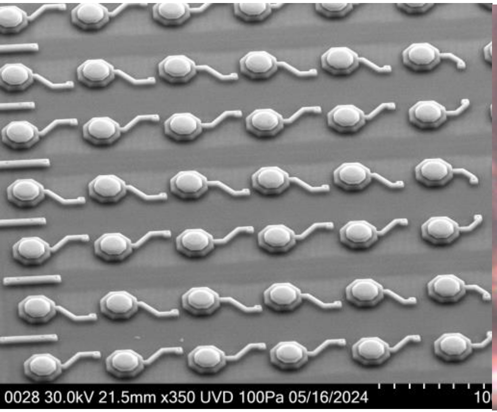
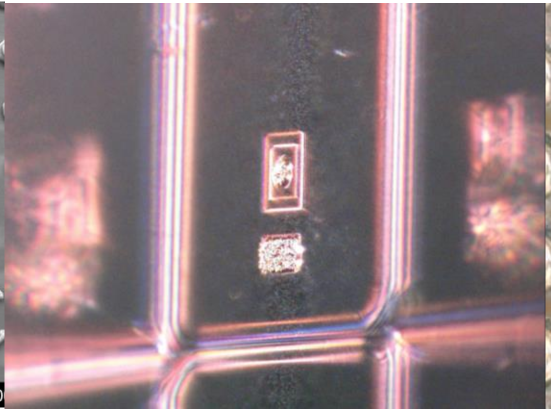
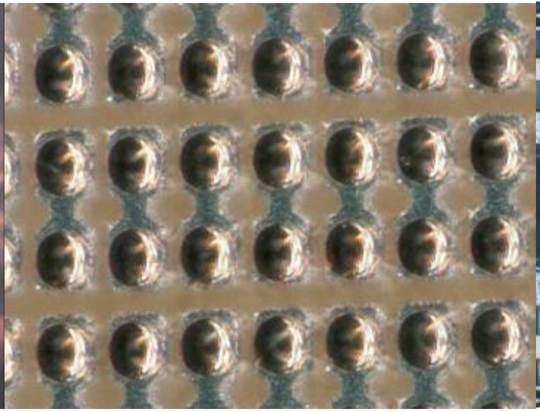
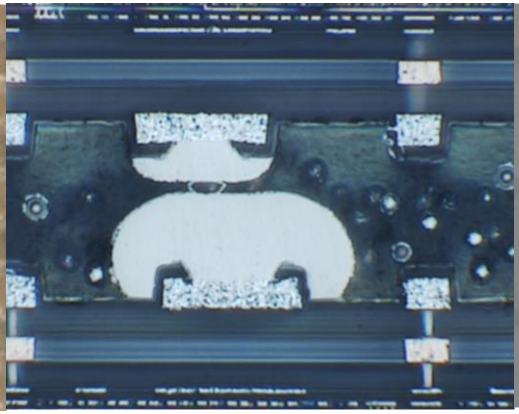
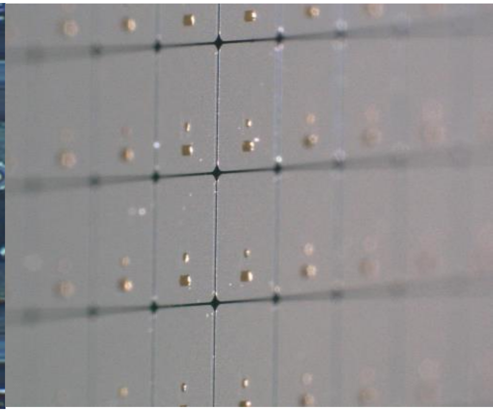
EP-DT
Detector Technologies

EP R&D

Development of in-house plating and hybridisation technologies for pixel detectors



2nd DRD3 week

02–06 Dec. 2024

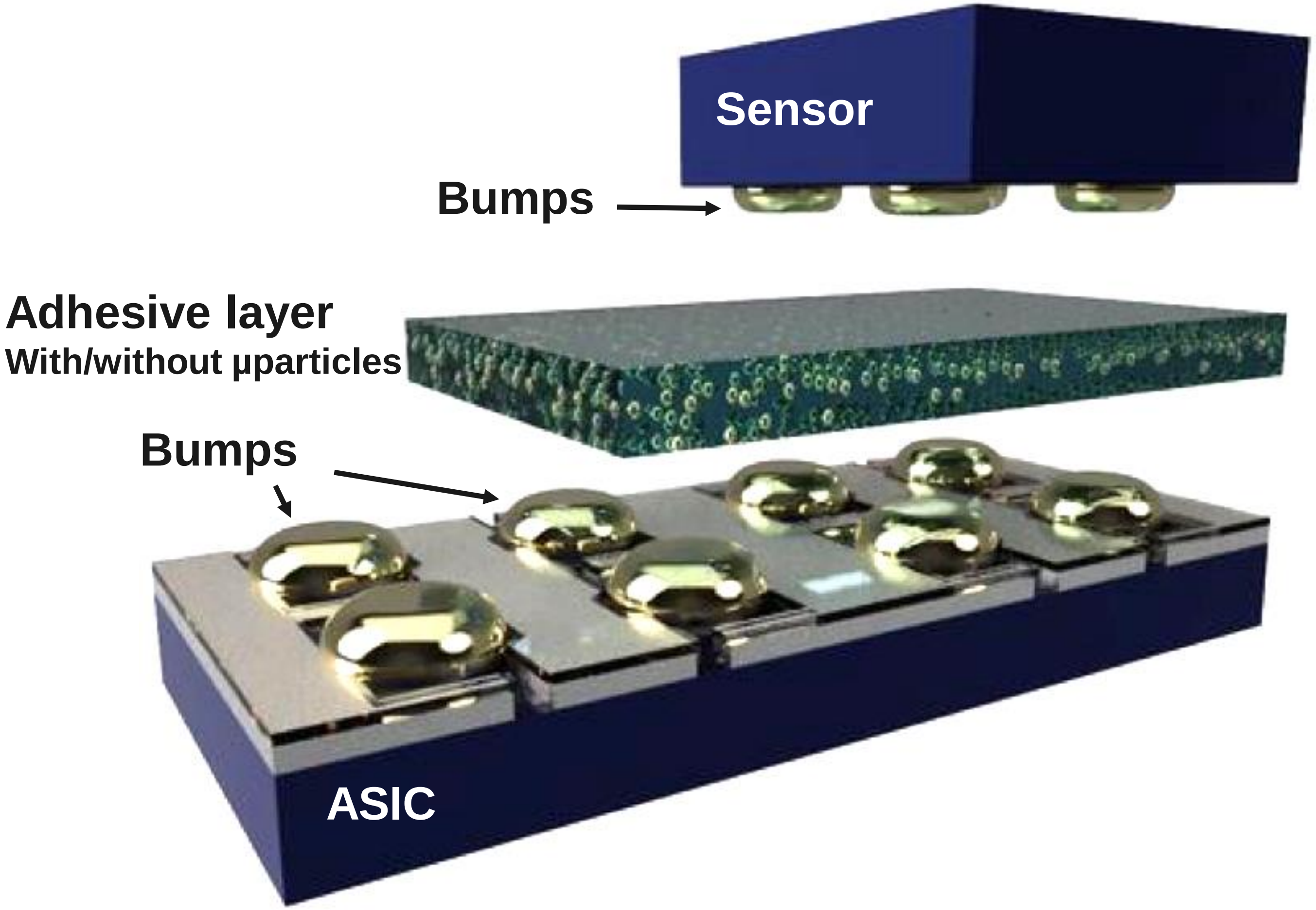
Haripriya Bangaru[1], Giovanni Calderini[3], Dominik Dannheim[1], Rui De Oliveira[1], Ahmet Lale[1], Mateus Vicente Barreto Pinto[4], Janis Viktor Schmidt[5], Peter Svihra[1], Alexander Volker[5], Xiao Yang[1]

1: CERN 2: Hamburg University 3: LPNHE-Paris, Centre National de la Recherche Scientifique
4: Universite de Geneve 5: KIT - Karlsruhe Institute of Technology

Introduction

Development of an in-house module hybridization technique in two main steps:

1. Bumping: creation of bumps on the pads of Sensor and ASIC with ENIG plating, gold studs…
2. Flip-chip assembly with an anisotropic conductive layer or non-conductive layer between the chips



Advantages:

- Single die processing
- Adaptable to the application
- Low temperature process
- Maskless
- In-house (short turnaround time, quick adjustments)

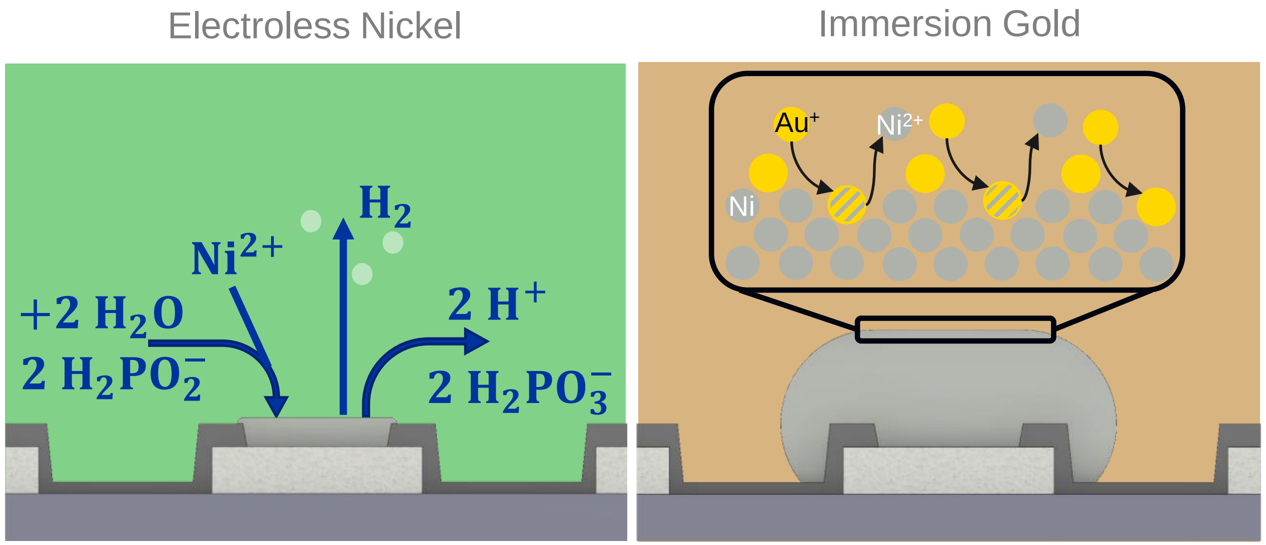
- **ENIG: E**lectroless **N**ickel **I**mmersion **G**old
- **ACF: A**nisotropic **C**onductive **F**ilm
- **ACP: A**nisotropic **C**onductive **P**aste
- **NCP**: **N**on-**C**onductive **P**aste

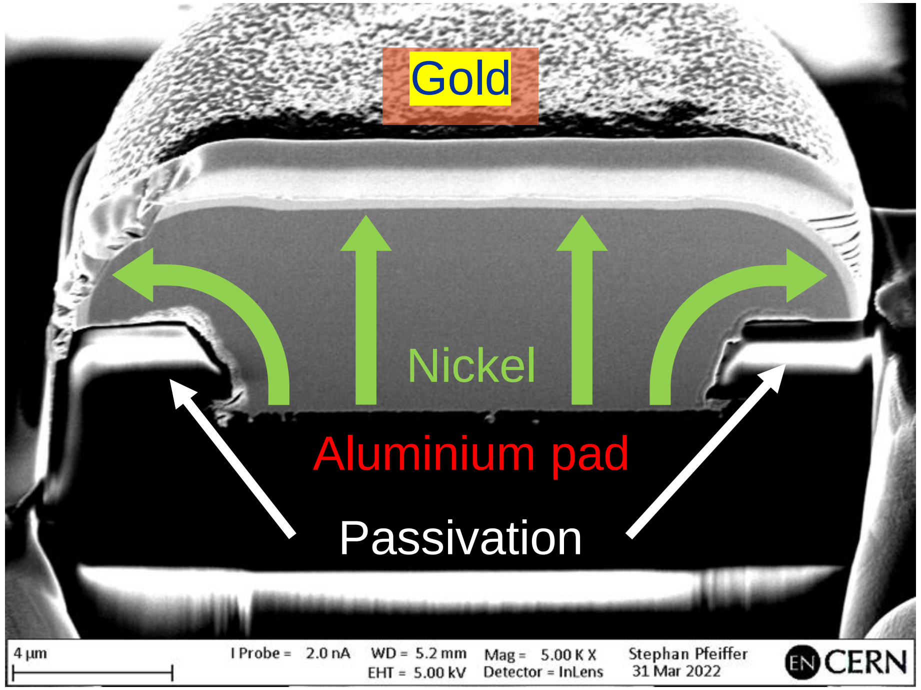
1) Chips bumping with ENIG plating

Introduction

3 main steps for Electroless Nickel Immersion Gold (ENIG) plating:

1. Pre-treatment and zincation of the aluminium pad (electroless)
2. Electroless Nickel deposition (creation of the bump)
   - Self-catalytic reaction on pad surface, bump height controlled by immersion time
3. Immersion Gold
   - Corrosion protection, bondable surface, very thin layer (< 1 µm)



