Status of the HGTD Sensors upgrade

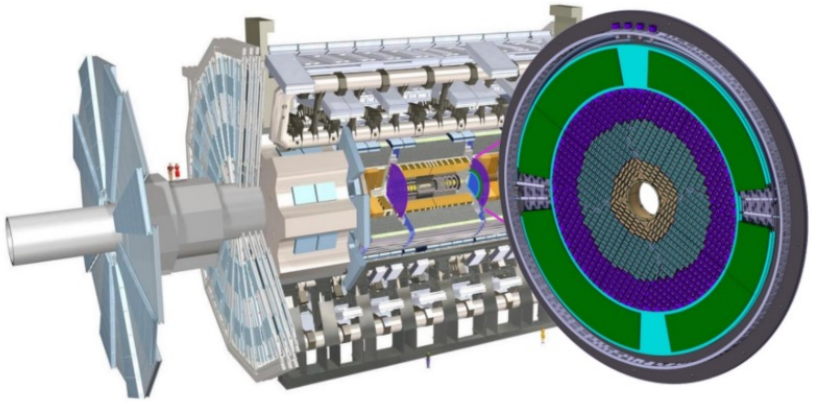
Tianyuan Zhang, Mei Zhao, Zhijun Liang

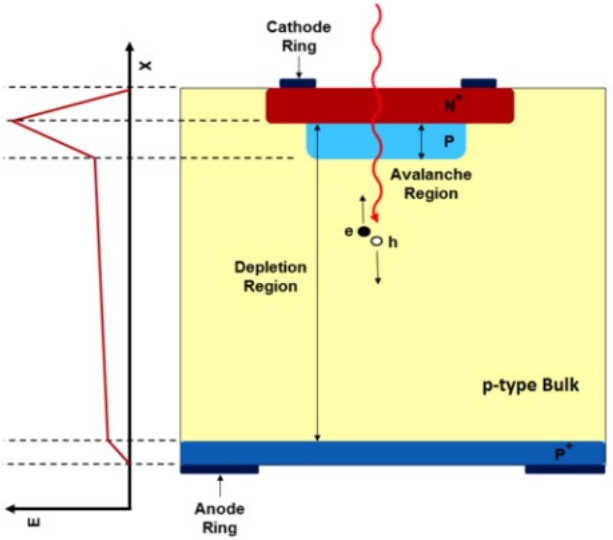
on behalf of HGTD Sensor Group

30-10-2025

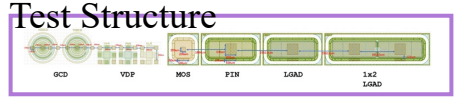
Content

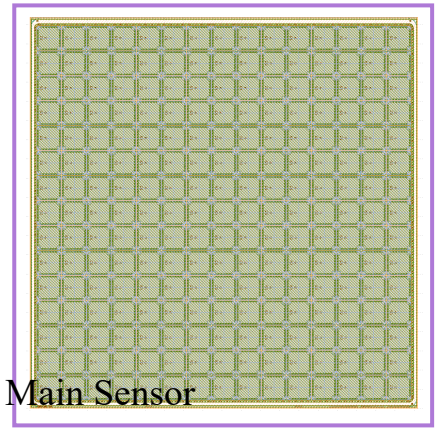
High-Granularity Timing Detector (HGTD)





QC Test Structure





Main Sensor

Following the HL-LHC upgrade,

- The collisions per Bunch Crossing(BX): 140~ 200 with 1.5 vertex/mm on average along the z axis;
- The High-Granularity Timing Detector based on Low Gain Avalanche Detector (LGAD): provides timing information to enhance vertex reconstruction and luminosity monitoring.

Sensor production:

- About 21800 sensors;
- IHEP-IME: 90% (pilot batch + 5 batches);
- USTC-IME: 10%.

LGAD Technology:

- N-in-P diode structure with extra p-type gain-layer;
- Gain: 10 ~ 20.

LGAD sensor for HGTD:

- Active thickness: 50 μm;
- 15x15 pads with 1.3 × 1.3 mm² cells;
- Carbon-enriched gain-layer for radiation hardness;
- Radiation tolerance : 2.5×10^{15} n_{eq}/cm^2, 200Mrad
- Time resolution: ≈ 35ps (start); ≈ 70ps (end of lifetime);
- Min. charge: 4fC;

HGTD Sensor Acceptance Criteria

IME → Some companies → IME, USTC

Wafer processing, **Company Quality Control (CQC)**

Dicing , picking, and packing

Sensor Quality Control (SQC)

- $V_{bd} = \mathrm{Min}(V_{bd,15\ pad}) \rightarrow 165V < V_{bd} < 195V$, $\frac{\mathrm{RMS}(V_{bd,15\ pad})}{\mathrm{AVERAGE}(V_{bd,15\ pad})} < 5\%$
- Current spread: $\mathrm{Max}(\mathbf{I_{15\ pad}}$ at $0.8 \cdot \mathbf{V_{bd}})/\mathrm{Min}(\mathbf{I_{15\ pad}}$ at $0.8 \cdot \mathbf{V_{bd}}) \leq 2.5$

CERN

Process Quality Control (PQC)

- LGAD CV → $\frac{\mathrm{RMS}(V_{gl})}{\mathrm{AVERAGE}(V_{gl})} < 2\%$
- LGAD IV
- MOS CV
- Sheet resistors

