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Bundesministerium für Bildung und Forschung

Wafer-to-wafer bonded hybrid pixel detectors

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2) University of Bonn

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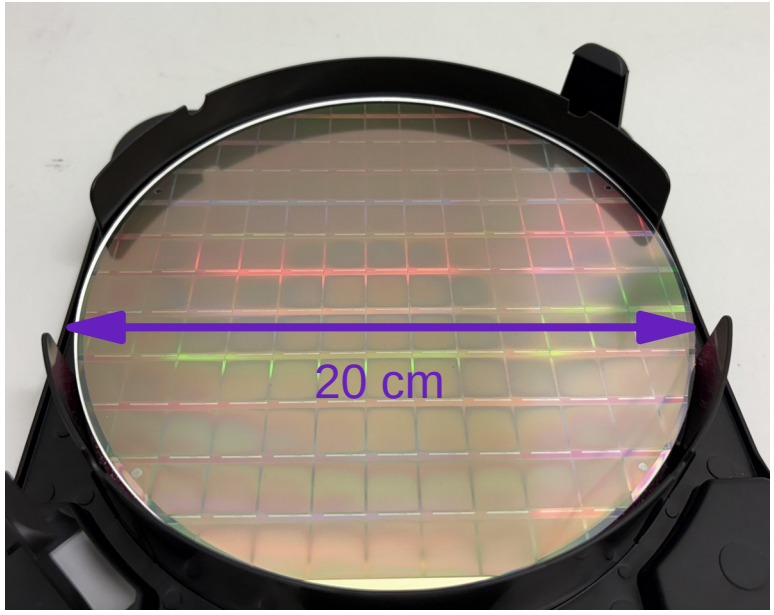
Herbstschule of High-Energy Physics 2025

Manufacturing of Hybrid Pixel Detectors

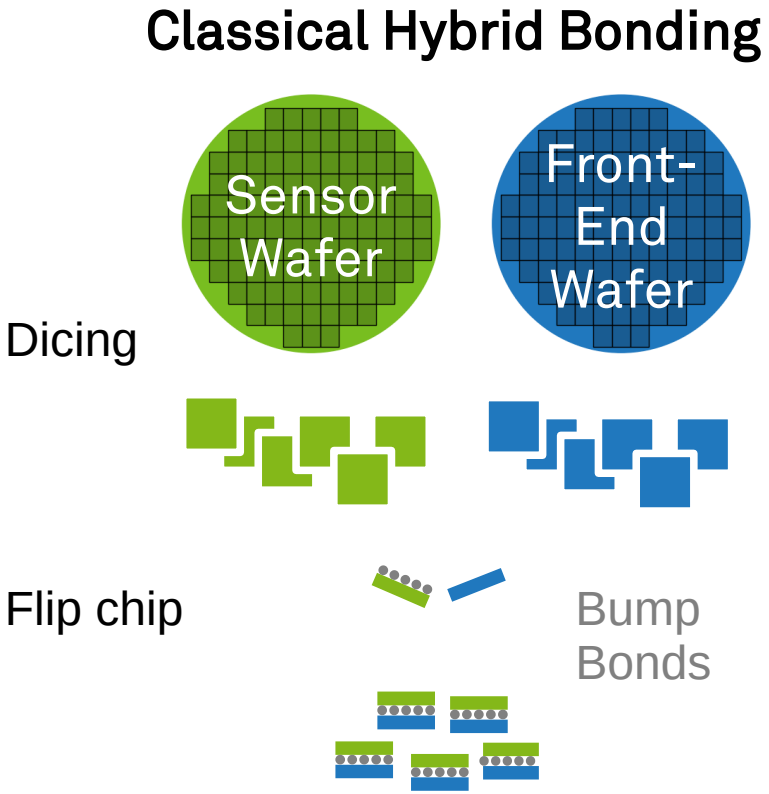


Hybrid semiconductor pixel detectors are widely established in HEP and medical physics

Sensor: Active volume to detect particles

Front End (FE): Amplification & Pulse shaping

Manufacturing of Hybrid Pixel Detectors



Hybrid semiconductor pixel detectors are widely established in HEP and medical physics

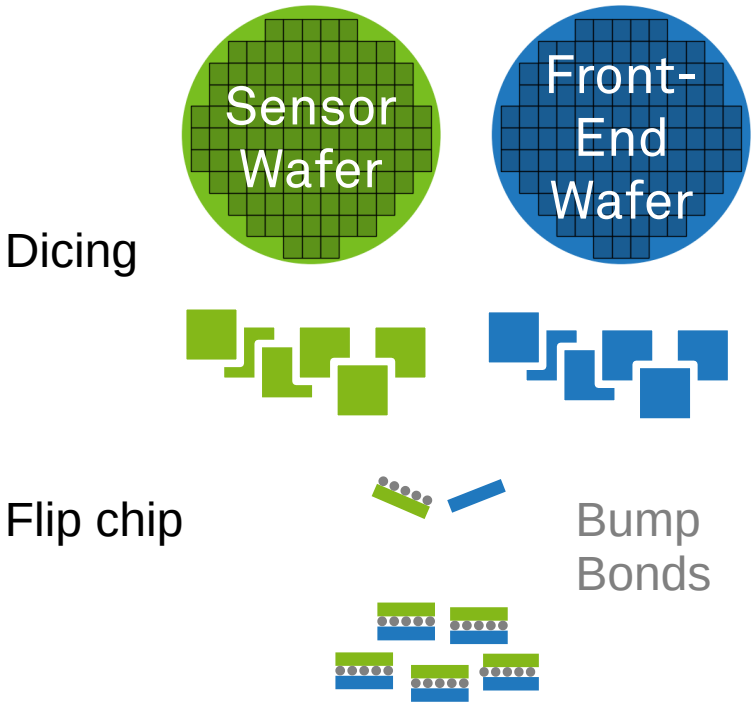
Sensor: Active volume to detect particles

Front End (FE): Amplification & Pulse shaping

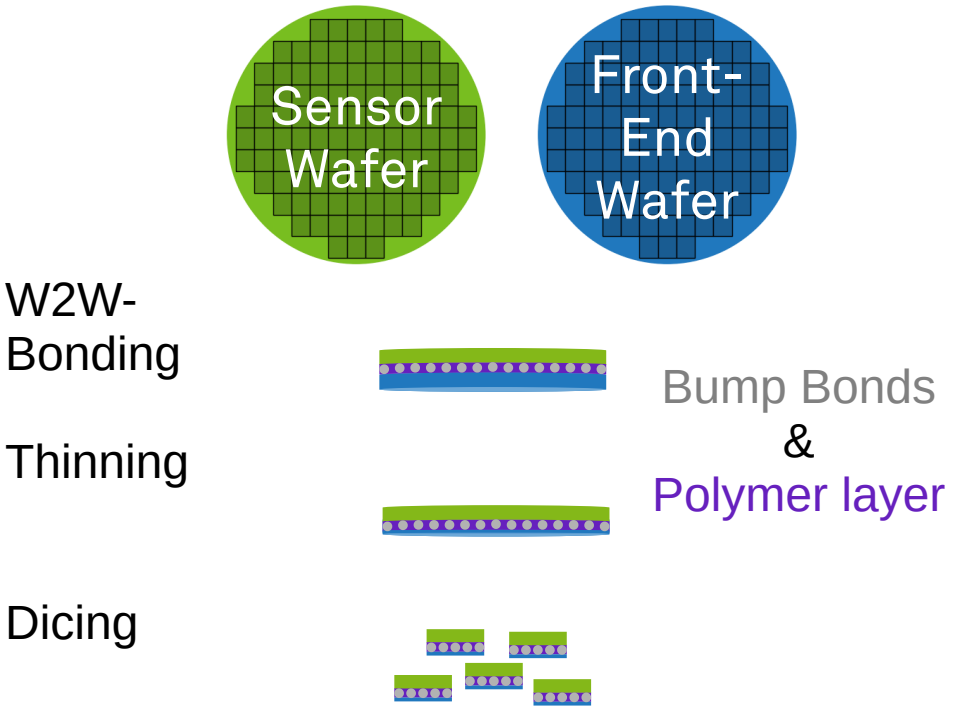
- Current manufacturing process:
  - Limited area
  - Limited thinness
  - Uses outdated industry processes

Manufacturing of Hybrid Pixel Detectors

Classical Hybrid Bonding



Wafer-to-wafer bonding (W2W)



