

Design and Fabrication of Air-core Inductors for Power Conversion

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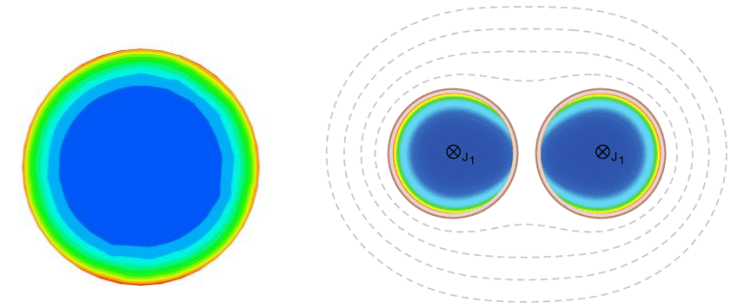
$$f(x+\Delta x) = \sum_{i=0}^{\infty} \frac{(\Delta x)^i}{i!} f^{(i)}(x)$$

$$\int_a^b \varepsilon \Theta + \Omega \int \delta e^{i\pi} = \{2.7182818284\}$$

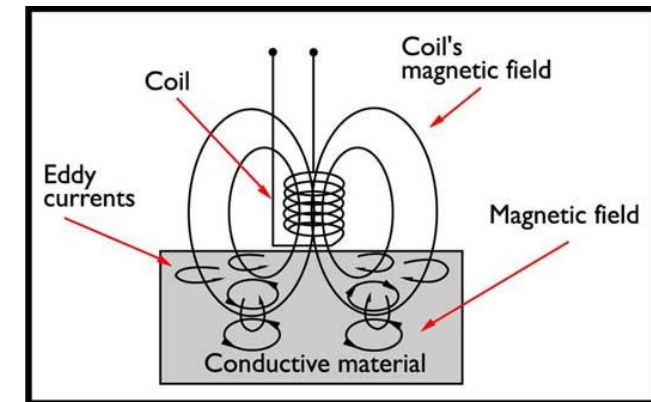
PwrSoC Inductor

- ❑ CMOS-compatible
- ❑ Small footprint ($\sim 1\text{-}2\text{ mm}^2$)
- ❑ High frequency (30–300 MHz)
 - Losses caused by eddy current effects
 - Electromagnetic interference (EMI)
 - $Q > 10$, 1-100 nH, 1-2A

Eddy current effects



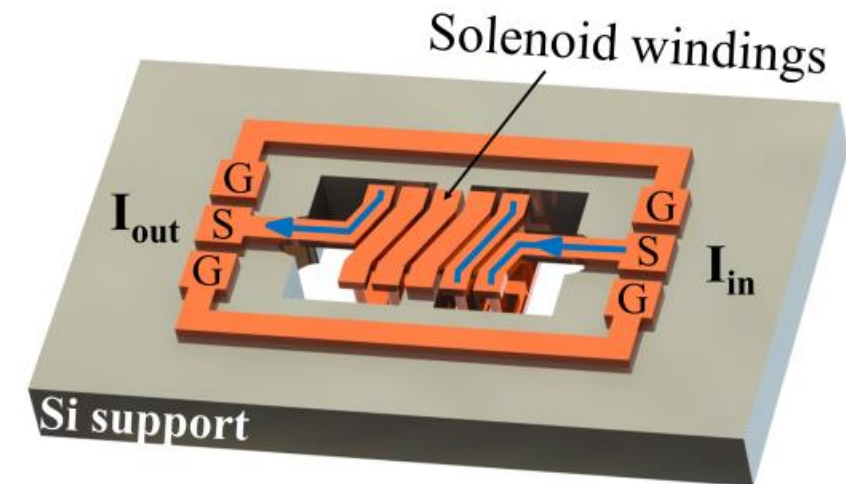
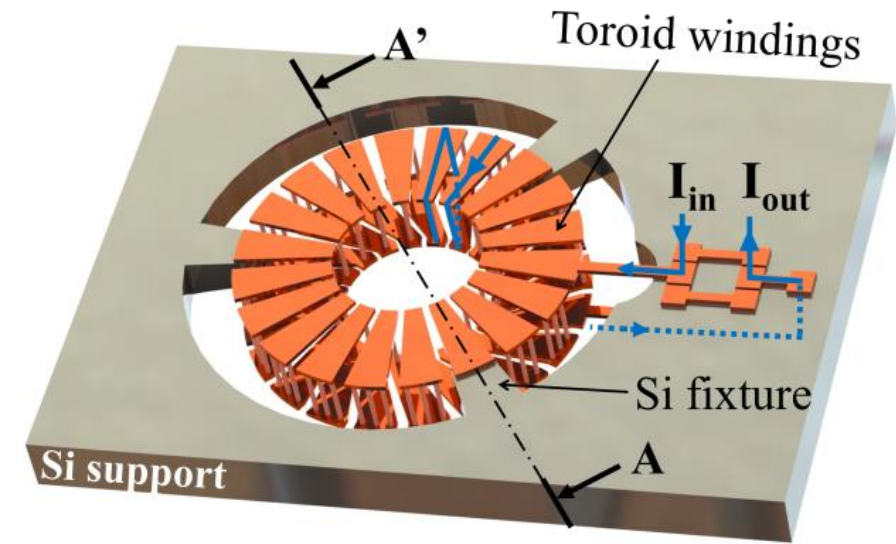
Skin effect Proximity effect



Eddy current losses in substrate

Our Aims

- 2D & 3D inductor for PwrSoc
 - Spiral
 - Solenoid
 - Toroid for low EMI
 - Transformer
 - Universal core geometry
- Custom inductor design
- TSV & footprint
- CMOS compatible
- Robust



