中国科学技术大学
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The IV and CV measurement for Large-Array LGAD sensors at USTC

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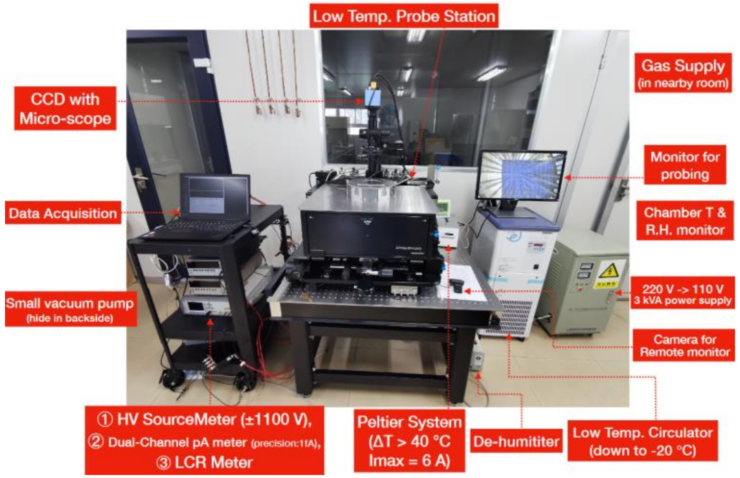
Overview

- Introduction
  - parameters, probe card
- IV measurement of large-array sensors
  - VBD, leakage current, VGL
- CV measurement of Large-array sensors
  - doping profile, VGL
- Inter-pad measurement
  - resistance, capacitance

Test devices



Probe station

15x15 probe card and digital switcher

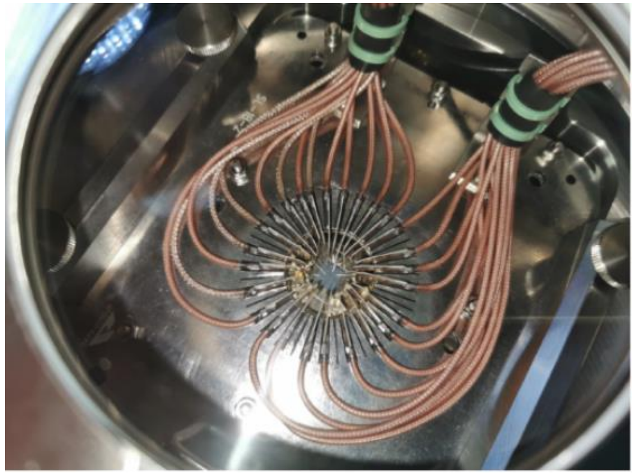
Probe card:

ensure all pads and GR grounded during testing

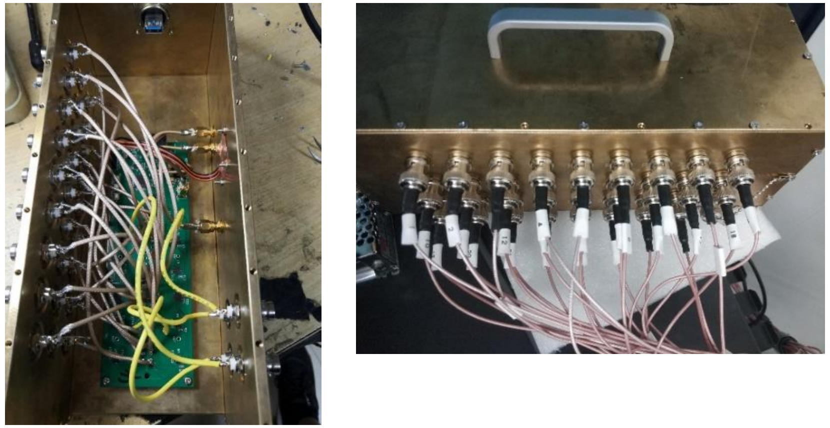
digital switcher (designed by Jiajin):

Each pad or GR connected to one channel of the switcher.

→ make pads and GR grounded and read their IV/CV data.



5x5 probe card



5x5 digital switcher and shielding box

For 5x5 digital switcher, use BNC connector to control the pad grounded or floating:

connect → grounded

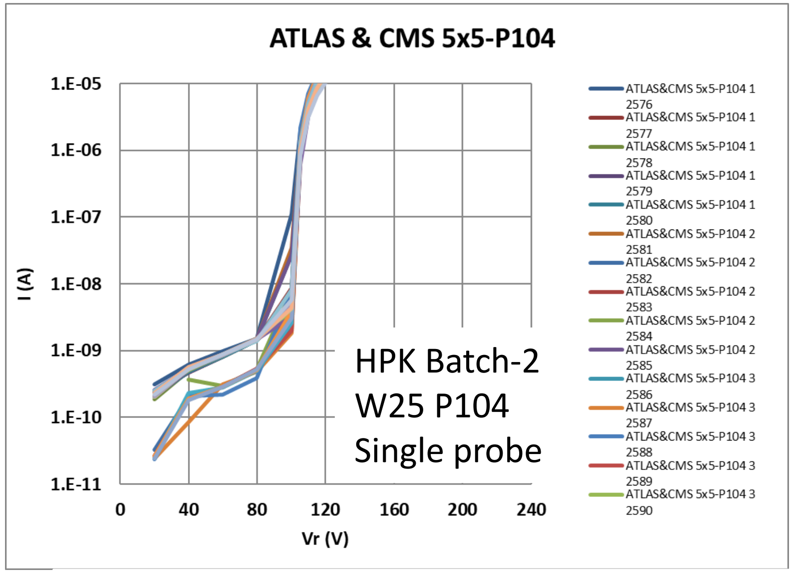
disconnect → floating

What we can know from IV&CV test

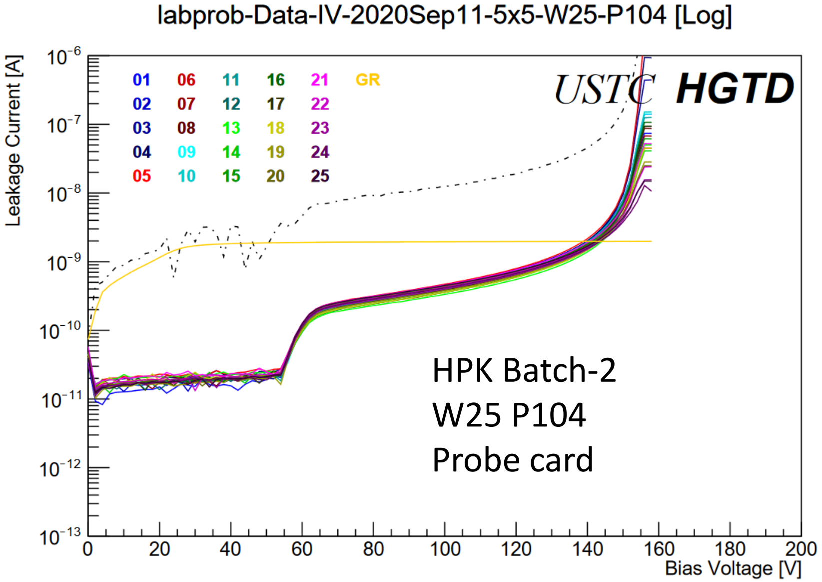
Test method	Characteristics	Comment
IV test	VBD (breakdown voltage)	Upper limit of working voltage
	Leakage current	Power consumption of circuit
	VGL (voltage required to deplete the gain layer)	Information about gain layer
CV test	Doping profile	
	VFD (voltage required to deplete the bulk)	Lower limit of working voltage
	VGL (voltage required to deplete the gain layer)	Information about gain layer
Fitting of VGL on different radiation fluences	C-factor	Parameter representing sensor's radiation hardness
Other	Inter-pad resistance/capacitance	Contribution of crosstalk

For large array sensors, parameters' distribution of each pad is also important to know sensors' uniformity

Why use probe card



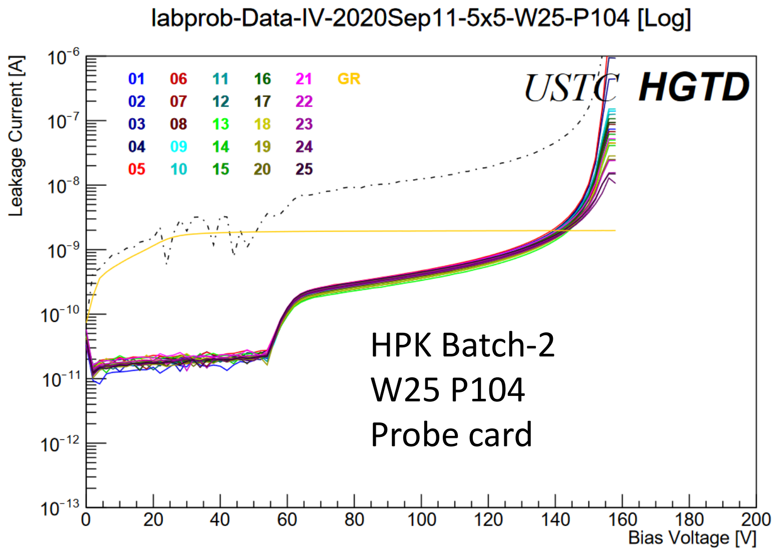
measured by HPK with automatic probe station (VBD < 120V)
Other pads and GR floating



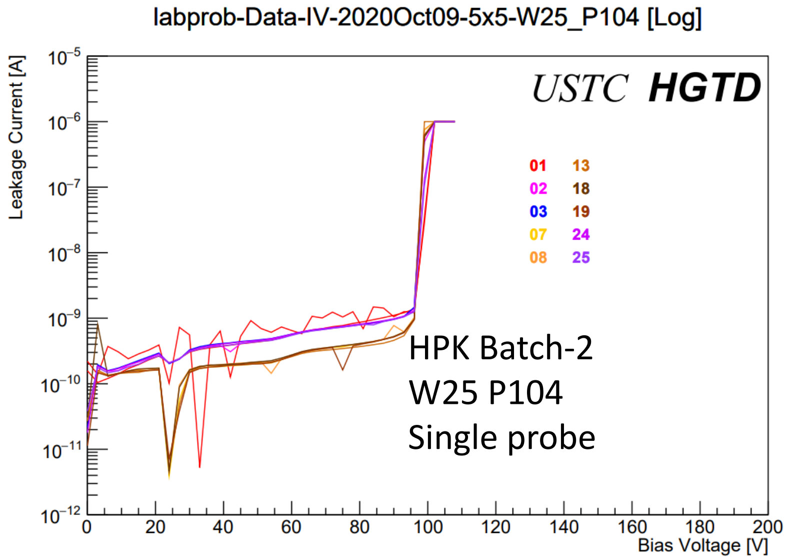
W25 P104 measured with probe card (VBD > 150V)
All pads and GR grounded

- Before we use probe card, current of large array sensors are measured with single probe.
- The IV data measured by single probe usually shows bad leakage current uniformity.
- For the same sensor, IV measured by probe card have lower current, better current uniformity and sometimes higher VBD.