Manufacturing of Hybrid Pixel Detectors

+ Individual development of wafers

+ Thinning after bonding possible

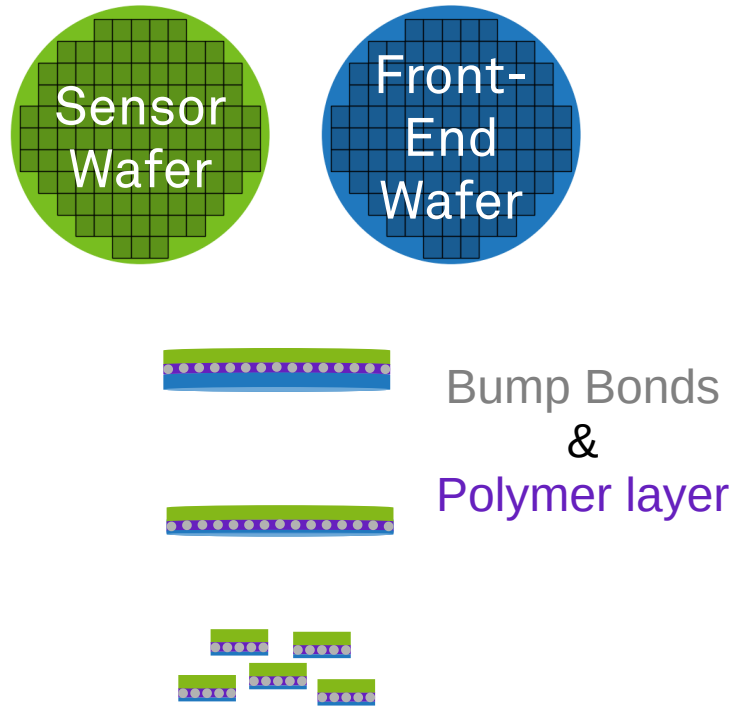
+ Larger surface area

- Layout needs to match on wafer level

- Surface needs to be uniform, plane and smooth

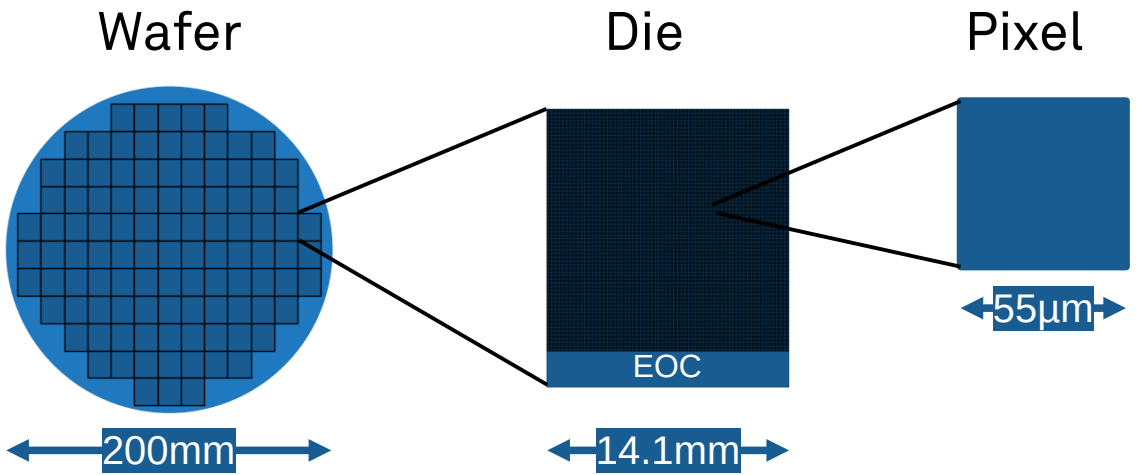
- Need of through silicon vias

Wafer-to-wafer bonding (W2W)



Ultimate Goal

Investigate new wafer-to-wafer (W2W) bonded hybrid pixel detectors using Timepix3 FE wafers and dedicated sensor wafers



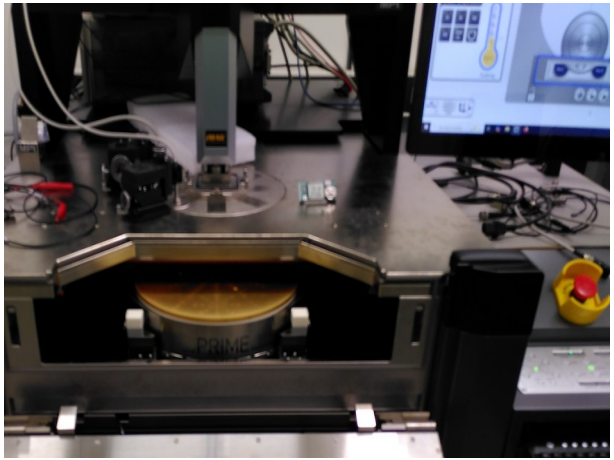
23 wafer with 105 dices and 246 x 256 pixels each

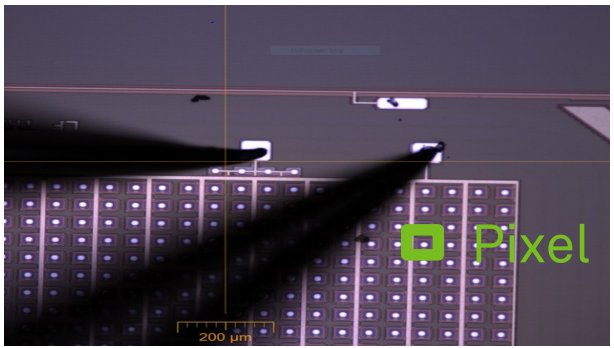
Ultimate Goal

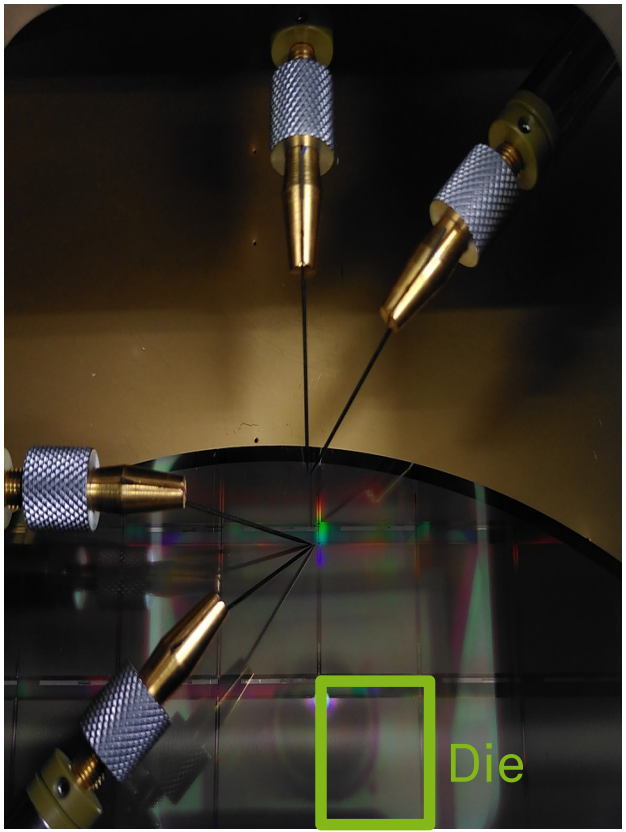
- Complete characterization of all sensors on sensor wafer (IV & CV curves, breakdown voltage, depletion voltage)
- Investigation of W2W-bonds on non-detector wafers
- Implementation of Timepix 3 readout system
- Investigation of W2W bonded detector wafers before dicing
- Investigation of W2W bonded detector wafers after dicing
- Thermal stability of bonds
- Test beam measurements

Measurement Setup

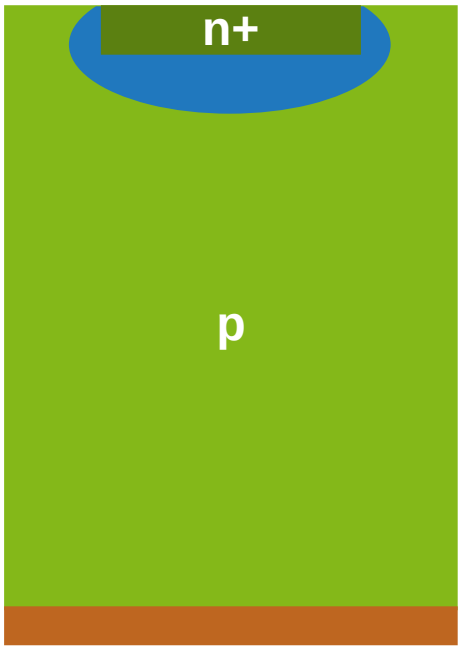
- Semi automatic wafer prober station
  - Ambient temperature: 20°C ± 1°C
  - Dehumidified air
  - Light shielding
  - Electromagnetic interference shielding
- Voltage applied via probes on bias pads and chuck on backside metallization
- Automatic measurement of several dices





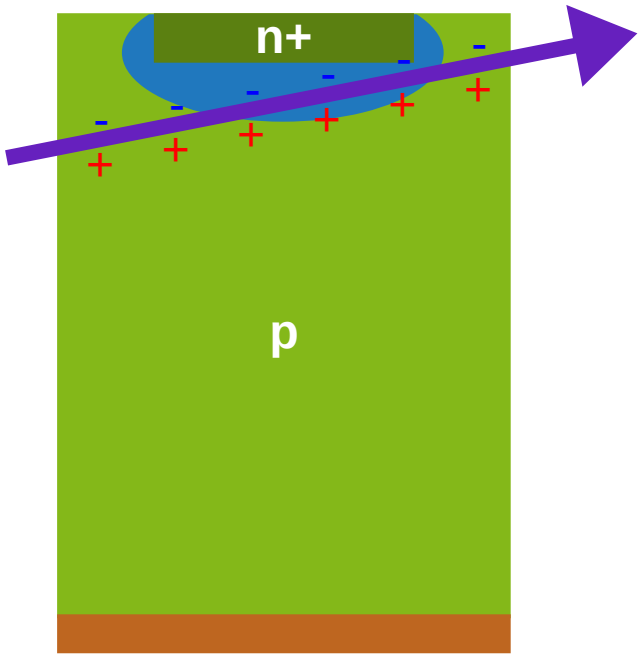


Biasing the Sensorwafer



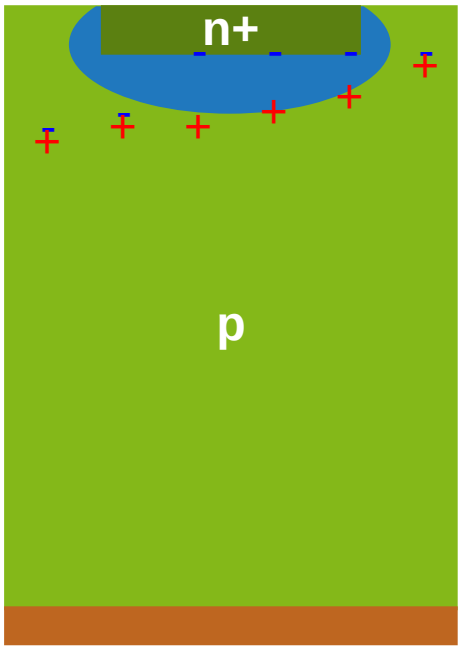
- Charge carrier free **depletion zone** where n+ and p doped regions meet

