Diamond Pixel Fabrication
PhD Seminar 2019

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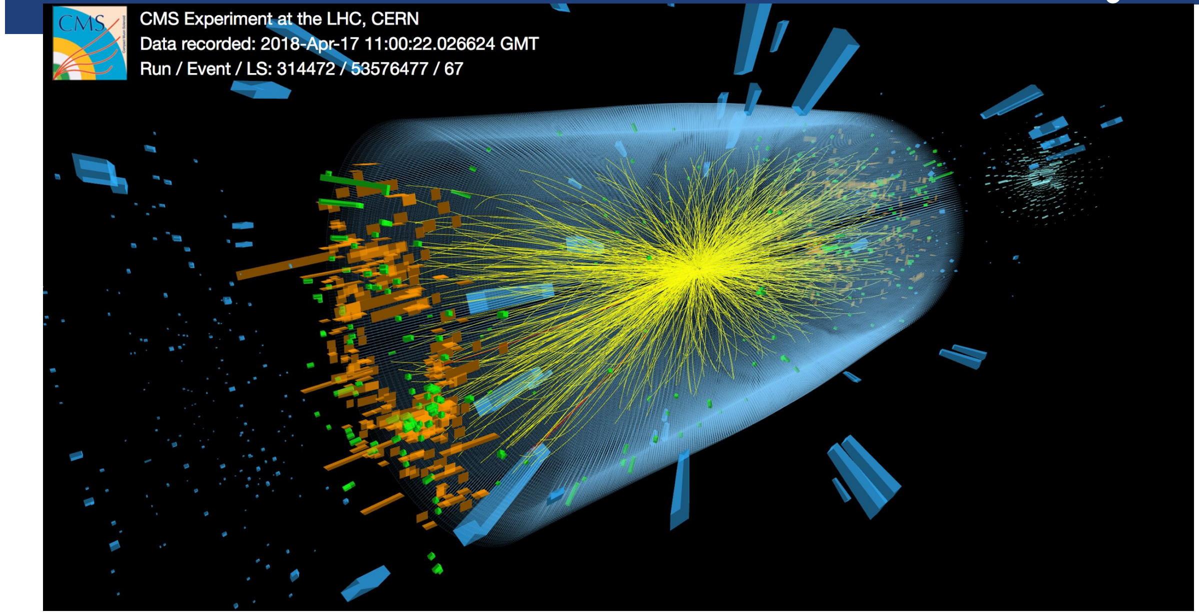
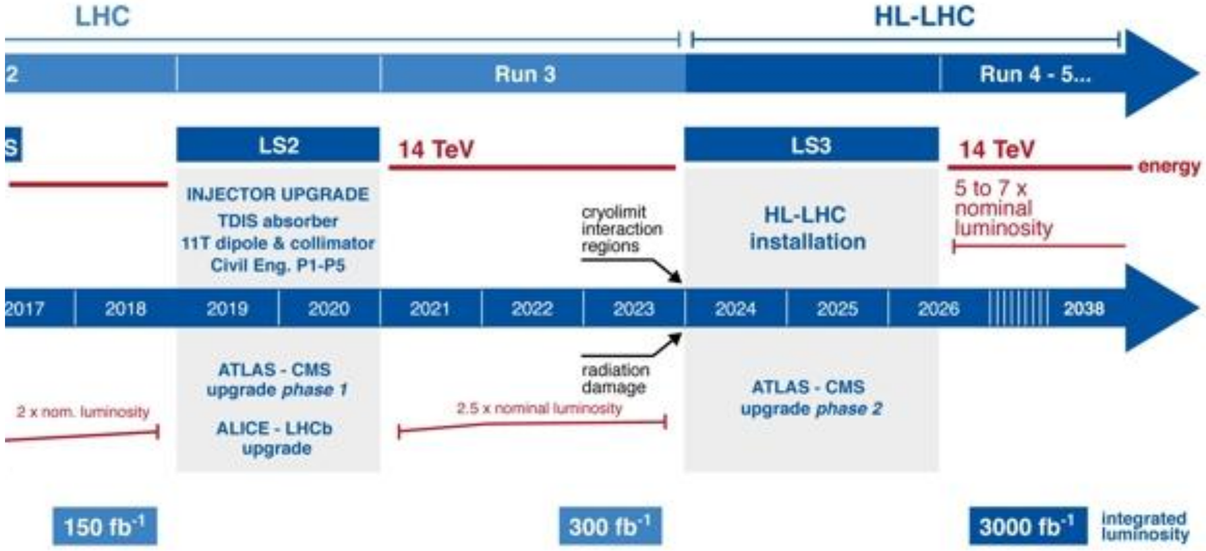
Overview

- Why Diamonds?
- Planar Hybrid Pixelated Detectors
- Microfabrication Techniques
- Samples Preparation
- Fabrication Process
- Preliminary Results (Testbeam September 2019)

Why Diamonds?





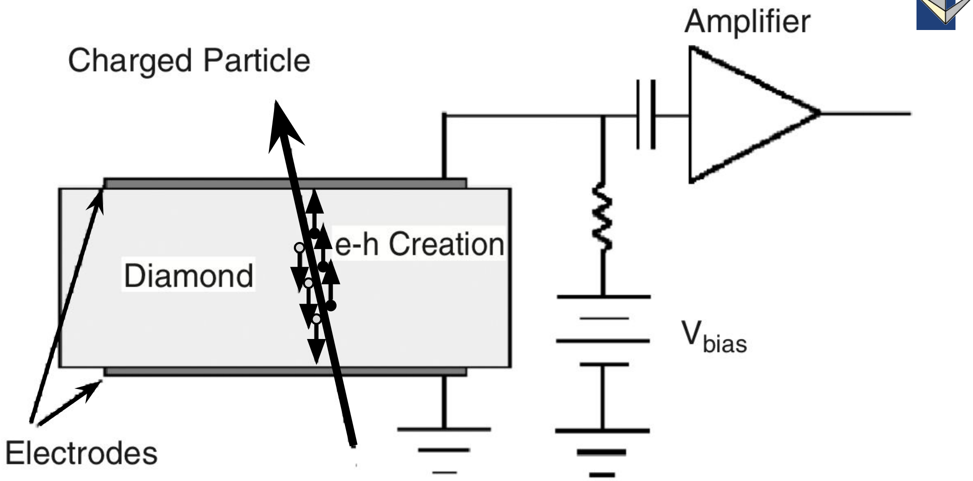
- The innermost detectors in HL-LHC experiments will be exposed to a total fluence of 2x10^{16} hadrons/cm^2 (~1 GHz/cm^2; ~500 MRad)

- Diamond is the best radiation tolerant sensor material in locations with no cooling

Make pixel detectors for future HEP experiments at ETH

Why Diamonds?

Characteristic	Silicon	Diamond	Comment
Band Gap [eV]	1.12	5.45	Low Leakage Current
Electron Mobility [cm^2/Vs]	1450	1714	Fast Signals
Hole Mobility [cm^2/Vs]	500	2064	Fast Signals
Saturation Velocity [cm/s]	0.8 x 10^7	~ 1 x 10^7	Fast Signals
Breakdown Field [V/m]	3 x 10^5	2.2 x 10^7	Withstand High Fields
Resistivity [Ω m]	3200	> 10^{40}	Low Leakage Current
Dielectric Constant	11.9	5.7	Low Input Capacitance
Displacement Energy [eV]	**13-20**	**43**	**Radiation Hardness**
Thermal Conductivity [W/cmK]	1.5	22	Efficient Heat Spreading
e-h Creation Energy [eV]	3.6	13	Small Signal
Average e-h Pairs per MIP per µm	89	36	Small Signal
Charge Collection Distance / thickness	100%	50% polycrystalline - 100% single crystal	Small Signal



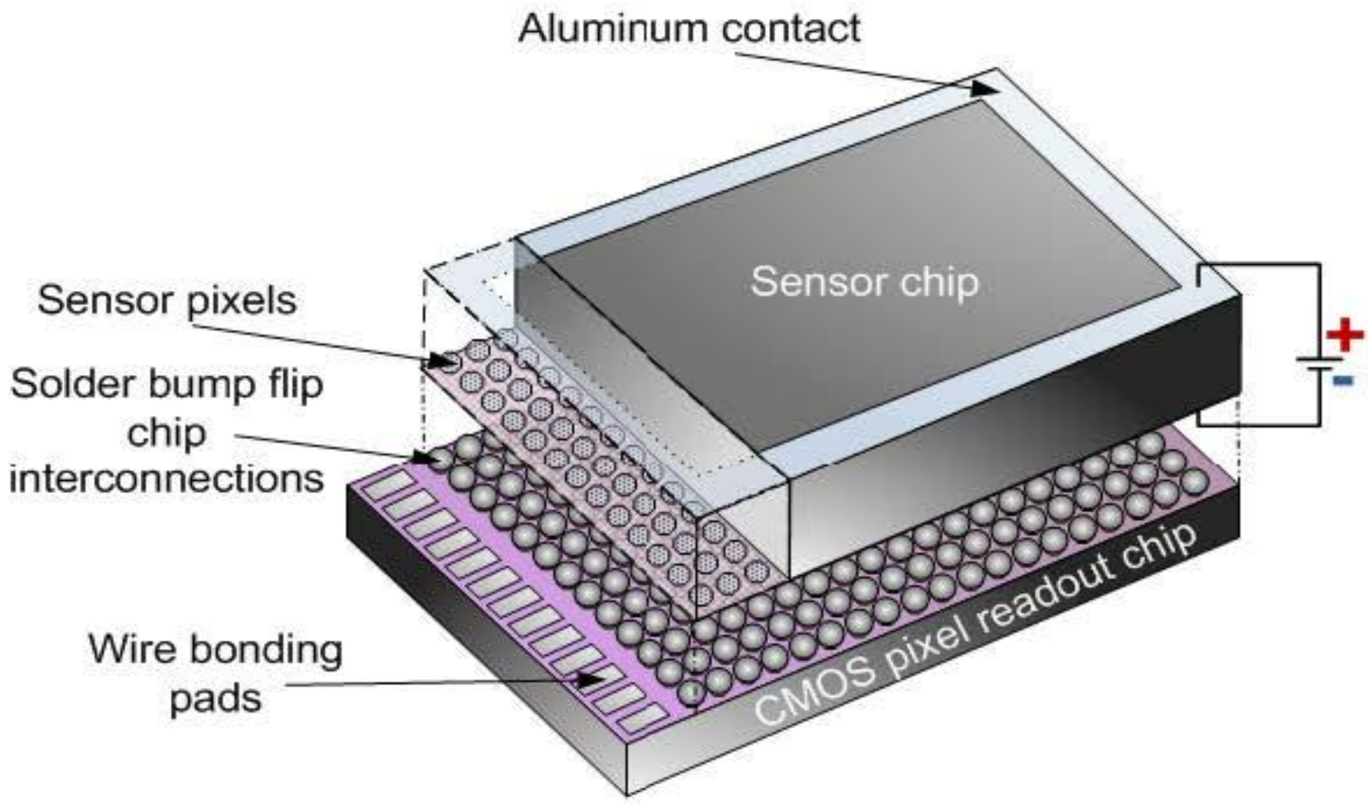
Artificially grown diamonds by chemical vapor deposition:

- Single crystal (large signals but up to ~8x8mm^2; more expensive)
- Polycrystalline (small signals but up to ø6in wafers; cheaper)

Diamond detectors are operated as ionisation chambers. Different from silicon sensor detectors

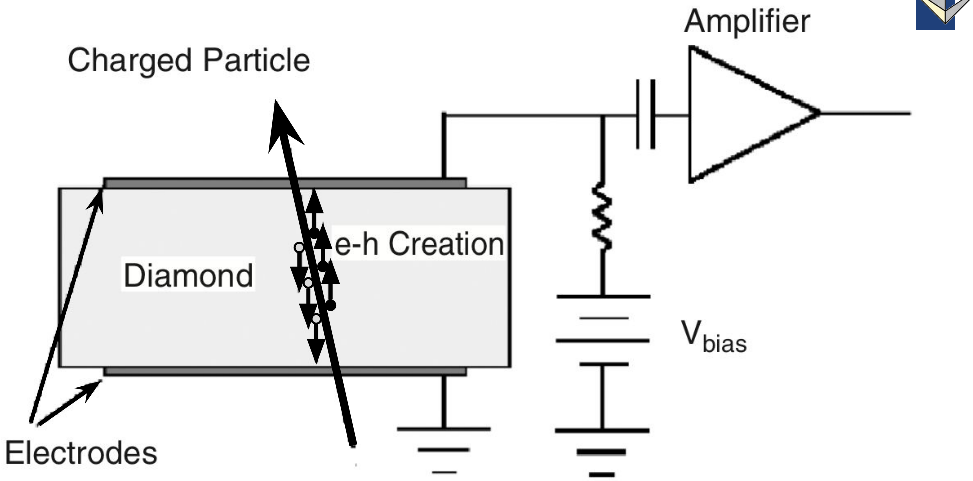
Planar devices are the first step before attempting more advanced geometries (i.e. 3D detectors)

Planar Hybrid Pixelated Detectors



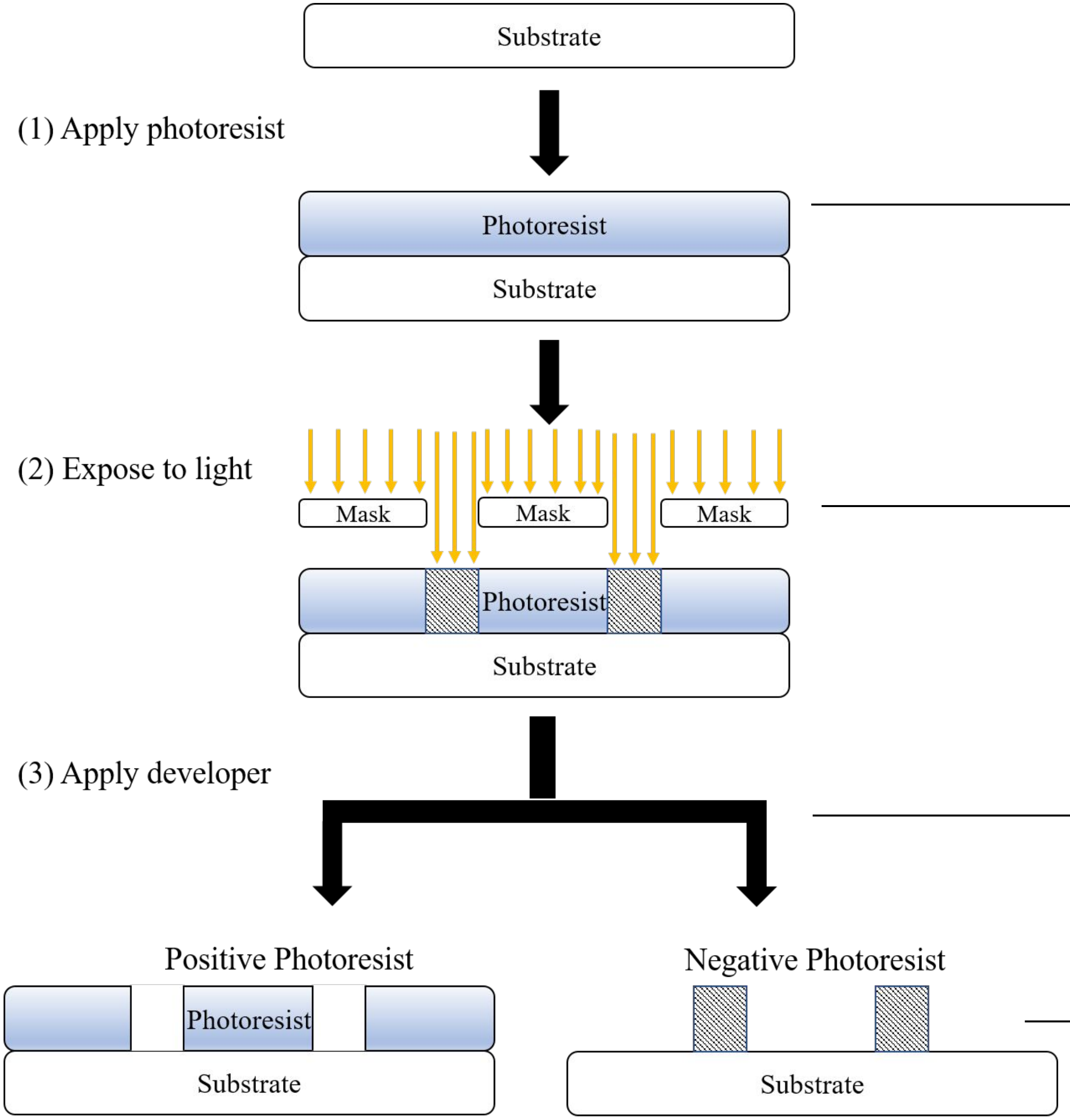
Generic pixel detector

Quality Issues in Current and Future Silicon Detectors workshop 3-November-2011



- Sensors are typically 500µm thick polycrystalline diamond of 1cm x 1cm
- Readout chip used is the psi46digV2.1 respin
  - Used for CMS layer 2 - 4
- **Develop microfabrication techniques to couple the diamond sensor with the silicon readout chip**
  - **Standard silicon microfabrication recipes don’t work with diamond**

Microfabrication Techniques - Patterning



Substrate

(1) Apply photoresist

Photoresist
Substrate

(2) Expose to light

Mask | Mask | Mask
Photoresist
Substrate

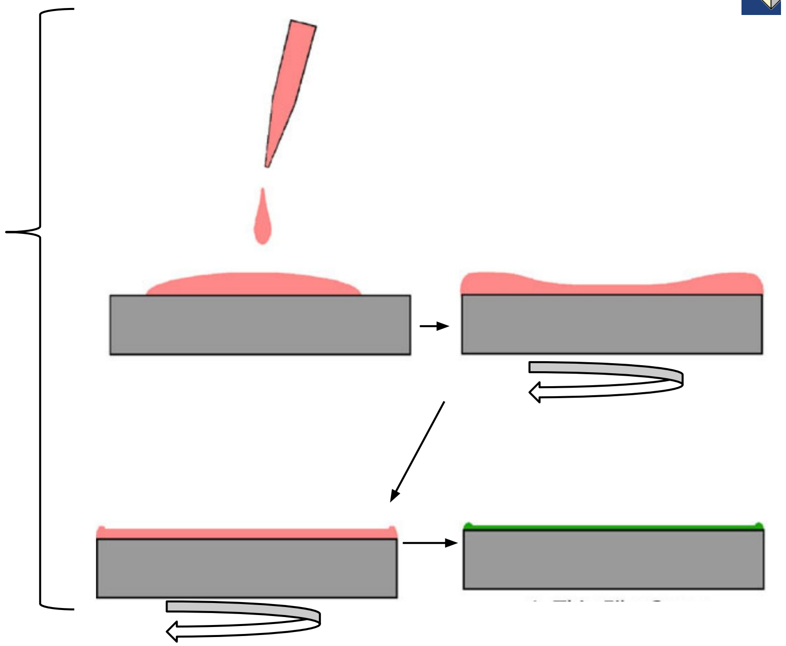
(3) Apply developer

Positive Photoresist
Photoresist
Substrate

Negative Photoresist
Substrate

https://en.wikipedia.org/wiki/File:Photoresist_of_Photolithography.png

Thickness of photoresist tuned by spinning

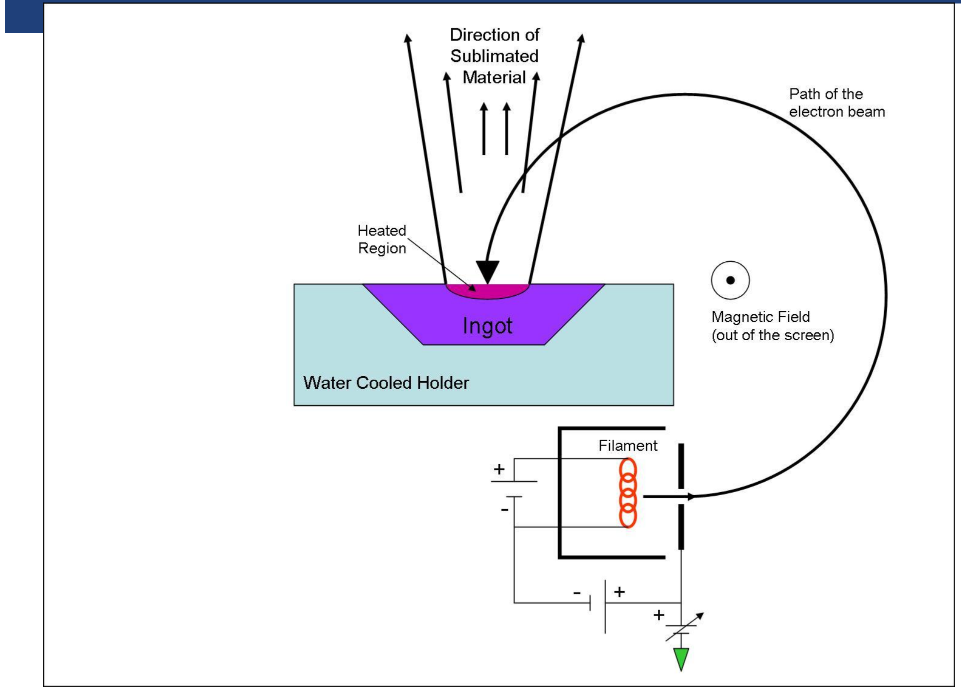


Glass mask with transparent/dark patterns

Development parameters (temperature, time and exposure to UV depend on substrate)

Photoresist layer shields desired regions on the substrate

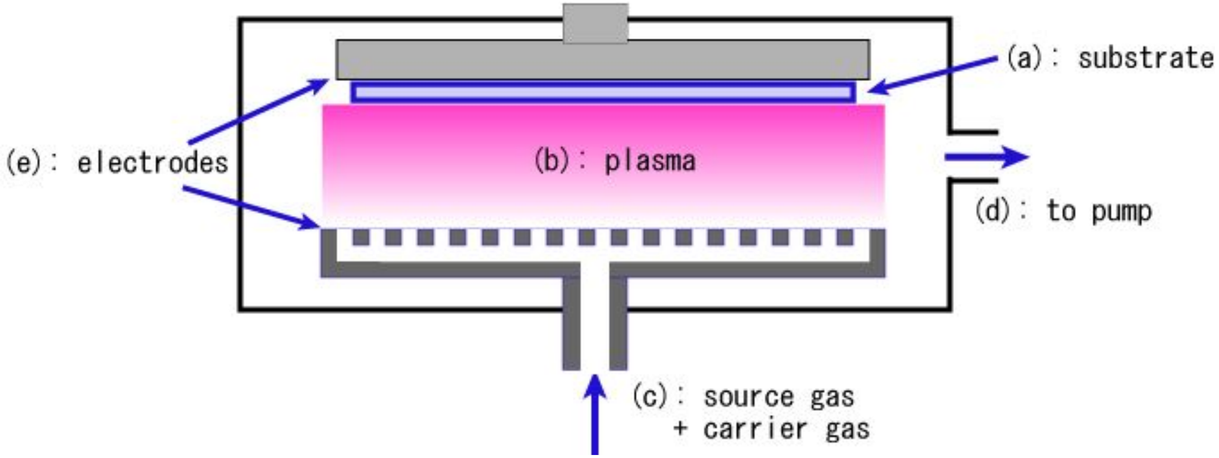
Microfabrication Techniques - Deposition



https://en.wikipedia.org/wiki/File:Electron_Beam_Deposition_001.jpg

Evaporation

- Metals are heated in a vacuum chamber
- Metal vapors rise and coats surface on top
- Suitable metallizations that form good contacts with diamond were tested

