The 37th RD50 Workshop
(Zagreb -- online Workshop)

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Institute of High Energy Physics
Chinese Academy of Sciences

中国科学院微电子研究所
INSTITUTE OF MICROELECTRONICS OF CHINESE ACADEMY OF SCIENCES

Simulation and testing results of the low gain avalanche diodes developed by IHEP and IME in China

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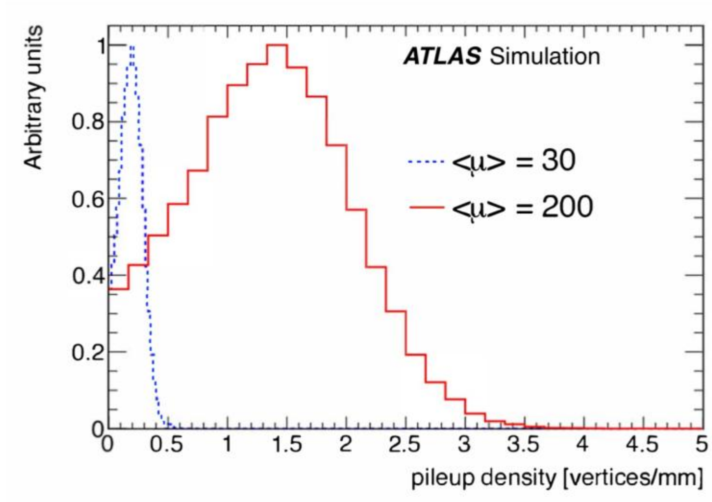
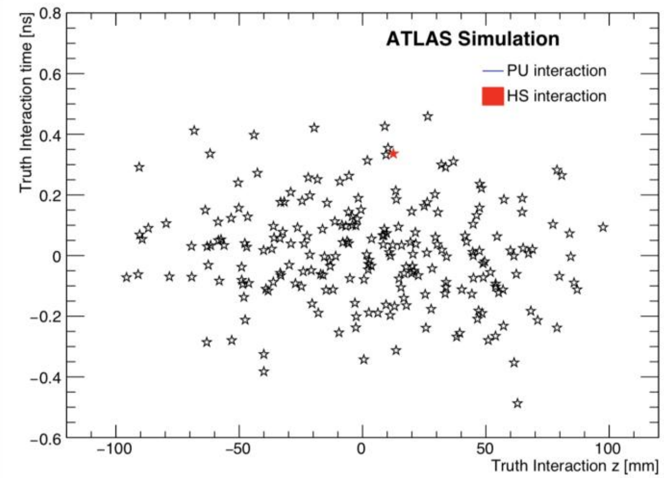
HL-LHC & ATLAS HGTD

The high-luminosity (HL) phase of the Large Hadron Collider (LHC) at CERN aims to deliver an integrated luminosity of up to 4000fb^{-1}.

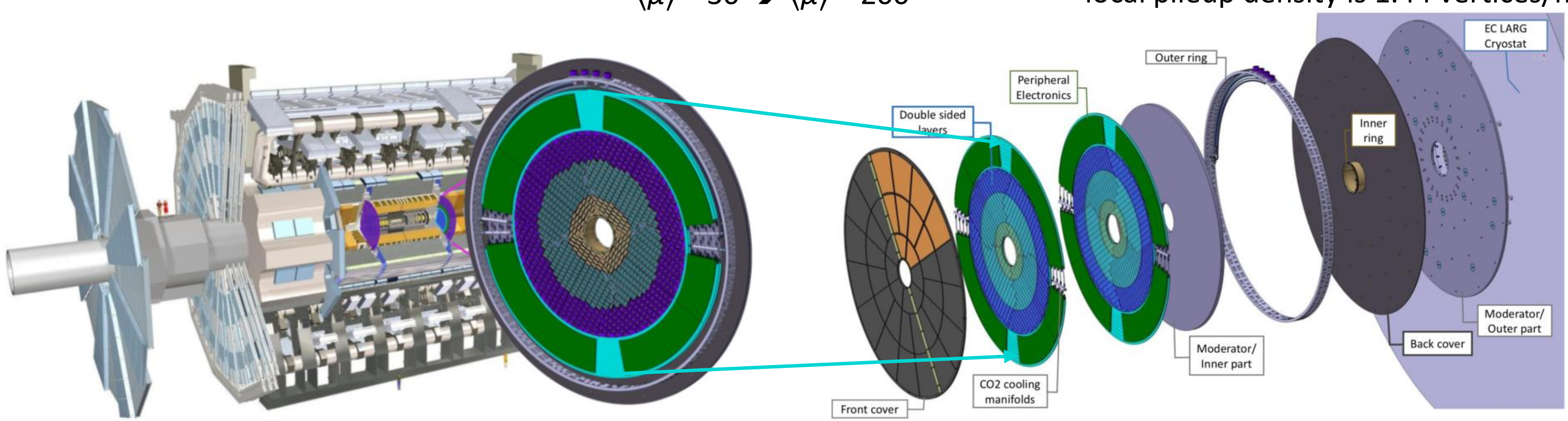
The High Granularity Timing Detector (HGTD) project has been approved as a part of the LHC Phase-II Upgrade .



$\langle\mu\rangle = 30 \rightarrow \langle\mu\rangle = 200$



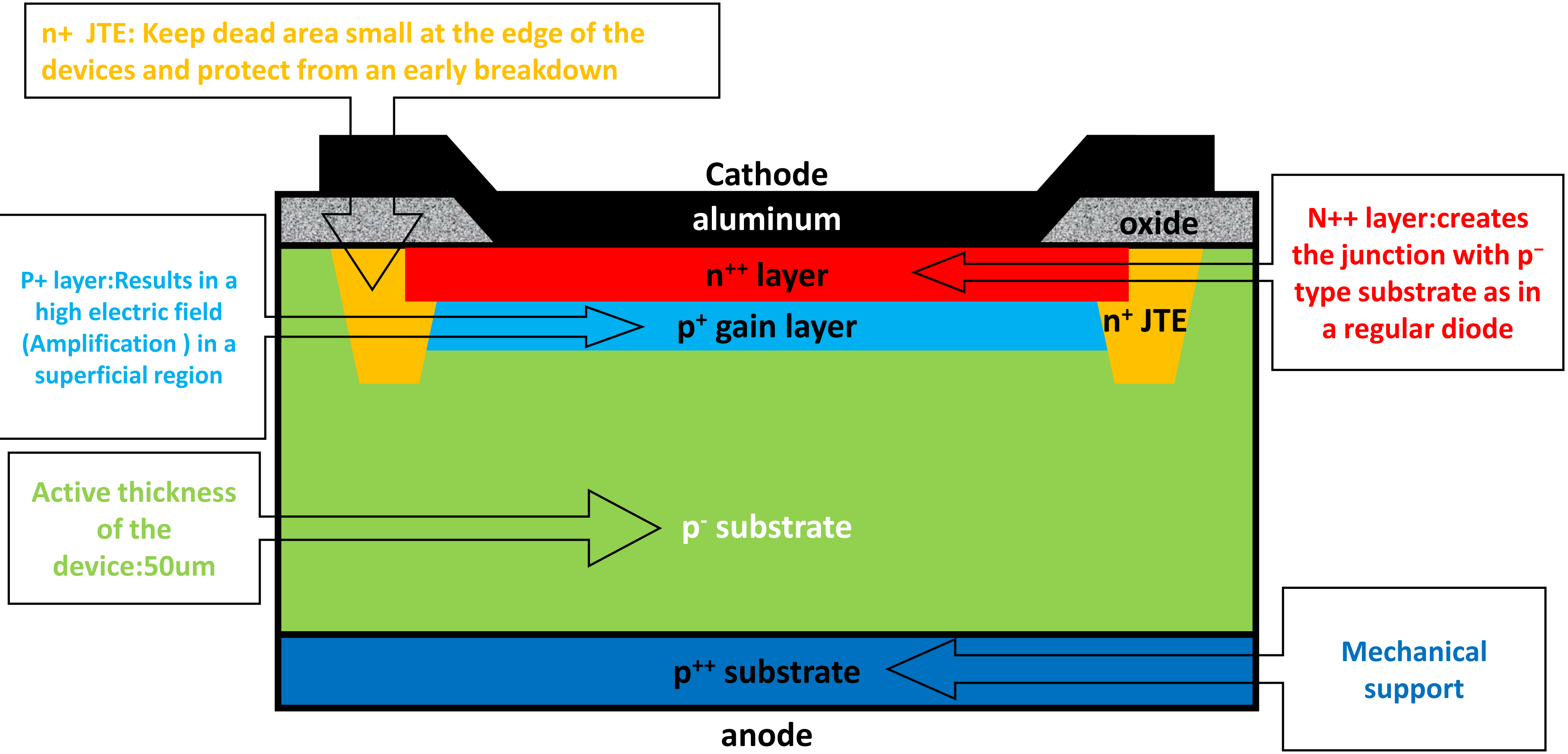
local pileup density is 1.44 vertices/mm



