Florian Ziegler, 14.09.2023, microtec nord 2023

PowderMEMS - Technology for innovative MEMS
The Fraunhofer-Gesellschaft
Application-oriented research for the benefit of business and for the benefit of society

30,000 employees

76 institutes and research centers

More than 70% is derived from contracts with industry and from publicly financed research projects.

Almost 30% is contributed by the German federal and states Governments

Finance volume

2021

2.5 billion €

2.9 billion €

Major infrastructure capital expenditure & defense research

Contract research
Fraunhofer ISIT - the Institute for Silicon Technology
Research and development center for power electronics and MEMS

In Itzehoe since 1996
Competence Center MEMS in Kiel (CAU)
Cooperation with Heide (FHW)

Prof. Dr. Holger Kapels
Acting Managing Director

Prof. Dr. Marco Liserre
Dep. Managing Director

160 employees
(+ 40 students)

Initial Investment:
125 million €
- 250 million € Industry
- 42 million € Cleanroom II
- 20 million € FMD*

Budget
27 million €

Certified according to
ISO 9001:2015

Location Partner

Spin-offs

*FMD – Forschungsfabrik Mikroelektronik Deutschland
The heart of the institute: Our clean rooms and labs

- Professional semiconductor production line for development and production for 200 mm wafers on 2500 m² clean room area
- Professional MEMS production line for development and production for 200 mm wafers on 1000 m² clean room area
- Chemical mechanical polishing (CMP), grinding and sawing on 300 m² clean room area
- Various development and measurement laboratories on 900 m²
- Development and pilot production line for lithium polymer accumulators
Our fab
s.fhg.de/isit360
PowderMEMS
Wafer-level fabrication process for 3D functional microstructures

1. Dry filling of microcavities
2. Solidification by atomic layer deposition
3. Substrate conditioning for post-processing

**Unique set of properties:**

- Production of miniaturized magnets possible:
  - Lateral dimensions: approx. 30 to 4000 µm
  - Depth approx. 30 to 1000 µm
- Precise wafer level integration
- Wide choice of powder material
- Low process temperature (75 to 300 °C)
- No organics or sintering involved
- BEOL compatible
- Integration before / after / within standard manufacturing flow possible

More details on the PowderMEMS manufacturing process:
https://doi.org/10.3390/mi13030398
PowderMEMS
Current areas of application

- Wafer-level packaging
- Micromagnets
- Energy harvesting
Wafer-level chip scale packaging for environmental Sensors
Wafer level packaging of porous caps for environmental Sensors

Processing with only two mask layers

1. 1st lithography and etching of cavities using DRIE.
2. Insertion of dry, μm-sized particles.
3. In-situ agglomeration of the loose particles by ALD.
4. 2nd lithography on the backside and etching of the silicon by DRIE.
PowderMEMS WLCSP - connections on frontside or via TSV possible
PowderMEMS cap does not reduce sensitivity
Demonstrator: humidity sensor SHT35 with PowderMEMS cap
Energy harvesting
Energy Harvesting
A road to battery-free IoT devices

Thermogenerator
- Energy harvesting from thermal gradients.

Solar cells
- Energy harvesting light

Sweet spot:
- Non of the other sources available
- Hard to reach / costly to replace battery
- Size / costs matters

Piezoelectric energy harvesting
- Harvests energy from vibration/shocks
What differentiates us?

General Challenges for vibrational MEMS Energy Harvester

- „High“ resonant frequency
- Resonant frequency fixed by design
- High quality factor – low power output out-of-resonance

\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}}
\]

USP Fraunhofer ISIT magneto-mechanical MEMS Energy Harvester

- Integration of magnets: high magnetic coupling forces
- Integration of high-density materials, e.g. tungsten: increased mass compared to conventional Si
- Integration of AlScN:

\[
FOM |\hat{E}_{\text{max,out}}| \approx d_{31} g_{31} = \frac{d_{31}}{\varepsilon \varepsilon_r}
\]

<table>
<thead>
<tr>
<th></th>
<th>AlN</th>
<th>AlScN</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_{31}) (pm/V)</td>
<td>1,97</td>
<td>5,45</td>
</tr>
<tr>
<td>(\varepsilon_r)</td>
<td>10,5</td>
<td>16,9</td>
</tr>
<tr>
<td>FOM ((10^{-12} \text{ m}^2/\text{J}))</td>
<td>0,042</td>
<td>0,2</td>
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</table>
Versatile PowderMEMS energy harvesting platform

Tuning of mechanical properties in the same design

### Top View

- Si
- NdFeB
- Epi-Poly
- AlN

### Cross section

**Tungsten content (vol.%)**

<table>
<thead>
<tr>
<th>Powder material</th>
<th>Density (g/cm³)*</th>
<th>Resonance frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure silicon</td>
<td>2.33</td>
<td>1.41</td>
</tr>
<tr>
<td>NdFeB</td>
<td>3</td>
<td>1.24</td>
</tr>
<tr>
<td>Tungsten</td>
<td>8</td>
<td>0.77</td>
</tr>
</tbody>
</table>

*For the seismic mass, powder filling factor 42%*
Harvester with integrated NdFeB micromagnet array
One MEMS device - Several applications

- Energy harvesting from rotating magnets at excitation frequencies far away from resonance.
- Current sensing in resonance with exceptionally high sensitivity of 43.4 kV/T.
- Zero-power wake-up using one of the excitation schemes shown above.

https://doi.org/10.3390/mi13060863
https://doi.org/10.1016/j.sna.2019.111560
https://doi.org/10.3390/mi13030407
https://doi.org/10.1109/ICM54990.2023.10101917
Micromagnets
PowderMEMS enables integration of 3D hard and soft micromagnets
Custom shape, different materials and arrangements on wafer level

Example: NdFeB magnets in silicon frame

- Custom geometries and arrangements.
- Mechanically stable and easy to handle.
- Various materials, e.g. NdFeB, SmCo, Ferrite, Fe, etc.
- Particles are protected by ALD layer.
- Various substrates suitable, e.g. Si, glass, etc.

https://doi.org/10.1109/TRANSDUCERS.2019.8808804
Magnetic properties of hard magnetic PowderMEMS micromagnets

Example: two NdFeB powders with mean particle size $d_{50} = 5 \, \mu m$ and $d_{50} = 25 \, \mu m$

- More information on durability in open access publication [https://doi.org/10.3390/mi13050742](https://doi.org/10.3390/mi13050742)
PowderMEMS micromagnets - application in Hall and xMR sensors
High miniaturization and cost-effective wafer-level integration

Conventional back-biased setup

- Discrete mounting of the magnet
- Relatively large magnet
- Magnet must be placed precisely according to its magnetization

Integrated PowderMEMS magnet for back or in-plane bias

- Modification of existing Hall or xMR sensor designs
- Backside-integration saves wafer device area
- Wafer-level low-temperature process (75 °C to 300 °C)
- Flexible field shaping by custom magnet design
- Reduction of package size
Demonstrator: Integrated PowderMEMS micromagnets for magnetic sensors
Back biased 3D Hall sensor as proof of concept

- Rotation detection of gear wheel demonstrated with 3D Hall sensor and integrated PowderMEMS magnet
- PowderMEMS allows for magnetic field shaping
- Advantage of frame-like field shaping for back-bias:
  - Static field at sensor is close to zero
  - Higher sensitivity due to higher sensor gain
Demonstrator: Integrated PowderMEMS micromagnets for magnetic sensors
Back biased 3D Hall sensor as proof of concept

Si chip with integrated micromagnet

https://doi.org/10.3390/mi13020235
Wafer-level inspection tools available at Fraunhofer ISIT

Qualitative and Quantitative testing equipment

- Vibrating scanning magnetometer for B-H loop determination on chip level.
- Magneto-optical microscope for fast qualitative inspections and semi-quantitative determination of $B_z$ on wafer-level.

- Developed within Fraunhofer: Hall-sensor-based tool with automatic positioning for fast quantitative 3D measurements on wafer-level.

Line and 3D measurements of a frame-type magnet at a distance of 360 µm.
Group Agglomerated Microsystems

Head of Group  
Dr. Björn Gojdka

Technology  
Dr. Thomas Lisec, Finn Klingbeil, Mani Teja Bodduluri

Simulations  
Dr. Niels Clausen

Non-Magnetic application  
Dr. Ole Behrmann, Julia Cipo

Energy Harvester  
Dr. Torben Dankwort, Minhaz Ahmed

Integrated Micromagnets  
Florian Ziegler

Students  
Philipp Hickisch, Tina Höppner, André Lange-Clary, Niklas Kyoushi
Thank you for your attention!

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