Biasing the Sensorwafer



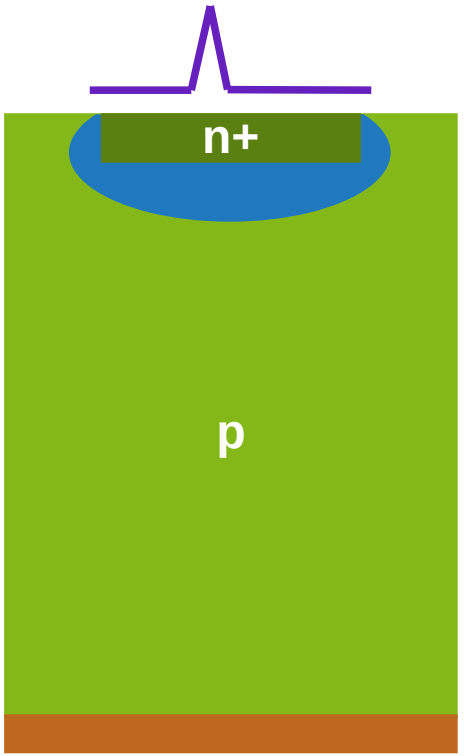
- Charge carrier free **depletion zone** where n+ and p doped regions meet
  - Particles induce charges in depletion zone

Biasing the Sensorwafer



- Charge carrier free **depletion zone** where n+ and p doped regions meet
  - Particles induce charges in depletion zone
  - Outside of depletion zone charges recombine
  - Electric field in depletion zone let charges drift and can be measured

Biasing the Sensorwafer



- Charge carrier free **depletion zone** where n+ and p doped regions meet
  - Particles induce charges in depletion zone
  - Outside of depletion zone charges recombine
  - Electric field in depletion zone let charges drift and can be measured
  - Collected charges can be measured

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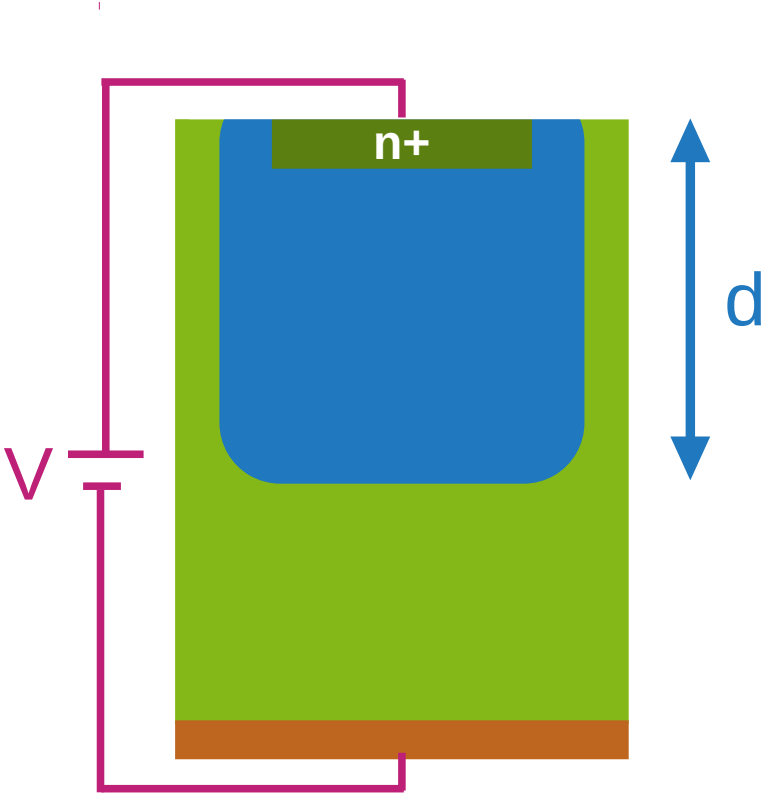
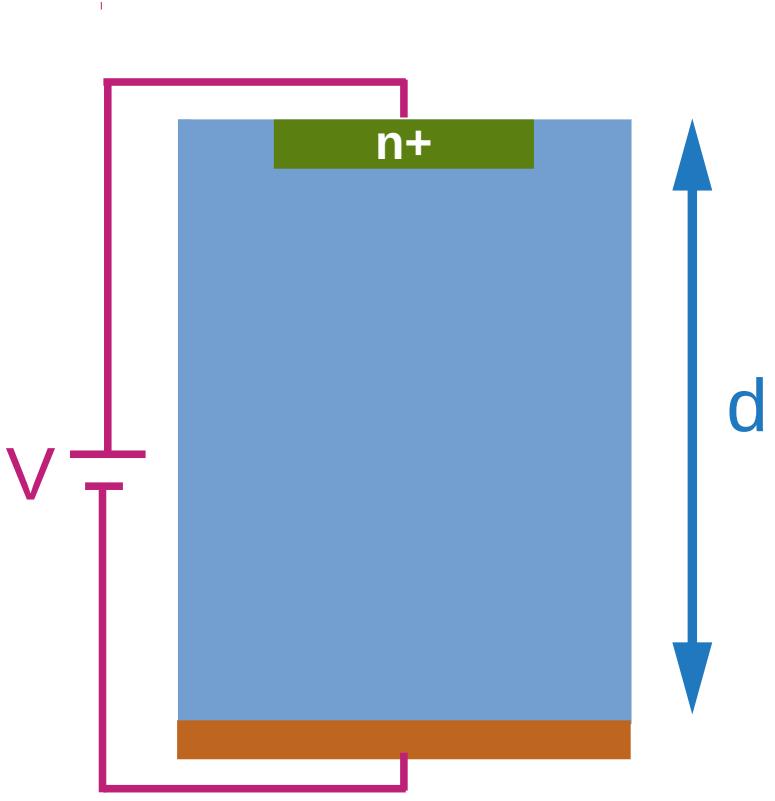


- Charge carrier free **depletion zone** where n+ and p doped regions meet
- Reverse bias voltage increases thickness of depletion layer

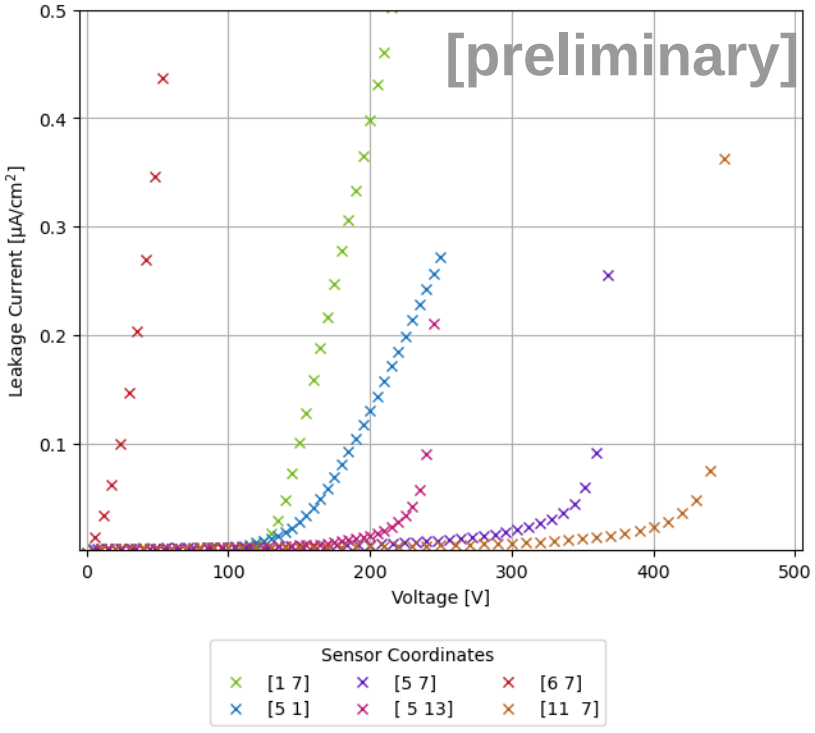
Biasing the Sensorwafer

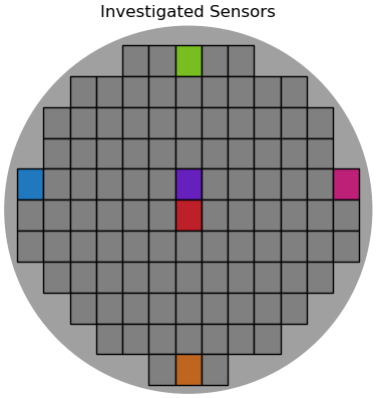


- Charge carrier free **depletion zone** where n+ and p doped regions meet
- Reverse bias voltage increases thickness of depletion layer
- Depletion zone reaches backplate metallization: **Fully depleted** sensor