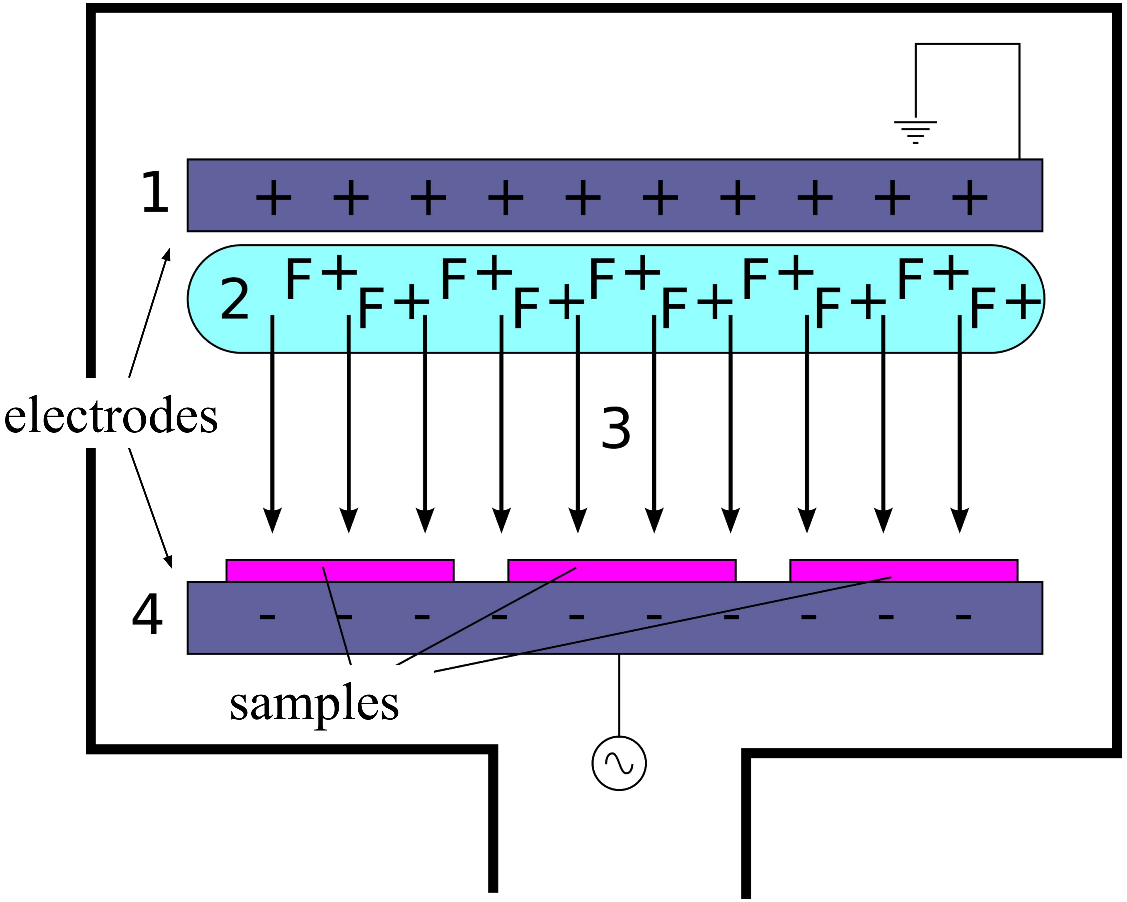


https://commons.wikimedia.org/wiki/File:PlasmaCVD.PNG

Chemical Vapor Deposition

- Layers of a material are grown on a substrate under specific chemical reactions
- The mixture of gases, and chamber conditions determine the properties of the deposited material and the deposition rate
- A compatible recipe with the process was developed to grow a passivation/protective layer

Microfabrication Techniques - Etching



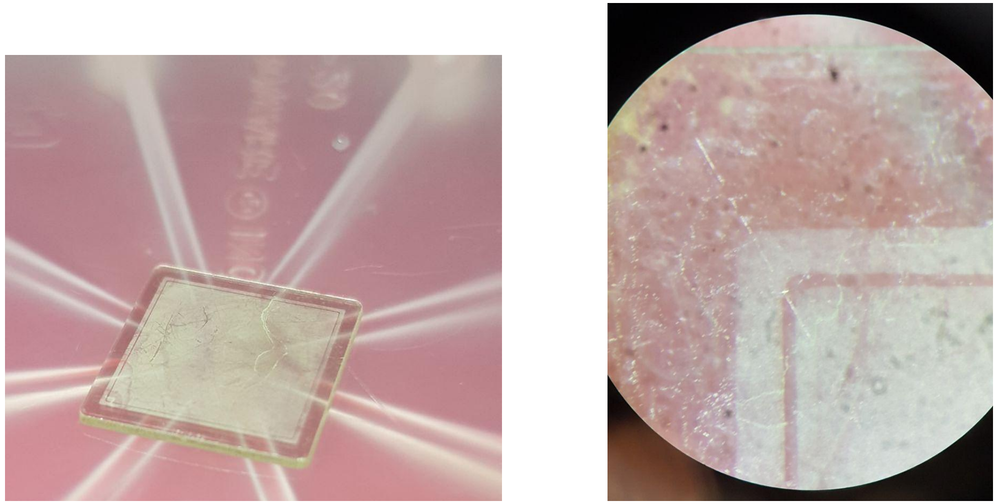
https://commons.wikimedia.org/wiki/File:Rieoperation.svg

Reactive Ion Etching

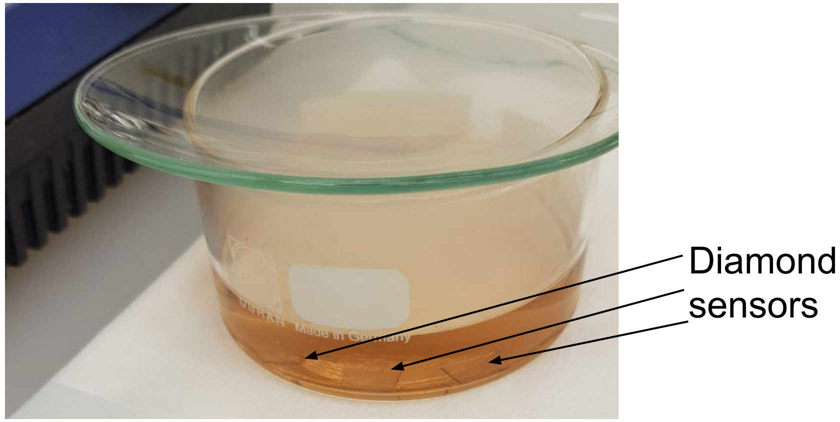
- A plasma of a gas mixture is used to remove desired material
- A specific recipe to etch through the passivation layer was developed and characterized

Samples preparation

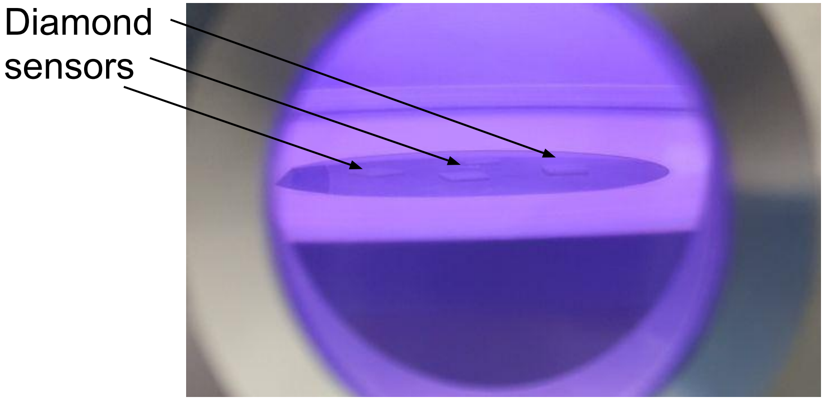
- Clean with different acids at boiling temperatures to remove any surface contamination
  - From the diamond growth
  - From previous detectors (we reuse diamonds)
- Etch with Reactive Ion Etching tuned with Ar/Cl_2 and O_2 plasmas to remove ~2µm of diamond from each side
- Clean with solvents in ultrasound bath



Pictures taken in between boiling acids cleaning. It is evident the residue from old-fabrication in the sample



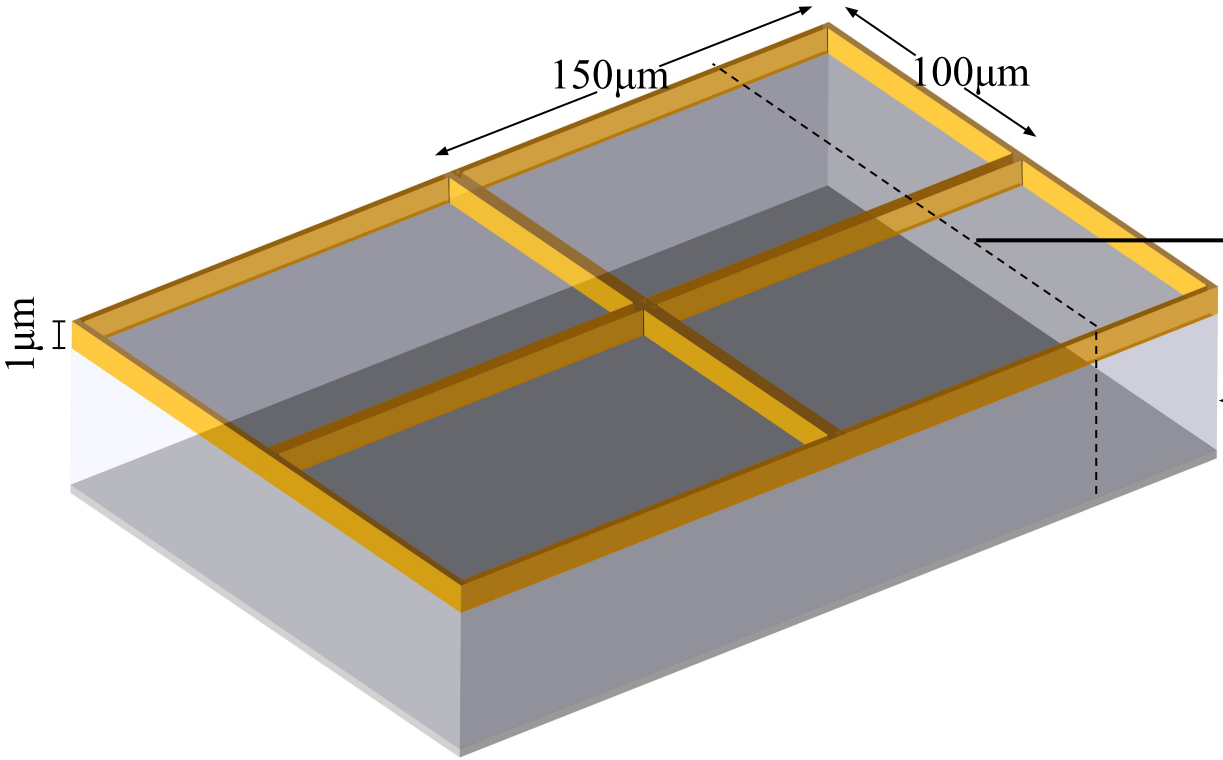
Sensors cooling down after Aqua-regia cleaning

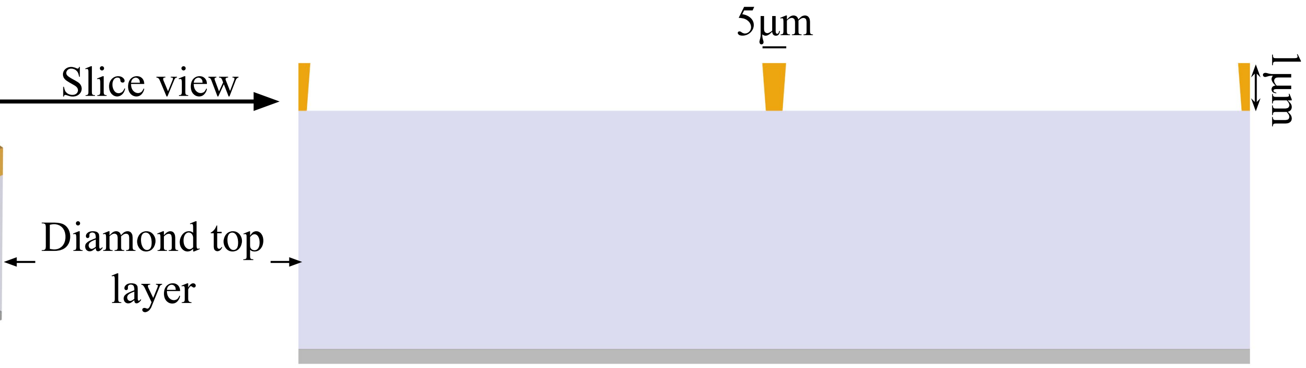


Plasma etch with Ar/Cl_2

Fabrication Process

1. Pixels metallization - Photoresist mask





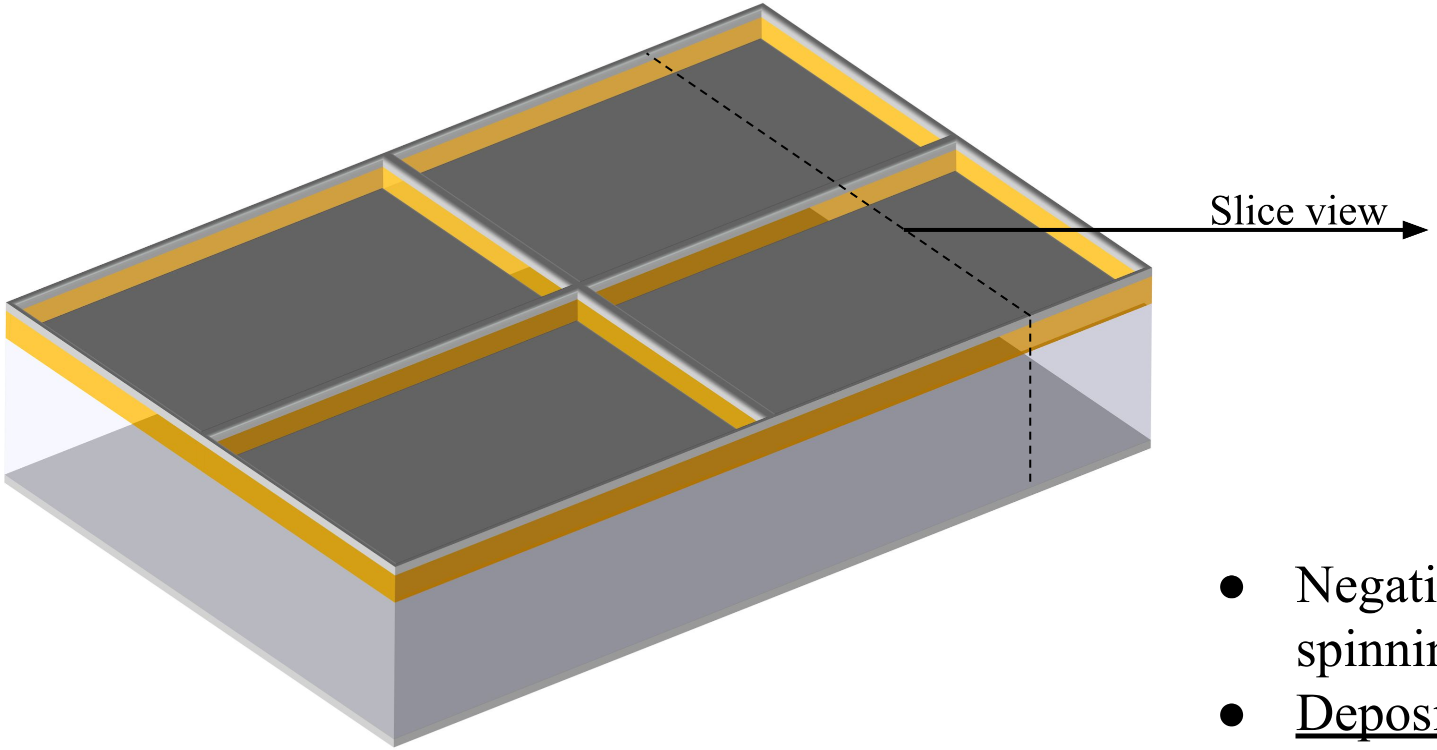
Sensor slice view - thickness (vertical) scaled by 10x)

- Negative Photoresist mask (~1µm thick by spinning) for pixel delimitation

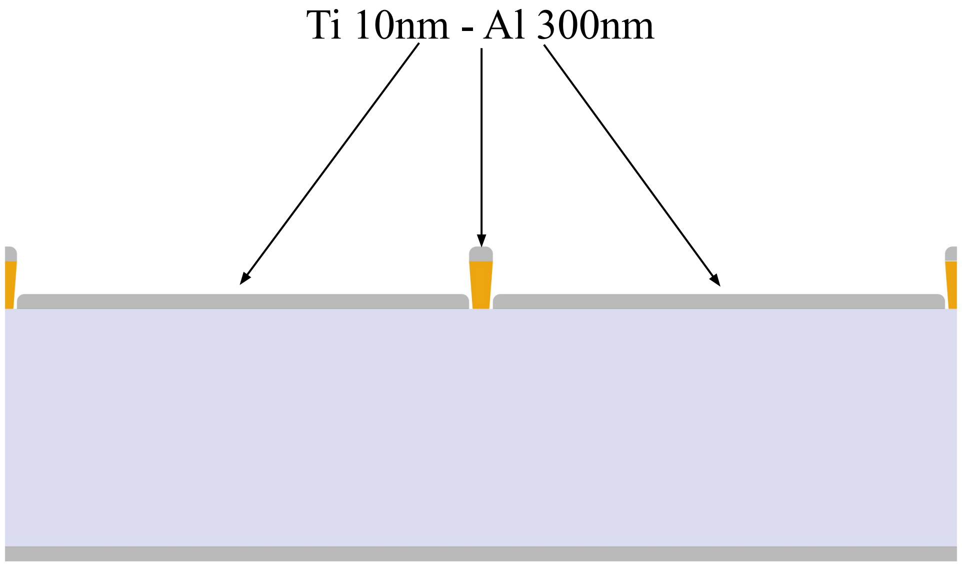
Sensor top surface view - thickness scaled by 10x

Fabrication Process

1. Pixels metallization - Metal deposition (electron beam evaporation)



Sensor top surface view - thickness scaled by 10x

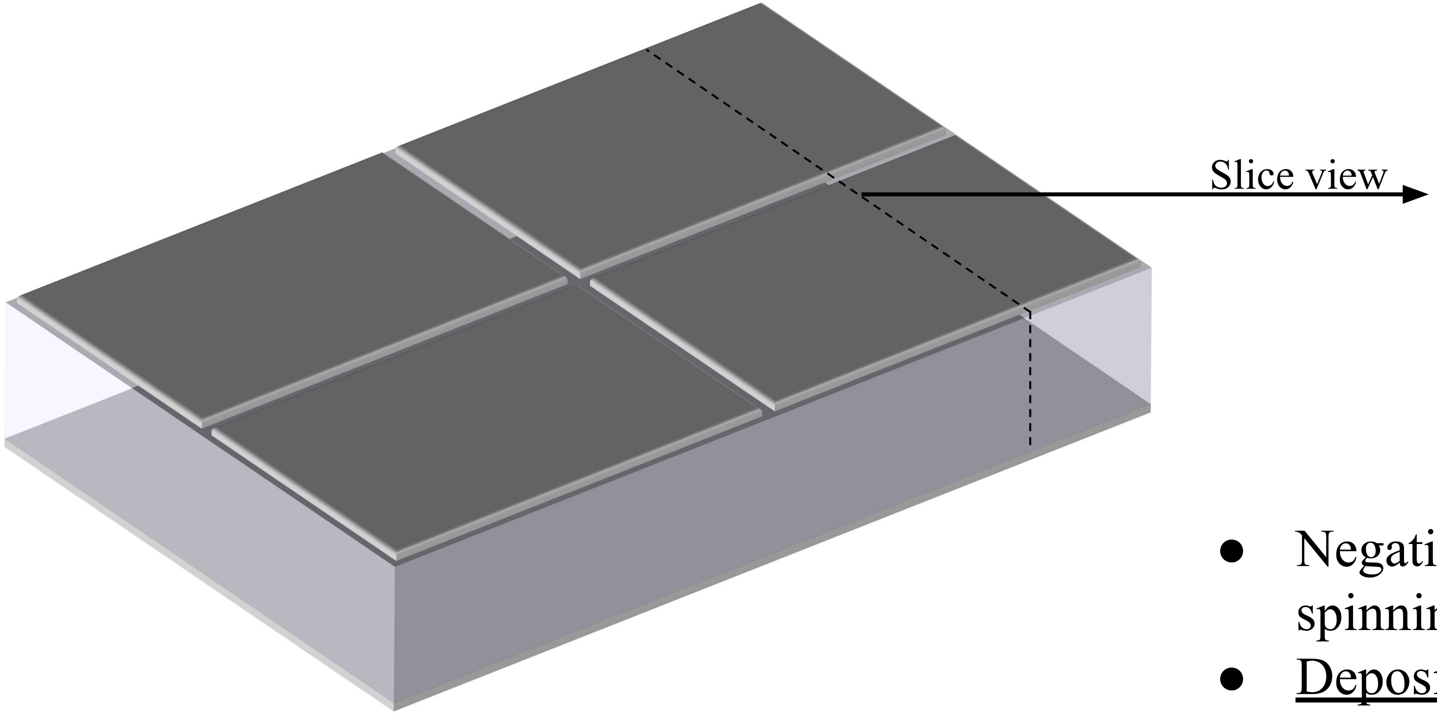


Sensor slice view - thickness (vertical) scaled by 10x)

- Negative Photoresist mask (~1µm thick by spinning) for pixel delimitation
- <u>Deposition of 10nm of Ti and 300nm of Al</u>

Fabrication Process

1. Pixels metallization - Lift-off and annealing



Sensor top surface view - thickness scaled by 10x

Sensor slice view - thickness (vertical) scaled by 10x)

- Negative Photoresist mask (~1μm thick by spinning) for pixel delimitation
- <u>Deposition of 10nm of Ti and 300nm of Al</u>
- Photoresist and excess metal lift-off using solvents
- 400°C annealing with Ar → carbide binding (C-Ti) for ohmic contact formation on the diamond

