Integrated Inductors with Magnetic Materials for On-Chip Power Conversion

Donald S. Gardner

Collaborators: Gerhard Schrom, Fabrice Paillet,

Tanay Karnik, Shekhar Borkar

Circuits Research Lab &
Future Technology Research

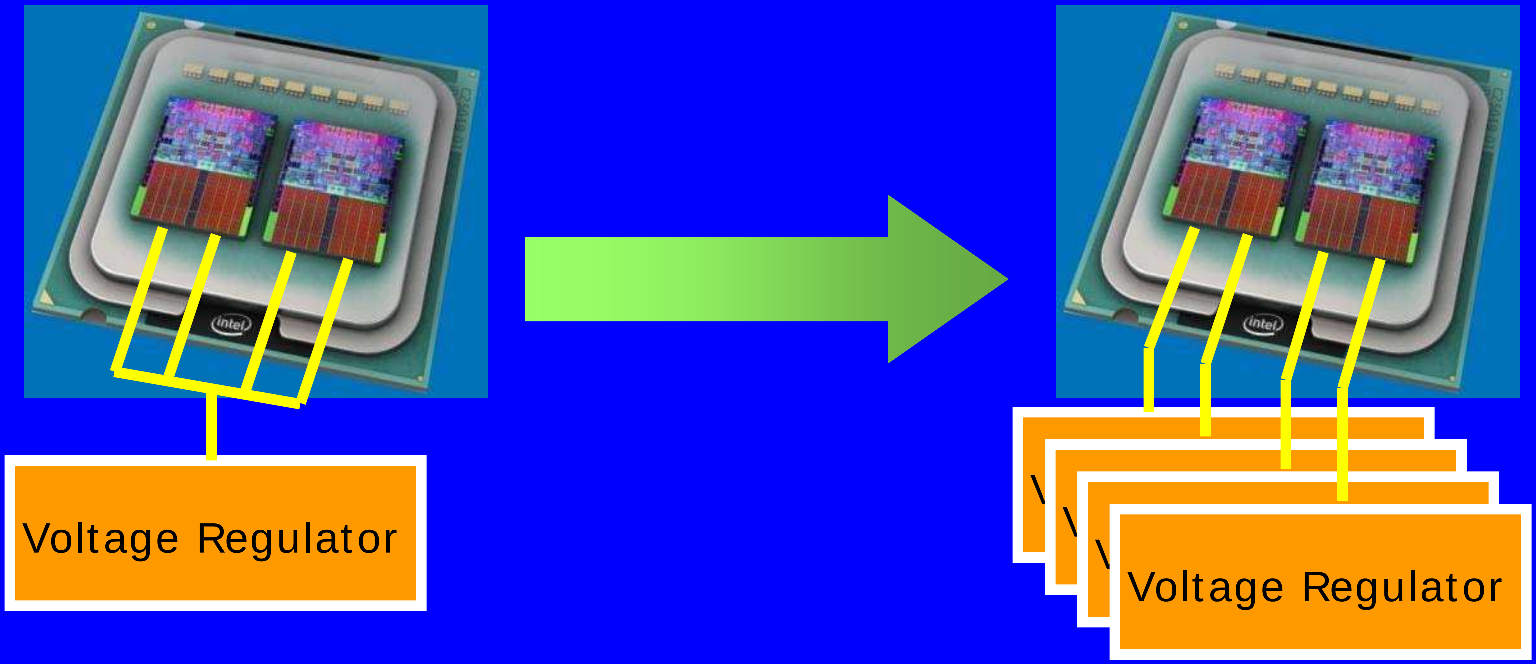
Intel Labs

Intel Corporation

Outline

- DC Voltage Converters
  - Comparison of buck converters
  - Comparison of inductors with magnetic films
- Magnetic material properties
  - Magnetic hysteresis loops
  - Complex permeability spectra
- Inductors
  - Structure cross sections
  - Inductance measurements
  - Eddy current and skin effect
  - Sheet and shunt inductance

Multi-Core Power Management

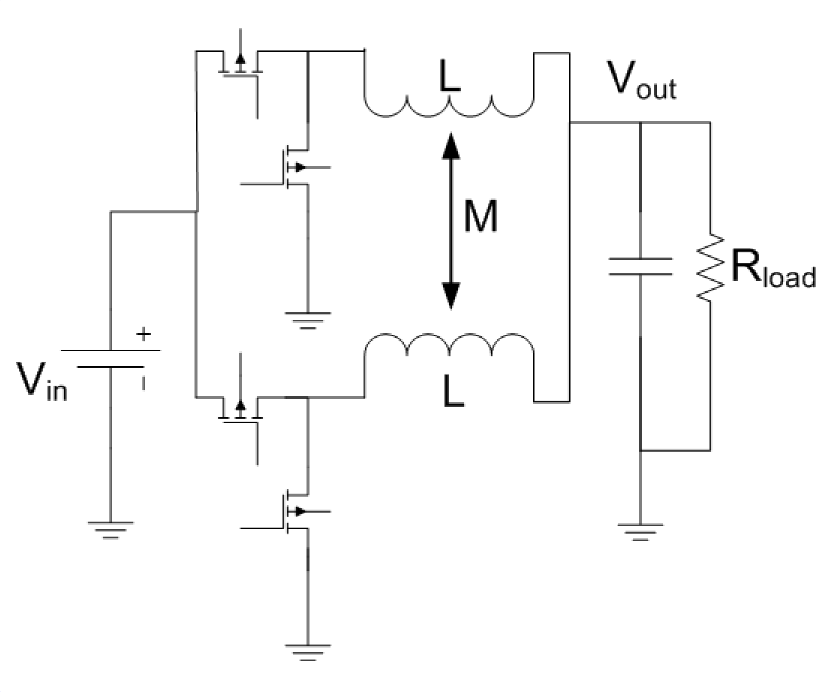


Voltage Regulator

Voltage Regulator

- **Today - Coarse Grain Power Management**
  - – **same voltage to all the cores, variable voltage**
- **Future – Fine Grain Power Management**
  - – **each core or cluster of cores operates at the optimum voltage**

Two-Phase Buck Converter with Coupled Inductors



Inductor Power Losses

DC loss component

AC loss component

$$P_{LOSS} = R_{DC} \times I_{Lavg}^{\;2} + R_{AC} \times \frac{\Delta I_{p-p}^{\;2}}{12} + P_{hys}$$