The ATLAS Collaboration, *Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, **CERN-LHCC-2020-007 ATLAS-TDR-031**

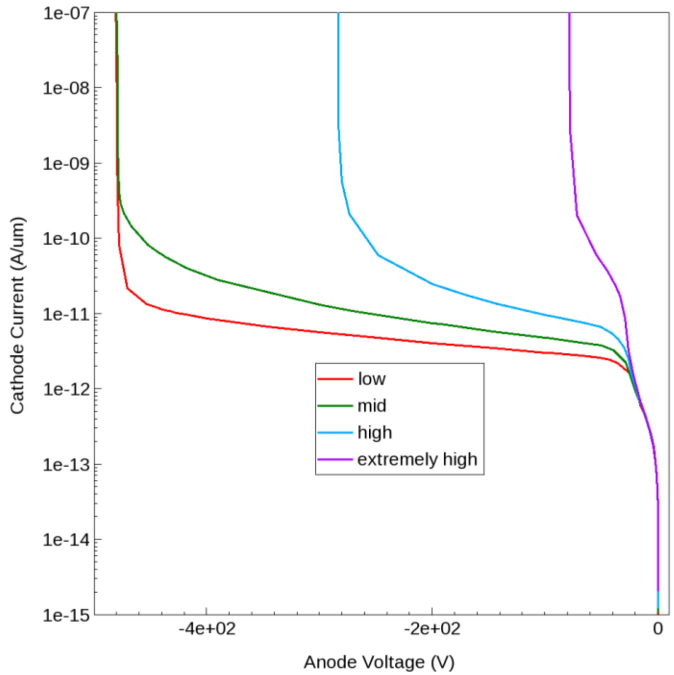
LGAD Sensor structure

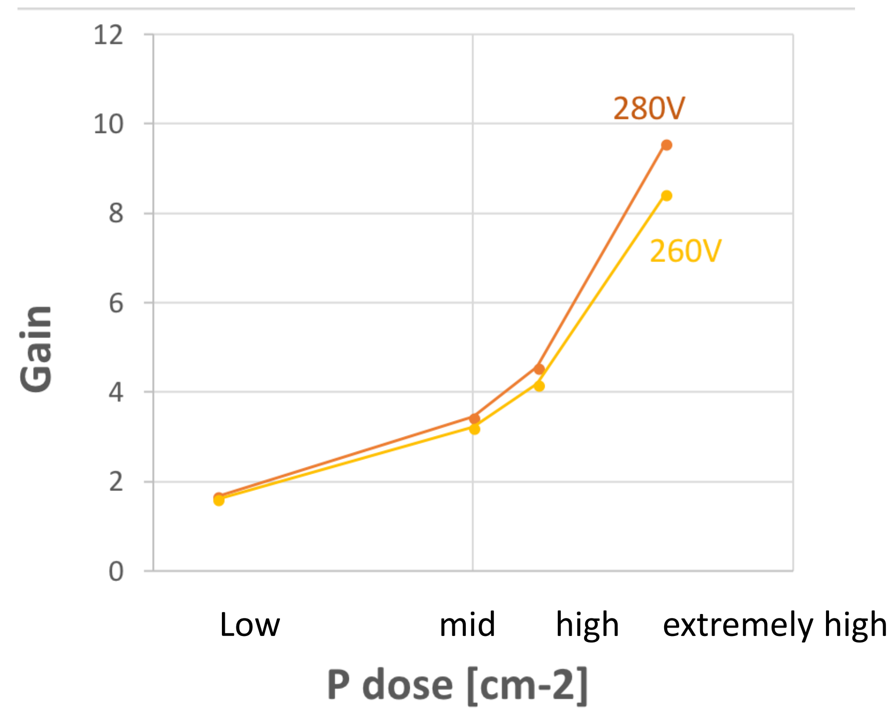
- The Low- Gain Avalanche Detector (LGAD) with time resolution better than 50ps is the key technology to separate collisions in limited space.
- LGAD is an avalanche detector working at voltage before breakdown voltage, and has gain factor larger than 20 before irradiation. The radiation hardness should be larger than $2.5x10^{15}n_{eq}/cm^2$.



Process Simulation

- p+ layer boron implantation dose





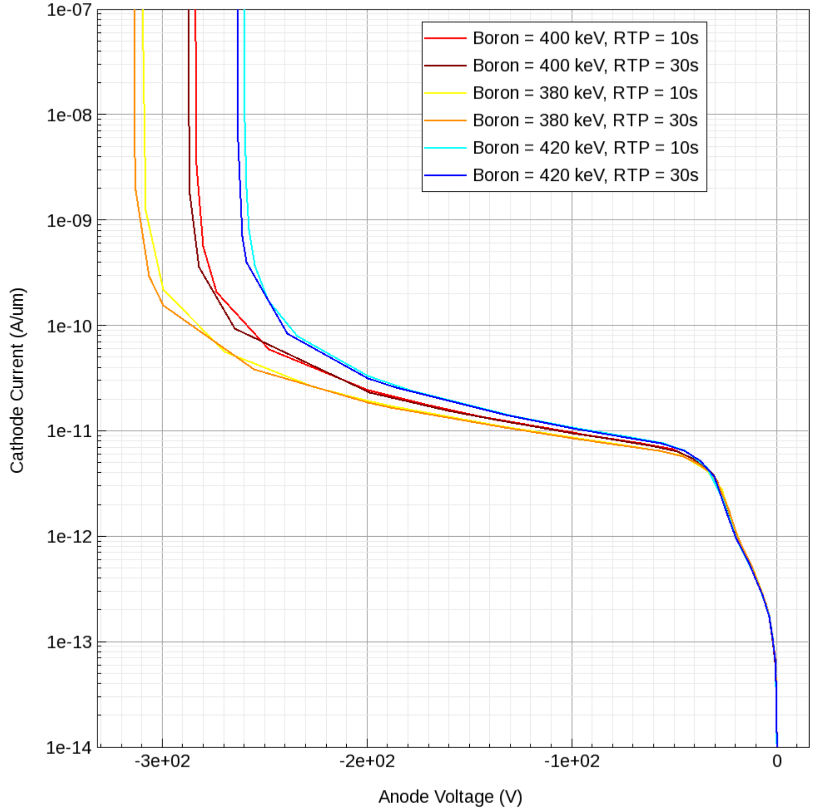
□I-V Curves for different p+ layer implantation dose: higher dose leading to lower breakdown voltage(**V_{BD}**)