Fabrication Process

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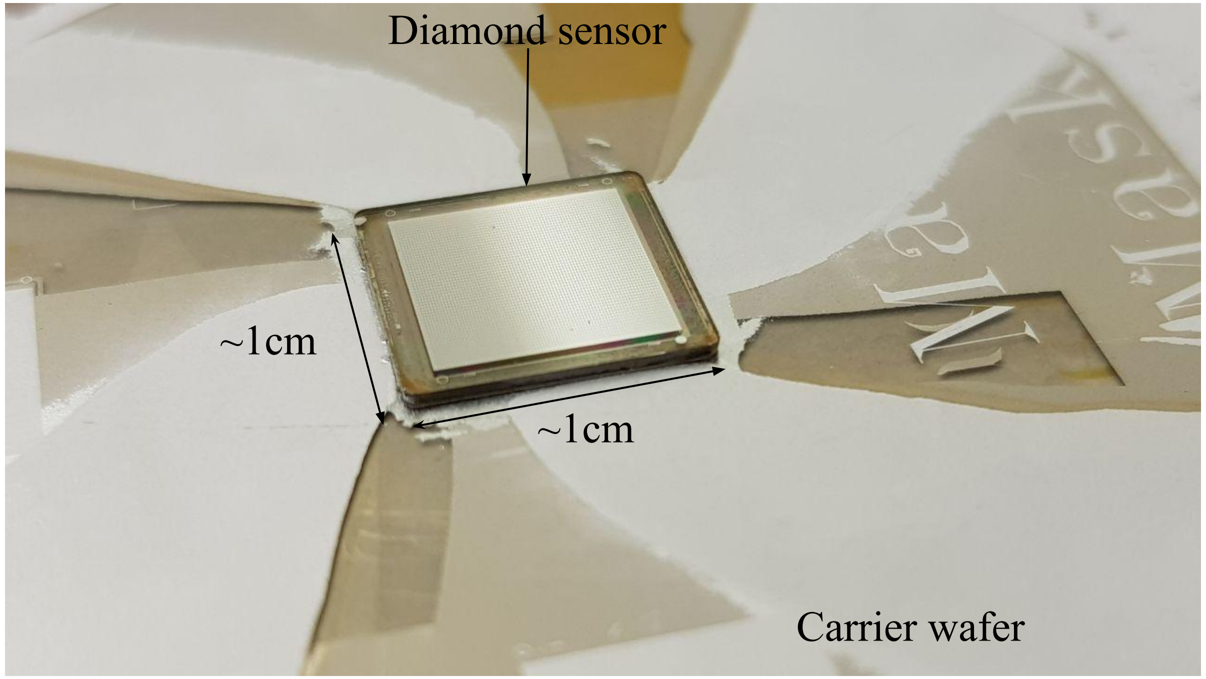


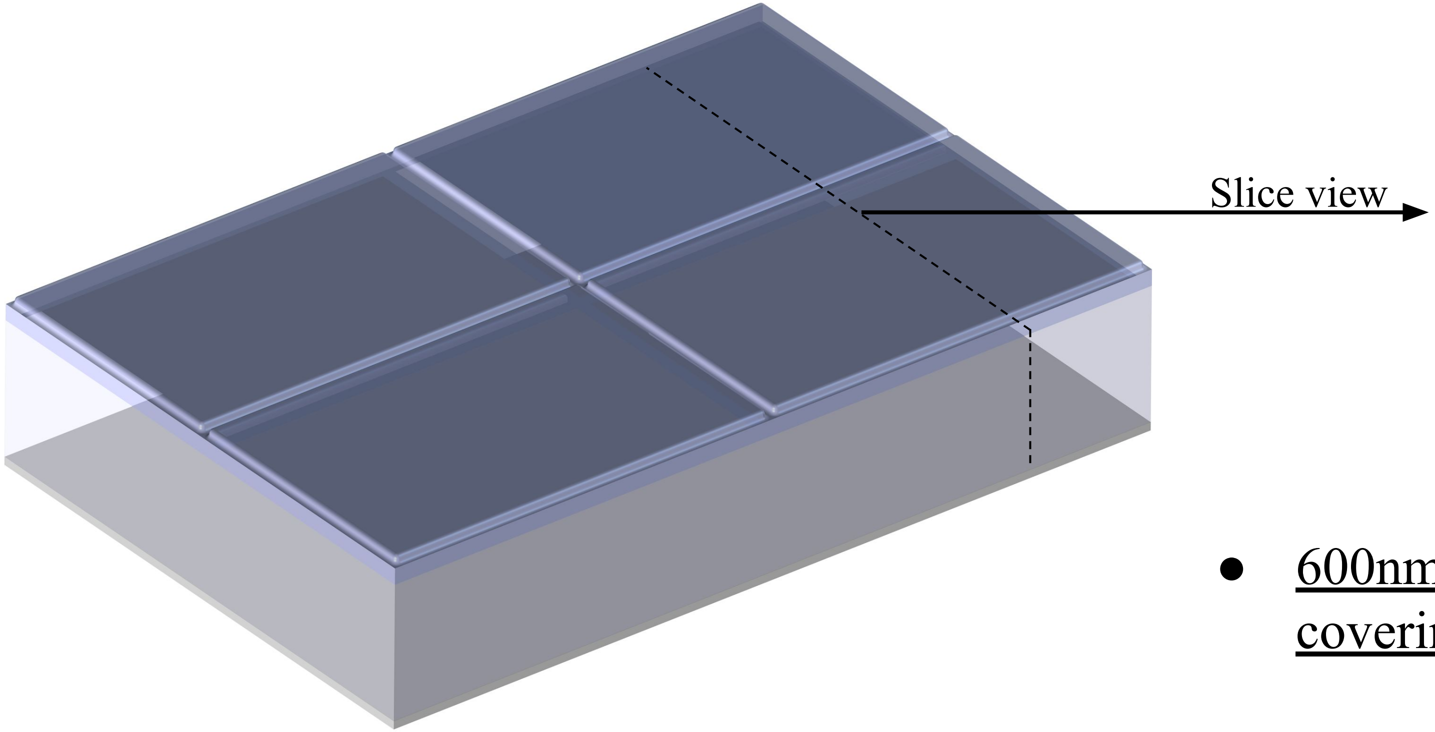
Picture of diamond sensor after first evaporation and lift-off

Sensor slice view - thickness (vertical) scaled by 10x)

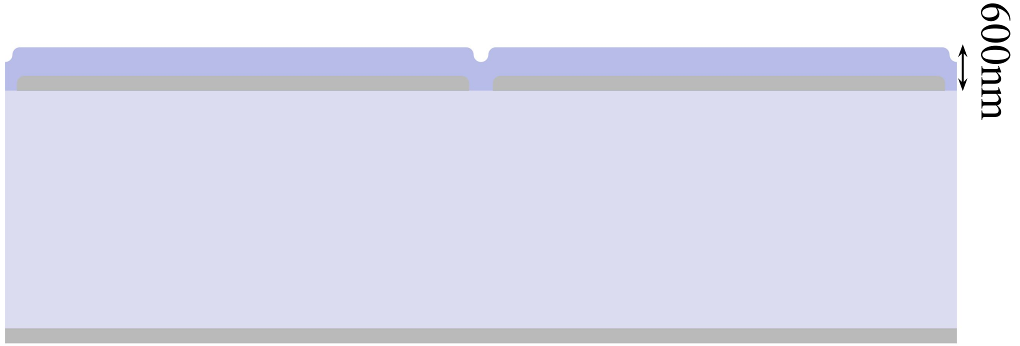
- Negative Photoresist mask (~1µm thick by spinning) for pixel delimitation
- Deposition of 10nm of Ti and 300nm of Al
- Photoresist and excess metal lift-off using solvents
- 400°C annealing with Ar → carbide binding (C-Ti) for ohmic contact formation on the diamond

Fabrication Process

2. Passivation layer - Plasma enhanced chemical vapor deposition (peCVD) of SiO_xN_y



Sensor top surface view - thickness scaled by 10x

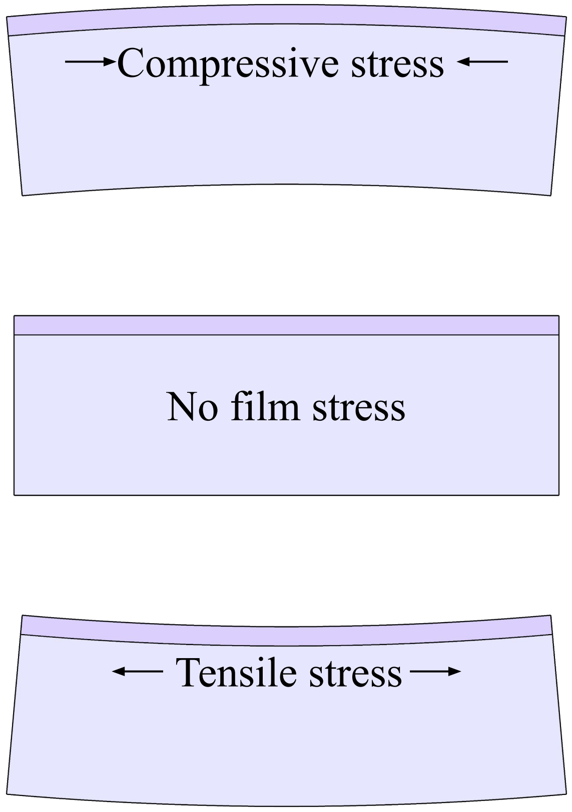


Sensor slice view - thickness (vertical) scaled by 10x)

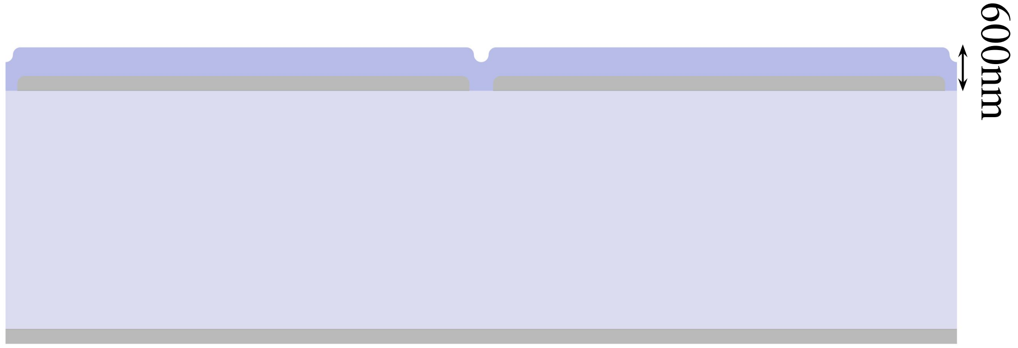
- 600nm low-stress film deposition of SiO_xN_y covering all the sensor's surface

Fabrication Process

2. Passivation layer - Plasma enhanced chemical vapor deposition (peCVD) of SiO_xN_y



Remanent stress can crack the deposited SiON film and also the metallic layers below → Low stress is desired for our detector



Sensor slice view - thickness (vertical) scaled by 10x)

- <u>600nm low-stress film deposition of SiO_xN_y covering all the sensor’s surface</u>

Fabrication Process

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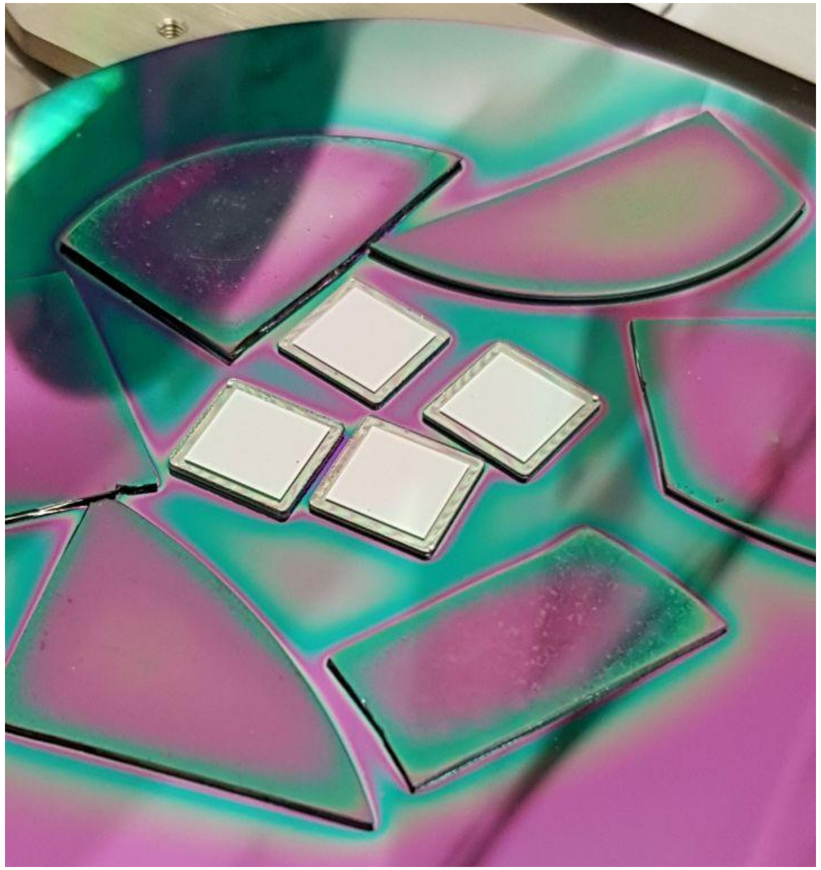
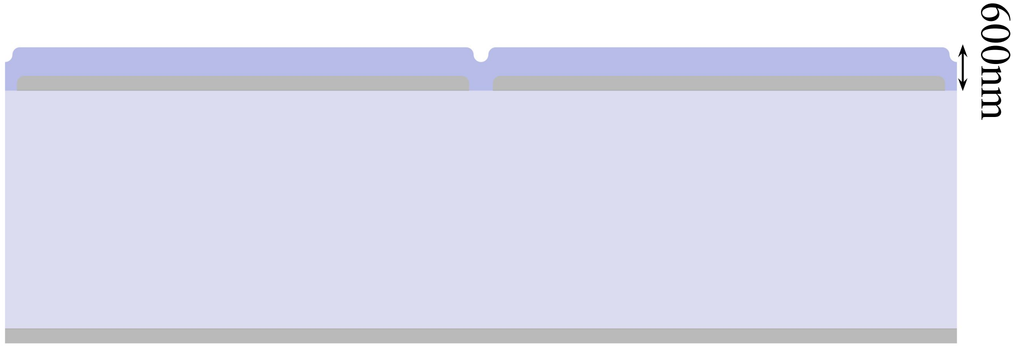


Picture of 4 diamond samples and silicon carriers after SiON deposition

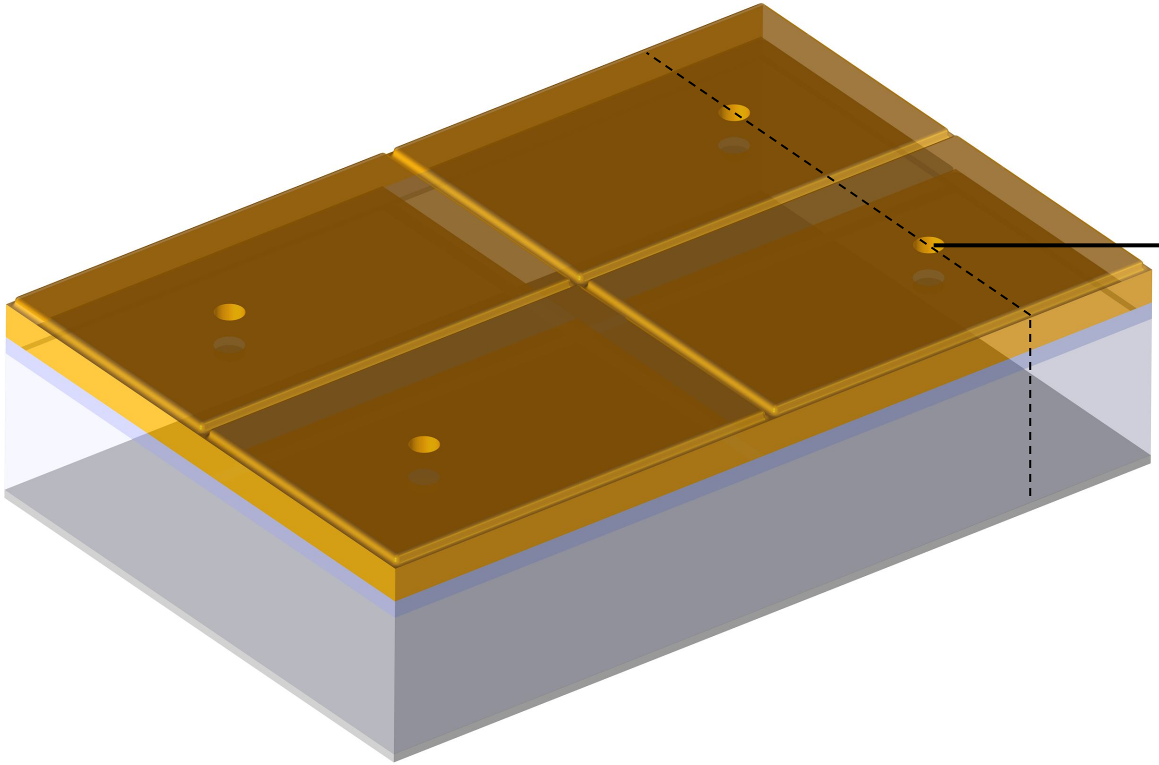


Sensor slice view - thickness (vertical) scaled by 10x)

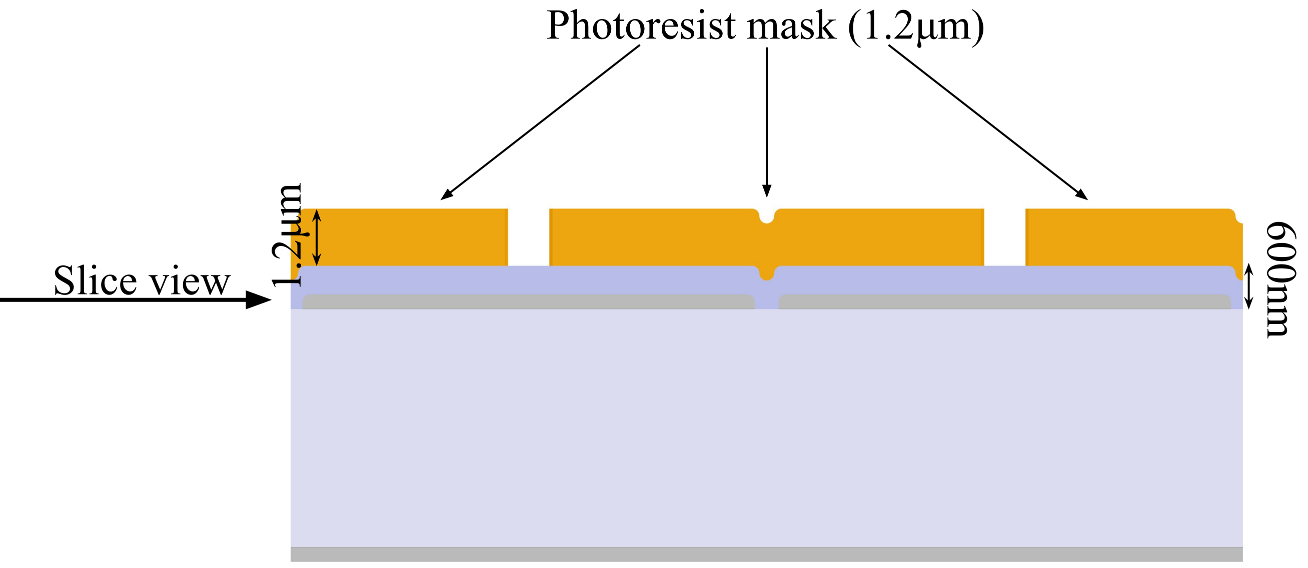
- <u>600nm low-stress film deposition of SiO_xN_y covering all the sensor's surface</u>

Fabrication Process

2. Passivation layer - Reactive ion etching (RIE) through passivation layer



Sensor top surface view - thickness scaled by 10x

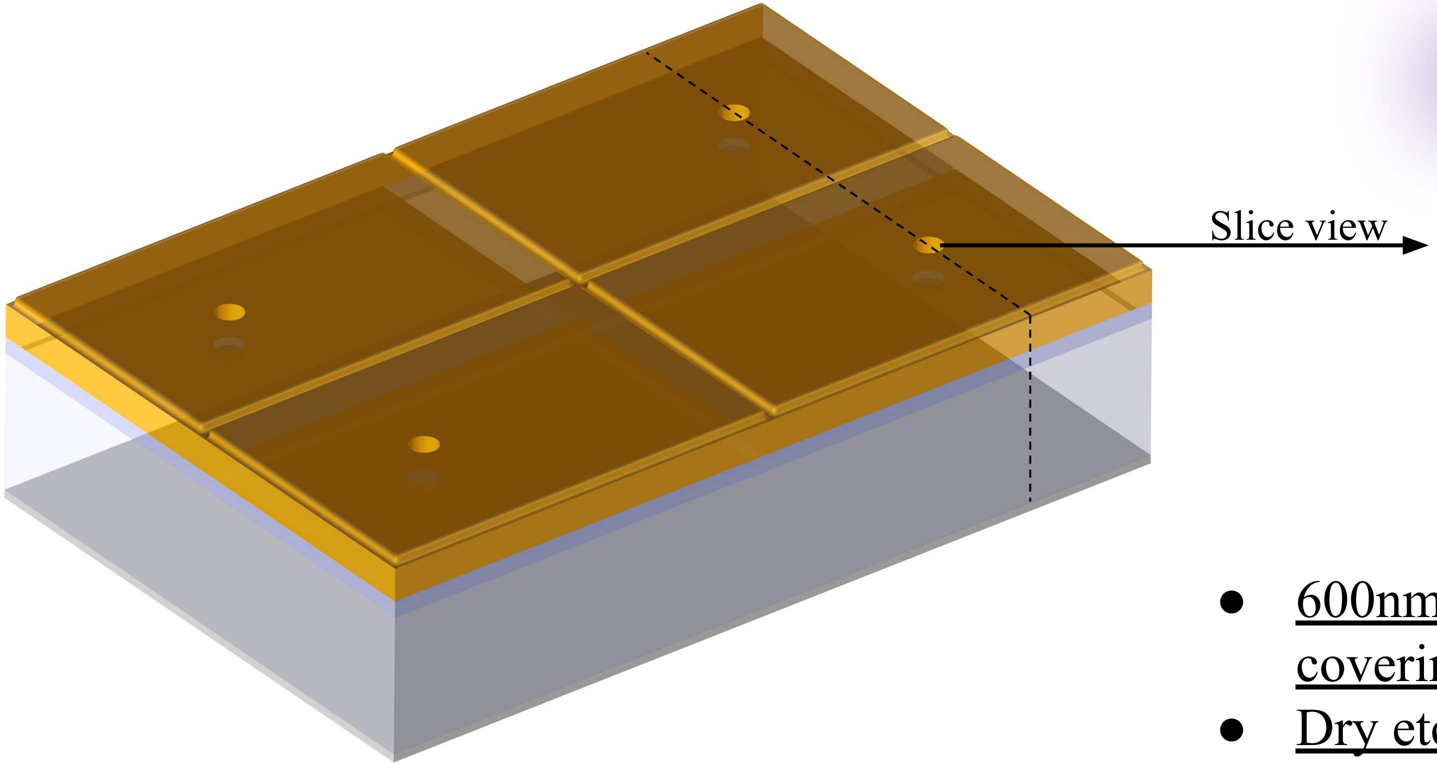


Sensor slice view - thickness (vertical) scaled by 10x)

