Performance of Thin Irradiated n-in-p SOI Detectors

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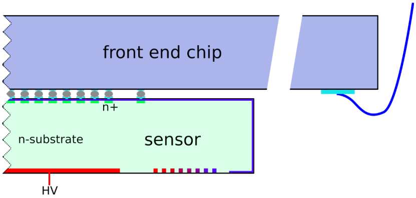
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

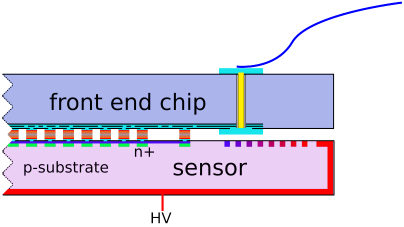
In collaboration with
Fraunhofer
EMFT

Our Pixel Module Concept

Present design



Thin sensors + ICV-SLID

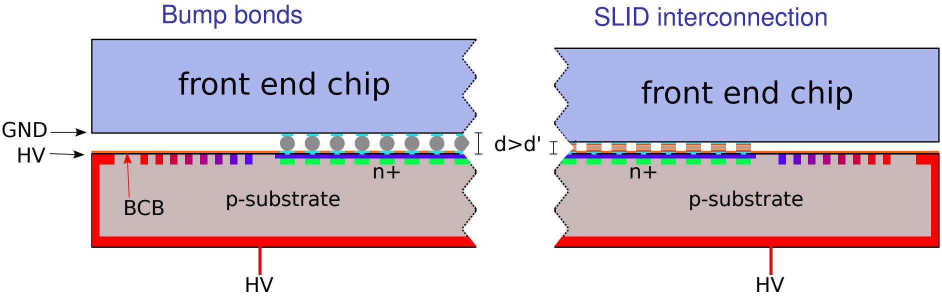


Four new technologies

- N-in-p bulk material
  - Cost reduction
- Thin sensors (MPP-HLL process)
  - Higher signals after irradiation
  - Less multiple scattering
- SLID: Solid Liquid Inter-Diffusion
  - Allows for vertical integration/separation of analogue and digital parts (with ICV))
- ICV: Inter-Chip-Vias
  - More compact: „balcony“ for signal-extraction not needed
  - Enlargement of active area

Benzo Cyclo Butene (BCB)

n-in-p: HV is on sensor side facing the chip → danger of sparks!



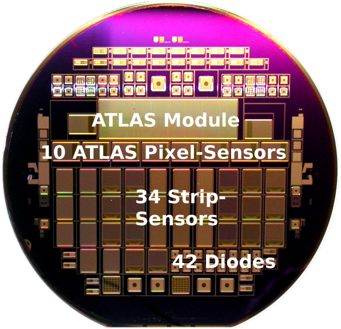
Alternative interconnection technologies like SLID (Solid Liquid Interdiffusion; Cu+Sn pad) further reduce the distance!

Solution: Cover sensor with a thin insulating layer of BCB (Benzo Cyclo Butene)

HV-stability tested @ 1000 V over several hours in the laboratory and for several days @ 800 V at the testbeam.

Thin Pixel Production at MPP/HLL

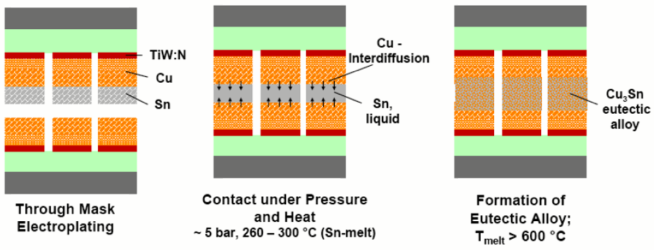
8 × 6″ Wafer



- 4 wafers of 150 µm and 4 wafers of 75 µm active thickness (on handle wafer)
- Proton & neutron irradiations with fluences up to $10^{16}\,n_{eq/cm^2}$ at
  - KIT (25 MeV protons)
  - CERN PS (24 GeV protons)
  - Lubljana (reactor neutrons)

1. Implant backside on sensor
2. Bond sensor wafer to handle wafer
3. Thin sensor side to desired thickness
4. Process on top side
5. Structure resist, etch backside up to oxide