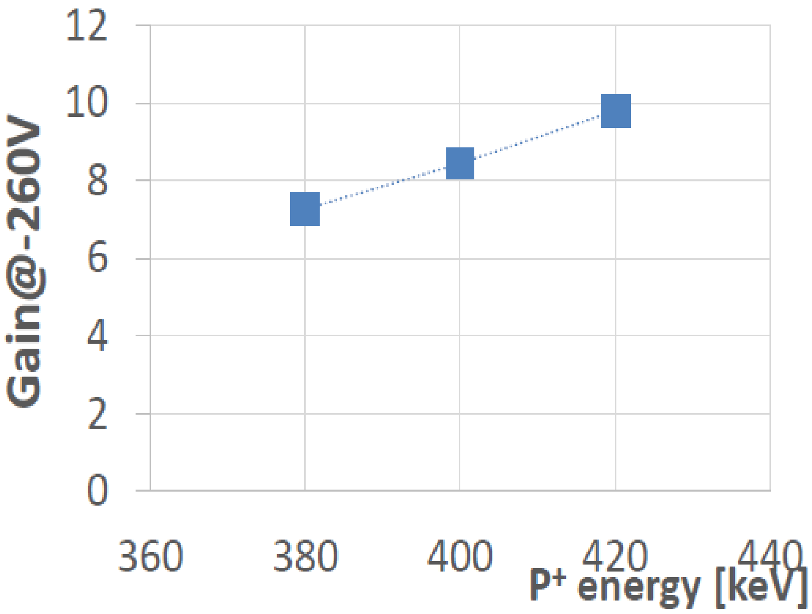
P+ DOSE ±5%，**V_{BD}** ±70V

□Gain curve with different p+ layer dose: higher dose leading to higher gain

Process Simulation

- p+ layer boron implantation energy





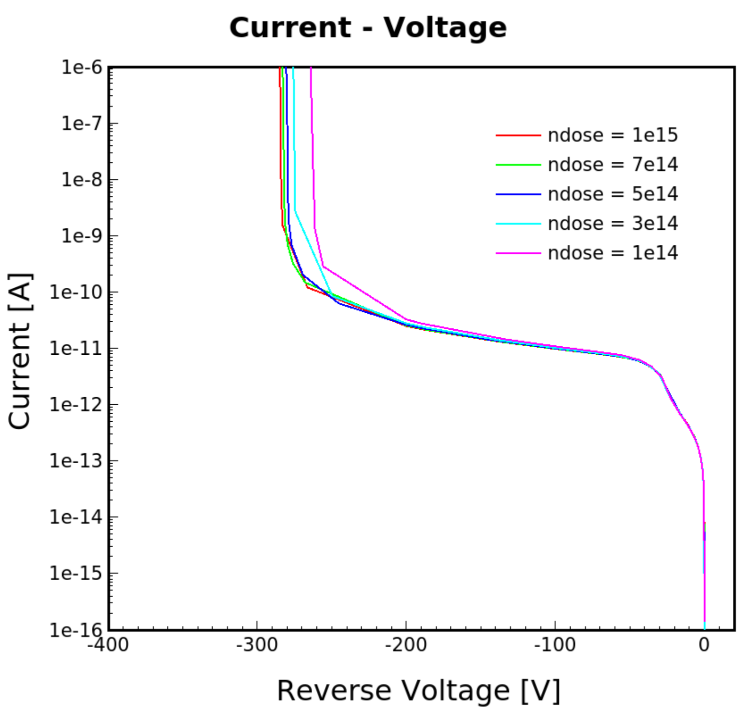
☐I-V Curves for different p+ layer implantation energy: higher energy leading to lower breakdown voltage

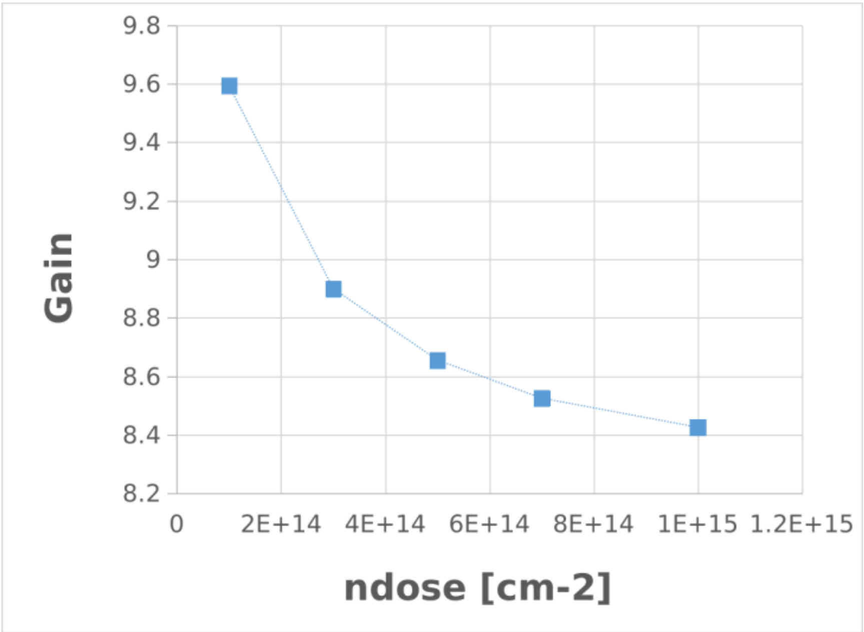
☐Gain curve with different p+ layer implantation energy: higher energy leading to higher gain(at same work voltage)

p+ layer energy ±5%， $\mathbf{V_{BD}}$±25V

Process Simulation

- n++ layer phosphorus implantation dose





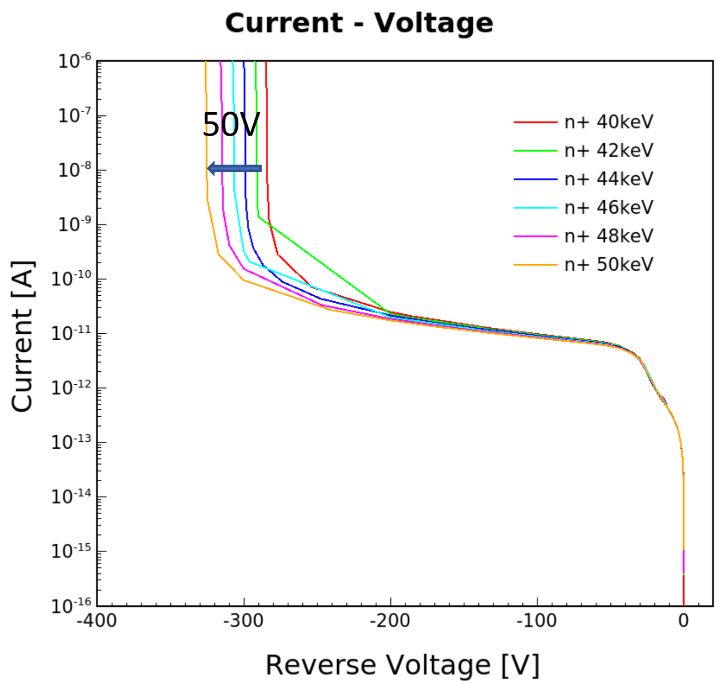
□I-V Curves for different n++ layer implantation dose: VBD change a little

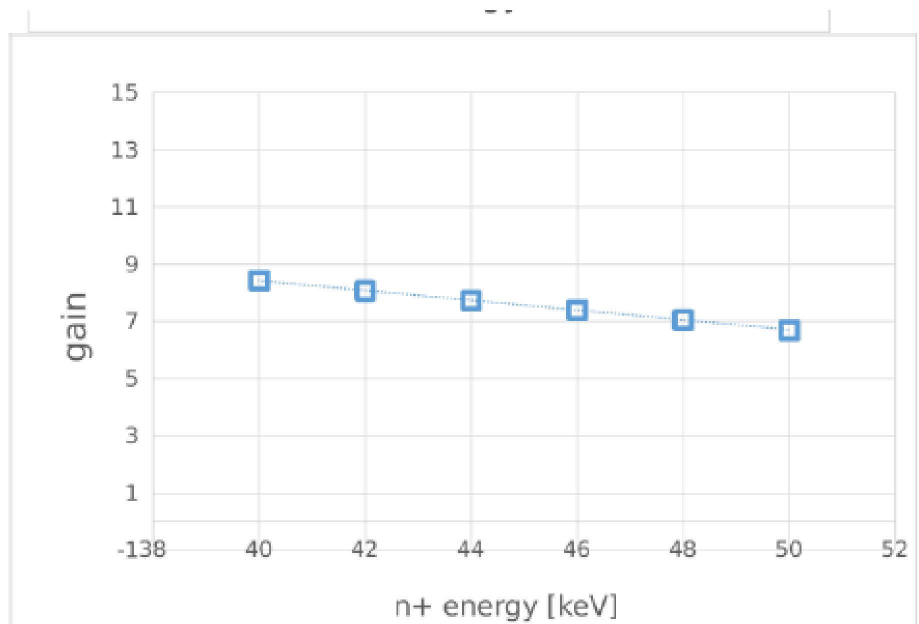
□Gain curve with different n++ layer implantation energy: Gain change a little(at same work voltage)