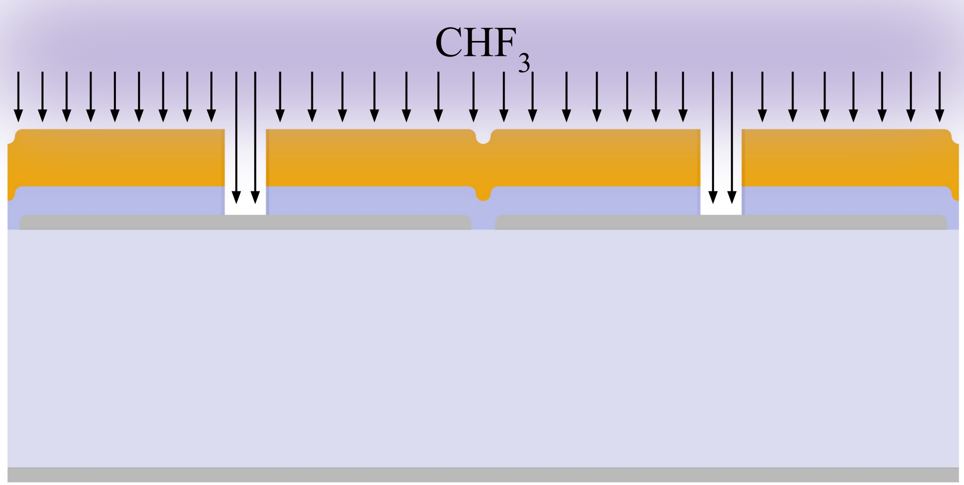
- 600nm low-stress film deposition of SiO_xN_y covering all the sensor's surface
- Dry etching with a reactive plasma of CHF_3 until the metallization is reached

Fabrication Process

2. Passivation layer - Reactive ion etching (RIE) through passivation layer



Sensor top surface view - thickness scaled by 10x

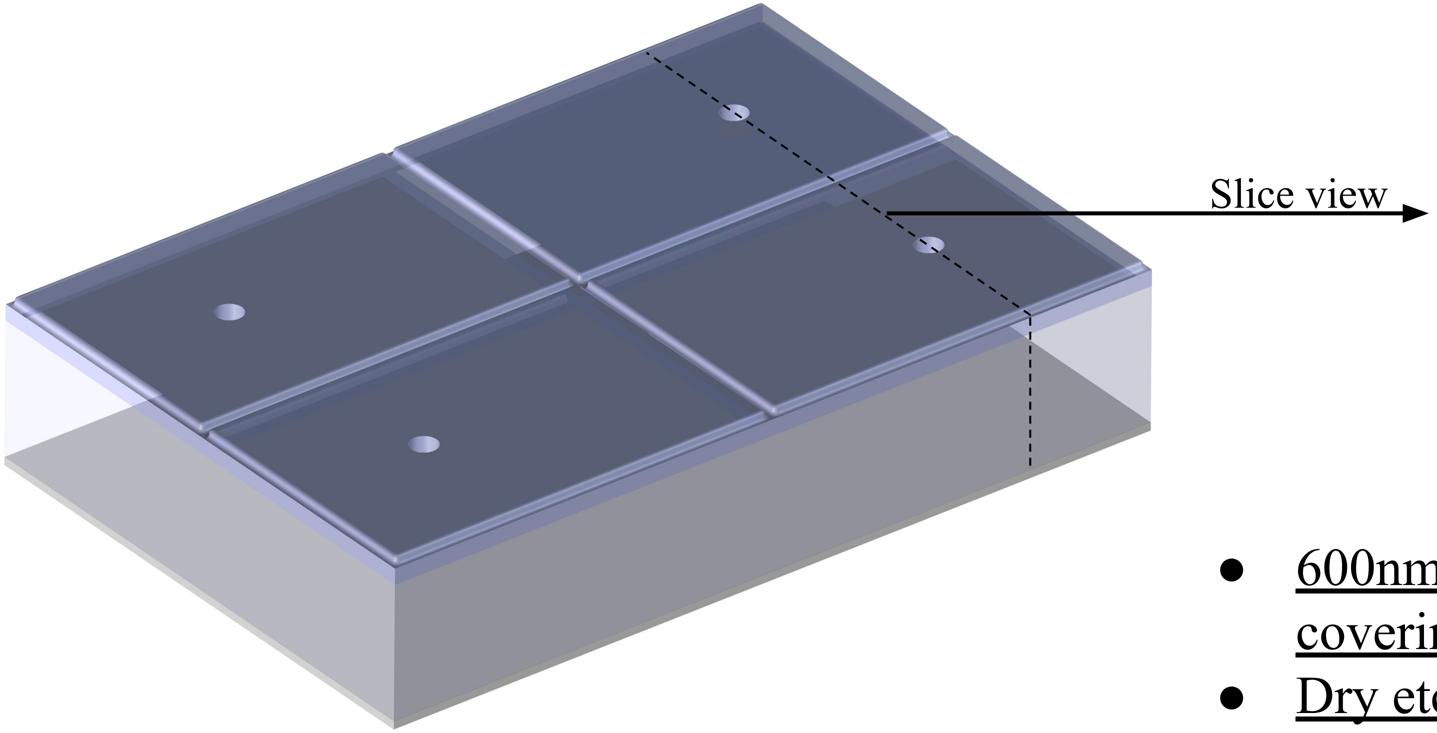


Sensor slice view - thickness (vertical) scaled by 10x)

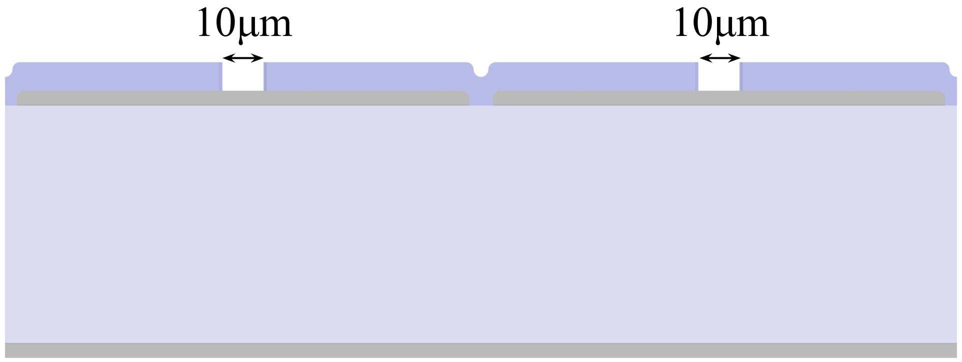
- 600nm low-stress film deposition of SiO_xN_y covering all the sensor’s surface
- Dry etching with a reactive plasma of CHF_3 until the metallization is reached

Fabrication Process

2. Passivation layer - Photoresist removal



Sensor top surface view - thickness scaled by 10x



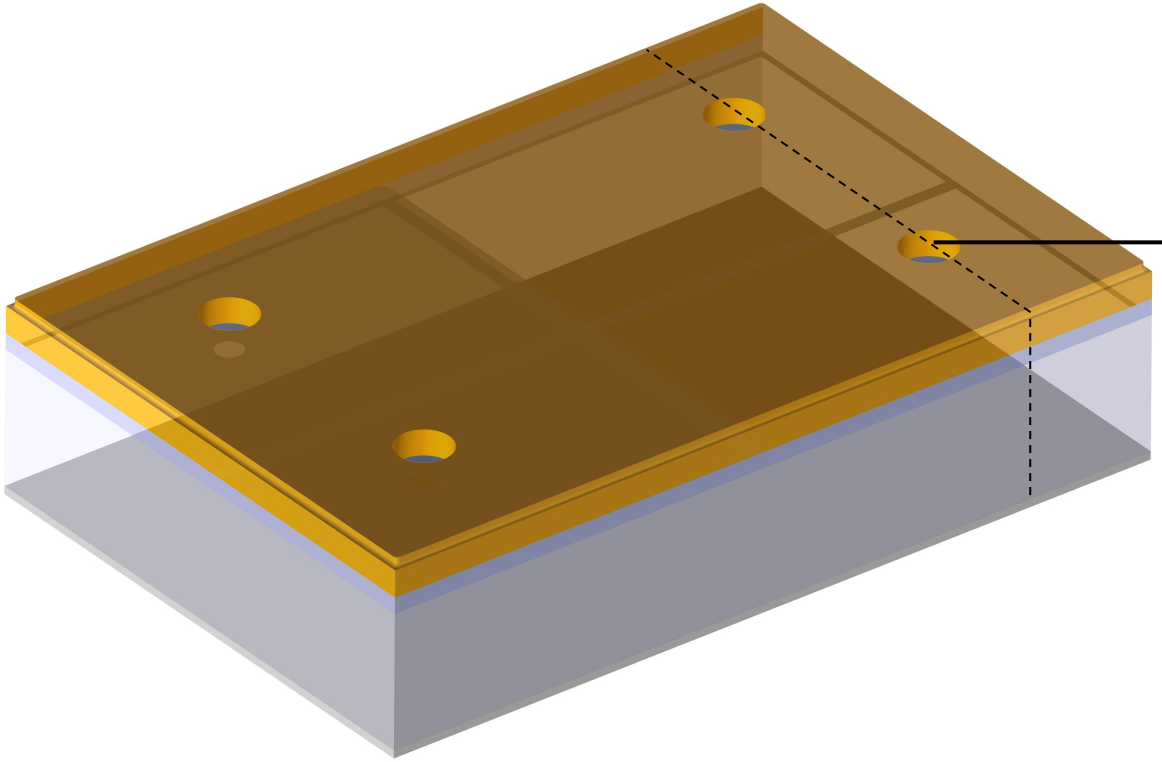
Sensor slice view - thickness (vertical) scaled by 10x)

- 600nm low-stress film deposition of SiO_xN_y covering all the sensor's surface
- Dry etching with a reactive plasma of CHF_3 until the metallization is reached
- Photoresist stripping with solvents

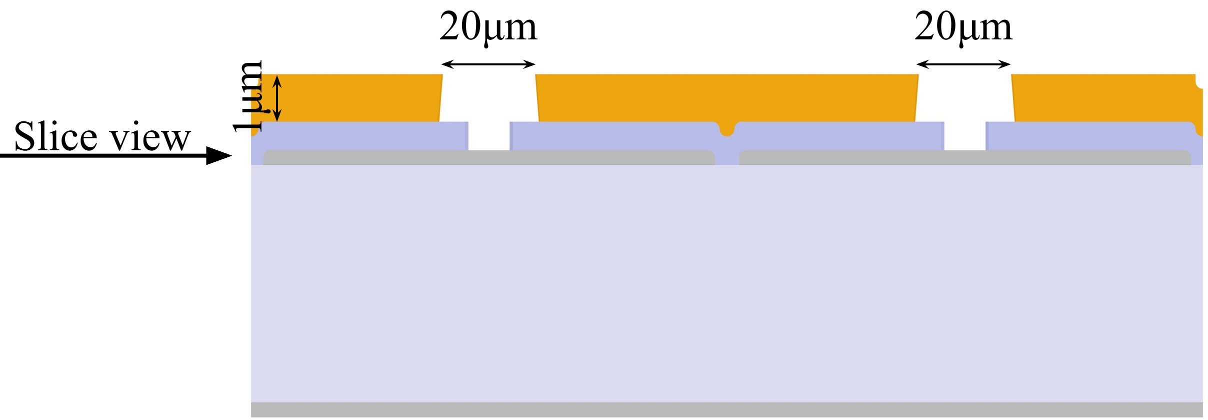
Fabrication Process

3. Under bump metallization (UBM) - Photoresist mask

Metallization required for bumps to stick in the correct position



Sensor top surface view - thickness scaled by 10x



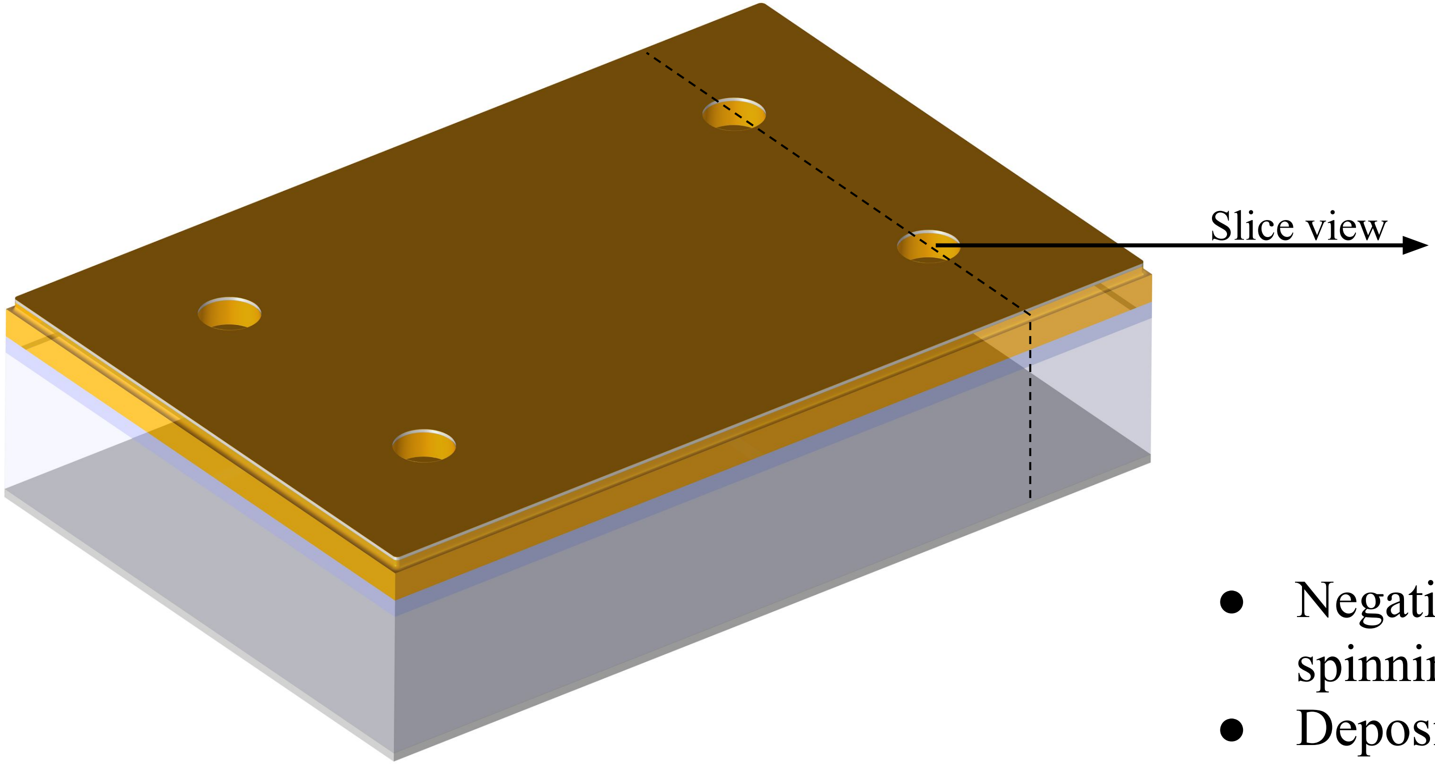
Sensor slice view - thickness (vertical) scaled by 10x)

- Negative Photoresist mask (~1µm thick by spinning) for UBM delimitation

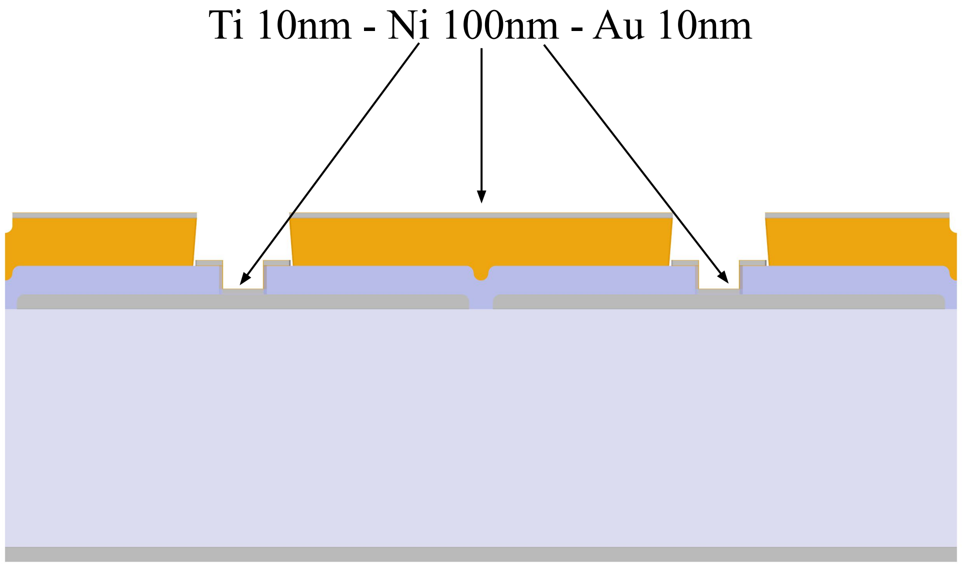
Fabrication Process

3. Under bump metallization (UBM) - Metal deposition (electron beam evaporation)

→Metallization required for bumps to stick in the correct position



Sensor top surface view - thickness scaled by 10x



Sensor slice view - thickness (vertical) scaled by 10x)

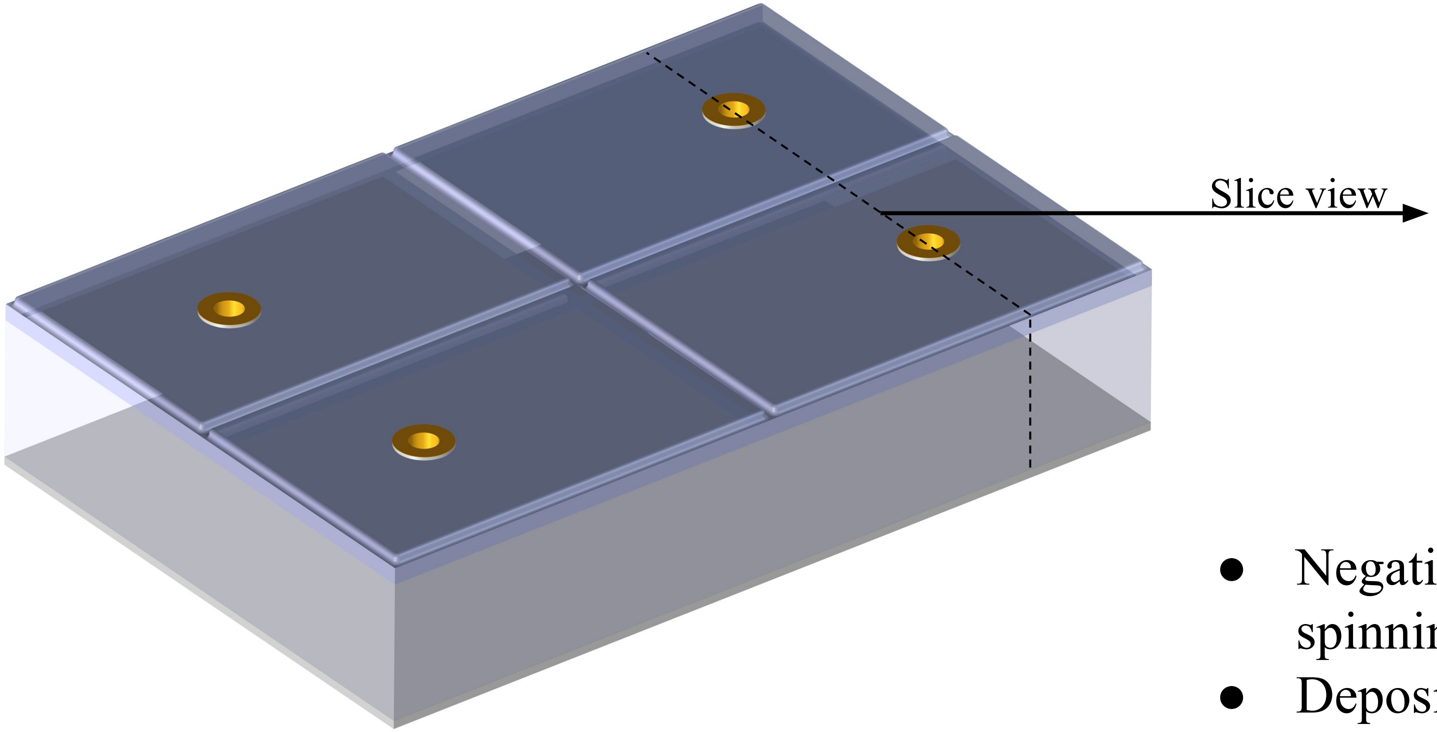
- Negative Photoresist mask (~1µm thick by spinning) for UBM delimitation
- Deposition of 10nm of Ti, 100nm of Ni and 10nm of Au

