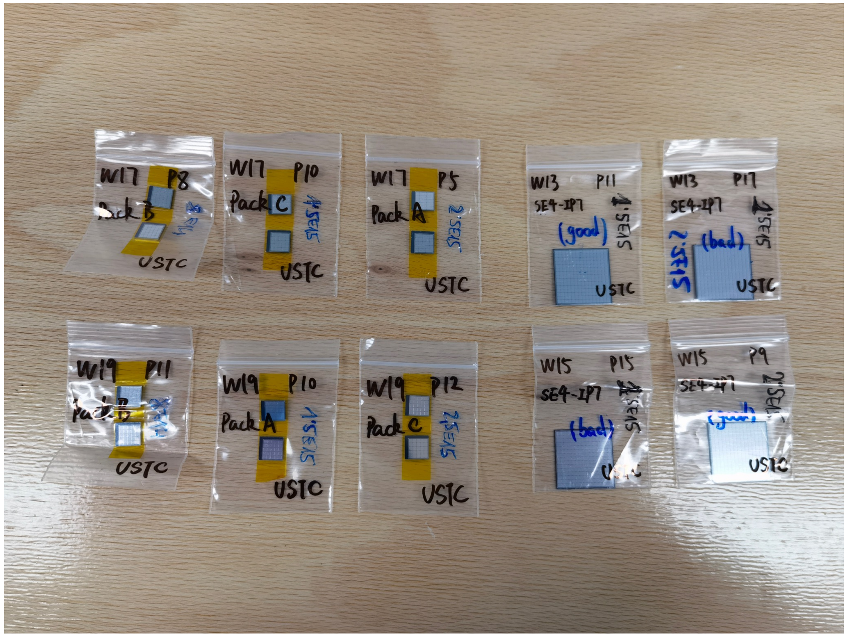


roadmap

Production version	Wafer No.	GL.Dose	Implantation	Layout arrays	VBD_medium	UBMed	Diced	c-factor [1e-16*cm^2]
USTC-1.1	W7	Low (High energy)	B	Mixed	~370	No	✅	5.79
	W8	Medium (Medimum energy)	B	Mixed	~295	✅	✅	4.12
	W9	Medium (Ultra-high energy)	B	Mixed	~295	✅	✅	7.25
	W10	Medium (High energy)	B	Mixed	~320	✅	✅	5.72
	W11	Medium (High energy)	B+C	Mixed	~300	✅	✅	1.85
USTC-2.0	W12	Low	B	Small	~174	✅	✅	~3.66
	W13	Low	B	15x15	~172	✅	✅	
	W14	High	B	Small	~84	✅	✅	~3.38
	W15	High	B	15x15	~100	✅	✅	
	W16	High	B+10C	Small	~50	✅	✅	~1.36 -1.49
USTC-2.1	W17	Medimum	B+1C	Small	~190	✅	✅	~1.23
	W18	Medimum	B	15x15	~190		✅	
	W19	Medimum	B+2C	Small	~165	✅	✅	~1.31
	W20	Medium (High energy)	B+C (W11 like)	15x15	~220	✅	✅	
	W21	Medium (High energy)	B+C (W11 like)	Small	~215	✅	✅	~2.15

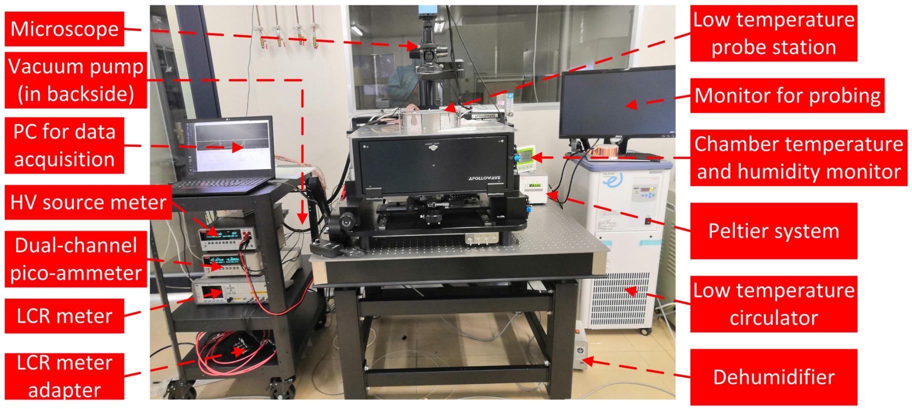
Irradiated campaigns (USTC-IME v2.x)

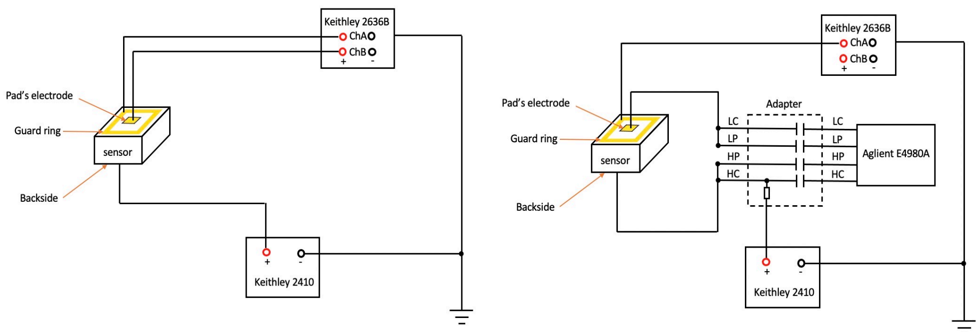


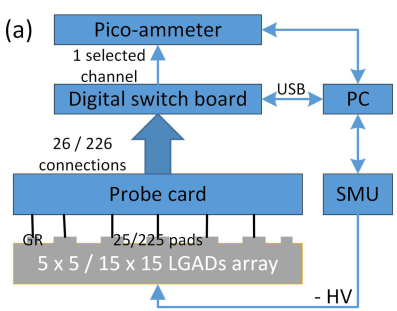


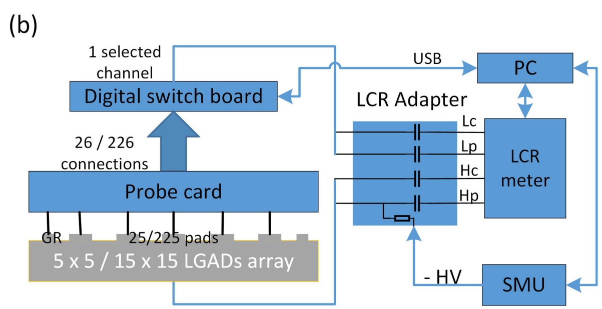
- Irradiated to 3 fluences at Jožef Stefan Institute (JSI) with reactor **neutrons.**
- Annealed for 80 minutes @60 ^{o}C, then kept in the fridge (-30 ^{o}C).
- For 5x5 array sensors, annealing probably has happened during shipment (~ 40 ^{o}C for 7 days) and parameters we extracted are close before and after standard annealing (80min@60^{o}C for LGADs) [link]. So we didn't anneal sensors except 5x5 array sensors of W19 which were annealed before annealing studies.

