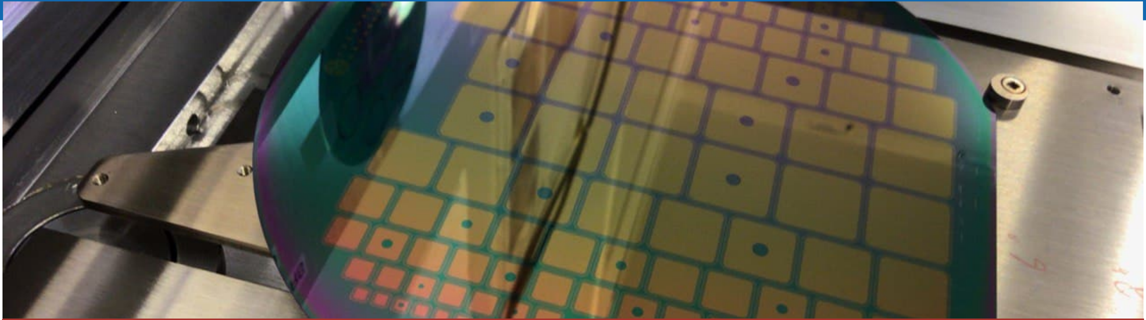
ETH zürich

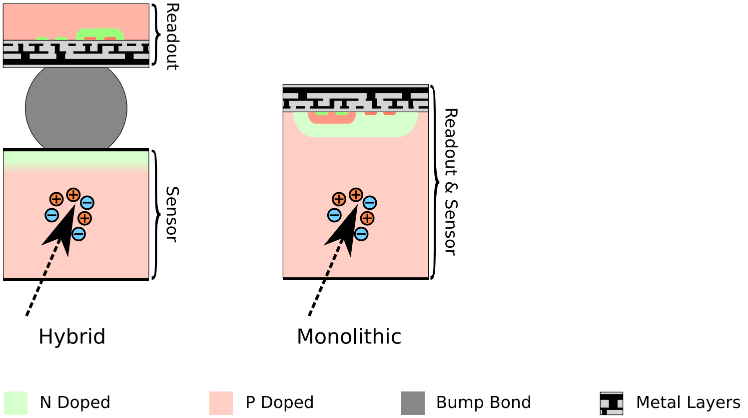


Results from low temperature wafer-wafer bonded pad-diodes for particle detection

SPS Annual Meeting 2024

Johannes Wüthrich
Rubbia Group – Institute for Particle Physics and Astrophysics – ETHZ

Semiconductor Pixel Detector Structures



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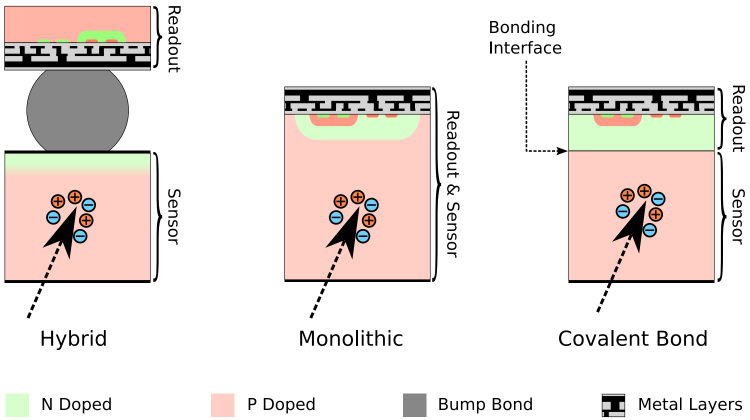
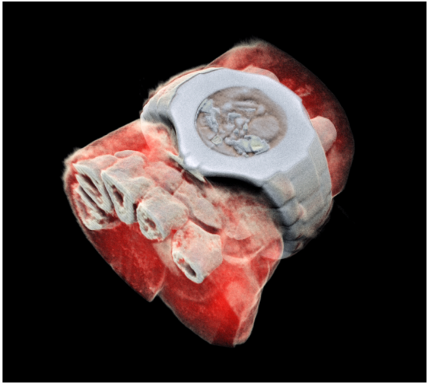