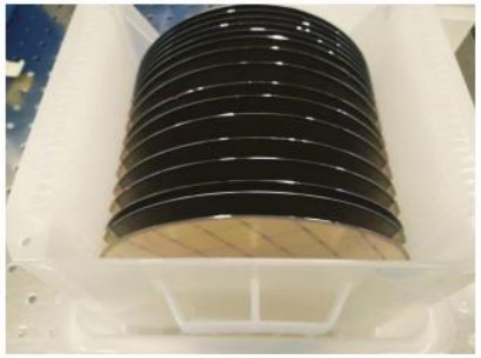
USP

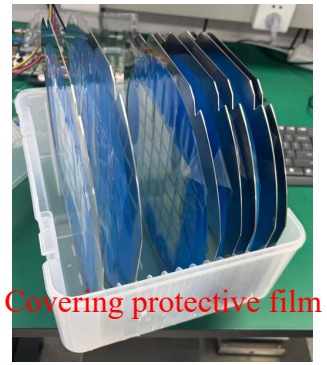
Process Quality Control (PQC)

JSI

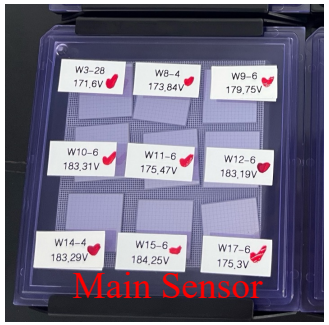
Irradiation Test (IT)

- Gain @ 100V(TCT)
- V_{gl} (CV after irradiation)

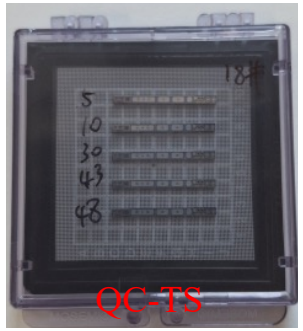




Covering protective film



Main Sensor



QC-TS

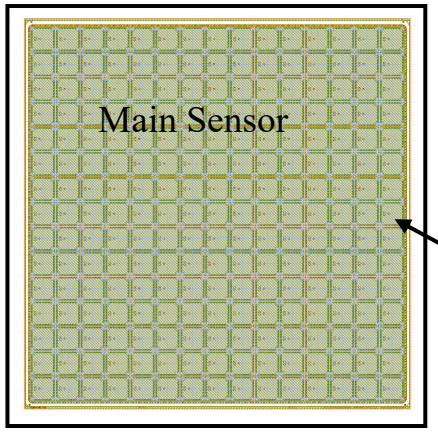
Content

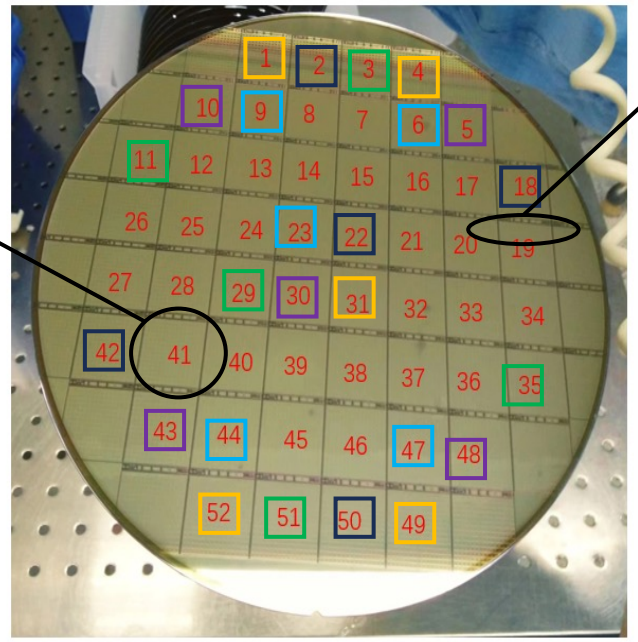
- Introduction
- Company Quality Control (CQC)
- Sensor Quality Control (SQC)
- Process Quality Control (PQC)
- Irradiation Tests (IT)
- Summary

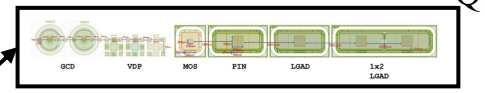
Company quality control(CQC)

Wafer layout

- 52 complete sensors on the entire wafer;
- One sensor consisting of a main sensor and Quality Control Test Structures (QC-TS).







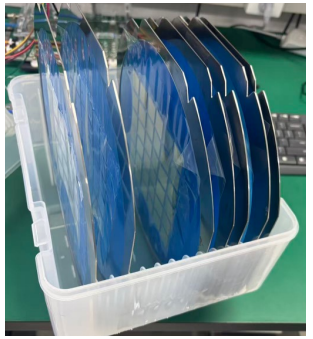
QC-TS

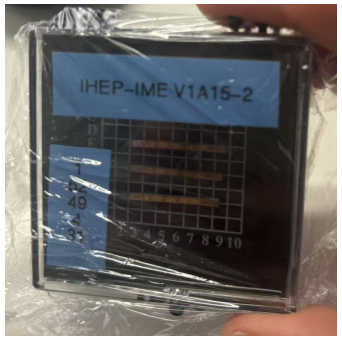
- Five QC-TS structures are selected at five distinct positions on the wafer.

Allocated to	TS grouping	TS Position Number
CERN	1	2、18、22、42、50
	2	6、9、23、44、47
USP	1	1、4、31、49、52
	2	3、11、29、35、51
JSI	1	5、10、30、43、48

IV test

- **IHEP**: 15x1 probe card IV measurements on sensors by IME before dicing;
- **USTC**: single-needle per-pad measurements on all sensors by IME before dicing.





- IME uploads the IV test data to HGTD database;
- IME provides classification results based on IV test data without temperature correction;
- Some companies perform dicing, selecting Class A sensors and QC-TS structures from five different positions are gathered together.

28929 20WS0010400002 Wafer IHEP-IME Testing upload 8 tianyuan

Sensor Acceptance Criteria

- A: sensor passes all the acceptance criteria.

at 20°C

Break down current:

$I_{bd,15\ pad} = 15 \cdot I_{pad,bd} \rightarrow V_{bd,15\ pad}$ is defined at $I_{15\ pad} > 7500$ nA, where $I_{pad,bd}$ is the pad current breakdown threshold.