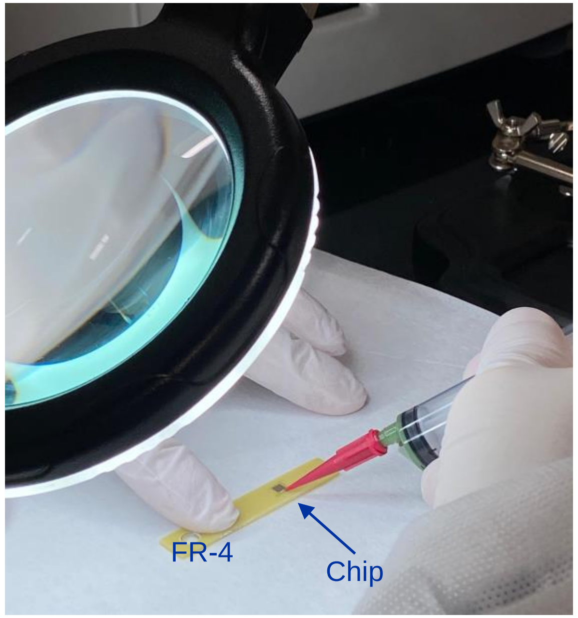


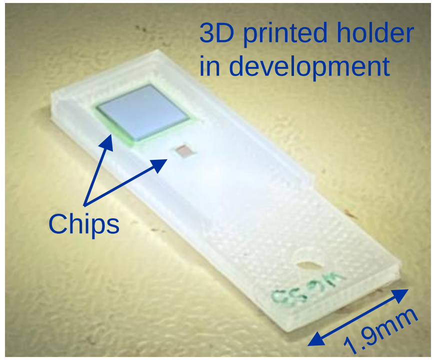
FIB cross-section of an ENIG bump on an aluminium pad

Sample preparation improvements

Samples preparation:

- Gluing the chip on holder
- Protection of bonding pads

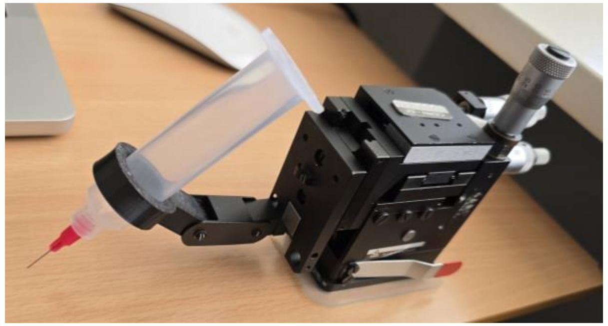


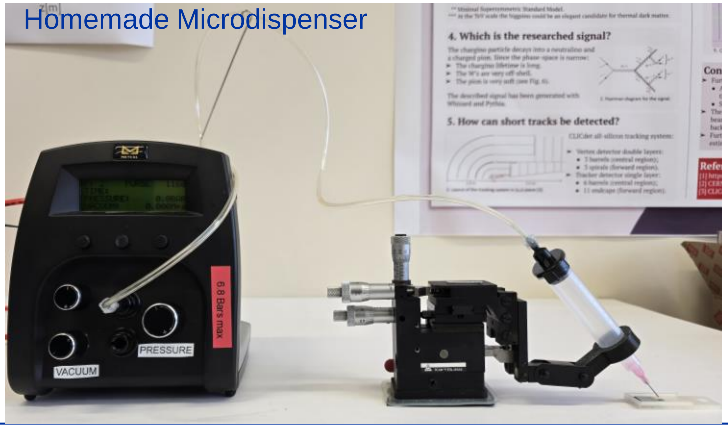


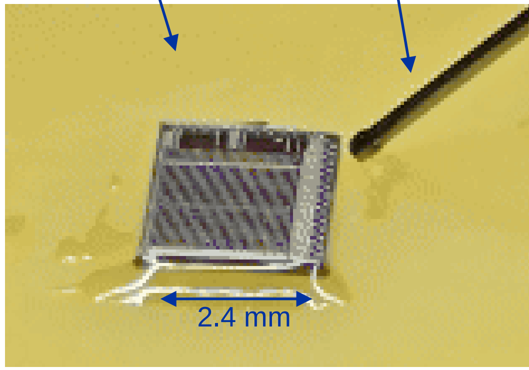
Challenges for the preparation of small-sized chips (handling, gluing, protection of bonding pads)

Development of a microdispenser for small chips gluing

3D printed adaptor

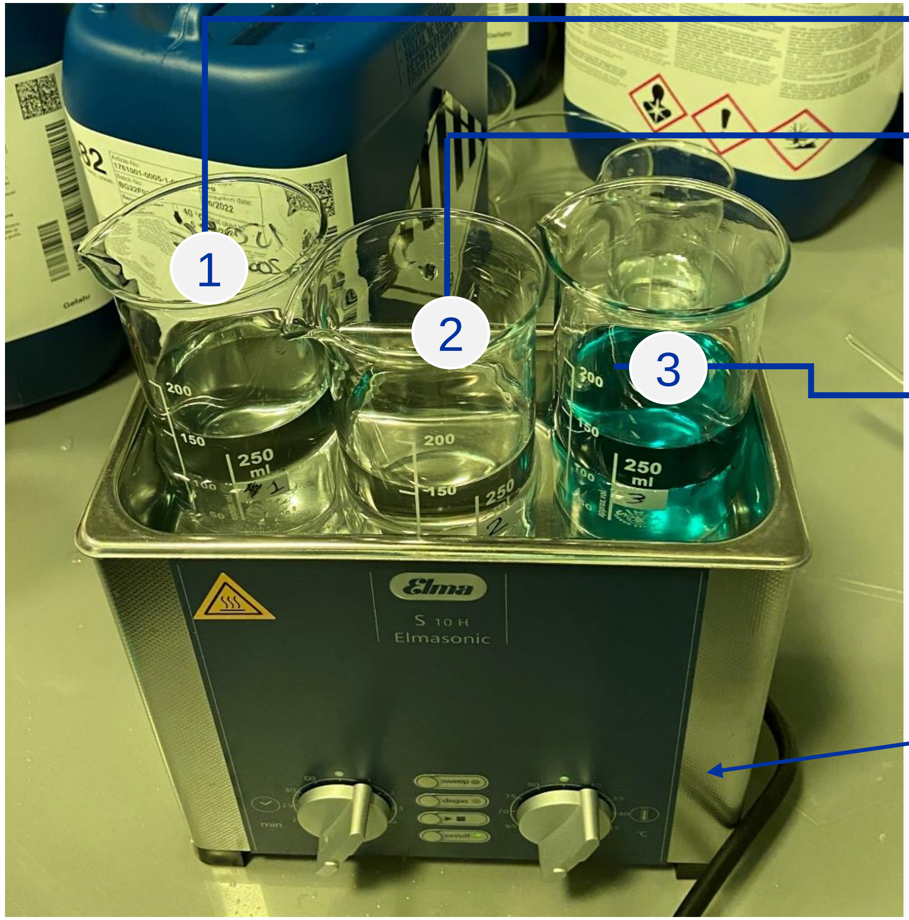






Pre-treatment setup

Pre-treatment: ultrasound + manual movements



Conditioner

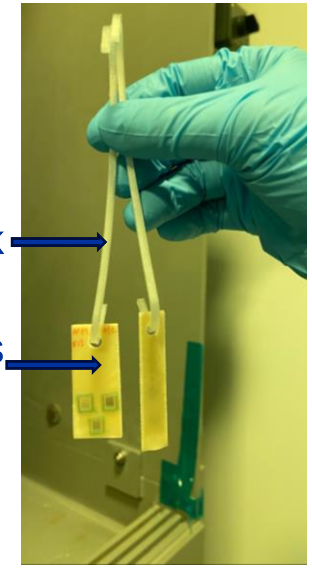
Al Etch

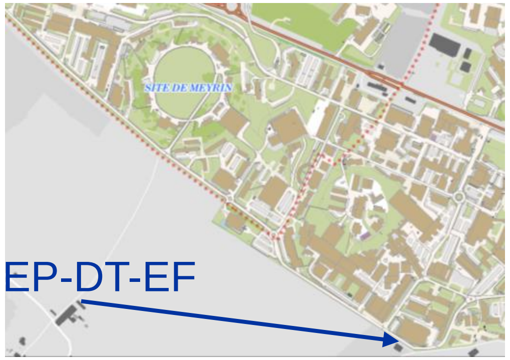
Zincate

Ultrasonic bath

Hook

Samples

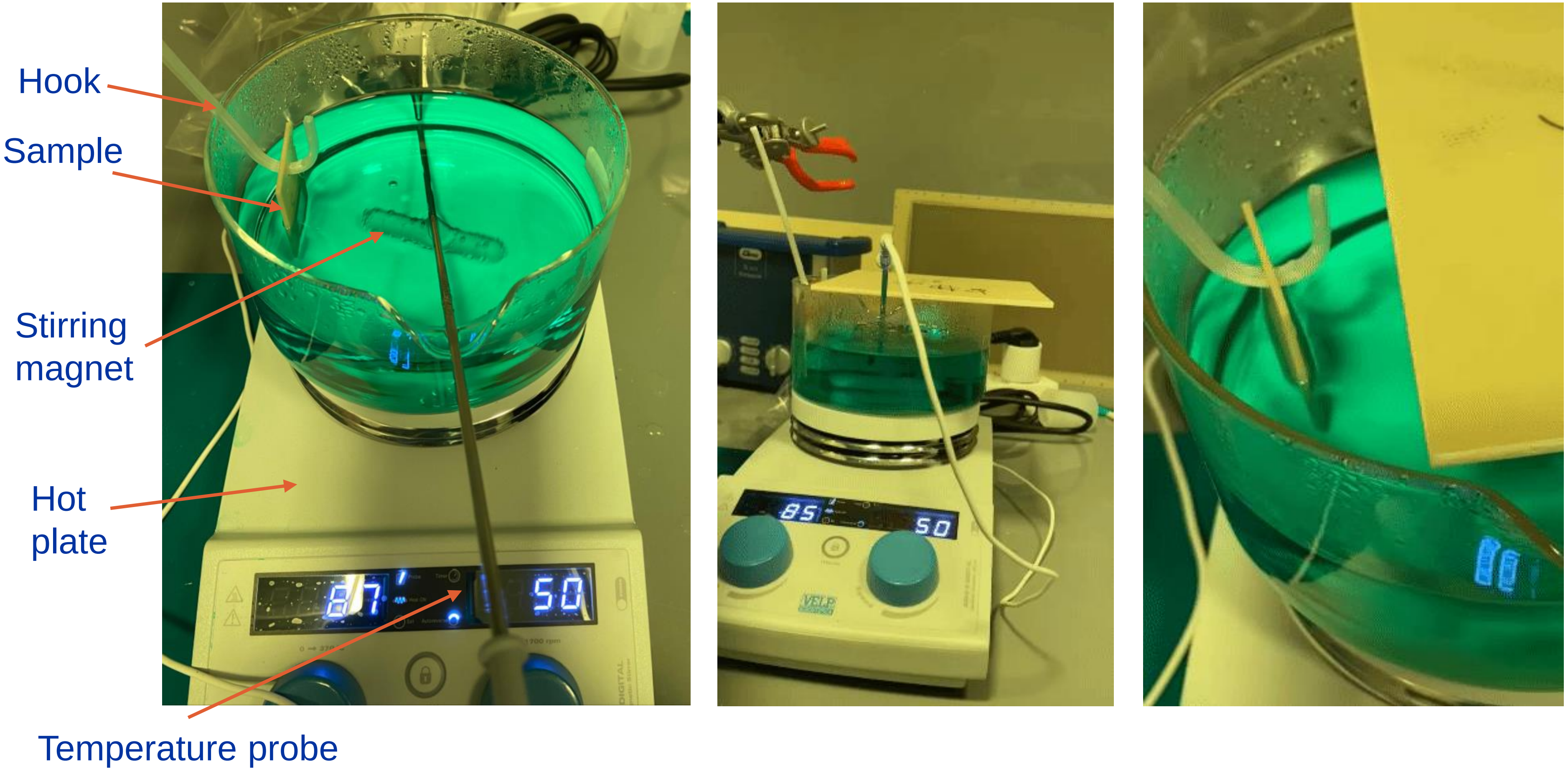




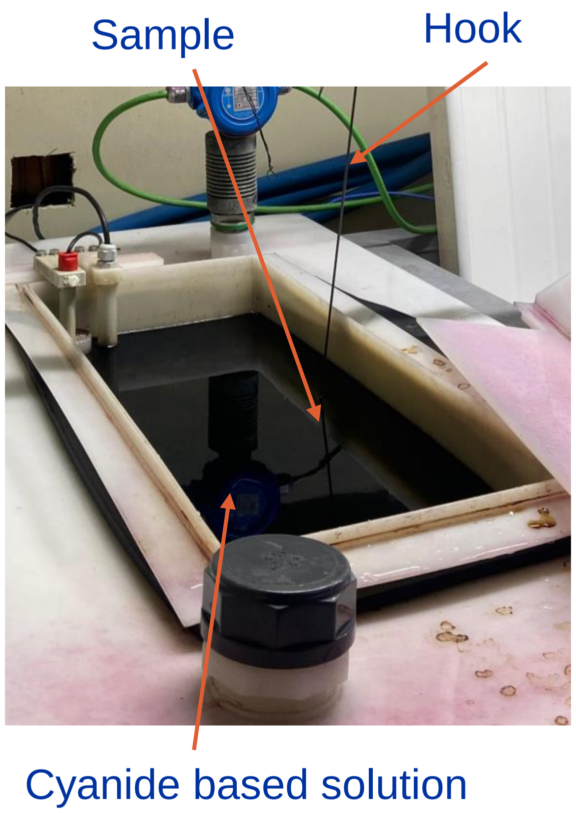
Setup at EP-DT-EF lab B107

Nickel Plating setup and gold plating

Setup for nickel plating



Setup for gold plating



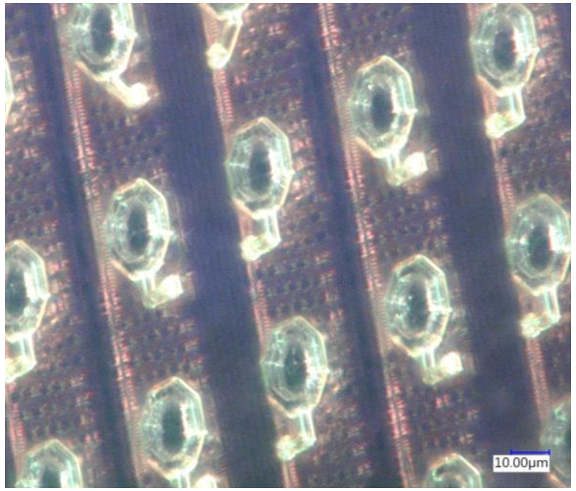
ENIG plating results on functional chips