Probe card vs. single probe



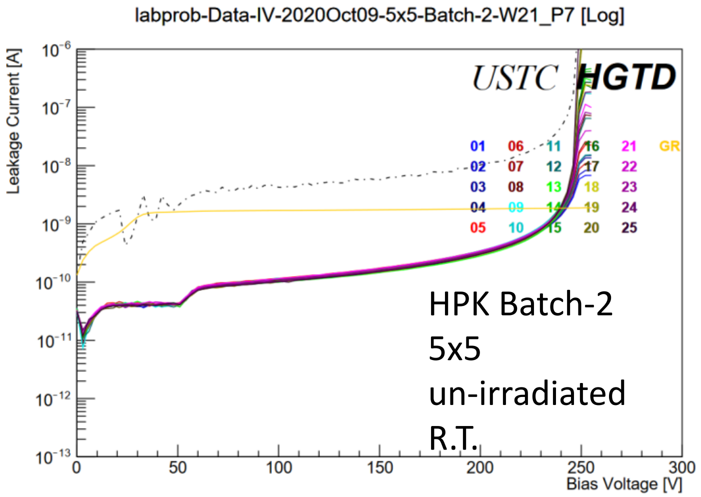
All pads and GR grounded

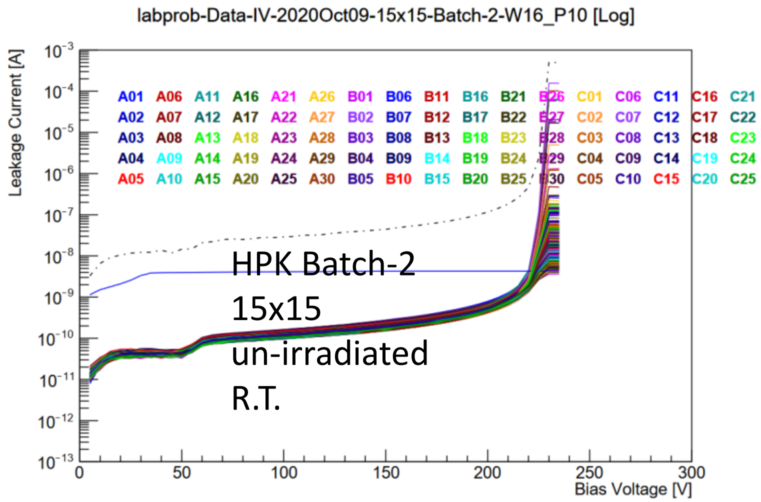


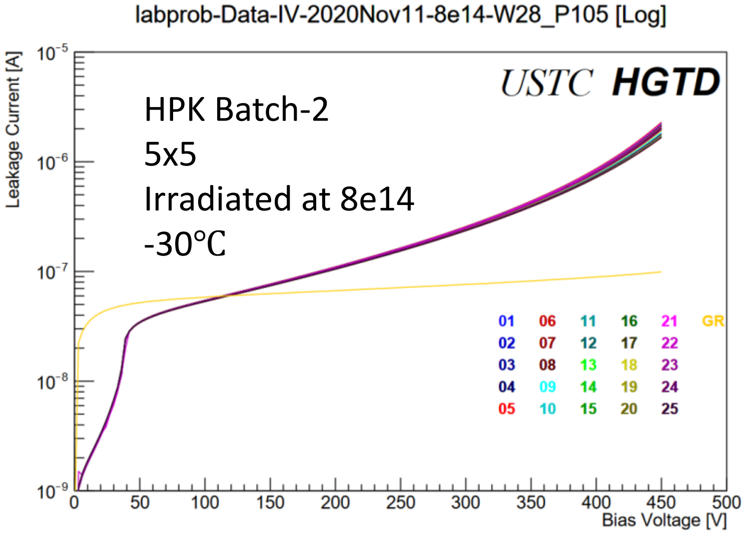
Other pads and GR floating measured at USTC

- When measured with single probe, the neighbor floating pads and GR will contribute additional current to the measured current by punch-through effect [link], causing larger current than measured with probe card.
- Because GR's current >> normal pad's current, the outer pads have larger measured current than inner pad when measured with single probe.
- Large-array sensors' all pads and GR are designed to be grounded at working situation.

