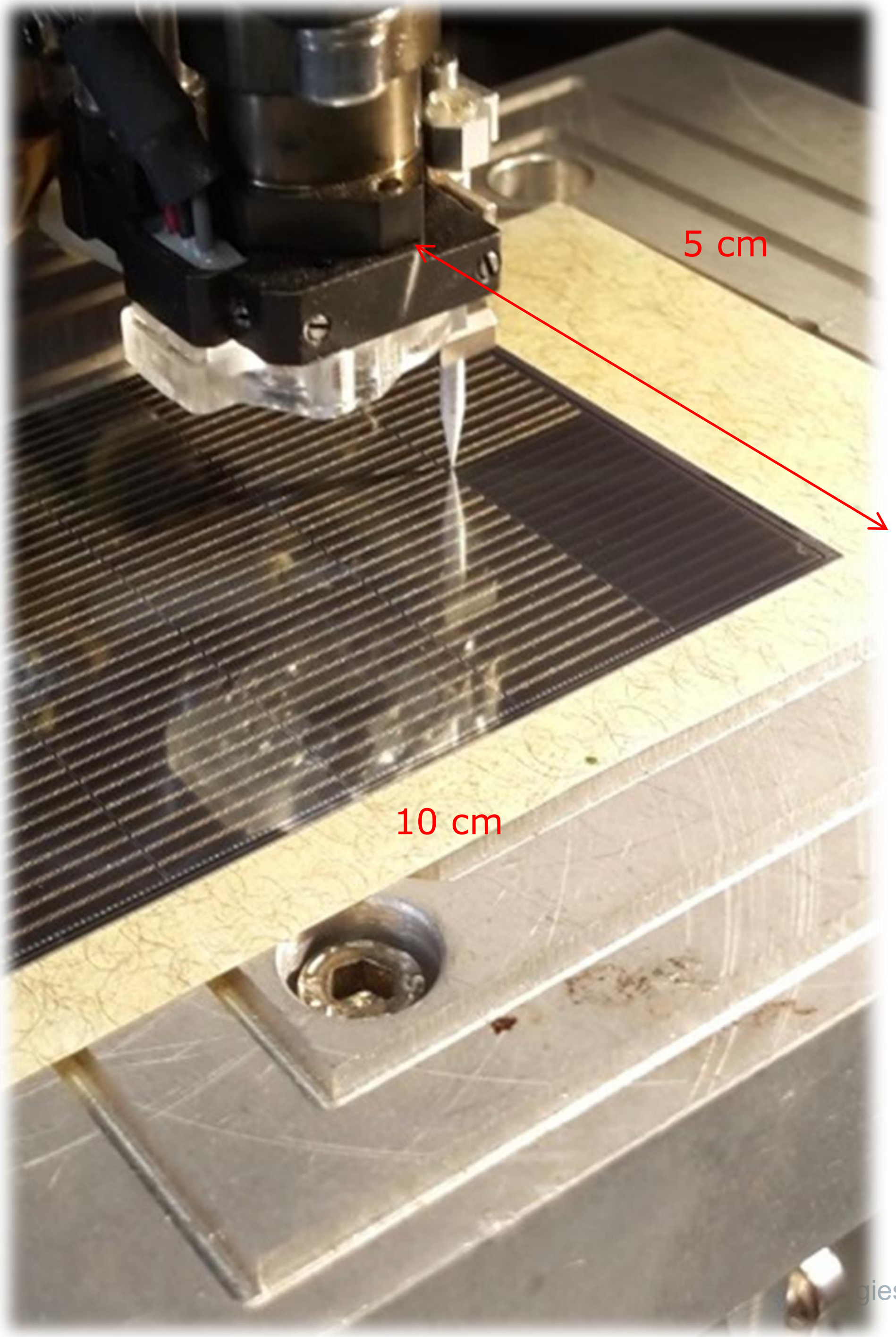
ECFA DRD 7.6b

First workshop on Future Detector Technologies

Detector Technologies and Future Perspectives at KIT

Michele Caselle, Felix Steiner and Mathias Wegner

2 and 3 Sept. 2025
KIT - Campus South



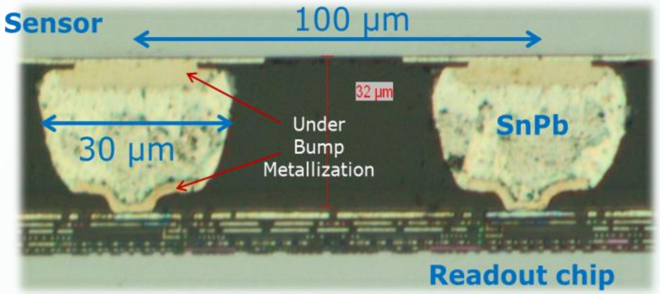
Detector Technologies: Outlook

- Bump-bonding technologies
- TSVs formation (machine and infrastructures):
  - DRIE machine
  - Maskless laser drilled process
- Electroless and electroplating metal deposition
- Sputtering cluster for cryogenic sensor and detector technologies
- Silicon photonic and optical packaging

Bump-bonding technology at KIT

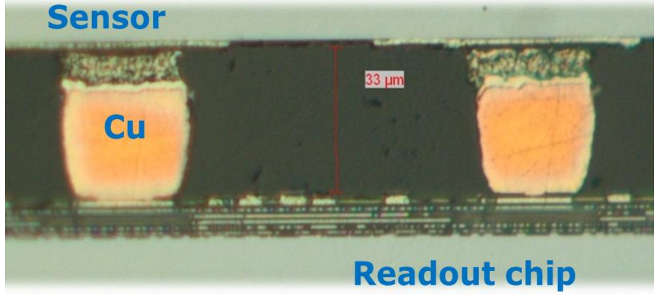
Mature Bump-Bonding Technologies at KIT

SnPb and Pb-free bonding



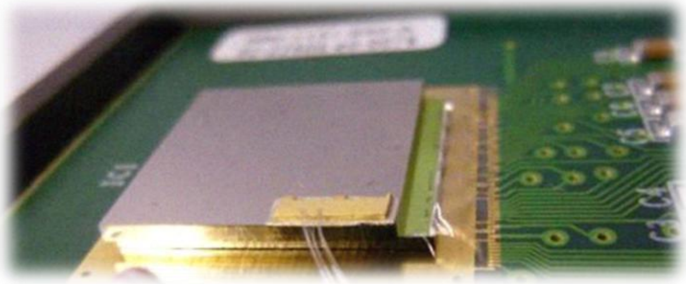
Standard C4 (Controlled Collapsed Chip Connection)
Application: production CMS pixel detector Phase 1-Upgrade

Cu-pillar bonding



Internal R&D: very high-density technology bump (5 µm)
Application: fine-pitch pixel detector & 3D-ASICs technology

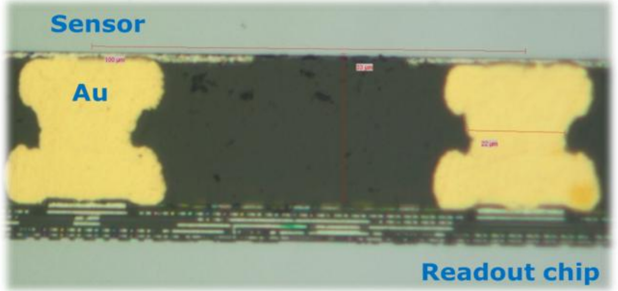
Low-temperature bonding



Low temperature flip-chip process < 120°C

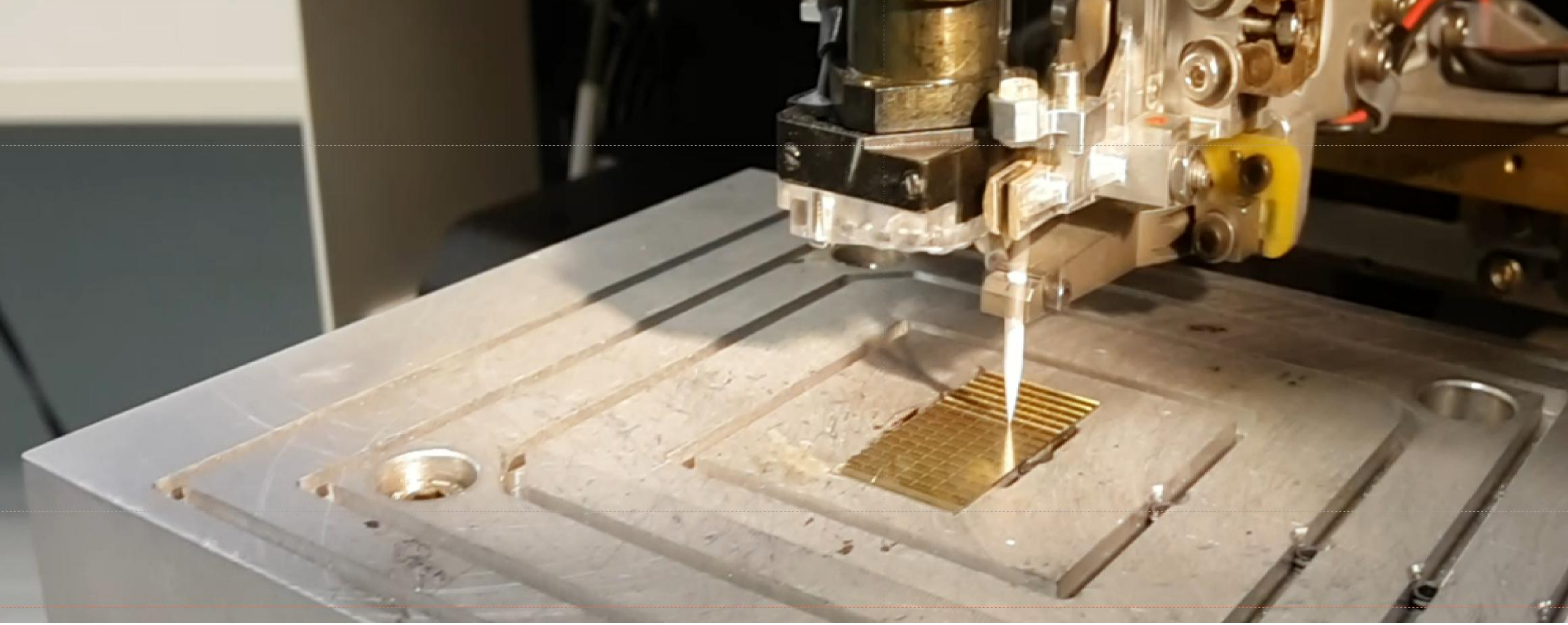
Application: High-Z sensors i.e. Cd(Zn)Te, GaAs, InGaAs, etc.

Gold stud bonding



Mature technology high mechanical strength and reliability

Several applications: fast prototyping of new pixel, RF-ASIC, astroparticle detector, photon science detector



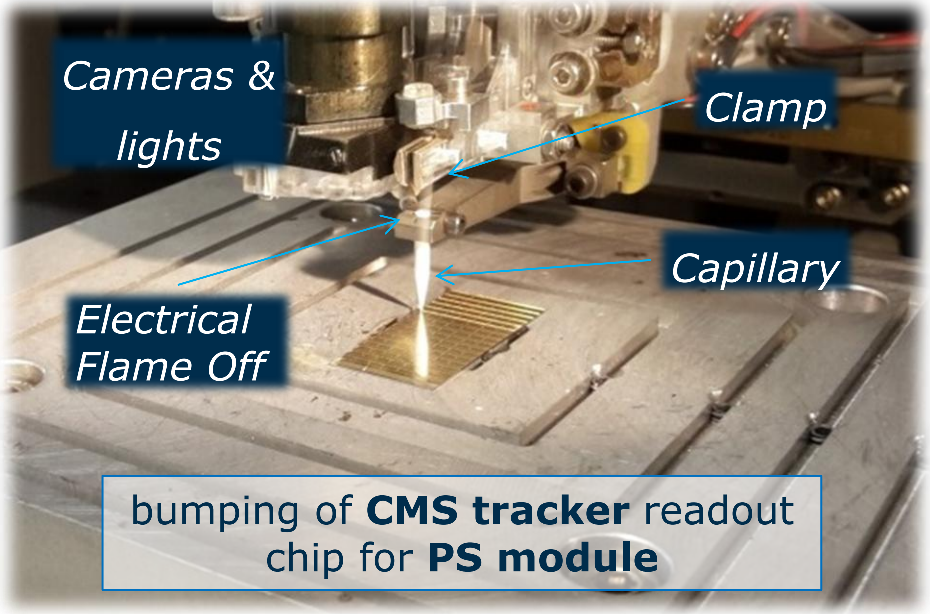
In-house bumping technology

Low-cost, fast deposition process with minimal setup time, ideal for rapid prototyping