n++ layer dose ±5% , $\mathbf{V_{BD}}$ ±8V

Process Simulation

- n++ layer phosphorus implantation energy





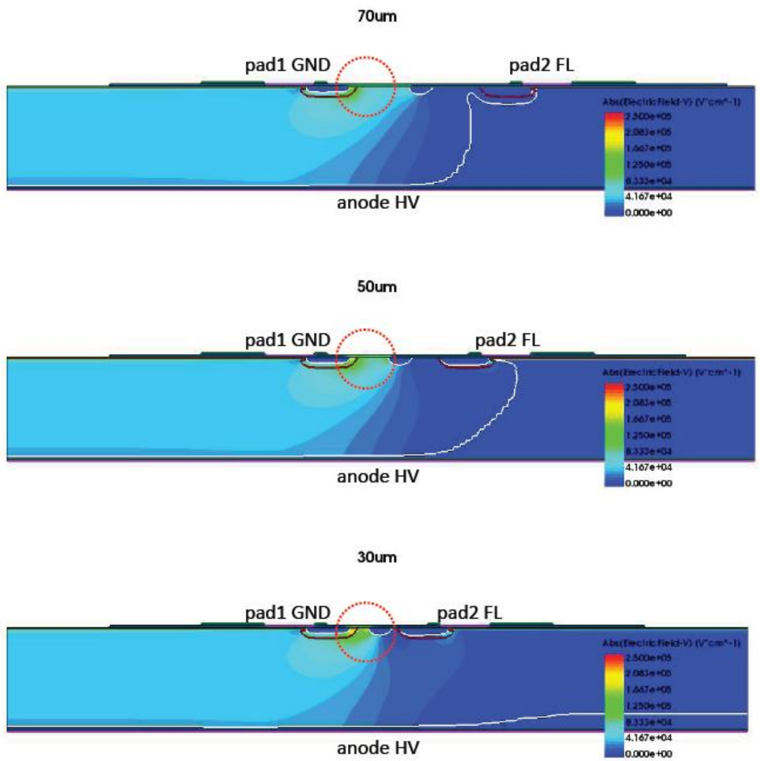
☐IV Curves for different n++ layer implantation energy: higher energy leading to higher breakdown voltage

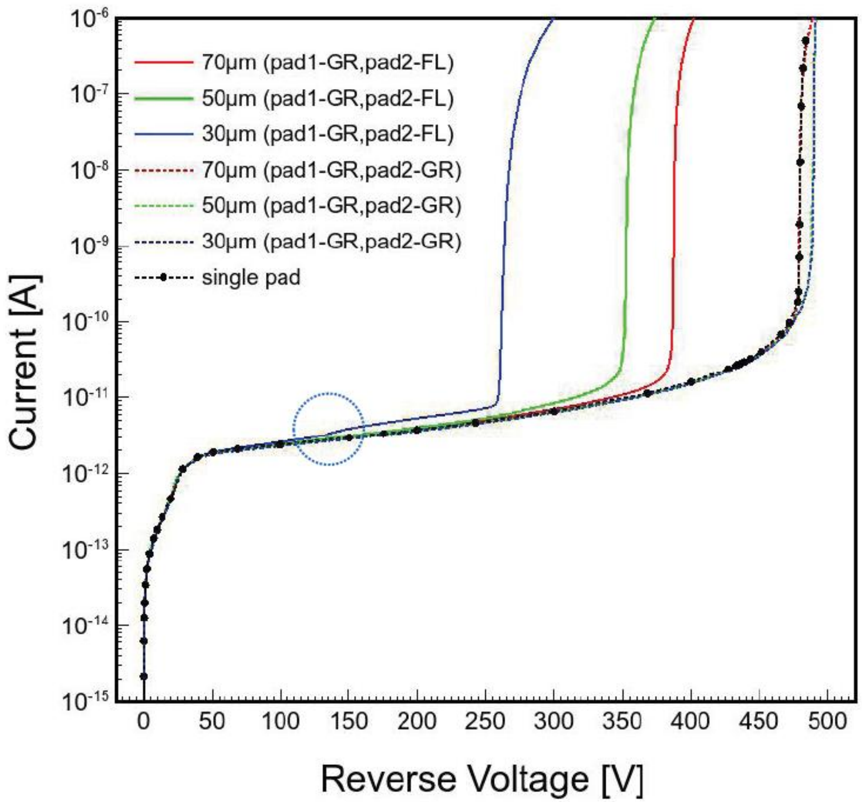
☐Gain curve with different n++ layer implantation energy: higher energy leading to lower gain

n++ layer energy +10keV , $\mathbf{V_{BD}}$ +50V

Structure simulation

Inner pad gap simulation: 100um, 80um, 50um
One pad is grounded, the other is floating(FL) / grounded(GR)

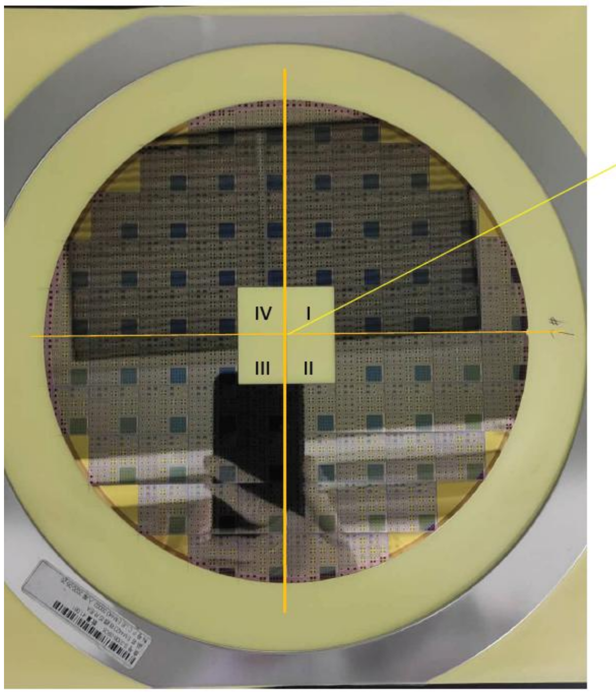




- ◻V_{BD} for single sensors with different structure are same, and when all pad are grounded, **V_{BD}** for sensor array with different structure is same with single sensors.
- ◻But when one pad is grounded, the other one is floating, **V_{BD}** for sensor array is different with single sensor even they have same structure.
- ◻And the **V_{BD}** decreases as reducing the inner pad gap

IHEP-IMEv1 sensors

- Four wafers: #1,#3, #7, #8. (50um 1kΩcm epi, 8 inch)
- Four quadrants: I, II, III, IV.



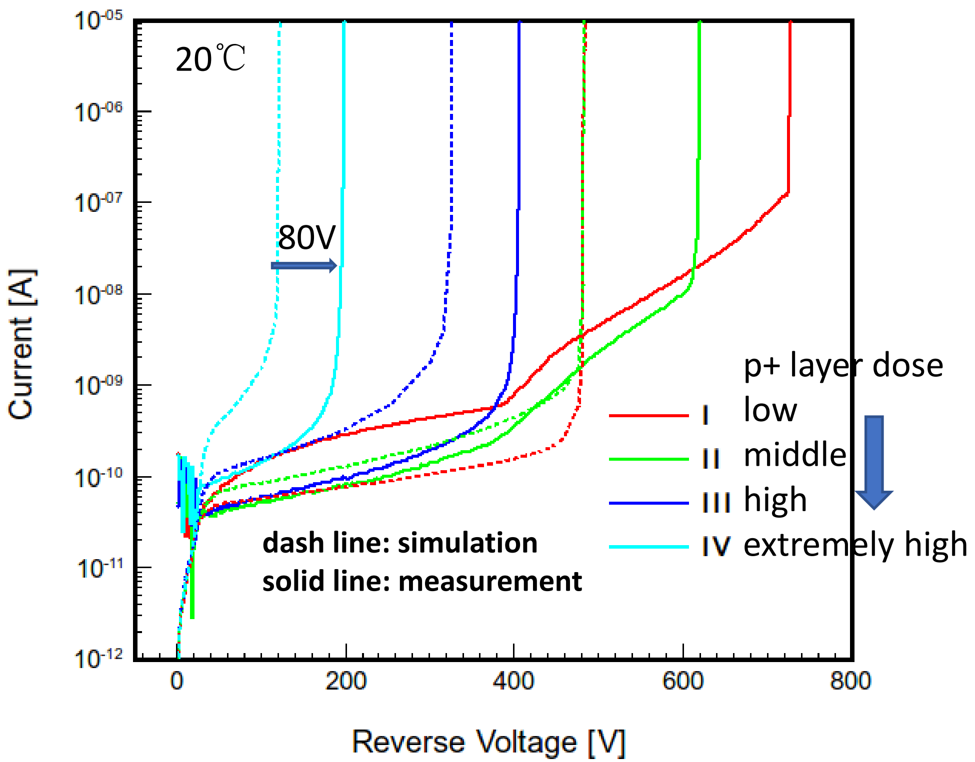
Wafer	Phosphorus Energy	Carbon
1#	Low	+
3#	Low	-
7#	Low	-
8#	high	-