Single Photon Counting for X-Ray Imaging



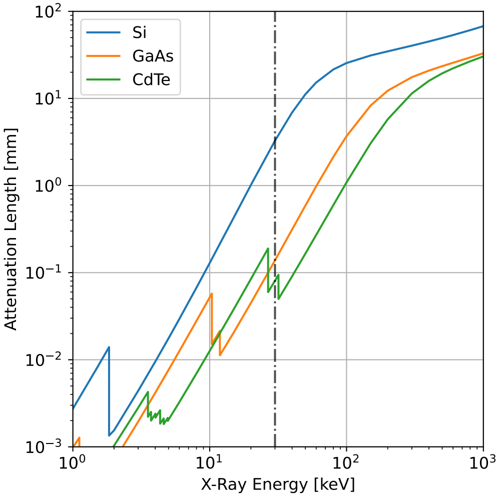
Credits: MARS Bioimaging Ltd

Detection of individual X-ray photons

- Suppression of detector noise
- Measurement of the photon energy
- Enables X-ray *color* imaging

See recent summary presentation from the 7th SpecXray workshop

High-Z Materials for X-Ray Imaging



Based on data from NIST XCOM

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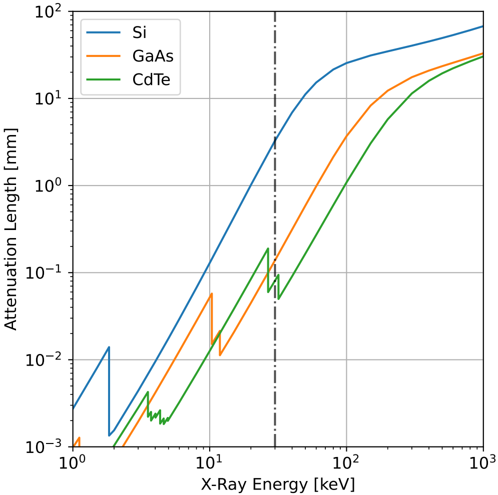

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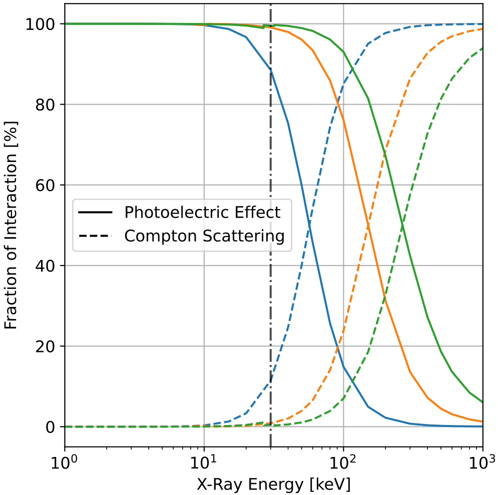

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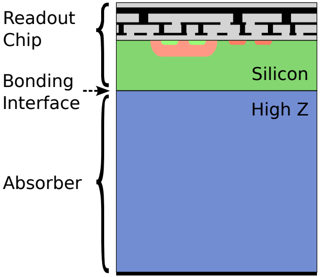
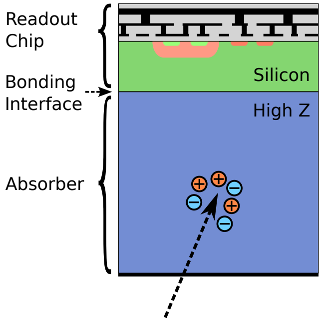
Wafer-Wafer Bonded Particle Detectors



- Goal is to build hetero-structure detectors.
  - Absorber is bonded to fully processed CMOS wafer.
  - **Bonding needs to be CMOS compatible (temperature).**