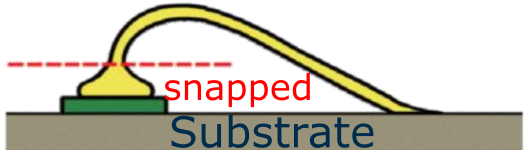
Stud Ball Bumping (SBB) process

➡ *IPE clean rooms visit*

- Gold stud bumping is an evolution of the ~ 60 years-old wire bonding process. Gold stud ball: the wire is snapped off after the ball is initially connected to the substrate



✓ **Low-cost process**: direct deposition on Al pad (No UBM, lithography process)



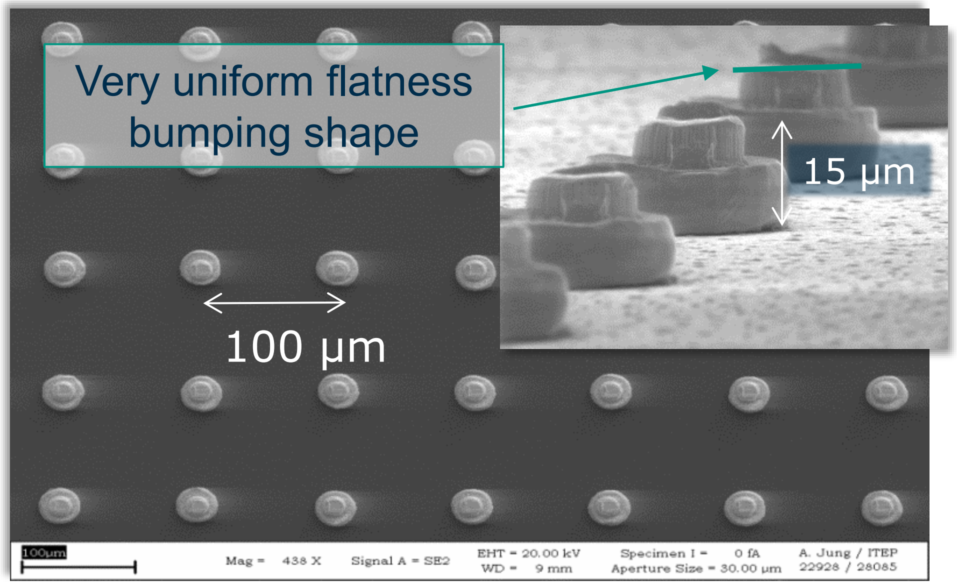
Gold Ball-wedge wire-bonding

✓ **Fast deposition**: 20 bumps/s

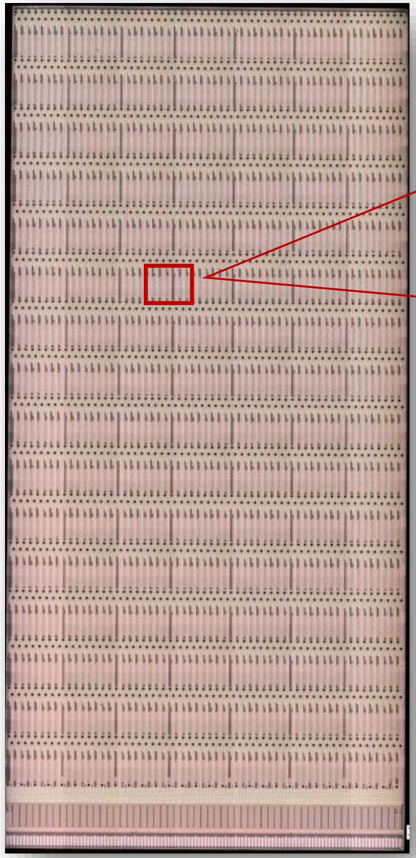
✓ **Short setup time**: ideal for single die bump-bonding (i.e. prototype and R&D)

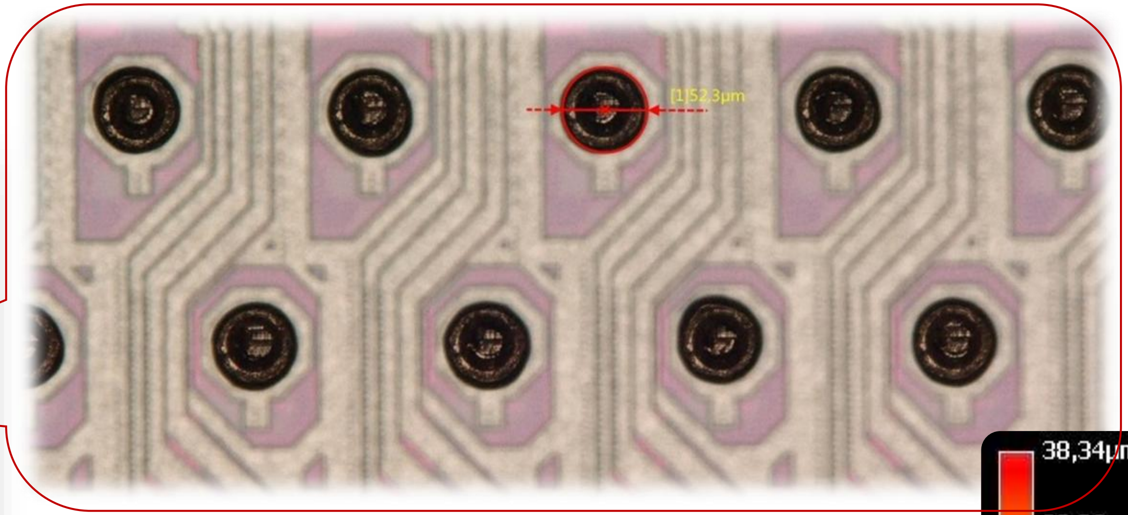
Achieved Bump & pitch size

Au wire diameter (µm)	Bump diameter (µm)	Minimum pitch (µm)
25	60	100
15	30	50
12.5	23	30

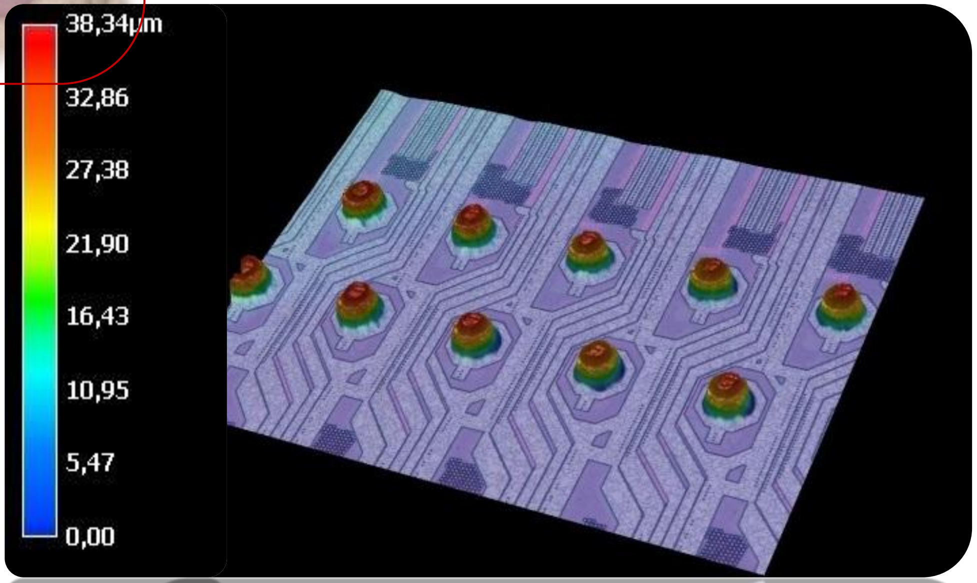


Bumping – uniformity
Bump-bonding of the MPA and sensor of CMS Phase-2





- Gold wire of 23 µm



Stud ball bumps uniformity:

- Uniform stud ball size of 52 µm
- Uniform stud ball height of 38 µm

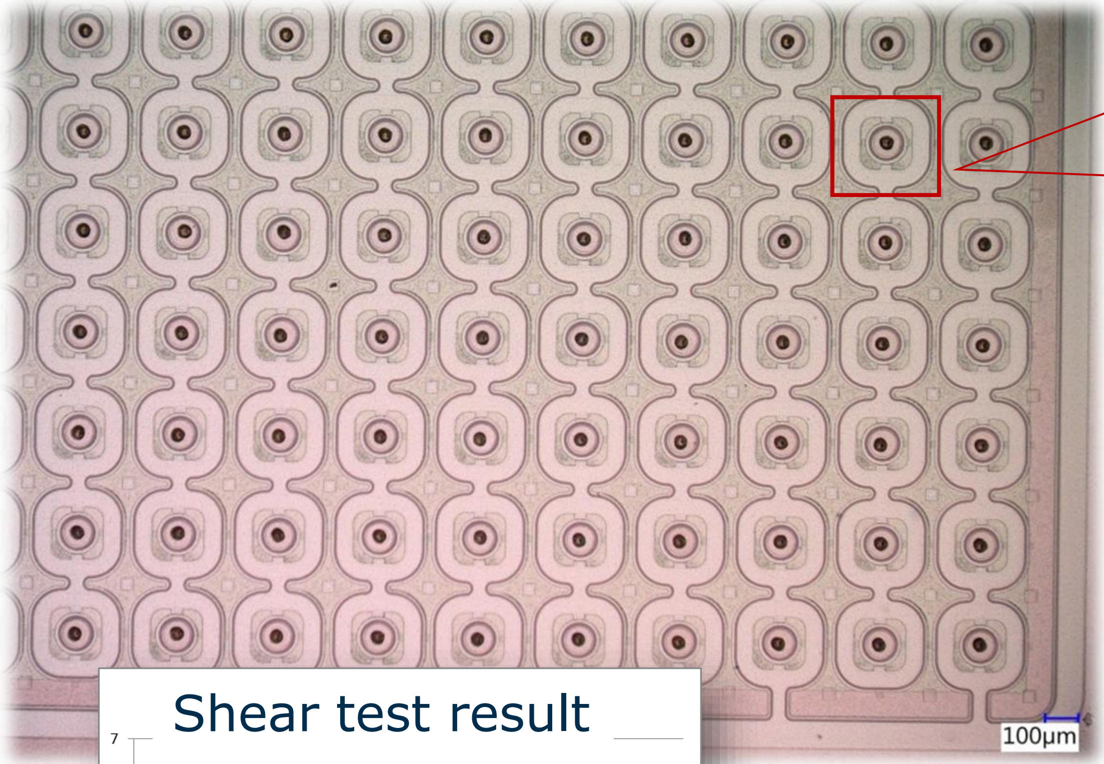
Shear test:

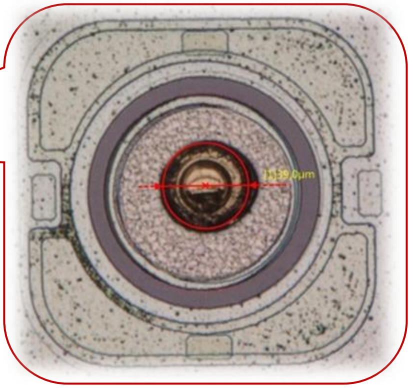
- MPA : 32 ± 1.6 gr
- Sensor: 52 ± 4 gr

Bumping – uniformity

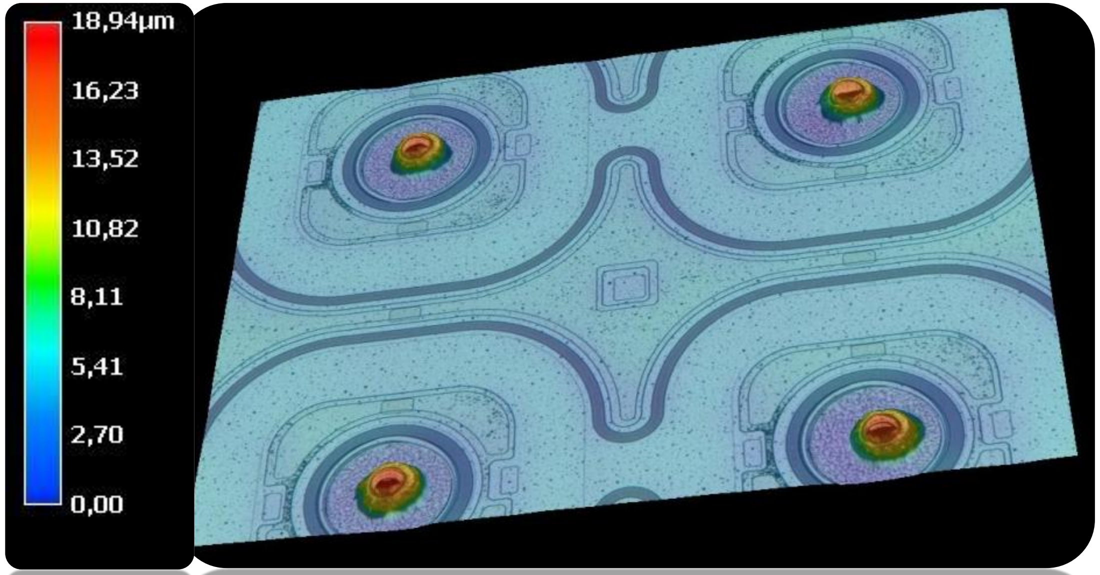
Bump-bonding of the PixDD soft X-ray pixelated drift sensors

