REFERENCING WORK FROM EP R&D WORK PACKAGE 1.3

SMALL PITCH PIXEL DETECTOR HYBRIDISATION AND INTEGRATION

CEPC 24-28/10/2022

PETER SVIHRA, EP-DT-TP @ CERN

24.10.2022

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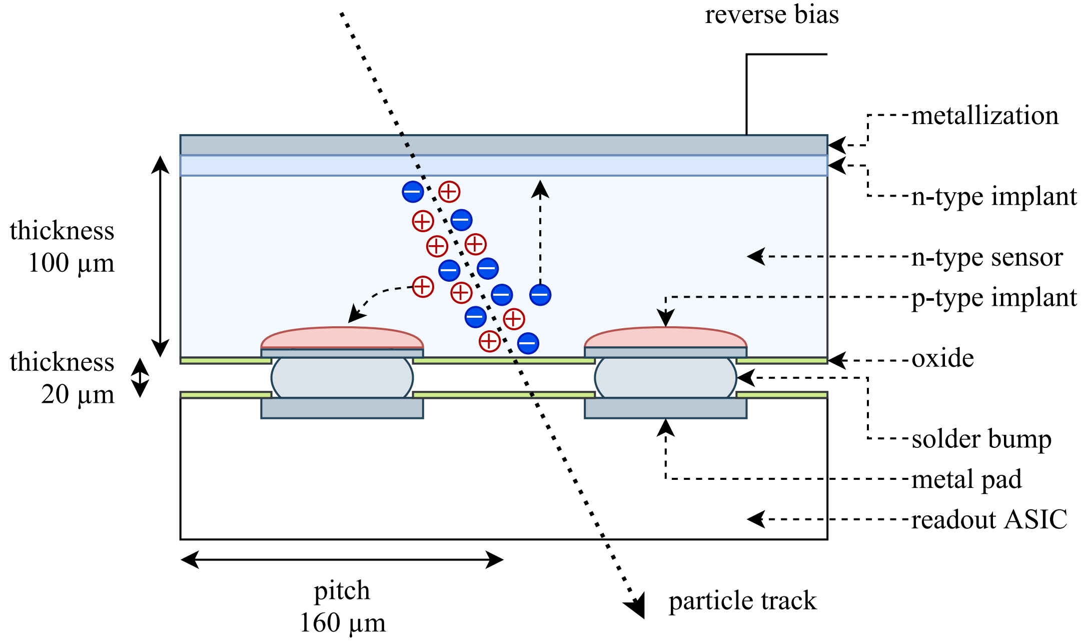
EP R&D WP1.3 – MODULE DEVELOPMENT

- R&D programme focused on study and development of modules for hybrid and CMOS pixel detectors

- Development of new processes and workflows for modules and their integration (relying on previous sensor and ASIC productions of CLICpix2, Timepix3, MALTA, …)
- Collaboration with industrial partners to develop and test new technologies (Conpart, Dexerials, FBK, …)
- Development of new procedures and processes within CERN (Micropattern lab EP-DT-EF, Bondlab, QARTlab, …)
- Collaboration with other institutes for validation and concept development (UniGe, LPNHE, AIDAinnova, …)

MOTIVATION – IN A NUTSHELL

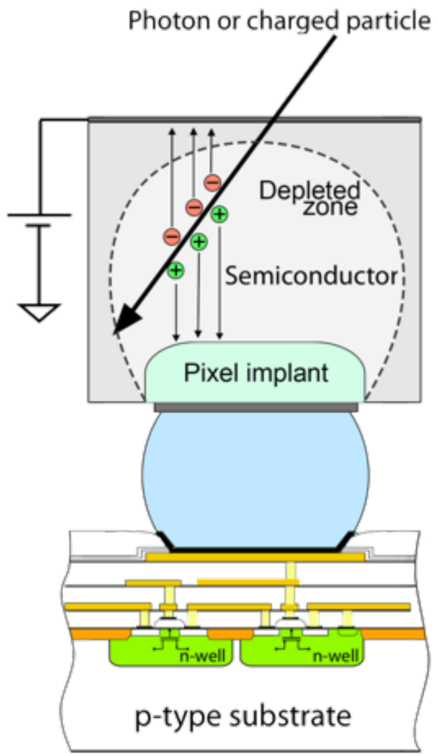


Generic hybrid pixel detector with planar p-on-n silicon sensor

- Ever increasing requirements for the spatial/temporal precision of tracking and vertexing detectors require lot of R&D and prototyping
- Hybrid detectors
  - Independent R&D of sensor and ASIC
  - Difficult prototyping and interconnect on a full wafer scale
  - Need for a single die hybridisation process
- Development of single-die process utilising already existing devices

CLICpix2	Timepix3
- 25 µm pixel pitch	- 55 µm pixel pitch
- 128 x 128 pixels	- 256 x 256 pixels
- 3.2 mm x 3.2 mm	- 14 mm x 14 mm

SINGLE DIE SMALL PITCH BONDING



CERN EP R&D

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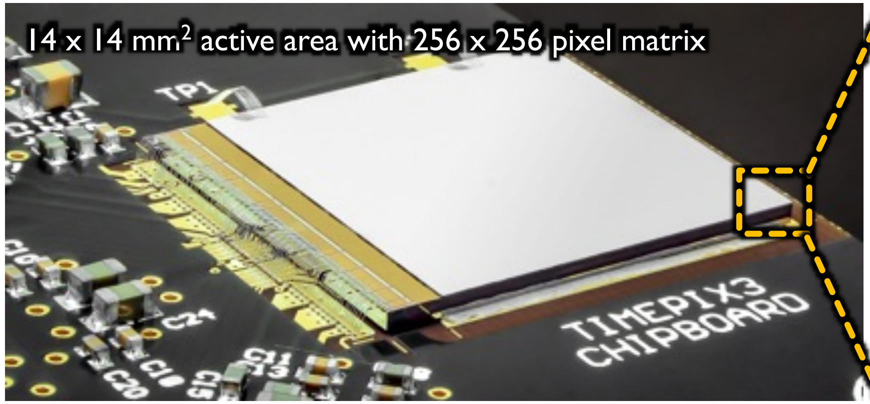
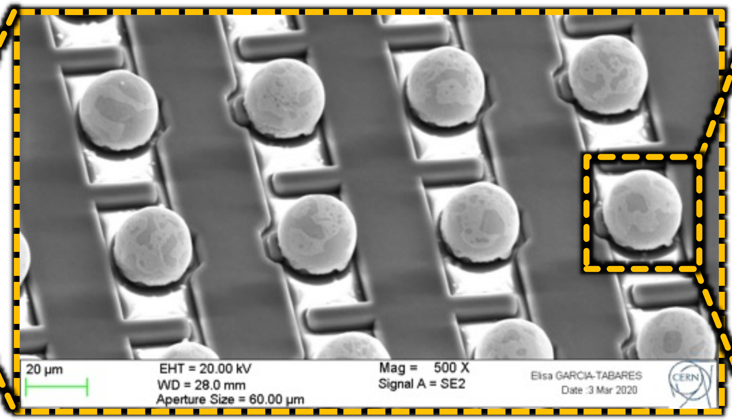
BUMP-BONDING

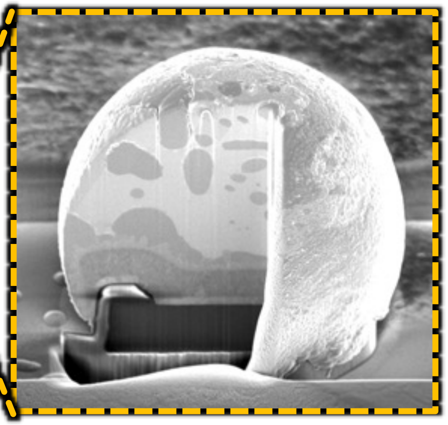
Timepix3 ASIC bump-bonded to a 50 µm active edge silicon sensor



Solder bumps on the Timepix3 pixel matrix



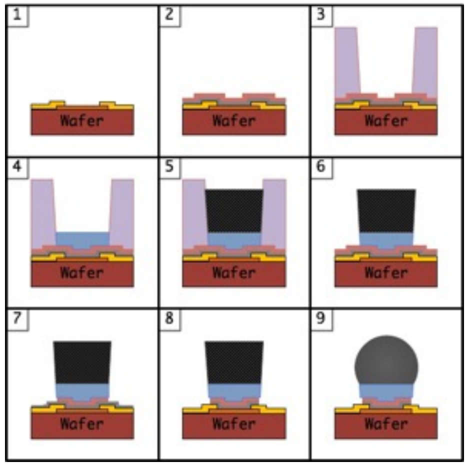
Bump cross-section



- Standard hybrid pixel detector interconnection technology
- Complex and expensive process, requires full wafers for processing
  - Not suited for R&D of new devices or multi project wafers
- Good yields for pixel pitch **> 50 µm**

Bump deposition process

1) cleaning of wafers
2) field metal deposition
3) thick photoresist lithography
4) electroplating of UBM
5) electroplating of solder
6) stripping of photoresist
7) wet etching of seed layer
8) wet etching of adhesion layer
9) solder reflow



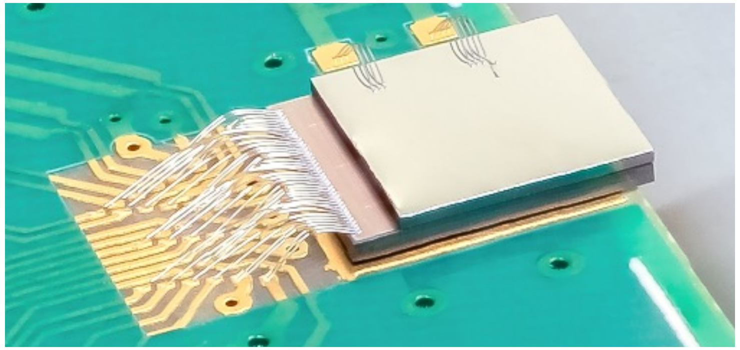
BUMP-BONDING – R&D FOR SINGLE DIES

- Bump-bonding of small pitch detectors is still very challenging
  - Technology needs to keep up with the ongoing pixel miniaturisation

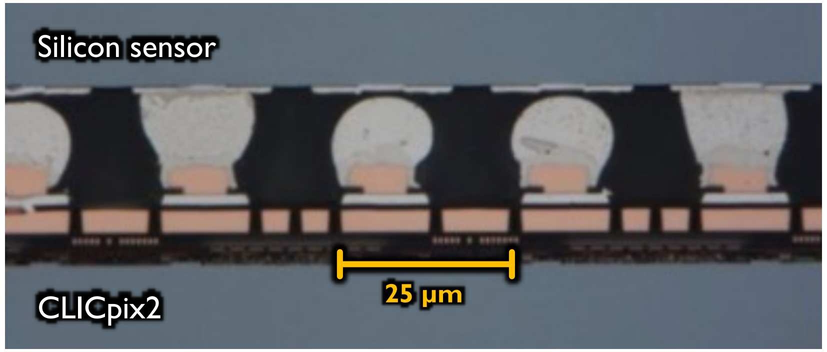
- R&D with IZM has developed single die bonding process for **25 μm pixel pitch**
  - Preparation of carrier wafers with mask alignment marks and bond layer
  - Bond each single ASIC die on an individual carrier wafer
  - Bump deposition: sputtering of plating base, resist lithography, Cu+SnAg-galvanic, resist removal and etching of plating base outside bumps, reflow of bumps
  - Removal of ASICs from carrier wafer
  - UBM deposition on sensor wafers (at Advacam / IZM)
  - Singularisation of sensors (at Advacam / IZM)
  - Flip-chip of ASICs and sensors
  - X-ray measurements for quality control.

Fraunhofer IZM

CLICpix2 ASIC bump-bonded to an active edge silicon sensor



Cross-section of some failed connections



First stage of the process characterised in the thesis of Morag Williams

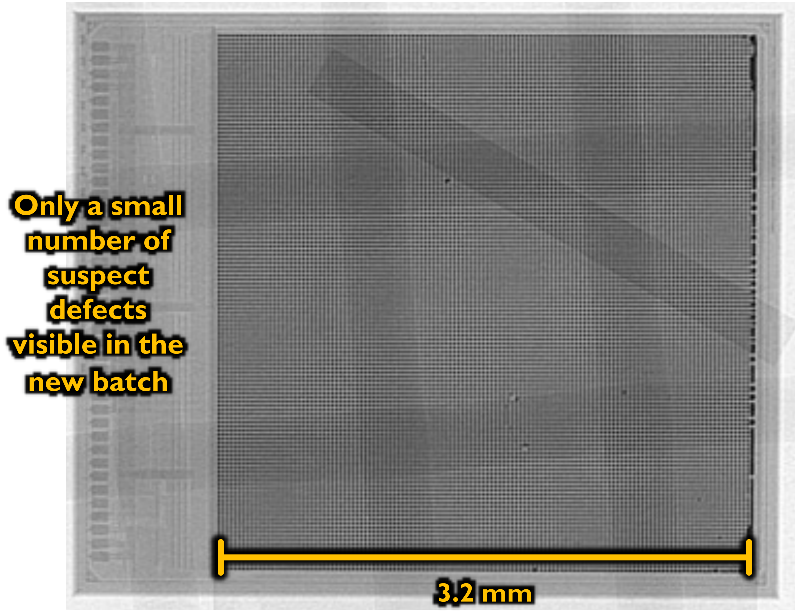
BUMP-BONDING – R&D FOR SINGLE DIES

- The process has been optimised after the first (feasibility) stage

- Recently a new batch of CLICpix2 and FBK active edge sensor (from AIDA2020) assemblies bonded at IZM
  - Different guard-ring configurations
  - **50 µm, 100 µm** and **130 µm** sensor thickness

- How to characterise interconnect quality?