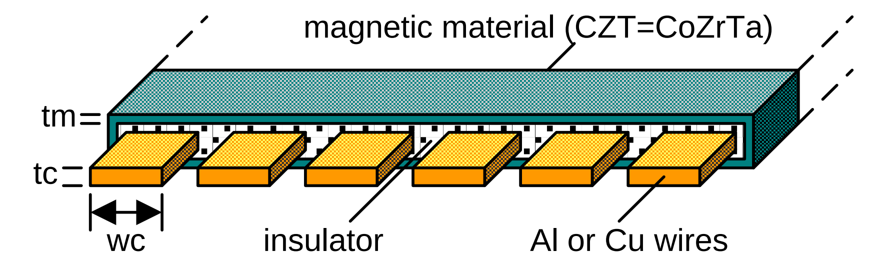
Load dependent

Frequency dependent

$$\Delta I_{p\_p} = \frac{(1-D)\,V_{out}}{f_s\,L_{eff}}$$

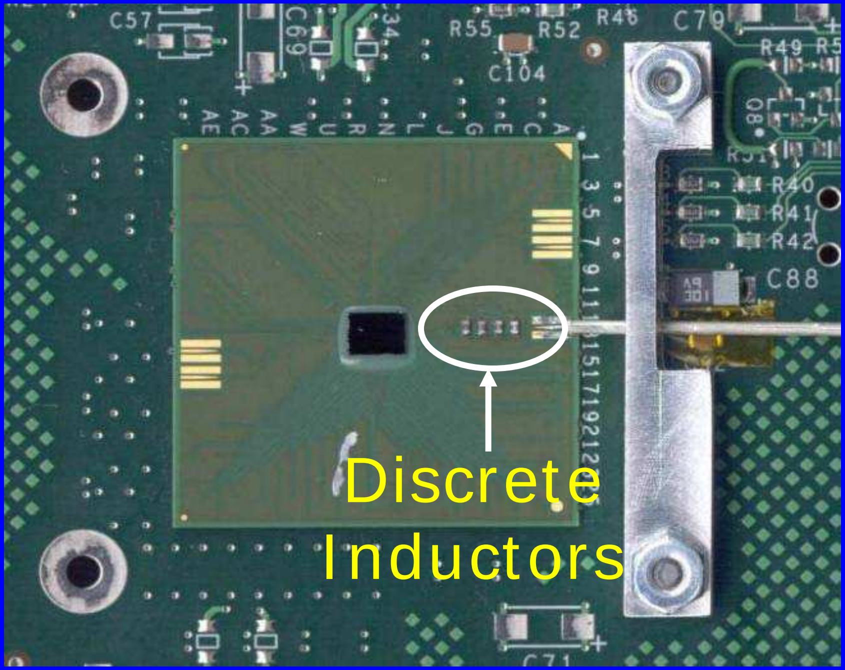
$$D = dutycycle$$

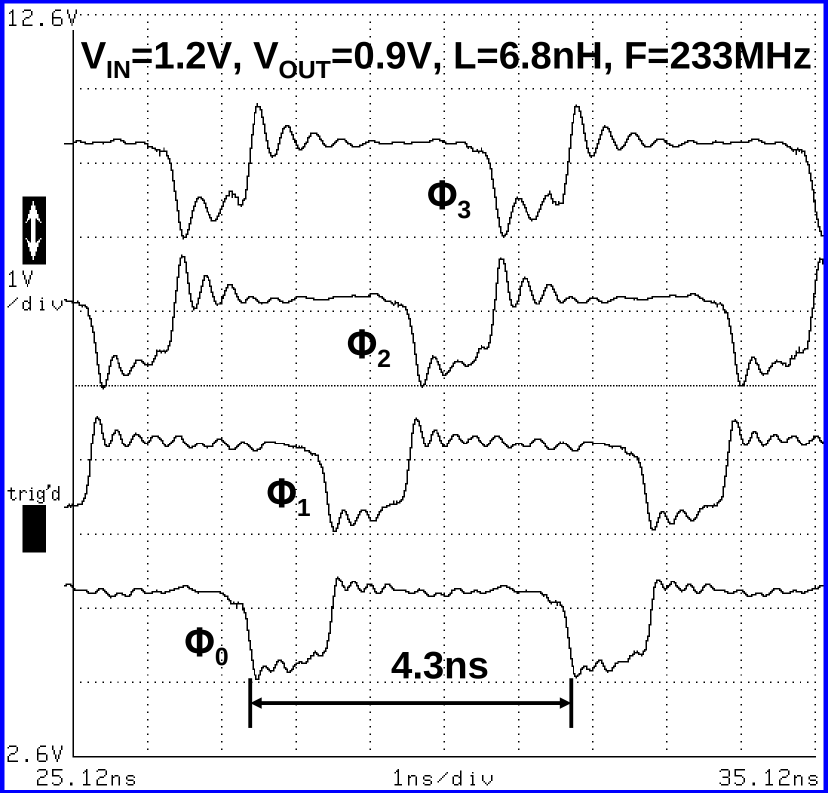
$$f_s = frequency$$



Fundamentals of Power Electronics by Robert W. Erickson

100~480 MHz Switching Regulator





- **High frequency**
- **Hysteretic multi-phase topology 1ns response**
- **88% efficiency**

Schrom, Gardner, et.al., IEEE PESC 2004 and IEEE VLSI Symp. 2004.

Comparison of DC Converters

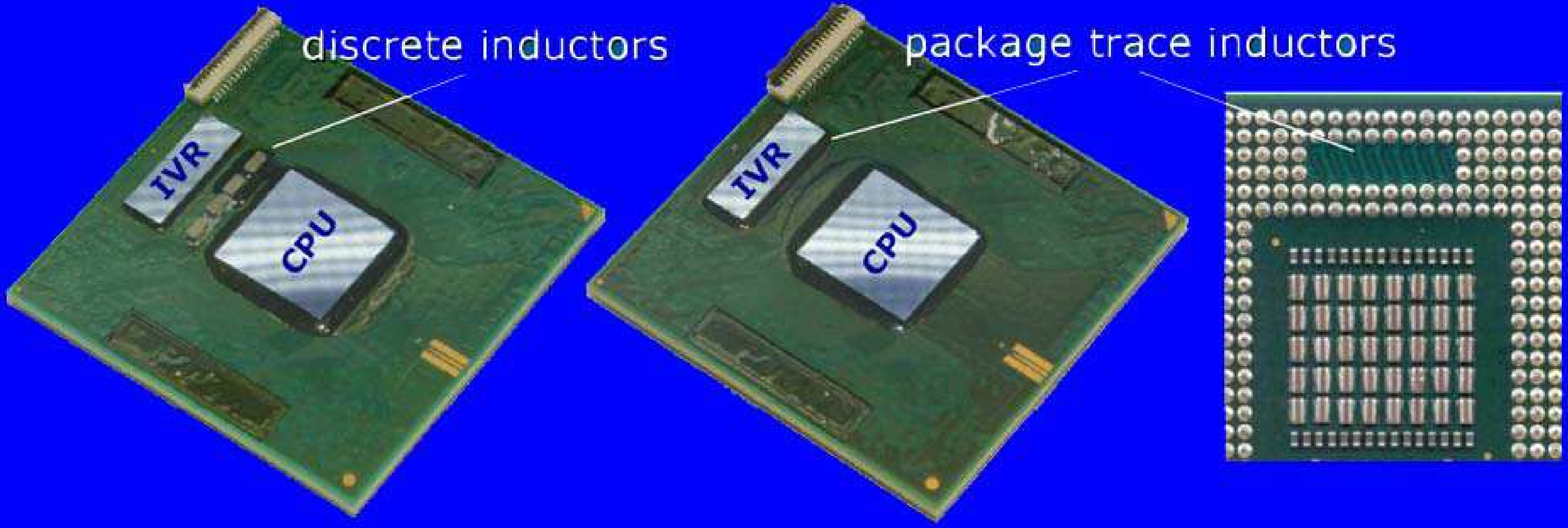
	[3]	[4]	[5]	[6]	[7]	**Pavo-1**
Year	1996	1999	2000	2002	2002	**2004**
Tech [µm]	n/a	0.25	n/a	0.25	n/a	**0.09**
# phases	1	1	1	1	1	**4**
V_{IN} [V]	4	3	4	2.5	3.6	**1.2**
V_{OUT} [V]	3.3	2	3	1.4	2.7	**0.9**
f [MHz]	1.6	0.5	3	0.75	1.8	**233**
Eff. [%]	85	94	83.3	95	80	**83.2**
L_{TOT} [µH]	3	10	1	15.2	1	**0.0017**
C [µF]	n/a	47	1	21.6	n/a	**0.0025**
I_{MAX} [A]	0.3	0.25	0.33	0.25	0.3	**0.3**
Area [mm^2]	n/a	0.46	20	0.35	n/a	**0.14**

100x

higher f

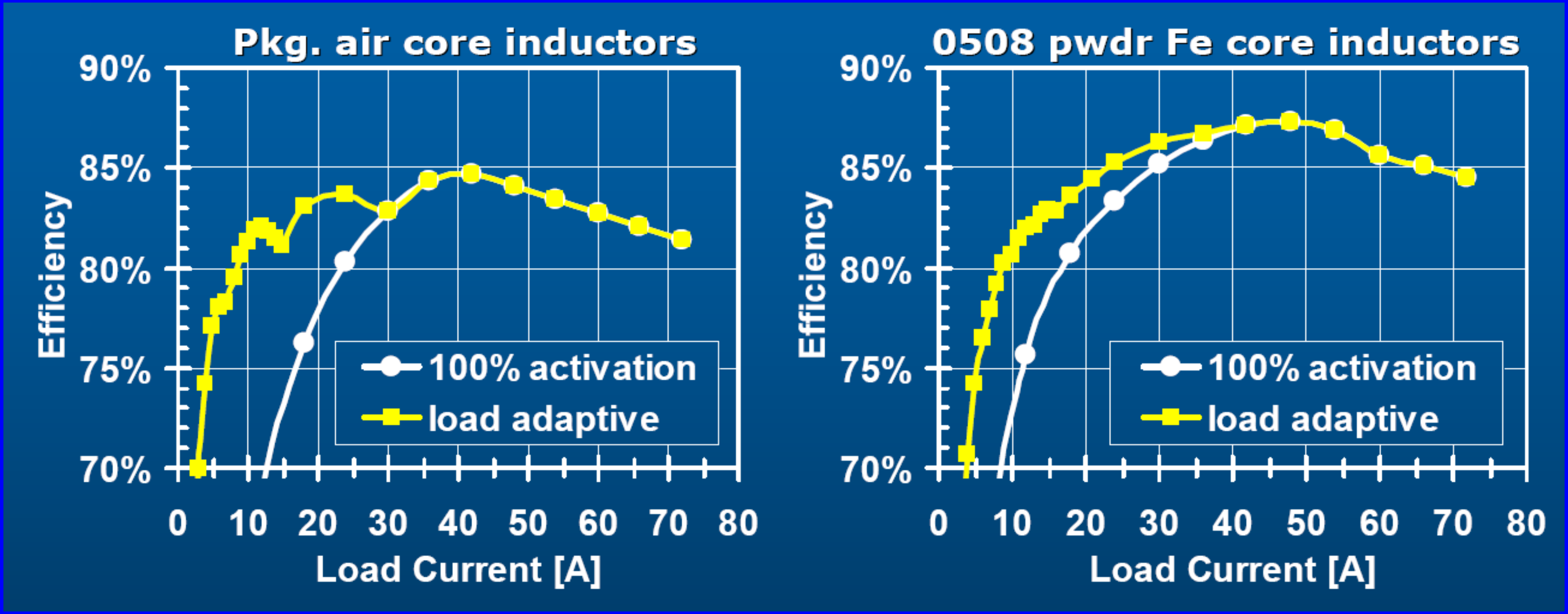
1000x
Smaller
L and C

Package-Integrated VR with Intel® Core™2 Duo Processor



- Vin = 3V, Vout = 0~1.6V
- f = 10~100 MHz
- Current = 50 Amps / 75 Amps peak
- Size = 37.6 mm^2, 130 nm CMOS