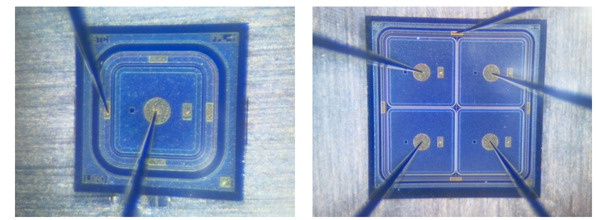
IV & CV setup



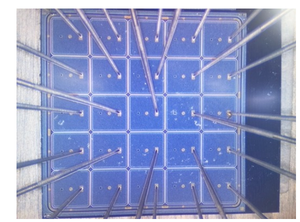








Tested by probe needles



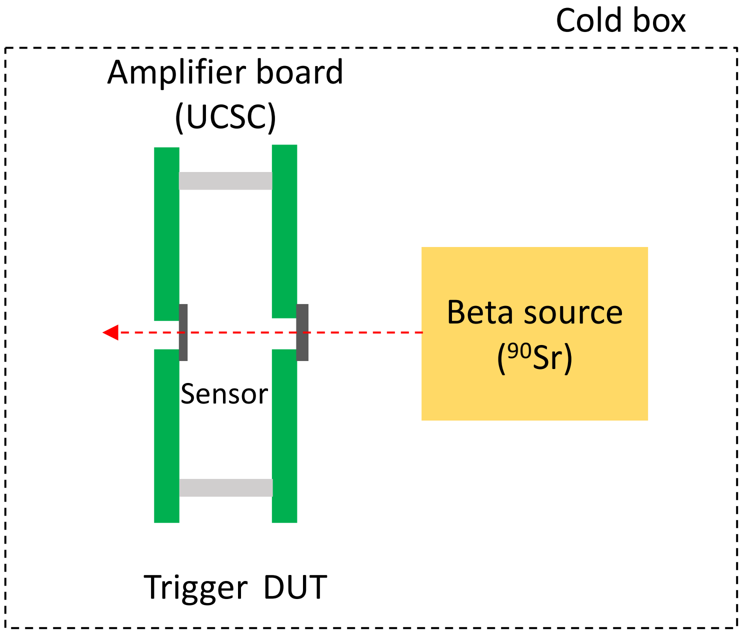
Tested by probe card

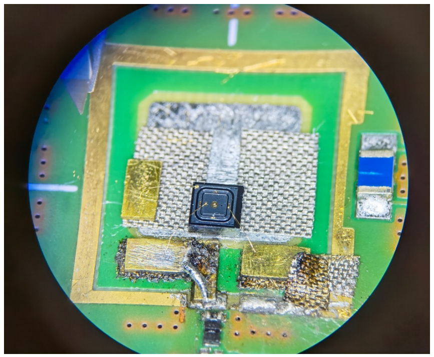
J.J. Ge, NIMA, 2021

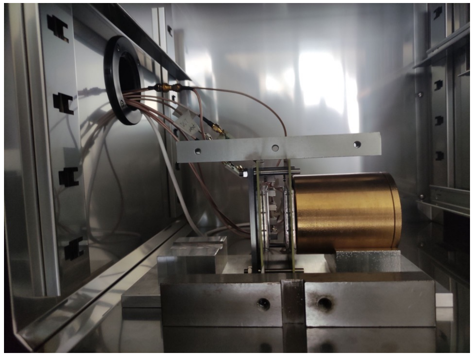
β- scope setup

C.H. Li, NIMA, 2022

- Temparetrue: -30 °C
- Trigger
  - Sensor (HPK Type1.1, un-irradiated) & Pre-amplifier board
  - With the 2nd stage amplifier
  - Bias: -165.00 V
  - σ_t: 33.88 ps
- DUT (Device Under Test)
  - Sensor & Pre-amplifier board
  - With the 2nd stage amplifier
- Oscilloscope
  - Sampling rate: 20 Gs/s
  - Bandwidth: 1 GHz







The uncertainties on c-factor

Assume the error of V_{GL}:

$$\sigma_{total}^2 = \begin{cases} (\overline{V_{GL}^I} - \overline{V_{GL}^C})^2 + ([V_{GL}^I]_{RMS})^2, & for\ irradiated\ sensors \\ ([V_{GL}^C]_{RMS})^2, & for\ unirradiated\ sensors \end{cases}$$

Fitting model:

$$ln\frac{V_{GL}(\Phi)}{V_{GL}(0)} = -c \cdot \Phi$$

$$\begin{cases} y = ln\frac{V_{GL}(\Phi)}{V_{GL}(0)} \\ x = \Phi \end{cases}$$

Definition of the Chi2:

$$\chi^2 = (y_1 - bx_1 \quad y_2 - bx_2 \quad y_1 - bx_2)\Sigma^{-1}\begin{pmatrix} y_1 - bx_1 \\ y_2 - bx_2 \\ y_3 - bx_3 \end{pmatrix}$$

*$b = -c$

*Σ: error matrix

Error matrix:

$$\Sigma_{ij} = Cov[(y_i - bx_i)(y_i - bx_i)] = E\big[(y_i - bx_i - \bar{y_i} + b\bar{x_i})\big(y_j - bx_j - \bar{y_j} + b\bar{x_j}\big)\big]$$

$i = j$: $\sigma_{y_i}^2 + b^2\sigma_{x_i}^2$

$$i \neq j: \begin{cases} \sigma_{\ln V_{GL}(0)}^2 + b^2\sigma_{x_i}\sigma_{x_j}, & \sigma_{x_i}\ and\ \sigma_{x_J}\ are\ correlated \\ \sigma_{\ln V_{GL}(0)}^2, & \sigma_{x_i}\ and\ \sigma_{x_J}\ are\ not\ correlated \end{cases}$$

Correlation in c-factor fitting model

W12		Ignore correlation	Consider correlation $\sigma_{\ln V_{GL}(0)}$, σ_{x_i} *and* σ_{x_j}	Consider correlation $\sigma_{\ln V_{GL}(0)}$
$\frac{\Delta\Phi}{\Phi} = 0\%$	c-factor	3.138 ± 0.128	3.084 ± 0.158	3.084 ± 0.158
	chi2/ndof	0.362	0.720	0.720
$\frac{\Delta\Phi}{\Phi} = 5\%$	c-factor	3.150 ± 0.160	3.084 ± 0.221	3.125 ± 0.193
	chi2/ndof	0.265	0.720	0.416
$\frac{\Delta\Phi}{\Phi} = 10\%$	c-factor	3.166 ± 0.228	3.084 ± 0.347	3.159 ± 0.256
	chi2/ndof	0.148	0.720	0.185

