Irradiated Thin Pixel Sensor Modules with SLID Interconnection for the ATLAS Upgrades

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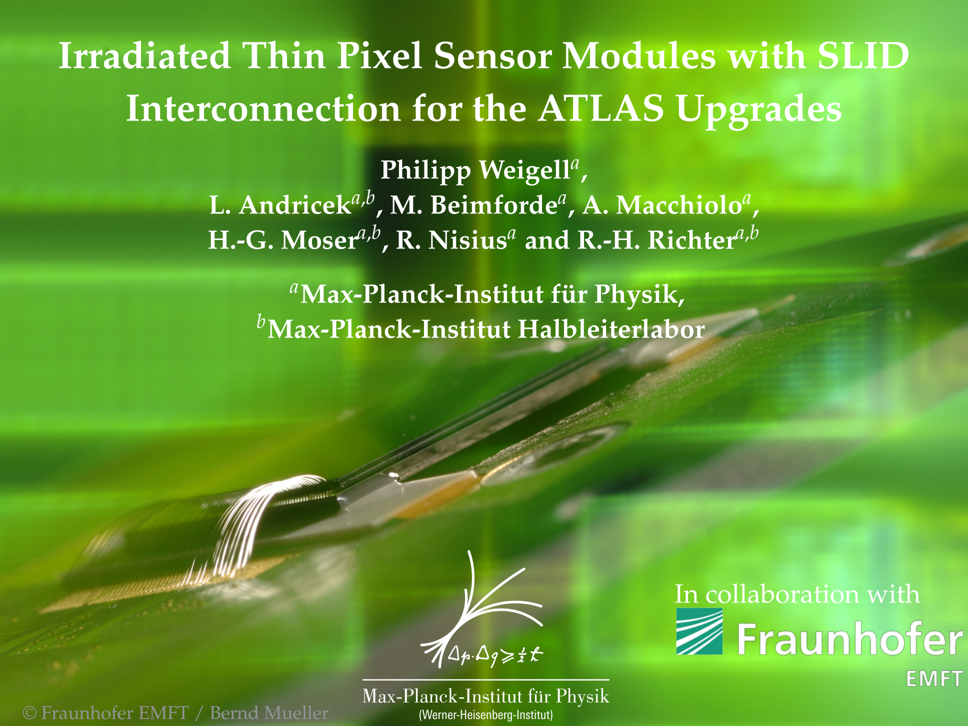

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In collaboration with
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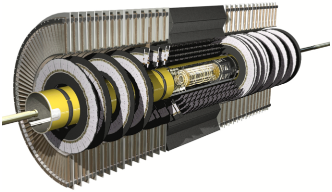
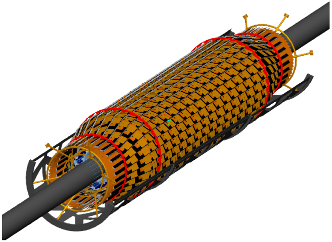
Future of ATLAS and LHC



NewPix



Keystones for upgrade

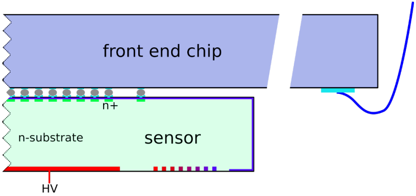
- Twofold upgrade:
  - Insertable B-Layer (IBL) ∼2013/4
  - Full replacement depending on performance ∼2018 (Under discussion)
- Luminosity: $(2-3)\cdot 10^{34} - 10^{35}/(\text{cm}^2\text{s})$
- $\Rightarrow$ radiation dose: $\phi_{\text{eq}} \approx 10^{15} - 10^{16}\,\text{n}_{\text{eq}}/\text{cm}^2$

