# Novel Back-End-of-Line Compatible Method for Integration of Inductances With Magnetic Core in Applications Like DC/DC Converters

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# Agenda

- Motivation
- Fabrication process
- Finite element method (FEM) simulations
- Characterization of test samples
- Development of a 20MHz DC/DC converter with inductor test samples
- Summary and future steps



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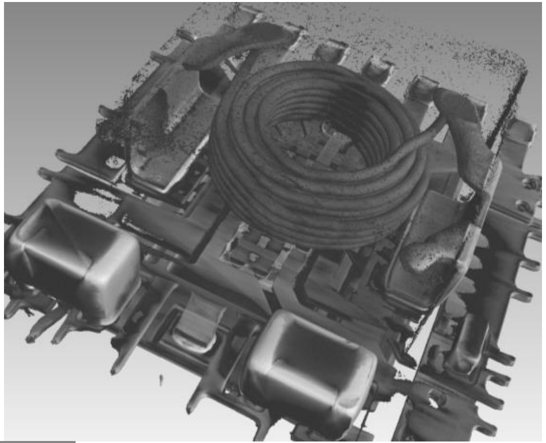
# Motivation

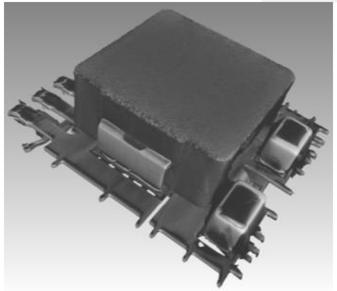
- Wide bandgap devices enable higher switching frequencies with low losses
- Increasing demand of smaller passive components
- Advantages of integrated solutions –

  higher efficiency, higher reliability and smaller packages

- Advantages of ISITs PowderMEMS technology:
  - Due to low process temperature inductors can be fabricated on silicon, PCB and ceramic substrates
  - Intrinsic structure of the core material suppresses eddy currents – suitable for high frequency applications
  - Core material with high thermal stability – can be used for temperature critical solutions like GaN and LED drivers

Today's state-of-the-art:





Out off the shelf:

**Variable step down regulator module**

- Voltages below 50 V
- Max. power 36 W
- Switching frequency 200-800kHz
- Max. operating temperature 125°C
- Package size 10mm x 14mm x 5mm





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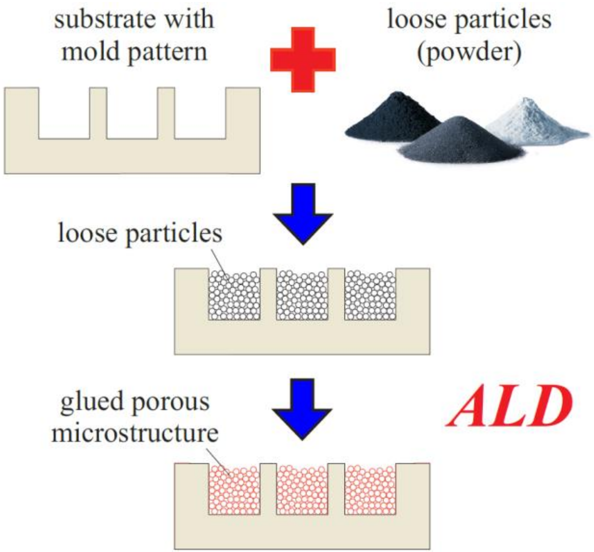
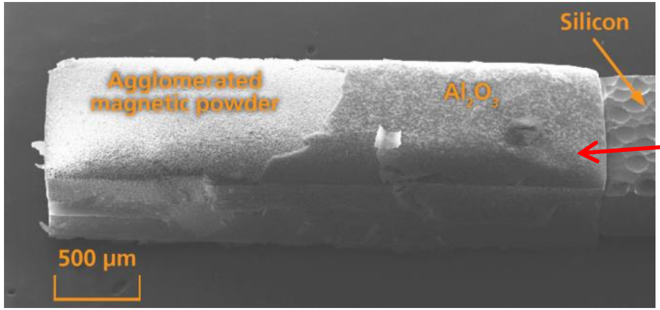
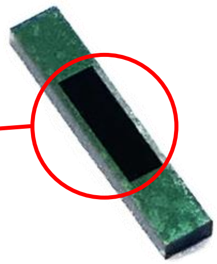
# Our concept: Innovative BEOL-compatible particle based process

- Main processing steps:
  - Creating cavities on silicon substrate (8 inch) by deep reactive ion etching (DRIE)
  - Filling of micro mold pattern with micron-sized soft magnetic particles (dry powder)
  - Atomic layer deposition of 75nm $Al_2O_3$ at 75°C to agglomerate the loose particles to rigid porous structures

- Since no pressure is applied during agglomeration, the particles have only a point-to-point connection between each other. The remaining surface of each particle is covered by the oxide layer.