SLID: Solid Liquid Inter-Diffusion



Alternative to bump bonding

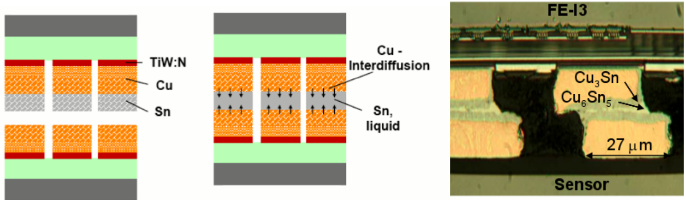
Pros

- Allows for vertical integration (T_{melt}).
- Arbitrary geometries possible and smaller pitches.
- Less process steps → lower cost.
- Wafer to wafer and chip to wafer possible.
- Strength: 0.01 N per connection

Cons

- Planarity of 1 μm needed.
- No rework possible
- Chip-to-chip not possible at the moment
- Homogeneous pressure needed

SLID: Solid Liquid Inter-Diffusion



Through Mask Electroplating

Contact under Pressure and Heat
~ 5 bar, 260 – 300 °C (Sn-melt)

Formation of Eutectic Alloy; $T_{melt} > 600$ °C

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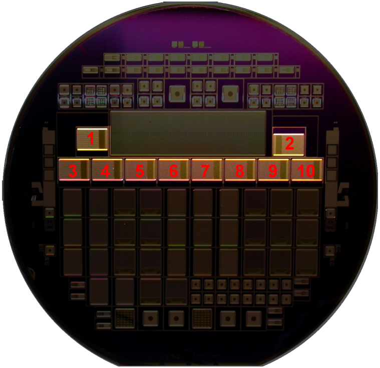
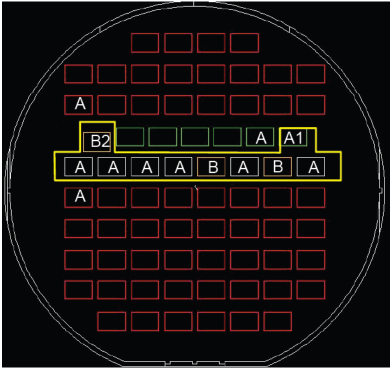
Chip to Wafer Interconnection

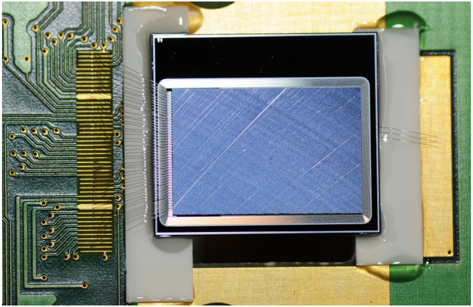
Challenge: Alignment precision

The handle wafer has to be populated with chips, then both wafers have to be aligned





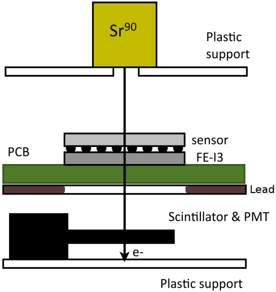
Pad size: 27 × 60 μm^2 and minimal pad distance of 23 μm
Alignment precision is ≈10 μm but rotations are also involved.
⇒ Five working modules with 75 µm active thickness.

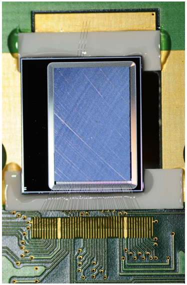


SLID Module Measurements

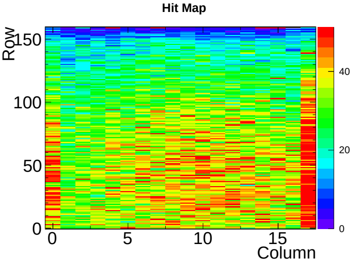
Source Measurements

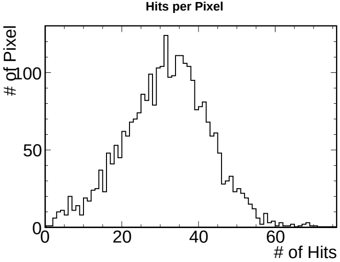
- ^{90}Sr and ^{241}Am sources are used to to determine the charge collection.
- External trigger via scintillator (for ^{90}Sr) and internal chip trigger (for ^{241}Am).





