Karlsruher Institut für Technologie

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

CERN

EP R&D

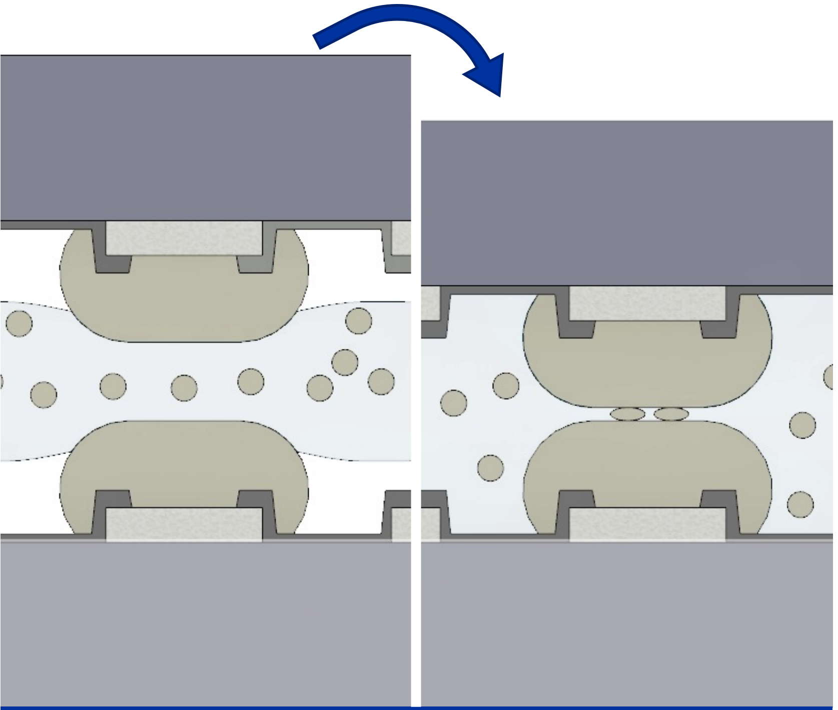
AIDA innova

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

Pixel Detector Hybridisation with Anisotropic Conductive Adhesives (ACA)

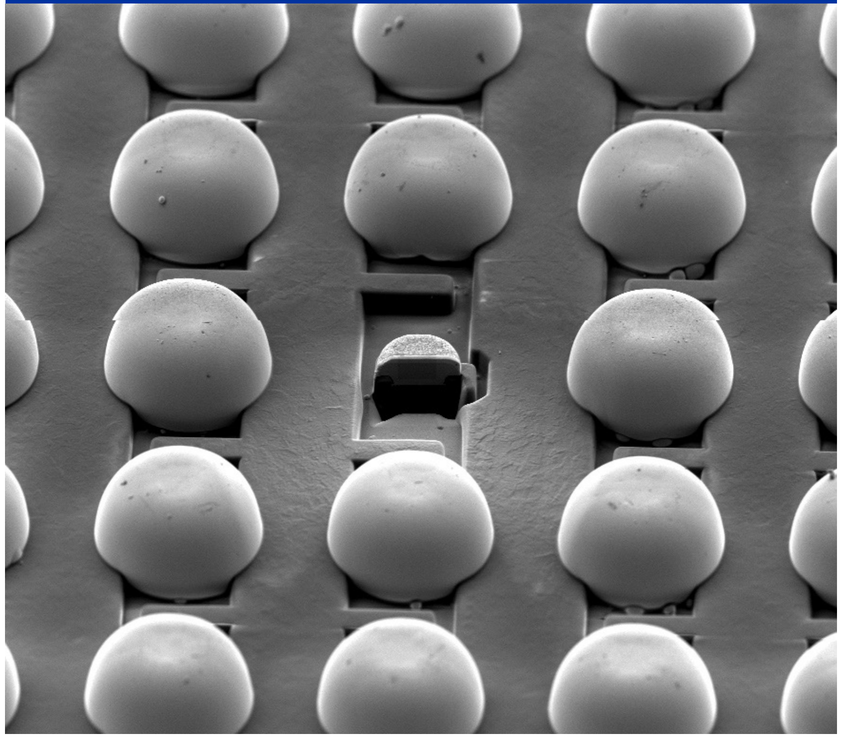
Dominik Dannheim, Rui De Oliveira, **Janis Viktor Schmidt,** Peter Svihra,
Mateus Vicente Barreto Pinto, Alexander Volker

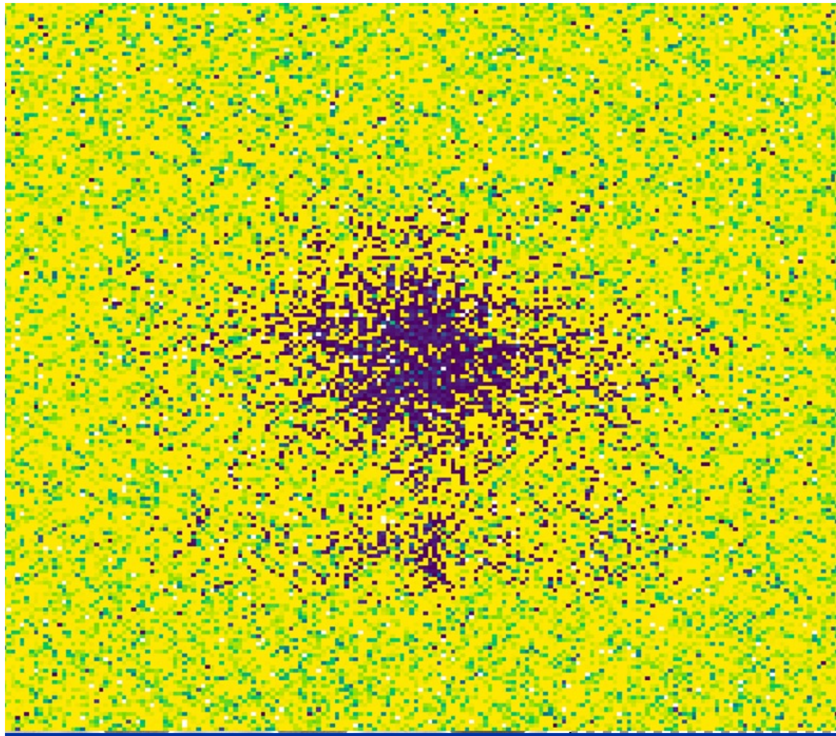
Outline



Bonding with
Anisotropic Conductive Adhesives
(ACA)

Electroless Nickel
Immersion Gold
plating (ENIG)



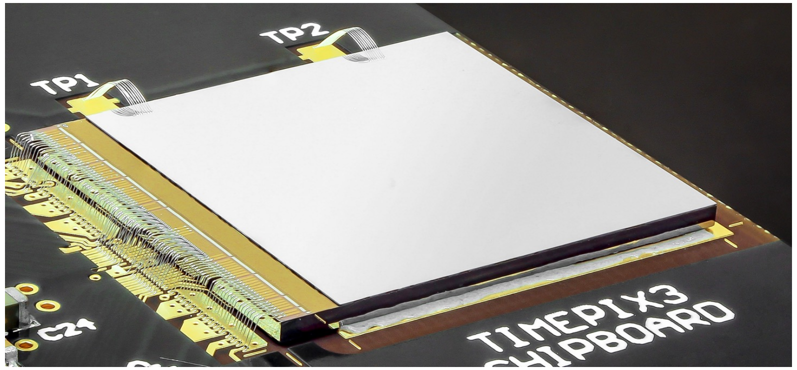


Results

Motivation

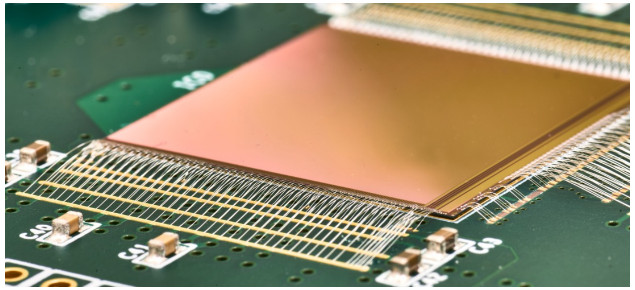
- Development of new interconnect process
  - Affordable option for prototyping
  - Difficult to obtain single-die hybridisation externally
- Maskless in-house post-processing and bonding
  - Single-die processing
  - Short turnaround time
- Wide range of applications
  - Hybridisation (tested with Timepix3, SPHIRD with 55-50 µm pitch)
  - Module integration (tested with MALTA with ~30 micron pad distance)
  - 100µPET, XIDER, PicoPix, Timespot

Timepix3



CLICpix2

MALTA



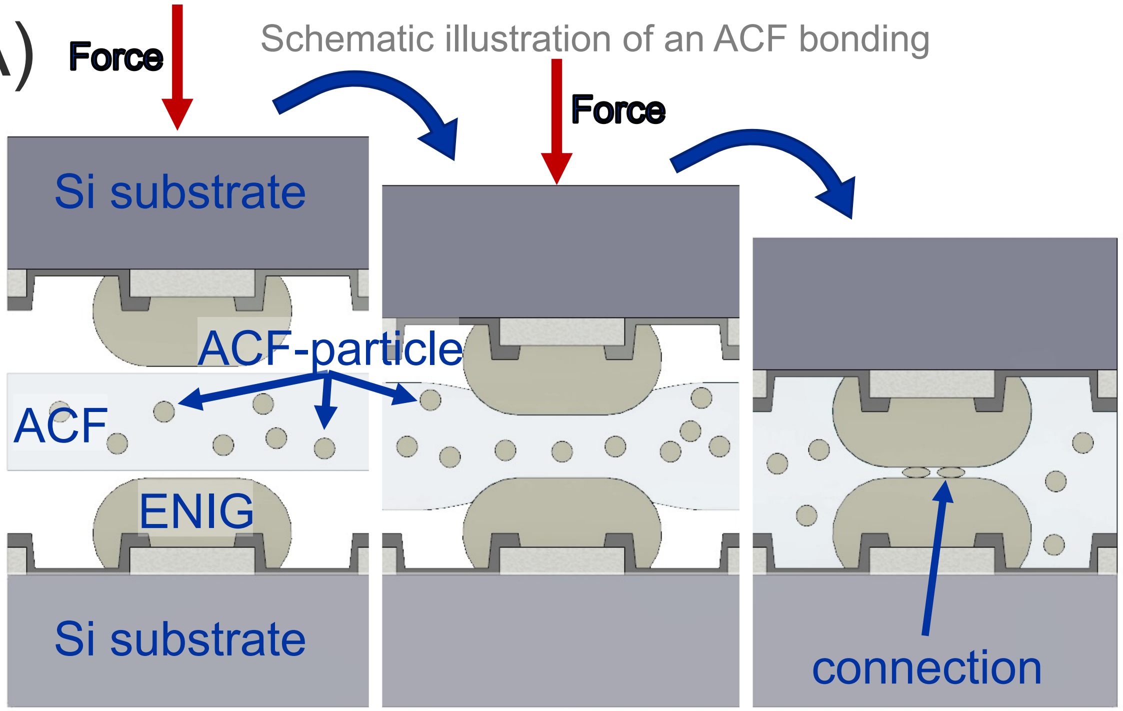
Introduction

- Anisotropic Conductive Adhesive (ACA)
  - Anisotropic Conductive Film or Paste (ACF, ACP)
  - Embedded conductive particles in epoxy
  - ACFs are widely used for display production

  → Transfer to small pitch of hybrid pixel detectors

- Thermocompression bonding process
  - Anisotropic/Vertical electrical connection via compressed conductive particles
  - Permanent mechanical bonding via cured epoxy film

Schematic illustration of an ACF bonding

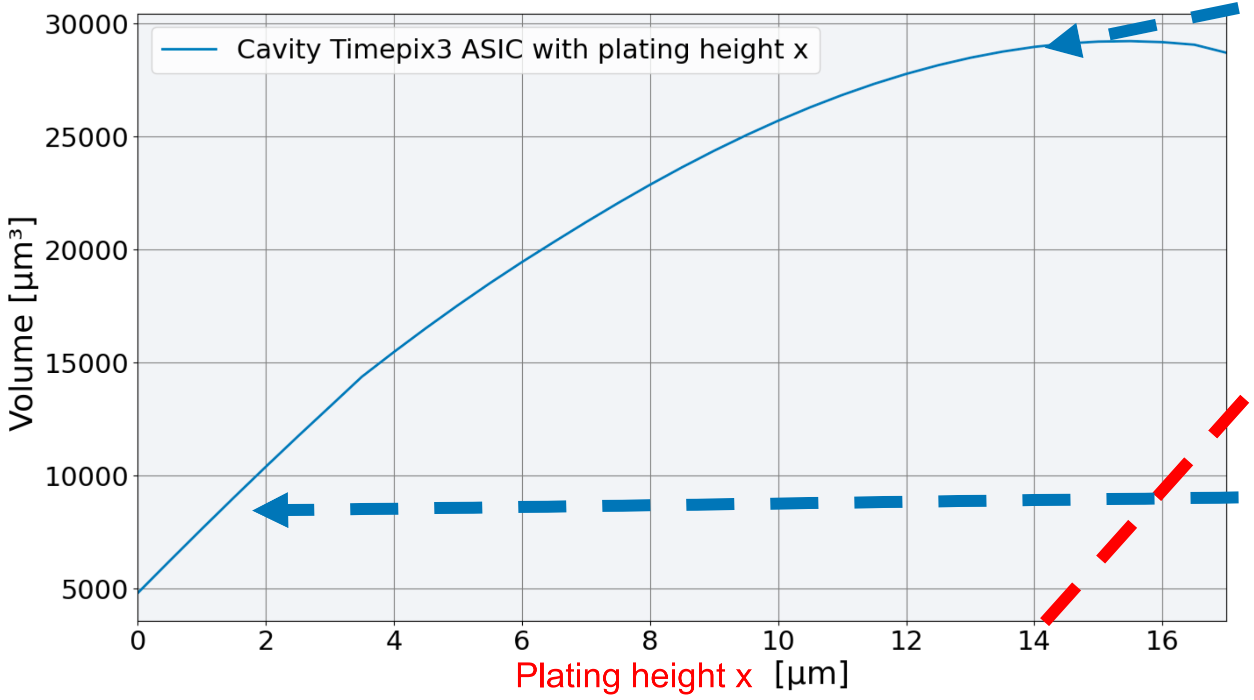


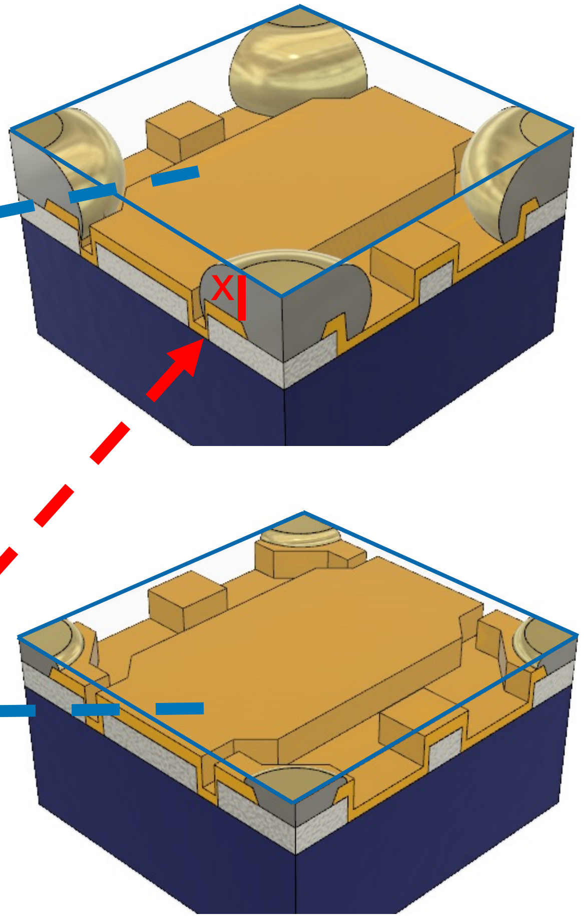
ENIG plating – need for increased height

Need for sufficiently large cavity volume between sensor and ASIC after bonding to fit excess adhesive

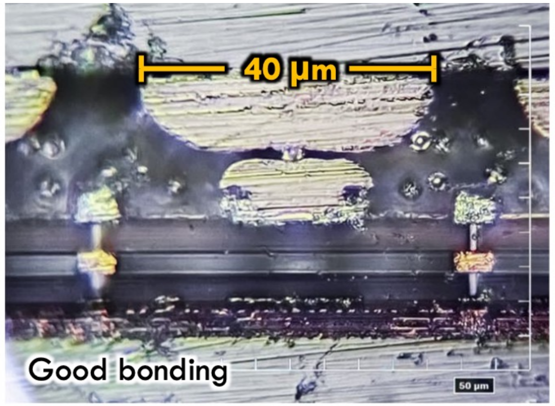
- **Volume** directly related to **plating height x**
- Developed approximate model for calculation