SEM image of a free-standing soft magnetic powder core

T. Lisec, T. Reimer, M. Knez, S. Chemnitz, A. V. Schulz-Walsemann, and A. Kulkarni, "**A Novel Fabrication Technique for MEMS Based on Agglomeration of Powder by ALD**," Journal of Microelectromechanical Systems, vol. 26, no. 5, pp. 1093–1098, Oct. 2017.

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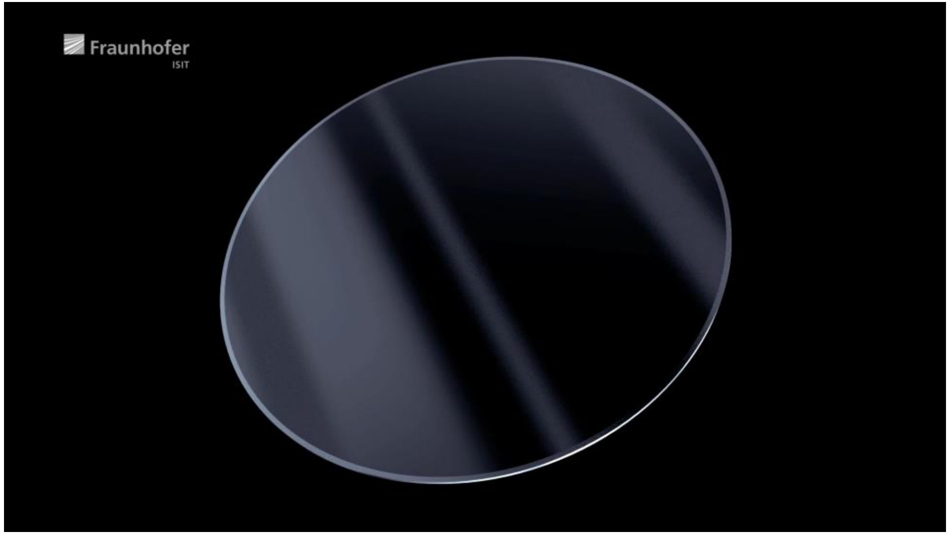
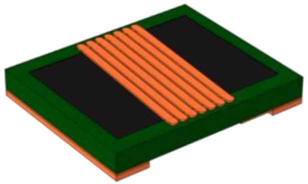
# The fabrication process !




Full video about PowderMEMS Technology at Fraunhofer ISIT:
https://www.isit.fraunhofer.de/content/dam/isit/de/video/Powder MEMS Technology.mp4