Example SLID 10, 250 k events

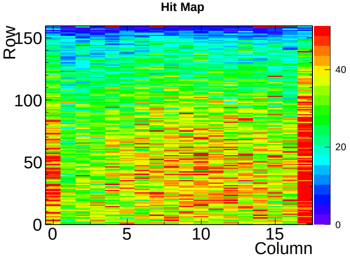


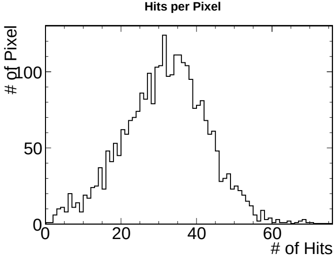


Not Connected Channels

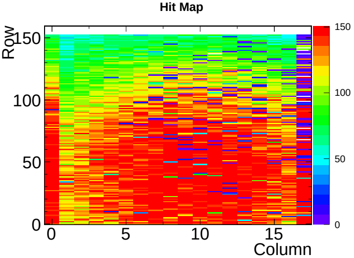
Source scan can also be used to determine not connected channels:

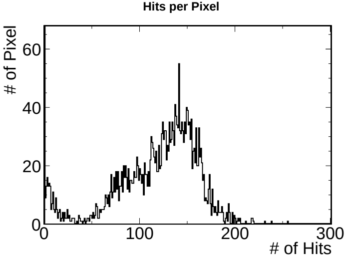
All channels connected





Not connected channels





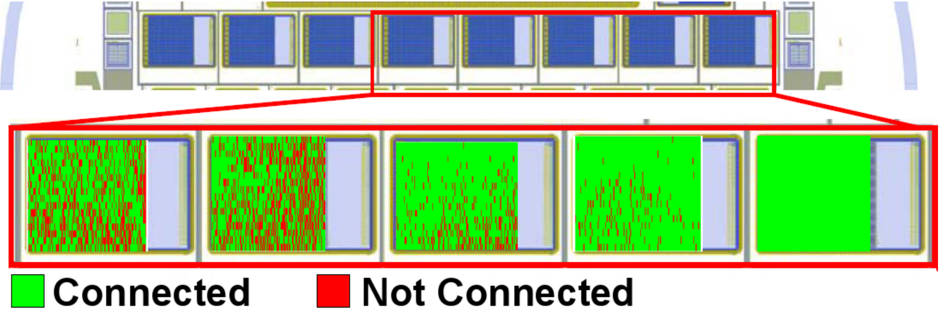
Two bumps correspond to not connected + noise and connected channels

Overview of the SLID Interconnection Efficiency

Chip	Discon. Pixel	%
6	731	30
7	713	29
8	274	11
9	134	6
10	0	0

Percentage given w.r.t not masked channels

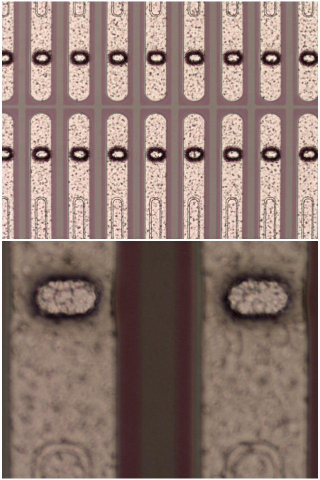
- Number of not connected channels is rising towards centre of wafer due to imperfect opening of the BCB.
- Stable after irradiation up to $2 \cdot 10^{15}\, n_{eq}/cm^2$ and thermal cycling (-50 – 20) °C.



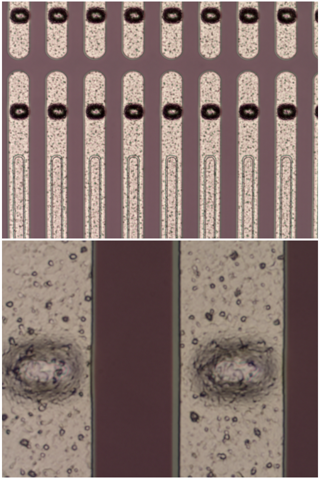
Cause: BCB-Imperfections

The BCB has to be opened to allow for the contact between chip and sensor. This operation did not fully succeed.