Wafer-Wafer Bonded Particle Detectors



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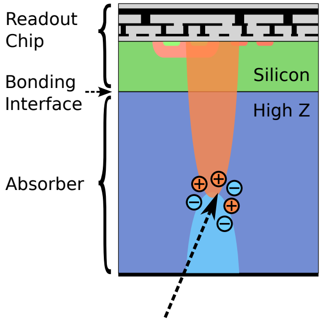
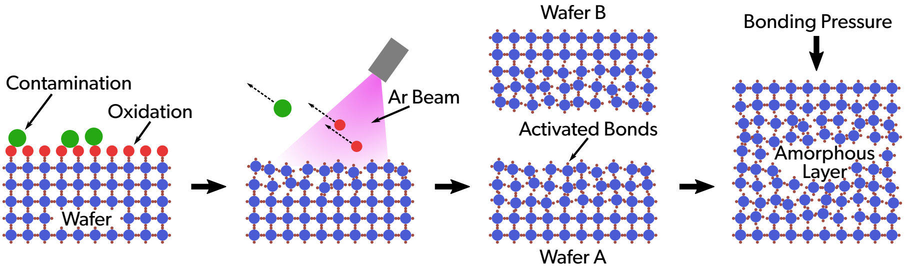


- Goal is to build hetero-structure detectors.
  - Absorber is bonded to fully processed CMOS wafer.
  - **Bonding needs to be CMOS compatible (temperature).**
- Signal is generated in the absorber and detected in the CMOS bulk.
  - **The bonding interface needs to be electrically conductive.**

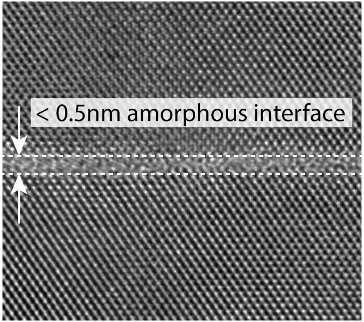
Surface Activated Wafer Bonding (SAB)



Pioneered by Takagi et. al in 1996 [1]

- In ultra-high vacuum (5×10^{-8} mbar)
- Processing at room temperature
- Needs polished surfaces (roughness < 0.5 nm)

Amorphous Interface with SAB



Credits: G-Ray Medical Sàrl

- Amorphous layer due to Ar sputtering
- High local density of crystal defects
- Influence on detector signal was unknown

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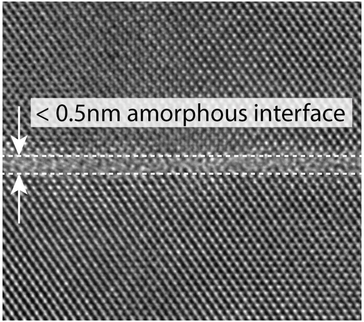

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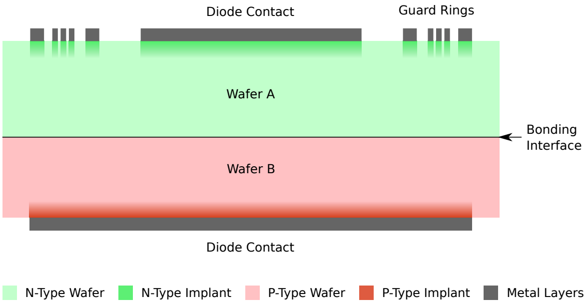
How does the amorphous layer influence signal generation / collection in wafer-wafer bonded sensors?

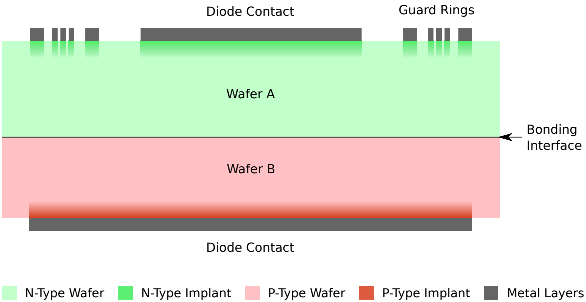
Fabrication of Simple Bonded Diodes



- Using high-resistivity (float-zone) wafers
- Bonding silicon to silicon

Fabrication of Simple Bonded Diodes

Processed at the ETHZ/IBM Binnig and Rohrer Nanotechnology Center and external companies.