Basic test structure

First prototype with hand-wound wire



Future samples with TSVs

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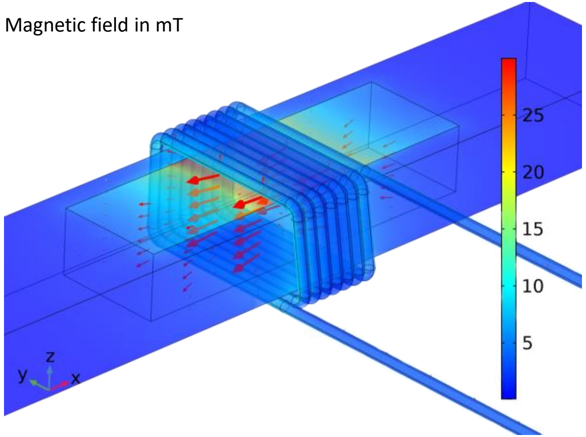
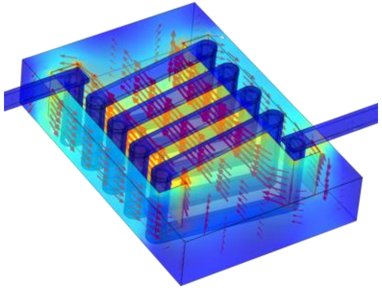
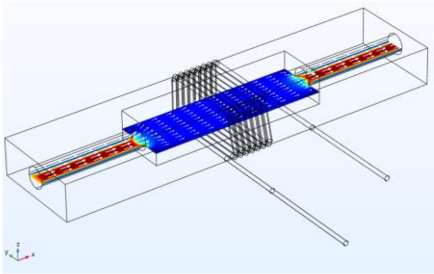
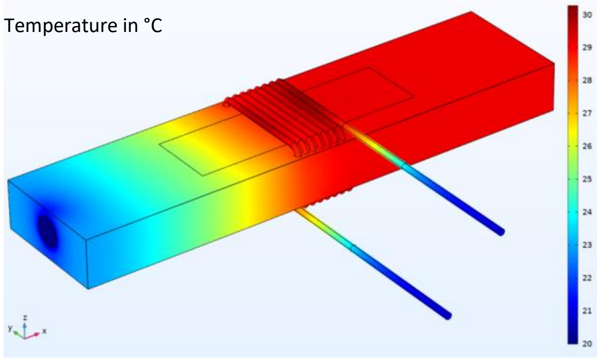
# The development of FEM simulations

- Implementation of the fabricated sample in Comsol Multiphysics
  - Geometry, meshing, constraints, etc.
- Electro-magnetics investigations
  - Parameter tuning for the „new“ core material
  - Calculations (L,R,Q) and analysis / optimization of new designs
- Thermal investigations
  - Estimation of the expected component temperature depending on the current
  - Thermal optimization, cooling pads to PCB
  - Possibility for active cooling with gas or liquid flow through the porous structure











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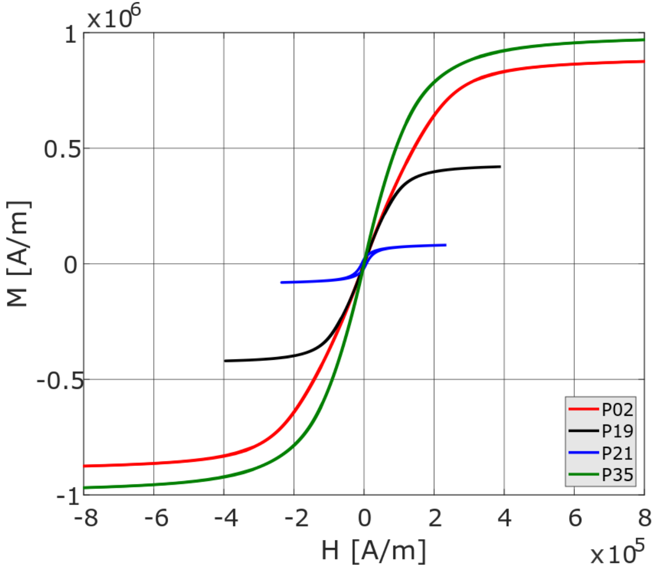
# A wide spread of different powders was investigated to find the right one

- Core material fabricated from various powders from different suppliers (in total 21 powder samples + 8 mixed powders)

- Particles sizes between 1-100µm

- Measurements on a Vibrating Sample Magnetometer (LakeShore VSM 7400)

| | Min | Max |
|---|---|---|
| $B_{sat}$ [T] | 0.34 | 2.16 |
| µ | 2.6 | 7.3 |




Carbonyl iron powder (P02), NPX Insultating Powder FeSi (P19), BaZnCuCo (P21), mixed powder (P35)

M. Paesler, T. Lisec and H. Kapels, "**Novel back-end-of-line compatible method for integration of inductances with magnetic core on silicon**," CIPS 2020; 11th International Conference on Integrated Power Electronics Systems, Berlin, Germany, 2020.