- **Sensor break down voltage:**

$V_{bd} = \mathrm{Min}(V_{bd,15\ pad}) \rightarrow 165V < V_{bd} < 195V$

- **Break down spread:**

$\mathrm{RMS}(V_{bd,15\ pad})/\mathrm{AVERAGE}(V_{bd,15\ pad}) < 0.05$

- **Current spread:**

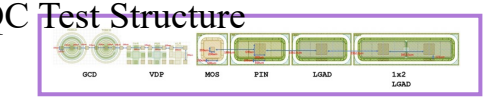
$\mathrm{Max}(\mathbf{I_{15\ pad}}\ \text{at}\ 0.8 \cdot \mathbf{V_{bd}})/\mathrm{Min}(\mathbf{I_{15\ pad}}\ \text{at}\ 0.8 \cdot \mathbf{V_{bd}}) \leq 2.5$

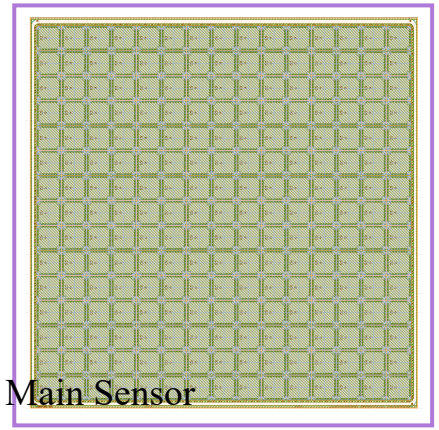
- B1: sensor with $150V < V_{bd} < 165V$, fills the leakage current requirement
- B2: sensor fill Current spread criteria with

$2.5 < \mathrm{Max}(I_{15pad}\ \text{at}\ 0.8 \cdot V_{bd})/\mathrm{Min}(I_{15pad}\ \text{at}\ 0.8 \cdot V_{bd}) < 10.$

- C: sensor fills any of the tests and are not of category B.

QC Test Structure



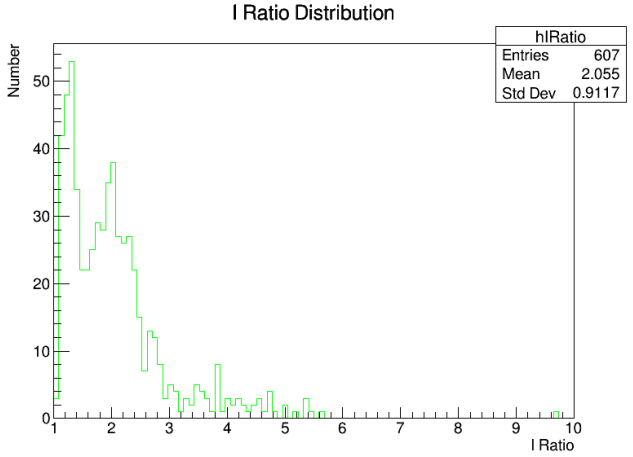


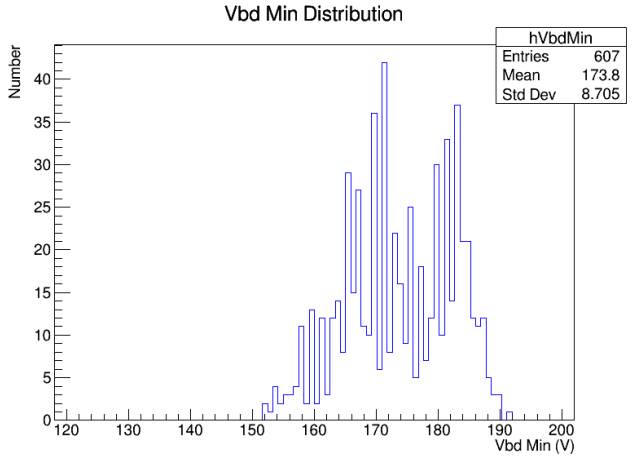
Main Sensor

Company Quality Control (CQC)

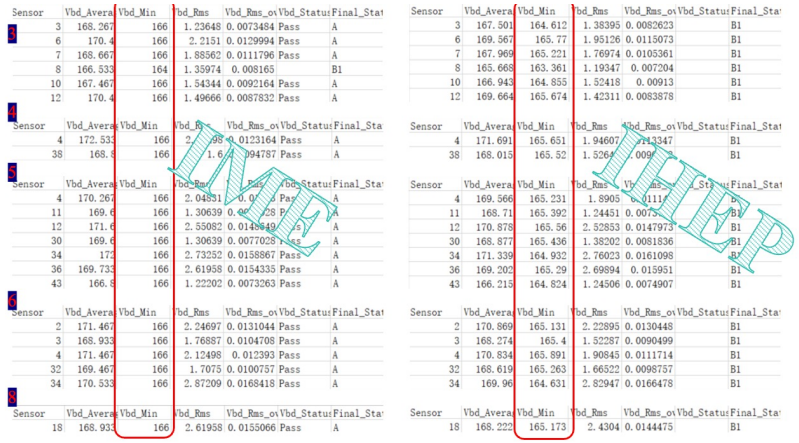
17 wafers of IHEP Pilot Batch

- Class A sensors according to IME analysis results is 403;
- Class A sensors according to IHEP analysis results **with temperature correction** is 372;
- **Information of sensors from 17 wafers from IME test data**
  - V_{bd} distribution:
    - A+B1+B2: from 152V to 192V;
  - Leakage current ratio at $0.8V_{bd}$:
    - Except for one main sensor(type B2) with an IRatio of 9.7, the rest (A+B1+B2) are less than 5.8.