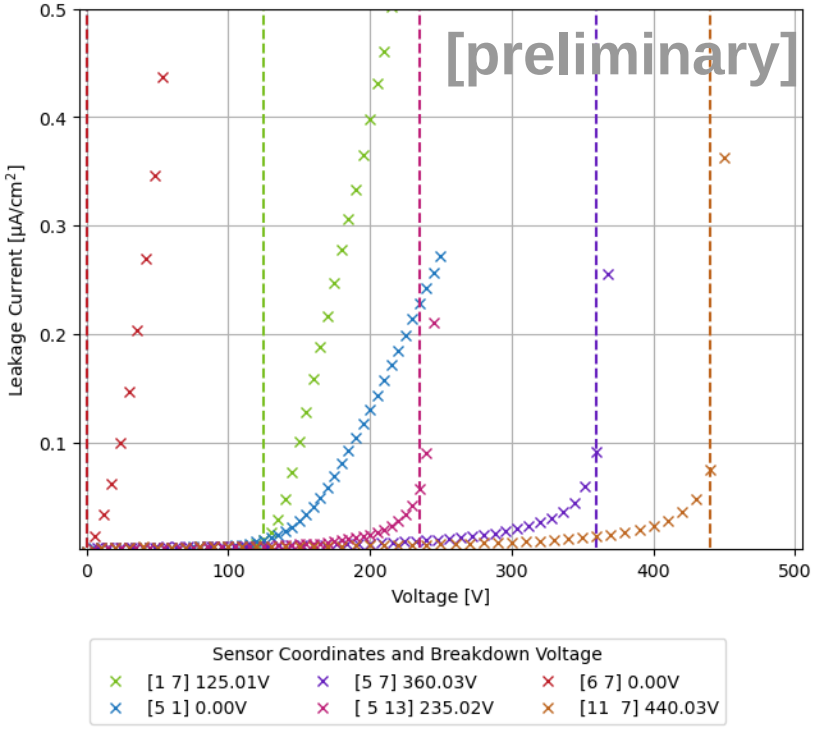
  → **maximum active volume**

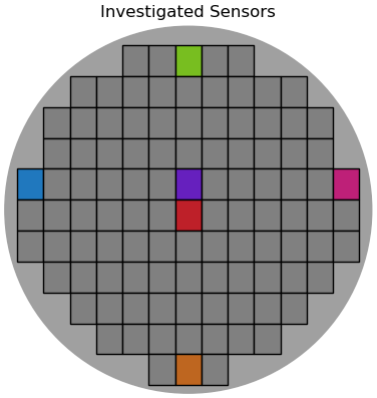
IV Curve Measurement





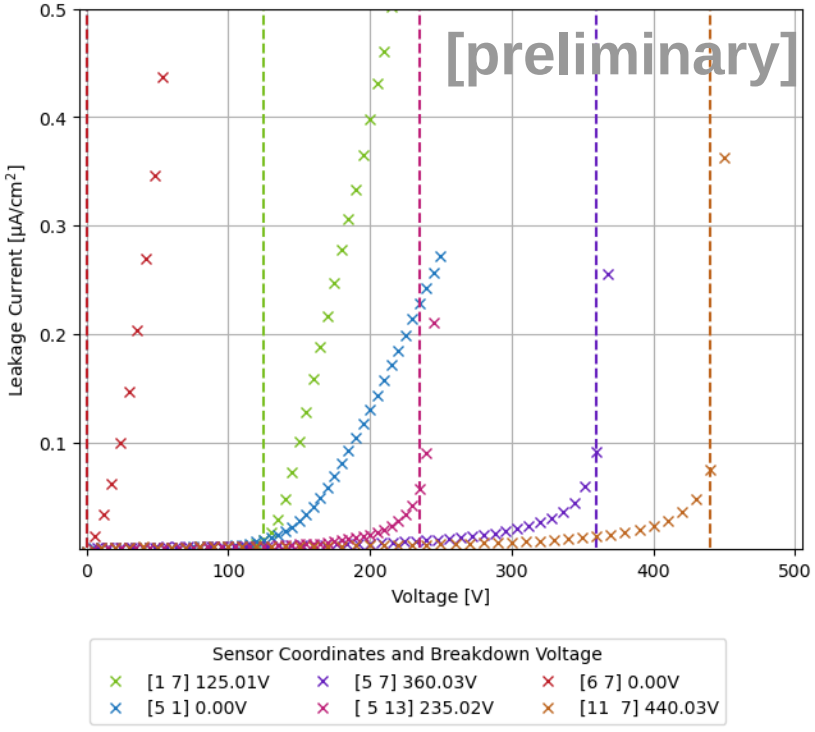
IV Curve Measurement

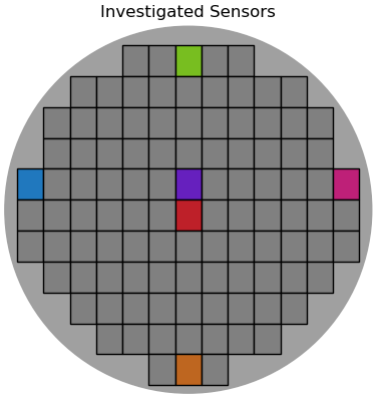


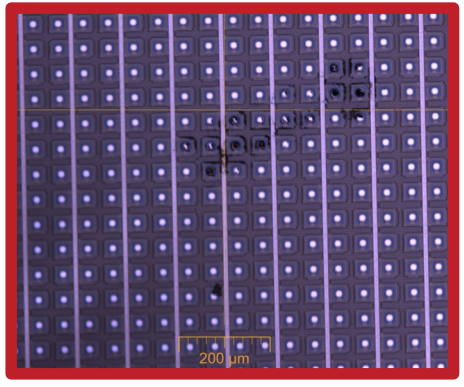


- High currents might break the sensor and need to be avoided!
- Breakdown voltage: 20% current increase during 5V step

IV Curve Measurement

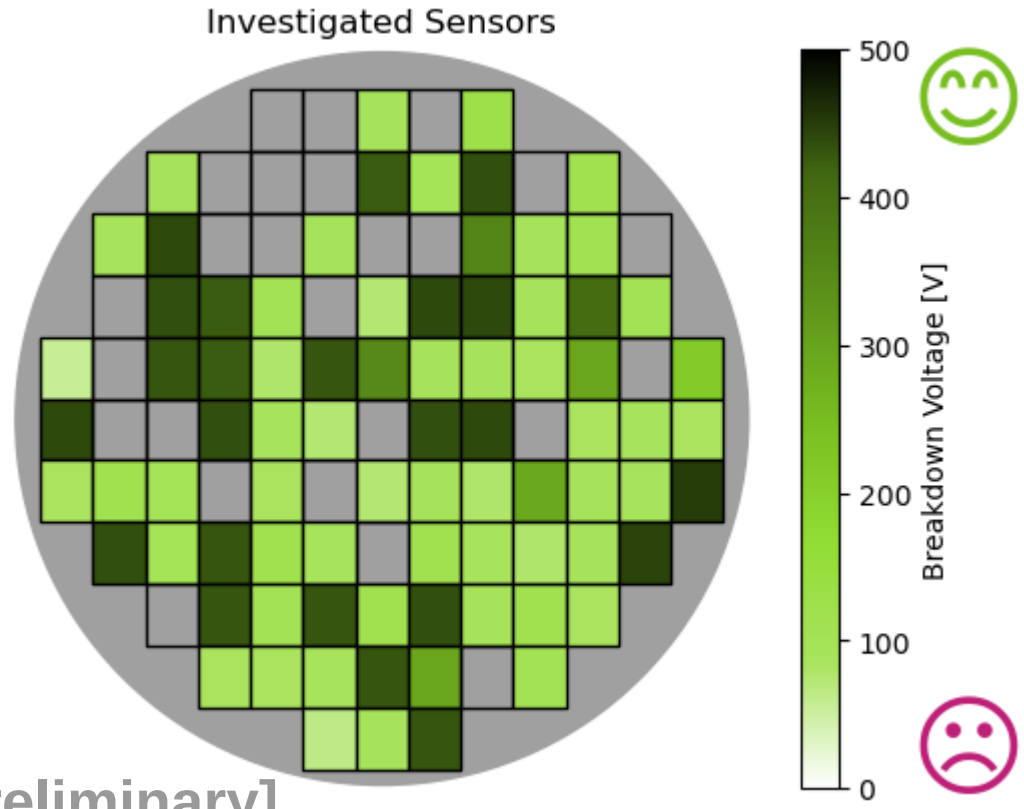






- High currents might break the sensor and need to be avoided!
- Breakdown voltage: 20% current increase during 5V step
- Early break down caused by physical damages
- 20/105 dices with early breakdown

IV Curve Measurement

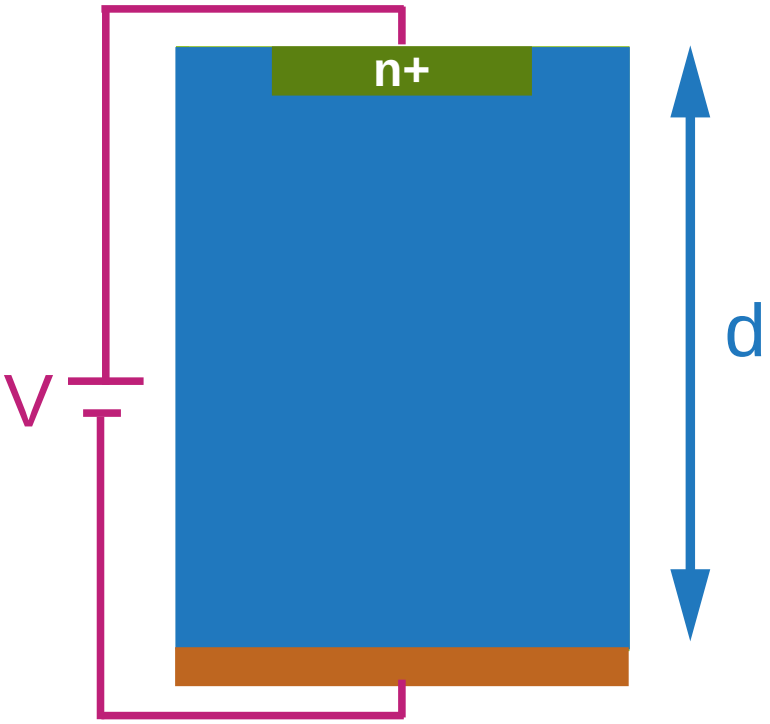


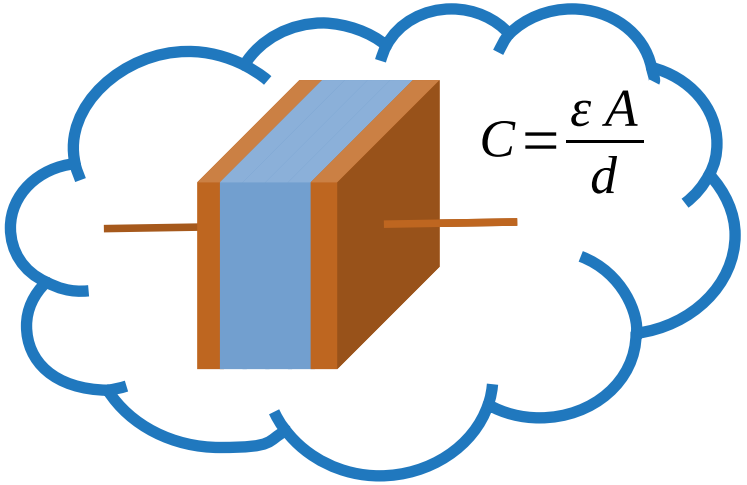
[preliminary]