W16		Ignore correlation	Consider correlation $\sigma_{\ln V_{GL}(0)}$, σ_{x_i} *and* σ_{x_j}	Consider correlation $\sigma_{\ln V_{GL}(0)}$
$\frac{\Delta\Phi}{\Phi} = 0\%$	c-factor	1.445 ± 0.088	1.429 ± 0.088	1.429 ± 0.088
	chi2/ndof	0.021	0.031	0.031
$\frac{\Delta\Phi}{\Phi} = 5\%$	c-factor	1.447 ± 0.104	1.429 ± 0.114	1.436 ± 0.120
	chi2/ndof	0.018	0.031	0.024
$\frac{\Delta\Phi}{\Phi} = 10\%$	c-factor	1.452 ± 0.136	1.429 ± 0.168	1.446 ± 0.164
	chi2/ndof	0.012	0.031	0.015

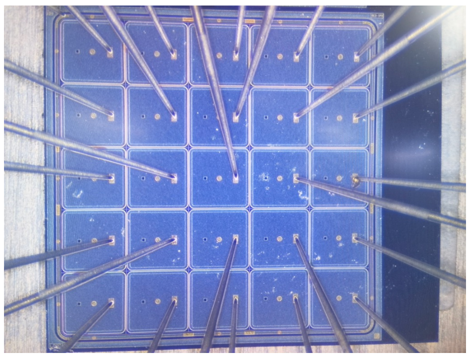
Wafer	Fluence (n_{eq}/cm^{-2})	$<V_{gl}>$ (V)		σ_{total} (V)	
		CV	IV	σ^{CV}_{total}	σ^{IV}_{total}
W12	0E0	24.490	/	0.485	/
	8E14	18.464	18.720	0.084	0.269
	1.5E15	15.796	15.500	0.116	0.336
	2.5E15	11.653	11.183	0.192	0.520
W16	0E0	26.275	25.600	0.550	0.675
	8E14	23.358	24.433	0.278	1.131
	1.5E15	21.043	22.083	0.567	1.203
	2.5E15	18.356	19.700	0.261	1.359

Wafer	V_{gl} sources	$\Delta\Phi/\Phi$	c-factor (cm² x1E-16)	σ_c/c
W12	$V^{C}_{gl}(0)$ & $V^{I}_{gl}(\Phi)$	5 %	3.125 ± 0.193	6.176 %
W16	V^{C}_{gl}	5 %	1.436 ± 0.120	8.357 %

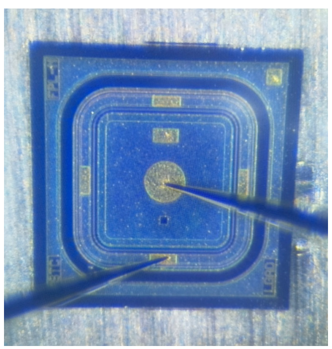
Comparison of V_{GL}^{C} from 5x5 and single sensors

- **Configuration: Temperature:** 20 °C, **Frequency:** 1 kHz, **VAC:** 0.51 V, **GR grounded.**

Pictures

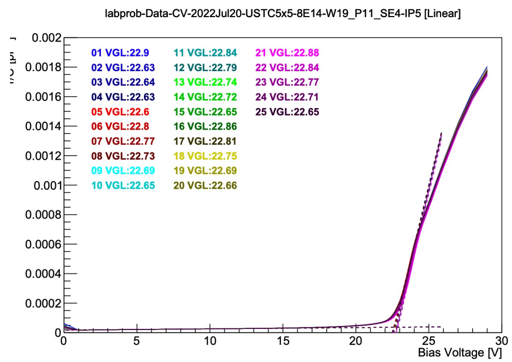


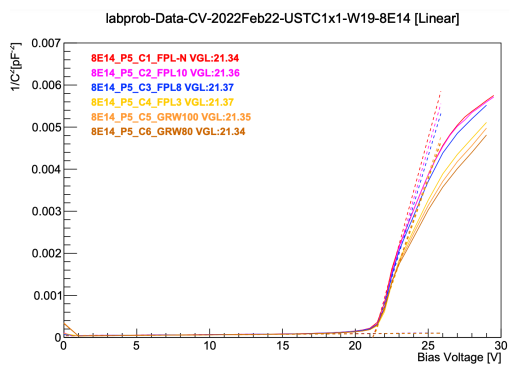
One 5x5 sensor: 25 pads



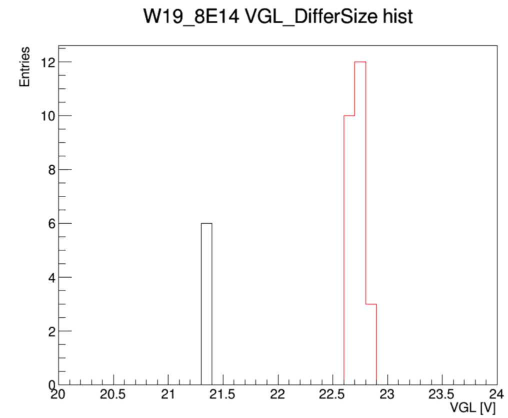
One single sensor *6

1/C²-V curves





V_{GL} comparison



Black histograms:

V_{GL} extracted from single sensors

Mean: 21.36 V, RMS: 0.0138 V

Red histograms:

V_{GL} extracted from 5x5 sensors

Mean: 22.72 V, RMS: 0.0618 V

$V_{GL,5\times5}^{C} - V_{GL,1\times1}^{C} \sim 1.4$ V, possible reasons:

- Circuit's difference (probe card, switch board)
- Sensor's difference (neighboring pads…)
- Configuration's difference (step around V_{GL}, 0.5 V for single sensors and 0.2 V for 5x5 sensors…)
- Irradiation fluence uncertainty
- ……

Comparison of V_{GL}^{C} with different configurations

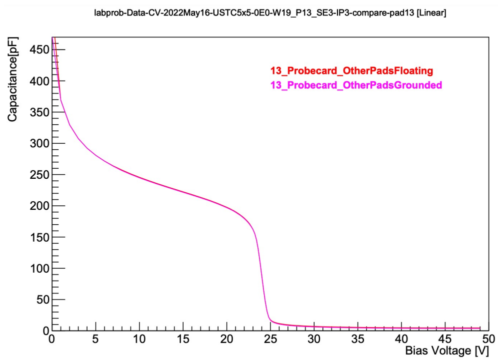
[Comparison of probecard and probeneedles: Xiangxuan, 7th CLHCP, Nov 26th, 2021.]