Temperature correction:



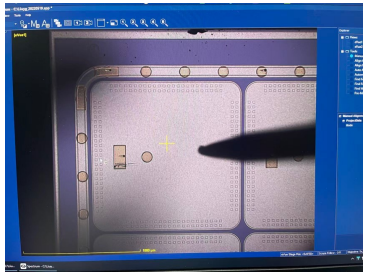
Class	A	Yield
A	372	42.08%
B1	119	13.46%
B2	116	13.12%
total	607	68.66%

Content

Sensor Quality Control (SQC)

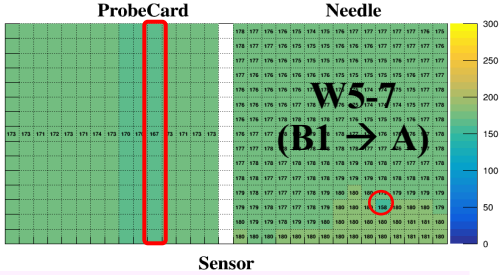
- SQC: IHEP per-pad tested one Class-A sensor per wafer from 17 wafers;

  SQC:
  Class A : 17 in total;
  Class B1 : 2 in total;
  Class B2 : 4 in total;
  Class C : 1 in total;



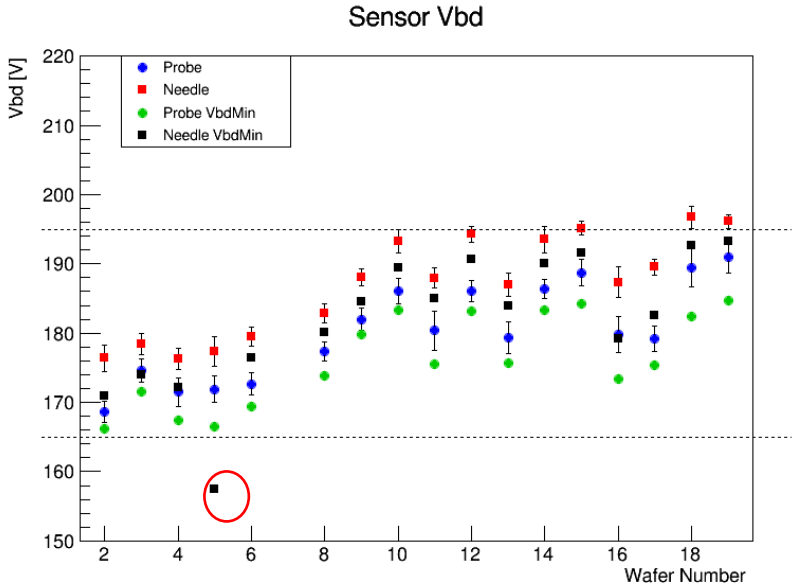
  - Single needle per-pad IV measurements at 20°C
  - GR: floating, identical to IME
  - Each sensor requires approximately 2 hours for needle test.

- Research into B1 and B2 class sensors to determine whether they can be accepted

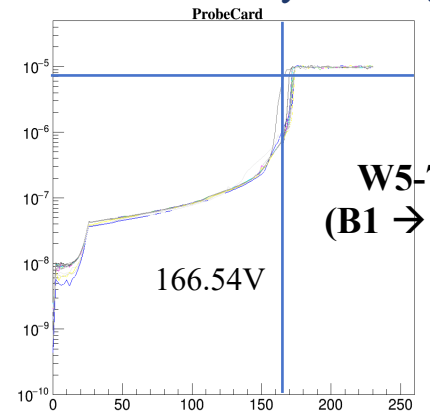


17 Class-A at IHEP, 3 Class-A at JSI:

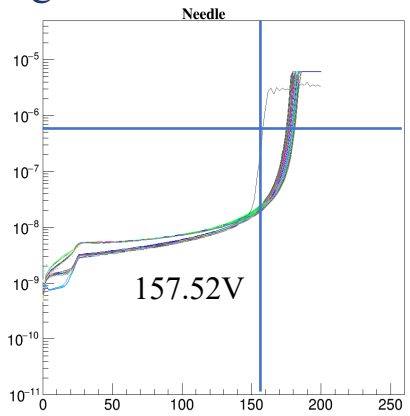
- 19 remain A;
- 1 (W5P7) → B1(V_{bd} < 165V);
- **Vbd from the needle test (by IHEP and JSI) was 2.41~10.15 V higher than the probe card test;**



The V_{bd} values from IHEP's needle test results are higher than those from IME's probe card test results. We are currently investigating the reason.



W5-7
(B1 → A)



Sensor Quality Control (SQC)

2 Class-B1 at IHEP, 5 Class-B1 at JSI :

- 3 B1 → A(V_{bd} >165V); 2 B1 → B2; 2 B1 → C(with one bad pad near GR);

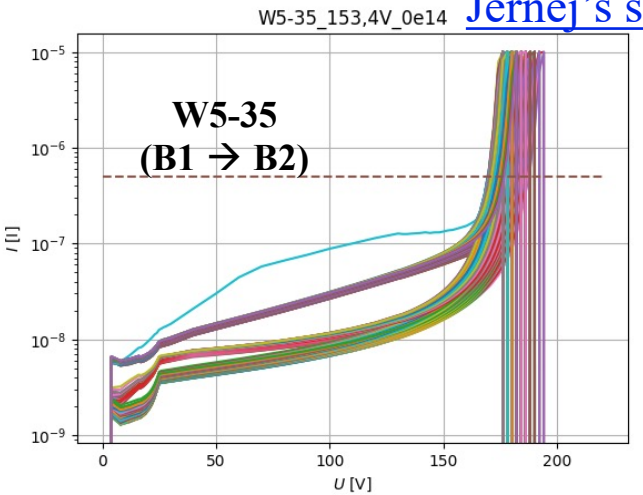
4 Class-B2 at IHEP, 5 Class-B1 at JSI :