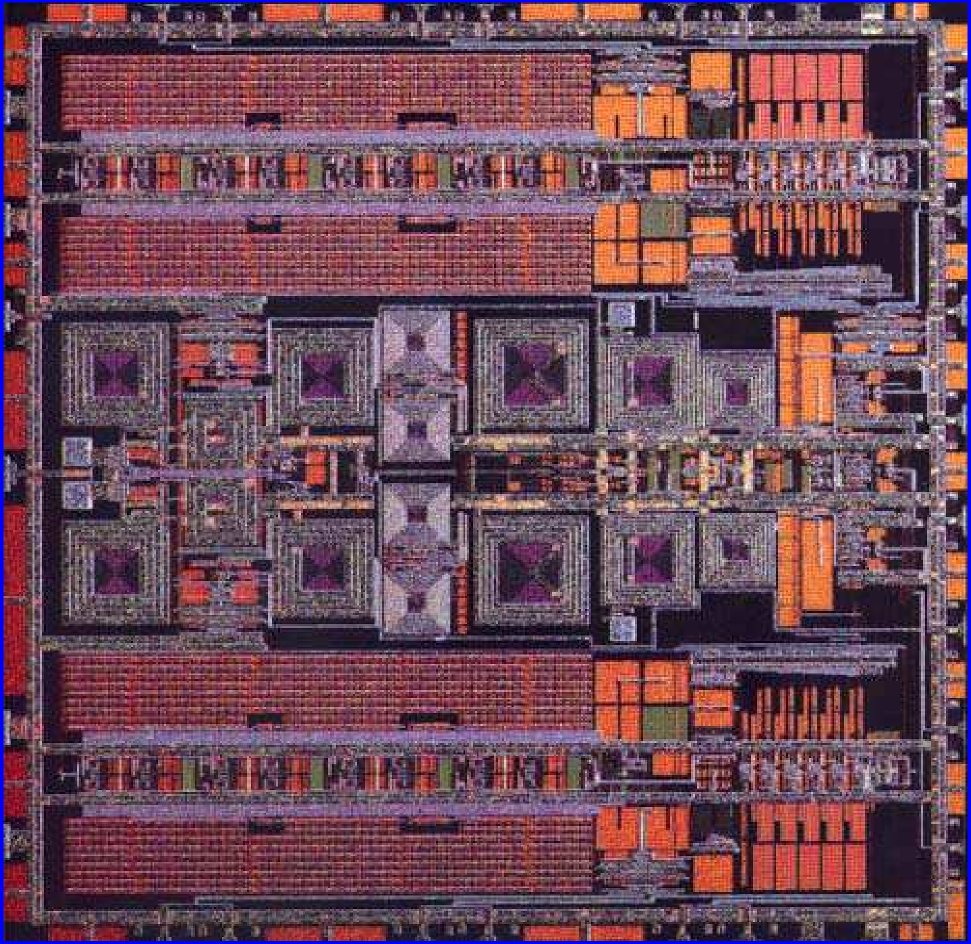
Efficiency Measurements



- Package embedded air core inductors: 84.9%
- Discrete powdered Fe core inductors:87.9%
- Load adaptive bridge activation improved by >10%

G. Schrom et. al., APEC, Paper #SP1.4.2, p. 75, 2010

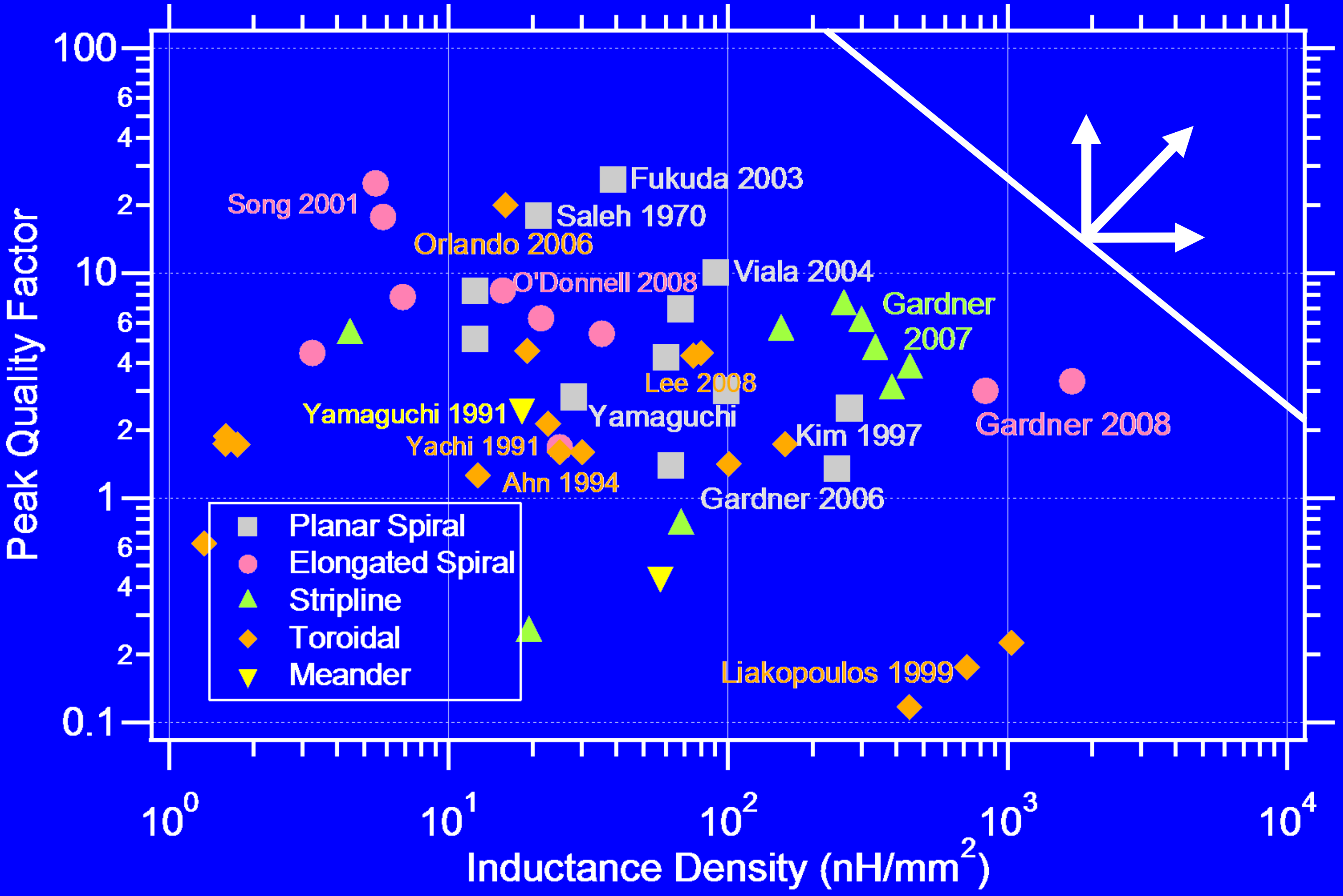
RF CMOS Integrated Circuit



Inductors make up 24% of this chip

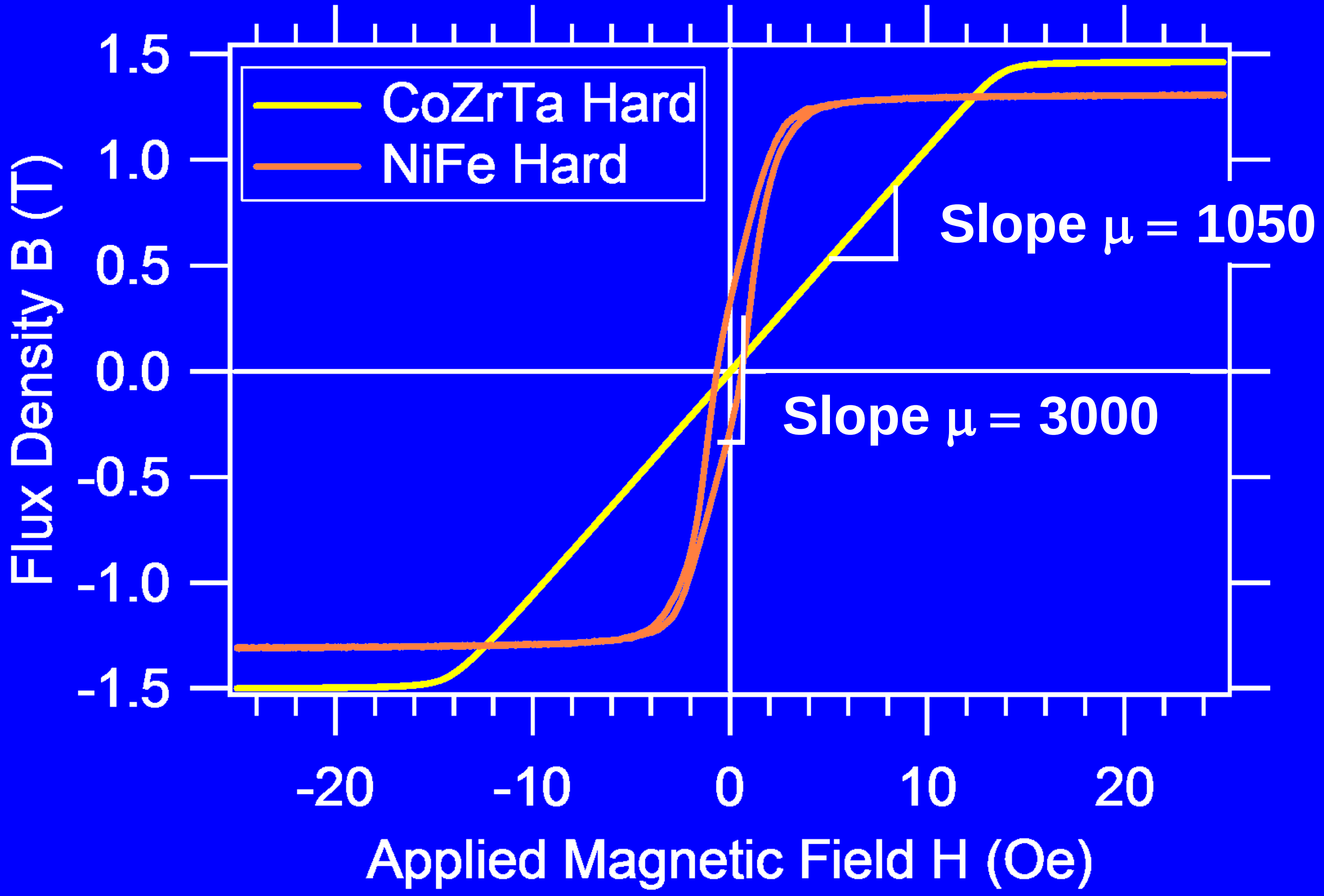
Inductance density of spirals is small (<100 nH/mm^2)