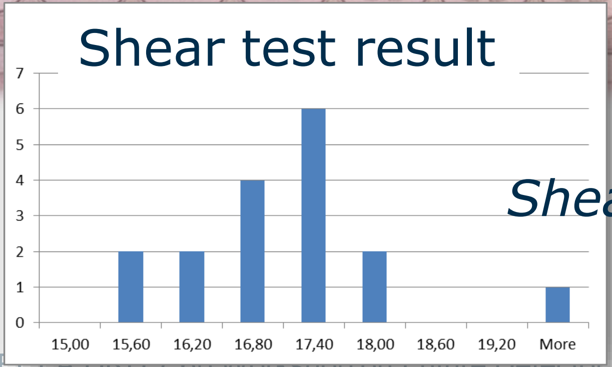
- Ball size uniformity by automated optical inspection





- Gold wire of 15 µm
- Bumps size of 39 µm
- Bump height of 19 µm



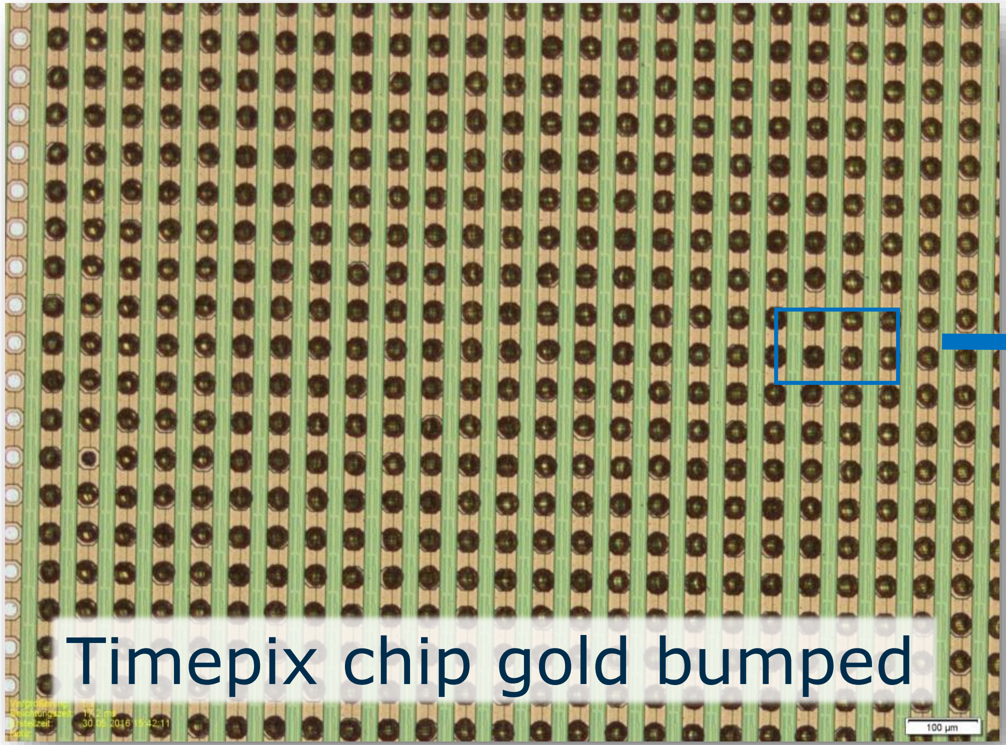


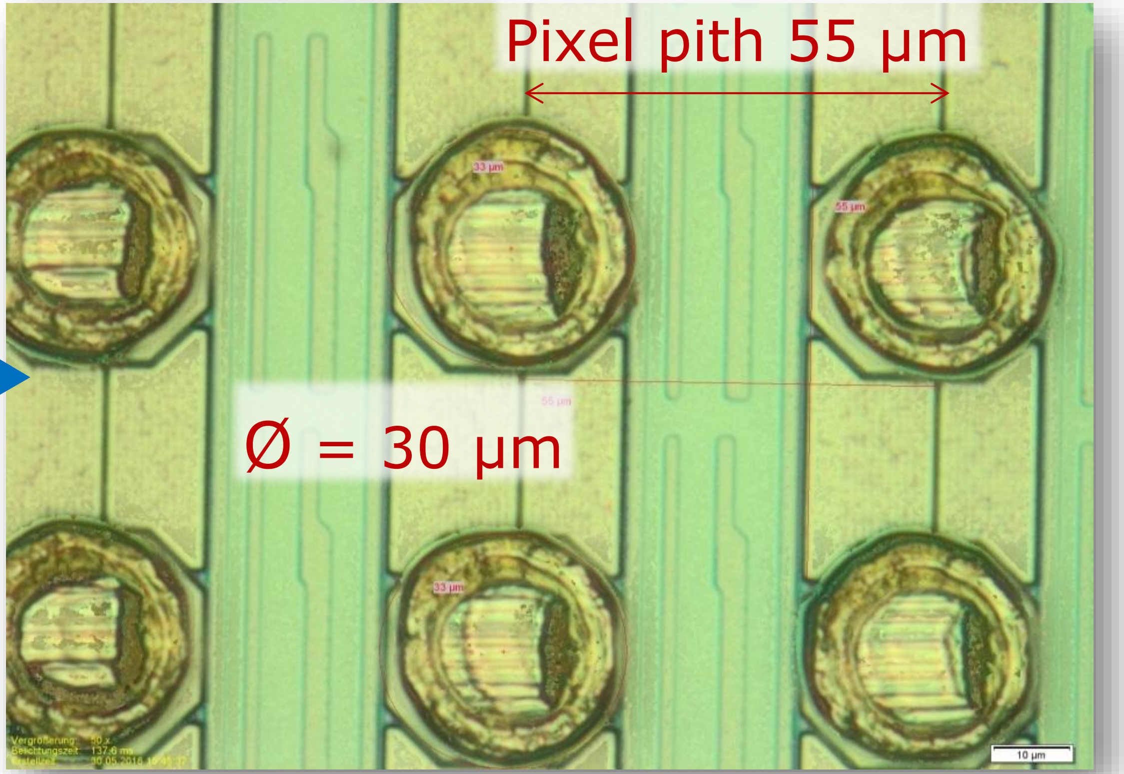
Shear test: 18.86 ± 1 g

Gold-Stud bumping on Timepix/Medipix chips

Fine-pitch bump-bonding by 12.5 µm Au wire

- Pixel pitch of 55 x 55 µm², passivation opening < 20 µm





- Gold wire of Ø = 12.5 µm, bond force = 15 gr, bond time = 8 ms, USP = 25 mA, Temp = 170 °C

Flip-chip technology

Key enabler for 2D high-density interconnections and chiplet integration

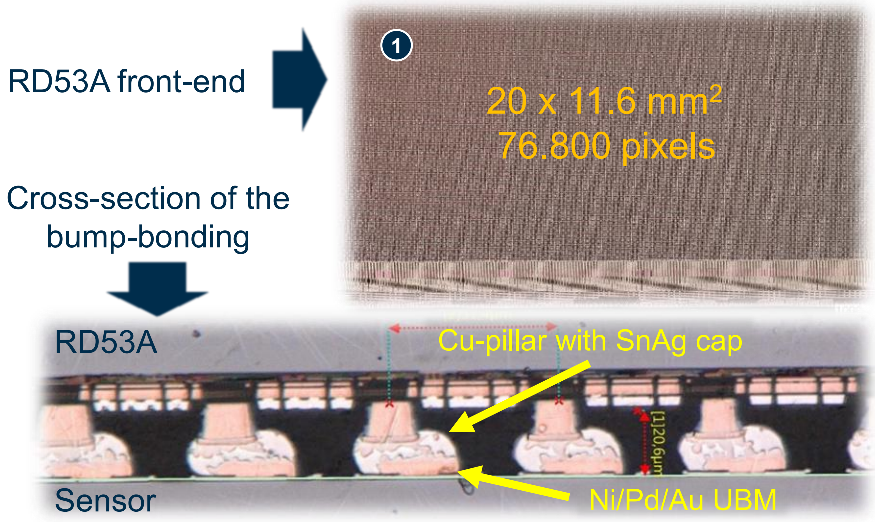
Bump-bonding technologies
Advanced packaging for HEP, Photon Sciences & Medicine

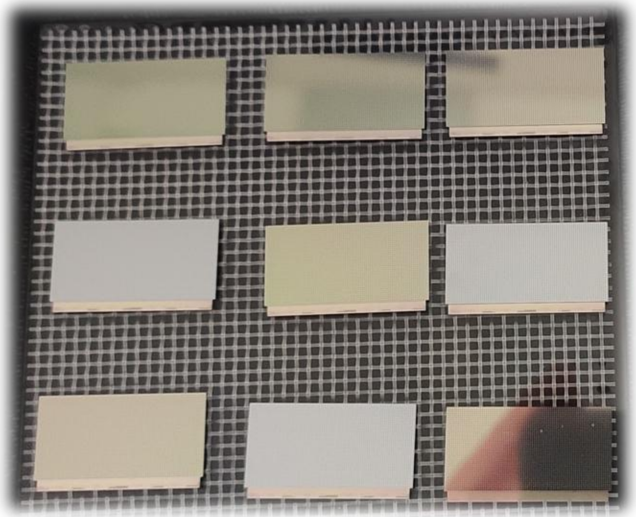
High-density and large-area bump-bonding technology

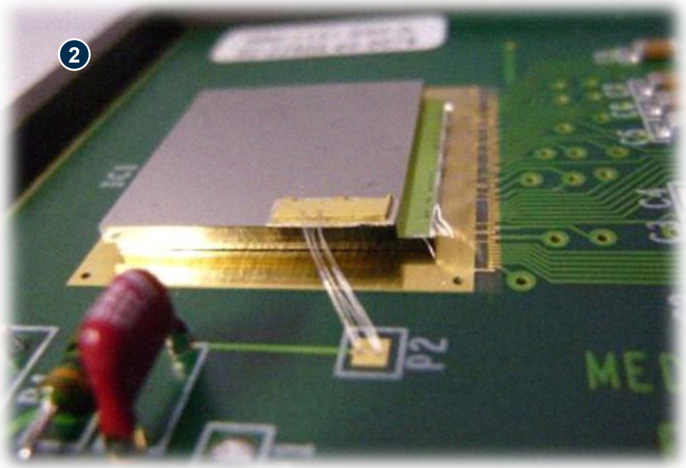
❶ Advancing the next-generation pixel detector for the CMS experiment with large active areas and high-density integration (33 kPix/cm²) at a 50 µm pixel pitch. The bonding process utilizes solid-to-liquid thermo-compression with in-situ reflow using formic acid.

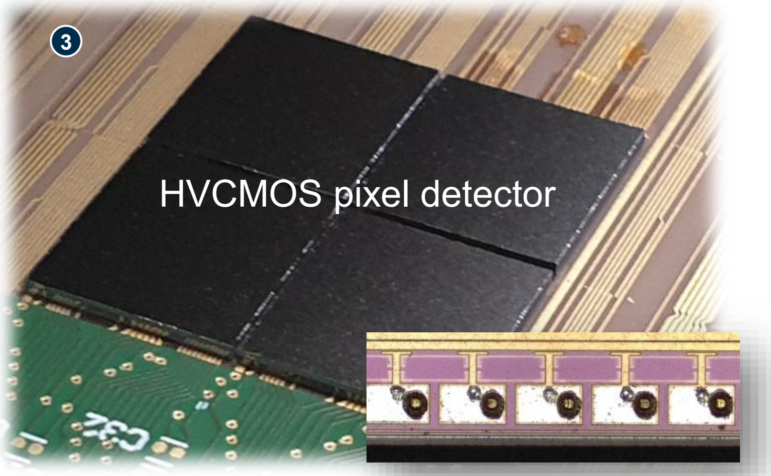
❷ Developing a high-density, low-temperature bump-bonding process for CdTe sensors with a 55 µm pixel pitch, optimized for photon science imaging applications.