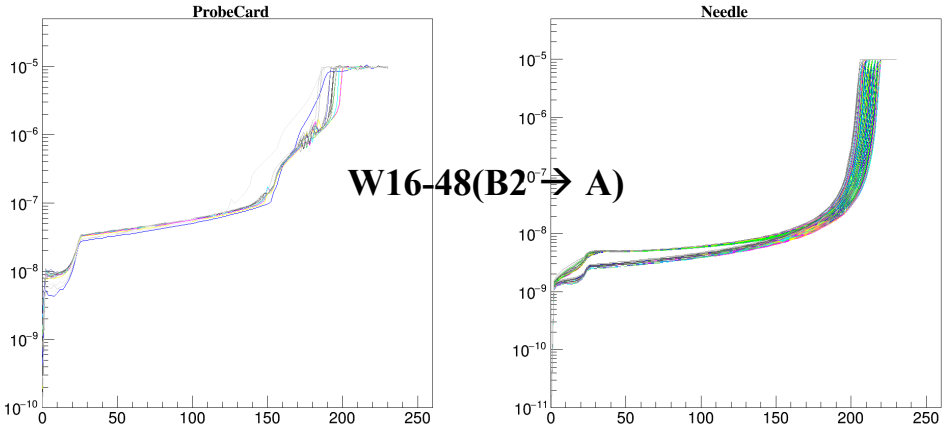
- 5 B2 → A;
- 4 B2 → C(early breakdown);

1 Class-C:

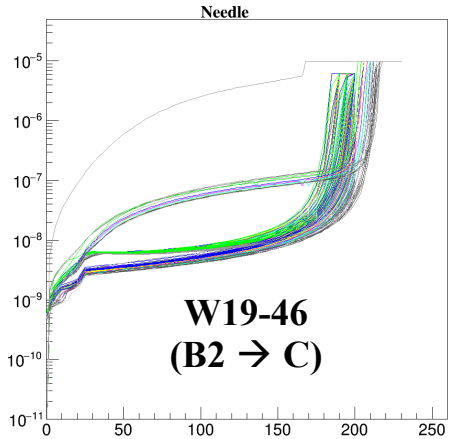
- Remains C;
- Probecard test and needle test yielded identical lower columns of the V_{bd}.

Jernej's slides

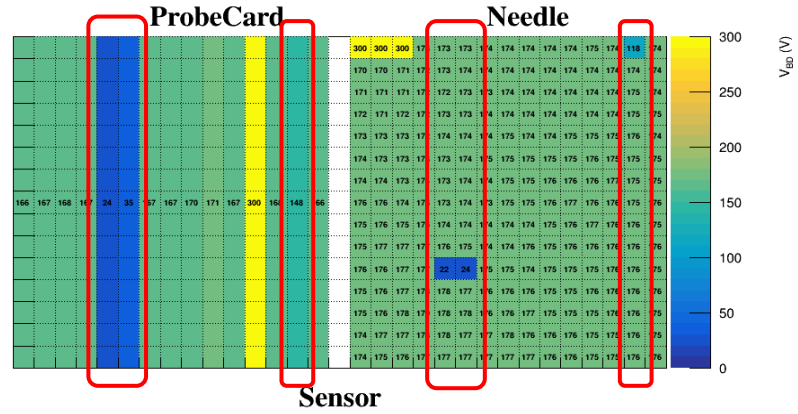




become smoother



Early breakdown



W3-9 (C)

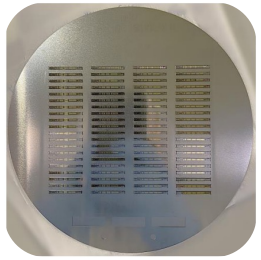
Content

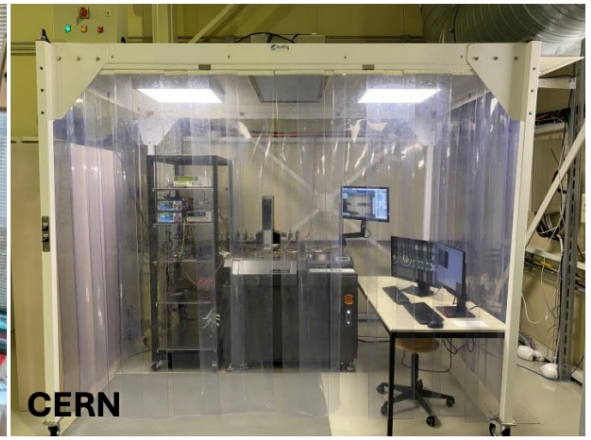
- Introduction
- Company Quality Control (CQC)
- Sensor Quality Control (SQC)
- **Process Quality Control (PQC)**
- Irradiation Tests (IT)
- Summary

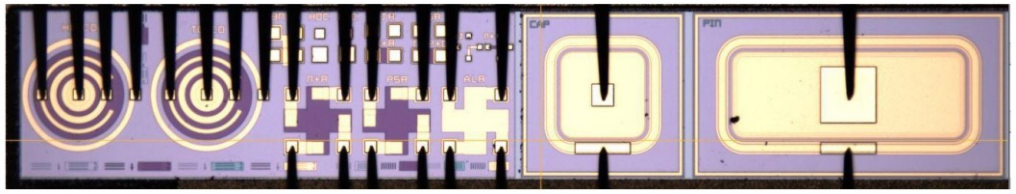
Process Quality Control (PQC)

17 wafers of IHEP-IME Pilot batch

- 10 QC-TS/wafer at CERN and USP
- Probe card: needles contacting all 30 pads
- 5 minutes/structure
- 80-position stencil from USP
- Temperature: T=20°C
- The acceptance of the wafers will be based on spread of gain-layer depletion voltage:
  - Spread $= \frac{\mathrm{RMS}(V_{gl})}{\mathrm{AVERAGE}(V_{gl})} < 2\%$

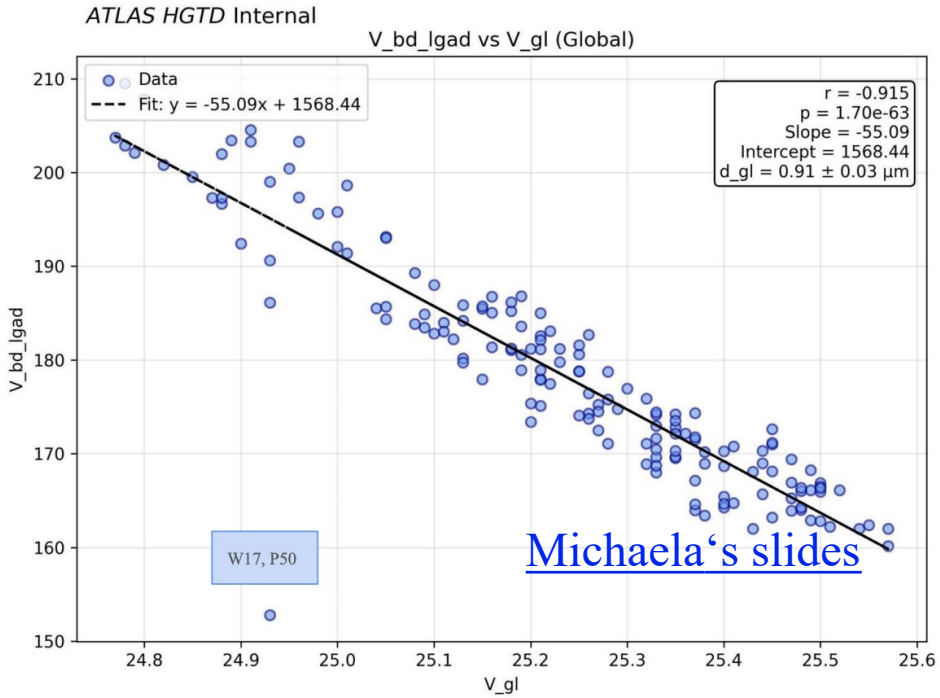




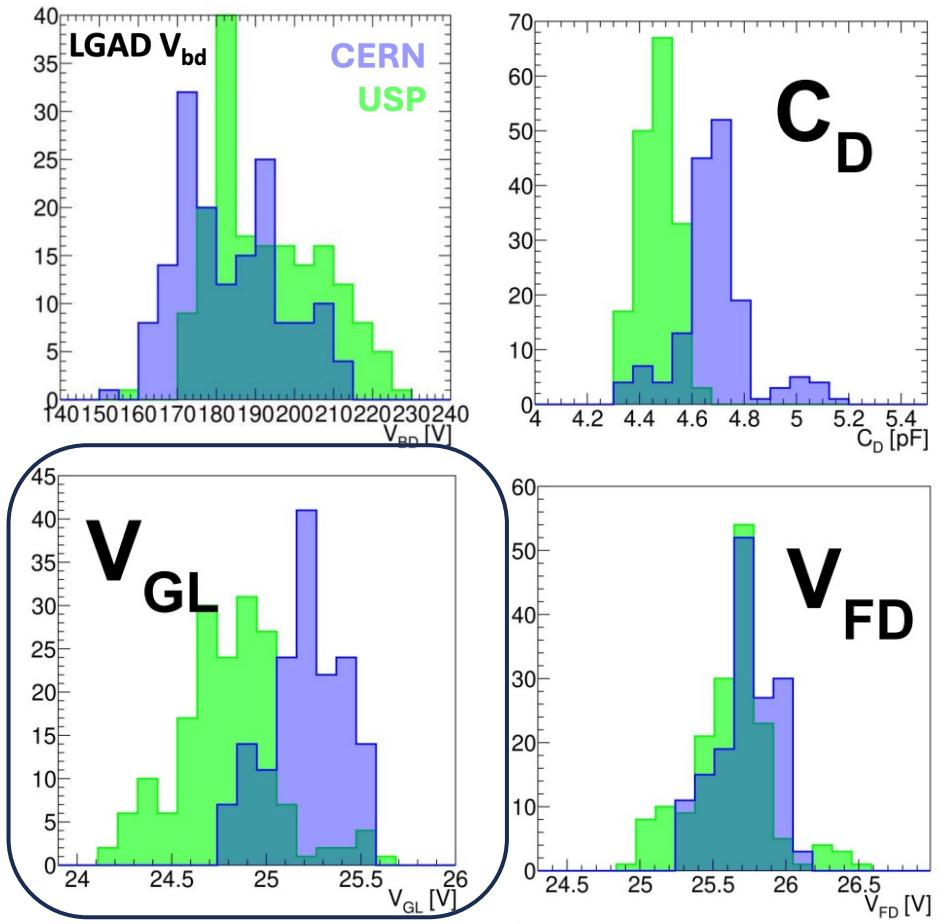


Process Quality Control (PQC)

- LGAD IV and CV: Results for sites individually ok, slight discrepancy between USP and CERN in V_{gl} and C_D
  - **V_{gl} spread**
    - ✓ USP 17/17 wafer would **pass** PQC
    - ✓ CERN 17/17 wafer would **pass** PQC
  - **C_D** : average of 4.45 pF
- V_{gl} vs. V_{bd} : strong correlation observed as expected (unlike for preproduction)