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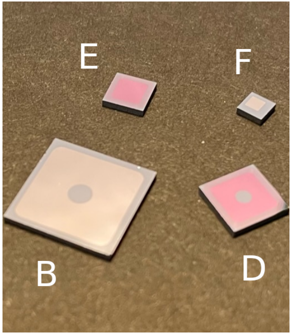
Fabricated Diodes

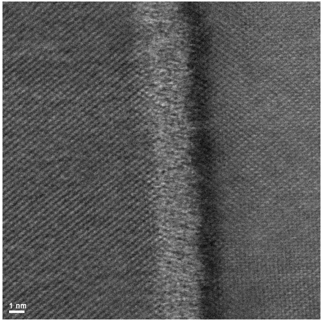


Bonded Pad Diode Fabrication Runs

Run 2 (2022)

STEM Imaging

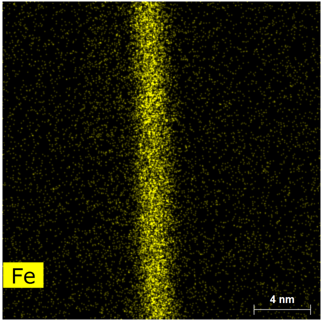
Scanning transmission electron microscopy



Bonded Pad Diode Fabrication Runs

Run 2 (2022)

EDXS (Iron K-Line)
Energy dispersive x-ray spectroscopy



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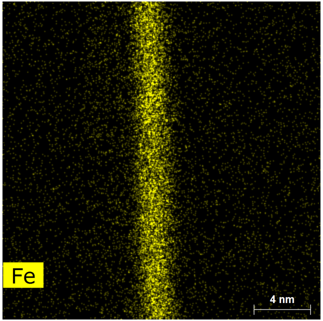
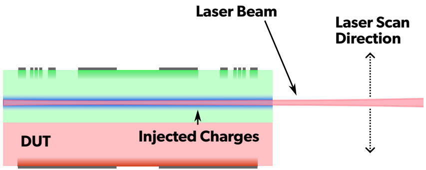


Run 3 (2024)

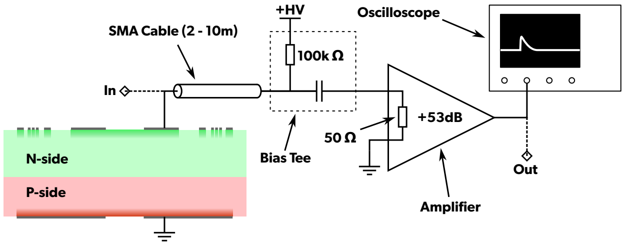
EDXS (Iron K-Line)
Energy dispersive x-ray spectroscopy

Transient Current Technique (TCT)

Edge TCT



Biasing and Signal Acquisition



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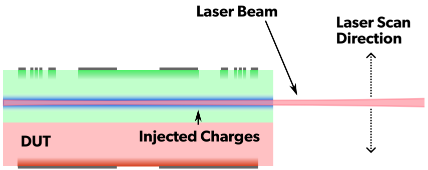

