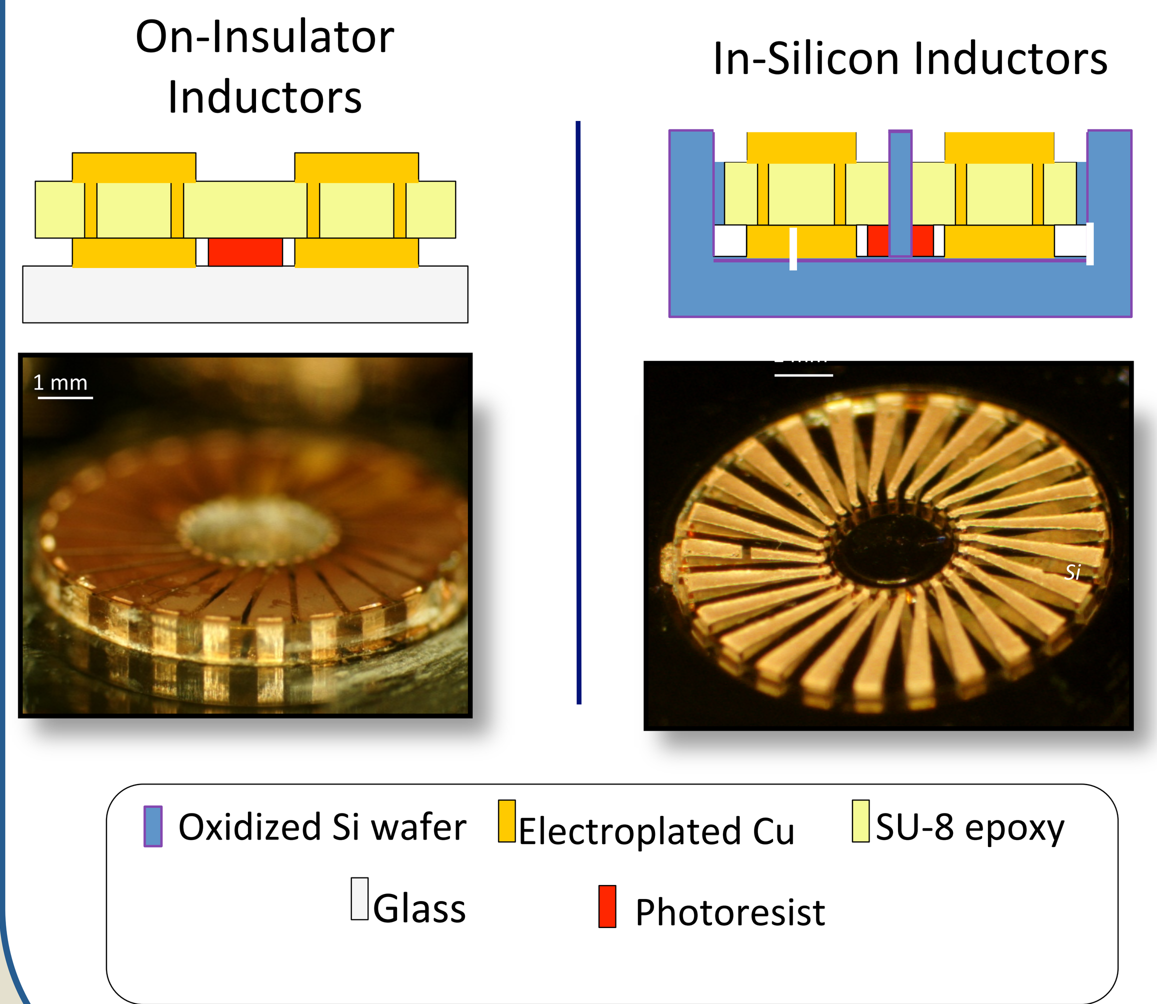
MEMS Toroidal Inductors for Integrated Power Electronics

Mohammad Araghchini & Jeffrey H. Lang
Massachusetts Institute of Technology, Cambridge, MA, USA

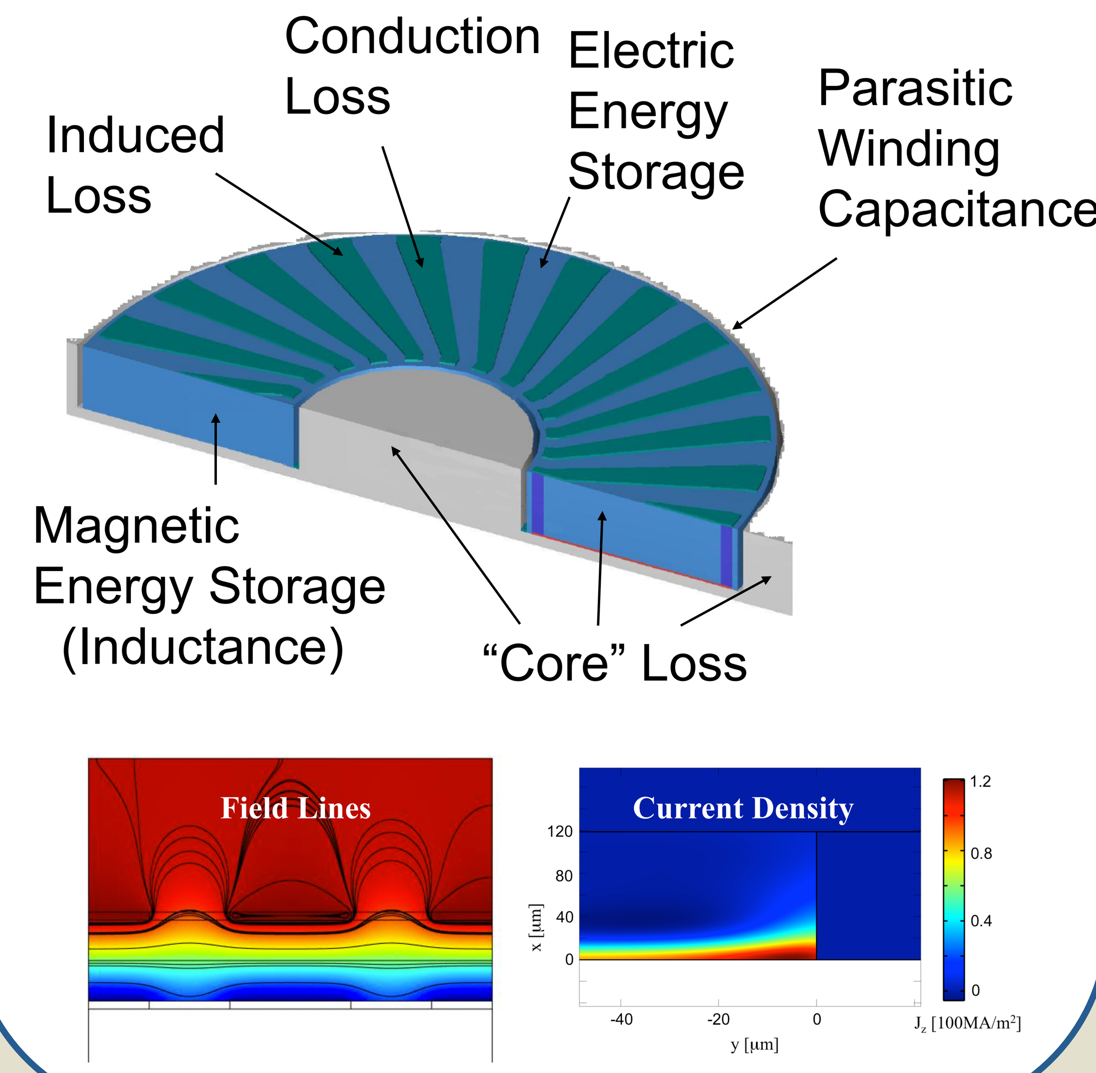
Introduction

- Increasing power density in power electronics circuits requires higher frequencies. As switching frequencies rise, the size of the magnetics fall, and new fabrication strategies such as MEMS fabrication become possible.
- Our goal is to integrate the magnetics into the power electronics circuits to achieve yet higher power densities.
- Focus on toroidal inductors since they produce minimal external fields, external losses and electromagnetic interference problems.
- Magnetics can be on insulator or silicon-embedded.
- Circuit and magnetics co-optimization requires equivalent circuit models for the magnetics.
- Different models are required for magnetics built on top of an insulating substrate as opposed to embedded in the silicon substrate.

Toroidal Magnetics

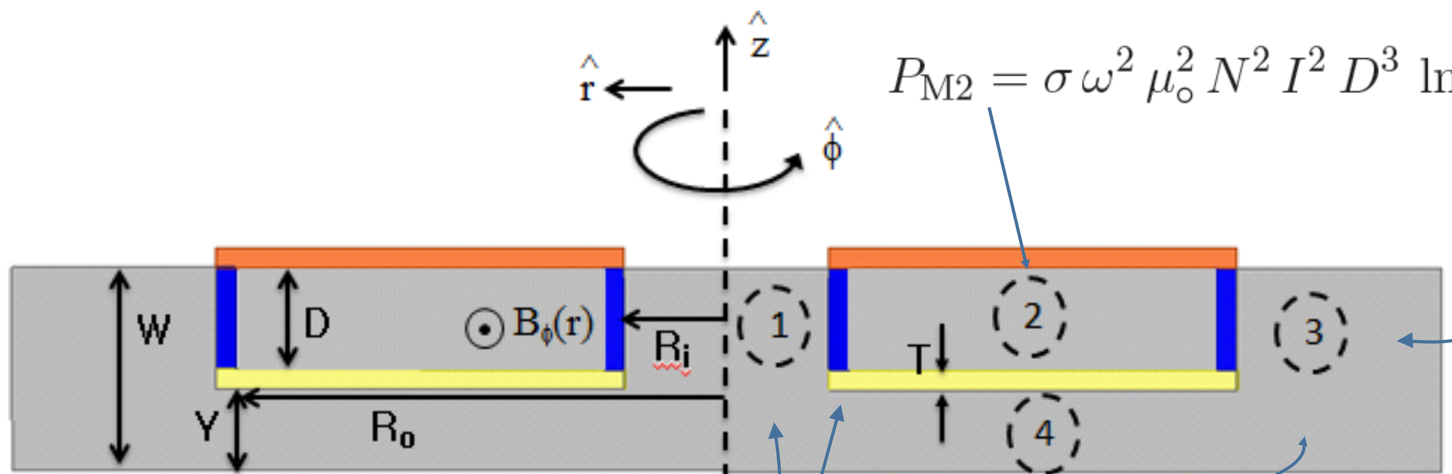


Modeling Objectives



Closed-Form Solutions for Losses

Analytical models are developed for electrically-driven and magnetically-driven losses, and parasitic capacitance.



$$P_{M2} = \sigma\,\omega^2\,\mu_o^2\,N^2\,I^2\,D^3\,\ln(R_o/R_i)\,/\,(48\,\pi)$$

$$P_{E3} = \sum_{m=1}^{\infty} \frac{2\pi\,D\,\sigma\,V^2\omega^2\epsilon_I^2}{m\,(\Gamma_{\omega\epsilon}^2 + \Gamma_\sigma^2)}$$

$$\Gamma_{\omega\epsilon} = \omega\left(\frac{R_o}{R_o+\Delta}\right)^m (\epsilon_I - \epsilon_{Si}) + \omega\left(\frac{R_o+\Delta}{R_o}\right)^m (\epsilon_I + \epsilon_{Si})$$

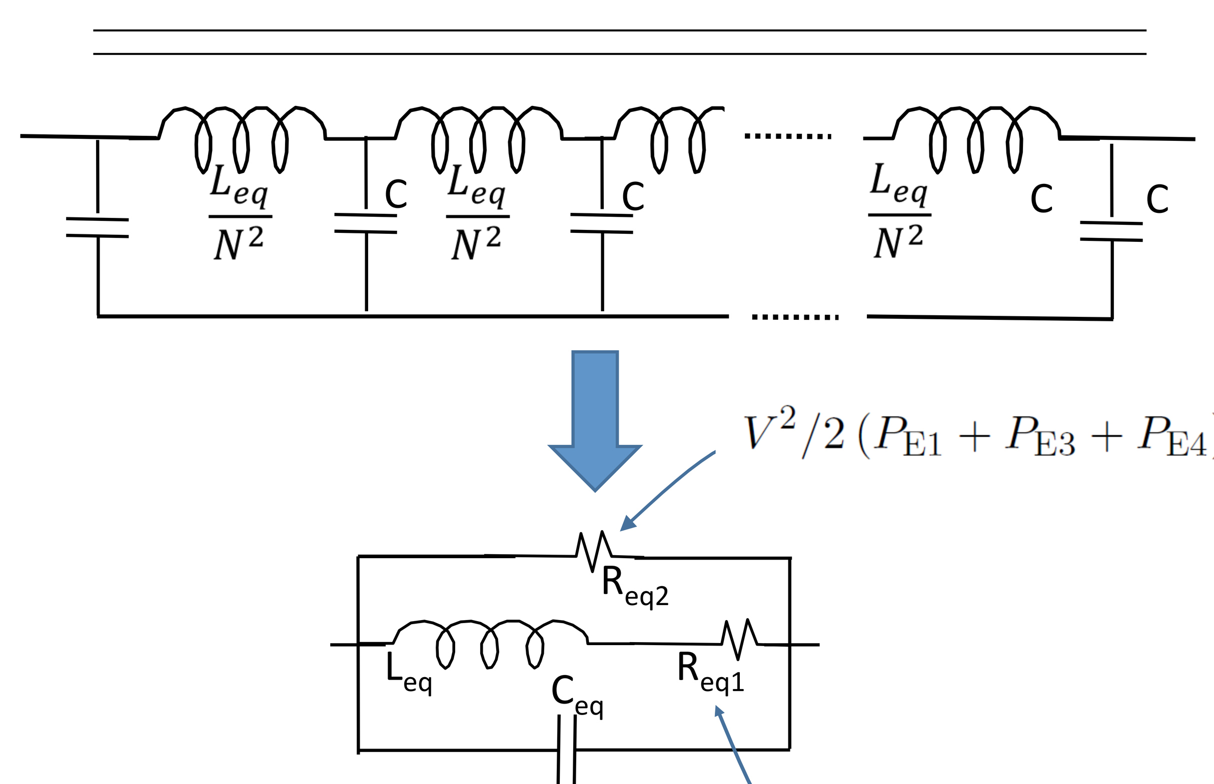
$$P_{M1} = \sigma\,W\,\omega^2\,L_P^2\,I^2/(16\,\pi)$$

$$P_{M3} = D\,\sigma\,\omega^2\,L_p^2\,I^2/(8\,\pi)$$

$$\Gamma_\sigma = \sigma_{Si}\left(\left(\frac{R_o+\Delta}{R_o}\right)^m - \left(\frac{R_o}{R_o+\Delta}\right)^m\right)$$

$$C = 2\,\pi\,F\,\epsilon_I\,(R_oD + R_iD + 0.5(R_o^2 - R_i^2))\,/\,(N\,\Delta)$$

Equivalent Circuit



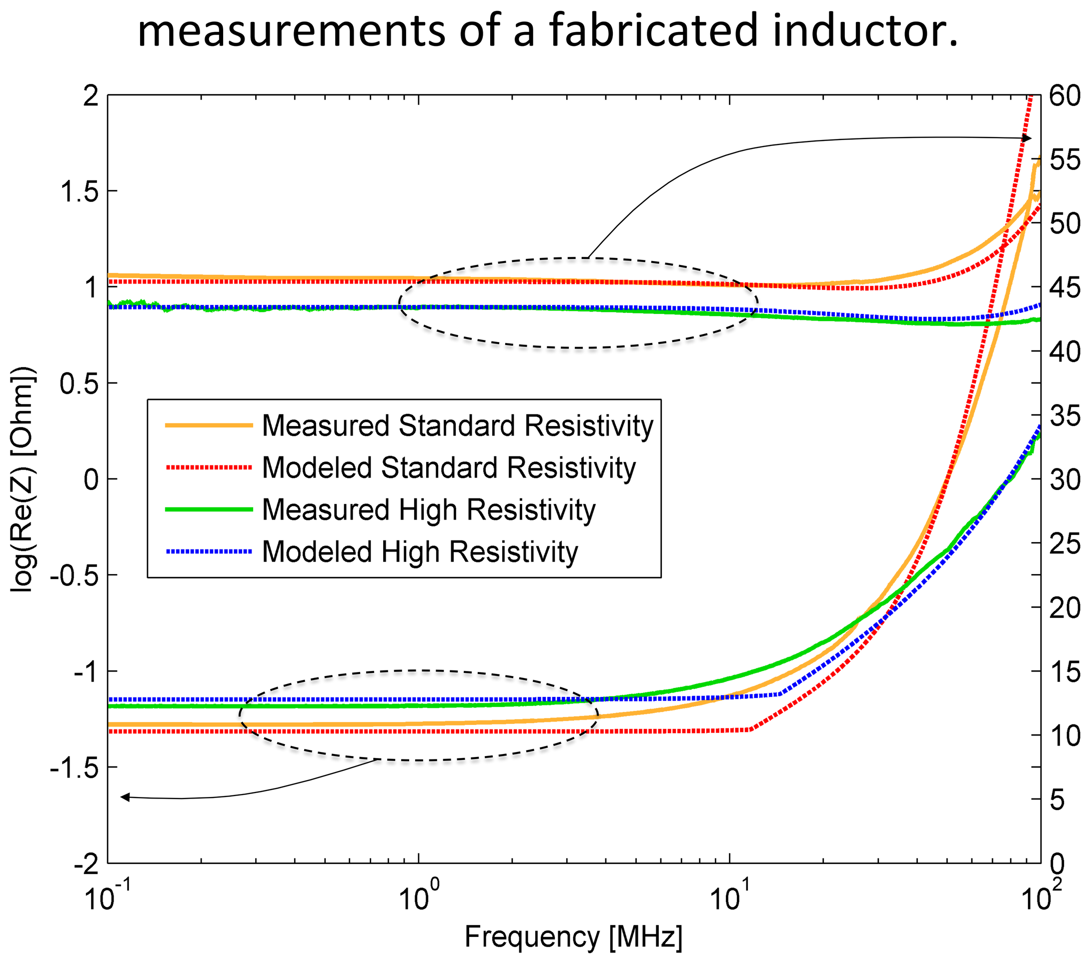
$$V^2/2\,(P_{E1} + P_{E3} + P_{E4})$$

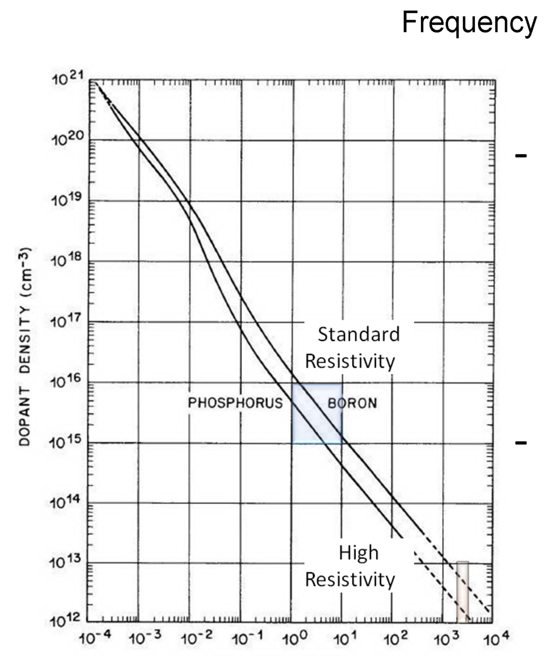
$$C_{eq} = C\,(N^2 - 1)\,/\,(12\,N)$$

$$2\,(P_{M1} + P_{M2} + P_{M3})\,/\,I^2$$

Measurement Vs. Models

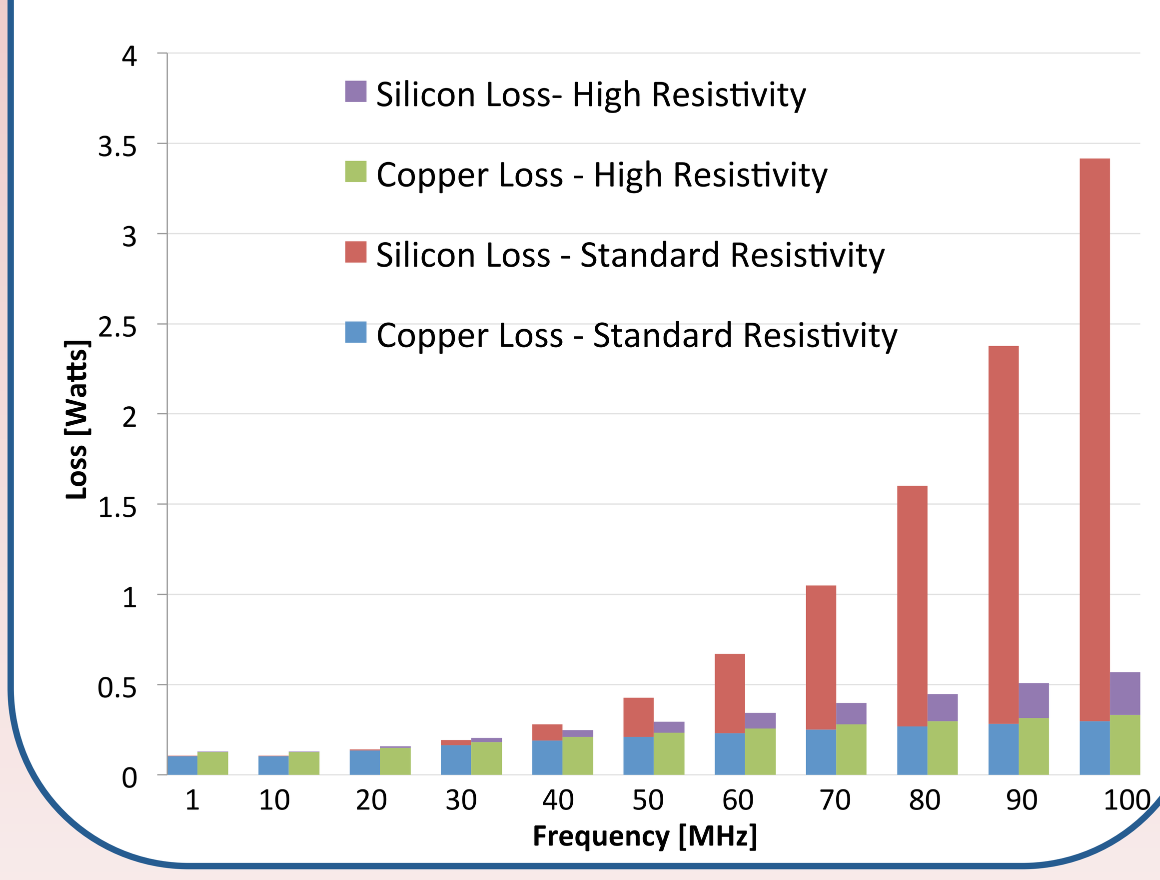
Models compared to impedance-analyzer measurements of a fabricated inductor.





- Other experiments have demonstrated 690 nH for an on-insulator inductor of similar style.
- A maximum quality factor of 20 is measured for an in-silicon inductor (high resistivity wafer).

Loss Distribution



References

- M. Araghchini, (MEMS) Toroidal Inductors for Integrated Power Electronics, Ph.D. Thesis, MIT.
- M. Araghchini, et al., "A technology overview of the powerchip development program, IEEE Transactions on Power Electronics, vol. 28, no. 9, pp. 4182–4201, 2013.
- M. Araghchini, et al. , "Modeling and measured verification of stored energy and loss in mems toroidal inductors, IEEE Transactions on industry Applications, vol. 50 (3), pp. 2029-2038, 2014.

Conclusions

- The equivalent circuit model matches well the measured behavior of silicon-embedded and on-insulator toroidal inductor.
- Silicon-embedded toroidal inductors are viable for integrated power electronics.
- As long as the silicon is removed from the toroidal core of the inductor at high doping densities, the close proximity of silicon need not greatly degrade inductor quality factor.
- Winding loss dominates the quality factors modeled and measured here for frequencies up to 40 MHz, making winding optimization more important than silicon selection
- For higher frequencies, quality factor is a strong function of silicon resistivity as expected, making its selection more important than winding design. At these frequencies, electrically-driven silicon losses appear to be dominant, making large resistivity an important fabrication objective.

Acknowledgements

- X. Yu, J. Kim, F. Herreault, Prof. M. Allen from GIT
- ARPA-E under ADEPT grant DE-AR0000123