Considerations

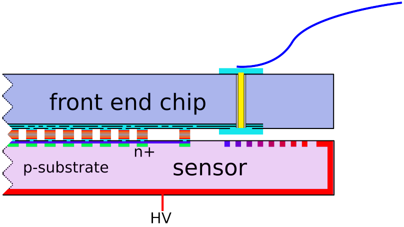
- Sensor-technology tbd for upgrades after IBL: n-in-p is an excellent candidate for large volumes.
  - Only one side needs processing → reduced cost.
  - Radiation hardness comparable to n-in-n
- Compact design wanted
- Present workhorse for R&D: present ATLAS front-end chip

Our Pixel Module Concept

Present design



Thin sensors + ICV-SLID

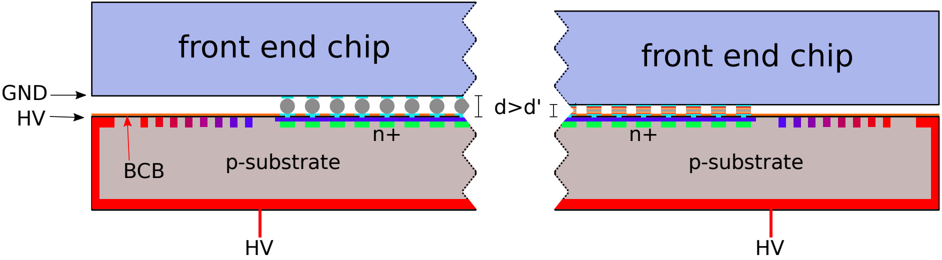


Four new technologies

- 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 Clyclo Butene (BCB)

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



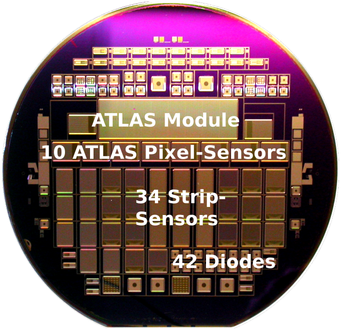
Alternative interconnection technologies like SLID (Solid Liquid Interdiffusion; Cu+Sn pad) further reduce the distance!

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

HV-stability observed @ 1000 V over several hours.

Thin Pixel Production at MPP/HLL

12 × 6″ Wafer

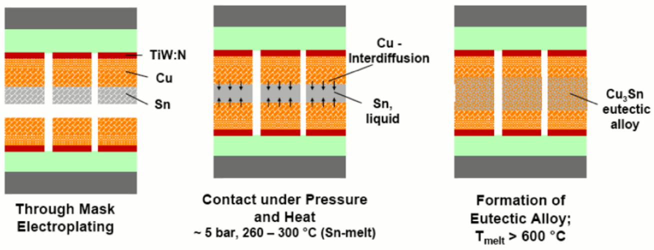


- 4 wafers of 150 µm and 8 wafers of 75 µm active thickness (on handle wafer)
- Proton & neutron irradiations with fluences up to $10^{16}\ n_{eq/cm^2}$ at
  - KIT (25 MeV protons)
  - CERN PS (24 GeV protons)
  - Lubljana (reactor neutrons)

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

SLID: Solid Liquid Inter-Diffusion



Alternative to bump bonding

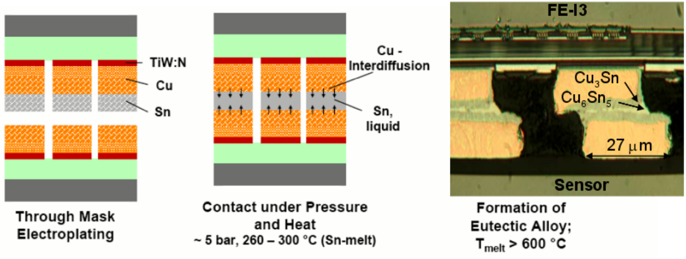
Pros

- Less process steps → lower cost.
- Arbitrary geometries possible, especially smaller pitches.
- Allows for vertical integration (Melting point!).
- Wafer to wafer and chip to wafer possible.
- Strength: 0.01 N per connection