X-ray scan of bonded CLICpix2, 973-3-A3



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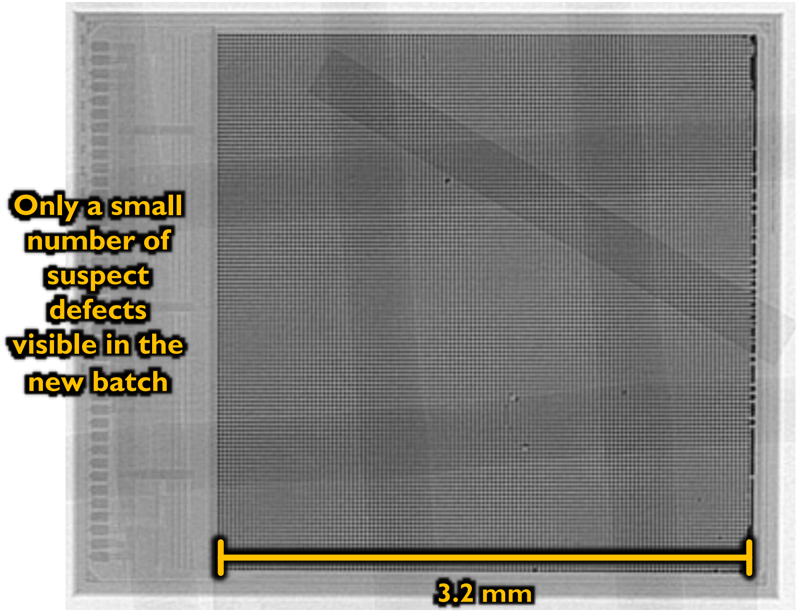


Characterisation

- Electrical characterisation
  - Voltage – current (IV)
  - Voltage – capacitance (CV)

Electronic response

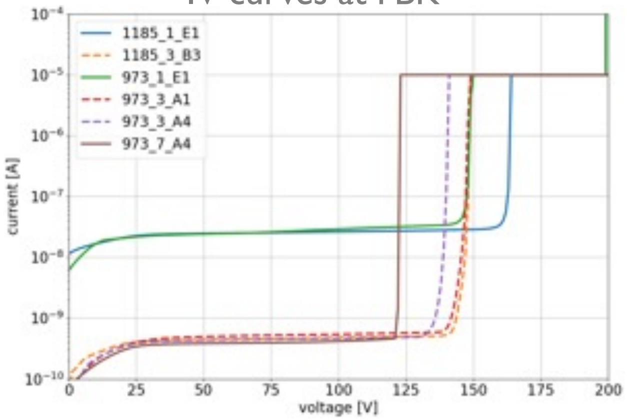
- ASIC testpulse injection
- Radioactive source measurement
- Interconnect yield

Beam-test

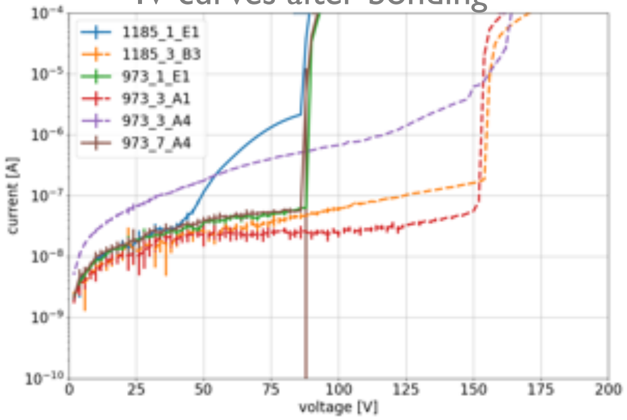
- Hit collection efficiency
  - Voltage/threshold dependency
  - Interconnect yield
- Timing performance

Electrical characterisation

IV curves at FBK



IV curves after bonding



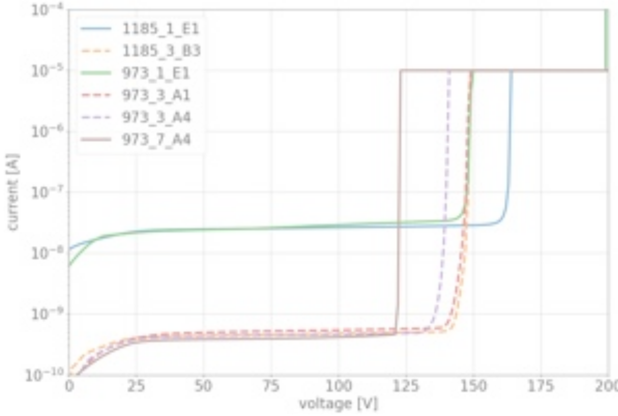
- Effect of different guard-ring layouts visible
  - Floating GR leads to higher breakdown

Wafer	Device	Sensor Thickness	Guard ring	Breakdown voltage [V]
973	1-E1 / 7-A4 3-A1 / 3-A4	50 µm	no float	-91 / -91 -160 / -161
1185	1-E1 / 3-B3	100 µm	no / float	-88 / -170
3826	4-B4 / 7-A5	130 µm	no	-85 / -85

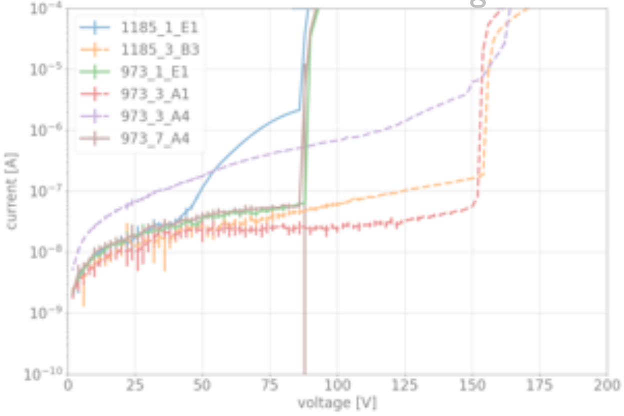
LAB TESTS

Electrical characterisation

IV curves at FBK



IV curves after bonding



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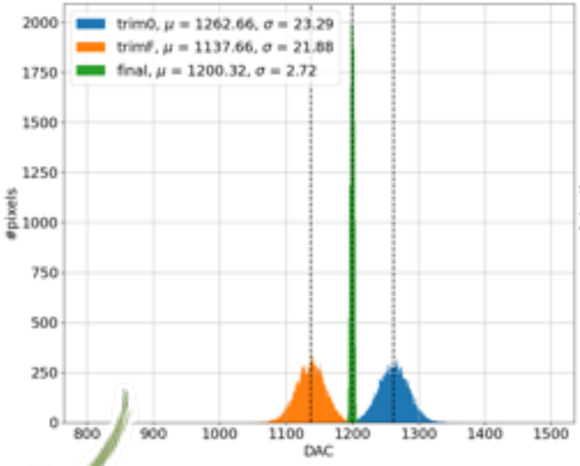
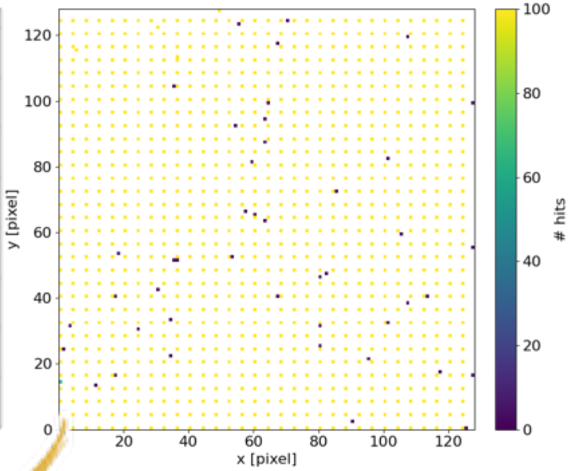
Electronic response

Pixel equalisation of CLICpix2, 973-1-E1



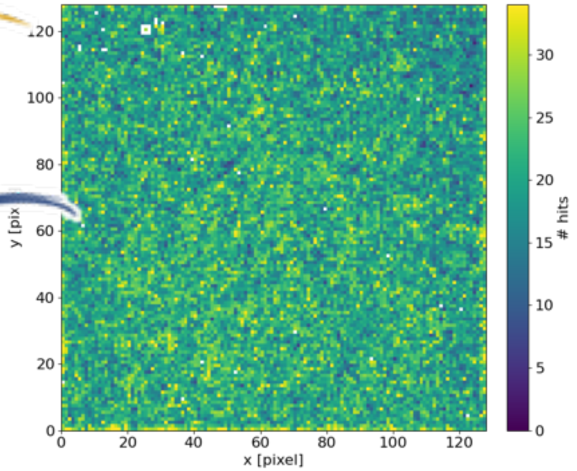
Testpulse raw data of CLICpix2, 973-1-E1



always noisy

linked testpulse response to neighbours

Sr90 response of CLICpix2, 973-1-E1



no hits from Sr90

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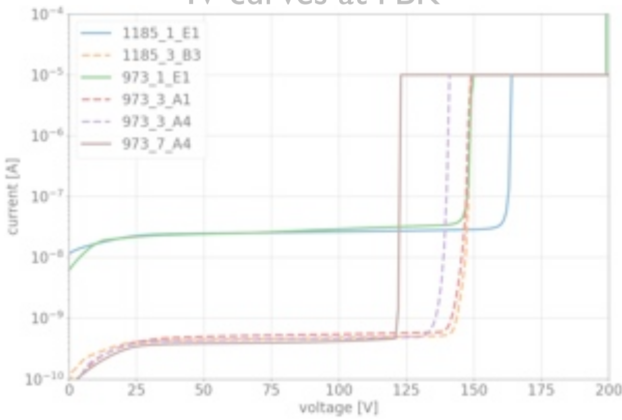
Electrical characterisation

IV curves at FBK



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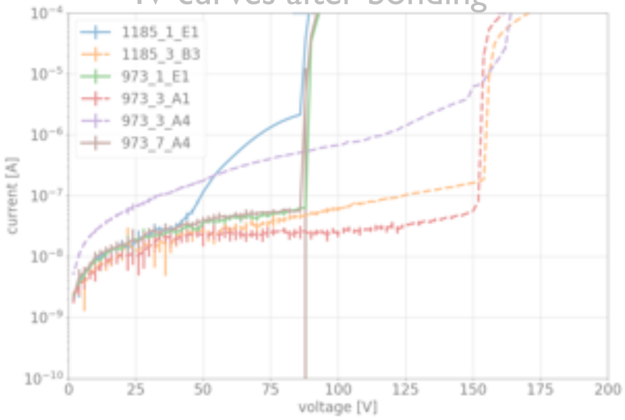

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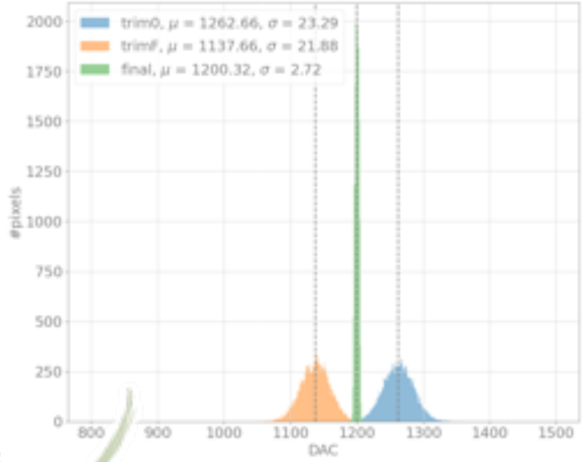

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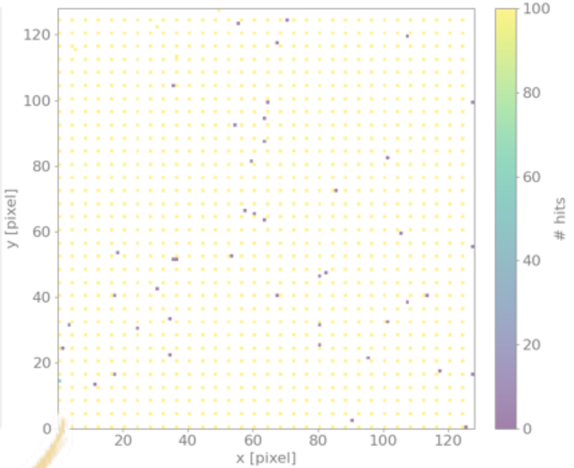

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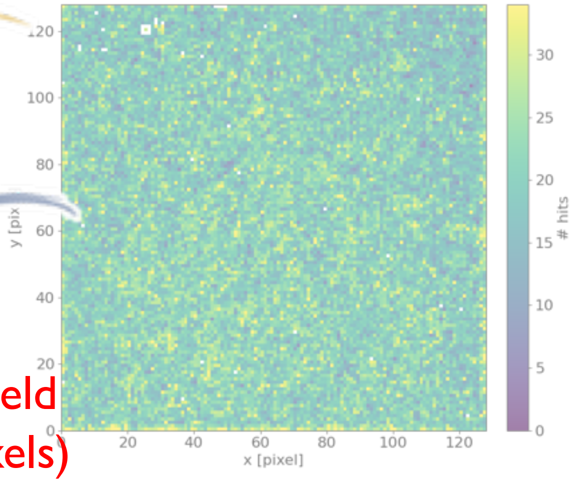

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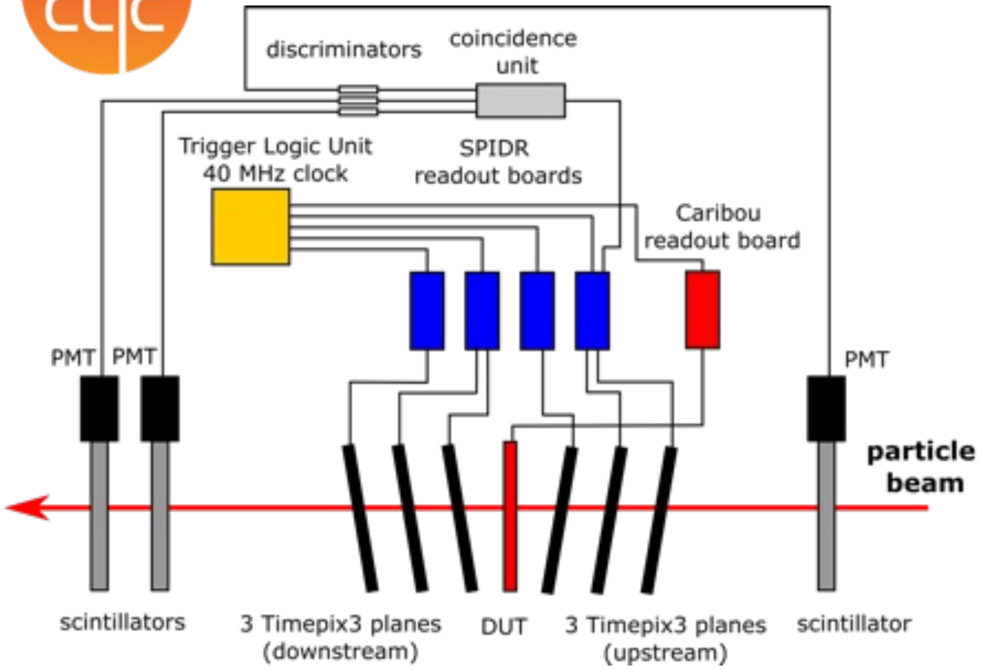
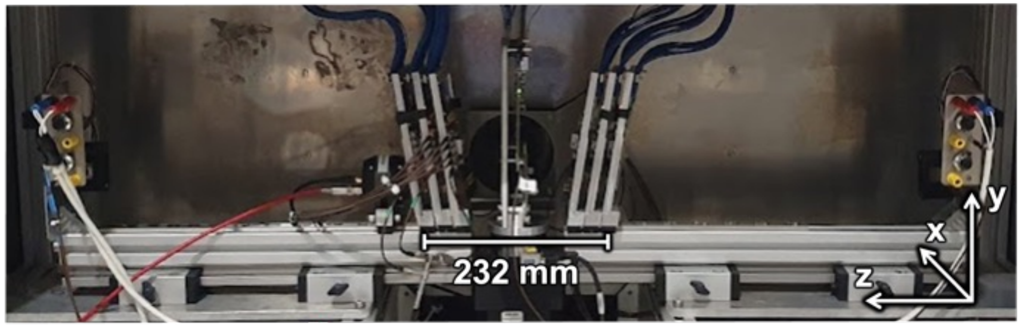
> 99.7% interconnect yield (total 16384 pixels)