ETH zürich

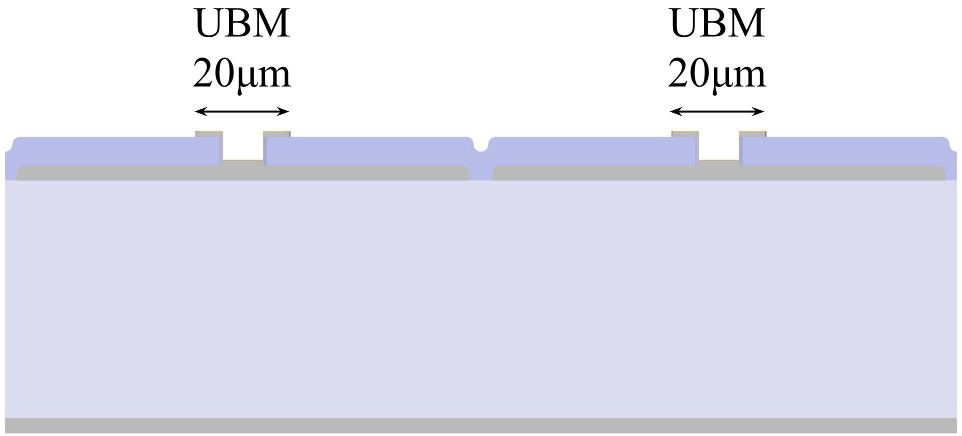
Fabrication Process

3. Under bump metallization (UBM) - Lift-off

→ Metallization required for bumps to stick in the correct position



Sensor top surface view - thickness scaled by 10x



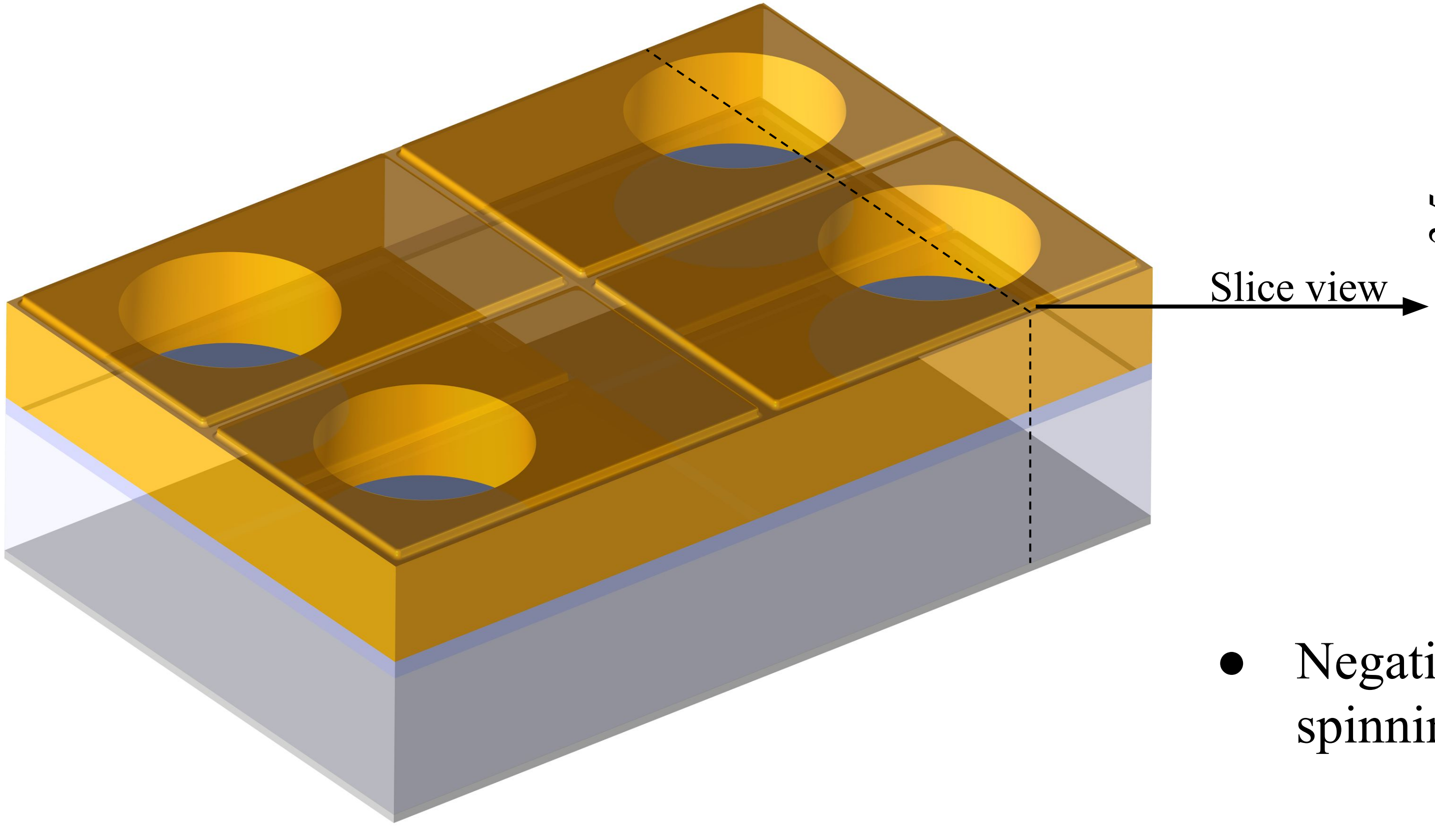
Sensor slice view - thickness (vertical) scaled by 10x)

- Negative Photoresist mask (~1µm thick by spinning) for UBM delimitation
- Deposition of 10nm of Ti, 100nm of Ni and 10nm of Au
- Photoresist and excess metal lift-off using solvents
- UBM is required for correct bump formation

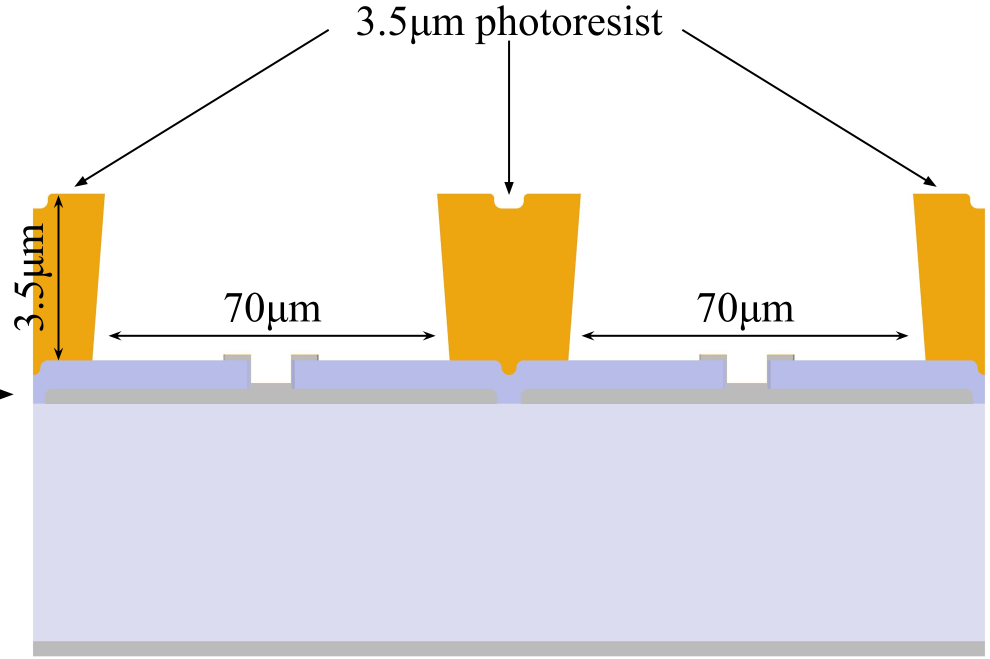
IPA

Fabrication Process

4. Indium bumps - Photoresist mask



Sensor top surface view - thickness scaled by 10x

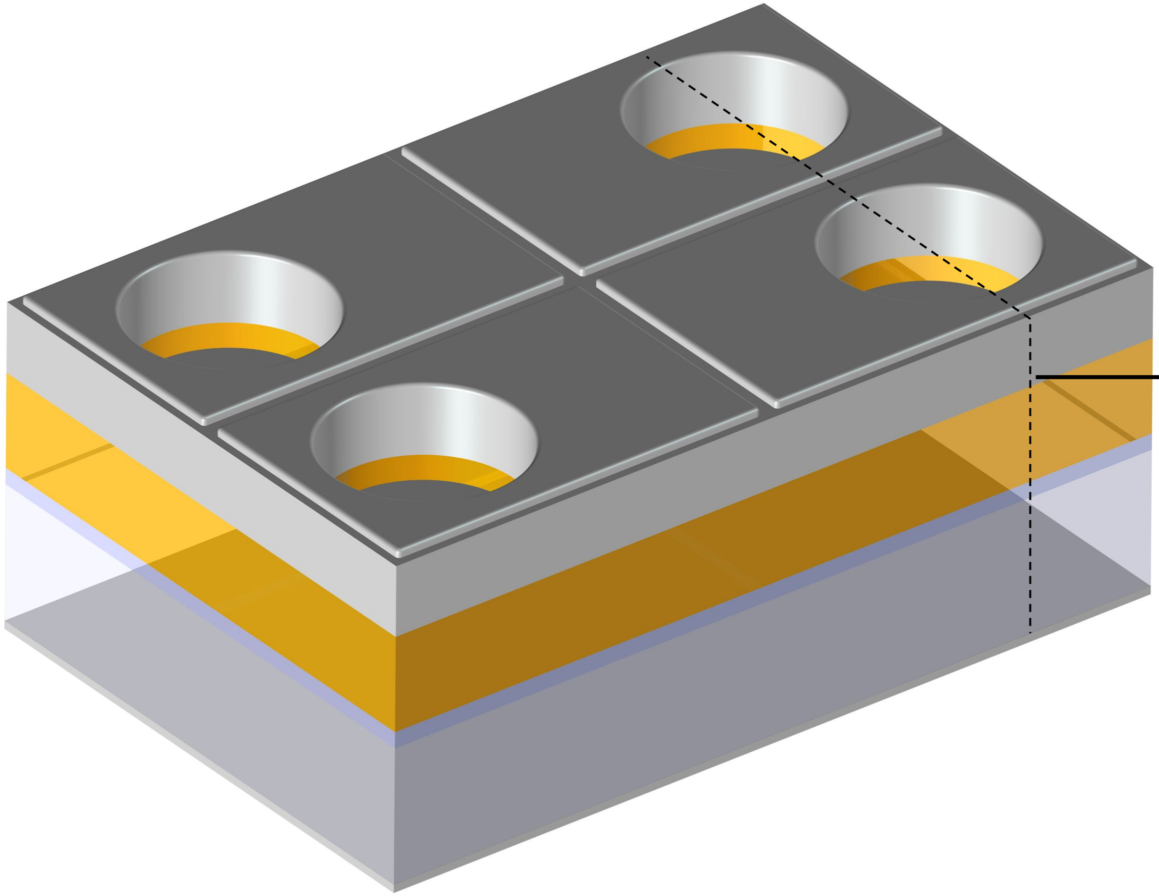


Sensor slice view - thickness (vertical) scaled by 10x)

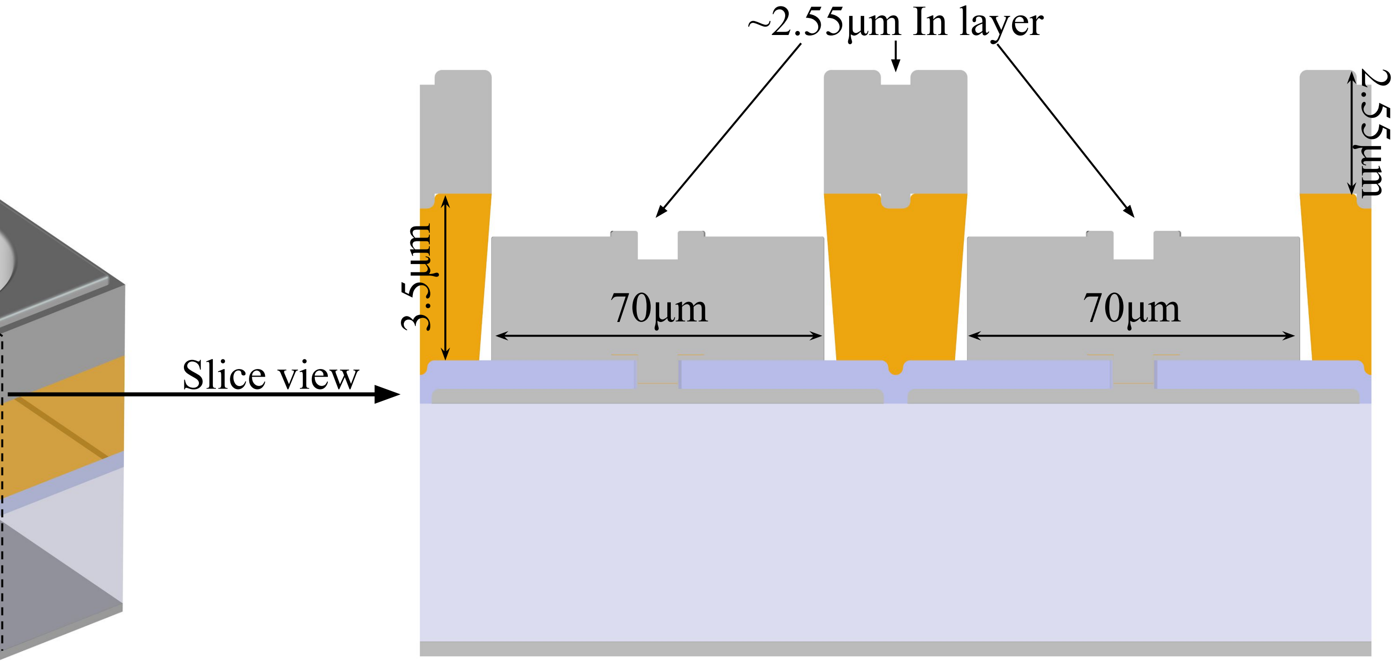
- Negative Photoresist mask (~3.5µm thick by spinning) for In delimitation

Fabrication Process

4. Indium bumps - Indium evaporation



Sensor top surface view - thickness scaled by 10x

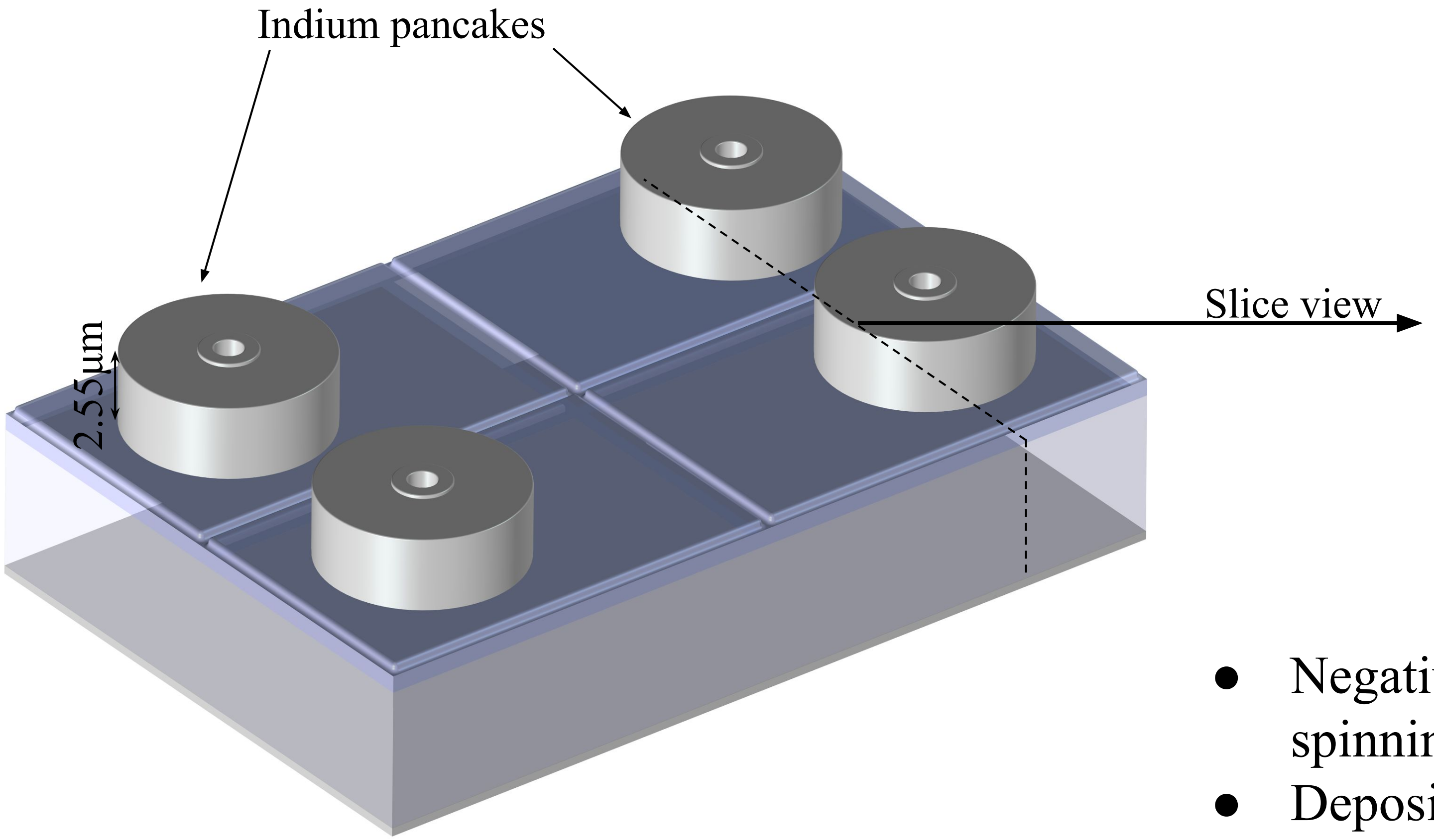


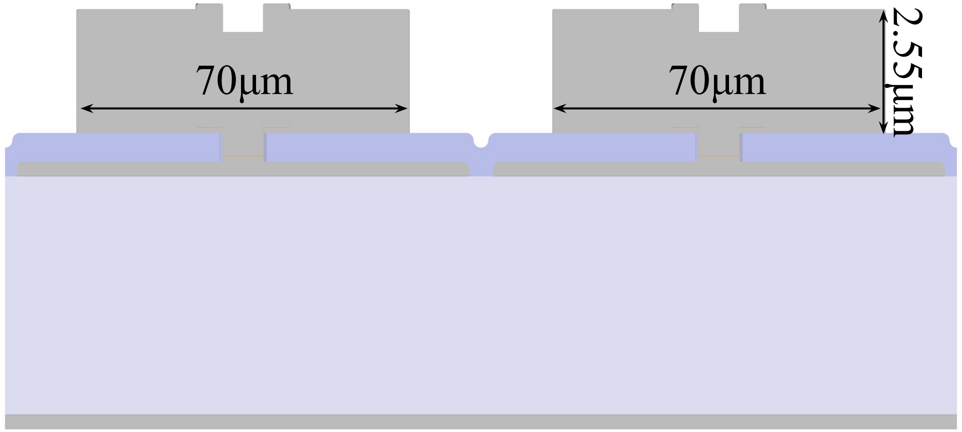
Sensor slice view - thickness (vertical) scaled by 10x)

- Negative Photoresist mask (~3.5µm thick by spinning) for In delimitation
- Deposition of 2.55µm of In (3g)

Fabrication Process

4. Indium bumps - Lift-off; Indium pancakes formation





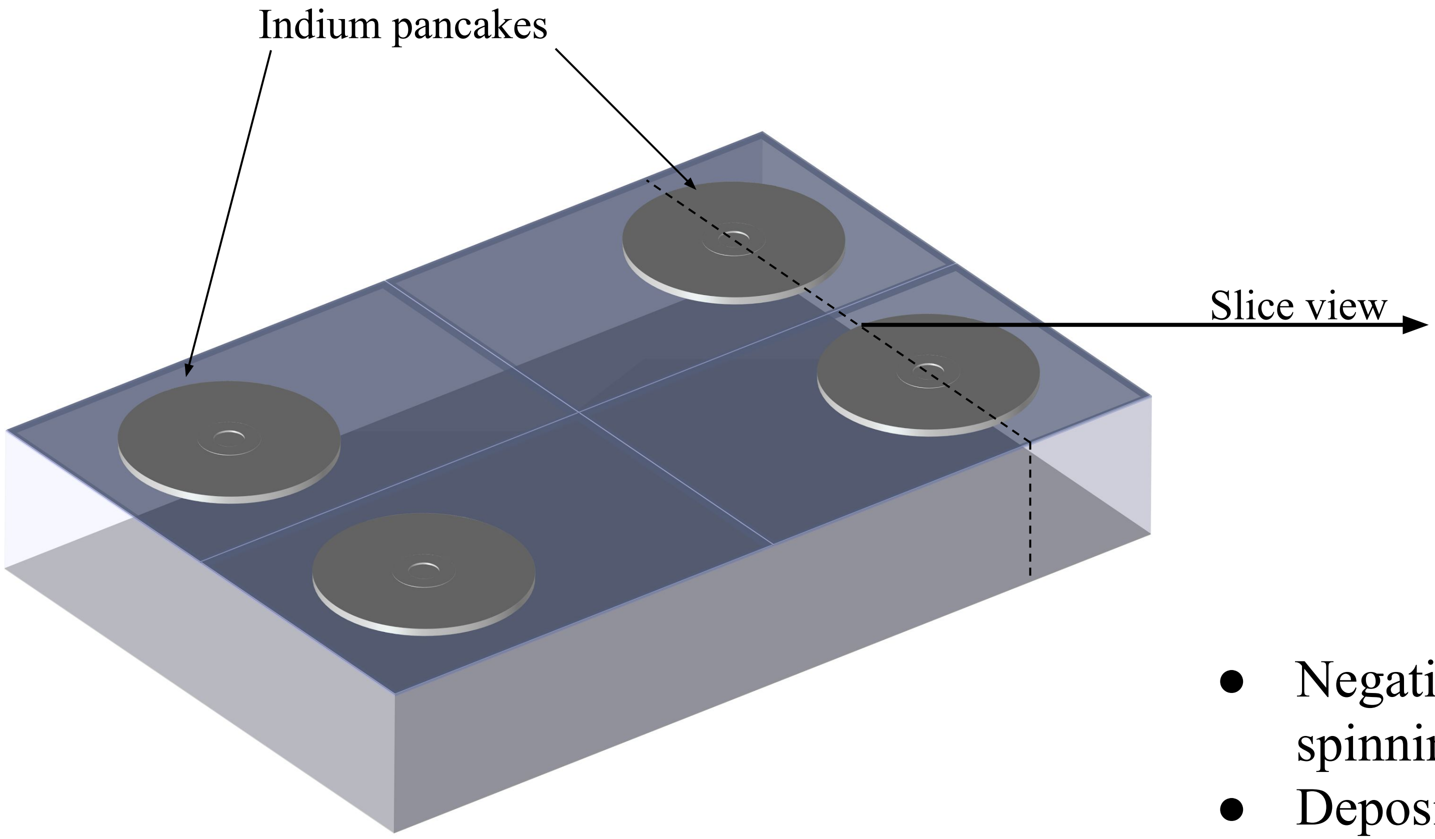
Sensor slice view - thickness (vertical) scaled by 10x)

- Negative Photoresist mask (~3.5µm thick by spinning) for In delimitation
- Deposition of 2.55µm of In (3g)
- Photoresist and excess metal lift-off using solvents

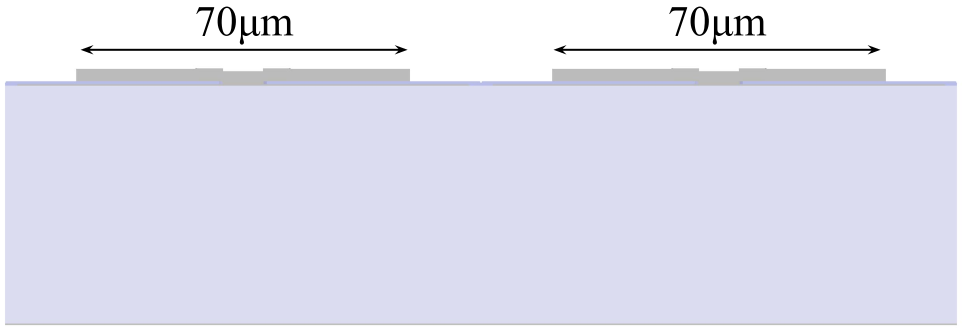
Sensor top surface view - thickness scaled by 10x

Fabrication Process

4. Indium bumps - Lift-off; Indium pancakes formation



Sensor top surface view (actual thickness)