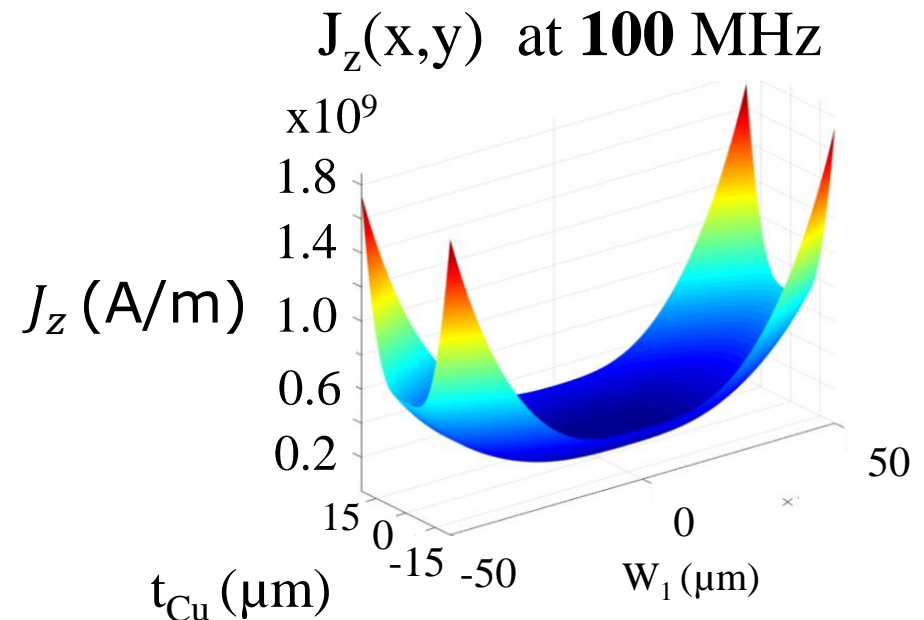
Inductor Modeling

- ❑ Inductance and resistance are frequency dependent due to eddy current effects.
- ❑ Inductance $L = L_{\text{external}} + L_{\text{internal}}$
- ❑ Equations:

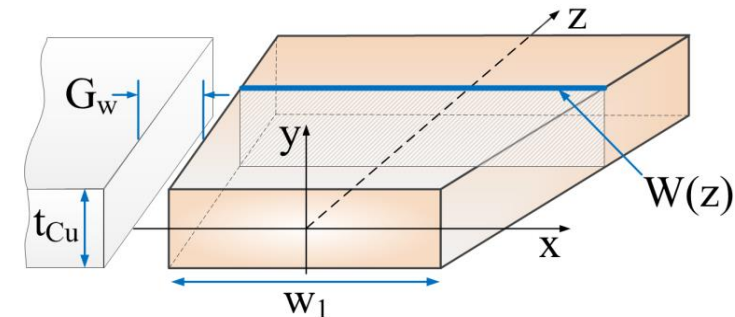
$$J_z(x, y) = C \cdot \text{Cosh}(k(z) \cdot x) \text{Cosh}(l(z) \cdot y)$$

$$L = \frac{N^2 h \mu_{\text{air}}}{2\pi} \ln\left(\frac{R_o}{R_i}\right) + \frac{R_o + R_i}{2} \mu_0 \left[\ln\left(8 \cdot \frac{R_o + R_i}{R_o - R_i}\right) - 2 \right] + \frac{\mu_0}{2} \frac{\iiint |\mathbf{H}|^2 dV}{\iint \mathbf{J} dS}$$

$$R_{AC} = 2\rho \frac{\iiint |J|^2 dV}{\iint J dS} \quad \nabla \times \mathbf{J} = -\rho \mu_0 \frac{\partial \mathbf{H}}{\partial t} \quad Q = \frac{\text{Im}(Z)}{\text{Re}(Z)}$$

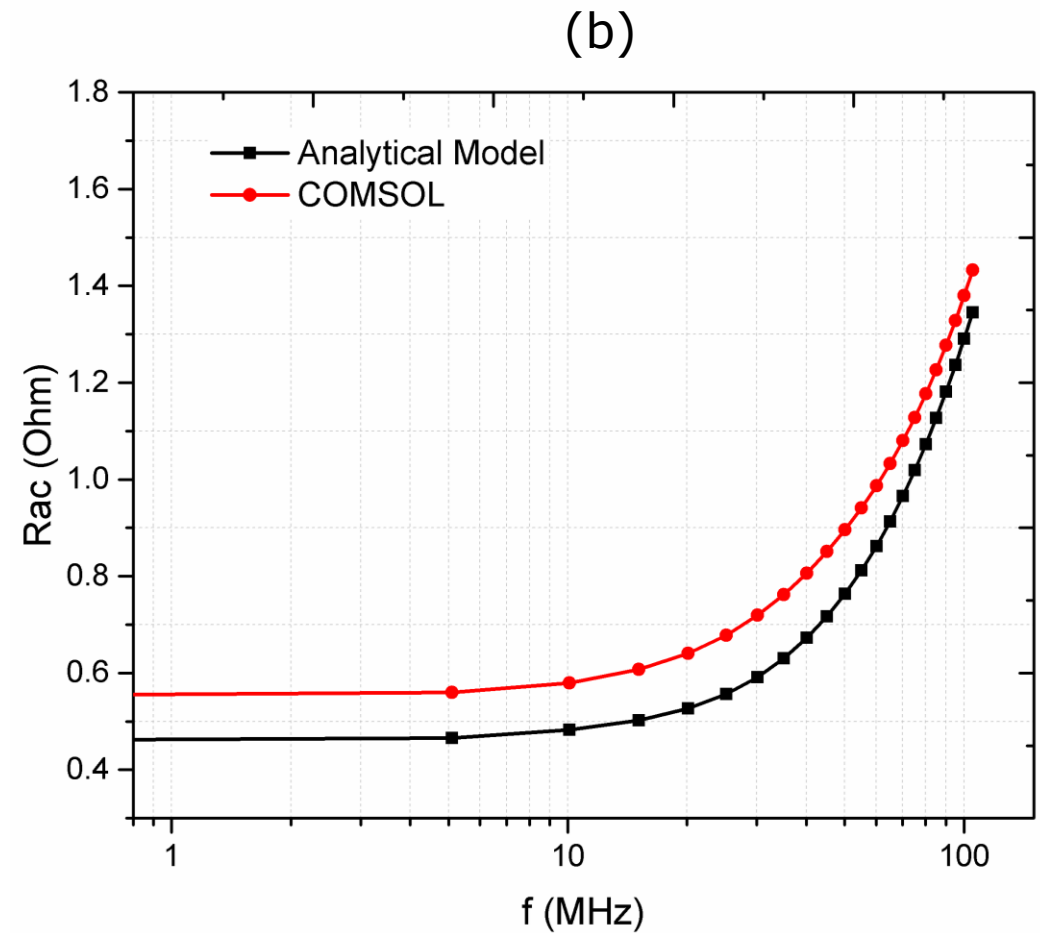
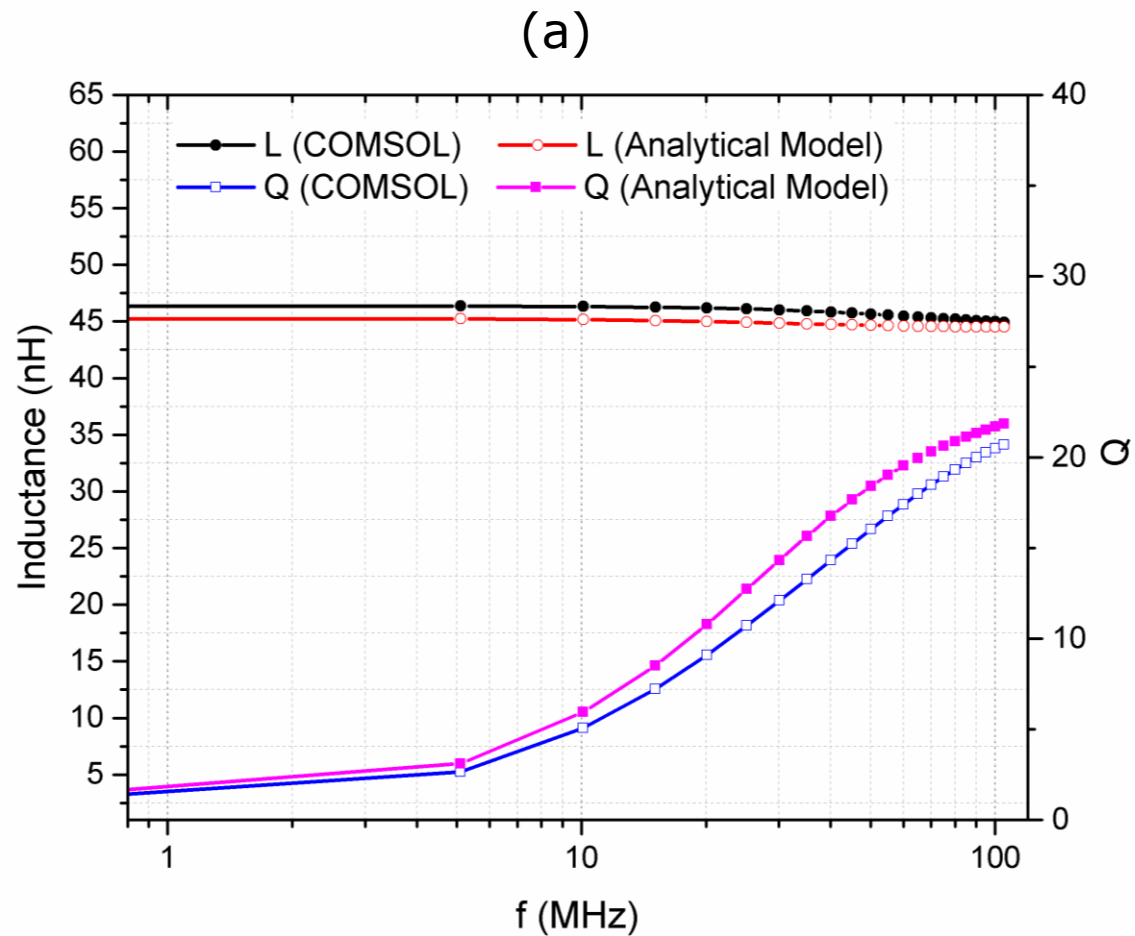