❸ Establishing advanced flip-chip technology for large-area HVCMOS pixel sensors on PCB, addressing beam monitoring requirements in hadron therapy. This process integrates fine-pitch gold-stud bumping on the front-end chip with Anisotropic Conductive Adhesive, ensuring a high fill factor across large detector areas.



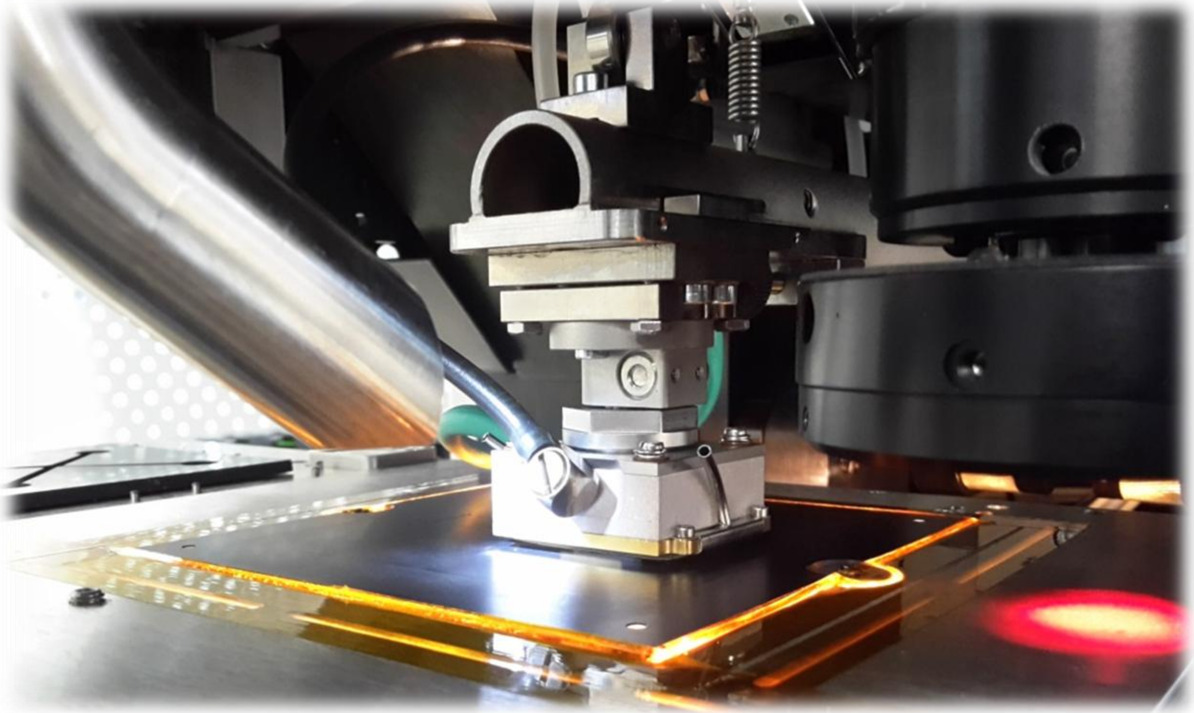


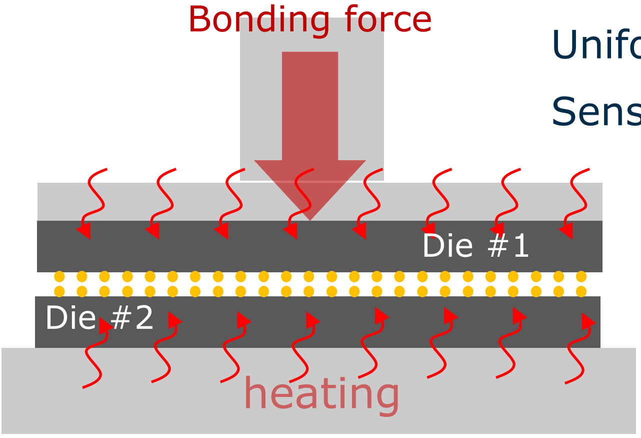




Bonding process at KIT

Bonding process is based on metal-to-metal diffusion process

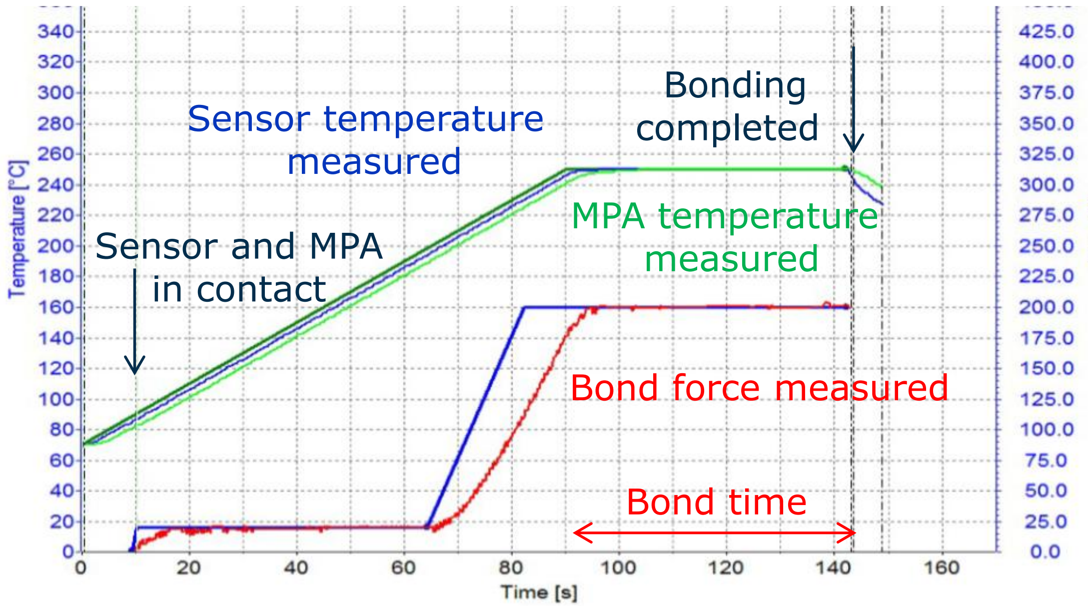




Thermo-compression Bonding process

Uniform temperature on both Sensor and Readout Chip

Gold bumps on both sides (Sensor and Readout chip)



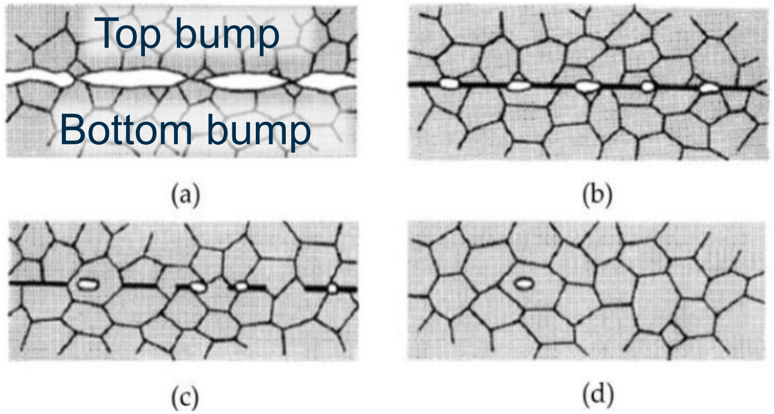
Bonding parameters:

- Bond Force: ~ 2 gr/bumps
- Bond Temp: > 180 °C
- Bond Time: ~ 50 sec

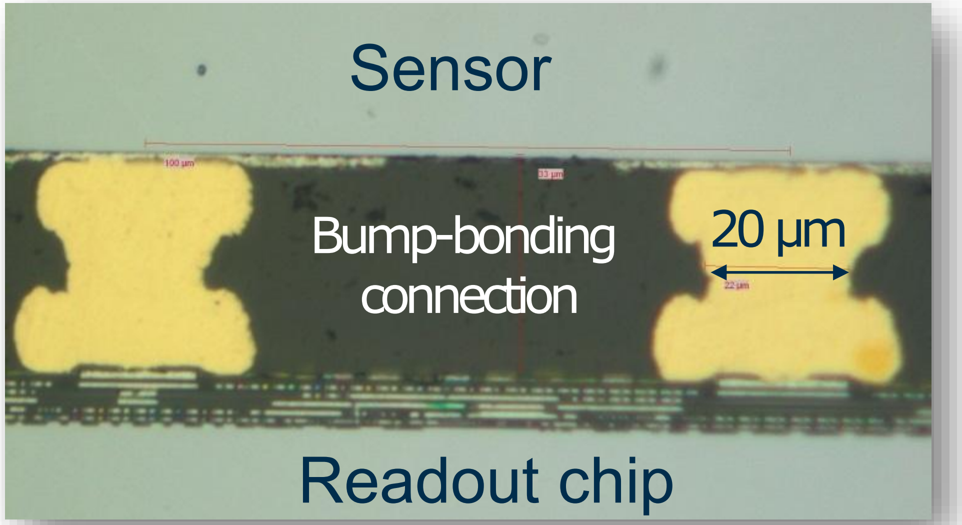
Bonding process at KIT

Bonding process is based on metal-to-metal diffusion process

- Metal diffusion bonding, also known as Thermo compression bonding (TCB), is a direct solid-state diffusion bonding process and is based on atomic contact. In this bonding technique, two metals are brought into contact by applying heat and force simultaneously after which the atoms diffuse to form the bond interface



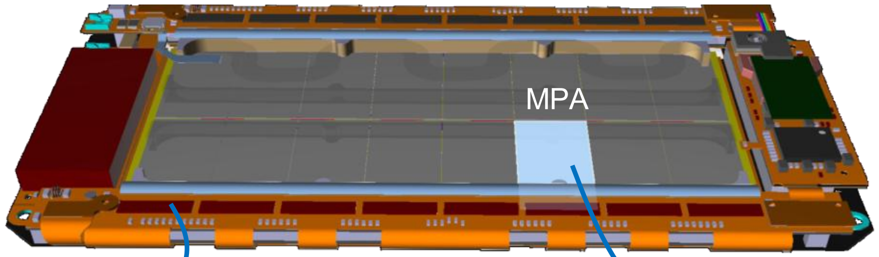
- The **diffusion rate** depends on the chosen **temperature** and applied **pressure** where grain boundary diffusion in both sides

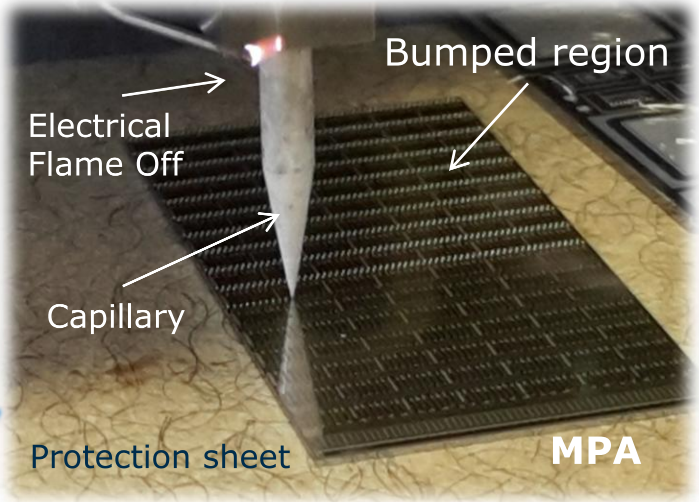


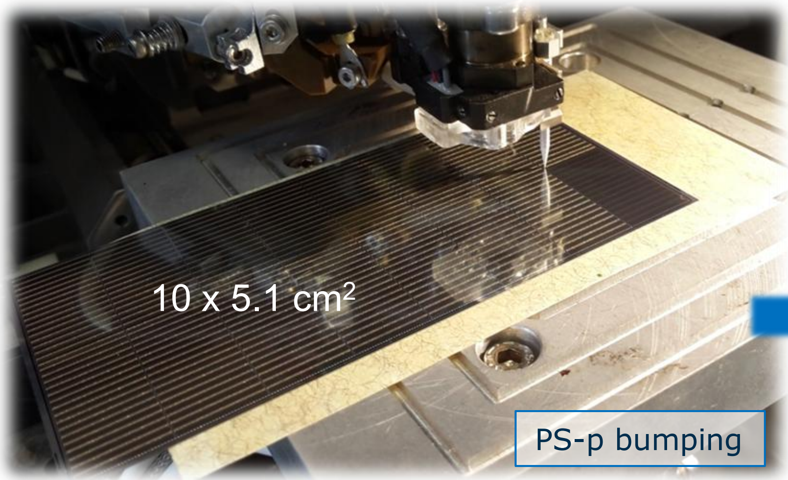
- ✓ High mechanical strength > **5 gr/bump**
- ✓ **No µ-voids** (inside the bumps)
- ✓ **No intermetallic** layers (AuxAly)