TimeSpot ASIC
Functional chip
55µm pitch, 19µm pads

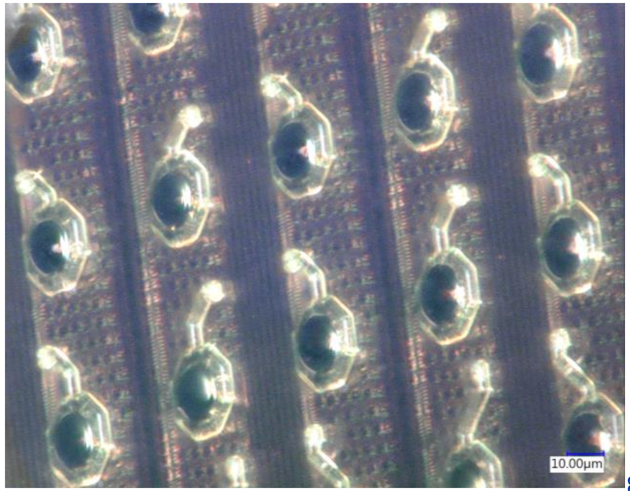
Excellent ENIG results:
- 100% of pads correctly plated (1184 pads)
- No overplating
- Bumps height: 10 µm (+/-0.5 µm) 1h deposition

Collaboration with INFN Cagliari (Angelo LOI, Adriano LAI)
https://web.infn.it/timespot/

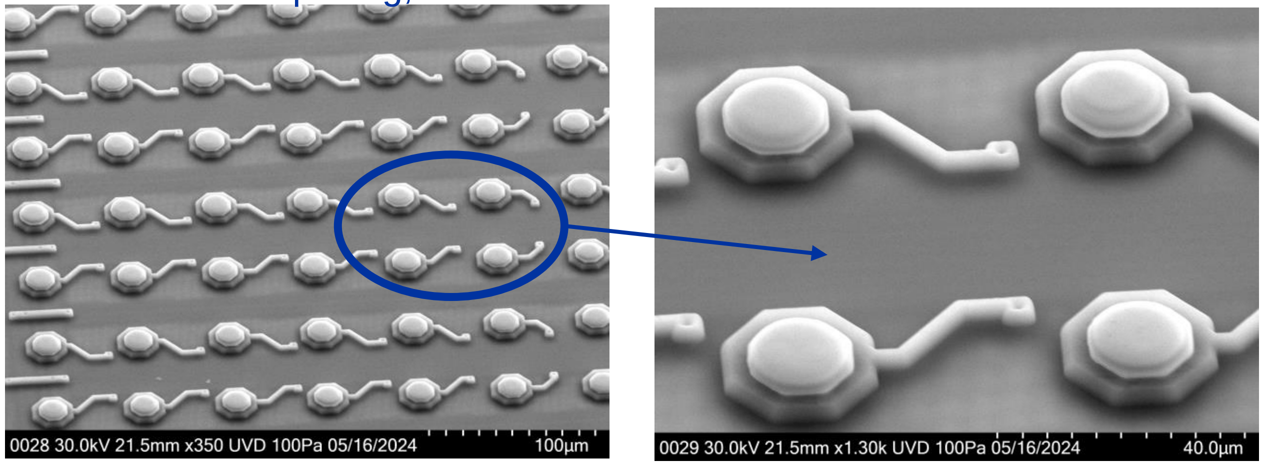
Before plating, optical microscope



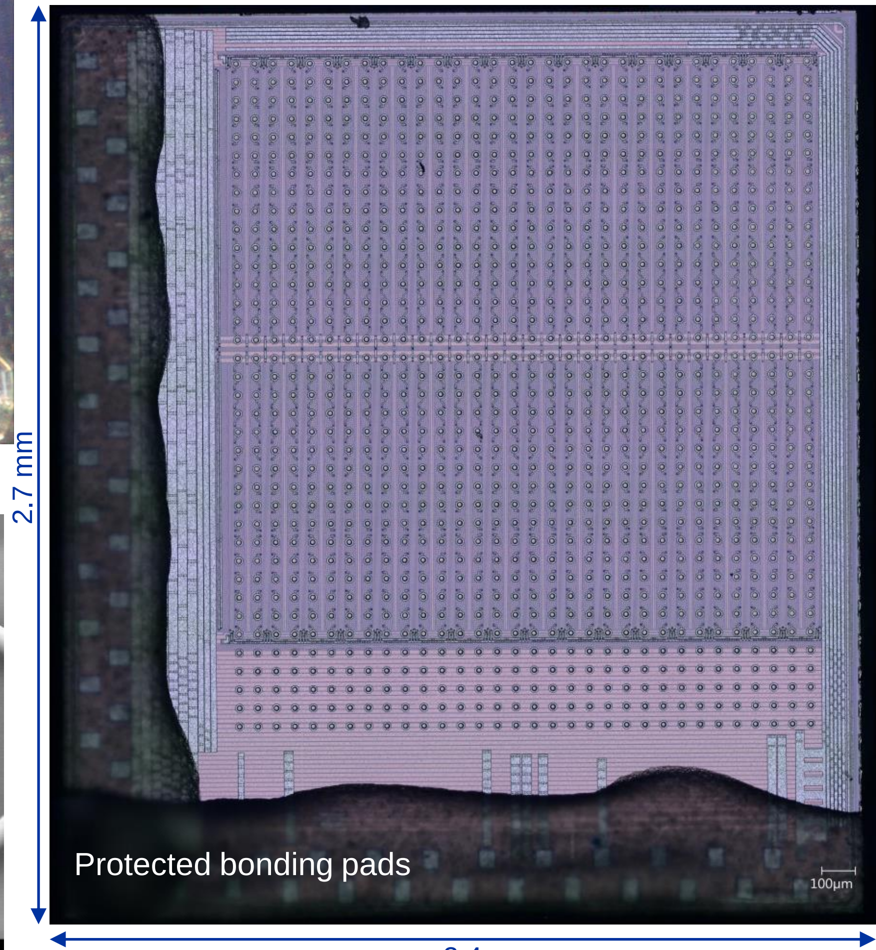
After 1h plating, optical microscope



After plating, SEM



TimeSpot ASIC



ENIG plating results on functional chips

KEK AC-LGAD
Sensors and ASICs

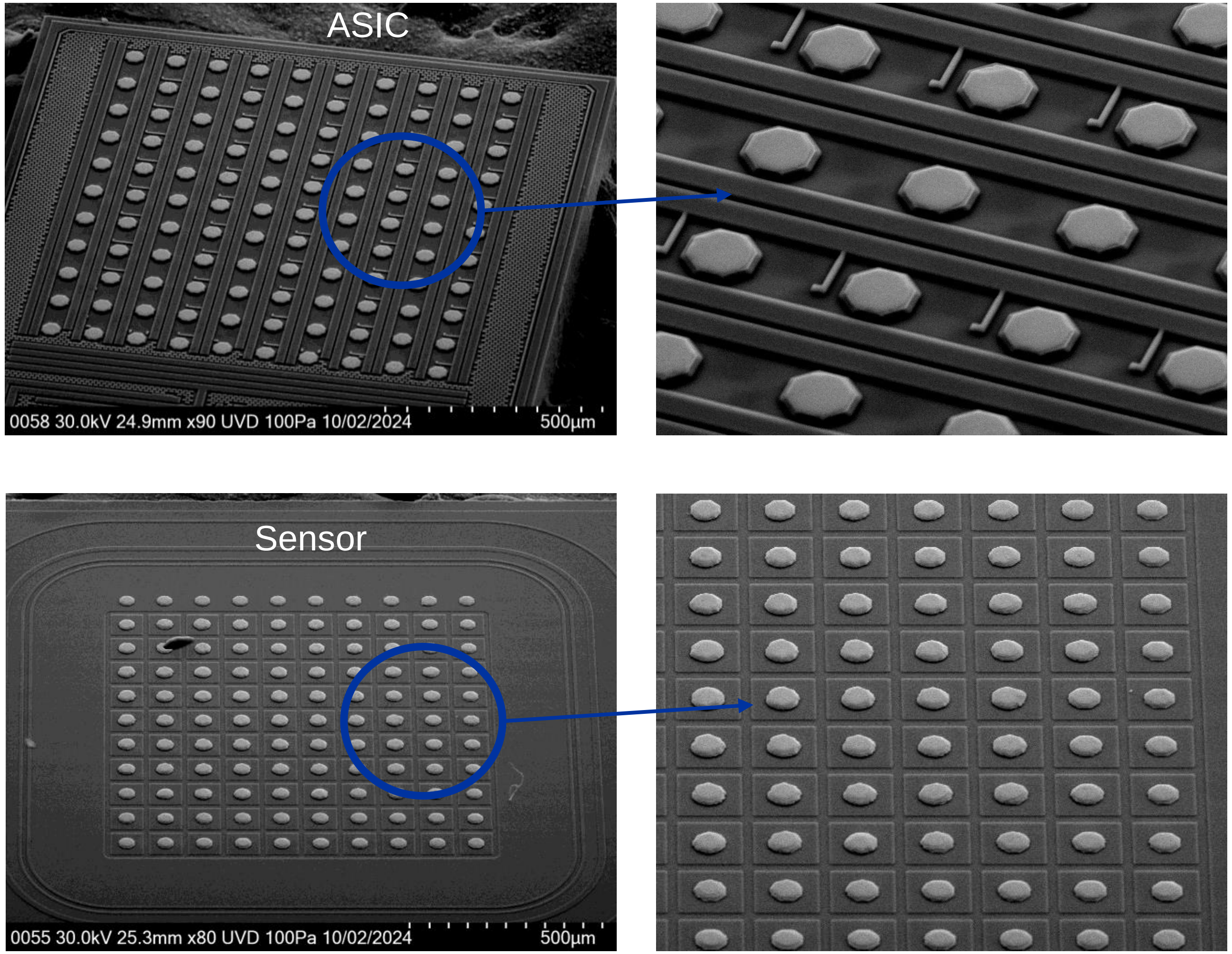
Functional chips
100 µm pitch, 40 µm diameter pads

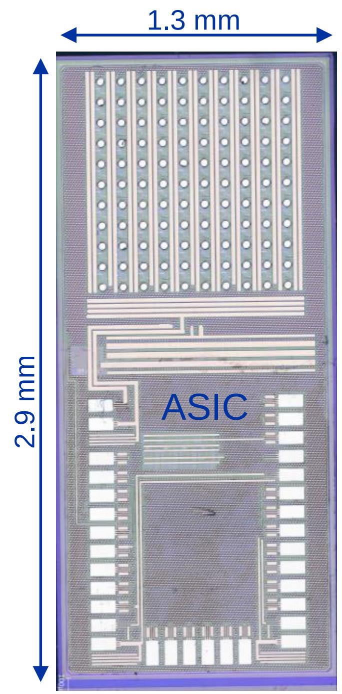
Excellent ENIG results:
- 100% of pads correctly plated (100 pads)
- No overplating
- Bumps height: 8.5 µm (± 0.6 µm)

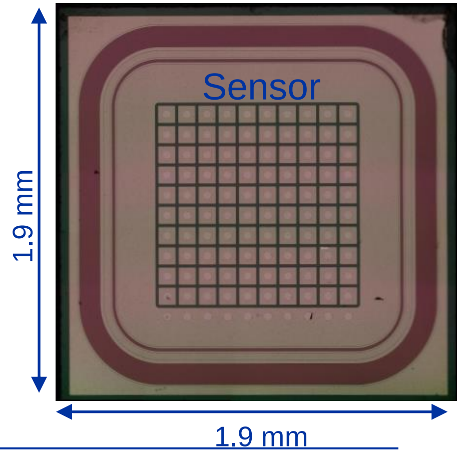
Collaboration with KEK (Koji NAKAMURA) and University of Geneva (Lorenzo PAOLOZZI)

Tomoka Imamura, Sayuka Kita, Koji Nakamura, and Kazuhiko Hara, "Development of HPK Capacitive Coupled LGAD (AC-LGAD) detectors", PoS, vol. VERTEX2023, pp. 032, 2024

After plating, SEM







ENIG plating results on functional chips

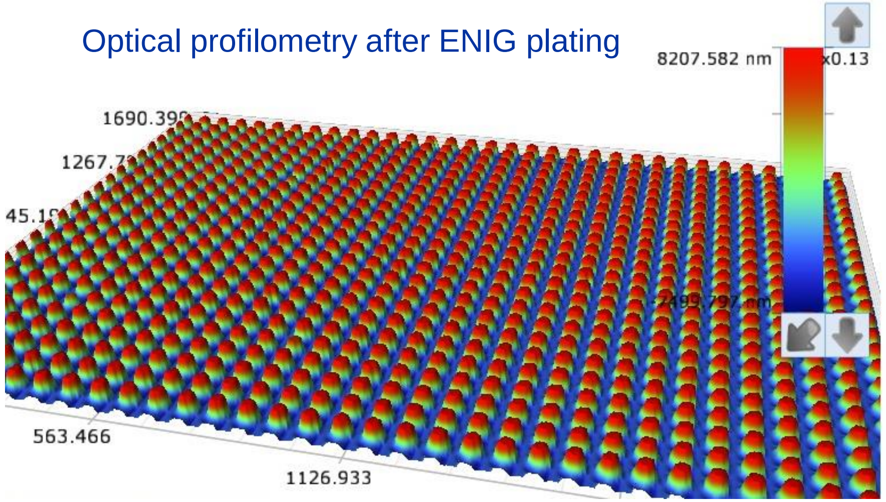
ColorPix2 Functional chips 70 µm pitch, 40 µm pads