CLICdp Timepix3 telescope





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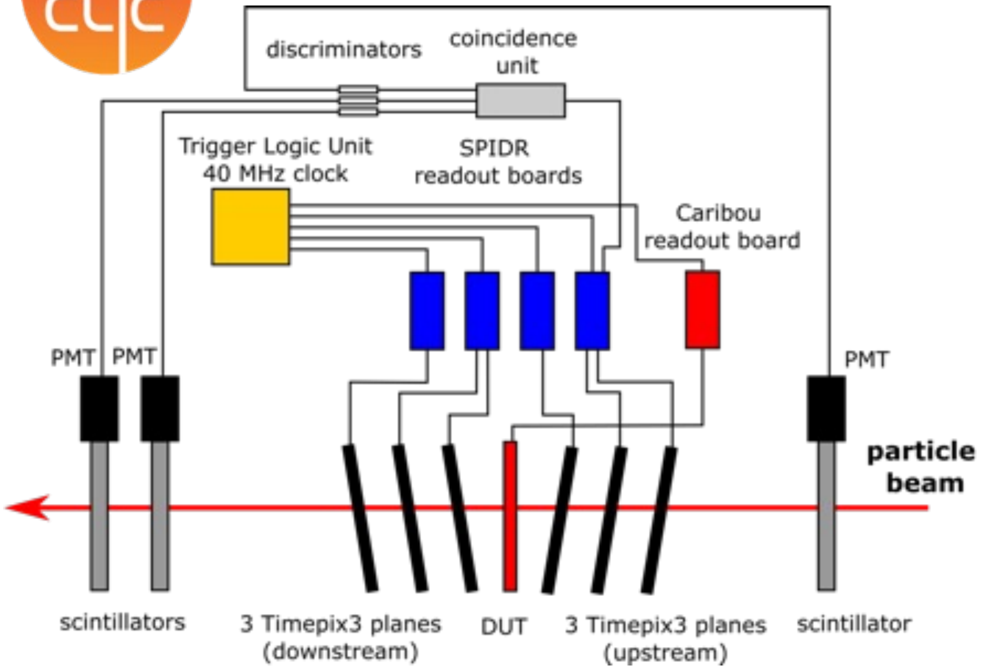
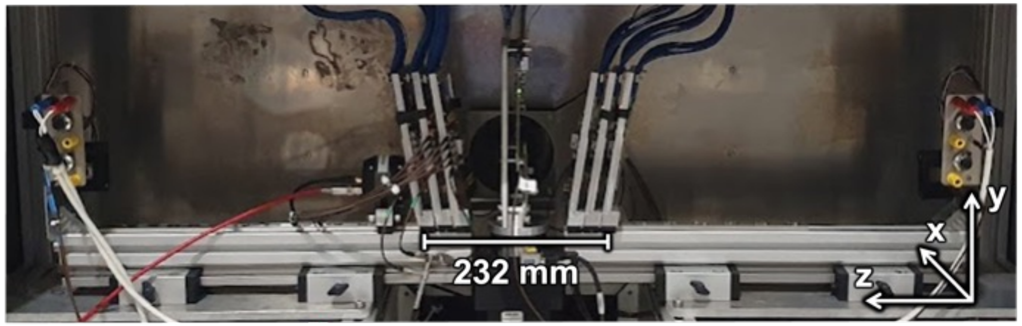
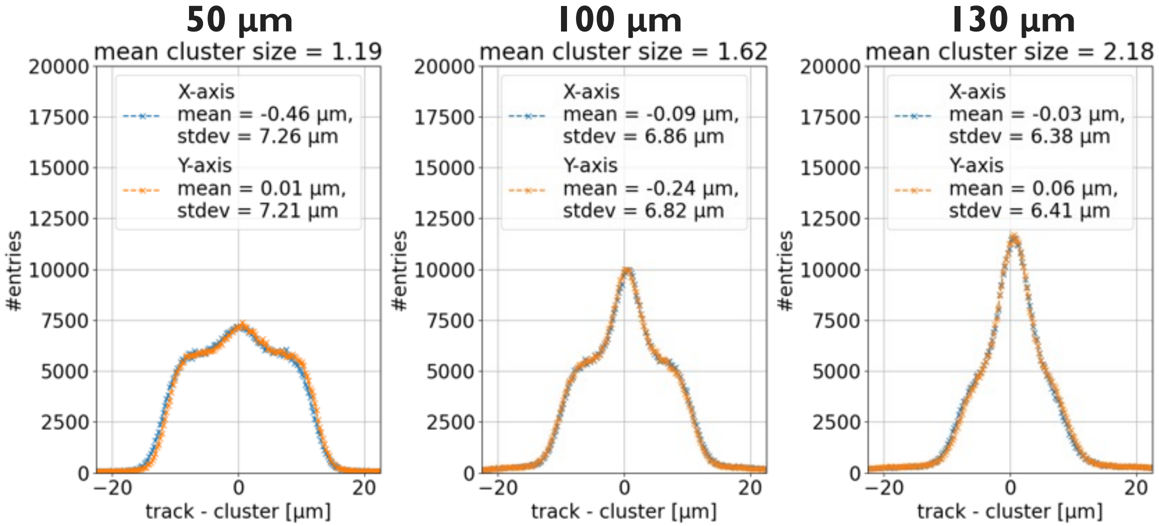
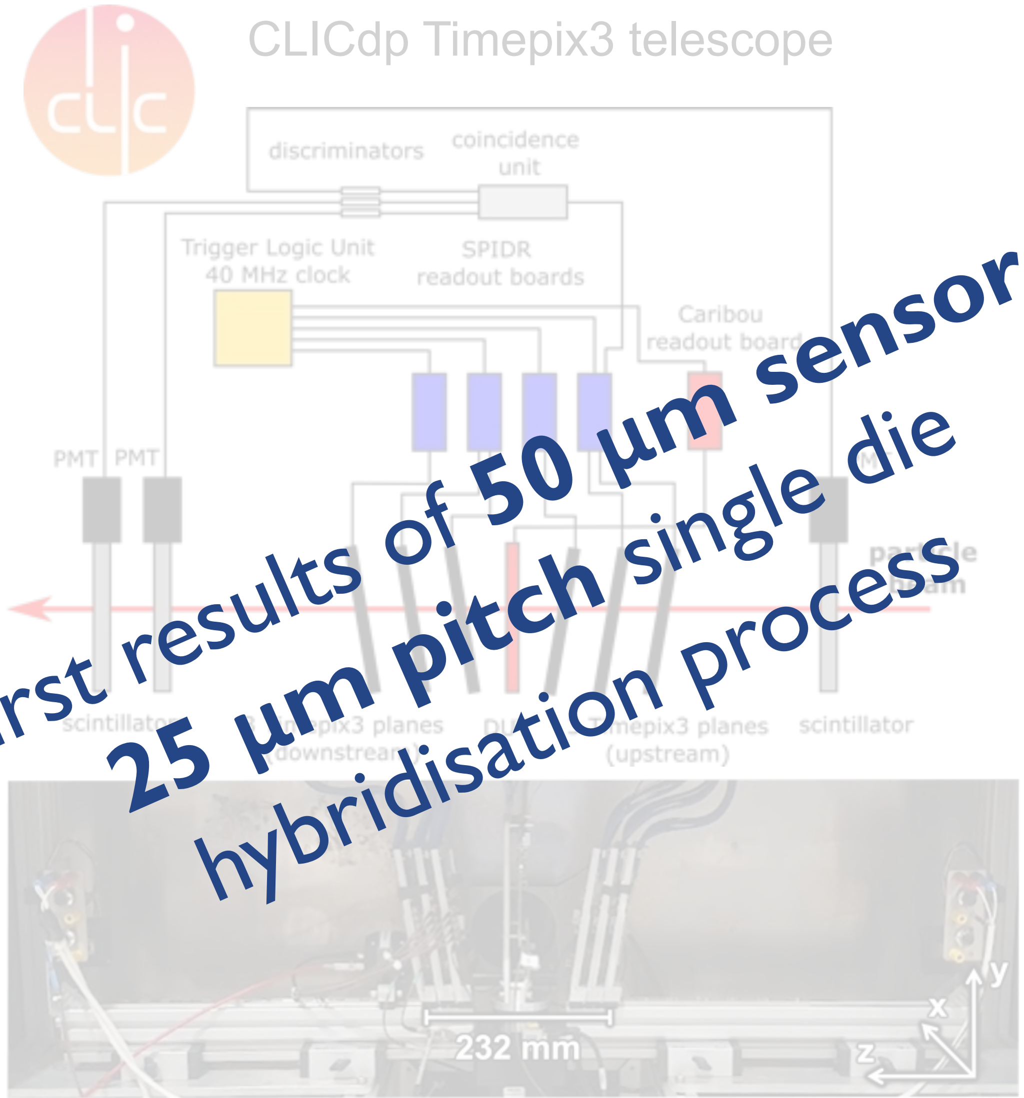




- Tracking matches expectation based on cluster size





First results of **50 μm sensor, 25 μm pitch** single die hybridisation process

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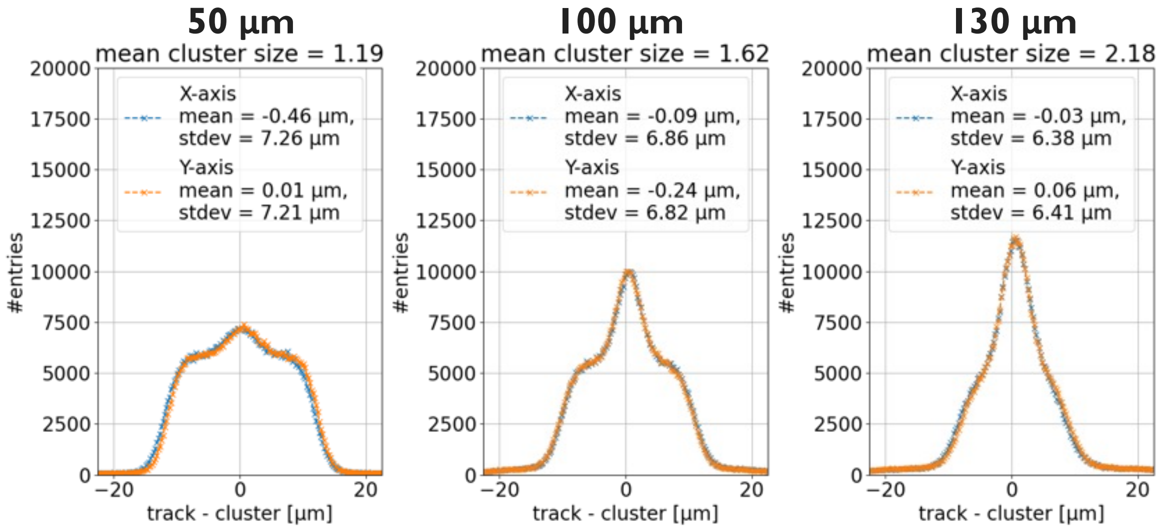
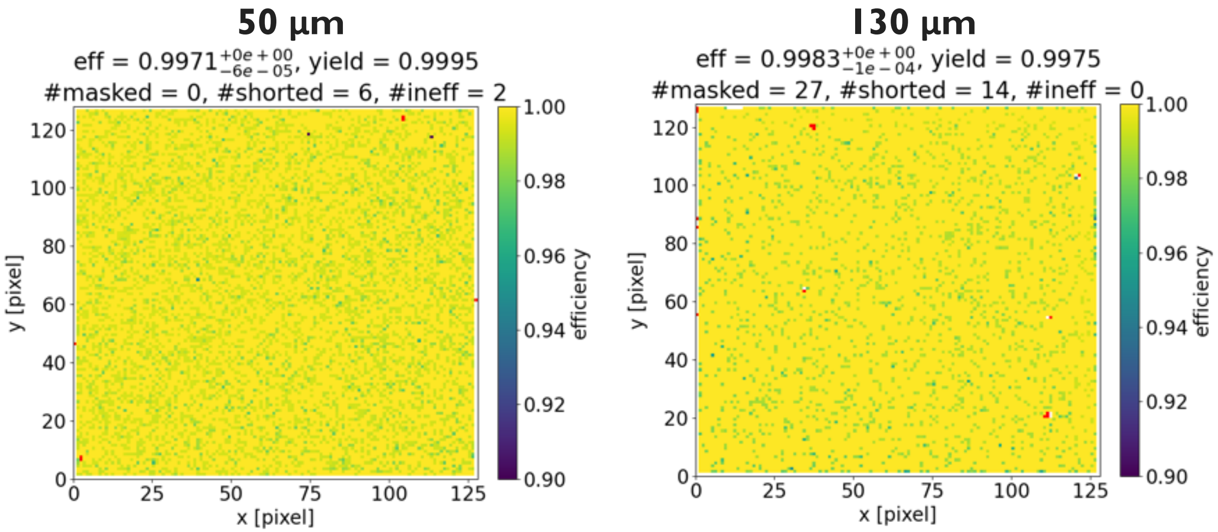
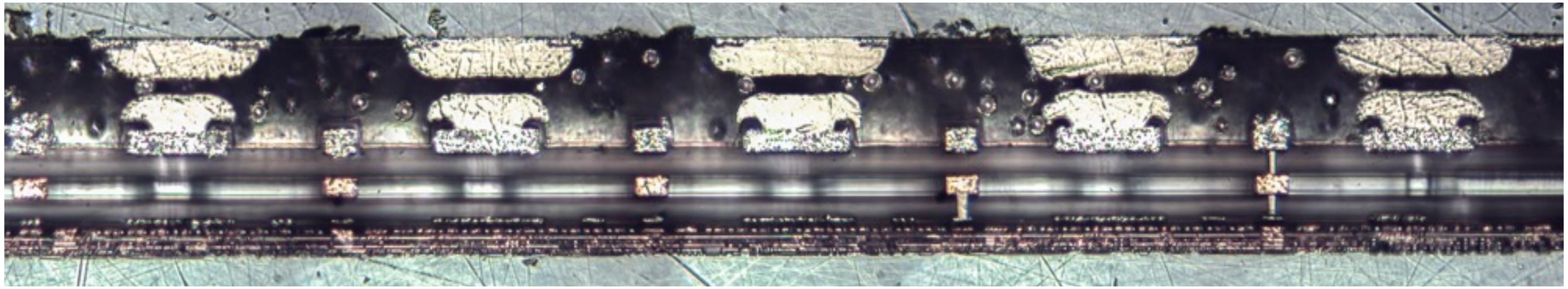






ANISOTROPIC CONDUCTIVE FILM (ACF) INTERCONNECT

ACF HYBRIDISATION WORKFLOW

- **Anisotropic Conductive Film (ACF)**
  - Epoxy film with small (3µm) conductive particles
    - Widely used in industry (chip-on-flex, display manufacture, …)
    - Alternative in-house process compared to standard bump-bonding, needs R&D to adapt to pixel detectors
  - **Thermocompression bonding** via compressed conductive particles
    - Permanent mechanical connection via cured epoxy film
- **Under Bump Metallisation (UBM) required**
  - Electroless Nickel (Electroless Palladium) Immersion Gold – EN(EP)IG
  - In-house mask-less single die **ENIG** under development @CERN

