Structural characterization of silicon channels for fluidic applications

Richard Meunier

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CERN | EP-DT Detector Technologies

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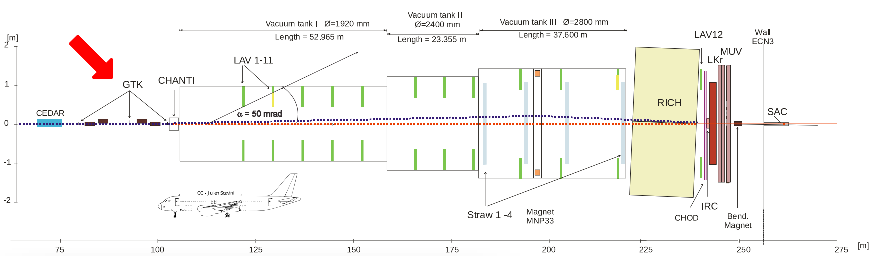
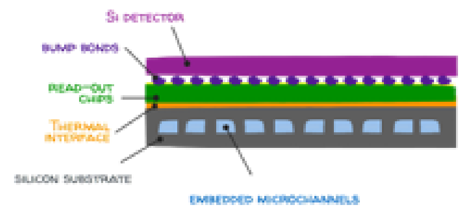
Introduction

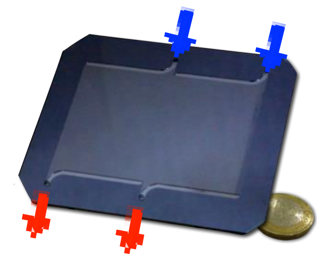
- Thermal management of detectors electronics
  - Cooling large surface detectors
  - Keeping the detectors cool at all time
- Problems and constraints
  - Confined space with very limited access
  - Different types of liquid coolants
  - Using material with low particle interaction
- Envisioned solution
  - Silicon micro-channels
  - Ideally integrated in a monolithic detector

NA62-GTK – SILICON MICROCHANNEL COOLING

- NA62 is the first experiment to use silicon microcooling plates for the thermal management of their GTK pixel detectors (since 2014).







- 3 detector modules
- Liquid C_6F_{14}
- T_{op} below -10ºC
- Power dissipation 25W-48W over 6x4cm^2

A. Mapelli *et al.* 2012 JINST 7 C01111
P. Petagna *et al.*, Microelec. Journal 44 (2013) 612–618
G. Romagnoli *et al.*, Microelec. Eng. 145 (2015) 133-137

Silicon Microchannel Cooling

- Why Silicon or SiC?
  - Detectors are in silicon
  - Controlled interaction with particles
  - Availability
  - Extensive processing knowledge and technologic applications (Micro-electronics, MEMS, etc)

- Interest and goals:
  - Size advantage
  - Design advantage: large pattern possibility
  - Can be integrated in the detector's fabrication process combining versatility of standard micro-fabrication processes with high thermal efficiency of micro-fluidics

- Mechanical problematics:
  - Young's modulus of 169 GPa <110> or 130 GPa <100> or 187 GPa <111> or…?
  - Possible fatigue in monocrystalline silicon can accumulate and lead to rupture
  - Lots of publications and tests on silicon mechanical properties, but so far no link between them…

- Two different approaches:
  - Wafer bonding
  - Buried micro-channels

- Wafer bonding
  - Etching step
  - Wafer bonding
  - Problem: wafer bonding can be tricky

WAFER BONDING APPROACH

Low material budget microfabricated cooling devices for particle detectors and front-end electronics

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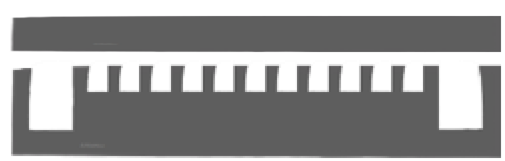
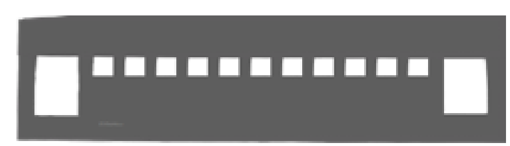
Nuclear Physics B (Proc. Suppl.) 215 (2011) 349–352





FBK-CERN Embedded Channels

- Buried channels
  - Trench through Bosch Process etching
  - Channel engraving with SF_6 isotropic etching
  - Channel filling with PE/LPCVD poly-silicon

BURIED CHANNELS APPROACH

Silicon buried channels for pixel detector cooling

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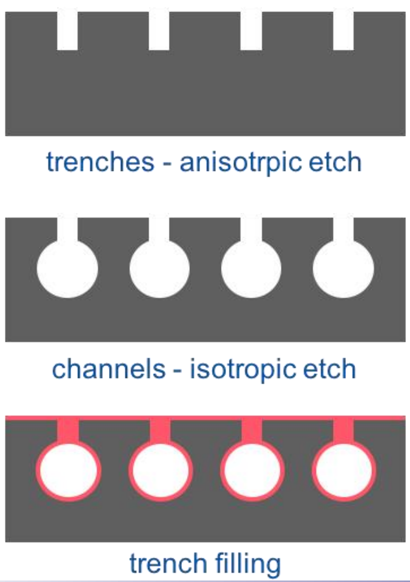
[c] Istituto Nazionale di Fisica Nucleare, Sez. di Pisa, L.go B. Pontecorvo 3, I-56127 Pisa, Italy

Nuclear Instruments and Methods in Physics Research A 718 (2013) 297–298



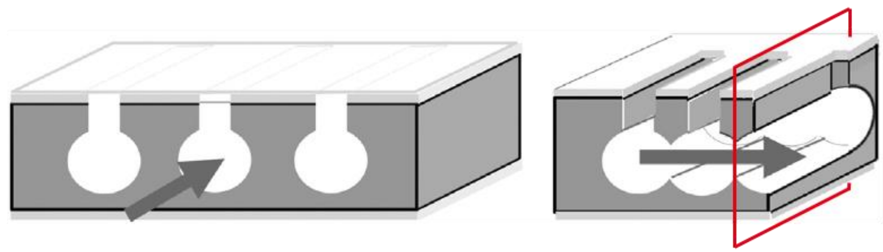
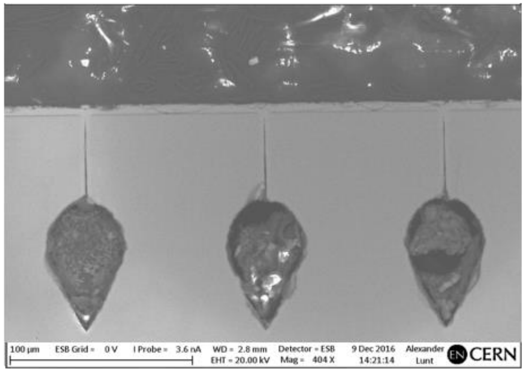
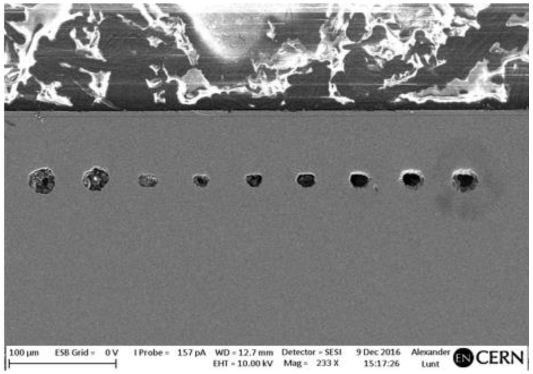


Fig. 1. Process sections for longitudinal and transverse channels.