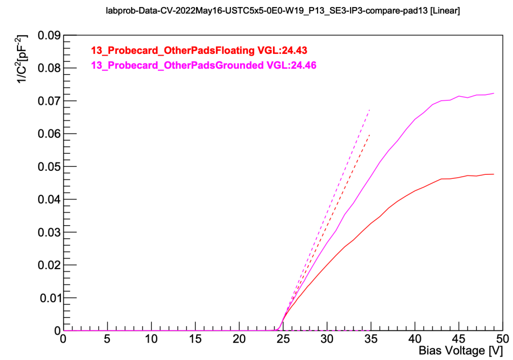
- **Configuration:**
- **Temperature:** 20 °C, **Frequency:** 1 kHz, **VAC:** 0.51 V, **Step:** 1.0 V/0.2 V, **GR grounded.**
- **Probecard**: Other Pads Grounded (standard method) **or** Other Pads Floating, **Probeneedles**: Other Pads Floating.

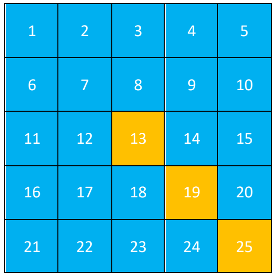
CV curves

1/C²-V curves

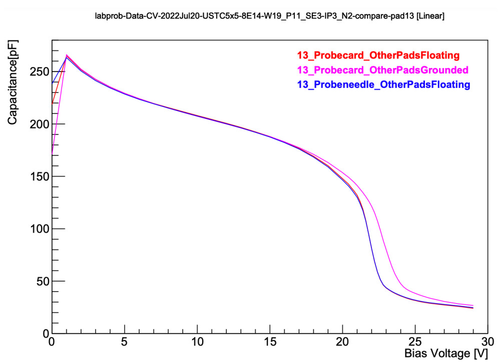
Unirradiated

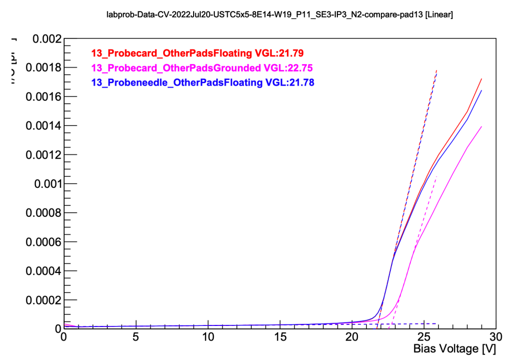






Irradiated

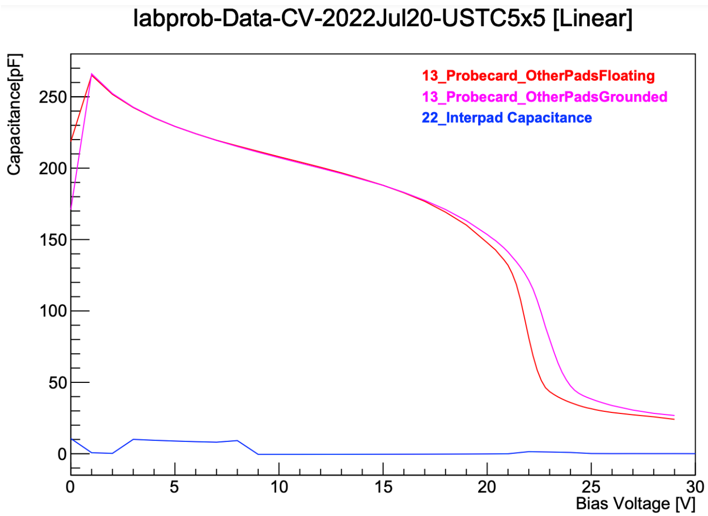


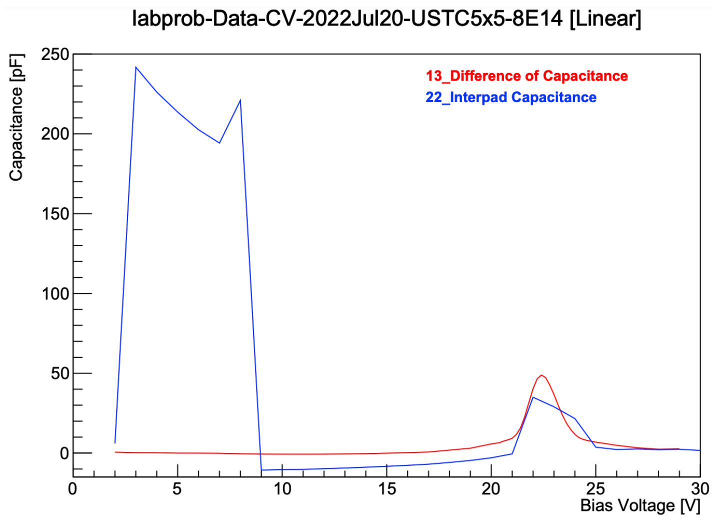


Sensor	V_{GL} [V]	Pad	Probecard_ OtherPadsGrounded	Probecard_ OtherPadsFloating	Probeneedles_ OtherPadsFloating
Unirradiated	V_{GL}^{C}	13	24.43	24.46	/
		19	24.42	24.45	/
		25	24.42	24.44	/
Irradiated	V_{GL}^{C}	13	22.75	21.79	21.78
		19	22.64	21.77	21.77
		25	22.61	21.75	21.76

- Three pads of different location were measured. The results of pad 19 and pad 25 are in backup.
- For irradiated sensors, the measured capacitance is increased when other pads are grounded -> the V_{GL}^{C} can be shifted by about 1V.

Bump on the inter-pad capacitance vs bias curves





- Difference of Capacitance is equal to (Capacitance with Other Pads Grounded - Capacitance with Other Pads Floating).
- The inter-pad capacitance between pad 13 and pad 22 multiplies by a factor of 24 to increase the visibility.
- The peak in the difference of pad 13's capacitance and the bump on the inter-pad capacitance vs bias curves occur at nearly the same bias voltage.