Timepix3 pixel matrix with ACF

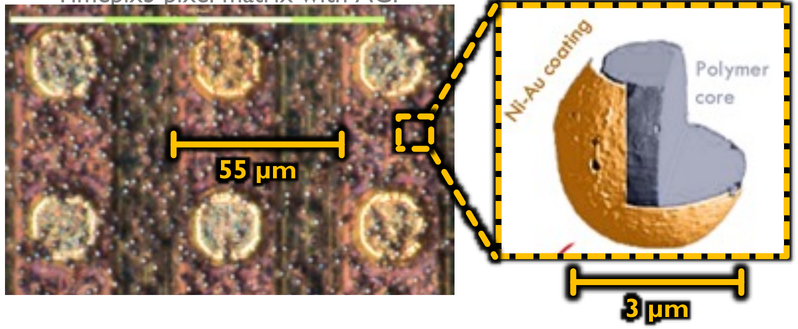
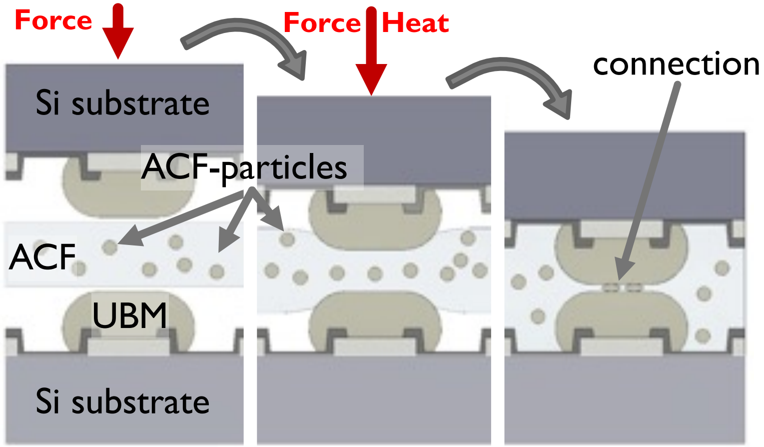


Illustration of ACF bonding



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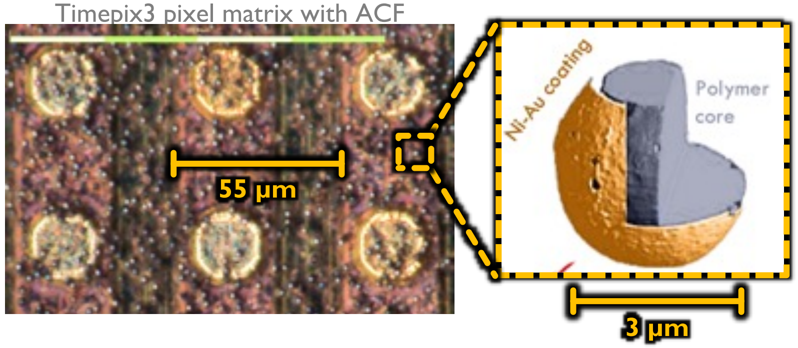

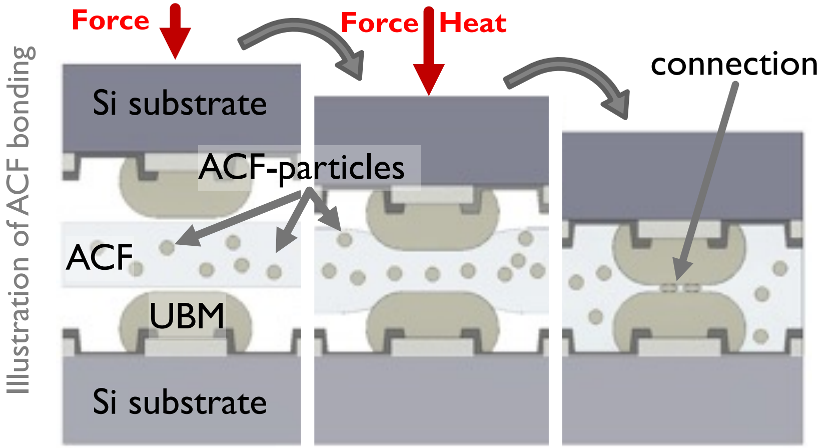

Preparation
- Sensor/ASIC/test structure procurement
- ACF material procurement

UBM plating
- ENIG
- Visual inspection

ACF bonding
- Lamination
- Flip-chip bonding

Testing
- Cross-sections
- Electrical/mechanical tests
- Test-beam and source measurements

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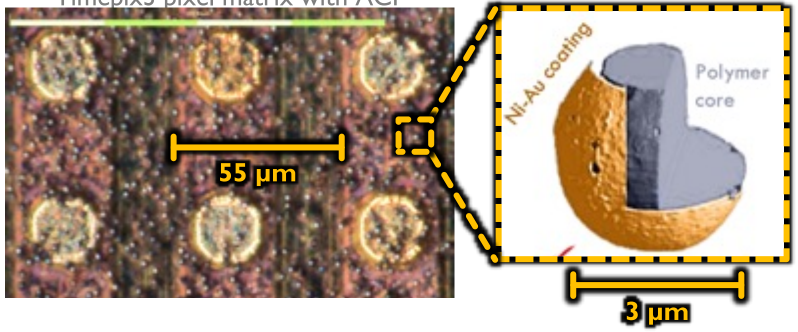

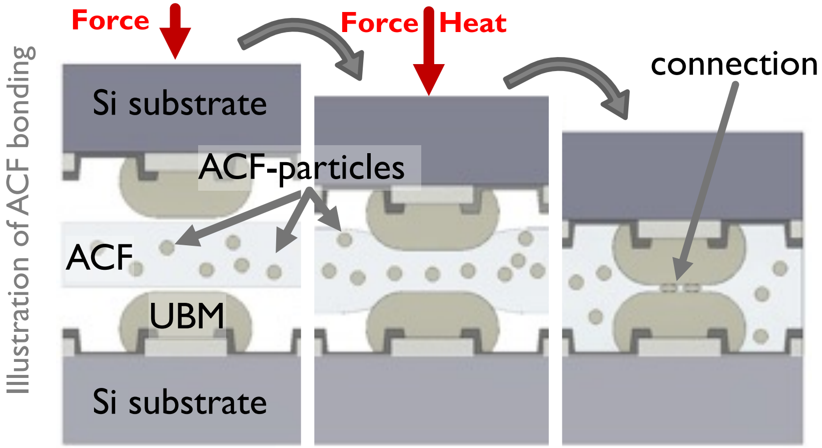

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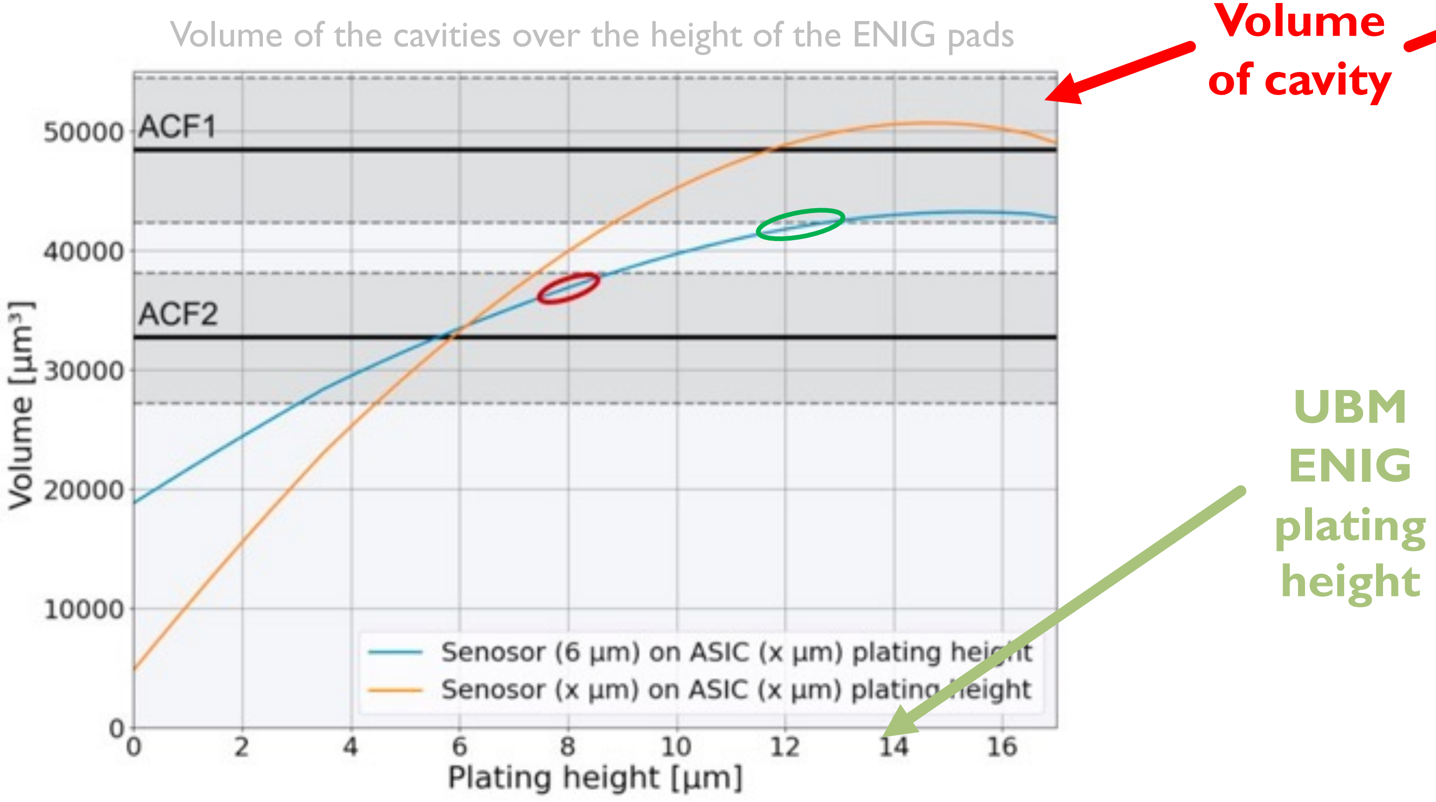
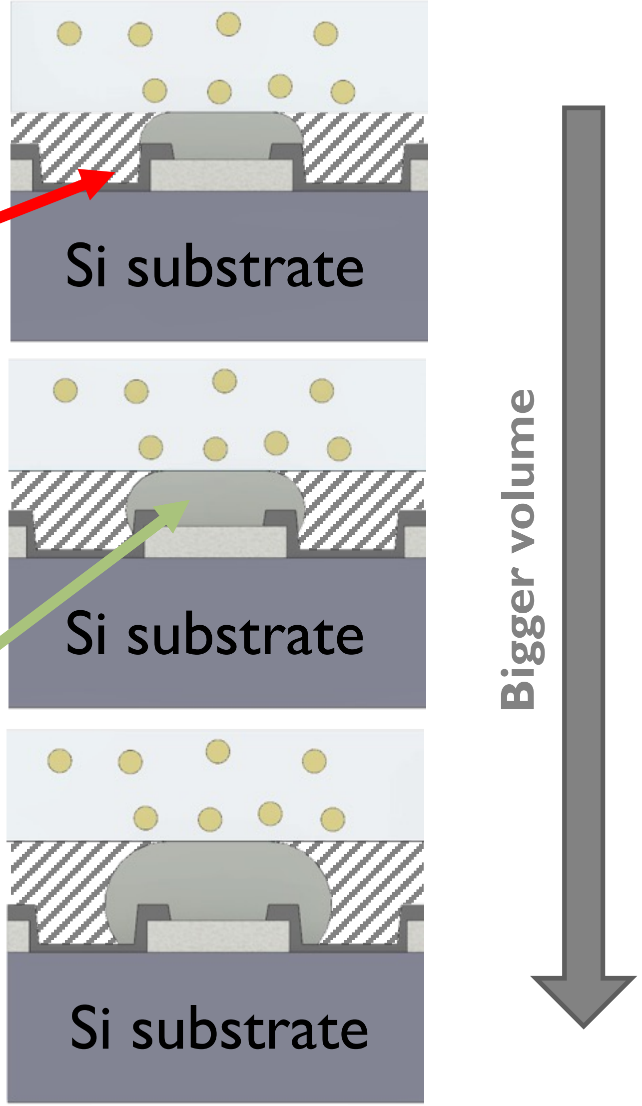
UBM PLATING – NEED FOR INCREASED HEIGHT

- Need for sufficiently thick and uniform UBM to achieve connection
  - Large enough cavities for the ACF fit in after the bonding





by Janis Schmidt

pad size 55 µm

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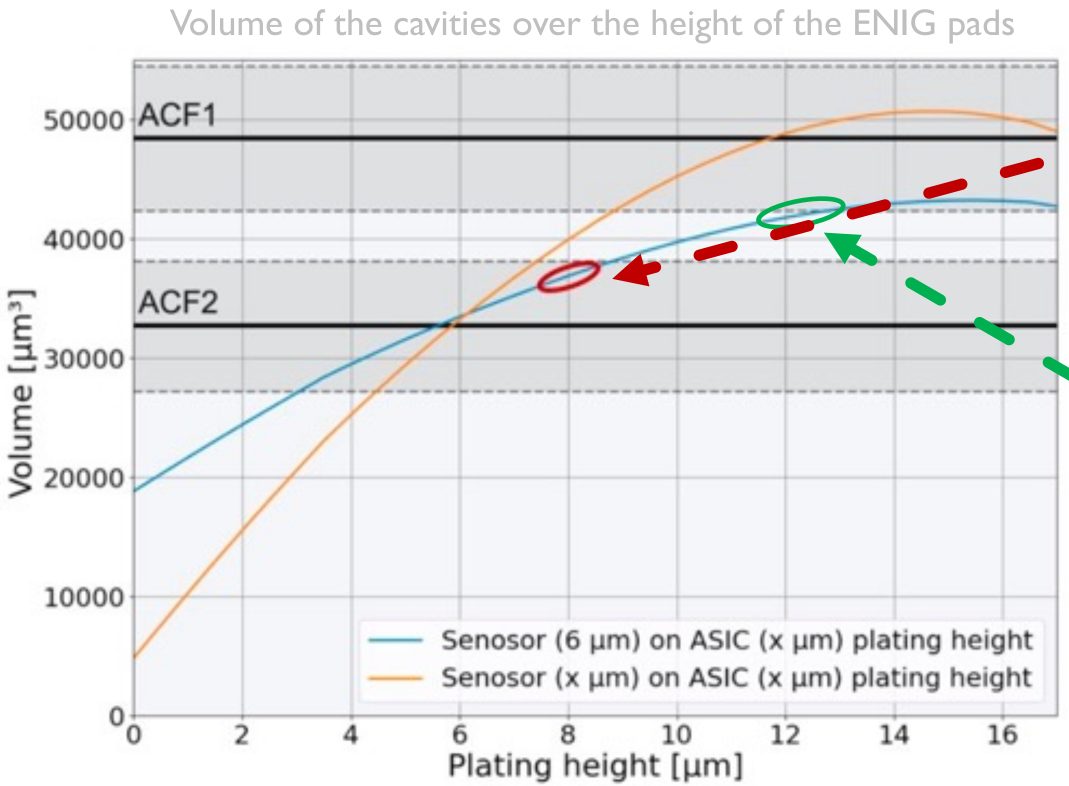
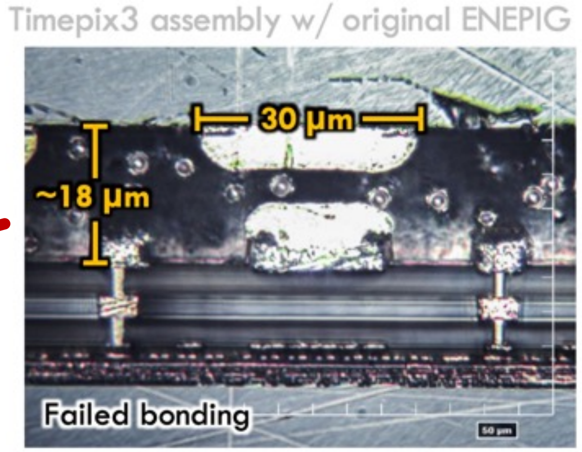
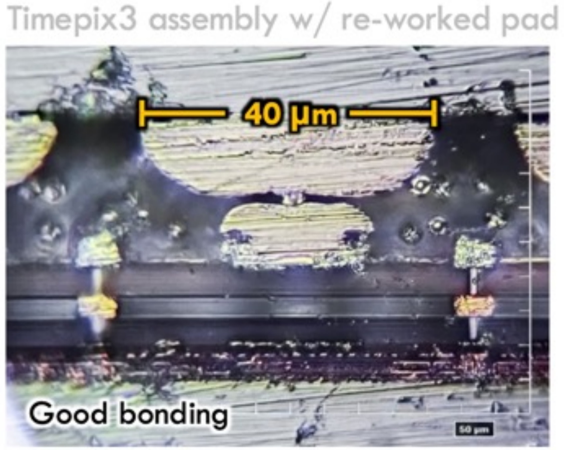


by Janis Schmidt

ACF1 (18 µm thick)