ASIC cavity volume based on plating height

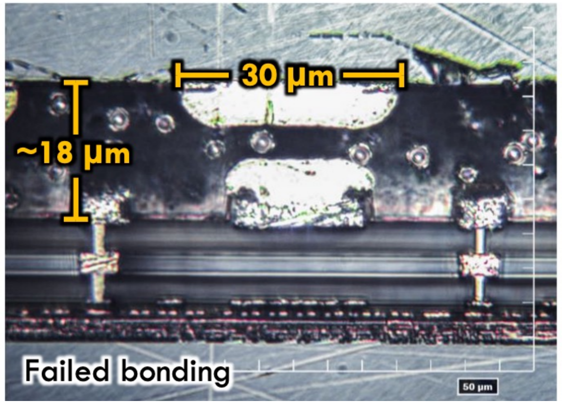




Timepix3 assembly larger pads



Timepix3 assembly smaller pads



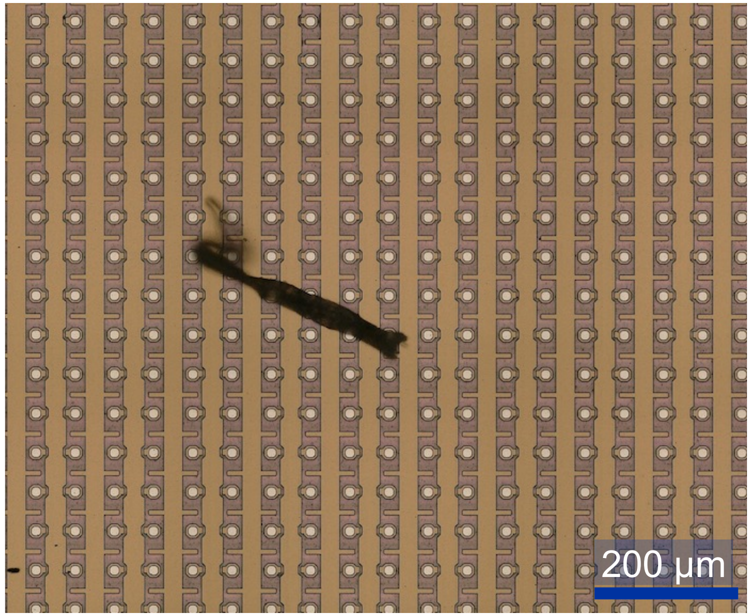
Process workflow

Preparation → ENIG plating → Bonding → Testing

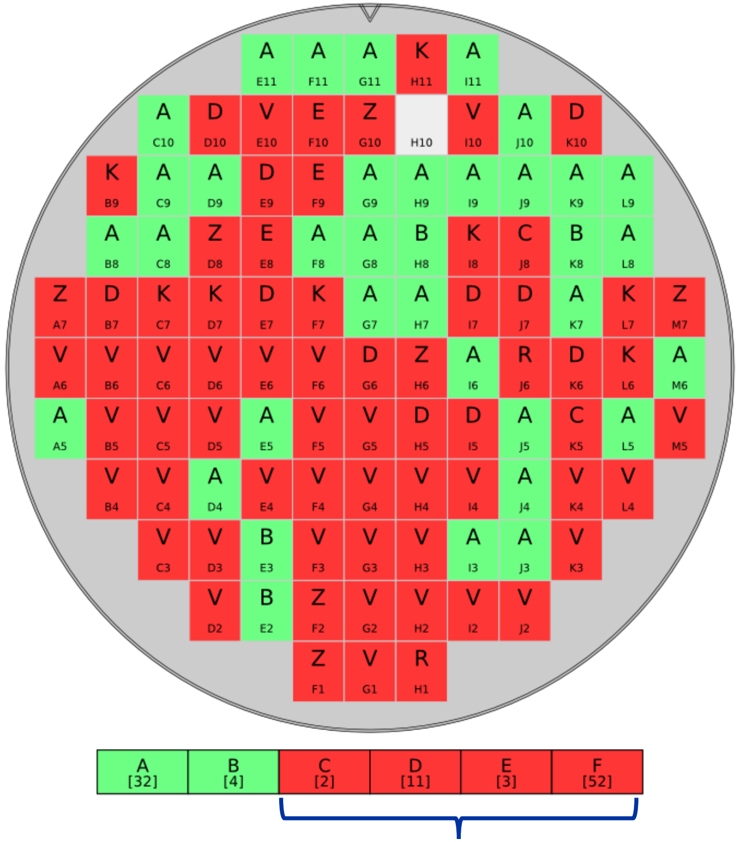
Preparation

- Electrical testing
- Visual inspection
  - Scratches
  - Contamination
- Cleaning
  - Ultrasonic bath (if needed)
  - Plasma cleaning (Ar/O_2) and reduction (Ar/H_2)

Particle contamination on Timepix3 ASIC



Waver overview after electrical testing



Dummies for process development

Preparation → ENIG plating → Bonding → Testing

Process workflow

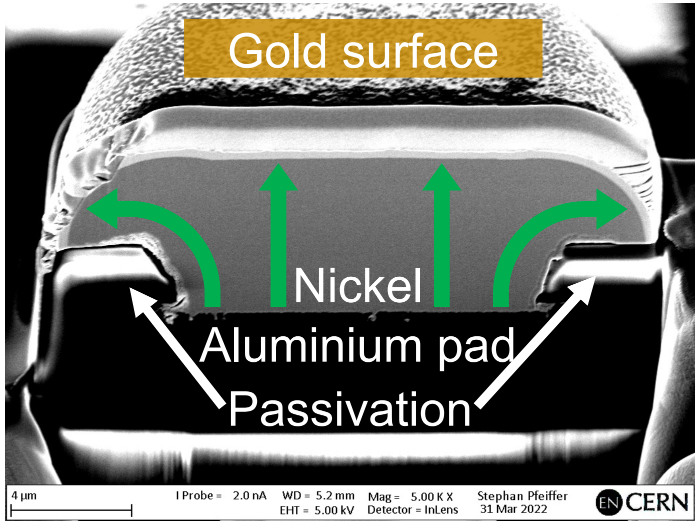
Preparation | **ENIG plating** | Bonding | Testing

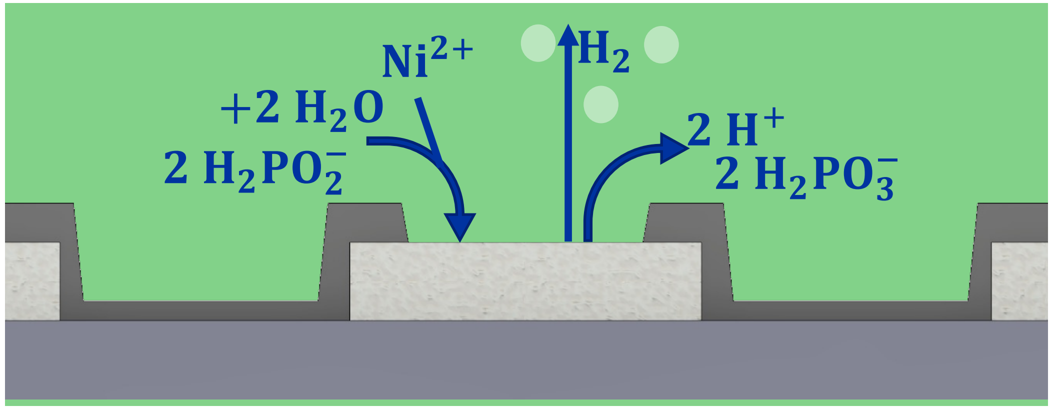
Electroless Nickel

- Reaction on catalytic surface
- Initiation of reaction on pad
- Nickel layer also catalytic surface

→ Self catalytic reaction

  - Pad heigh is time controlled
  - Continues until removal of sample





$$2\ H_2PO_2^-\ +\ Ni^2 +\ +2\ H_2O\ \rightarrow\ 2\ H_2PO_3^-\ +\ H_2\ +\ 2\ H^+\ +\ Ni_0$$

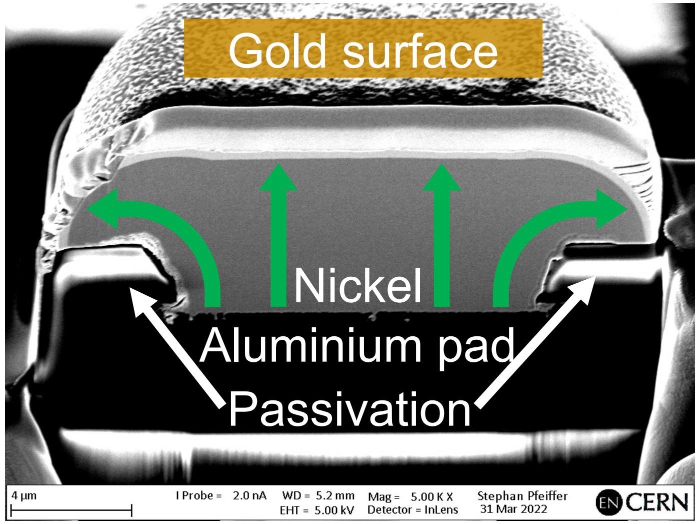
Preparation | **ENIG plating** | Bonding | Testing

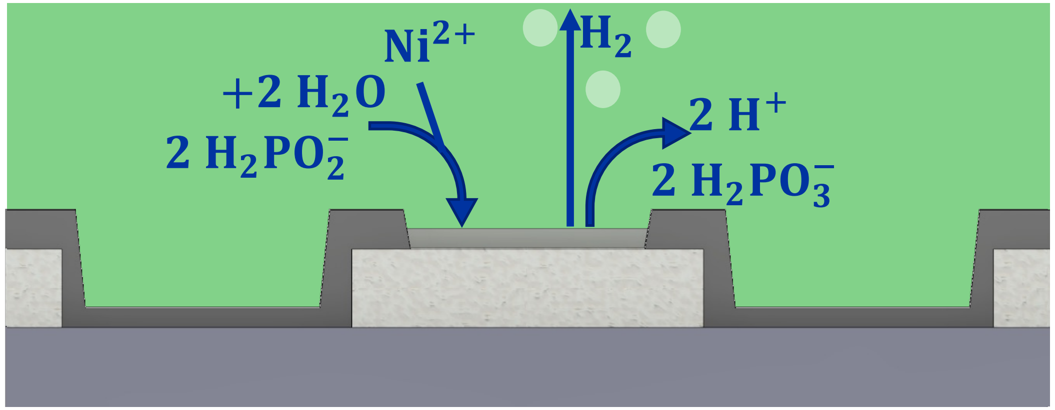
Electroless Nickel

- Reaction on catalytic surface
- Initiation of reaction on pad
- Nickel layer also catalytic surface

→ Self catalytic reaction

- Pad heigh is time controlled
- Continues until removal of sample





$$2\ H_2PO_2^- + Ni^2 + + 2\ H_2O \rightarrow 2\ H_2PO_3^- + H_2 + 2\ H^+ + Ni_0$$

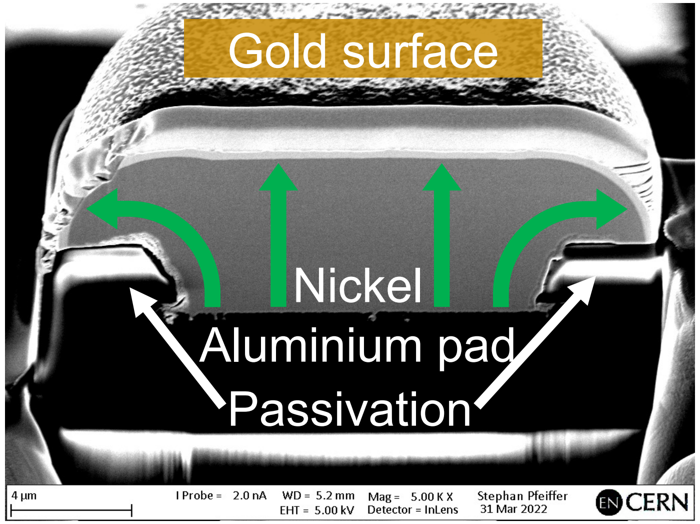
Preparation | **ENIG plating** | Bonding | Testing

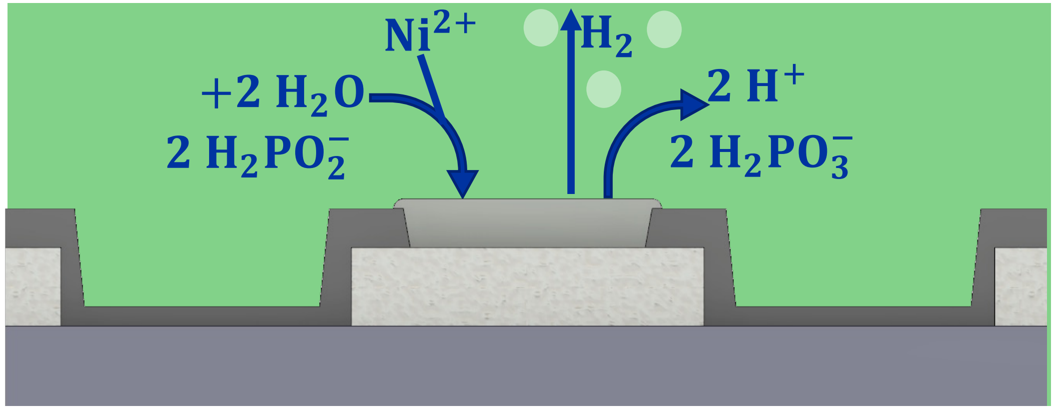
Electroless Nickel

- Reaction on catalytic surface
- Initiation of reaction on pad
- Nickel layer also catalytic surface

→ Self catalytic reaction

  - Pad heigh is time controlled
  - Continues until removal of sample



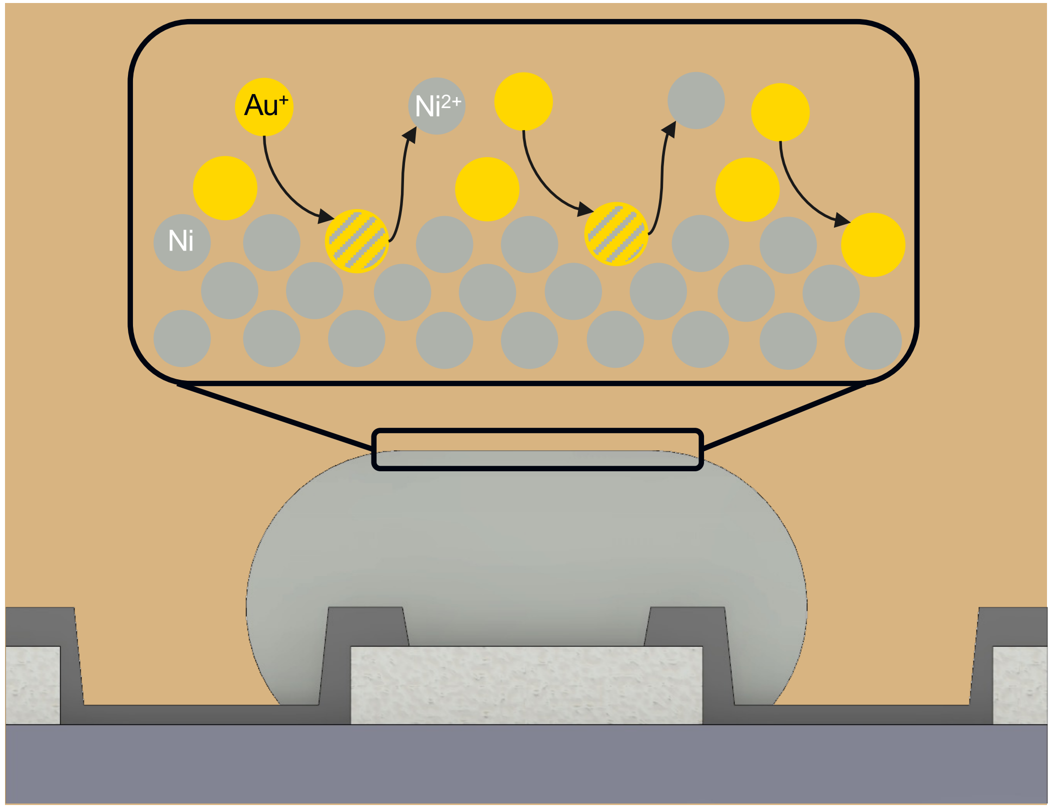


$$2\,H_2PO_2^- + Ni^2 + +2\,H_2O \rightarrow 2\,H_2PO_3^- + H_2 + 2\,H^+ + Ni_0$$

Preparation → **ENIG plating** → Bonding → Testing

Immersion Gold

- Electrochemical reaction
  - Replacing nickel atoms with gold atoms
- Corrosion protection
- Thickness of ~100 nm



$$Ni^0 + 2\,Au^+ \rightarrow Ni^{2+} + 2\,Au^0$$

Preparation | **ENIG plating** | Bonding | Testing

Challenges with ENIG

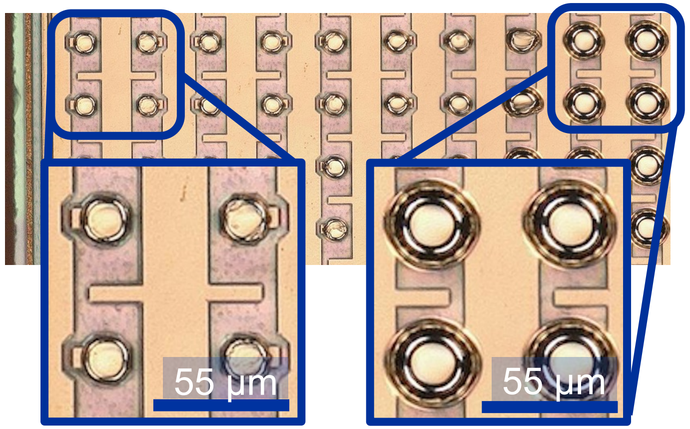
- Defective plating
  - Skip or step plating
  - Missing plating near edge

→Diffusion controlled catalyst poisoning

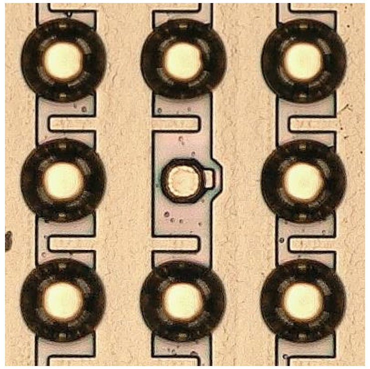
- Stabilizer and contamination are adsorbed on surface
- Termination of reaction at a certain surface concentration

Badly plated Timepix3

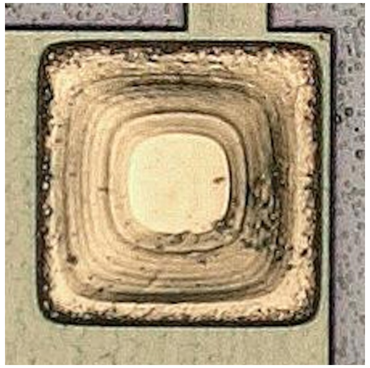
Missing plating at the edge

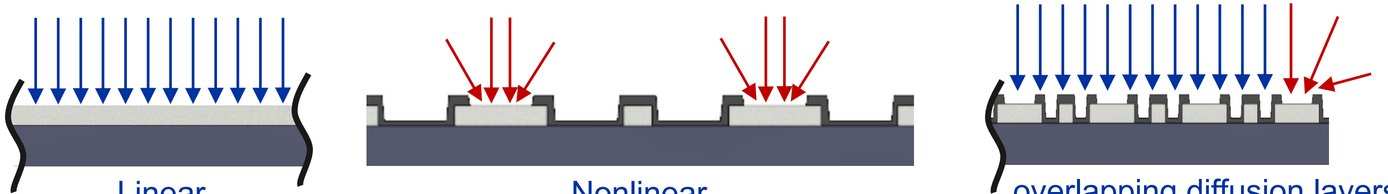


Skip plating



Step plating





Modified from S. Zhang et al 1999 J. Electrochem. Soc. 146 2870

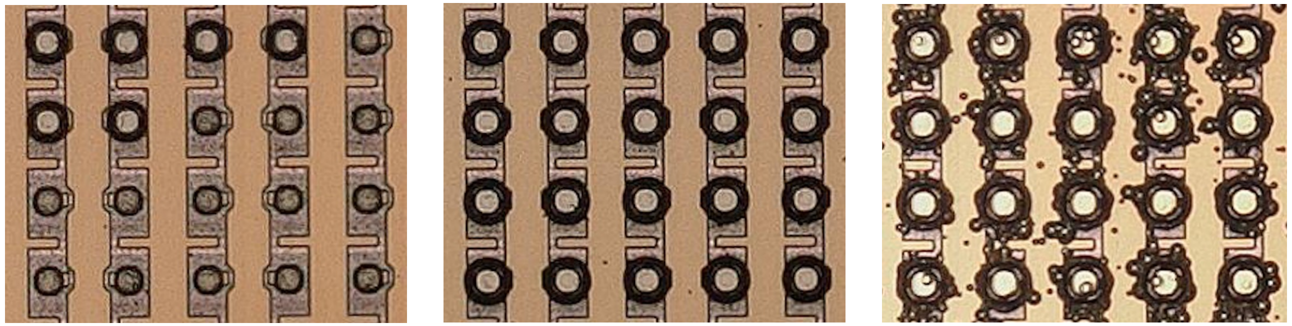
Preparation | **ENIG plating** | Bonding | Testing