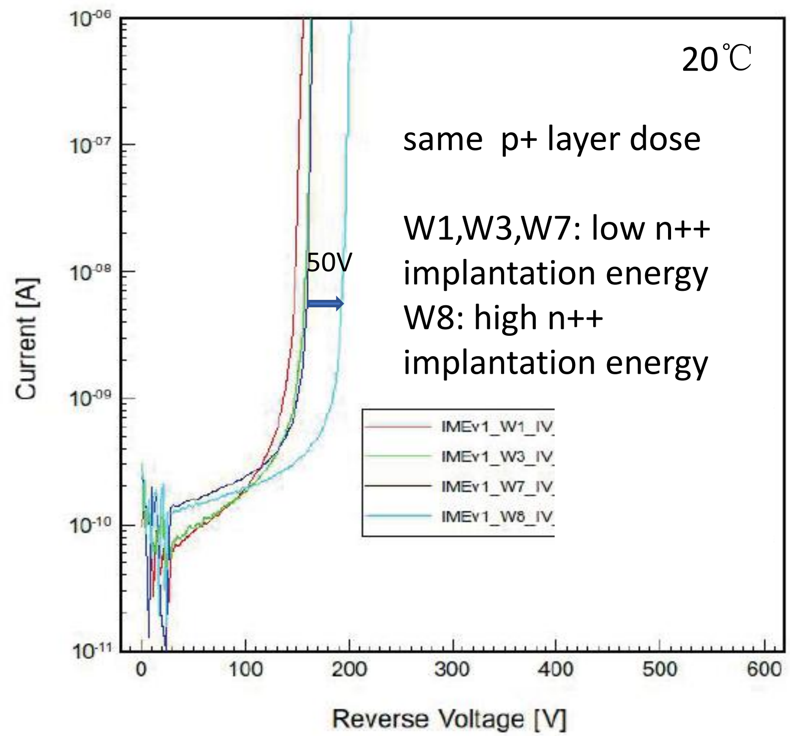
Quadrant	Boron dose
I	Low
II	Medium
III	High
IV	Extremely High

- 4 separate quadrants for each wafer are implanted different boron dose for p+ layer.
- #1, #3and #7 have low n++ implantation energy, #8 has high n++ implantation energy.
- Only #1 wafer has carbon implantation.
- Each quadrants has 14 fields, In one field, there are 29 single sensors, 9 types 2x2 array and 1 type 5x5 array.

I-V measurement

Wafer 8



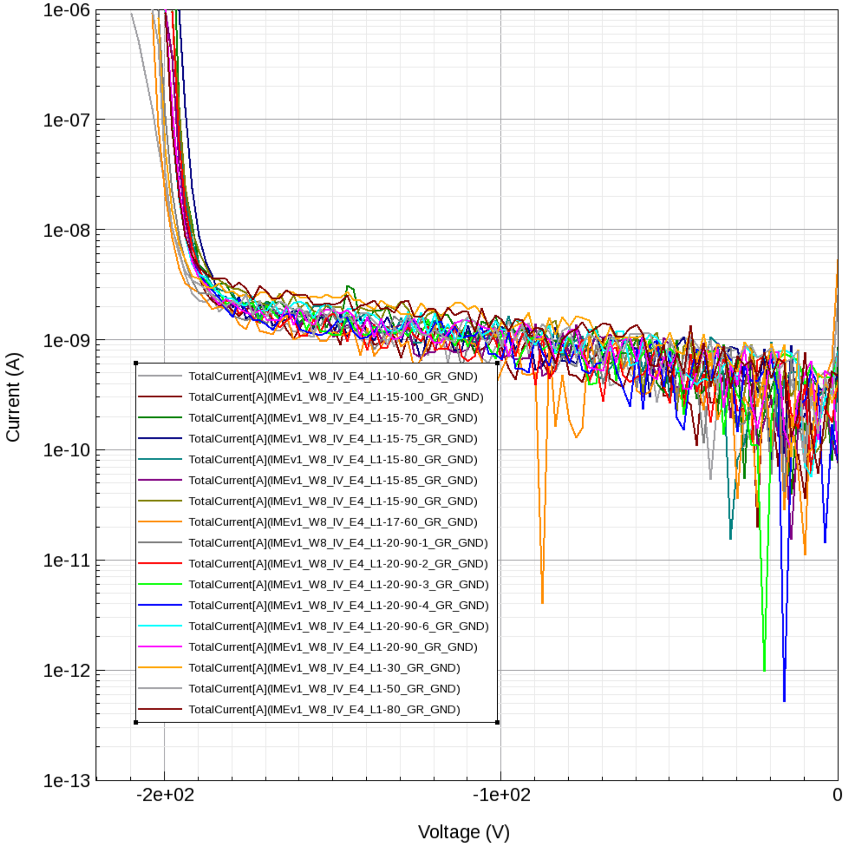


- Most of process configurations $I_{leakage}$ <100pA, except extremely high boron dose implantation which V_{BD}<200V.
- The testing results show that $\mathbf{V_{BD}}$ increase with p+ layer dose up, which fit with simulation, while $\mathbf{V_{BD}}$ for all the wafers from testing results are ~80V higher than simulation(W8-III, W8-IV).

- Process demonstrates good uniformity based on W3, W7 wafer I-V measurements.
- Wafer 8 with higher n++ implantation energy shows higher breakdown voltage(by 50V).
- Wafer 1 with carbon injection shows no increasing leakage current before irradiation.

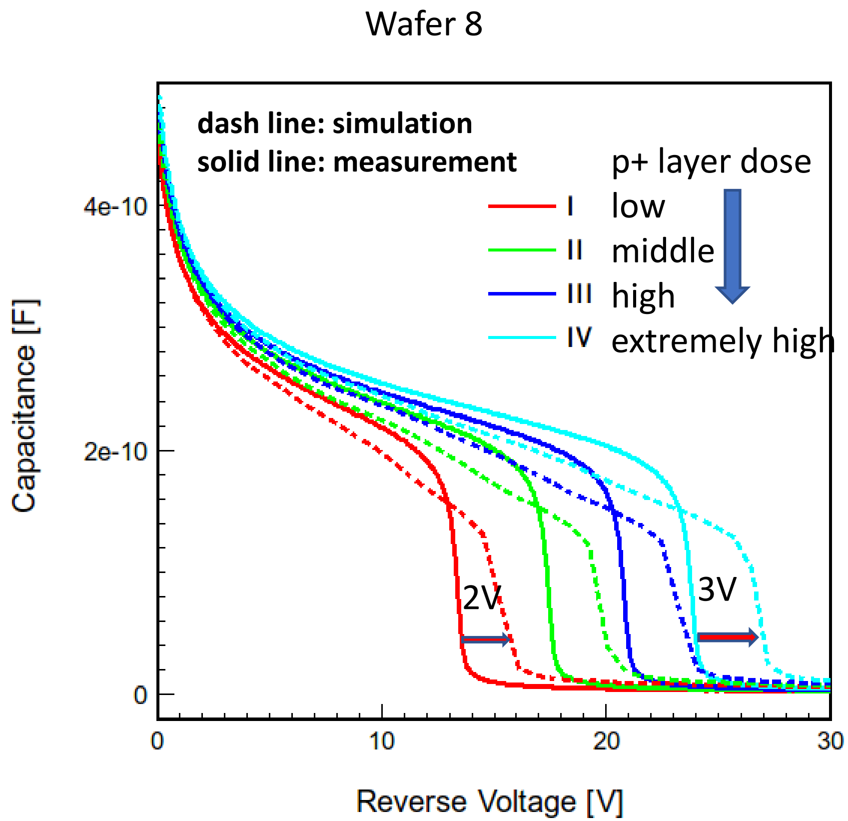
I-V measurement

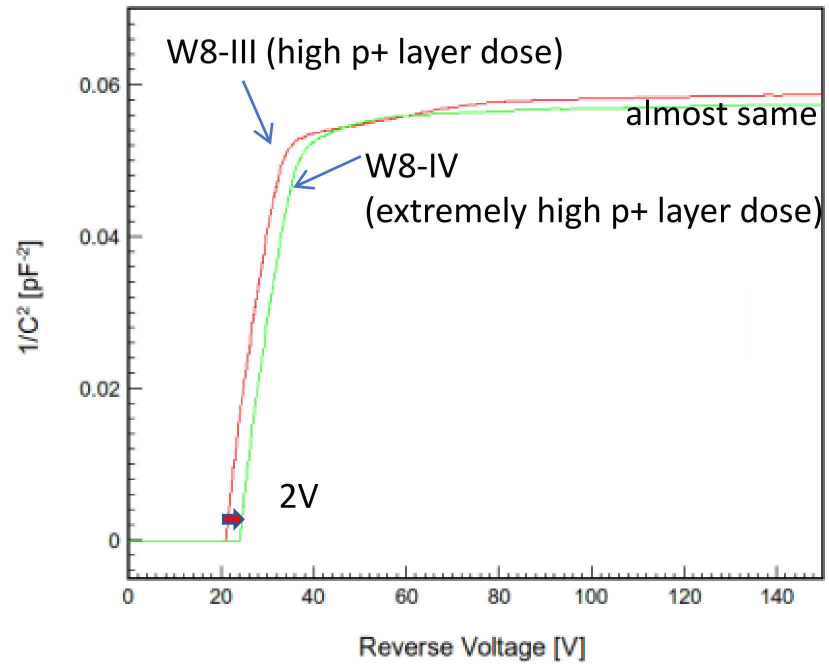
- Single sensors (W8-IV, extremely high p+ layer dose)with different structures



