中国科学院高能物理研究所
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Development of IHEP low gain avalanche devices for ATLAS HGTD project

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On behalf of IHEP HGTD sensor group

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ATLAS EXPERIMENT

Outline

- ATLAS HGTD project
- LGAD sensors
- HGTD LGAD sensors Specification
- Development of IHEP LGAD sensors

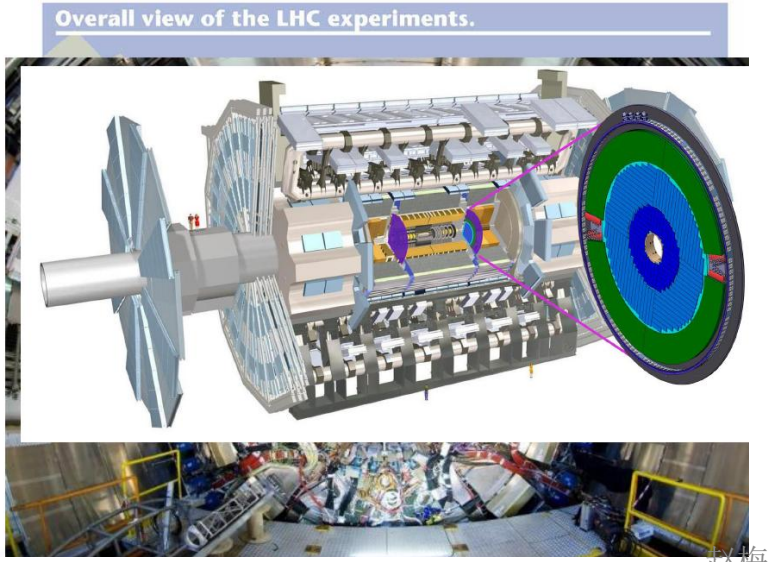
  IHEP-IME(v1-v2)

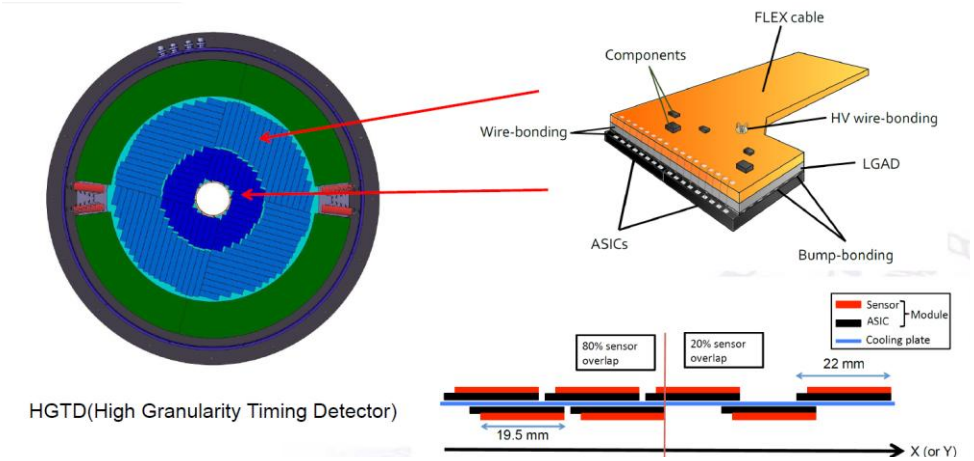
  IHEP-NDL(v3-v4)
- Summary

ATLAS HGTD project

- The High Luminosity of the Large Hadrons Collider (HL-LHC) will be started in 2027 and the instantaneous luminosity of the HL-LHC will increase from the 2.1×10^{34} $cm^{-2}s^{-1}$ to $7.5 \times 10^{34} cm^{-2}s^{-1}$.
- In order to separate collisions in limited space, ATLAS experiment High Granularity Timing Detector (HGTD) project choose thin Low Gain Avalanche Detectors(LGAD) as sensors, which have timing resolution better than 50ps.
- LGAD sensors have been developed by several silicon foundries and institutes including HPK、FBK、CNM、BNL 、NDL、IHEP、USTC and so on.

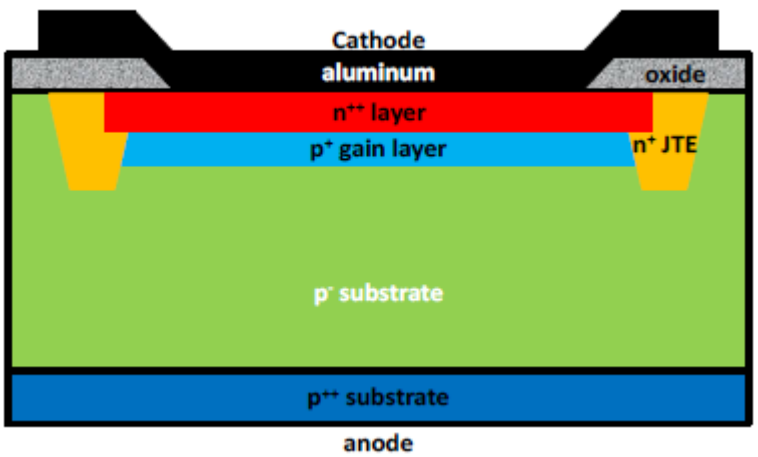
Around 16000 LGAD sensors segmented into an array of 15x15 1.3×1.3 mm^2 pads will be needed.





LGAD sensors

- 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
- The most important part of LGAD senor is the charge multiplication in the so called gain layer which is formed by a heavily doped 1–2μm thick p+ layer sandwiched between the n++ implant and the p substrate.



basic structure of Low Gain Avalanche Detectors(LGAD)

•The thickness of the p- substrate are as thin as ~50um for superior time resolution of around 35ps per detector layer.
•The negative anode voltages are applied from backside electrode to make sure the sensor works at the voltage before breakdown, while the signals of each sensor to be collected and analyzed form the top cathode electrode.

HGTD sensor specification

	Specification
Pad size	1.3 ×1.3 mm^2
Pad array	15 × 15
Substrate	p-type
Thickness (D)	50±5 µm (active) 300±30
HV biasing	back side
Time resolution	~35 ps at Vop (as prc
Charge collection	>15 fC at Vop (as prc
Passivation thickness	between 0.8 µm an
Bump-bo	
Bump-b	
In Dic D	
Target	

	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

Gain layer depletion (Vgl)	< 60 V
Full depletion (Vfd)	< Vgl + 90 V
Breakdown voltage (Vbd) (-30℃)Breakdown condition (-30℃)	(Vbd-Vgl)/D>0.7 V/um, Vbd>Vfd+30 V >200 nA/pad
Device leakage current (-30℃)	< 2 µA/cm^2 at Vop (~35 ps, >15 fC)
Pad leakage current (-30℃)	< 200 nA at Vop (~35 ps, >15 fC)
Inter-pad gap (IP)	40 mm < IP <100 µm (region with <4 fC , time resolution < 50 ps)

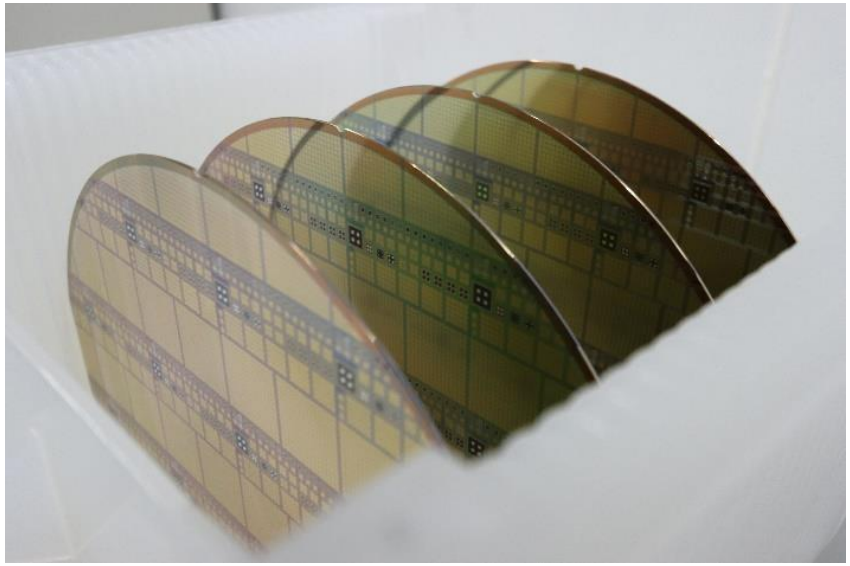
IHEP LGAD sensor status

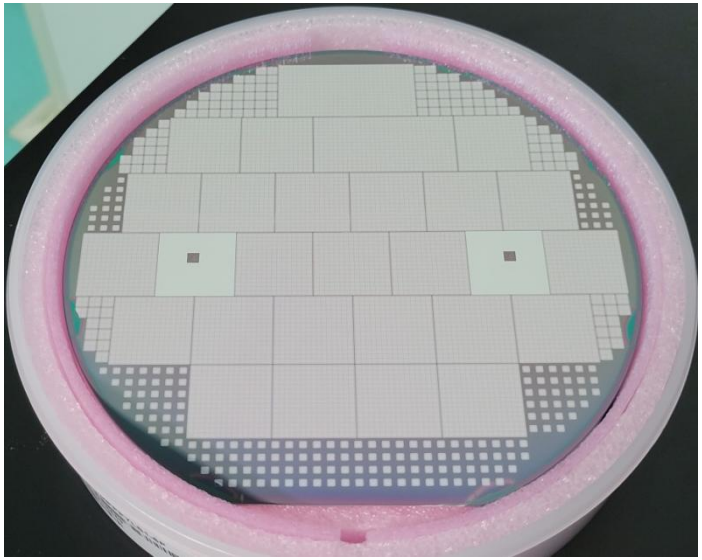
- IHEP-IME, v1→v2, 8 inch line

  8 inch EPI wafers, 400keV injection energy, carbon injection

  v1 (2020.9), v2(2021.4), v3 (under design)
- IHEP-NDL, V1→V4, 6 inch line

  6 inch wafers, about 100keV injection energy, no carbon



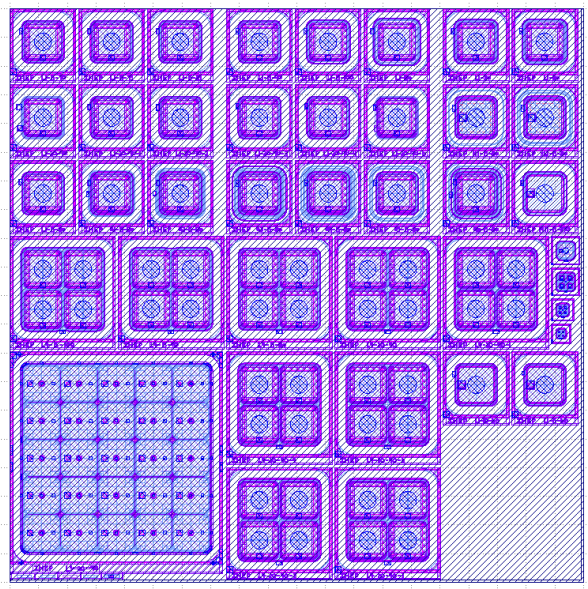


IHEP-IME v1

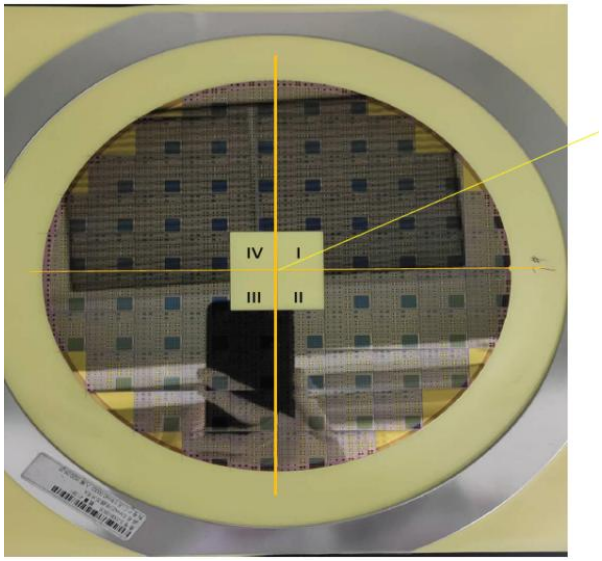
- Simulation was done about structure and process parameters
- 3 wafers(each wafer has 4 quadrant with different gain layer process parameters)
- Wafer 1 has carbon injection

Quadrant	P dose
I	low
II	mid
III	high
IV	extremely high

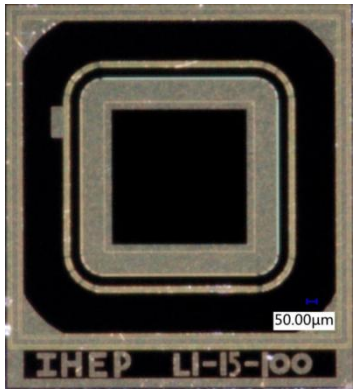
layout



Whole wafer

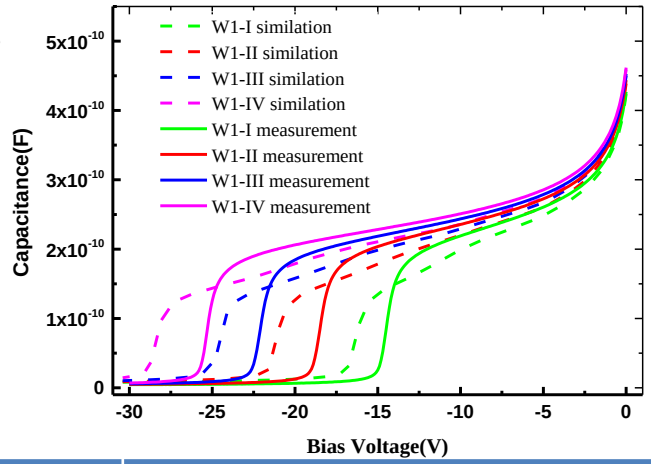


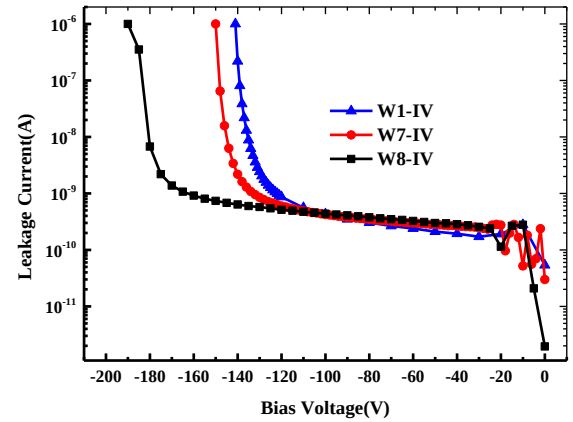
Single sensor



IHEP-IME v1

- IV CV test results agree with simulation
- As increasing p+ layer dose, breakdown voltage decreases and V_{gl} increases

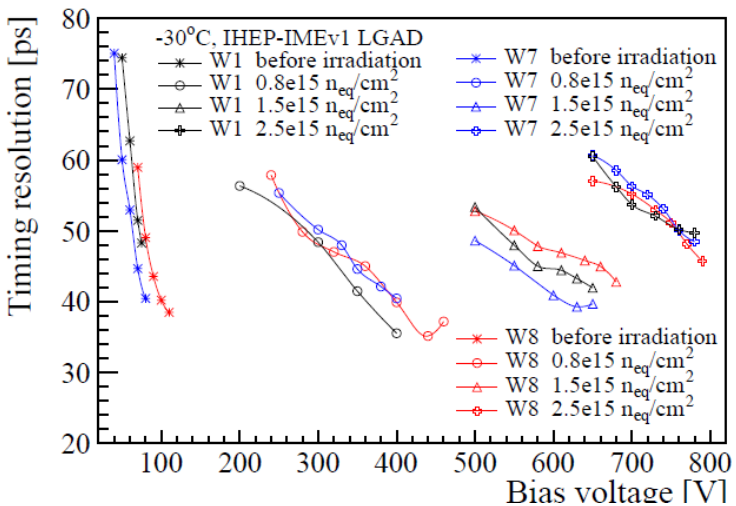


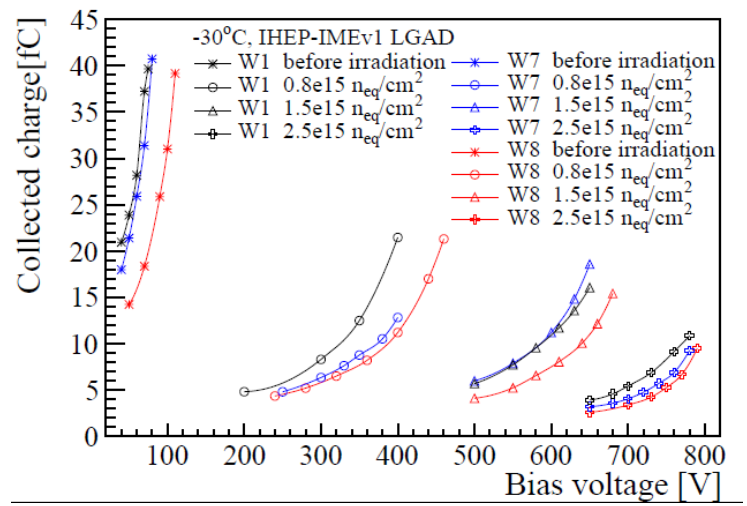


	HGTD Specification	W1	W7	W8
Target pad capacitance	**<4.5 pF (backplane+inter-pad)**	4.56pF	4.56pF	4.25pF √
Gain layer depletion (V_{gl})	**< 60 V**	25V √	25V √	24V √
Full depletion (V_{fd})	**< V_{gl} + 90 V**	37V √	37V √	36V √
Breakdown voltage (V_{bd}) (-30℃) **Breakdown condition (-30℃)**	**(V_{bd}-V_{gl})/D>0.7 V/um, Vbd>Vfd+30 V** **>200 nA/pad**	140V √	150V √	192V √
Device leakage current (-30℃)	**< 2 μA/cm² at V_{op} (~35 ps, >15 fC)**	<100nA √	<100nA √	<100nA √
Pad leakage current (-30℃)	**< 200 nA at V_{op} (~35 ps, >15 fC)**	<1nA √	<0.8nA √	<1nA √

IHEP-IME v1

- Sensor sent to JSI and had neutron irradiation(0.8e15cm^{-2}, 1.5e15cm^{-2}, 2.5e15cm^{-2})
- Time resolution and charge collection results before and after irradiation show that the sensor satisfy the project specification.
- Charge collection can reach 4fC at 670V after irradiation.
- W1 with carbon injection show good properties during beam testing.

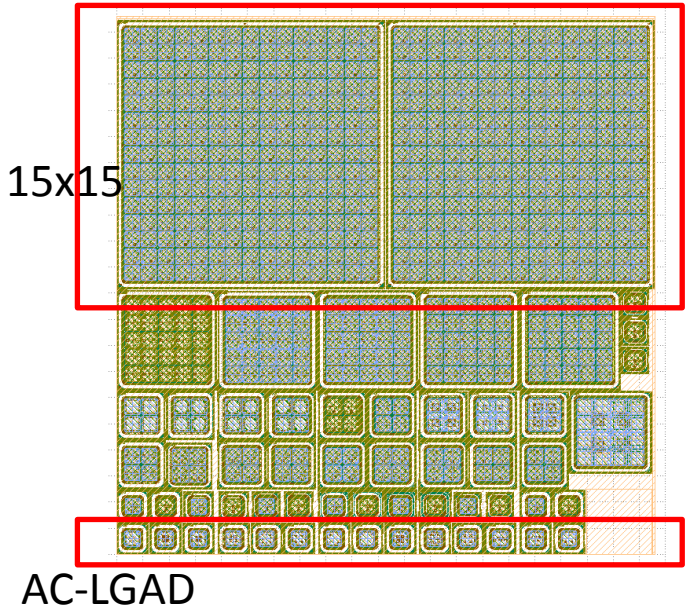


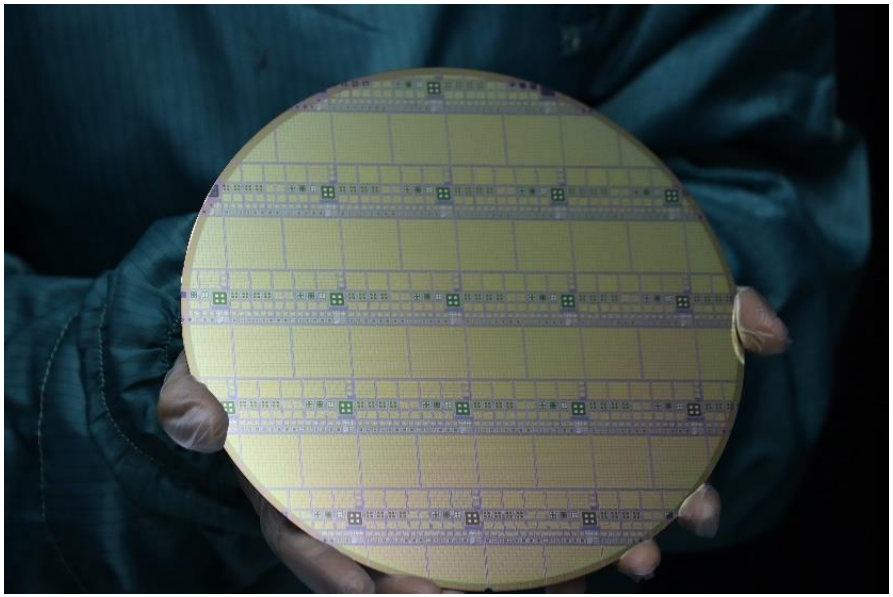


	HGTD Specification	W1	W7	W8
Time resolution	**<35 ps (<70ps) before(after) irradiation**	<35ps(<50ps)	<35ps(<50ps)	<35ps(<50ps)
Collected charge	**>15fC(start), >4fC(end of life time)**	>40fC(>5fC)	>40fC(>5fC)	>40fC(>5fC)

IHEP-IME v2

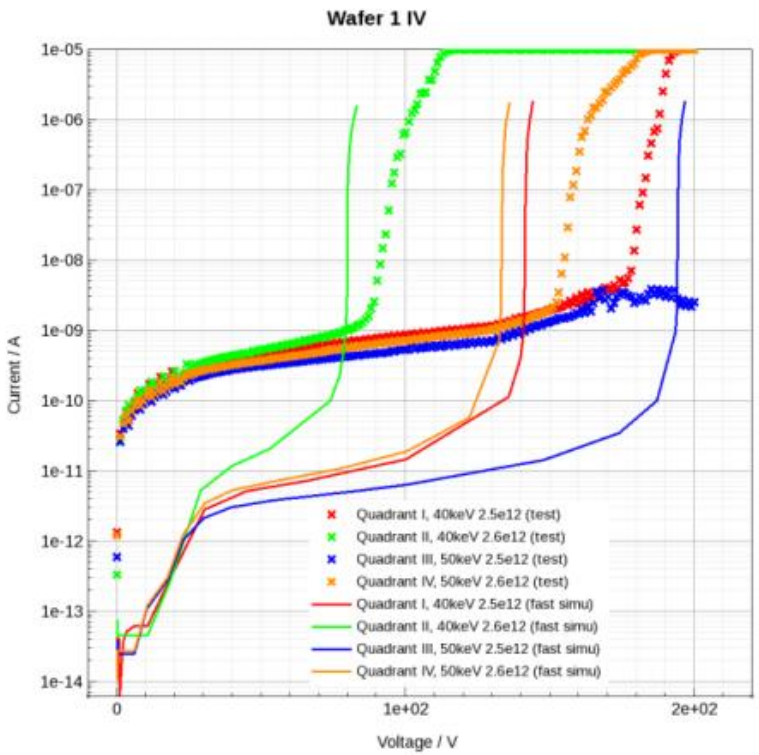
- Large array(15x15)
- Carbon injection parameters(to improve irradiation hardness)
- (W1 same as v1, W4,W7,W8 has carbon injection)

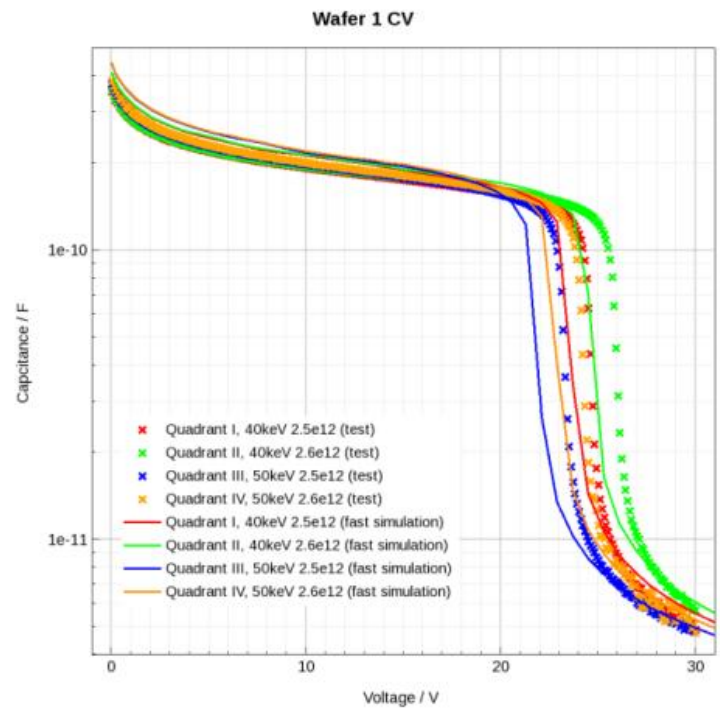




IHEP-IME v2

- The IV CV test results are consistent with the simulation and similar to the results of v1
- Finish wafer testing, now under UBM for bump bonding with ASIC

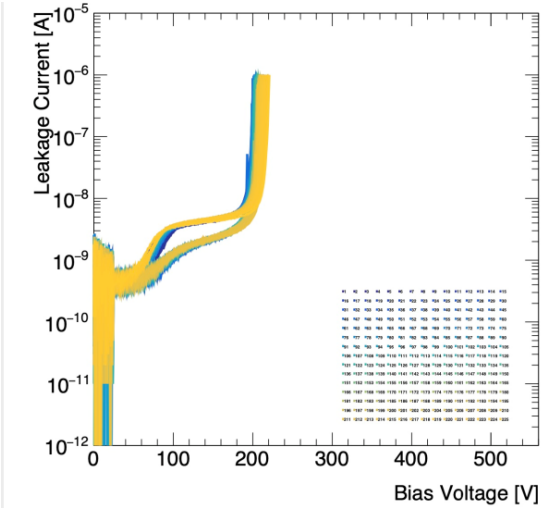




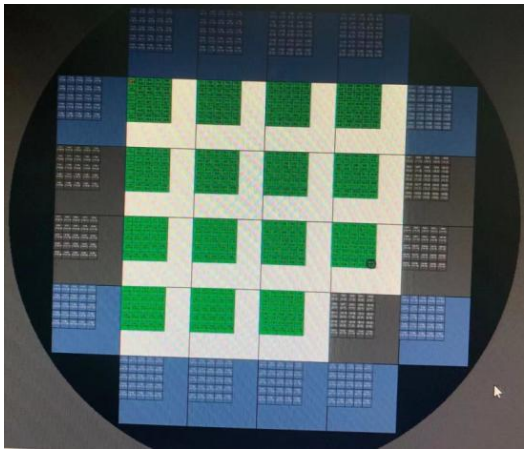
IHEP-IME v2

- Large array sensors
- Good uniformity
- Pad yield~99.3%
- 15x15 sensor yield ~50%(HPK~70%)

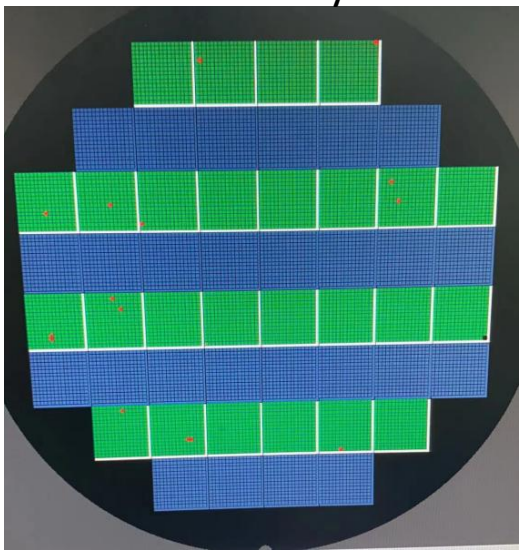
15x15 IV results



5x5 array

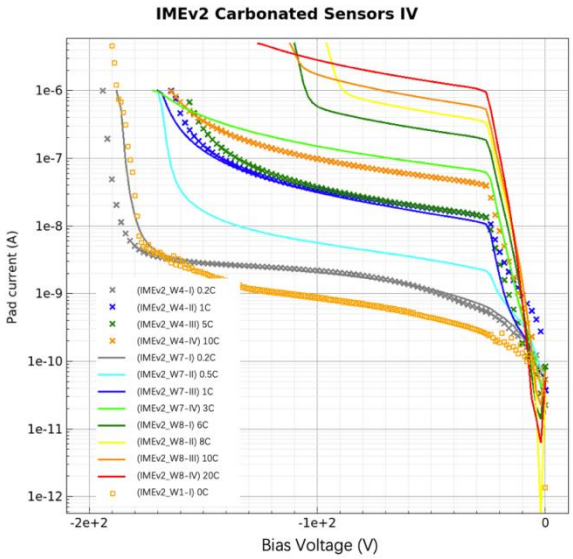


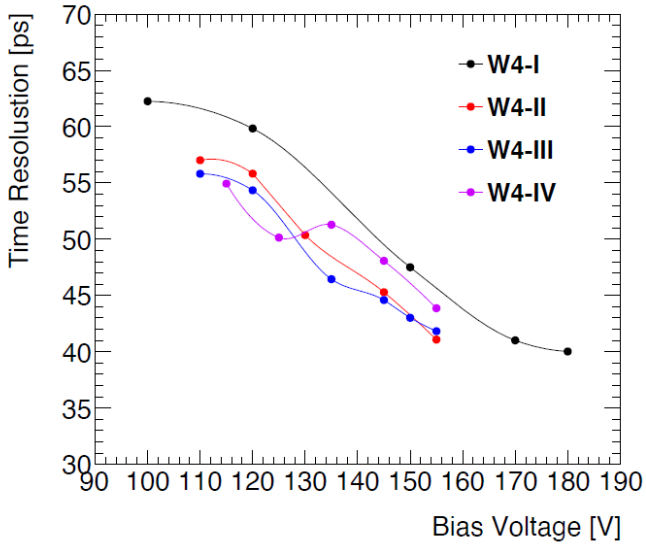
15x15 array

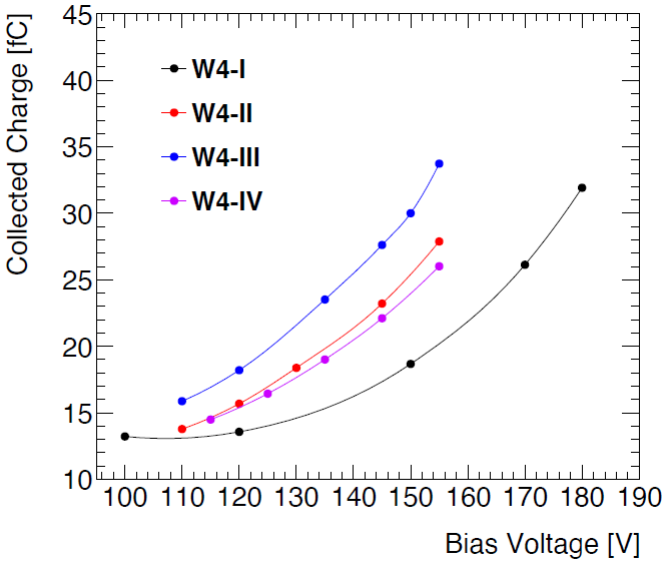


IHEP-IME v2

- Sensors with carbon injection
- Leakage current increases as increasing carbon injection dose
- Time resolution better than 40ps, charge larger than 15fC before irradiation

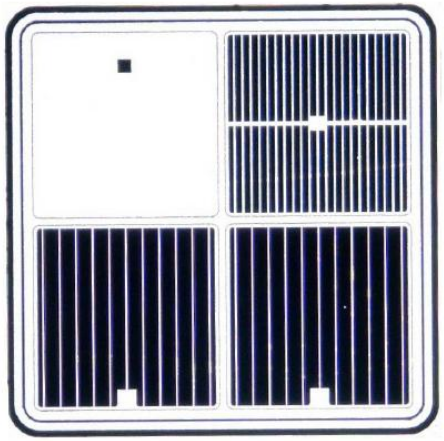






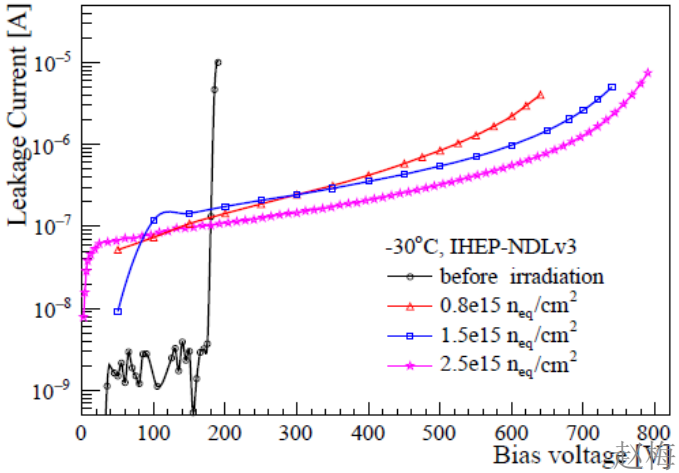
IHEP-NDL v3

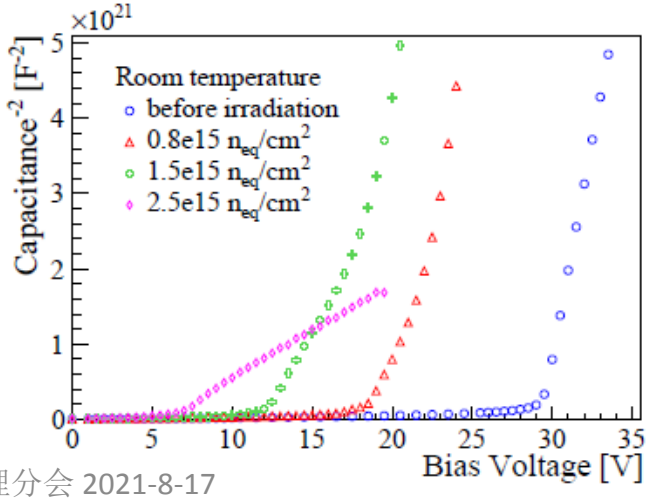
- The IV CV test results of NDL v3 before and after irradiation



The leakage current of the sensor before irradiation was at nA level, and its breakdowns at a voltage of 190V.

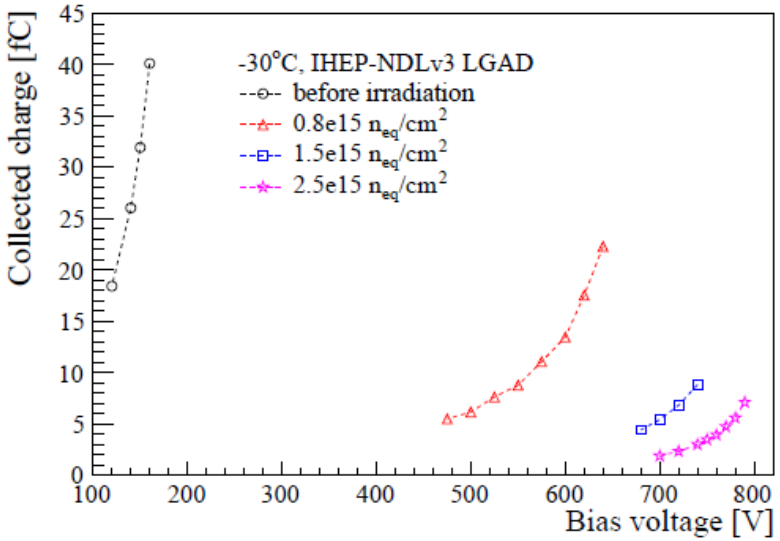
When the irradiation fluence increases to 2.5e15cm^{-2}, the total leakage current was 3.36 μA (50 μA/cm^2) at the bias voltage of 760V, which is lower than HGTD requirement.

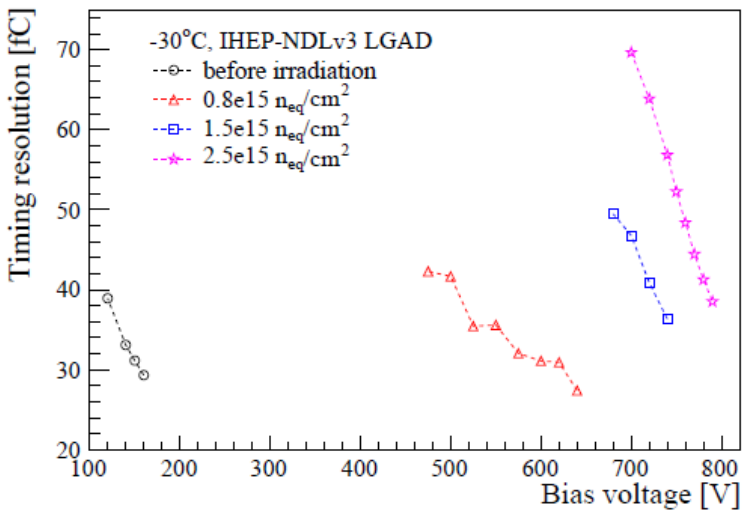




IHEP-NDL v3

- After irradiation with a fluence of 2.5e15cm^{-2}, the timing resolution can still reach 39 ps, which meets the HGTD requirements(70 ps)
- Charge collection can reach 4fC at 760V

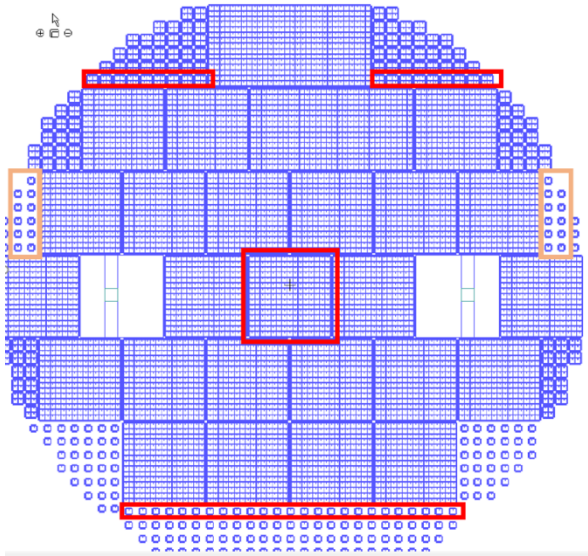




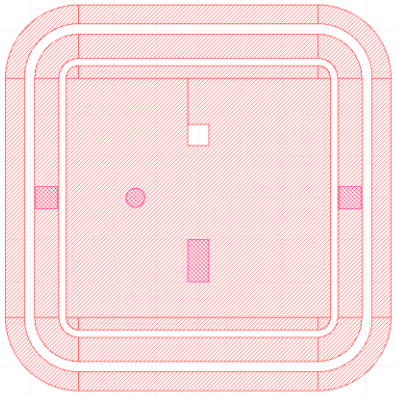
	HGTD Specification	NDL v3
Time resolution	**<35 ps (<70ps) before(after) irradiation**	<35ps(<50ps)
Collected charge	**>15fC(start), >4fC(end of life time)**	>35fC(>5fC)

IHEP-NDL v4

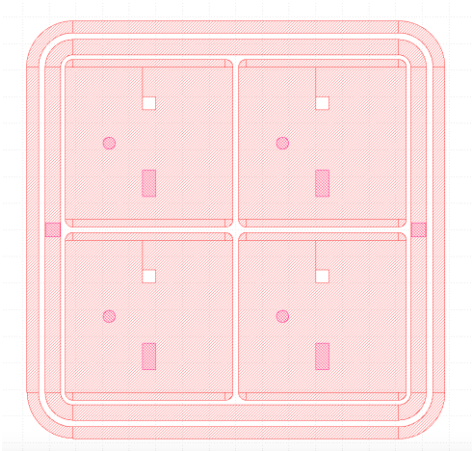
- 6 inch full wafer engineering runs
  - 15×30 full size sensor design
  - 1×1 and 2×2 LGAD/PIN
- 15 wafers (6 wafer with high resistivity)
  - 6 Si-Si wafers with high resistivity
  - 9 wafers with epi-layer
- Doping profile will be optimized for radiation hardness
- Add 15×15 sensors and single PIN
- IHEP-NDLv4 is ready at July 2021, now under testing

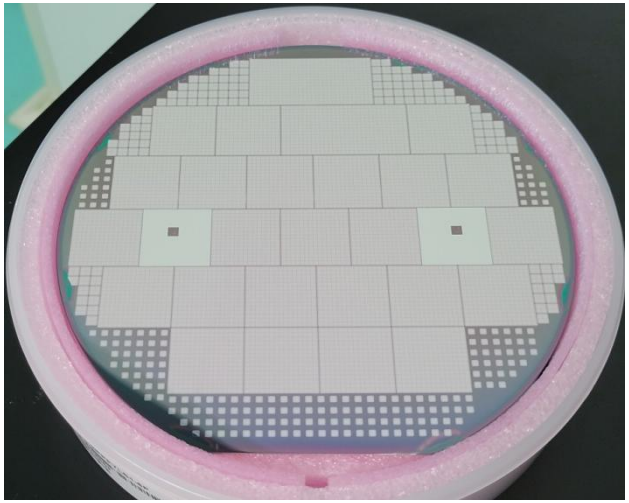


1×1 structure



2×2 structure





Summary

- IHEP-IME sensors

V1: All the testing results shows that the IHEP-IMEv1 sensors fulfill the specification of ATLAS HGTD sensors' requirement before and after irradiation.

V2: large array sensors has good uniformity and ~50% yield;

sensors with carbon injection show good time resolution and charge collection properties, will be irradiated soon.

some wafers are under UBM and will be bonded with ASIC for module.

- IHEP-NDL sensors

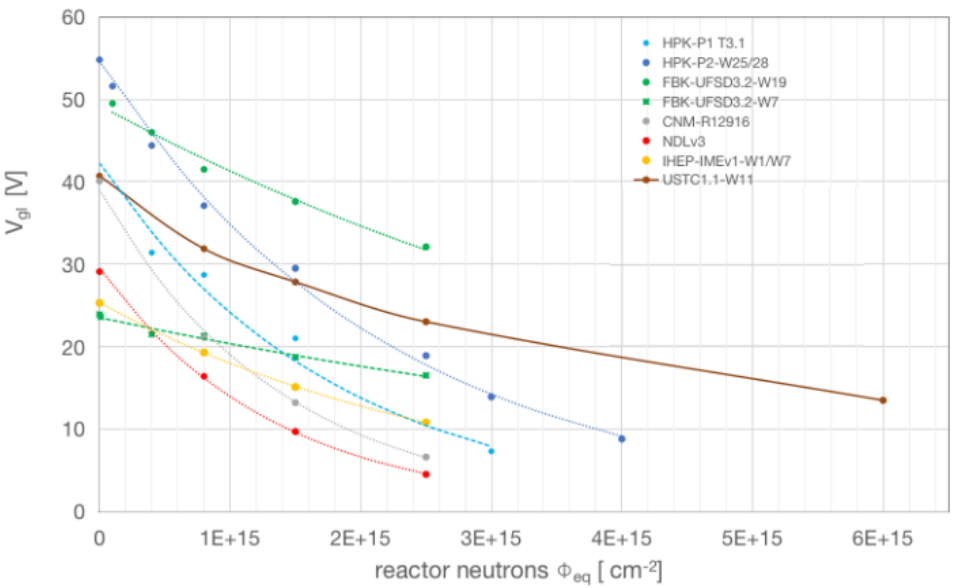
V3: All the testing results shows that the IHEP-NDLv3 sensors fulfill the specification of ATLAS HGTD sensors' requirement before and after irradiation.

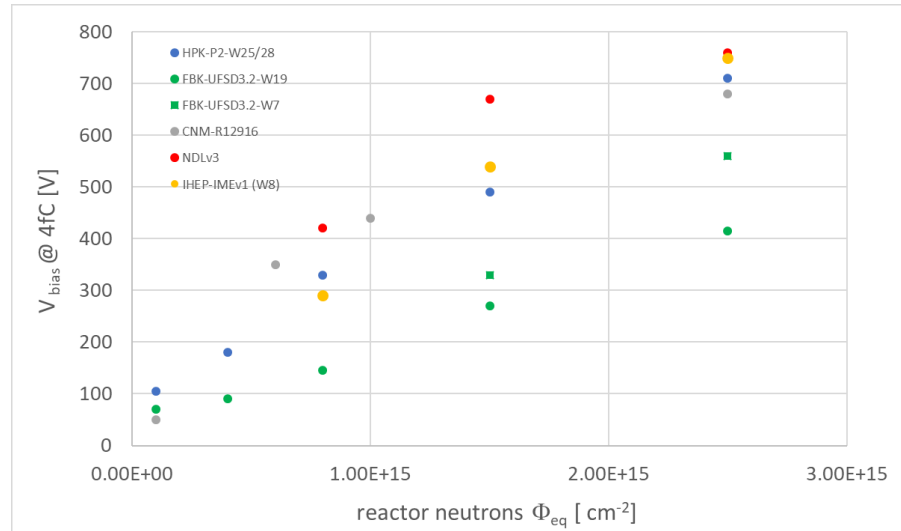
V4: design and fabricated, now under testing

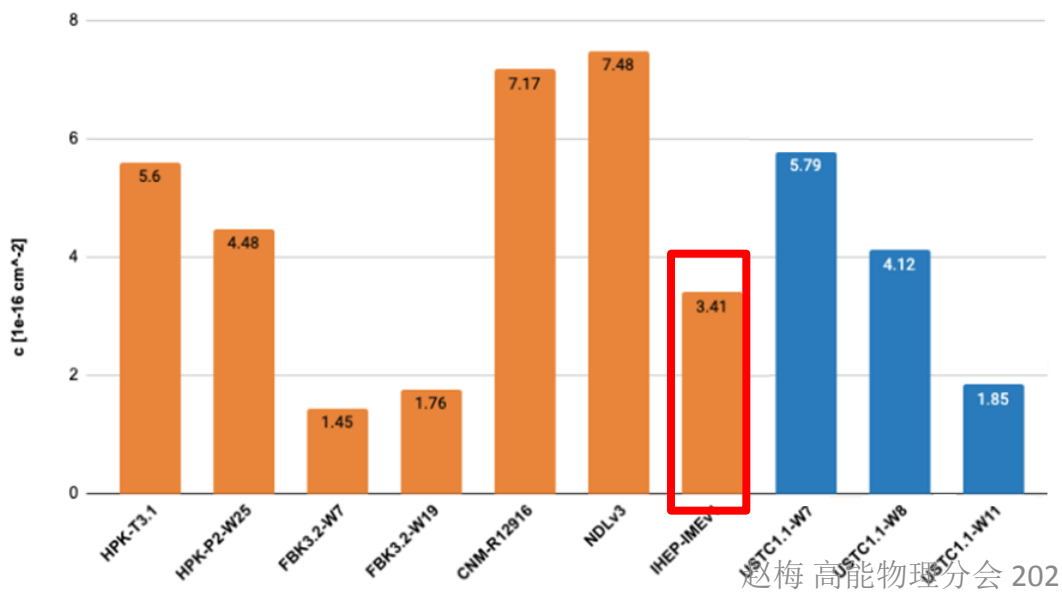
The IHEP LGAD sensor performs a good irradiation hardness and satisfy the project specification, has the potential to be used in the HGTD project for the ATLAS detector upgrade during the HL-LHC.

Backup

With other producers



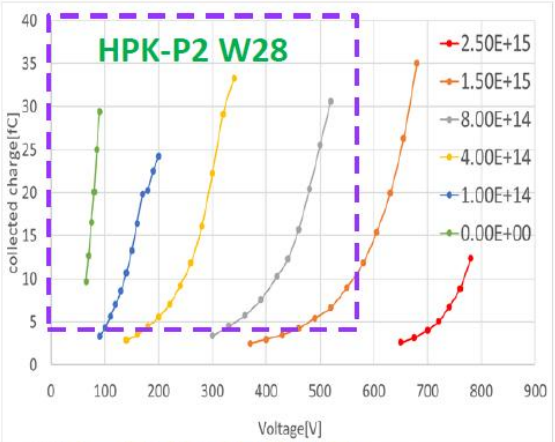


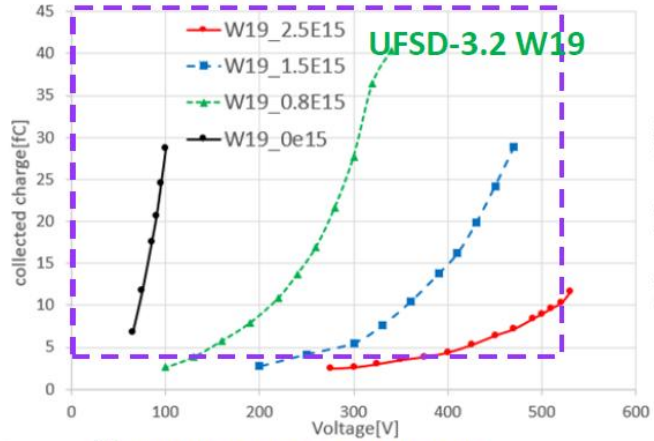


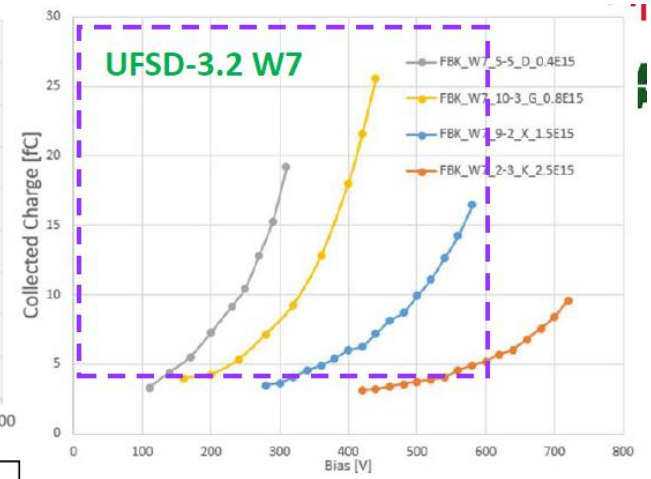
IHEP-IMEv2: have to improve

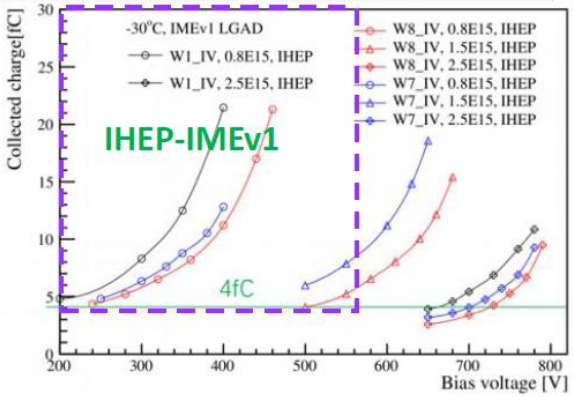
Large array
Thinning
Passivation
Edge reduced design
Larger Vgl
Smaller removal constant