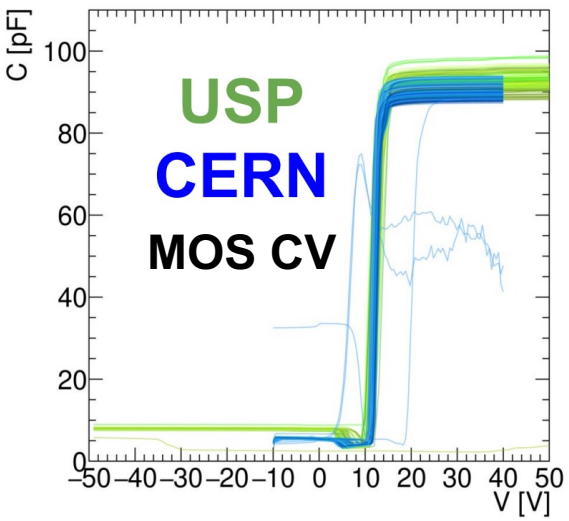
Michaela's slides

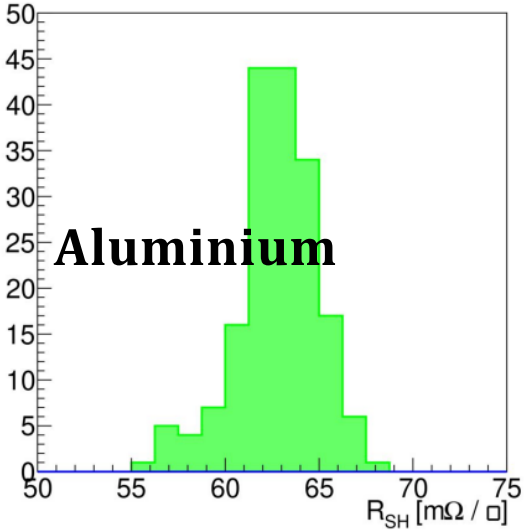


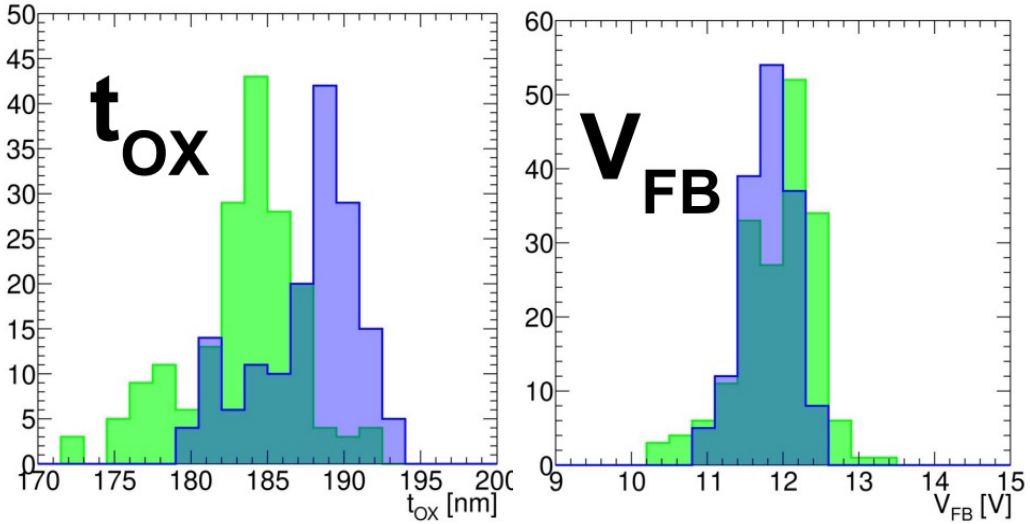
Guilherme's slides

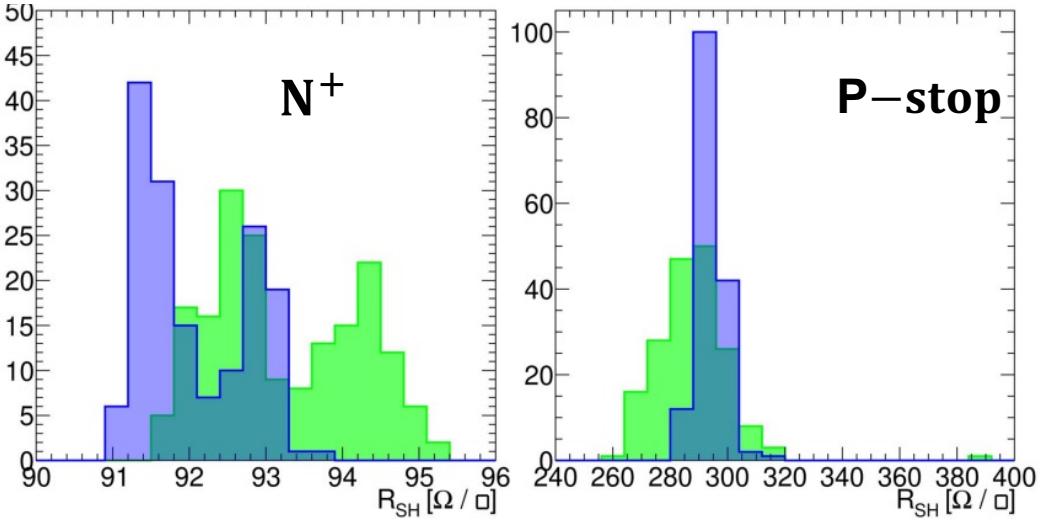
Process Quality Control (PQC)

- MOS CV: Much more stable measurement w.r.t. preproduction
  - V_{FB} : Good agreement between sites
  - Oxide thickness: slight tension between sites
- Sheet resistors:
  - N^+: Very low spread, indicating uniform doping profile
  - P-stop: Good agreement between sites
  - Aluminium sheet resistance with same spread as pre-production









Guilherme's slides

Content

- Introduction
- Company Quality Control (CQC)
- Sensor Quality Control (SQC)
- Process Quality Control (PQC)
- **Irradiation Tests (IT)**
- Summary