- ☐ The I-V testing results of single sensors(W8-IV) with different structures(inner pad gap and guard rings) are almost the same, which fit with simulation.(before irradiation)
- ☐ More testing will be done about 2x2 array with different structures .

C-V measurement

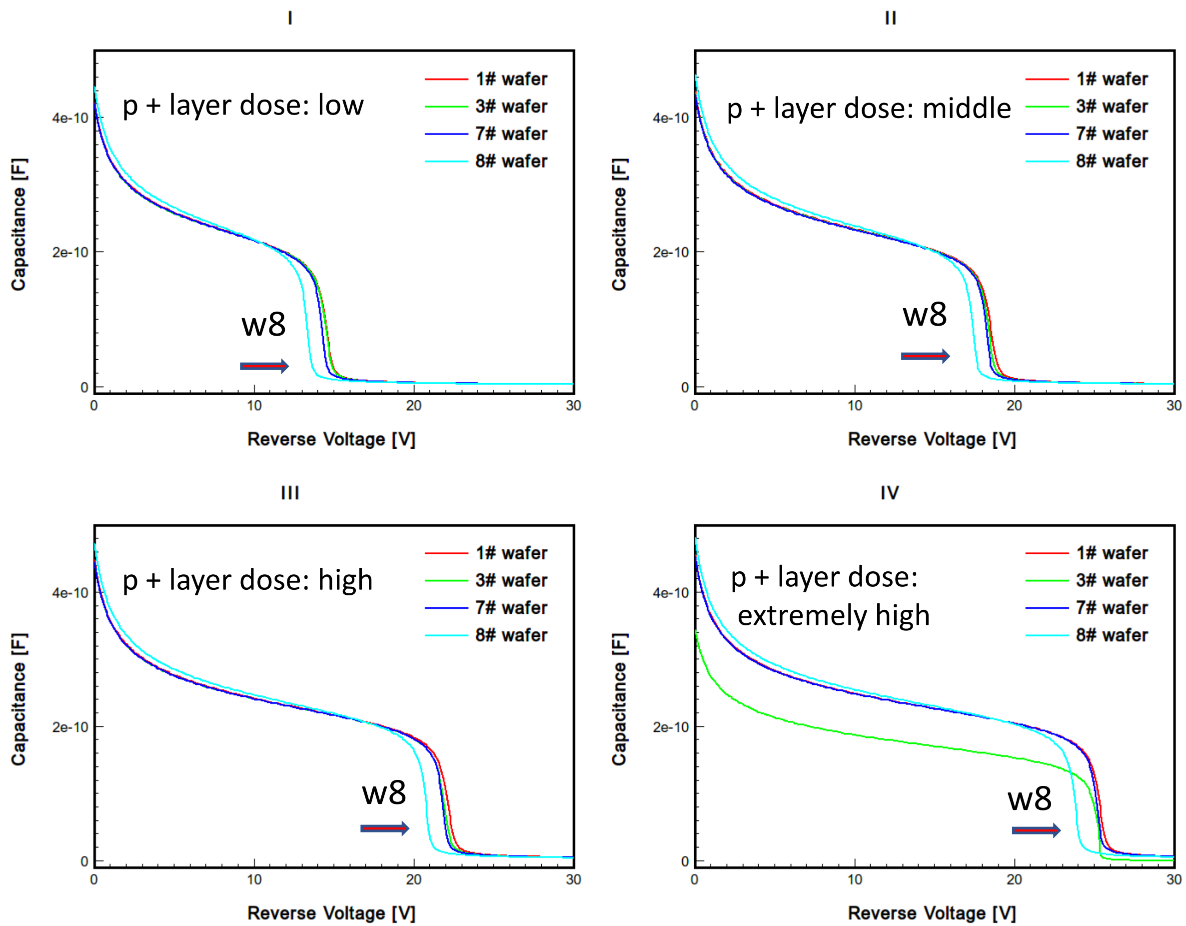




- Gain layer depletion voltage (V_{GL}) increase with p+ layer dose up.
- V_{GL} from testing results are about 2-3V lower than simulation.
- Capacitance at depletion voltage is about 4.1pF, while the capacitances with different p+ layer dose are similar at depletion voltage .

C-V measurement

Same quadrants

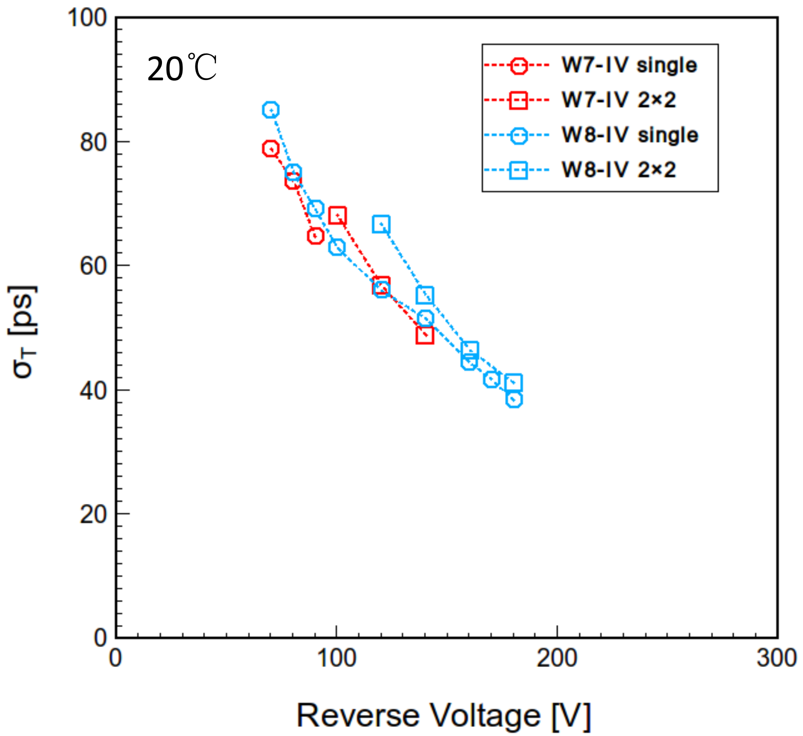


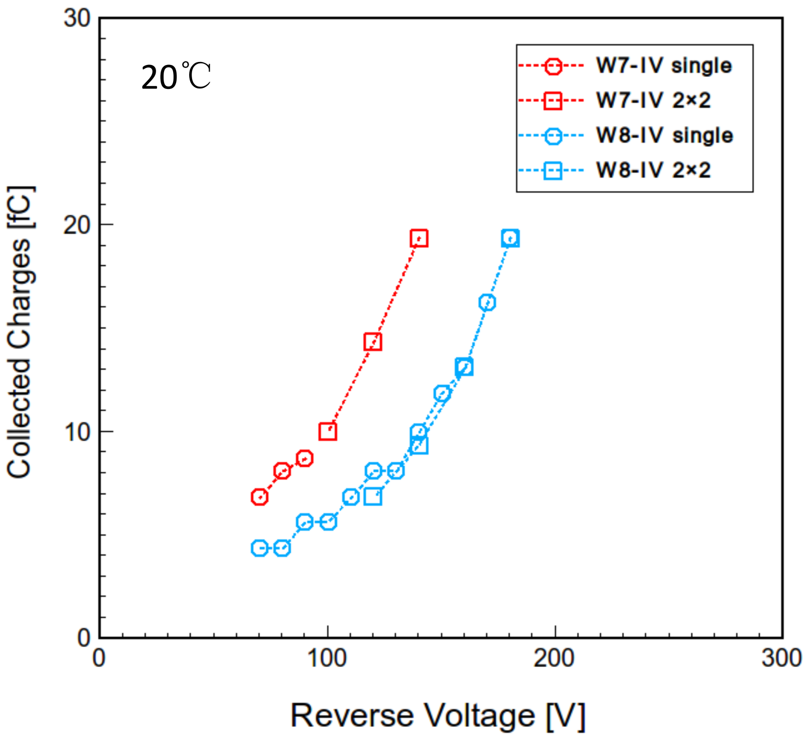
- Process demonstrates good uniformity based on W1, W3 and W7 C-V measurements(having same gain layer doping profile).
- W8 with higher energy for n++ layer implantation has lower $V_{GL.}$
- Carbon implantation has no distinct effects on measured capacitance before irradiation.

Beta testing:

Time resolution & Collected charges

W7-IV V_{BD}=150V **W8-IV V_{BD}=197V** extremely high p+ layer dose, different n++ implantation energy



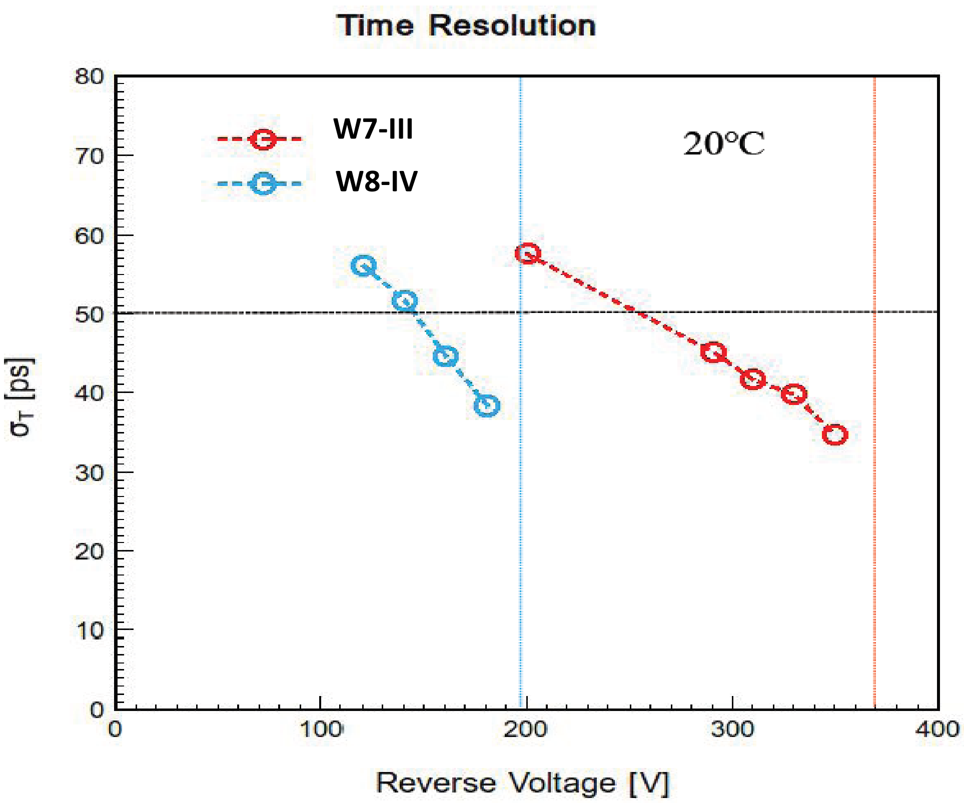


- The time resolution are better than 50ps, the collected charges are larger than 10fC for both W7-IV and W8-IV(with extremely high p+ layer dose) at room temperature.
- W7-IV(low n++ implantation energy) demonstrates higher time resolution and more collected charges than W8-IV under same collected charges voltage because of the higher electrical field

Beta testing:

Time resolution & Collected charges

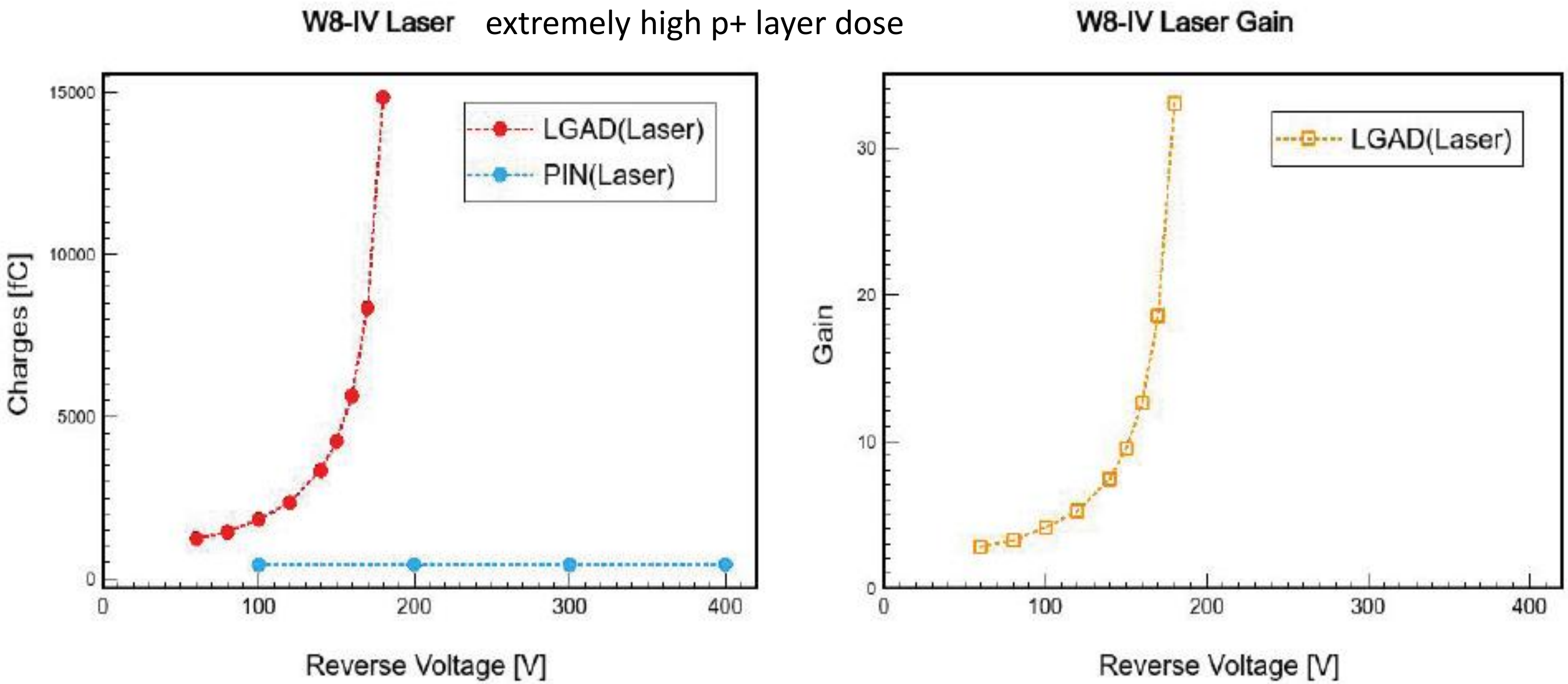
W7-III V_{BD}=370V W8-IV V_{BD}=197V different p+ layer dose



- W7-III (high p+ layer dose)demonstrates higher time resolution than W8-IV(extremely high p+ layer dose) under same collected charges condition, which could interpret by high drift velocity when large bias voltage in W7-III.