Good



Bad

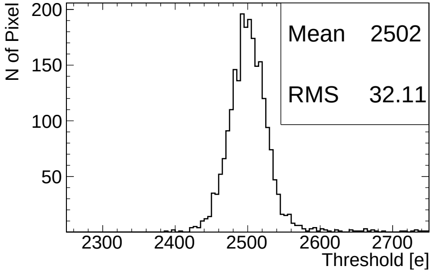


On unconnected wafers the trend towards the centere was seen.

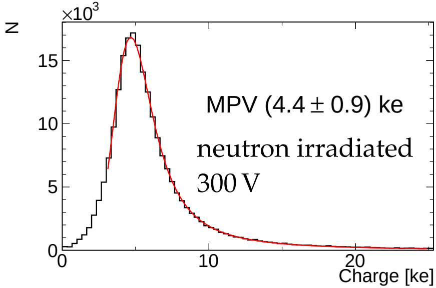
Charge Collection after Irradiation

- Irradiations
  - Ljubljana: $2 \cdot 10^{15}\,n_{eq}/cm^2$
  - KIT: $6 \cdot 10^{14}\,n_{eq}/cm^2$
- Tuned threshold of 2500 e, Noise of 170 e
- Full charge recovered for both fluences

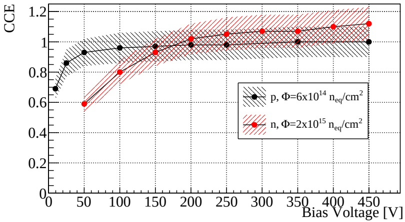
Tuning



^{90}Sr Measurement



CCE

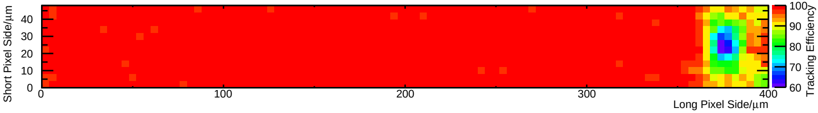


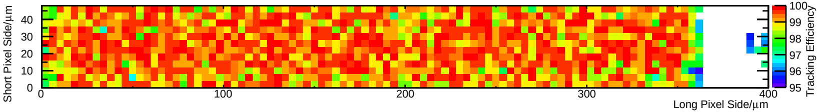
Efficiency Measurement in a Testbeam

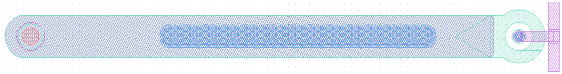
Not irradiated SLID SCM was studied in a testbeam at CERN-SPS.

- The high threshold of 2800 e as compared to an expected charge of 4.1 ke is challenging. $\Rightarrow \epsilon = 98.2\,\%$
- Main pixel region (wo punch through): $\epsilon = 99.3\,\%$.

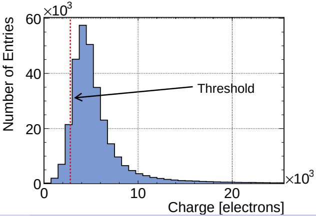
The PPS testbeam group:
M. Bomben, Ch. Gallrapp,
M. George, J. Idarraga, J. Jansen
T. Lapsien, A. Macchiolo,
R. Nagai, I. Rubinsky G. Troska,
Y. Unno, P. Weigell, J. Weingarten







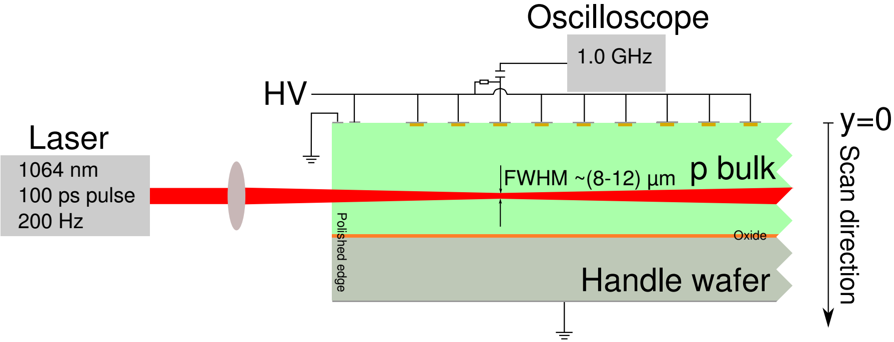
FE-I4 allows for much lower threshold ($\lesssim$1000 e)