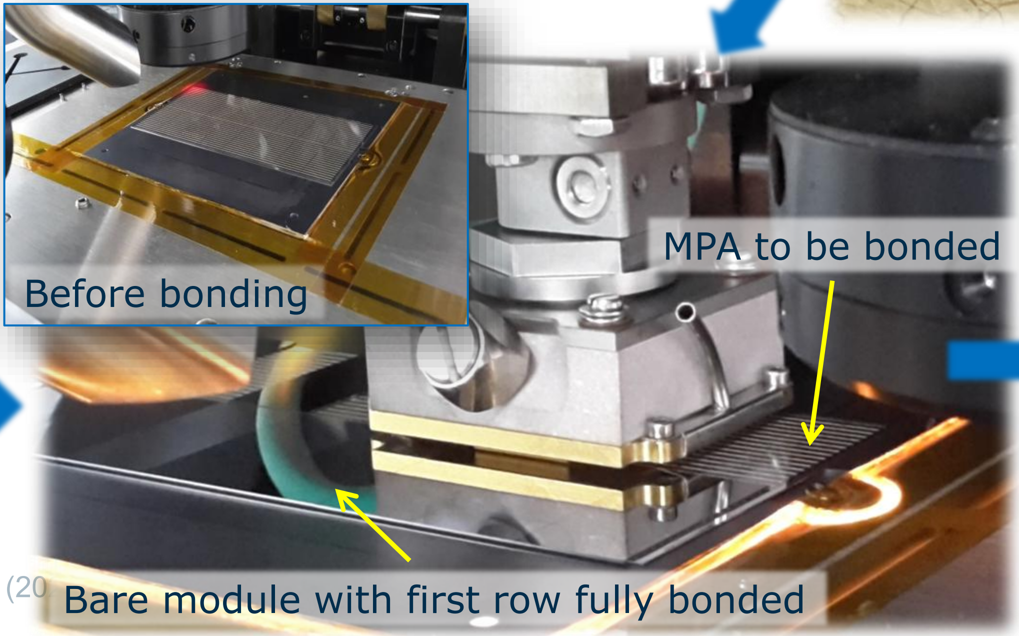
In-house bump-bonding technologies
First prototype of MPA detector CMS-PS module (Phase II)

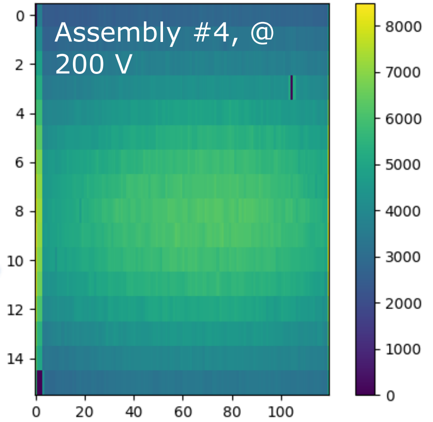
- First working prototype produced at KIT by Au-stud bump-bonding technology.
- Large active area sensor size: 10 x 5.1 cm^2
- Bonding process based on Au-stud
- Shear test:
  - MPA : 32 ± 1.6 gr/bump
  - Sensor: 52 ± 4 gr/bump
- First delivery: two singles and one-double assemblies sent to Hamburg for the electrical test and feedbacks







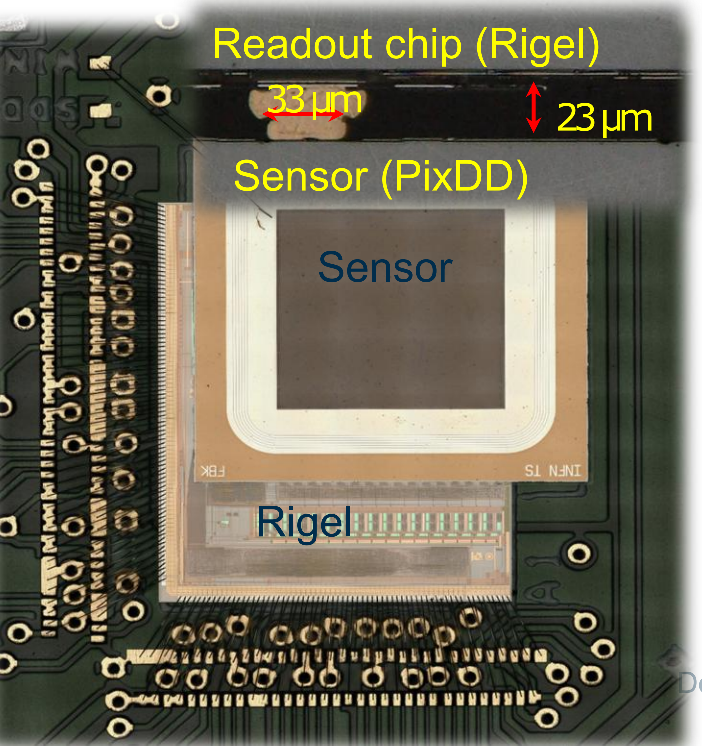




In-house bump-bonding technologies for space
PixDD (PIXelated Drift Detector)

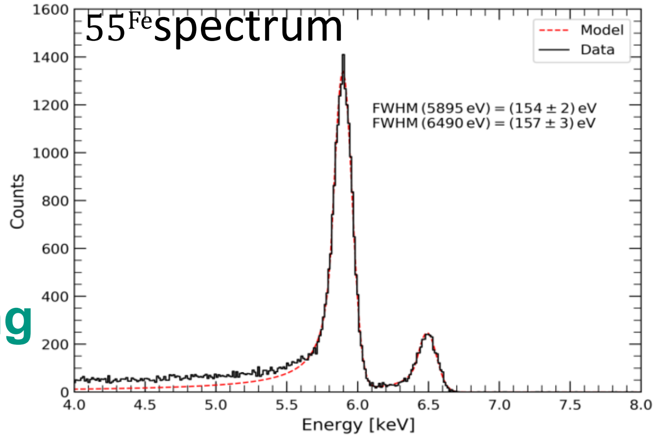
Scientific motivations:

- Study nucleonic matter in a unique regime, and exotic states of matter that could never exist in the laboratory
- Measuring the motions of matter close to the event horizon

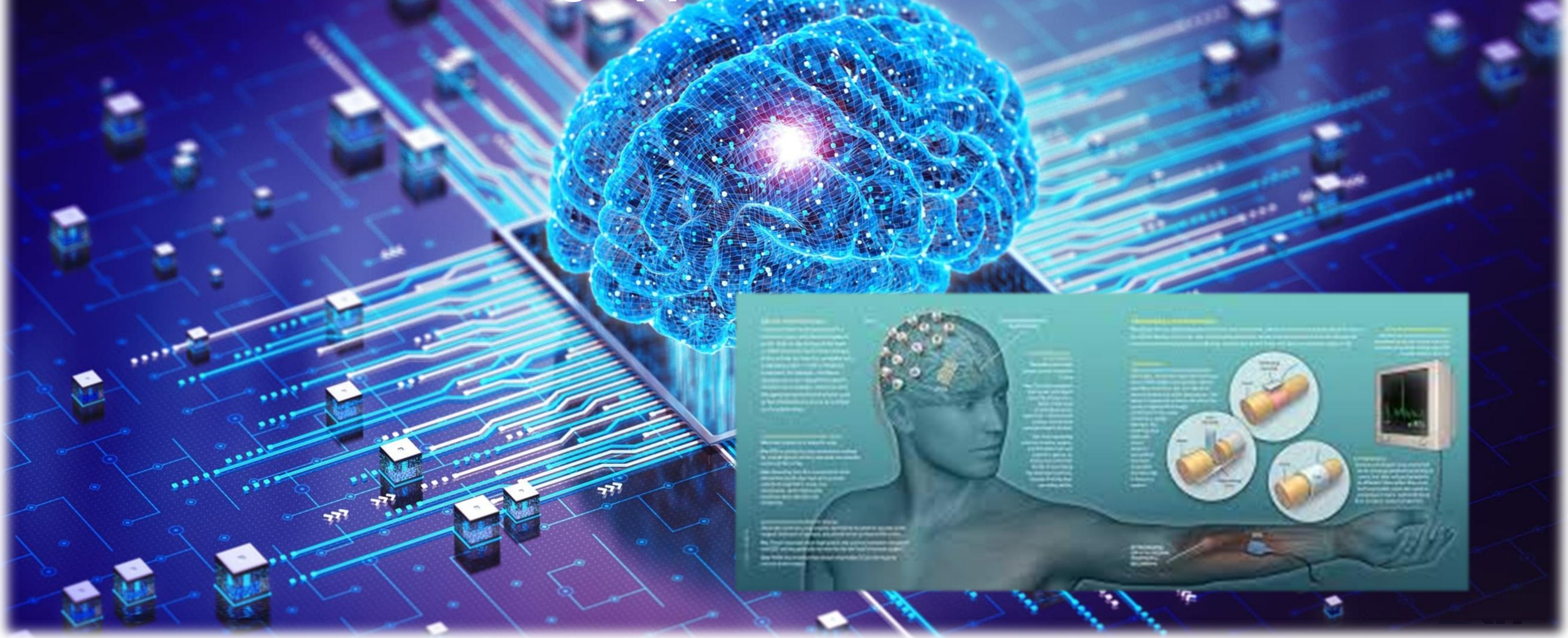


Bump-bonding technology for space detectors :

- **Asymmetrical** bump-bonding with "**customizable**" bumping position
- Very **low-noise** and **fragile thinned x-ray coating** → very special precautions
- High mechanical strength > 6 gr/bump
- Cost-effective interconnection technology
- **Final evaluation (26th July 2022) → outstanding**

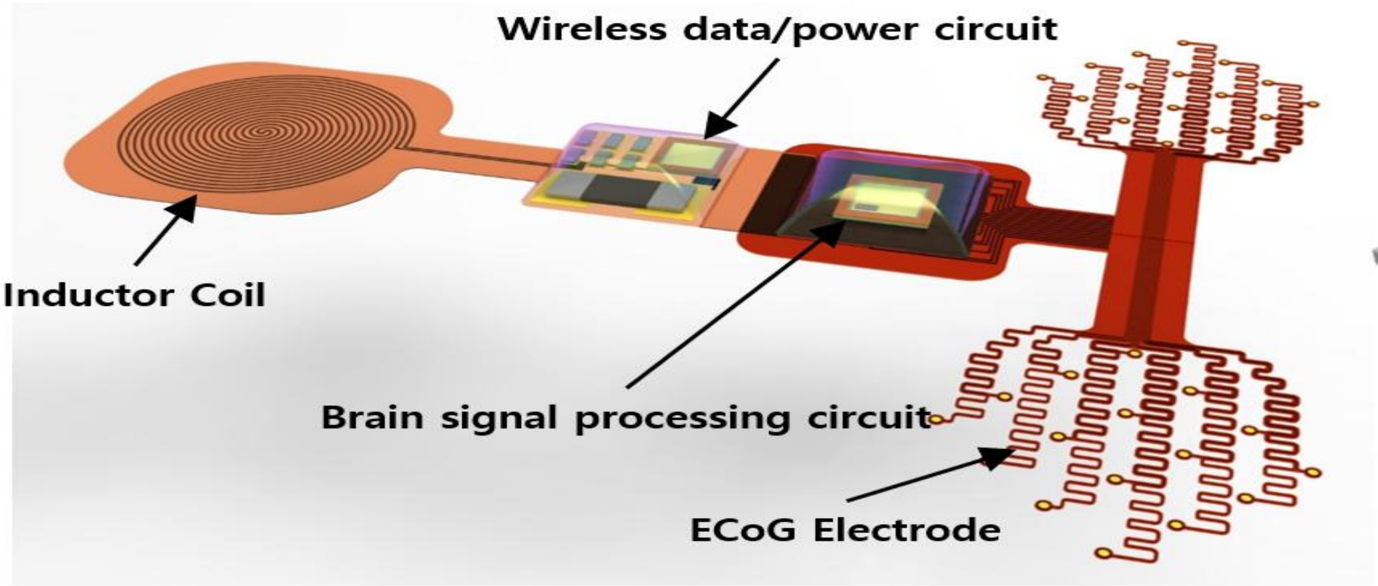


Implantable large-scale Electrocorticography (ECoG) brain machine interface for motor restoration and autonomous driving applications



