Radiation hard ultra-fast LGAD sensor R & D

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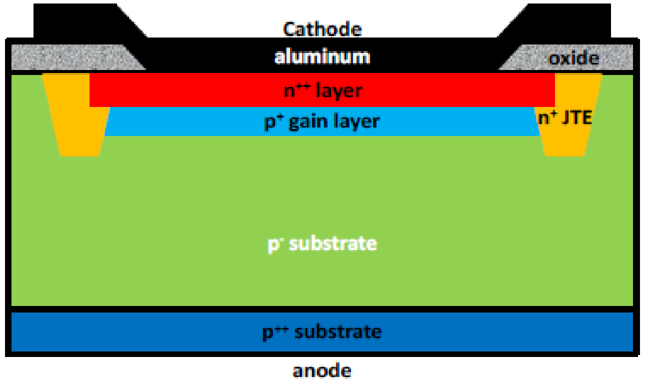
outline

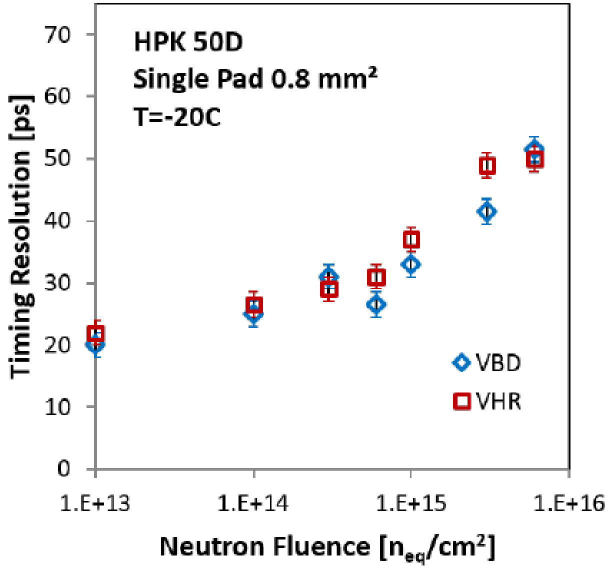
- LGAD-timing detector
- Specification of LGAD for ATLAS HGTD project
- IHEP LGAD sensor development
- Results of IHEP-IMEv2 LGAD sensors
- Design of IHEP-IMEv3
- Summary

LGAD

Low Gain Avalanche Detectors(LGAD) is an avalanche PN diode which work below breakdown voltage(liner mode) and with Gain >10 for effectively charge collection. Results show LGAD sensors have timing resolution better than 50ps .



LGAD sensor structure



Timing resolution of LGAD sensors

HGTD

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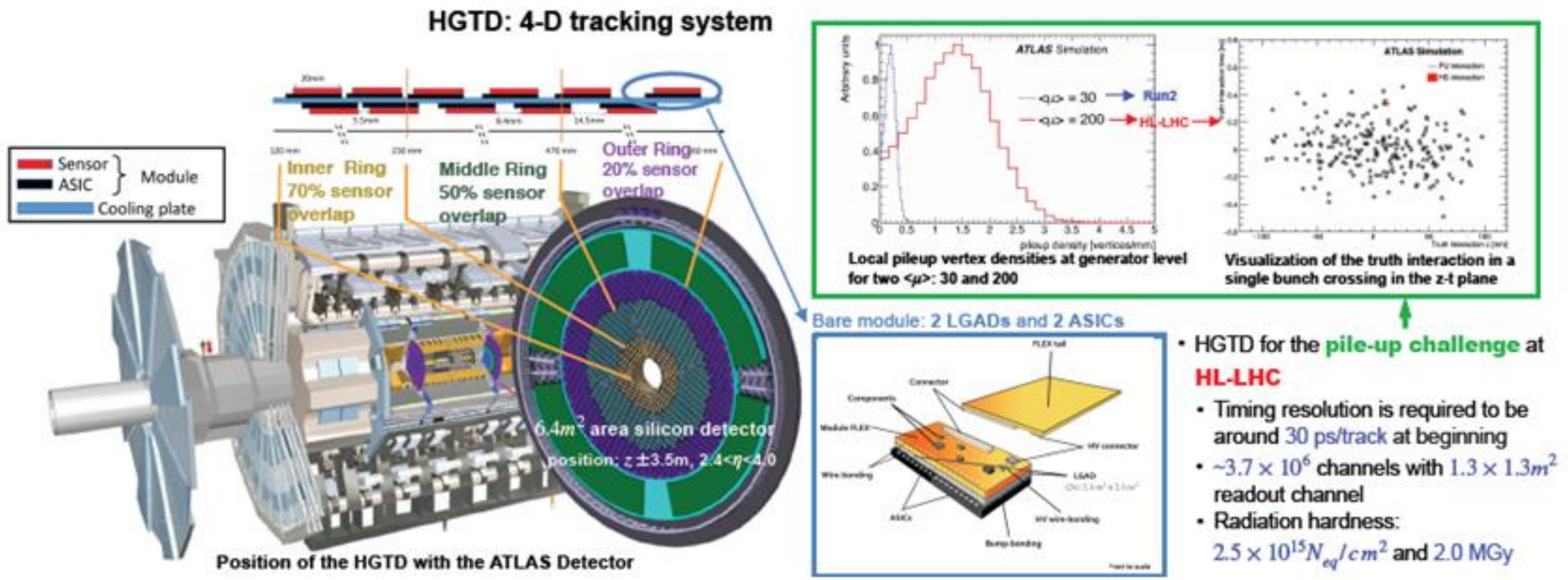
- High precision timing (per-track resolution of 35-50ps up to 4000 fb-1) to mitigate pileup effects and improve the ATLAS performance in the forward region ($2.4 \le |\eta| < 4.0$)

- Because of its good timing performance, LGAD has been chosen as sensors for tracking timing detectors, including ATLAS High Granularity Timing Detector (HGTD) project and CMS Endcap Timing Layer (ETL).



ATLAS HGTD Specification of LGAD

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	Specification
Pad size	1.3 ×1.3 mm^2
Pad array	15 × 15
Substrate	p-type
Thickness (D)	50±5 μm (active) 300±30 μm (total)
HV biasing	back side
Time resolution	~35 ps at Vop (as produced)
Charge collection	>15 fC at Vop (as produced)
Passivation thickness	between 0.8 μm and 5 μm
Bump-bonding pad opening	90 μm diameter
Bump-bonding pad size	95 mm diameter
Inactive edge Dicing chipping Dicing line	<300 μm <20 um 80 um

$2.5e15n_{eq}/cm^2$

Post-Irradiation performance

	Specification
Time resolution	<35 ps (<70 ps) before (after) irradiation
Collected charge	>15 fC (start), >4 fC (end of lifetime)
Maximum pad leakage current	5 μA
Maximum bias voltage at the sensor	800 V

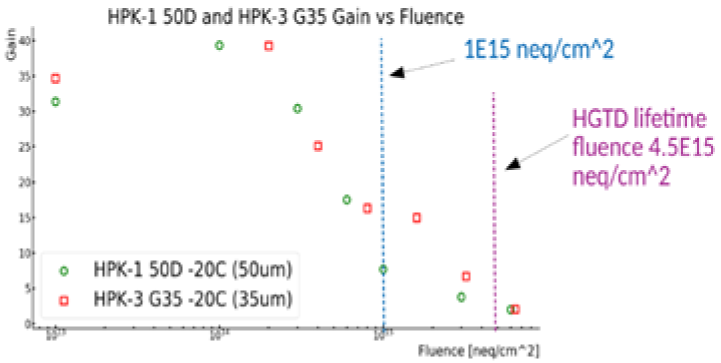
Vgl,pad spread over the sensor	(Max(Vgl,pad)-Min(Vgl,pad))/<Vgl,pad> <0.01
Vbd,pad spread over the sensor	RMS(Vbd,pad)/<Vbd,pad> <0.05
Pad leakage current spread at 0.9·Vbd	Peak-to-Peak within a factor of 3x