Excellent ENIG results:

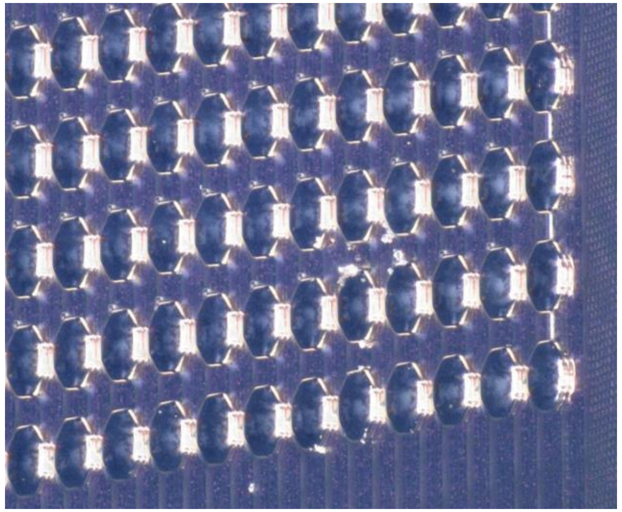
- 100% of pads correctly plated (1156 pads)
- No overplating
- Bumps height: 11 µm (± 0.5 µm) 1h deposition

"Color imaging of Xrays", FNSPE CTU in Prague
https://indico.cern.ch/event/829863/contributions/5053901/attachments/2567463/4426692/PIXEL2022_poster.pdf

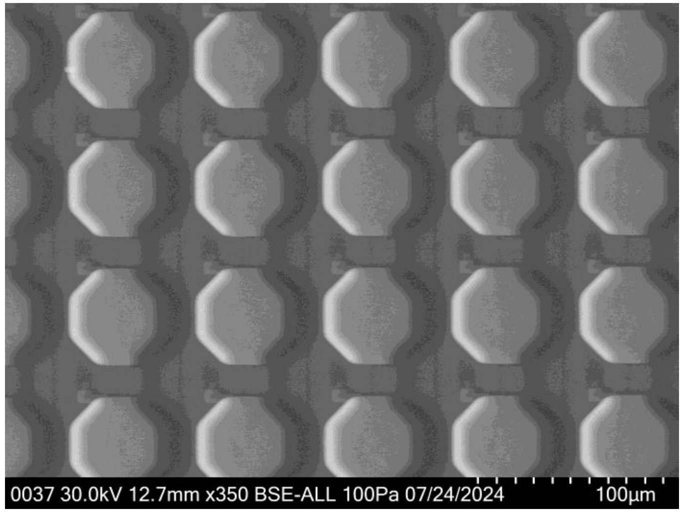
Optical profilometry after ENIG plating



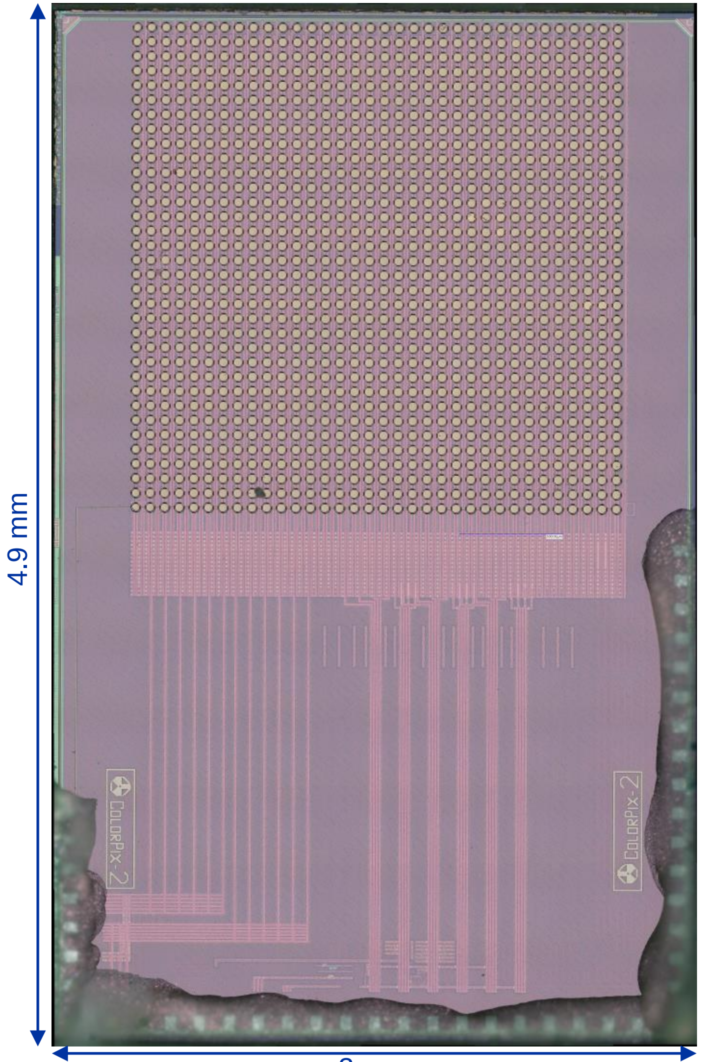
Optical microscope, 61° tilt



After plating, SEM



Optical microscopy after ENIG plating



Conclusion for ENIG plating

Optimised ENIG plating:

- Reproducibility
- No skipped pads
- No overplating
- Uniformity

Tested on different configurations:

- High pad density (20 µm pitch) and small pads (10 µm)
- Low pad density (1.3 mm pitch) and large pads (90 µm)
- Successful plating of functional chips TimeSpot, ColorPix, KEK AC-LGAD ASICs and sensors, and LGAD sensors for ALTIROC3

	Pad size	Pitch	ENIG height	Chip size
“Timepix3” daisy-chain test structures	12-22 µm	55 µm	10 µm	14x14 mm
“Small pitch” daisy-chain test structures	10x8 µm^2 (rectangular)	20 µm	4.5 µm	3.2x3.2 mm
TimeSpot ASIC	19 µm	55 µm	10 µm	2.4x2.7 mm
ATLAS HGTD LGAD sensors	90 µm	1.3 mm	8.5 µm	20x22 mm
KEK AC-LGAD Sensor and ASIC	40 µm	100 µm	8.5 µm	ASIC 1.3x2.9 mm Sensor 1.9x1.9 mm
ColorPix2	40 µm	70 µm	11 µm	3x4.9 mm

2) Flip-chip hybridisation

Hybridisation with flip-chip

Bonding done at Geneva University using semi-automatic flip-chip bonder

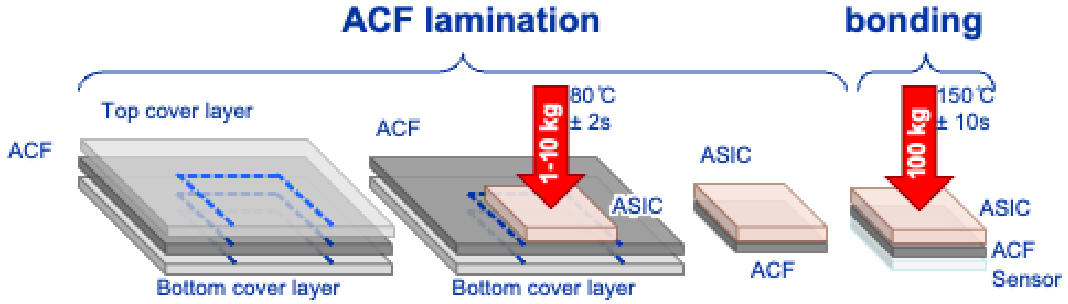
- Precise temperature, pressure and alignment control
- Heating up to 400℃ and force applied up to 100 kgf
- Available for bonding with **A**nisotropic **C**onductive and **N**on-conductive **F**ilm/**P**aste – **ACF/ACP** or **NCF/NCP**

UNIVERSITÉ
DE GENÈVE
FACULTÈ DES SCIENCES

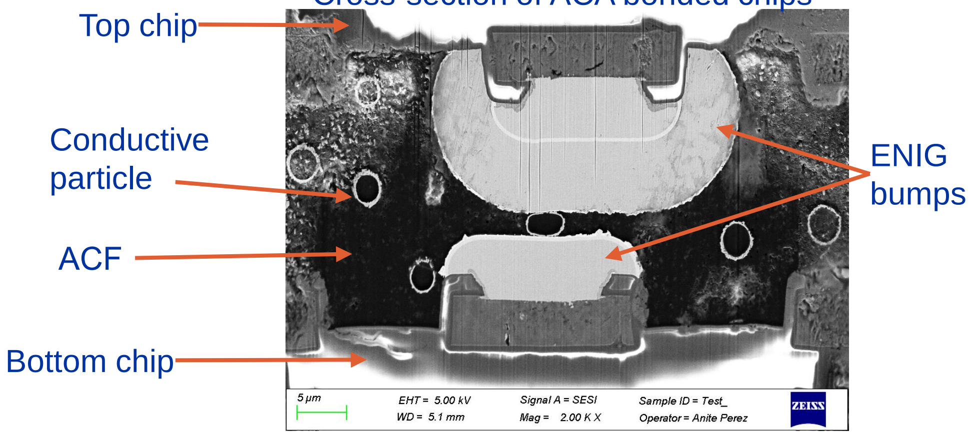
Flip-chip bonder SET ACCμRA100

ACF bonding has two steps: lamination and bonding

- ACF lamination at 80°C, ≈ 5 kg/cm2
- Bonding at 150°C, ≈ 50 kg/cm2



Cross-section of ACA bonded chips

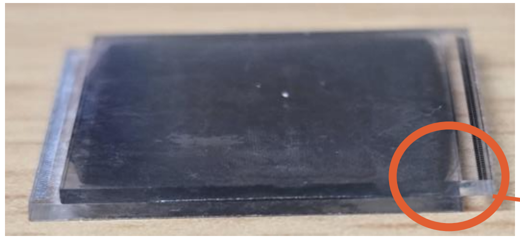


ACP bonding has three steps:

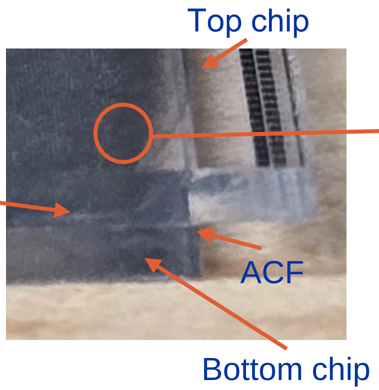
- Mixing the micro-particles with the liquid adhesive
- Dispensing the mix on the bottom chip
- Flip-chip bonding

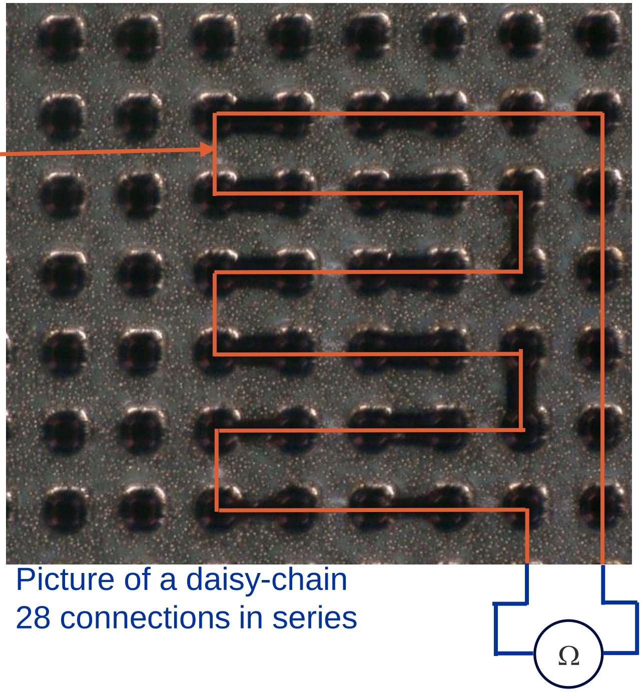
Characterisation of daisy-chain test structures

Anisotropic Conductive Film bonding

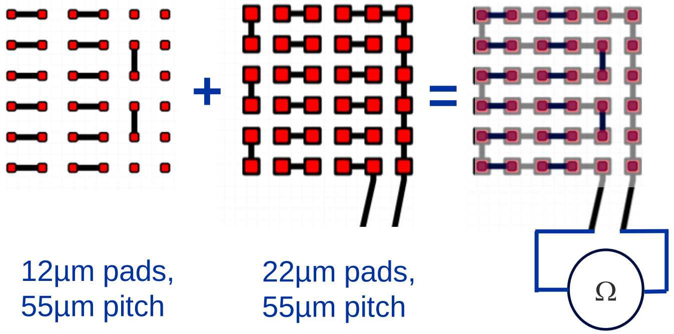


Timepix3 type daisy-chain test chips, flip-chip bonded with 18 µm ACF (3 µm particles)





Picture of a daisy-chain 28 connections in series



Resistance measurement (4-wire sensing)

After flip-chip bonding

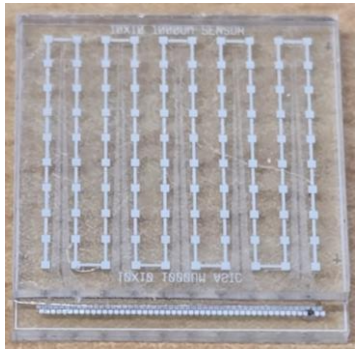
- 96.8 % of pads connected

After thermal cycling (25 cycles from -55°C to 60°C, 10°C/min):