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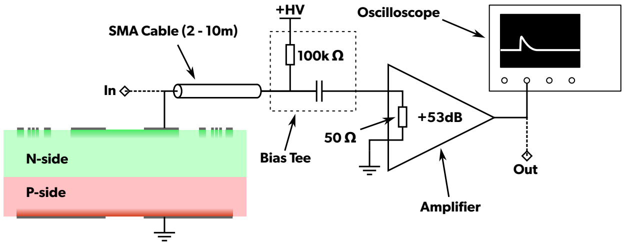
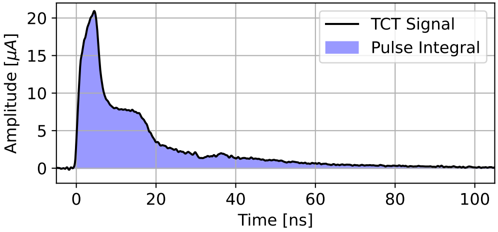
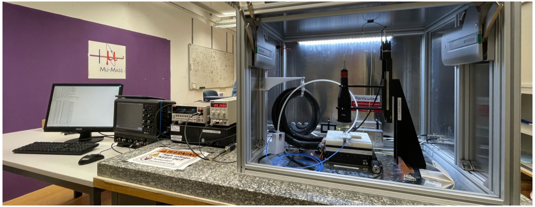
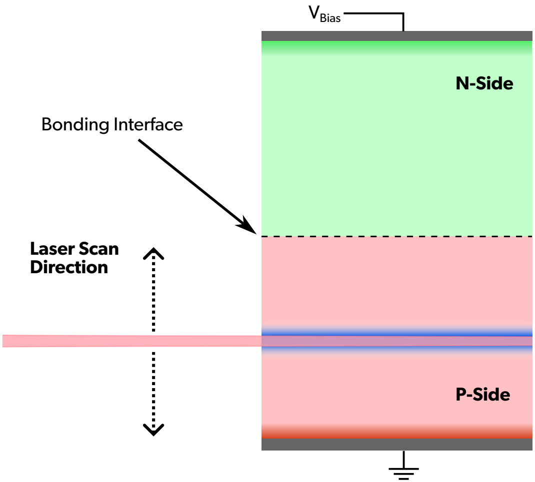
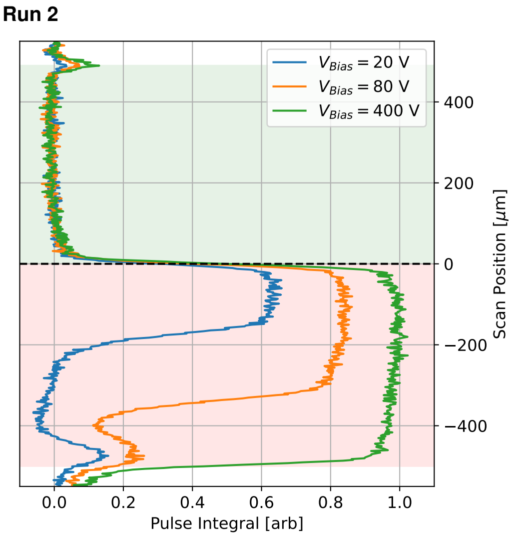






Edge-TCT Measurements





Edge-TCT Measurements

Run 2

- Only the P-side of the bonded structure is depleting.
- This implies that the interface acts as highly N++ doped layer.
- Due to the metal contamination of Run 2 it is not clear if this is an intrinsic effect of the interface.

Wüthrich *et al.* 2022 *JINST* 17 C10015 [2]
Wüthrich *et al.* 2023 *JINST* 18 P05004 [3]

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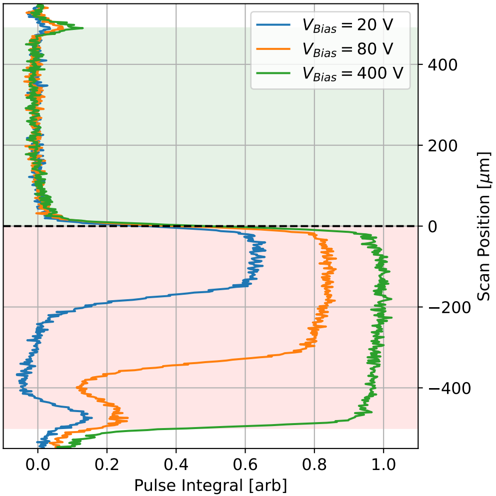

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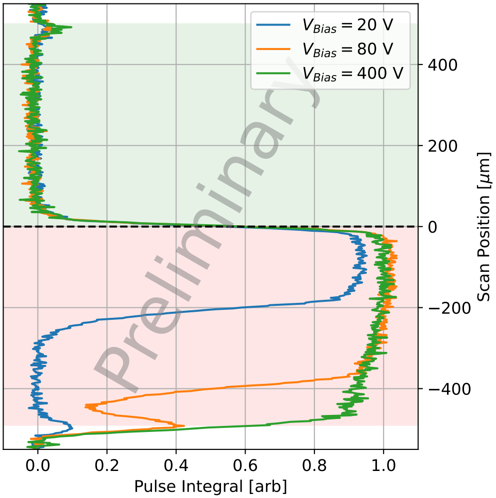
Run 3