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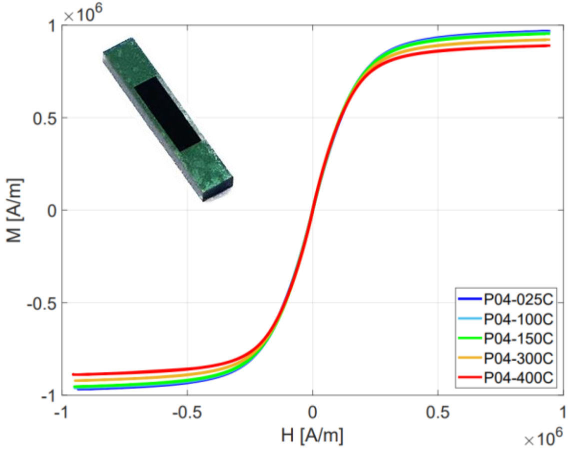
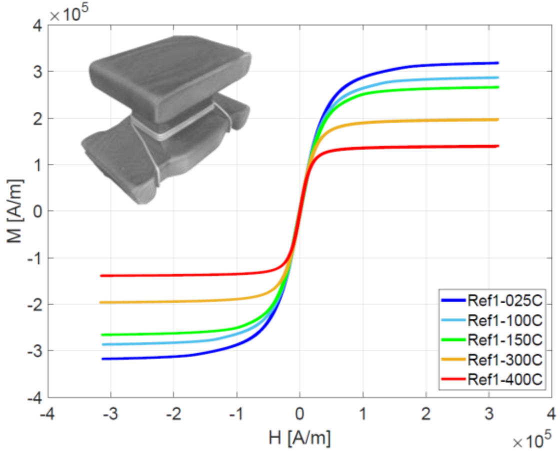
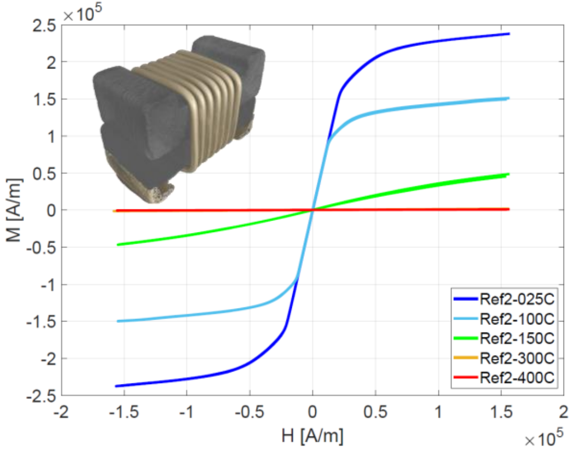
# Much better temperature stabilty compared to standard inductors

VSM measurements up to 400°C core temperature:

- ISIT sample P04: Nearly no degradation
- Commercial product 1: Noticable degradation above 150°C
- Commercial product 2: Significant degradation above 100°C







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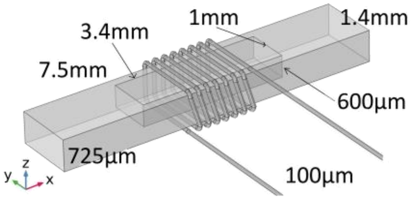
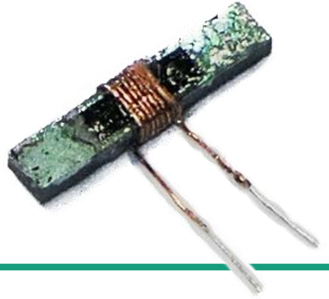
# Characterization of each sample by impedance analyzer

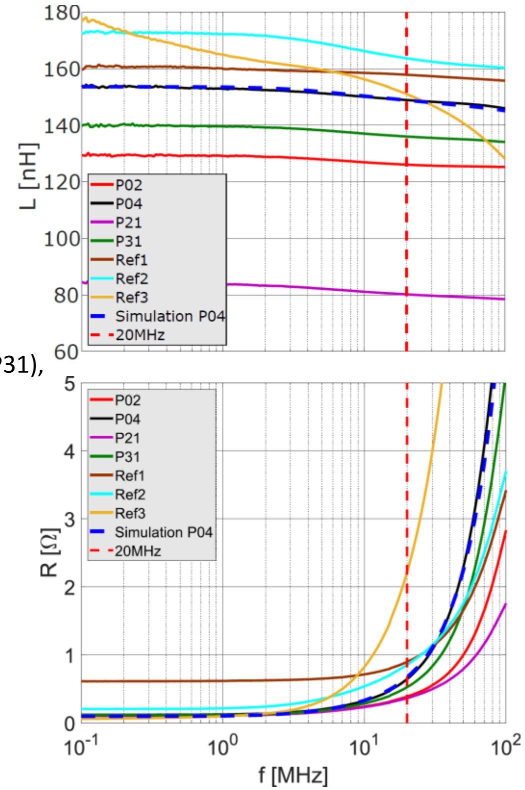
- Measurements on an impedance analyzer (Agilent 4294A) at 100kHz - 100MHz
- 8 turns of copper wire (100µm diameter) fixed with glue on the sample
- Simulated result of P04 matches the measurement results

| @ 20MHz | with core | | air core |
|---|---|---|---|
| | Min | Max | |
| L [nH] | 86 | 161 | 60 |
| R [Ω] | 0.37 | 1.40 | 0.31 |
| Q | 13 | 41 | 24 |