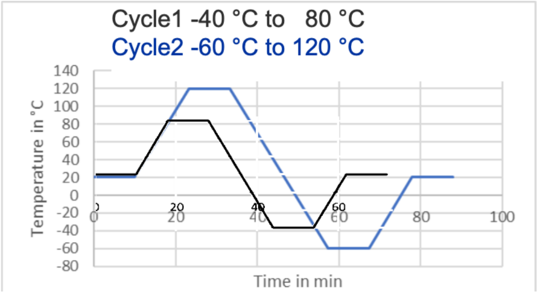
- 96.2 % of pads still connected

Anisotropic Conductive Paste bonding

Daisy-chain test chips with 10x10 connections, 300 µm pads, 1 mm pitch, flip-chip bonded with ACP (20 µm Ag particles)



- 98.6 % of pads connected
- After thermal cycling (20 cycles from -40°C to 80°C): 96.8 % pads still connected
- After thermal cycling (20 cycles from -60°C to 120°C): 95.7 % pads still connected

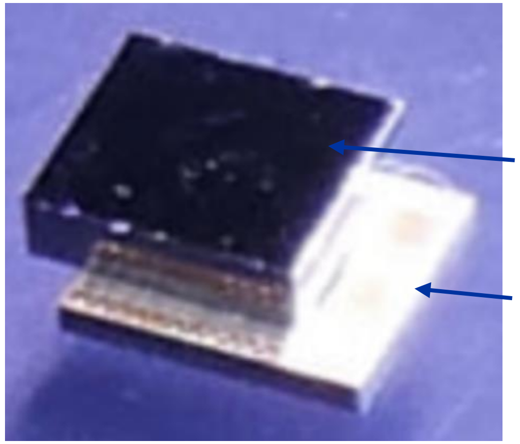


Hybridisation and characterisation of functional chips

TimeSpot:

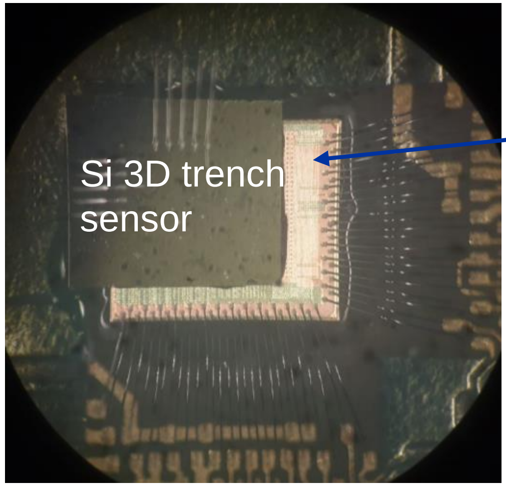
One hybrid realised with not optimised ENIG plating (first plating, before optimisation)

- 32x32 pixels, 55 µm pitch
- Si 3D trench sensor
    - ACF 18 µm thick
    - >85% connection yield *(Characterised by Angelo Loi INFN Cagliari)*



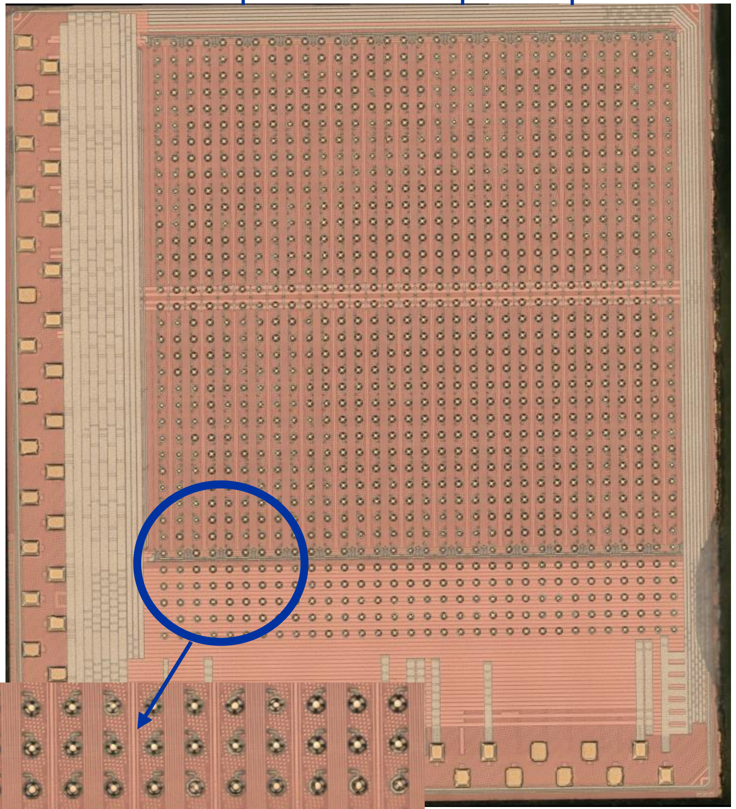
Si 3D trench sensor

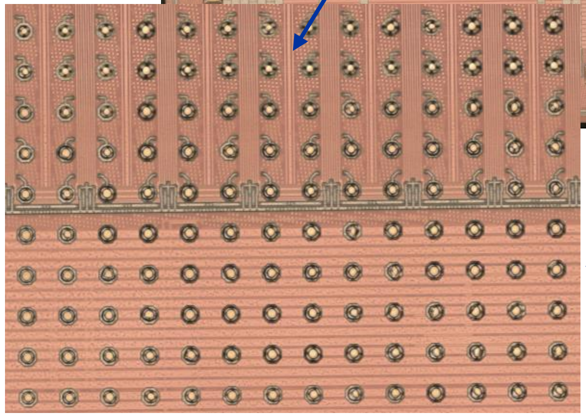
TimeSpot chip



TimeSpot chip

ENIG plated TimeSpot chip



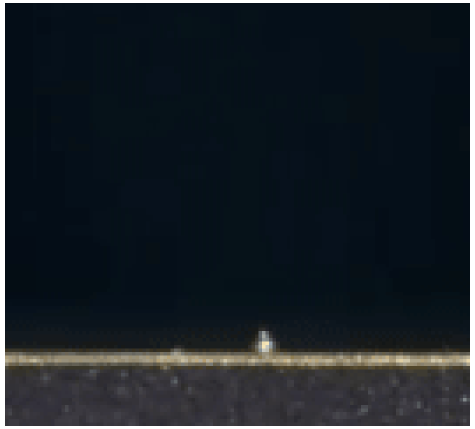


Before ENIG optimisations, variations of bump sizes

3) Hybridisation with gold studs

Gold-stud hybridisation of ALTIROC3/A and LGAD sensors

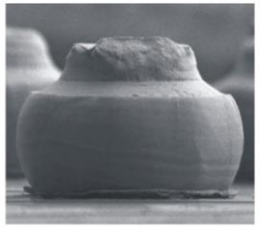
- Using ALTIROC3/A ASICs and LGAD sensors from ATLAS High-Granularity Timing Detector (HGTD) to develop new in-house bonding process for sensor and ASIC qualification
- Single and stacked double gold studs used for the connections between the chips, epoxy underfill for bonding
- Used for radiation-hardness qualification of LGAD sensors
- Low temperature process (60°C) to avoid uncontrolled annealing



Gold studs are deposited one by one

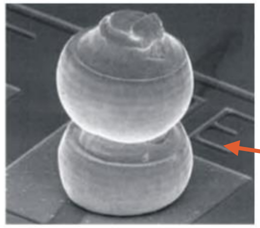
https://www.youtube.com/watch?v=ICRDBpmev4o&t=42s&ab_channel=TPT-Wirebonder

Gold stud



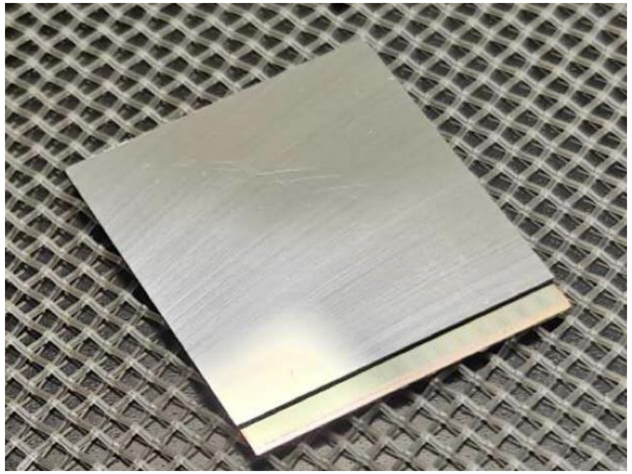
Pictures from Hybrid SA

Stacked Gold studs

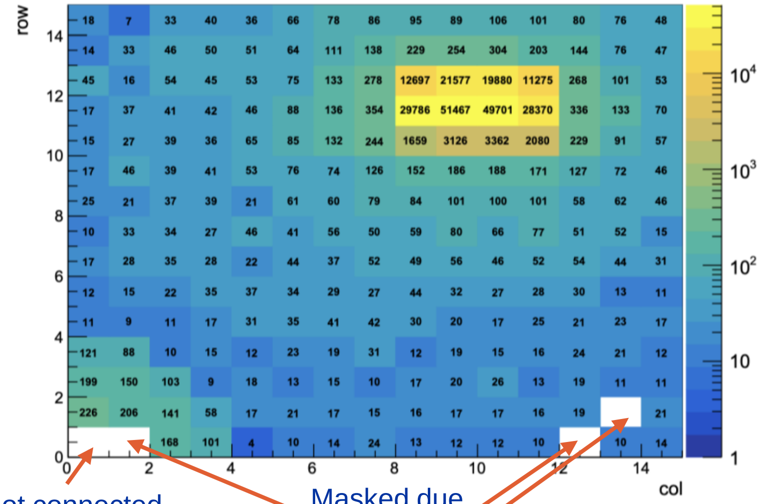


Preferred this solution to increase the gap between ASIC and sensor from 20 µm to 35 µm and thereby decrease coupling between them

ALTIROC/LGAD Hybrid
Flip-chip done with NCP (Araldite 2011)



Test-beam occupancy map of ALTIROC with double gold studs + irradiated LGAD sensor



Not connected by design

Masked due to high noise

Confirmation of good inter-connection with occupancy map (≈ 100%)

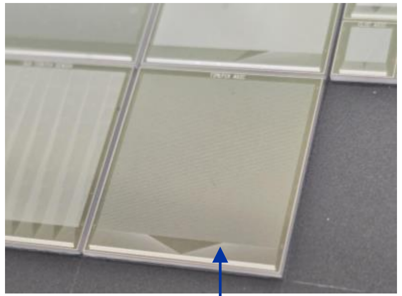
- High connection yield, reproducibility, low temperature process
- Only for large pitch (>100µm), large pads (>80µm) chips

Conclusion

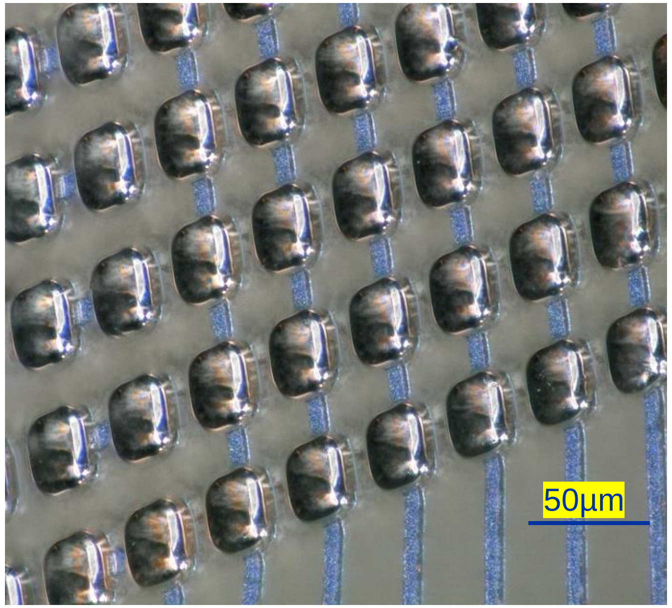
- **Optimised ENIG plating tested on many different configurations**
  - Functional chips, with different pad size, pitch, chip size…
- **Different approaches studied for hybridisation**
  - ACF, ACP, NCP, Gold Studs
- **Successful flipchip bonding of different chips with different sizes**
  - Optimisation of bonding parameters (pressure, time, temperature)
- **Reliability tests in climate chamber (ongoing)**
  - Good results for both the ACF and the ACP

ENIG plating results on test structures

Timepix3 type daisy-chain test structures, 22x22 µm pads and 55 µm pitch

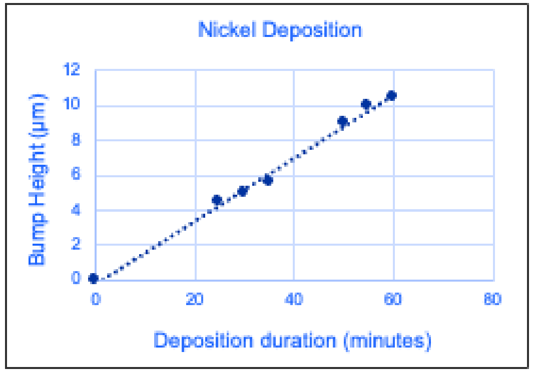


Timepix 3 type daisy-chain device test structure (14x14mm)

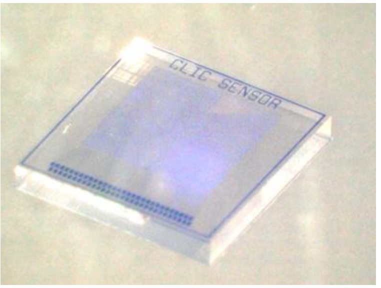


Excellent ENIG results:

- Good bump homogeneity
- >99% of 65536 pads correctly plated
- Bumps height: 10 µm (± 0.5 µm) 55min deposition