Comparison of V_{GL}^{I} with different configurations

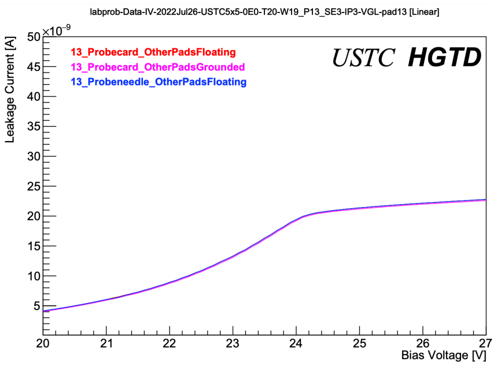
➢ **Configuration:**

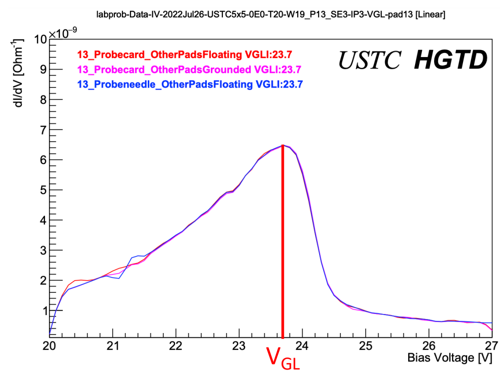
- **Temperature:** 20 °C, **Step:** 0.1 V, **GR grounded**.
- **Probecard**: Other Pads Grounded (standard method) **or** Other Pads Floating, **Probeneedles**: Other Pads Floating.

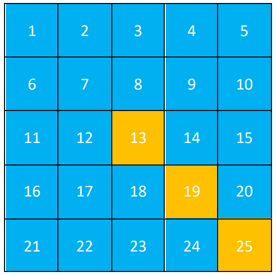
IV curves

dI/dV-V curves

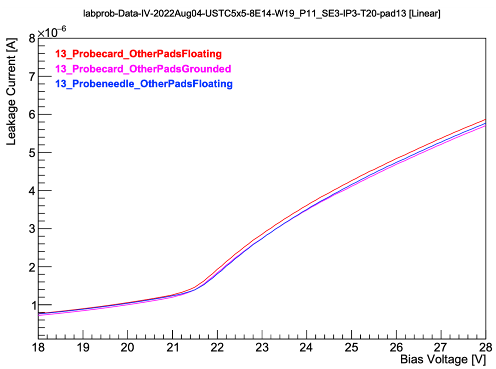
Unirradiated

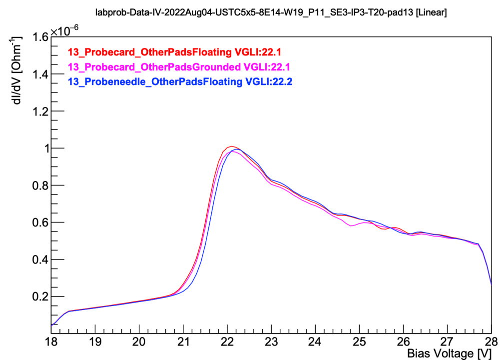






Irradiated





- Here we can extract V_{GL}^{I} from unirradiated sensors due to the higher current in carboned sensors.
- Three pads of different location were measured. The results of pad 19 and pad 25 are in backup.
- For both unirradiated and irradiated sensors, the V_{GL}^{I} is almost the same.

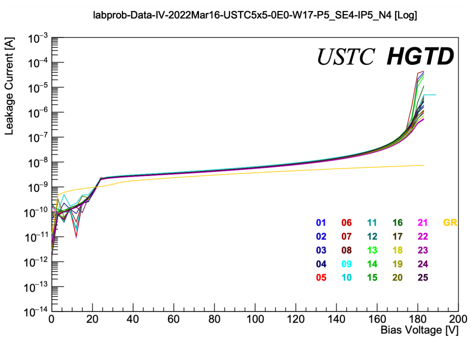
Sensor	V_{GL} [V]	Pad	Probecard_ OtherPadsGrounded	Probecard_ OtherPadsFloating	Probeneedles_ OtherPadsFloating
Unirradiated	V_{GL}^{I}	13	23.7	23.7	23.7
		19	23.7	23.7	23.7
		25	23.7	23.7	23.7
Irradiated	V_{GL}^{I}	13	22.1	22.1	22.2
		19	22.0	22.0	22.0
		25	22.1	22.1	22.2

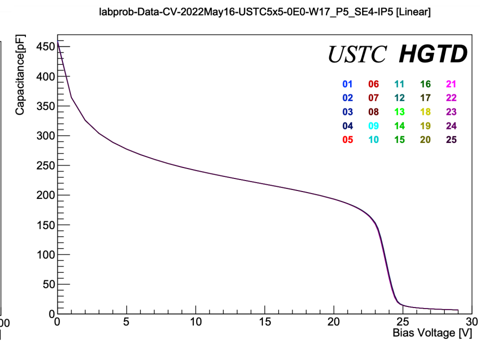
Uniformity of 5x5 array sensors (W17)

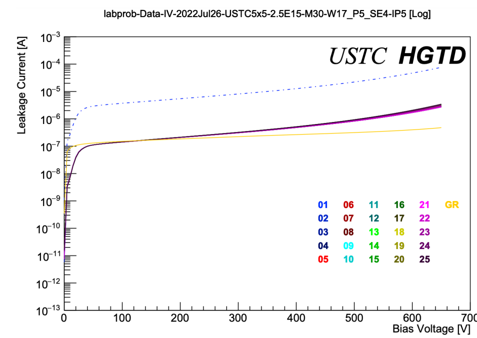
➢ **Tested by probe card, all pads and GR GND.**