Carbonyl iron powder (P02, P04), BaZnCuCo (P21), mixed powder (P31), Commercial product (Ref1,2,3)







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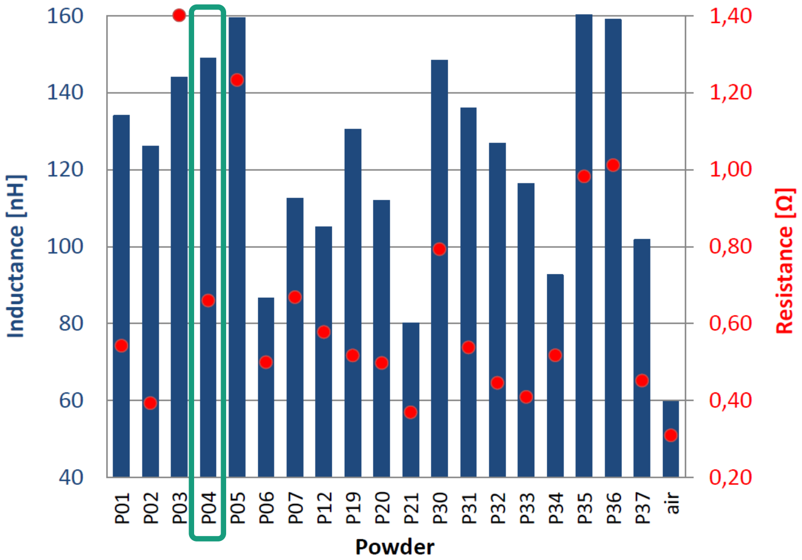
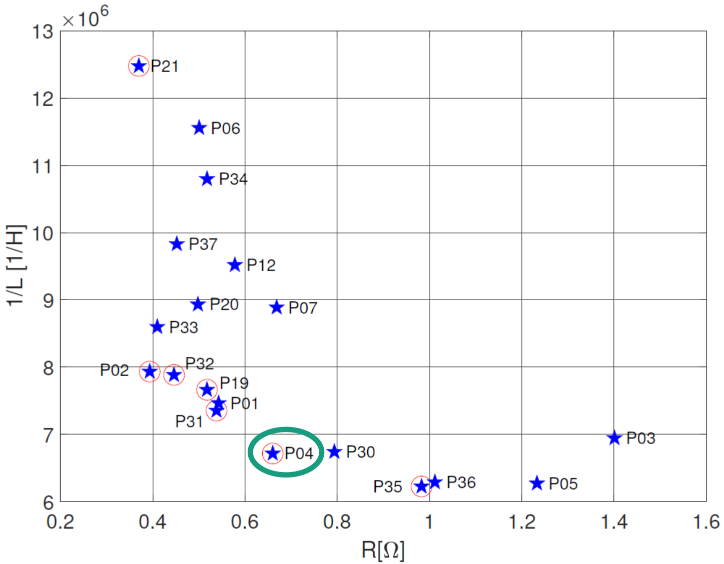
# Application specific best-fit in inductance & resistance

- In-depth analysis for 20MHz
  - Pareto optimal samples (red circle - P02, P04, P19, P21, P31, P32, P35)
  - Powder selection depending on the application (higher inductance vs. smaller resistance)
  - Sample P04 is picked for the following experiment on a DC/DC converter