Small pitch/small pads test structures, <u>20 µm pitch, 10x8 µm rectangular pad size</u> (High connection density)

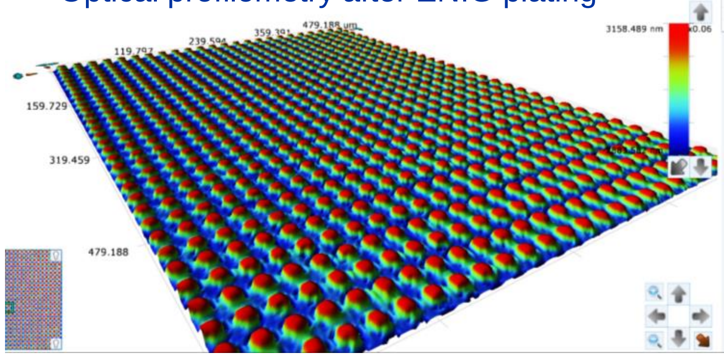


Small pitch/small pads test structures test structures (3.2x3.2mm)

Excellent ENIG results:

- Good bump homogeneity
- >99% of 16384 pads correctly plated
- Bumps height: 4.5 µm (± 0.2 µm) 25min deposition

Optical profilometry after ENIG plating



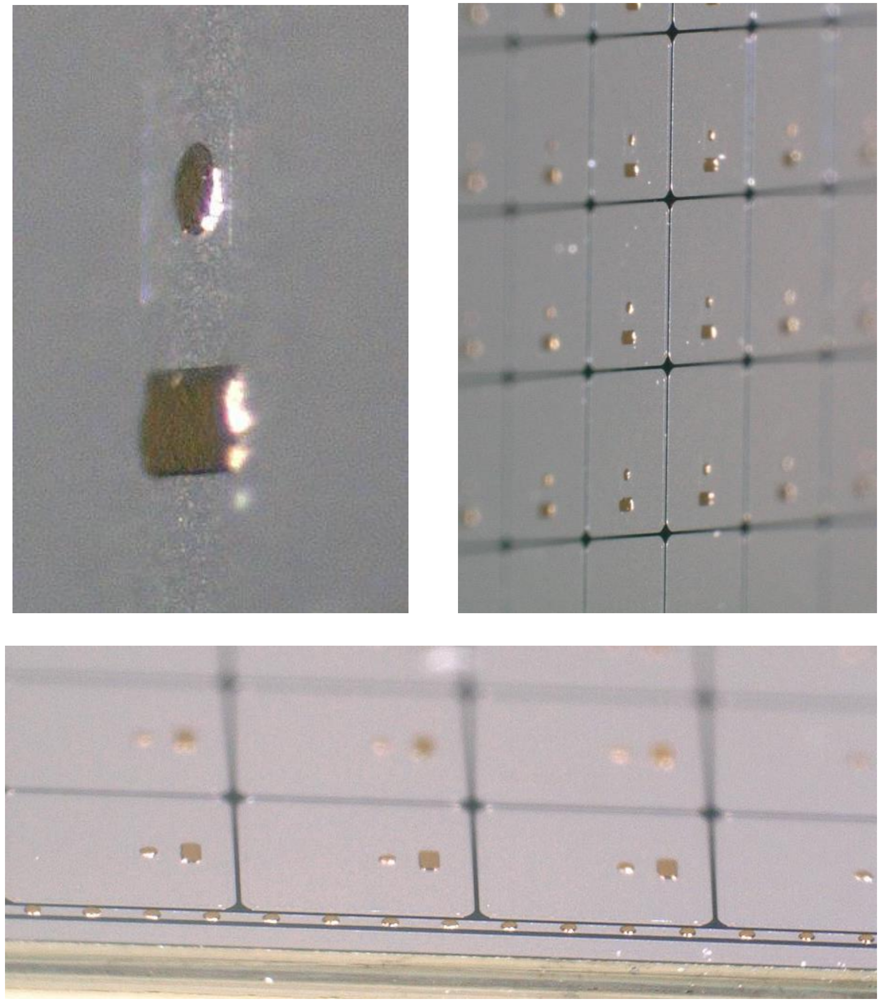
ENIG plating results on functional chips

ATLAS HGTD
LGAD sensors
Functional chips
1.3mm pitch, 90 µm diameter pads

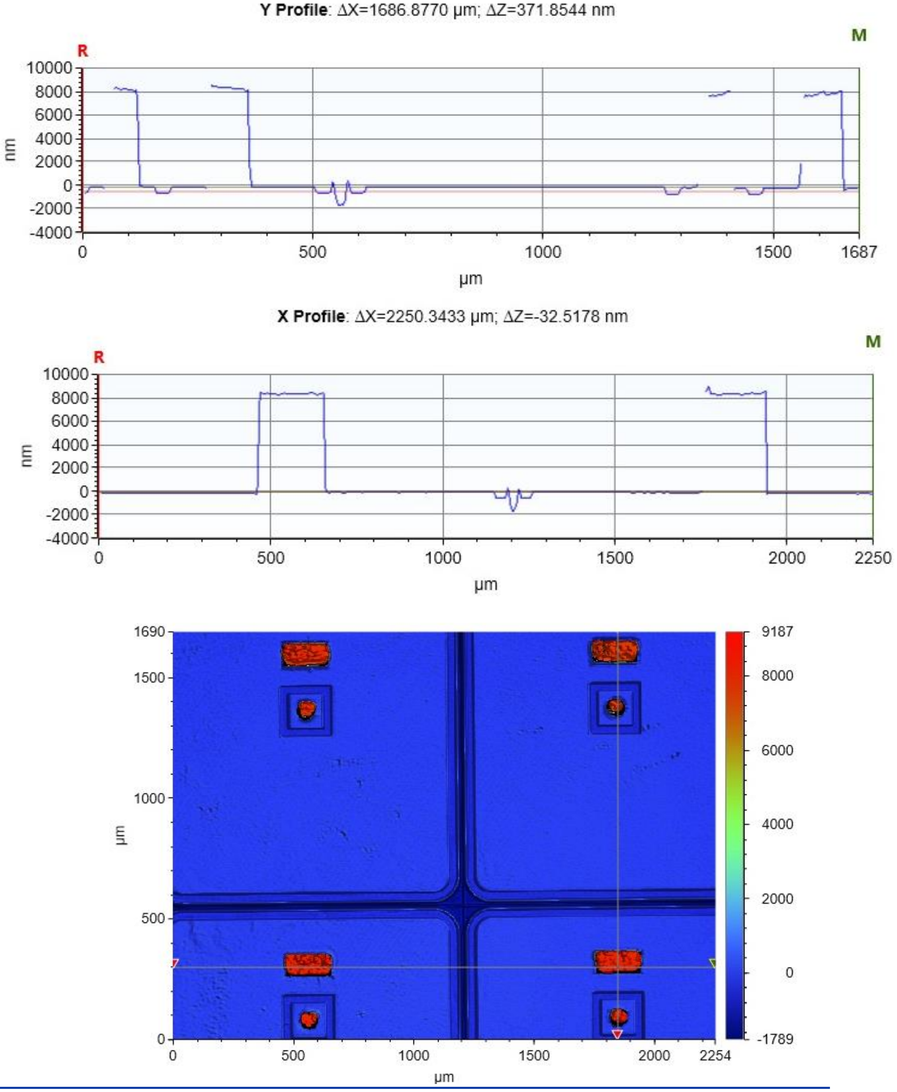
Good ENIG results:

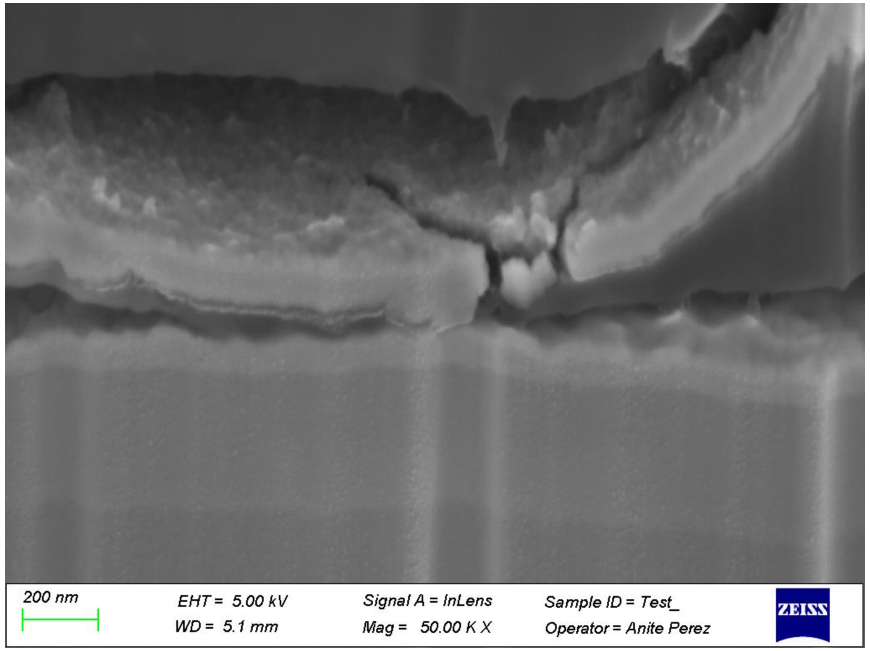
- Homogeneity of bumps achieved with no overplating
- 100% of pads correctly plated (225 pads)
- Bumps height: 8.5 µm (± 0.7 µm) (1h deposition)

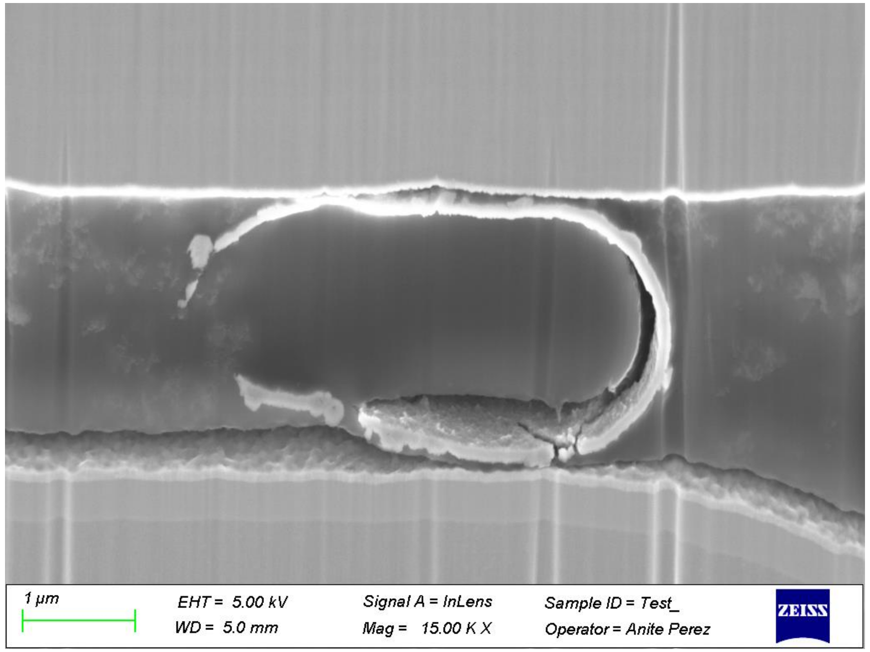
Optical microscope, 62° tilt



Optical profilometry after ENIG plating

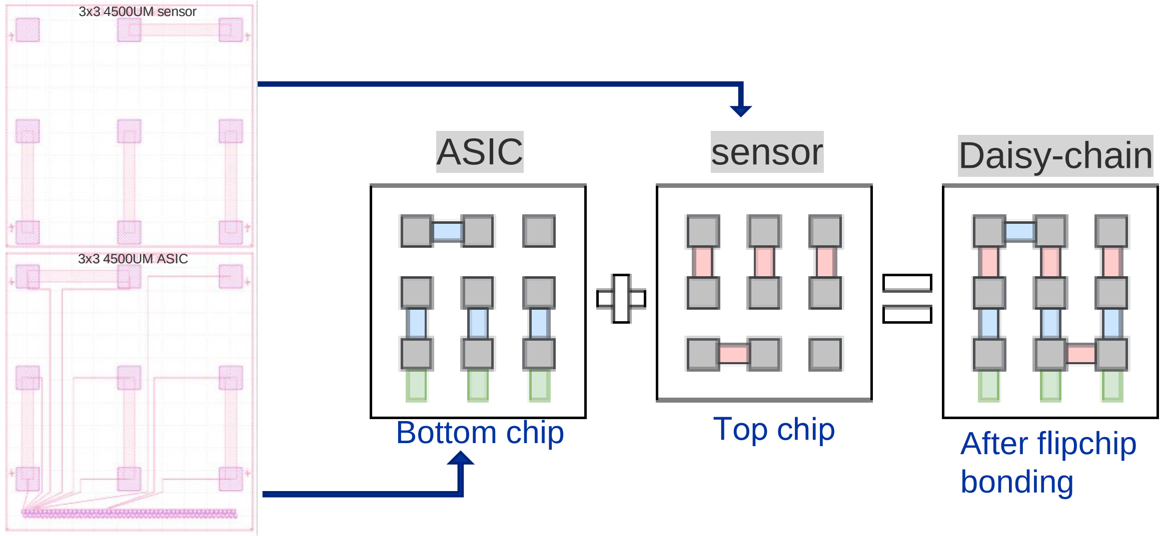



200 nm
EHT = 5.00 kV
WD = 5.1 mm
Signal A = InLens
Mag = 50.00 K X
Sample ID = Test_
Operator = Anite Perez
ZEISS