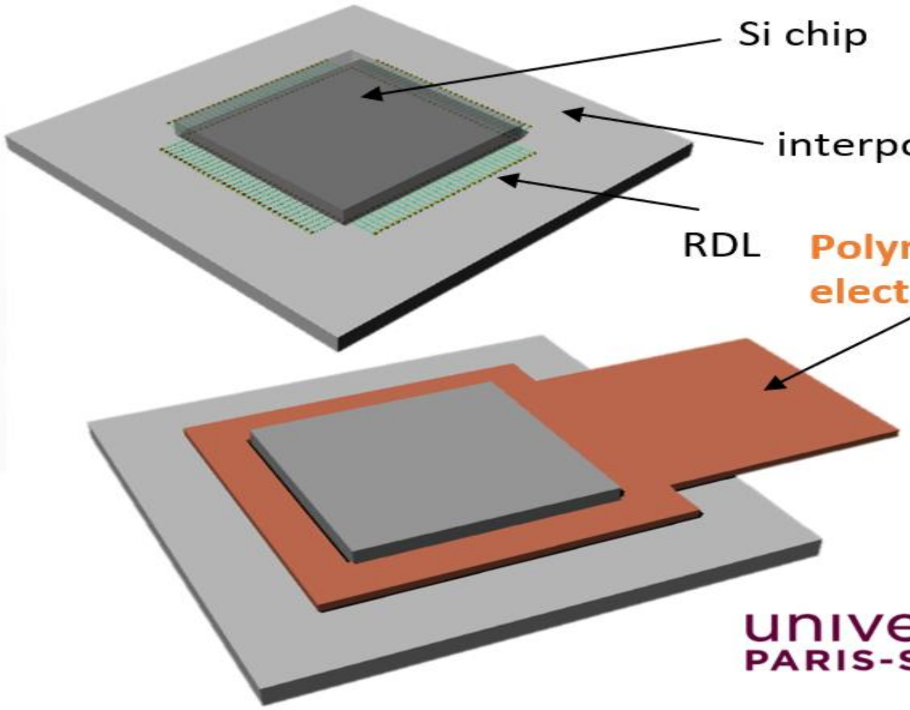
Projet Overview ➡ *Bumping Process Demonstration at IPE*

- Title: Implantable large-scale Electrocorticography (ECoG) brain machine interface for motor restoration and autonomous driving applications.
- Funding organization: KIAT and Ministry of Trade, Industry and Energy
- Period: August 1, 2024 – July 31 2027 (1^{st} stage)
- Partners: KETI, KIST, Univ.Pusan, Y-brain company (in Korea), ETHZ, CNRS, Univ.Pittsburgh (out of Korea)



ECoG concept for brain-machine interface

With KIT: Packaging and Integration of different components (Si chips, polymer neural electrodes, etc)



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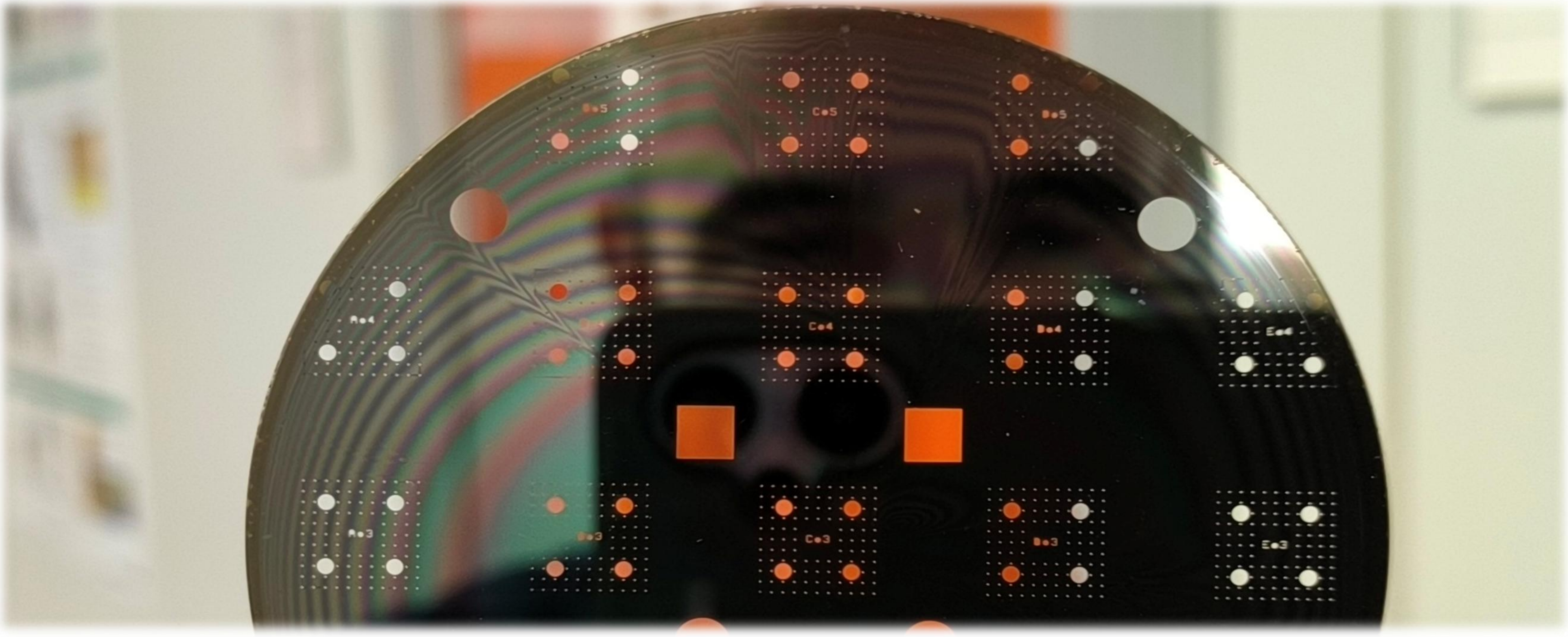


TSVs formation (machine and infrastructures)

Key enablers for next-generation chiplet and 3D-ASIC technologies

IMS clean rooms visit

TSV formation by DRIE

Three new machines from Oxford Instruments Plasma Technology

IMS clean rooms visit

Courtesy: Mathias Wegner

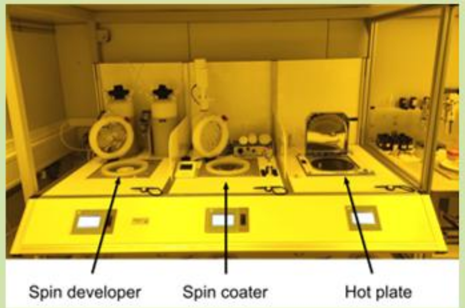
In operation | Delivered

Main HSS machinery

Photolithography

Maskless aligner

Custom-built wet bench



Deposition Systems

UHV sputter cluster

ICP-PECVD

Etching Systems

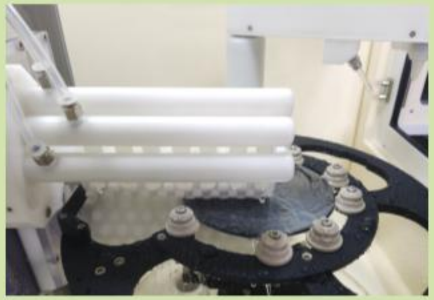
2x ICP-RIE (fluorine)

ICP-RIE (chlorine)