Cons

- Planarity of 1 μm needed.
- No rework possible

SLID: Solid Liquid Inter-Diffusion



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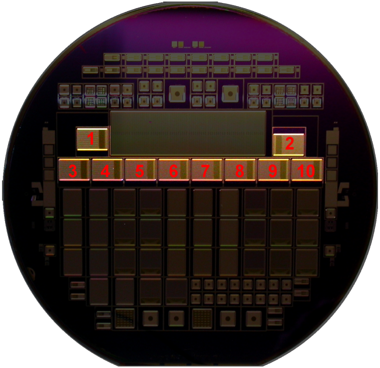
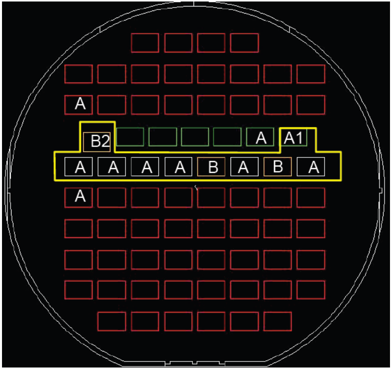
Chip to Wafer Interconnection

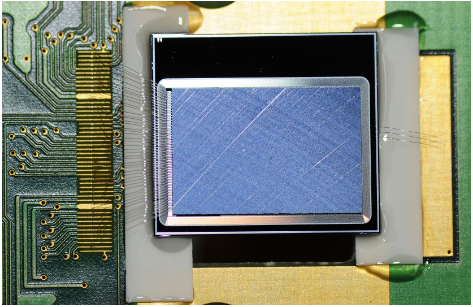
Challenge: Alignment precision

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





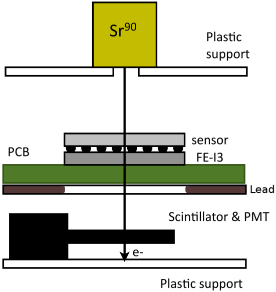
Pad size: 27 × 60 μm^2 and minimal pad distance of 23 μm
Alignment precision is ≈10 μm but rotations are also involved.
⇒ Five working modules.

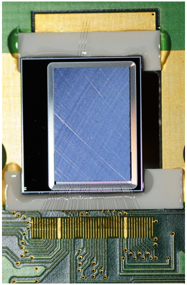


SLID Module Measurements

Source Measurements

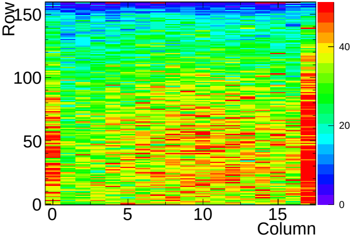
- ^{90}Sr and ^{241}Am sources are used to to determine the charge collection.
- External trigger via scintillator (for ^{90}Sr) and internal chip trigger (for ^{241}Am).



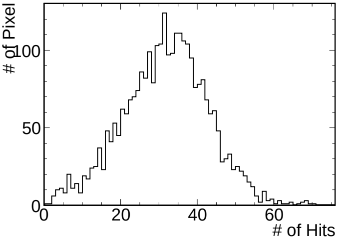


Example SLID 10, 250 k events

Hit Map

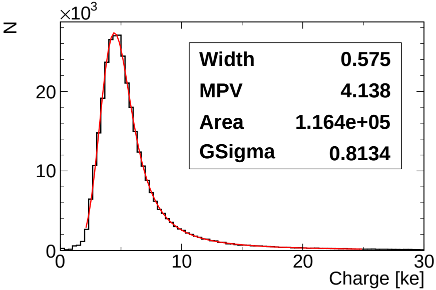


Hits per Pixel

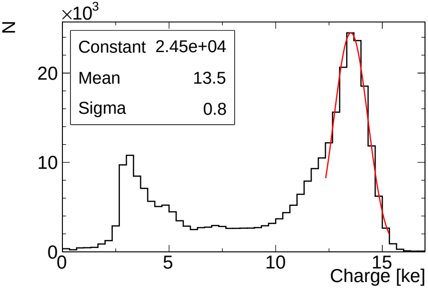


Performance Before Irradiation

- 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.



^{90}Sr Measurement

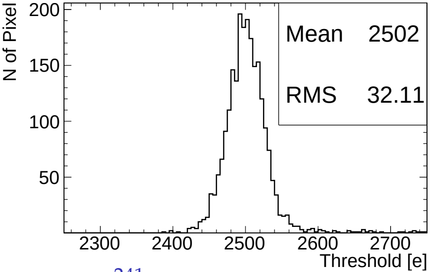


^{241}Am Measurement

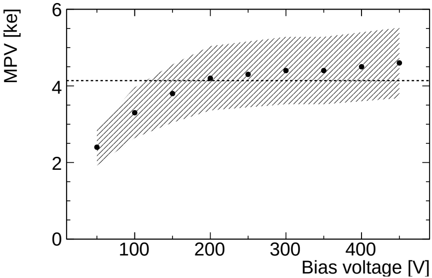
Charge Collection (Neutron Irradiated Sample)

- Irradiated to $2 \cdot 10^{15}\,n_{eq}/cm^2$ with reactor neutrons in Ljubljana.
- Tuned threshold of 2500 e, Noise of 170 e.
- MPV of collected charge constant above 200 V.

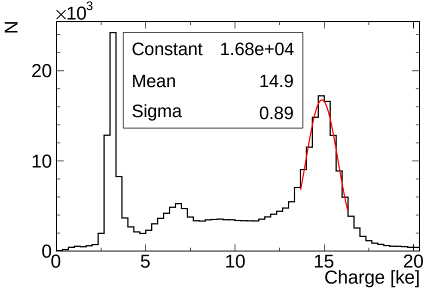
Tuning



^{90}Sr Measurement



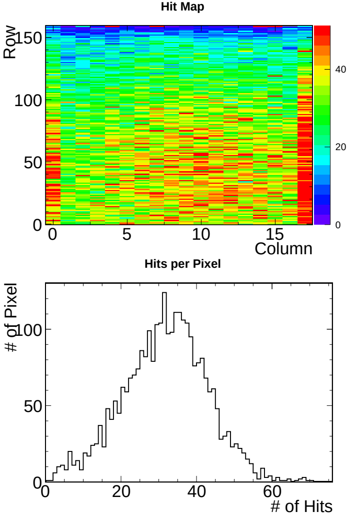
^{241}Am Measurement



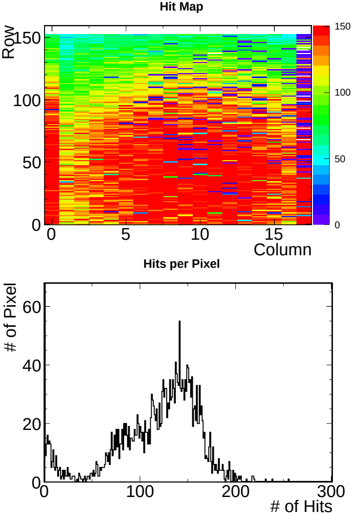
Not Connected Channels

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

All channels connected



Not connected channels



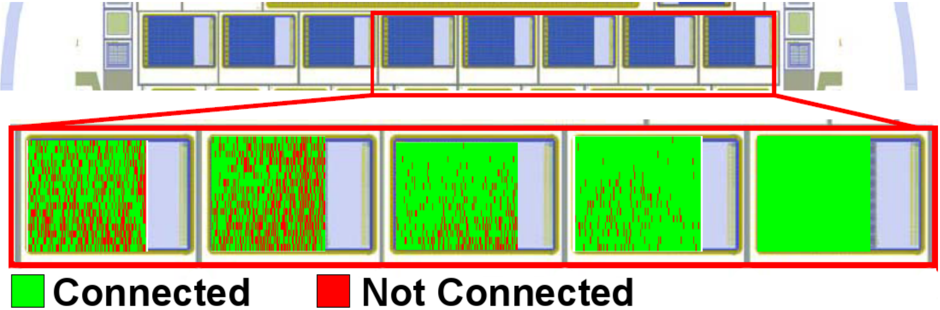
Two bumps correspond to not connected + noise and connected channels

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

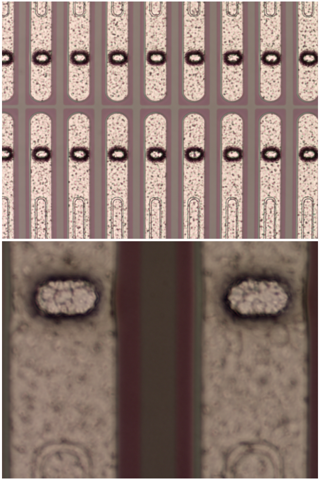
- Number of not connected channels is rising towards centre of wafer due to imperfect opening of the BCB.
- Stable after irradiation up to $2 \cdot 10^{15}\, n_{eq}/cm^2$ and thermal cycling.



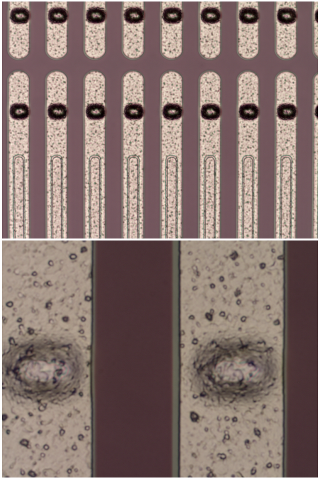
Cause: BCB-Imperfections

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 wafer was seen.

Inter-Chip-Vias (ICV)

Inter-Chip Vias (ICV)

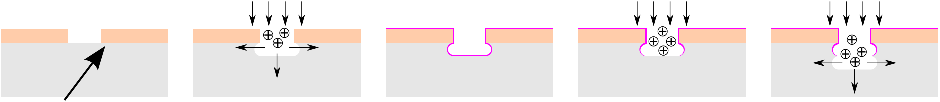


Photo resist

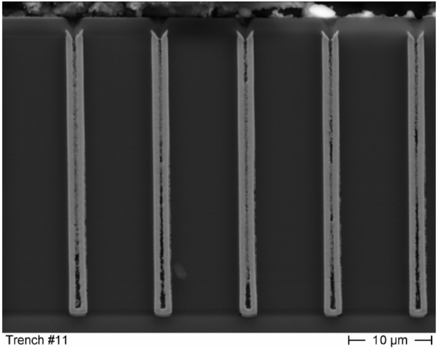
First etch (SF_6)

Passivation (C_4F_8)

Start of second etch

Second etch continues

1. Via etching exploiting Bosch process.
2. Filling of via with tungsten.
3. Thin chip down to desired thickness.
4. Electroplating at wafer-level for SLID interconnection.
5. Dicing and reconfiguring on 6" wafer for SLID interconnection.

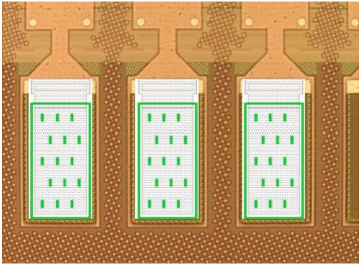


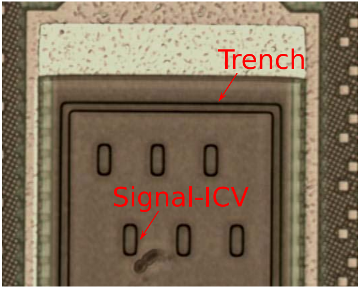
Wieland

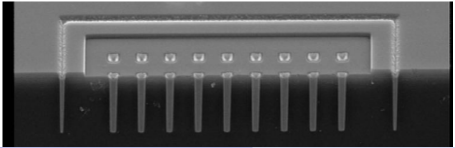
EMFT can achieve an aspect ratio of: 8:1 (Important for pixel-by-pixel connections).

Optimizing Trench and ICV Dimensions

- Etching trials on dummy wafer:
  - Performed on thinned designated test chip-wafer.
  - Etched to a depth of 50–60 μm.
  - Present development step: Optimizing Trench and ICV dimensions such that etching depth is comparable (different aspect ratios!).
- Plan for hot chip wafer:
  - Local planarisation of fan-out pads by depositing and etching of SACVD-Oxide.
  - Perform etching and filling of vias.
  - Connect to sensors via SLID.







Summary & Plans

Summary

- First single chip modules with SLID interconnection exhibit good performance in terms of:
  - Leakage currents & breakdown voltages
  - Collected charge (CC)
  - CC after irradiation
- Challenges with chip alignment on the handle wafer
- Trend of not connected channels towards centre of the wafer due to BCB imperfections → i. e. not related to the interconnection technology!

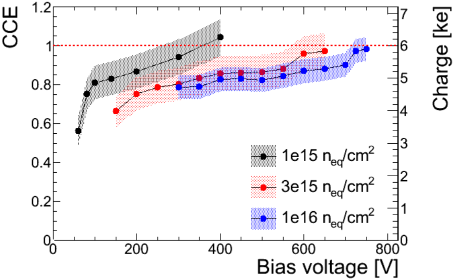
Plans

- Study irradiated structures in testbeam
- Full SLID assembly of sensors and front-end chips including ICV

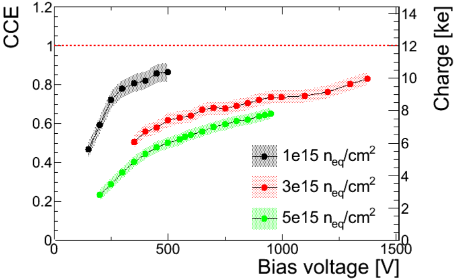
BACKUP

Charge Collection Efficiency for Thin Sensors

75 μm



150 μm

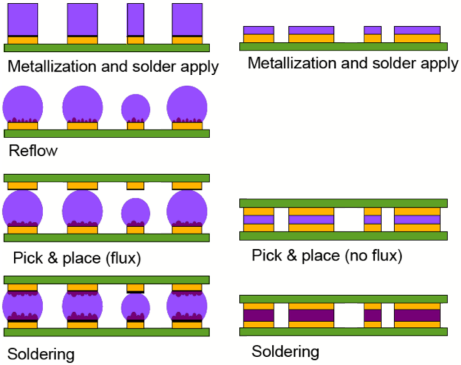


- After irradiation: Signal considerable higher than expected from simulation.

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

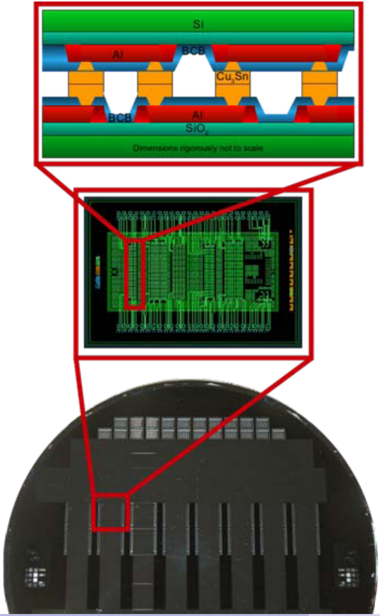
- Uncertainties correspond to 500 e^-, estimated for each point.
- Measurements before any intentional annealing: T=-30 °C ($\phi = 10^{15}\ \mathrm{n_{eq}/cm^2}$); T=-40 °C & T=-45 °C ($\phi = (3-10)\cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$); T=-50 °C ($\phi = 5\cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$).

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.

Efficiency Measurement in a Testbeam

One 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