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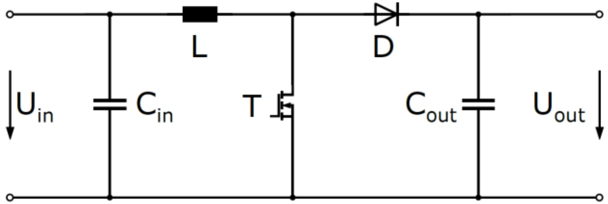
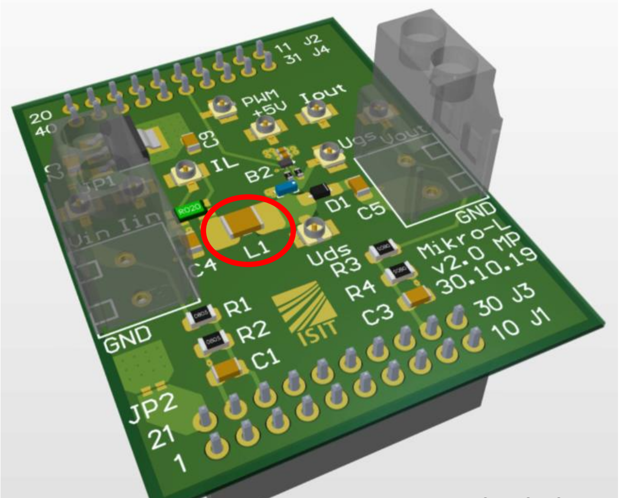
# Application evaluation in high-frequency DC/DC converter

- Topology: boost converter
- Components:
  - GaN FET (EPC8009)
  - GaN driver IC (LMG1020)
  - Schottky diode (DB2W40200L)

| Paramter | Value |
| --- | --- |
| Input voltage | $U_{in}$ = 15V |
| Fixed duty cycle | D = 0.4 (open loop) |
| Switching frequency | $f_{sw}$ = 20MHz |
| Inductor (Sample P04) | L = 150nH and R = 0.66Ω @ 20MHz |
| Load | R = 50Ω |
| Output voltage (expected) | $U_{out} = U_{in} \cdot \frac{1}{1-D} = 25V$ |
| Output power (expected) | $P_{out}$ = 12.5W |




PCB: 40x52mm

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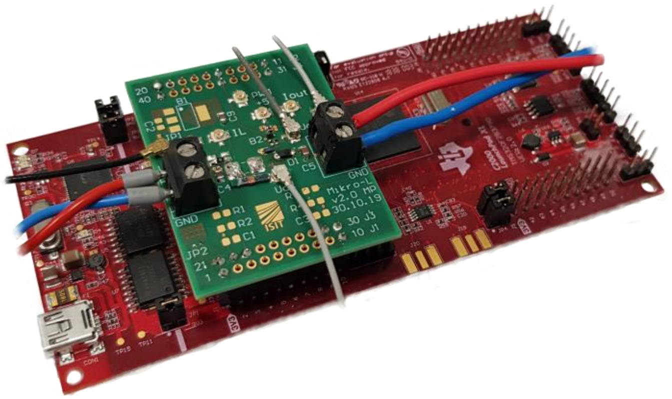
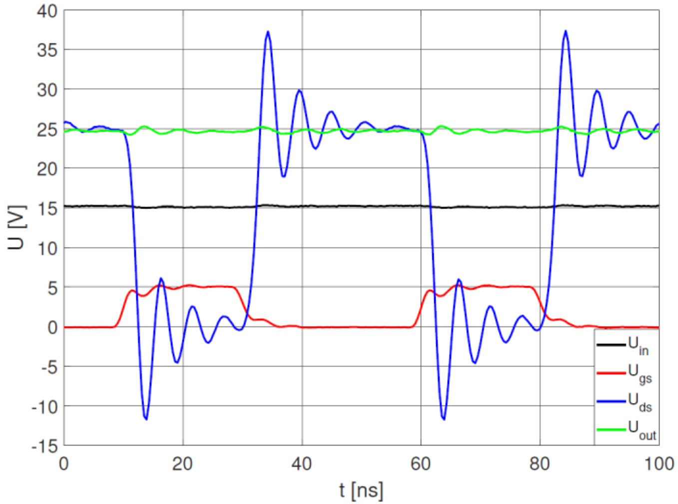
# DC/DC converter with ISIT inductor shows desired behaviour

- Control + PWM generation via C2000 LaunchPadXL (TI)
- Voltage feedback on ADC inputs (optional)
- Efficiency of the DC/DC converter board (measured)
  - $\eta = \frac{P_{out}}{P_{in}} \approx \frac{11.90W}{13.74W} \approx 86.8\%$






**Measurement results at 20MHz (T = 50ns):**

**Input voltage (15V)**

**Gate-Source voltage (0V → 5V)**

**Drain-Source voltage (0V → 25V)**

**Output voltage (25V)**


M. Paesler, T. Lisec and H. Kapels, "**Novel Integrated BEOL Compatible Inductances for Power Converter Applications**," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020.