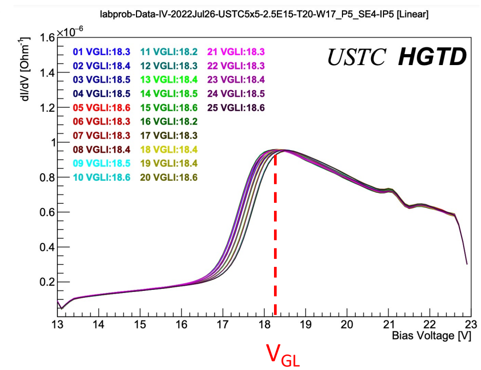
Unirradiated

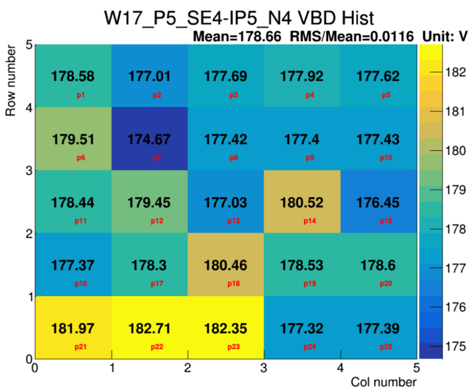
Irradiated @2.5E15 n_{eq}/cm^2

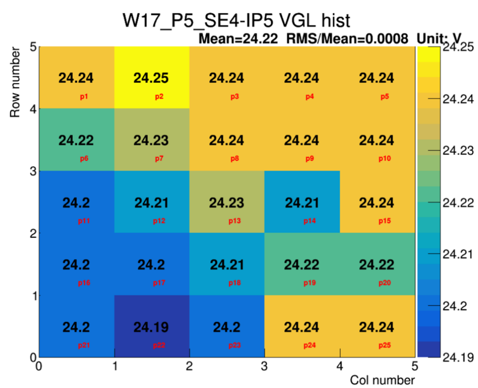


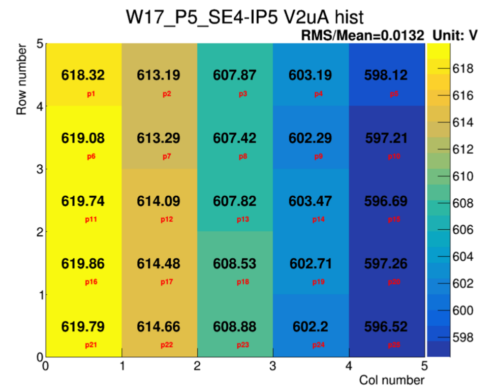


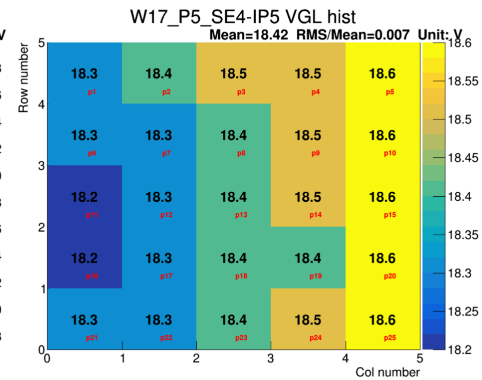










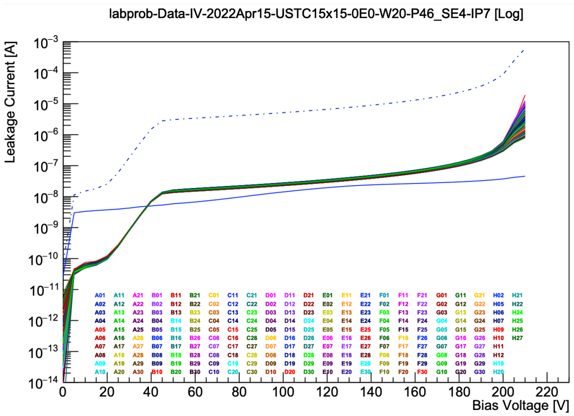


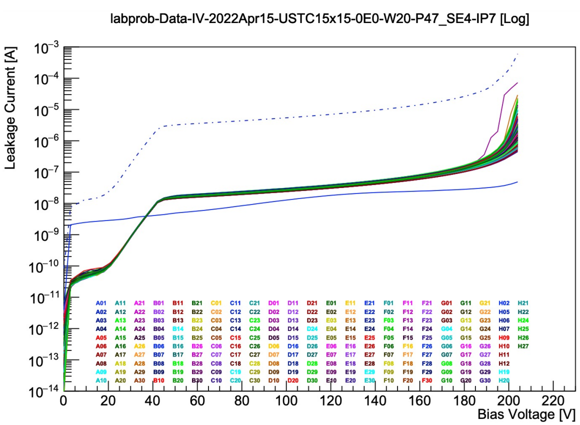
- The variation of V_{GL} and V_{BD} is smaller than 0.1% and 2%. (HGTD specification: 0.5% for V_{GL} and 5% for V_{BD}).
- The variation of V_{GL} and V_{BD} become worse after irradiation probably due to the non-uniformity of irradiation fluence across the large array sensors.

IV measurements of unirradiated full-size sensors (W20)

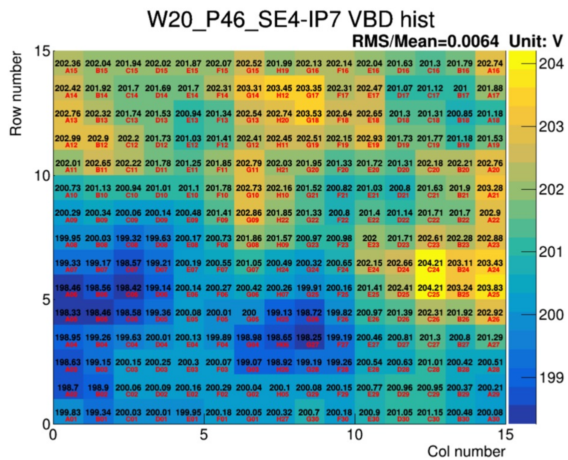
- **Configuration: Temperature:** 20 °C, **Step:** 3.0 V, **Compliance:** 600 uA, **By probe card.**