Rectangular conductor current density (J_z)



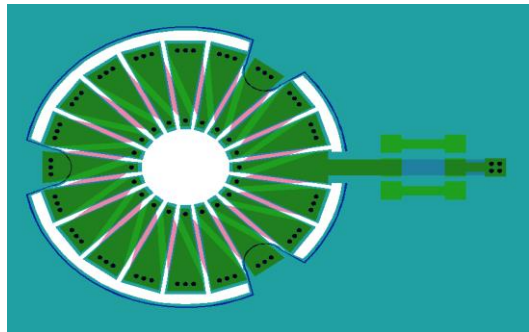
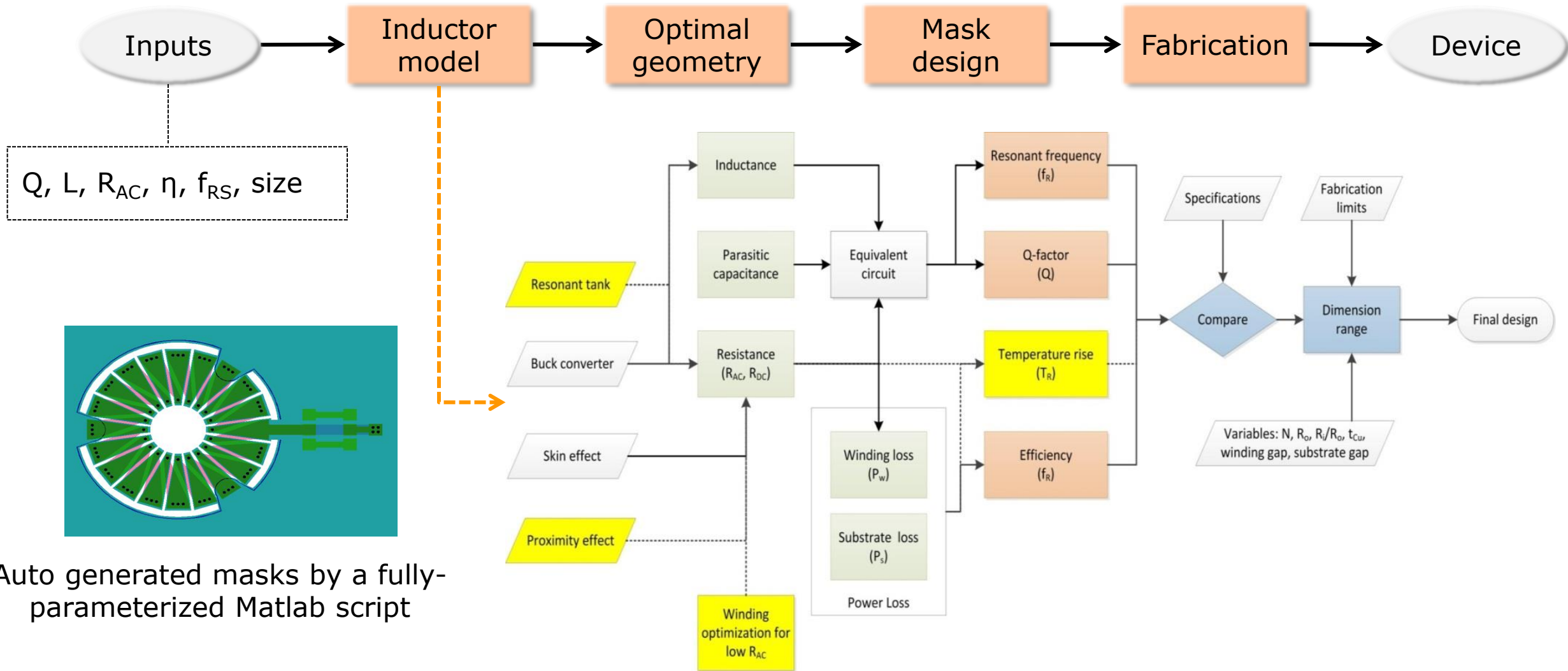
Geometry coordinate

Modeling Results



Comparison of calculated and simulated results. (a) Q , L and (b) R_{AC} versus frequency.