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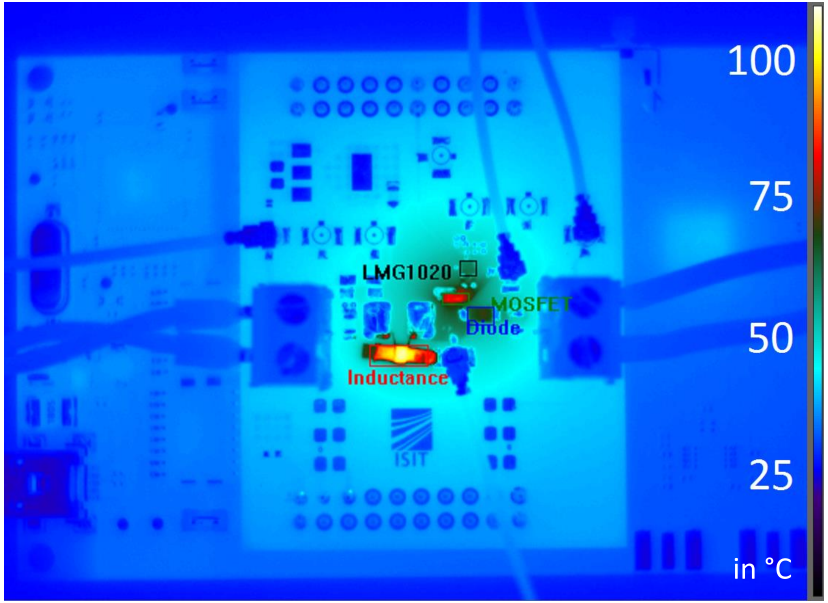
# Inductor concept successfully verified in application

- Total power loss (measured): 1.8 W
- Loss distribution verified with LTSpice simulations in this operating point
- Thermal measurements via IR camera

| Component | Power loss (simulated) | Max. temperature (measured) |
|---|---|---|
| Inductor | 802 mW | 108°C |
| GaN FET | 837 mW | 86°C |
| Diode | 241 mW | 69°C |
| Driver IC | | 63°C |

- Proper thermal connection between inductor and PCB (only soldered wire connection) easily improves max. temperature (compared to the pad connections between GaN FET and PCB)

Infrared image of FLIR A655sc



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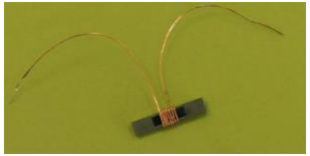
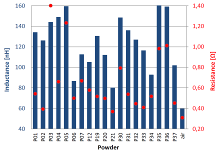
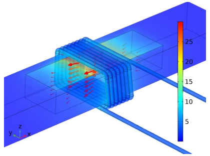
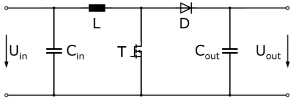
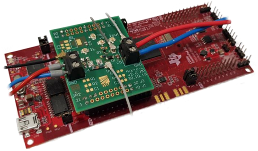
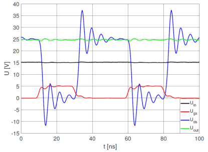
# Summary: Micro-inductances for DC/DC converter

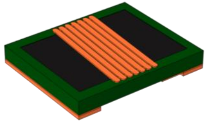
- Development and investigation of **Micro-inductances** (80-200nH) for **high-frequency applications** (1-80MHz)
- Development of **simulations tool chain** and generation of **material parameter** for future designs
- Measurements as proof-of-concept of a **DC/DC converter (20MHz) with micro-inductance**

- Objective: Proper integration of inductor and further components like GaN FET, diodes etc. on the same substrate
  - Increase of power density
  - Reduction of parasitic effects
  - Optimized thermal and cooling system
  - „Power supply on-a-chip“
  - Optimized inductor and transformer designs

**Next steps:**



- Realization of inductors with integrated wiring based on vertical feedthroughs
- Building up a DC/DC converter on those devices
- Fully integrated solution



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# Thank you for your attention!


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