- Breakdown voltage: 20% current increase during 5V step
  - Some curves too flat to determine $V_{Breakdown}$

→ Wide spread of breakdown voltages

CV Curve Measurement

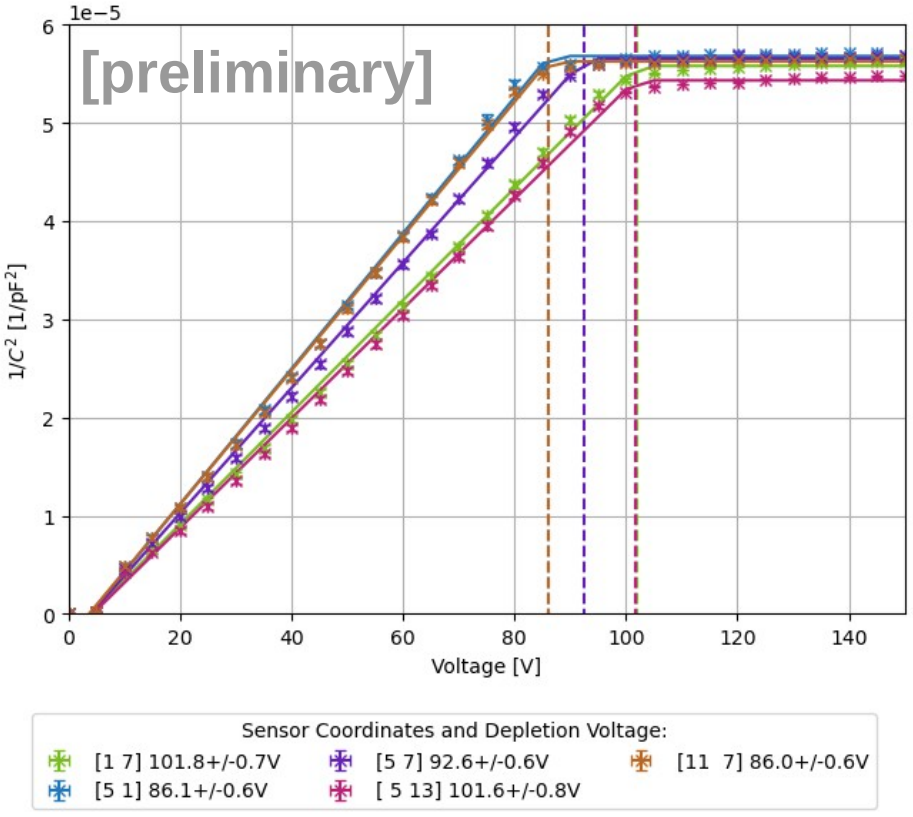


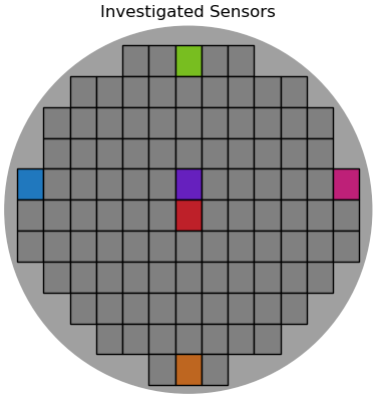


Additionally: $V_{depl} \sim d_{Sensor}{}^2$

Thus: $V_{depl} \sim \frac{1}{C^2}$

Capacitance-Voltage Dependency

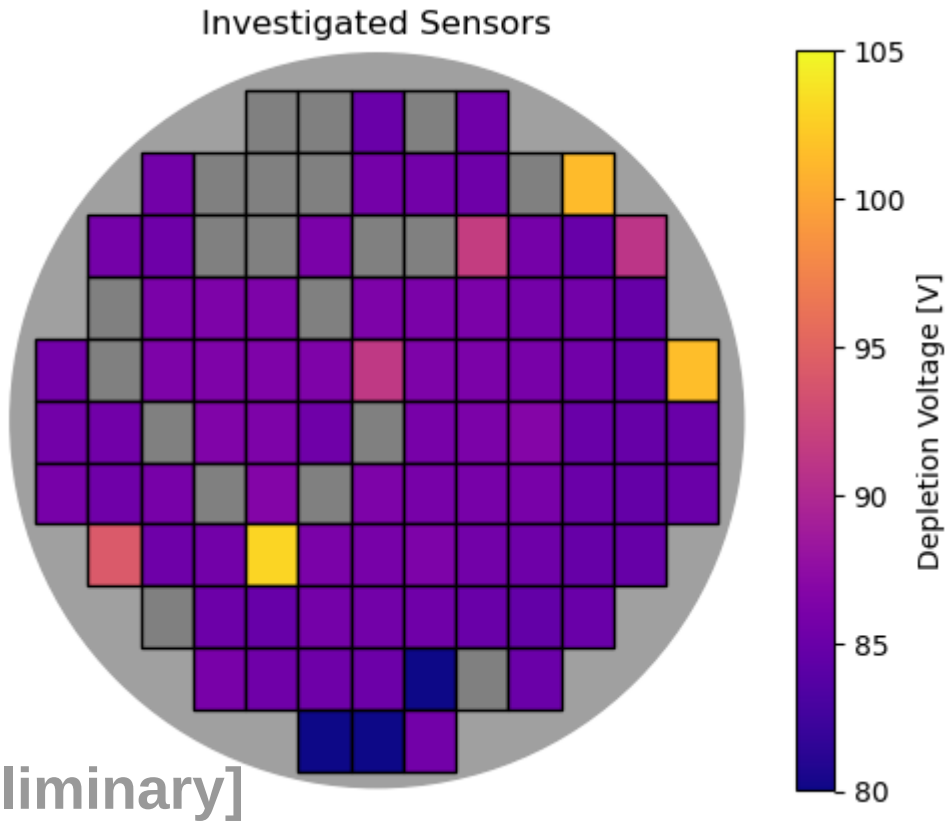




$$V_{depl} \sim \frac{1}{C^2}$$

- Impedance measurements using an LCR-meter
- Depletion voltage determined through fit

Sensor dependent depletion voltage



[preliminary]

- Depletion voltage between 85 V and 105 V
- Automatic measurement of **three dices** failed → missing contact?
- 12 dices with $V_{depl} > V_{breakdown}$ → possible issue w. backside?

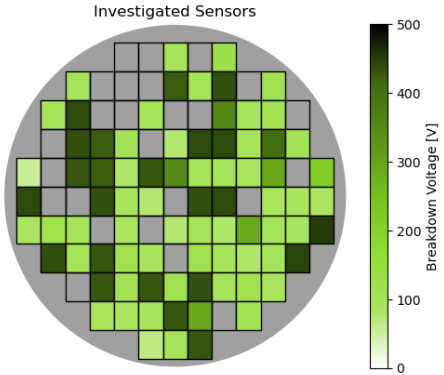
Conclusion

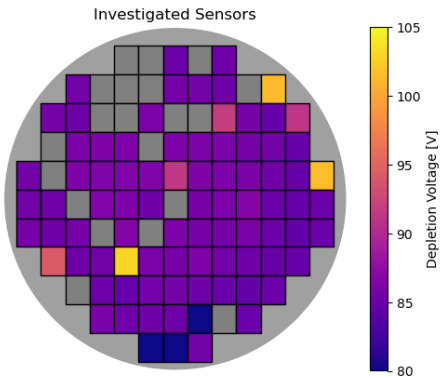
W2W bonding is a promising technology for ultra-thin, large-area hybrid pixel detectors

First sensor wafer has been successfully tested:

- Determination of breakdown voltage
- 20 broken sensors have been identified
- Determination of depletion voltage:
  - 3 failed measurements (missing contact)
  - 12 dices with Vdepl > Vbreakdown (defects at backside?)

70 / 105 dices
≈ 67% operational





Next: Investigation of bond quality using daisy chain wafer

Acknowledgments

Thank You!

Bundesministerium
für Bildung
und Forschung

Fraunhofer IZM

UNIVERSITÄT BONN

dortmund university

Y. Dieter
J. Dingfelder
F. Hügging
M. Mucha
S. Zhang

K. Kröninger
J. Vischer
J.Weingarten

Backup Slides

Outlook: Daisy Chain Wafers

- Use daisy chain wafers with copper pads to test bond quality

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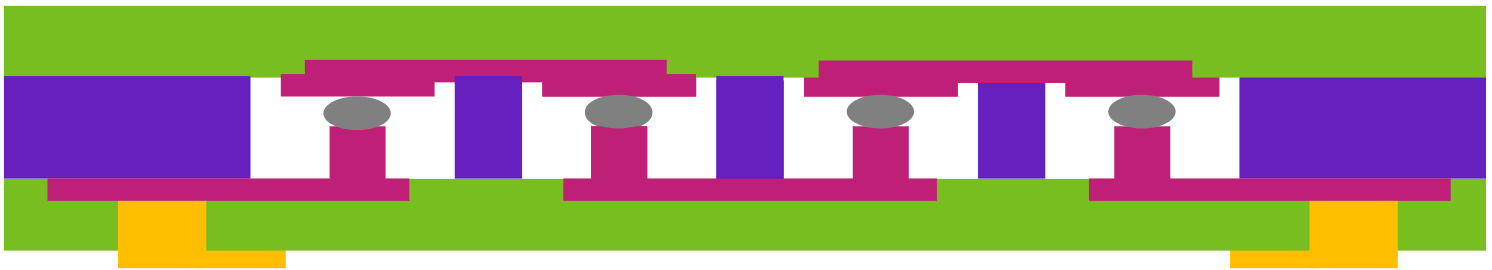
- Use daisy chain wafers with copper pads to test bond quality
  - W2W bond using copper pilars, bump bonds and polymer layer for stability