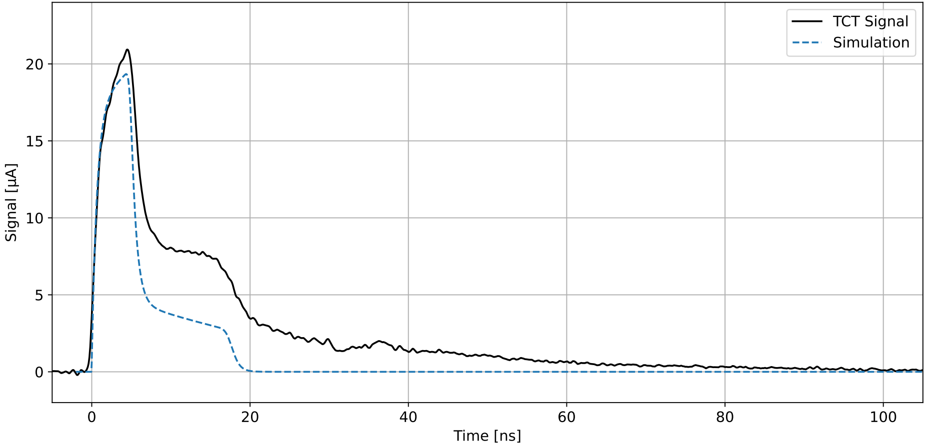
- Run 3 shows the same one-sided behaviour as Run 2!
- But Run 3 does not show any detectable metal contamination.
- This indicates that **the bonding interface has an intrinsic N++ behaviour**!

Run 3



Time Domain TCT Signal (Shockley-Ramo Theorem)

Run 2 TCT Signal



Note: Laser intensity is unknown.

Extended Shockley-Ramo Theorem

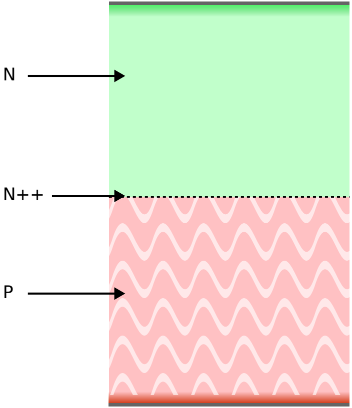
The Shockley-Ramo theorem [4, 5] is (strictly) only valid for

- charges moving in a vacuum,
- and signals induced on grounded electrodes.

$$I(t) = q\vec{v}_q(\vec{x}) \cdot \vec{W}_F(\vec{x})$$

It can be shown that it is also valid for

- fully depleted semiconductor detectors,
- and for non-grounded electrodes.



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W. Riegler [6] developed an extension to the Shockley-Ramo theorem for detectors with resistive (non-zero conductivity) elements:

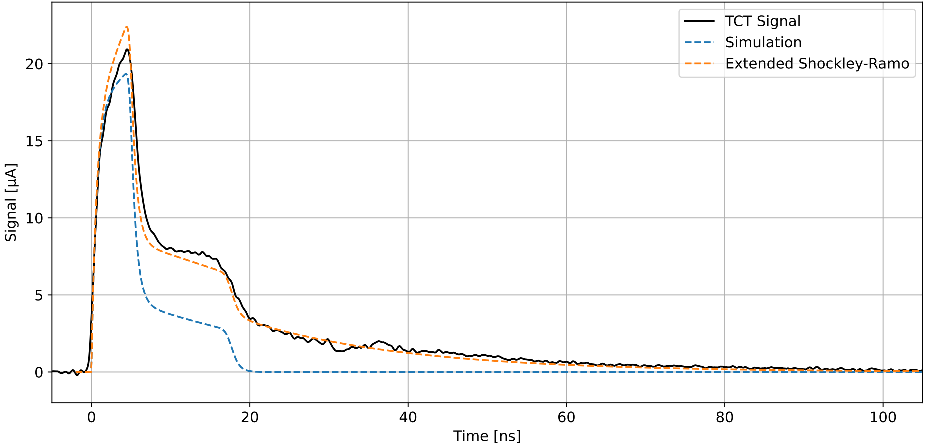
$$I^{ind}_{e,h}(t) = -\frac{q_{e,h}}{V_0}\int_0^t \vec{W}_V[\vec{x}_{e,h}(t'), t - t']\vec{v}_{e,h}(t')dt'$$