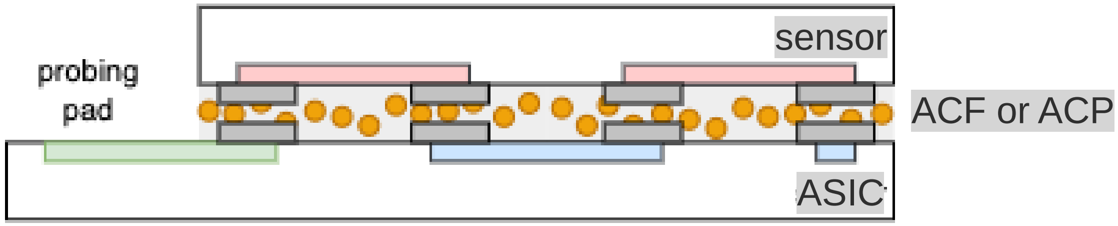

1 µm
EHT = 5.00 kV
WD = 5.0 mm
Signal A = InLens
Mag = 15.00 K X
Sample ID = Test_
Operator = Anite Perez
ZEISS

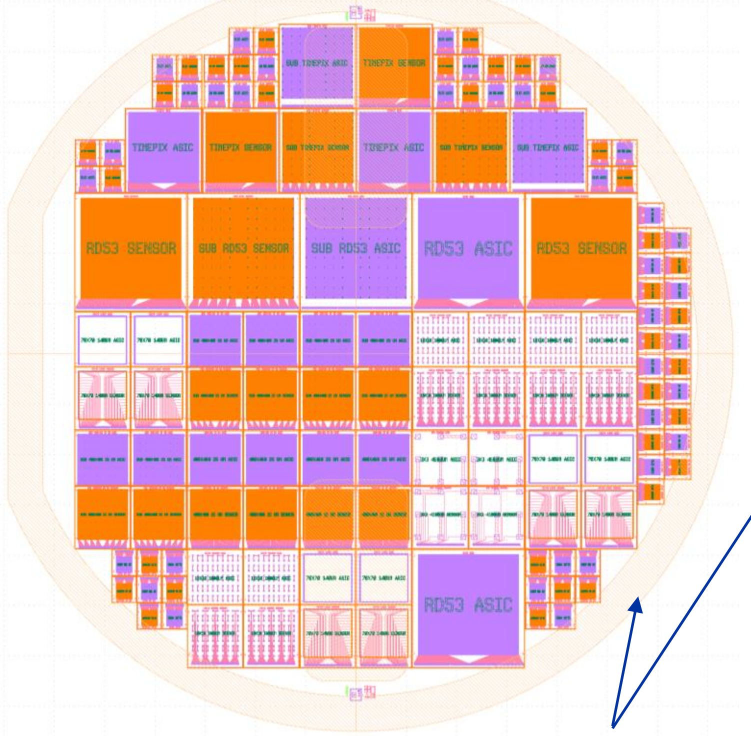
Test dedicated daisy-chain chips on glass wafer

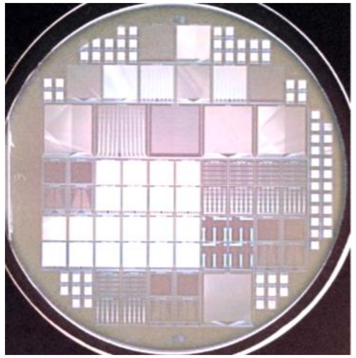
Top view



Side view







Daisy chain devices produced at FBK

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

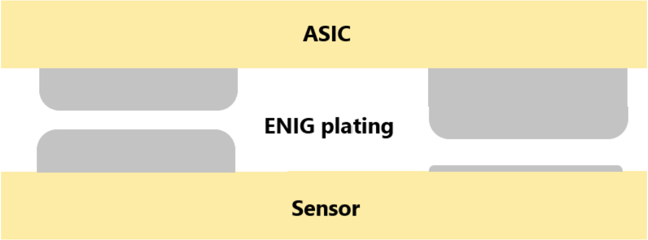
- 6” glass wafers, 625 µm thick
- Varying Bonding area, pad size and pitch, matching different target applications

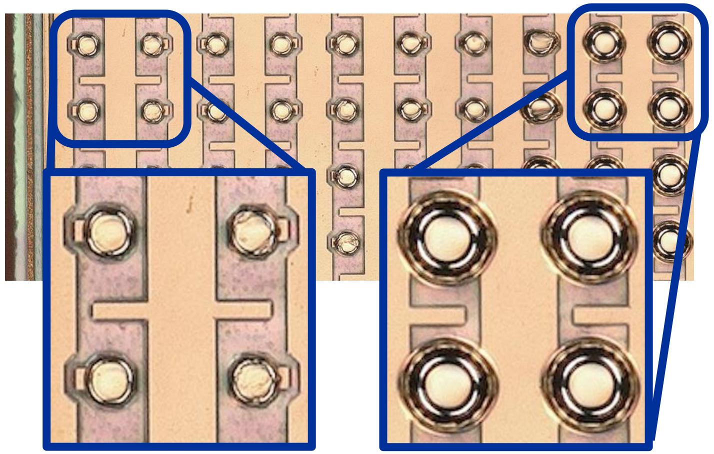
https://zenodo.org/records/7310324

LPNHE PARIS
FONDAZIONE BRUNO KESSLER
AIDA innova

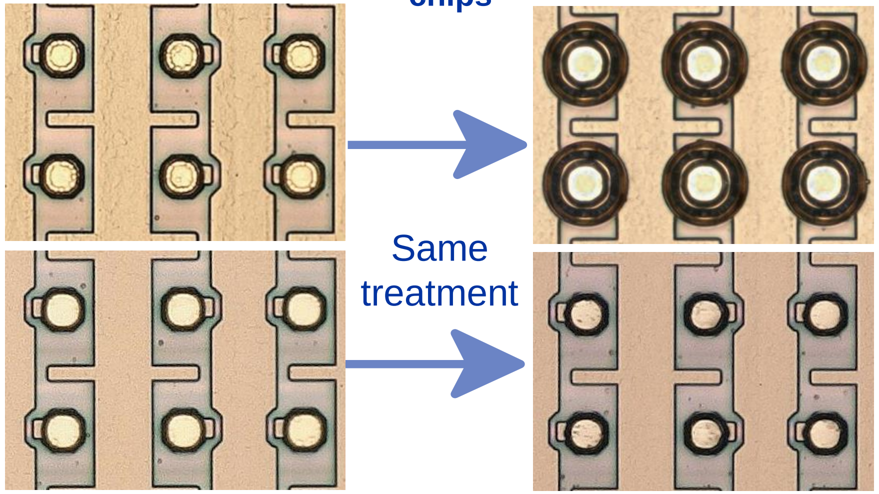
Challenges of initial platings

Uniformity of nickel bump height across the chips

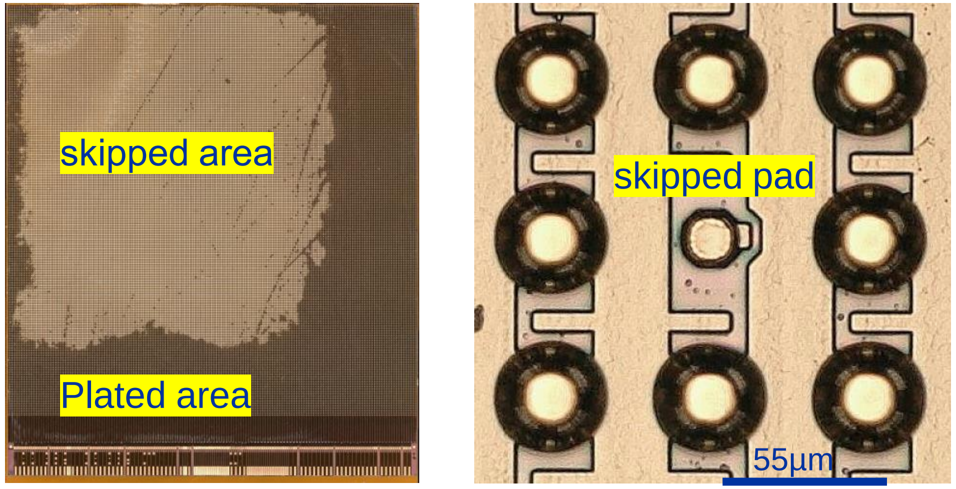




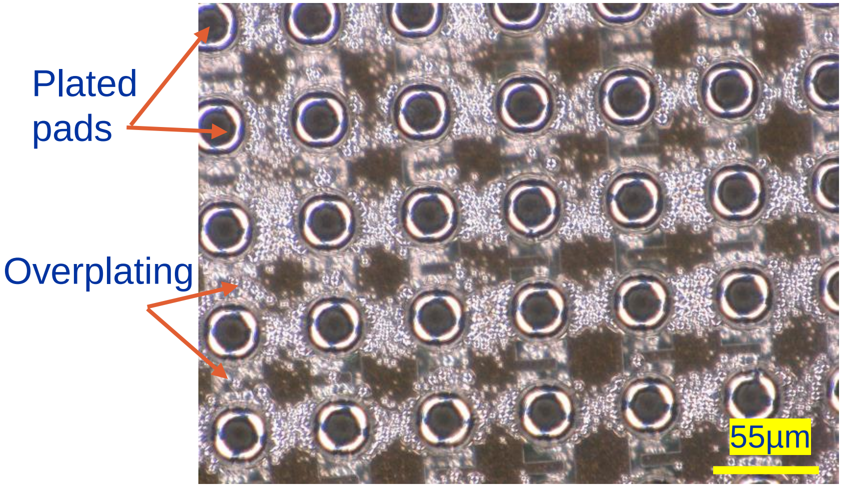
Deposition reproducibility on different chips



Non-plated or skipped pads/areas



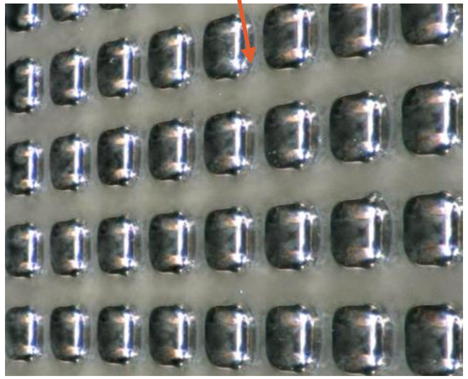
Overplating (plating on areas that should not be plated)



ENIG plating on high connection density chips (ex: CLICpix2, 12µm pads; 25µm pitch) !!