Outlook: Daisy Chain Wafers

- Use daisy chain wafers with copper pads to test bond quality
  - W2W bond using copper pilars, bump bonds and polymer layer for stability
  - Etch and fill Through Silion Vias (TSV) for contacting

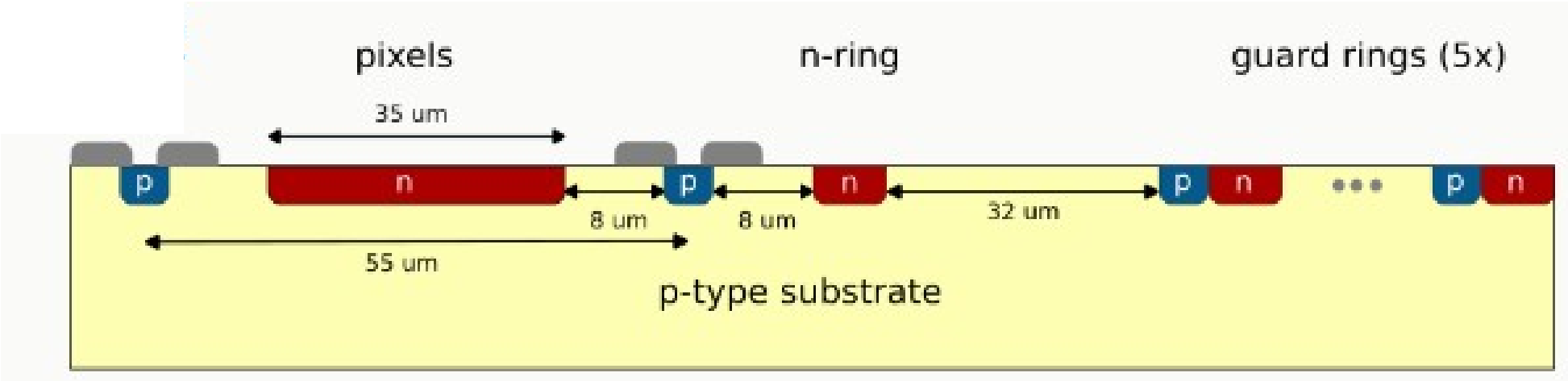
Outlook: Daisy Chain Wafers

- Test of bonds:
  - Resistance per bond
  - Bond quality before and after dicing
  - Thermal stability



Sensor Layout

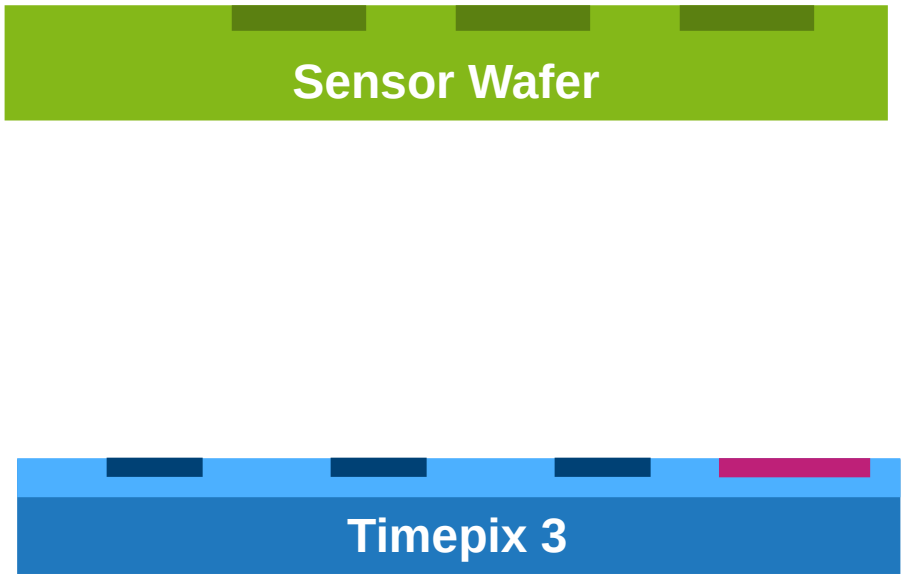
- Sensor edge:



"ULTRA-THIN HYBRID PIXEL DETECTORS USING WAFERTO-WAFER BONDING." Accessed: Dec. 10, 2024.

W2W Bonding Technique

1. Manufacturing of wafers



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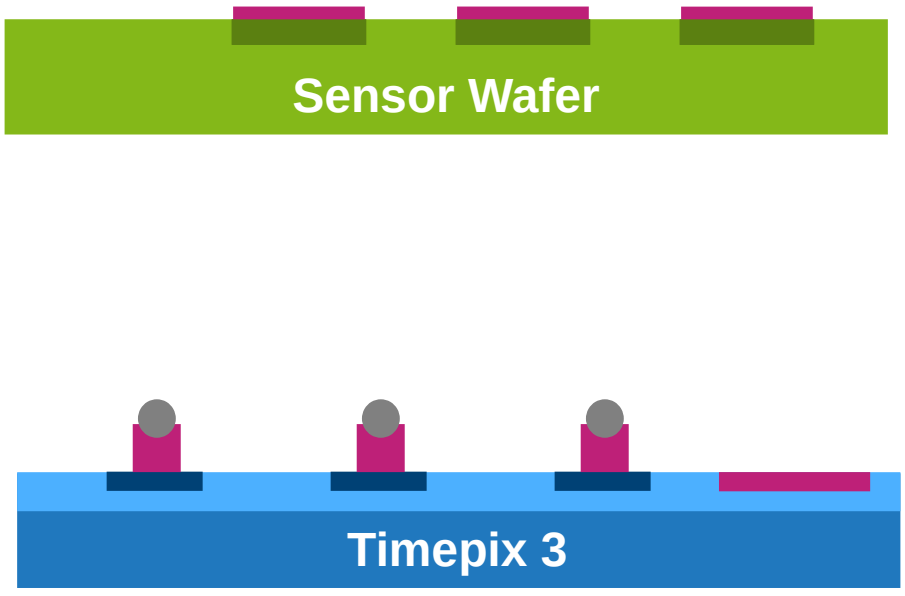
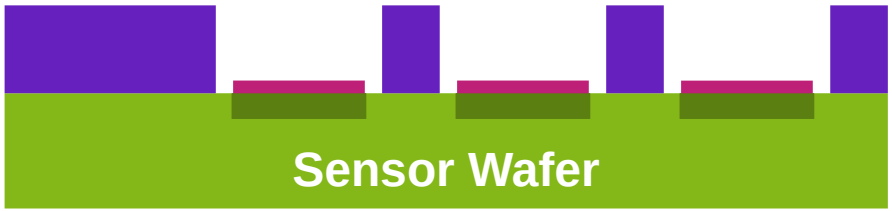
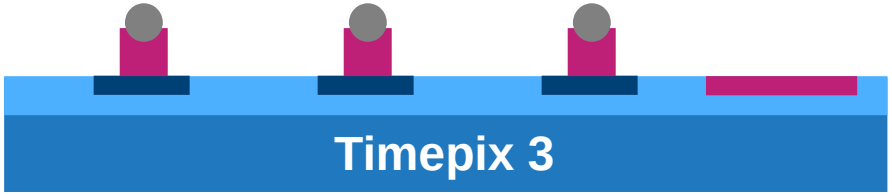


1. Manufacturing of wafers
2. Application of copper pads, pillars and solder bonds

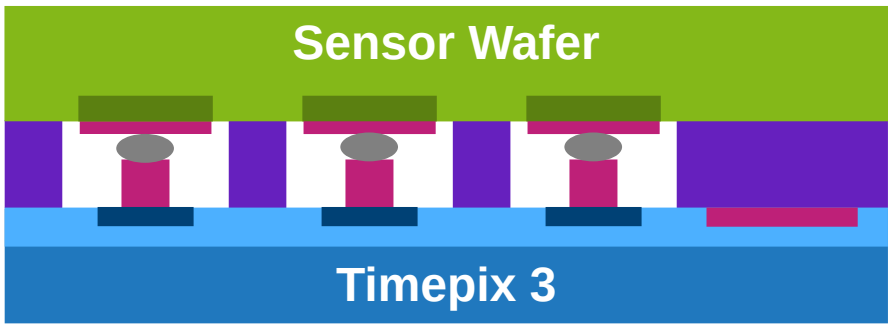
W2W Bonding Technique





1. Manufacturing of wafers
2. Application of copper pads, pillars and solder bonds
3. Application of photo-structured polymer layer

W2W Bonding Technique



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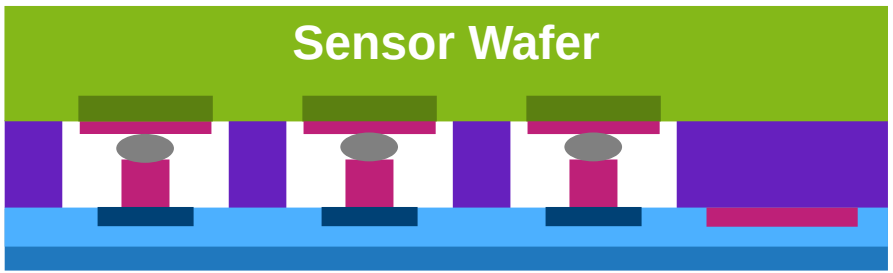
4. Wafer bonding

W2W Bonding Technique



1. Manufacturing of wafers
2. Application of copper pads, pillars and solder bonds
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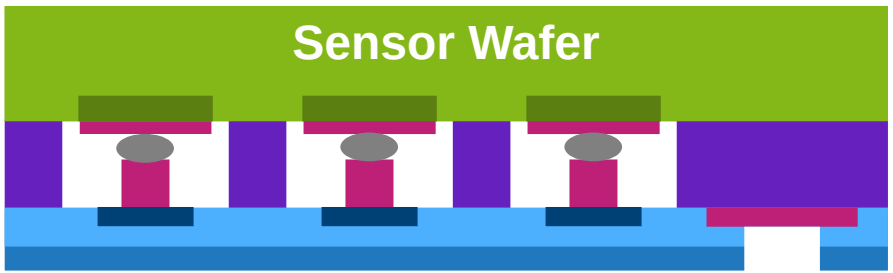
4. Wafer bonding
5. Backside grinding