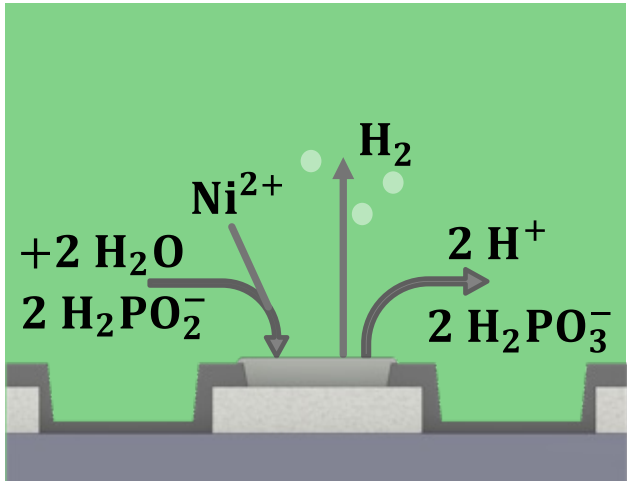


Bigger volume

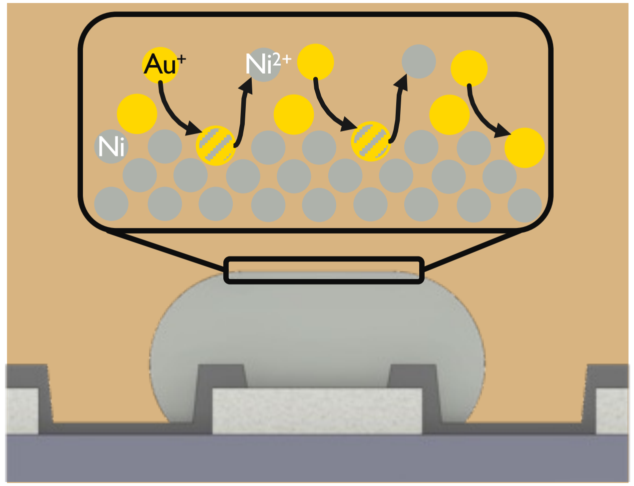
by Mateus Vicente

- Electroless Nickel
  - Self-catalytic reaction on pad surface
  - Performed on aluminium (activated surface) or on previous nickel deposits
- Immersion Gold
  - Corrosion protection, very thin layer (< 1 μm)
- Ongoing optimisation of the process in EP-DT Micro-Pattern Technologies lab
  - Cleaning, oxide removal, nickel bath stability,…
  - Optimisation performed for different pad topologies

Electroless Nickel



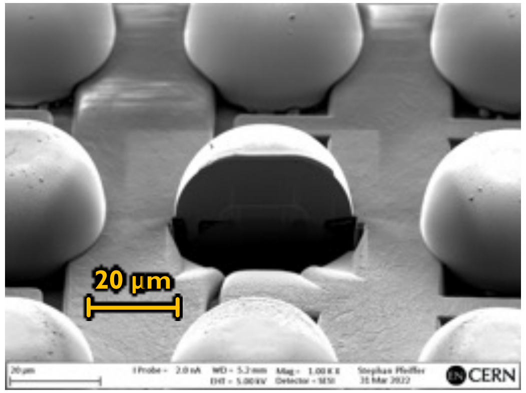
Immersion Gold



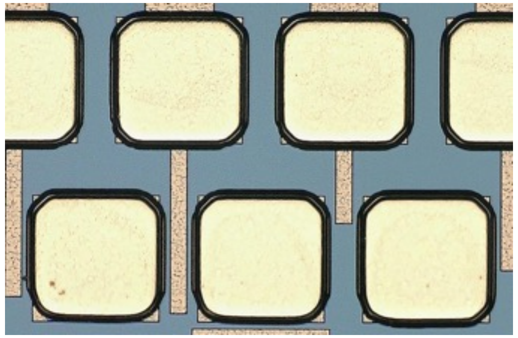
by Janis Schmidt, Rui de Oliveira

UBM PLATING – IN-HOUSE ENIG

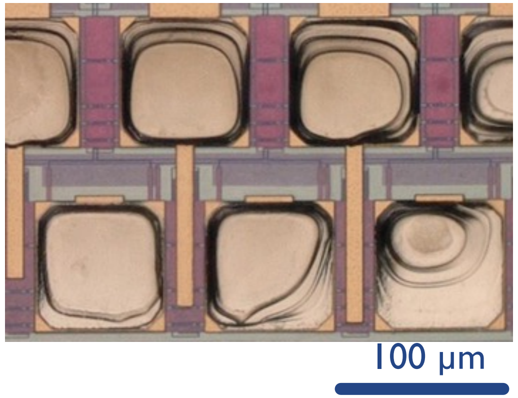
- Topology and uniformity of the UBM is critical
  - Diffusion of the stabiliser impacts plating
  - Results verified by visual inspections (microscopy, cross-sections) and SEM, EDS



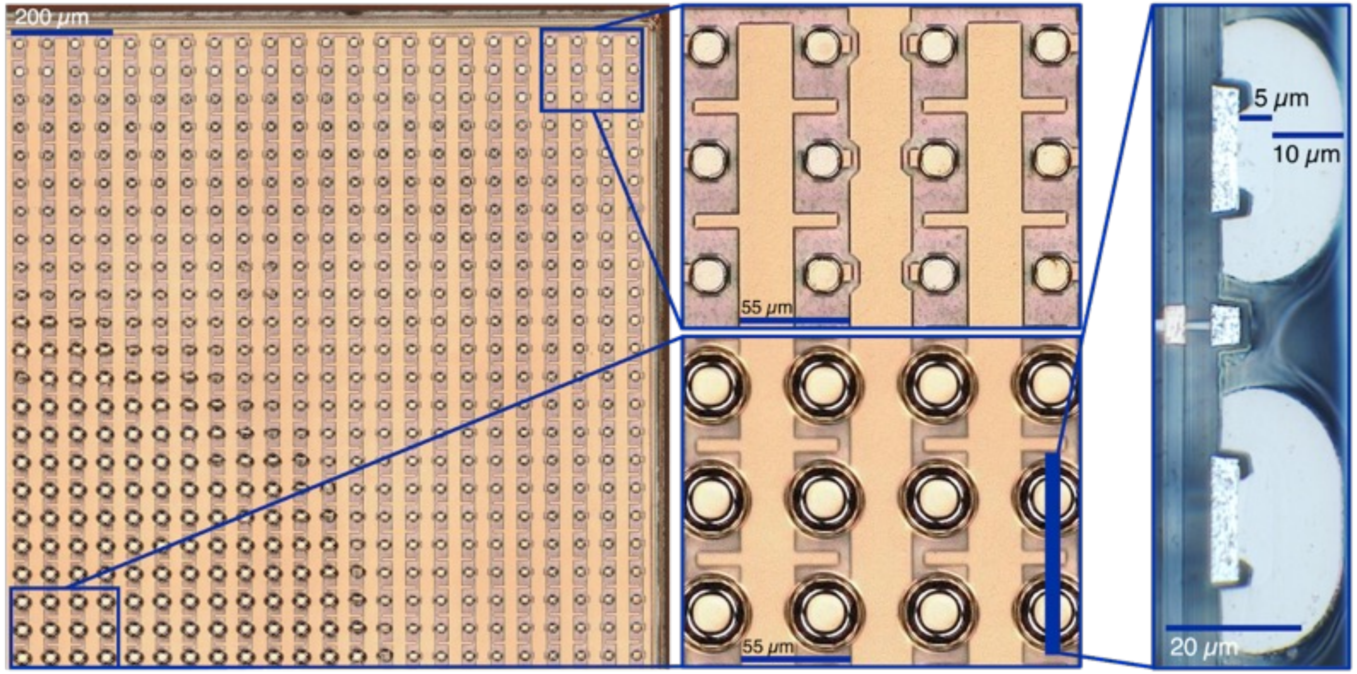
Good plating



Step plating



Non-uniformity



by Janis Schmidt, Rui de Oliveira

ACF BONDING

- ACF connection done at Geneva University using semi-automatic flip-chip bonder
  - Precise temperature, pressure and alignment control
  - Heating up to 400 ℃ and force applied by bonding arm up to 100 kg
- **Bonding has two steps – lamination and bonding**
  - Pressure applied to displace and compress particles
  - Epoxy cures at 150 °C

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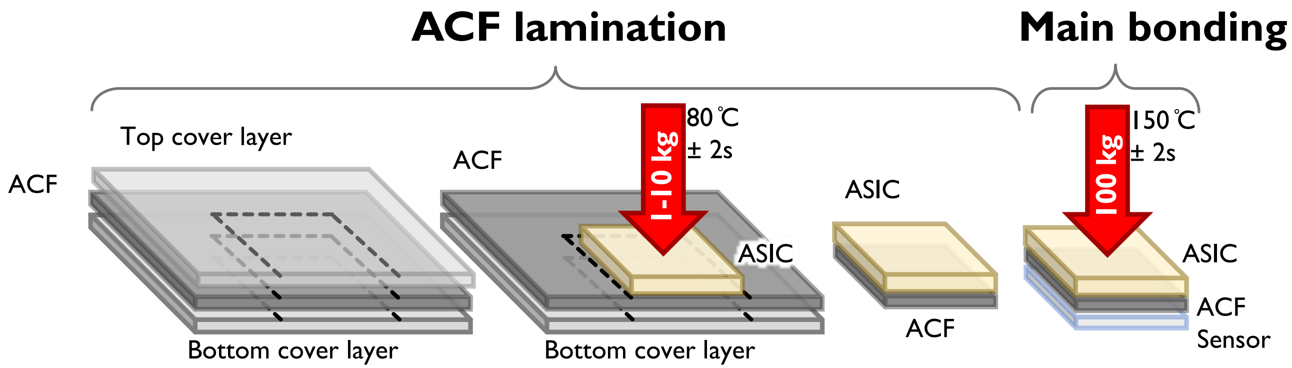
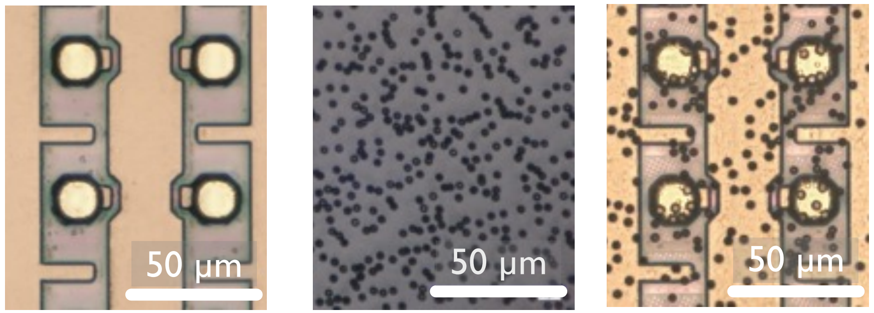
FACULTÈ DES SCIENCES

SET ACCμRA100





by Mateus Vicente

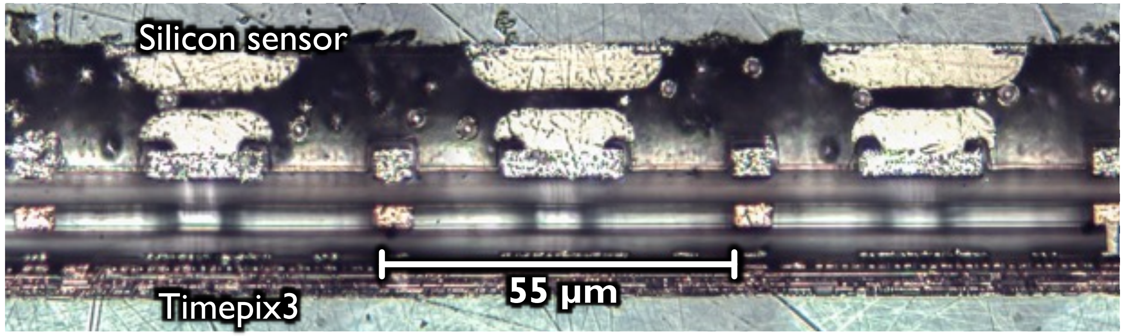
TESTING – CROSS SECTIONS

- Different ACF materials available for bonding and testing

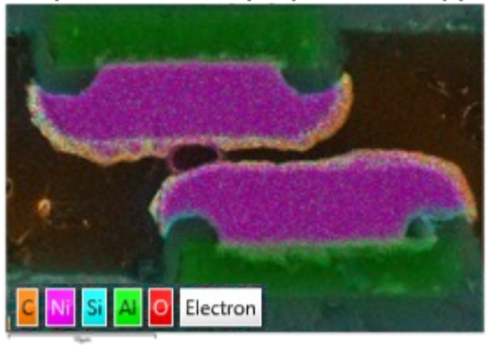
ACF	Part. diameter [µm]	Thickness [µm]	Part. density [pcs/mm^2]	Bonding pressure [Mpa]	Sheet/reel
1	3	18	71k	30-80	sheet
2	3	14	60k	50-90	reel

- Evaluation similar to single-die bump-bonding
  - Cross-sections on dummy samples to verify distance and alignment