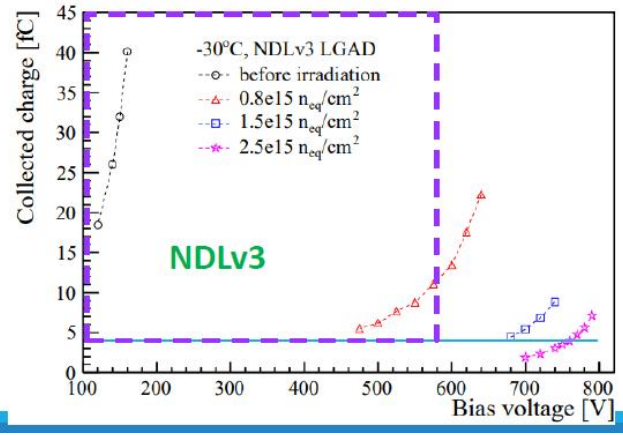
With other producers

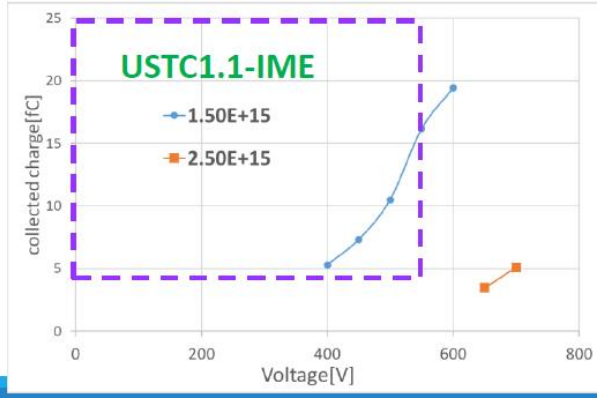












Beam results

Producer	Sensor	Size	Fluence	MinutesAnneaing@60C	Bias required	Start bias in TB	Last bias in TB	Temp at death [C]	RH at death	Time at last bias [h]	Disconnection notes
IME	IME_v1_W1-2V-Z4-L1-20-90-6	single	2.50E+15	80	650	600	740	-35	16	3.5	died in beam
IME	IME_v1_W1-2V-Z4-P2N-15-100	single	2.50E+15	80	-	600	660	-36	13	1	died in beam
USTC	USTC_W11-P14-16 CS	single	1.50E+15	80	400	350	590				
USTC	USTC_W11-P14_18 CS	single	2.50E+15	80	650	600	660	-33	12	4	died in beam
FBK	FBK_UFSD3.2_W13_Type10	2x2	2.50E+15	80	480	350	550				breakdown at 550V/-44C
FBK	FBK_UFSD3.2_W19_Type10	2x2	2.50E+15	80	380	180	420				
FBK	FBK_UFSD3.2_W13_Type10	2x2	1.50E+15	80	320	180	420				
FBK	FBK_UFSD3.2_W18_Type10	2x2	1.50E+15	80	360	180	420				
NDL	NDL_v3_B14_D3	2x2	1.50E+15	80	680	600	640	-33	18	1	broke in beam
NDL	NDL_v3_B14_G5	2x2	2.50E+15	80	760	-	-				broke during initial ramp up at 550V/-42C
FBK	FBK_UFSD3.2_W19_Type9	5x5	1.50E+15	80	250	180	360				thermal runaway at 360V/-40C
FBK	FBK_UFSD3.2_W3_Type9	5x5	2.50E+15	80	unknown	180	420				
HPK	HPK_P2_W25_SE3_IP7	5x5	1.50E+15	80	460	350	590				
HPK	HPK_P2_W31_SE3_IP5	5x5	1.50E+15	80	550	350	590				reached compliance at 590V
HPK	HPK_P2_W25_SE3_IP3	5x5	2.50E+15	80	700	600	640	-32	17	1.5	died in beam
HPK	HPK_P2_W31_SE5_IP7	5x5	2.50E+15	80	720	600	620	-34	27	3	died in beam
CNM	CNM_13002	single large	1.50E+15	80	740*	660	680	-29	14	3.5	died in beam
HPK	HPK-P2_W25_PIN	single	2.50E+15	80	700	660	660	-32	15	1	died in beam
HPK	HPK-P1_Type3.1_SE5	single	3.00E+15	20480	700*	580	620	-29	14	7.75	died in beam
HPK	HPK-P1_Type3.2_SE2	single	3.00E+15	20480	640*	580	640	-36	17	5.5	died in beam
HPK	HPK-P0_80d	single	4.00E+15	80	unknown	-	-				broke during initial ramp up at 400V
HPK	HPK-P0_80C	single	4.00E+15	80	unknown	-	-				dead from start
IMEv	IMEv1_W7_LGAD	2x2	1.50E+15	80	500/580**	480	660	-31	13	2	died in beam
IMEv	IMEv1_W7_LGAD	2x2	1.50E+15	80	500/580**	480	660				
FBK	FBK_UFSD3.2_W10_Type10	2x2	2.50E+15	80	400*	-	-				dead from start
FBK	FBK_UFSD3.2_W19	LGAD+PIN	2.50E+15	80	380	300	580	-32	13	1.25	died in beam
HPK	HPK-P1_Type1.1_SE2_IP9	2x2	1.50E+15	80	unknown	300	440	-38	19	4	died in beam
HPK	HPK-P1_Type1.2_SE3_IP5	2x2	1.50E+15	80	unknown	300	470	-29	13	1.33	died in beam
HPK	HPK-P2_W25_SE3_IP4	2x2	1.50E+15	80	460	420	620	-33	15	2	died in beam
HPK	HPK-P2_W25_SE3_IP7	2x2	1.50E+15	80	460	420	640	-30	17	3.8	died in beam
HPK	HPK-P2_W25_SE3_IP5	2x2	1.50E+15	80	460	420	660				
HPK	HPK-P2_W25_SE3_IP3	2x2	1.50E+15	80	460	420	660	-31	13	2.5	died in beam
IMEv	IMEv1_W7_LGAD	2x2	2.50E+15	80	700	660	660	-32.5	15.8	0.8	died in beam
IMEv	IMEv1_W7_PIN	single	2.50E+15	80	-	660	680	-34.3	14.5	1.5	died in beam
CNM	CNM_12916_W2_A208	2x2	2.50E+15	80	700	660	660	-33.1	14.2	0.2	died in beam
CNM	CNM_12916_W2_A205	2x2	1.50E+15	80	unknown	420	570				

*No measurements were available for this sensor type+fluence+annealing time combination. Value estimated based on similar sensors.
**IJS measured 500V, IHEP measured 580V

- Died in beam before reaching required bias
- Died in beam after reaching required bias
- PiN
- Survived testbeam and reached required bias