3D Integration of MEMS and IC: Design, technology and simulations

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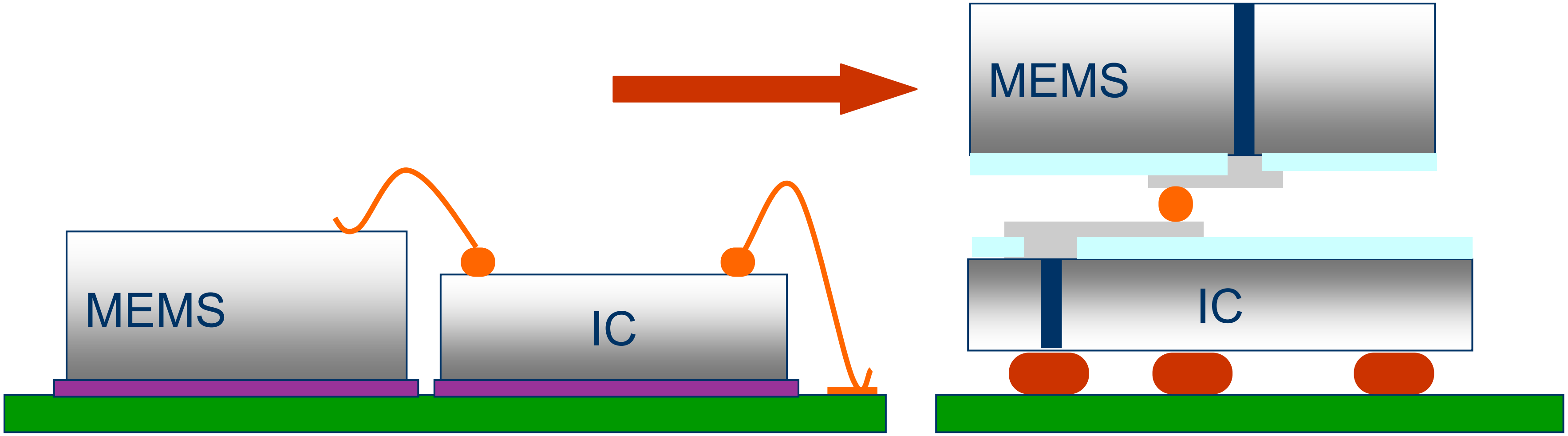
Outline

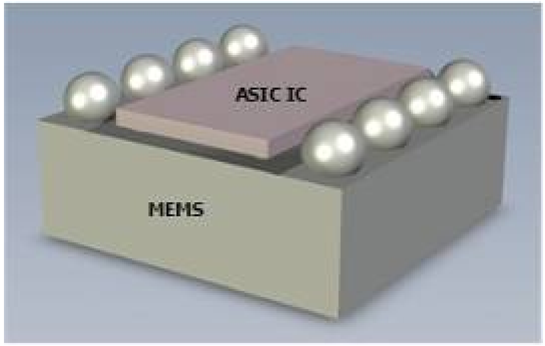
- 3D integration: Opportunities and trends
- e-CUBES: Tire pressure monitoring system (TPMS)
- Package design including thermo-mechanical modeling
- Technology development
  - Sensor packaging concept
  - Gold stud bump bonding
- Device characterization and testing
- Summary and outlook

MEMS, IC, 3D integration

- MEMS,- what we normally must explain…
- IC,- typically ASICs designed for the MEMS
- 3D integration
  - Vertically stacking
    - Mechanical and electrical interconnections
    - Through silicon/substrate vias (TSVs)

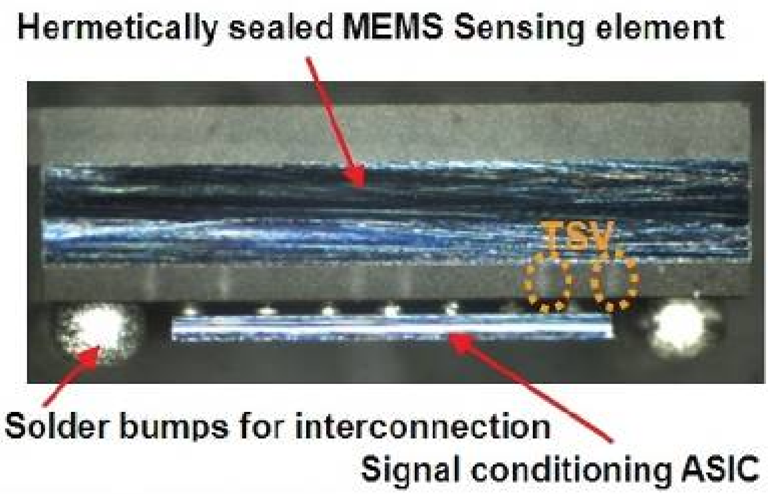


Benefits



Source: VTI

- Reduced footprint/size
- Packaged on wafer level
  - Wafer to wafer
  - Chip to wafer
  - Wafer level packaging (WLP)
    - Ready for surface mounting directly after dicing



- Shorter electrical signal lines
  - Improved time response and reduced parasitic capacitances
    - Sensors: Ideal for pixel detectors
    - IC: High bandwidth for microprocessor core to memory communication
- Reduced cost and improved performance

e-CUBES project

www.ecubes.org

- Miniaturized, autonomous systems for ambient intelligence
- Spring 2006 – spring 2009, 17 partners
- 3 demonstrators
  - Health and fitness
  - Aeronautics and space
  - Automotive

Health and fitness

Aeronautic

Automotive

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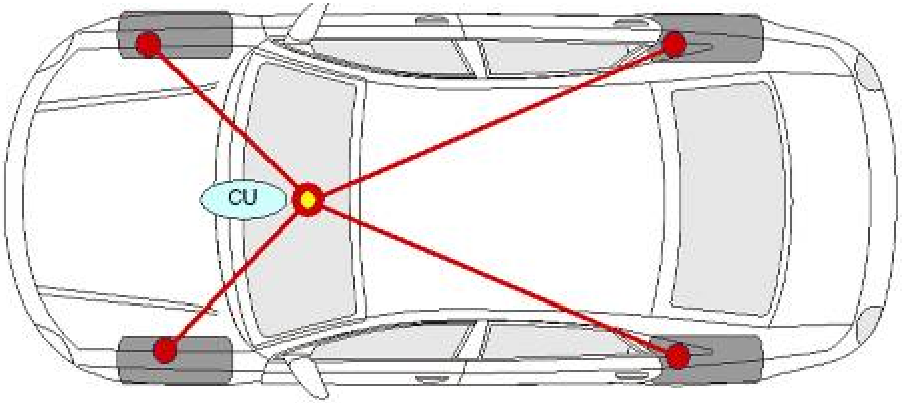
Tire Pressure Monitoring System (TPMS)

TPMS placement: rim → tire liner

First: Porsche 959 (1986)



Today:

Future:

- Additional sensing
  - Road condition
  - Tire wear out
  - Friction
  - Temperature
  - Side slip
  - Vehicle load
- Improved tracking
- Engine control

TMPS must be smaller

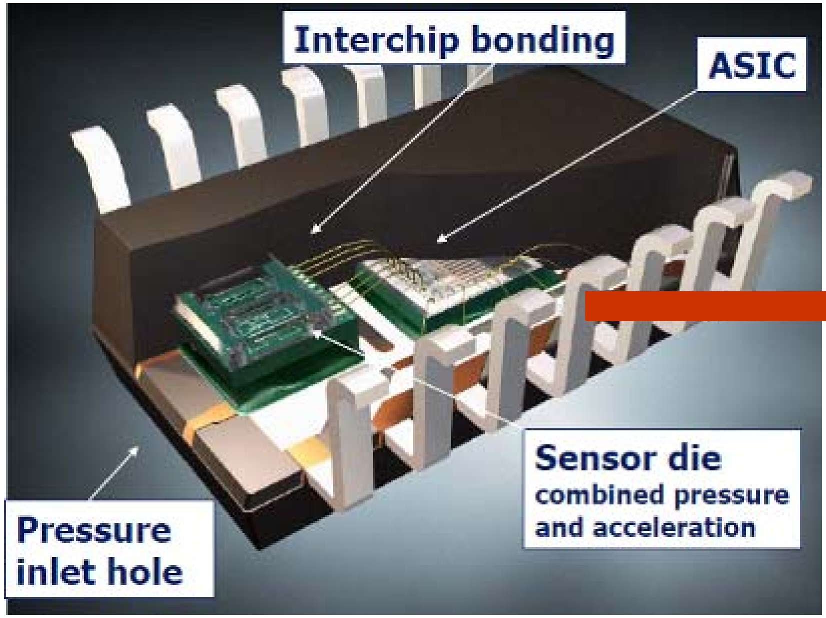
Wireless: 2.4 GHz ISM
Power: Battery → harvester

Today:

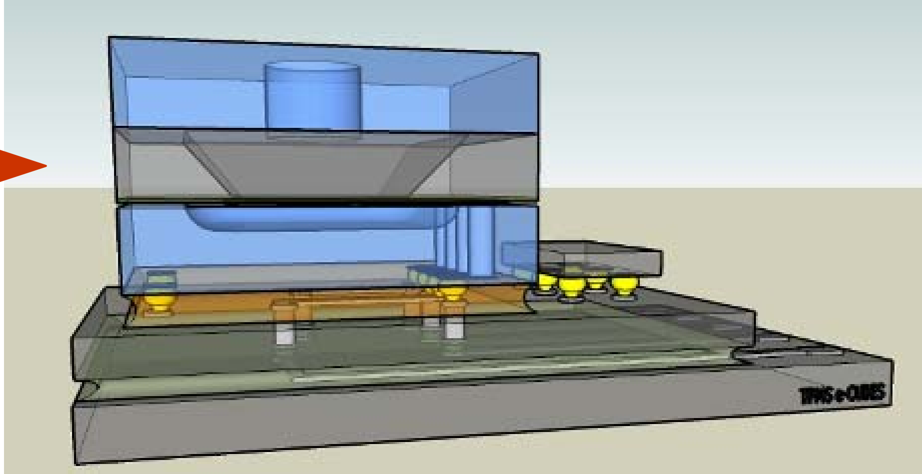
Current size: 36 cm^3

Future:

Target size: 1 cm^3

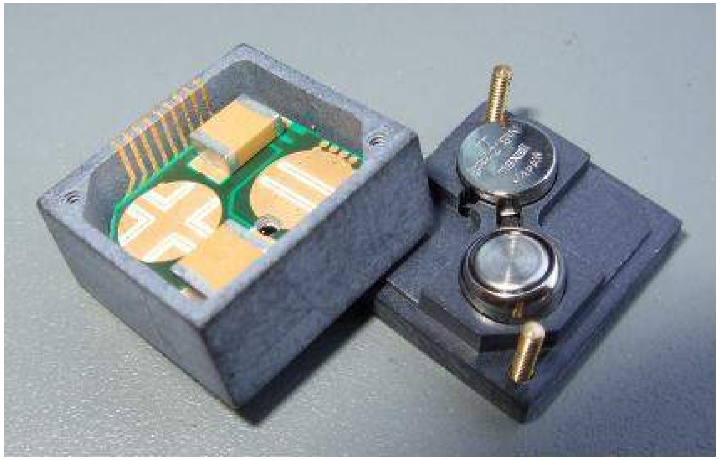


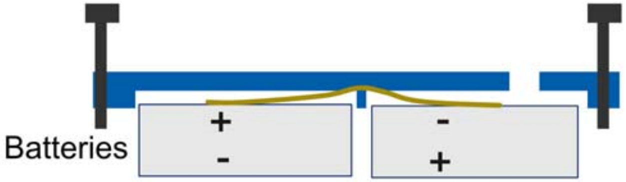
3D integration

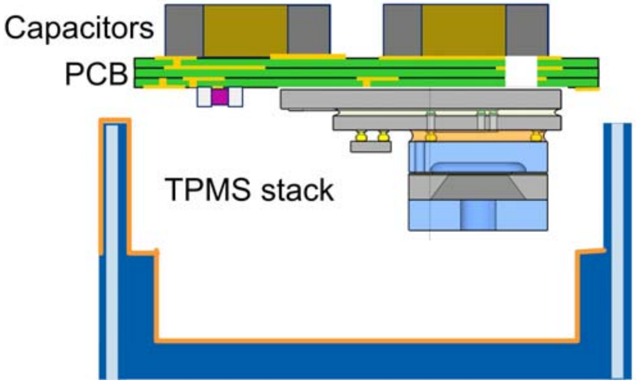


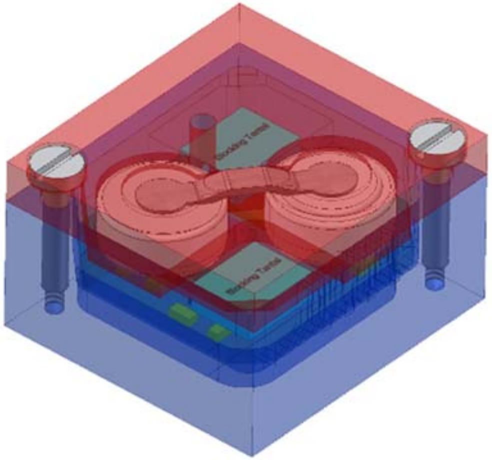
Package design and thermal simulations

- Molded Interconnect Device
- 11 × 10 mm^2 PCB









Hot tire over ice:

Tire @ 0°C and air 125°C

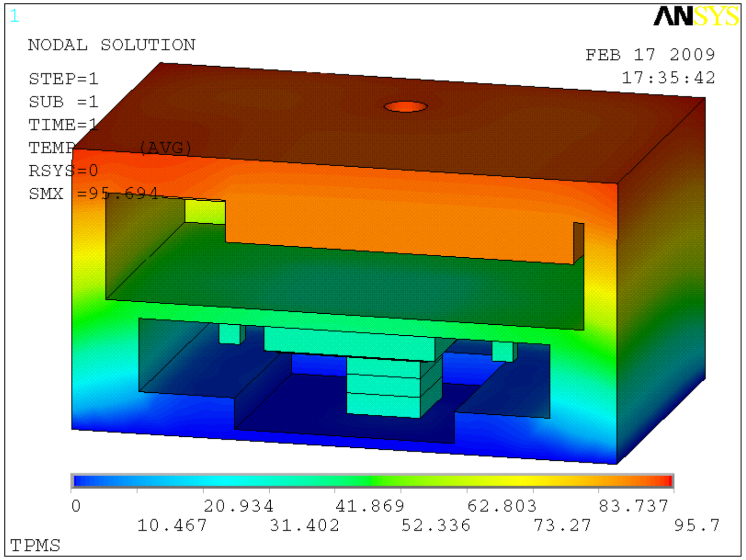
Simulation results

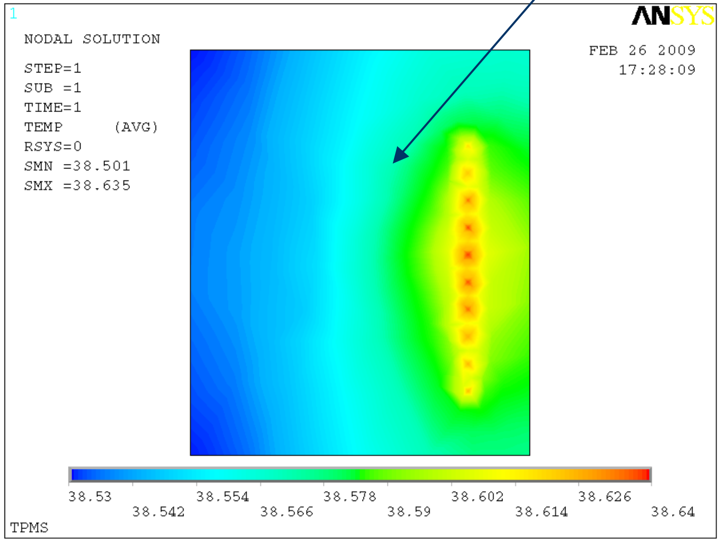
Hot tire over ice:

Tire @ 0^{o}C and
air 125^{o}C

- Thermo-mechanical stresses
- Uniformity required across membrane
  - Influence on piezoresistor values

Membrane
$\Delta T < 0.1$ K (OK)

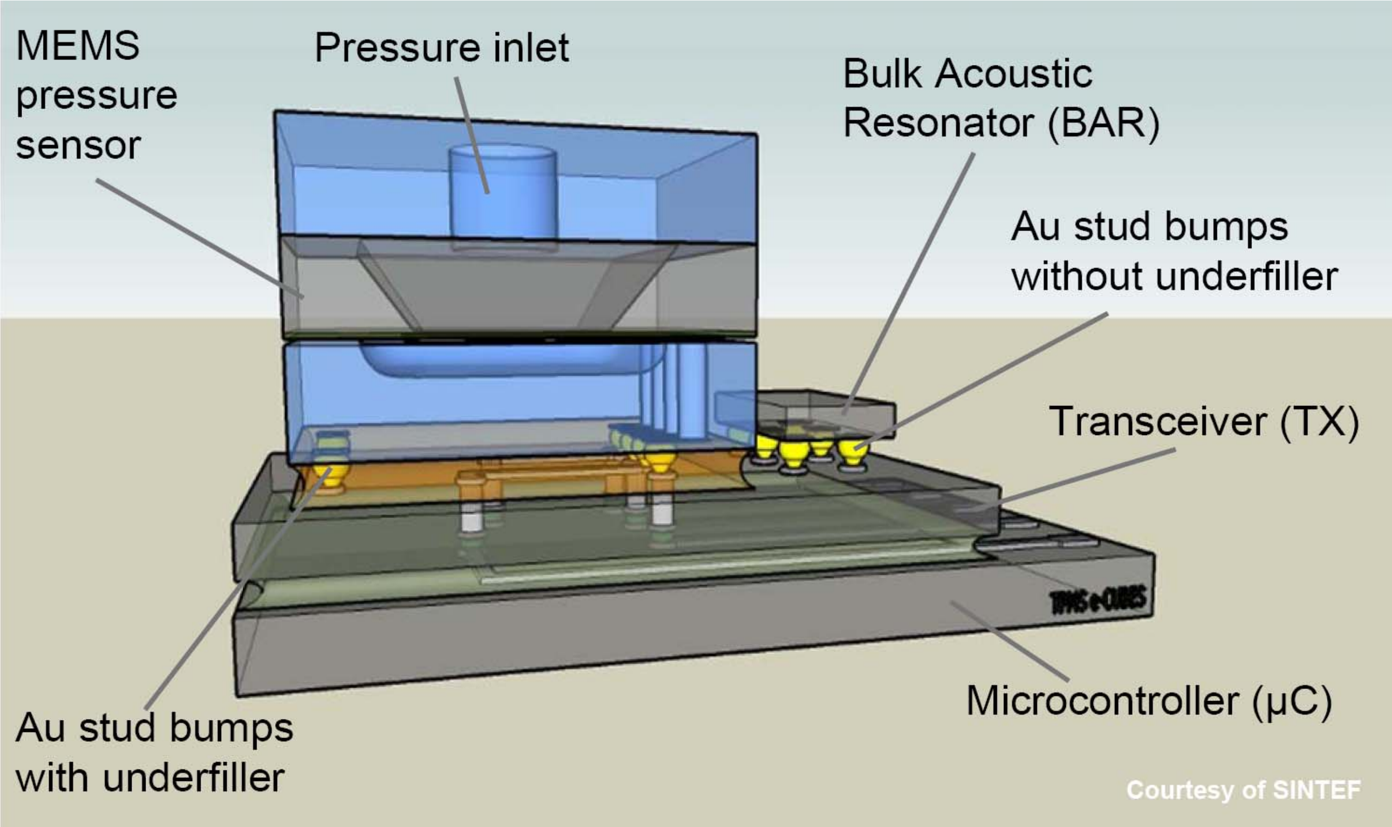




Thermal effects on the BAR: Prainsack et al., “Design Issues of BAW employment in 3D integrated Sensor Nodes”, DTIP 01-03 April, Rome, Italy, 2009

Silicon devices in the 3D stack

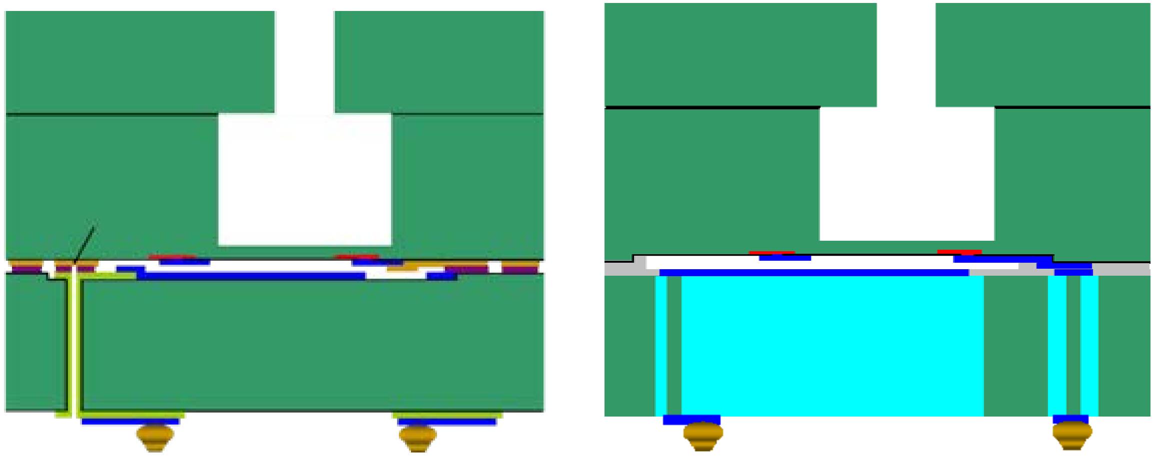
- Two ASICs: Transceiver and microcontroller
- Two MEMS: Pressure sensor and BAR

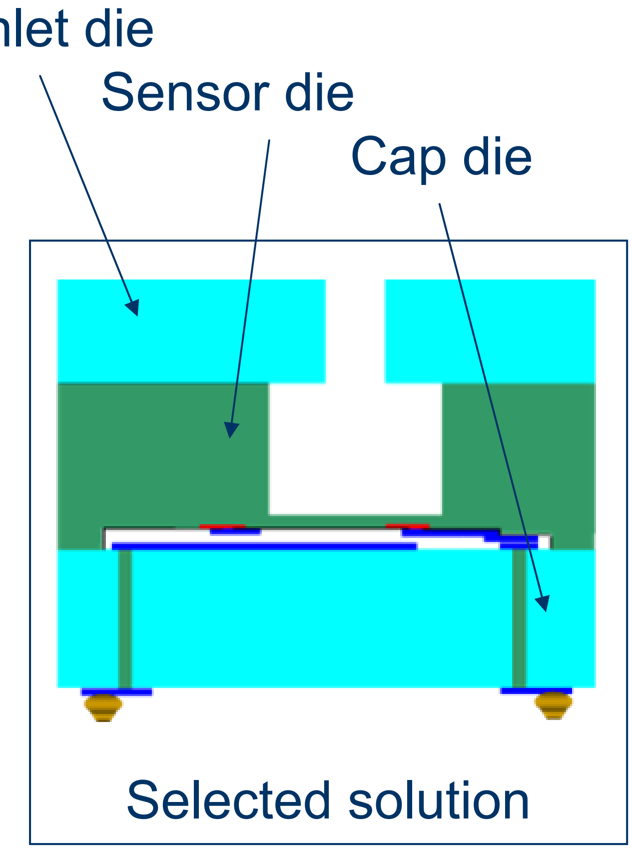


Courtesy of SINTEF

Sensor designs

- Bulk micro machining
- Piezo resistive device

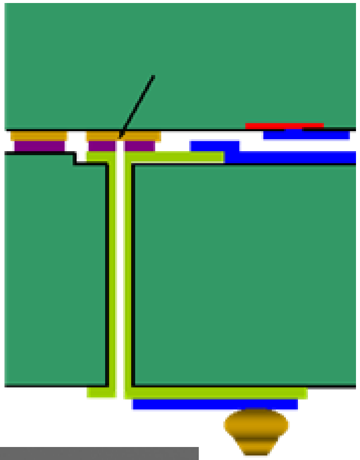




Selected solution

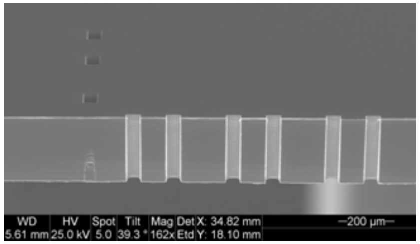
- Wafer level packaging alternatives
  - AuSn bonding and vias in silicon wafer
  - Direct bonding and vias in glass-silicon compound wafer
  - Glass-silicon bonding and glass-silicon compound wafer

Abandoned alternatives

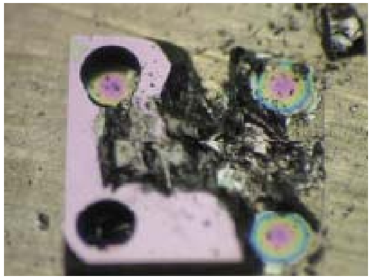


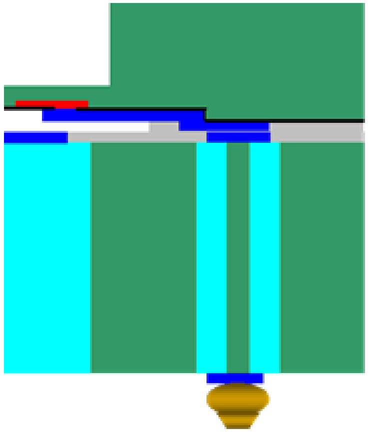
- AuSn
  - Plating required
    - Both wafers (inlets…)
    - Stand-off height > 10 µm (recess needed)

- Vias in silicon wafers
  - Hollow vias with polysilicon
    - Uncertain sealing of holes

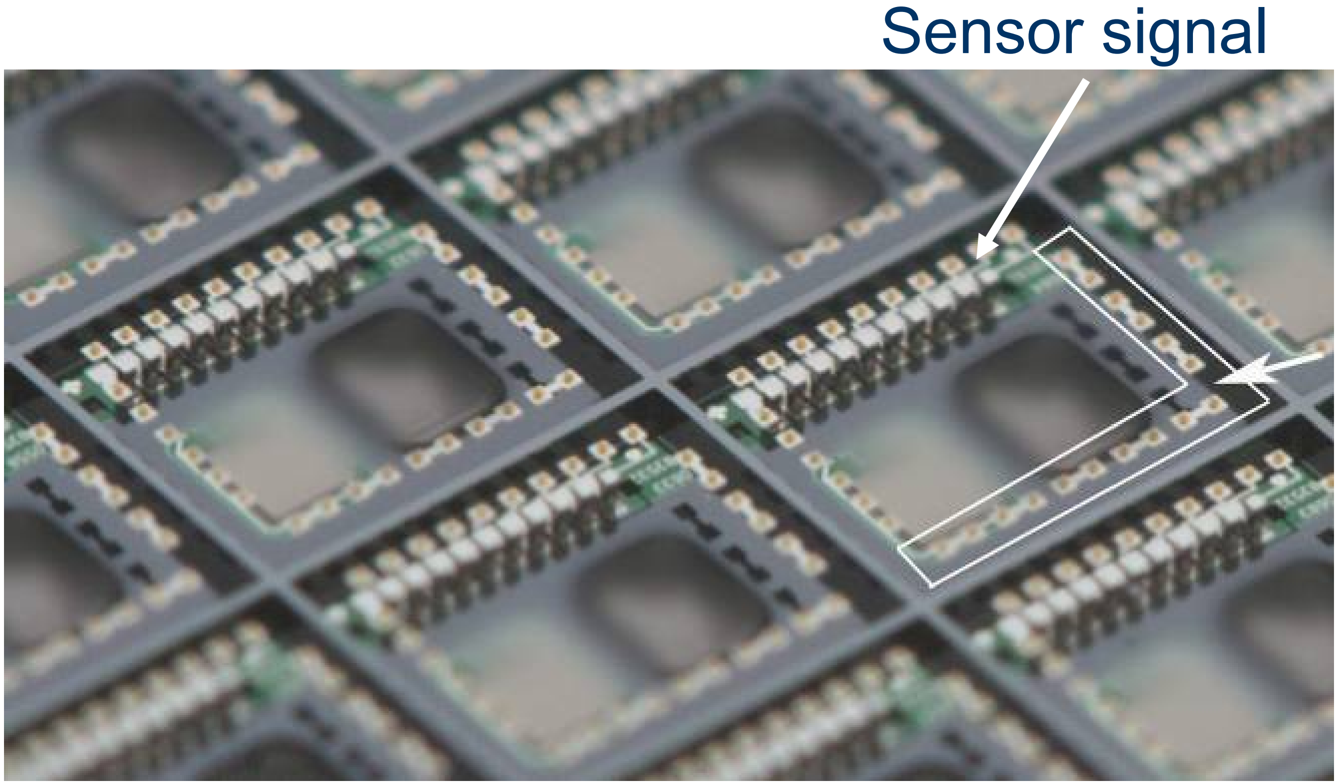


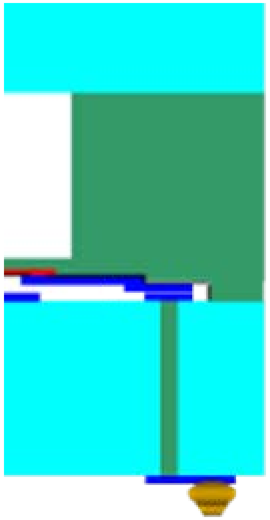
- Direct bonding Oxide/metal
  - CMP required
    - Both wafers (fragile)
    - Combined oxide/metal CMP
    - Hybrid bonding (bond wave/thermo compression)





Selected alternative



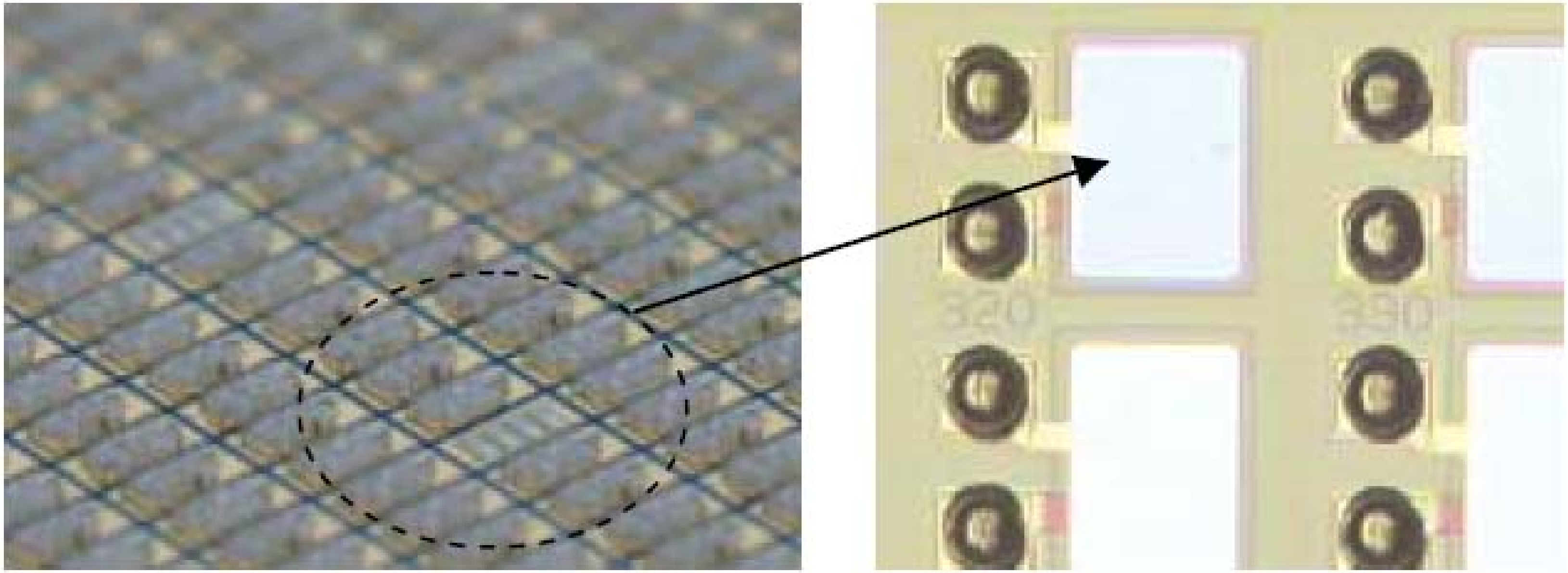


- Silicon-glass compound cap wafer and glass inlet wafer (SYMMETRY)
  - Modified bonding process (avoid short circuit despite Si pins)
- Al signal lines (patterned dry due to inlets)
- Au stud bumps (diameter 52 µm, height 30 µm)

PlanOptik

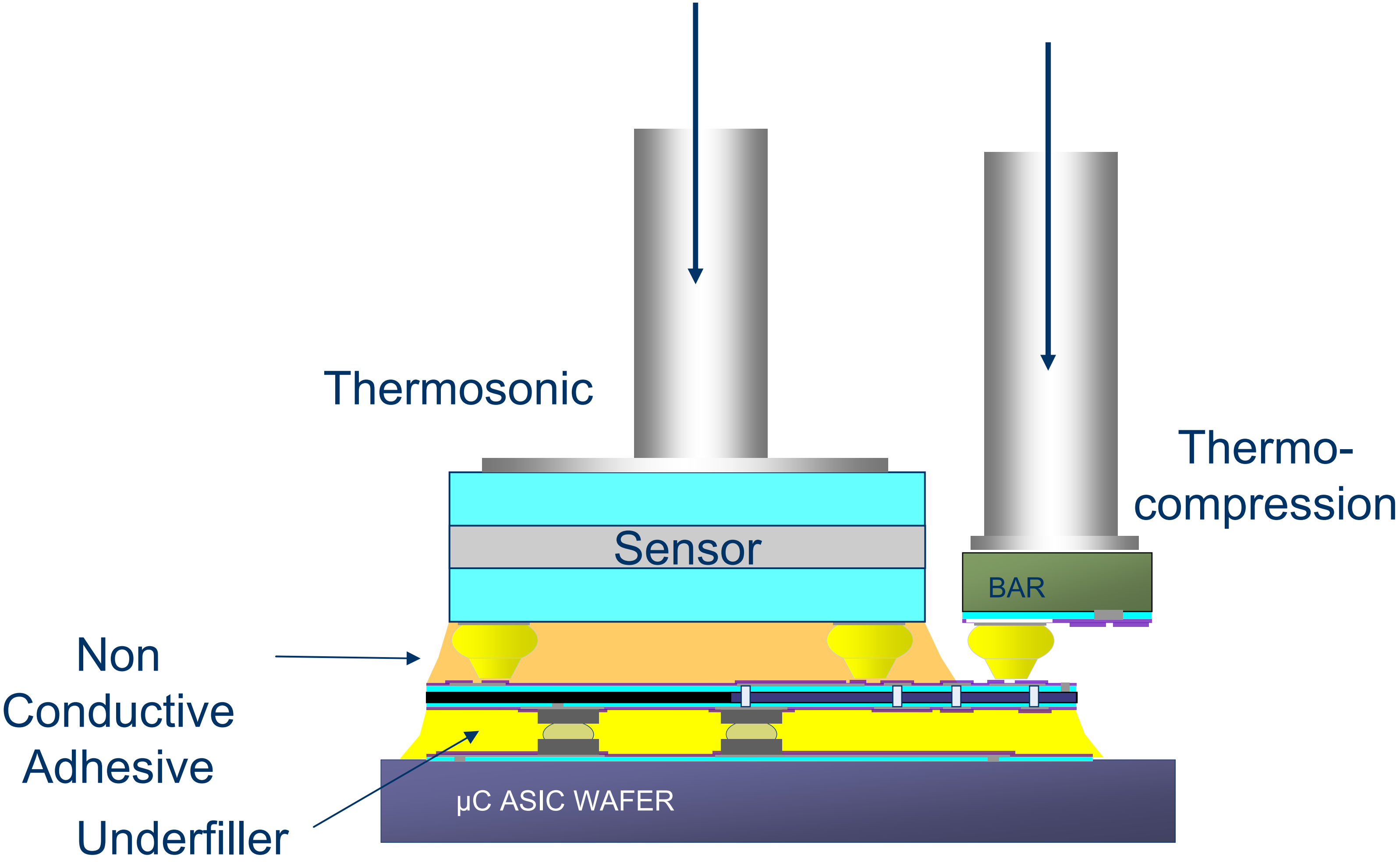
Close up of BAR devices

- Tiny devices: 0.8 x 1.3 mm^2, 200 µm thick
  - No TSVs
- Smaller bumps (diameter 47 µm, height 32 µm)



Source: SINTEF

Sensor and BAR bonding (chip to wafer)

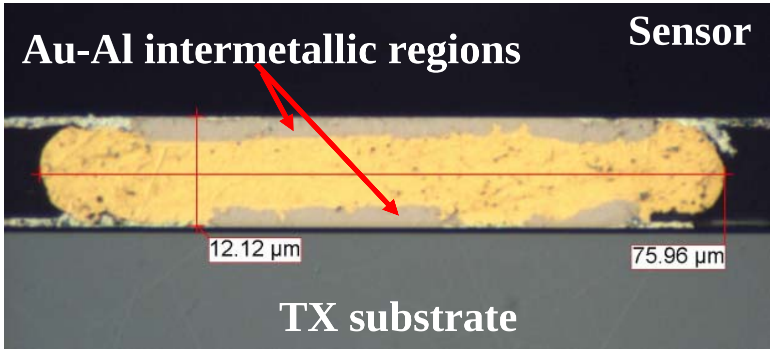


Optimized bonding parameters

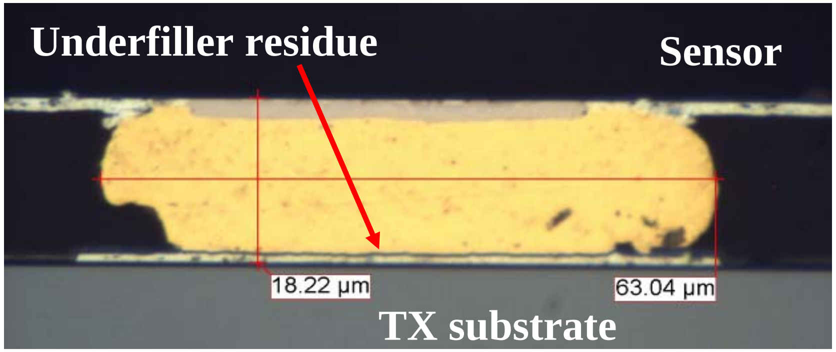
Method	Thermocompression	Thermosonic
Bond force (N) (32 bumps)	20 – 30	12 – 20
Bond time per die (s)	10	2
Tool temperature (°C)	200	20
Chuck temperature (°C)	120 – 140	120 – 140

Higher pressure and temperature ↔ Negative effect of ultra sound?

Au stud bump cross sections



Good



Bad

- Bump heights: 8 – 21 µm
- Bump diameters: 60 – 100 µm

- Thermal cycling (- 40°C to + 150°C) and 30 min at 260°C
  - No impact on the cross-sections

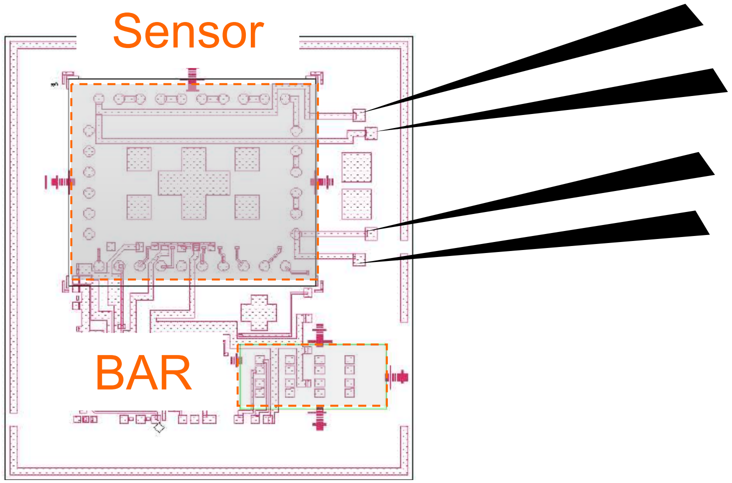
Au stud bump conduction and strength

- Electrical resistance : 0.10 Ω / bump

- Sensor devices (Epotek 353ND underfiller)
  - Shear strength 56 MPa after bonding
  - Increased to 57 MPa after thermal cycling (- 40°C to + 150°C)
  - Increased to 60 MPa after 30 min at 260°C
  - Fracture within the dies

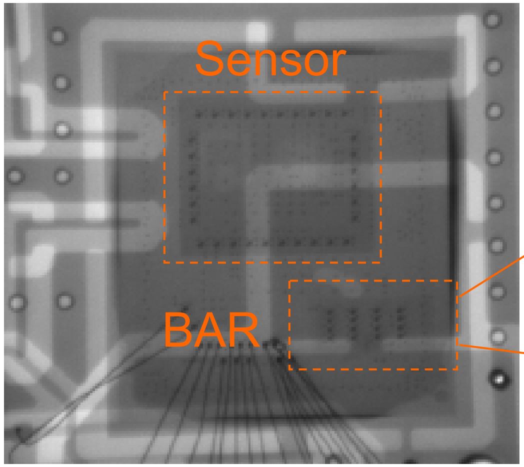
- BAR devices (bonded without underfiller) :
  - Shear strength 27.0 ± 2.3 MPa after bonding
  - Fracture through the bump or at interface with the Al pad

Quality inspection

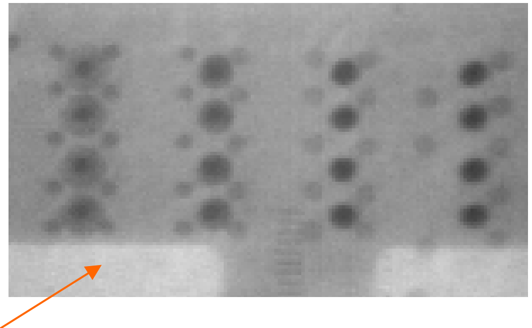


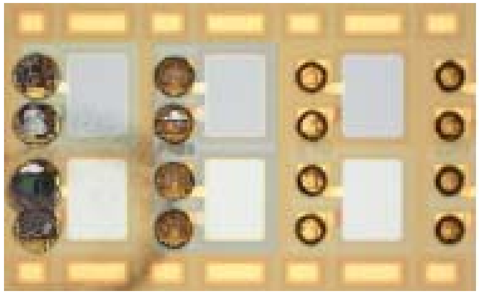
- Electrical tests of Daisy chains
  - Manual probing

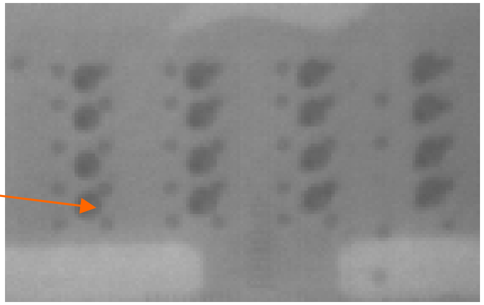
- X-ray inspection



Bad process (skew tooling) → Confirmed by shear tests

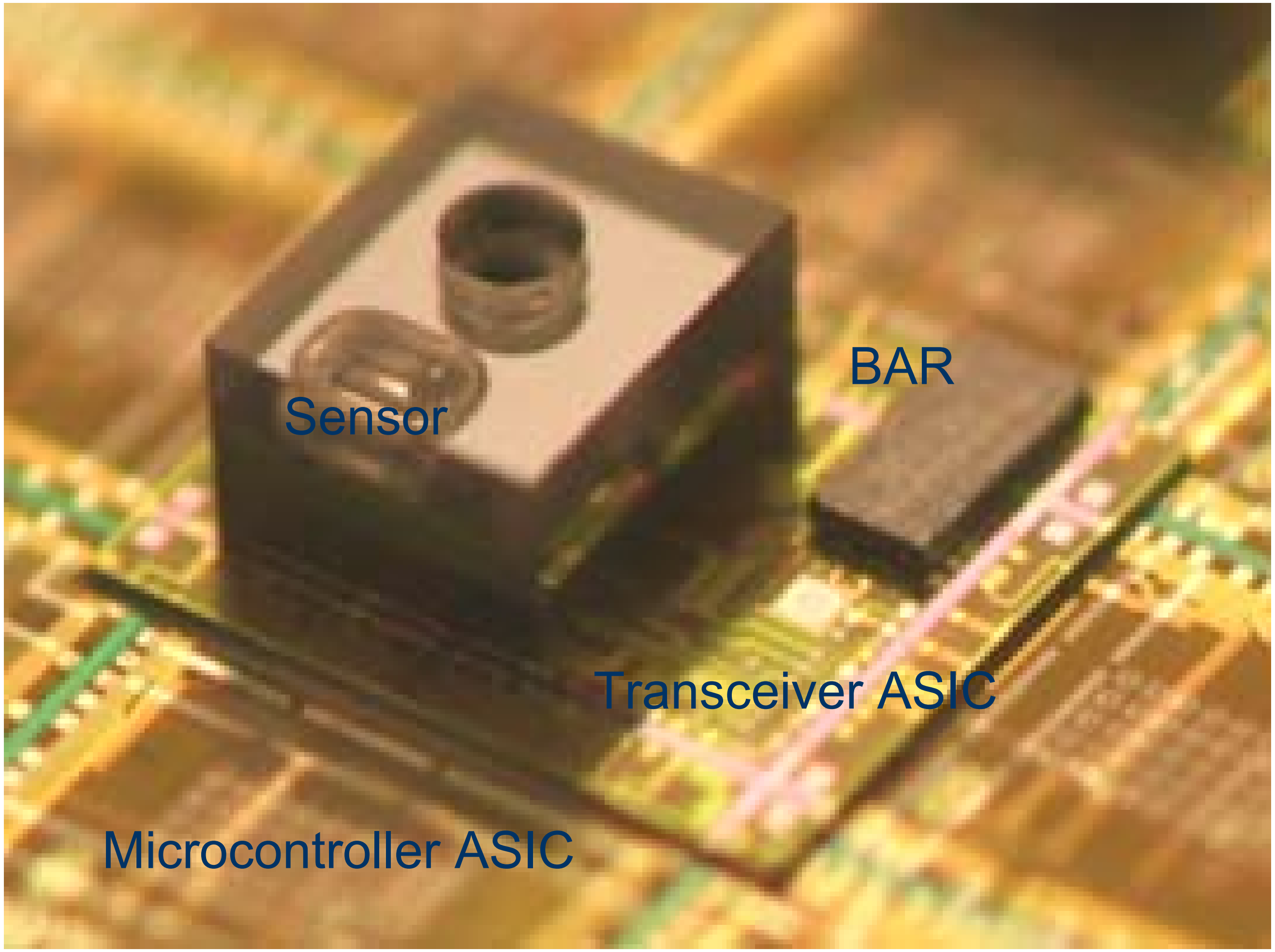






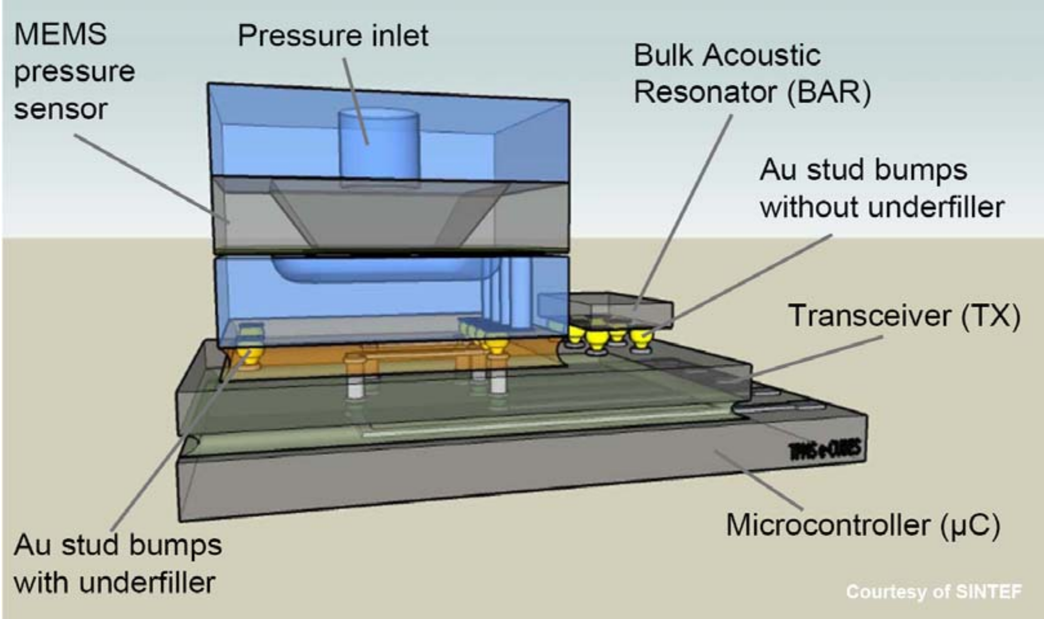
Good process (planar tooling)

Successfully bonded stack



Testing and results

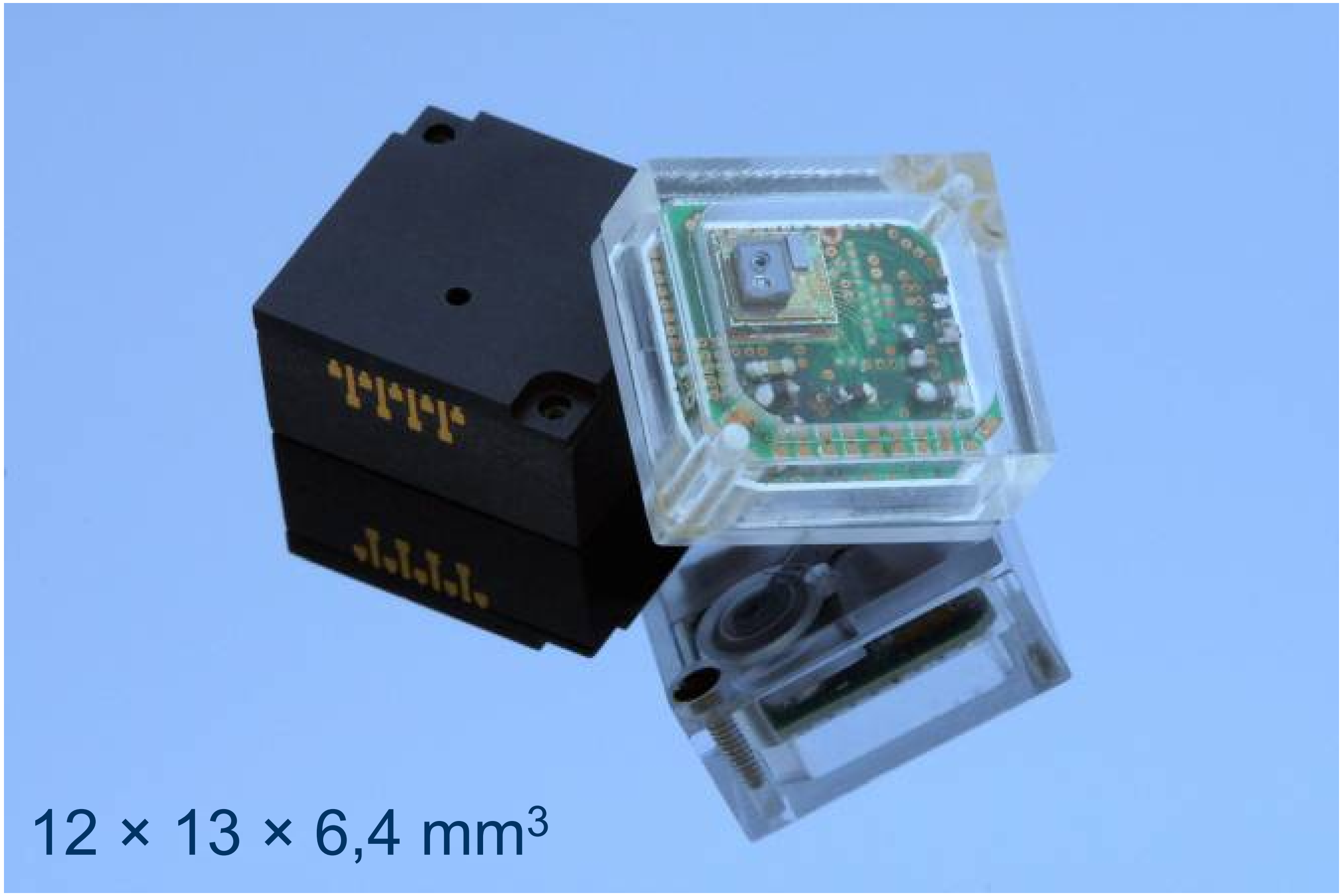
- Operation for 1 month, transmitting signals every 5 s
  - Communication with the TX is functional
  - Programming the µC is working
  - BAR is running at correct frequency



Courtesy of SINTEF

- To be verified: sensor communication

Finally packaged device: 0.998 cm^3



12 × 13 × 6,4 mm^3

infineon

Never stop thinking

Fraunhofer IZM

sensonor

SINTEF

Earlier presentations of the TPMS demo

- Taklo et al., “Technologies enabling 3D stacking of MEMS”, **IEEE workshop on 3D Sys-tem Integration**, München, Oct 01-02, 2007
- Taklo et al., “MEMS Sensor/IC Integration for Miniaturized TPMS (e-CUBES)”. Oral pres-entation at **SEMATECH meeting** “Manufacturing and reliability challenges for 3D ICs using TSVs”, San Diego, California, sep 25-26, 2008
- Taklo et al., “3D MEMS and IC Integration”, **MRS fall meeting** (Symposium E: Materials and Technologies for 3-D Integration), Boston-MA, des 01-05, 2008
- Lietaer, N., Taklo, M.M.V., Klumpp, A., Ramm, P., "3D Integration Technologies For Miniaturized Tire Pressure Monitor System (TPMS)", oral presentation at **IMAPS** 5th Inter-national Conference and Exhibition on Device packaging, Scottsdale, Arizona, 10-12 March 2009.
- Taklo et al., “3D stacked MEMS and ICs in a miniaturized sensor node”, **DTIP** 01-03 April, Rome, Italy, 2009
- K. Schjølberg-Henriksen, et al., "Miniaturised sensor node for tire pressure monitoring (e-CUBES)", in **Advanced Microsystems for Automotive Applications** - Smart systems for safety, sustainability, and comfort, edited by G. Meyer, J. Valldorf, W. Gessner, Springer, Berlin, pp. 313-332, Berlin, pp. 313-332, 5-6 May 2009

Summary and outlook

- Functional 3D integrated version of a miniaturized TPMS demonstrated
  - Several 3D integration technologies for MEMS emerge

- Further challenges for the real product
  - Reliability to be verified
  - Power demand
    - Energy harvester
  - Shape must better fit the inner liner of a tire

Acknowledgements

- Colleagues of the e-CUBES project
  - Supported by the European Commission under support-no. IST-026461 e-CUBES
- Vincent McTaggart, Kulicke and Soffa Industrial (KNS)
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- Gerhard Hillmann, Datacon Technology GmbH
  - For providing the chip to wafer bonding service and process development