Laser testing: Gain

extremely high p+ layer dose

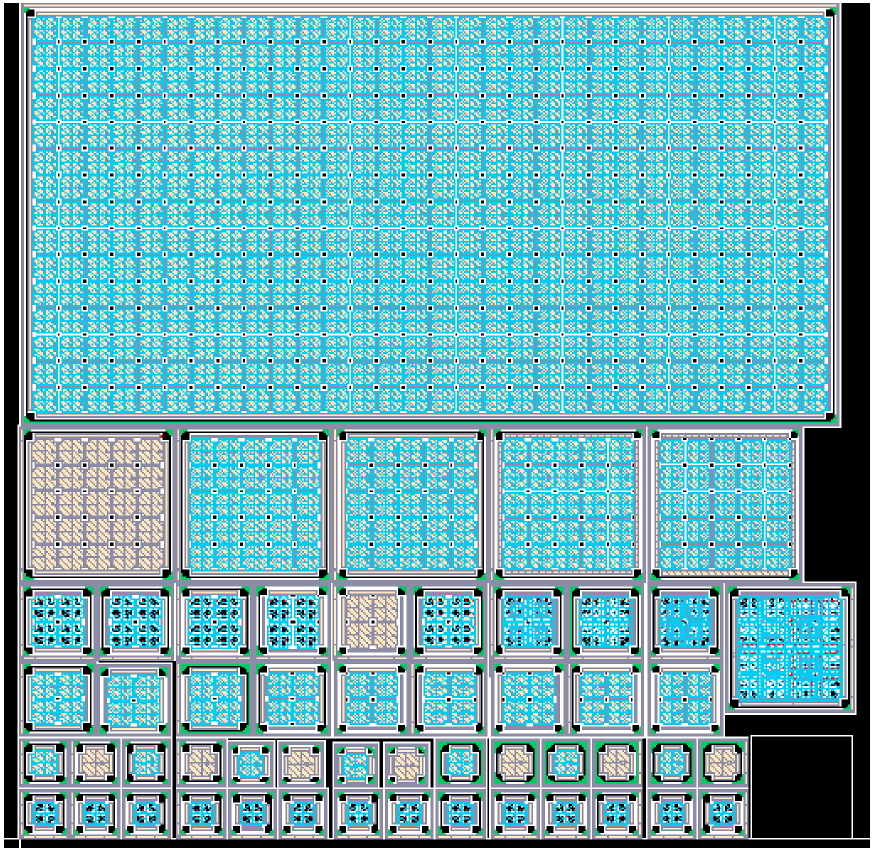


- Gain is higher than 20 for W8-IV(with extremely high p+ layer dose) at room temperature.
- Gain from laser testing is higher than simulation(10) but same as Beta testing results.

IHEP-IMEv2 design

- **Process:** (radiation hardness)
- higher p+ layer dose
- long time annealing
- increase carbon injection dose

- **Structure：**
- Full size sensor:15x30
  bump bonding pad
  (asic_alti_final GDS file)
- 5x5 sensors
  with different inner pad gap
  (50um, 70um, 100um,120um,150um)
- 2x2 sensors
  with different inner pad gap and Guard rings
- Single sensors with different Guard rings
- PIN with different Guard rings



Summary and Plan

- Simulation and testing results show that the $\mathbf{V_{BD}}$ changes as changing the gain layer dose and energy. By increasing p+ layer dose, the V_{GL} can be higher.
- Inner pad gap will affect the $\mathbf{V_{BD}}$ if one pad is grounded and the others are floating in array before irradiation.
- I-V and C-V testing results fit with simulation. While Gain from testing is higher than simulation.
- Wafer 1 with carbon injection shows no increasing leakage current before irradiation.
- The time resolution of IHEP-IMEv1 sensors are better than 50ps, the collected charges of IHEP-IMEv1 sensors are larger than 10fC, and Gain is larger than 20 before irradiation.

Plan:

- Higher dose , long time annealing , carbon injection to increase radiation hardness.
- More measurement will be done about sensors with different structures.
- Proton(CIAE) and neutron(JSI) radiation testing for IHEP-IMEv1 sensors.
- More radiation and large size sensors in IHEP-IMEv2 production, hope to get the sensors early next year.

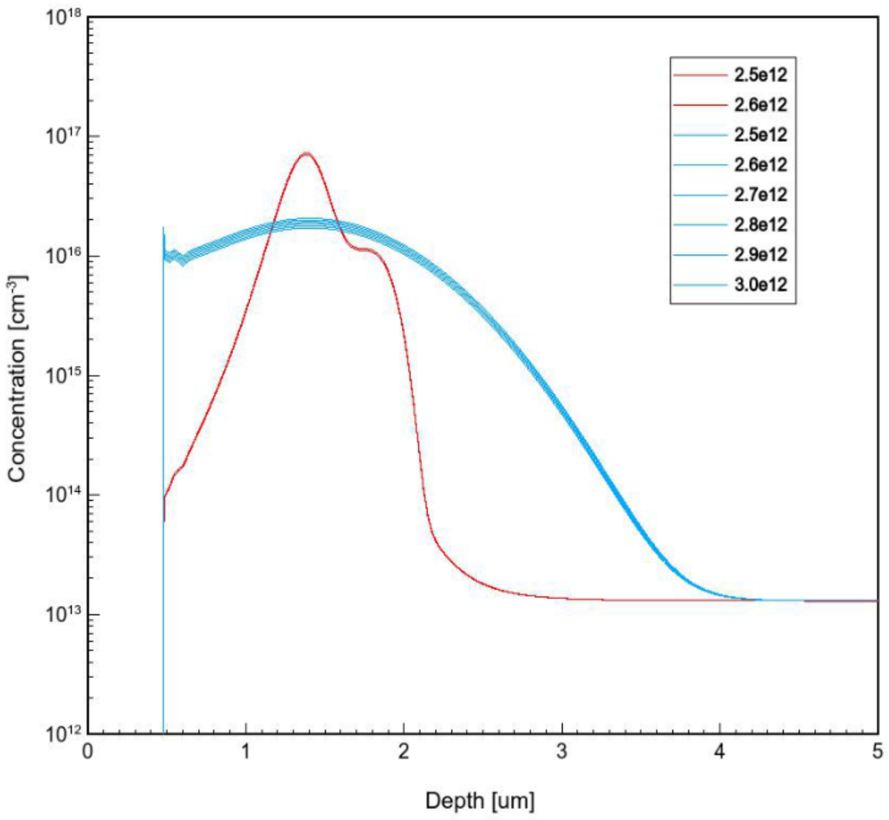
Thanks!
Q&A

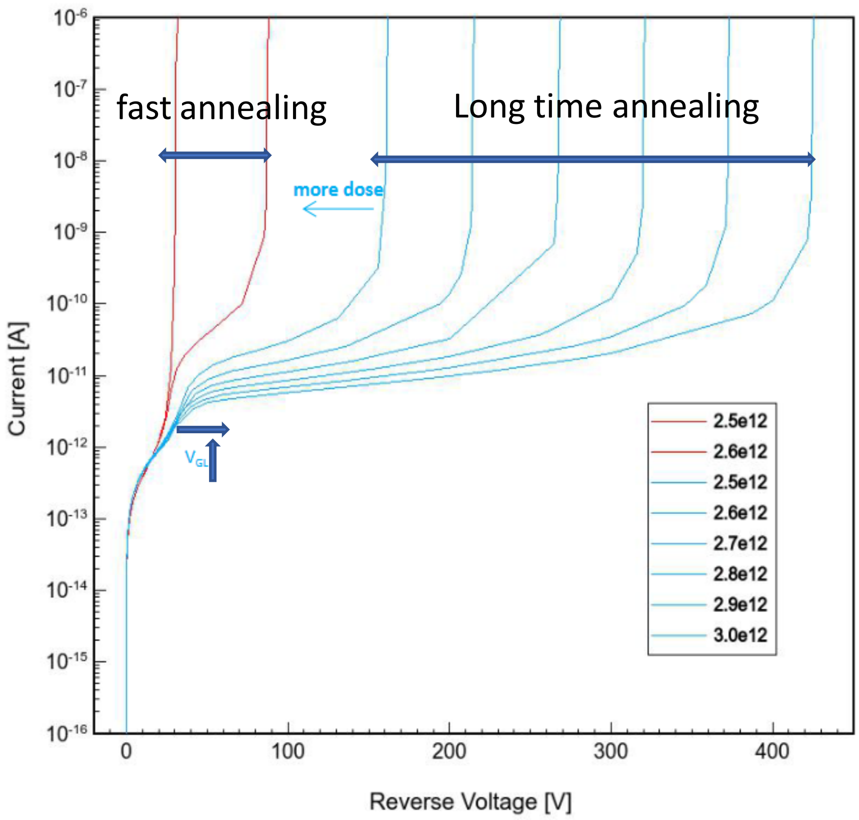
Backup

IMEV2

Red line : fast annealing

Blue line : long annealing (1150C 60min) -> deeper & higher dose





- Next step : V_{GL} from simulated CV, gain

Backup

- 5x5 array