W2W Bonding Technique



1. Manufacturing of wafers
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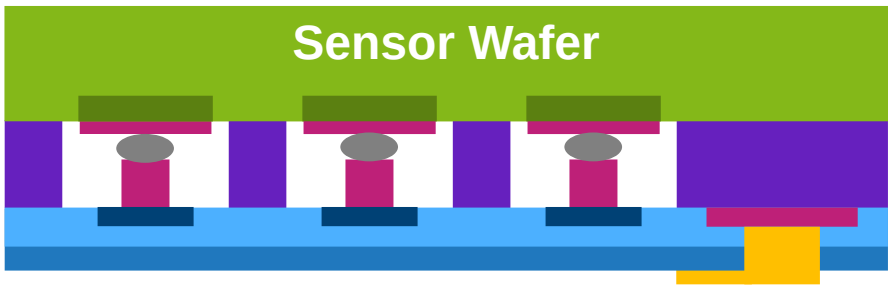
6. Etching of through silicon via (TSV)

W2W Bonding Technique



1. Manufacturing of wafers
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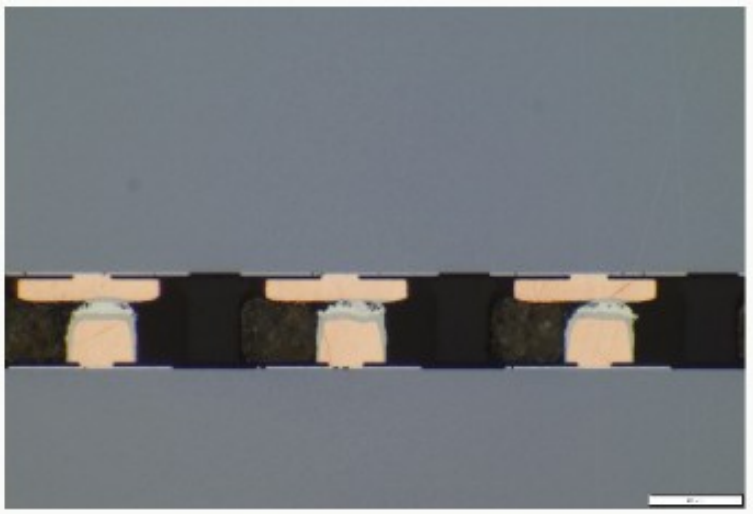
7. TSV filling and backside distribution layer

W2W Bonding Technique



Picture from Fraunhofer IZM, Berlin

1. Manufacturing of wafers
2. Application of copper pads, pillars and solder bonds
3. Application of photo-structured polymer layer
4. Wafer bonding
5. Backside grinding
6. Etching of through silicon via (TSV)
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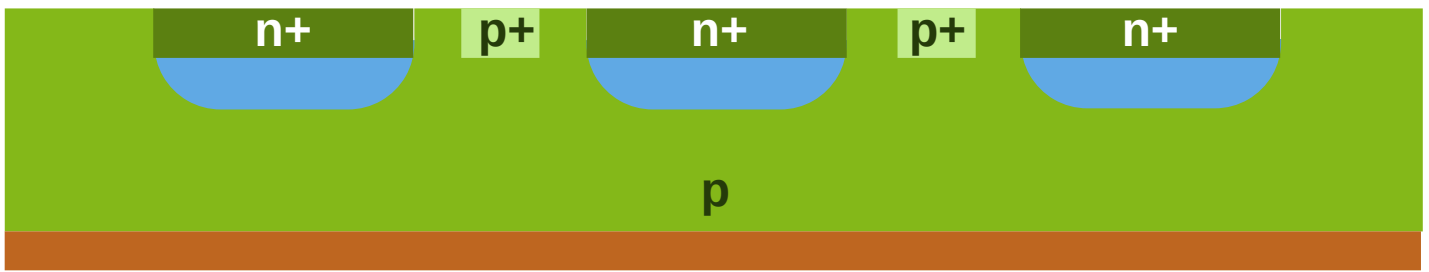
Biasing the Sensorwafer

- Charge carrier free **depletion zone** where n+ and p doped regions meet



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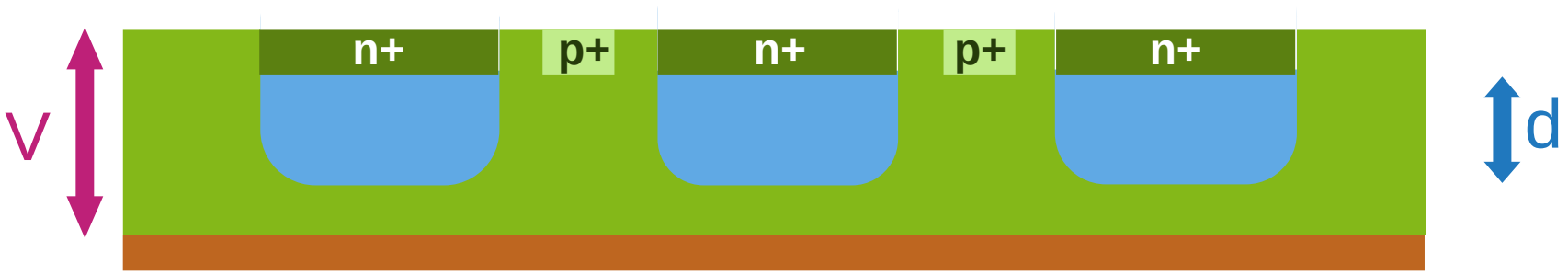
- Reverse bias voltage increases thickness of depletion layer



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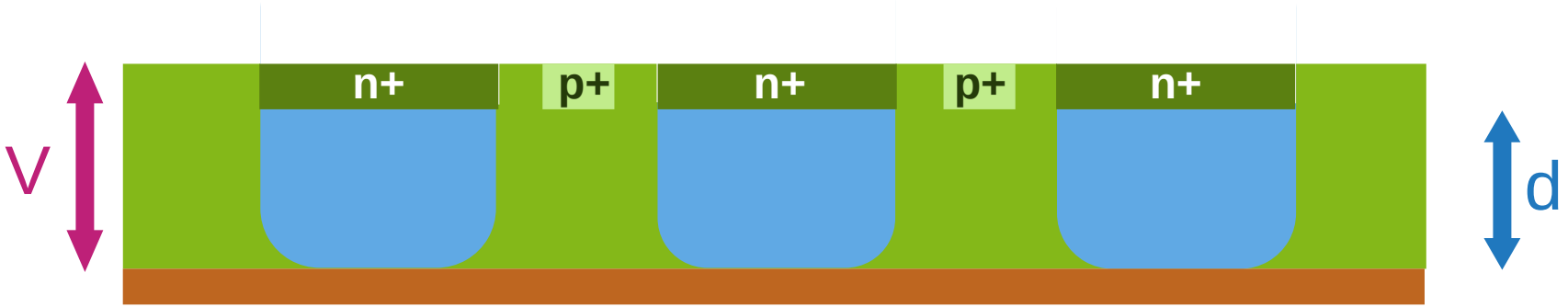
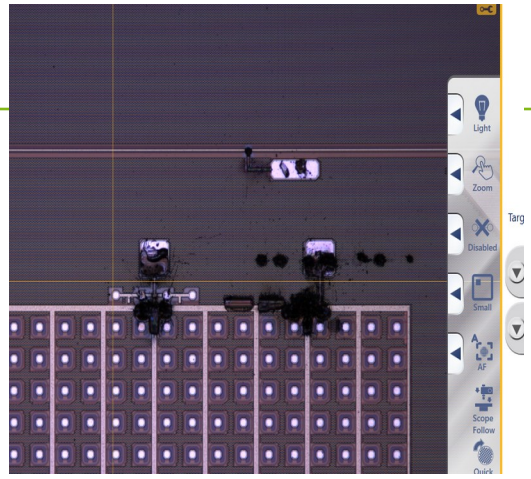
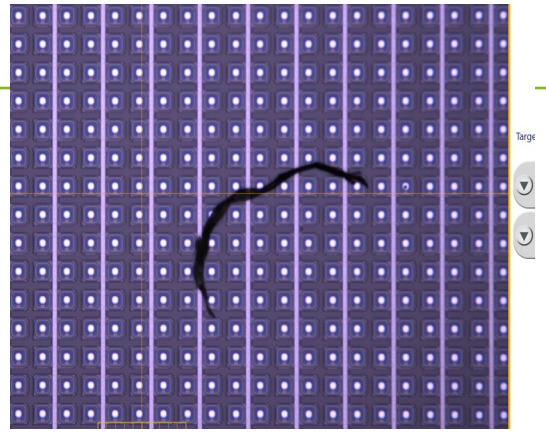
- Depletion zone reaches backplate metalisation: **Fully depleted** sensor