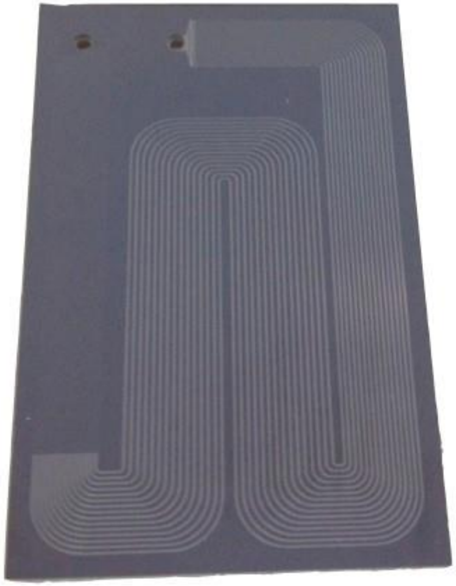




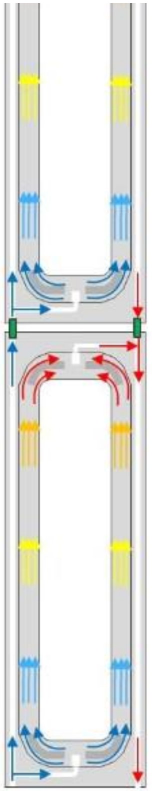
Characterization

- Objective at CERN: defining a standard procedure to validate and ensure reliability of the cooling systems ➔ Leak test and pressure tests
- Reasons to perform pressure tests:
  - Gaining a better understanding of the mechanical response of ScSi
  - Assess effect of channel geometry to optimize design of new devices
  - Evaluate wafer-to-wafer bond strength
  - Serve as quality control procedure

NA62 GTk



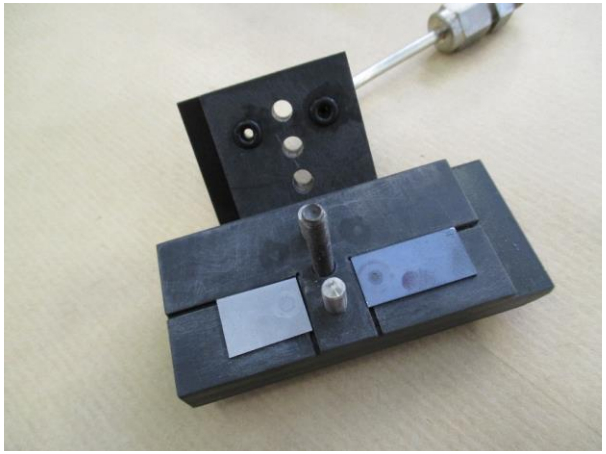
LHCb VELO



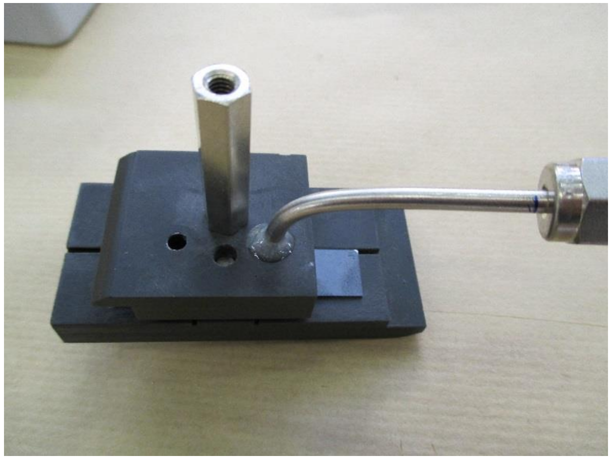
ALICE ITS

Leak Test

Positioning

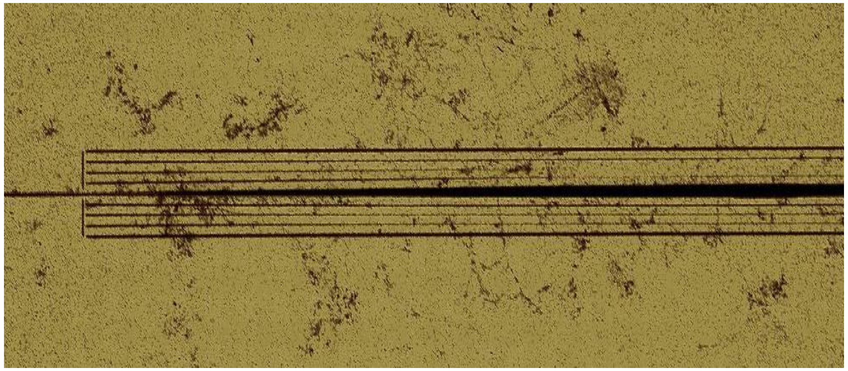


Pumping and leak recording

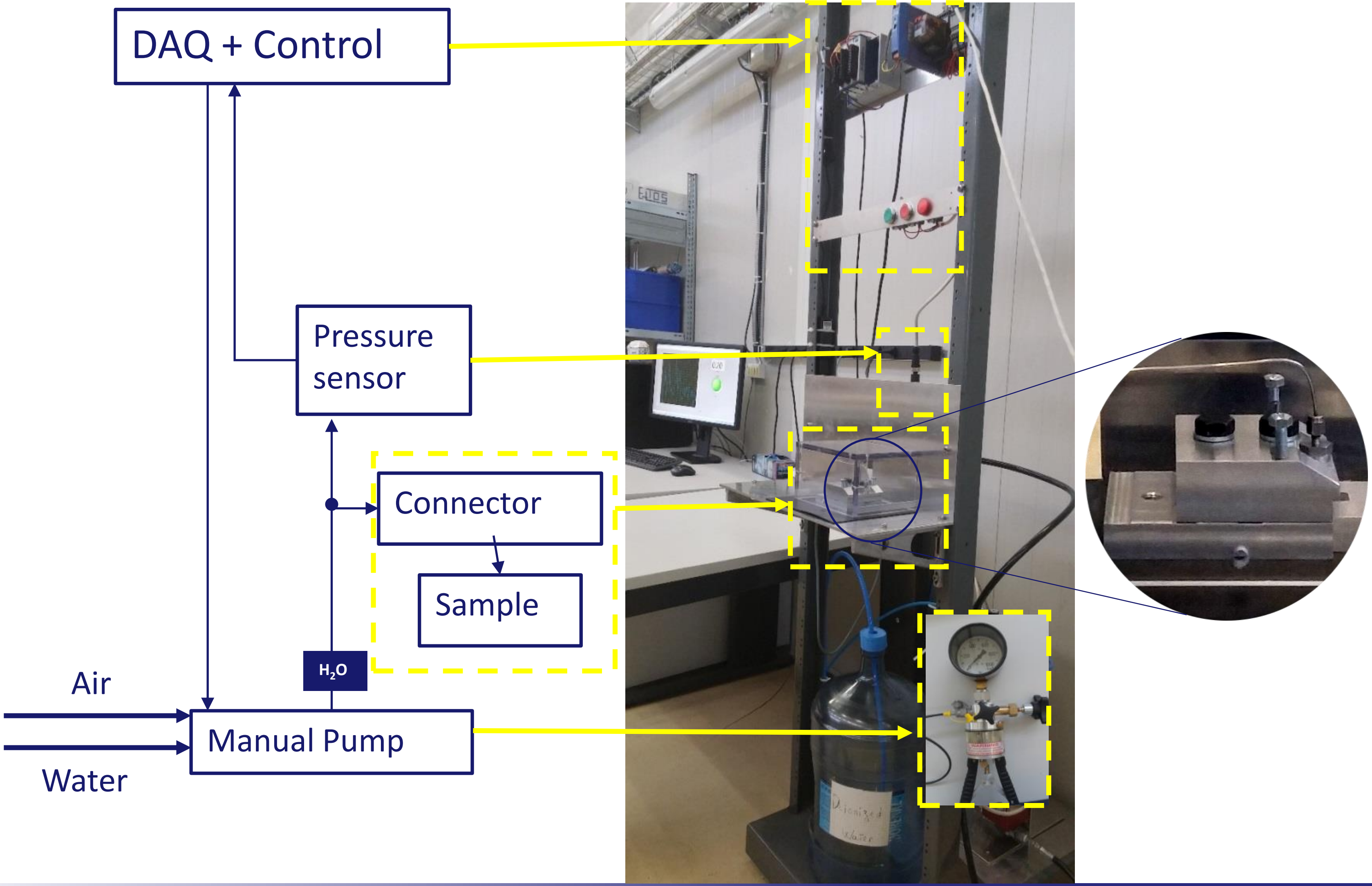


Objective:

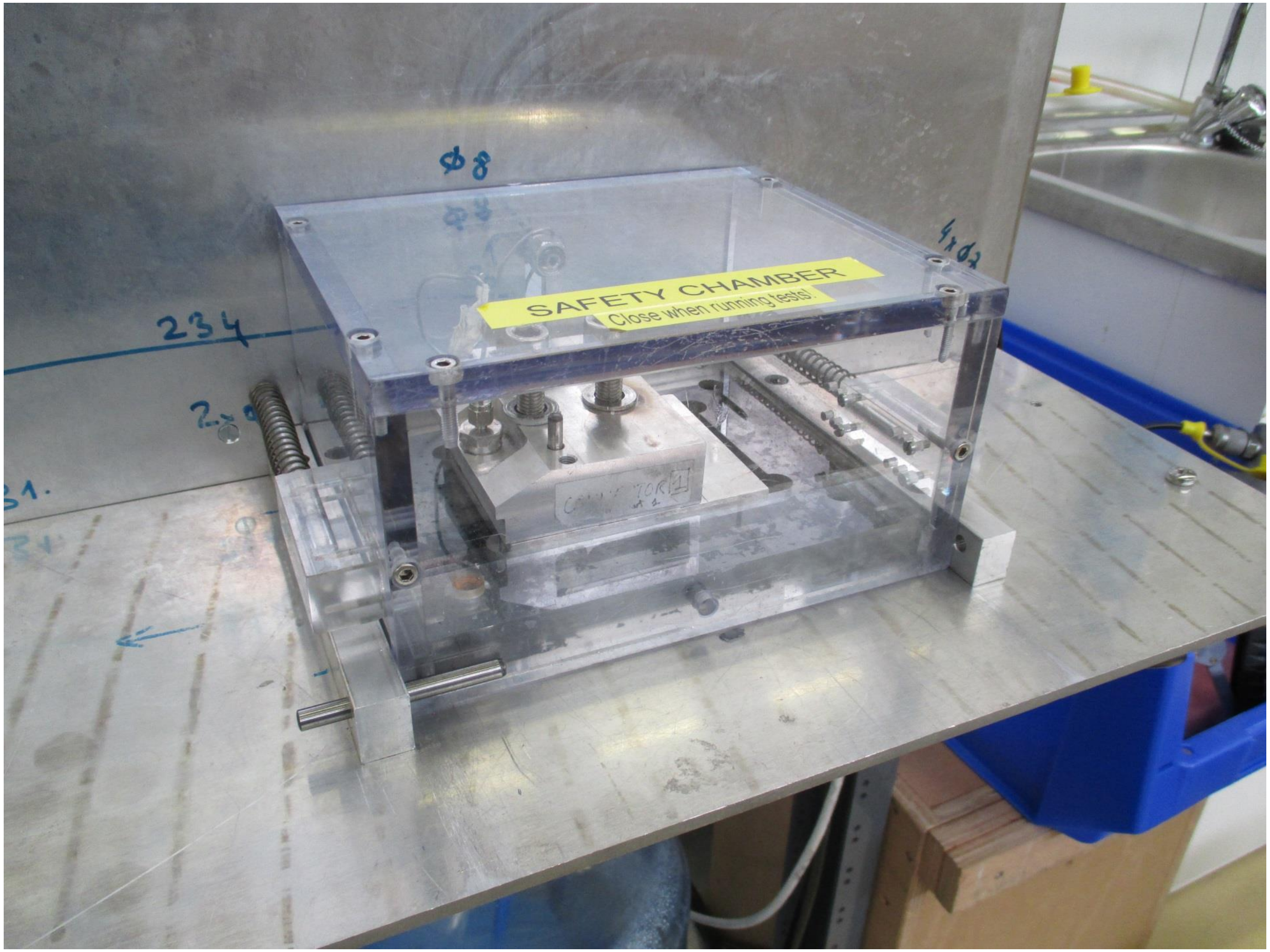
Testing if samples are leak tight



Pressure Test: Setup

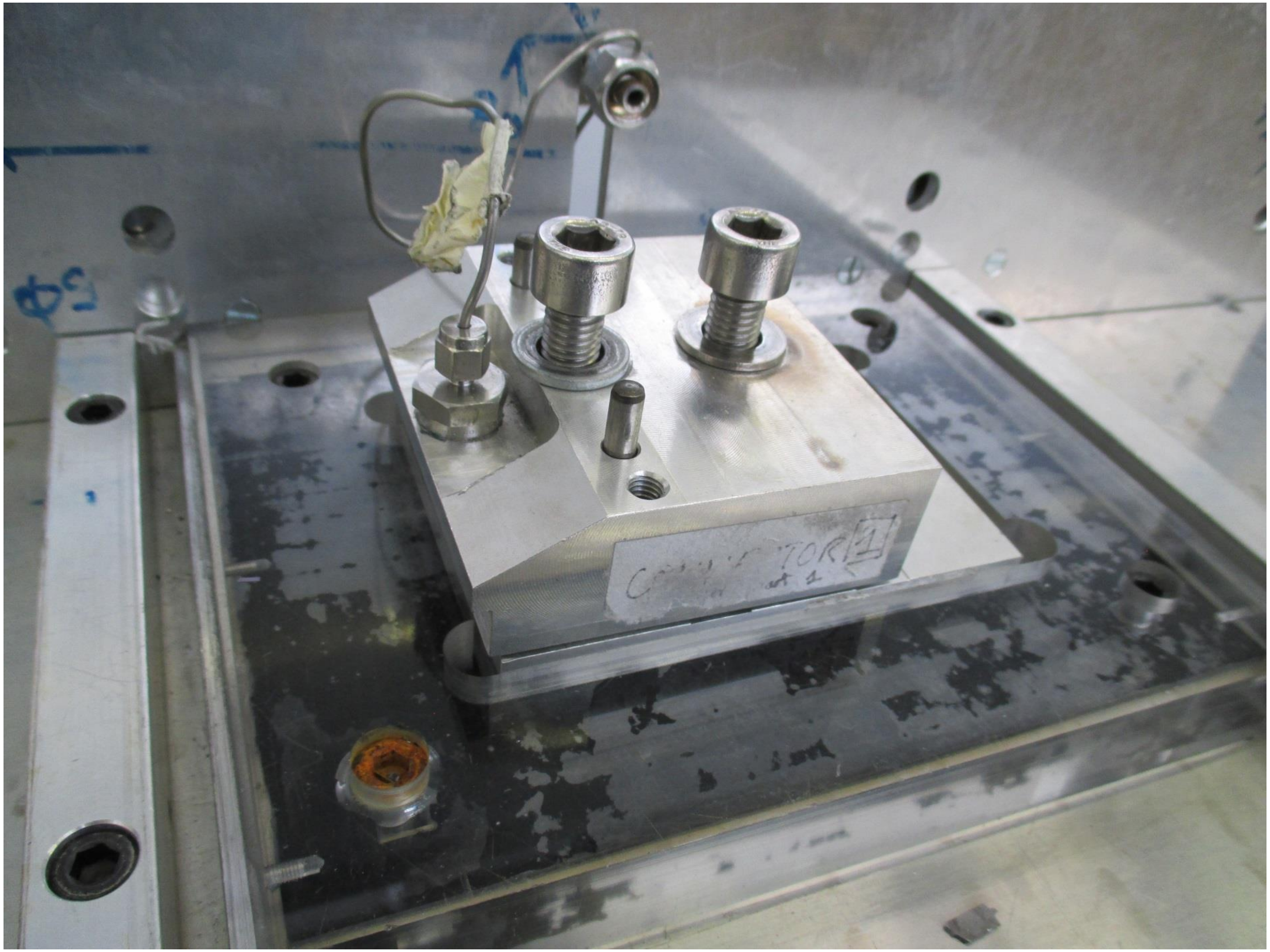


Safety Chamber

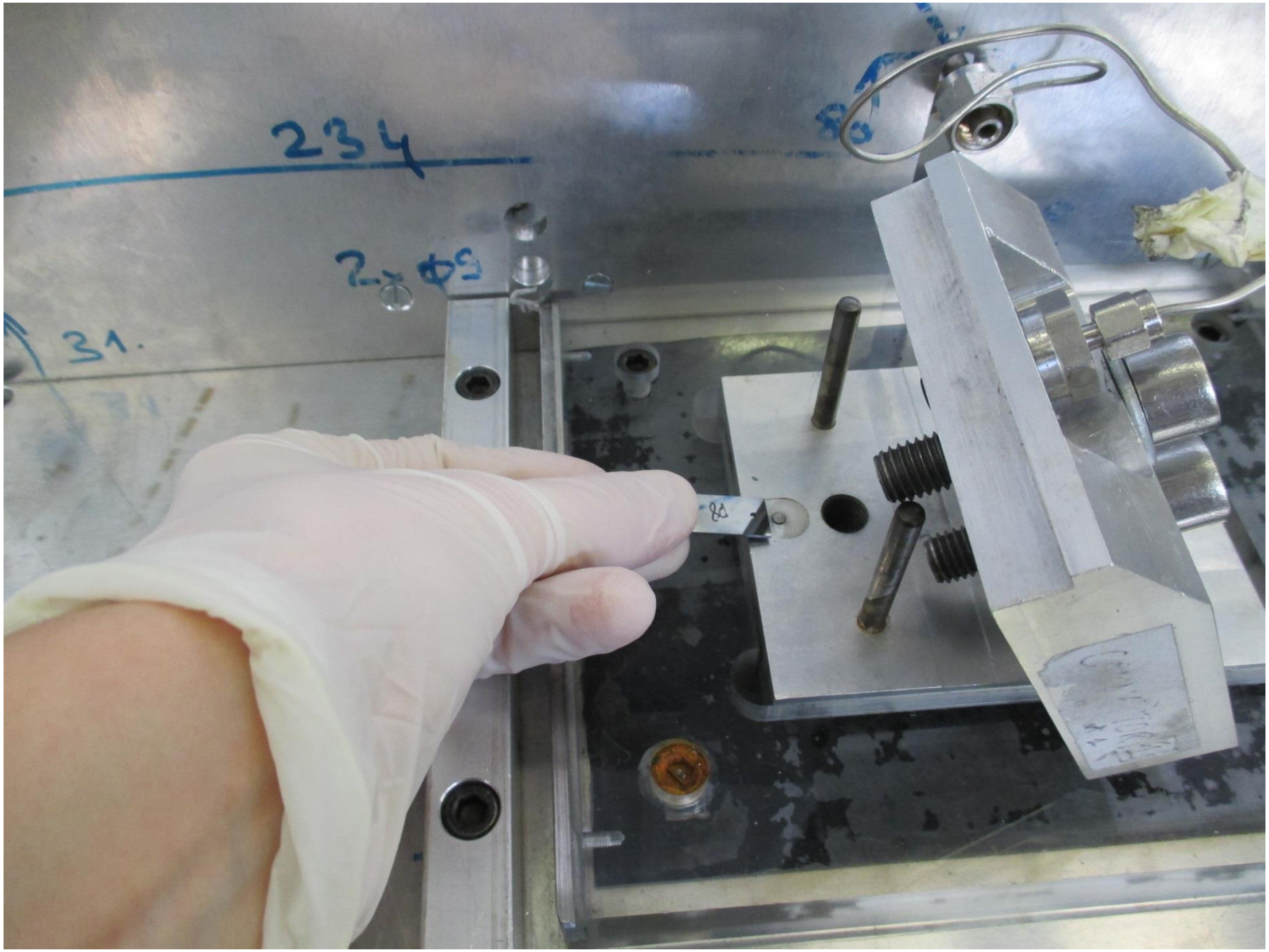


AIDA 2020

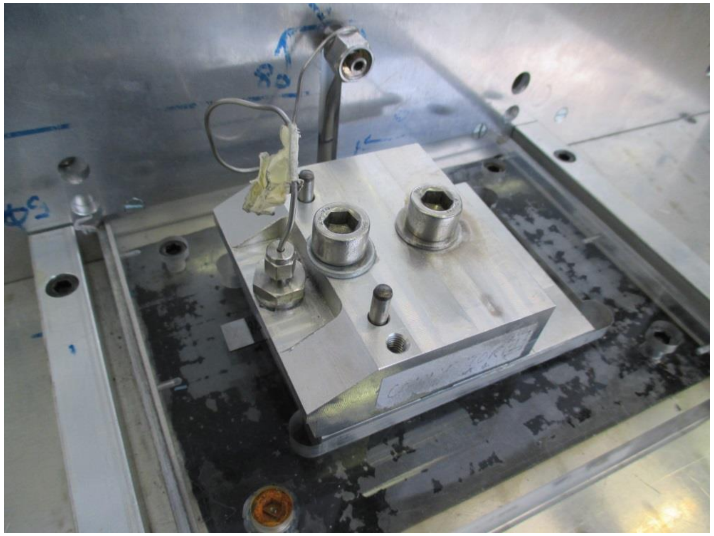
Sample Holder



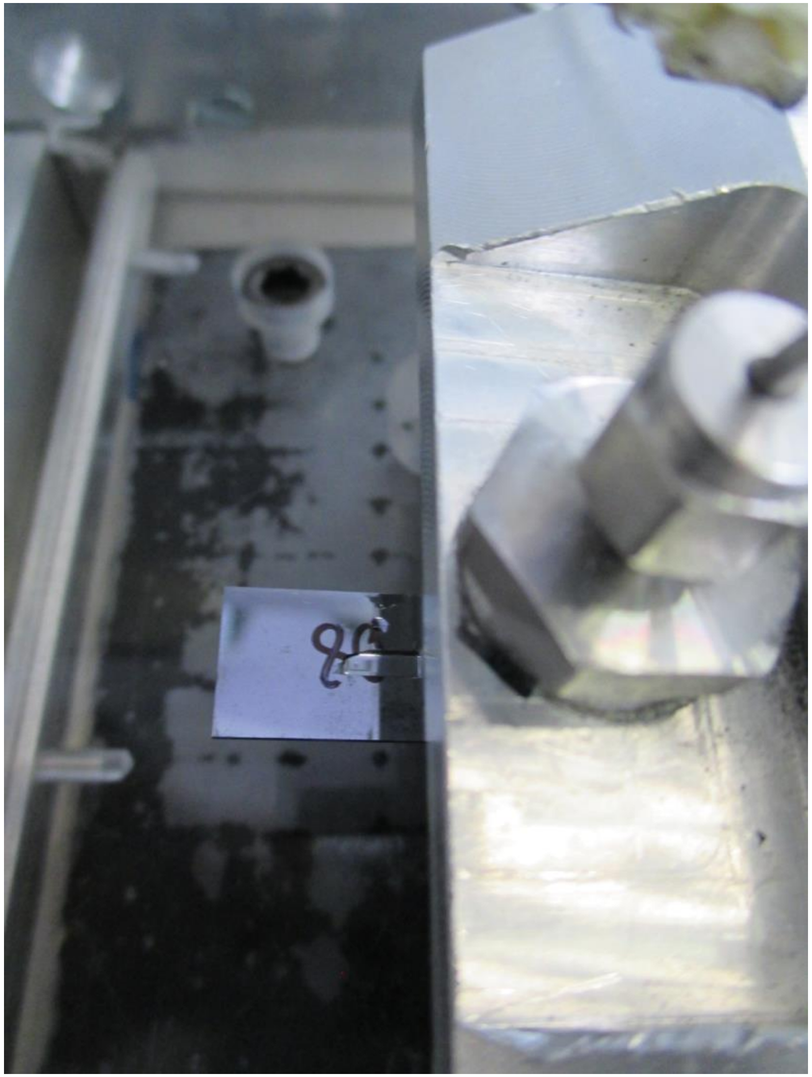
Sample Positioning



Pressure Test & Acquisition



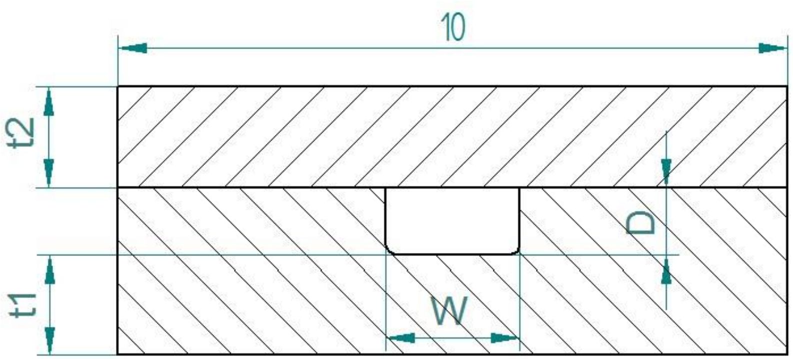
Failure

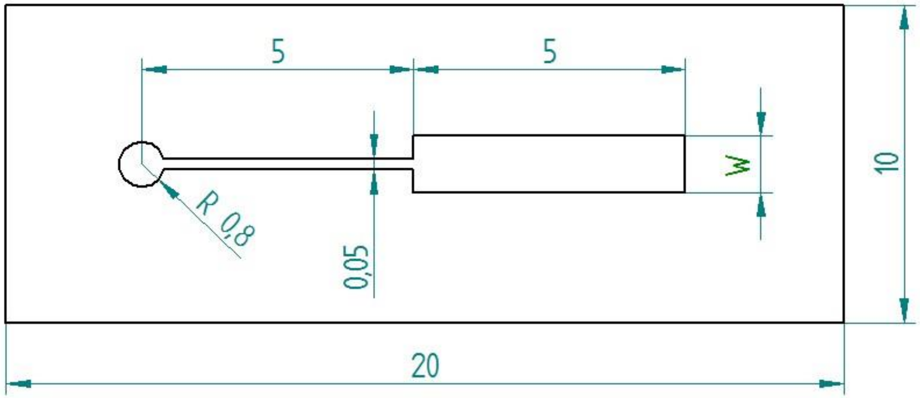


Results

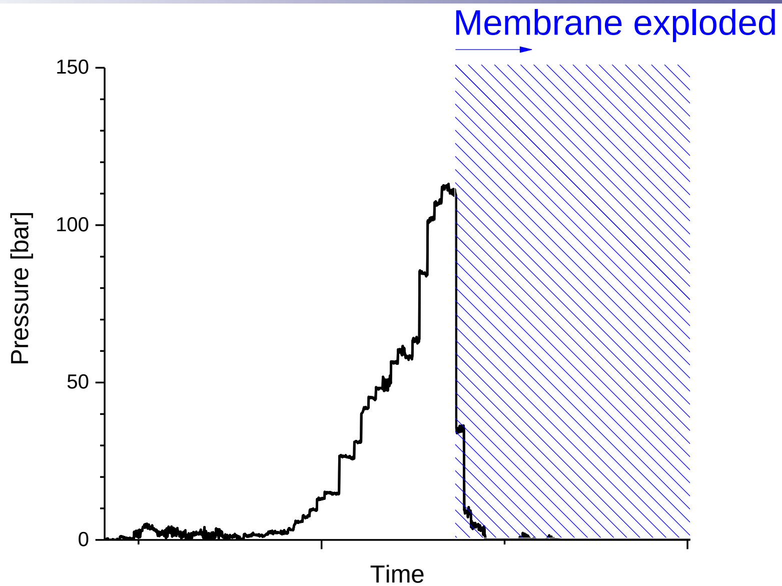
- Si-Si wafer bonding:
  - Good implementation
  - Pressure resistance depends on boding quality and channel geometry

- Single-channel samples
  - Etched together with real cooling devices for quality control of bond strength

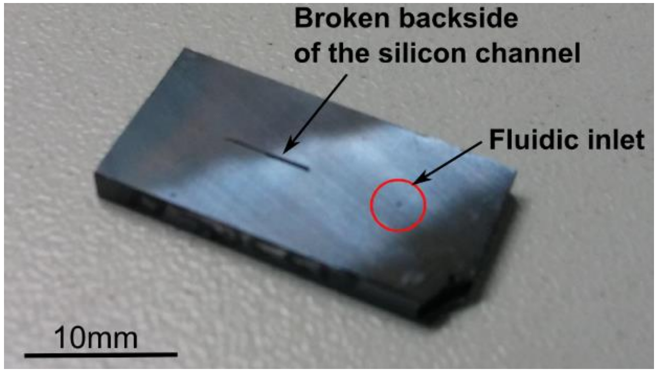




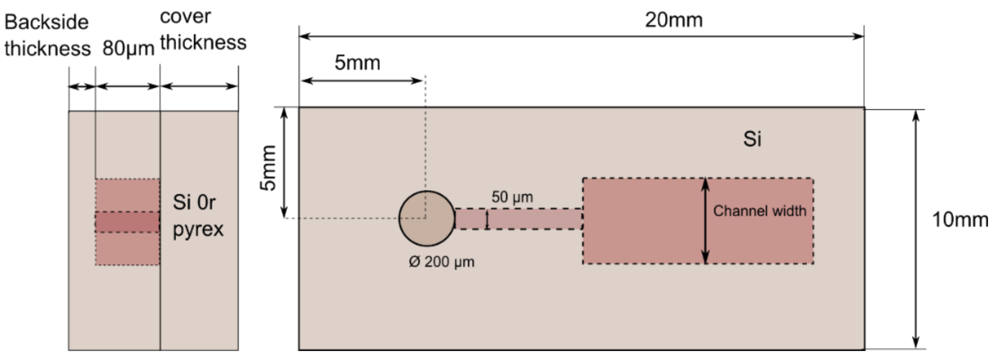
Observed with Si-Si bonded channels



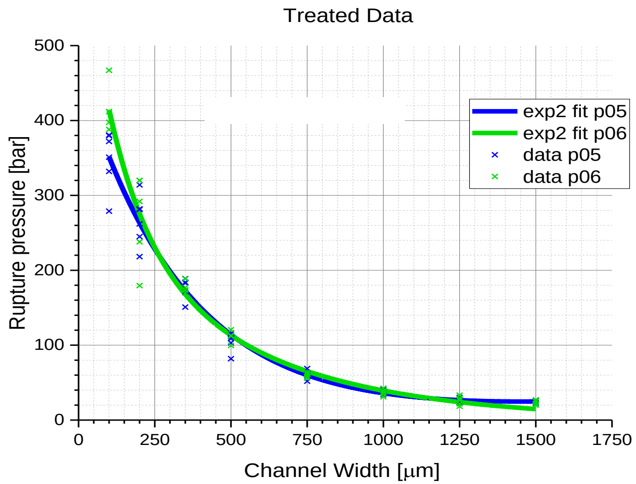
P06_B12: Graph of pressure vs time, sharp decrease of pressure at failure



Example of Si-Si bonded channel failure: Break visible to the naked eye

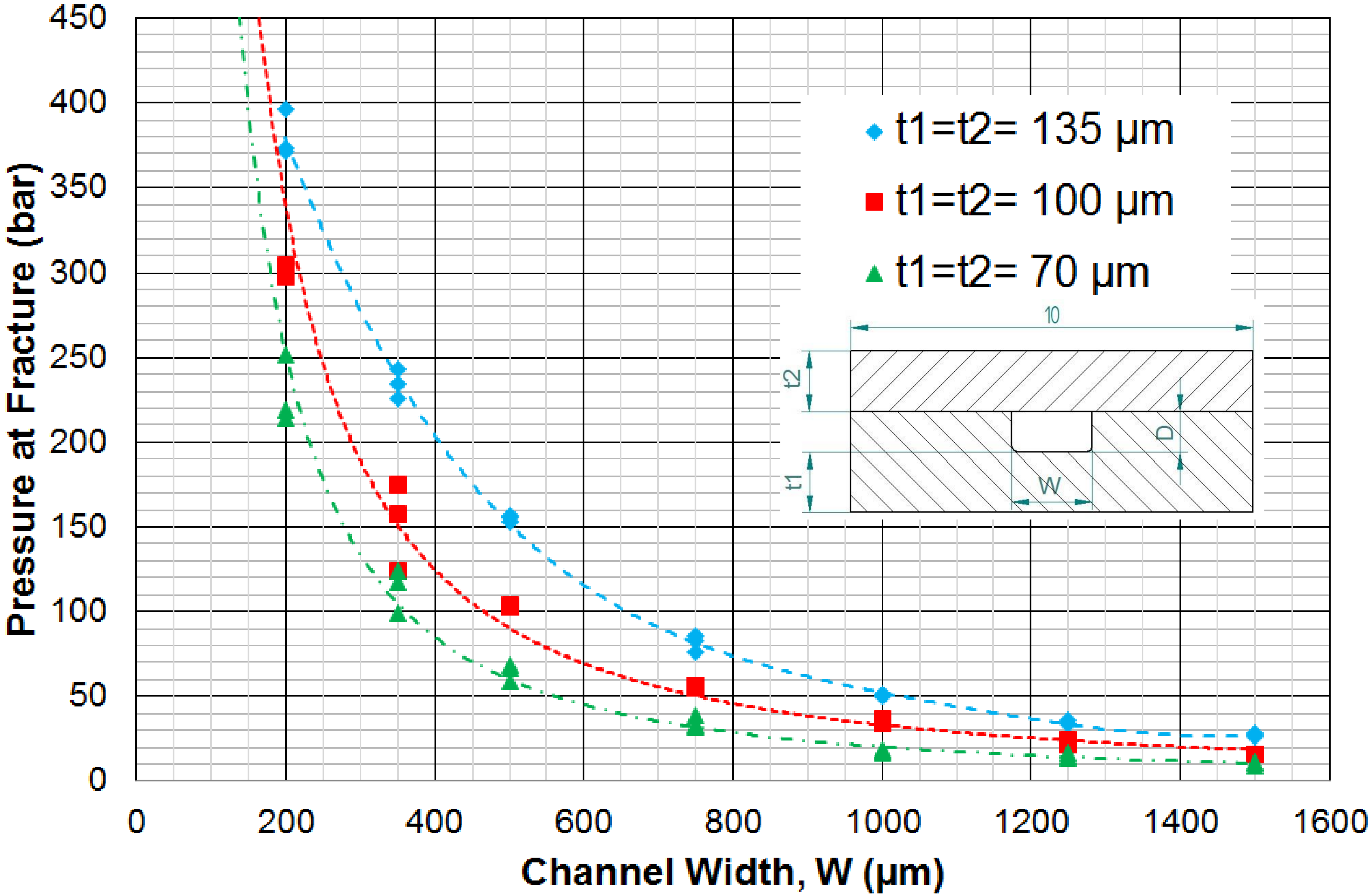


Si-Si bonded sample design



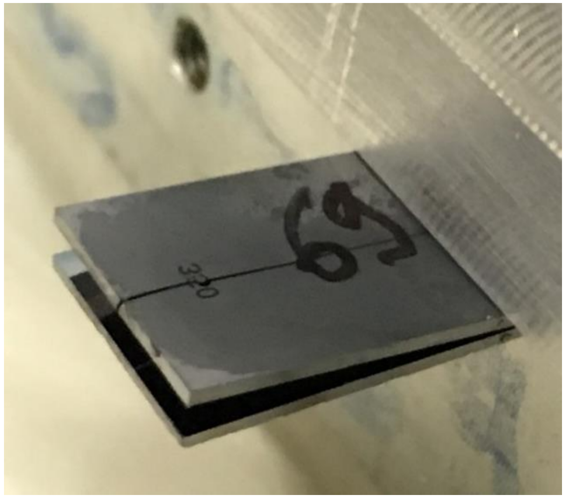
Repeatable pressure at rupture

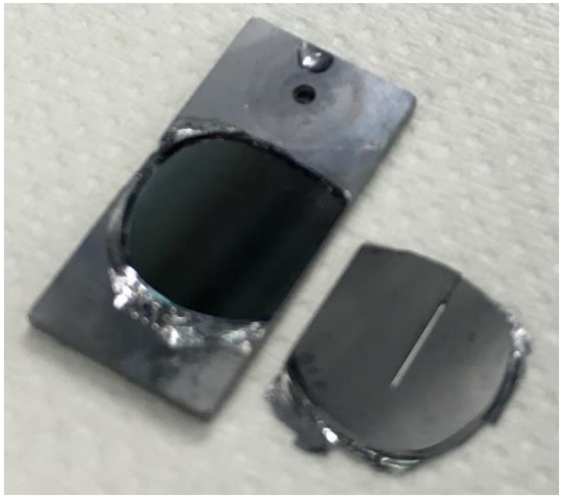
Failure in Silicon Cover

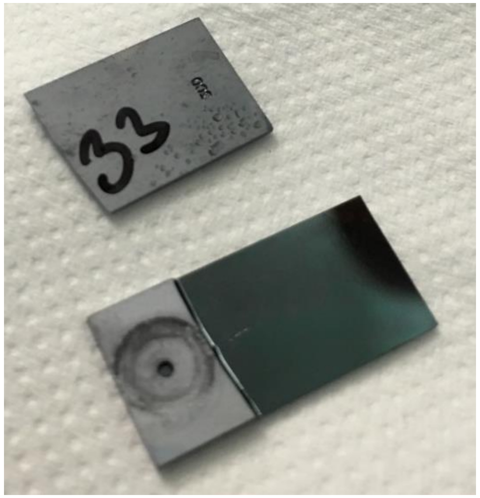


Experimental Results: Typical Failure Models

- Interfacial Failure
  - Clean surfaces observed after testing suggest poor wafer bonding

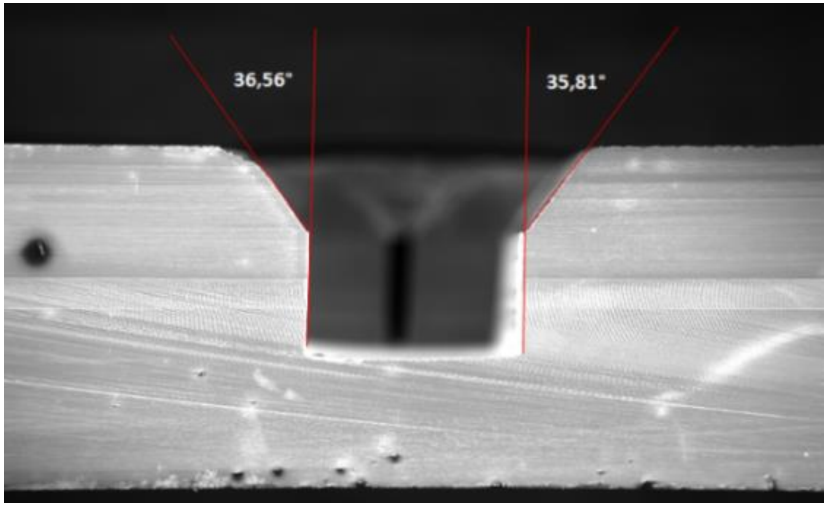






Experimental Results: Typical Failure Models

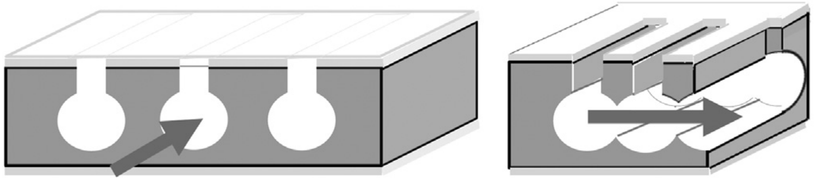
- Silicon Failure
  - Good bonding often results in the explosion of the channel cover



Results

- Buried micro-channels:
  - Challenging process
  - Very good leakage and pressure resistance

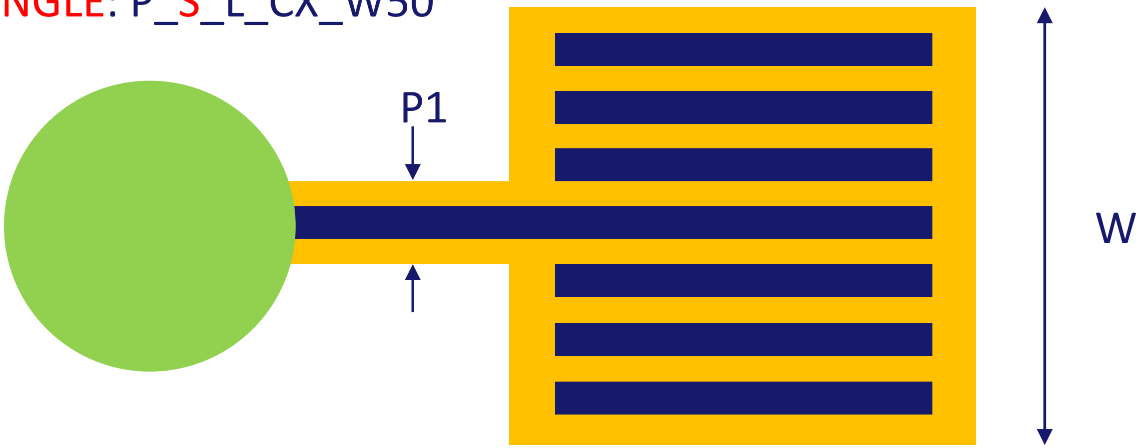
- Two types of channels:
  - Longitudinal channels
  - Transversal channels

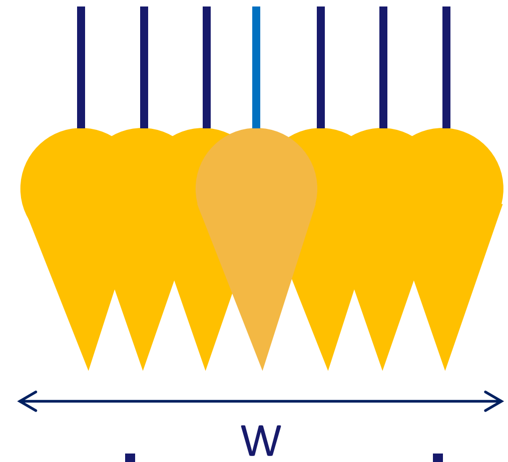


- Pressure test @250-300 bars

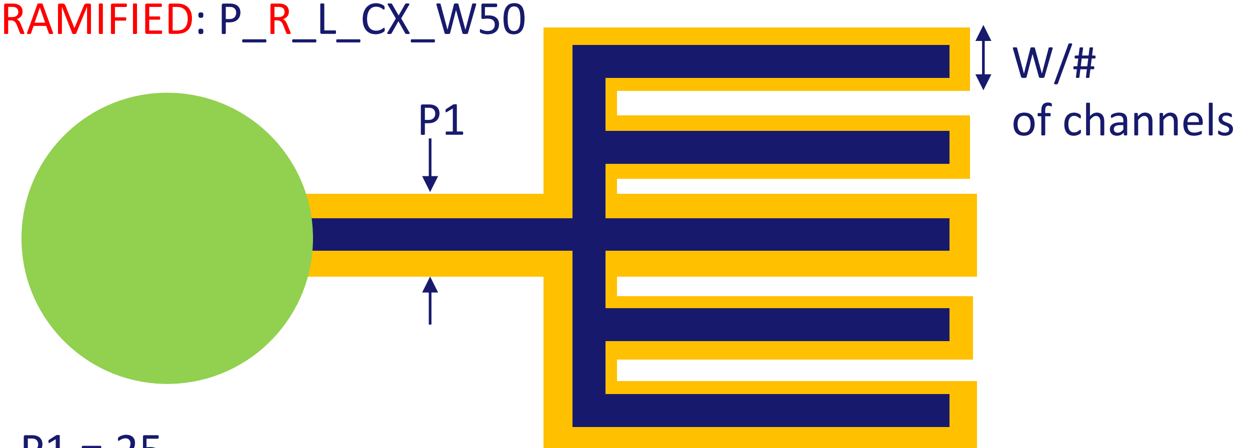
Pressure Samples Longitudinal

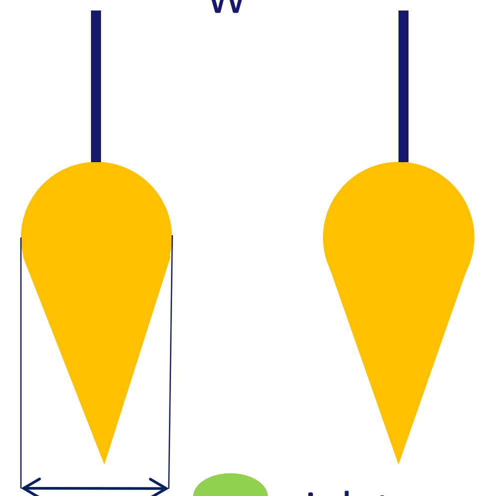
SINGLE: P_S_L_CX_W50





RAMIFIED: P_R_L_CX_W50



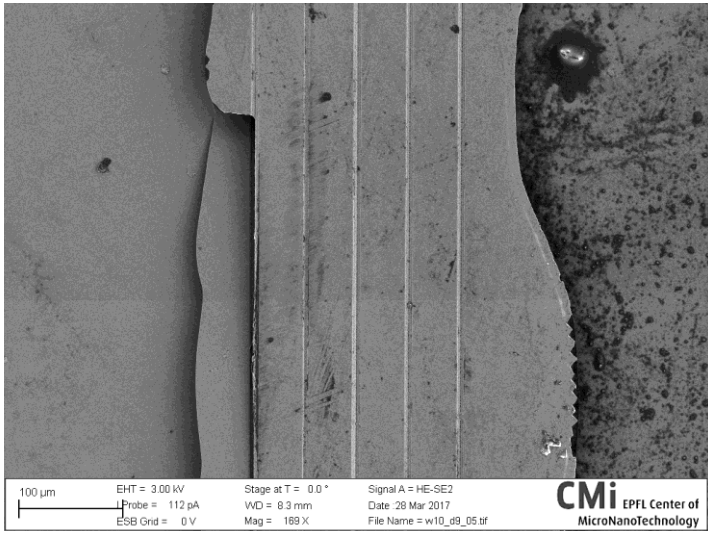


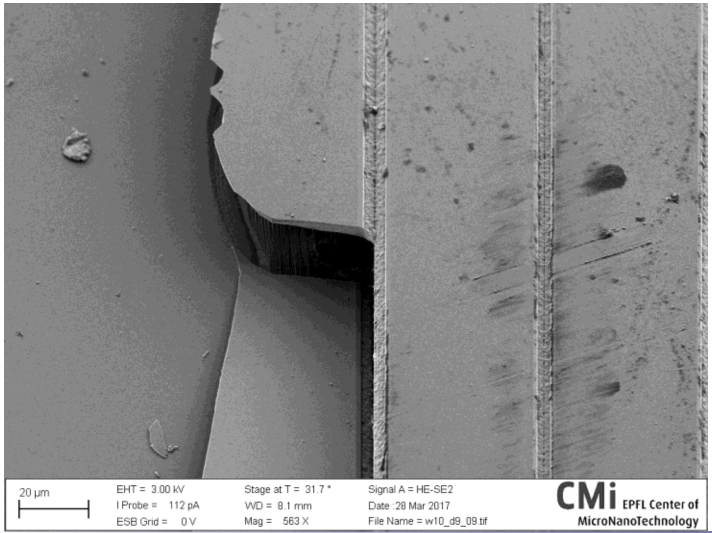
P1 = 25
W = 50; 100; 200; 350

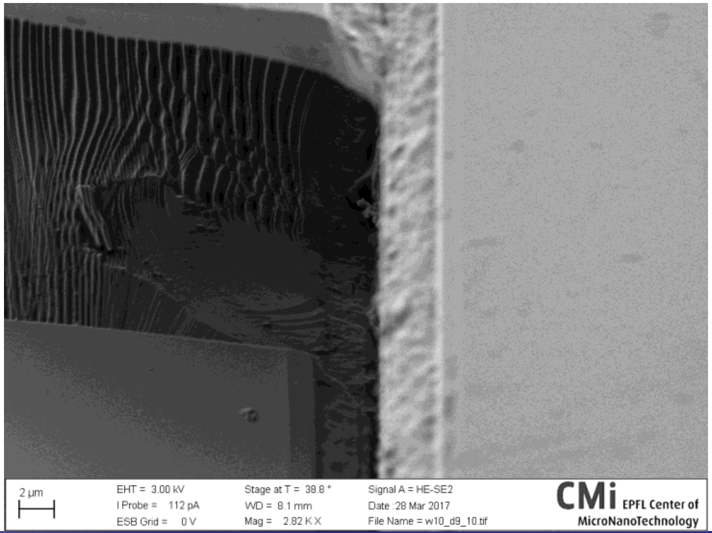
inlet
trench
Buried channel

W/# of channels

Failure in a Longitudinal Sample @ 236 bar

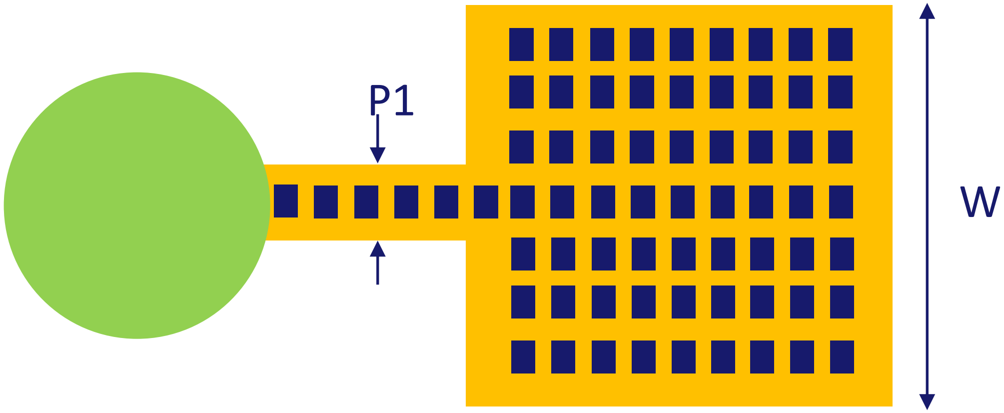


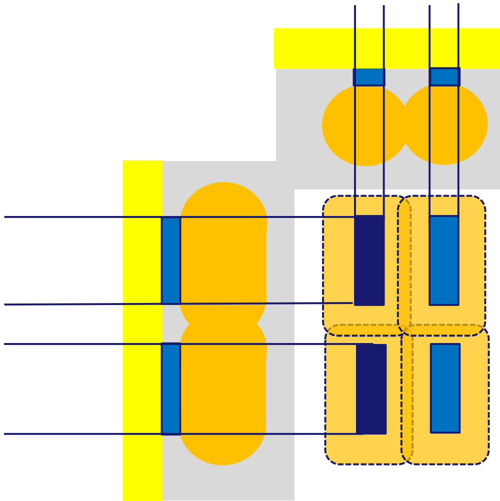




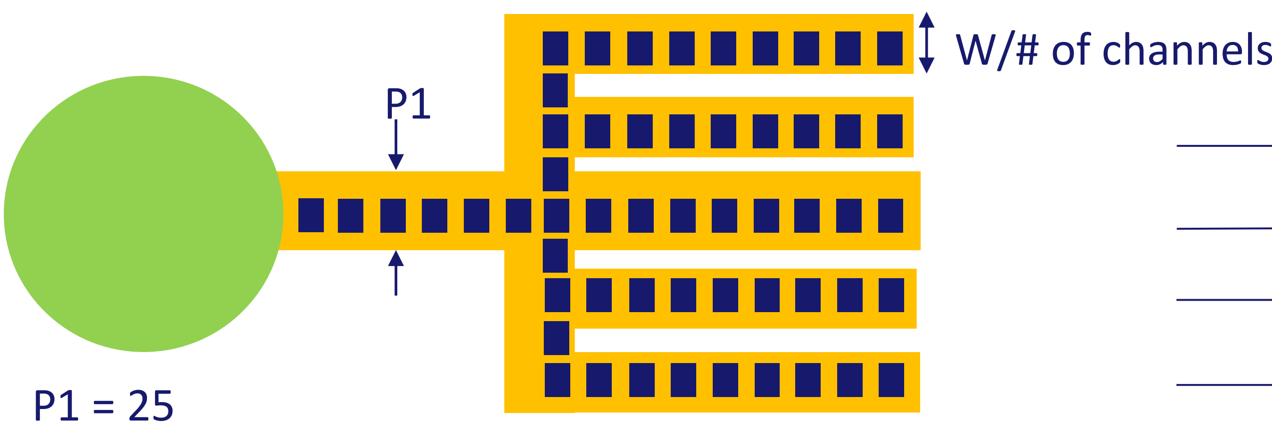
Pressure Samples Transversal

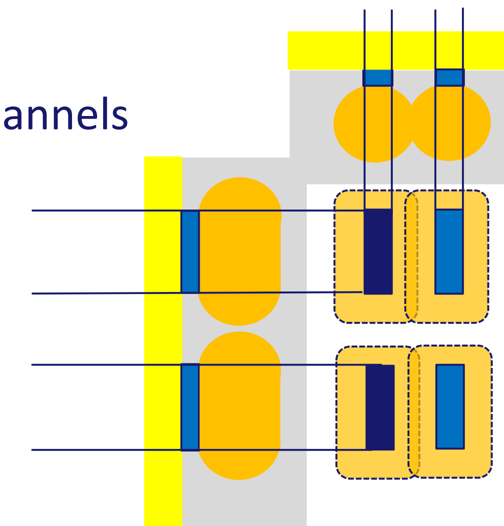
SINGLE: P_S_T_CX_W50





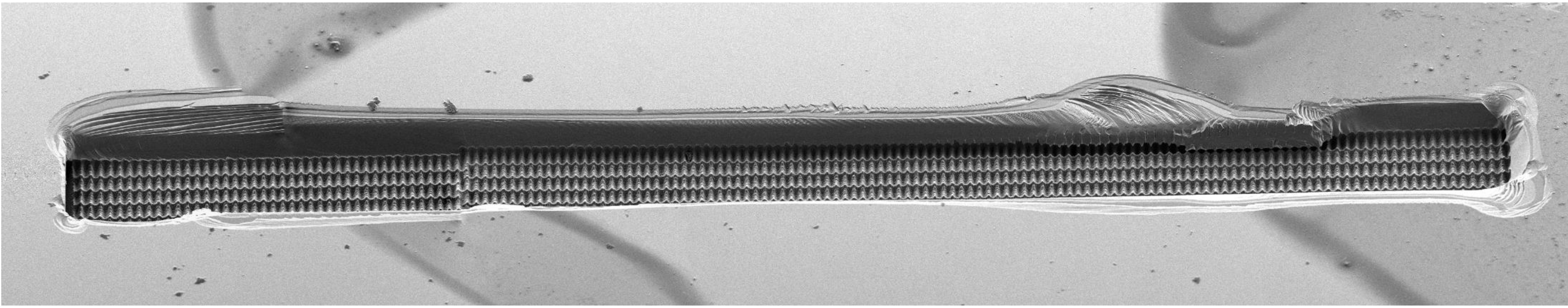
RAMIFIED: P_R_T_CX_W50



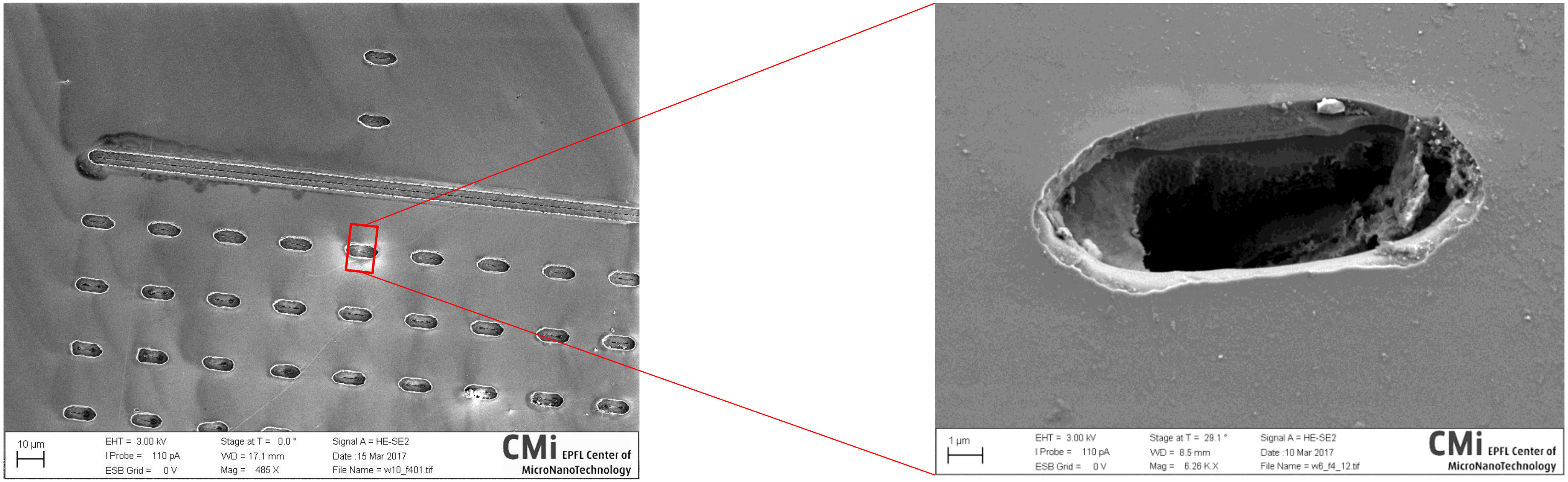


P1 = 25
W = 50; 100; 200; 350

Failure in a Transversal Sample @ 300 bar

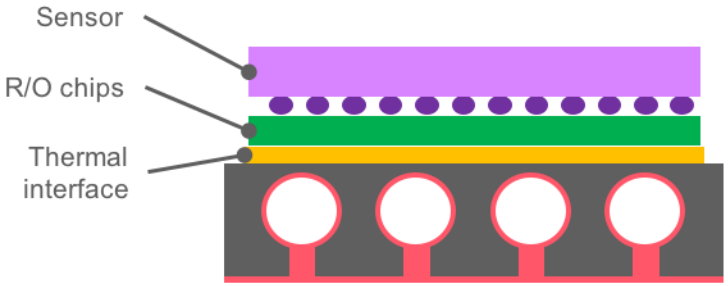


Transversal/Single/W=50, exploded at 335 bar

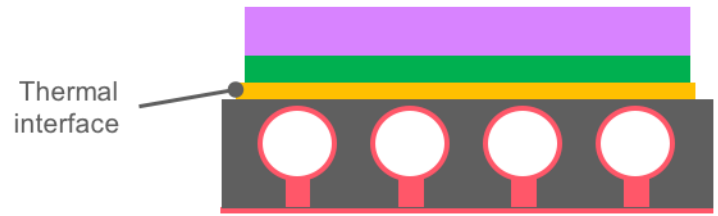


Monolithic Integration

- If not CMOS compatible ➔ separate channel processing, with direct wafer bonding at the end

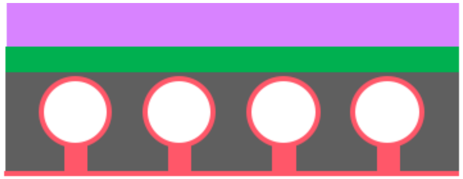


Hybrid sensor on cooling plate



Monolithic sensor on cooling plate

- If CMOS compatible ➔ direct integration at the end of detector processing



Monolithic sensor with embedded microchannels

- Ultimate objective: monolithic bloc for the detector requiring minimum intervention once installed

Full integration

Integrated, autonomous solutions for thermal management in high energy physics and space applications

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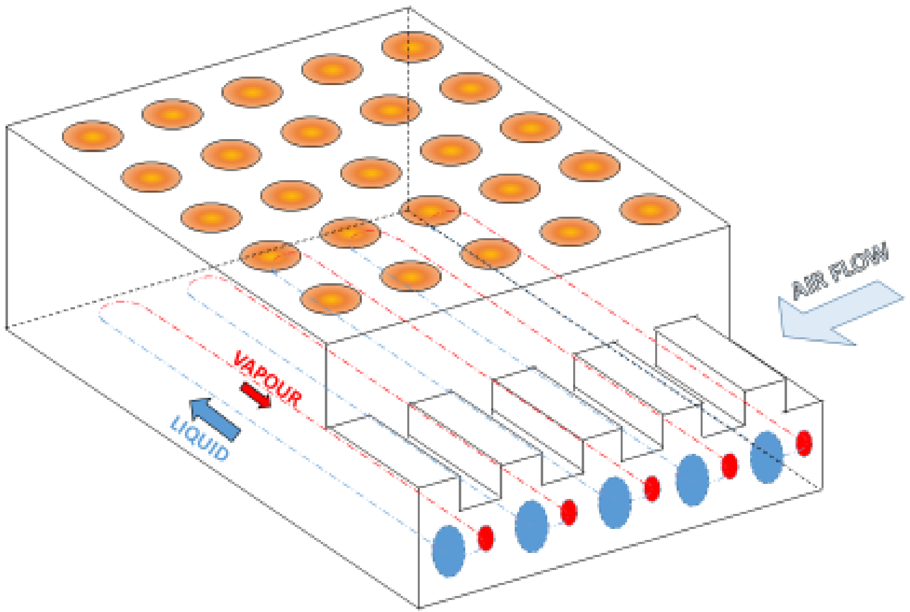
[2]*FBK, Fondazione Bruno Kessler, Trento, Italy*



Conclusion & Outlook

SCOPE OF AIDA-2020 TO GATHER THIS KNOWLEDGE AND BRING BUILDING BLOCKS TOGETHER

- Thermal management represents a major challenge in HEP.
- Continuous advances in micro-engineering have opened the door to the development of smaller and more efficient cooling devices capable of handling increasing power densities with a minimum mass penalty.
- AIDA-2020 is bringing together a community to develop and study silicon microchannel cooling devices and low mass mechanical structures .
- By 2019, a catalog of building blocks, design guidelines and standards for characterization and qualification of devices and systems for microchannel cooling (single phase and evaporative) will be available.
- Long term objective:
  - Fully understanding failure parameters and how to avoid failure
  - Full-proof characterization and reliability protocol

Thank you for your attention!