edgeTCT Measurements

EdgeTCT Setup & Devices

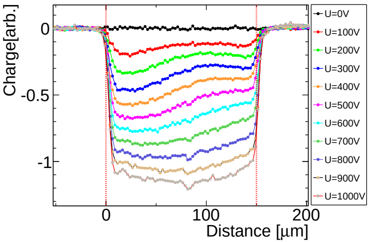
Measurements with edgeTCT setup in Ljubljana were performed.
Aim: Learn more about the charge collection behaviour for these thin devices.



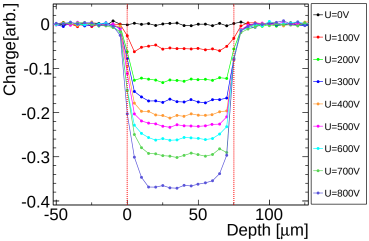
Used Sensors: Strip sensors with 75 μm & 150 μm active thickness, irradiated with reactor neutrons to $\Phi = 10^{16}\ \mathrm{n_{eq}/cm^2}$.
Measurements at lower fluences to be repeated in the near future (bond was missing)

– Thanks to: Gregor and Marko

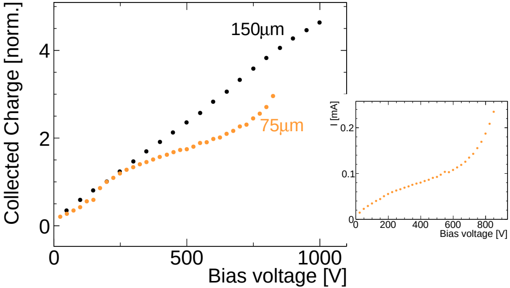
EdgeTCT Measurements (prelim.)



150 μm



75 μm



- 150 μm: Depleting from front side. Above 700 V almost homogeneous.
- 75 μm: From start homogeneous; depletion is not resolvable (illumination $\sim$10 %)?
- Increase of slope above 700 V for 75 μm thick sample, reflected in IV

Summary & Plans

Summary

- First single chip modules with SLID interconnection exhibit good performance in terms of:
  - Leakage currents & breakdown voltages
  - CCE after irradiation
  - Connection stability after: Irradiation to $2 \cdot 10^{15}\,\mathrm{n_{eq}/cm^2}$ and thermal cycling
- Challenging chip alignment on the handle wafer
- Trend of not connected channels towards centre of the wafer due to BCB opening imperfections → i. e. not related to the interconnection technology!
- EdgeTCT measurements performed: Increasing CC for 75 μm thick sample irradiated to $1 \cdot 10^{16}\,\mathrm{n_{eq}/cm^2}$ above 700 V

Plans

- Study irradiated structures in testbeam and extend fluence to $1 \cdot 10^{16}\,\mathrm{n_{eq}/cm^2}$
- Full SLID assembly of sensors and front-end chips including ICV
- Perform edgeTCT measurements before irradiation and at $5 \cdot 10^{15}\,\mathrm{n_{eq}/cm^2}$.

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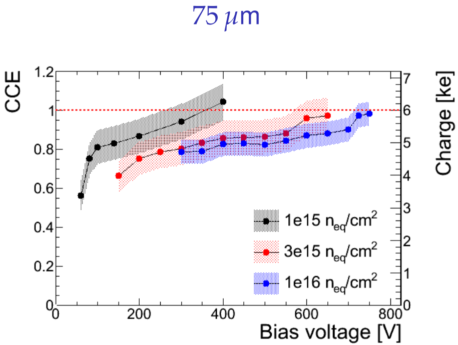
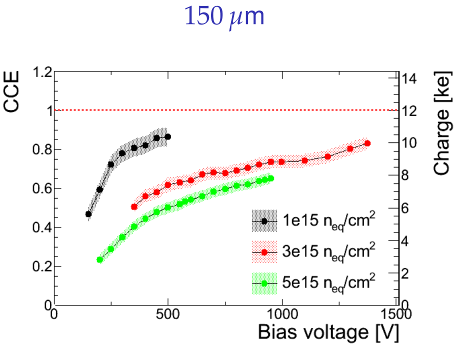
BACKUP