Process development

- Optimised chemistry
  - Higher purity
  - produced in clean room
  - Adjustable stabiliser concentration
- Forced convection
  - Low stabilizer concentration (~0.1 ppm)
  - Reduces diffusion effect

→ Less edge effect

Missing plating | Good plating | “Overplating” plating



Plating of an individual pad

$$\frac{e^{8924/T}}{\delta\ Q} < \frac{1}{D\ c_{stab}} \frac{[H_2PO_2^-]}{[H^+]^{0.2}} < \frac{e^{12717/T}}{\delta\ Q^{op}}$$

Thickness of diffusion layer (δ)

Poisoning of pad surface (Q)

Diffusion constant (D)

Stabilizer concentration (c_{stab})

Poisoning of overplated nickel (Q^{op})

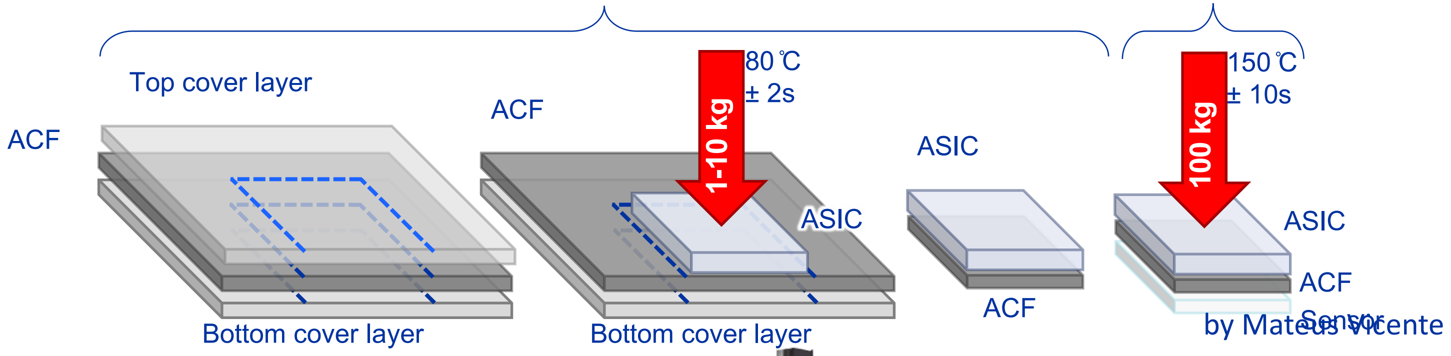
S. Siau et al. / Applied Surface Science 252 (2006) 2717–2740

Preparation → **ENIG plating** → Bonding → Testing

Process workflow

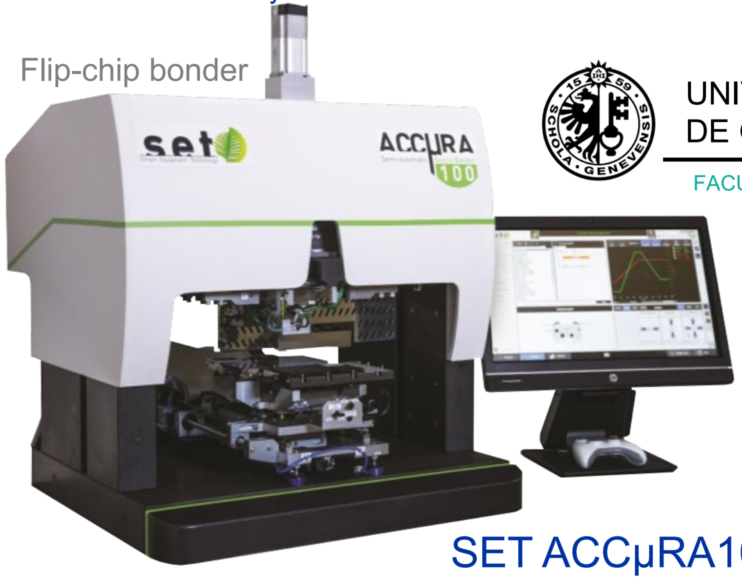
Preparation | ENIG plating | **Bonding** | Testing

ACF bonding



1. Lamination ACF on chip
2. Bonding
   - Displacement of epoxy
   - Compression of conductive particle (ideally 50%)
   - Curing of epoxy resin (<5 second at 150 °C)

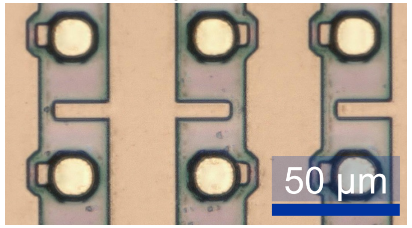
Flip-chip bonder



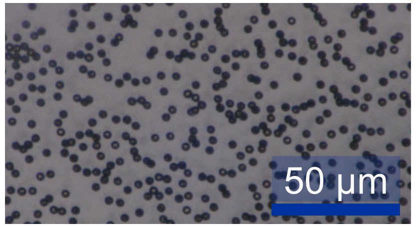
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

SET ACCμRA100

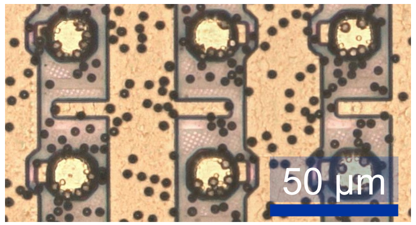
Timepix3 ASIC



ACF



ACF on Timepix3 ASIC



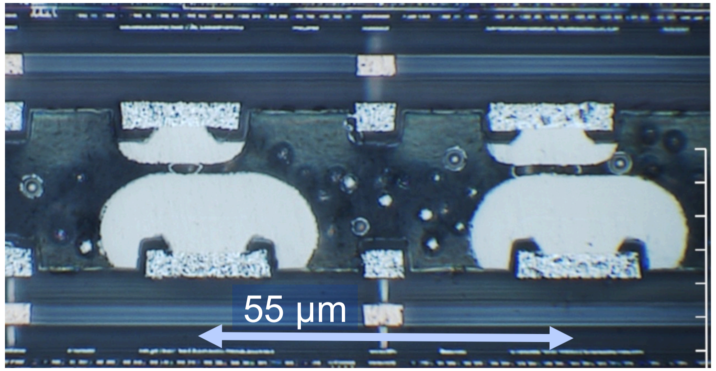
Preparation → ENIG plating → **Bonding** → Testing

Process workflow

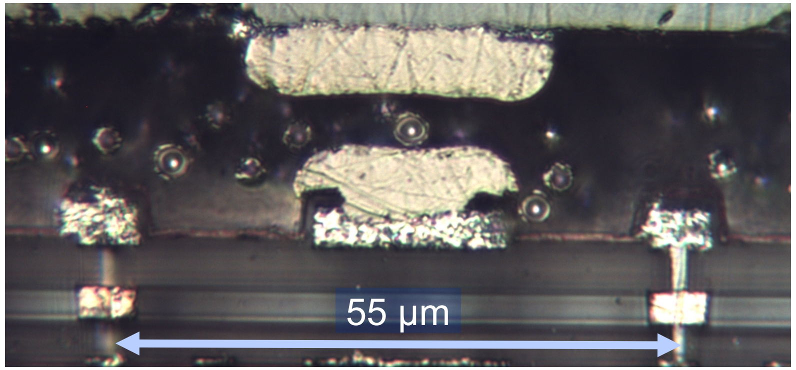
Preparation | ENIG plating | Bonding | **Testing**

Testing and evaluation

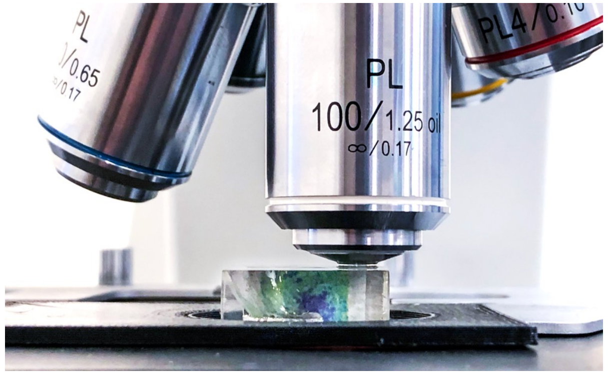
Cross-section Timepix3-Timepix3 ACF dummy sample



Cross-section Timepix3 ASCI-sensor ACF sample



- Cross-section
  - Pad distance
  - Alignment
- Source measurements in lab
- Test-beam measurements
- Further evaluation in future
  - Radiation hardness, electrical properties, mechanical strength…

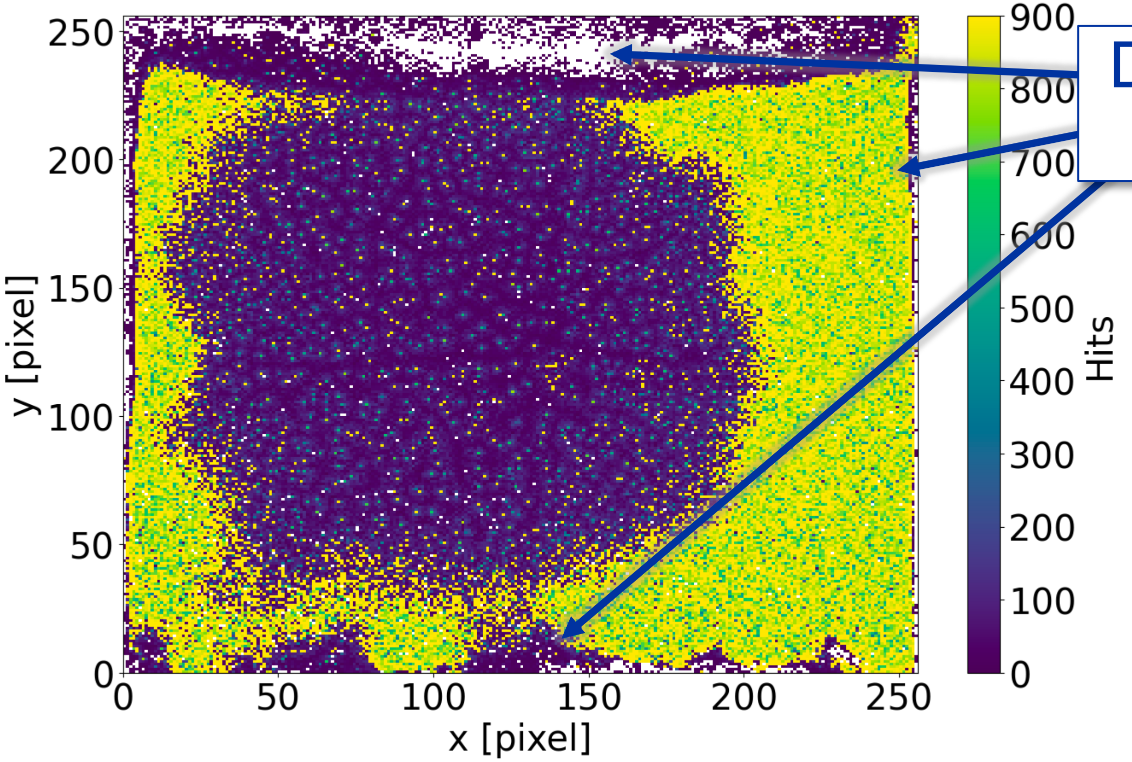


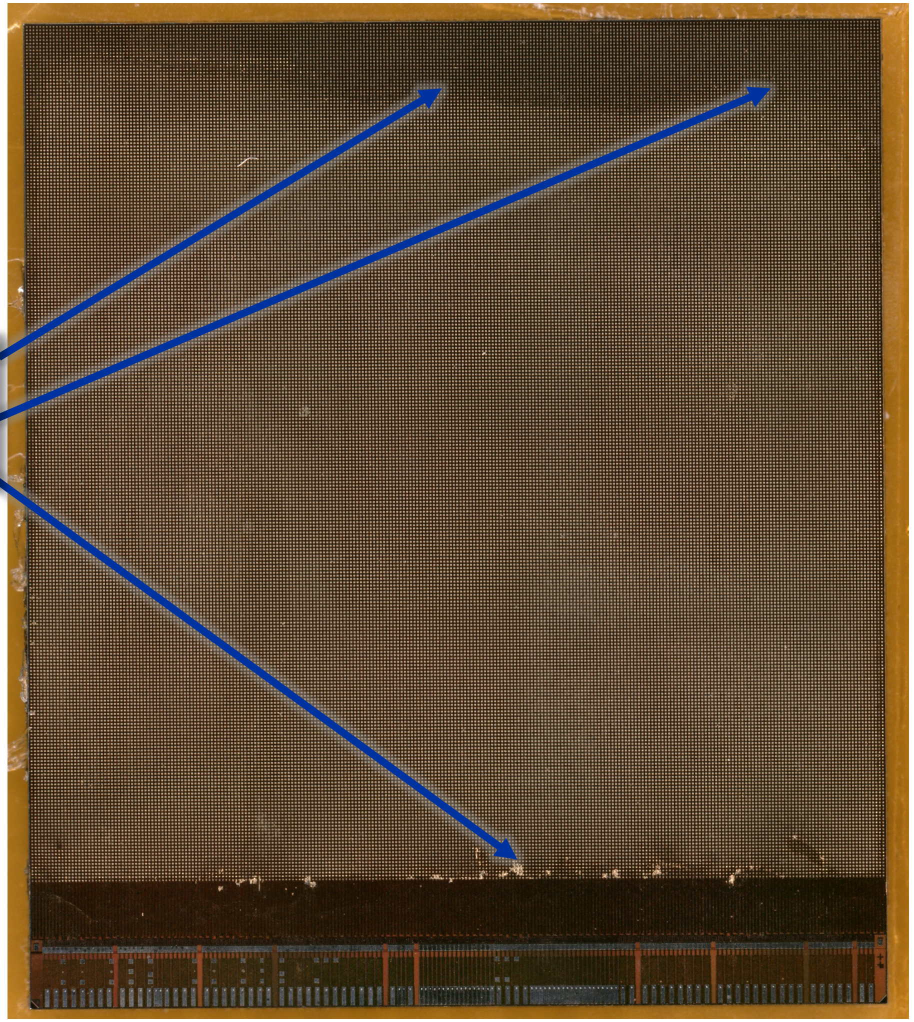
Preparation → ENIG plating → Bonding → **Testing**

Preliminary results with Timepix3

Sample 1:
100% coverage of 18 µm ACF

Hit-map from Sr^{90} illumination Timepix3

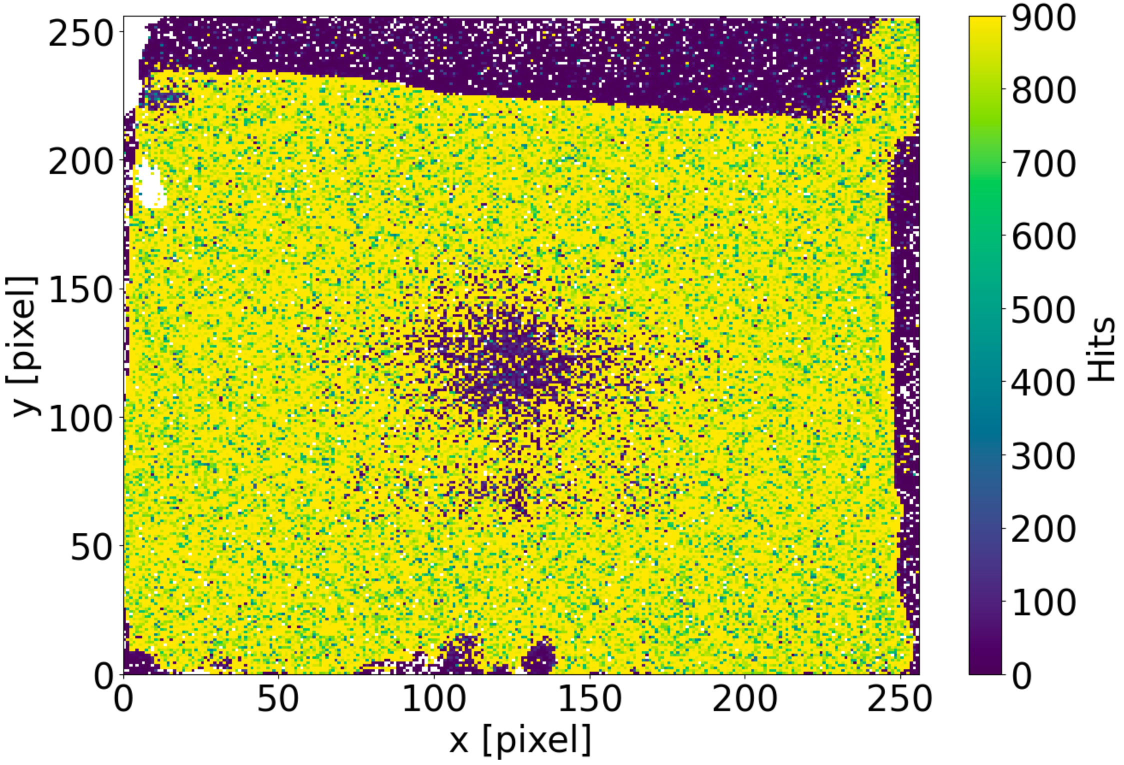




Preliminary results with Timepix3

Sample 2:
~90% coverage of 14 µm ACF

Hit-map from Sr^{90} illumination Timepix3



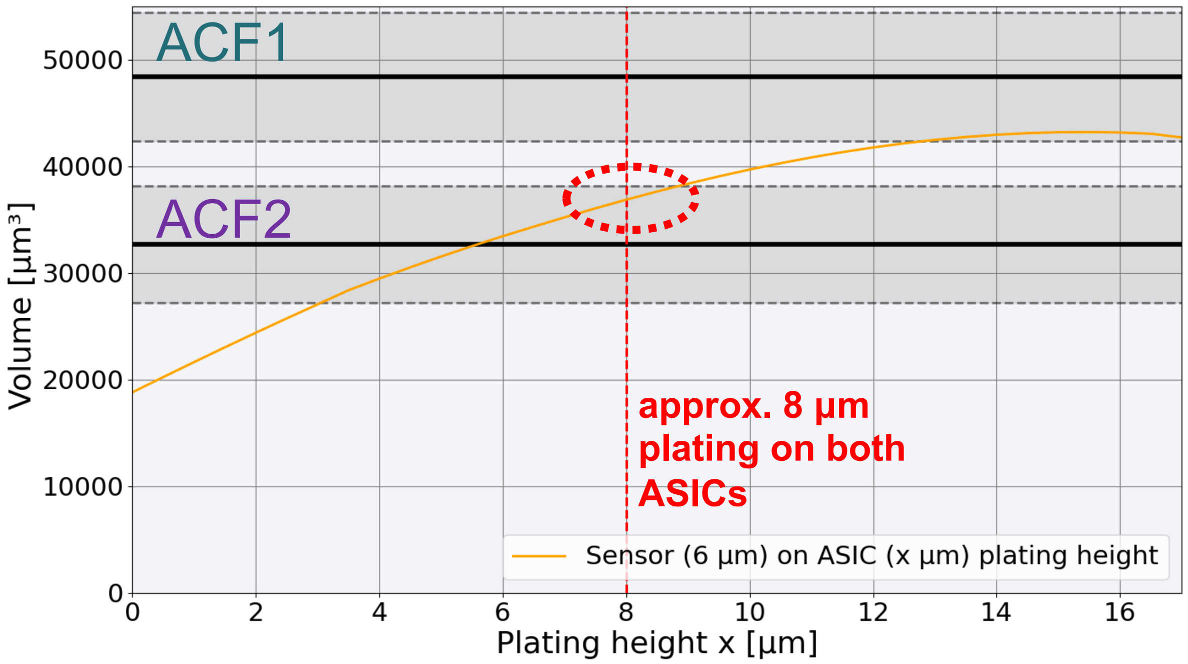
ACF coverage on Timepix3 ASIC

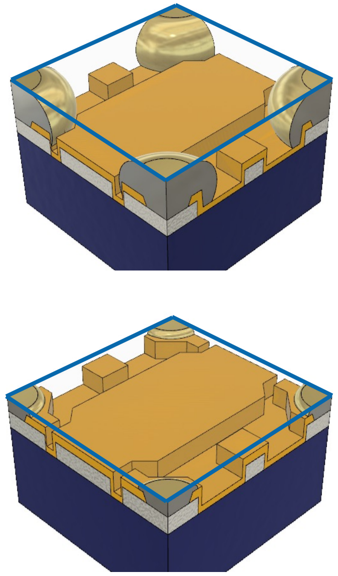
Preliminary results with Timepix3

Evaluation of plating height and different ACF materials using Sr^{90} exposure of electrical assemblies