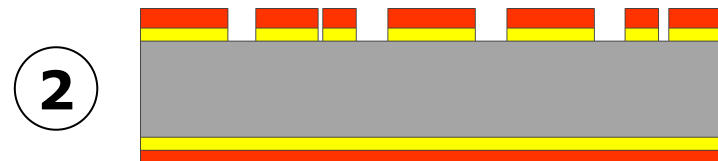
Inductor Design Guideline



Fabrication Process



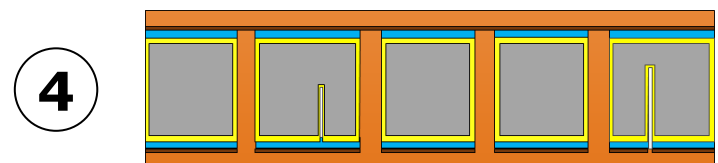
Deposition of Aluminum Oxide (Al_2O_3)



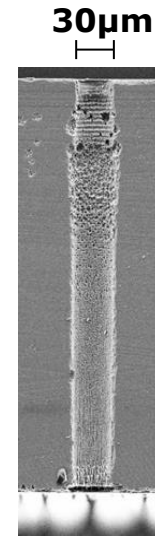
Photolithography + Al_2O_3 etching



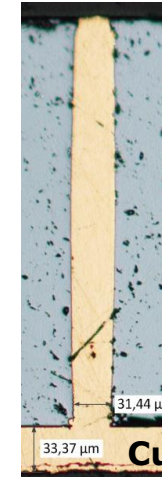
DRIE etching + mask stripping



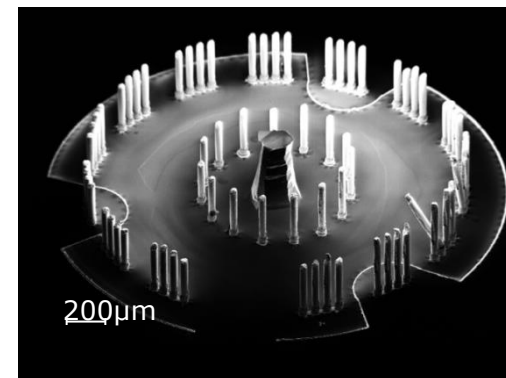
Copper electroplating



TSV

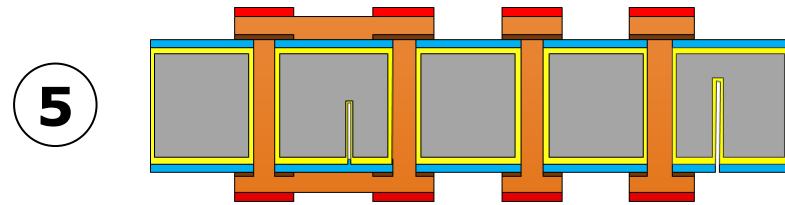


Cu-filled TSV

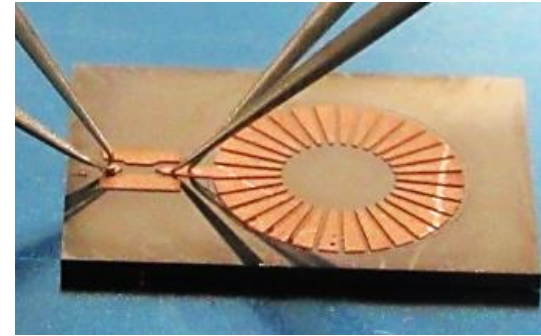


Cu TSVs (Si wafer removed - KOH)