Large array IV test by probe card

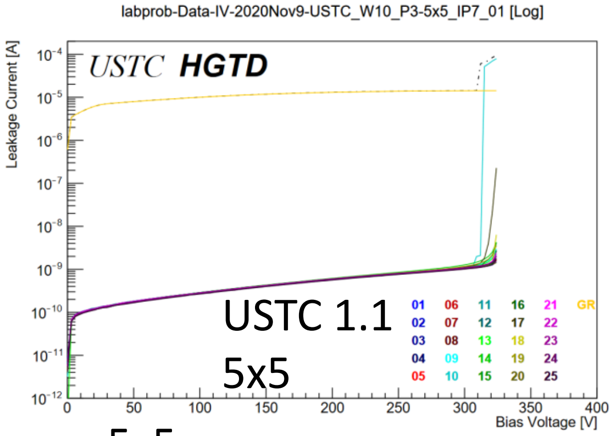




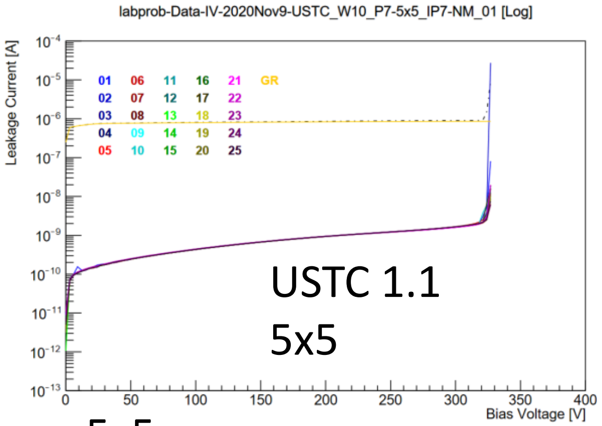


- Using probe card, IV of large-array sensors(5x5, 15x15) can be measured with all pads and GR grounded.
- Distribution of VBD and leakage current can be extracted from IV data to calculate the sensor's uniformity.
- Because irradiated sensors' current are quite large at R.T. IV of irradiated sensors should be measured at -30℃, which is sensors' working environment.

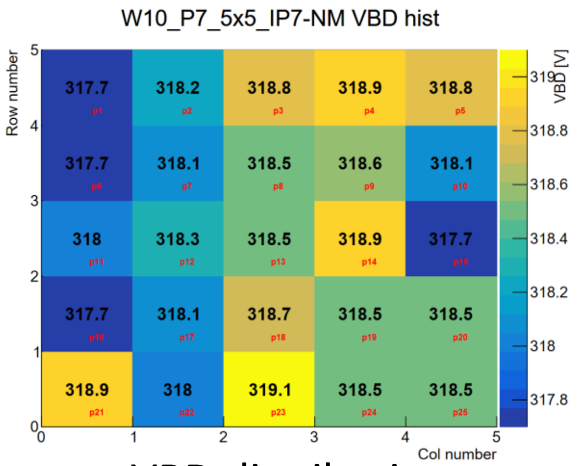
Uniformity of leakage current and VBD



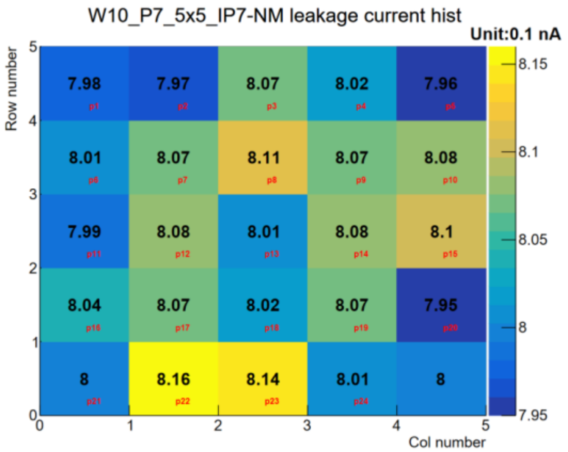
5x5 sensor
with bad VBD uniformity



5x5 sensor
with good VBD uniformity



VBD distribution

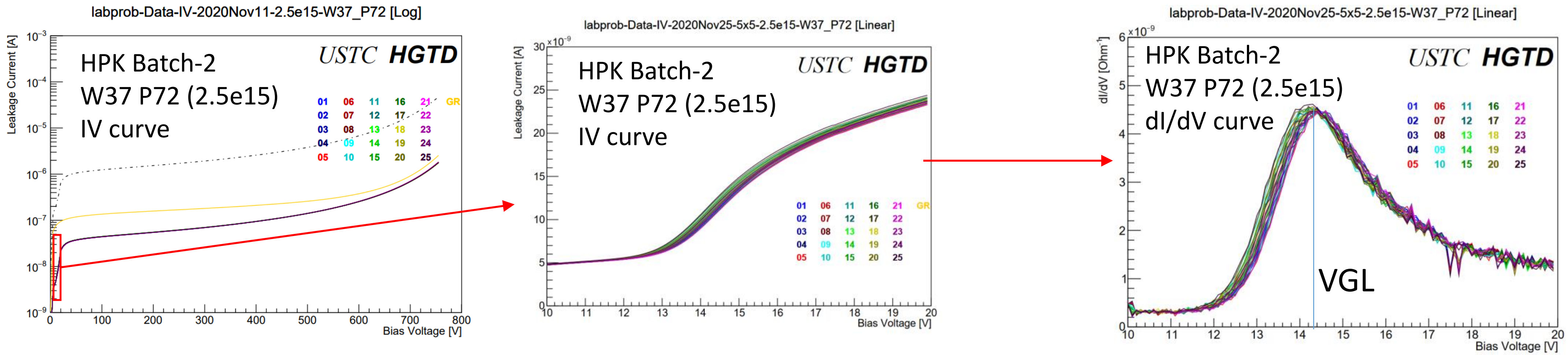


Leakage current distribution

For VBD, RMS/Average < 5%

- Use current at 0.8VBD of sensor as reference of leakage current.
- For the measurement of each pads' VBD:
  - On probe card, apply negative voltage which close to VBD to backside and apply small voltage to each probe one by one.
  - Because of punch-through effect, too large potential difference between pads will cause large inter-pad current. This method can only be used on sensors with good VBD uniformity