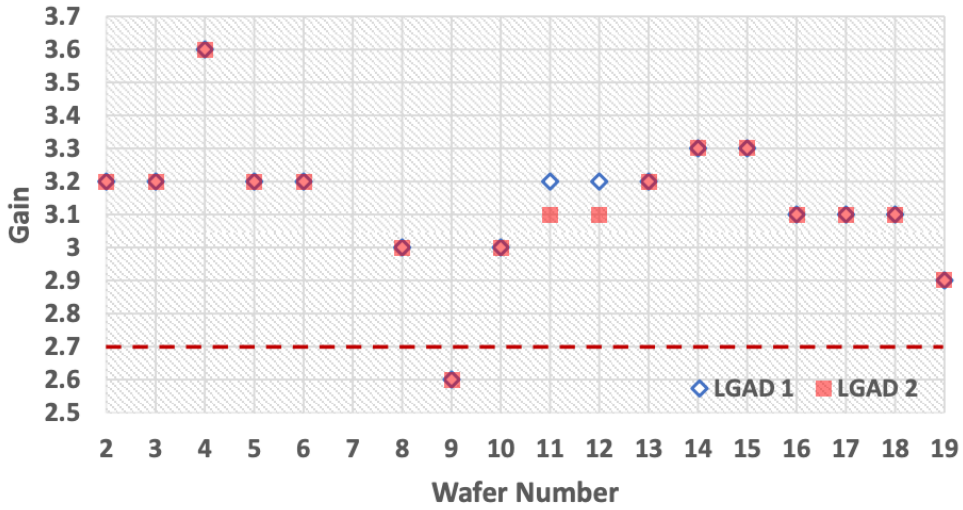
Irradiation Test (IT)

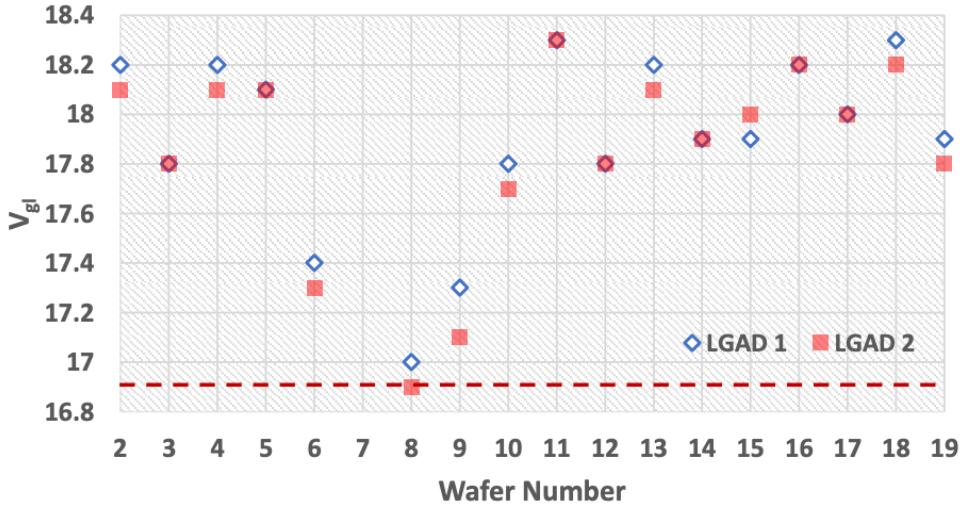
17 wafers of IHEP-IME Pilot batch

- Irradiation Test: QC-TS are irradiated at JSI with neutrons at end-of-life fluence(2.5×10^{15} n_{eq}/cm^2) (and are annealed for 80min at 60°C)
- Transient Current Technique (TCT) measurement:
  - Gain @ 100V measured the 1x2 LGAD of the QC-TS
- CV measurement: V_{gl}
- Defined after ^{90}Sr measurements on pre-production QC-TS:

Design	Gain @ 100 V	V_{gl}
IHEP	≥ 2.7	≥ 16.9V
USTC	≥ 1.4	≥ 16.6V

- 5 QCTS/wafer at JSI, 1 QC-TS/wafer tested by JSI
- Always position 30 measured – center of the wafer
- **All wafers pass V_{gl} requirements**
- **One wafer (9) barely fails gain criteria(to do ^{90}Sr measurements on W9)**





BRIGITA's slides

Summary

Pilot Batch

- PQC: done --- **all wafer accepted.**
- IT: done --- **all wafer accepted.**
  - 16/17 wafers passed – need to do ^{90}Sr for one wafer.
- CQC:
  - IME is testing A, B1 and B2 sensors that were tested also at IHEP.
- SQC:
  - **20 Class A sensors from 17 wafers passed SQC testing by IHEP and JSI.**
  - **SQC gives 2~10V higher V_{bd} than CQC(confirmed by IHEP and JSI).**

First Batch

- 50 wafers (containing a total of 1,371 Class A sensors) are currently undergoing dicing and picking by some companies.

Thanks!

Test temperature

Wafer	Temperature(°C)
B4-2	20.5
B4-3	21.3
B4-4	21.6
B4-5	21.0
B4-6	21.6
B4-8	21.1
B4-9	21
B4-10	21.1
B4-11	21

Wafer	Temperature(°C)
B4-12	20.7
B4-13	21.4
B4-14	21.2
B4-15	21
B4-16	20.9
B4-17	21.1
B4-18	21
B4-19	21.1

WAFER 9 – additional tests

Position 5

ATLAS ID	Wafer	Position	Vgl 1	Vgl 2	Gain 1	Gain 2
20WS2104000905	9	5	17.7	17.7	2.7	3.0
20WS2104000905 (repeat)	9	5	17.8	17.9	2.9	2.9

Position 30

ATLAS ID	Wafer	Position	Vgl 1	Vgl 2	Gain 1	Gain 2
20WS2104000930 (repeat 1)	9	30	17.1	17.2	2.6	2.6
20WS2104000930 (repeat 2)	9	30	17.1	17.3	2.6	2.6
20WS2104000930 (repeat 3)	9	30	17.3	17.2	2.8	2.7
20WS2104000930 (repeat 4)	9	30	17.4	17.3	2.8	2.8

Acceptance criteria (IHEP):
Vgl ≥ 16.9 V Gain (100 V) ≥ 2.7