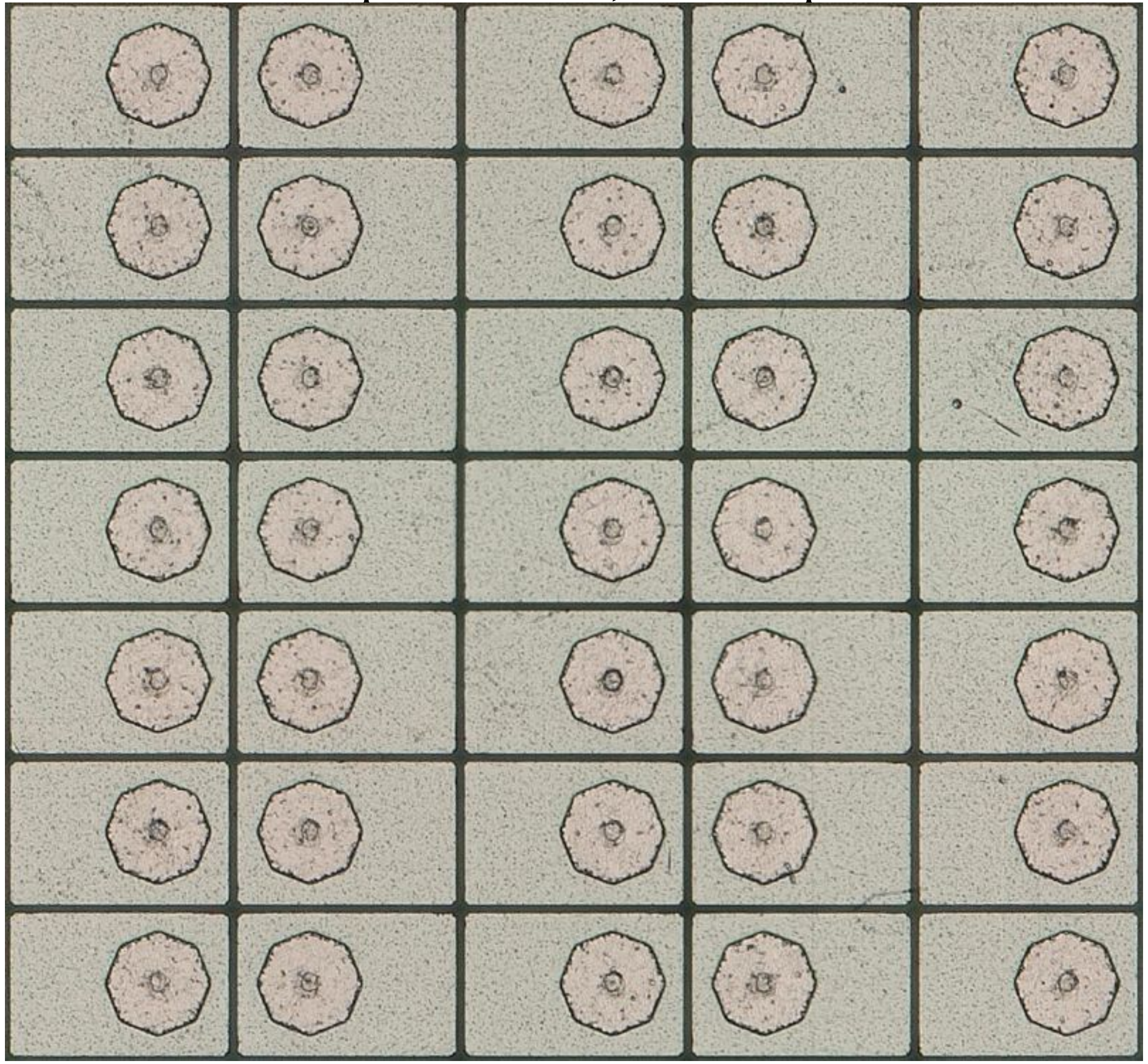


Sensor slice view (actual thickness)

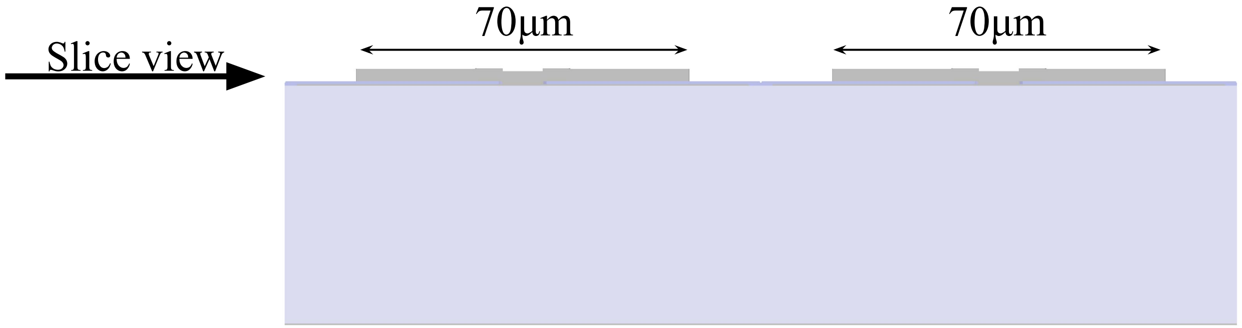
- Negative Photoresist mask (~3.5µm thick by spinning) for In delimitation
- Deposition of 2.55µm of In (3gr)
- Photoresist and excess metal lift-off using solvents
- Indium pancakes formation before reflow

Fabrication Process

4. Indium bumps - Lift-off; Indium pancakes formation



Microscope picture before first reflow



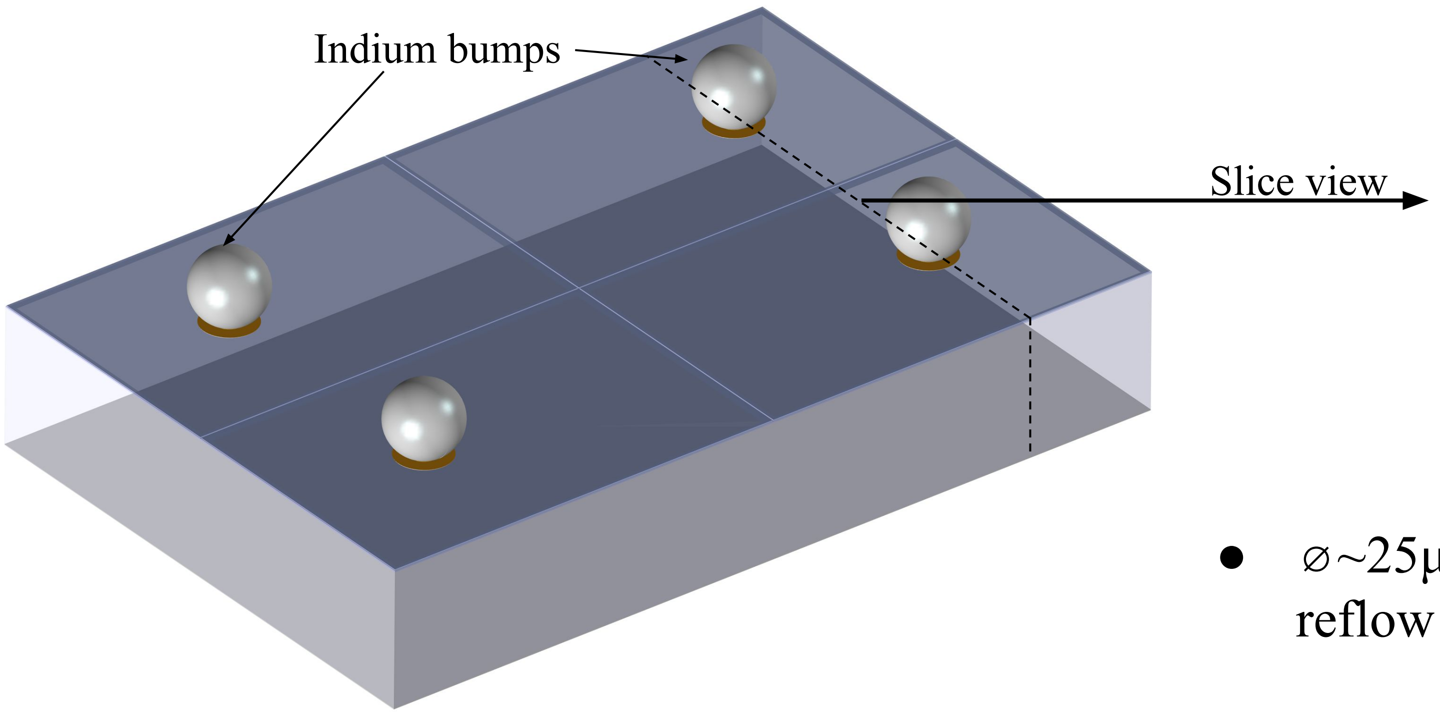
Sensor slice view (actual thickness)

- Negative Photoresist mask (~3.5µm thick by spinning) for In delimitation
- Deposition of 2.55µm of In (3g)
- Photoresist and excess metal lift-off using solvents
- Indium pancakes formation before reflow

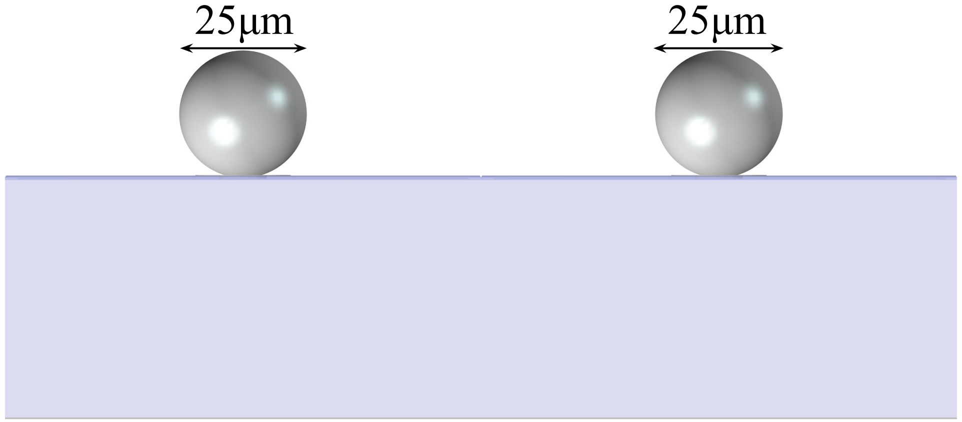
Fabrication Process

5. Bump bonding - First reflow

→ Reflow is a process used to form bumps using temperature in a controlled atmosphere



Sensor top surface view (actual thickness)

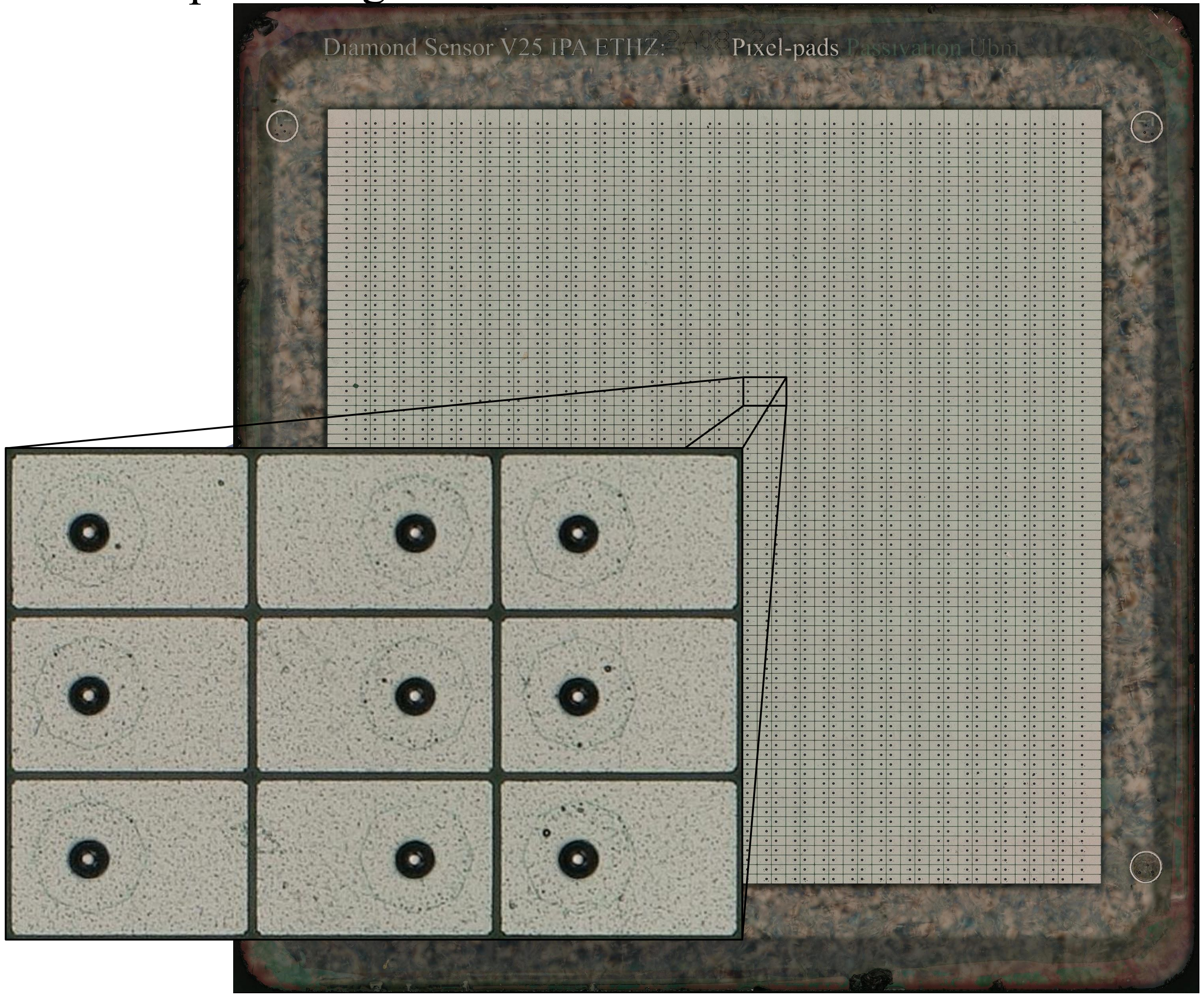


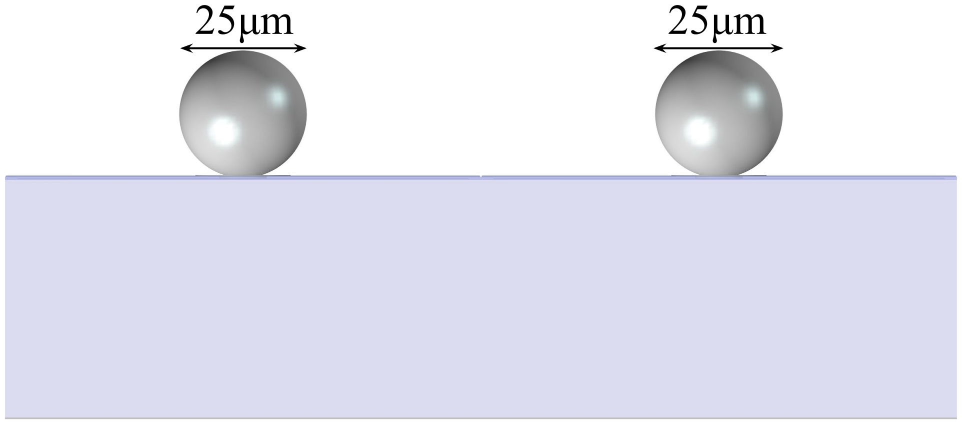
Sensor slice view (actual thickness)

- ⌀~25μm Indium bump formation through two-step reflow process

Fabrication Process

5. Bump bonding - First reflow





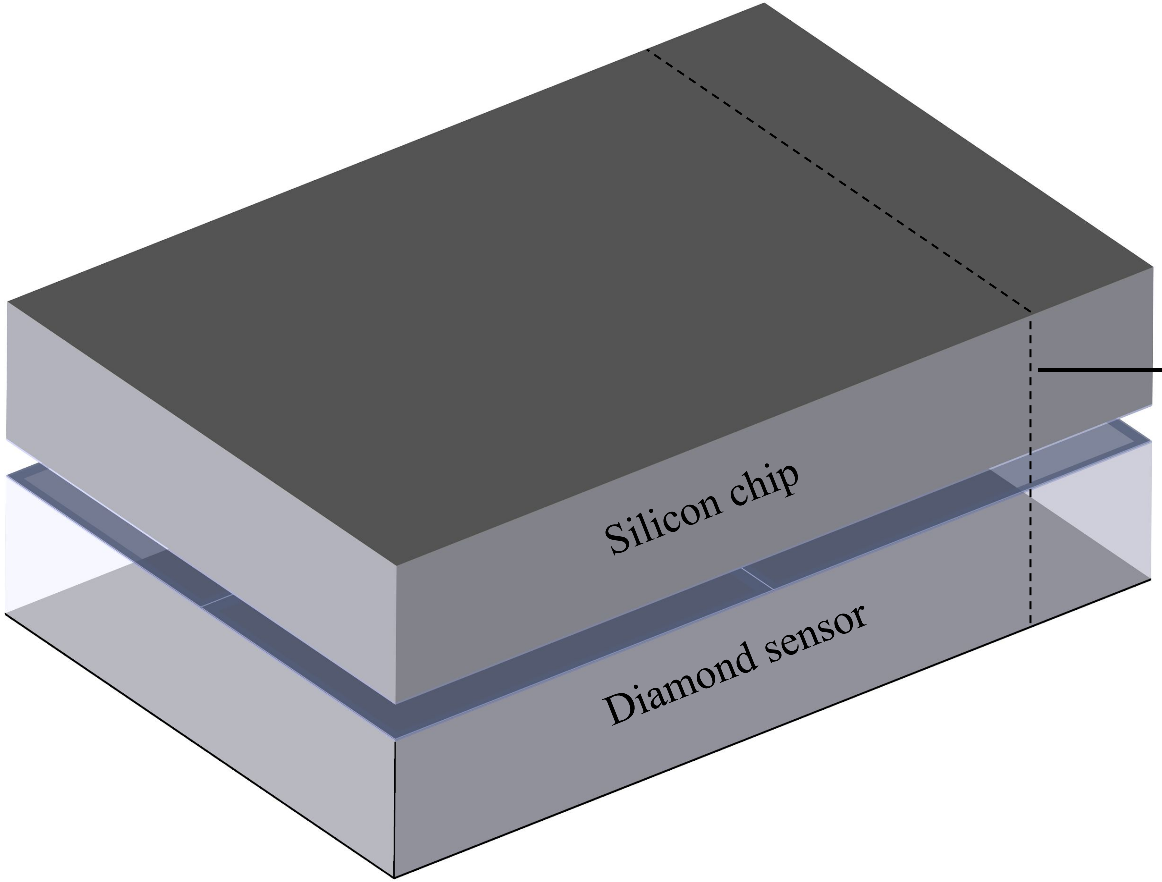
Sensor slice view (actual thickness)

⌀~25µm Indium bump formation through two-step reflow process

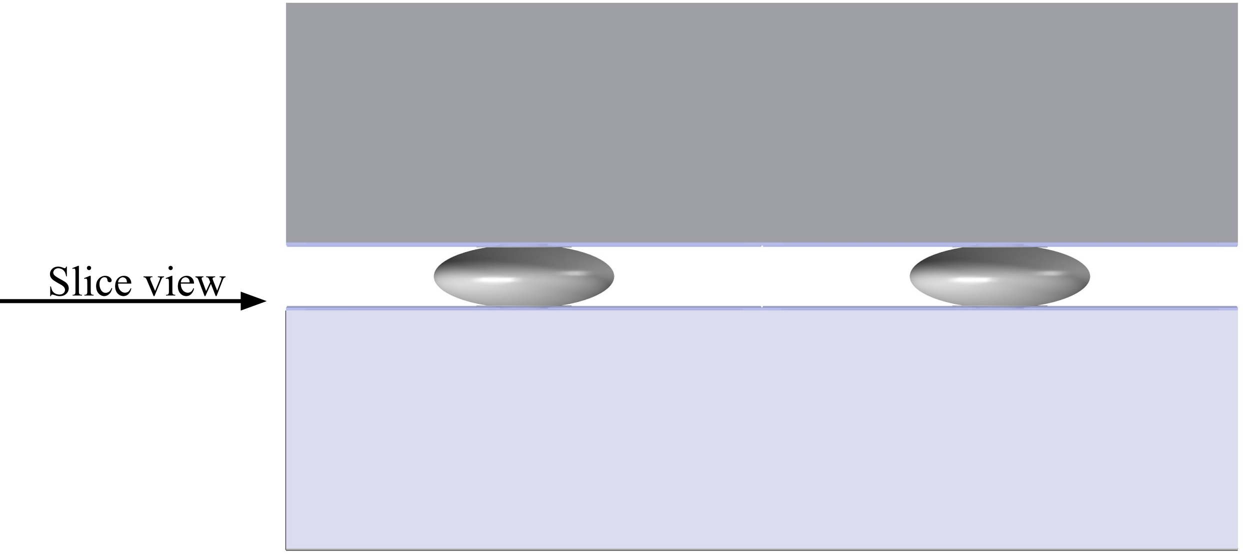
Microscope picture after first reflow: 99.9±0.1% correct bump formation (31 visually imperfect bumps on 4 detectors)

Fabrication Process

5. Bump bonding - Flip-chip pixels connection



Sensor top surface view (actual thickness)

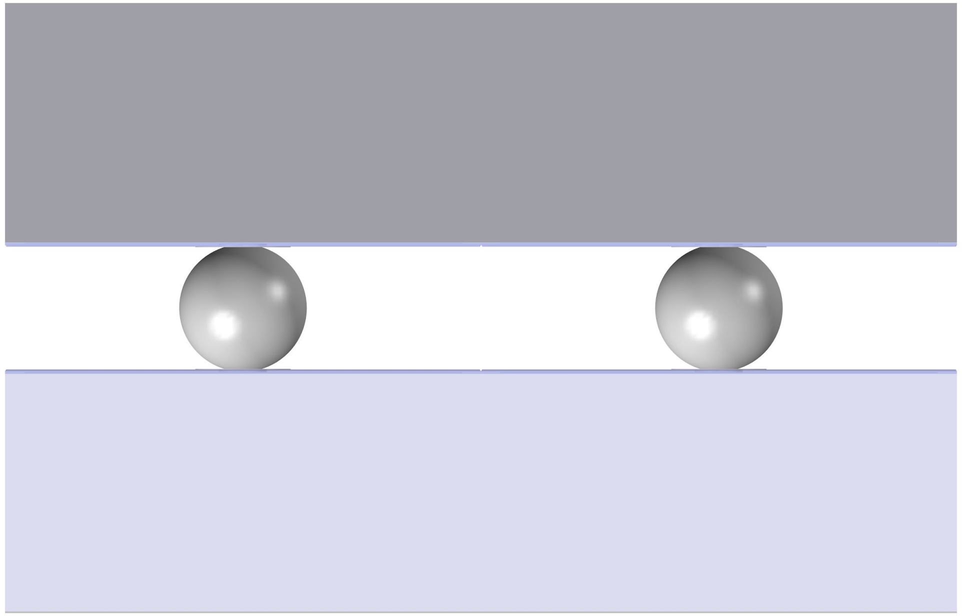


Sensor slice view (actual thickness)