Cross-section of ACF connections



Bonding interface Energy Dispersive X-Ray Spectroscopy



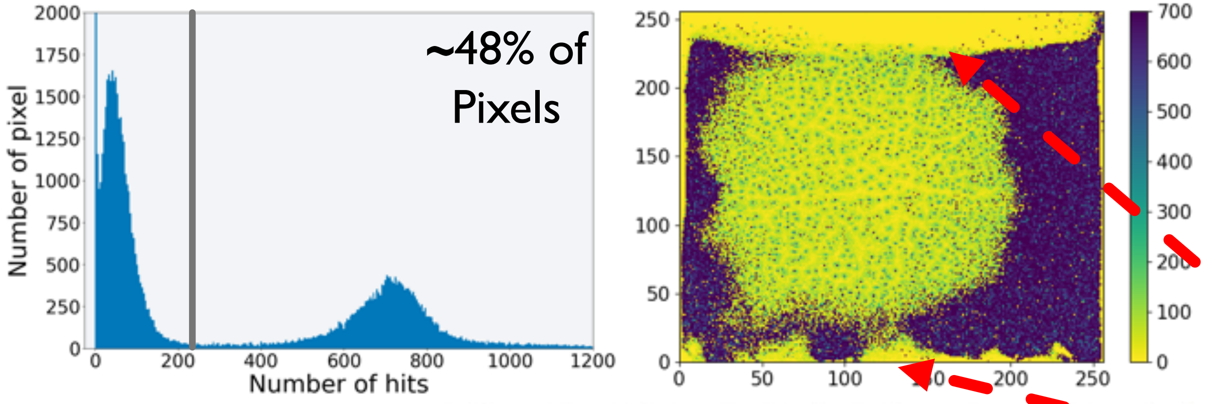
  - Source exposure to evaluate hit response
  - Beam-test to conclude the results

TESTING – SOURCE RESPONSE

- Two almost identical (non-ideal ENIG UBM) samples bonded with different ACF materials

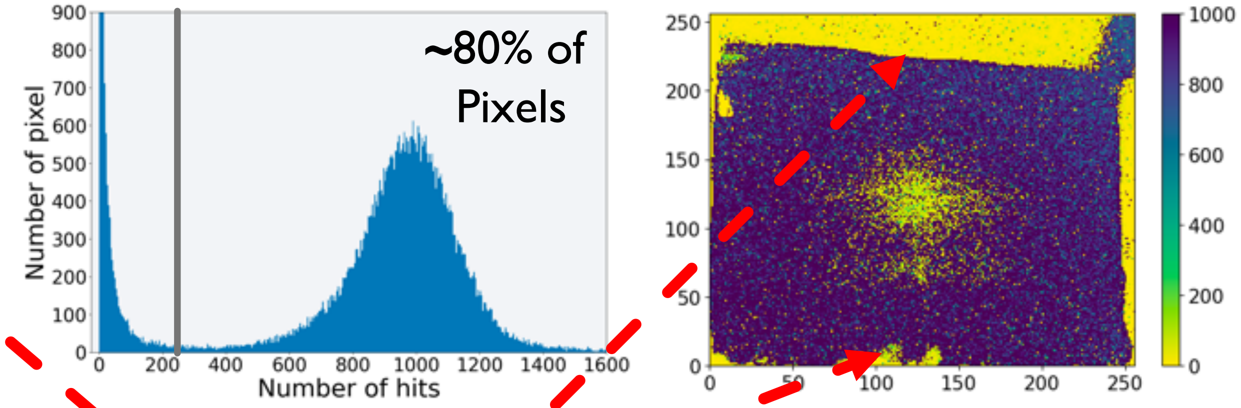
Sample 1: 100% coverage of 18 µm ACF1

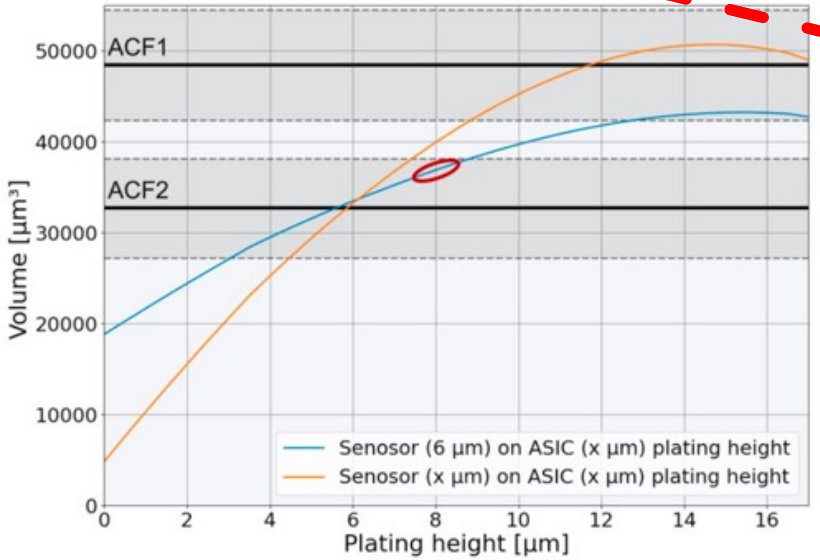
Histogram and hit-map from Sr^{90} illumination



Sample 2: 90% coverage of 14 µm ACF2

Histogram and hit-map from Sr^{90} illumination





Defective plating

by Janis Schmidt

TESTING – SOURCE RESPONSE

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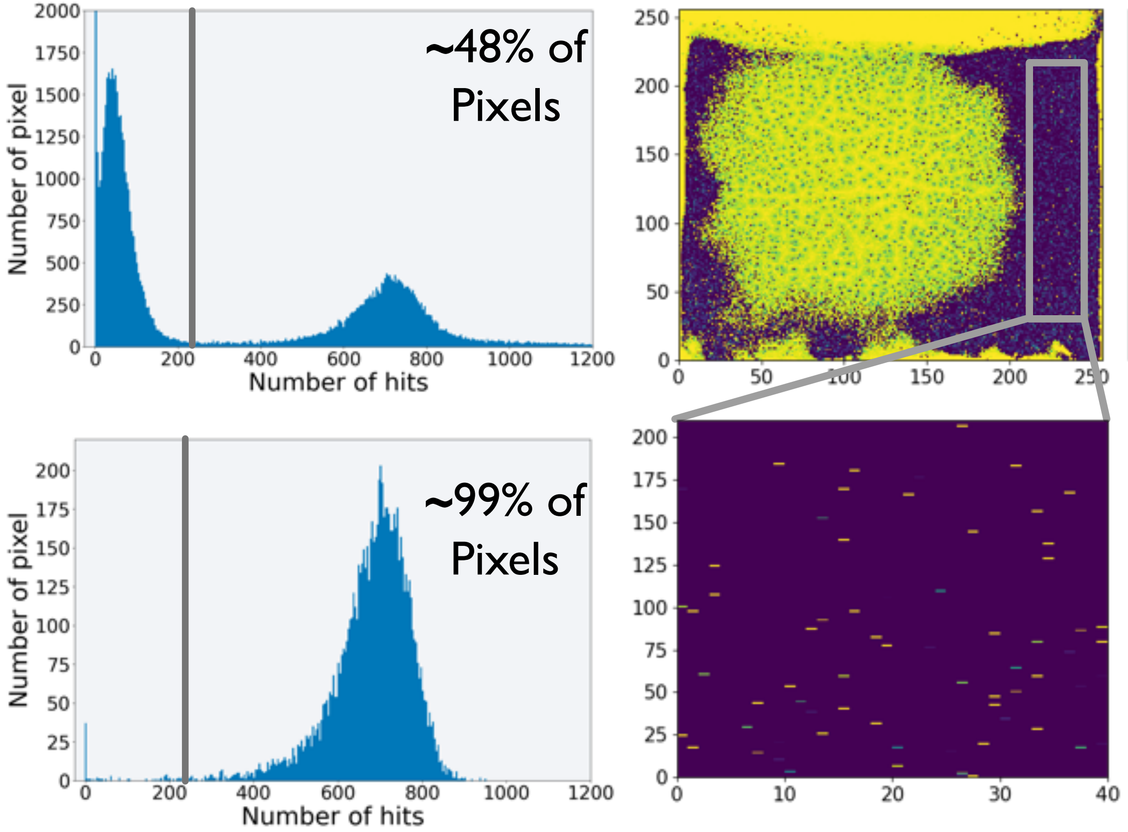

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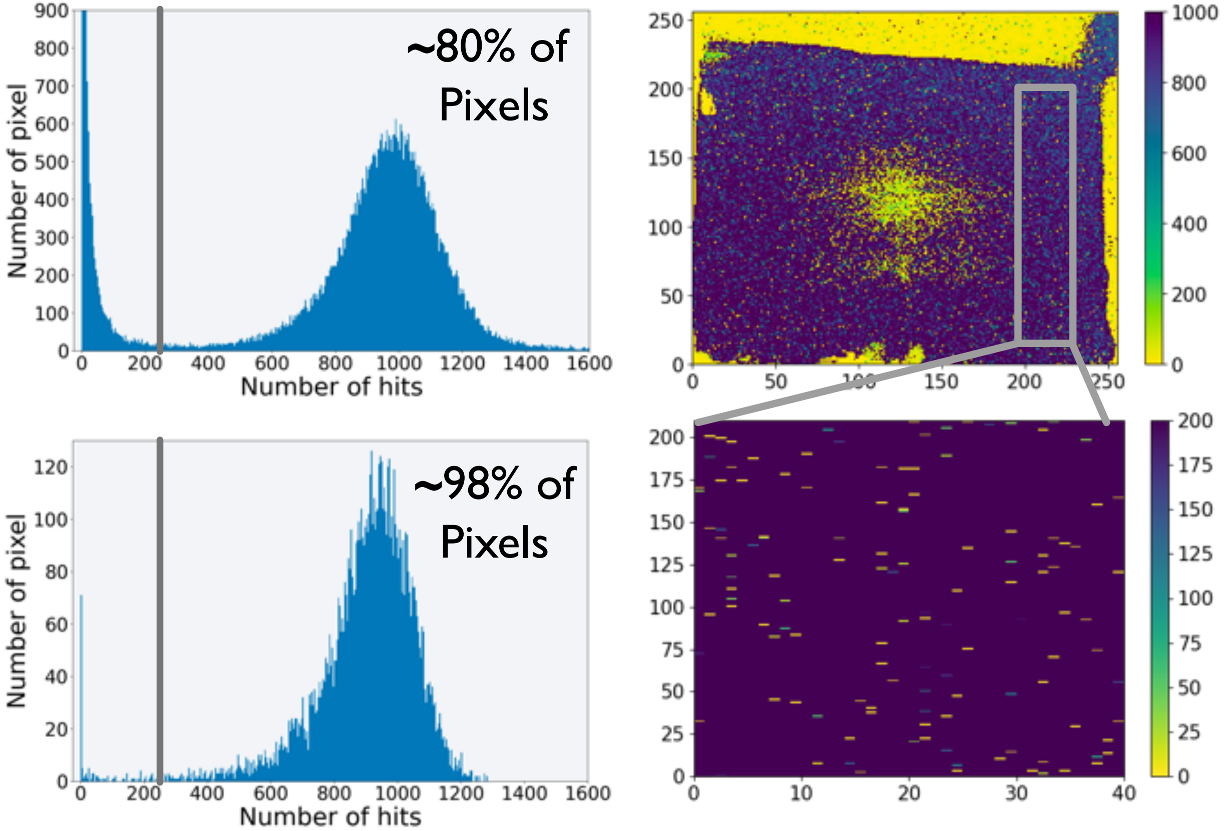

by Janis Schmidt

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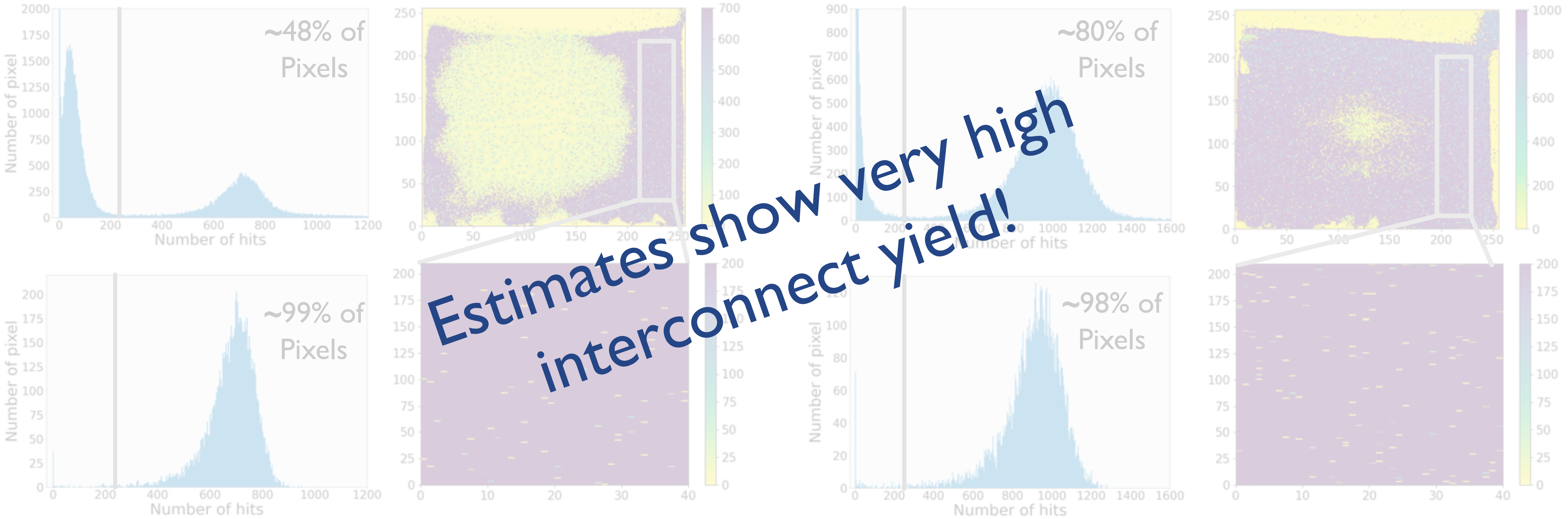


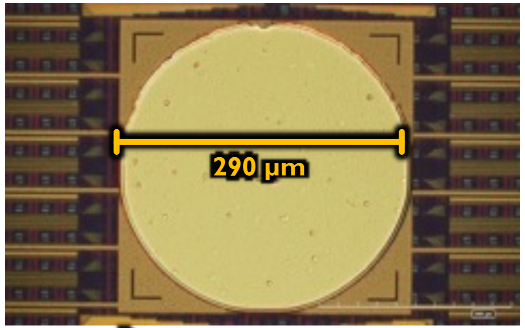
Estimates show very high interconnect yield!

by Janis Schmidt

DETECTOR MODULE INTEGRATION

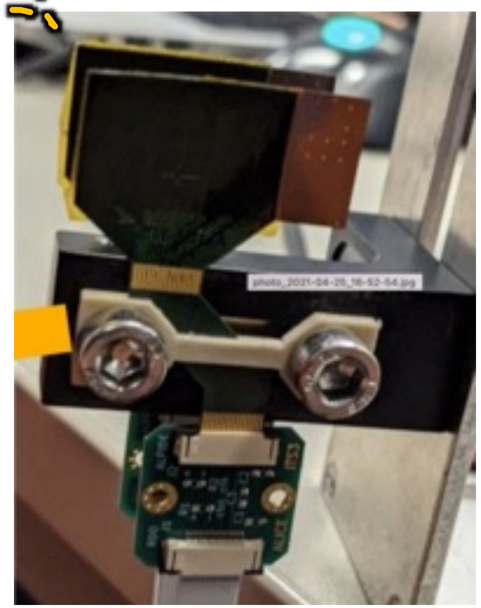
- ACF for connection of hybrid / monolithic detectors and PCB / flex
  - Alternative to wire-bonding – robust connection
  - Simpler compared to full pixel matrix bonding
    - Smaller amount of much larger pads
    - Lower bonding force required
- Monolithic pixel detectors MALTA and ALPIDE
  - MALTA – bridge connecting IO in multi-chip modules
  - ALPIDE – detector connection to flexible printed circuit