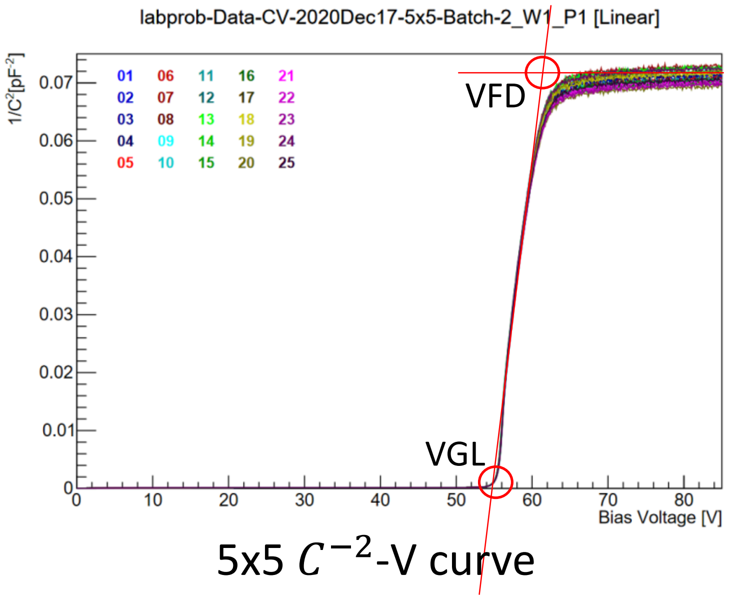
Extraction VGL from IV data



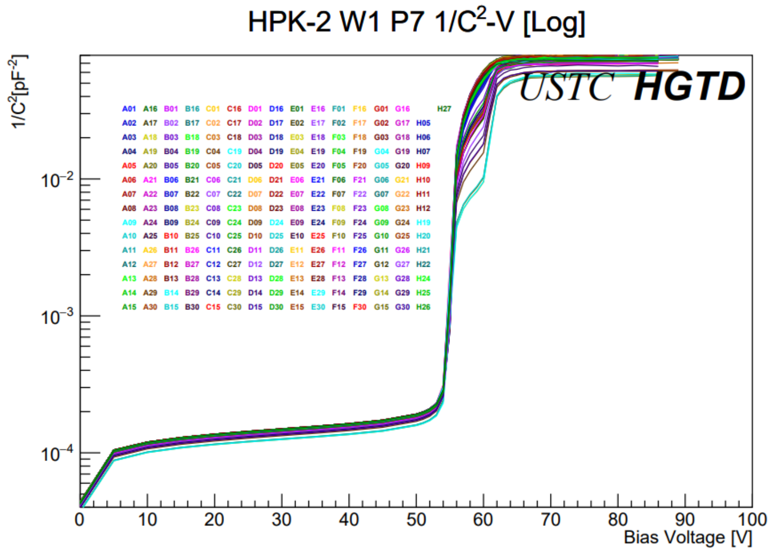
- For some sensors, use finer step(0.1V) to measure the IV curve around VGL, and take the maximum derivative to extract VGL.

Sensor	Fluence (cm^{-2})	VGL (V)
HPK Batch-2 W37 P102	8.00E+14	34.46 ± 0.11
HPK Batch-2 W37 P72	2.50E+15	14.34 ± 0.01

Large array CV test by probe card



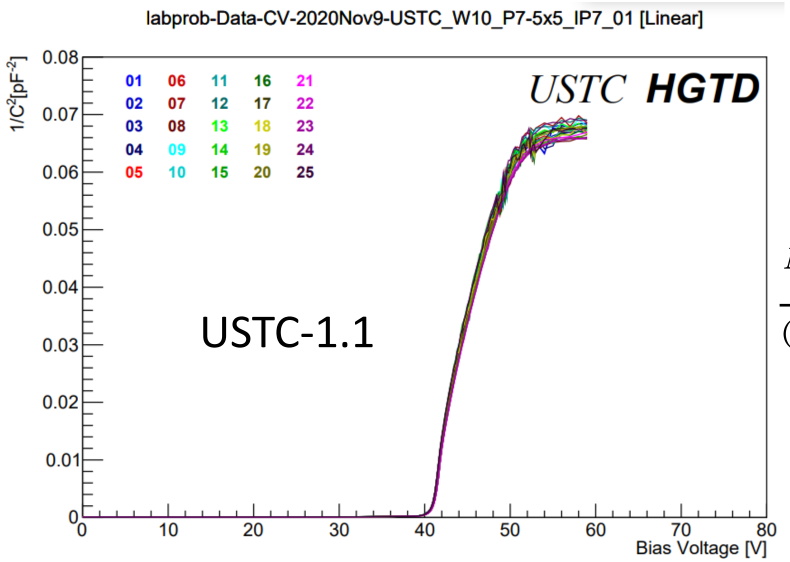
5x5 C^{-2}-V curve



15x15 C^{-2}-V curve

- Using probe card, CV of large-array sensors(5x5, 15x15) can be measured with all pads and GR grounded.
- Doping profile, VGL and VFD can be extracted from CV.
- Distribution of VGL can be extracted from CV data to calculate the sensor's uniformity.

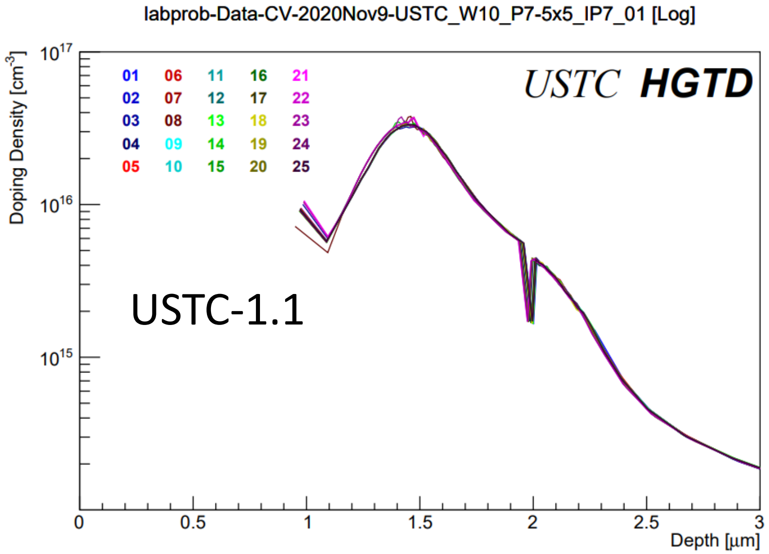
Doping profile



C^{-2}-V curve

$$N = \frac{2}{q\epsilon A^2}\frac{1}{d(1/C(V)^2)/dV},\ w = \frac{\epsilon A^2}{C(V)}$$

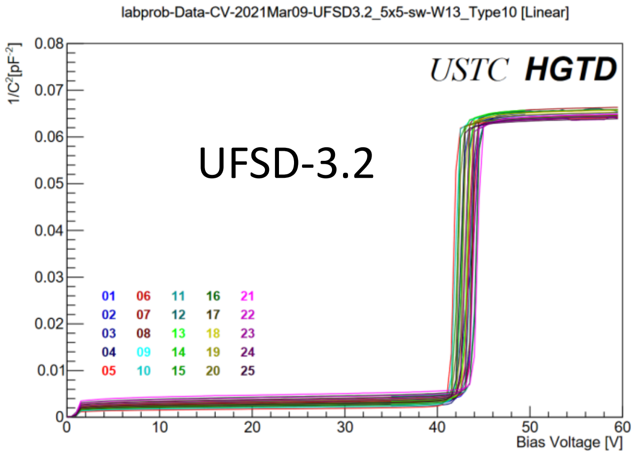
$(A\text{: area of sensor})$

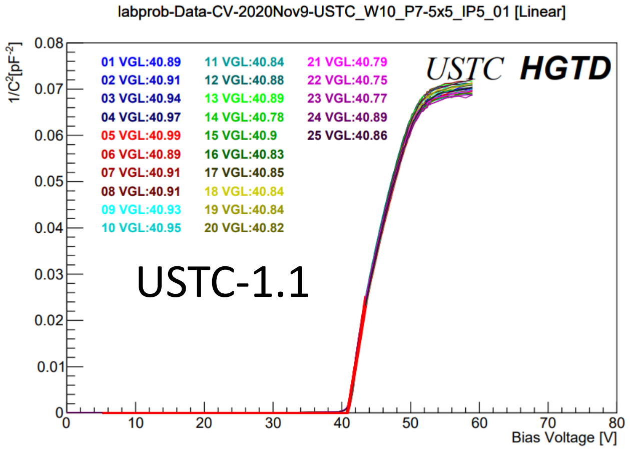


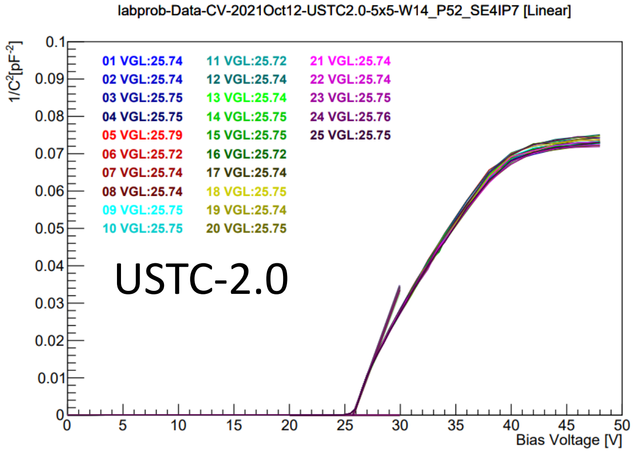
Doping profile

- Assuming the depleted region as plane-parallel capacitor, doping profile can be calculated from CV data.
- Doping profile and its uniformity can be used as reference of sensor design.

Extraction of VGL from CV data







Sensor	VGL (V)	100%*(Max-Min)/Average (VGL)
UFSD-3.2 W13 Type9	44.68 ± 0.17	1.57 %
USTC-1.1 W10 P7	40.87 ± 0.06	0.59 %
USTC-2.0 W14 P52	25.74 ± 0.02	0.27%

For VGL, 100%*(Max-Min)/Average < 1%

- Use finer step to measure the CV around VGL
- Use extrapolating line segments before and after VGL to extract VGL from CV and calculate the uniformity.

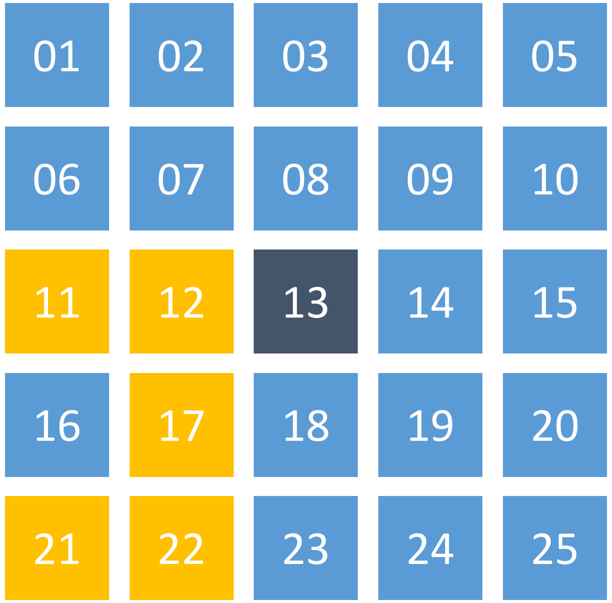
C-factor calculation

- After extracting VGL at different fluences from IV or CV, use the equation to calculate the sensors' c-factor.

$$\frac{V_{gl}(\phi_1)}{V_{gl}(\phi_2)} = Exp[-c(\phi_1 - \phi_2)]$$

Sensor	c-factor (cm^2)
HPK Batch-2 W28	~ 3.5E-16 (from IV)
UFSD-3.2 W13	~ 2.1E-16 (from CV)
USTC-1.1 W11	~ 1.8E-16 (from CV)

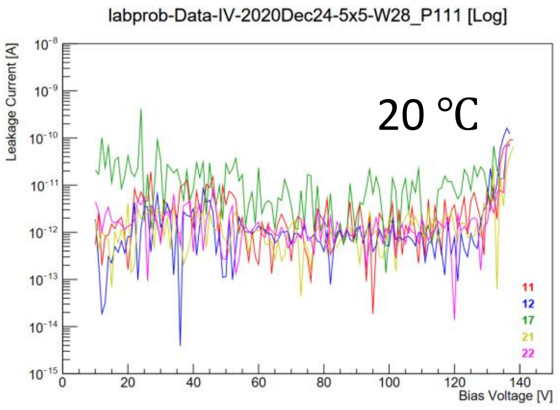
Method to check the inter pad resistance



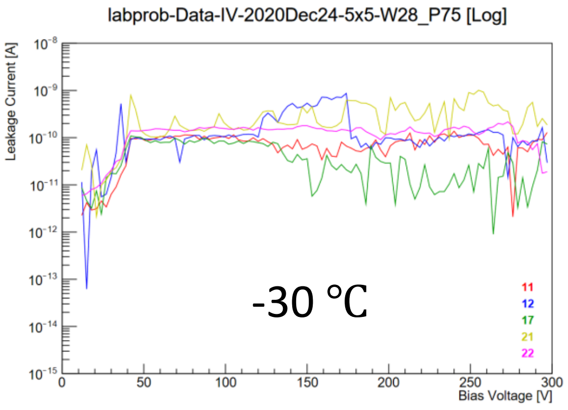
Inter-pad resistance need to be checked to see if the sensor can work normally.

- Apply 1V to the pad13's probe.
- Sensor's backside -- negative high voltage. Other pads and GR -- ground.
- Measure the currents of pad 11, 12, 17, 21, 22 and compare them to the current measured with pad13 grounded.
- Get the increased current and use it to estimate the lower limit of inter pad resistance.
- For normal sensor, the inter pad resistance should be in the order of several GΩ. So the increased current should < 1nA.