Inductance Densities vs. Q-Factor from the Literature

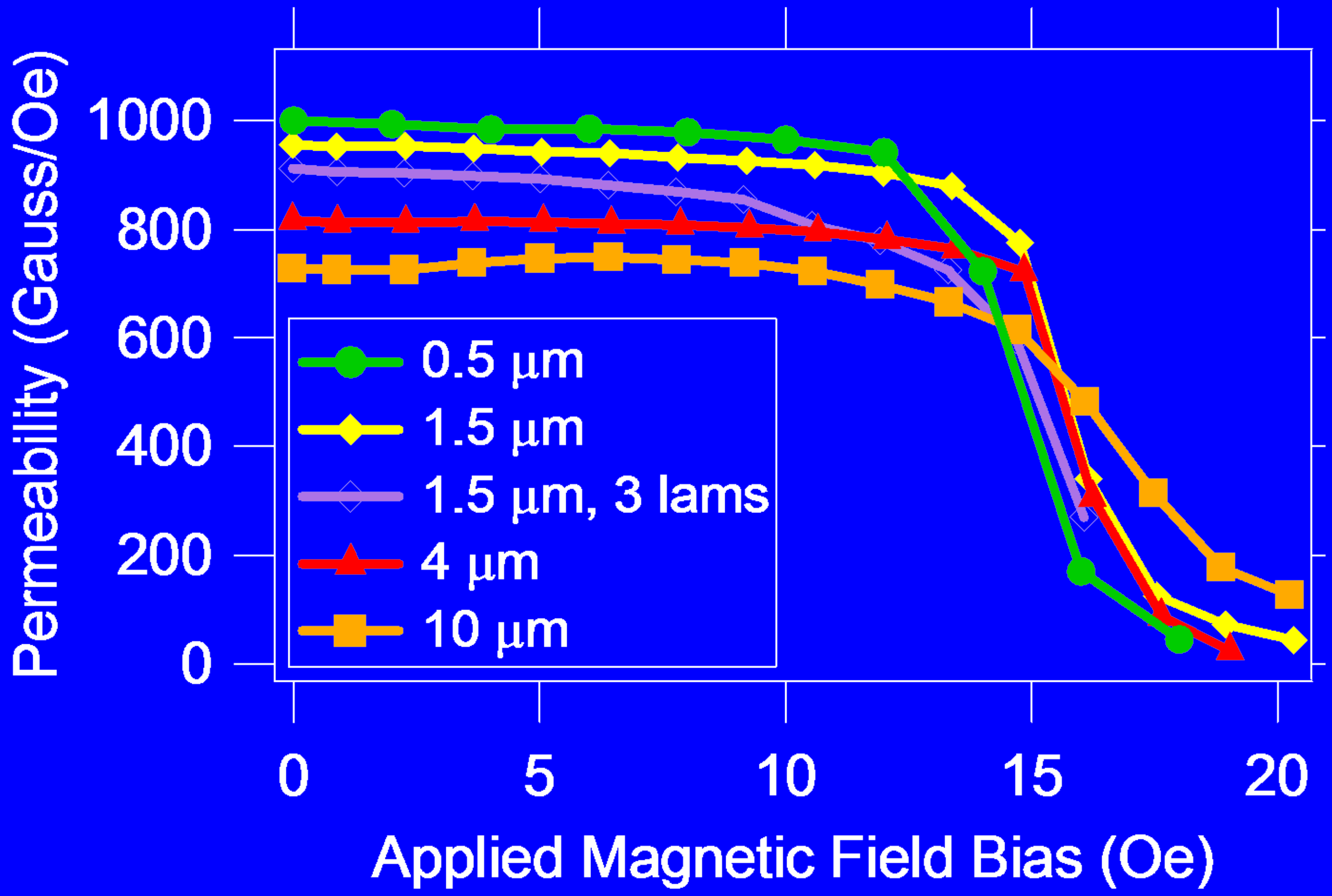


Gardner, Jamieson, et.al. IEEE Trans. Magnetics, 45, pp. 4760, 2009.

Magnetic Hysteresis Loops for CoZrTa & NiFe



Permeability vs. Applied Magnetic Field



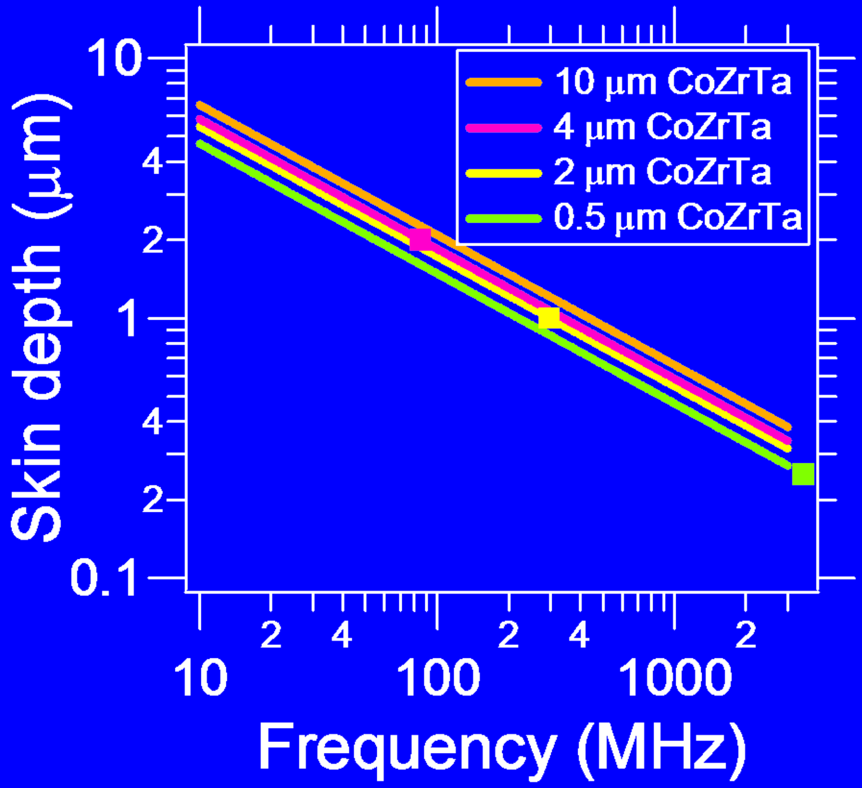
Magnetic anisotropy H_k has two components:

- The intrinsic induced anisotropy from the deposition
- The demagnetizing energy caused by the sample shape

Complex Permeability Model

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_i\mu_o}}$$

δ = skin depth
ρ = resistivity of magnetic film
ω = frequency
μ_i = relative dc permeability
d = film thickness

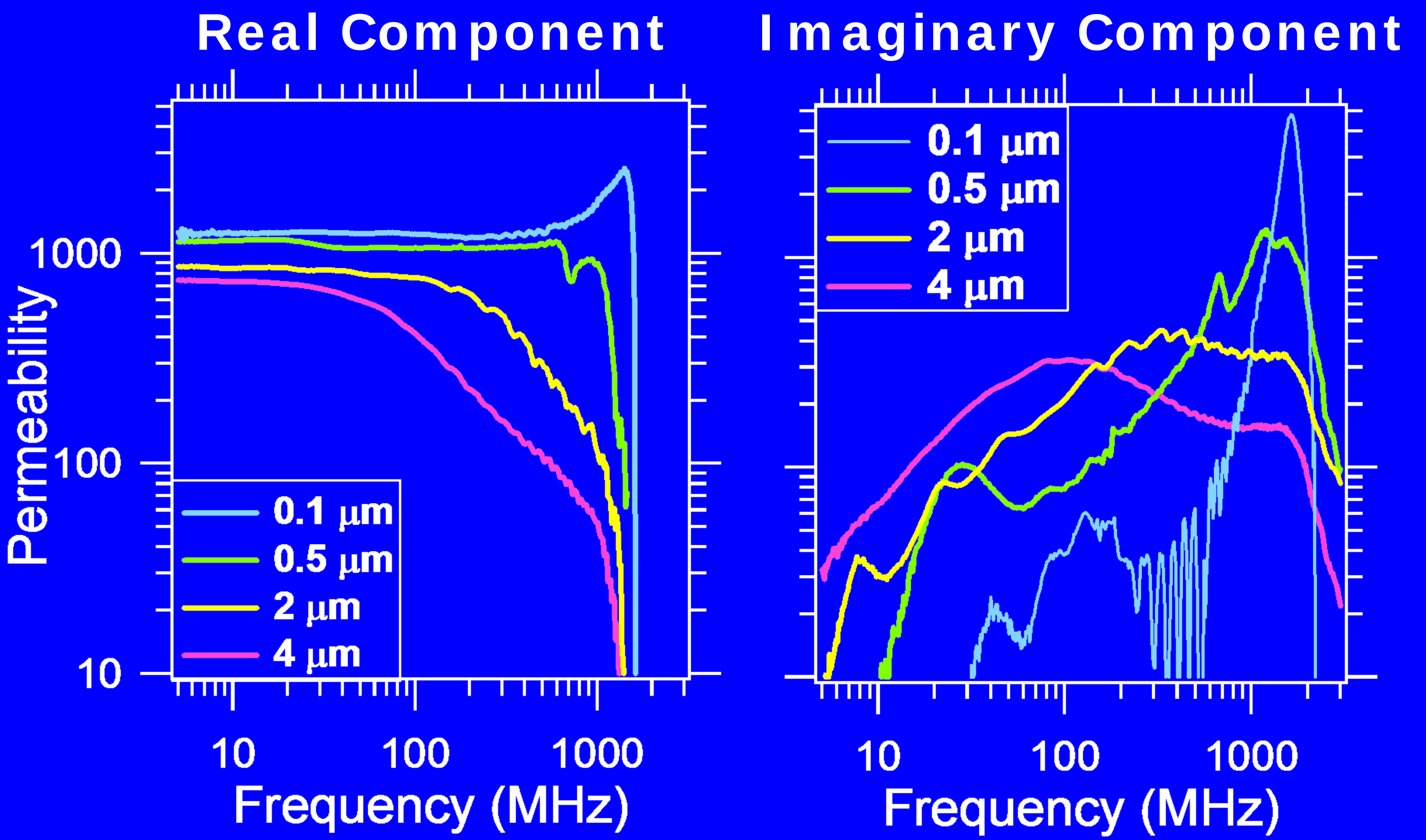


$$\mu = \mu_i \frac{2\delta}{(1+j)d}\tanh\frac{(1+j)d}{2\delta}$$

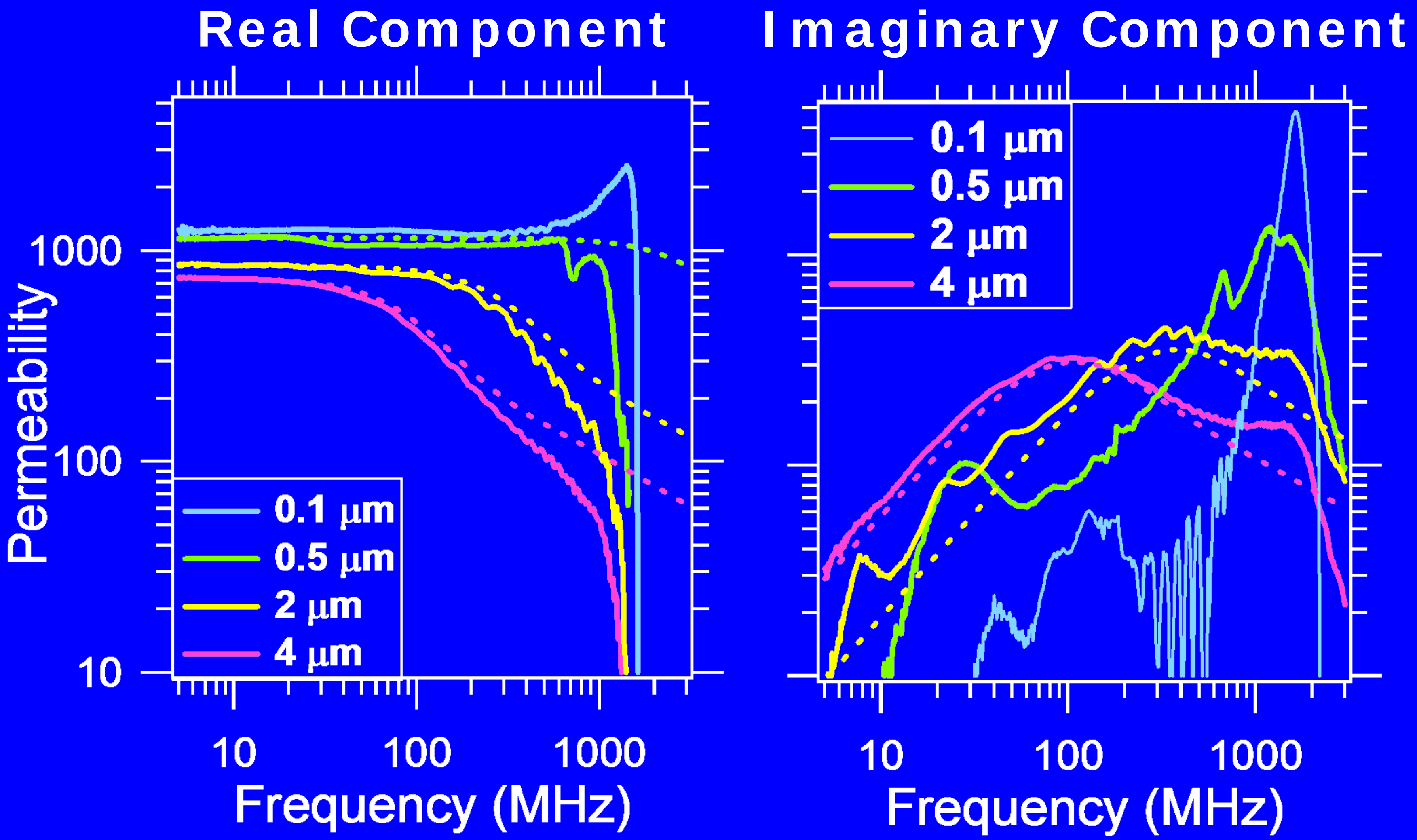
High resistivity materials are needed to reduce the eddy currents and increase the skin depth.

CoZrTa → ρ = 100 µΩ-cm

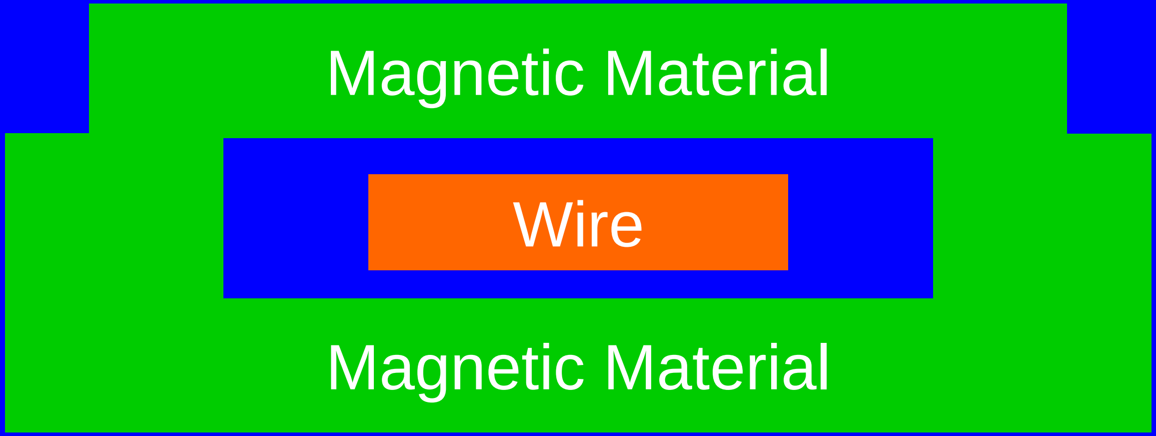
Permeability Spectra of CoZrTa



Permeability Spectra of CoZrTa



Inductance Modeling of Wire with Magnetic Material



Magnetic Material

Wire

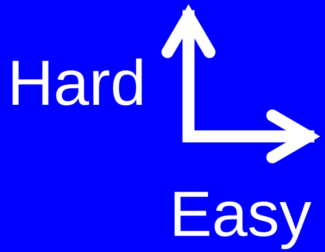
Magnetic Material

<u>Maximum Increase in Inductance</u>

1 layer magnetic film → $\leq 2 \times$

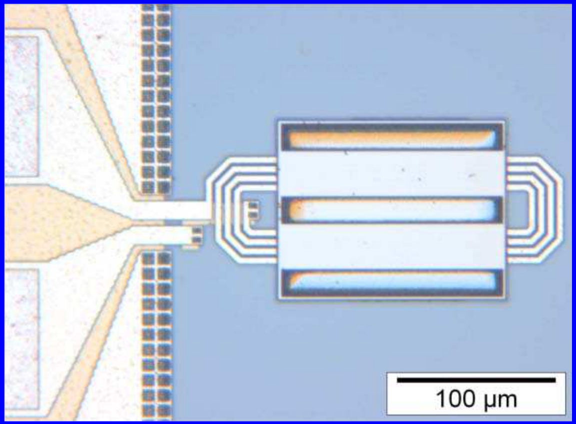
2 layers magnetic film → $\leq \mu_r \times$

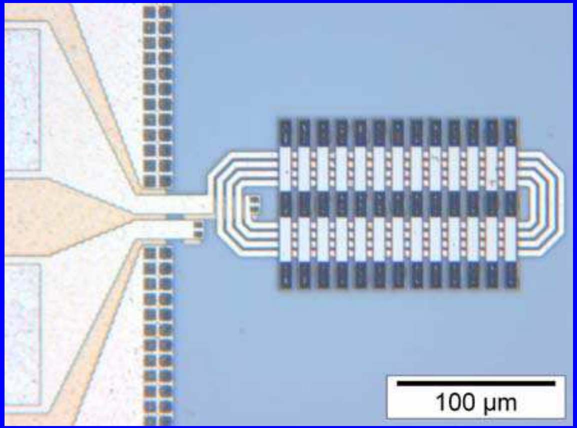
Spiral and Transmission Line Inductors

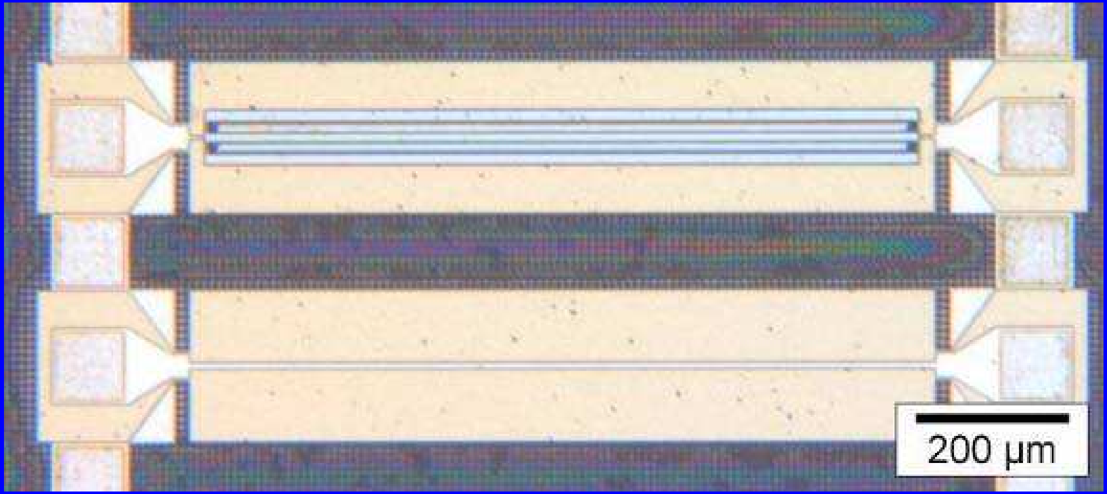


Hard

Easy

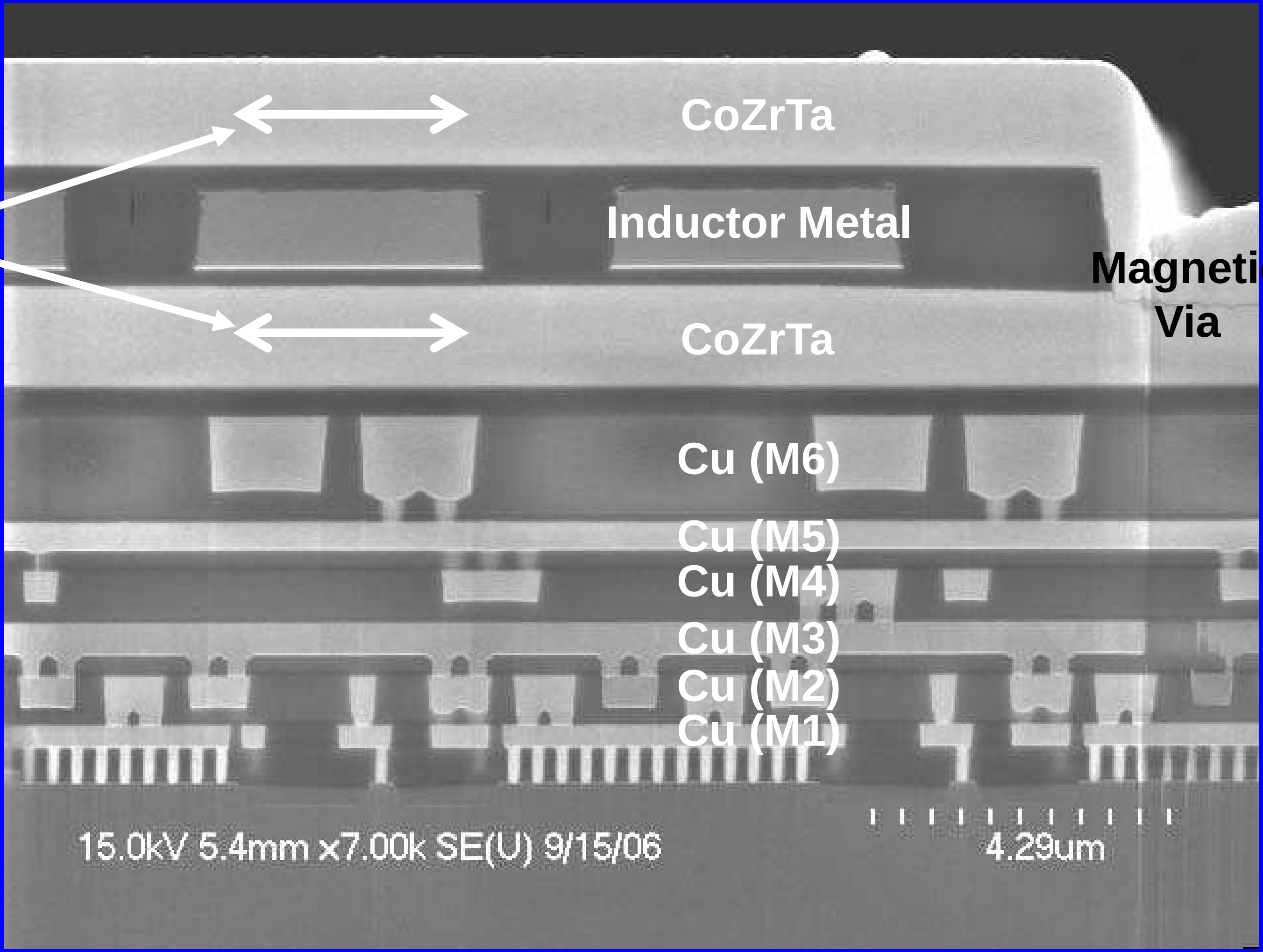




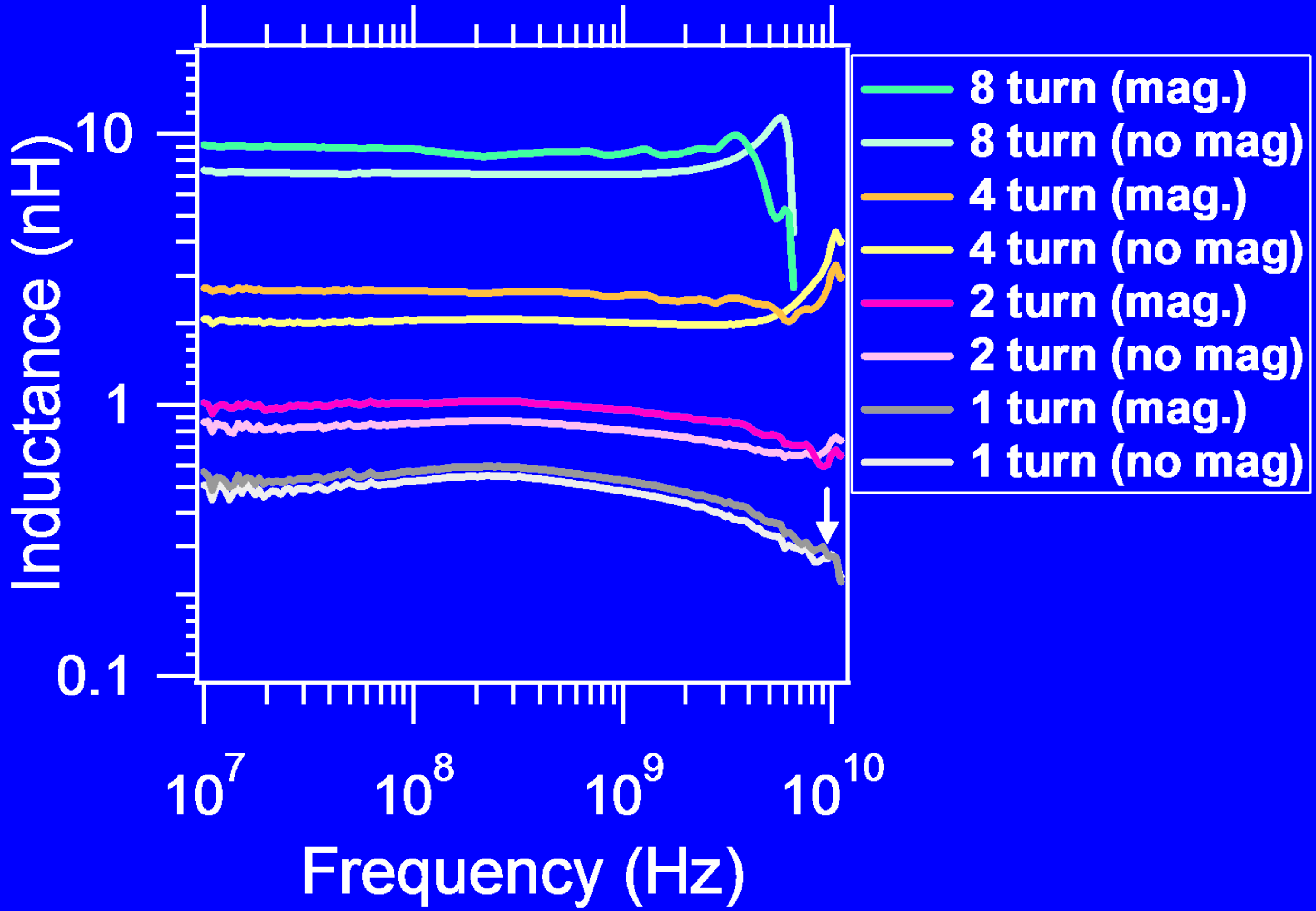


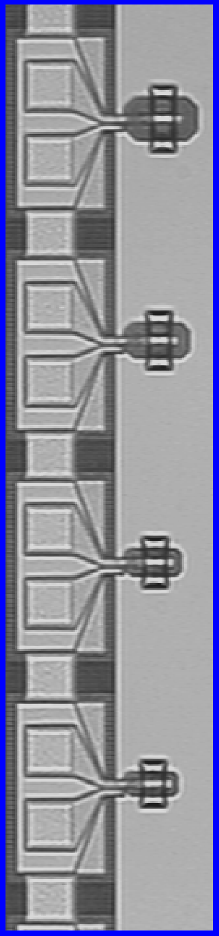
Structures take advantage of the uniaxial magnetic anisotropy.

Cross-Sectional Image of Inductor in 130 nm 6-level Metal CMOS Process



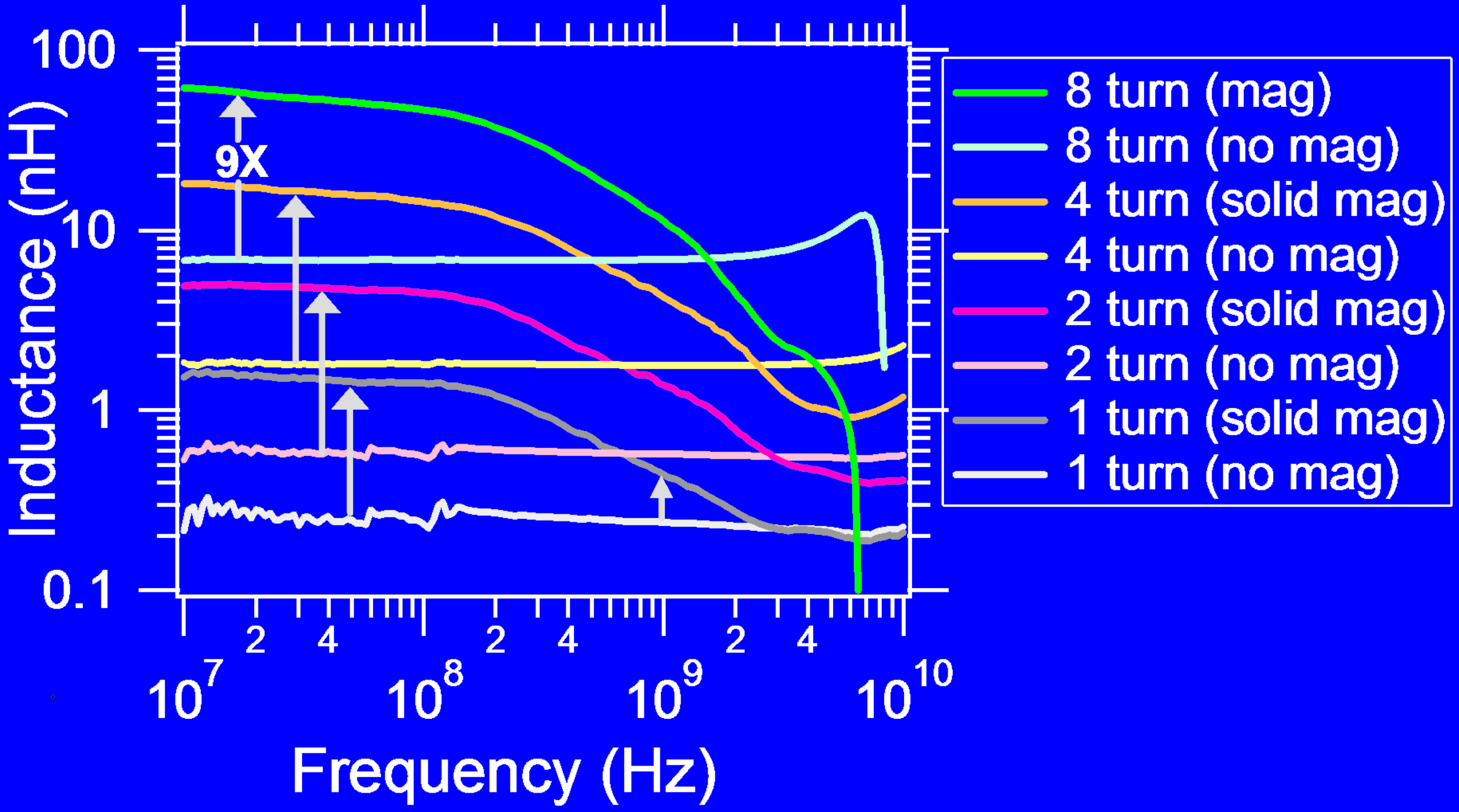
Spiral Inductors with Single Magnetic Layer





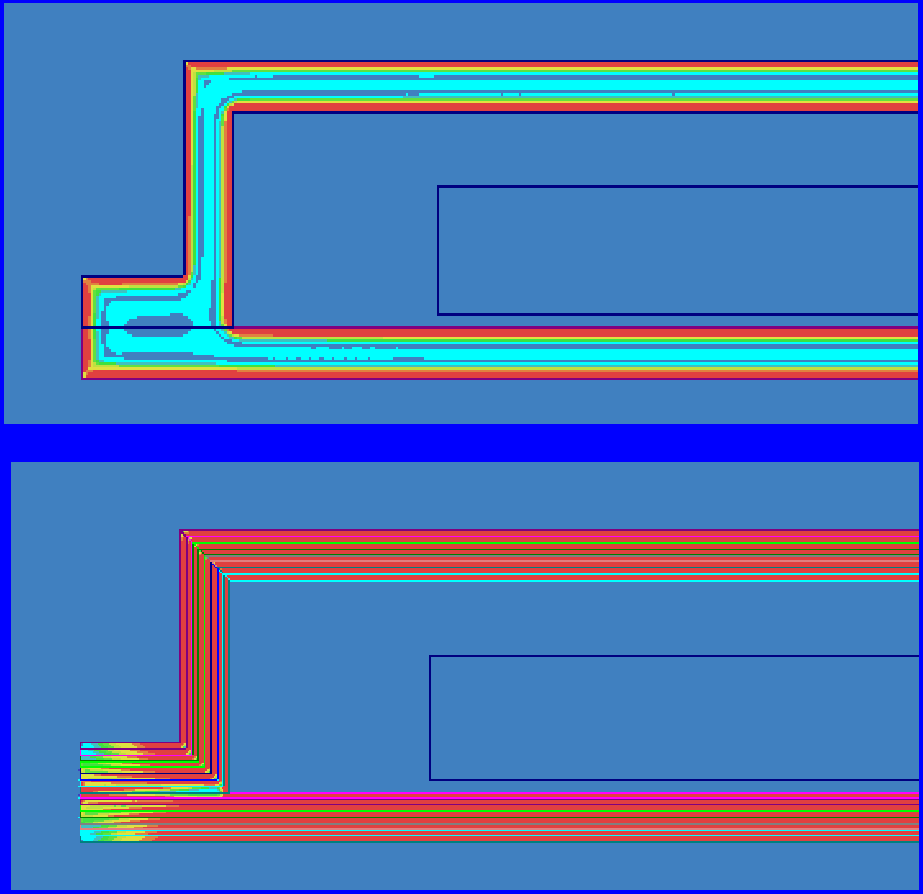
Increase in inductance is small (10~30% at up to 9.8 GHz)

Spiral Inductors with Two Magnetic Layers



Inductance increases by 9 ×

Magnetic Flux Density At 1GHz

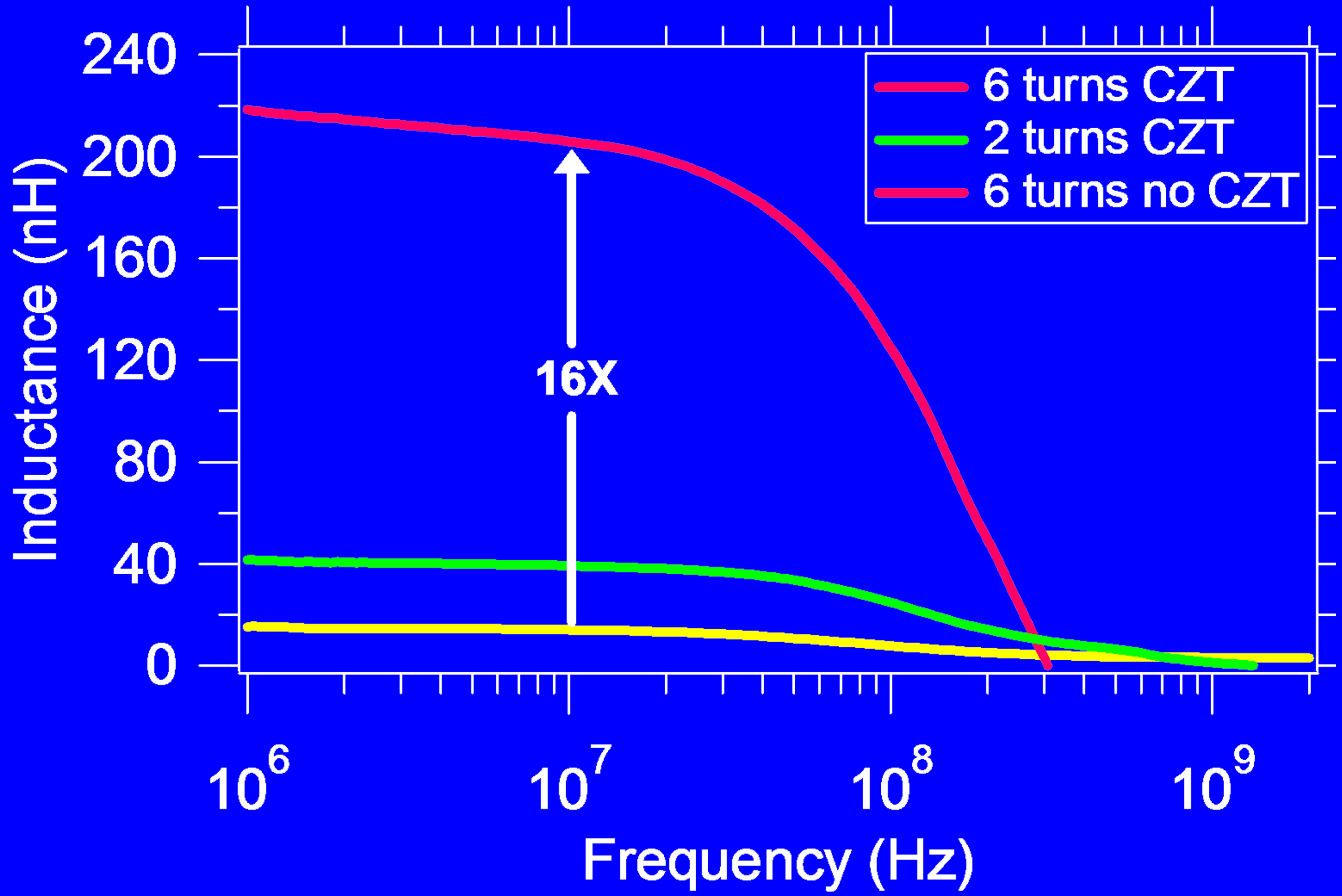


Unlaminated Cobalt alloy

Laminated Cobalt alloy

Skin-depth effect limits penetration of B-field.
Larger skin depth results in lower losses.