Layer Planarization

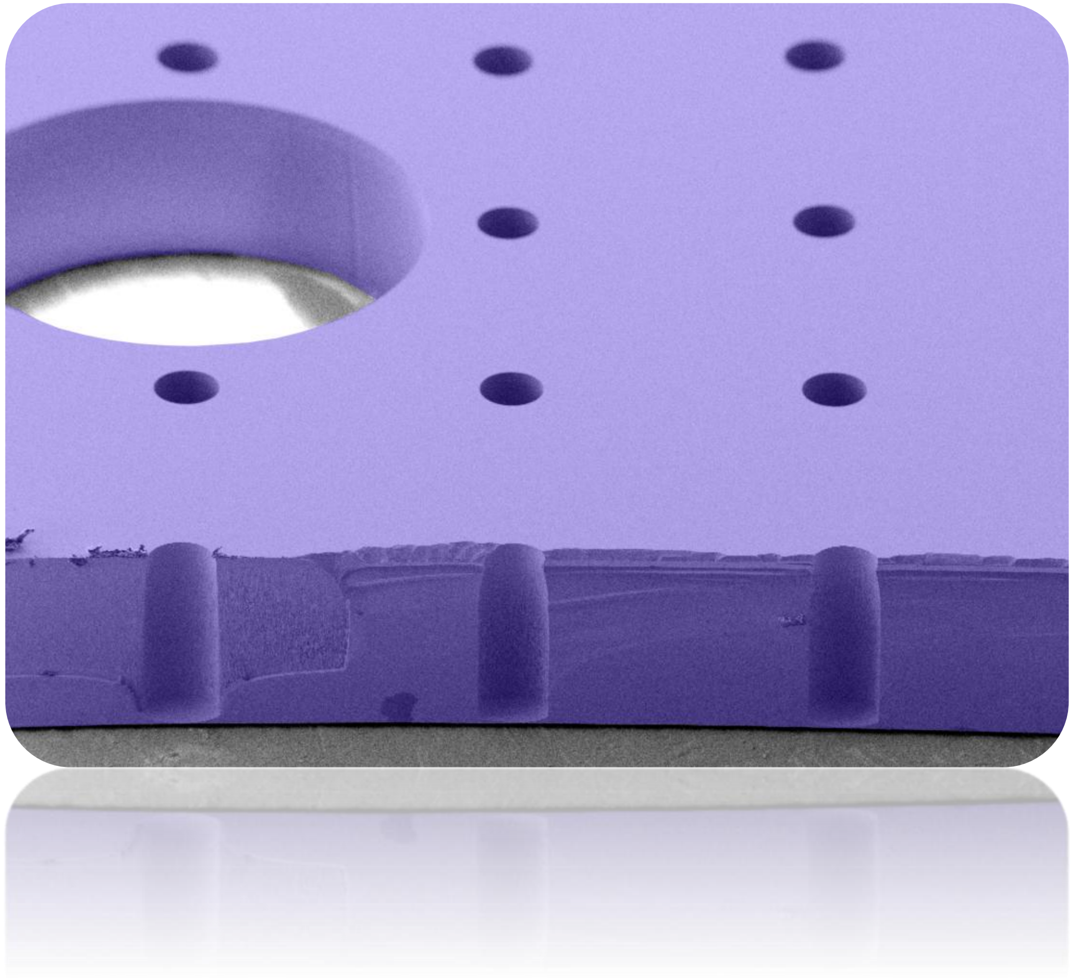
Chemical mech. polishing

Post-CMP scrubber



TSV formation by DRIE
Current status & results

Courtesy: Mathias Wegner



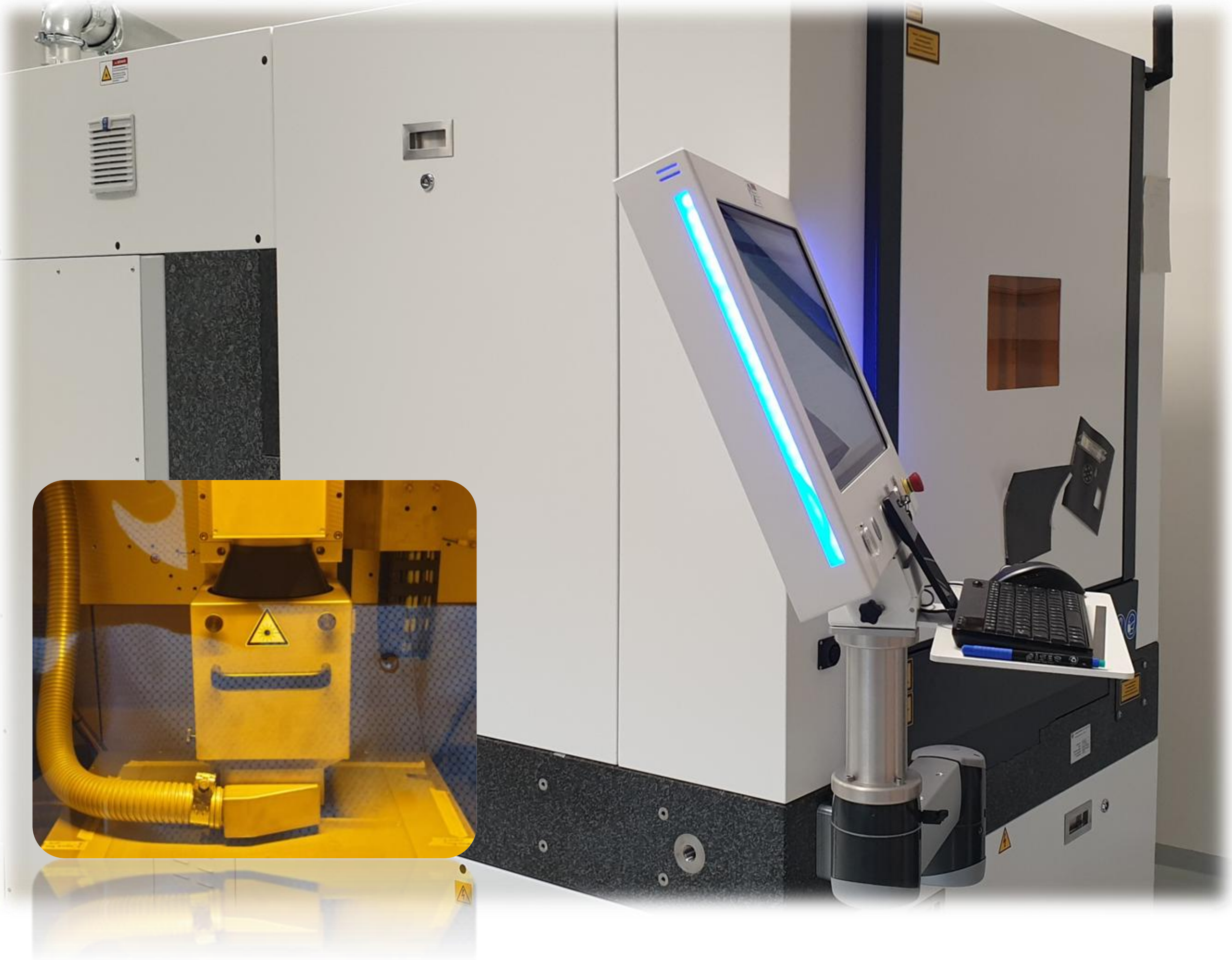
- All key equipment for TSV formation is installed and operational, including the MLA150 (Maskless Aligner), photoresist-based process flow, and the Oxford system using the Bosch profile.
- The target is to achieve small-size TSVs *O (10 μm)* thin substrates.
- High-density interconnections will be a major focus of investigation.
- Further details will be presented and discussed during the visit at IMS by Mathias

TSV formation by laser drilled

Maskless process for wafer and single die

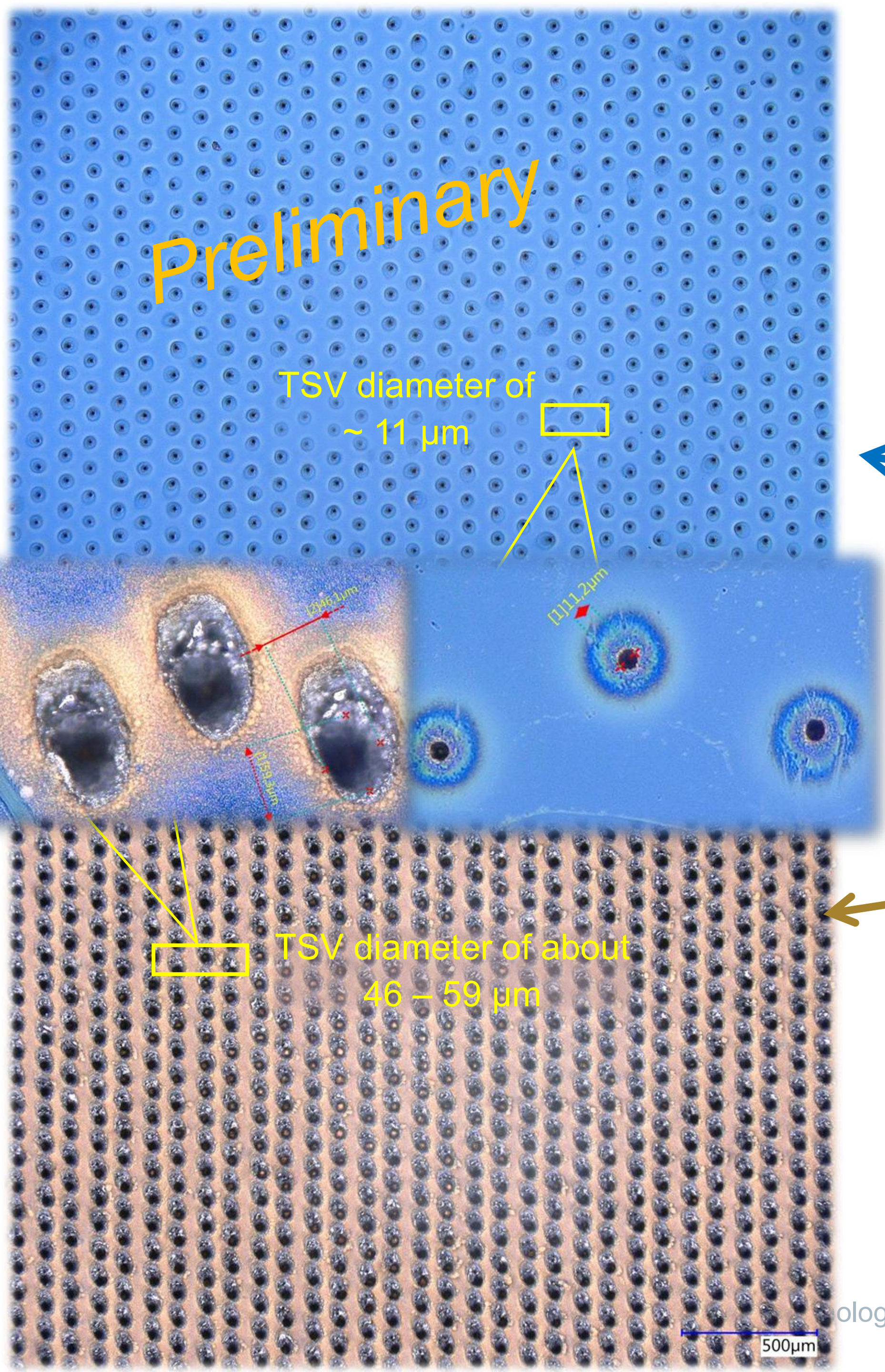
Courtesy: Felix Steiner and Thoms Blank

Laser machine DR2000 from Photonic System



- Laser spot diameter: 20 µm with a large working area (610 × 520 mm²)
- Fully installed and operational
- Enables precise Through-Silicon Via (TSV) hole formation
- Supports wafer dicing for edgeless sensor technologies

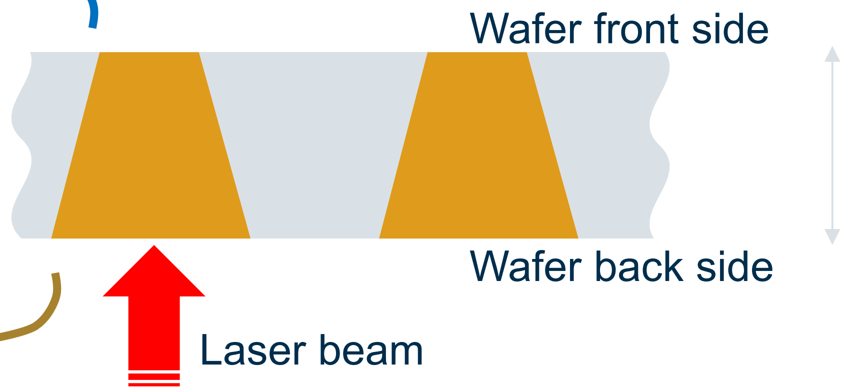
→ ***IPE clean rooms visit***



TSV formation by laser
Current status & results

Courtesy: Felix Steiner

- High-density TSVs are possible with laser-drilled formation, combined with outstanding flexibility in via placement since no photolithography process is required



- A burned area around the laser-drilled TSVs is evident, which can be removed by CMP
- Laser-drilled TSVs can be employed in interposer substrates or ASICs with large tolerance between the TSV region and active structures.

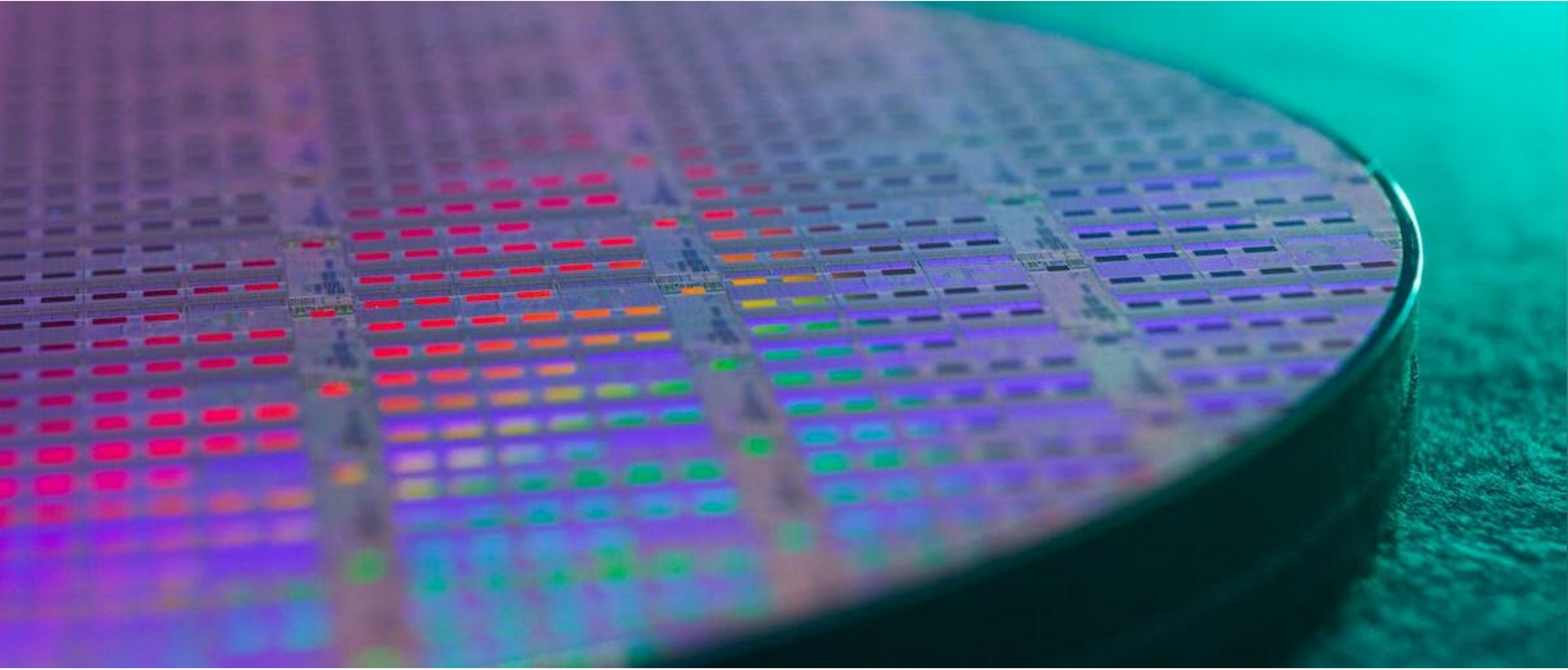
Electroless and electroplating (machine and infrastructures)

Enabling fine-pitch interconnects, and robust 3D integration for next-generation systems

Process capabilities (*near future*)