The weighting vector $\vec{W}_V$ represents the detector response when applying a voltage Dirac pulse $\delta(t)V_0$ to the readout electrode of interest.

- Can be calculated analytically for simple 1D-like structures.

Time Domain TCT Signal (Extended Shockley-Ramo Theorem)

Run 2 TCT Signal



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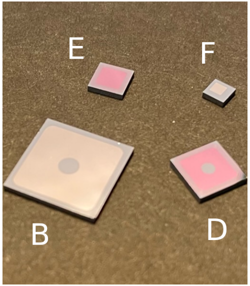
Conclusions

How does the amorphous layer influence signal generation / collection in wafer-wafer bonded sensors?



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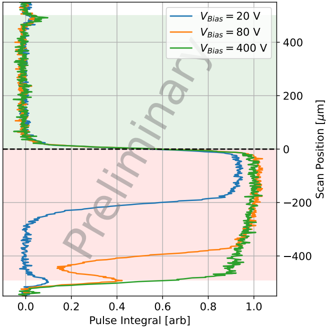

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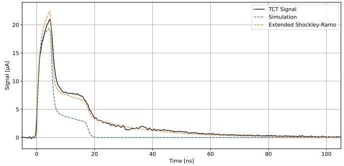

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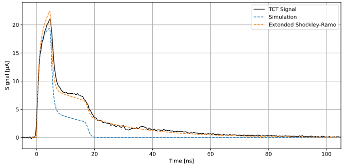

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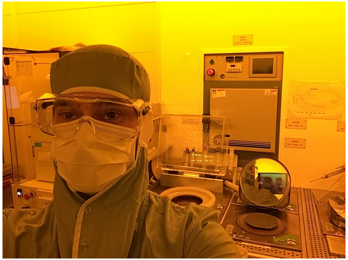
- Time domain signals can accurately be predicted from first principles.
  - This enables the prediction of the behaviour of more complex bonded detectors.
  - Simulation of charge sharing in strip detectors potentially allows to probe the defect density at the interface.
- The main influence of the bonding interface seems to be on the depletion behaviour.



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Thesis: Low-temperature wafer-wafer bonding for particle detection

Thank you very much for your attention.

References I

1. Takagi, H., Kikuchi, K., Maeda, R., Chung, T. R. & Suga, T. Surface activated bonding of silicon wafers at room temperature. Applied Physics Letters **68**, 2222. doi:10.1063/1.115865 (1996).
2. Wüthrich, J. & Rubbia, A. On the depletion behaviour of low-temperature covalently bonded silicon sensor diodes. Journal of Instrumentation **17**, C10015. doi:10.1088/1748-0221/17/10/C10015 (2022).
3. Wüthrich, J., Alt, C. & Rubbia, A. TCT investigation of the one-sided depletion of low-temperature covalently bonded silicon sensor P-N diodes. Journal of Instrumentation **18**, P05004. doi:10.1088/1748-0221/18/05/P05004 (2023).
4. Shockley, W. Currents to Conductors Induced by a Moving Point Charge. Journal of Applied Physics **9**, 635. doi:10.1063/1.1710367 (1938).
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6. Riegler, W. An application of extensions of the Ramo–Shockley theorem to signals in silicon sensors. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated **940**, 453. doi:10.1016/j.nima.2019.06.056 (2019).