	Part. diameter [µm]	Thickness [µm]	Part. density [pcs/mm²]	Bonding pressure [Mpa]	Sheet/reel
ACF 1	3	18	71k	30-80	sheet
ACF 2	3	14	60k	50-90	reel

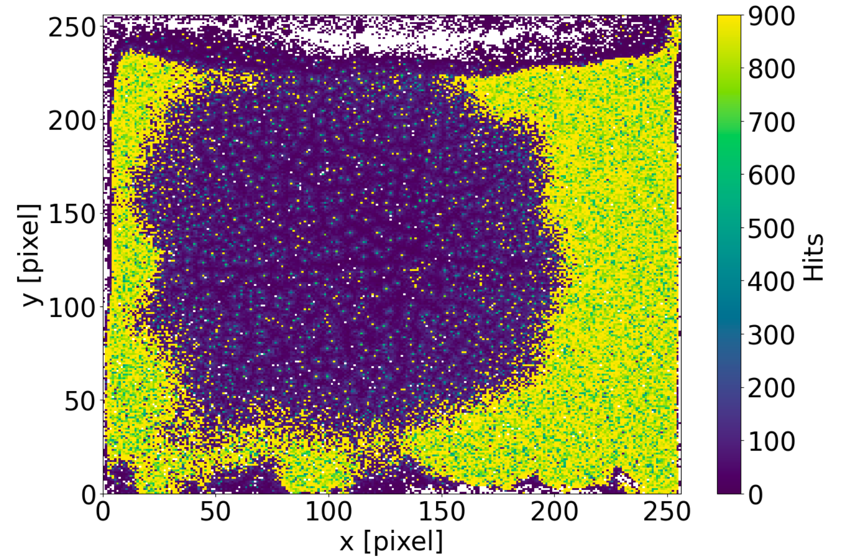
Cavity volume per pixel pad of Timepix3 ASICs as a function of plating height



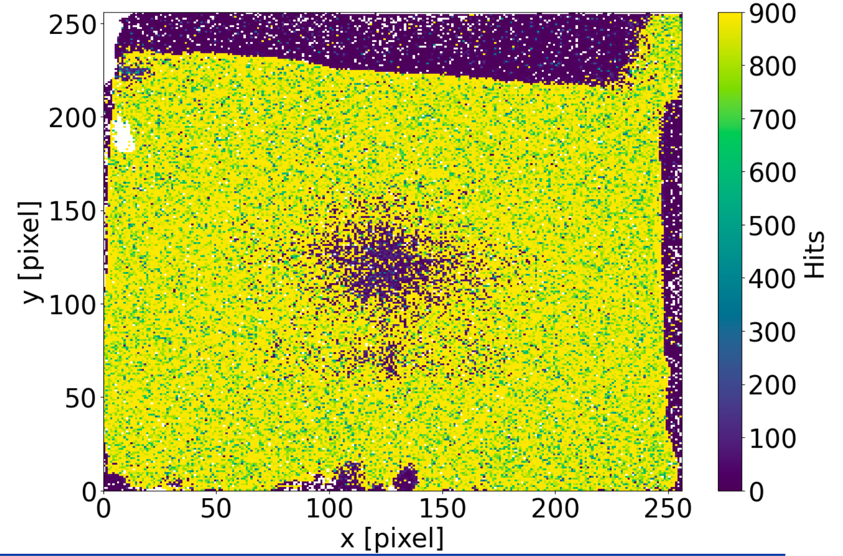


JINST 18 C01040 (2023)

Sample 1: 100% coverage of 18 µm ACF1



Sample 2: 90% coverage of 14 µm ACF2



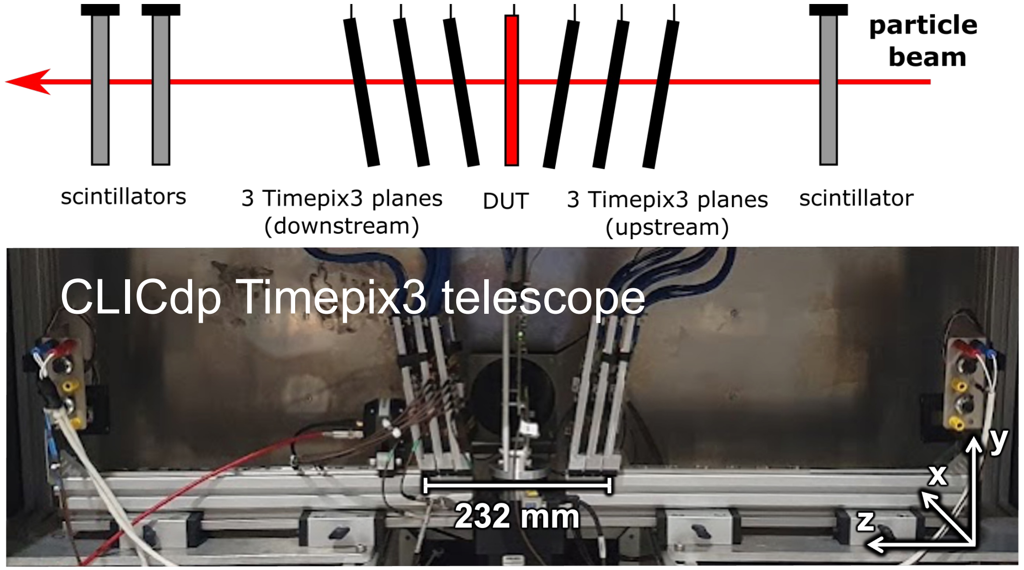
Testbeam evaluation

At CERN SPS beam-test facility

- Using minimum-ionising particles (120 GeV/c pions)

Six tilted Timepix3 planes, DUT in the middle

- Resolution of few μm @DUT



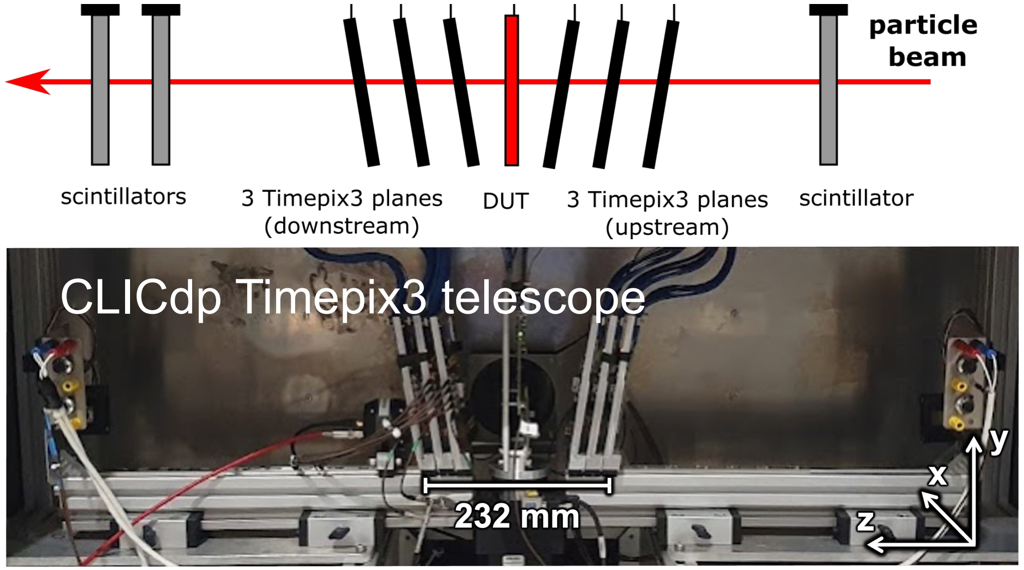
Testbeam evaluation

At CERN SPS beam-test facility

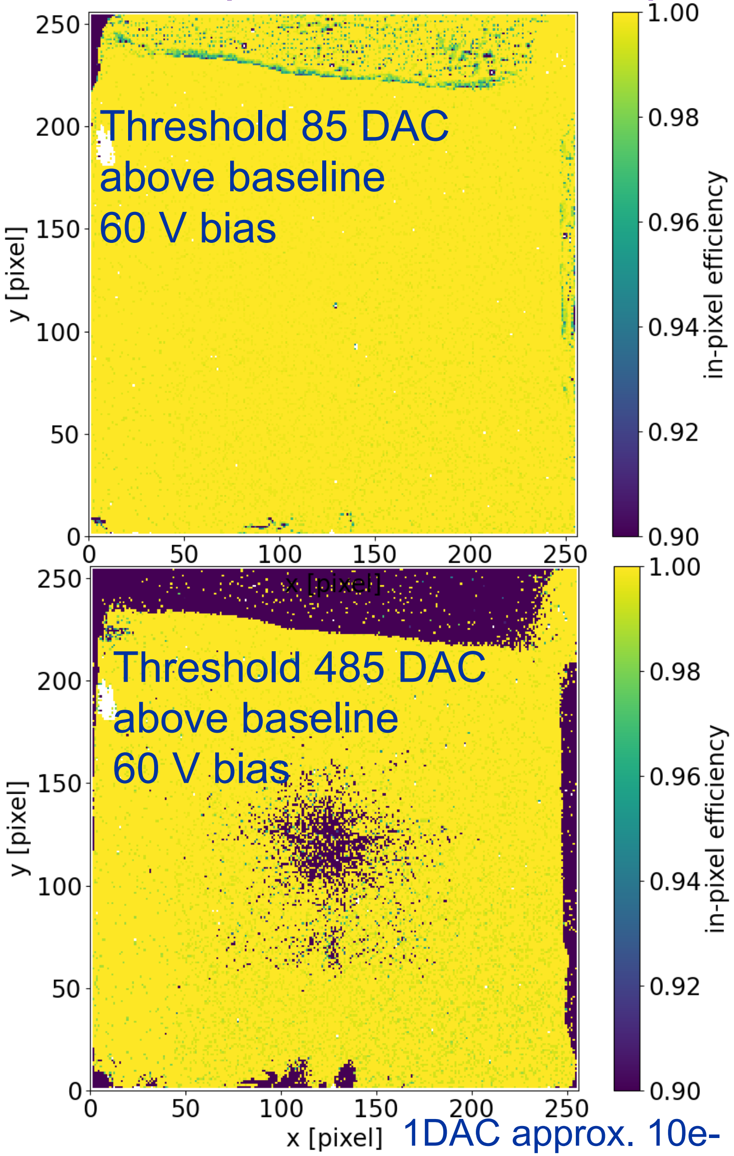
- Using minimum-ionising particles (120 GeV/c pions)

Six tilted Timepix3 planes, DUT in the middle

- Resolution of few μm @DUT



Sample 2 (~90% 14 μm ACF2):



1DAC approx. 10e-

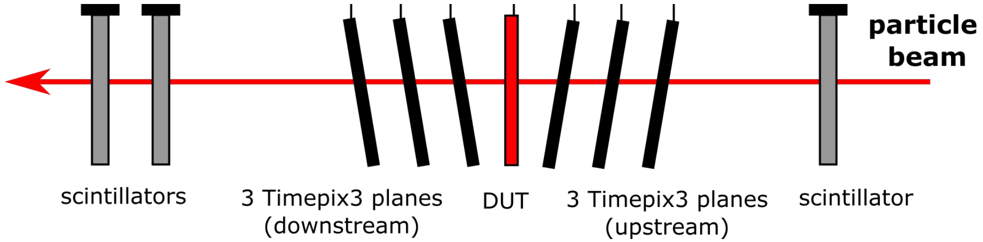
Testbeam evaluation

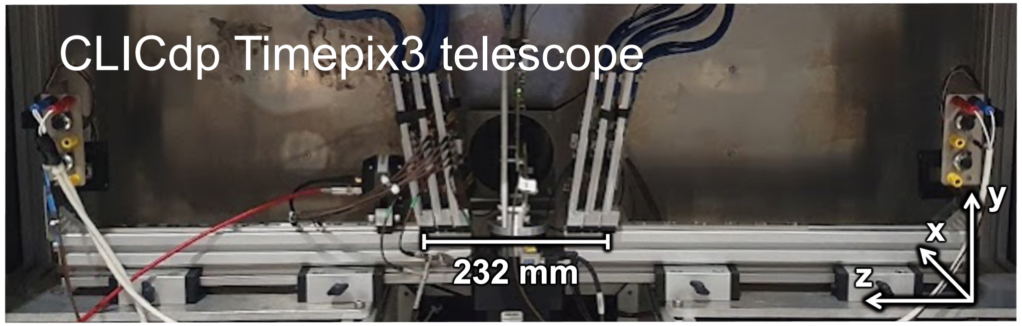
At CERN SPS beam-test facility

- Using minimum-ionising particles (120 GeV/c pions)

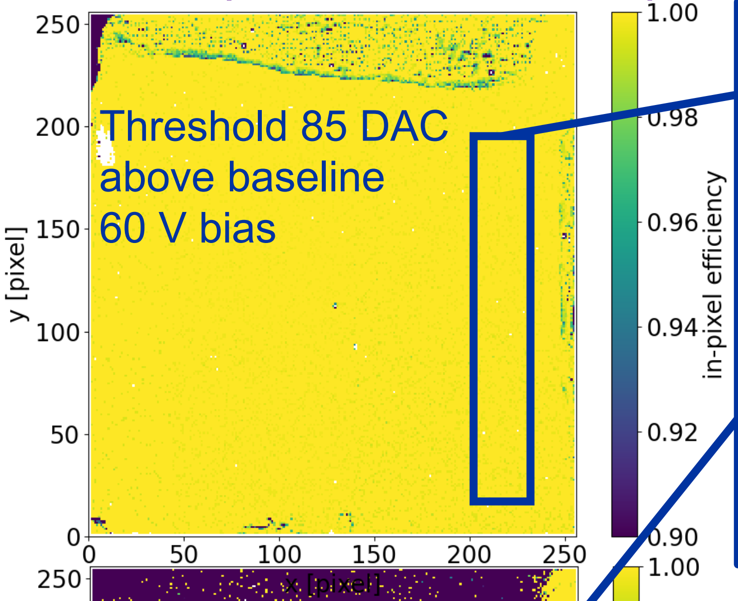
Six tilted Timepix3 planes, DUT in the middle

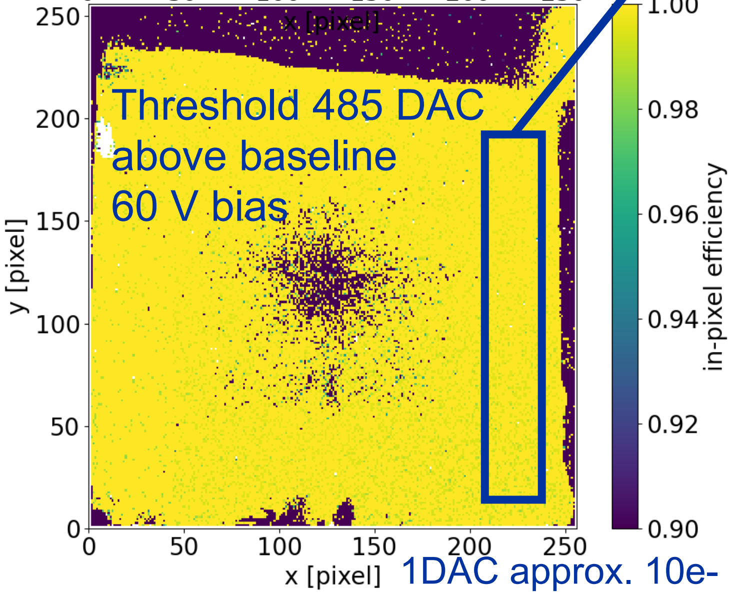
- Resolution of few μm @DUT

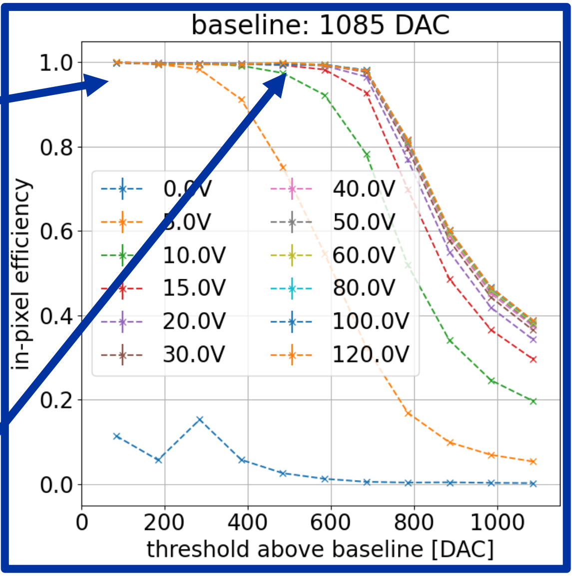




Sample 2 (~90% 14 μm ACF2):