- ⌀~25µm Indium bump formation through two-step reflow process
- Silicon ROC (psi46digV2.1 respin) pressed with ~4kg (9mN per bump) on the sensor

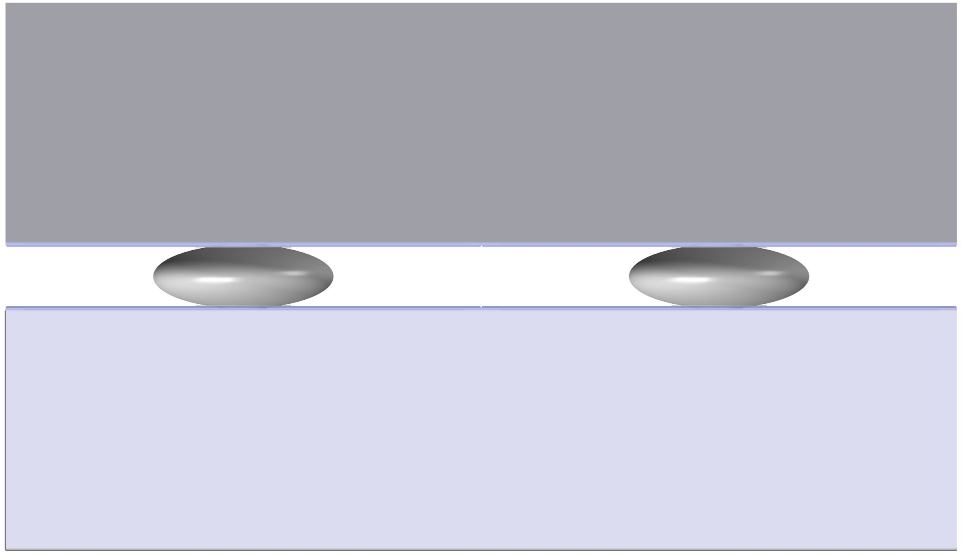
Fabrication Process

5. Bump bonding - Second reflow



Sensor slice view (actual thickness)

2^{nd} Reflow ←

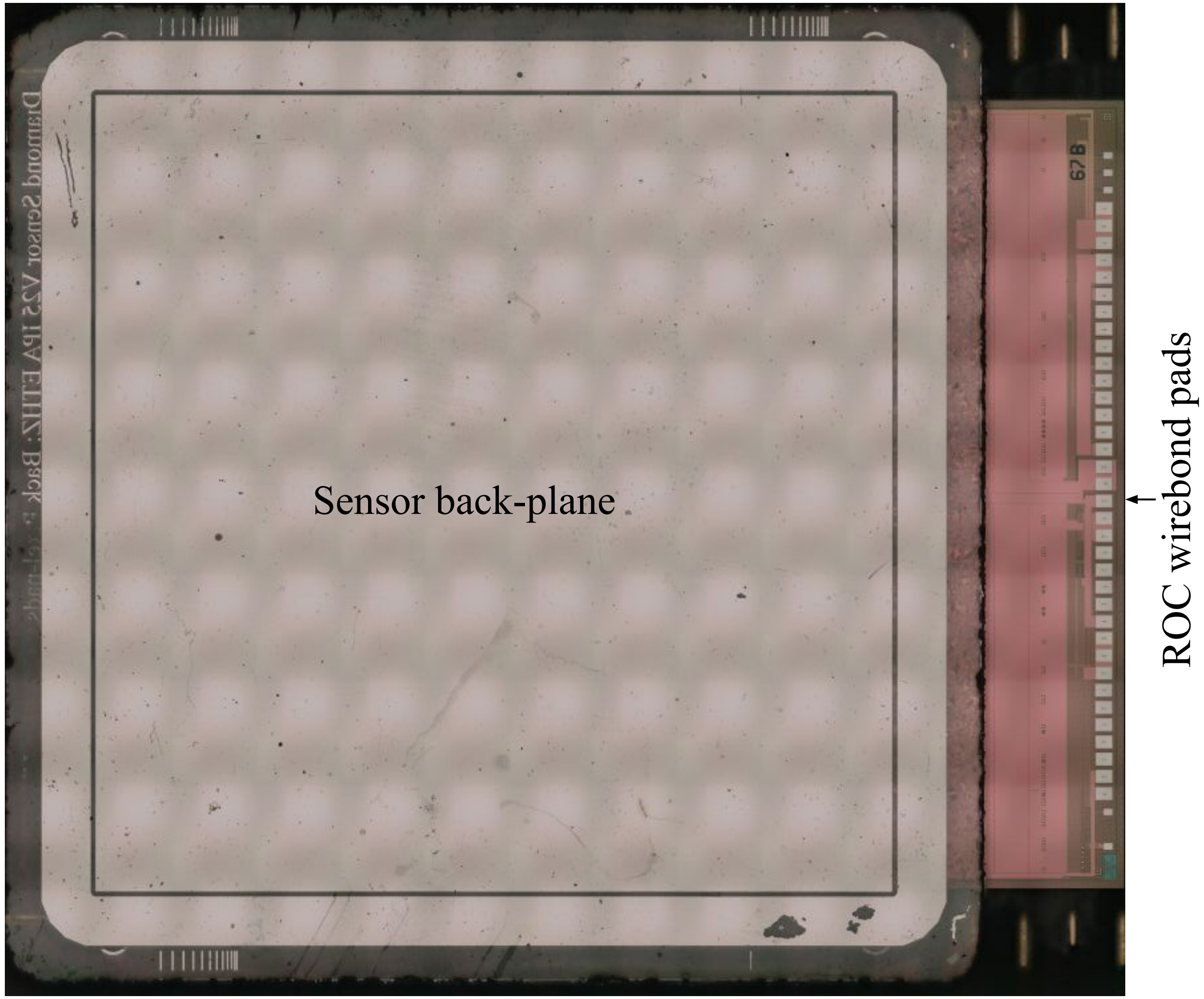


Sensor slice view (actual thickness)

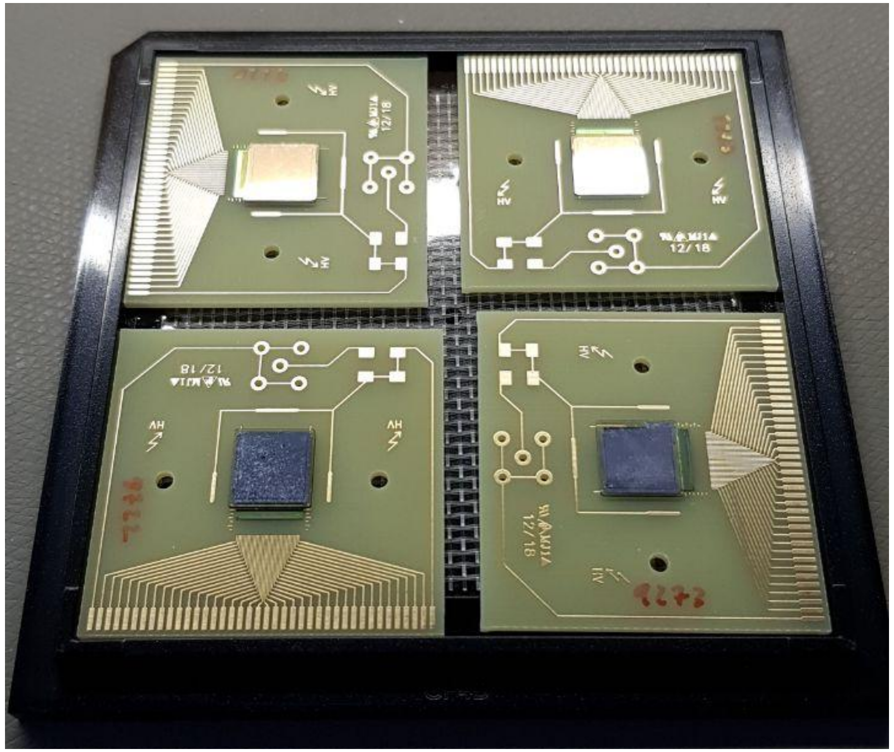
- ⌀~25µm Indium bump formation through two-step reflow process
- Silicon ROC (psi46digV2.1 respin) pressed with ~4kg (9mN per bump) on the sensor
- 2^{nd} reflow homogenizes the bump bonding and corrects misalignments

Fabrication Process

5. Bump bonding - Second reflow



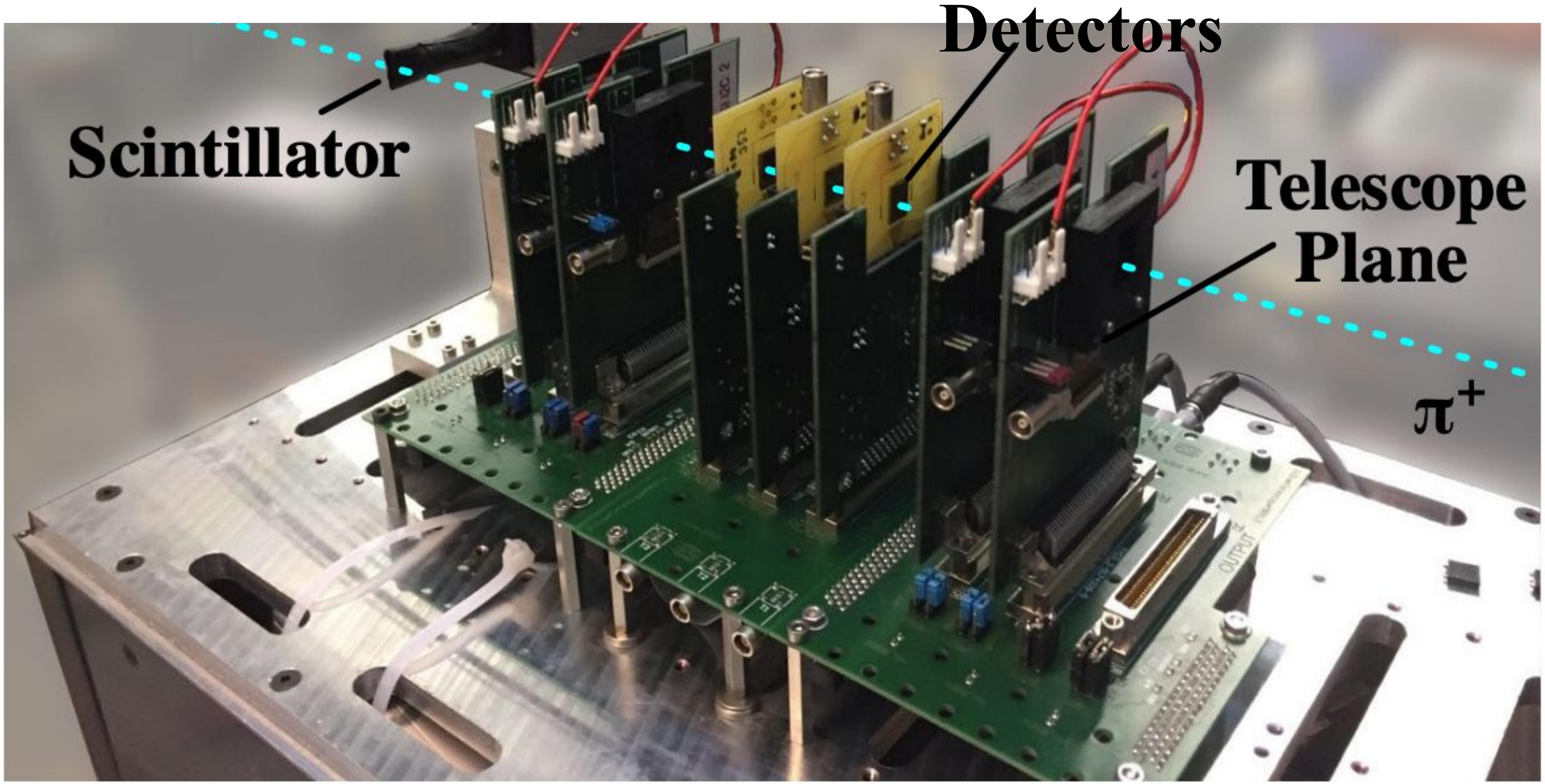
- Glue detector to adaptor board
- Wirebond Readout Chip (ROC) pads to adaptor board
- Wirebond sensor’s back-plane to High Voltage line



Prototypes 2019

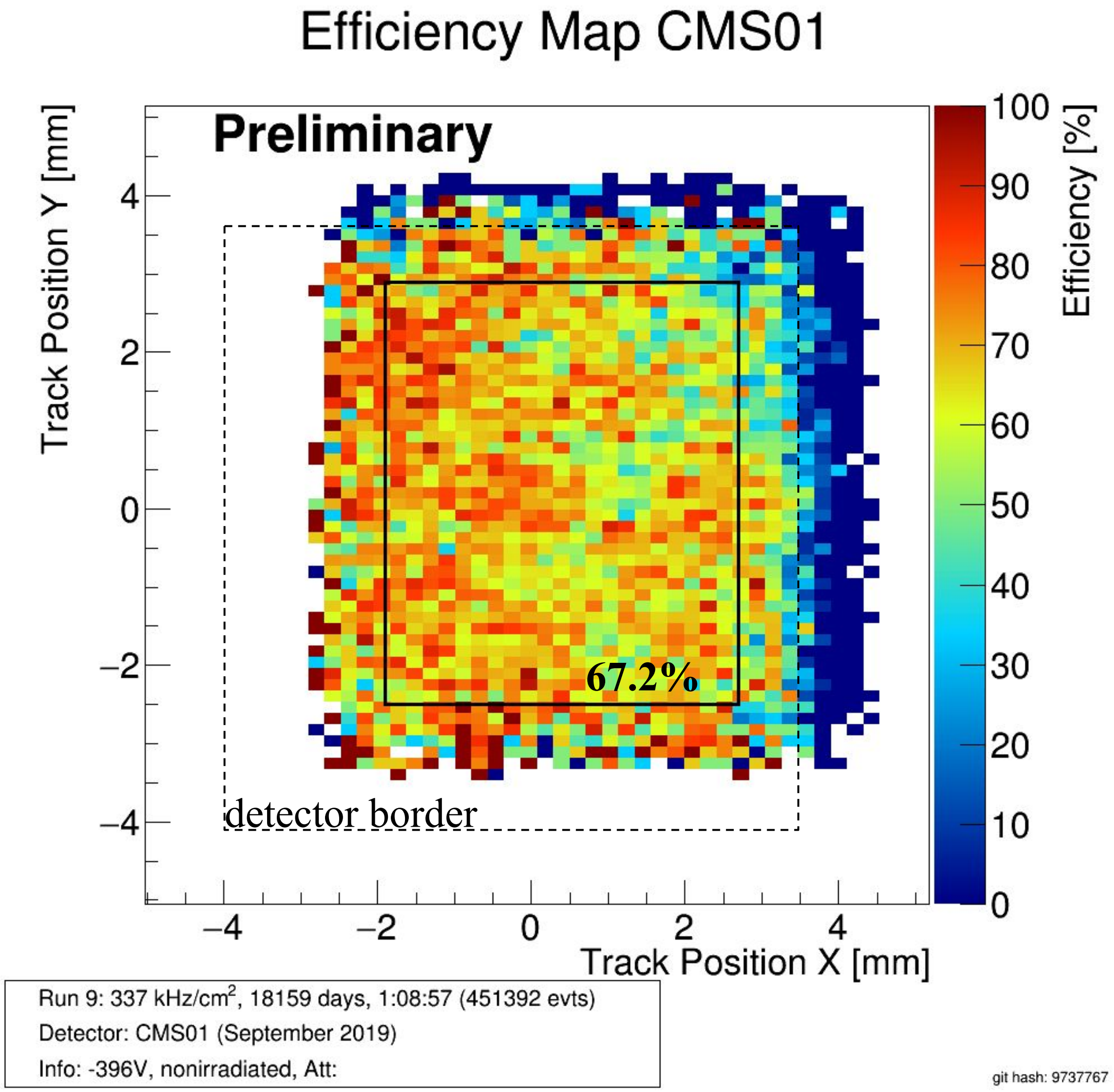
Preliminary results

Preliminary results

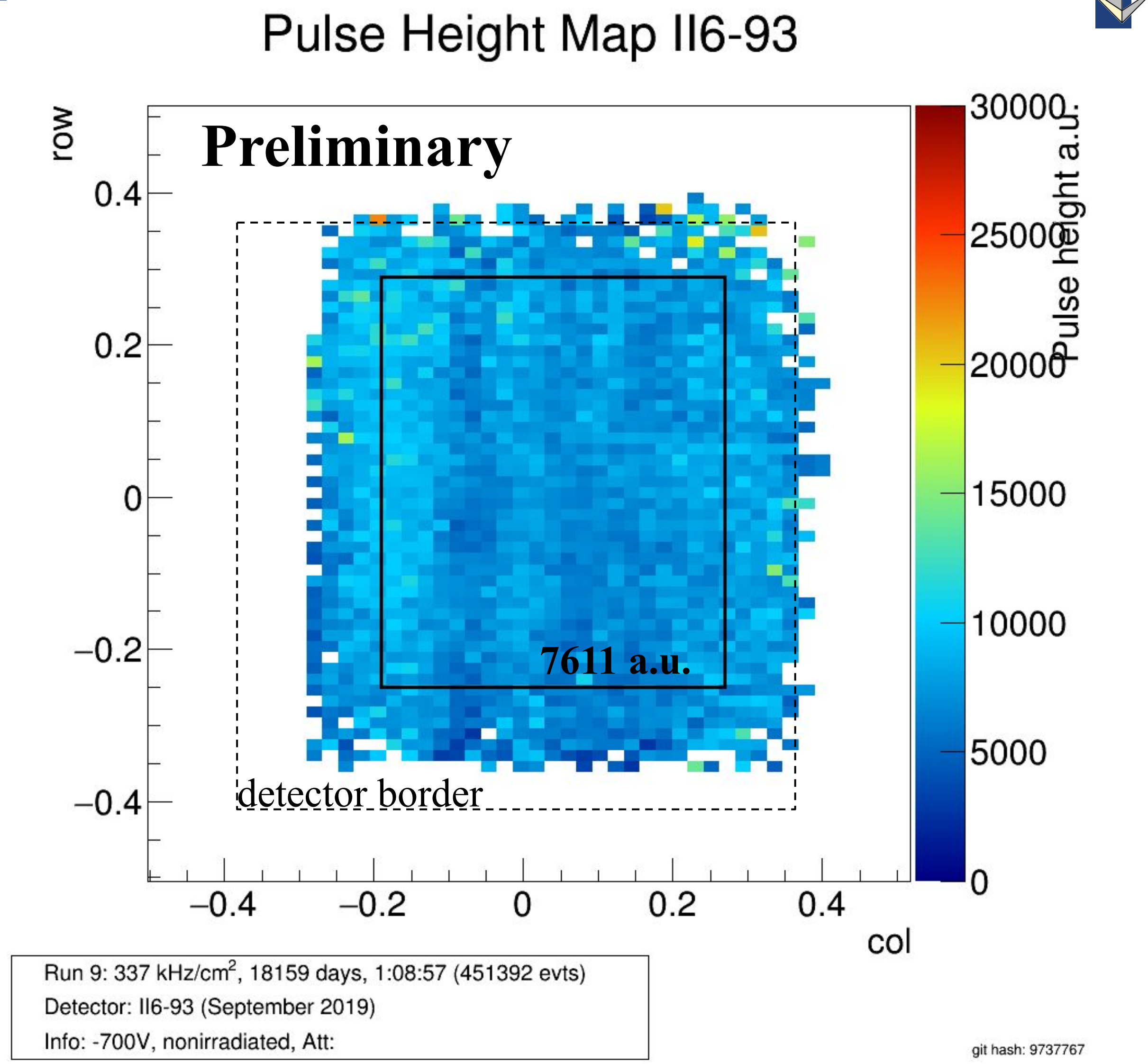


- ETH Telescope: Consists on 4 CMS analog pixel planes for tracking, a Scintillator for ns timing and up to 3 DUT (any digital detector)
- It has been used over the past 5 years at PSI Pi-M1 beam line (250MeV/c pions)

Preliminary results (Testbeam September 2019)

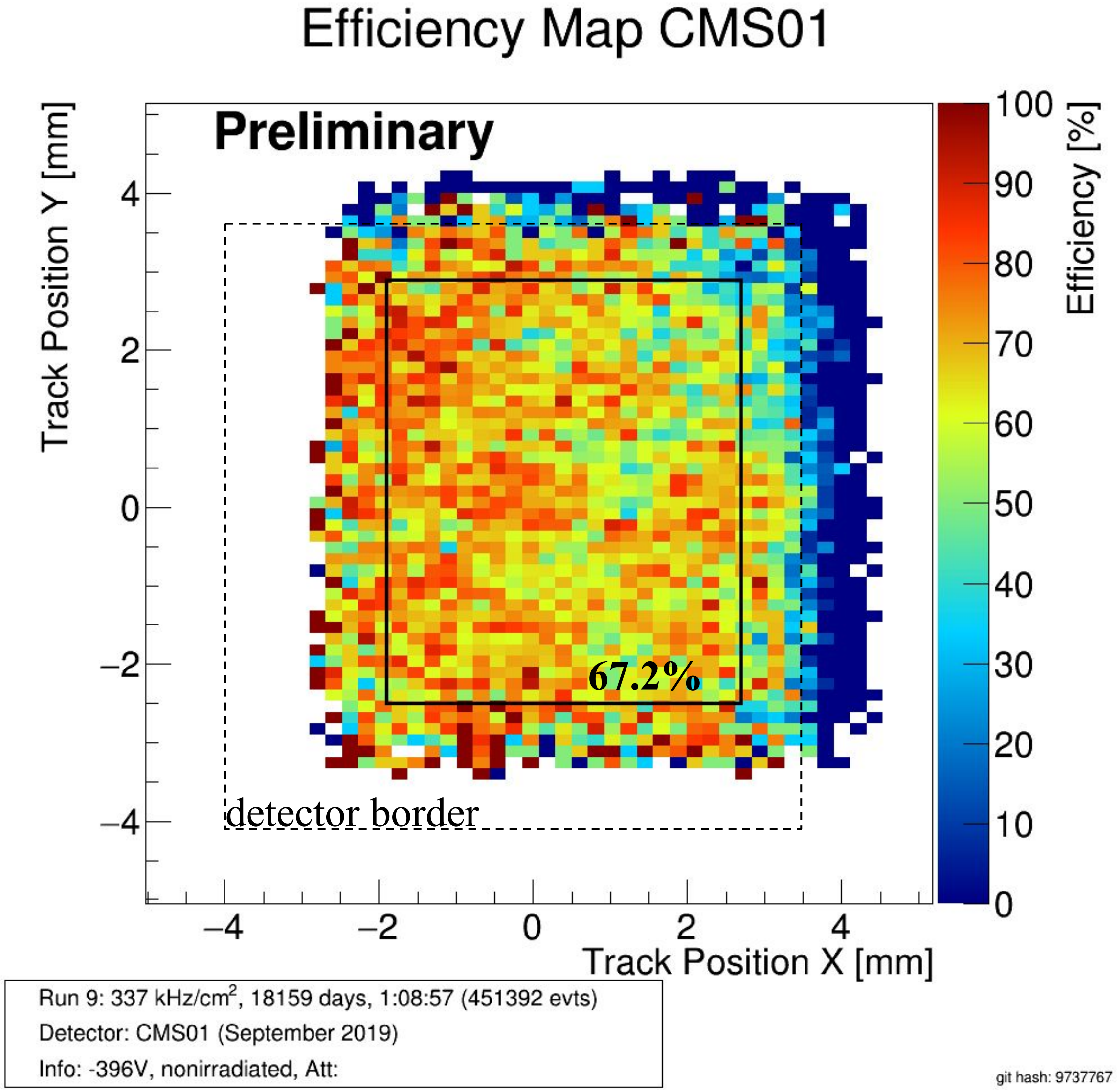


Run 9: 337 kHz/cm^2, 18159 days, 1:08:57 (451392 evts)
Detector: CMS01 (September 2019)
Info: -396V, nonirradiated, Att:



Run 9: 337 kHz/cm^2, 18159 days, 1:08:57 (451392 evts)
Detector: II6-93 (September 2019)
Info: -700V, nonirradiated, Att:

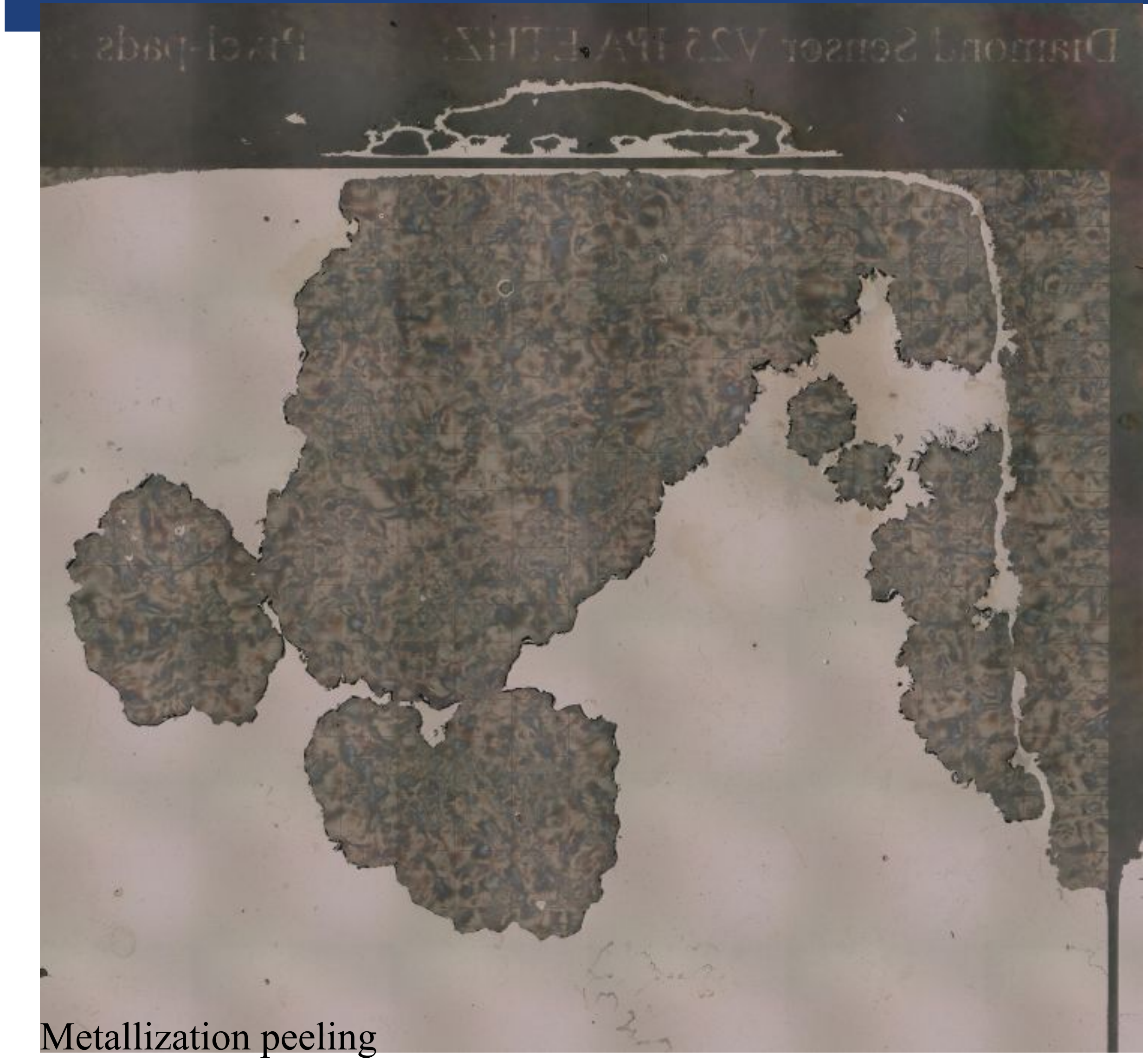
Preliminary results (Testbeam September 2019)



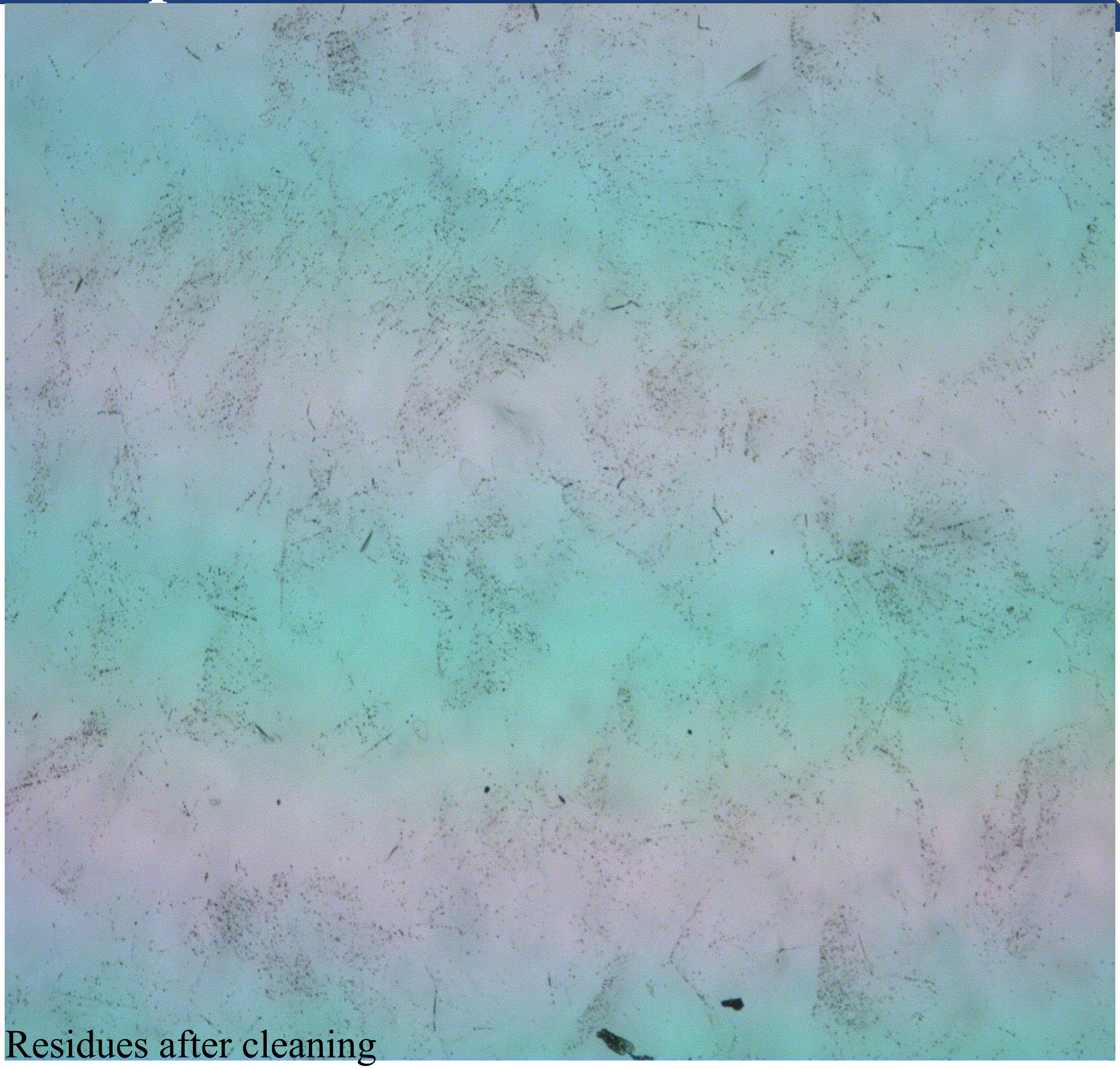
Run 9: 337 kHz/cm^2, 18159 days, 1:08:57 (451392 evts)
Detector: CMS01 (September 2019)
Info: -396V, nonirradiated, Att:

- As it is a polycrystalline diamond, the charge collection is at least 50% compared to a single crystal diamond
- Grain boundaries and lattice defects trap charges in different location in the diamond
- Different efficiency regions could be due to:
  - Polycrystalline features
  - Problems during the fabrication process
    - Metallization sometimes lifts from the diamond - Bad contact
    - Embedded features that remain after cleaning procedure in some samples - Improve cleaning
  - Diamond quality
  - Analysis problems
- This questions must be resolved before scaling the fabrication process to a full module (1 sensors with 16 readout chips)

Current fabrication problems



Metallization peeling



Residues after cleaning

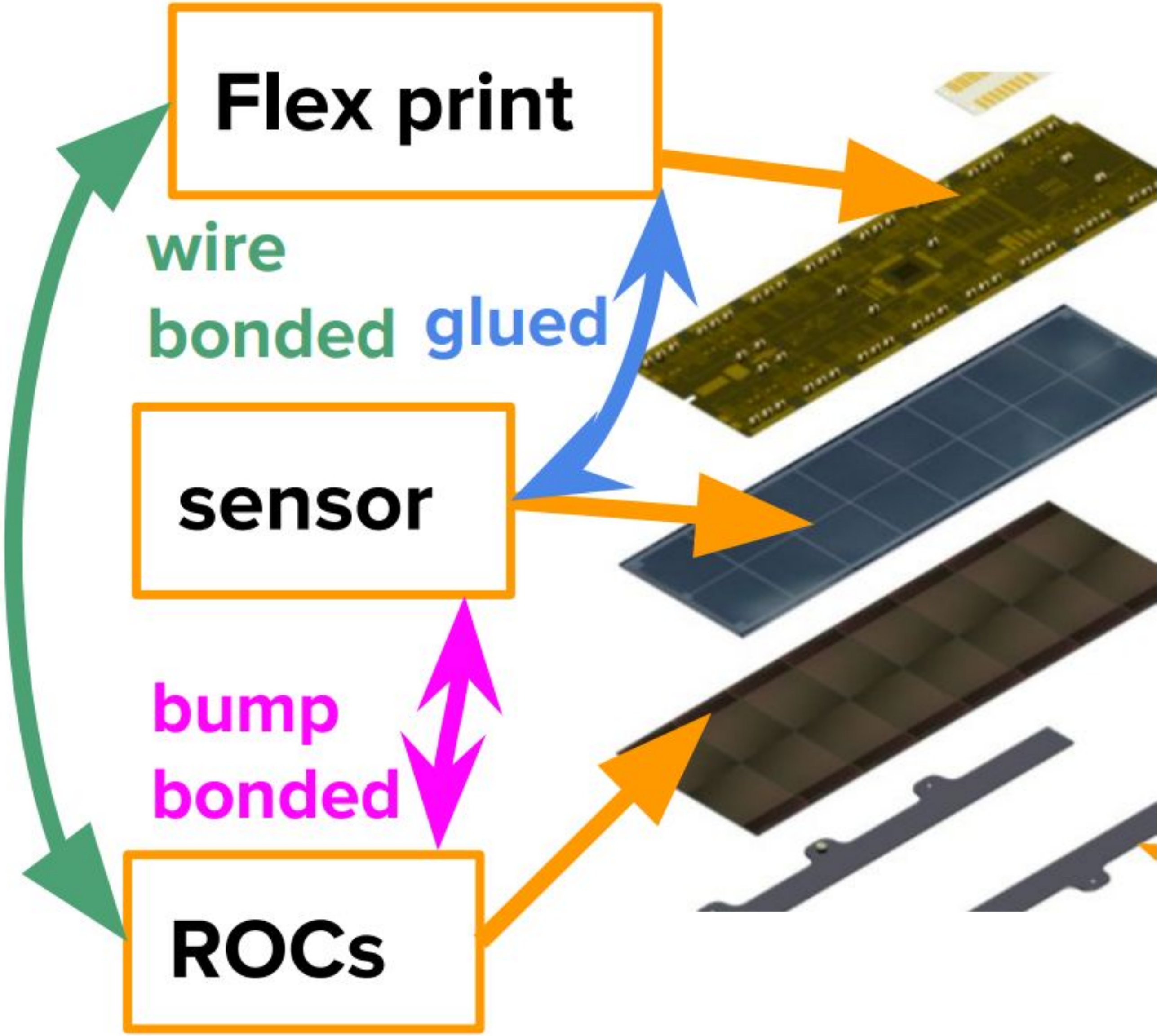
Conclusions

- A fabrication procedure to make diamond planar pixel detectors has been developed
- Five working devices have been fabricated and tested in Testbeams in the past year
- Preliminary results show that there are still issues that have to be solved before moving to the next step
- If successful, the next milestone is a full module fabrication (scaling up the process)

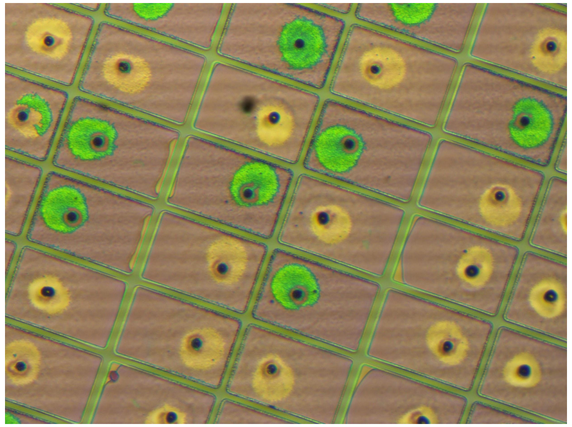
Thank you

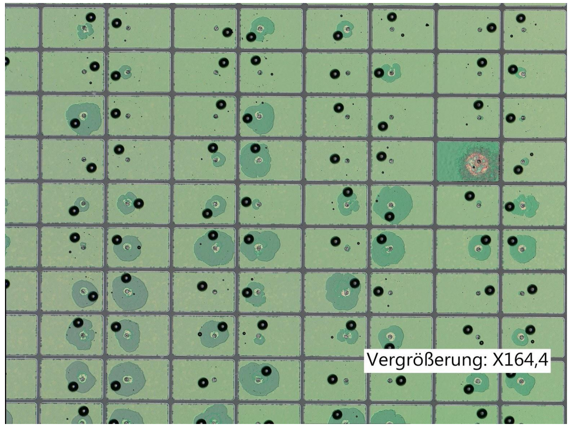
Backup

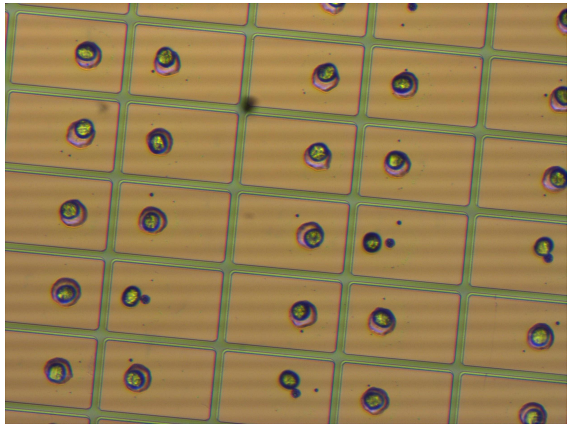
Full Module



Solved bump bonding problems

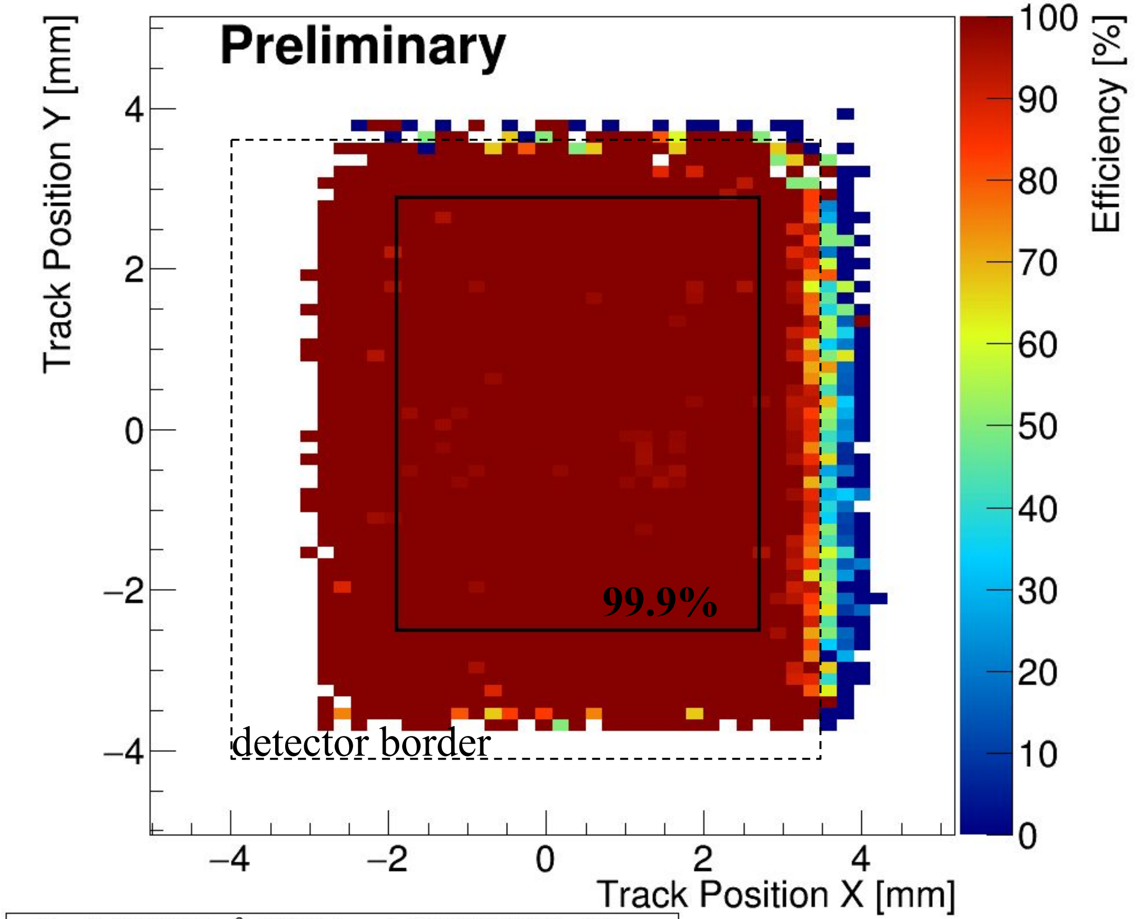






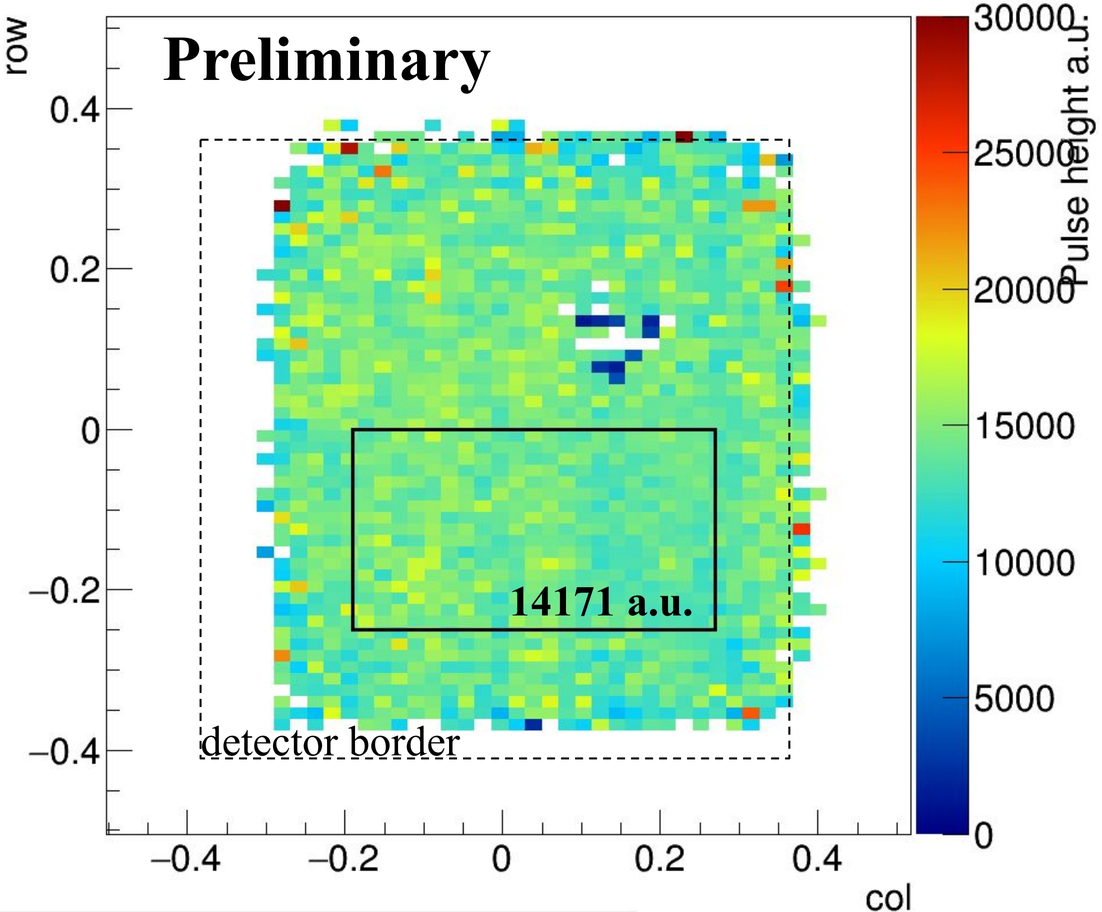
Preliminary results (Testbeam 2019)

Efficiency Map D2



Run 9: 337 kHz/cm^2, 18159 days, 1:08:57 (451392 evts)
Detector: D2 (September 2019)
Info: -200V, nonirradiated, Att:

Pulse Height Map SiD2



Run 9: 337 kHz/cm^2, 18159 days, 1:08:57 (451392 evts)
Detector: D2 (September 2019)
Info: -200V, nonirradiated, Att: