ECSA-2, Nov. 15th-30th, 2015

2nd Electronic Conference on Sensors and Applications:

2nd International
Electronic Conference on
Sensors and Applications
15–30 November 2015

Dirk Lehmhus, Stefan Bosse

Material-integrated Intelligent Systems: A Review on SoA, Challenges and Trends.

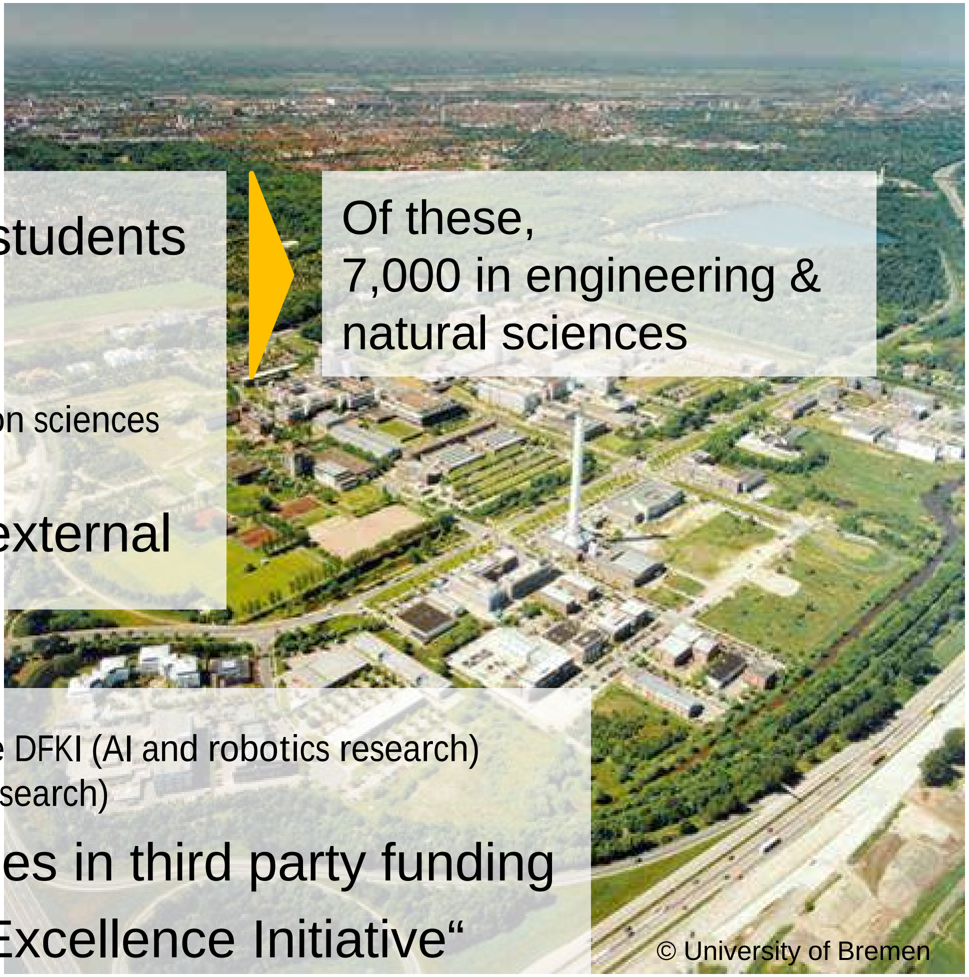
Overview

Material-integrated Systems: Spotlights.

- Introduction
  - The University of Bremen, MAPEX and ISIS
  - Sensorial Materials: Material-Integrated Intelligent Systems
- Challenges and Approaches towards Solutions
  - Focus mech./therm. Compatibility
  - Mechanical Stability against Production Processes
- Sensor Integration in Additive Manufacturing
- Conclusion, Outlook
- Announcements

Introduction

Bremen University.



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- mid-size University with 20,000 students

Of these,
7,000 in engineering &
natural sciences

- main research areas include
  - Materials and Production Technology
  - Information, cognition and communication sciences
  - Logistics
- close co-operation with several external institutes, such as
  - Fraunhofer IFAM, IWT, Fibre, BIAS (materials and production technology)
  - German Institute for Artificial Intelligence DFKI (AI and robotics research)
  - DLR Raumfahrtsystems (space systems research)
- one of the top German Universities in third party funding
- recently winner in the German „Excellence Initiative“
- endowed chairs supported by Airbus, Daimler, OHB-System, …

Introduction

Bremen University.

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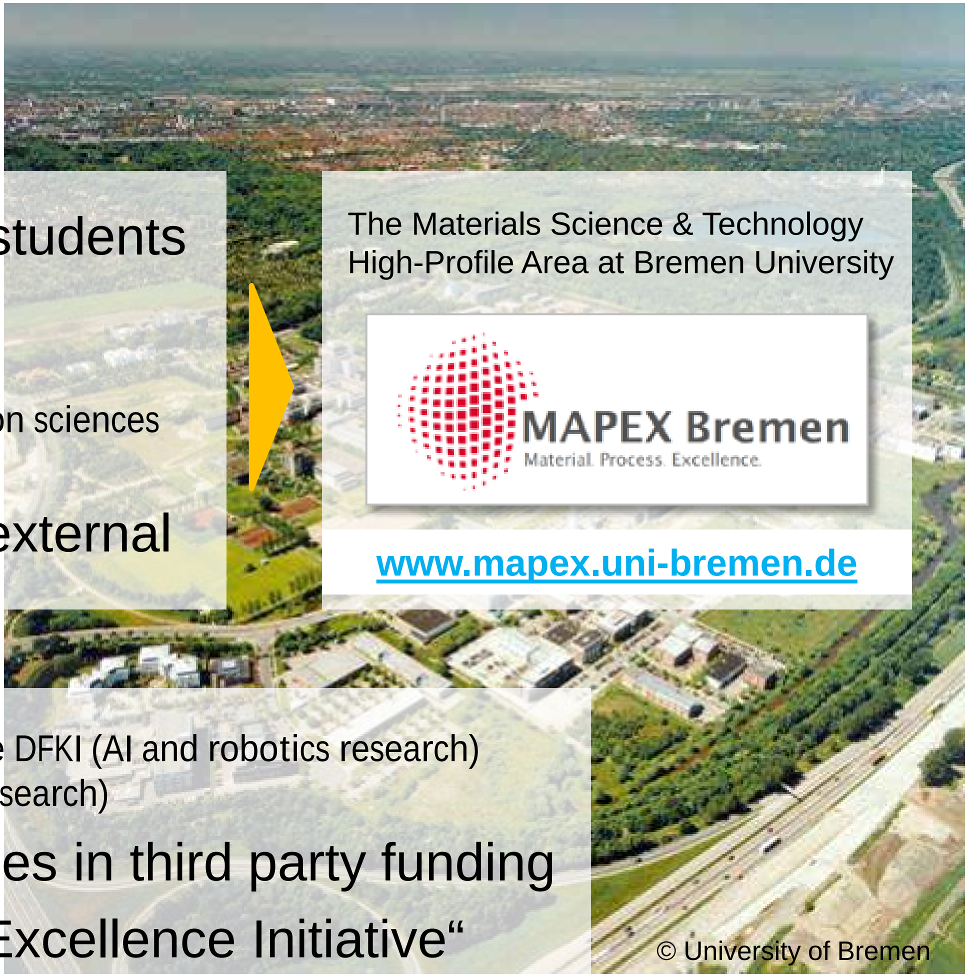

The Materials Science & Technology High-Profile Area at Bremen University

MAPEX Bremen
Material. Process. Excellence.

www.mapex.uni-bremen.de

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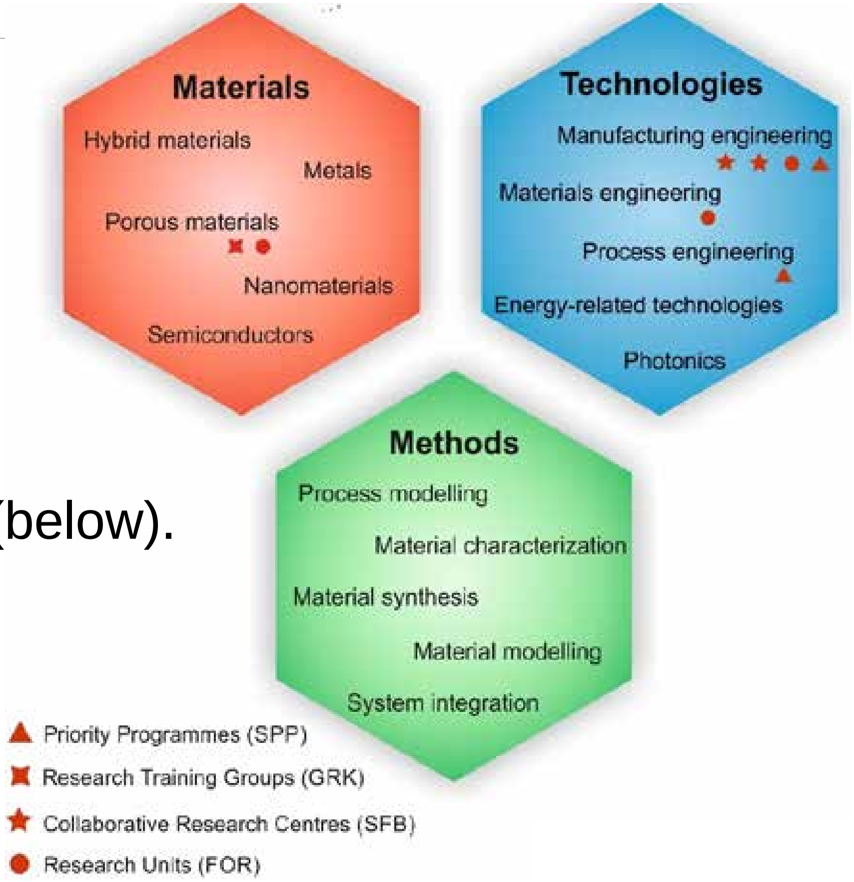
Introduction

MAPEX Topics.

MAPEX, its topics (right) and the University‘s other High-Profile Areas (below).

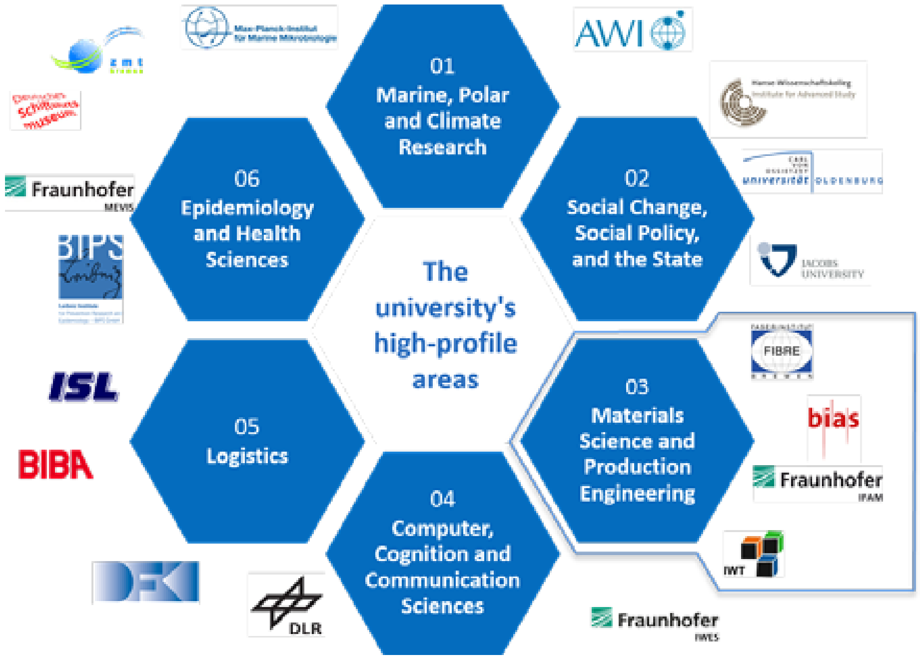


Materials
Hybrid materials
Metals
Porous materials ✖ ●
Nanomaterials
Semiconductors

Technologies
Manufacturing engineering ★ ★ ● ▲
Materials engineering ●
Process engineering ▲
Energy-related technologies
Photonics

Methods
Process modelling
Material characterization
Material synthesis
Material modelling
System integration

▲ Priority Programmes (SPP)
✖ Research Training Groups (GRK)
★ Collaborative Research Centres (SFB)
● Research Units (FOR)



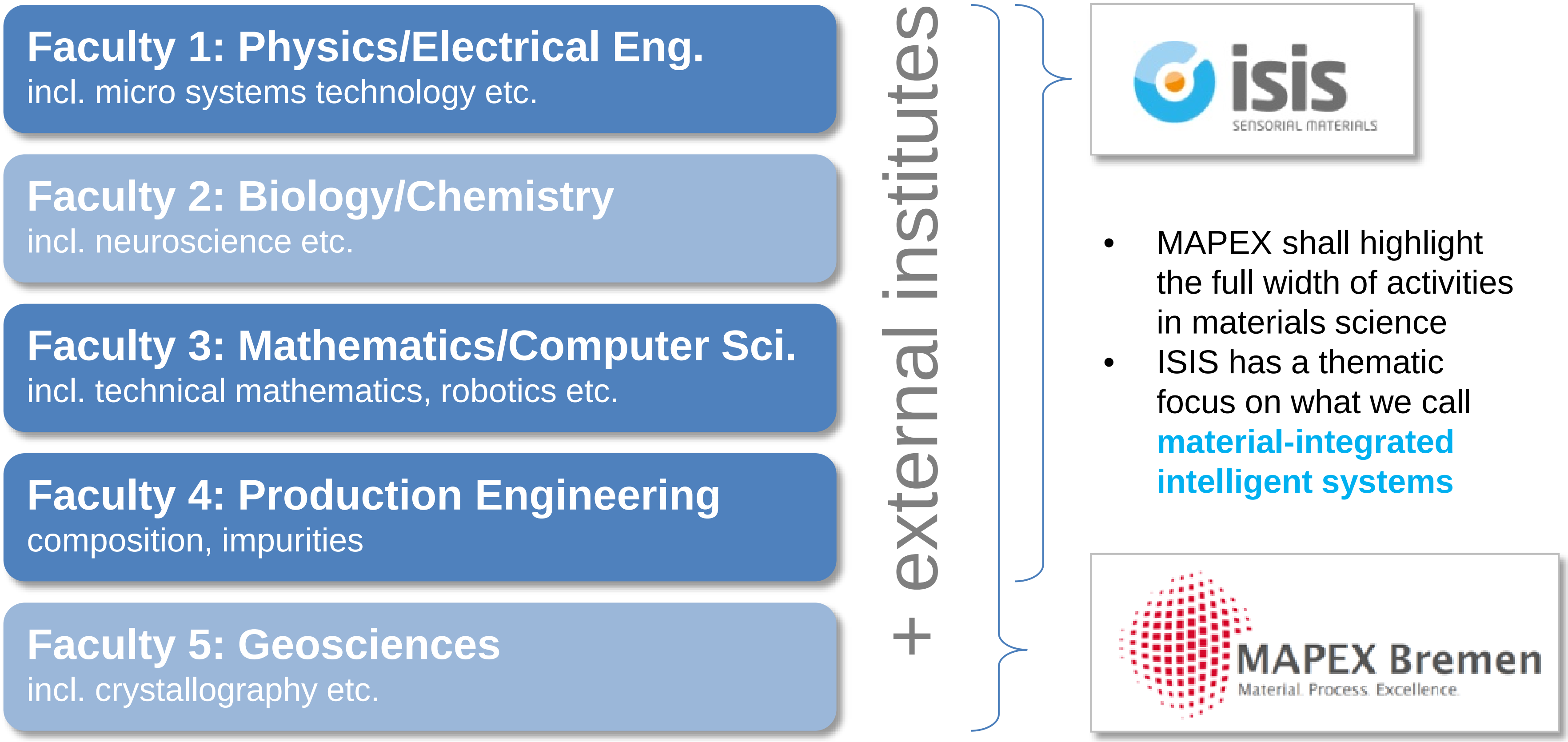
The university's high-profile areas

01 Marine, Polar and Climate Research
02 Social Change, Social Policy, and the State
03 Materials Science and Production Engineering
04 Computer, Cognition and Communication Sciences
05 Logistics
06 Epidemiology and Health Sciences

> *„MAPEX and ISIS are at home in almost the same faculties and maintain links to an almost identical set of external institutes - in the case of ISIS, BIBA (Logistics) is additionally involved.“*

Introduction

Bremen University: MAPEX, ISIS Faculties.



Faculty 1: Physics/Electrical Eng.
incl. micro systems technology etc.

Faculty 2: Biology/Chemistry
incl. neuroscience etc.

Faculty 3: Mathematics/Computer Sci.
incl. technical mathematics, robotics etc.

Faculty 4: Production Engineering
composition, impurities

Faculty 5: Geosciences
incl. crystallography etc.

+ external institutes

- MAPEX shall highlight the full width of activities in materials science
- ISIS has a thematic focus on what we call **material-integrated intelligent systems**

Introduction

ISIS Sensorial Materials Sci. Centre: Vision.

„Sensorial Materials gather data about their environment and/or their own state. They process these data locally and use the information derived internally, or communicate it to the external world.“

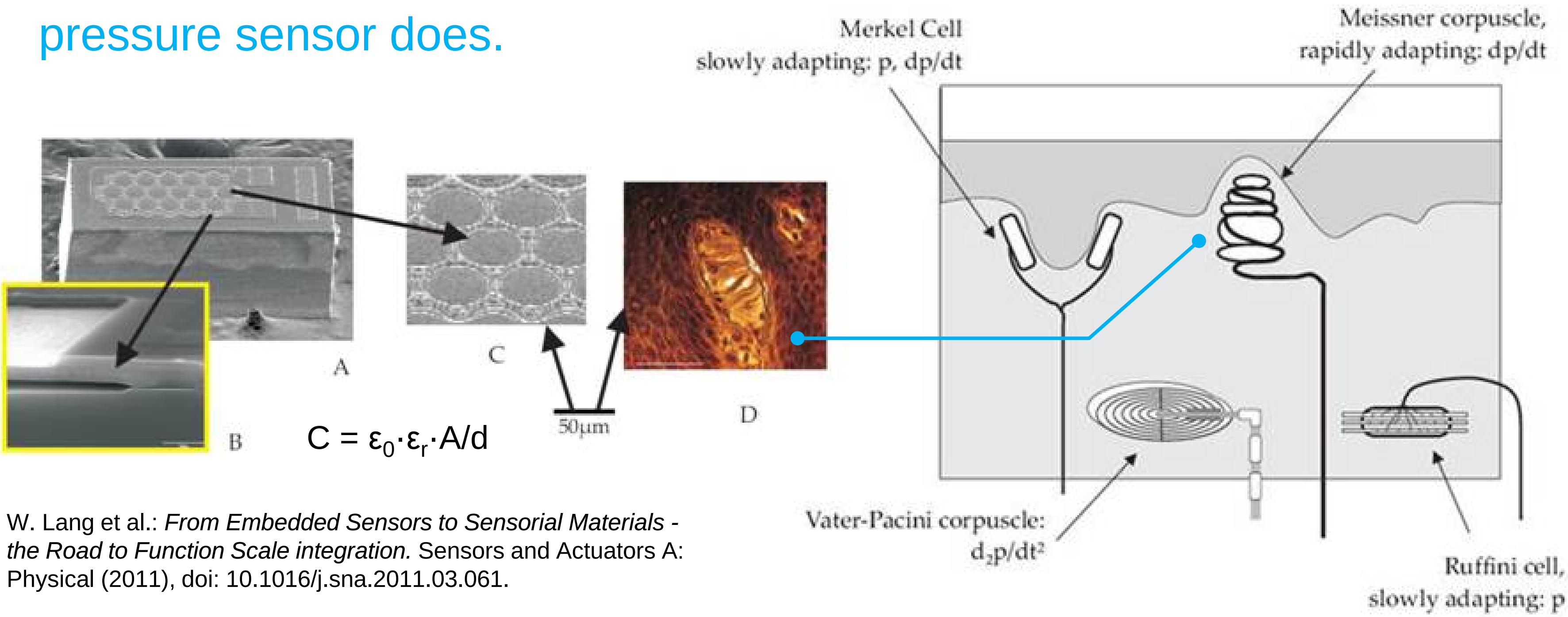
Introduction

Delimitation: An Example.

> *„Tactile sensing is more than just a pressure sensor – instead, it links several types of sensor signals and includes levels of distributed and centralized data evaluation.“*

Tactile sensing - more than merely sensors:

What the skin, and what a pressure sensor does.



$C = \varepsilon_0 \cdot \varepsilon_r \cdot A/d$

W. Lang et al.: *From Embedded Sensors to Sensorial Materials - the Road to Function Scale integration.* Sensors and Actuators A: Physical (2011), doi: 10.1016/j.sna.2011.03.061.

Introduction

Delimitation: Sensor vs. Sensorial Materials.

Sensor/transducer material

Provision of a transducer or conversion effect, i.e. the material reacts to an external, physical or chemical stimulus by showing an easily measurable, well defined response (property change or other).

Sensorial Material

The transducer material is a central part of the sensorial material, which however includes additional elements like signal processing, A/D-conversion, data processing and evaluation, energy supply, communication facilities etc.

- *Piezoresistivity: Change of el. resistivity as consequence of mechanical load.*
- *Piezoelectricity: Potential difference as consequence of mechanical load.*
- *Thermoelectricity: Potential difference as a consequence of temperature difference.*
- *Triboluminescence: Light emission as consequence of mechanical load.*
- *etc.*

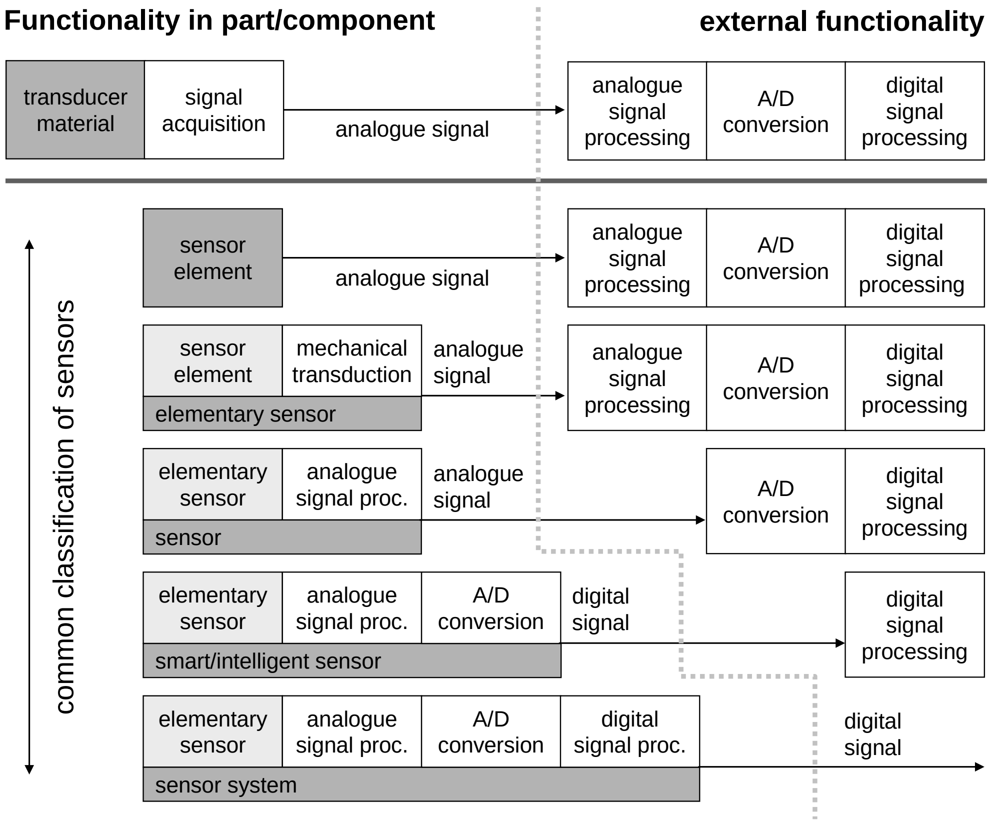
Introduction

Moving Functionality into the Material.

Moving from sensorized structure to material integration, we relocate functionality from the external world first to the surface, then into the volume of a host material.

> *„The drawing to the right describes the steps from a sensor to an integratable sensor node - as yet without data evaluation.“*

Adapted from Lee, S. H., 2010, Diploma thesis, Bremen Institute for Mechanical Engineering (BIME), Supervisor: Prof. K. Tacht.



Functionality in part/component

external functionality

transducer material | signal acquisition → analogue signal → analogue signal processing | A/D conversion | digital signal processing

sensor element → analogue signal → analogue signal processing | A/D conversion | digital signal processing

sensor element | mechanical transduction (elementary sensor) → analogue signal → analogue signal processing | A/D conversion | digital signal processing

elementary sensor | analogue signal proc. (sensor) → analogue signal → A/D conversion | digital signal processing

elementary sensor | analogue signal proc. | A/D conversion (smart/intelligent sensor) → digital signal → digital signal processing

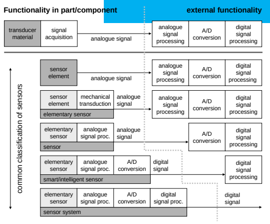
elementary sensor | analogue signal proc. | A/D conversion | digital signal proc. (sensor system) → digital signal

common classification of sensors

Introduction

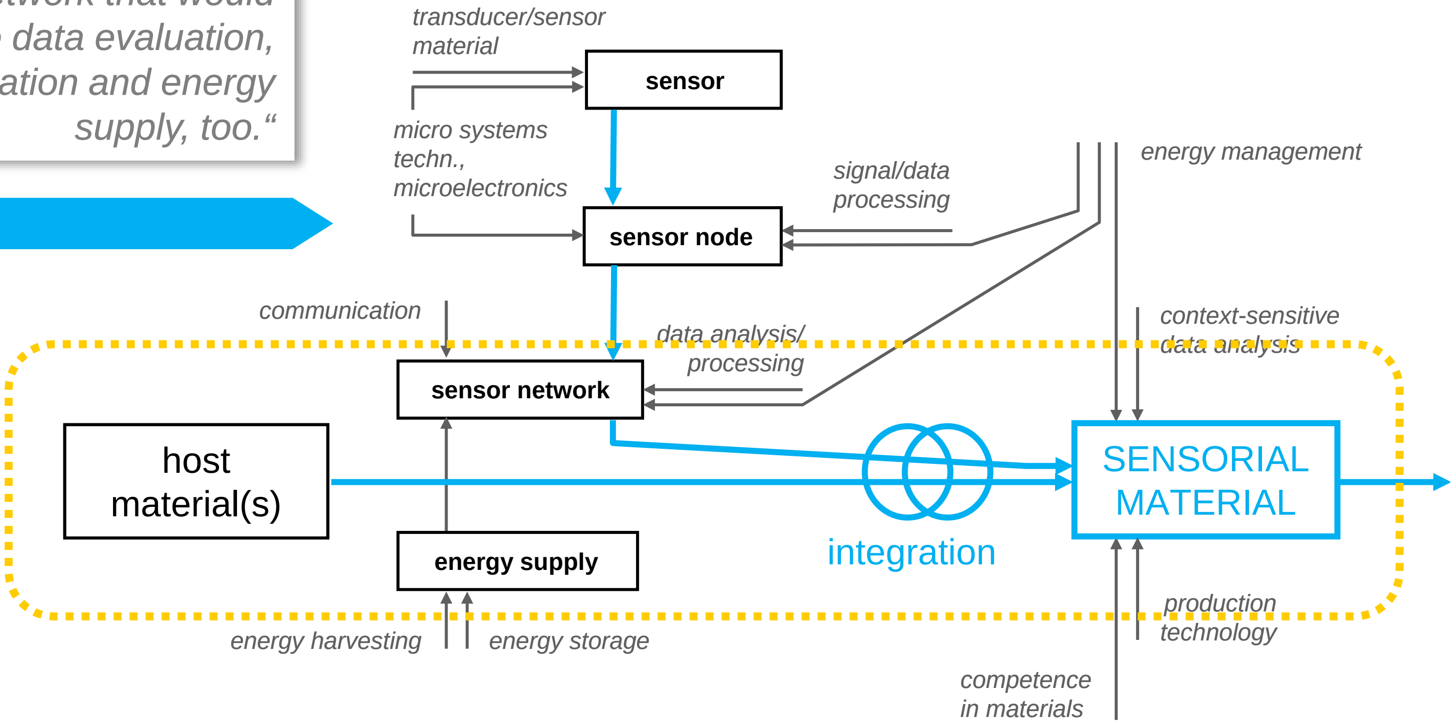
Moving Functionality into the Material.

> *„A Sensorial Material would comprise several such sensor nodes in a network that would provide data evaluation, communication and energy supply, too.“*



material integration

Adapted from D. Lehmhus et al.: *When nothing is constant but change: Adaptive and Sensorial Materials and their impact on product design*. J. Intelligent Mat.l Syst. and Struc. (2013), DOI: 10.1177/1045389X13502855.



Introduction

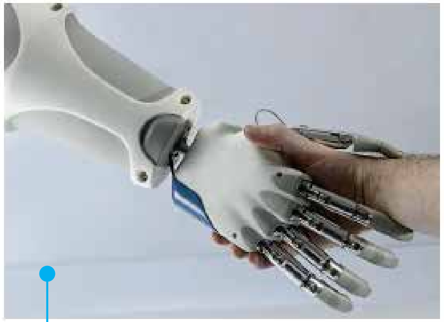
Sensorial Materials: Fields of Application.

Shape Change

autonomous
flight
(fly-by-feel)

Load-bearing Structures

Structural Health Monitoring/SHM
Health Management (MoD, predictive maintenance)



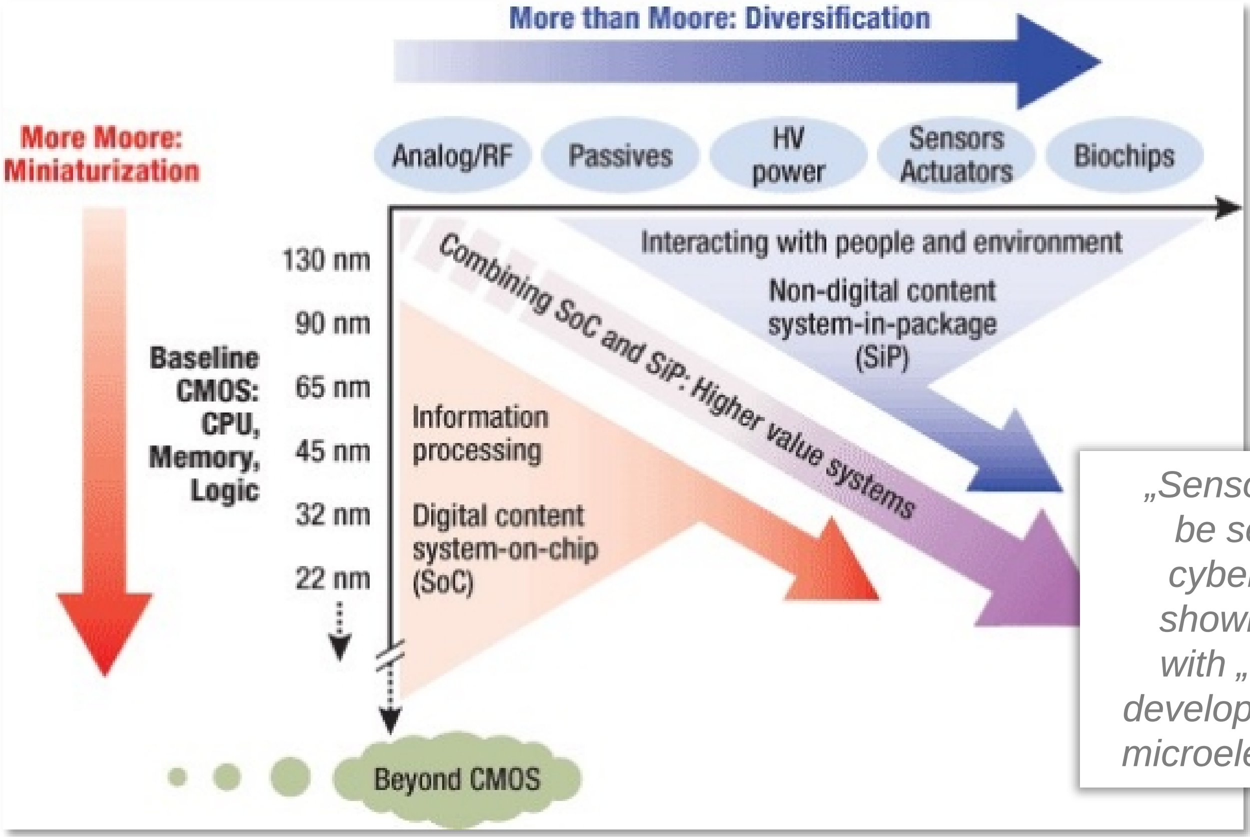
Tactile Sensing

safe/cooperative robotics
Human-Machine-Interaction
new user interfaces (tangible UI etc.)

Source: McEvoy. M. A., Correll, N. Materials that combine sensing, actuation, computation and communication. Science 347 (2015) 1261689-1 bis -8 .

Introduction

Cyber-Physical Systems (CPS)



Quelle: http://electroiq.com/blog/2011/01/itrs-2010__a_more-than-moore/

„Sensorial Materials can be seen as a form of a cyber-physical system, showing commonalities with „More than Moore“ development directions in microelectronics & MST.“

Challenges

Areas of Research.

- energy supply
- stability against production processes
- data evaluation
- simulation, design & testing
- system-/host-compatibility

Challenges

Areas of Research.

energy supply

stability against production processes

data evaluation

simulation, design & testing

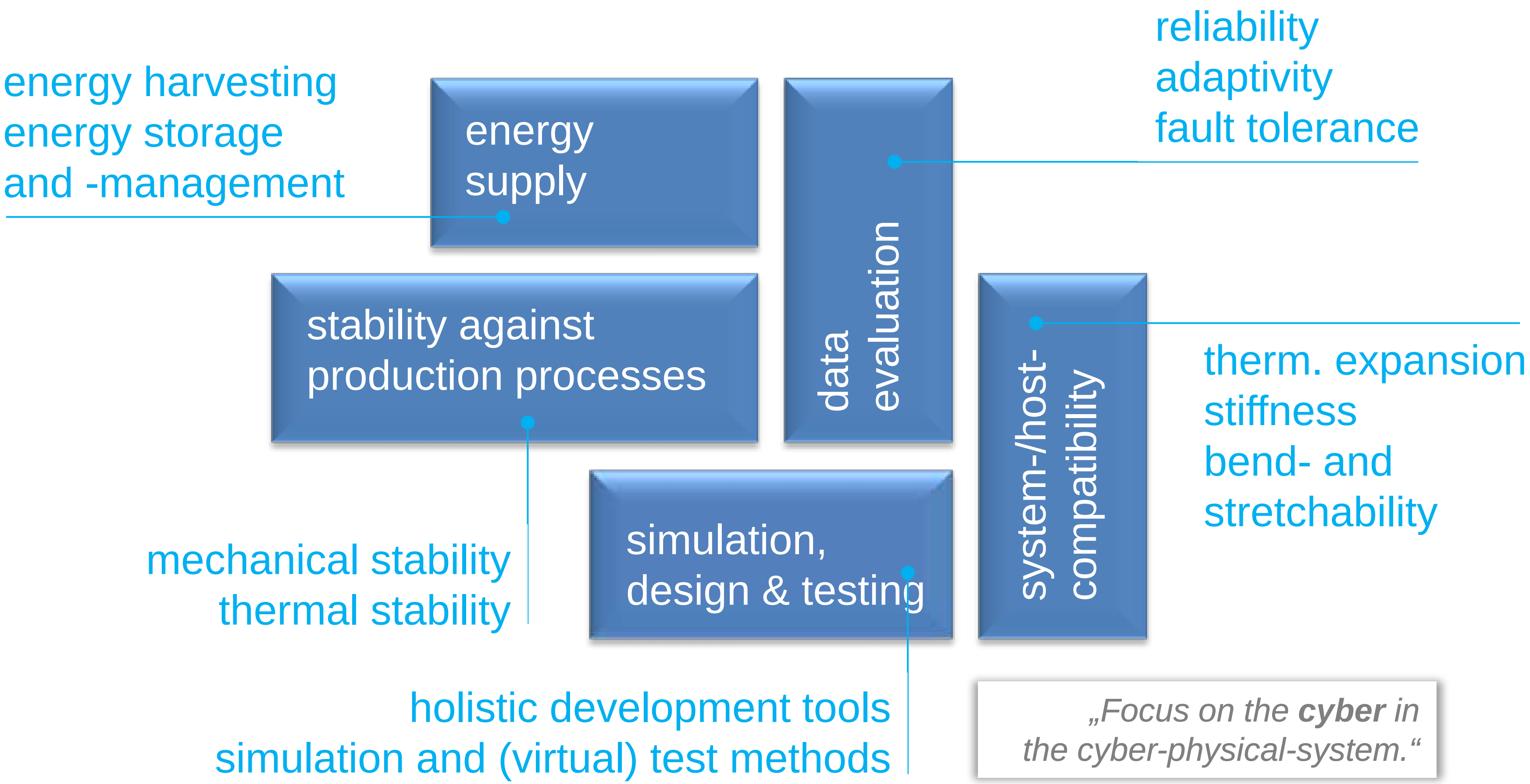
system-/host-compatibility

In addition, for all aspects:

Transferability to
(large scale-) series prioduction - **Economic Viability.**

Challenges

Areas of Research: Our Focus.



energy harvesting
energy storage
and -management

energy supply

data evaluation

reliability
adaptivity
fault tolerance

stability against production processes

system-/host-compatibility

therm. expansion
stiffness
bend- and
stretchability

mechanical stability
thermal stability

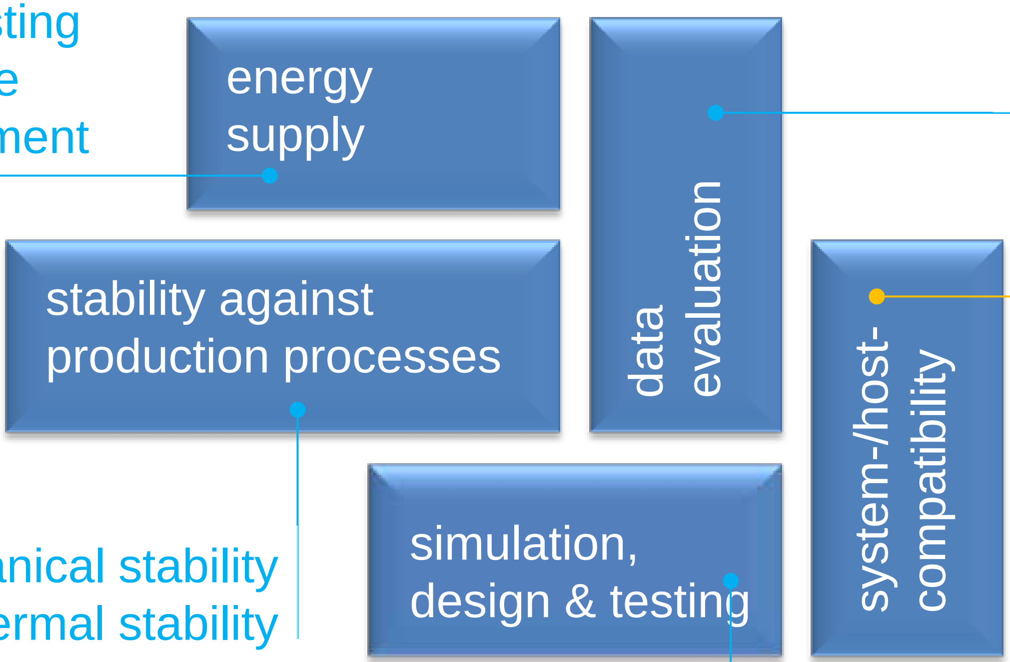
simulation, design & testing

holistic development tools
simulation and (virtual) test methods

*„Focus on the **cyber** in the cyber-physical-system.“*

Challenges

Areas of Research: Our Focus.



energy harvesting
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therm. expansion
stiffness
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simulation, design & testing

holistic development tools
simulation and (virtual) test methods

> *„Focus on the **physical** in the cyber-physical-system."*

Challenges

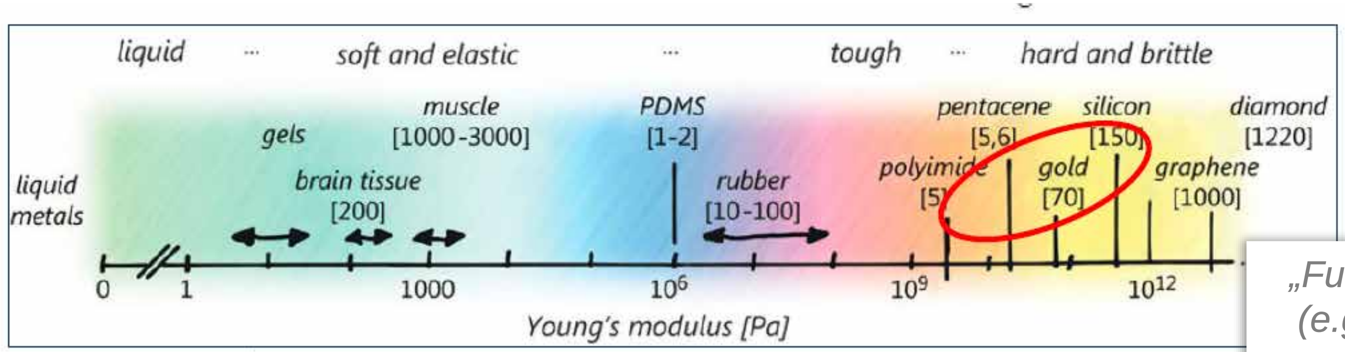
The many Hardships of Bulk Integration.

- Mechanical stability
  to sustain mechanical loads during production & service life
- Thermal stability
  to sustain thermal loads during production & service life
- Compliance
  - Mechanical compliance
    matching of stiffness, yield etc., flexibility, stretchability, interface, internal kerfs, …
  - Thermal compliance
    matching of CTE, *maintenance of functionality under thermal influences* …
  - Chemical and other compliance issues
    reaction to environmental influences like humidity, special chemical environments etc.
- Other/combined effects
  residual stresses induced in manufacturing, superimposed thermal stresses in service, energy, data evaluation, …

major issue
during manufacturing
of materials/structures
incorporating sensor
systems

Challenges

Diversity in Materials, and Properties.



Source: www.ats.net

> *„Functional and structural (e.g. substrate) materials used in MST differ greatly both in their thermal and mechanical properties.“*

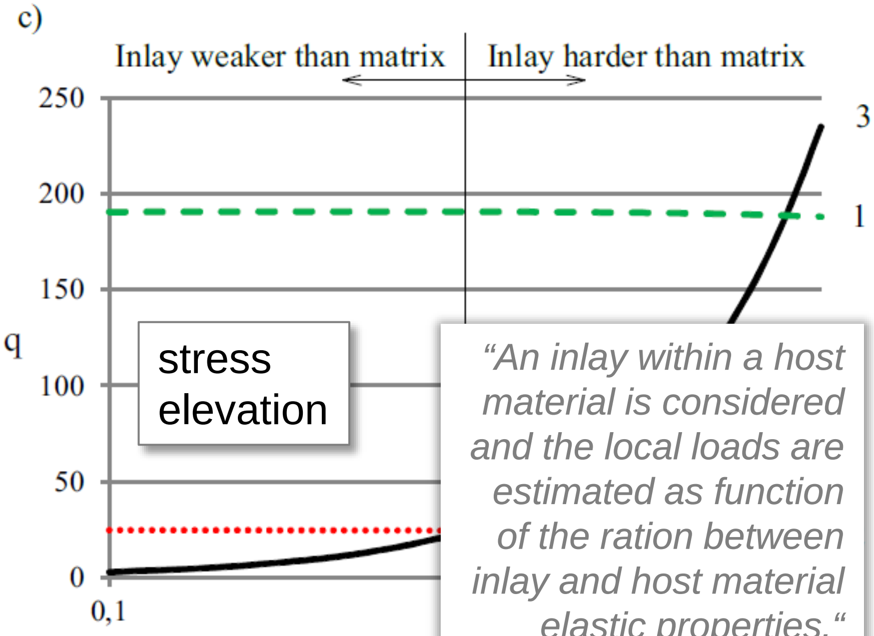
Problem: Materials with good stretchability show low thermal conductivity and vice versa.

- microchips are made of silicon - E approx. 150 GPa
- passives like capacitors, resistors are often made from ceramics – titanates, niobates with E approx. 75 GPa
- conductive paths are made from Cu (E = 120 GPa) or Au (E = 70 GPa)
- soldered connections are made from Cu, Ag or Sn alloys - E approx. 30-50 GPa
- polymeric substrates - E approx. 1 - 1000 MPa

Mechanical Compatibility.

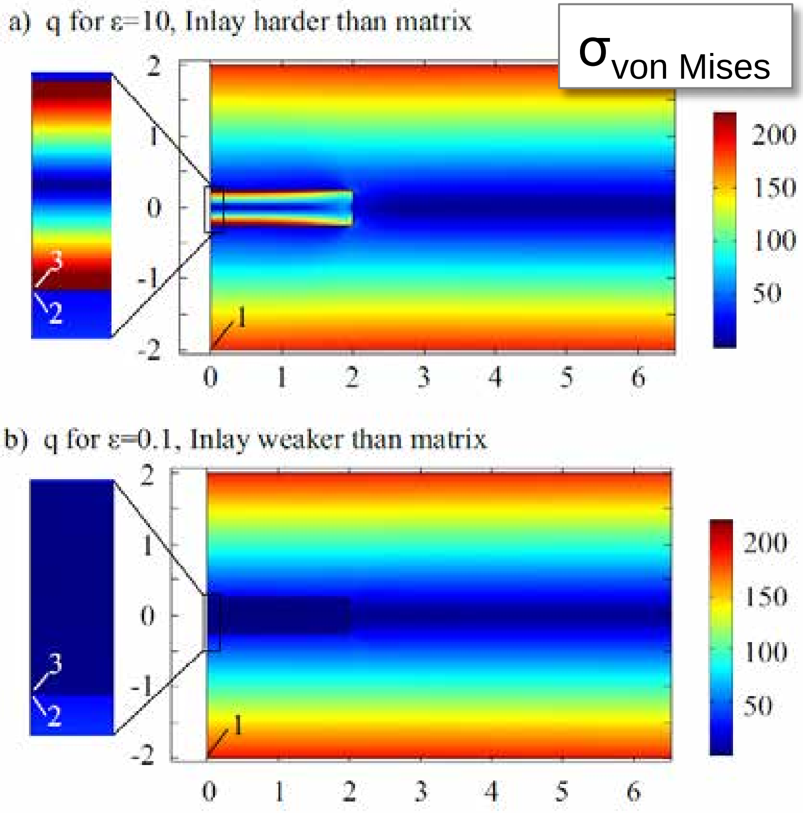
Stiffness mismatch and local loads.

Bending load I



stress elevation

“An inlay within a host material is considered and the local loads are estimated as function of the ration between inlay and host material elastic properties.“



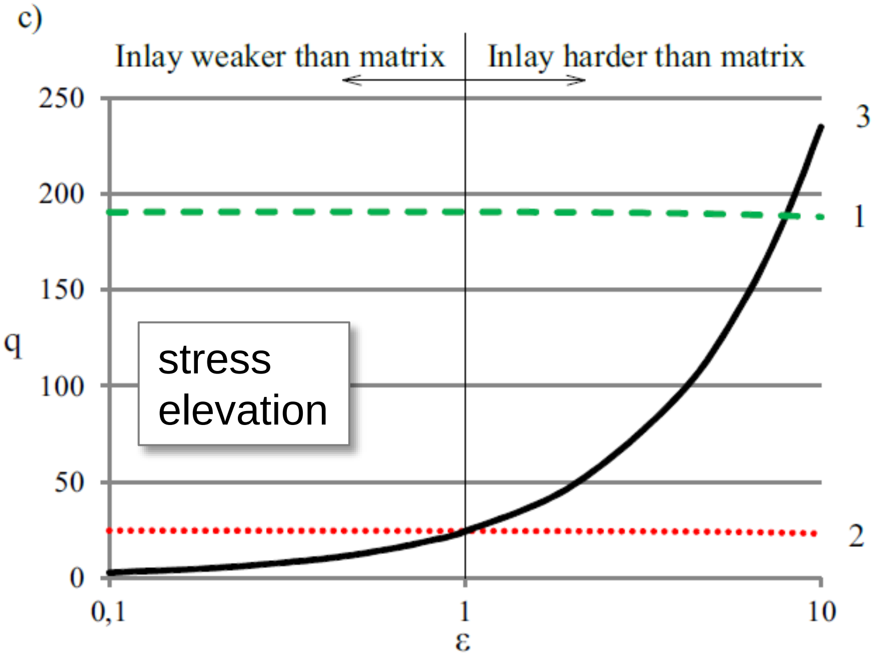
$\sigma_{von\ Mises}$

G. Dumstorff et al.: *Integration without disruption: The basic challenge of sensor integration*. IEEE Sensors Journal 14 (2014) 2102-2111.

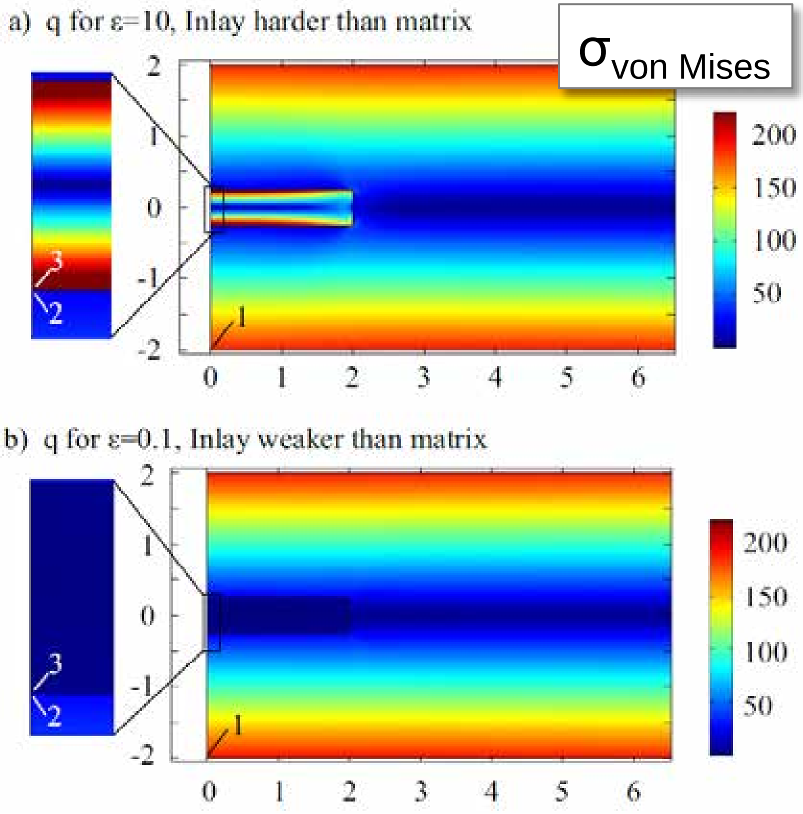
Mechanical Compatibility.

Stiffness mismatch and local loads.

Bending load I



stress elevation


a) q for ε=10, Inlay harder than matrix

$\sigma_{\text{von Mises}}$

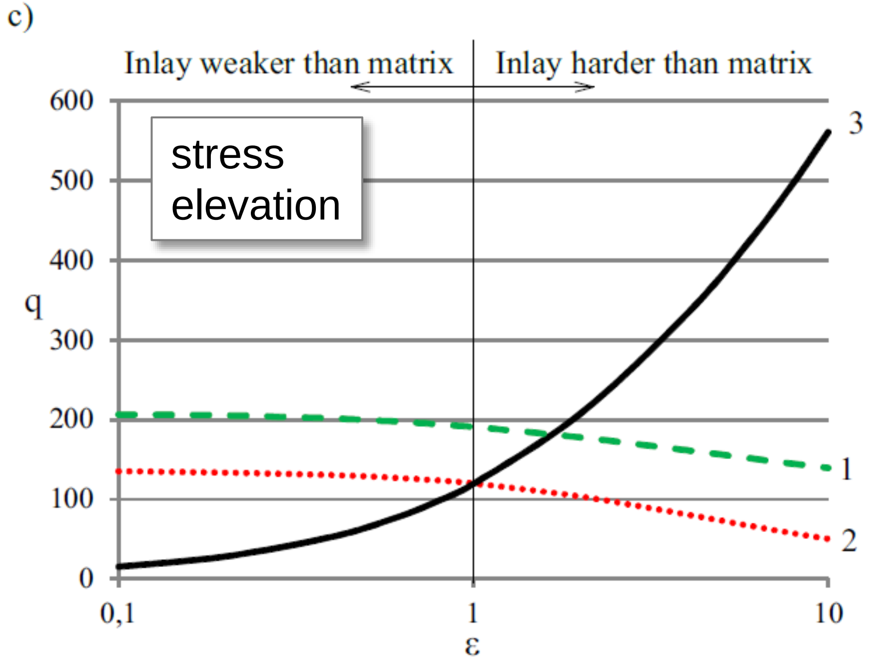
b) q for ε=0.1, Inlay weaker than matrix

G. Dumstorff et al.: *Integration without disruption: The basic challenge of sensor integration*. IEEE Sensors Journal 14 (2014) 2102-2111.

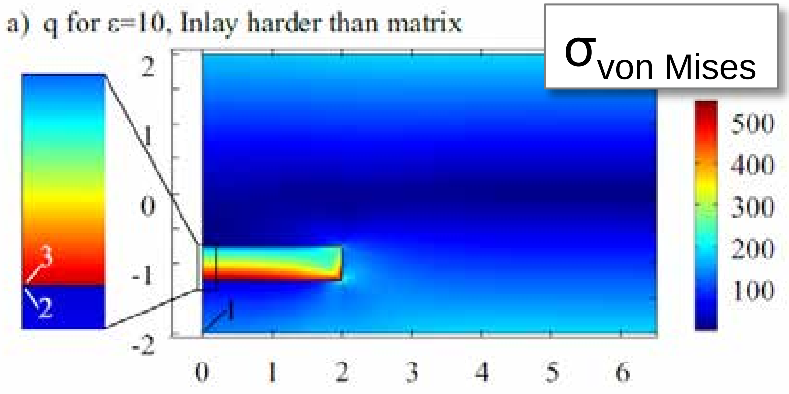
Mechanical Compatibility.

Stiffness mismatch and local loads.

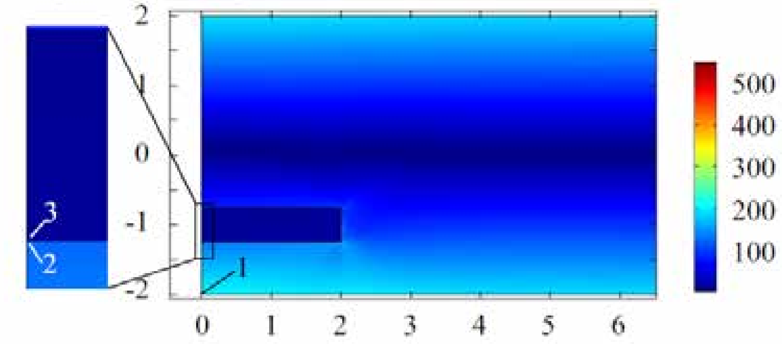
Bending load II



a) q for ε=10, Inlay harder than matrix



b) q for ε=0.1, Inlay weaker than matrix

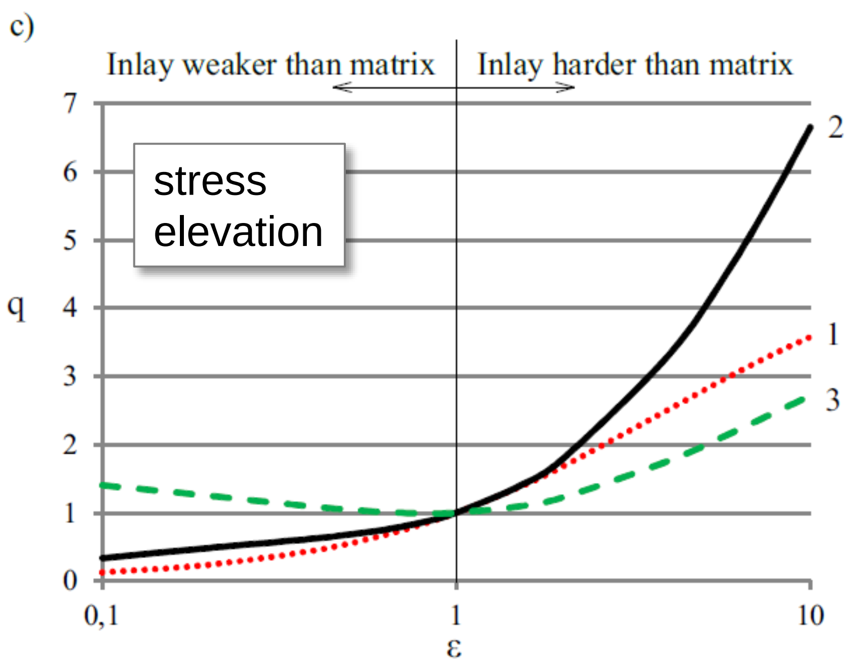


G. Dumstorff et al.: *Integration without disruption: The basic challenge of sensor integration*. IEEE Sensors Journal 14 (2014) 2102-2111.

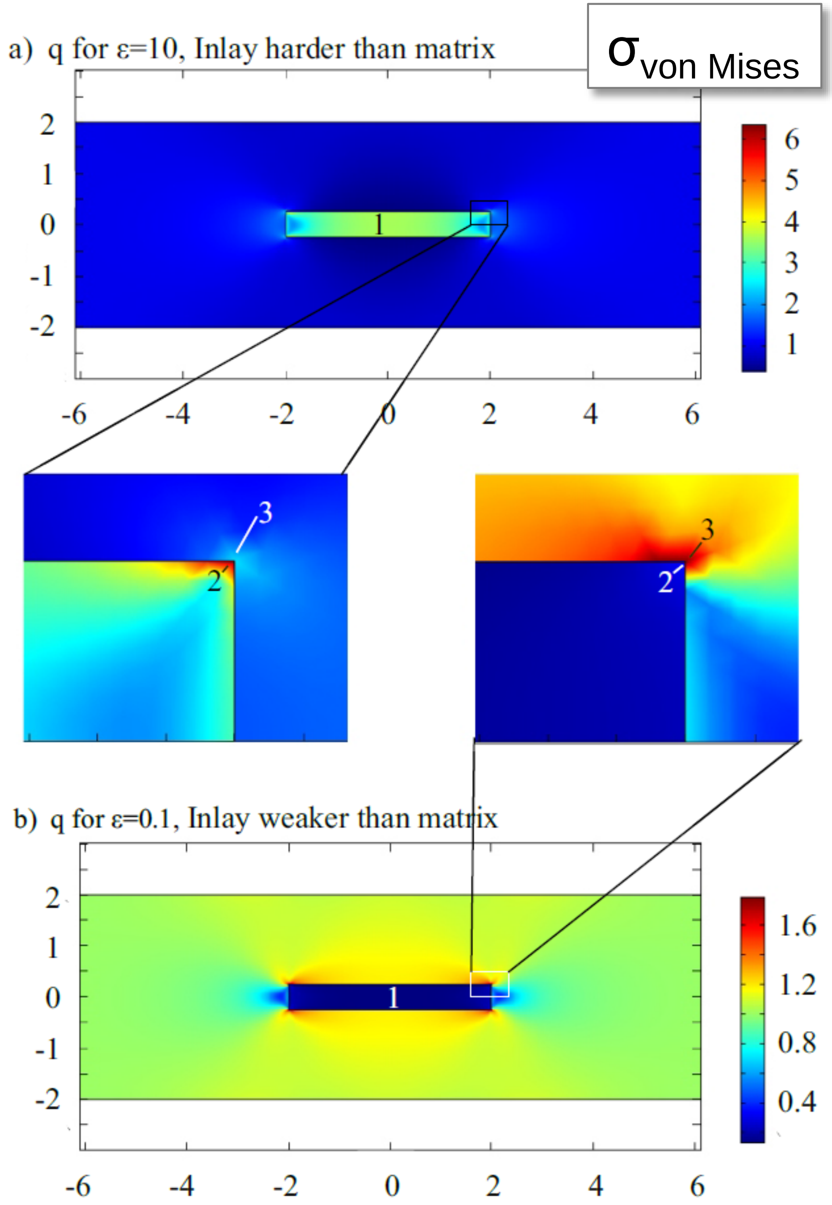
Mech. Compatibility.

Local loads.

Tensile load.



stress elevation



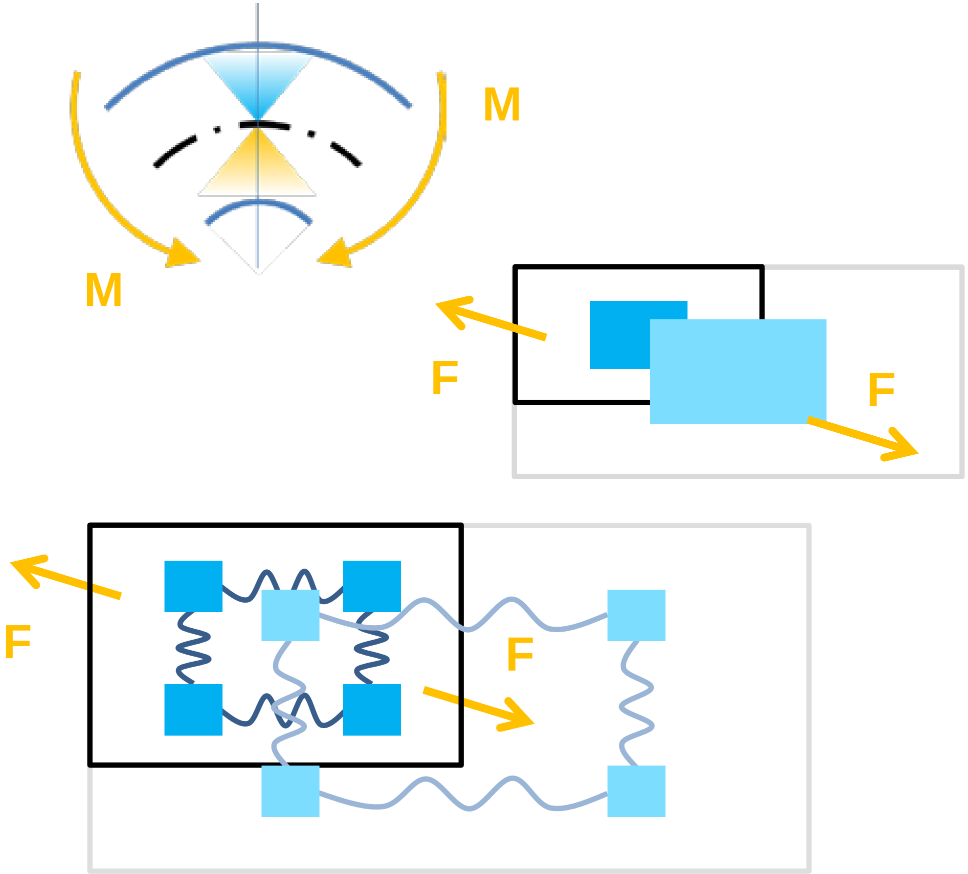
$\sigma_{\text{von Mises}}$

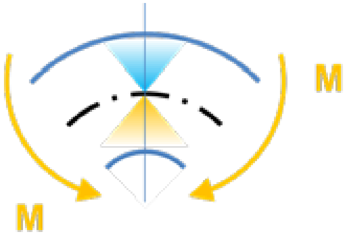
G. Dumstorff et al.: *Integration without disruption: The basic challenge of sensor integration*. IEEE Sensors Journal 14 (2014) 2102-2111.

Mechanical Compatibility.

Some Basic Principles.

- „neutral plane engineering“
- Bendable and stretchable components via material selection:
  → *organic electronics*
- stretachble interconnects between conventional and/ or bendable components, with the latter as rigid „Islands“ within the material



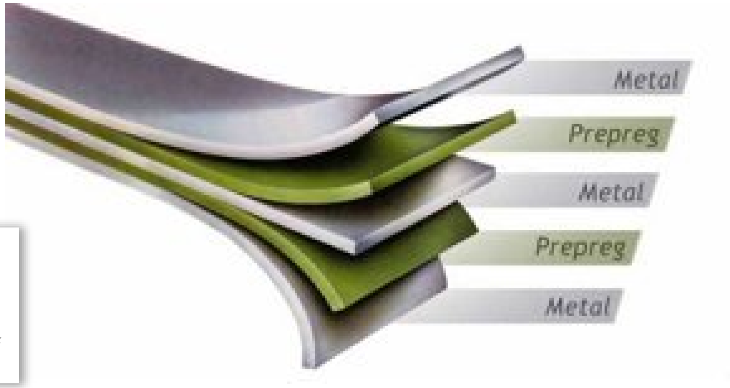


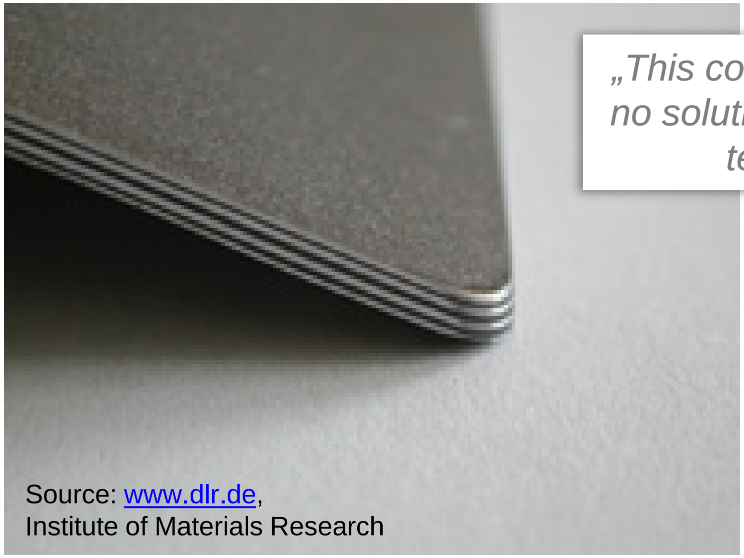
Mechanical Compatibility.

Bending load: Use of neutral fibre/plane.

Locating functionality in the neutral plane to account for in-plane bending stresses:

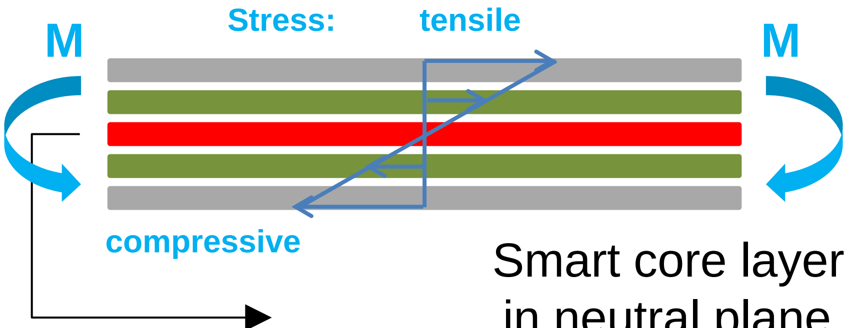
Source: www.utwente.nl



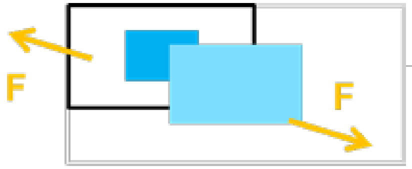


„This concept provides no solution for in-plane tensile loading.“

Source: www.dlr.de, Institute of Materials Research



Smart core layer in neutral plane.

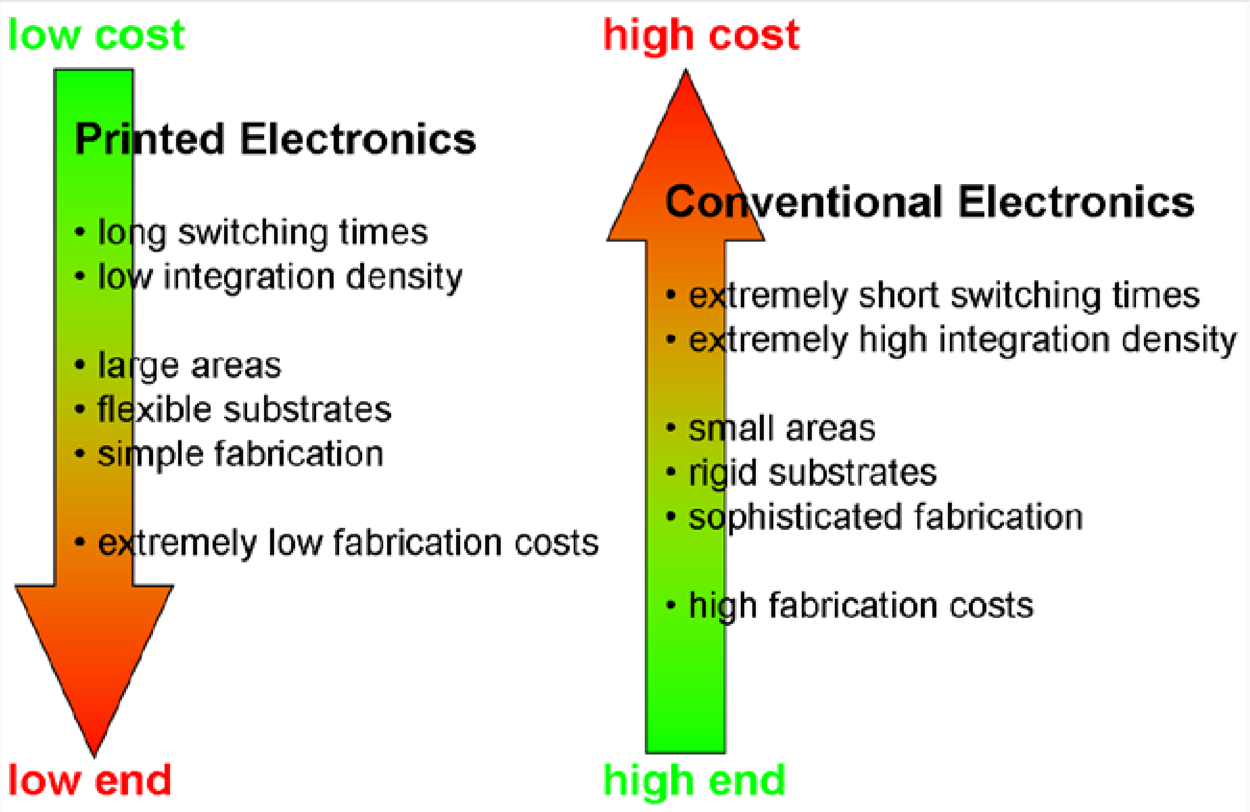


Mechanical Compatibility.

„Plastic Logic“: Organic/Printed Electronics.

„Cost“ of the better match in mechanical properties:

Still a niche for printed elektronics available?



low cost

Printed Electronics

- long switching times
- low integration density

- large areas
- flexible substrates
- simple fabrication

- extremely low fabrication costs

low end

high cost

Conventional Electronics

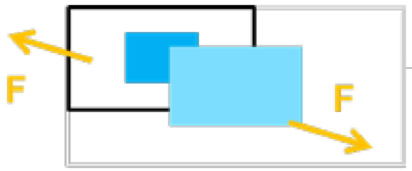
- extremely short switching times
- extremely high integration density

- small areas
- rigid substrates
- sophisticated fabrication

- high fabrication costs

high end

Quelle:
www.wikipedia.org,
„Complementary Technologies“
Heiko Kempa, Institute of
Print and Media Technologies,
TU Chemnitz



Mechanical Compatibility.

„Plastic Logic“: Organic/Printed Electronics.

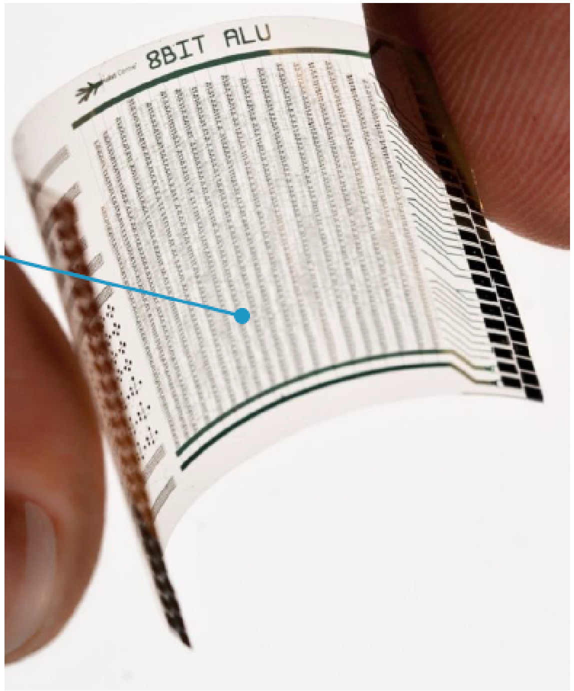
Organic electronics solutions for a low cost, bendable and within limits stretchable system.

Holst Centre

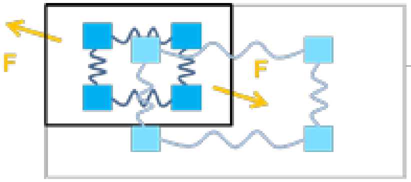
Open Innovation by IMEC and TNO

Plastic microprocessor

- **Unipolar p-type pentacene only logic**
- **Dual-gate technology**
- **4,000 transistors**
- **Thickness 25 µm**



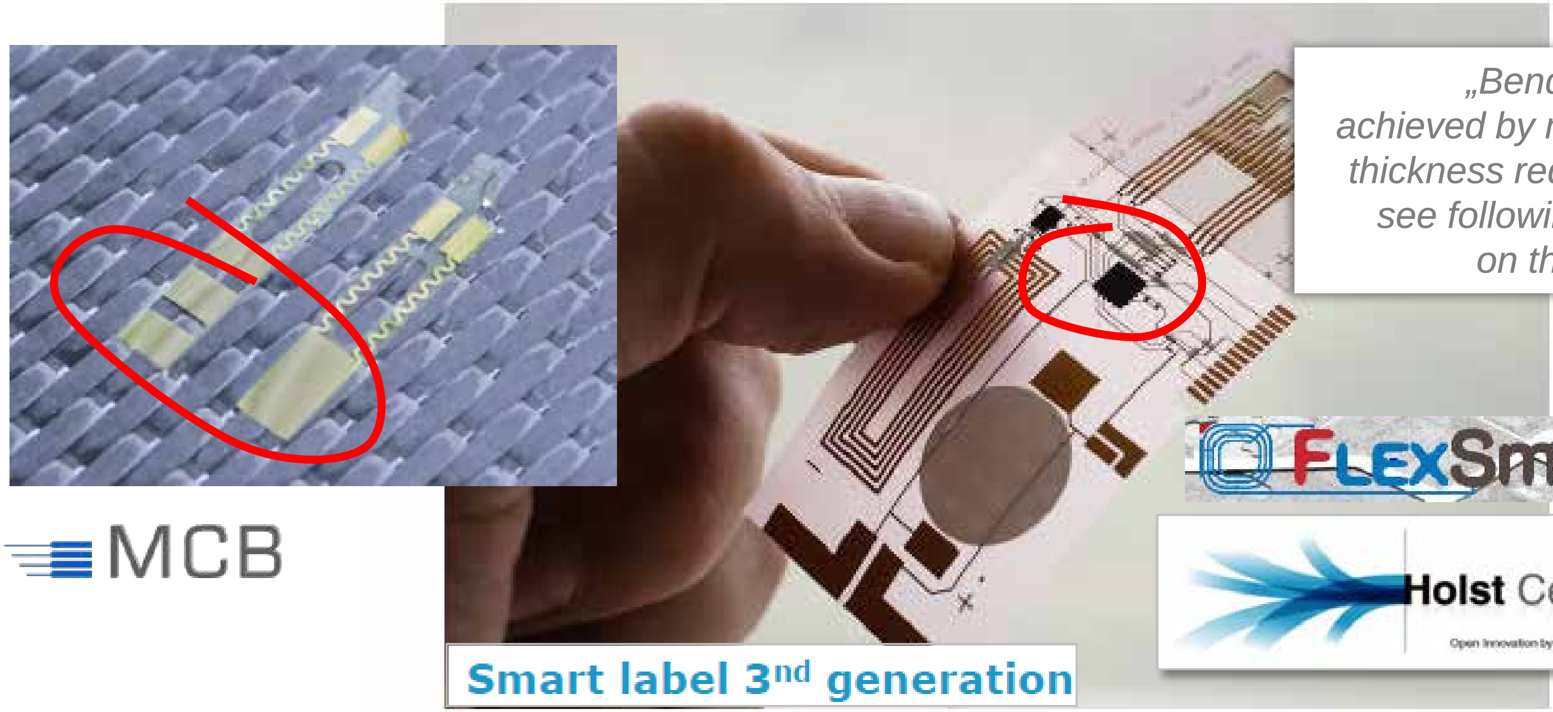
"It has the processing power of a 1970s silicon chip and executes commands at about 6 instructions/sec, but it is flexible. Allowing uses in flexible displays, or as sensors wrapped around food, pharmaceuticals or as intelligent sensors."



Mechanical Compatibility.

Rigid Islands in a stretchable world.

Red lines denote specific islands of this kind, i. e. a Si-based microchip (right):



MCB

„Bendability is achieved by means of thickness reduction – see following slides on this topic.“

FlexSmell

Holst Centre

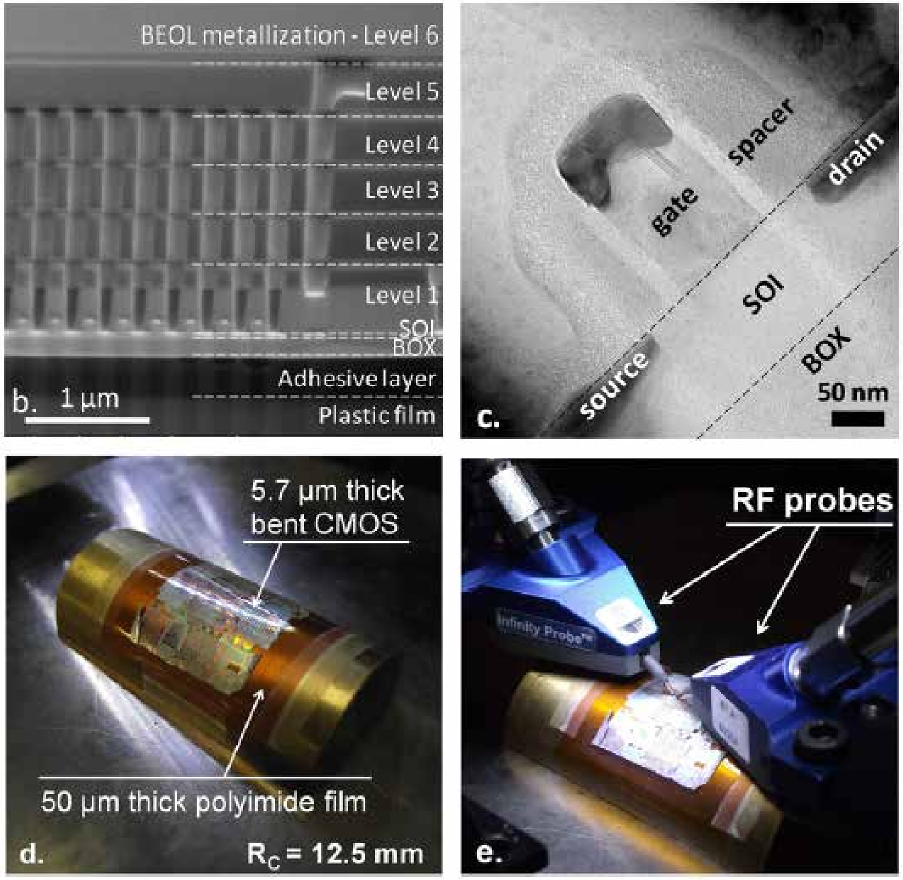
Open Innovation by IMEC and TNO

Smart label 3rd generation

Mech. Compatibility: Individual Solutions.

Ultimate Thinning & Transfer Bonding (UTTB)

Production of bendable electronic components by combined grinding and etching processes in order to reduce µC thickness to the functionally necessary.



<u>Related concept:</u>

UTCP = Ultra-Thin Chip Packaging

A. Lecavelliers des Etangs-Lavellois et al.:
A converging route towards very high frequency, mechanically flexible, and performance stable integrated electronics.
Journal of Applied Physics 113 (2013) ID 153701

Mech. Compatibility: Individual Solutions.

Ultimate Thinning & Transfer Bonding (UTTB)

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<u>Related concept:</u>

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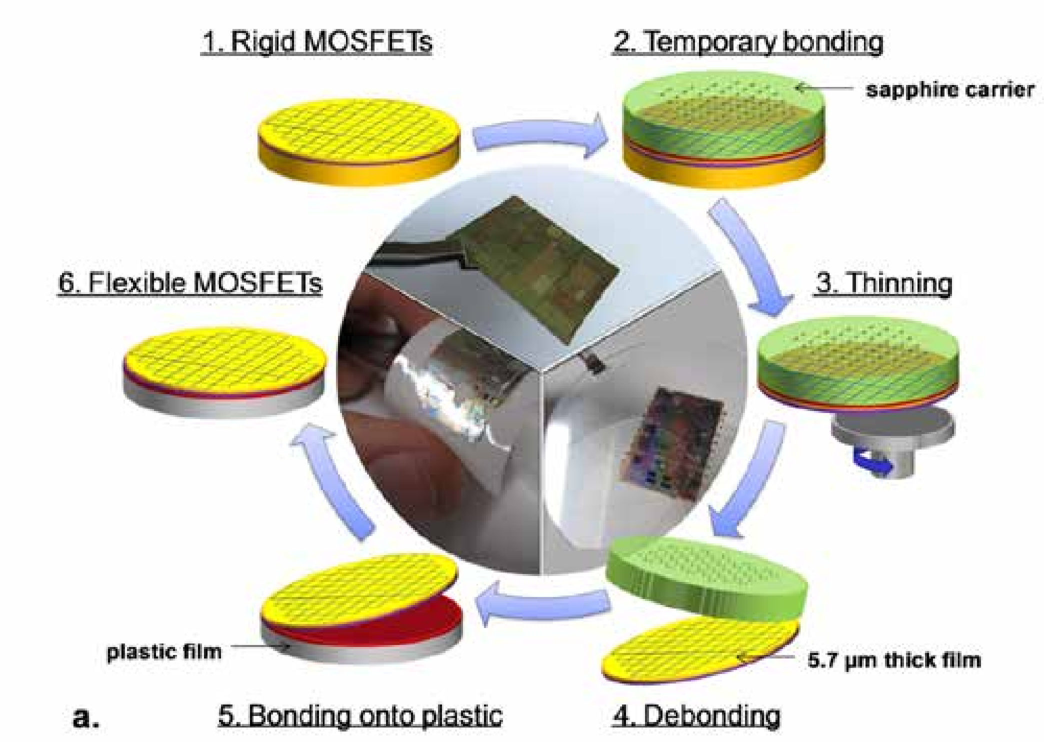


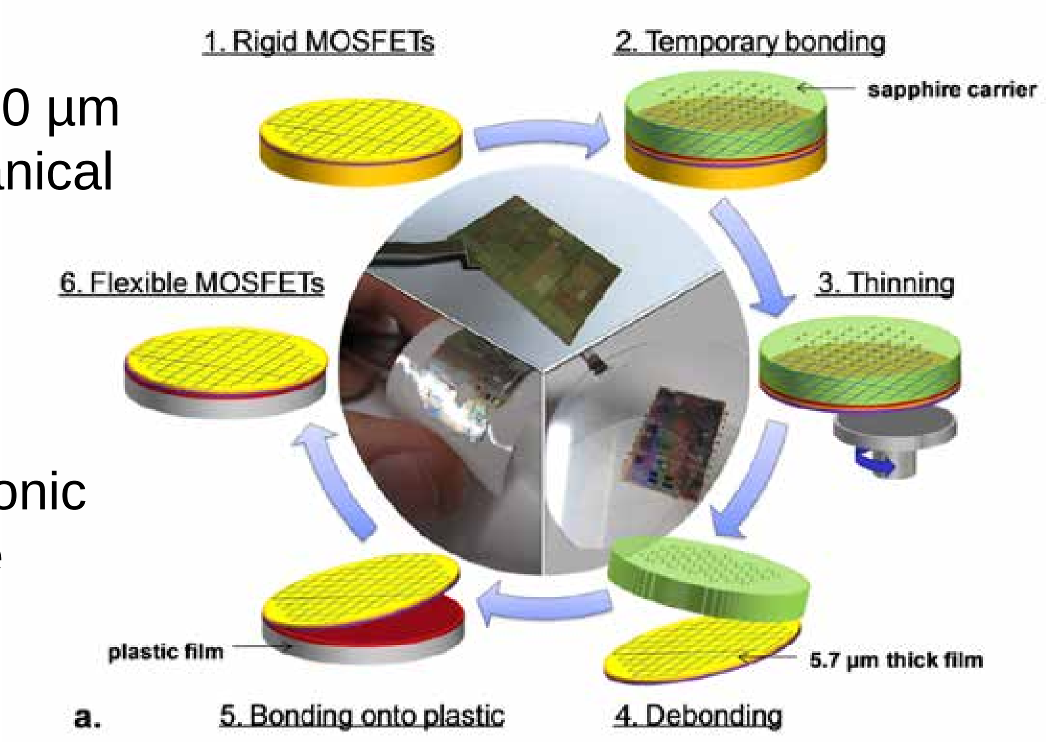
A. Lecavelliers des Etangs-Lavellois et al.: *A converging route towards very high frequency, mechanically flexible, and performance stable integrated electronics*. Journal of Applied Physics 113 (2013) ID 153701

Mech. Compatibility: Individual Solutions.

Ultimate Thinning & Transfer Bonding (UTTB)

Starting material Silicon-on-Insulator (SOI)-Wafer with 780 µm thickness (Si) to allow mechanical handling, on top of this a 65 nm Buried Oxide (BOX) layer for electrical insulation and a 60 nm thick, functional SOI layer, in which the electronic components (MOSFETs) are embedded.

Aim: Transfer of SOI layer to polymer substrates.



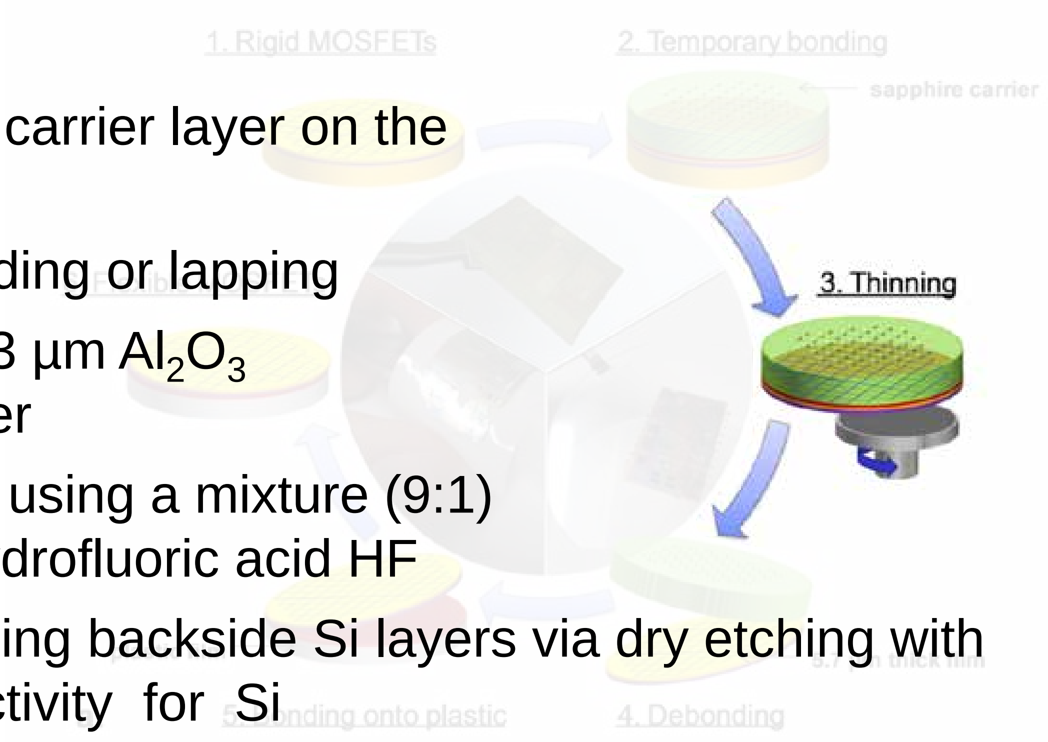
A. Lecavelliers des Etangs-Lavellois et al.: *A converging route towards very high frequency, mechanically flexible, and performance stable integrated electronics*. Journal of Applied Physics 113 (2013) ID 153701

Mech. Compatibility: Individual Solutions.

Ultimate Thinning & Transfer Bonding (UTTB)

Thinning process steps:

- deposition of a temporary carrier layer on the front side, followed by
- chemical-mechanical grinding or lapping
- mechanically using 15 to 3 µm Al_2O_3 particles in deionized water
- chemically by wet etching using a mixture (9:1) of nitric acid HNO_3 and hydrofluoric acid HF
- removal of the last remaining backside Si layers via dry etching with XeF_2, due to its high selectivity for Si

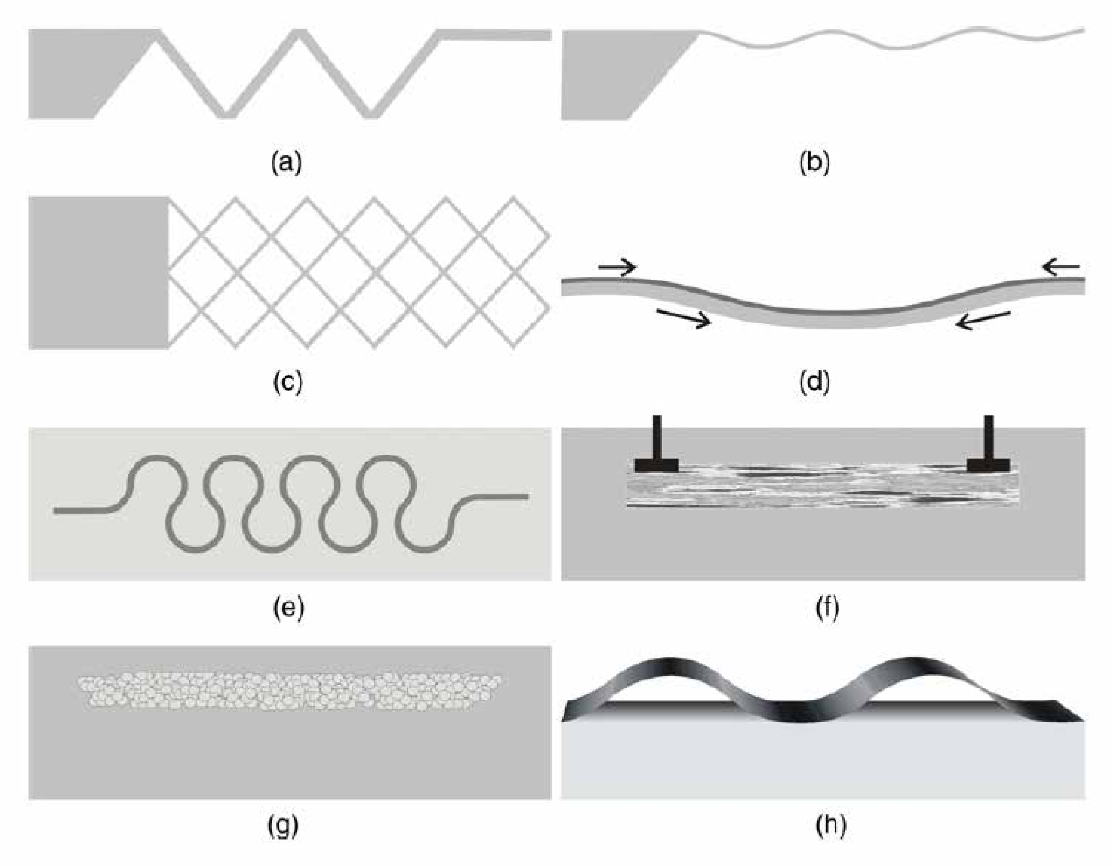


$$2\,XeF_2 + Si \rightarrow 2\,Xe\,(g)\uparrow + SiF_4\,(g)\uparrow$$

A. Lecavelliers des Etangs-Lavellois et al.: *A converging route towards very high frequency, mechanically flexible, and performance stable integrated electronics*. Journal of Applied Physics 113 (2013) ID 153701

Mech. Compatibility: Individual Solutions.

Flexible, stretchable, bendable interconnects.

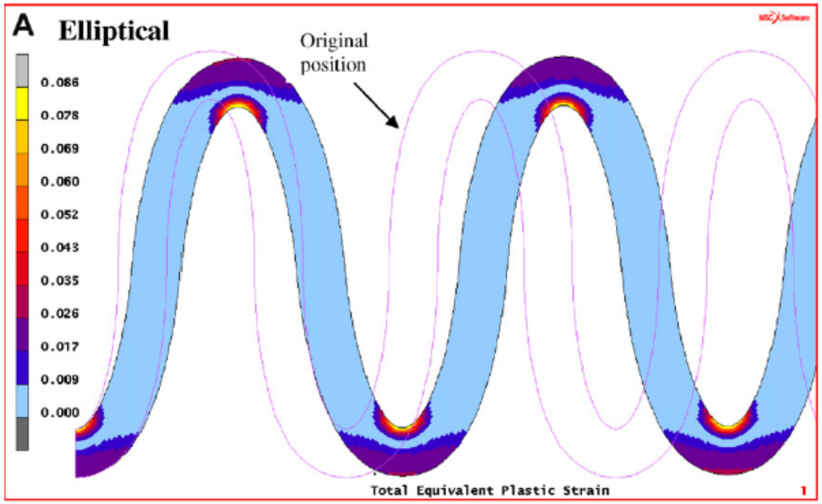


a) etched „accordion“ in Si
b) corrugated membrane
c) etched mesh in Si
d) metal deposition on stretched silicon
e) horseshoe on PDMS
f) impl. Au clusters in Si
g) liquid indium in PDMS
h) undulating Si structure

W. Lang et al.: *From embedded Sensors to Sensorial Materials – the Road to FSI*.
Sensors and Actuators A 171 (2011) 3– 11

Mechanical Compatibility.

Stretchability: Horseshoe.



Basic principle meander shape for achieving stretchability in the overall direction of the conductive path, comparison of various geometries:

Aim: Reducing local loads, results: Horseshoe geometry.

M. Gonzalez et al.: *Design of metal interconnects for stretchable electronic circuits*. Microelectronics Reliability 48 (2008) 825-832.

Mechanical Compatibility.

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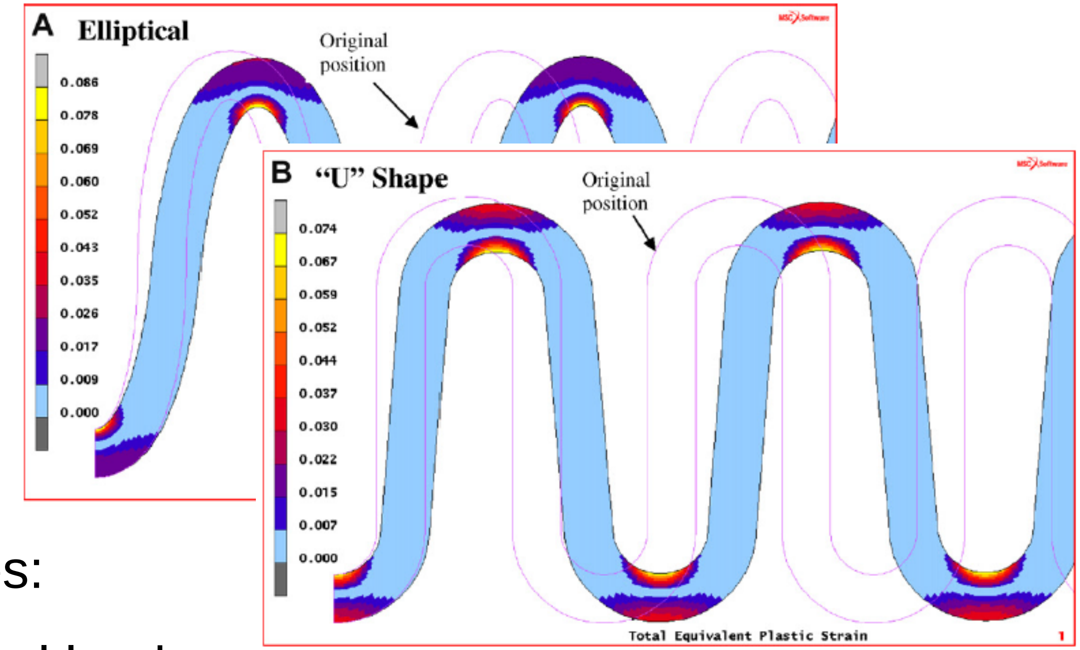

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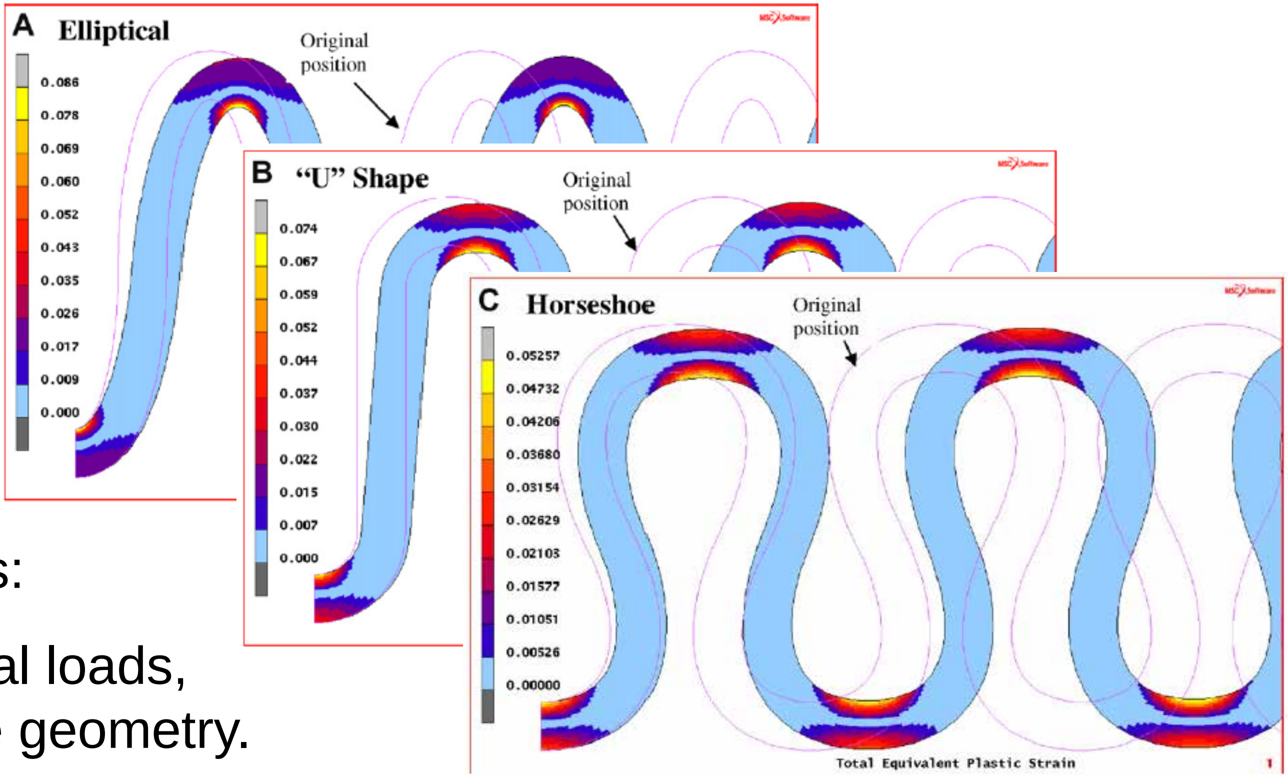

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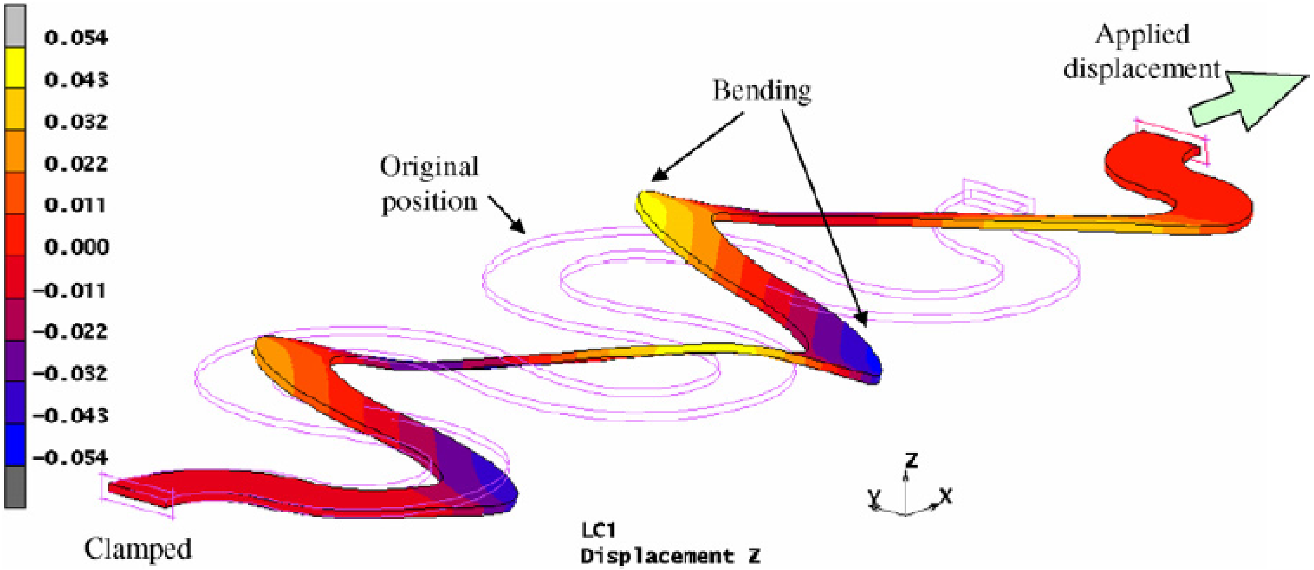
Mechanical Compatibility.

Out-of-plane Displacement.

Problem of strain perpendicular to the plane in which stretching occurs, here illustrated by Gonzalez et al.



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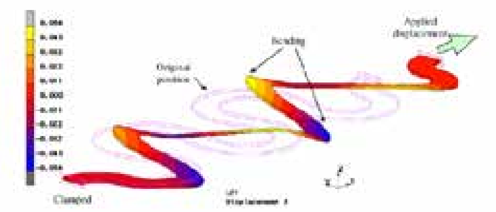
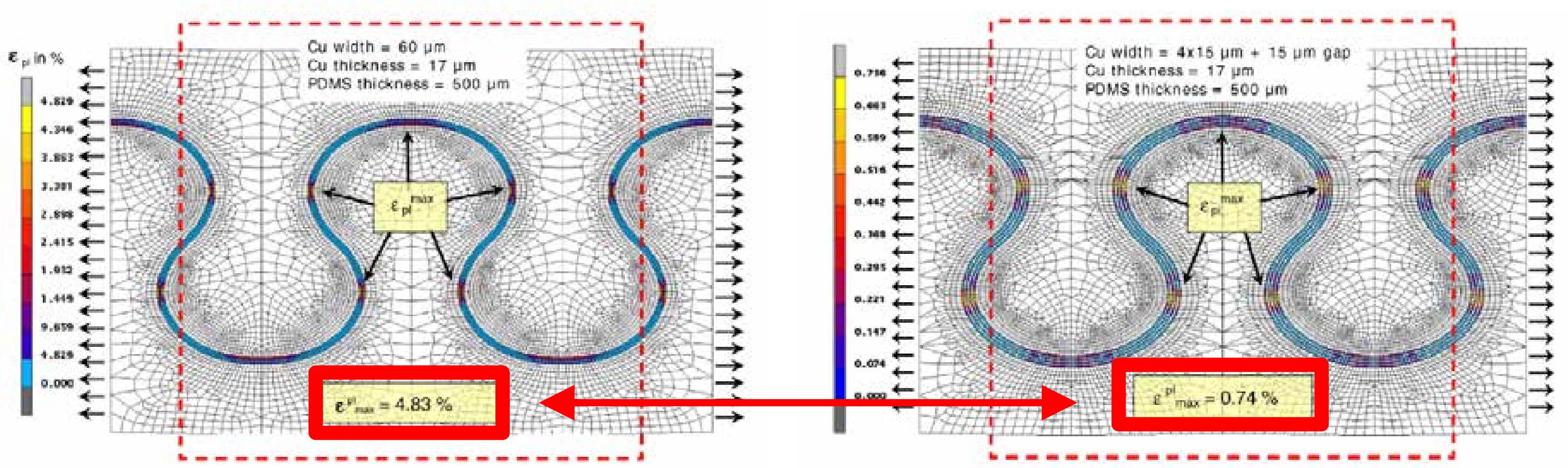
Mechanical Compatibility.

Out-of-plane Displacement.



Problem of strain perpendicular to the plane in which stretching occurs , and a possible solution: Instead of one, several parallel paths with reduced aspect ratio (width:thickness).



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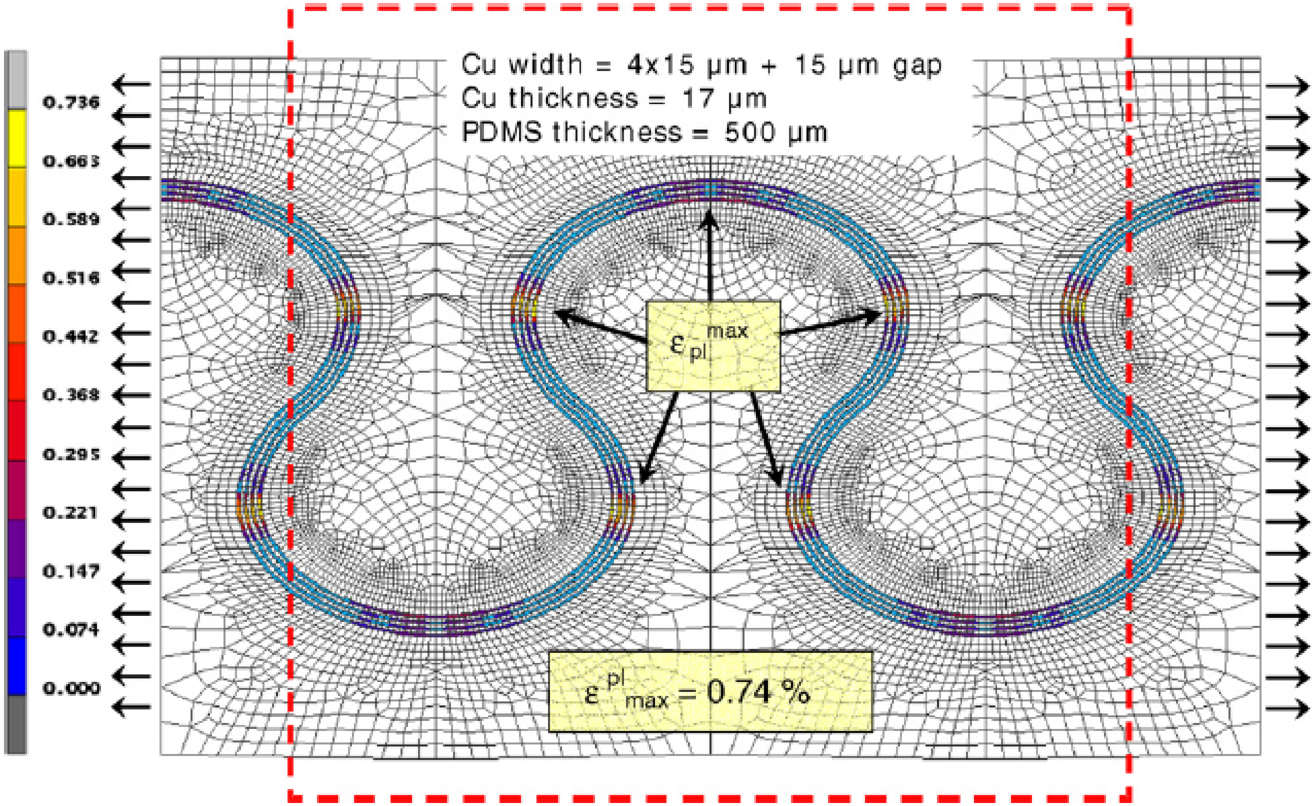
Mechanical Compatibility.

Out-of-plane Displacement.



M. Gonzalez et al.: *Design of metal interconnects for stretchable electronic circuits*. Microelectronics Reliability 48 (2008) 825-832.

Poisson effect observed during a uniaxial tension test for a multiple conductor line. Dashed line shows the original dimensions of the substrate.

Mechanical Compatibility.

Stretchability: Waves.

Via several etching steps, a silicon membrane is produced on a SOI wafer. Following production, the membrane is detached and transferred to a PDMS substrate.

Transfer and attachment to the new substrate is done at elevated temperatures of approximately 180°C.

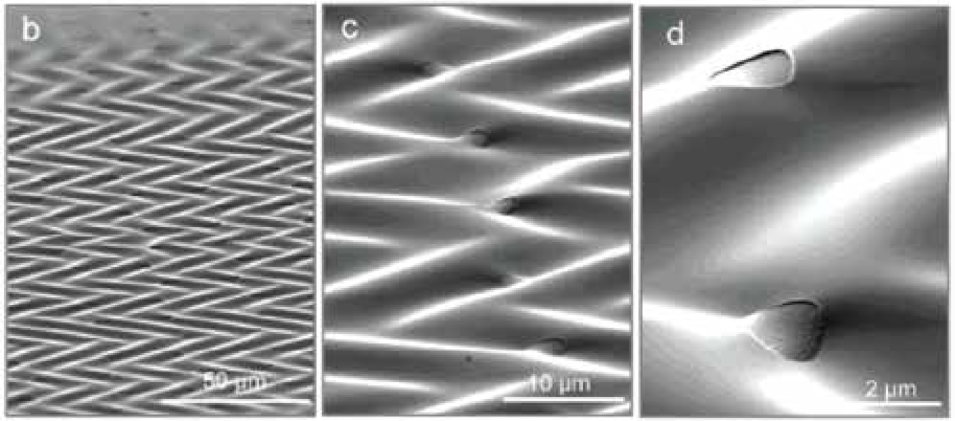
Since the coefficient of thermal expansion of Si is much lower than that of PDMS, the substrate shrinks to a much higher degree than the Si membrane. In consequence, the above wave/fold shape is generated. The folds allow in-plane stretching of the membrane up to the point at which the structure is fully flattened again.

W. M. Choi, J. Song, D.-Y. Khang, H. Jiang, Y. Y. Huang, J. A. Rogers, Biaxially stretchable "wavy" silicon nanomembranes, Nano Letters 7 (6) (2007) 1655–1663, pMID: 17488053.

Mechanical Compatibility.

Stretchability: Waves.

Schematic representation of method and images of structures: Here, 100 nm Si and 3.8 % thermal expansion/ contraction (note 2D character!).



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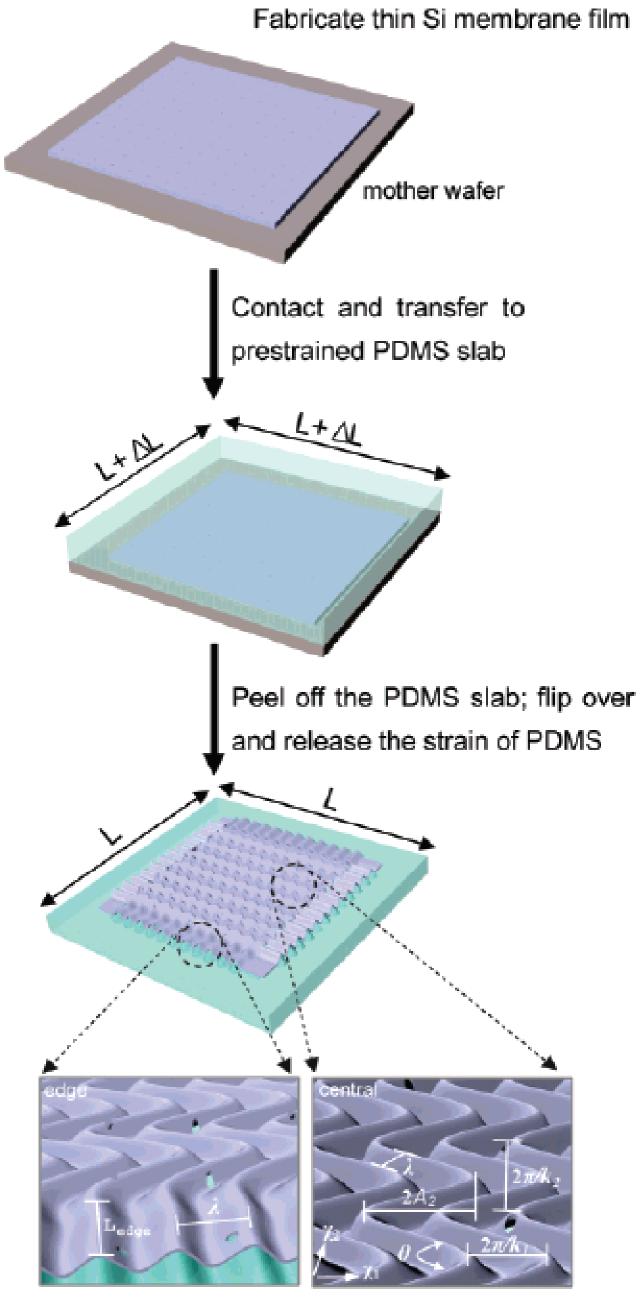

Fabricate thin Si membrane film

Contact and transfer to prestrained PDMS slab

Peel off the PDMS slab; flip over and release the strain of PDMS

Thermal Compatibility.

Coefficient of thermal expansion α [10^{-6}/K]

Deviations in the coefficient of thermal expansion between embedded components and the host material may lead to mechanical stresses building up in the components (note that some of the measures aimed at creating stretchable interconnects actually make use of this effect)

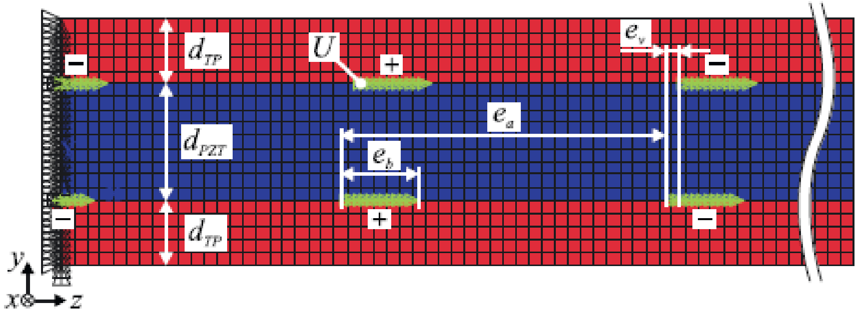
- … if during use of the system temperatures deviate from an originally stress-free “ground state”.
- … if during production the connection between such differently reacting components is created at a temperature that deviates from the typical temperature of use of the system.

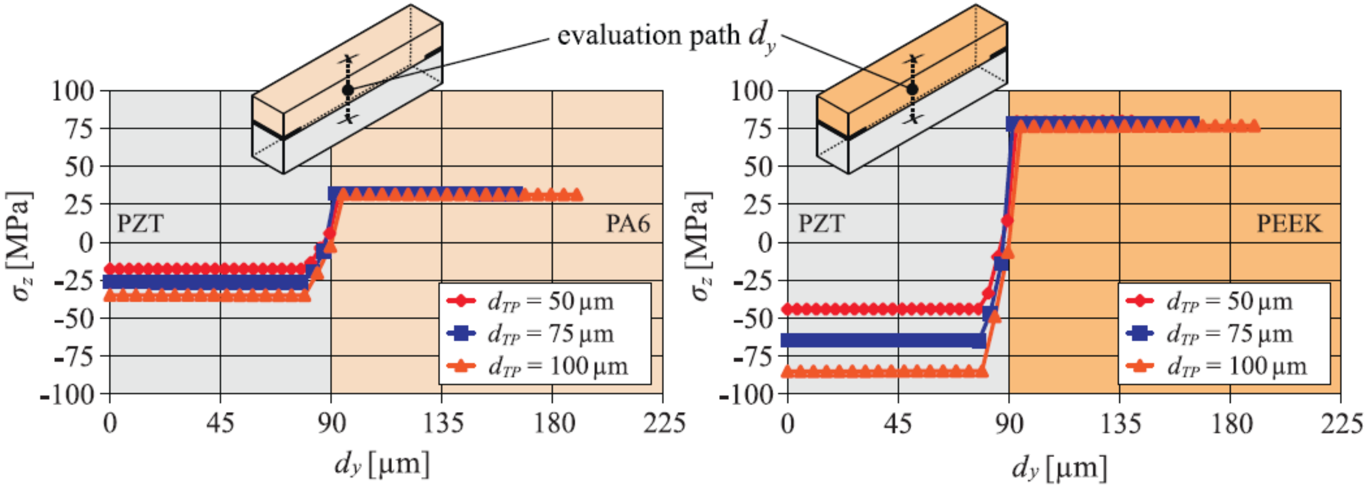
Stresses of this kind will be superimposed to those induced by other loads acting on the component. They can thus also be beneficial.

Thermal Compatibility.

Residual Stress for PZT in PEEK, PA.

Thermally induced residual stresses in a piezo-ceramic module designed fo embedding in FRP, variation of substrate material and -thickness.

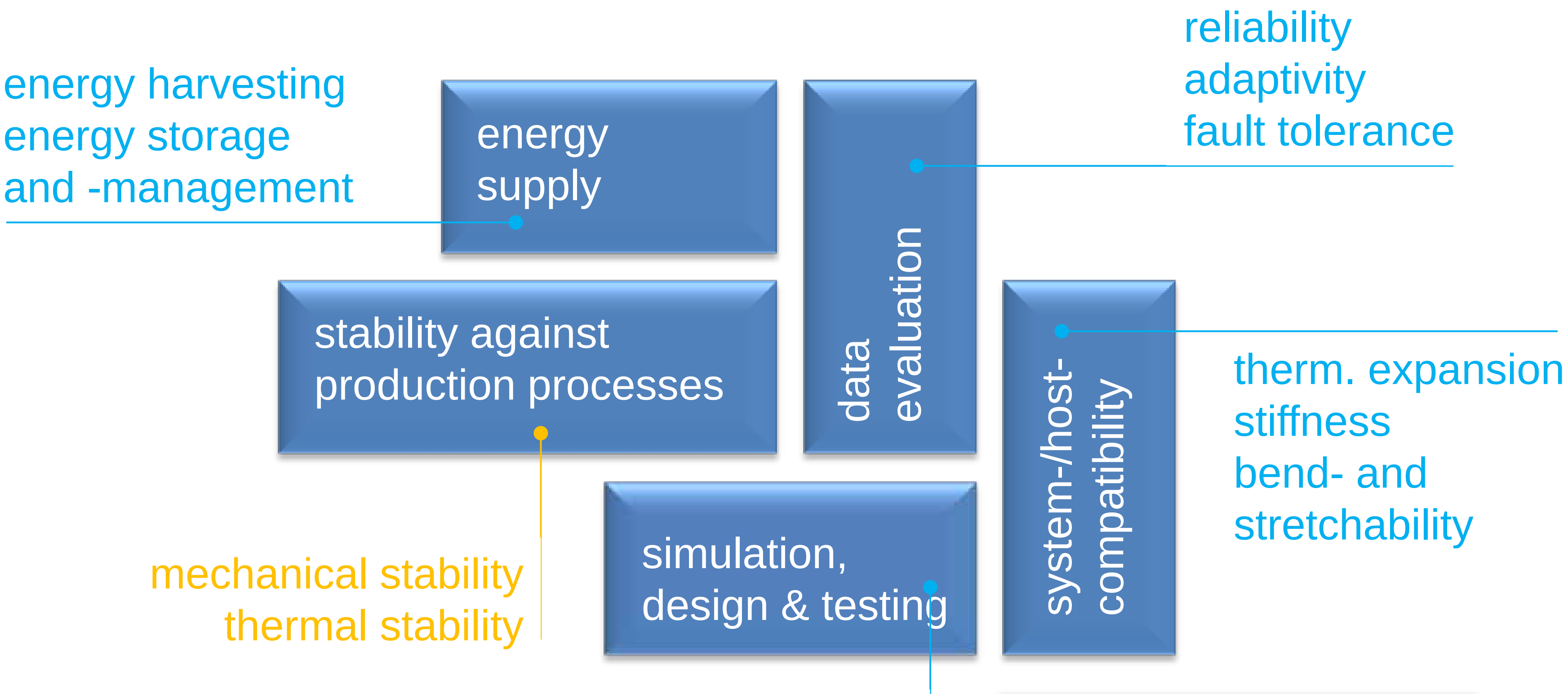




T. Heber et al.: *Production process adapted design of thermoplastic-compatible piezoceramic modules.* Composites Part A 59 (2014) 70-77.

Challenges

Areas of Research: Our Focus.



energy harvesting
energy storage
and -management

energy supply

reliability
adaptivity
fault tolerance

data evaluation

stability against production processes

mechanical stability
thermal stability

system-/host-compatibility

therm. expansion
stiffness
bend- and
stretchability

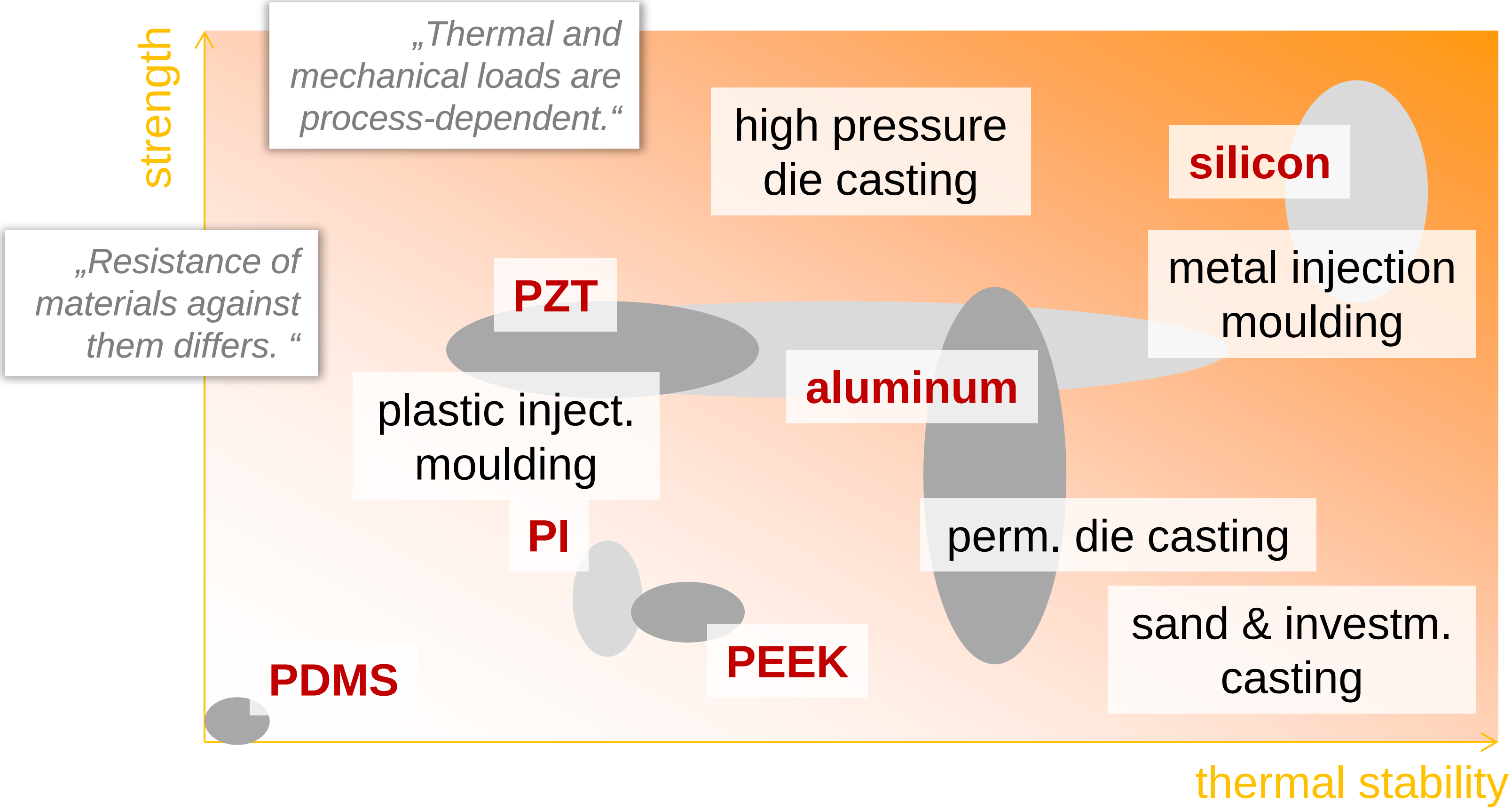
simulation, design & testing

holistic development tools
simulation and (virtual) test methods

„Focus on the ***cyber*** *in the cyber-physical-system.“*

Stability against Production Processes.

Integration Challenge: Material vs. Process.



Stability against Production Processes.

Production process perspective.

	metals		polymers	ceramics
primary shaping	**metal casting (V)** powder metallurgy (V) spray forming (V)	hybrid mat. like fibre metal laminates (S/V)	resin transfer moulding (V) laminating proc. (V) injection moulding (V)	
forming	**formable sheet metals (S)**		formable polymers and polymer matrix composites (V)	
cutting				
joining				
Coating	thermal spraying (S)		powder coating (S)	

„Several different manufacturing processes have been considered for sensor integration. Two examples will follow.“

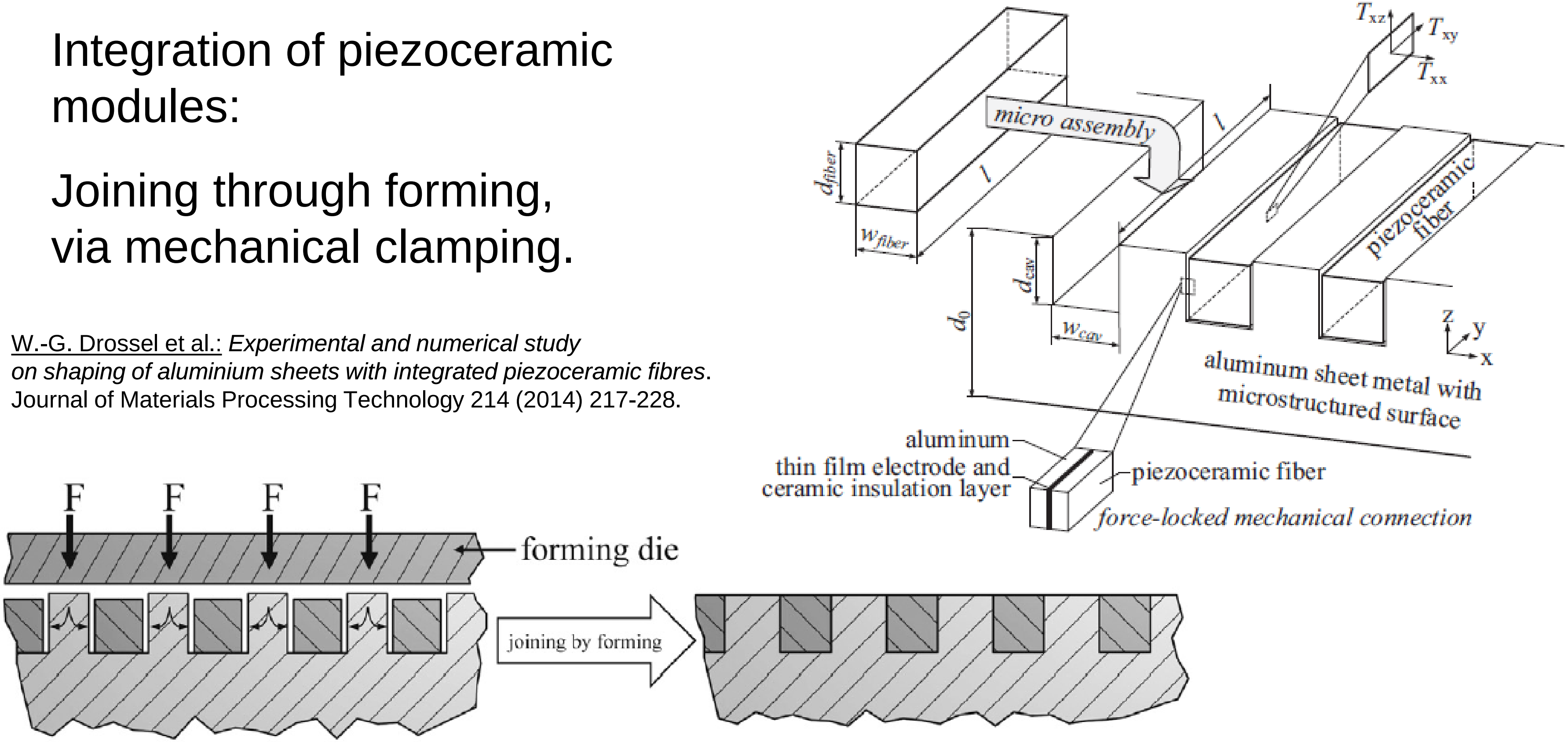
Stability against Production Processes.

Piezoelectric sensors in sheet metal.

Integration of piezoceramic modules:

Joining through forming,
via mechanical clamping.

W.-G. Drossel et al.: *Experimental and numerical study on shaping of aluminium sheets with integrated piezoceramic fibres*. Journal of Materials Processing Technology 214 (2014) 217-228.

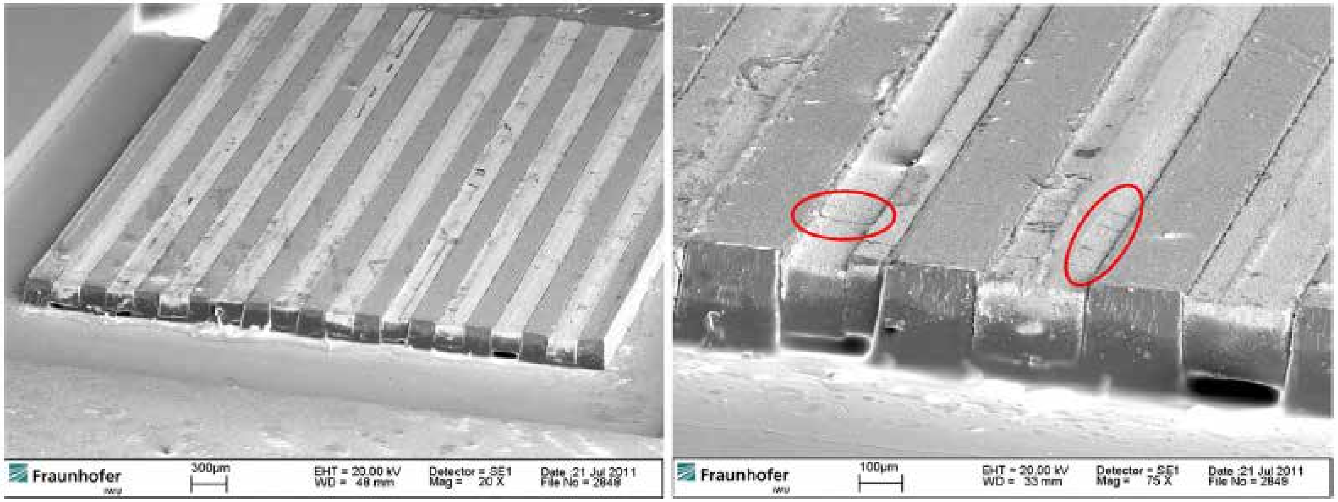


Stability against Production Processes.

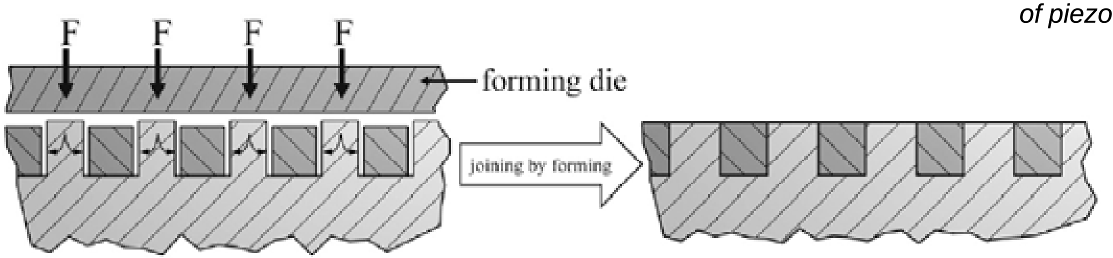
Piezoelectric sensors in sheet metal.

Micrograph of embedded piezoceramic fibres,

showing local cracks.



A. Schubert et al.: *Smart metal sheets by direct functional integration of piezoceramic fibers in microformed structures.* Microsystems Technology 20 (2014) 1131-1140.



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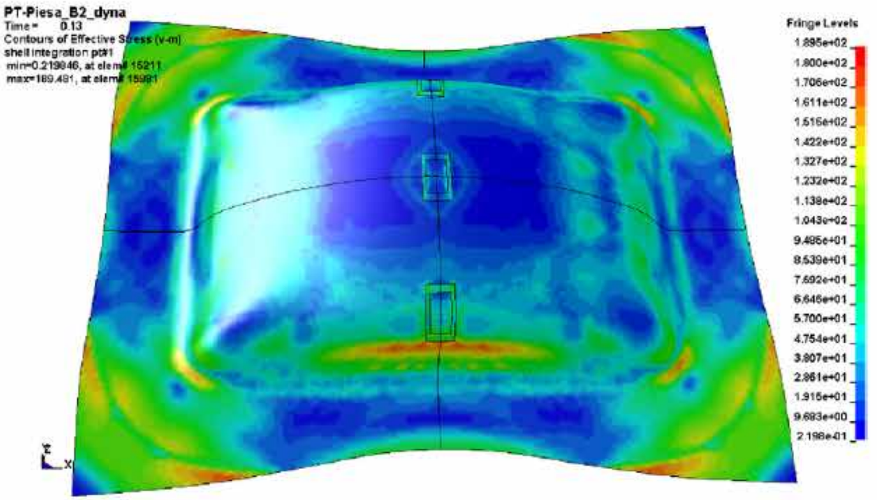
Stability against Production Processes.

Piezoelectric sensors in sheet metal.

Sheet metal forming of the sensor-containing component in the course of progressing from semi-finished material to product:



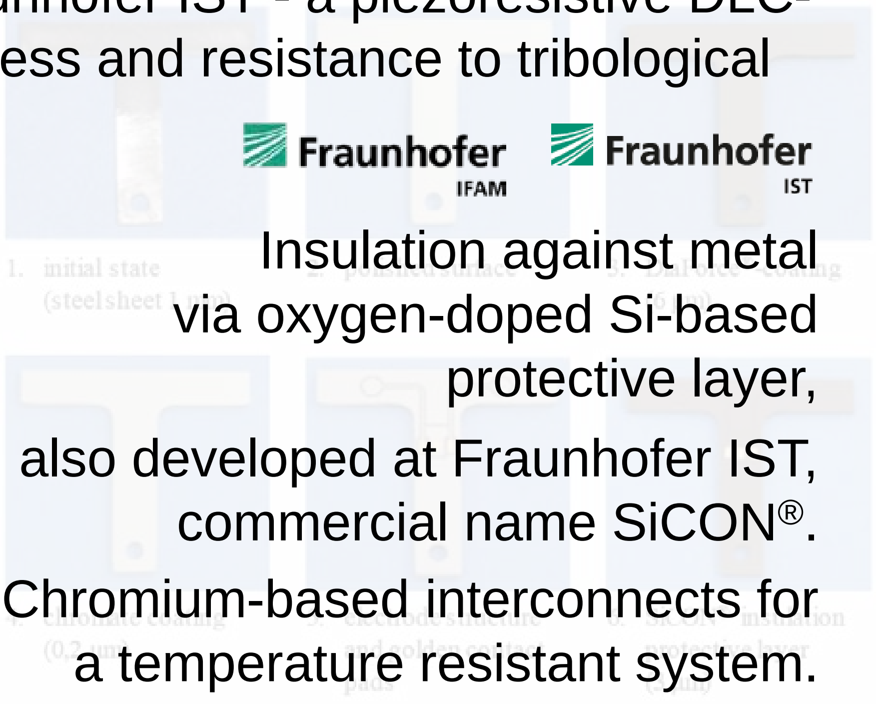
W.-G. Drossel et al.: *Experimental and numerical study on shaping of aluminium sheets with integrated piezoceramic fibres*. Journal of Materials Processing Technology 214 (2014) 217-228.

Stability against Production Processes.

Strain Sensor in Al castings: Layout.

DiaForce® sensor developed at Fraunhofer IST - a piezoresistive DLC-thin film sensor with very high hardness and resistance to tribological load. Extremely thin film of approx. 9-10 µm.

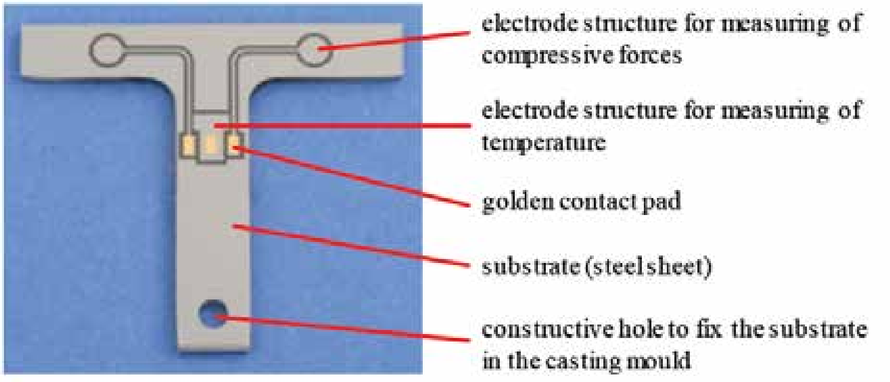
Fraunhofer IFAM Fraunhofer IST



Insulation against metal via oxygen-doped Si-based protective layer,

also developed at Fraunhofer IST, commercial name SiCON®.

Chromium-based interconnects for a temperature resistant system.

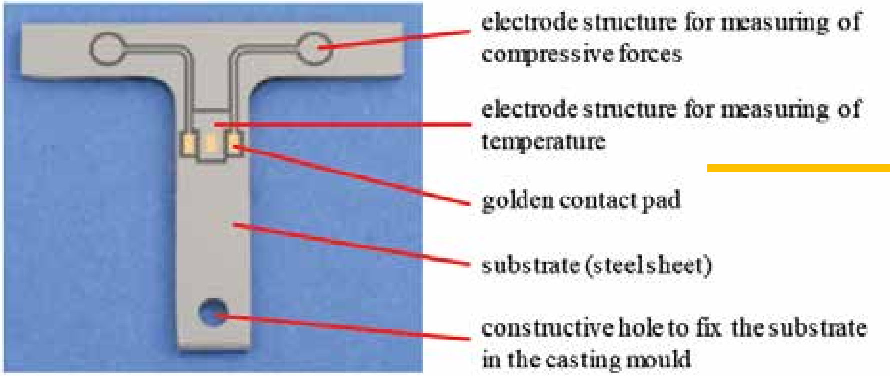


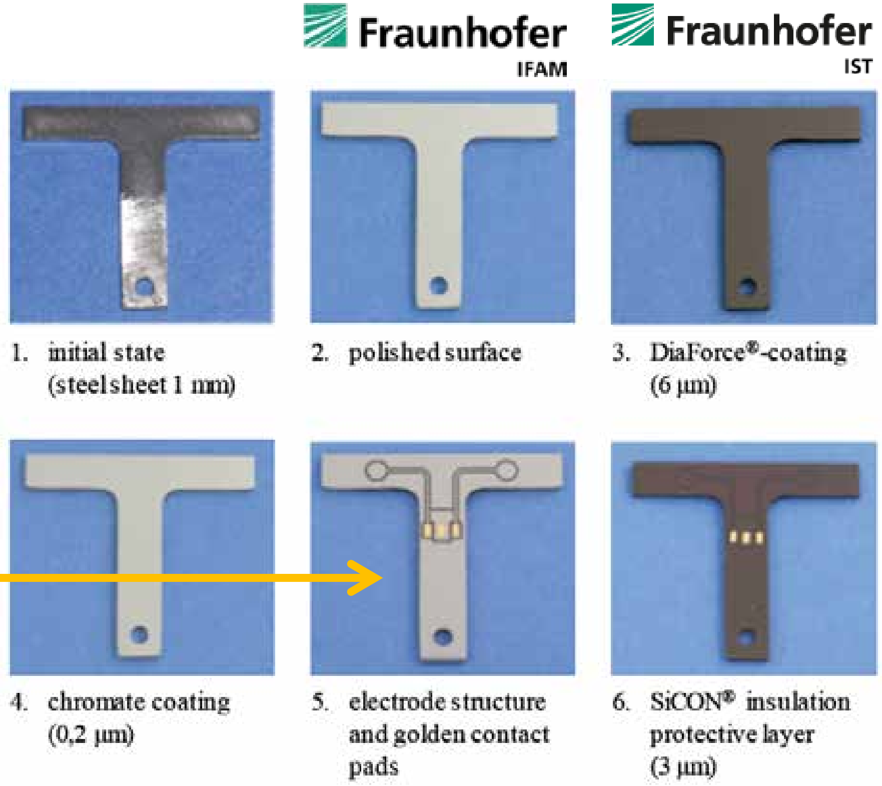
C. Pille et al.: *Encapsulating piezoresistive thin film sensors based on amorphous diamond-like carbon in aluminium castings*. Proceedings of the SysInt 2012 Conference, Hannover, 27.-29. Juni 2012.

Stability against Production Processes.

Strain Sensor in Al castings: Layout.

Temperature and tribologically stable piezoresistive sensor (Diamond-Like Carbon, DLC) protected by a coating based on oxygen-doped Si.





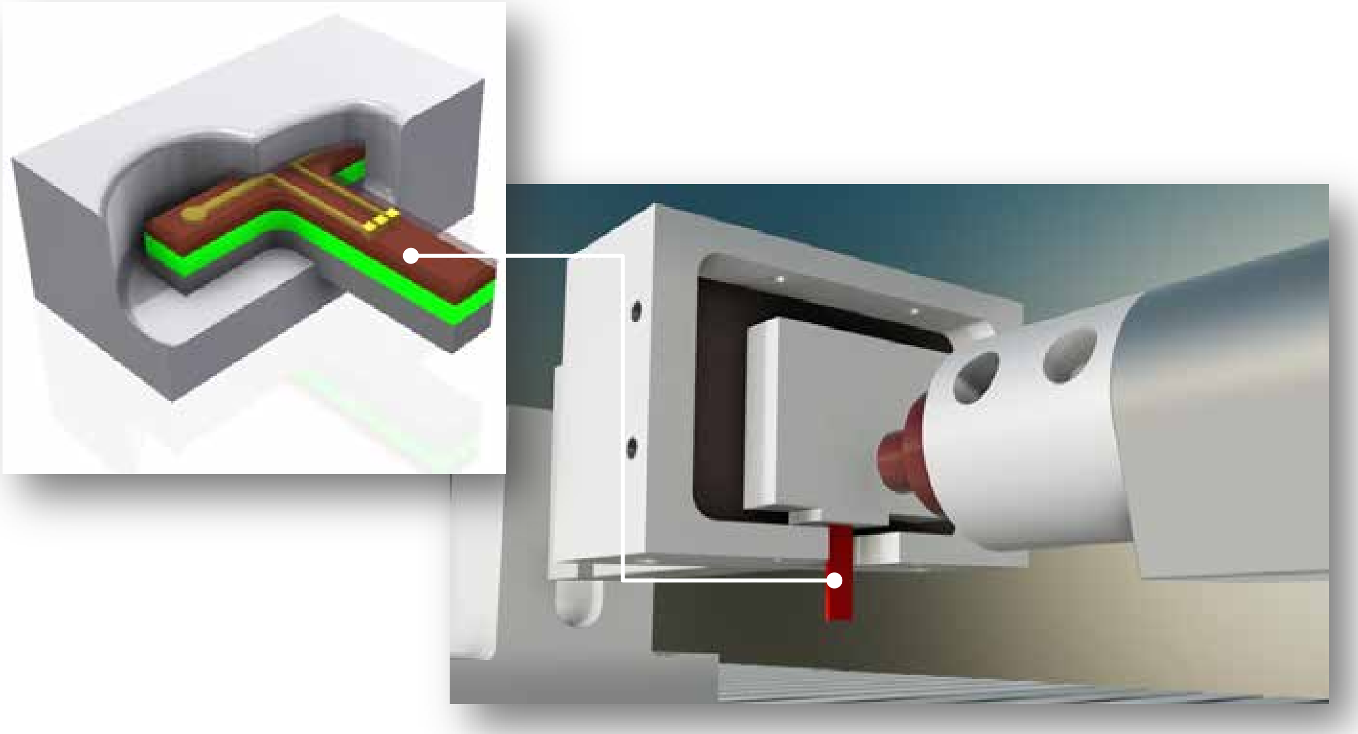
1. initial state (steel sheet 1 mm)
2. polished surface
3. DiaForce®-coating (6 µm)
4. chromate coating (0,2 µm)
5. electrode structure and golden contact pads
6. SiCON® insulation protective layer (3 µm)

C. Pille et al.: *Encapsulating piezoresistive thin film sensors based on amorphous diamond-like carbon in aluminium castings*. Proceedings of the SysInt 2012 Conference, Hannover, 27.-29. Juni 2012.

Stability against Production Processes.

Strain Sensor in Al castings: Layout.

Diaforce® DLC-based piezores. strain sensors adapted for embedding in Al castings.



Fraunhofer IST

Fraunhofer IFAM

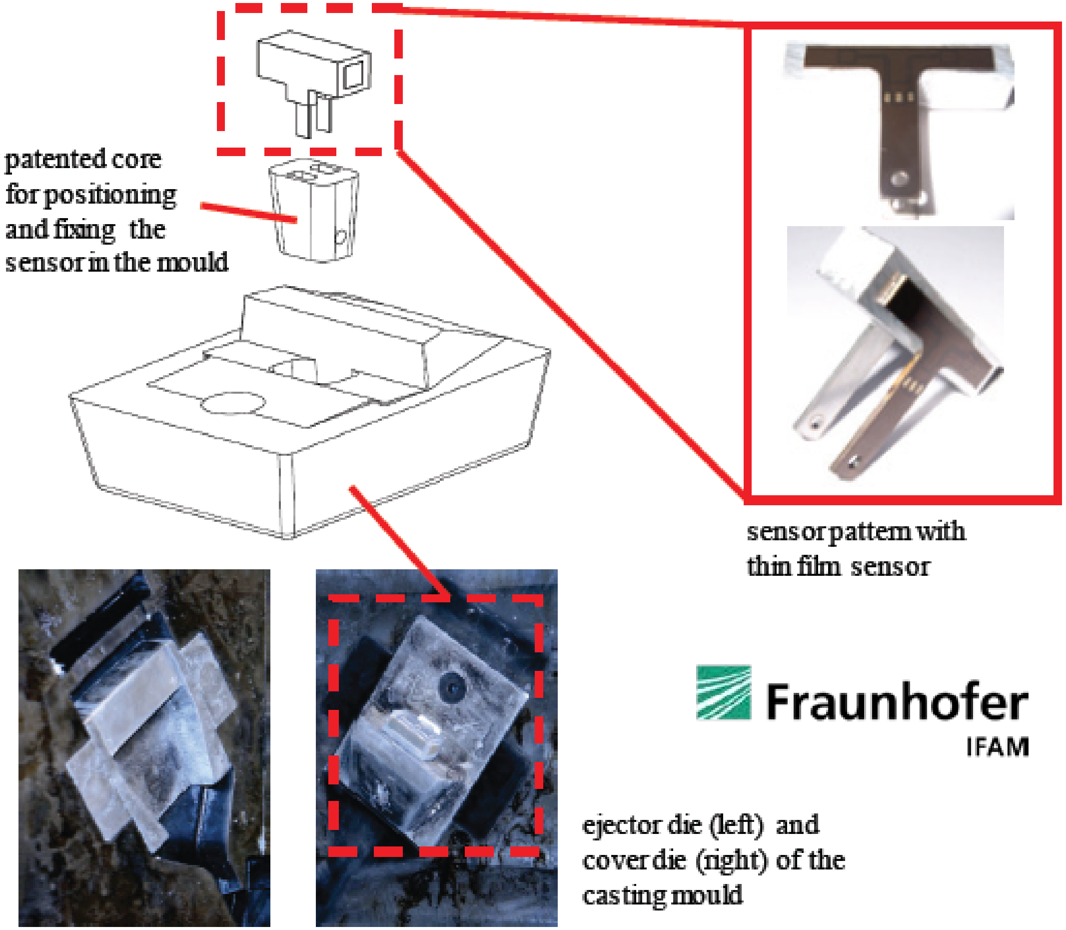
C. Pille et al.: *Encapsulating piezoresistive thin film sensors […] in aluminium castings* . Proc. of the SysInt 2012 conference, June 27th-29th, 2012, Hanover, Germany.

Stability against Production Processes.

Sensor fixation.

Specially developed fixation and positioning device for integration as a core in a high pressure die casting HPDC mould:

Defined positioning, avoiding any movement induced by melt during mould filling (AlSi9MgMn, Silafont-36, casting temperature ca. 700°C).



patented core for positioning and fixing the sensor in the mould

sensor pattern with thin film sensor

ejector die (left) and cover die (right) of the casting mould

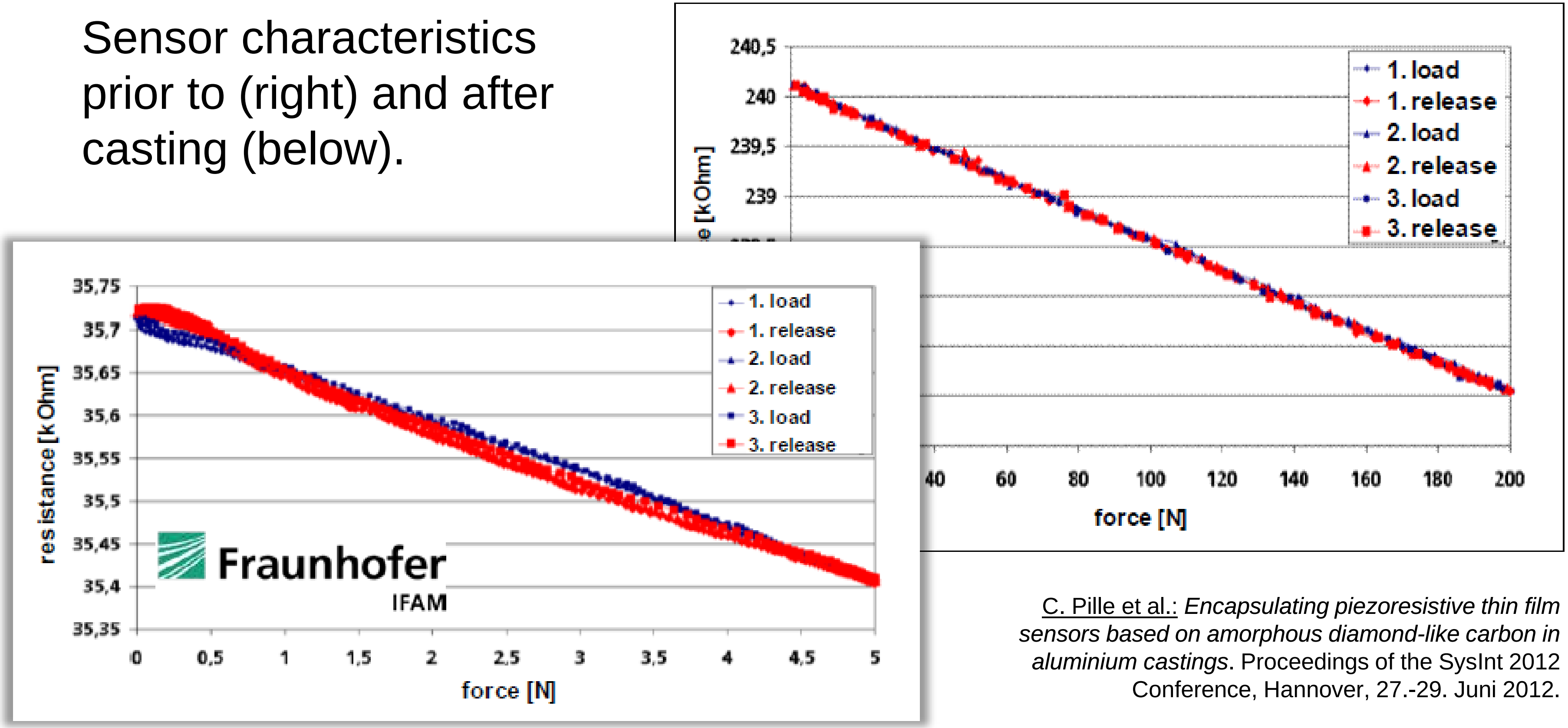
Fraunhofer IFAM

C. Pille et al.: *Encapsulating piezoresistive thin film sensors based on amorphous diamond-like carbon in aluminium castings*. Proceedings of the SysInt 2012 Conference, Hannover, 27.-29. Juni 2012.

Stability against Production Processes.

Pre-/Post-casting sensor characterization.

Sensor characteristics prior to (right) and after casting (below).



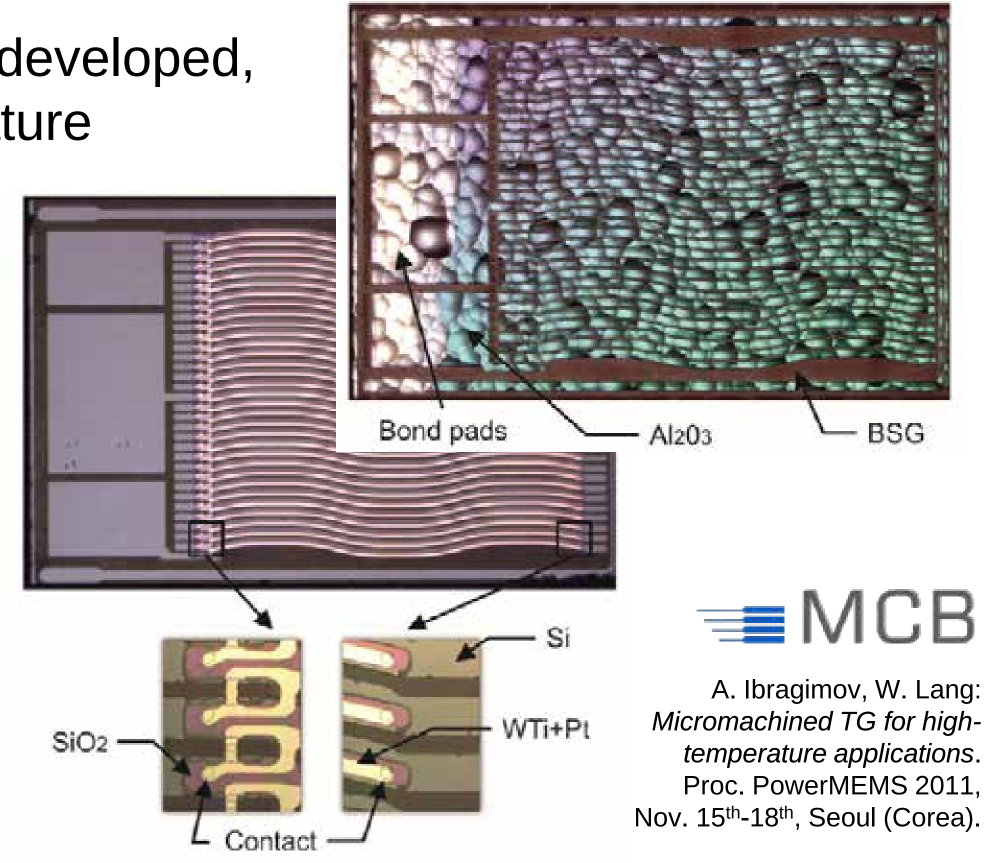
<u>C. Pille et al.:</u> *Encapsulating piezoresistive thin film sensors based on amorphous diamond-like carbon in aluminium castings*. Proceedings of the SysInt 2012 Conference, Hannover, 27.-29. Juni 2012.

Stability against Production Processes.

Thermogenerator in Al castings: Layout.

A thermogenerator specifically developed, through choice of high temperature materials, for being directly embedded in an aluminum part produced by high pressure die casting at a melt temperature of approx. 770°C.

Build-up of the thermo-generator.



A. Ibragimov, W. Lang: *Micromachined TG for high-temperature applications*. Proc. PowerMEMS 2011, Nov. 15th-18th, Seoul (Corea).

Stability against Production Processes.

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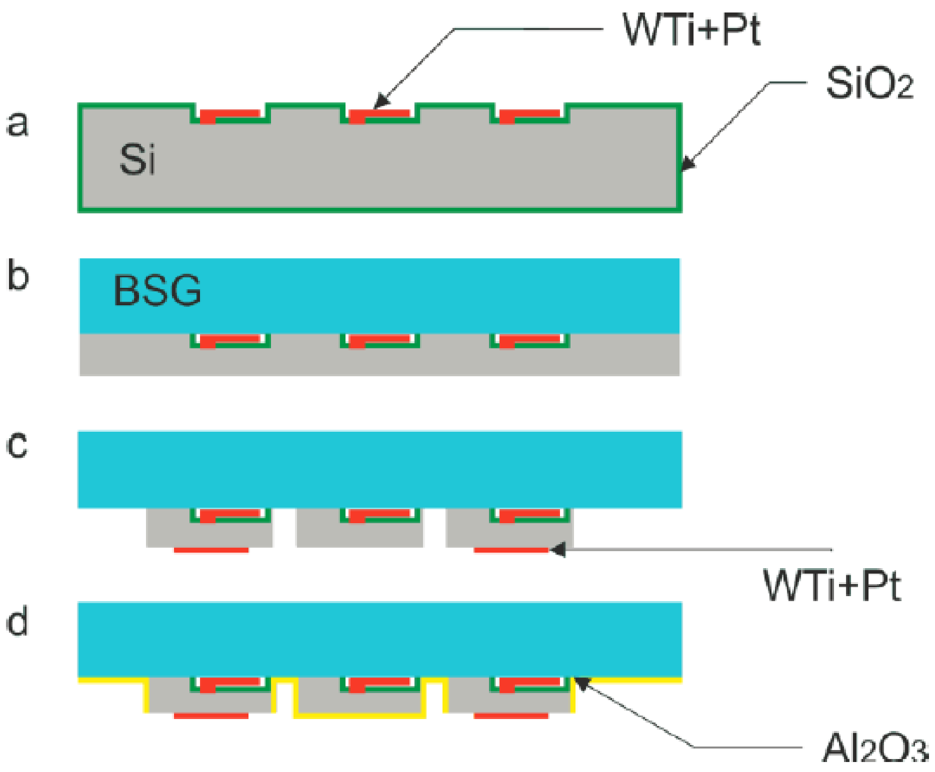


Stability against Production Processes.

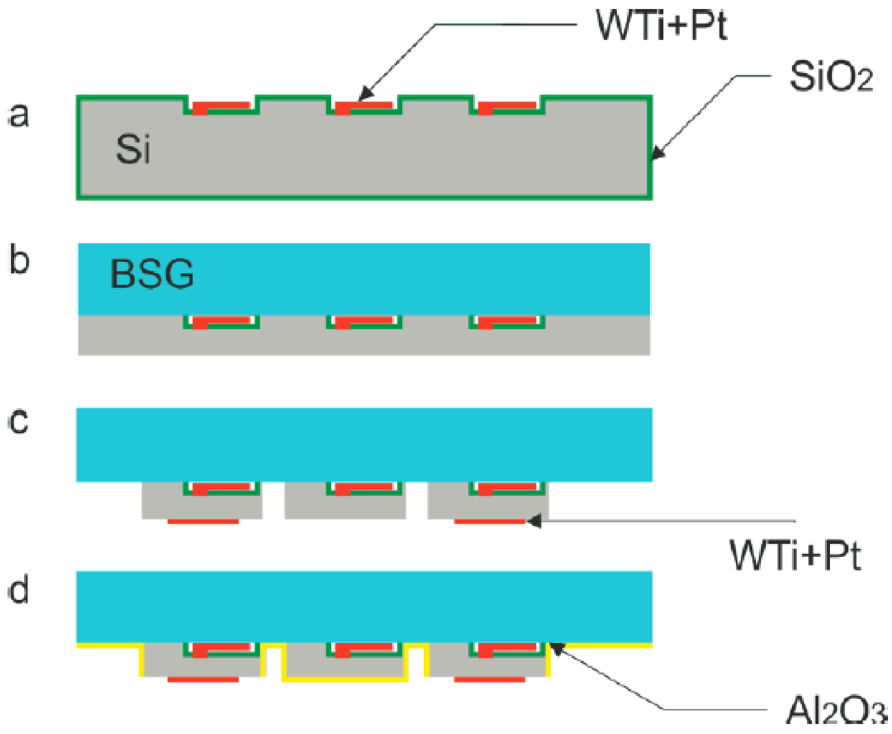
Thermogenerator in Al castings: Layout.

(a) oxidized Si wafer with metal parts of thermocouples in groves and with contact windows (contacting betw. partners Si and WTi+Pt)

(b) partial Si removal, anodic bonding, wafer thinning

(c) contact pads, DRIE

(d) insulation layer deposited



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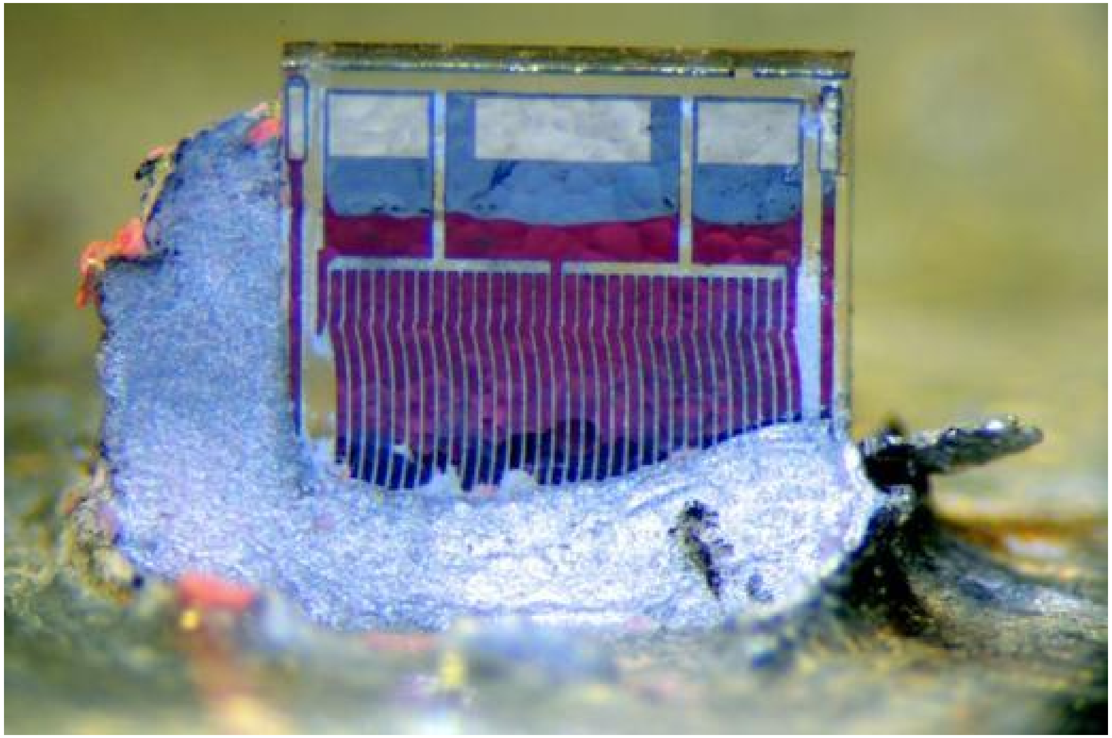
Micromachined TG for high-temperature applications.
Proc. PowerMEMS 2011, Nov. 15th-18th, Seoul (Corea).

Stability against Production Processes.

Thermogenerator in Al castings: Layout.

Thermogenerator after casting, partly embedded in aluminum, contact pads visible and accessible for contacting.



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Stability against Production Processes.

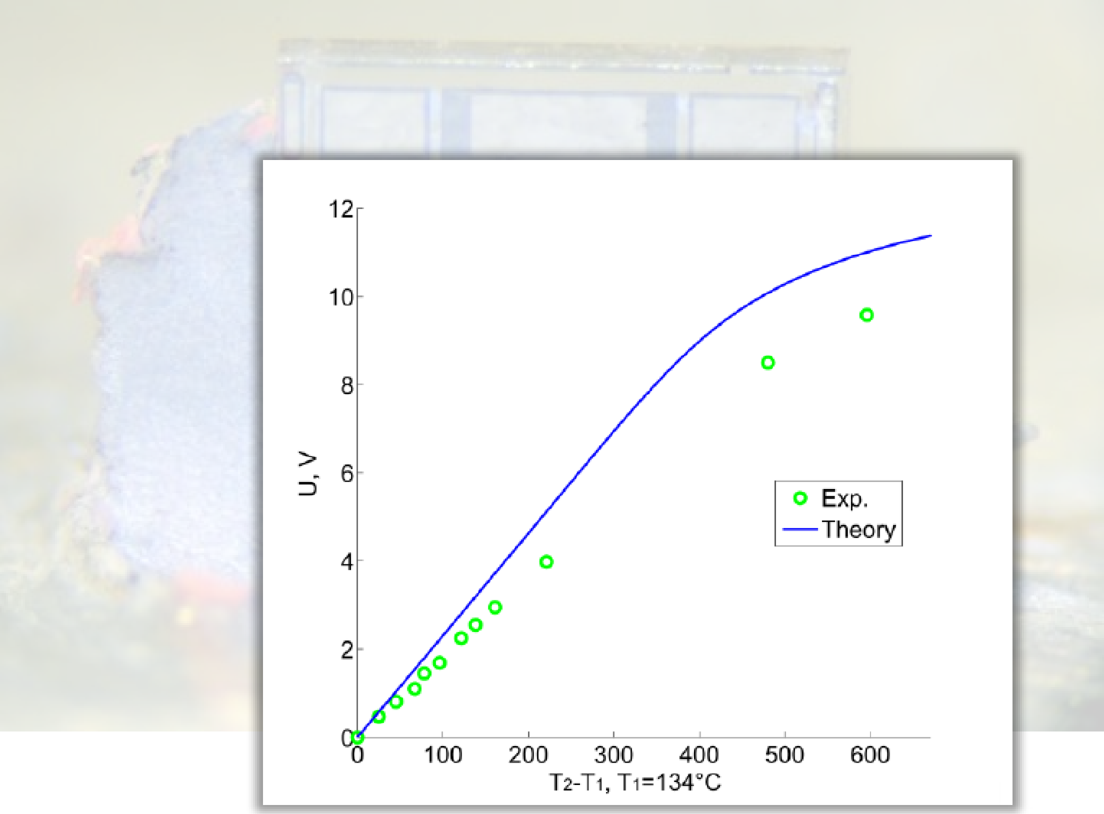
Thermogenerator in Al castings: Layout.

Post-casting testing of thermoelectric performance of the embedded structure: Generated voltage roughly in line with expectations.

Fraunhofer IFAM

MCB

A. Ibragimov, W. Lang: *Micromachined thermogenerator for high-temperature applications*. Proc. PowerMEMS 2011, Nov. 15th-18th, Seoul (Corea).



Introduction to AM.

Definition and classification.

According to ASTM international committee F42, **Additive Manufacturing** is the process…

"… of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining."

ASTM further defines the process classes to the left. For all of them, metal-based variants are known.

- binder jetting
- directed energy deposition
- material extrusion
- material jetting
- powder bed fusion
- sheet lamination
- vat photopolymerization

Introduction to AM.

Processes by material state.

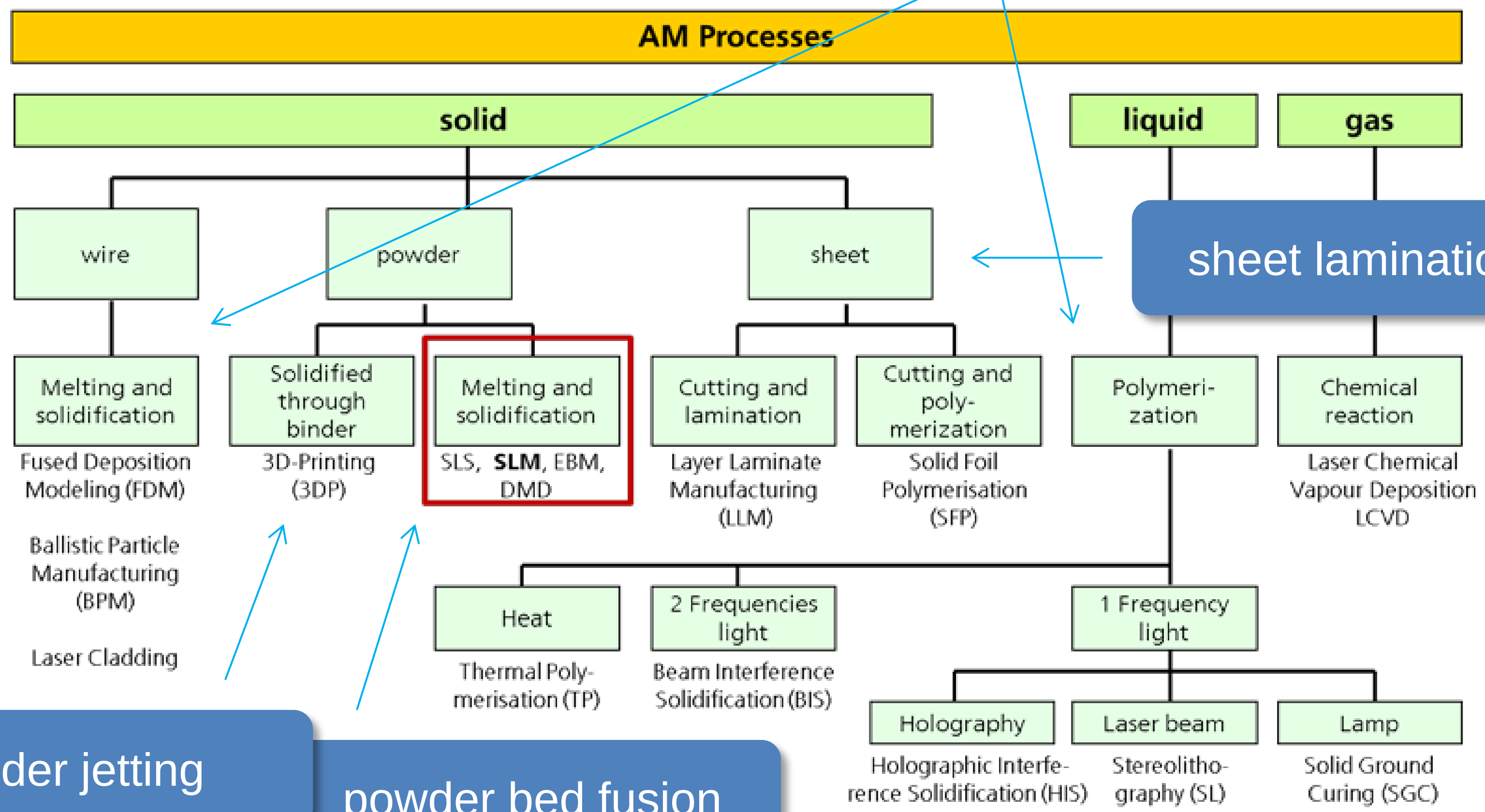
vat photopolymerization

material extrusion

sheet lamination

binder jetting

powder bed fusion



AM Processes

solid

- wire
  - Melting and solidification
    - Fused Deposition Modeling (FDM)
    - Ballistic Particle Manufacturing (BPM)
    - Laser Cladding
- powder
  - Solidified through binder
    - 3D-Printing (3DP)
  - Melting and solidification
    - SLS, **SLM**, EBM, DMD
- sheet
  - Cutting and lamination
    - Layer Laminate Manufacturing (LLM)
  - Cutting and poly-merization
    - Solid Foil Polymerisation (SFP)

liquid

- Polymeri-zation
  - Heat
    - Thermal Poly-merisation (TP)
  - 2 Frequencies light
    - Beam Interference Solidification (BIS)
  - 1 Frequency light
    - Holography
      - Holographic Interference Solidification (HIS)
    - Laser beam
      - Stereolitho-graphy (SL)
    - Lamp
      - Solid Ground Curing (SGC)

gas

- Chemical reaction
  - Laser Chemical Vapour Deposition LCVD

AM Process Review.

An abbreviated history of AM.

Stage 1:
Rapid
Prototyping

Stage 1a: Design Prototype
See what your component looks like, almost immediately.

Stage 1b: Simple Functional Prototype
Does your component really do what it‘s supposed to?

Stage 1c: Performing Prototype
Will your component meet requirements?

Stage 2: Rapid Tooling
Don‘t just build component prototypes, build the tools to make the real thíng.

Stage 3: Additive Manufacturing
Don‘t just build component prototypes, build your part, directly.

AM Process Review.

An extension to the AM timeline.

Stage 1: Rapid Prototyping

Stage 1a: Design Prototype
See what your component looks like, almost immediately.

Stage 1b: Simple Functional Prototype
Does your component really do what it's supposed to?

Stage 1b: Performing Prototype
Will your component meet requirements?

Stage 2: Rapid Tooling
Don't just build component prototypes, build the tools to make the real thing.

Stage 3: Additive Manufacturing
Don't just build component prototypes, build your part, directly.

„There are several lines of research and development along which AM may develop. Below, some of these are named. Others, like optimization for economic aspects like productivity, have deliberately been ommitted here.“

Stage 4: All the future has in store (Well, part of it).

- Don‘t assemble, just build! Multi-material & multi-component in one go.
- Don‘t just build assemblies, integrate more functions by building (smart) systems.
- Don‘t just build components, build materials.

AM Process Review.

3D Material Control: The „complication“ view.

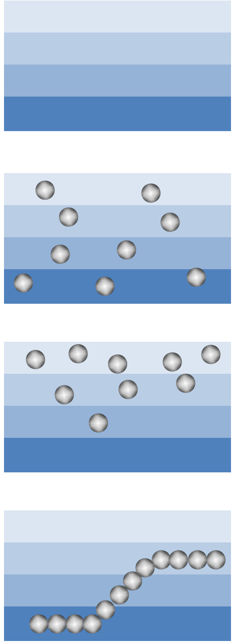
Distinction between levels of material structural control at.

Level 1: Homogeneous Material
No control of material spatial positioning required or foreseen.

Level 2: Uniform Composite
Same as above, difference is that a heterogeneous powder mixture is processed.

Level 3: Graded Composite
Heterogeneous powder mixtures and limited spatial control of composition/dilution.

Level 4: Full Structural Control
3D material placement capability for >2 materials, allowing build-up of component-integrated structures with change of material and full geometrical control.

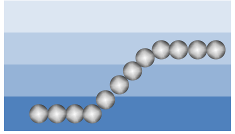


AM Process Review.

3D Material Control: Suitability of processes.

Suitability of process variants for 3D material control.

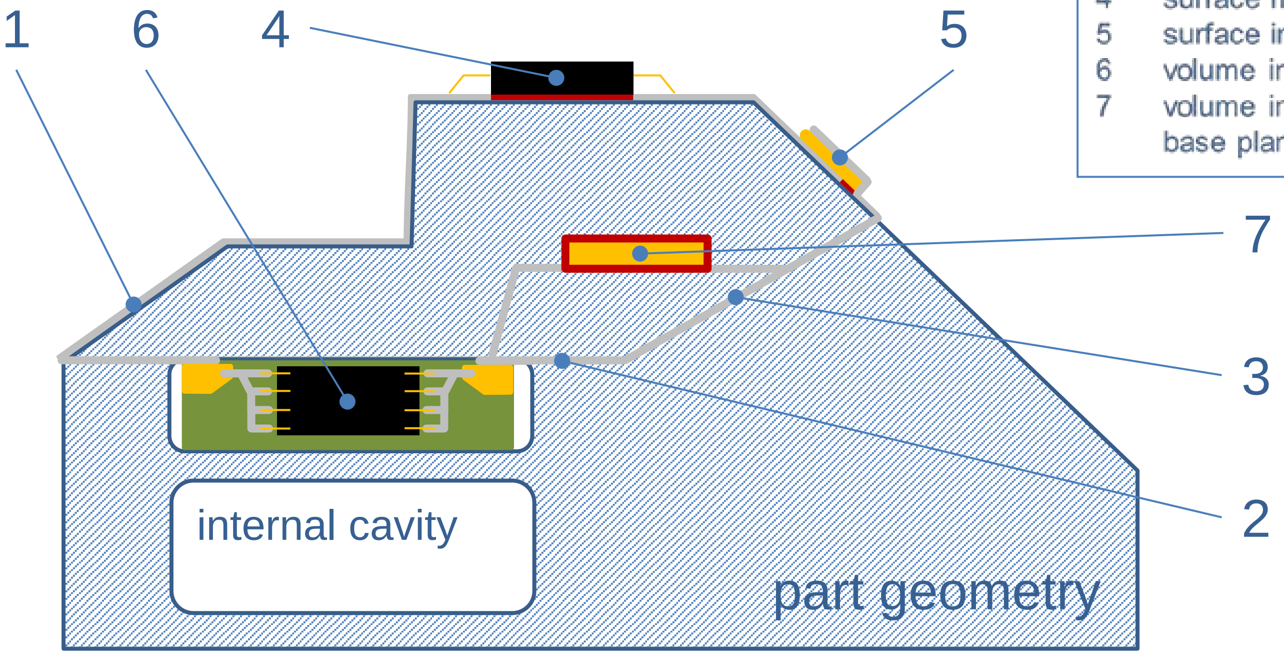
Level 4: Full Structural Control
3D material placement capability for >2 materials, allowing build-up of component-integrated structures with change of material and full geometrical control.



- General advantage for processes that (a) allow multi-material parts from the start and (b) facilitate simple exchange of materials.
- Advantage for (a) directed energy deposition, (b) material jetting, (c) material extrusion over power bed fusion or vat photopolymerization.

Sensor Integration in AM

An Attempt at Classification - Graphical.



1 surface applied/integrated conductive path
2 internal conductive path, on building plane
3 cross-plane internal conductive path
4 surface mounted sensor/electr. device
5 surface integrated (printed) sensor
6 volume integrated sensor/electr. device
7 volume integrated (printed) sensor, base plane equaling building plane

Basic concept with some application scenarios discussed to be submitted for publication soon: Watch out in Sensors (http://www.mdpi.com/journal/sensors) for an OpenAccess-paper by T. Wuest, S. Wellsandt, D. Lehmhus, S. Bosse et al., hopefully to be published autumn this year.

Sensor Integration in AM.

An Attempt at Classification.

Further distinction w. r. t. sensor/sensor system production:
(a) entirely separate, (b) separate process & manufacturing system,
(c) separate process, integrated system, (d) same process

Level 1: Surface Integration
Sensors/sensor systems are positioned on part surfaces (flat/curved distinction).

a) b) c) d)

Level 2: 2D Volume Integration, on building planes
Similar to Level 1, but the planes are now the internal building planes.

Level 3: 2D Volume Integration, cross build. planes
Similar to Level 2, i. e. 2D systems, but these may transgress building planes.

Level 4: 3D Volume Integration
The sensor system is in itself of 3D geometry, i. e. the transgression of the building planes is a given thing.

Sensor Integration in AM

Case Studies from Literature.

	(a) entirely separate process	(b) sep. process & manufact. system	(c) sep process, integrad system	(d) same process
Level 1: Surface Integration	**[Hoe14]** **[Joh06]**	**[Pau12]** **[Hoe14]**		
Level 2: 2D in-plane Vol. Int.	**[Hoe14]**	**[She15]** **[Li_14]**		
Level 3: 2D Volume Integr.		**[She15]**		
Level 4: 3D Volume Integration	**[Hoe14]** **[Mac14]**	**[Joh06]**	**[Lop14]** **[Esp14]** **[Hoe14]**	

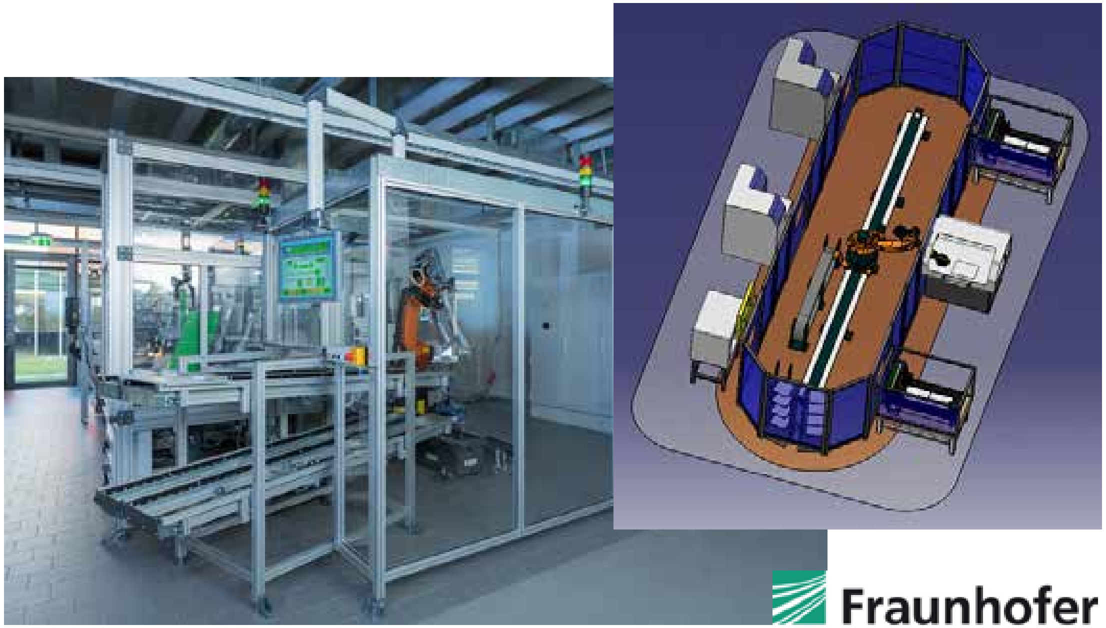
„Details of the references cited here are given in the annex of this presentation.“

AM Sensor Int. Technology Showcases

Level 1a/b: Printing functionality on AM parts.

AM parts are equipped with printed sensors as well as signal and data processing - part is 1a (electronics), part is 1b (printing of sensors, conductive paths).

> *„The concept combines several different processes not in a single manufacturing System, but in a dedicated manufacturing cell.“*



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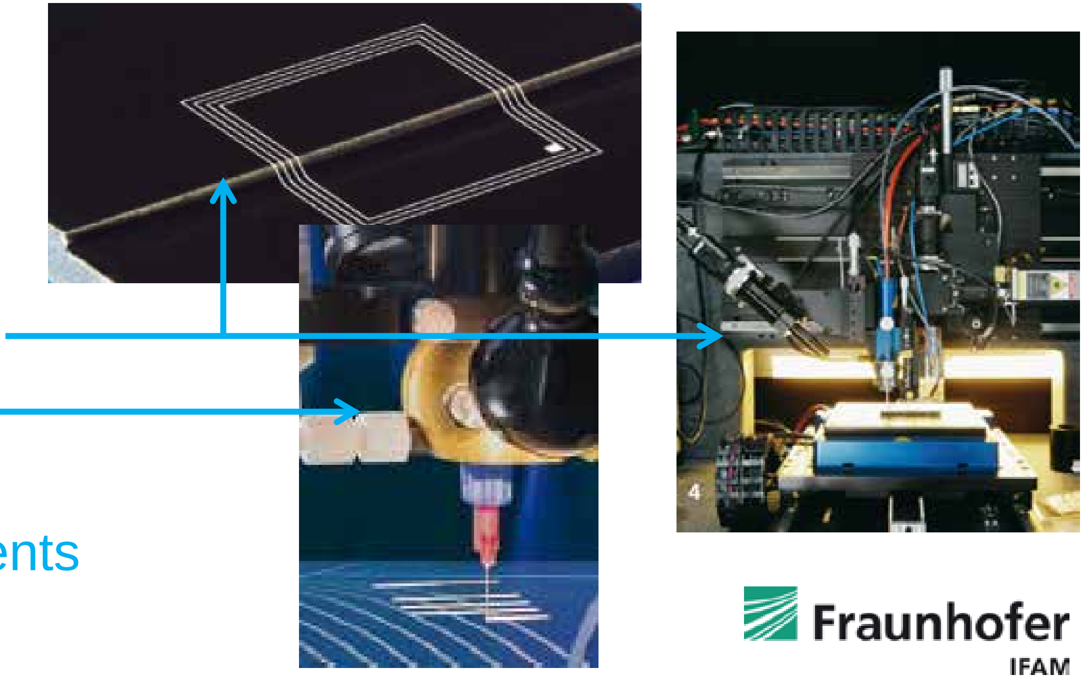
AM Sensor Int. Technology Showcases

Level 1a/b: Printing functionality on AM parts.

AM parts are equipped with printed sensors as well as signal and data processing - part is 1a (electronics), part is 1b (printing of sensors, conductive paths).

Integrated technologies:

- inkjet printing
- screen printing
- Aerosol Jet^{TM} printing
- microdispensing
- spray coating
- drying, thermal treatments
- handling system



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AM Sensor Int. Technology Showcases

Level 3a: RFIDs in metal AM parts.

Application background: Already today, in surgery, there are approaches towards automatically tracking all instruments and objects that might „get lost“.

Additional scenarios for RFID integration include scenarios in logistics as well as measures against product counterfeiting.

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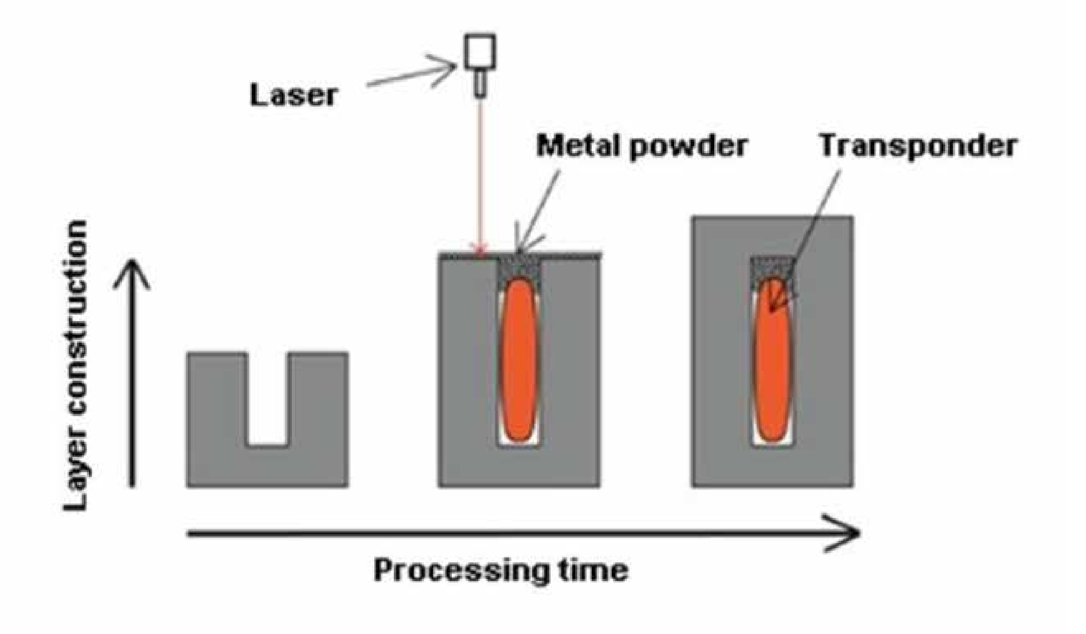
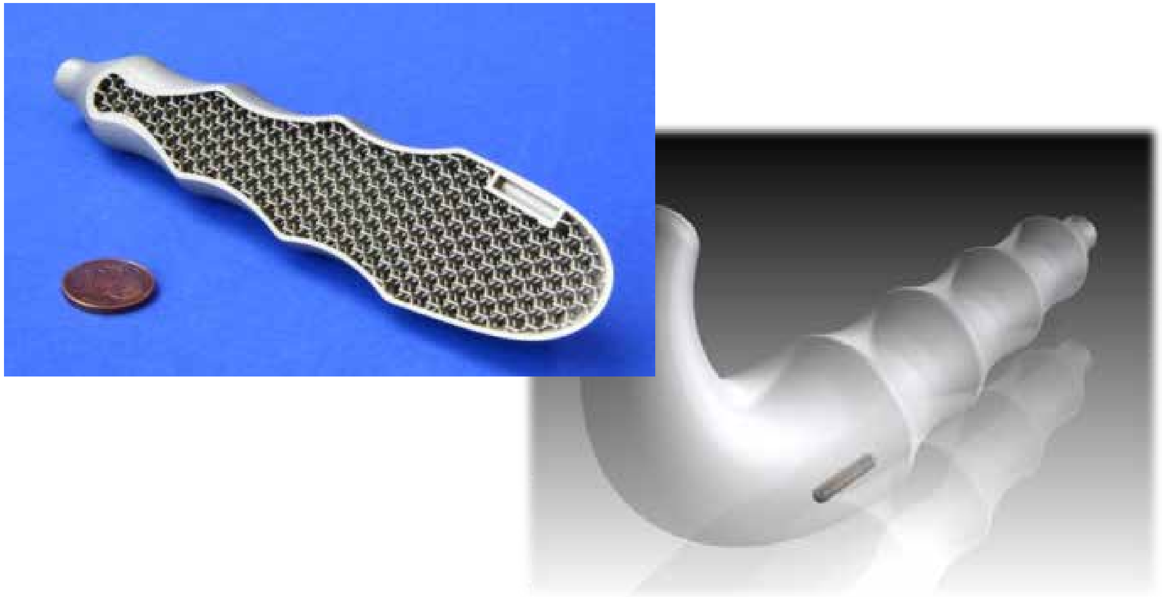


AM Sensor Int. Technology Showcases

Level 3a: RFIDs in metal AM parts.

Application background: Already today, in surgery, there are approaches towards automatically tracking all instruments and objects that might „get lost“.

Additional scenarios for RFID integration include scenarios in logistics as well as measures against product counterfeiting.

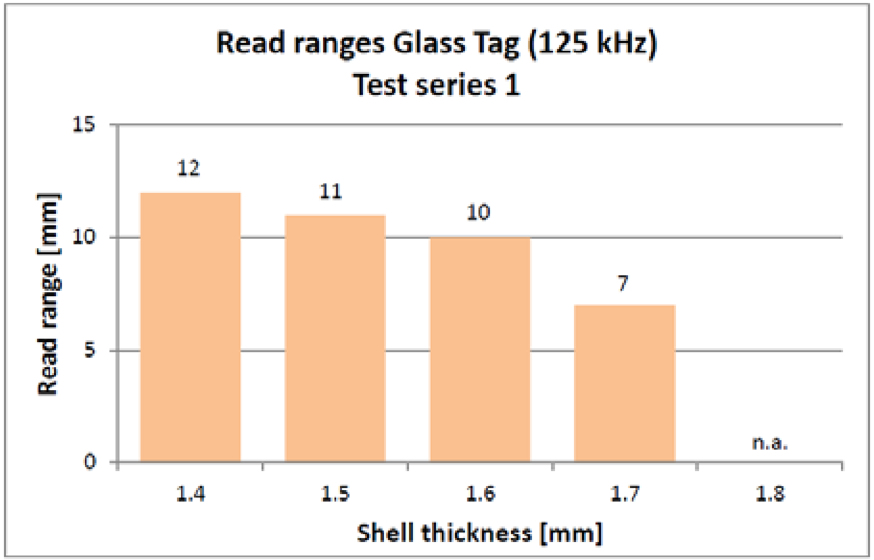


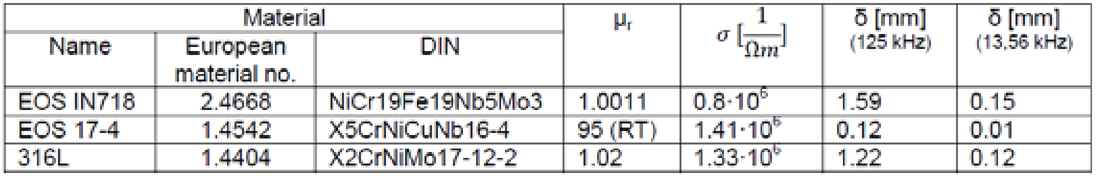
AM Sensor Int. Technology Showcases

Level 3a: RFIDs in metal AM parts.

Application background: Already today, in surgery, there are approaches towards automatically tracking all instruments and objects that might „get lost“.

Additional scenarios for RFID integration include scenarios in logistics as well as measures against product counterfeiting.





Material			μ_r	$\sigma\ [\frac{1}{\Omega m}]$	δ [mm] (125 kHz)	δ [mm] (13,56 kHz)
Name	European material no.	DIN				
EOS IN718	2.4668	NiCr19Fe19Nb5Mo3	1.0011	$0.8 \cdot 10^6$	1.59	0.15
EOS 17-4	1.4542	X5CrNiCuNb16-4	95 (RT)	$1.41 \cdot 10^6$	0.12	0.01
316L	1.4404	X2CrNiMo17-12-2	1.02	$1.33 \cdot 10^6$	1.22	0.12

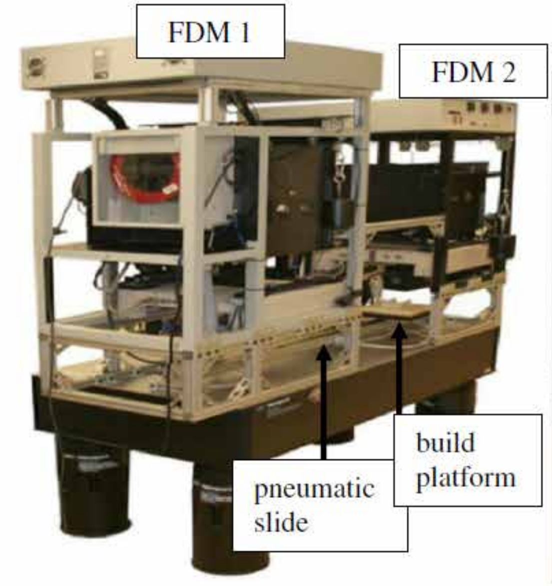
AM Sensor Int. Technology Showcases

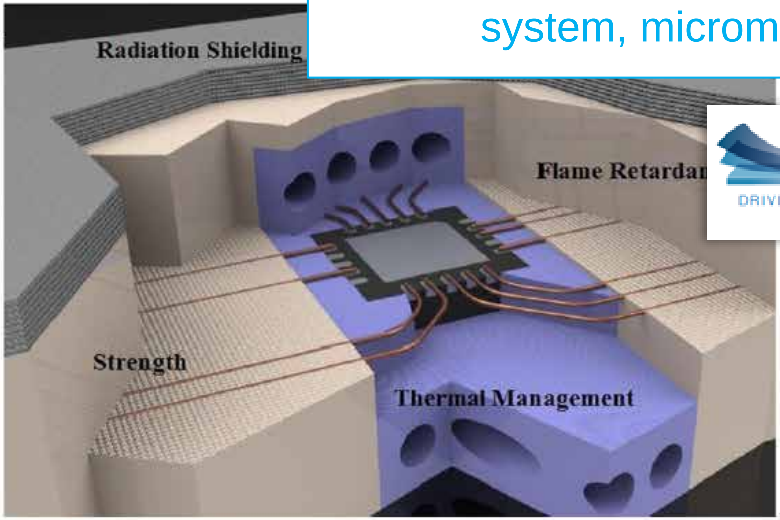
Level 4c: Integrated Manufacturing System.

Many activities in this field by University of Texas at El Paso, Ryan B. Wicker.

UTEP/Keck integrated manufacturing system:

Combining 2 FDM systems, wire embedding, component pick-and-place system, printing and/or microdispensing system, micromachining system etc.



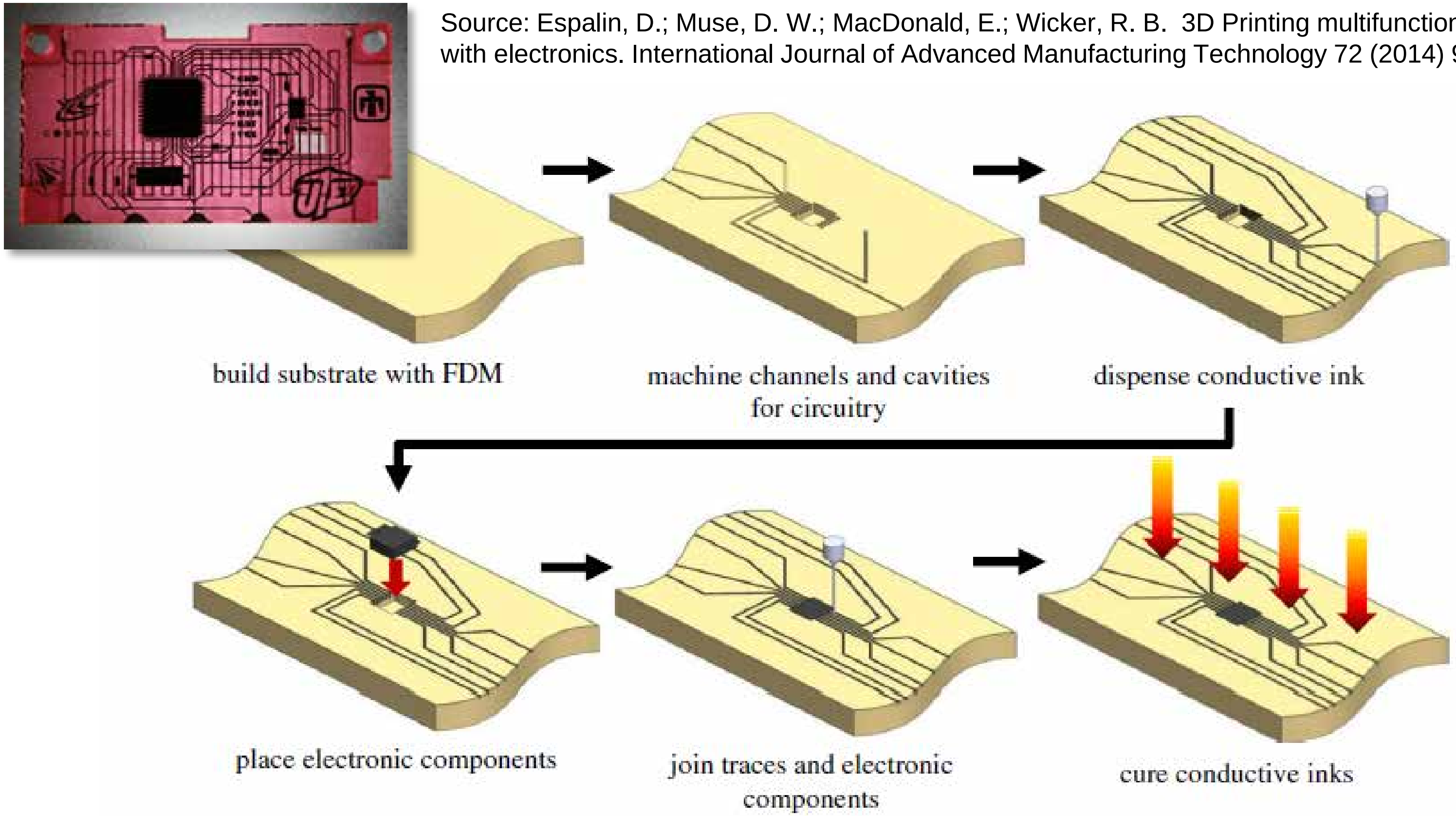


W.M. KECK CENTER
FOR 3D INNOVATION
DRIVING THE ADDITIVE MANUFACTURING REVOLUTION
2014-2015

Source: Espalin et al.,
3D printing multifunctionality:
structures with electronics.
Int. J. Adv. Manuf. Techn.
72 (2014) 963-978.

AM Sensor Int. Technology Showcases

Level 4c: Integrated manufacturing system.



Source: Espalin, D.; Muse, D. W.; MacDonald, E.; Wicker, R. B. 3D Printing multifunctionality: structures with electronics. International Journal of Advanced Manufacturing Technology 72 (2014) 963–978.

Business Cases: Why sensors in AM?

A vision: With PLM, AD and AM to CBM.

Based on integrated sensors, products constantly feed back information about their usage (a) to their manufacturer (b) into the cloud.

Manufacturer or cloud-based automated services evaluate the information and adapt the product design accordingly (AD input).

Whoever wants to make a product of this type, can download (a) the original version, (b) a generally optimized version, (c) a version optimized for his user group needs, or (d) a personalized version.

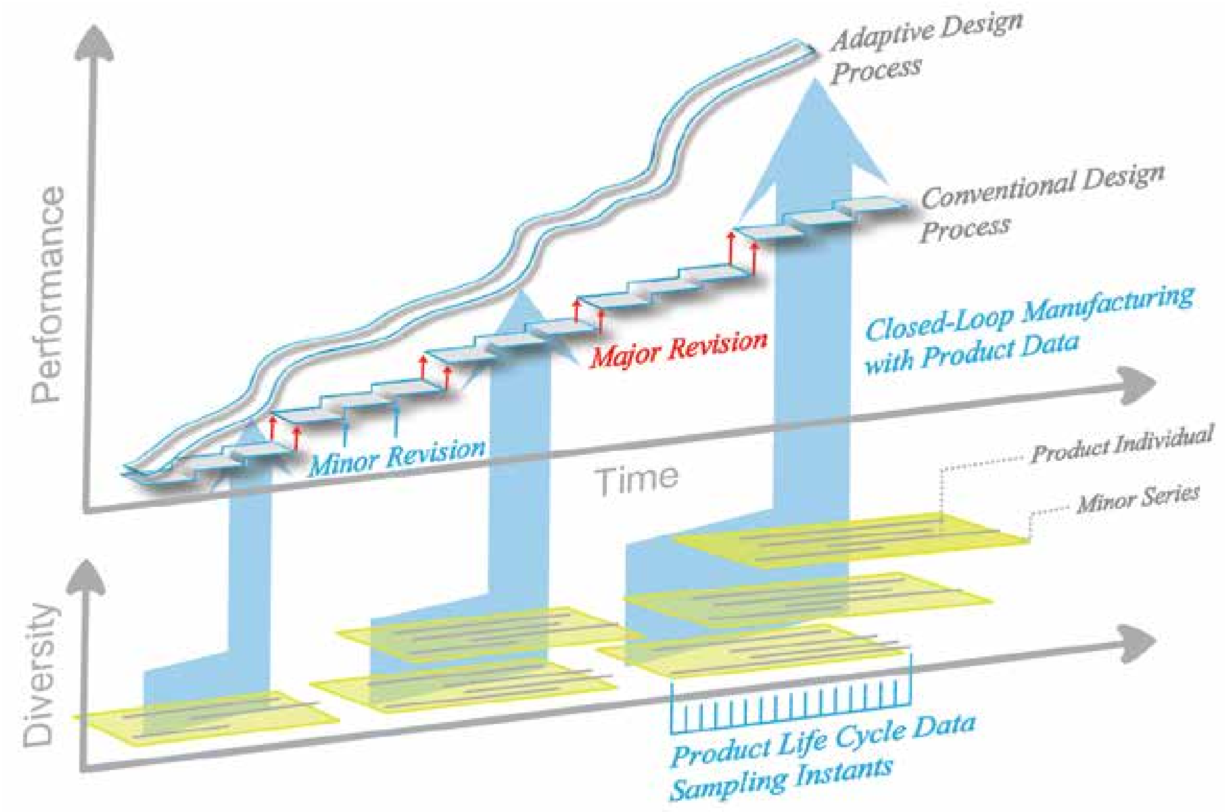
„Whoever wants to produce“ implies decentralized production at several facilities (not previously known) rather than classic concepts of production (product-specific manufacturing plants, specialized eq. etc.)

Business Cases: Why sensors in AM?

A vision: With PLM, AD and AM to CBM.

Changes in design and production process related to the joint PLM/ AD/AM approach:

A sketch.



Business Cases: Why sensors in AM?

A vision: With PLM, AD and AM to CBM.

Abbreviations explained:

PLM:	Product Life Cycle Management.
AD:	Automated Design.
AM:	Additive Manufacturing.
CBM:	Cloud-based Manufacturing.

Basic concept with some application scenarios to be submitted for publication soon: Watch out in Sensors (http://www.mdpi.com/journal/sensors) for an OpenAccess-paper by T. Wuest, S. Wellsandt, D. Lehmhus et al., hopefully to be published autumn this year.

Conclusion, Outlook I

Focus on Material Integration in General.

- Challenges (and thus research needs) remain e. g. regarding the integration processes, compatibility, durability, robustness and reliability on component- and data evaluation level.
- Energy supply is another challenge of primary importance.
- The ability of systems to cope with changes of their state must be developed further.
- Material-integrated systems require a holisitic perspective that must be reflected in design already and requires appropriate tools.
- Simulation and (virtual) test methods have to be developed to allow a ex ante-verification of safety levels even under conditions of system states changing.

Conclusion, Outlook II

Focus on Additive Manufacturing.

- Combining current development trends like customization an the rise of additive manufacturing on the one, smart everyday objects on the other hand, there is good reason for studying sensor integration in AM parts.
- Levels of sensor integration can be distinguished by level of complexity, starting from surface application to cross-layer volume integration, or by in-process vs. separate production of sensors.
- In principle, AM processes that allow easy switching of materials are favoured for full integration.
- First lab scale unis, however, are designed as hybrid manufacturing systems, integrating several processes in a single system.

Announcements

Want to stay up to date? Join the LinkedIn-Group

Sysint - System-Integrated Intelligence

www.linkedin.com/grp/home?gid=5144092

SysInt 2016

3rd Int. Conference on System-integrated Intelligence

June 13th-15th, 2016, Paderborn, Germany

Enabling technologies from computer science to MEMS to materials, applications in perceptive robotics, SHM, intelligent production & logistics.

Deadline Call for Papers **November 20th, 2015**

Proceedings in Procedia Technology directly following the event, additional post-conference Special Issues in suitable journals planned.

Find out more soon at www.sysint-conference.org

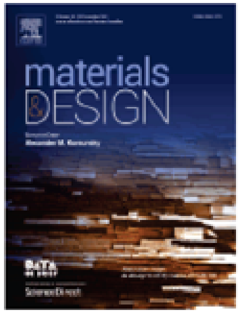
MS&T 2016

„Additive Manufacturing (AM) of Composites and Complex Materials“

October 23rd-27th, 2016, Salt Lake City, USA

MS&T16
MATERIALS SCIENCE & TECHNOLOGY

Virtual Special Issue of
Materials & Design
linked to the symposium



ELSEVIER

Impact Factor:
3.501 JCR 2014

Homo-/heterogen. composites, functionally graded materials, sensor integration, ICME, …

Additionally, aspects like implications of AM for production engineering on a wider scale incl. cyber security issues will be considered.

Deadline Call for Papers: March 15th, 2016

Find out more soon at www.matscitech.org

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