1DAC approx. 10e-

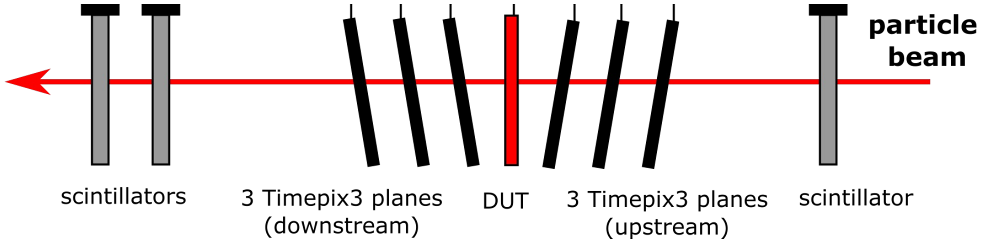
Testbeam evaluation

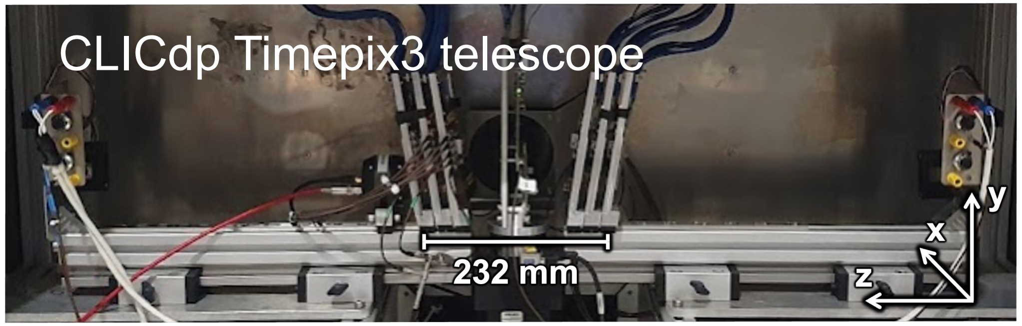
At CERN SPS beam-test facility

- Using minimum-ionising particles (120 GeV/c pions)

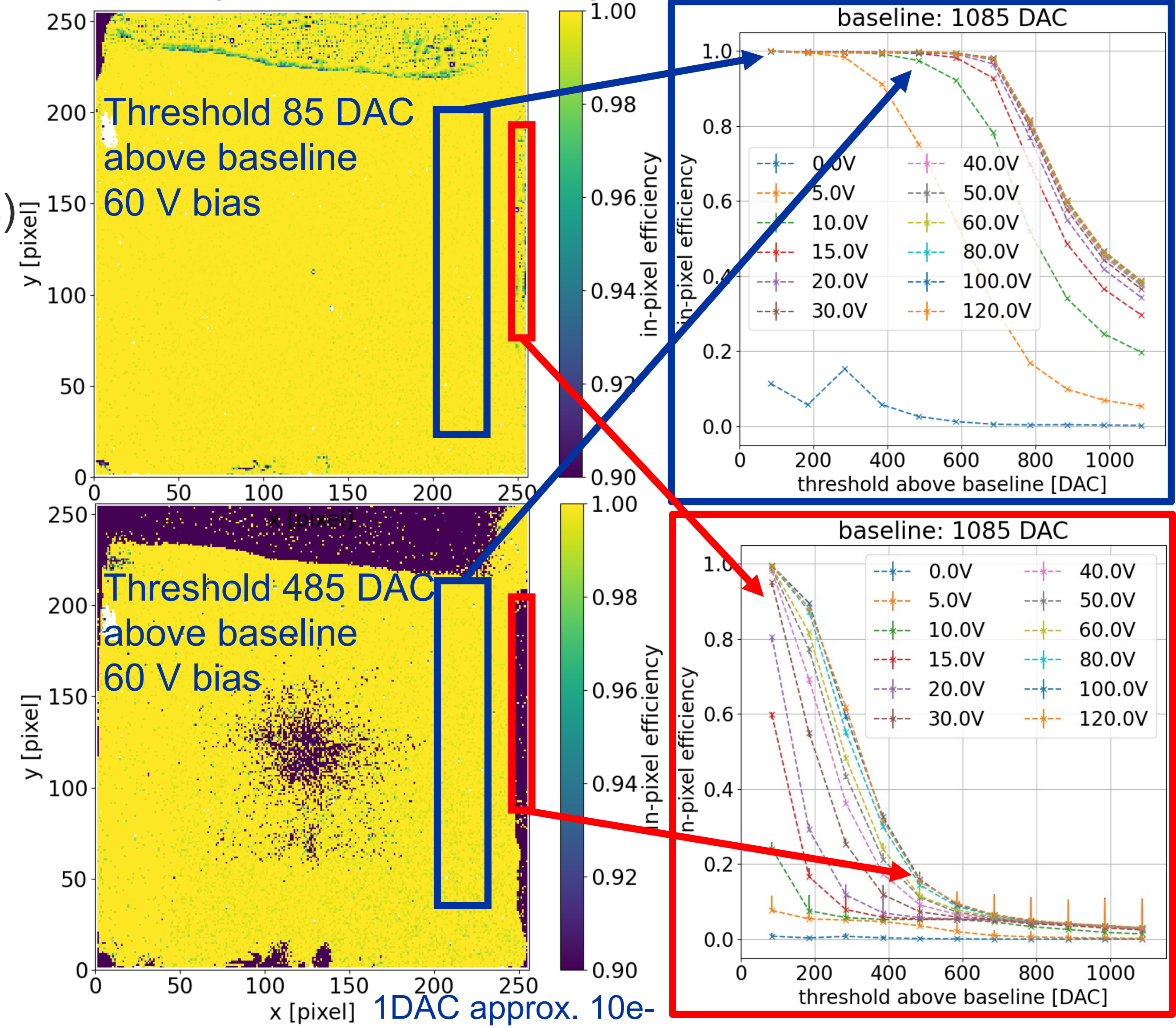
Six tilted Timepix3 planes, DUT in the middle

- Resolution of few µm @DUT





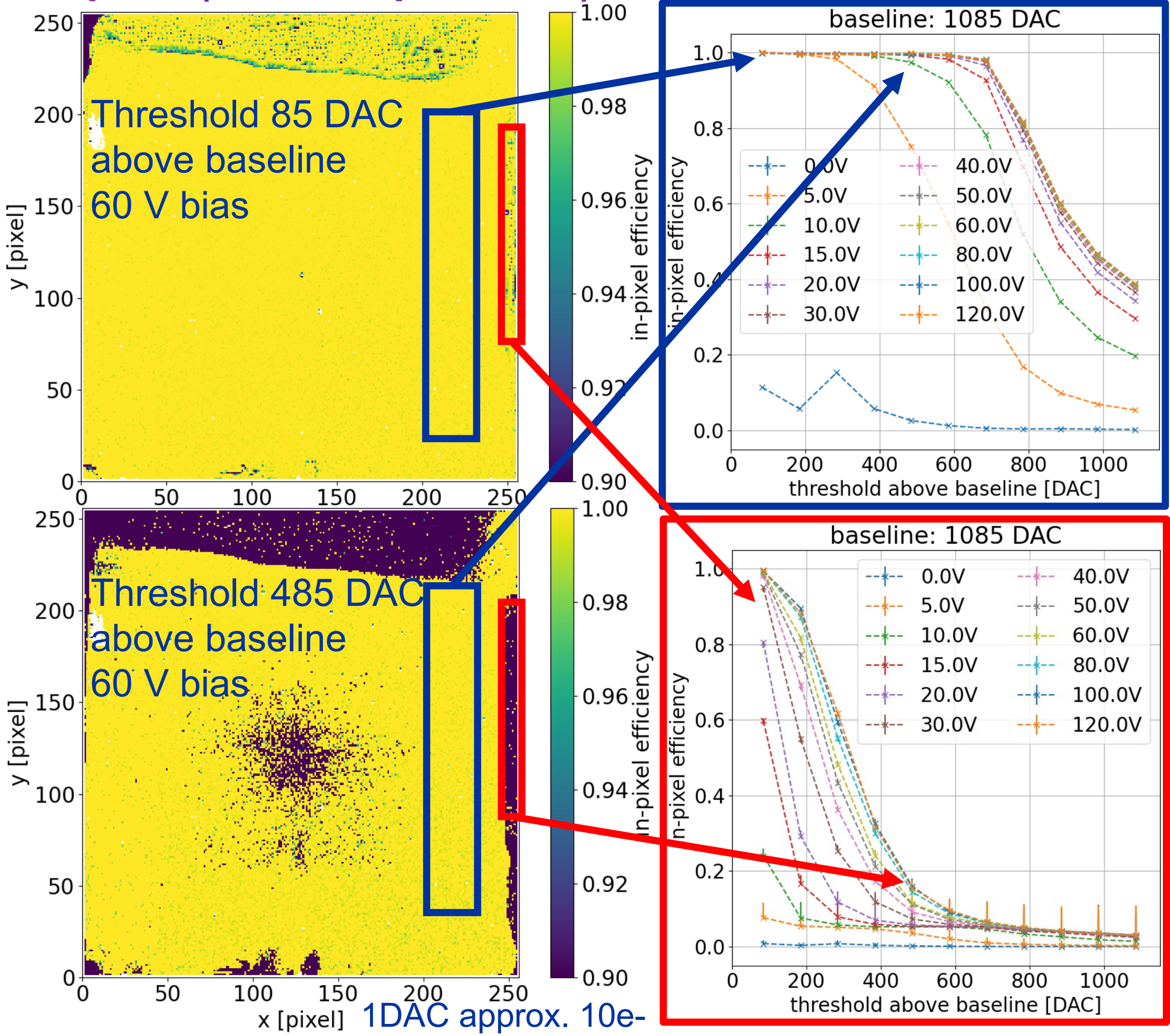
Sample 2 (~90% 14 µm ACF2):



Testbeam evaluation

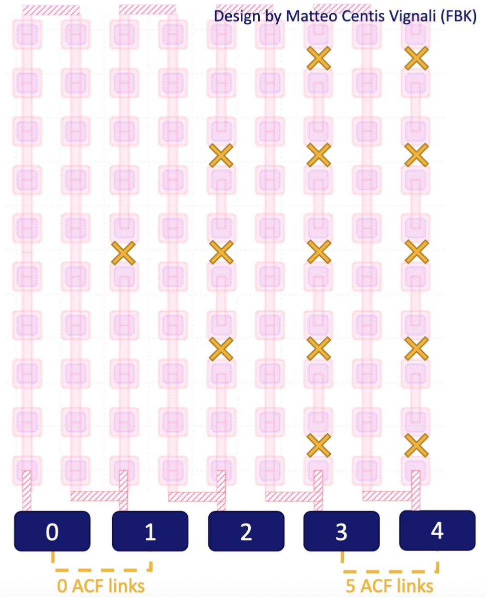
- High in-pixel efficiency at low thresholds
- Different behaviour at higher thresholds
  - 99.96% to 99.89% in the “good” area
  - 99.05% to 11.4% in the area with low plating
    85 DAC to 485 for 60 V bias
- Weak coupling in areas with low plating

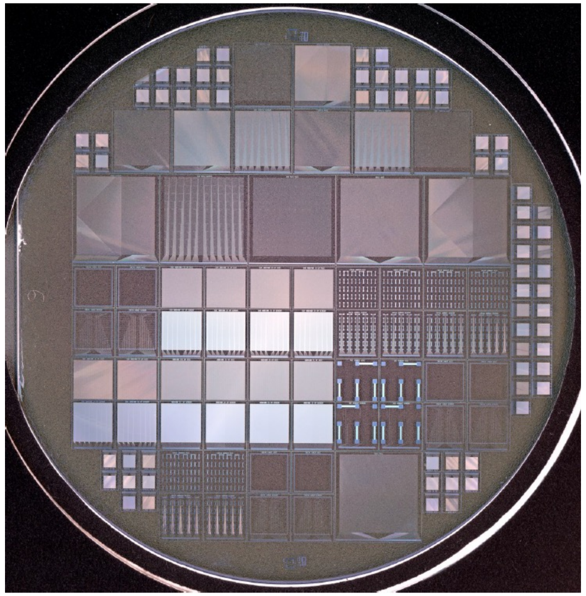
Sample 2 (~90% 14 µm ACF2):



Daisy-chain devices

Daisy-chain 6” quartz wafer with 625 µm thickness designed and produced at FBK



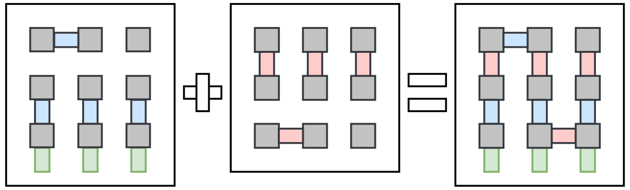


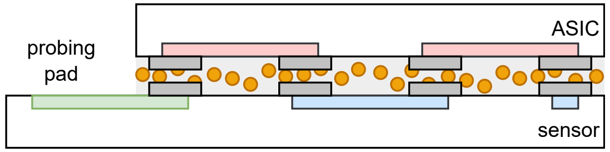
Study of ACA interconnection properties

- Low-pitch and large-pitch reliability
- Resistance measurements
- Mechanical analysis

Surface properties similar to typical ASICs and sensors

- Al metal pads 2.5 µm thick
- 950 nm thick passivation





	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

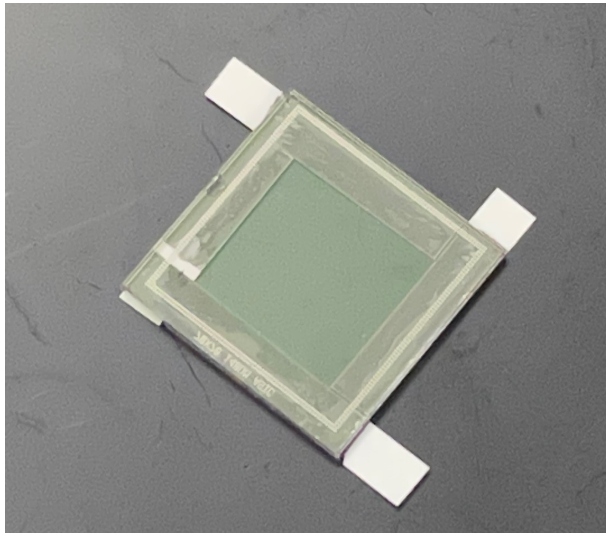
First measurements on slide 30

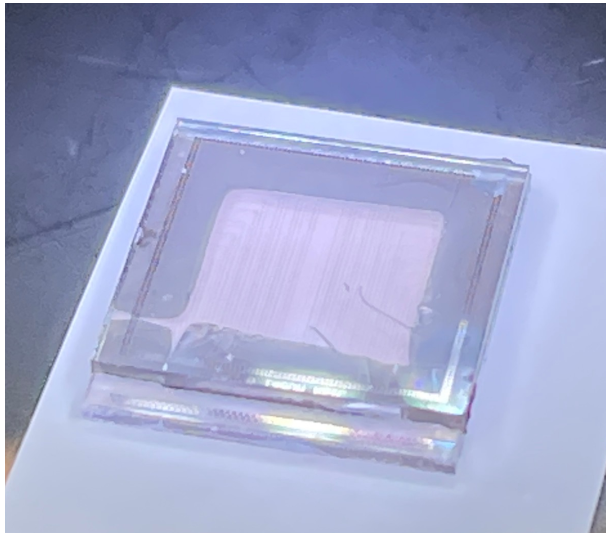
Conclusion and Outlook

- **Successful hybridisation with Anisotropic Conductive Adhesive**
  - High efficiency in “good” areas
  - Week coupling in the centre due to insufficient cavities
- **Development of single-die ENIG process at CERN**
- **Further evaluation and improvement of parameters**
  - Plating height
  - ACA properties (particle density, viscosity, volume…)
  - Flip-chip bonding (pressure, compression time…)
- **Ageing and radiation-hardness studies**
- **Collaboration with more projects**

CERN

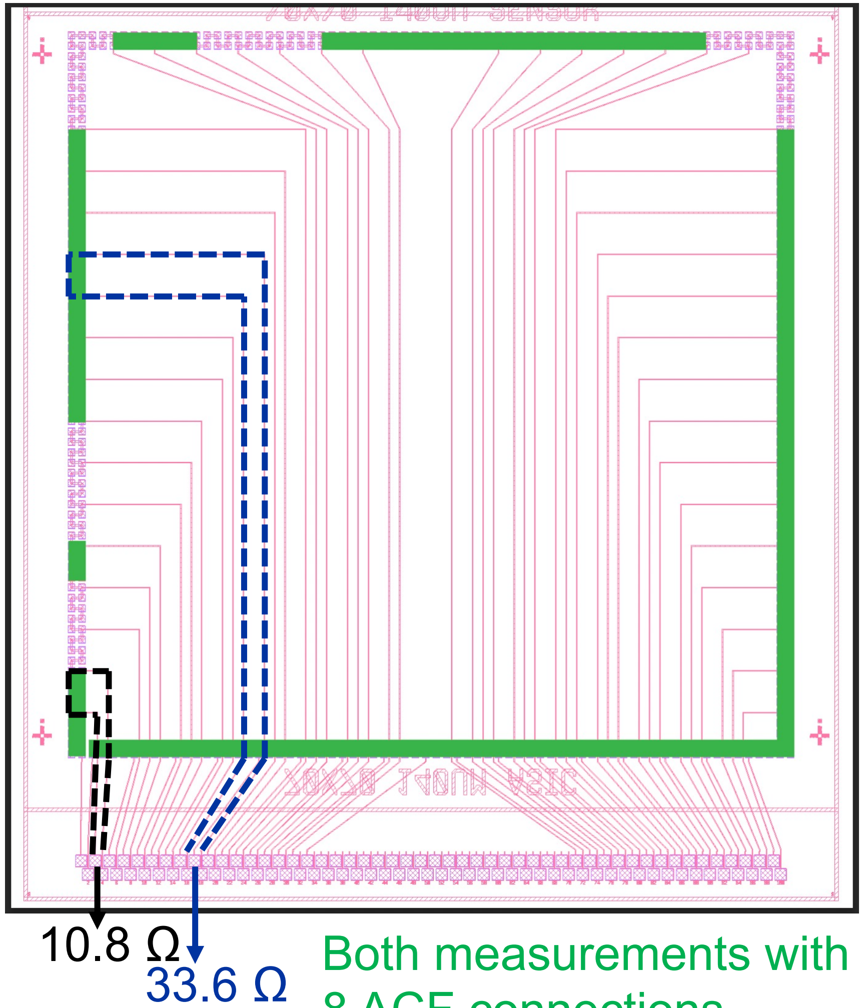
Daisy-chain devices Testing





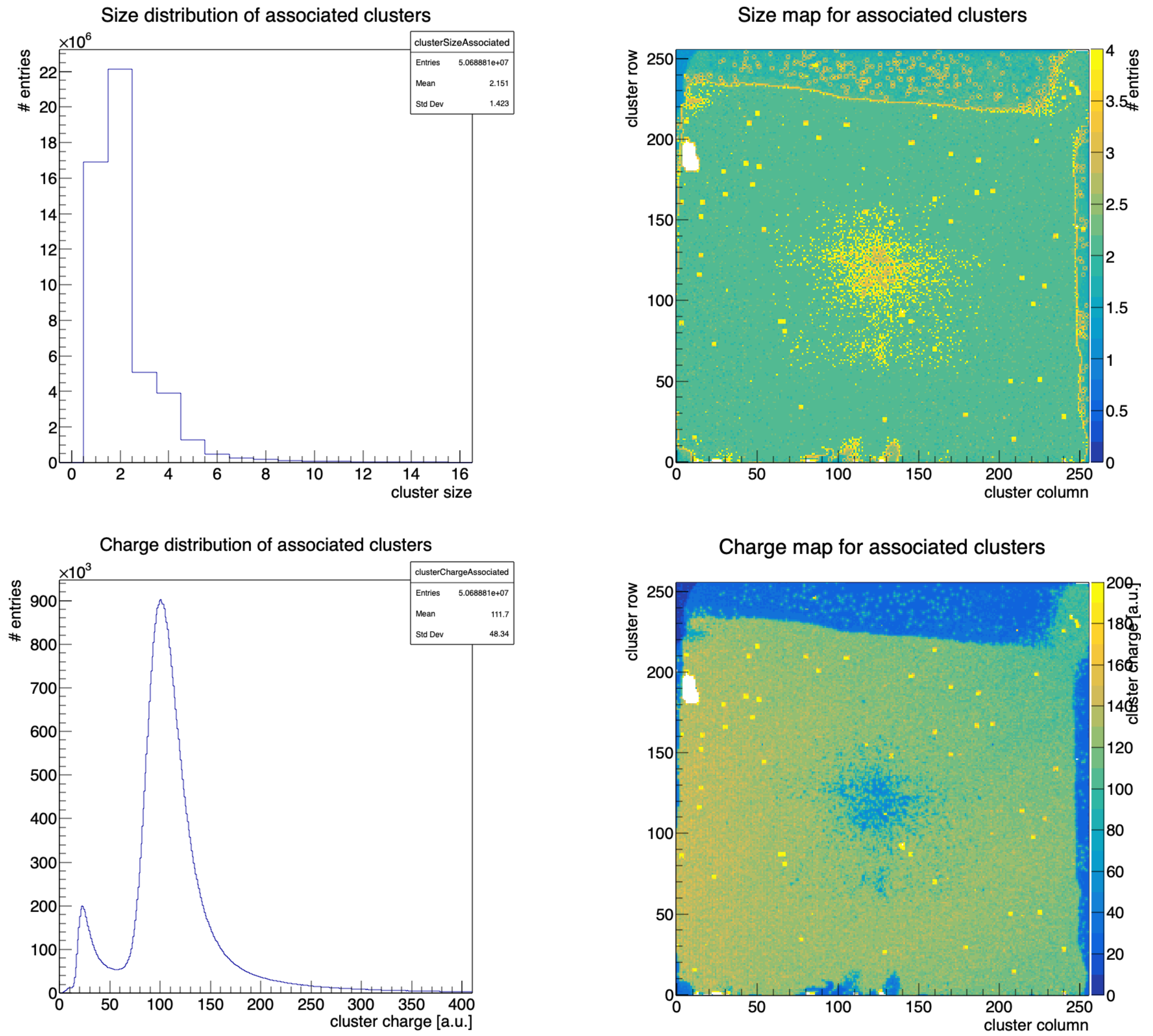
- Bonded peripheral-type device (mimic MALTA integration)
  - Used 2 mm ACF film (14 µm thickness)
- Good connection yield
  - Missing connections due to ACF lamination / mechanical damage
  - 2-wire measurement of resistivity, dominated by metal line length
- Ramping-up with plating/bonding/testing

Verified connections



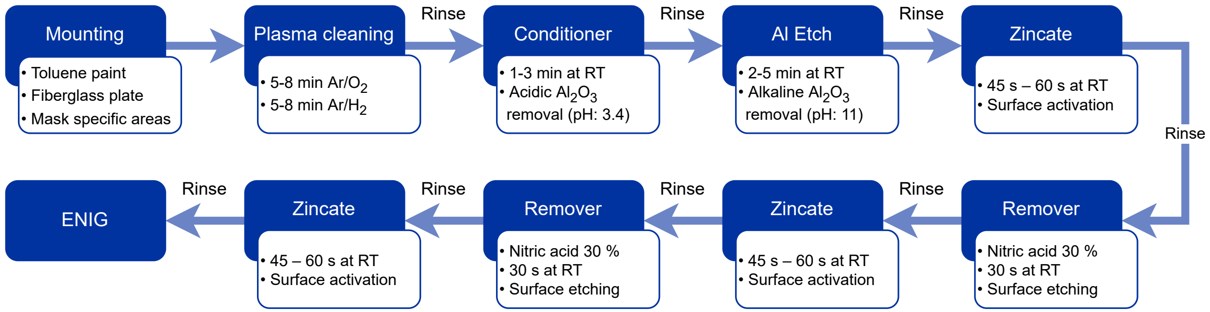
Both measurements with 8 ACF connections

Cluster size and charge

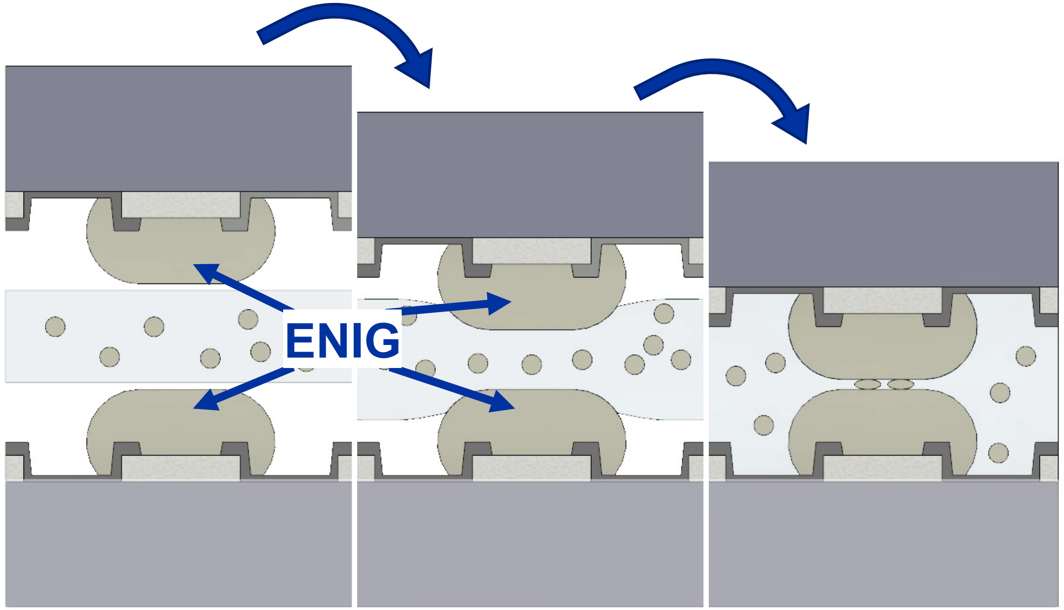


Electroless Nickel Immersion Gold plating (ENIG)

- Topology for connection
  - Surface for particle compression
  - Cavities between pads for excess epoxy
- Maskless single-die in-house post-processing at CERN



Schematic illustration of an ACF bonding

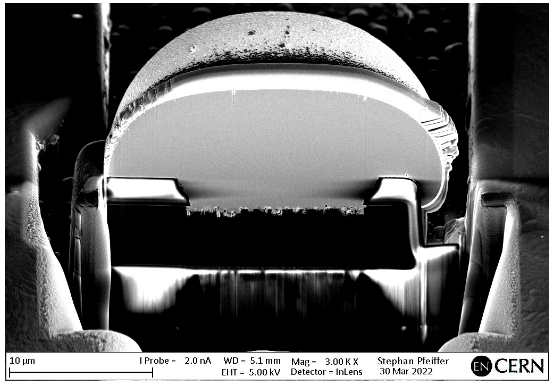


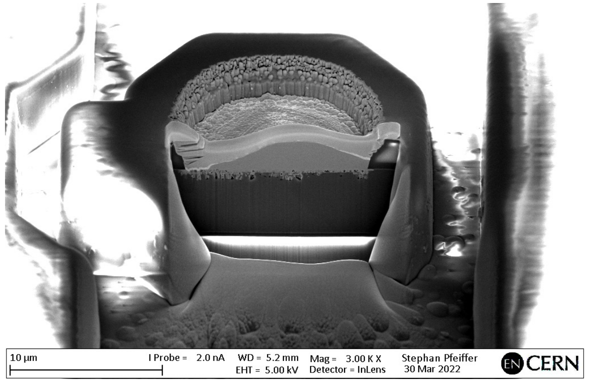
Preparation | **ENIG plating** | Bonding | Testing

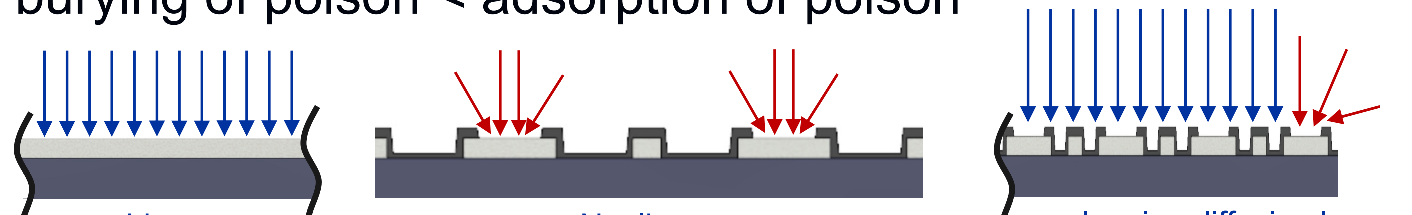
Diffusion controlled catalyst poisoning

Stabilizer and contaminations poison catalytic surface of pad

- Poison is adsorbed on surface
- Faster diffusion to small pads
- Diffusion layer is reduced by convection
- Termination of reaction if
  burying of poison < adsorption of poison





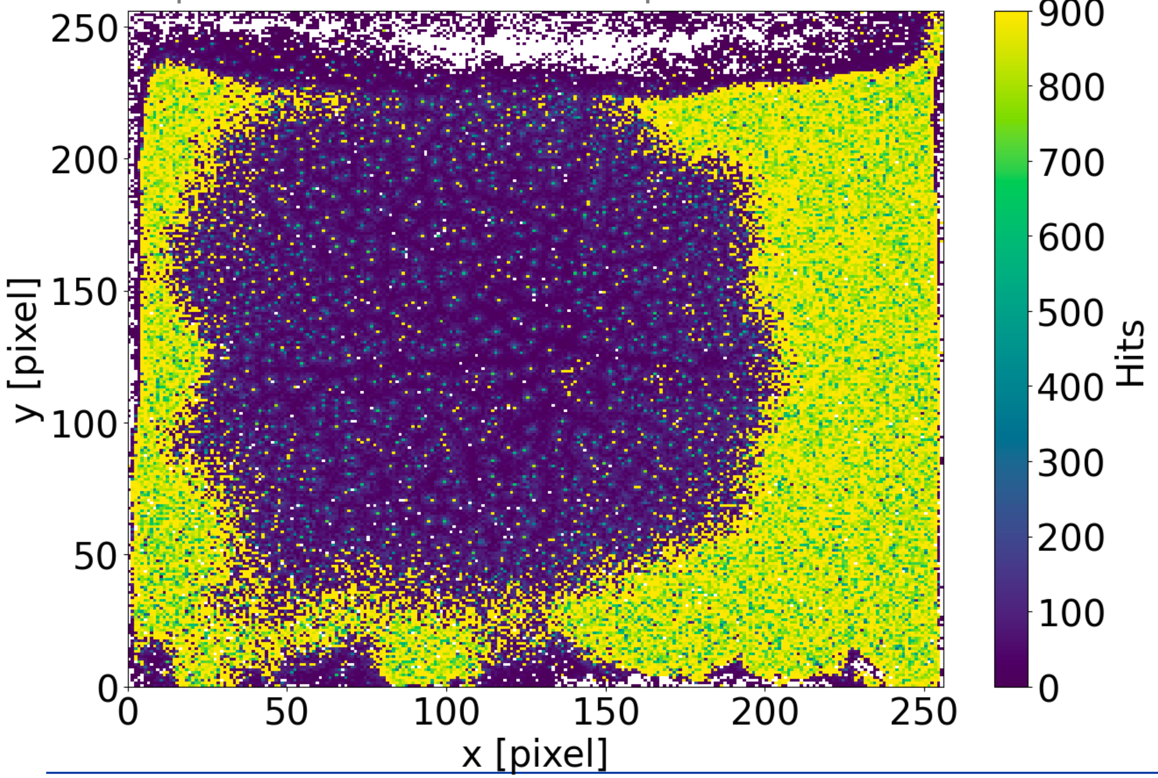


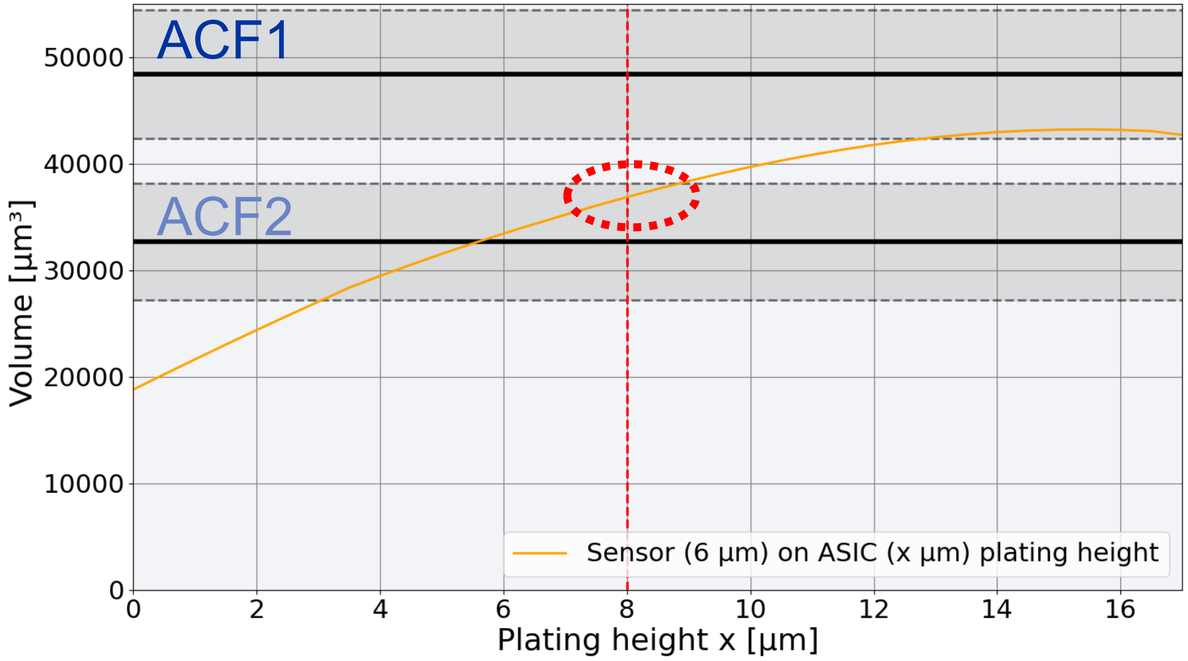
Preparation | **ENIG plating** | Bonding | Testing

Influence of ACF thickness

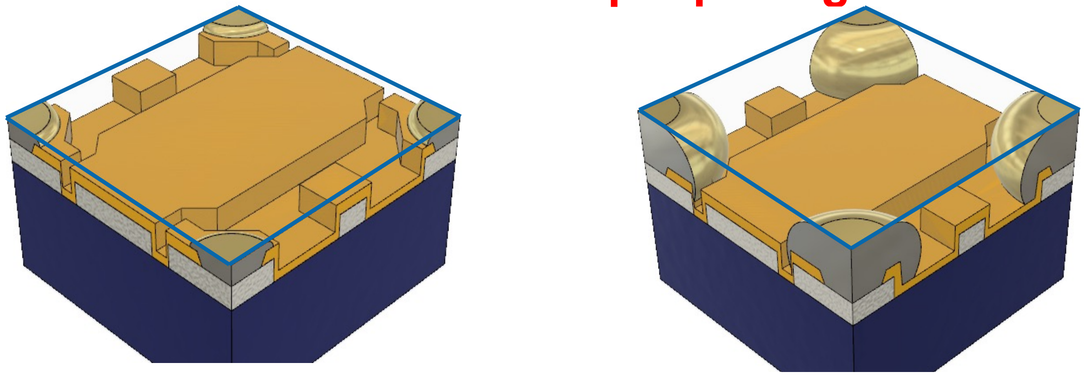
Sample 1: 100% coverage of 18 µm ACF

Hit-map from Sr^{90} illumination Timepix3





approx. 8 µm plating

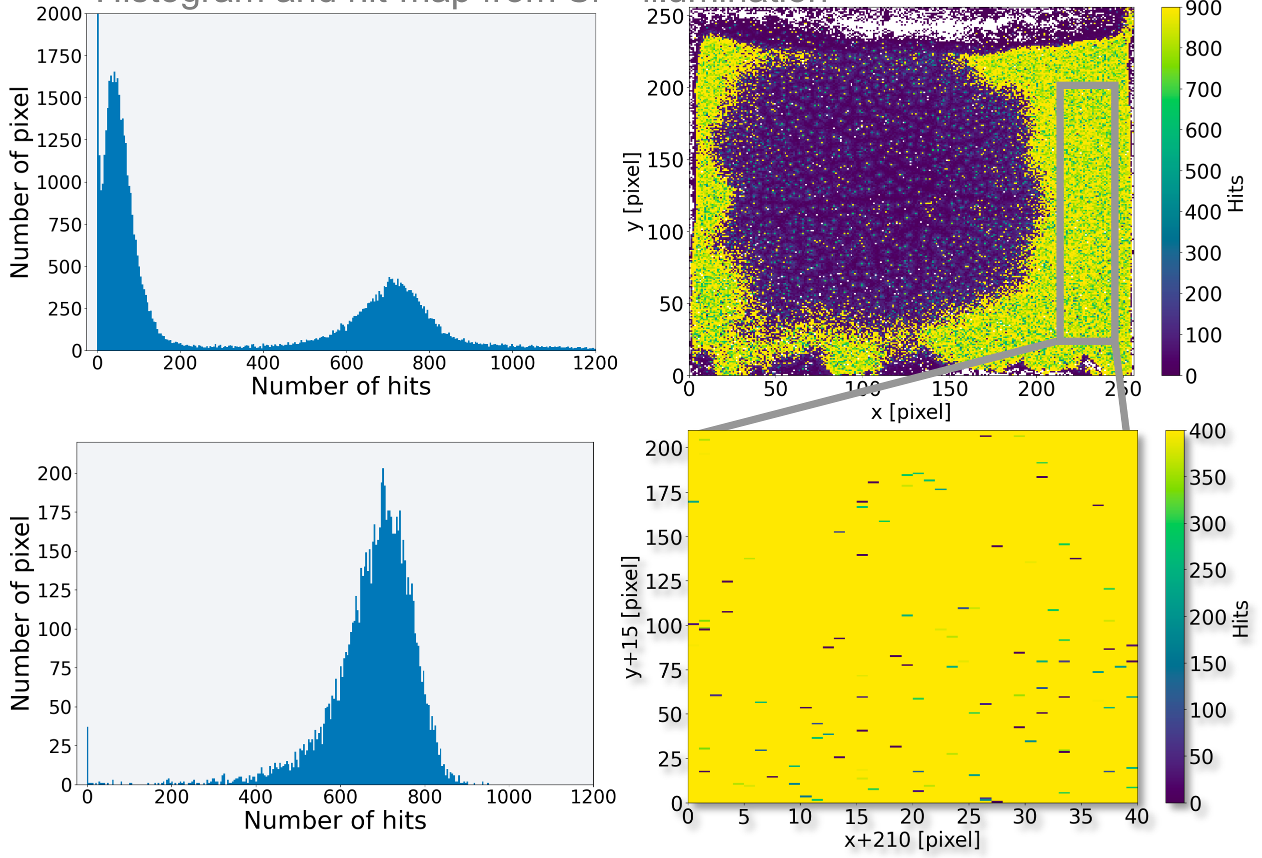


→ Bad interconnect yield in central region due to insufficient cavity volume

Preliminary results with Timepix3

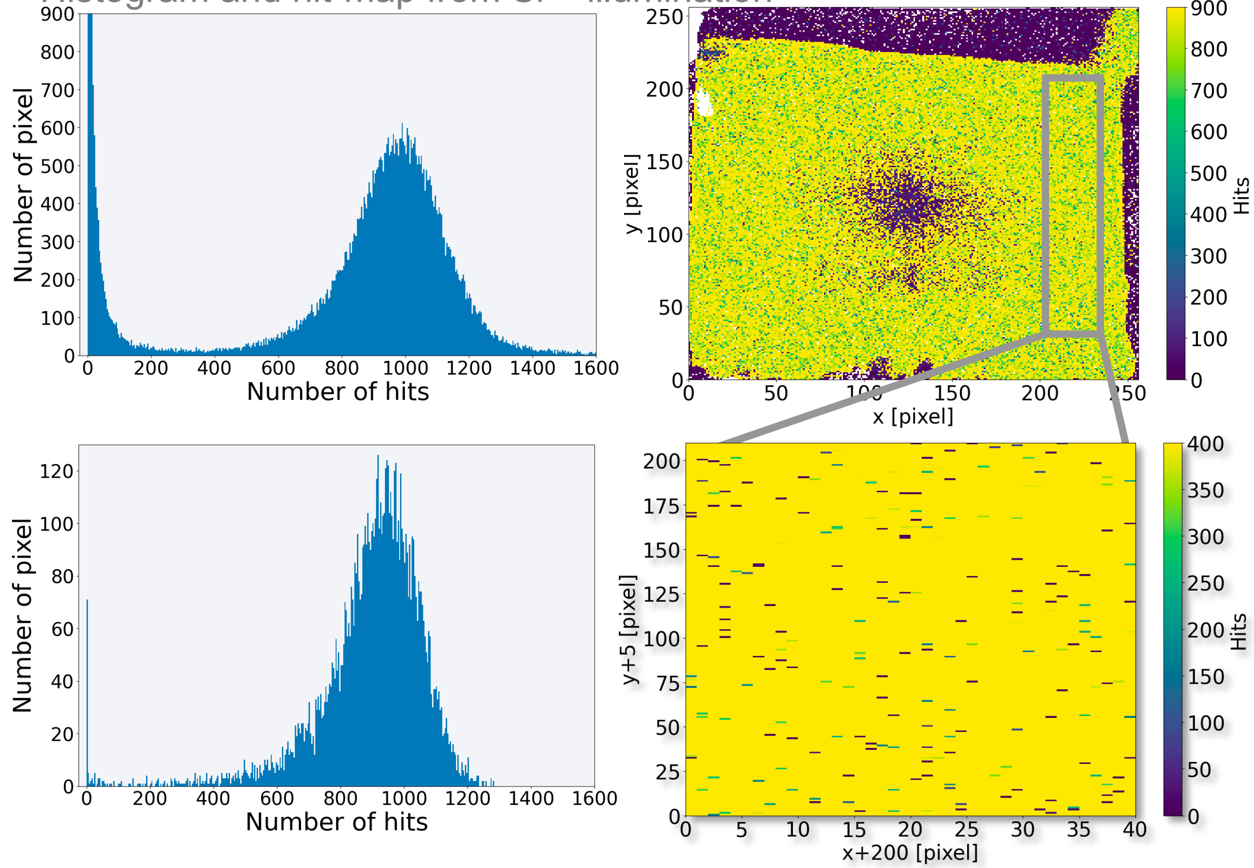
Sample 1: 100% coverage of 18 µm ACF

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



Sample 2: ~90% coverage of 14 µm ACF

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

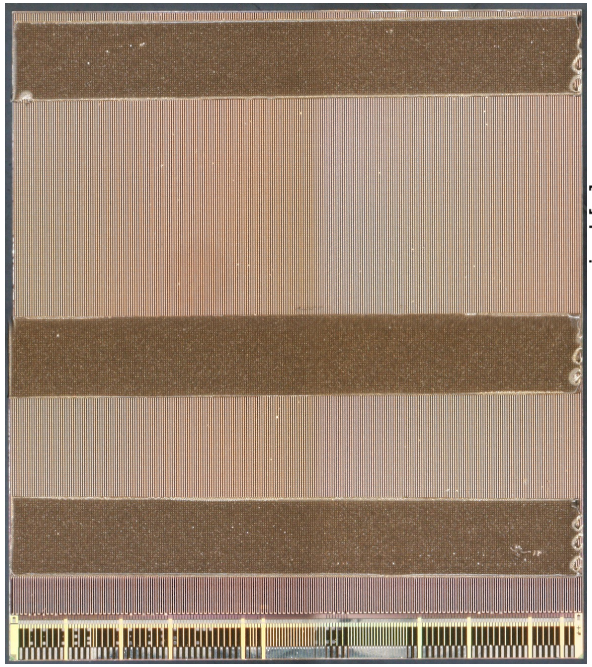


Modifying ACF/ACP coverage

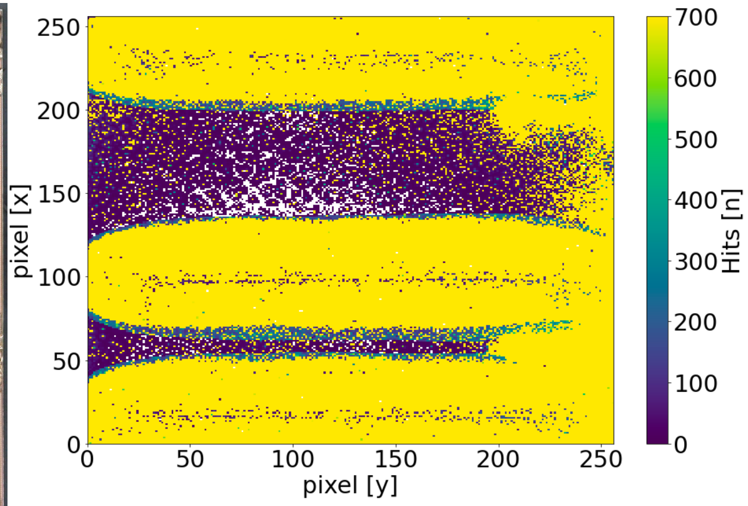
- ACF and ACP flows beyond the applied area
- Reduction of total adhesive volume possible
- Using the flow behaviour of ACF and ACP for a better connection

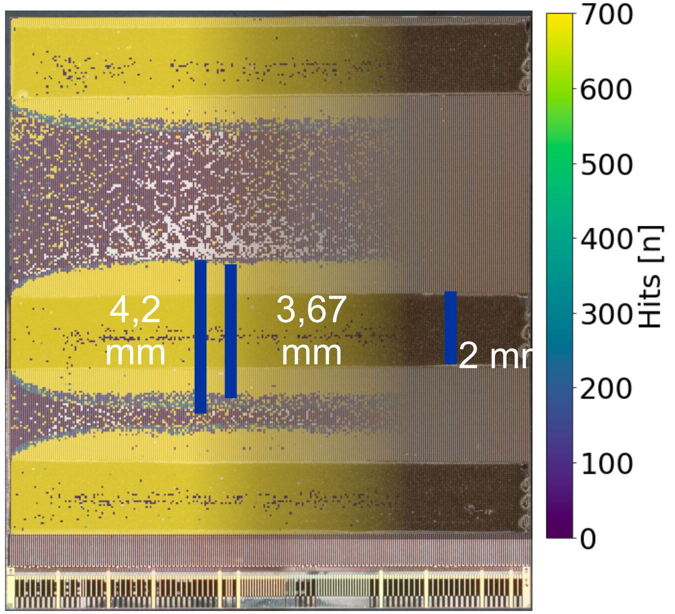
→ Possible yield improvement through gaps in the ACF/ACP coverage

ACF coverage on Timepix3 ASIC



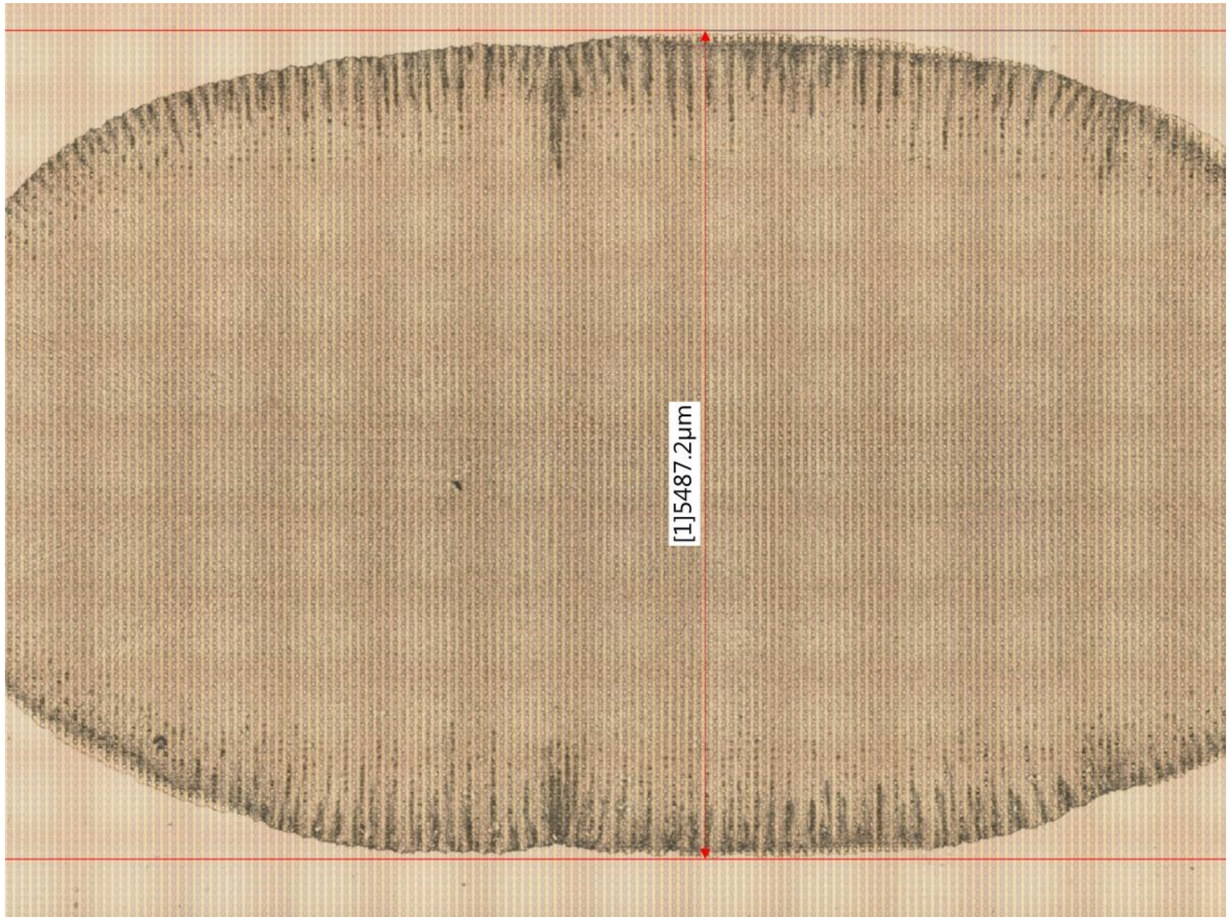
Related Hit-map



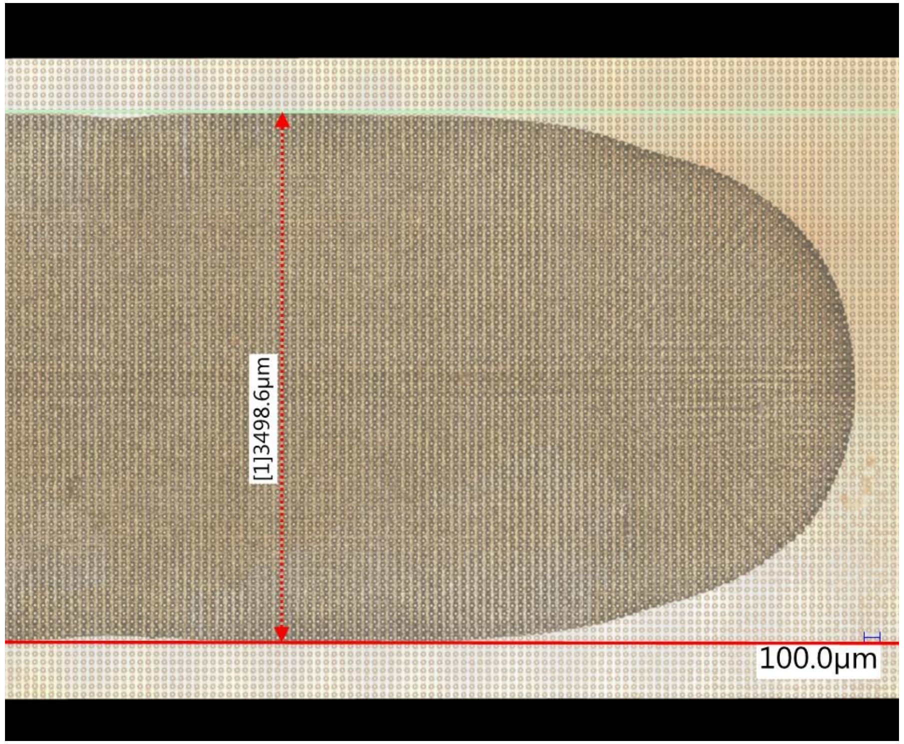


Glass bonded on Timepix3 ASIC with ACF
No plating vs. 11 µm plating height

2 mm 14µm ACF stripe Timepix3 ASIC w/o ENIG and glass

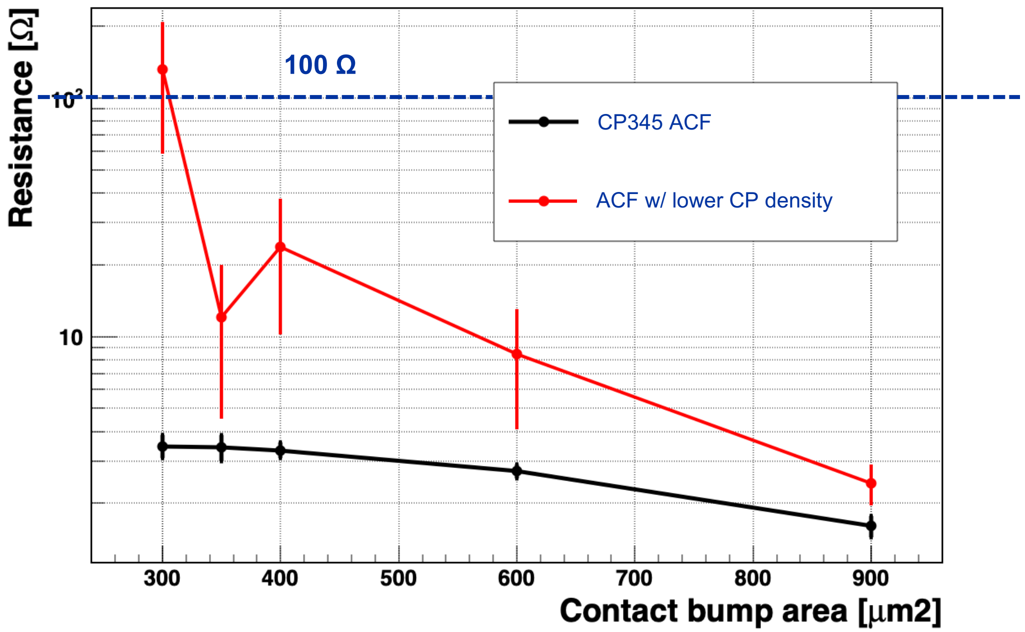


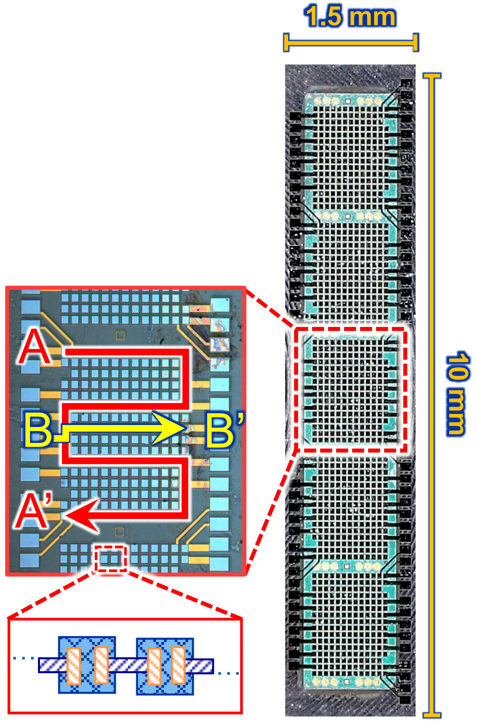
2 mm 14µm ACF stripe Timepix3 ASIC 11µm ENIG and glass

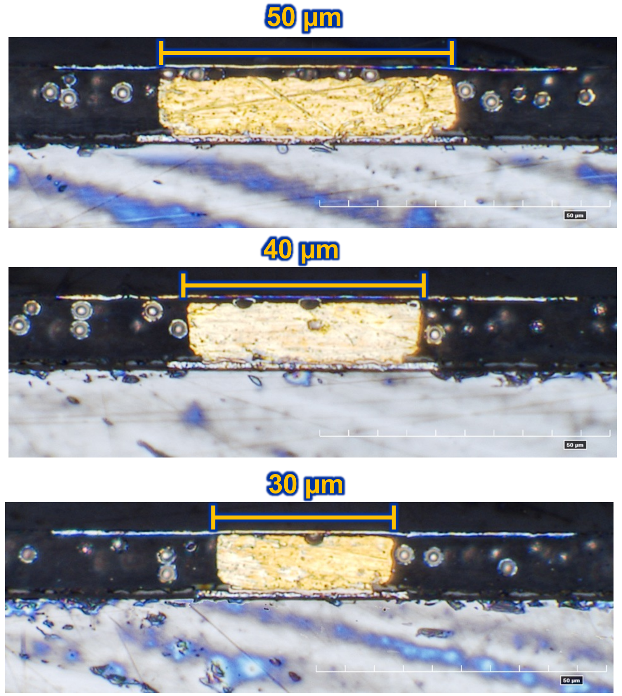


ACF bonding
resistance measurement

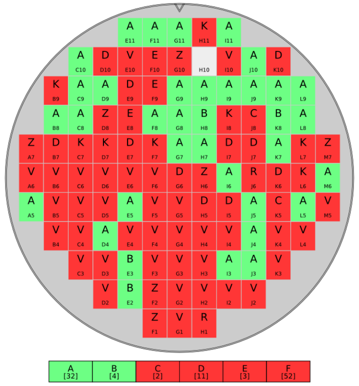
- **Test structure with 5 matrices of pads with different sizes**
  - Resistance scales with the (pixel) **pad size** and film **particle count**
  - Acceptable resistance in hybrid pixel detectors is ≲ **100 Ω**

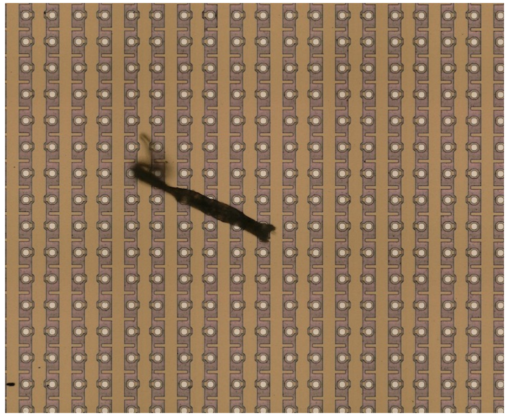


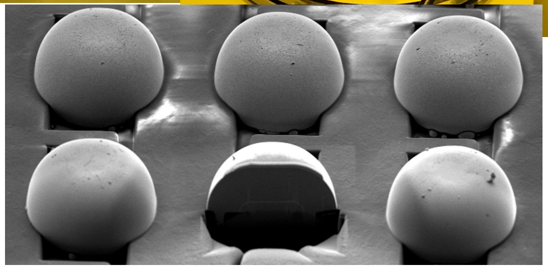




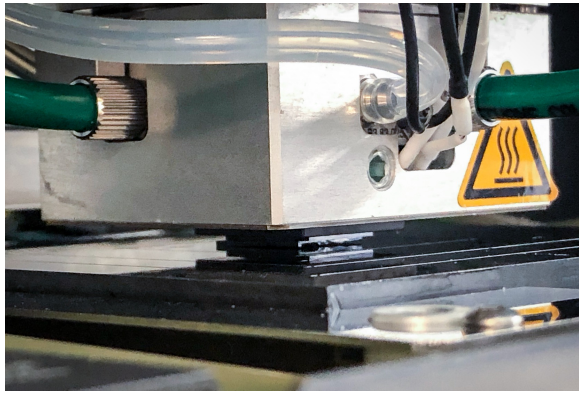
Process workflow

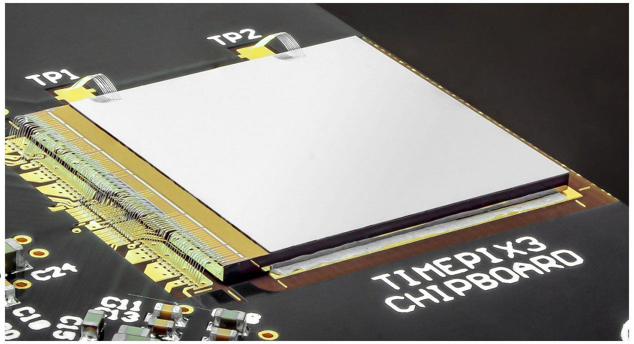


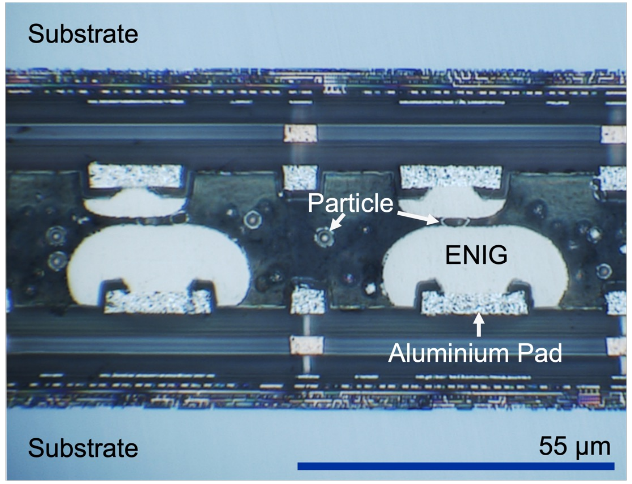




Flip-chip bonder







Preparation

- Electrical testing
- Visual inspection

ENIG

- Nickel growth
- Pad topology

ACF

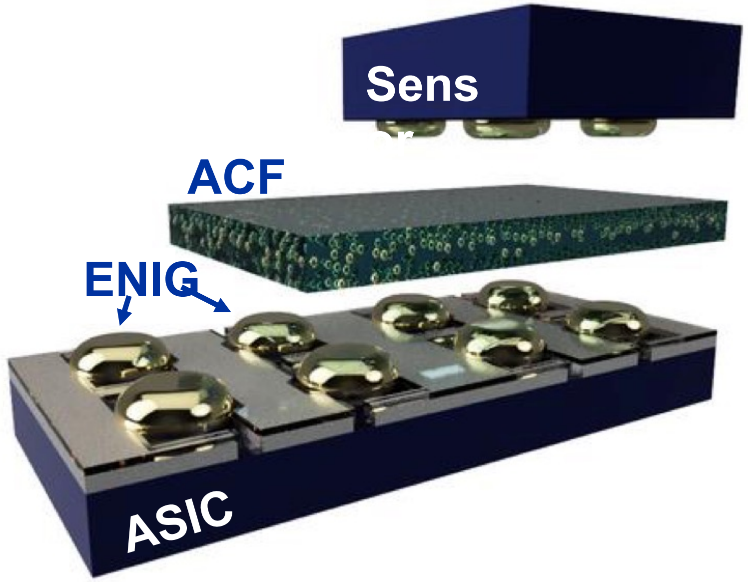
- Lamination
- Flip-chip bonding

Testing

- Cross-section
- Source and Test-beam measurement

ACF bonding

Illustration of the layers for ACF bonding before bonding

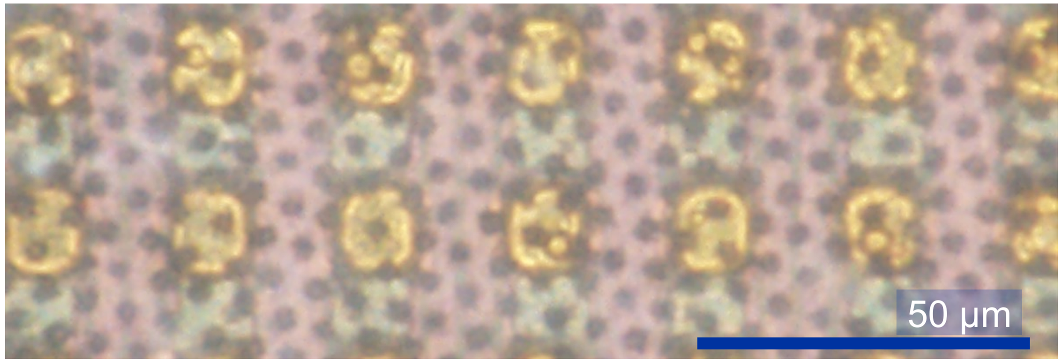


Some of the available ACFs

ACF	1	2	3	4	5
Part. diameter [µm]	3	3	3.5	10	3.2
Thickness [µm]	18	14	16	50	18
Particle density [pcs/mm^2]	71k	60k	23k	-	28k
Pressure [MPa]	30-80	50-90	40-90	30-50	40-80
Aligned	no	no	Particles at same depth	no	surface grid**
Sheet or reel	Sheet	Reel*	Sheet	Reel*	Reel*

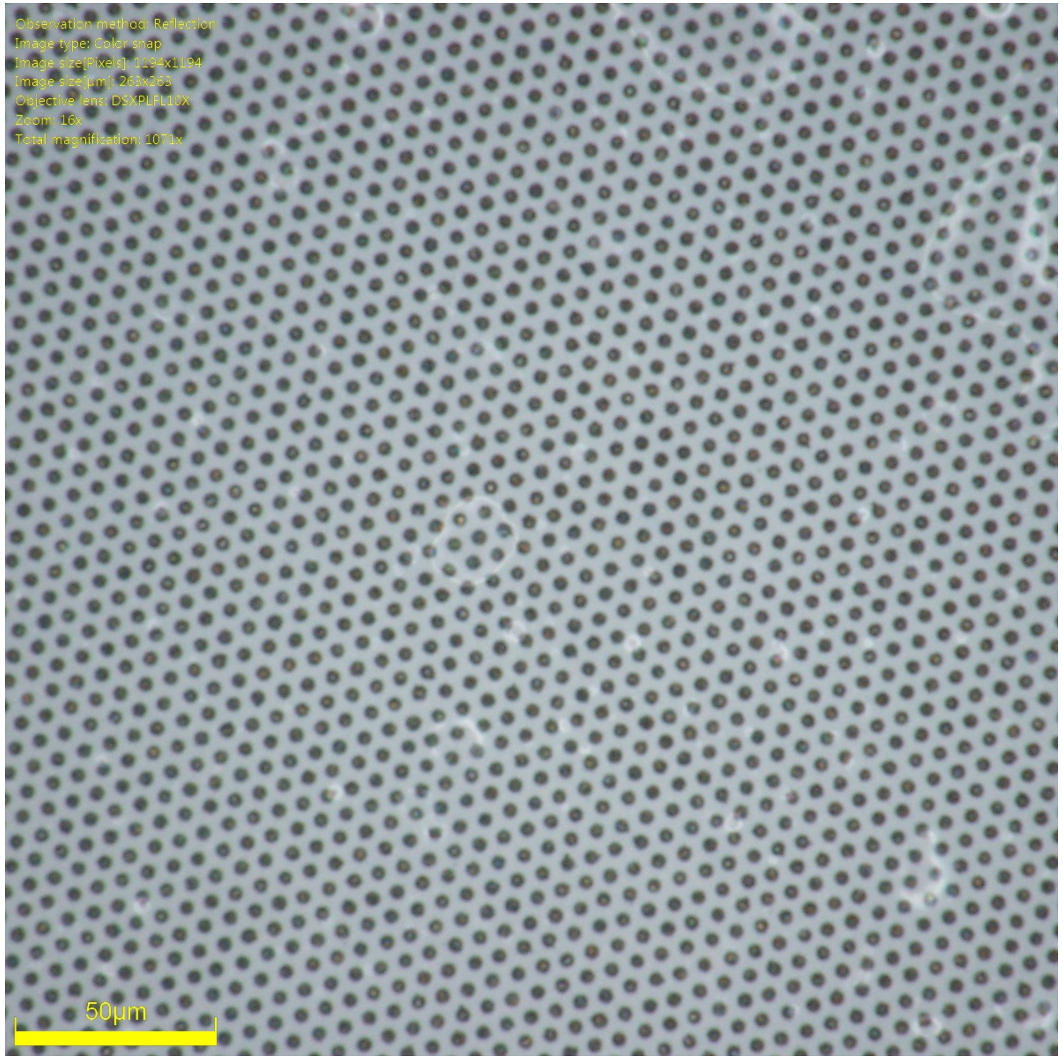
*Reels are used in the industry mostly with a few mm width

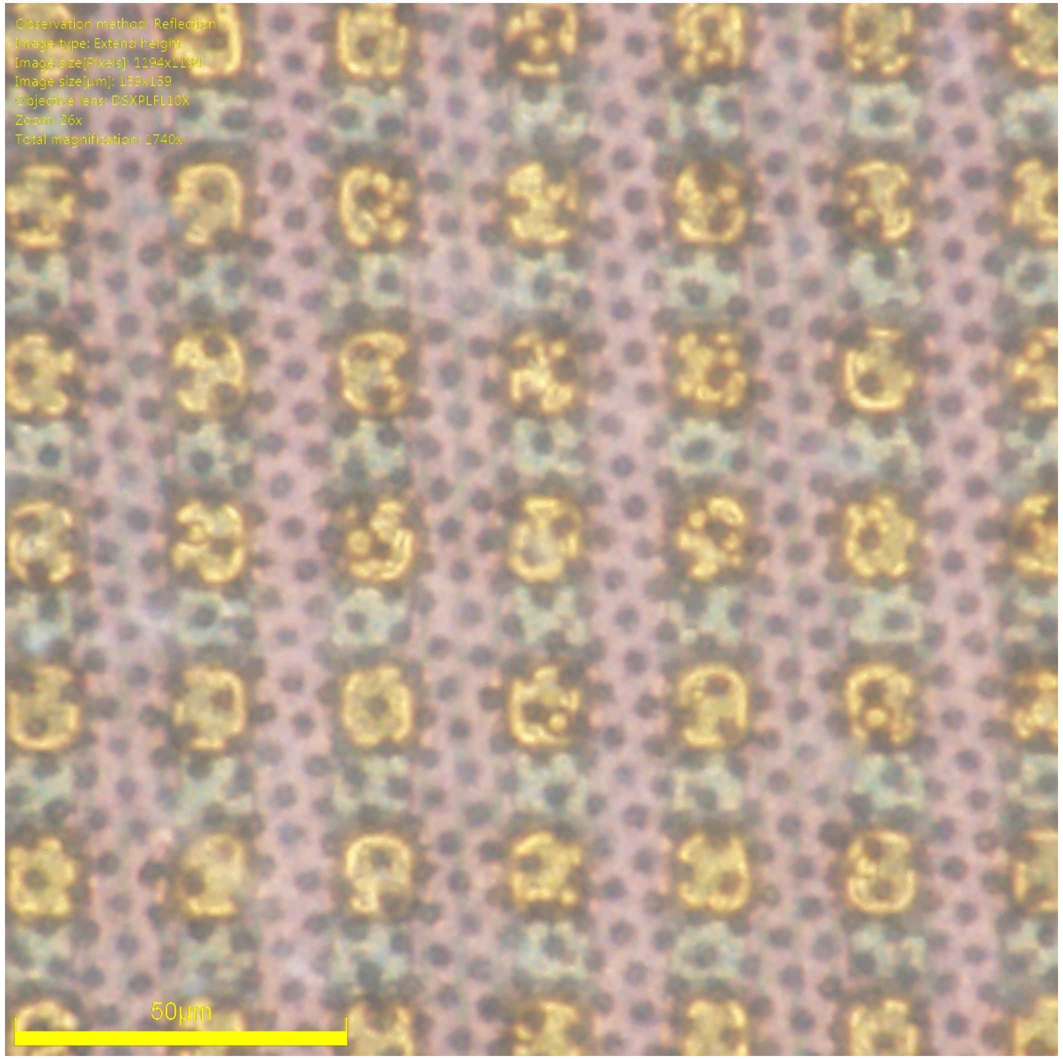
**Microscope image of an aligned ACF on a CLICpix2 ASIC



Preparation → ENIG plating → **Bonding** → Testing

ACF 5


Observation method: Reflection
Image type: Color snap
Image size[Pixels]: 1194x1194
Image size[µm]: 263x263
Objective lens: DSXPLFL10X
Zoom: 16x
Total magnification: 1071x
50µm

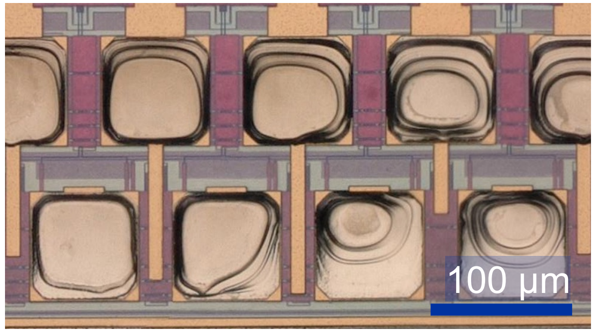

Observation method: Reflection
Image type: Extend height
Image size[Pixels]: 1194x1194
Image size[µm]: 159x159
Objective lens: DSXPLFL10X
Zoom: 26x
Total magnification: 1740x
50µm

Diffusion controlled catalyst poisoning

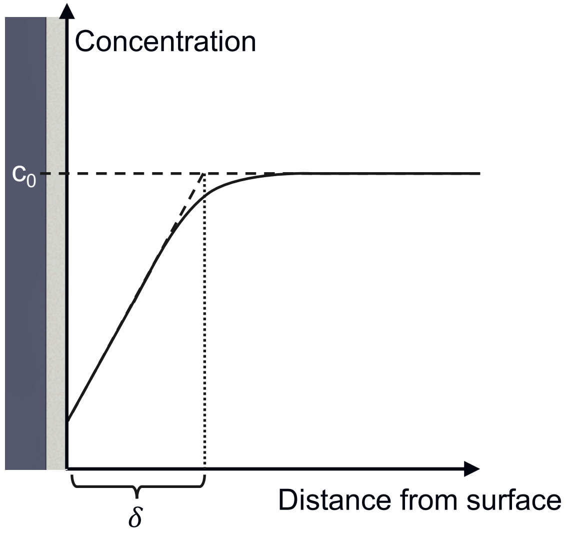
Stabilizer and contaminations are catalyst poison

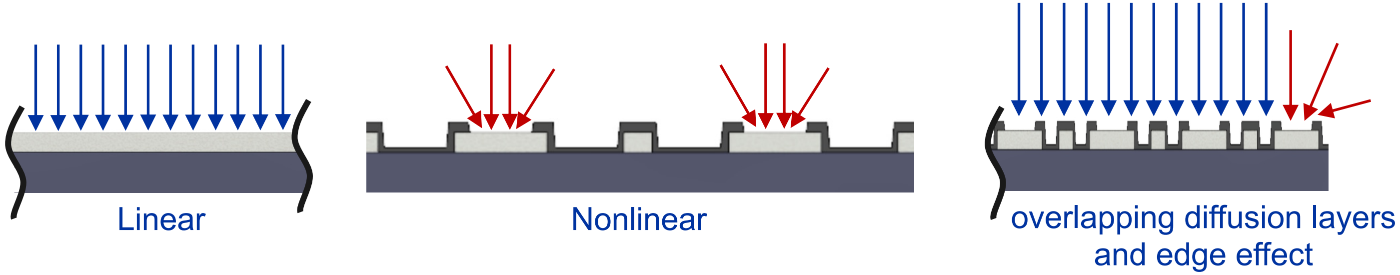
- Poison is adsorbed on surface
- Faster diffusion to small pads
- Diffusion layer is reduced by convection
- Termination of reaction if burying of poison < adsorption of poison

Step plating on MALTA



Nernst diffusion layer model





S. Zhang *et al* 1999 *J. Electrochem. Soc.* **146** 2870