ALPIDE interface pad with ENIG

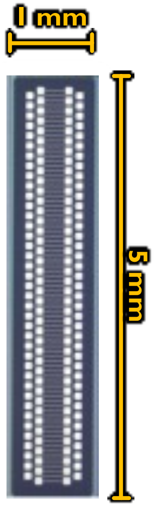


ALPIDE flexible printed circuit

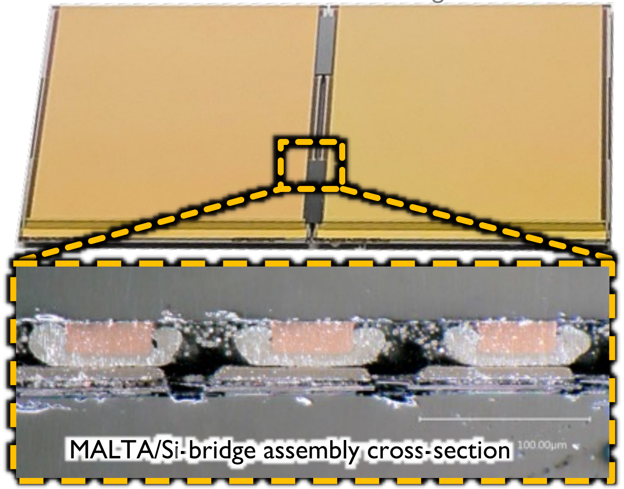
ALPIDE ACF module in DESY TB



Si-bridge



Double MALTA with two Si-bridges ACF bonded



Julian Weick ,
Florian Dachs,
Magnus Mager

CONCLUSIONS

- **Small pitch bump bonding**
  - Single die process developed for 25 µm pitch CLICpix2 hybrid assemblies
    - Very good efficiency results for 50 µm thick sensors
  - Laboratory and beam-test results show excellent yield of above 99.7 %

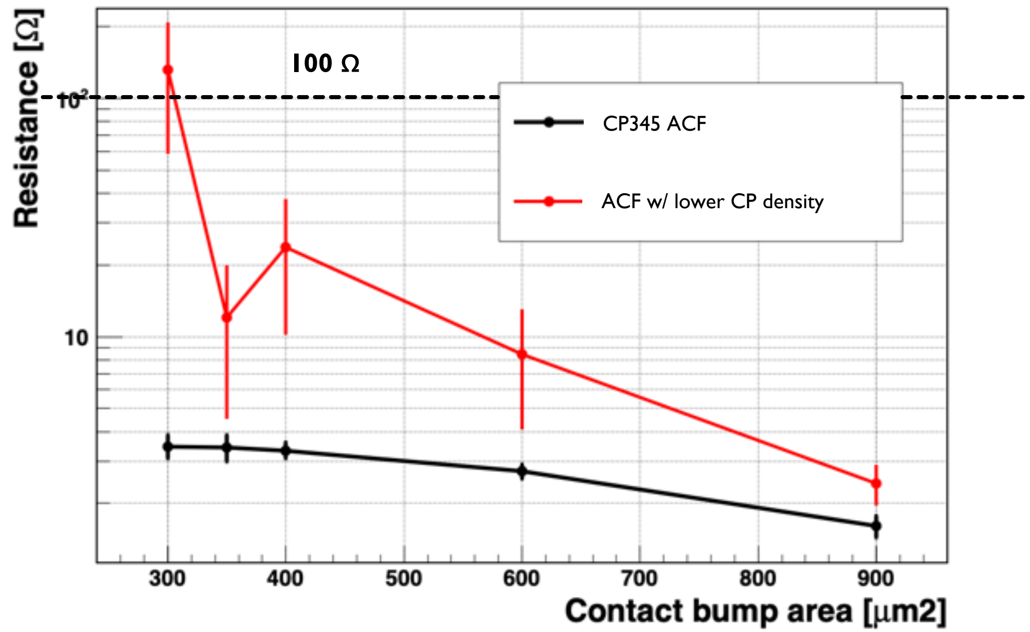
- **ACF interconnect**
  - In-house UBM plating and in-house ASIC-sensor connection
    - Extensive ENIG studies to achieve uniform metal growth
  - Good yield achievable for 55 µm pitch, better control of ENIG required

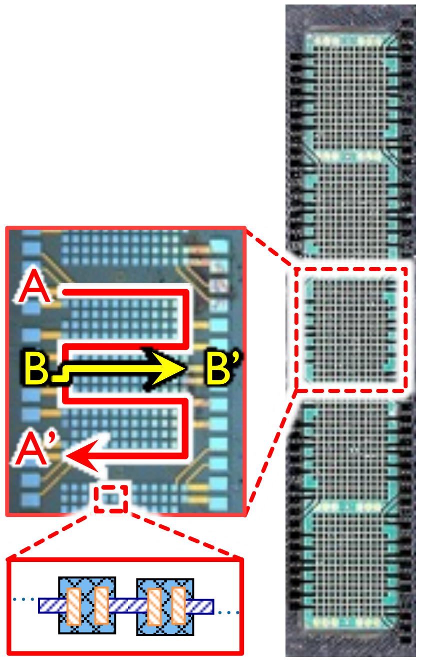
  - Ongoing improvements of the bonding parameters and ACF materials
  - ACF can be also used for module integration

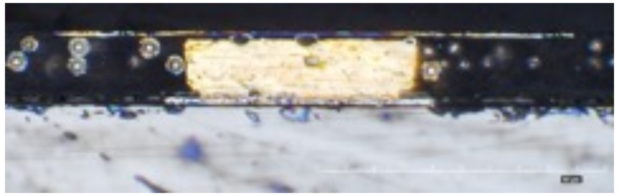
BACKUP

ACF BONDING – RESISTANCE MEASUREMENT

- Test structure with 5 matrices of pads with different sizes
  - Resistance scales with the (pixel) **pad size** and film **particle count**
  - Acceptable resistance in hybrid pixel detectors is **≲ 100 Ω**







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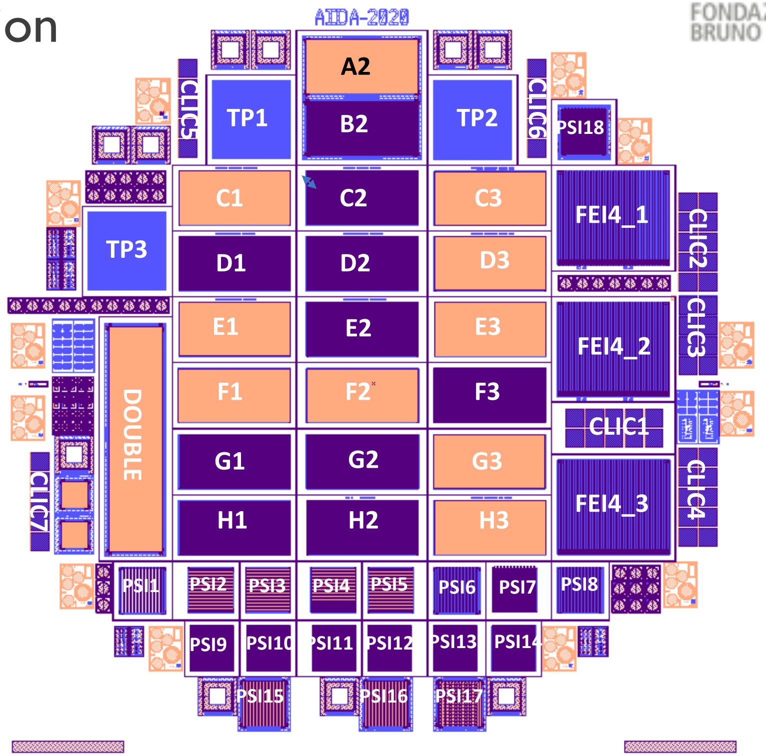
PREPARATION – SENSORS/ASICS

- Available sensors from FBK AIDA-2020 MPW active-edge production
- 6" wafers of different thickness
  - 50µm, 100µm, 130µm
  - Remaining sensors at IZM (not diced due to complex layout)
- Sufficient quantities of ASICs and sensors for testing
  - From 25µm to 55µm pitch
  - Tens of dummy as well as grade A
- Devices available both with **existing UBM** as well as **bare aluminium pads**



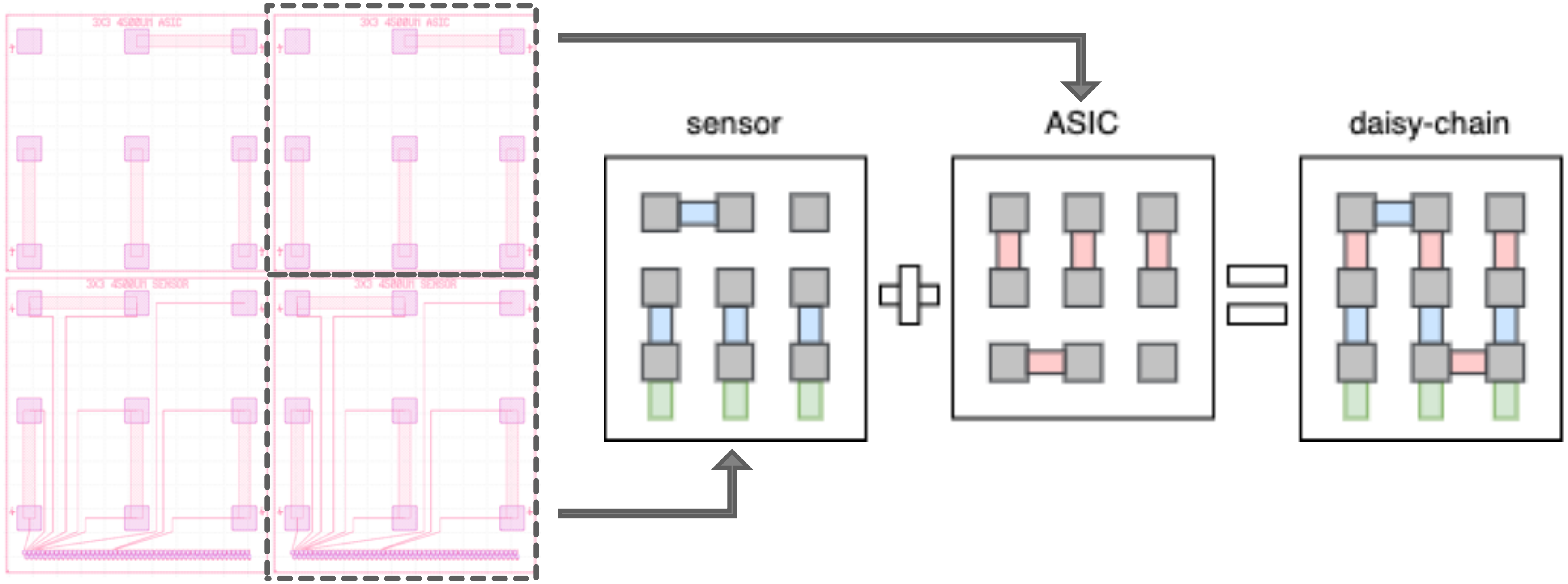
PREPARATION – DAISY-CHAIN DEVICES

- Need to validate interconnect yield, electrical resistance, thermo-mechanical stress

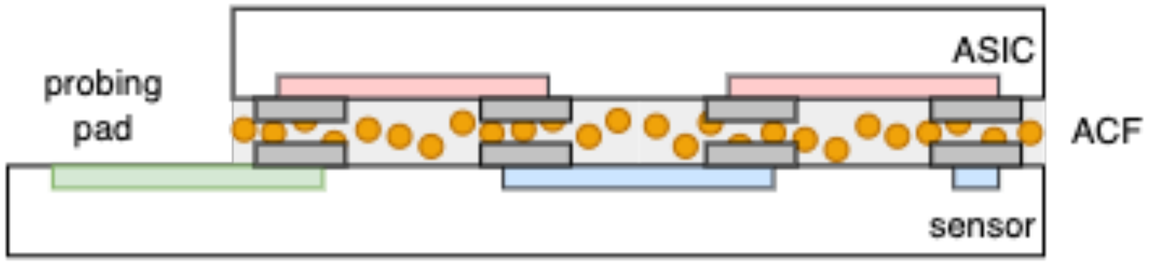
Design by Matteo Centis Vignali (FBK)

Top view:

3x3, pitch 4500um, diceable



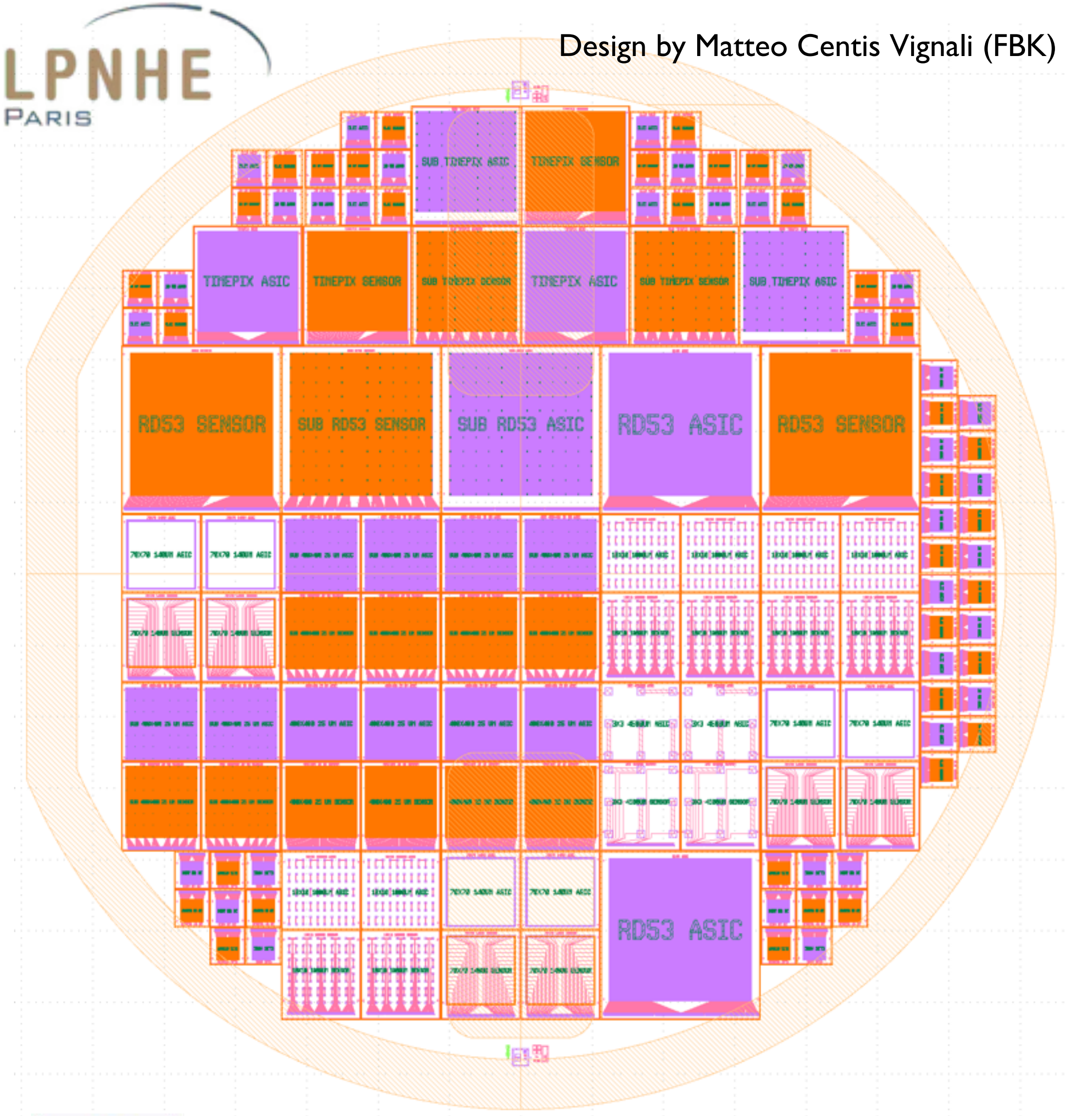
Side view:



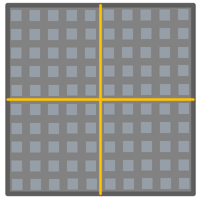
PREPARATION – DAISY-CHAIN DEVICES

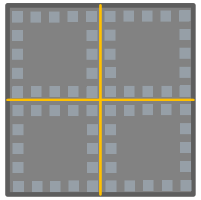
- Design being produced at FBK
  - 6” glass wafers, up to 650µm thick
  - Increased metal thickness (2 µm instead of standard 1 µm) and standard passivation thickness to better match topology of typical sensor/ASIC pairs
- Delivery expected in the following months
  - 70-150 probing pads based on the device
  - About 8 wafers in total

Design by Matteo Centis Vignali (FBK)



	pitch	size in mm	connections	per wafer	type	diceable
160x160 20um	20 um	3.2 x 3.2	25600	36	grid	no
CLICpix2	25 um	3.2 x 3.2	16384	34	grid	no
400x400 25um	25 um	20 x 20	640000	5	grid	yes
Timepix3	55 um	14 x 14	65536	4	grid	no
Timepix3 islands	55 um	14 x 14	65536	4	grid	no
RD53	50 um	20 x 20	160000	4	grid	no
RD53 islands	50 um	20 x 20	160000	2	grid	no
70x70 140um	140 um	20 x 20	2112	3	peripheral	yes
10x10 1000um	1000 um	20 x 20	400	3	grid	yes
3x3 4500um	4500 um	20 x 20	36	1	grid	yes


grid

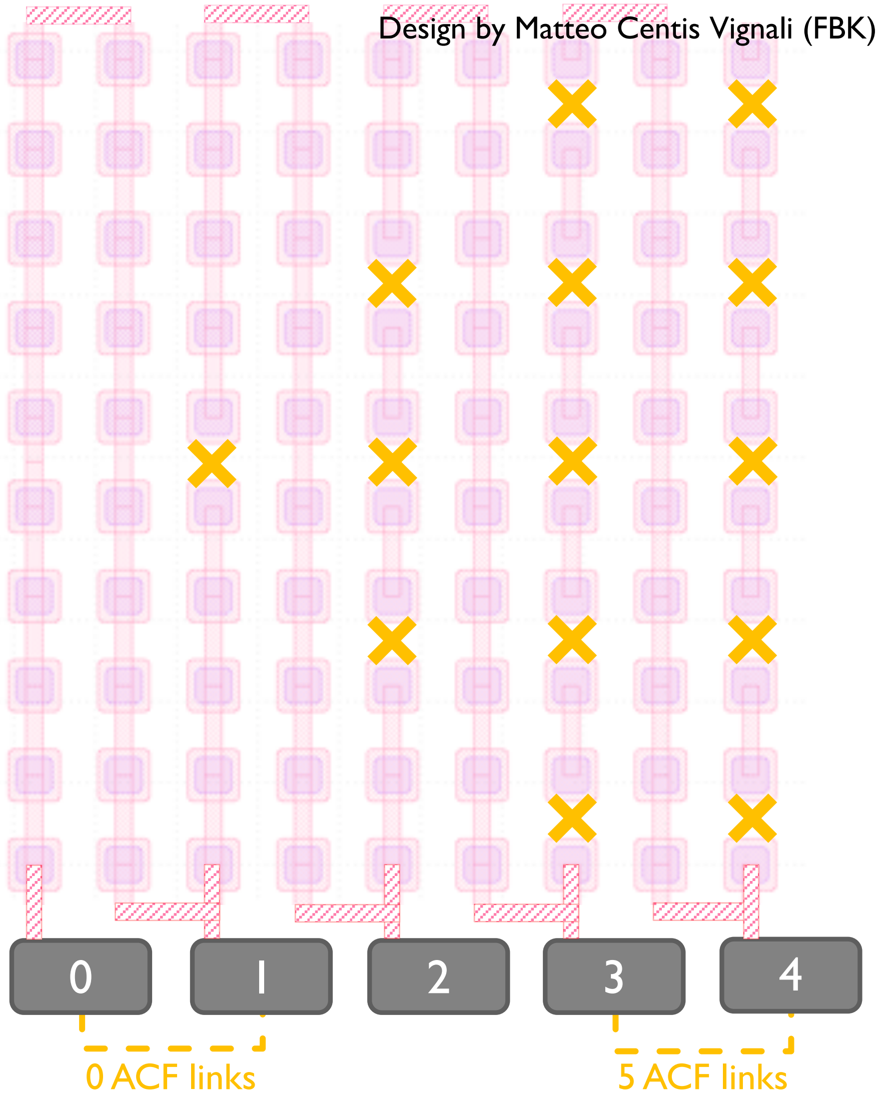

peripheral

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA no 101004761.

PREPARATION – DAISY-CHAIN DEVICES

- Plan to use devices to optimise and investigate the yield
  - The test devices match the topology of the real ASICs
  - Single missing connection in the chain will prohibit measurement
  - Problems more prominent when many links are present between two probe points (two to four pixel columns between pads)
    - About 1% of all links is between two closest probe points
  - Devices designed with an increasing number of links from full metal lines (pads 0-1) to all connections (pads 3-4) in this example
    - Designed to be sensitive to a wide range of interconnect yields

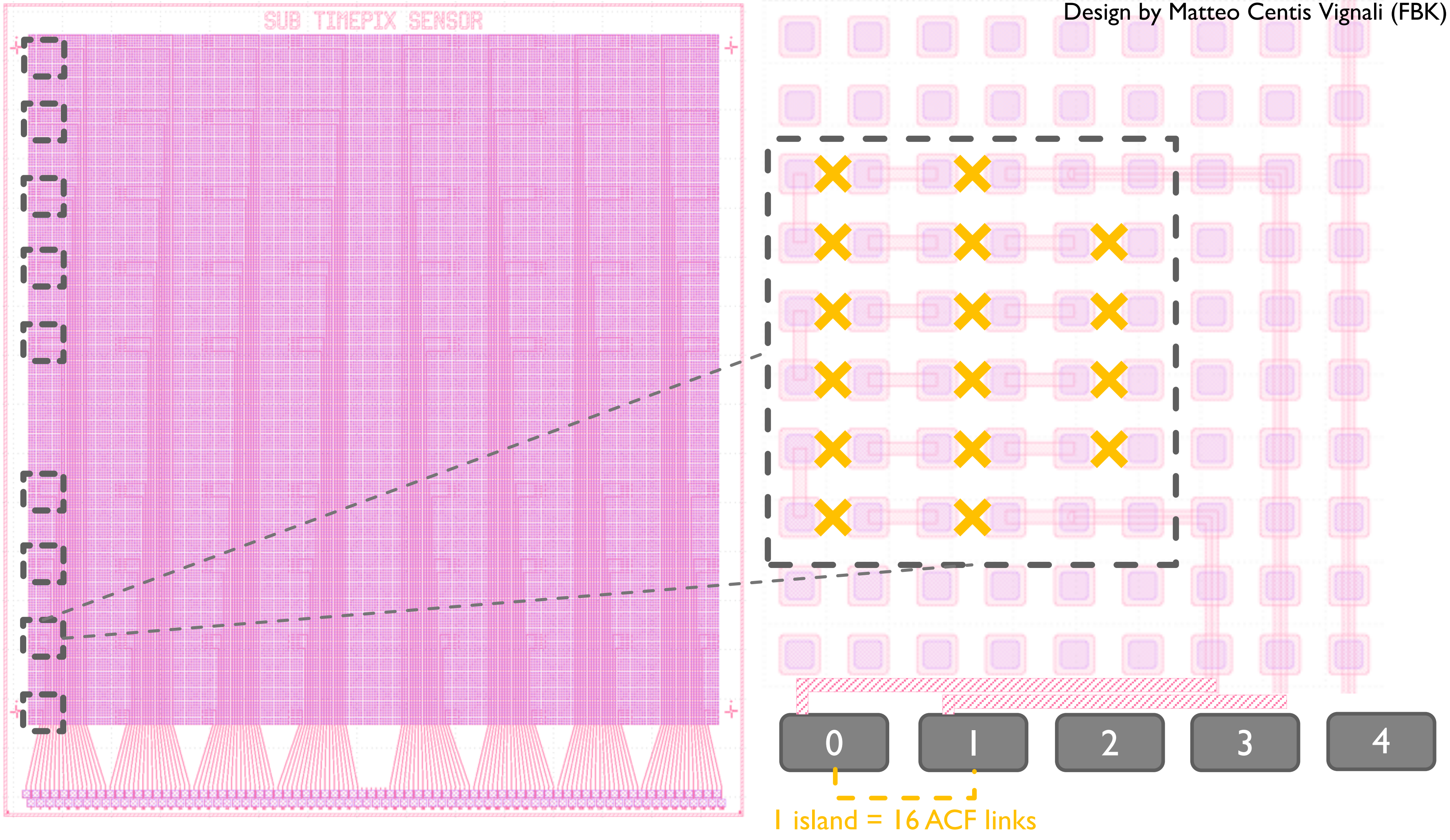
Design by Matteo Centis Vignali (FBK)



PREPARATION – DAISY-CHAIN DEVICES

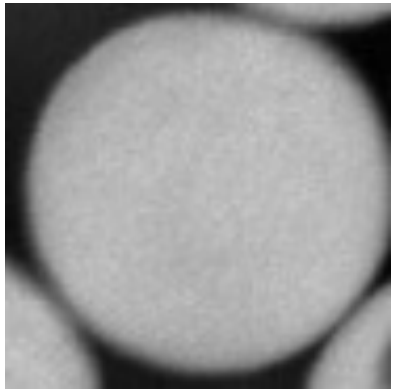
- Plan to use devices to optimise and investigate the yield
  - Different design to probe local yield across the whole device
  - 8 x 9 sub matrices (islands) of 16 connections each

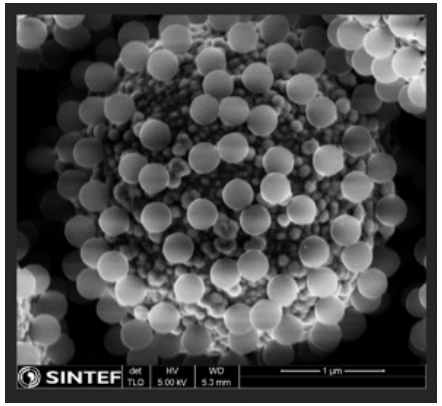
Design by Matteo Centis Vignali (FBK)

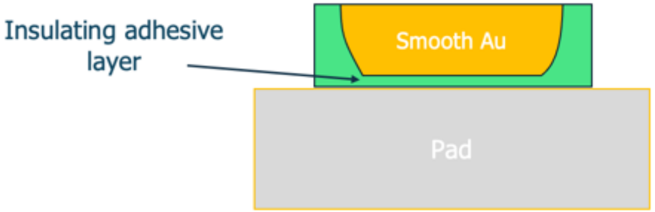


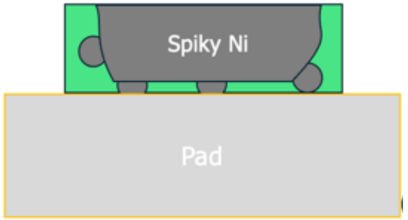
PREPARATION – CONDUCTIVE PARTICLES

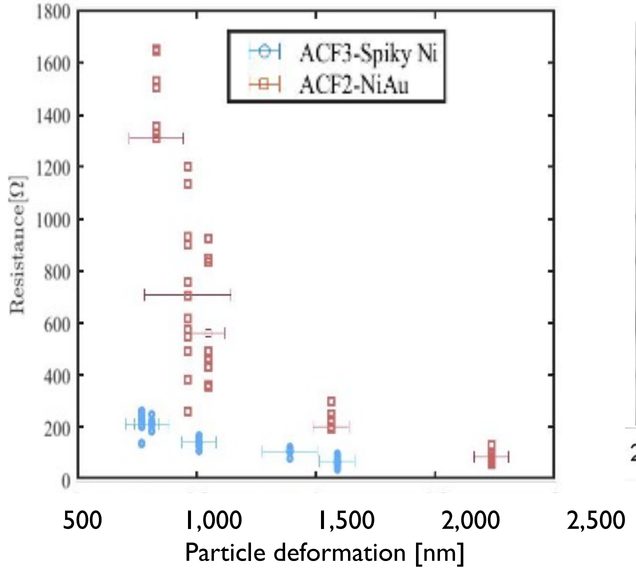
- Different variants available based on application
  - **Paste**: low viscosity, 10-30 μm particles
  - **Film**: high viscosity, 3 μm particles
- Contact resistance affected by residual adhesive
  - Comparison of "smooth" and "spiky" particles

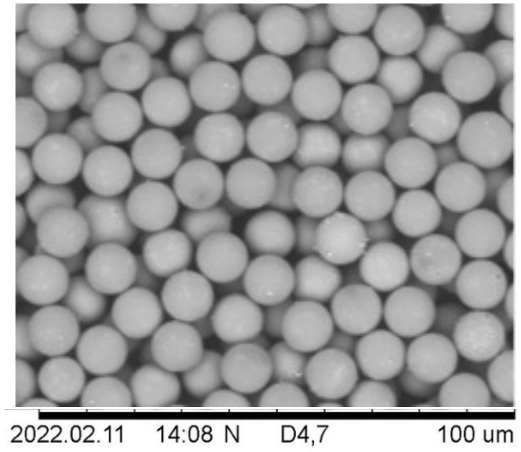












Resistance per particle	NiAu	Spiky Ni
Single particle test	2 -10 Ω	60-150 Ω
ACF bonding	300-900 Ω	100-140 Ω

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We connect.

Results from Conpart and other industry partners