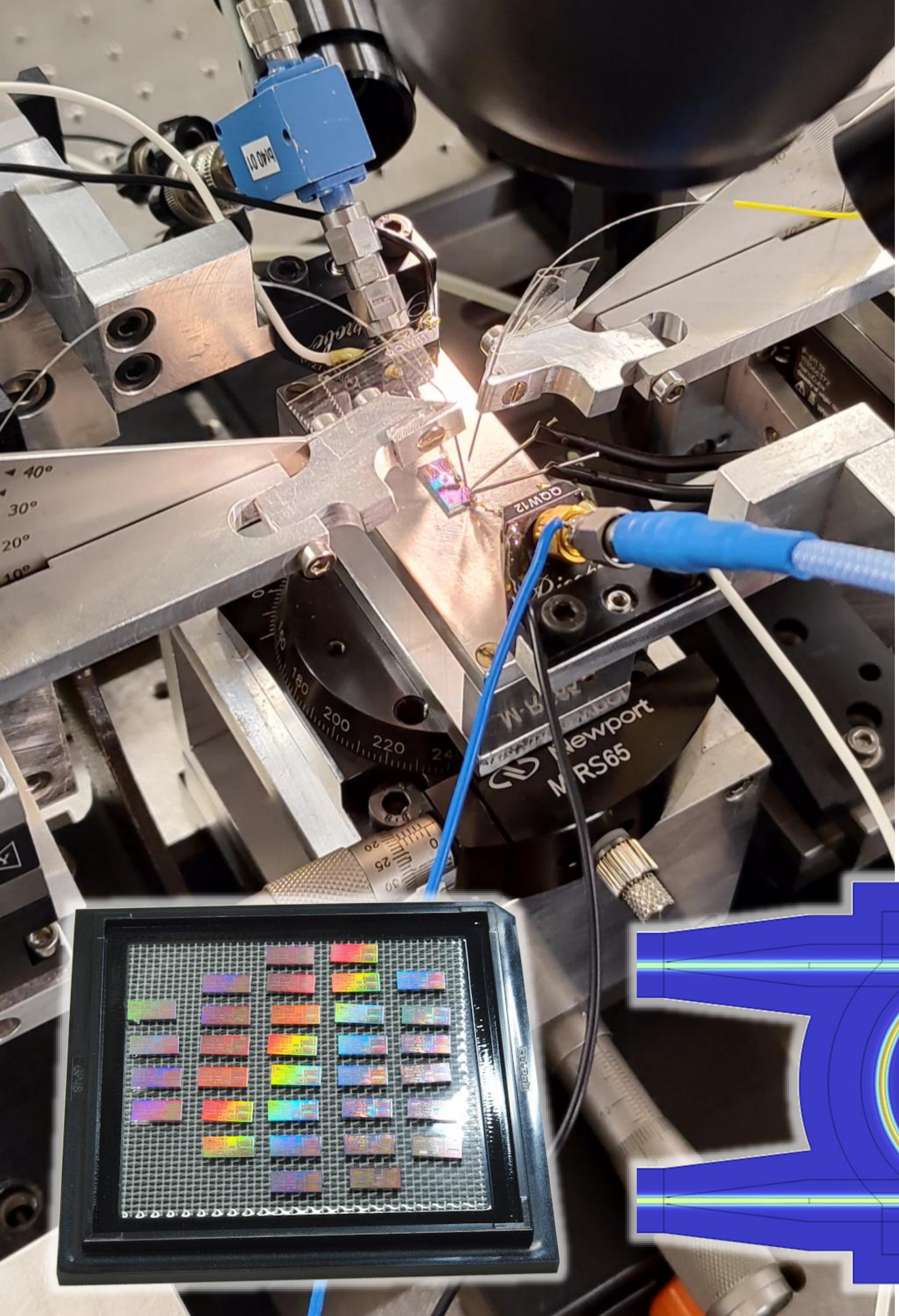
- Electroless immersion: 4” and 6” wafers
- Dedicated electroless plating stations, each optimized for a specific metal
  - Metals: Zn, Pd, Ni, Au, Cu, Sn (exchangeable with Ag)
- Electroplating stations, single and double-side wafer processing
  - Metals: Cu, Au, Ni
- Applications: TSV metallization, Redistribution layers (RDL) on wafers and interposers
- Advanced packaging for next-generation detector modules

➡ ***IPE clean rooms visit***



Silicon photonics and optical packaging

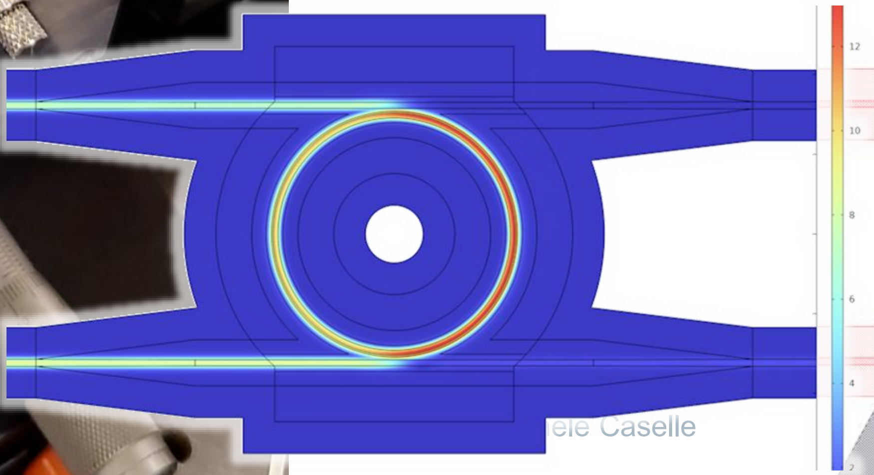
Silicon photonics is a game-changer for future detector modules, enabling fast, low-power optical data links tightly integrated with electronics

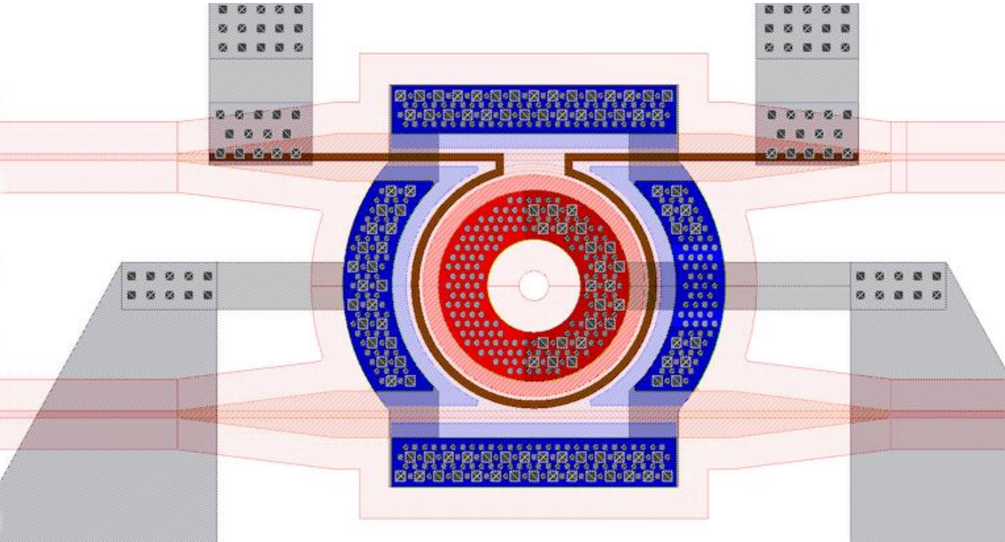


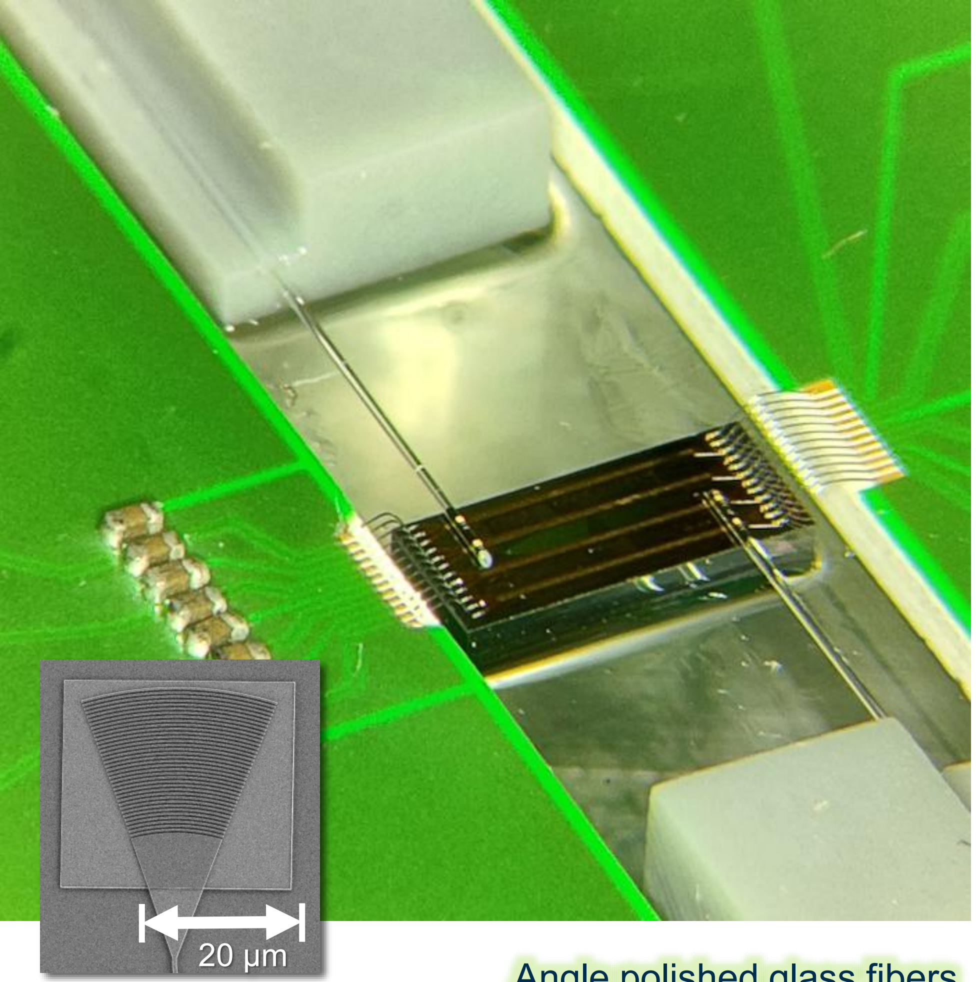
Silicon photonic design

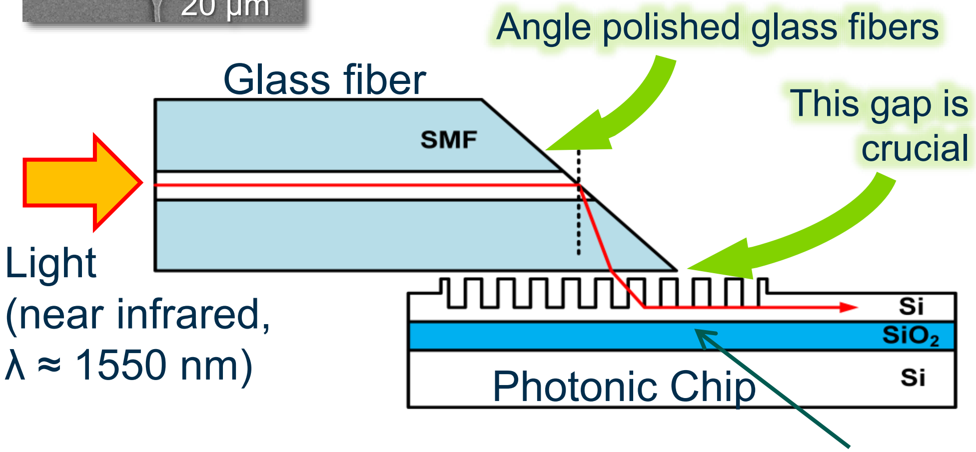
- KIT contribute to design in DRD 7.1
- Now focusing on ring modulators with drop port and photodiode for working point control AND RX-operation:
  - Design, simulations, layout
- New chip almost ready for submission (deadline 17.9.2025)
- Driver design ongoing, too

➡ ***IPE clean rooms visit***









SiPh packaging & fiber attachment

- SiPh packaging and fiber-attachment at detector-module essential for next-generation optical data links
- Automated fiber alignment using pick-and-place machines should enhance assembly throughput

Coupling geometries (SiPh ↔ fiber):

- Edge couplers: to be investigated within SoPhIE (Helmholtz InnoPool); high coupling efficiency, broadband and negligible polarization dependence, but more complex passive alignment (sub-micron tolerances, GRIN lenses required, on-chip components still polarization sensitive)
- Grating couplers: significant experience at KIT, compatible with wafer-level testing and probing, simple vertical fiber access, but slightly higher insertion loss, polarization sensitive

➡ ***IPE clean rooms visit***

We are pleased to host you and describe those processes in our laboratories during your visit

Many thanks for your attention