中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Carbon doped low gain avalanche devices with improved radiation hardness for ATLAS HGTD

抗辐照性能改良的掺碳LGAD器件研究

MEI ZHAO(赵梅)

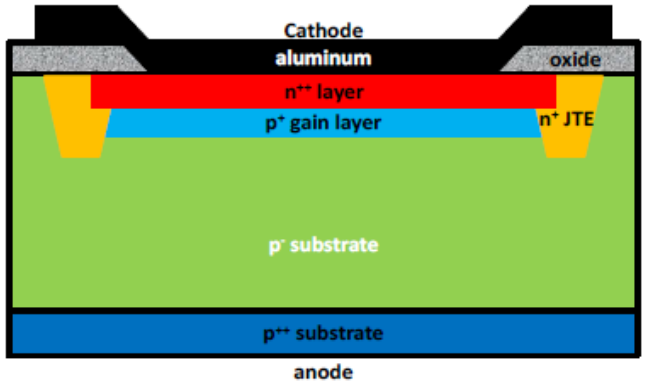
ON BEHALF OF IHEP HGTD SENSOR GROUP

NOV 26, 2021

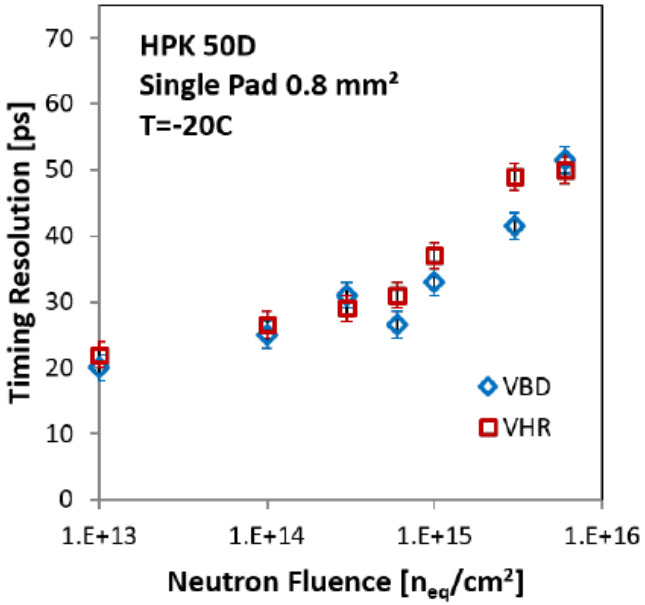
目录

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

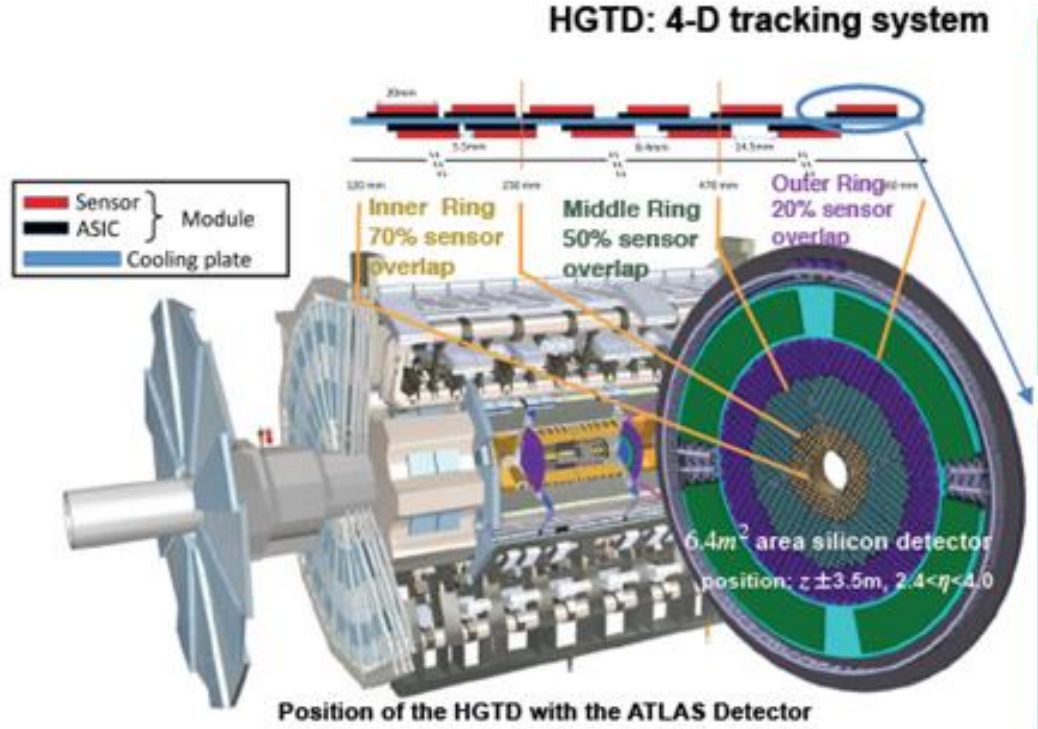


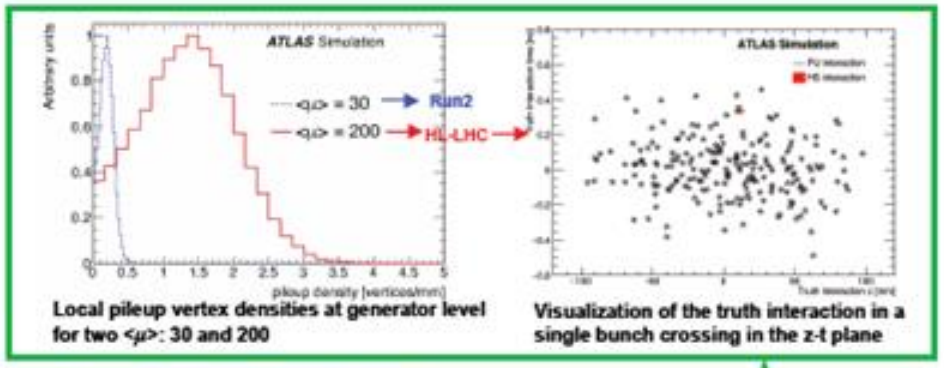
Timing resolution of LGAD sensors

HGTD

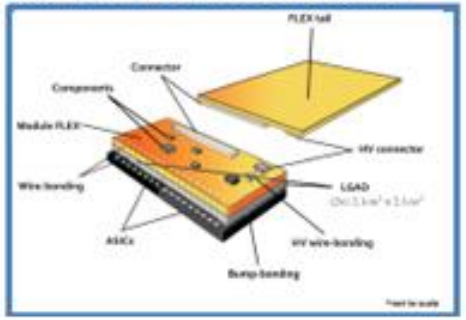
- High precision timing (per-track resolution of 35-50ps up to 4000 fb-1) to mitigate pile-up effects and improve the ATLAS performance in the forward region ($2.4 \leq |\eta| < 4.0$)

- 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).





Bare module: 2 LGADs and 2 ASICs



- HGTD for the **pile-up challenge** at **HL-LHC**
  - Timing resolution is required to be around 30 ps/track at beginning
  - ~3.7×10^6 channels with $1.3 \times 1.3 m^2$ readout channel
  - Radiation hardness: $2.5 \times 10^{15} N_{eq}/cm^2$ and 2.0 MGy

ATLAS HGTD Specification of LGAD

	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

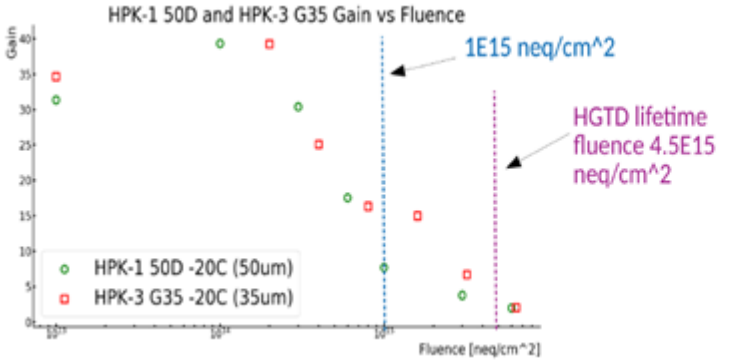
	Specification
Time resolution	<35 ps (<70 ps) before (after) irradiation
Collected charge	>15 fC (start), >4 fC (end of lifetime)
Maximum pad leakage current	5 μA
Maximum bias voltage at the sensor	800 V

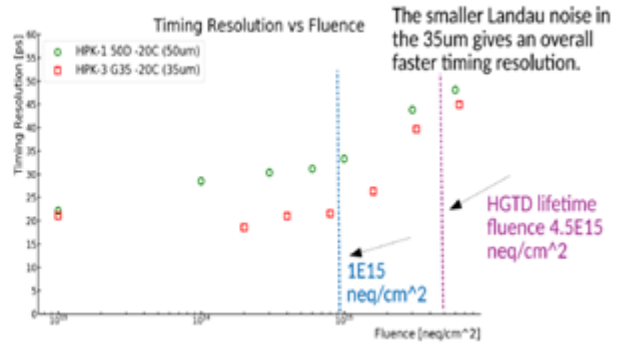
LGAD for ATLAS HGTD

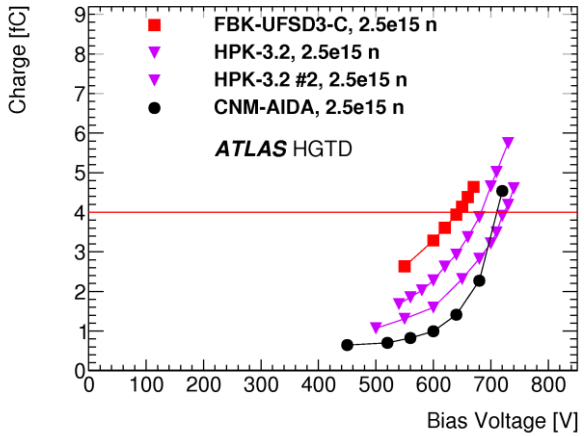
After irradiation Issue: ➢The major limitation for their use is radiation damage 辐照后性能变差与失效问题

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

受主移除效应造成探测器性能下降

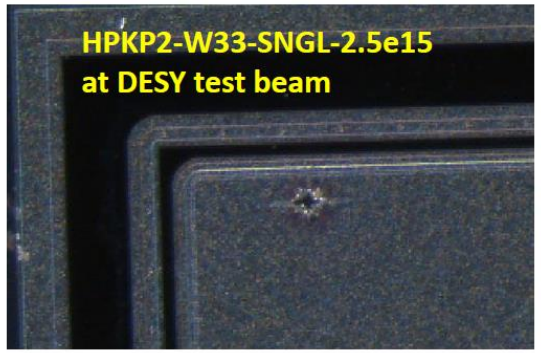






工作电压高

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



单粒子击穿

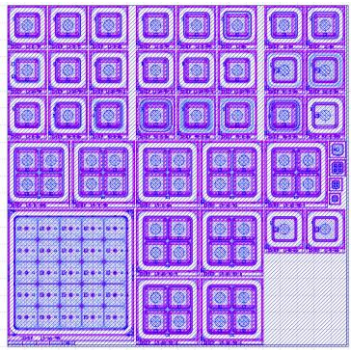
It is observed that destructive breakdowns of sensors at very high bias voltage ~600+/-50V for 50um thick detectors in the test beam

IHEP LGAD sensor design

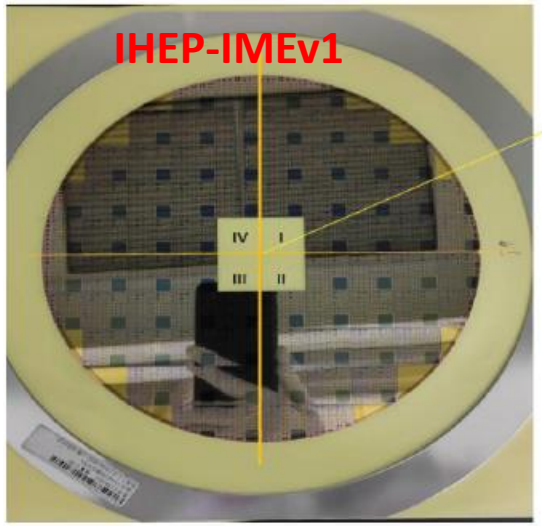
◆IHEP-IME have been produced:

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

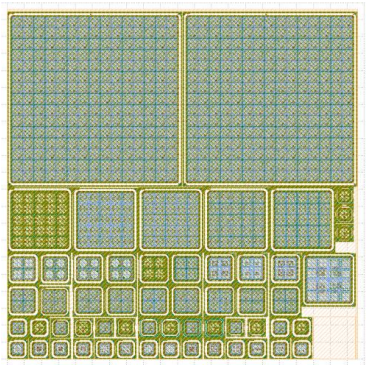
第一版



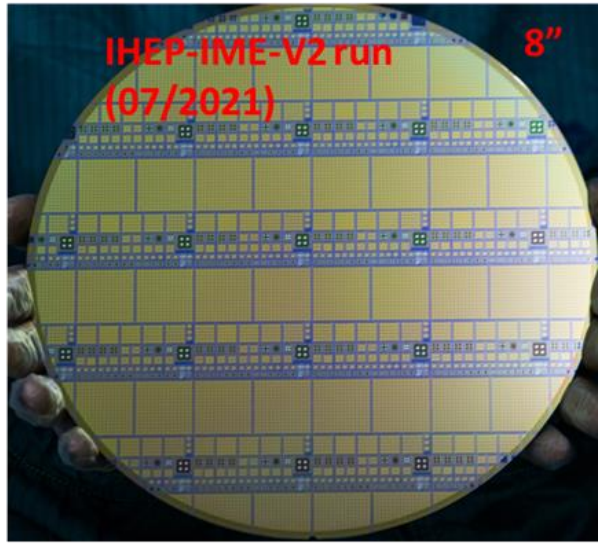
IHEP-IMEv1
Layout



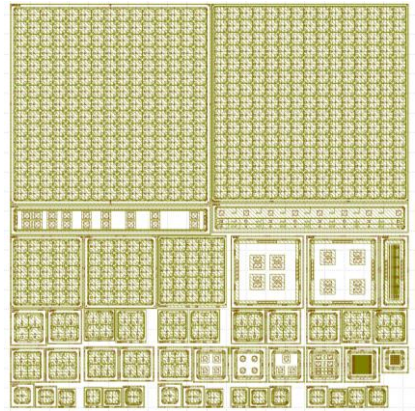
第二版



IHEP-IMEv2
Layout



第三版



IHEP-IMEv3
Layout

Design and Results of IHEP-IMEv1

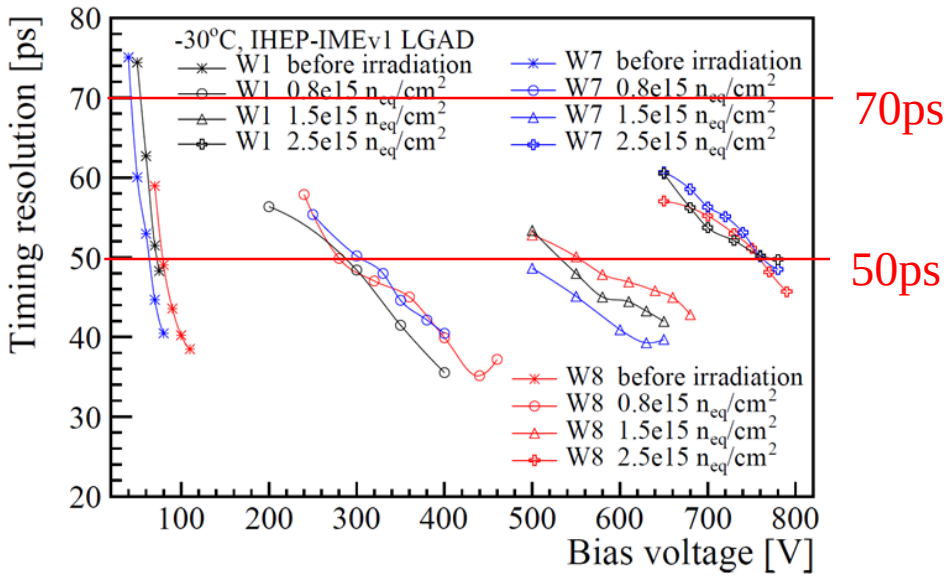
Results of IHEP-IMEv1:

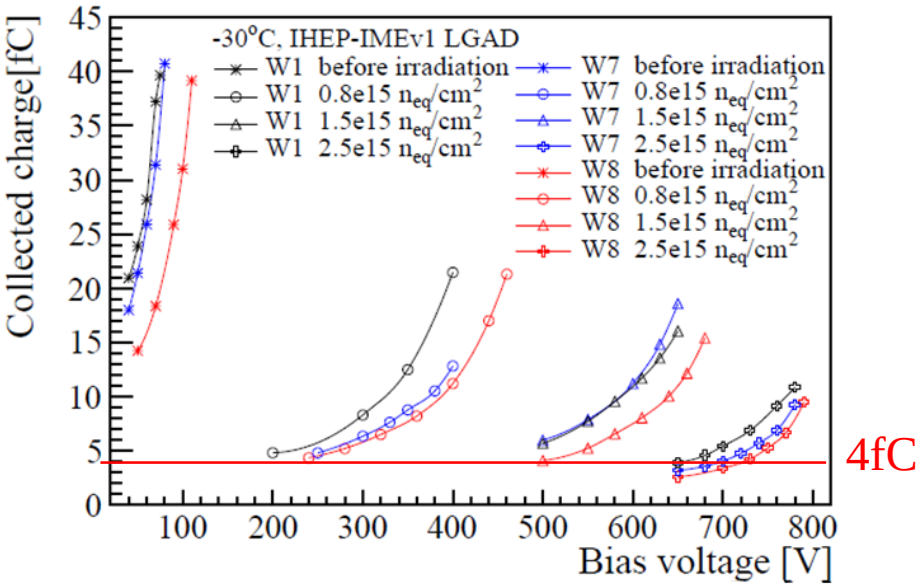
8 inch wafers with 50um EPI layer were used.

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.

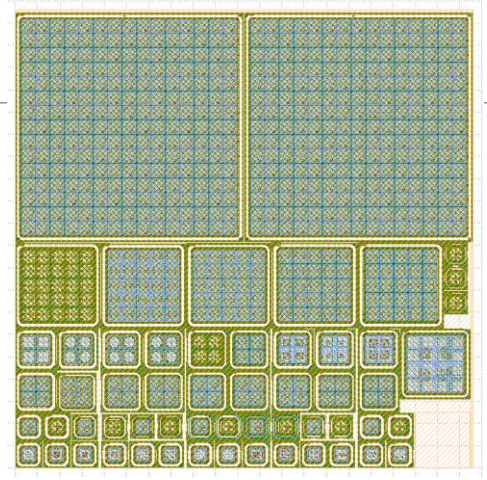




掺碳器件(v1W1)工作电压低于其他器件但仍高于600V，可在DESY束流下长时间工作

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



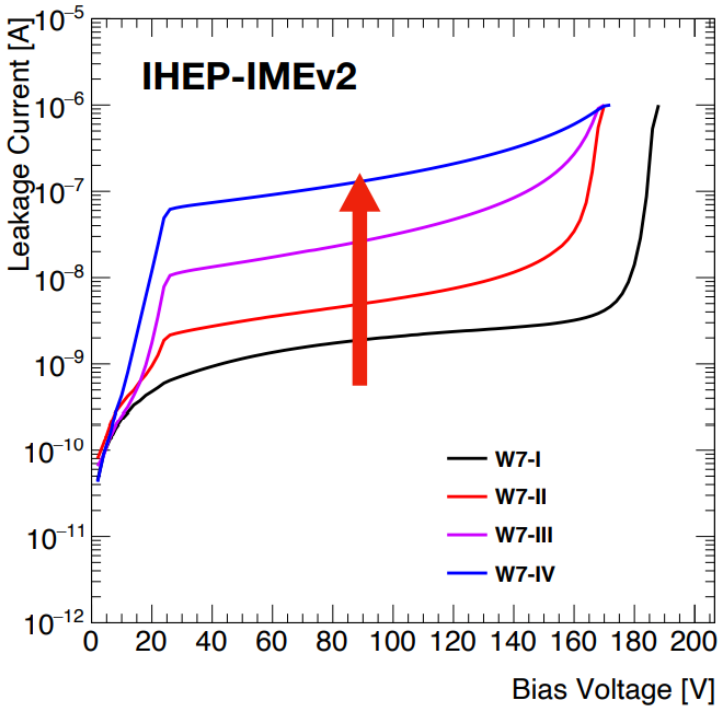
- Three wafers implanted with carbon
- Four quadrants have different carbon dose(I, II, III, IV)

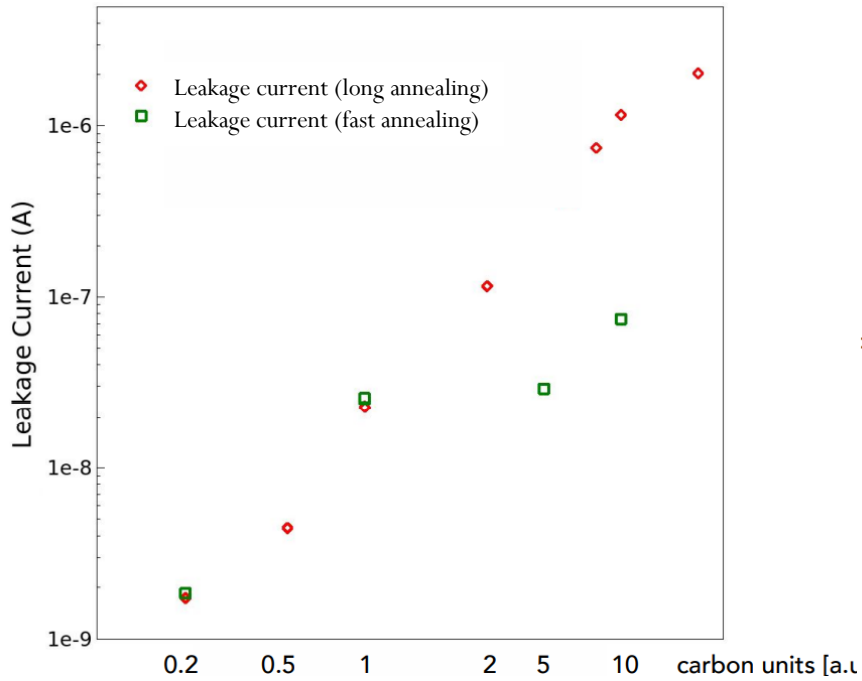
	I	II	III	IV
W4 (fast annealing)	0.2	1	5	10
W7 (long annealing)	0.2	0.5	1	2
W8 (long annealing)	3	6	8	10

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

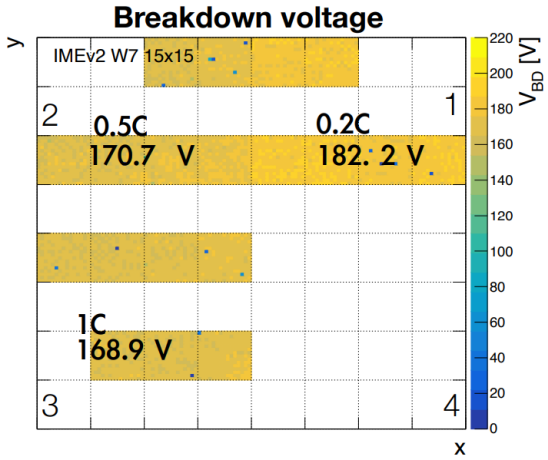
Results of IHEP-IMEv2 sensors

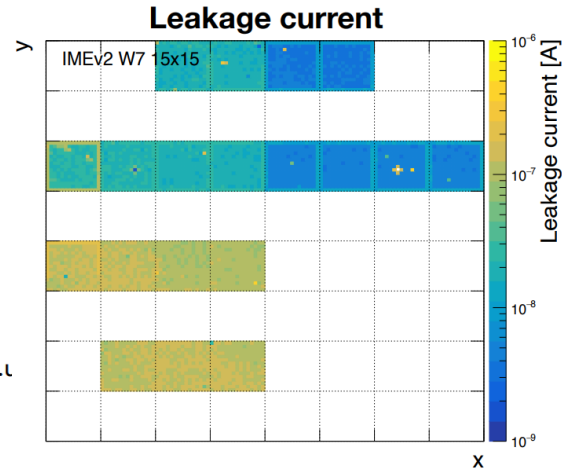
Before irradiation: I-V performance [辐照前I-V特性]





W7:

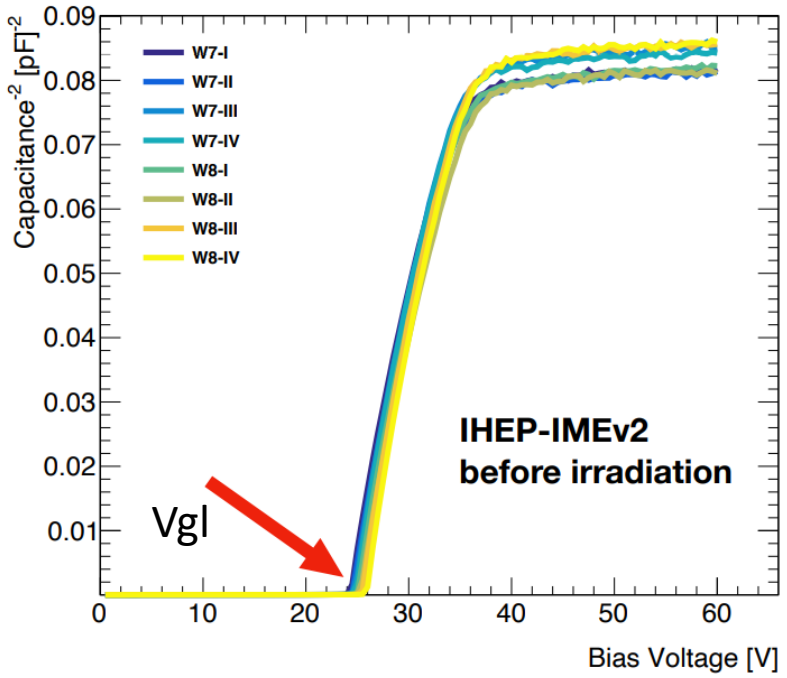


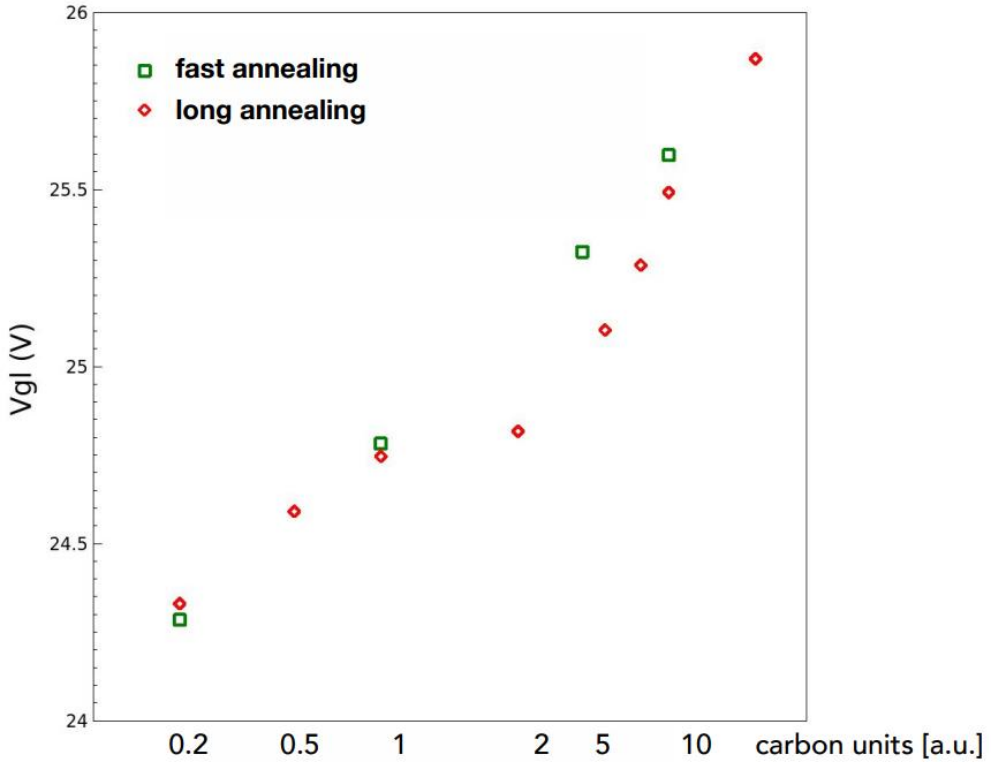


- Increasing carbon dose: the breakdown voltage decreases, Leakage current increases
- W4 with fast annealing show lower leakage current (same carbon dose)
- W4\W7 were chosen for irradiation

Results of IHEP-IMEv2 sensors

Before irradiation: C-V performance [辐照前C-V特性]





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

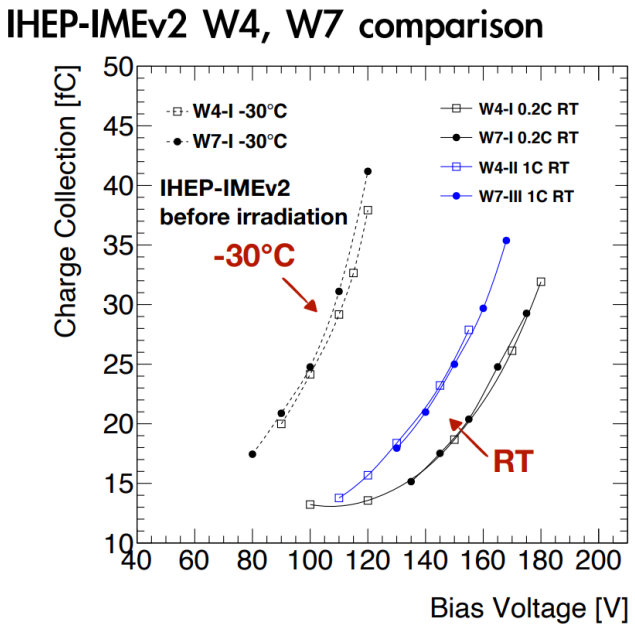
Results of IHEP-IMEv2 sensors

Before irradiation: (RT)