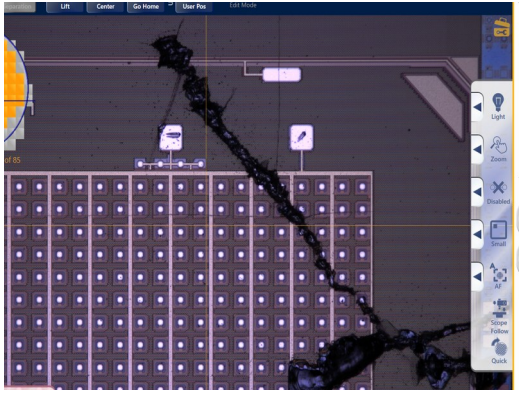


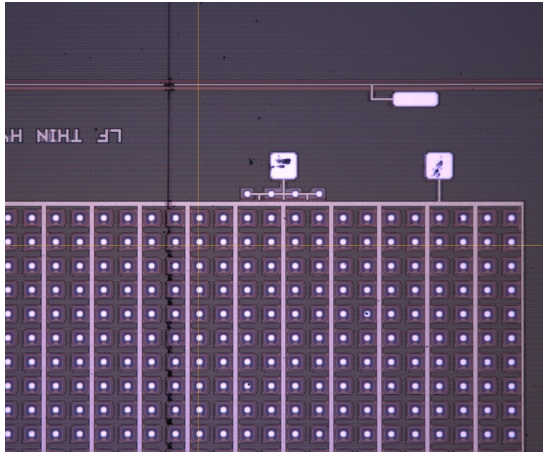
Visual Defects

- Careful handling of wafer
- Don’t apply too high current!
- Protected transport
- Limit handling
- Work in clean room

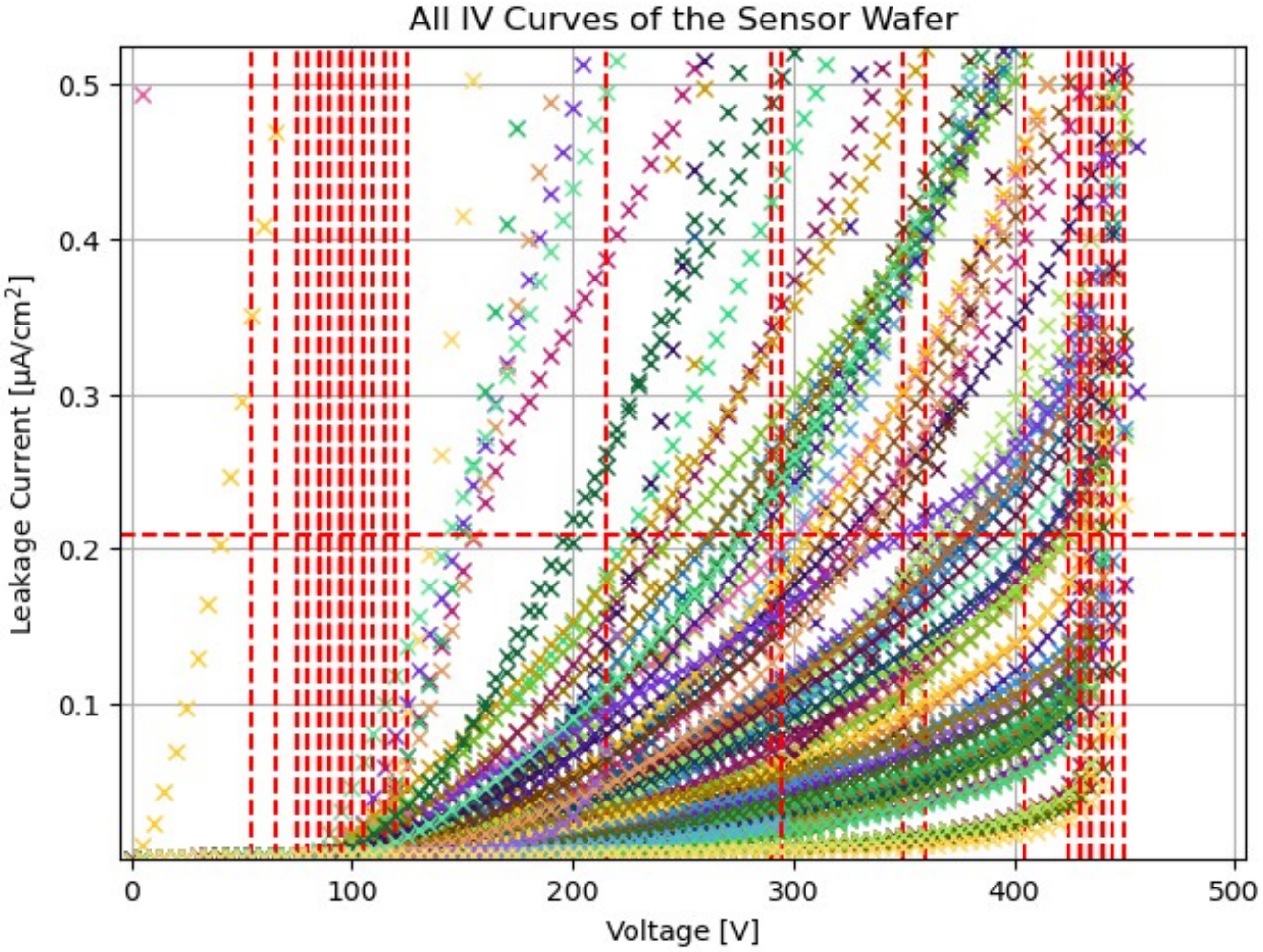




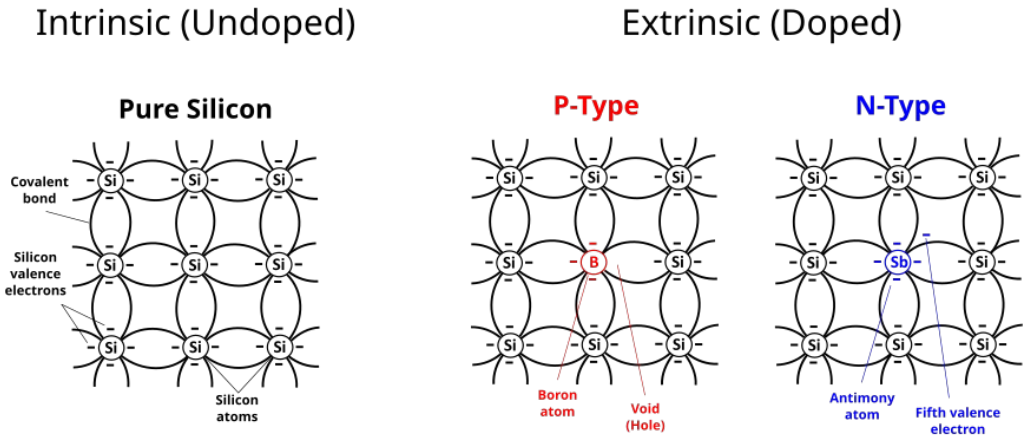




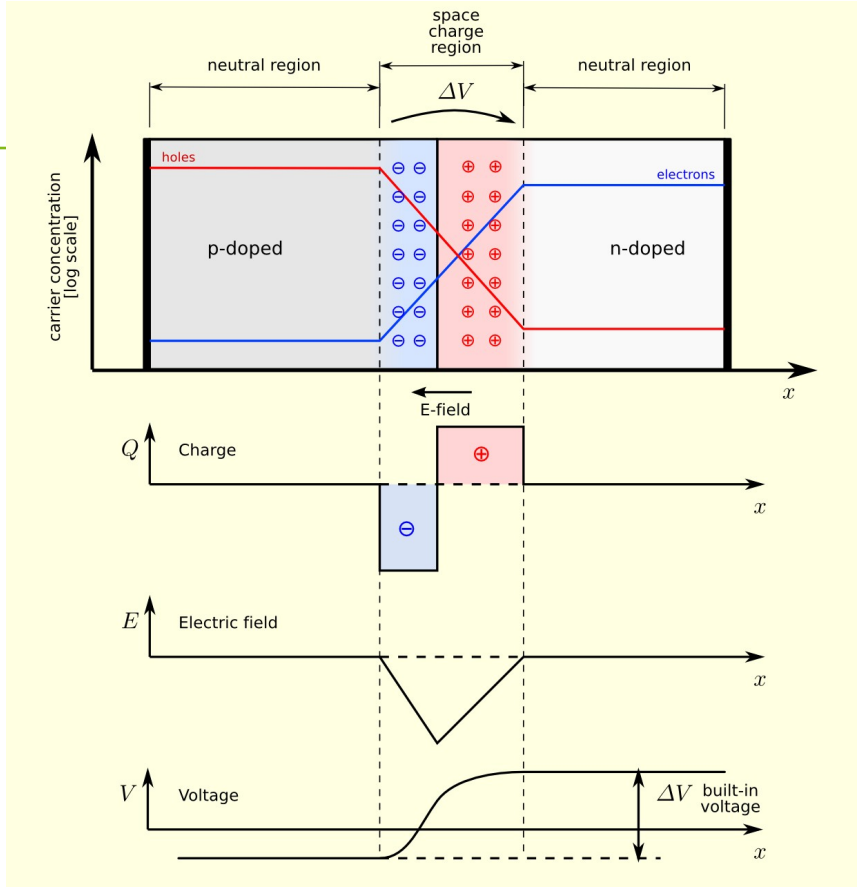
IV


All IV Curves of the Sensor Wafer
Leakage Current [µA/cm²]
0.1
0.2
0.3
0.4
0.5
0
100
200
300
400
500
Voltage [V]

Depletion Zone



“Basic diagram showing examples of P and N Type dopings on pure silicon” by VectorVoyager (2024), via Wikimedia Commons. Licensed under CC BY-SA 4.0.



“A PN junction in thermal equilibrium [...]” by TheNoise (2007), via Wikimedia Commons. Licensed under CC BY-SA 3.0.

Si Si Si

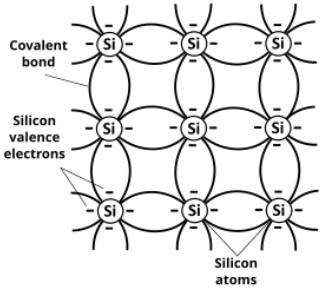
Si Si Si

Si Si Si

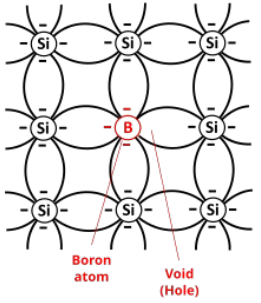
Intrinsic (Undoped)

Extrinsic (Doped)

Pure Silicon



P-Type



N-Type