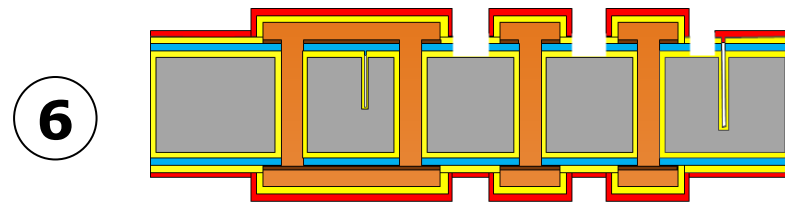
Fabrication Process



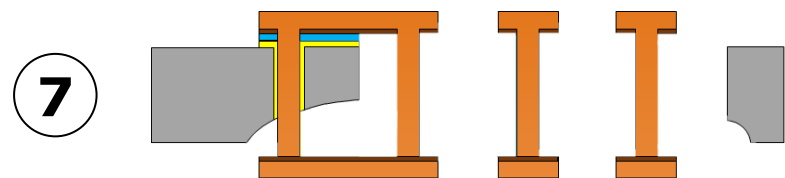
Copper wet etching



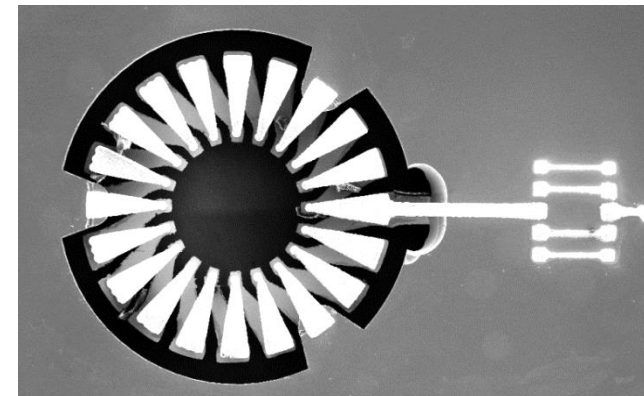
Si-core toroidal inductor



Photolithography + Al_2O_3 etching



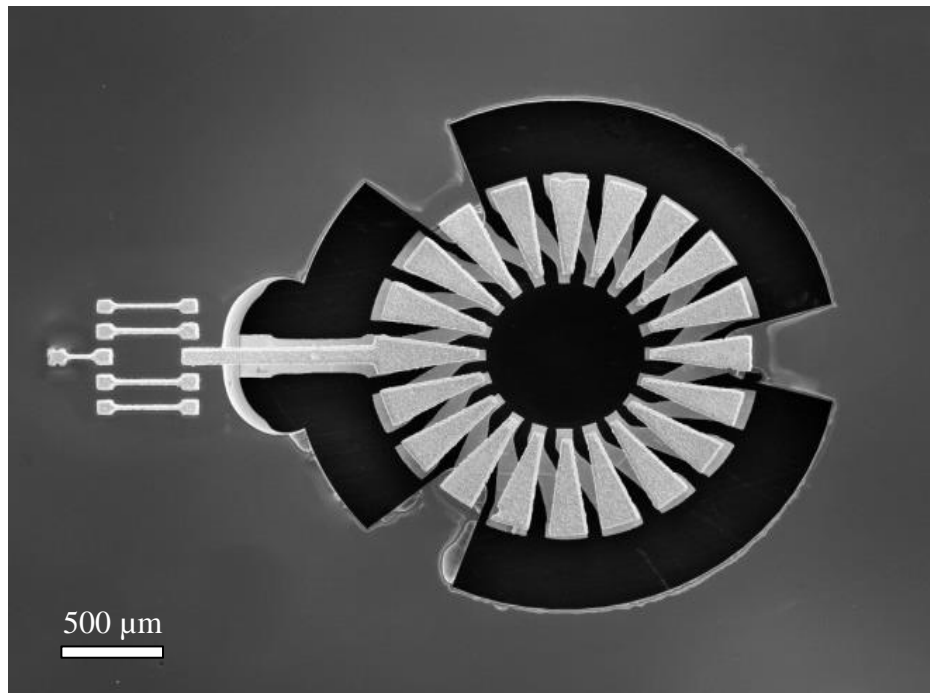
Inductor releasing



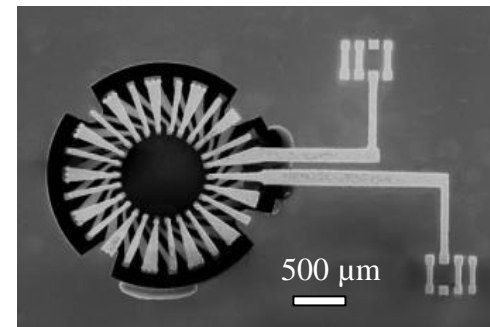
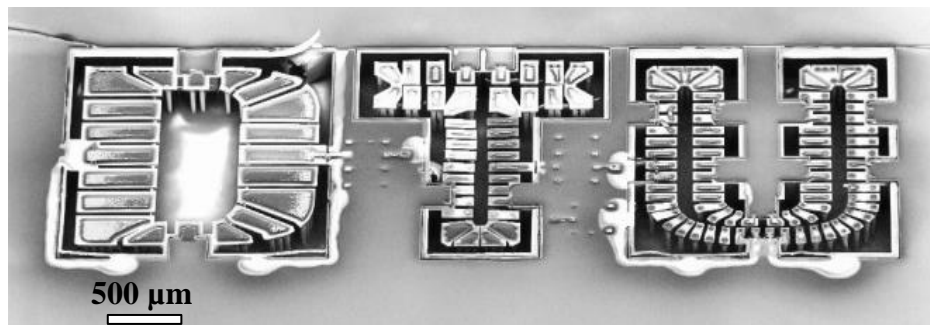
Air-core toroidal inductor

Fabrication Results

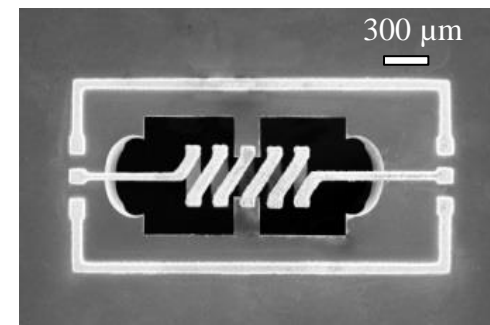
Toroidal inductor



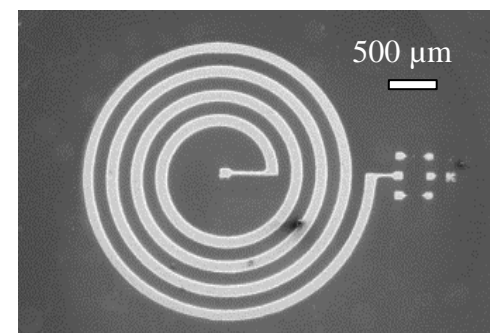
"DTU" inductor



Transformer

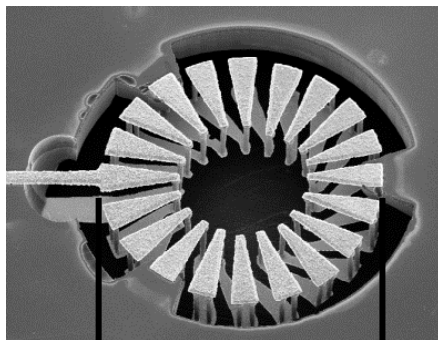


Solenoid

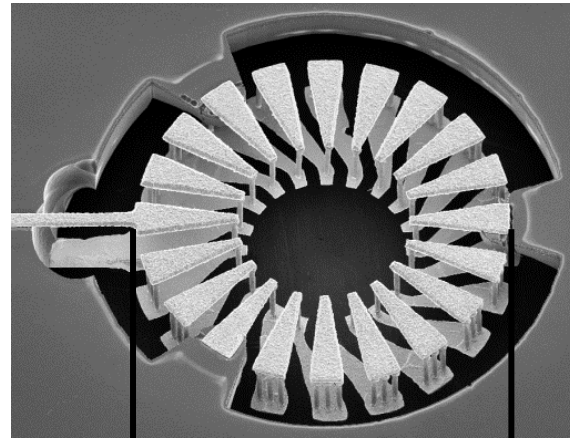


Spiral

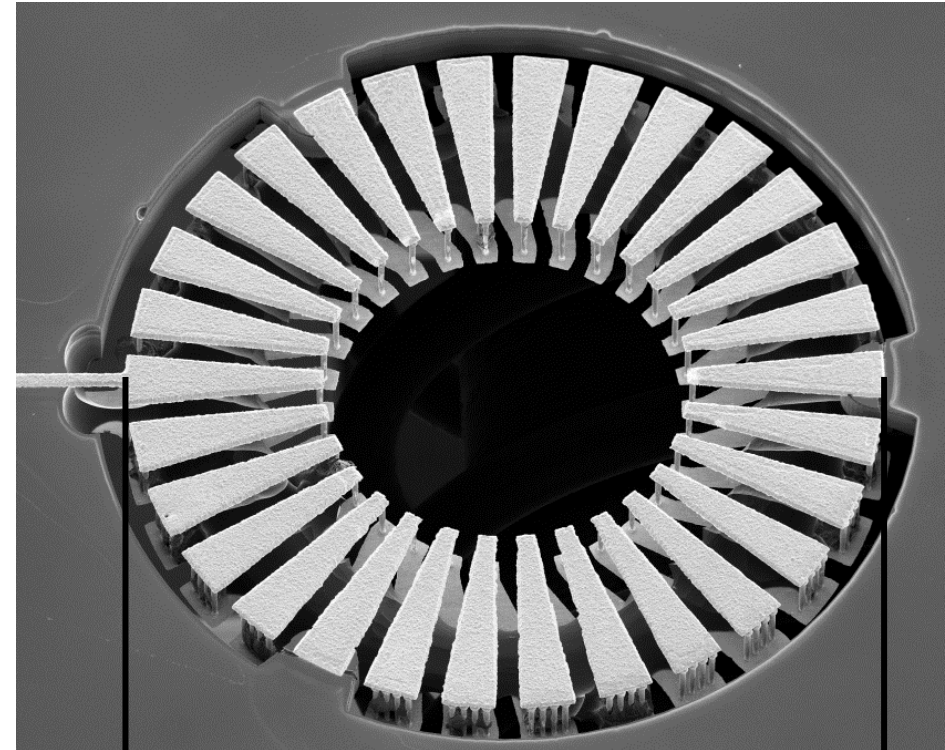
Fabrication Results



1.5 mm



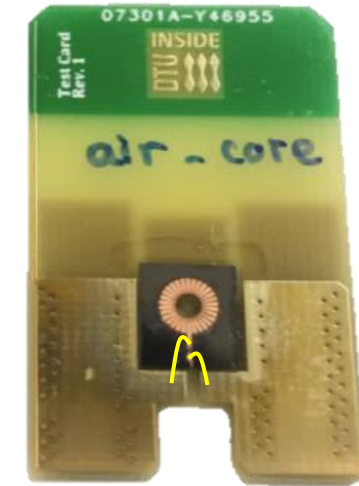
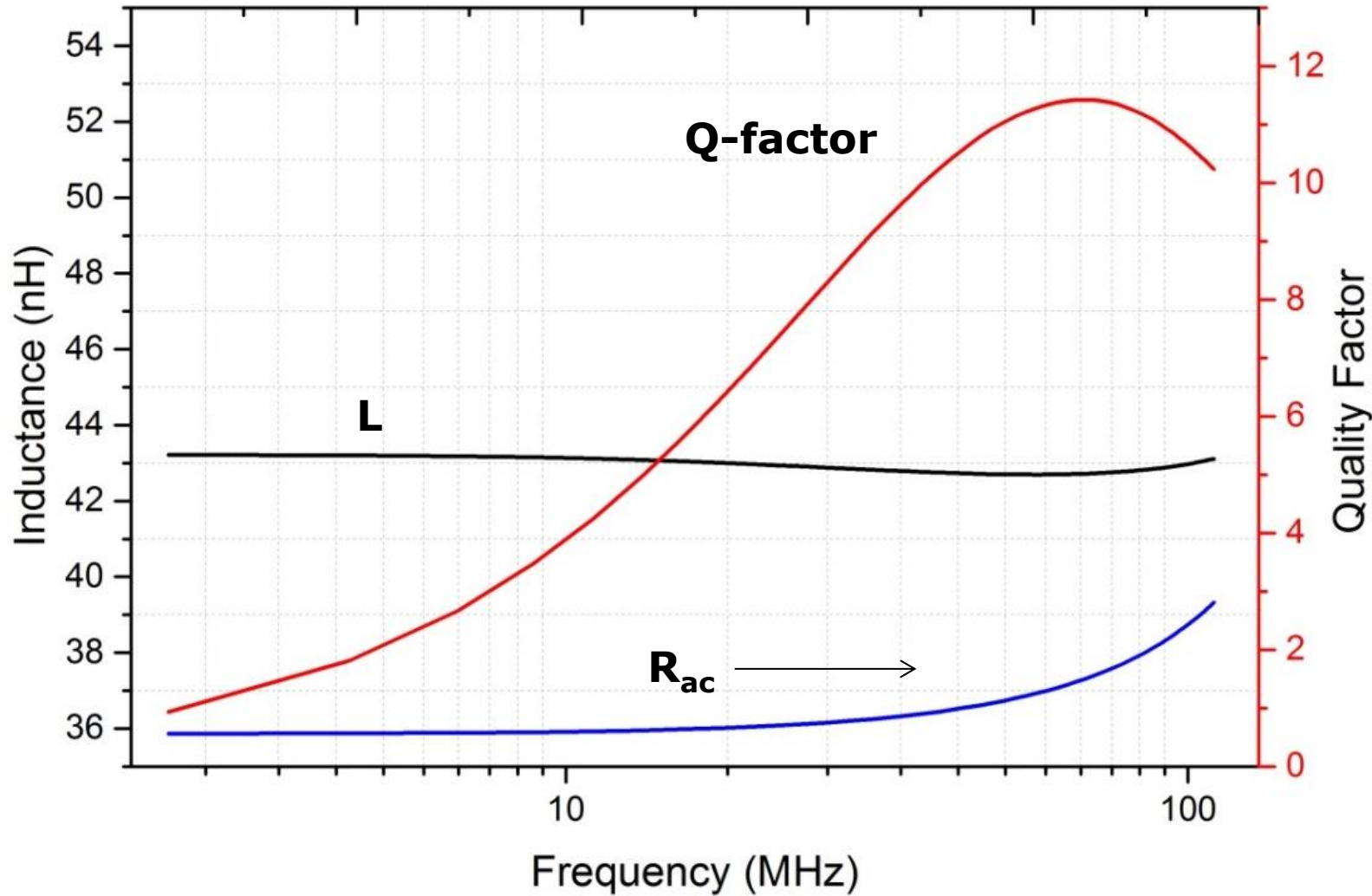
2 mm



4 mm

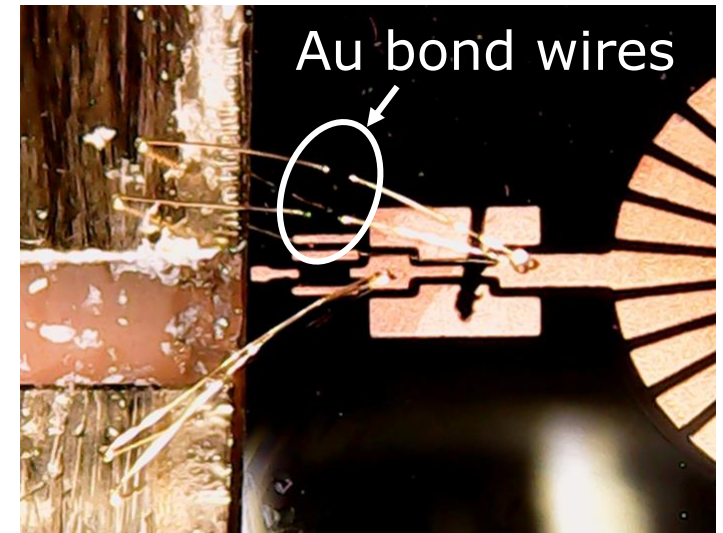
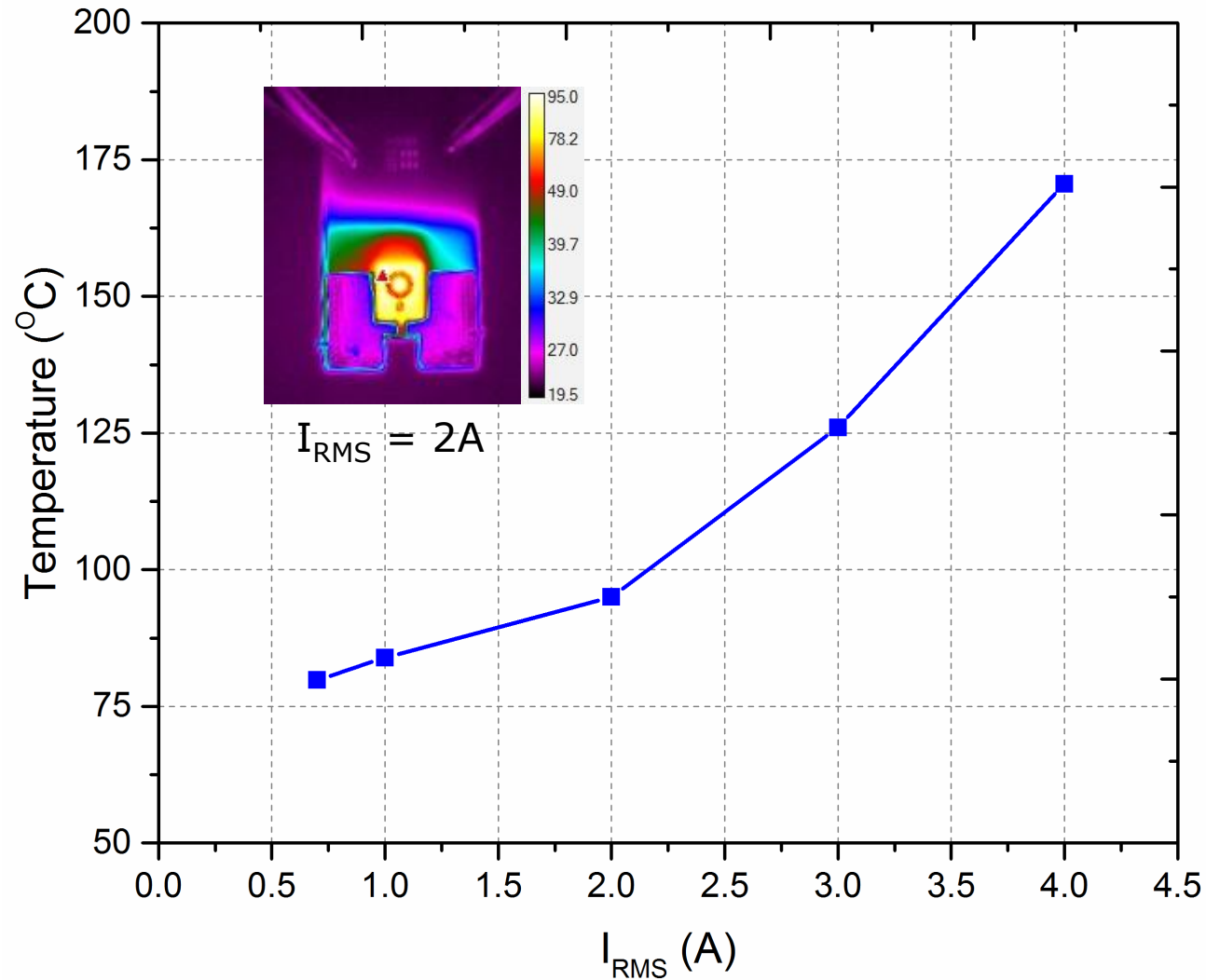
Characterization

Preliminary results



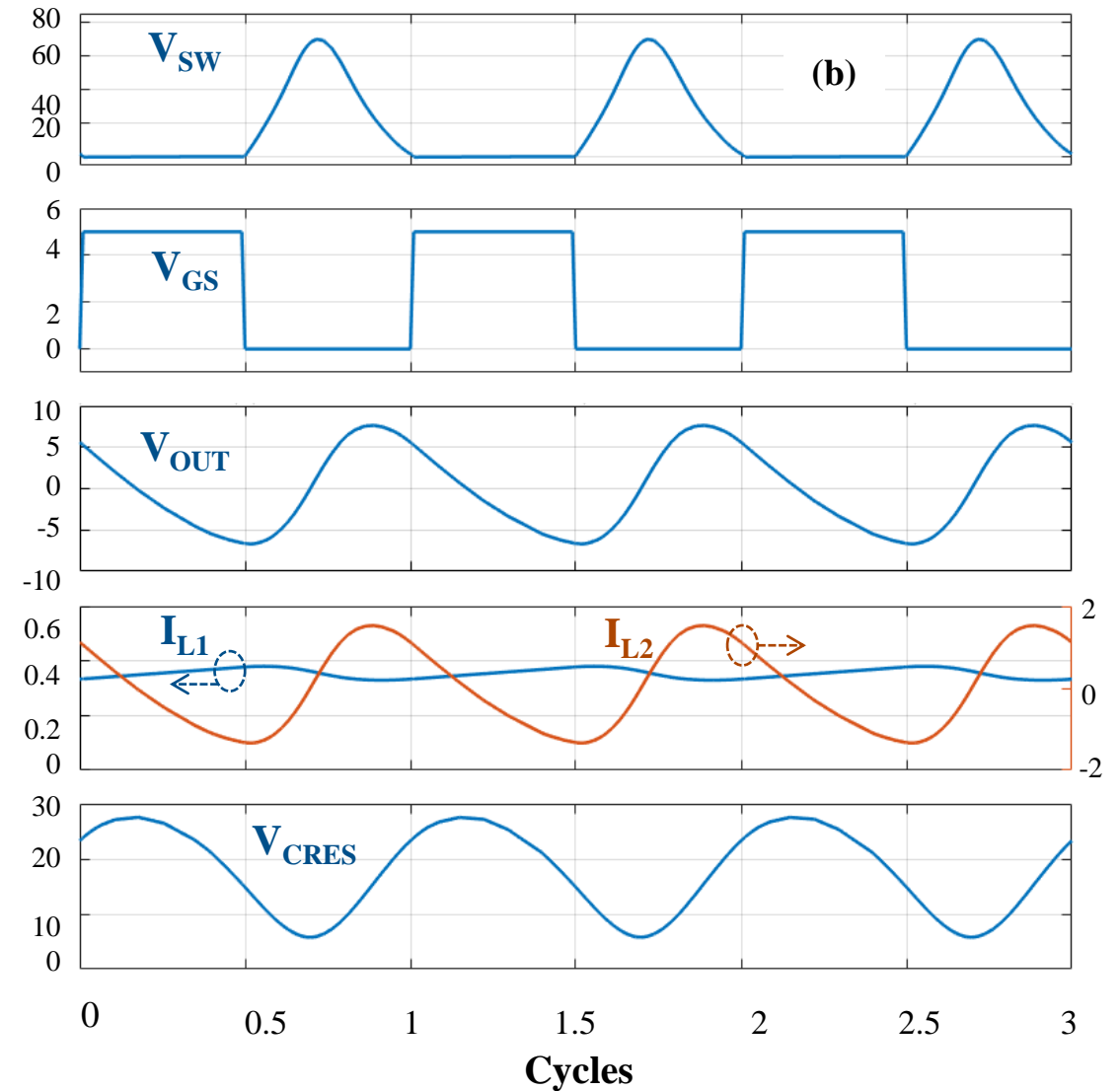
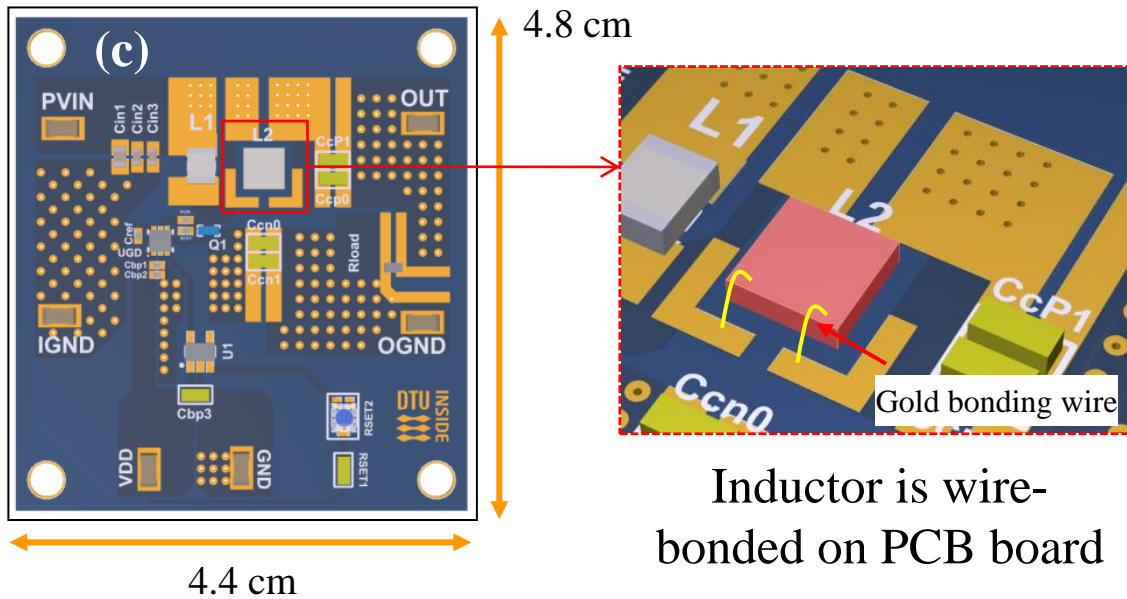
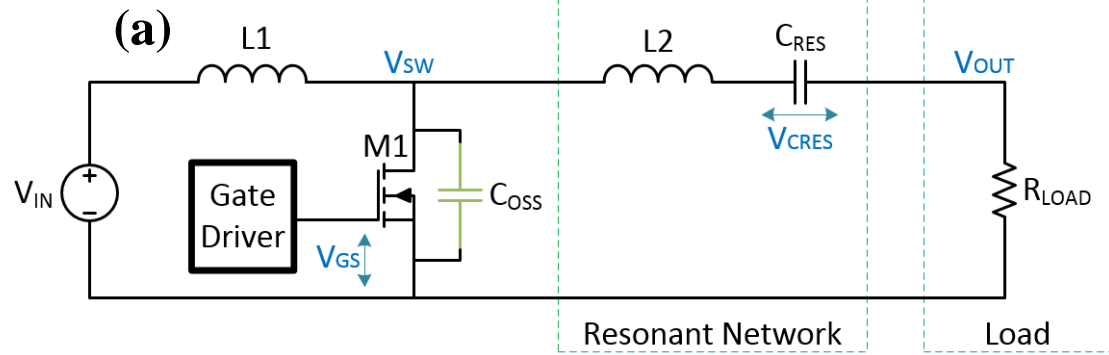
Toroidal inductor is wire-bonded on PCB test board ($N=20$, $R_o=1$ mm, $R_i=0.5$ mm)

Temperature Rise



$$I_{fusing} = 5.5A$$
$$(R_{DC} = 0.52 \Omega)$$

Design of 100 MHz Class E Inverter



Conclusion

□ Inductor Modeling

- f-dependent L_{internal} , R_{AC}
- COMSOL
- Design guideline

□ Fabrication Process

- CMOS-compatible
- Cu-Si robust
- 2D & 3D air-core inductors
- Through-Si Vias

□ Customized Inductor

- Number of turns
- Inner & outer radius
- Specs

□ Future Works

- Test on SMPS
- Packaging
- Magnetics

Acknowledgement

DTU Danchip

National Center for Micro- and Nanofabrication



DTU Electrical Engineering

Department of Electrical Engineering



Innovation Fund Denmark

RESEARCH, TECHNOLOGY & GROWTH

Fund No. 67-2014-1



TinyPower