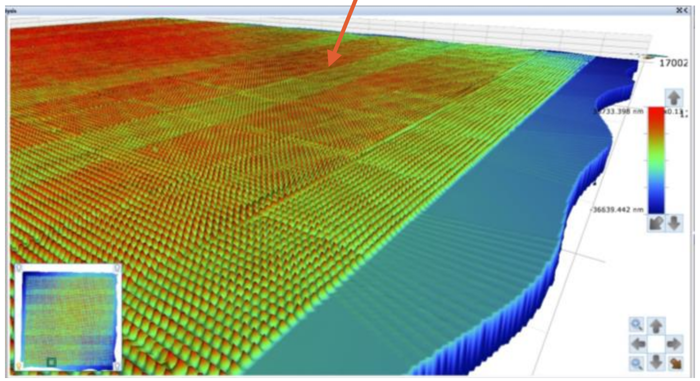
Characterisation of ENIG plating

Keyence optical microscope



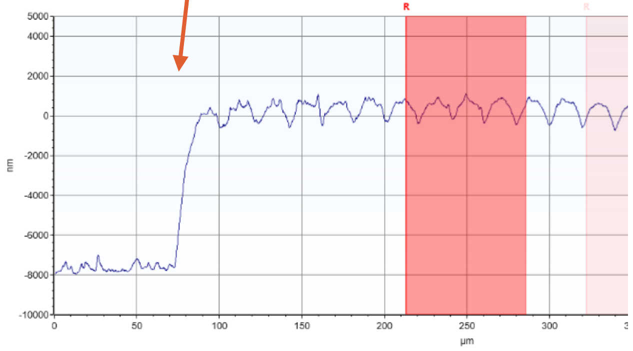
Optical profilometer

Bruker Contour



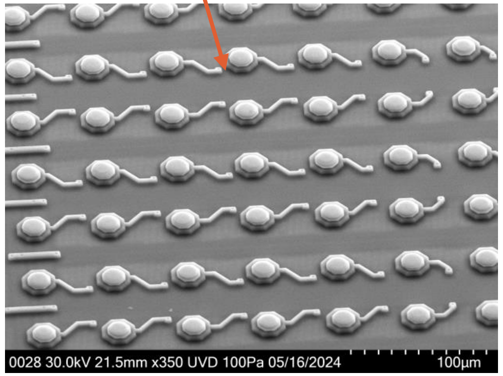
Mechanical profilometer

Bruker Dektat XT Stylus



SEM

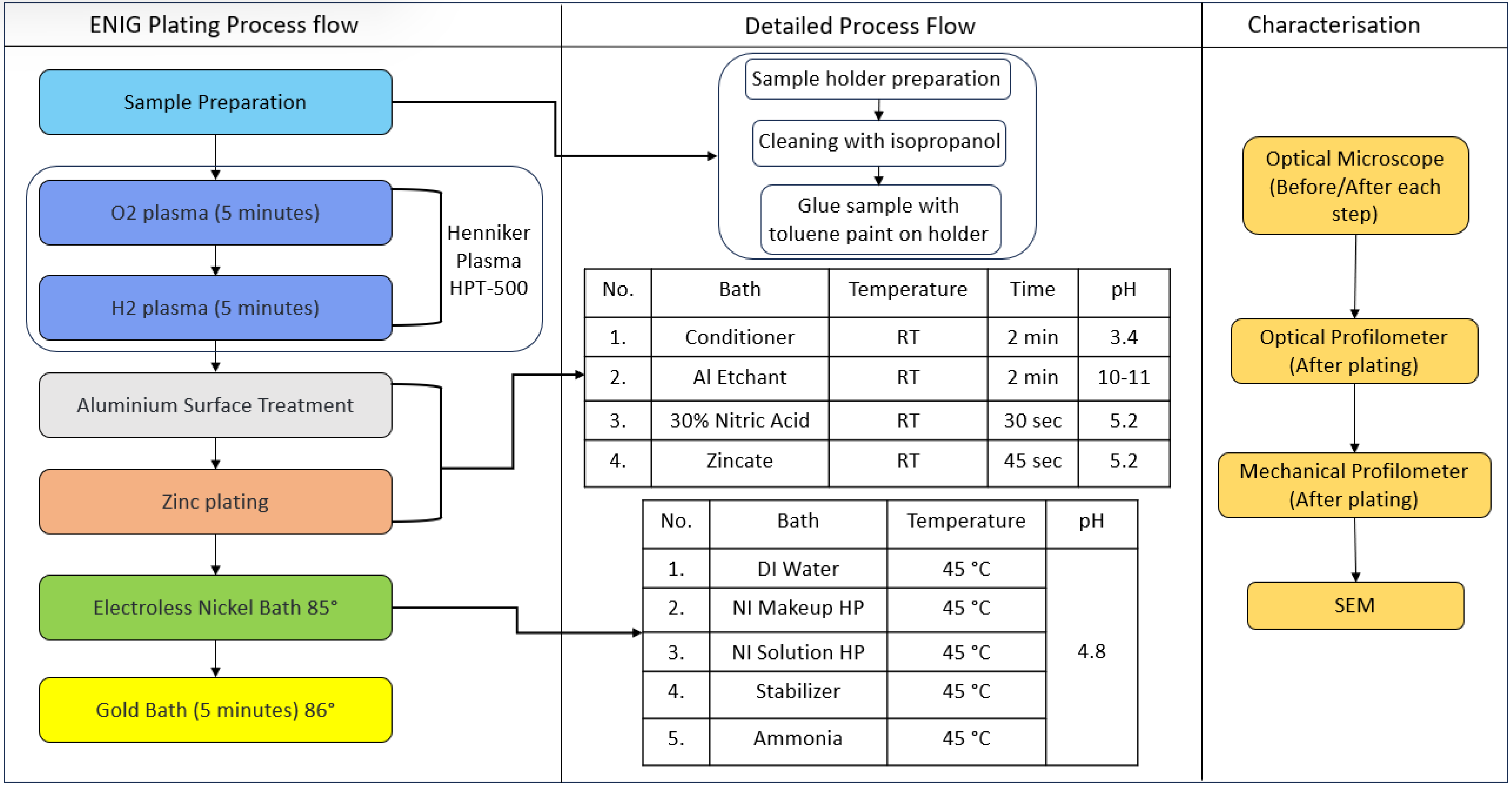
Hitachi SU5000



Process flow documentation

Systematic studies:

- Process flow
- Experimental design
- Quality control
- Detailed reports
- …



No.	Bath	Temperature	Time	pH
1.	Conditioner	RT	2 min	3.4
2.	Al Etchant	RT	2 min	10-11
3.	30% Nitric Acid	RT	30 sec	5.2
4.	Zincate	RT	45 sec	5.2

No.	Bath	Temperature	pH
1.	DI Water	45 °C	4.8
2.	NI Makeup HP	45 °C	
3.	NI Solution HP	45 °C	
4.	Stabilizer	45 °C	
5.	Ammonia	45 °C	

1. Given Data

- Total number of samples: $65,536$.
- Samples are grouped into 72 groups of 28 samples each.
- Out of these 72 groups:
  - 29 groups are good.
  - 43 groups are bad.

---

2. Probability That a Group is Good

A group of 28 samples is considered **good** only if all 28 samples in that group are good.
Let p represent the probability that a single sample is good.
The probability that a group of 28 samples is good is then given by:

$$P(\text{group good}) = p^{28}$$

Conversely, the probability that a group is bad is:

$$P(\text{group bad}) = 1 - p^{28}$$

3. Observed Proportion of Good Groups

From the test results, 29 out of 72 groups are good.
Therefore, the observed proportion of good groups is:

$$\hat{P}(\text{group good}) = \frac{29}{72} \approx 0.4028$$

Since the observed proportion of good groups is an estimate of $P(\text{group good})$, we have:

$$P(\text{group good}) = p^{28} = \hat{P}(\text{group good})$$

Substituting the observed proportion:

$$p^{28} = \frac{29}{72}$$

---

4. Solving for p

To find p, take the 28^{th} root of $\frac{29}{72}$:

$$p = \left(\frac{29}{72}\right)^{\frac{1}{28}}$$

Computing this:

$$p \approx 0.968$$

Thus, the probability that a single sample is good is approximately 96.8%.

---

5. Estimating the Total Number of Good Samples

To estimate the total number of good samples among the $65,536$ samples, multiply p by the total number of samples:

$$N_{\text{good}} = p \times 65,536$$

Substituting $p \approx 0.968$:

$$N_{\text{good}} \approx 0.968 \times 65,536 \approx 63,442$$

Final Results:

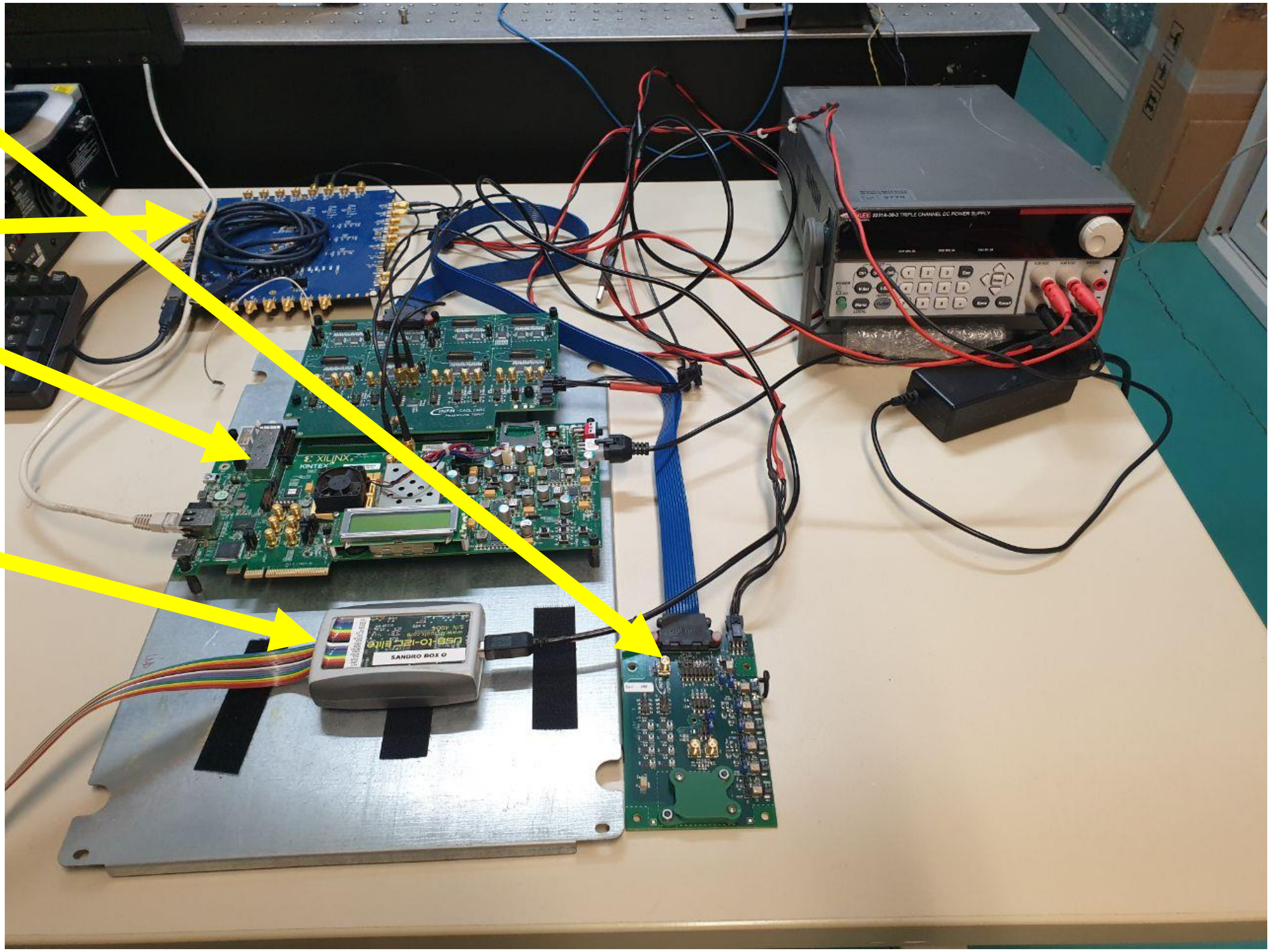
1. **Probability that a single sample is good:** $p \approx 0.968$ (96.8%).
2. **Estimated number of good samples:** $N_{\text{good}} \approx 63,442$.

This means that approximately $63,442$ samples out of $65,536$ are good, based on the group test results.

Setup:

Setup

- DUT: Timespot-1 Hybrid on Tspot-1 board
- Clock generator
- FPGA and dedicated mezzanine
- IIC interface



Device exposed to Sr90 source

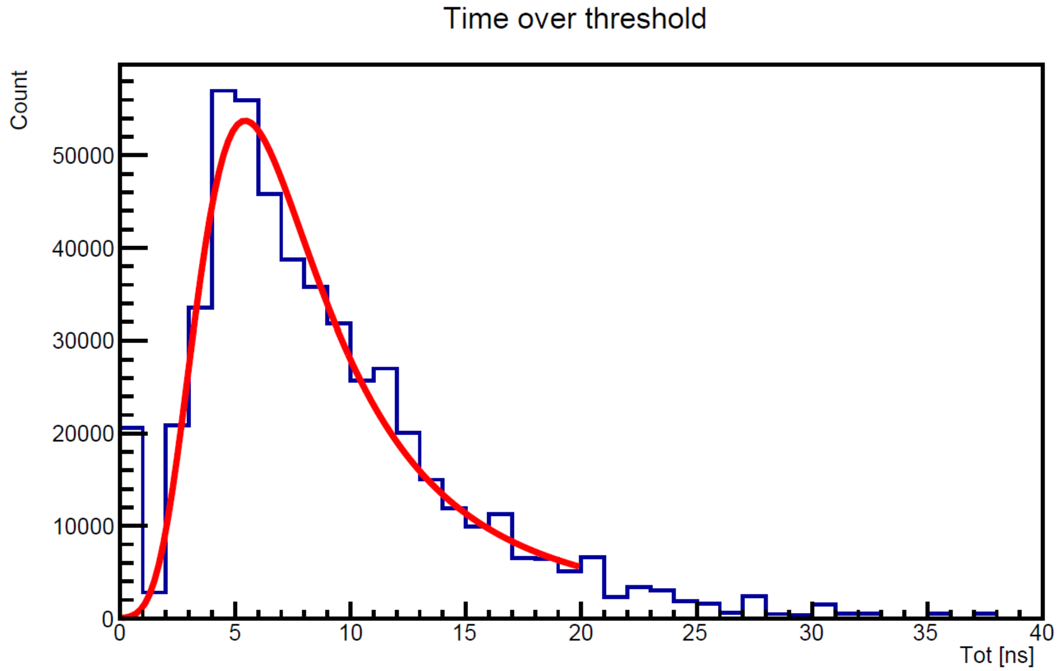
Approach

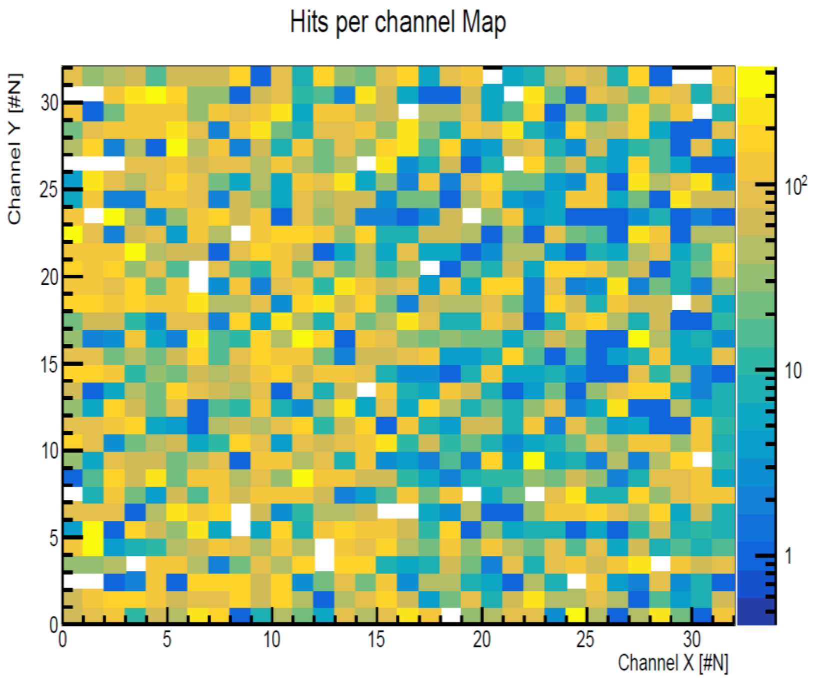
Mutiple acquisition runs performed

Method:

- Distribution of the Time Over Threshold analysed
  - TOT proportional to released charge
  - Set a cut below 3 ns which is considered mostly noise contribution

- Hit map generated after setting the threshold on the TOT





Bonding efficiency

Due to intrinsic design flaws of the hybrid it's not possible to determine exactly the bonding efficiency

TCT has been considered but the already very thick support wafer still attached on the active volume absorbs most of the NIR radiation

Bonding efficiency estimated by applying an increasing threshold on the counted events pe channel

- Above 5 counts per channel, trend is more constant.
  - We conclude that efficiency estimation is at the lowest 85.5 %