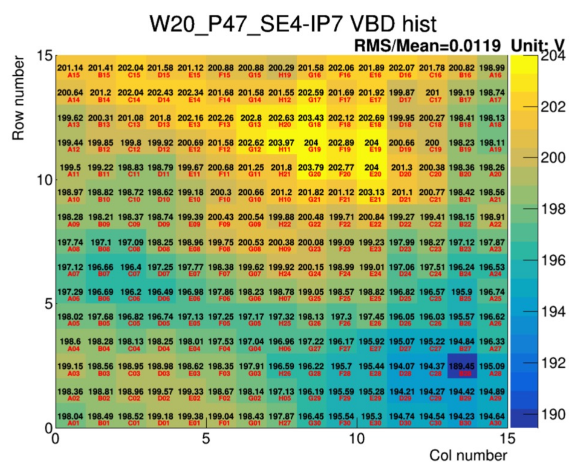
IV results



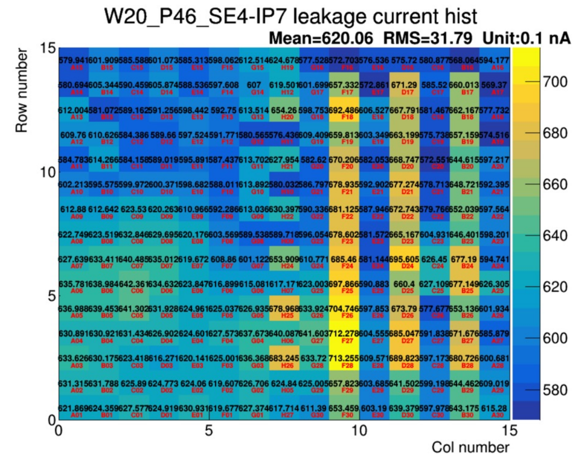


V_{BD} distribution

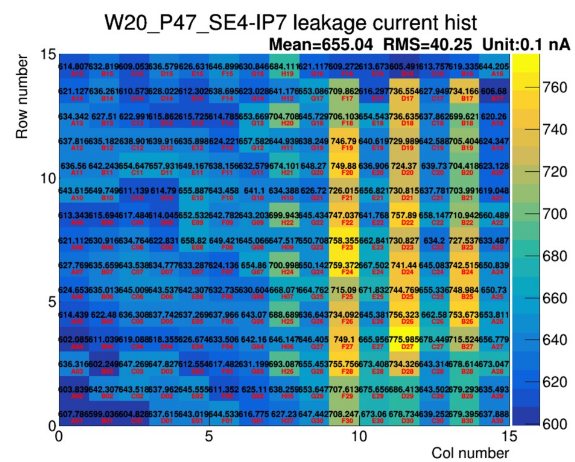




$I@0.8V_{BD}$ distribution



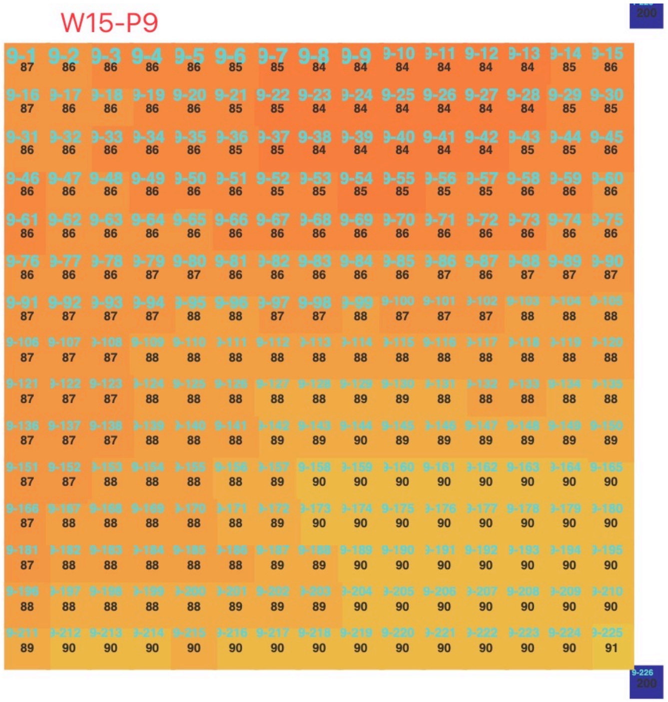
Max/Min($I@0.8V_{BD}$) = 1.26 (<3)

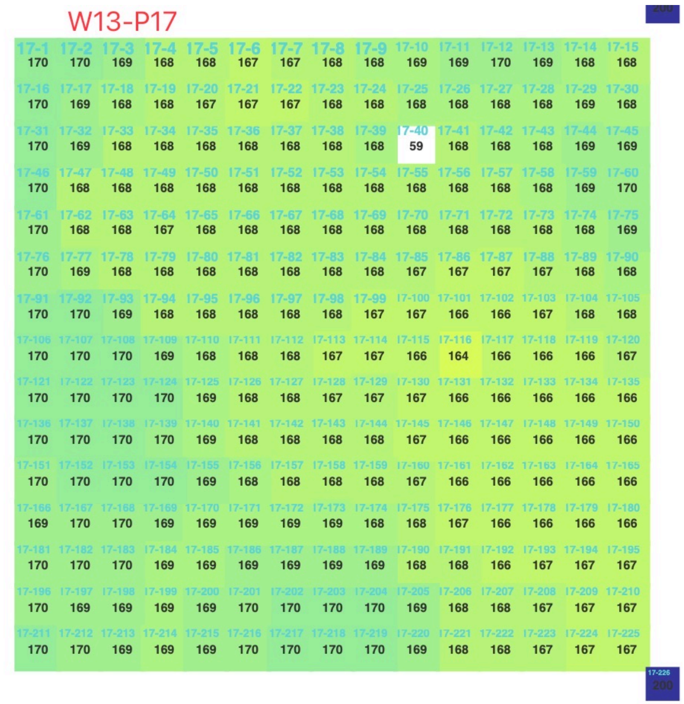


Max/Min($I@0.8V_{BD}$) = 1.30 (<3)

IV measurements of 15x15 sensors @R.T.

- **On wafer level test before irradiation.** [Xiao, Sensor Meeting, Oct 11st, 2021]

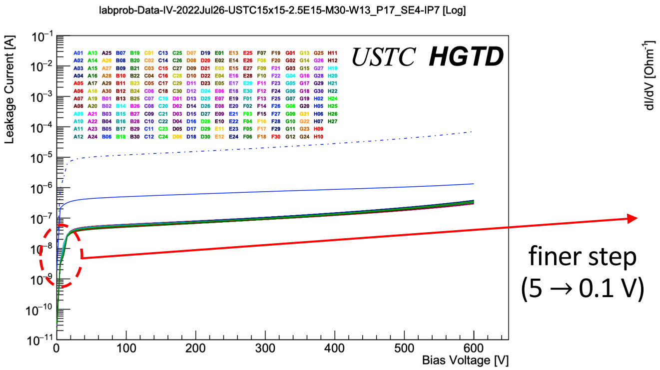


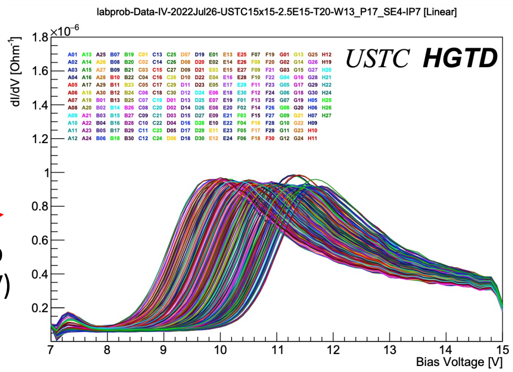


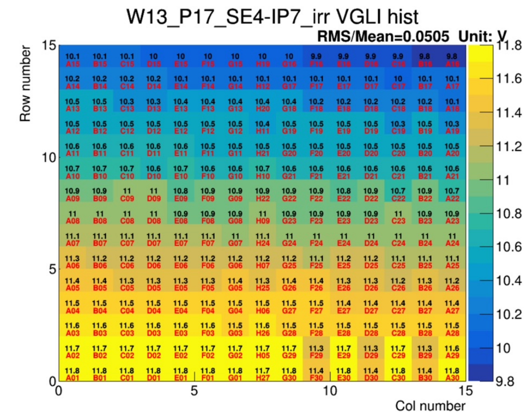
IV results of irradiated 15x15 array sensors (W13)

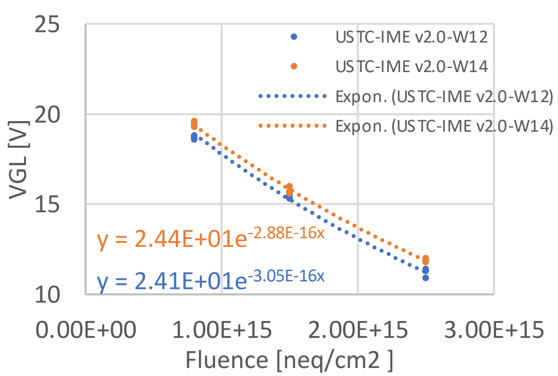
- **Tested by probe card, all pads and GR GND.**
- **Irradiation fluence (neutron):** 2.5E15 n_{eq}/cm^2, **Design**: SE4-IP7

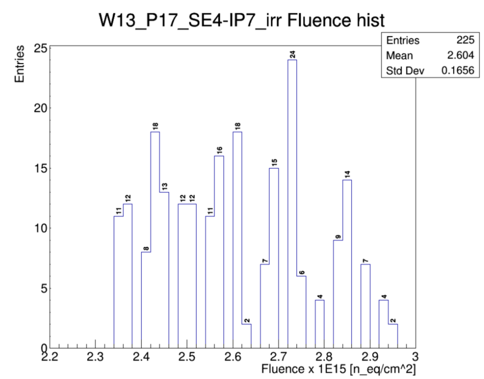
$$\frac{V_{GL}(\Phi_{eq})}{V_{GL}(0)} = e^{-c \cdot \Phi_{eq}}$$

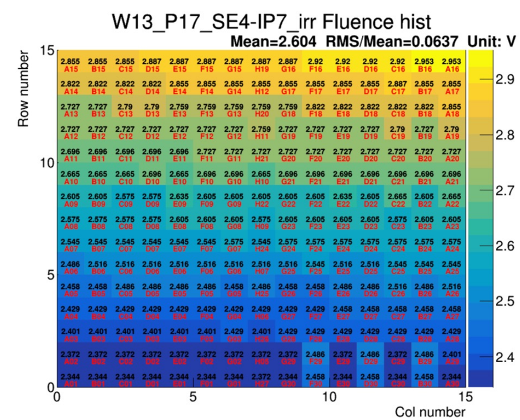










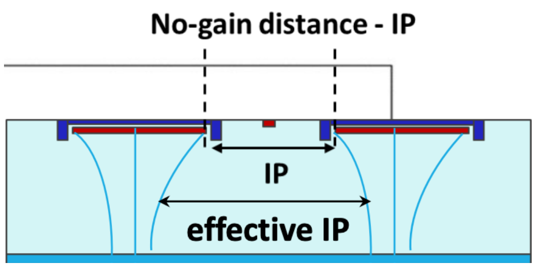


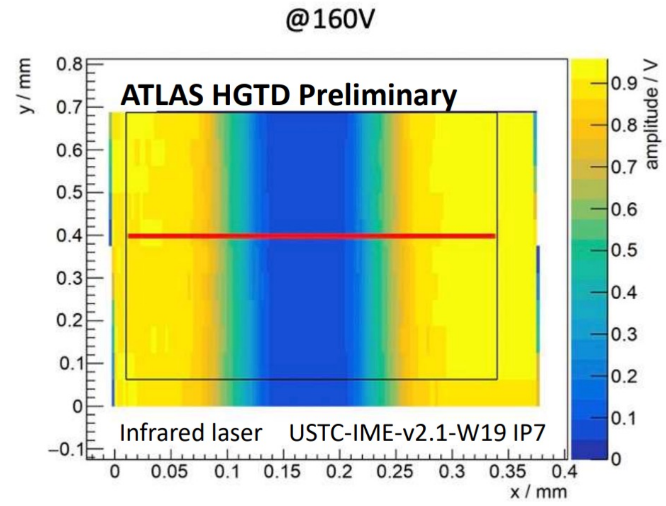
- Get the fitting function from the single sensors and calculate the fluence after getting V_{GL} of each pad.
- The variation of V_{GL} become worse after irradiation probably due to the non-uniformity of irradiation fluence across the large array sensors. The relative error of fluence is about 6.4% for this sensor.

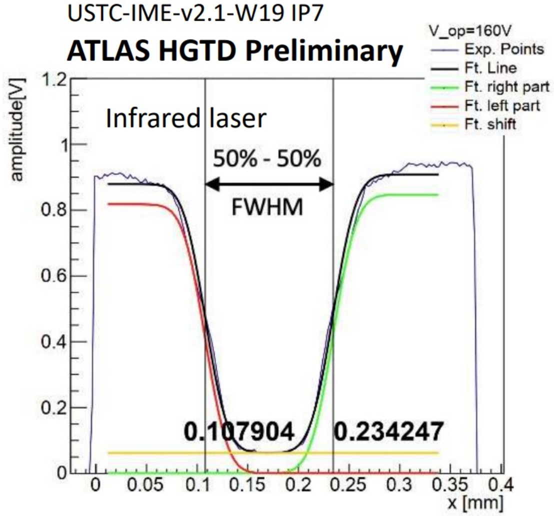
Inter-pad (IP) gap measurements

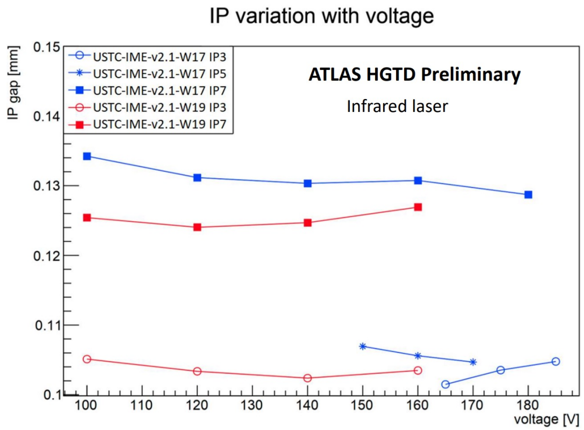
Laser (infra-red, 1064 nm)

ATLAS HGTD Public Plots









Wafer	$IP_{nominal}$ (Nominal IP)	IP_{eff} (Effective IP)	IP_{eff} - $IP_{nominal}$
W17	30um	100um	70um
	50um	107um	57um
	70um	130um	60um
W19	30um	103um	73um
	70um	124um	54um

- For IP3 and IP5, the effective IP gap is about 100 um. For IP7, the effective IP gap is about 130 um.
- Effective IP gap is large than nominal IP gap from 50-75 um.