【辐照前电荷收集与时间分辨特性】

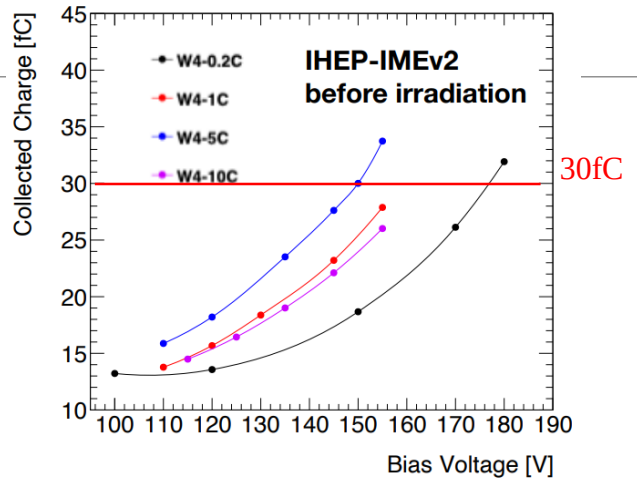
Charge collection >30fC

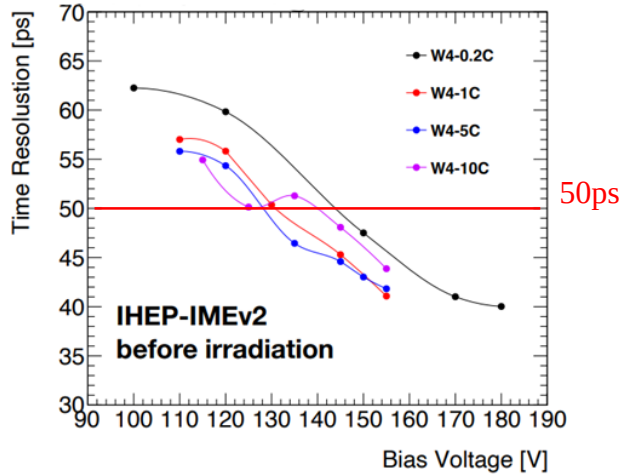
and time resolution< 40ps



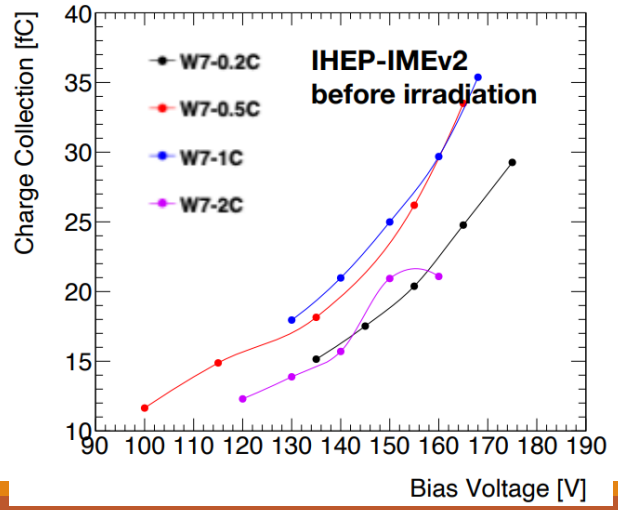
Different annealing methods, same carbon dose, similar collected charge performance