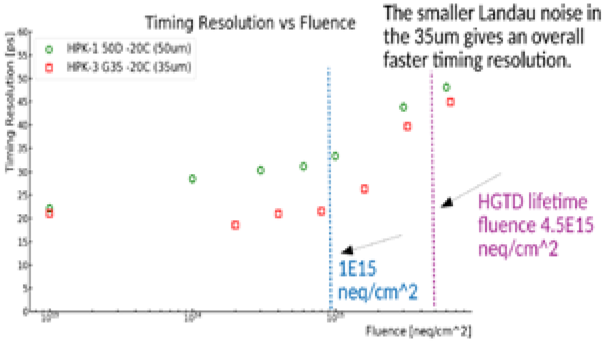
LGAD for ATLAS HGTD

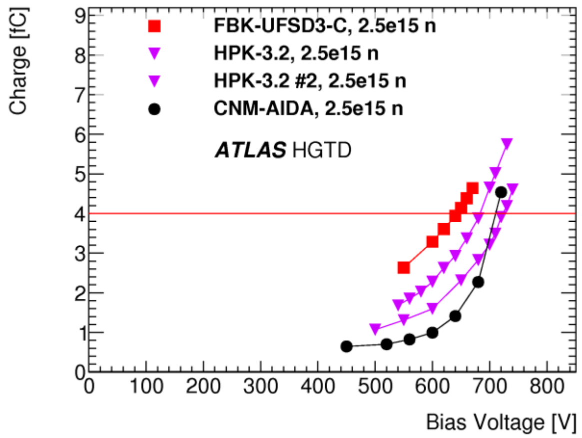
After irradiation Issue:

➢The major limitation for their use is radiation damage

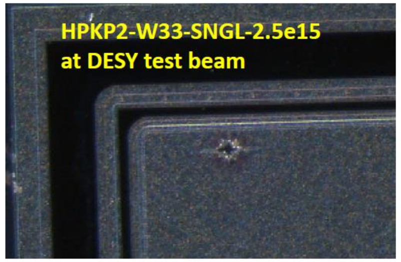
- ➢ Gain decreases and timing performance change worse as increasing the irradiation fluence [Acceptor removal]
- ➢ high voltage needed to get enough charge after 2.5e15 n irradiation was large than 600V
- ➢ mortality problem during beam testing







Higher than 600V voltage for 4fC charges (higher electrical field)

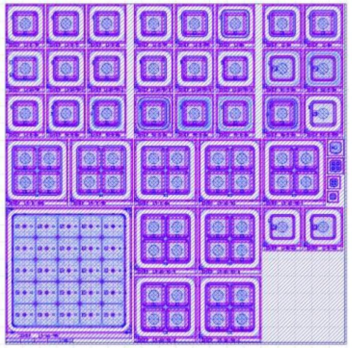


It is observed that destructive breakdowns of sensors at very high bias voltage ~600+/-50V for 50um thick detectors in the test beam

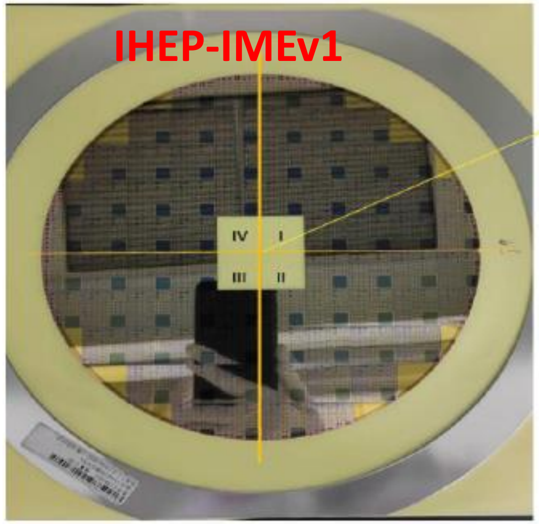
IHEP LGAD sensor development

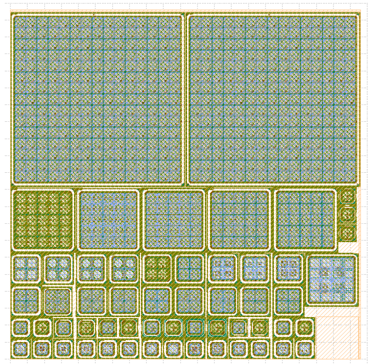
◆IHEP-IME sensors:

- IHEP-IMEv1 was submitted in May 2020, finished in September 2020
- IHEP-IMEv2 was submitted in January 2021, finished in April/June 2021
- IHEP-IMEv3 is under fabrication

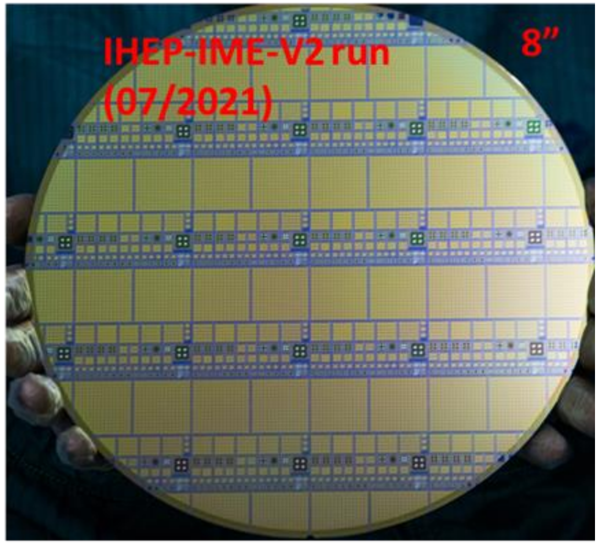


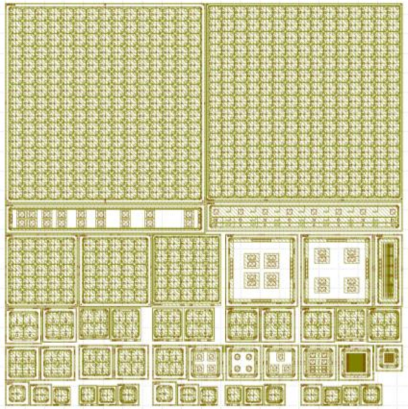
IHEP-IMEv1 Layout





IHEP-IMEv2 Layout





IHEP-IMEv3 Layout

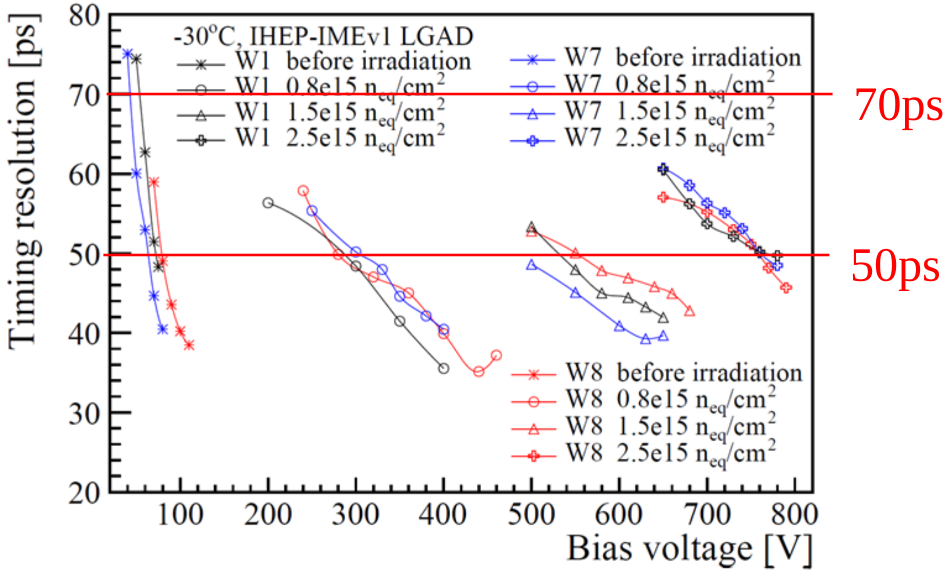
Design and Results of IHEP-IMEv1

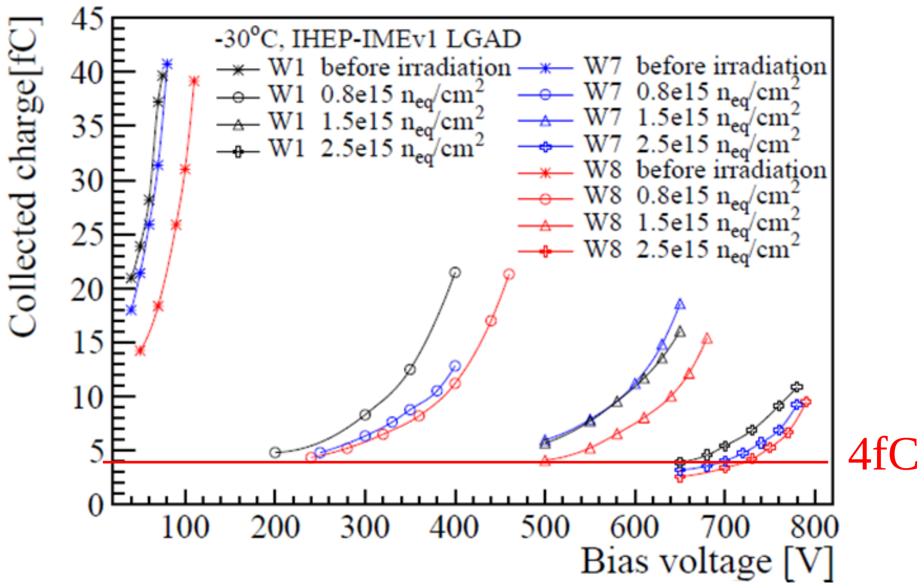
Results of IHEP-IMEv1:

- 8 inch wafers with 50um EPI layer were used.
- 3 wafers have been taped out.

All sensors form IHEP-IMEv1 has time resolution better than 50ps before and after irradiation.

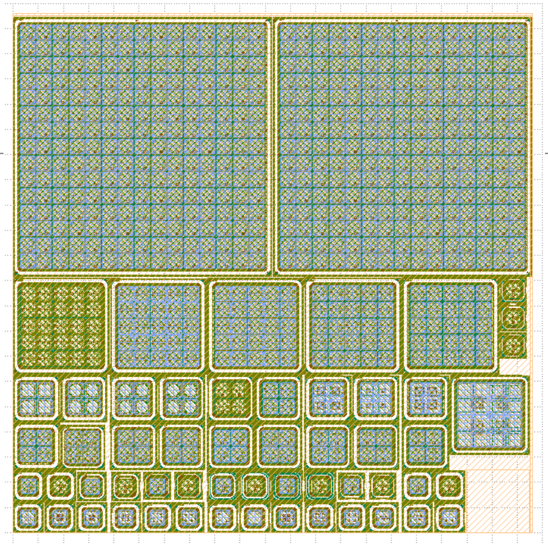
IHEP-IME v1W1 with carbon implantation shows lower voltage for 4fC after irradiation.





Design of IHEP-IMEv2

- IHEP-IMEv2
  - 8 inch wafers with 50um EPI layer
  - Submit at Jan 2021, finish at April, 2021
- Layout: Add 15x15 sensor array
- Process: Carbon injection to improve irradiation hardness



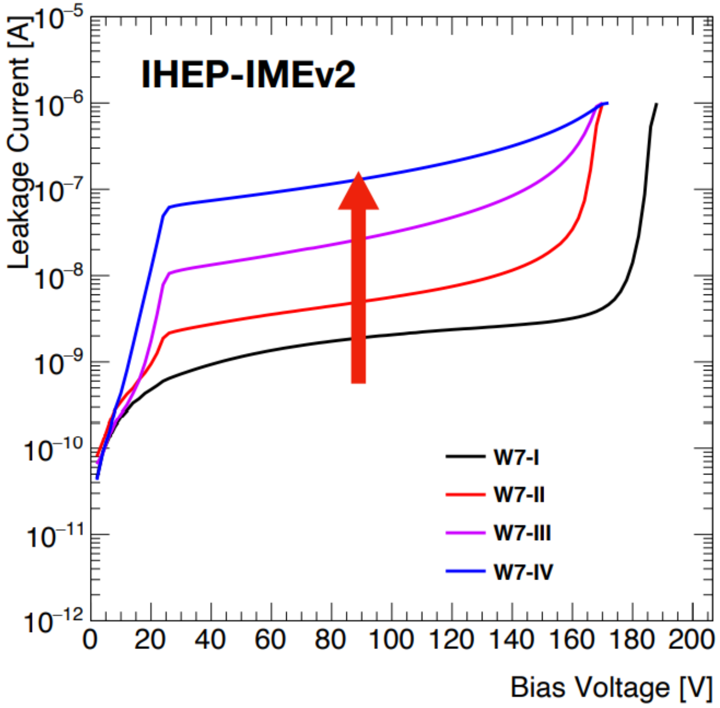
- Three wafers implanted with carbon
- Four quadrants have different carbon dose(I, II, III, IV)

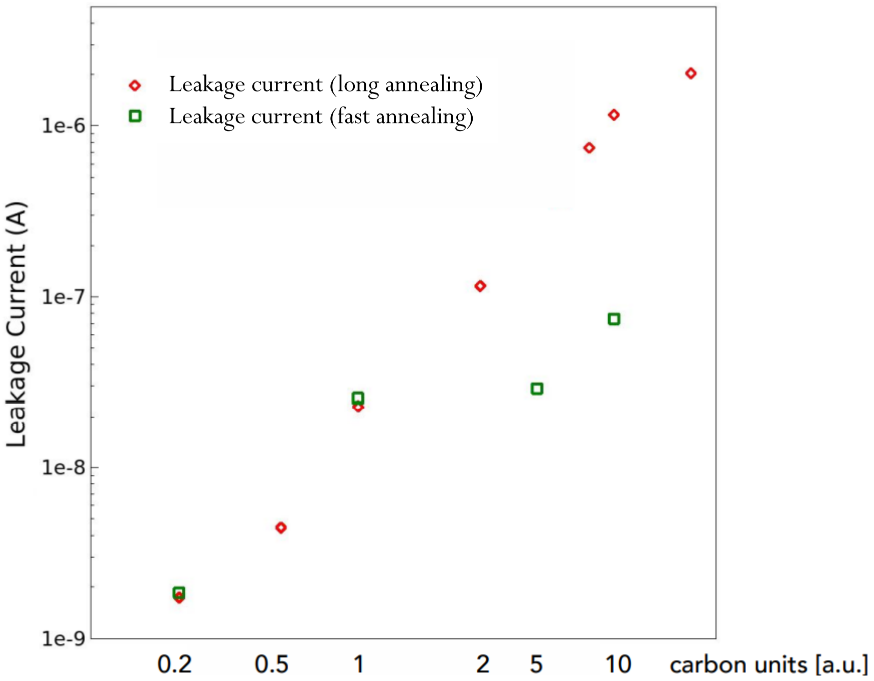
	I	II	III	IV
W4(fast annealing)	0.2	1	5	10
W7 (long annealing)	0.2	0.5	1	2
W8 (long annealing)	3	6	8	10

Carbon dose [a.u.] (noted as "C")

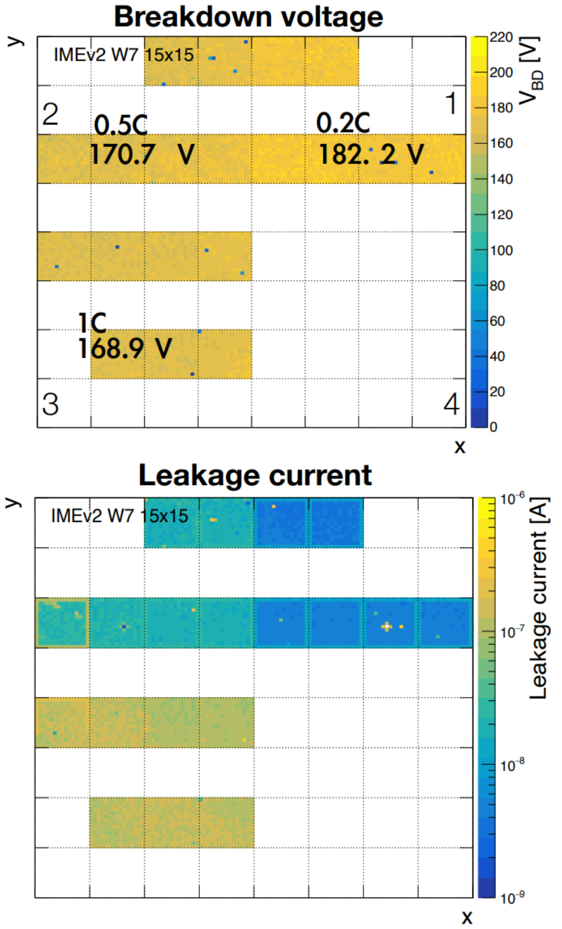
Results of IHEP-IMEv2 sensors

Before irradiation I-V performance





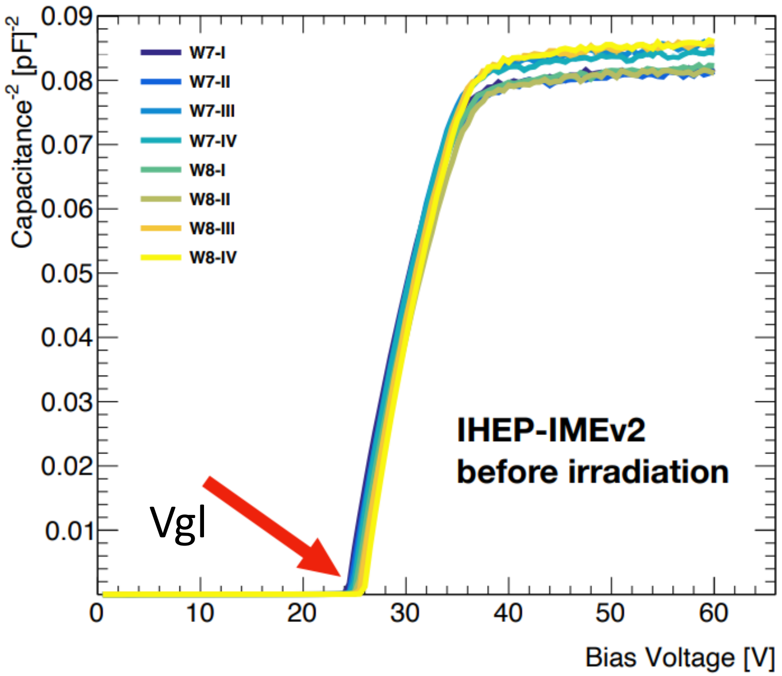
W7:

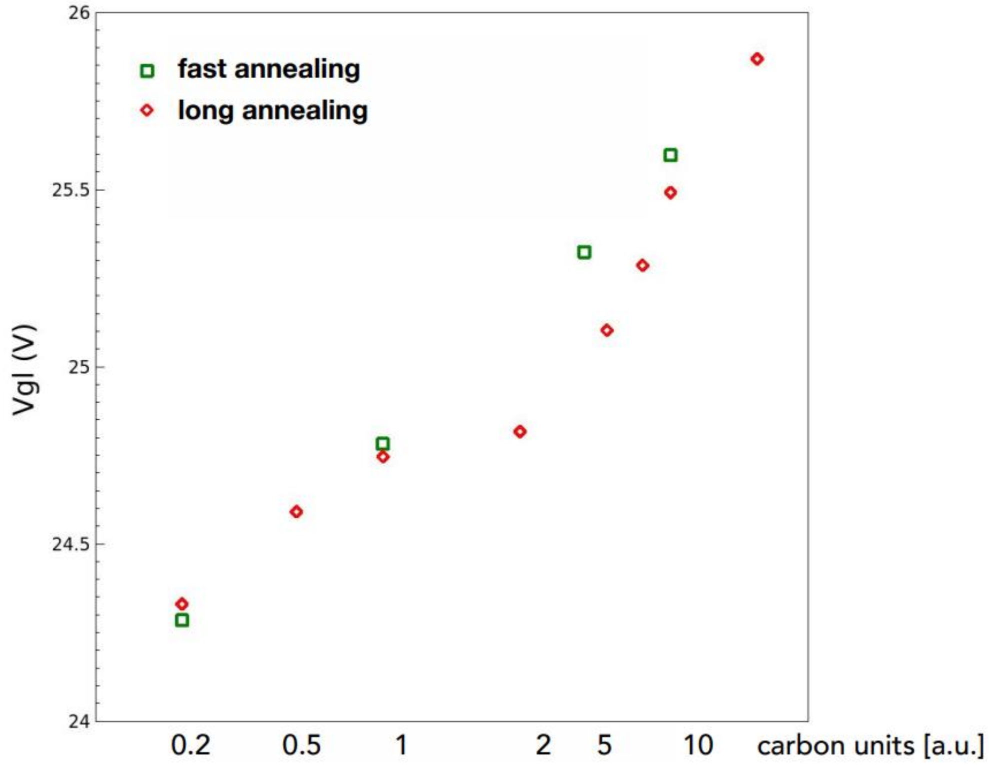


- ➢ Increasing carbon dose: the breakdown voltage decreases, Leakage current increases
- ➢ W4 with fast annealing show lower leakage current (same carbon dose)
- ➢ W4\W7 were chosen for irradiation

Results of IHEP-IMEv2 sensors

Before irradiation C-V performance





- V_{gl} ~24-26V
- V_{gl} increases as increasing carbon dose

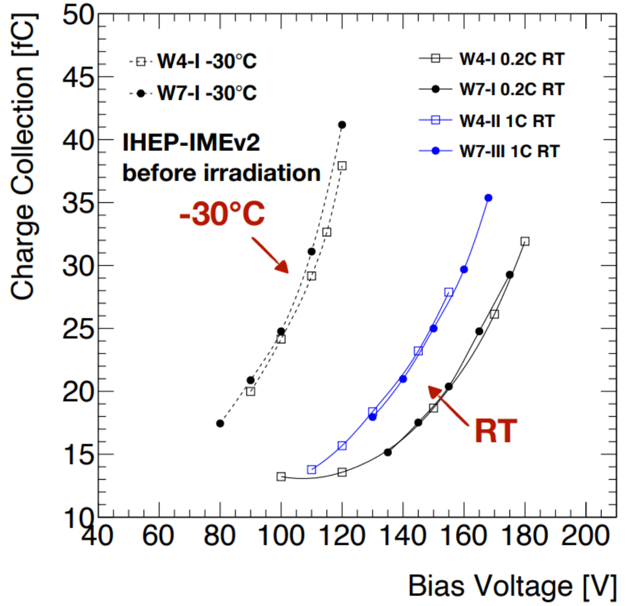
Results of IHEP-IMEv2 sensors

Before irradiation: (RT)

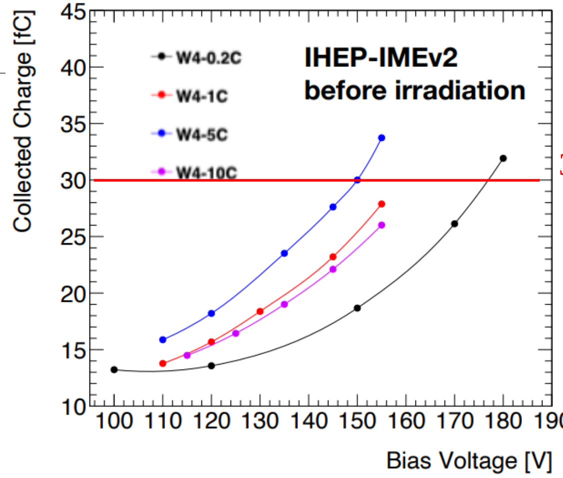
Charge collection >30fC

and time resolution< 50ps

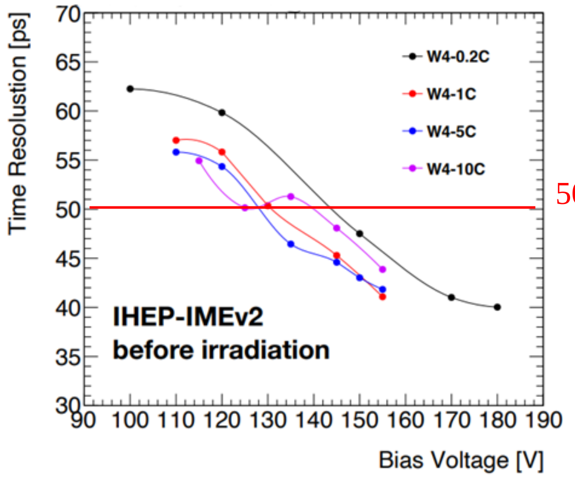
IHEP-IMEv2 W4, W7 comparison



W4

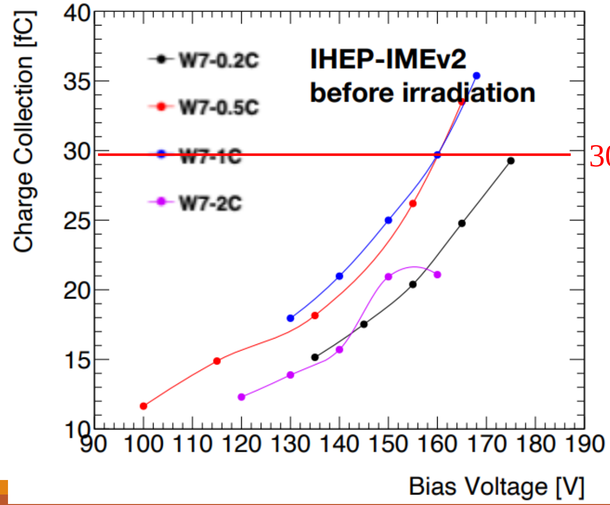


30fC

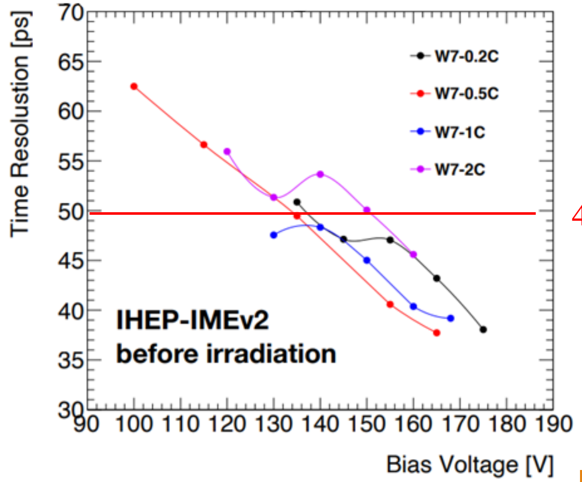


50ps

W7



30fC



40ps

Different annealing methods, same carbon dose, similar collected charge performance before irradiation

Results of IHEP-IMEv2 sensors

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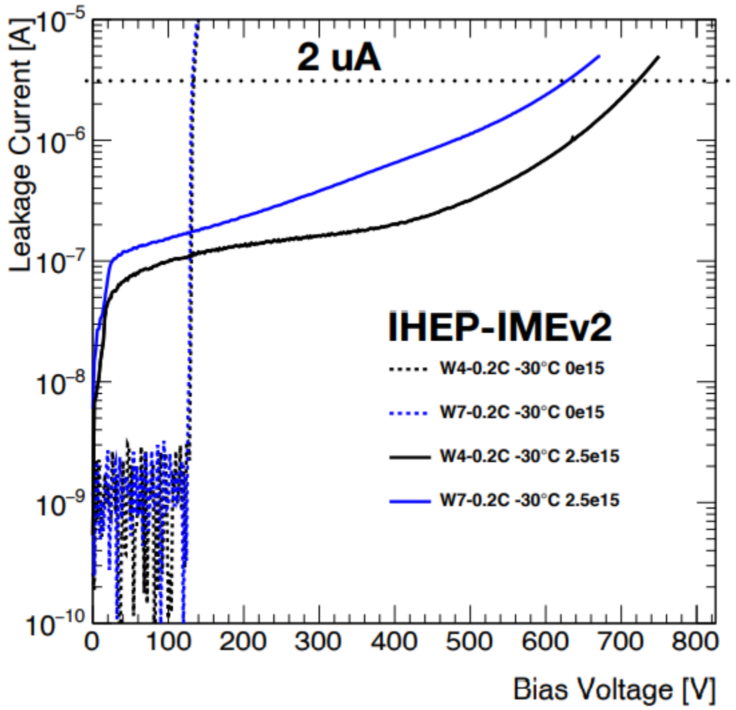
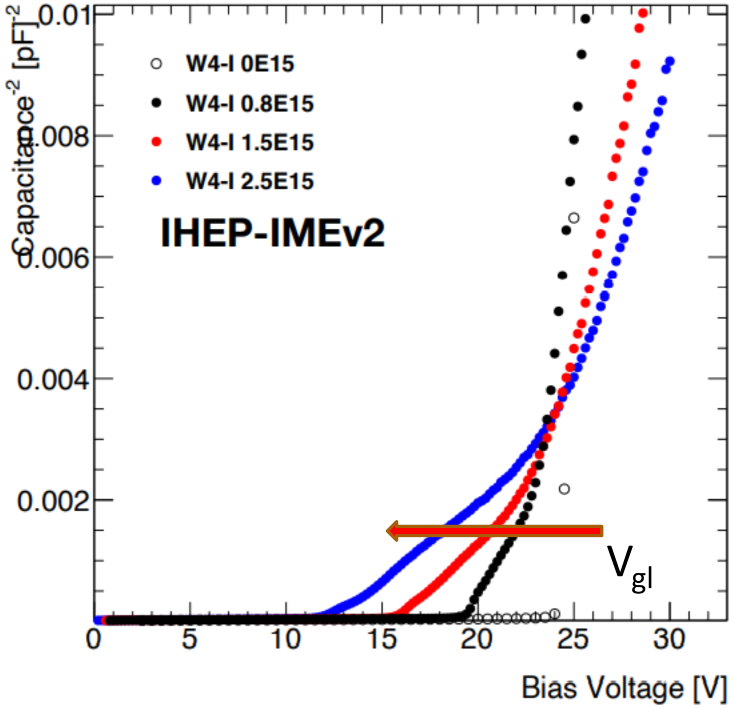
After irradiation I-V C-V performance

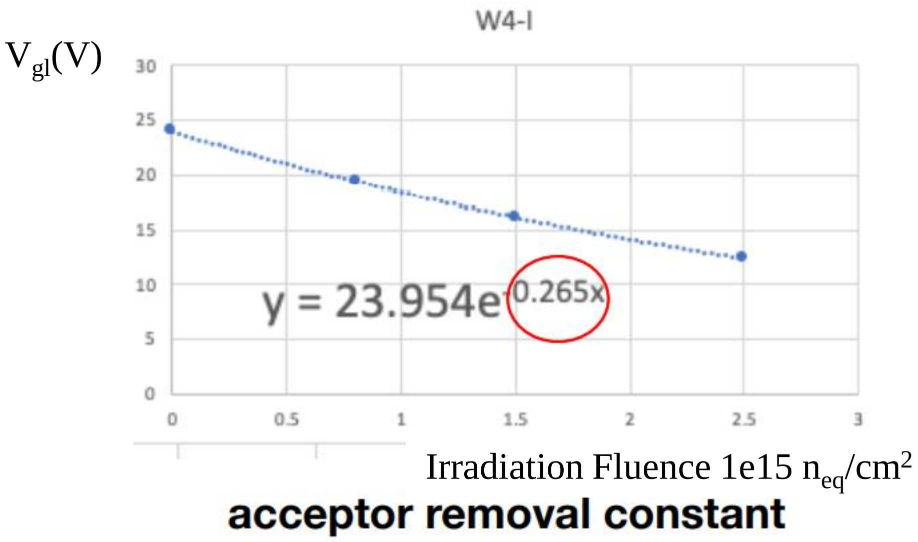


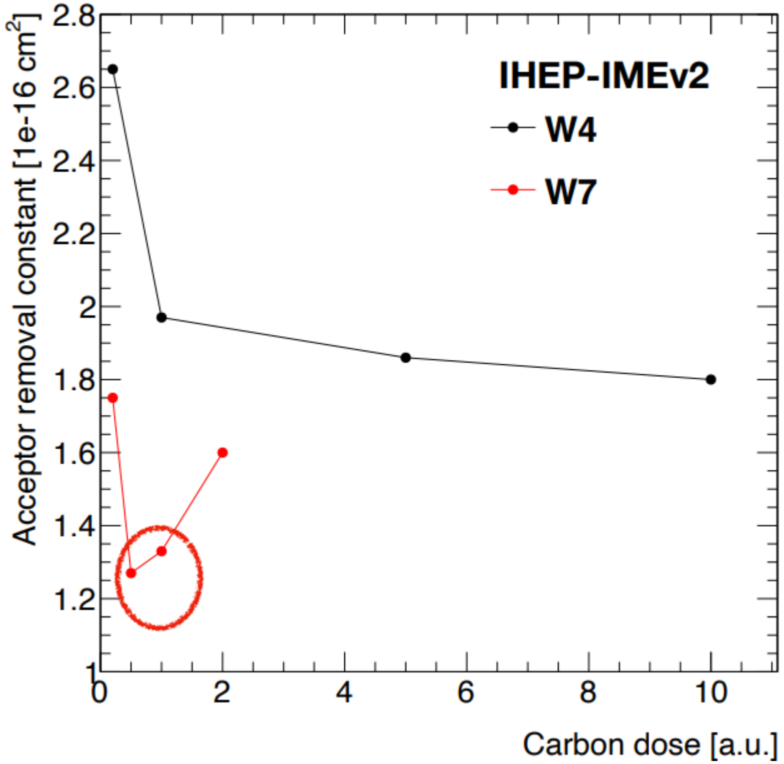


- I-V testing： The leakage current increase nA->100nA (<2uA HGTD requirement)
- C-V testing: V_{gl} decrease with the irradiation fluence

Results of IHEP-IMEv2 sensors

The acceptor concentration is reduced - (Acceptor removal constant)

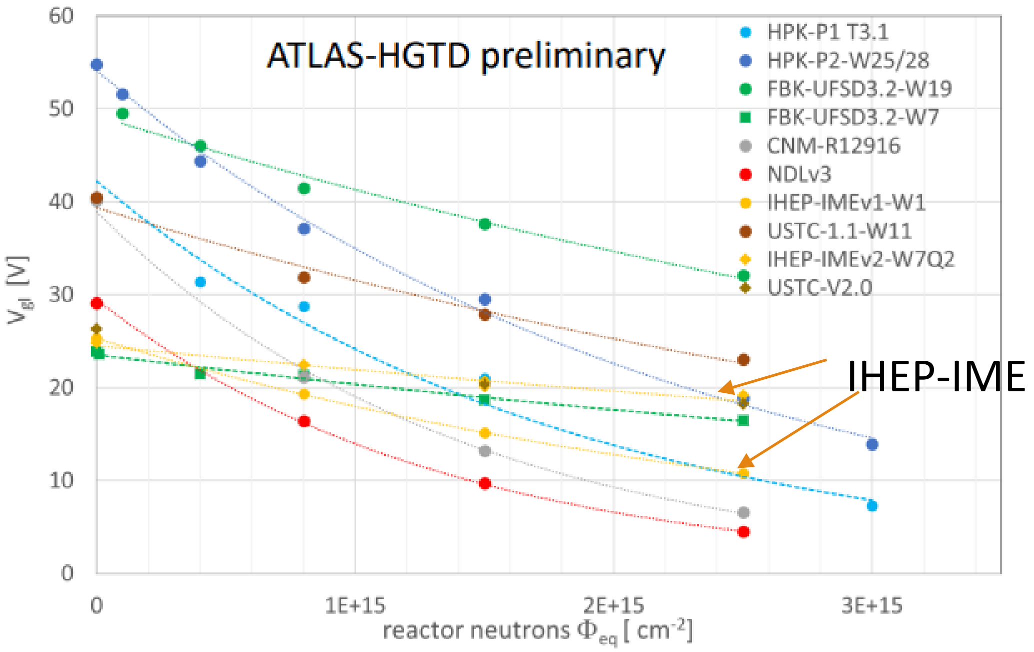


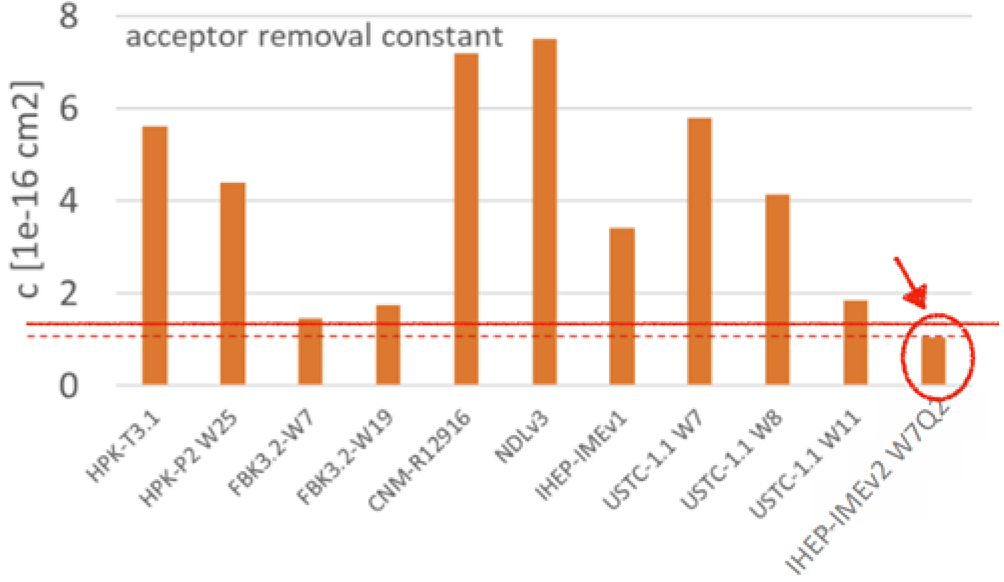


Most acceptor removal constant below 2, the best (W7-II) is about 1.27.
For fast annealing, constant reduces as increasing carbon dose.
For long time annealing, a lowest point shows at around 0.5C carbon dose.

Results of IHEP-IMEv2 sensors

Compare with other sensors:





Acceptor removal constant of IHEP-IMEv2 W7Q2 is lest than other sensors.

Results of IHEP-IMEv2 sensors

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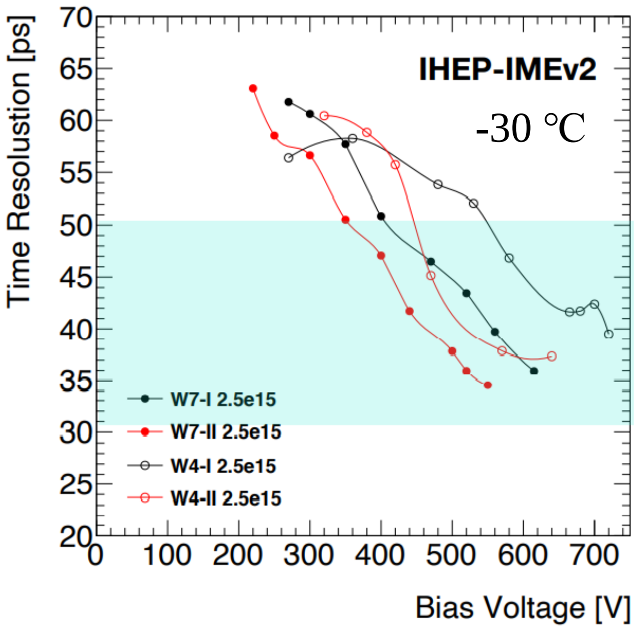
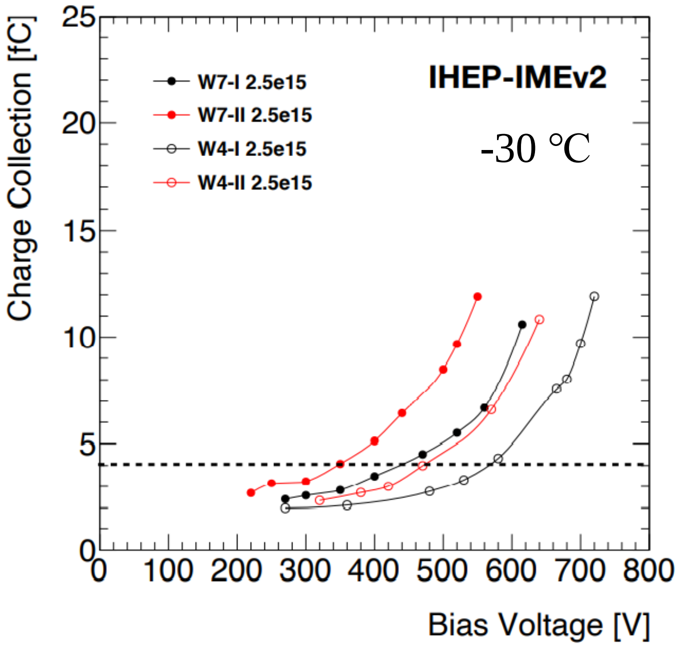
After irradiation, (2.5e15 n_{eq}/cm^2)

For or W7-I, W7-II, with carbon implantation and long-time annealing, the sensors can collected 4fC charge at voltage <450V(around 700V, the timing resolution is better than 50ps

For or W4-I, W4-II, with carbon implantation and fast annealing, the sensors can collected 4fC charge at voltage <560V, the timing resolution is better than 50ps





4 fC at:

W7-II(0.5C): 350 V 50.5 ps

W7-I(0.2C): 440 V 48 ps

W4-II(1C): 470 V 45.1 ps

W4-I(0.2C): 560 V 49 ps

Results of IHEP-IMEv2 sensors

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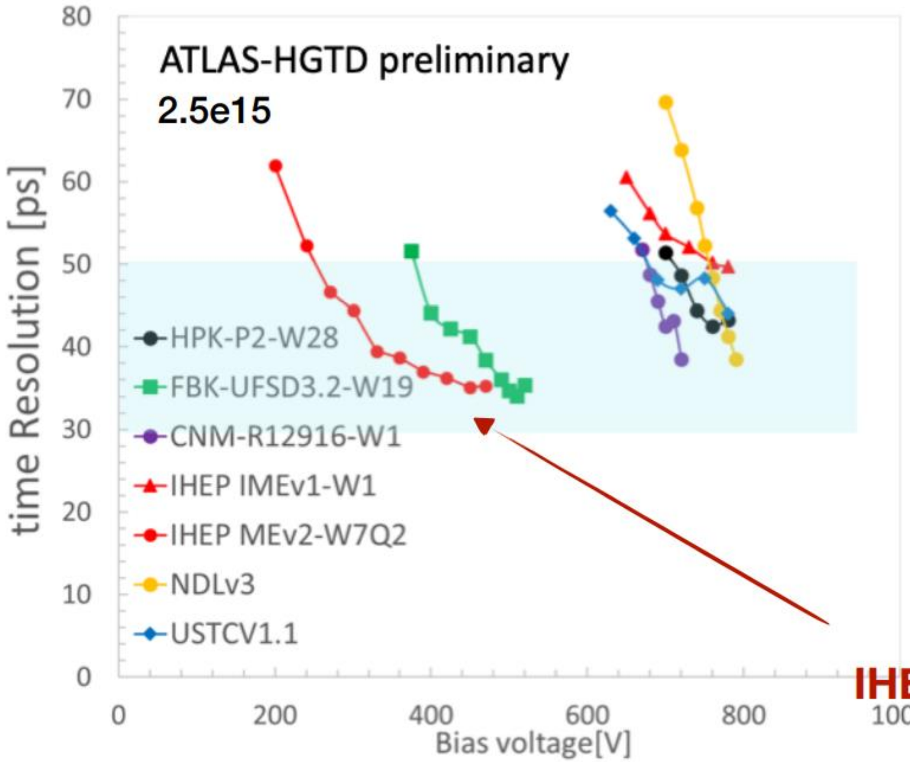
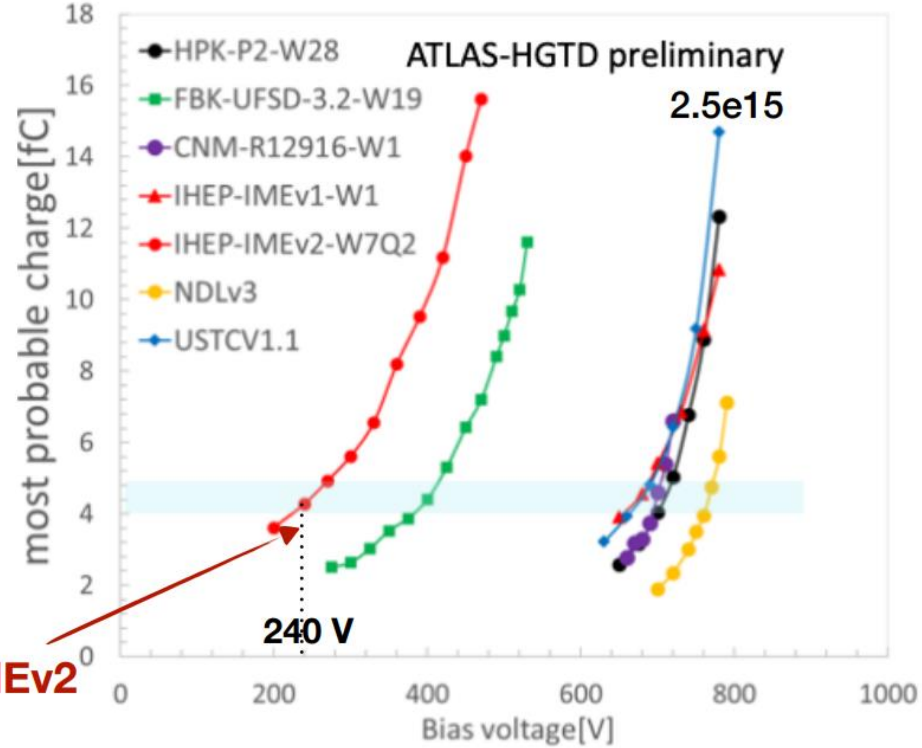
Compare with other sensors：





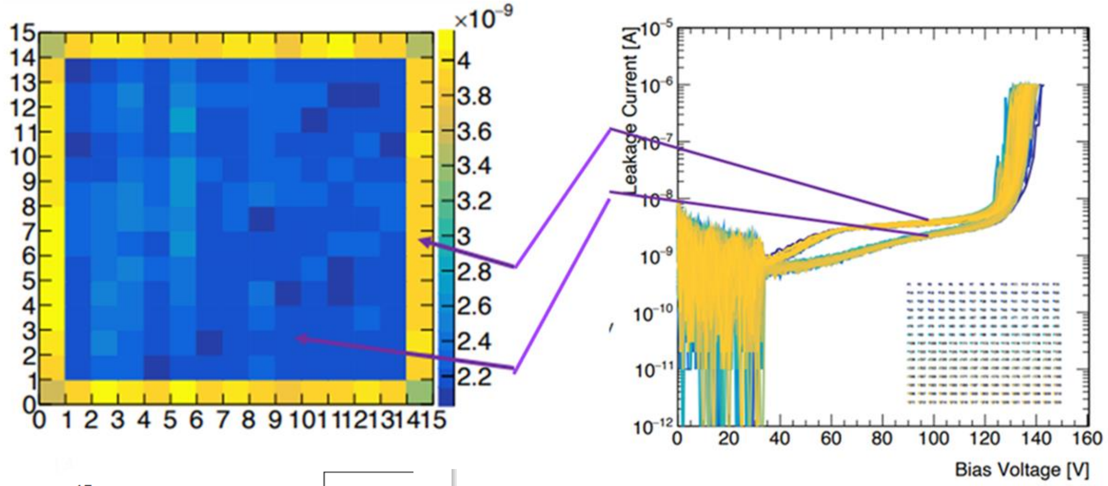
IHEP-IMEv2

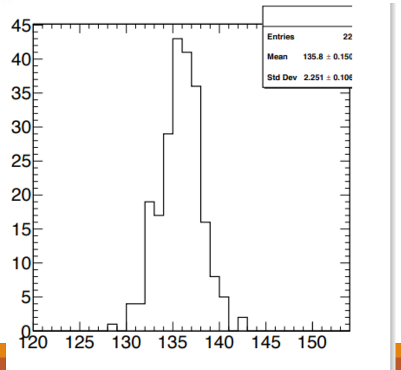
- ➢ The effect of the C-enrichment is clearly very beneficial and allows the sensors to be operated at much smaller voltages.
- ➢ No mortalities were seen from IHEP-IMEv2(w4, w7) sensors with carbon implantation.

Results of IHEP-IMEv2 sensors

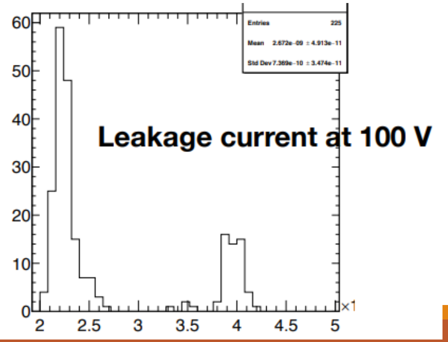
Full size 15x15 sensors:

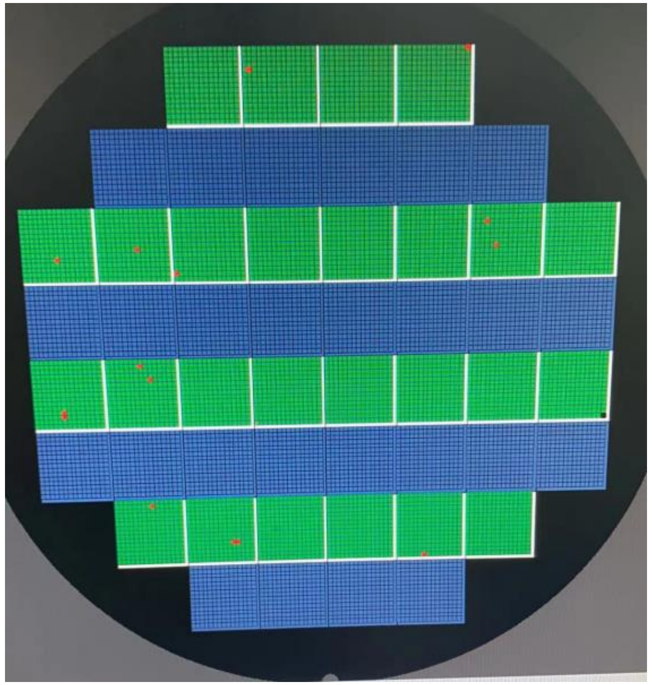
- Good uniformity: BV Spread over 15x15 sensor<4%, Leakage current Spread < 3%
- Yield: Pad yield~99%, 15x15 sensors~50%





BV distribution





Red point: early breakdown

Design of IHEP-IMEv3

Layout of one view field

15x15 sensors (2)

5x5 sensors (3)

With different edge (500um, 300um)

2x2 sensors (13)

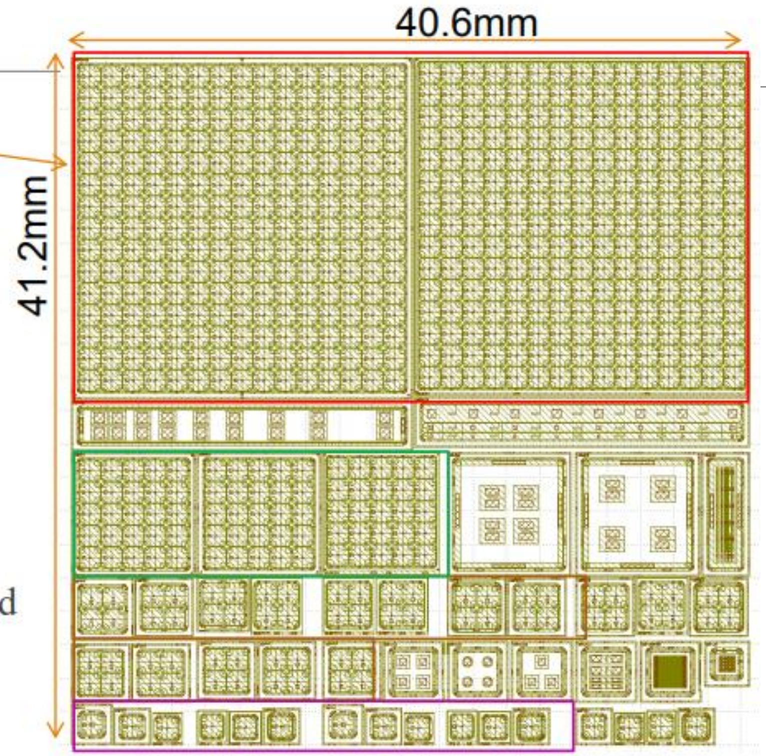
With different IP design (50um, 60um, 70um, 80um, 90um, 100um)

Single sensors (12)

With different edge (644um, 500um, 360um, 300um) and GR design

Others

7 PINs and some AC-LGAD



12 wafers(EPI~50um), 2 wafers(EPI~65um), 2 wafers(EPI~80um)

Optimized carbon implantation and large sensor layout

Summary

- IHEP-NDL sensors and two versions of IHEP-IME LGAD sensors have been fabricated.

- Resent results of IHEP-IMEv2 sensors were shown. IHEP-IMEv2 LGAD sensors with carbon implantation showed promising results for the ATLAS HGTD project before and after irradiation.
- For IHEP-IMEv2, carbon implantation for the irradiation hardness was optimized.W7-II show the best properties after irradiation, collected >4fC charge at voltage< 400V and time resolution is < 50ps.
- At SPS beam testing, no mortalities were seen from IHEP-IMEv1 (w1)and IHEP-IMEv2(w4, w7) sensors with carbon implantation.
- Large size sensors show good uniformity and yield.
- IHEP-IMEv3 is under fabrication.