Charge Collection Efficiency for Thin Sensors



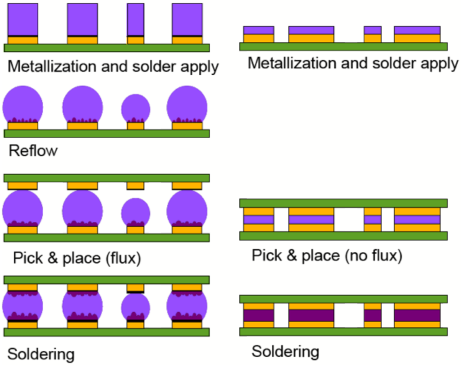


- After irradiation: Signal considerable higher than expected from simulation.

75 µm	Signal height recovered within uncertainties
150 µm	Signal height lower than before irrad. (Higher voltages needed)

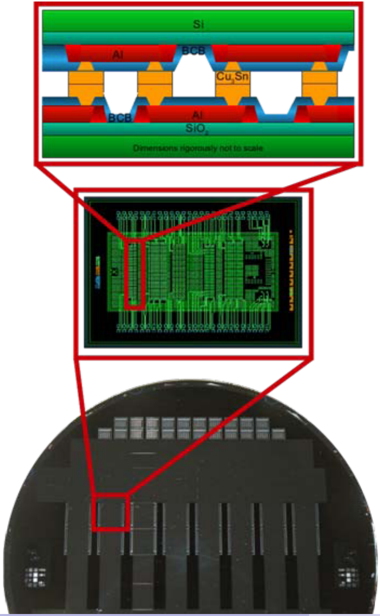
- Uncertainties correspond to 500 e^-, estimated for each point.
- Measurements before any intentional annealing: T=-30 °C ($\phi = 10^{15}$ n_{eq}/cm^2); T=-40 °C & T=-45 °C ($\phi = (3-10) \cdot 10^{15}$ n_{eq}/cm^2); T=-50 °C ($\phi = 5 \cdot 10^{15}$ n_{eq}/cm^2).

SLID vs. Bumb Bonding



1. Apply metal layer to sensor and chip.
2. For bump bonding, the sensor is heated such that the solder-metal layer melts and become ball like. Smaller pads result in smaller balls (less material).
3. Chip and sensor a brought together.
4. The stack is heated. For bump bonding smaller balls cannot form a good connection.

Daisy Chains: Wafer-to-Wafer SLID



- Aim: Determine the feasibility of the SLID interconnection within the parameters needed for ATLAS pixels.
- Deliberate aplanarity were introduced to study the sensibility → Up to 1 μm aplanarities do not affect efficiency.
- SLID efficiencies measured with daisy chains structures (wafer to wafer connections).

Pad width in μm^2	Pitch in μm	Aplanarity	SLID inefficiencies
30×30	60	0	$< 1.2 \times 10^{-4}$
80×80	115	0	$< 8.9 \times 10^{-4}$
80×80	100	0	$< 7.8 \times 10^{-4}$
27×60	50, 400	0	$< (5 \pm 1) \times 10^{-4}$
30×30	60	100 nm	$< (10 \pm 4) \times 10^{-4}$
30×30	60	1 μm	$< (4 \pm 3) \times 10^{-4}$

Connection Strength

The chips of the lower half of the wafer are pulled off to.

- get an idea of the connection strength.
- to see if there are systematics, hinting to problems in the process.

Findings:

- Order of 0.01 N per connection. similar to other interconnection technologies.
- There is no clear correlation between strength and alignment (extreme cases not considered).
- Caveat: Underlying structures are not homogeneous.

Performance Before Irradiation

- Leakage current below 100 nA for all SCMs.
- Breakdown voltages exceed 120 V – full depletion around 40 V.
- The charge collection performance is homogeneous over the five devices.
- Tuned thresholds between 2800 and 3500 e.