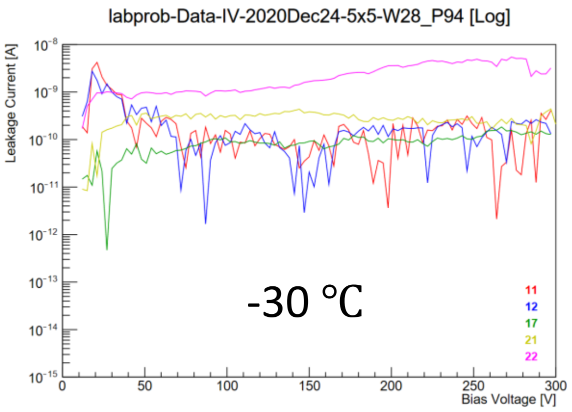
The inter pad leakage current (1V)



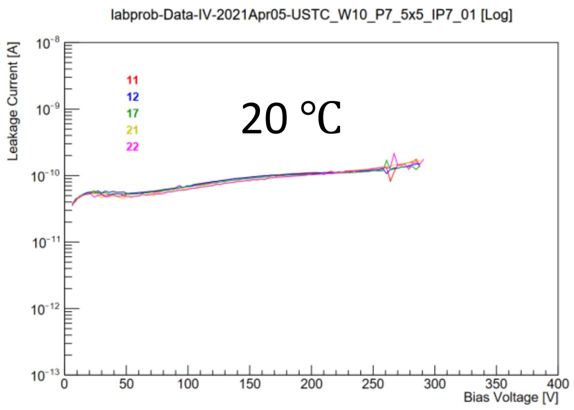
HPK Batch-2
Unirradiated sensor



HPK Batch-2
8e14



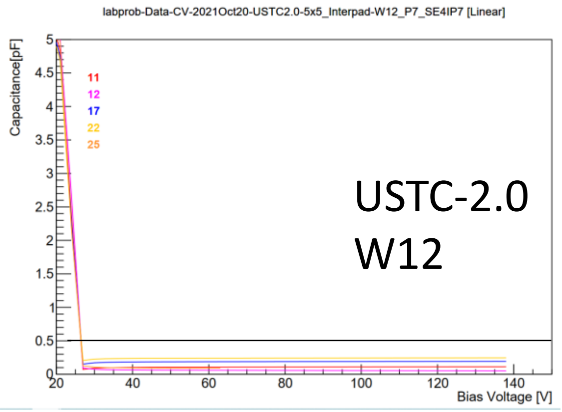
HPK Batch-2
2.5e15

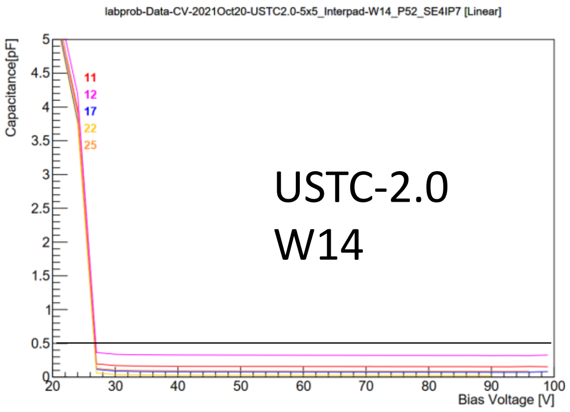


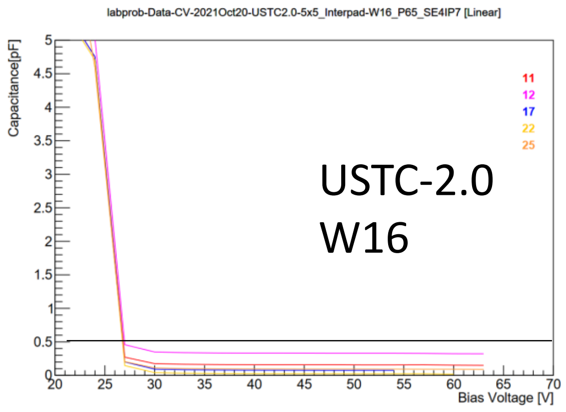
USTC-1.1
Unirradiated sensor

- For the measured sensors, only irradiated sensors (at 2.5e15) from HPK have current >1nA.
- But the leakage current of 2.5e15 sensor is <10nA, with resistance >0.1GΩ.
- Because radiation can decrease the inter-pad resistance by values of several tens to hundreds of MΩ, this result is acceptable. So the inter-pad resistance will not affect the uniformity too much.

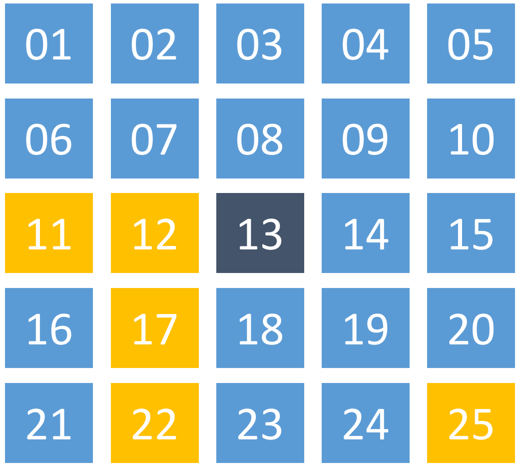
Measurement of inter-pad capacitance







Frequency: 10kHz,
VAC: 1V
Step: 3.0V
GR and all pads grounded
T: R.T.



- Sensor's backside -- negative high voltage. All pads and GR -- ground.
- Measure the capacitance between pad 13 and pad 11, 12, 17, 22, 25.
- When voltage > 30V, all measured inter-pad capacitances < 0.5pF.

Summary

- The IV data measured by probe card is more reliable.

- With probe card and digital switcher, IV&CV test can be done well to know the performance of large array sensors at USTC.

- By now, >100 5x5 sensors from HPK, USTC, FBK and >30 15x15 sensors from HPK, USTC have been measured and plenty of result have been taken at USTC.