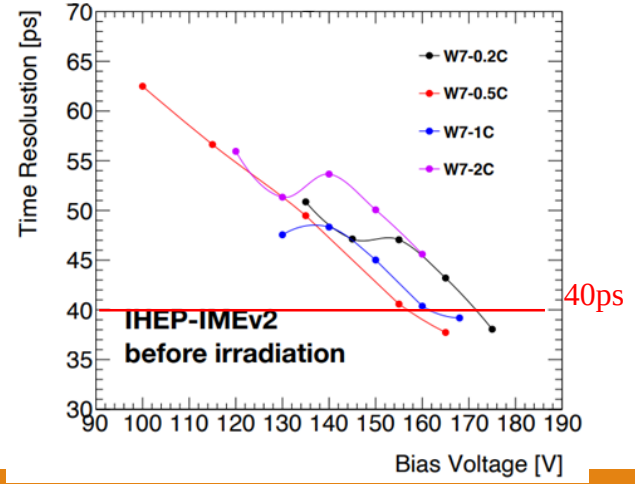
W4





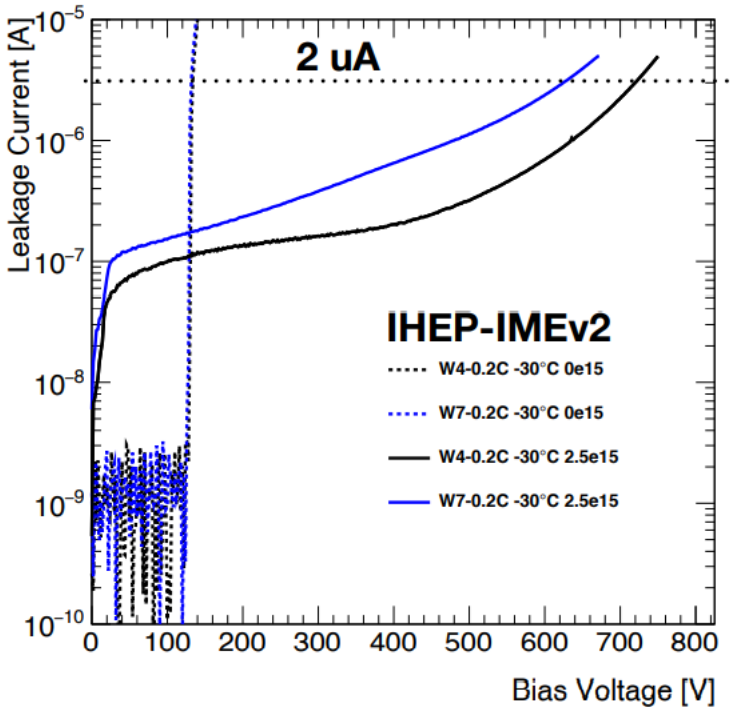
W7

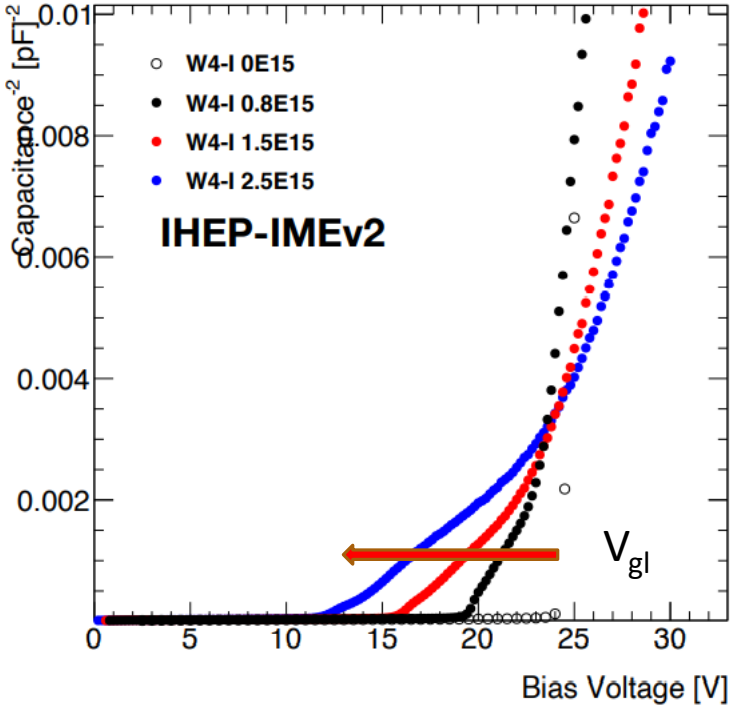




Results of IHEP-IMEv2 sensors

After irradiation： I-V C-V performance 【辐照后I-V C-V特性】

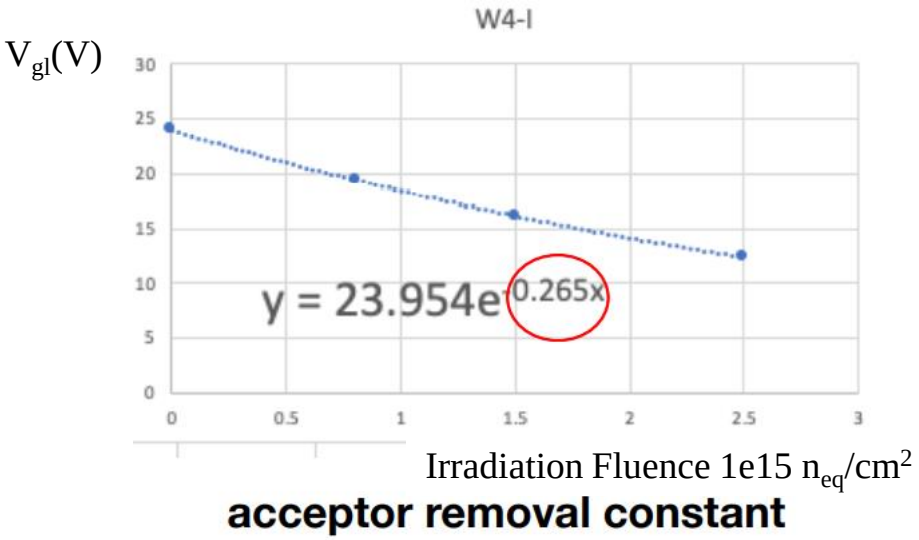


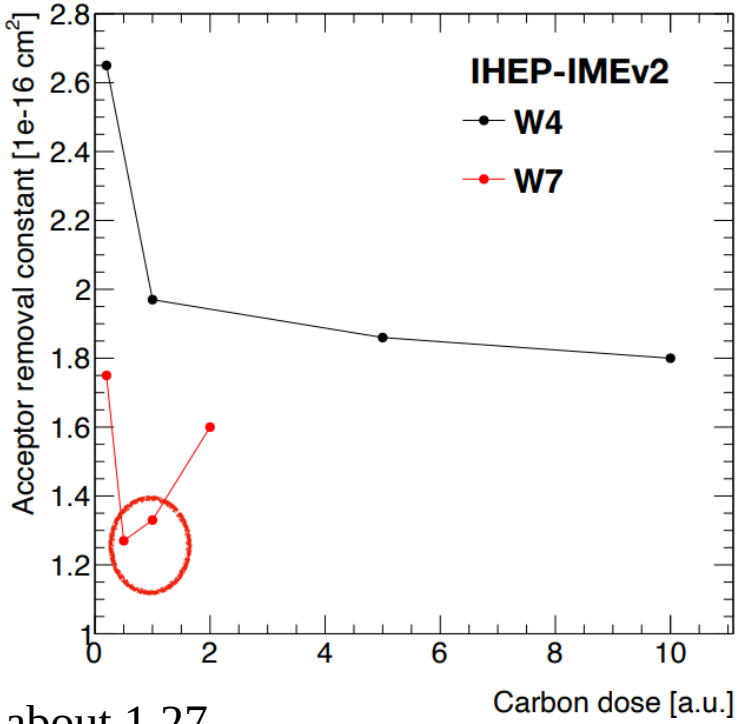


- I-V testing： The leakage current increase nA->100nA
- C-V testing: V_{gl} decrease with the irradiation fluence

Results of IHEP-IMEv2 sensors

The acceptor concentration is reduced - (Acceptor removal constant) 【受主移除率】

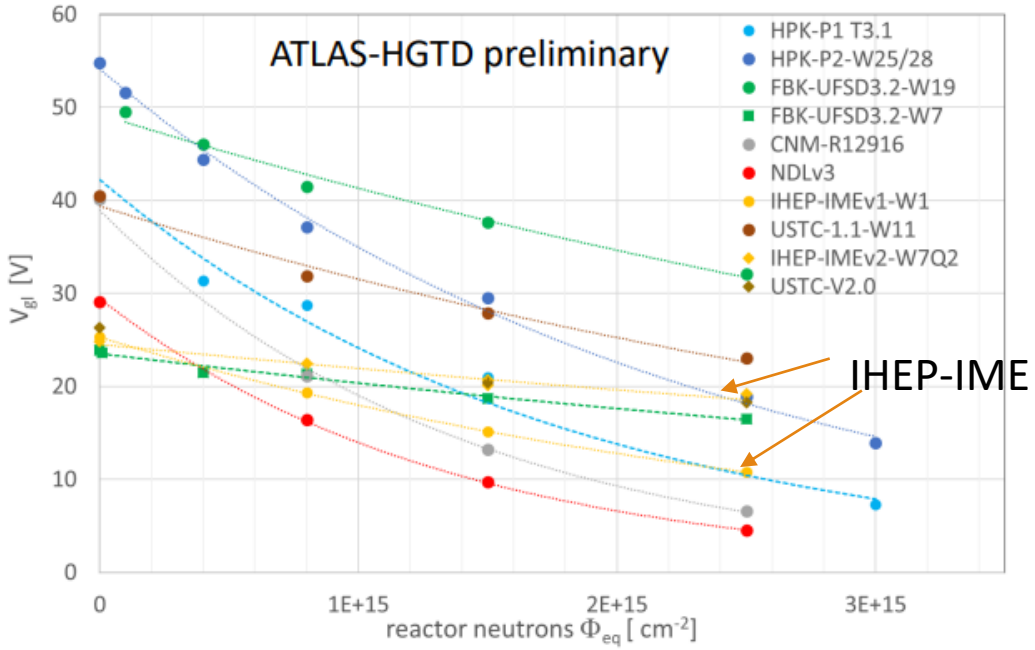


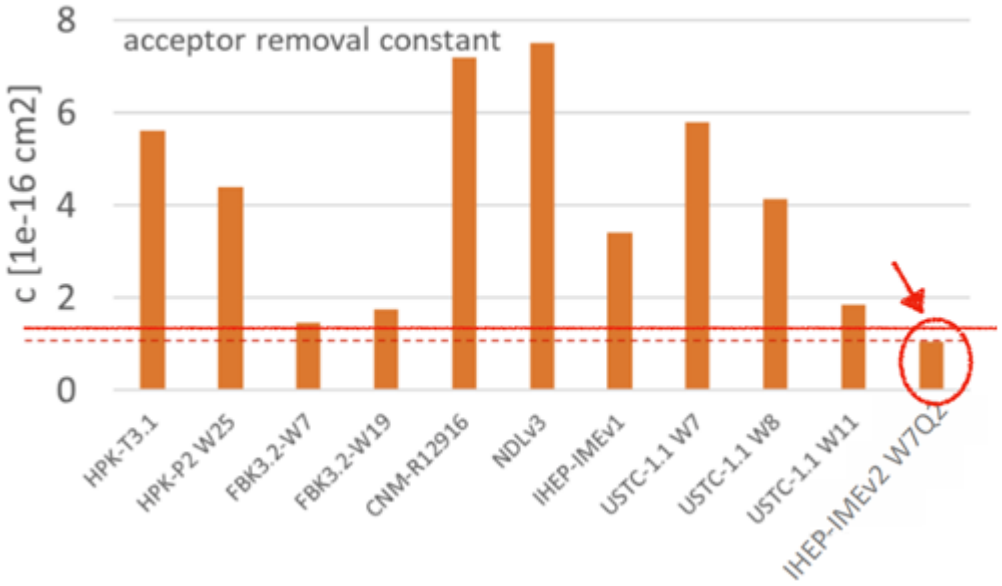


Most acceptor removal constant below 2, the best (W7-II) is about 1.27.
For fast annealing, constant reduces as increasing carbon dose.
For long time annealing, a lowest point shows at around 0.5C carbon dose.

Results of IHEP-IMEv2 sensors

Compare with other sensors：【受主移除率】





最低受主移除率:

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

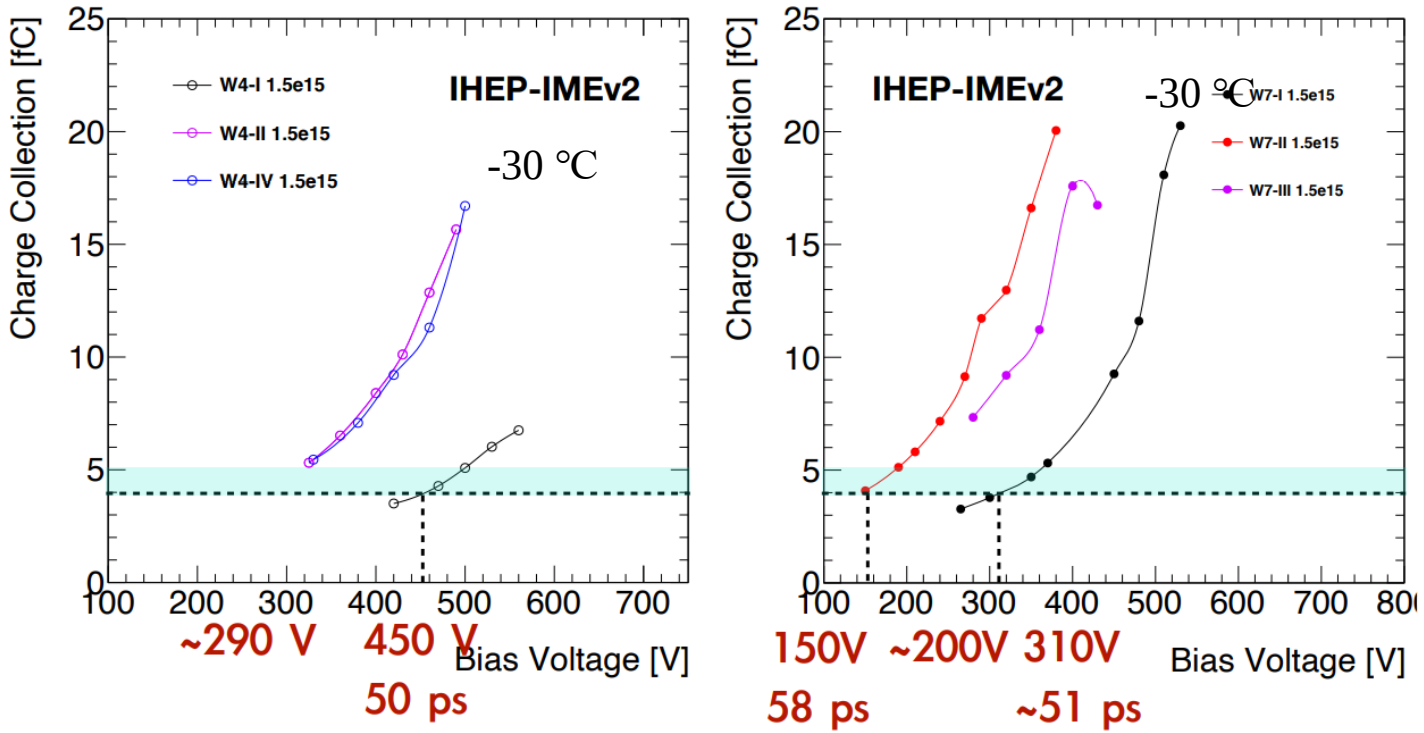
Results of IHEP-IMEv2 sensors

After irradiation: (-30℃)

1.5e15 n_{eq}/cm^2

Charge collection >10fC

Time resolution< 50ps



碳剂量相同，温度处理不同

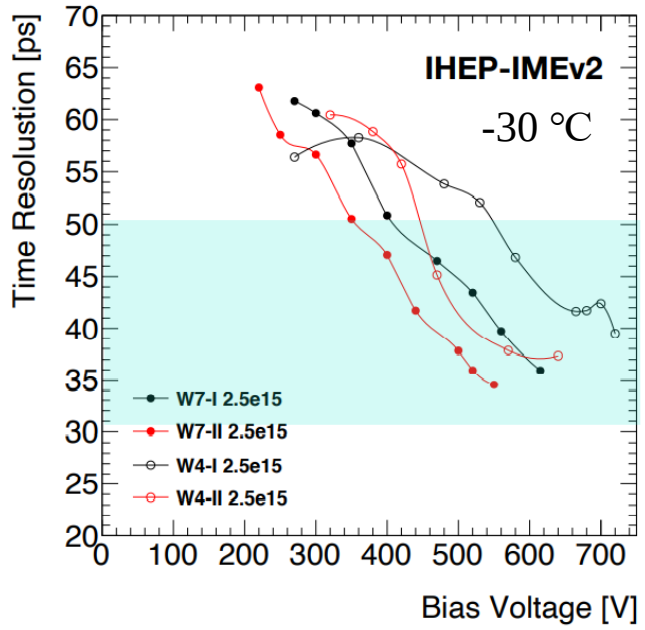
W7-I(0.2C) W4-I(0.2C), and W7-III(1C) W4-II(1C) same carbon dose, different thermal treatment
Compared the voltage for 4fC, long annealing (W7) is lower than fast annealing (W4) when the carbon dose is the same

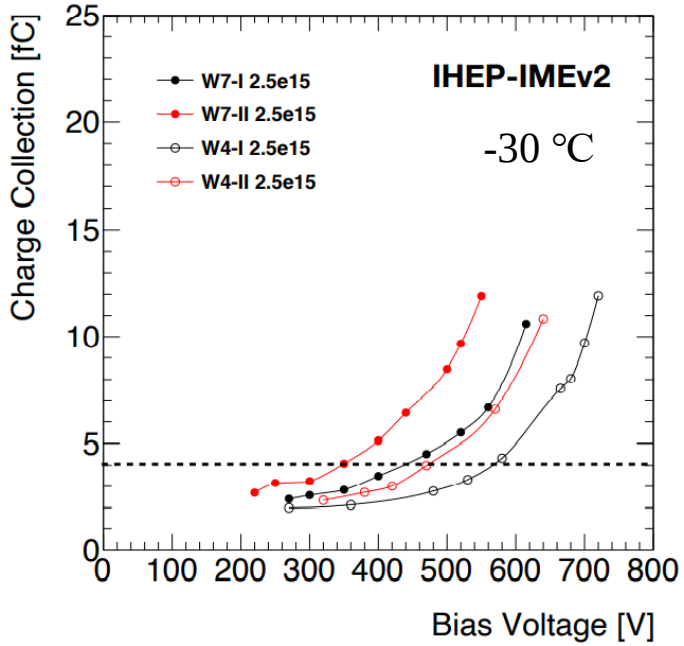
Results of IHEP-IMEv2 sensors

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

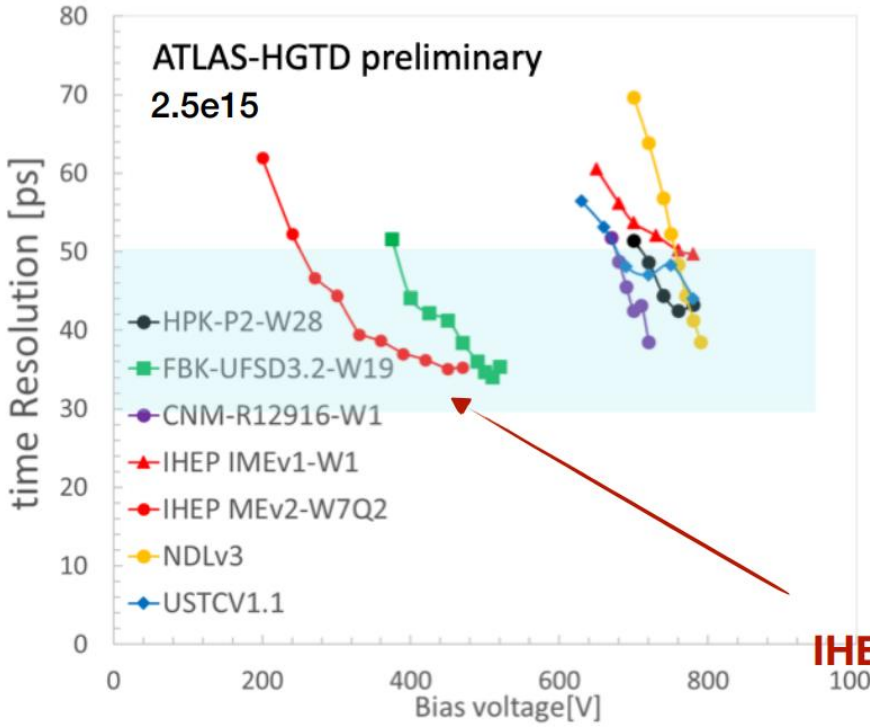
W4-II(1C): 470 V 45.1 ps

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

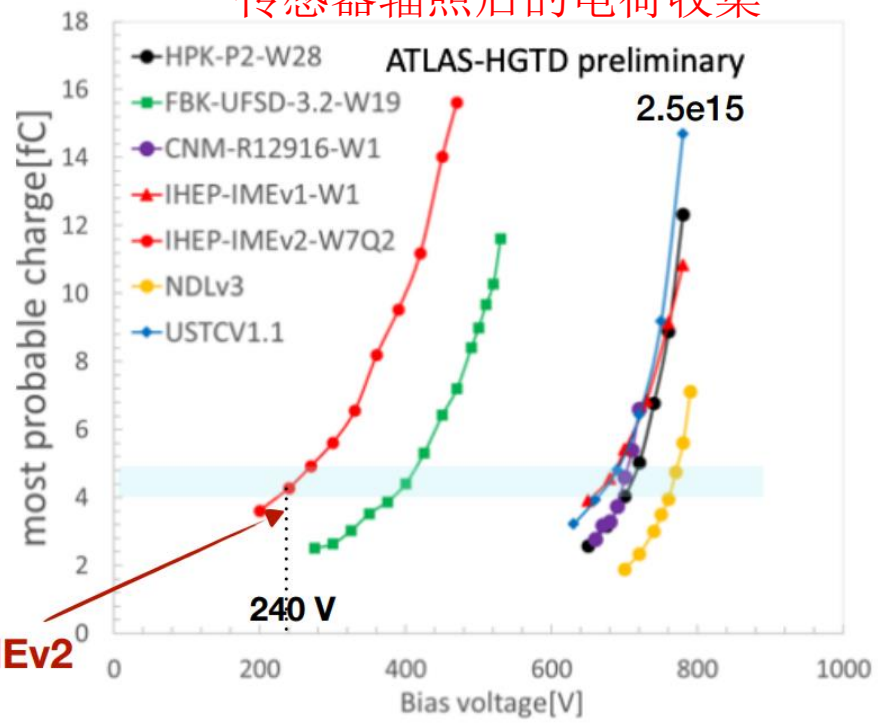
Results of IHEP-IMEv2 sensors

Compare with other sensors：

传感器辐照后的时间分辨



传感器辐照后的电荷收集



IHEP-IMEv2

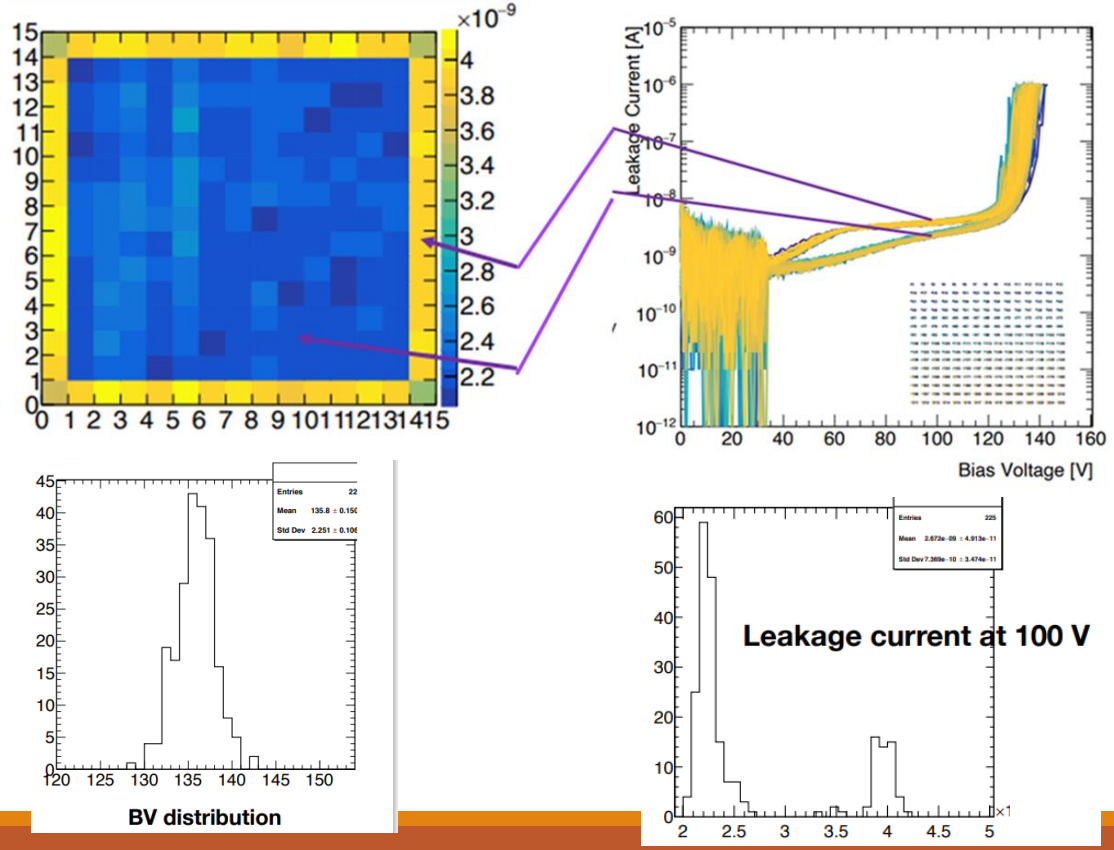
辐照后IHEP掺碳LGAD器件工作电压最低：The effect of the C-enrichment is clearly very beneficial and allows the sensors to be operated at much smaller voltages

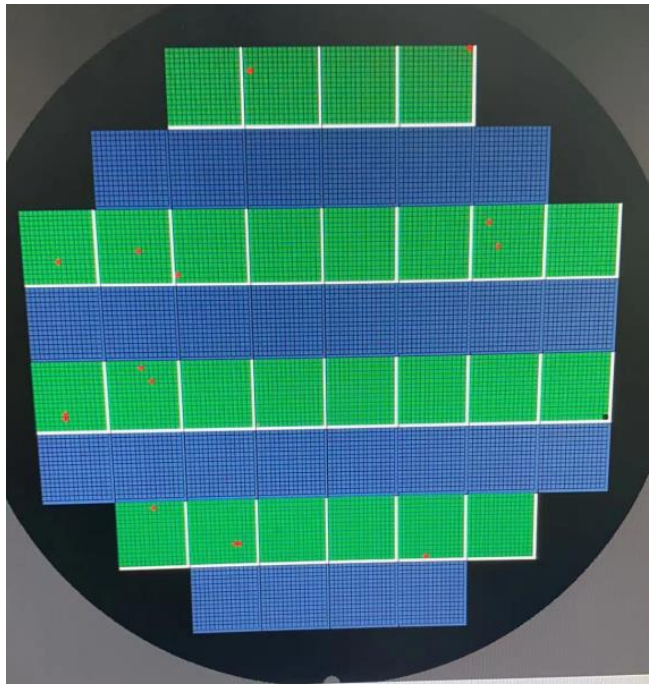
CERN 高流强质子的测试结果显示IHEP掺碳LGAD器件无一失效：At SPS beam testing, no mortalities were seen from IHEP-IMEv1 (w1)and IHEP-IMEv2(w4, w7) sensors with carbon implantation.

Results of IHEP-IMEv2 sensors

Full size15x15 sensors:

- IHEP-IMEv2 Good uniformity: 一致性良好 BV Spread over 15x15 sensor<4% , Leakage current Spread < 3%
- IHEP-IMEv2 Yield：成品率高 Pad yield~99.3%，15x15 sensors~50%





Red point: early breakdown

Summary

- Two versions of IHEP-IME LGAD sensors have been fabricated and the third version is under fabrication.

- Resent results of IHEP-IMEv1 and v2 sensors were shown. IHEP-IME LGAD sensors showed promising results for the ATLAS HGTD project before and after irradiation.

- 优化掺碳工艺的LGAD器件具有很好的抗辐照特性

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.

- 束流测试无一击穿失效

At SPS beam testing, no mortalities were seen from IHEP-IMEv1 (w1)and IHEP-IMEv2(w4, w7) sensors with carbon implantation.

- 大阵列器件很好的一致性和成品率

Large array sensors show good uniformity and yield.