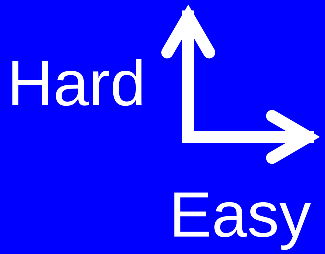
Inductance vs. Frequency of Spirals



Inductance density is 1,700 nH/mm^2

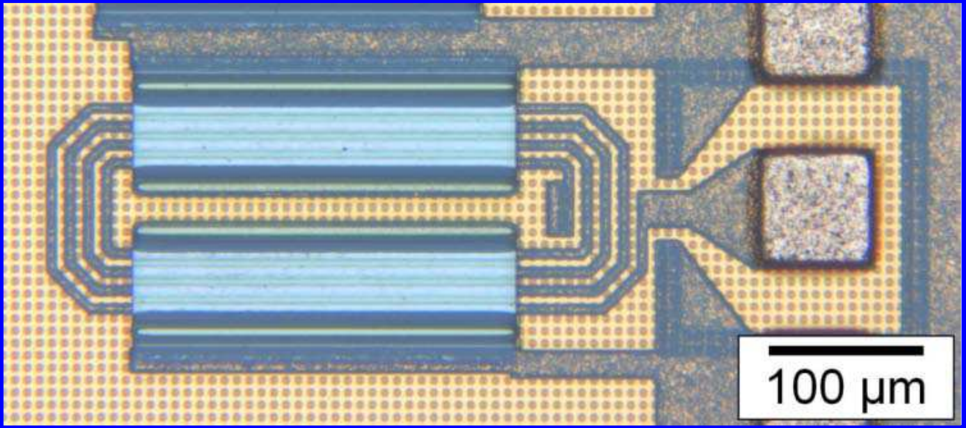
Roll off is from resonance ($1/\sqrt{LC}$) of inductor.

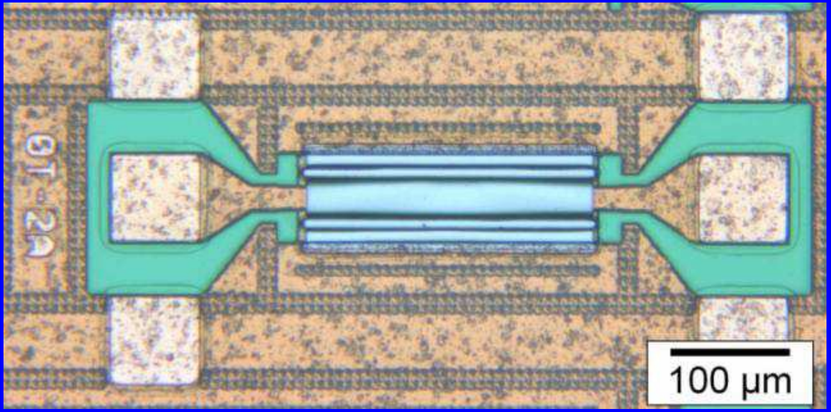
Spiral and Stripe Inductors Using 5um thick Copper

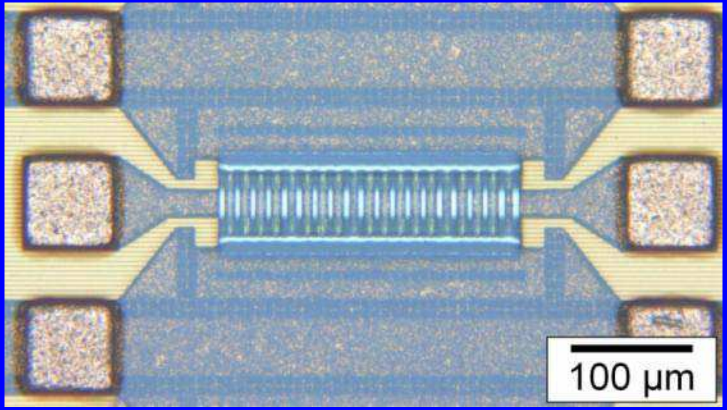


Hard

Easy





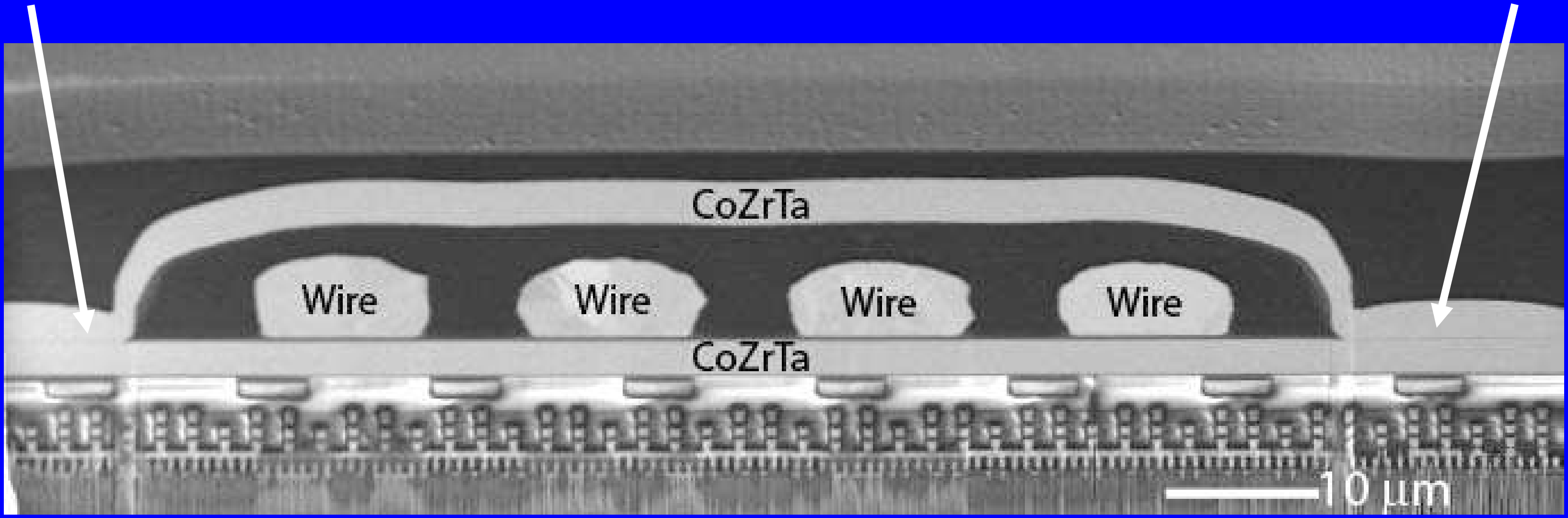


Structures take advantage of the uniaxial magnetic anisotropy.

Cross-Sectional Image of Inductor in 90 nm CMOS Process

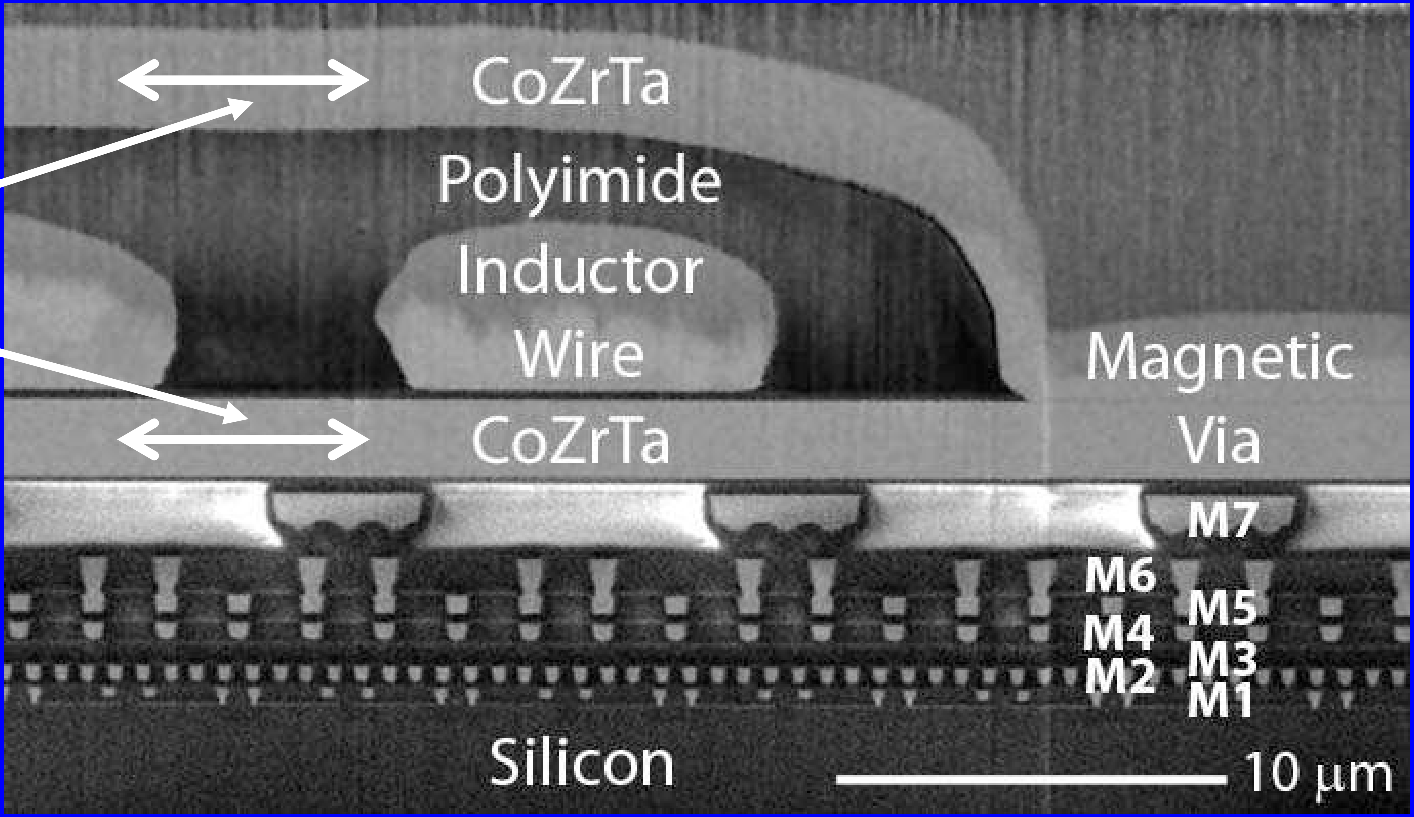
Magnetic Via

Magnetic Via

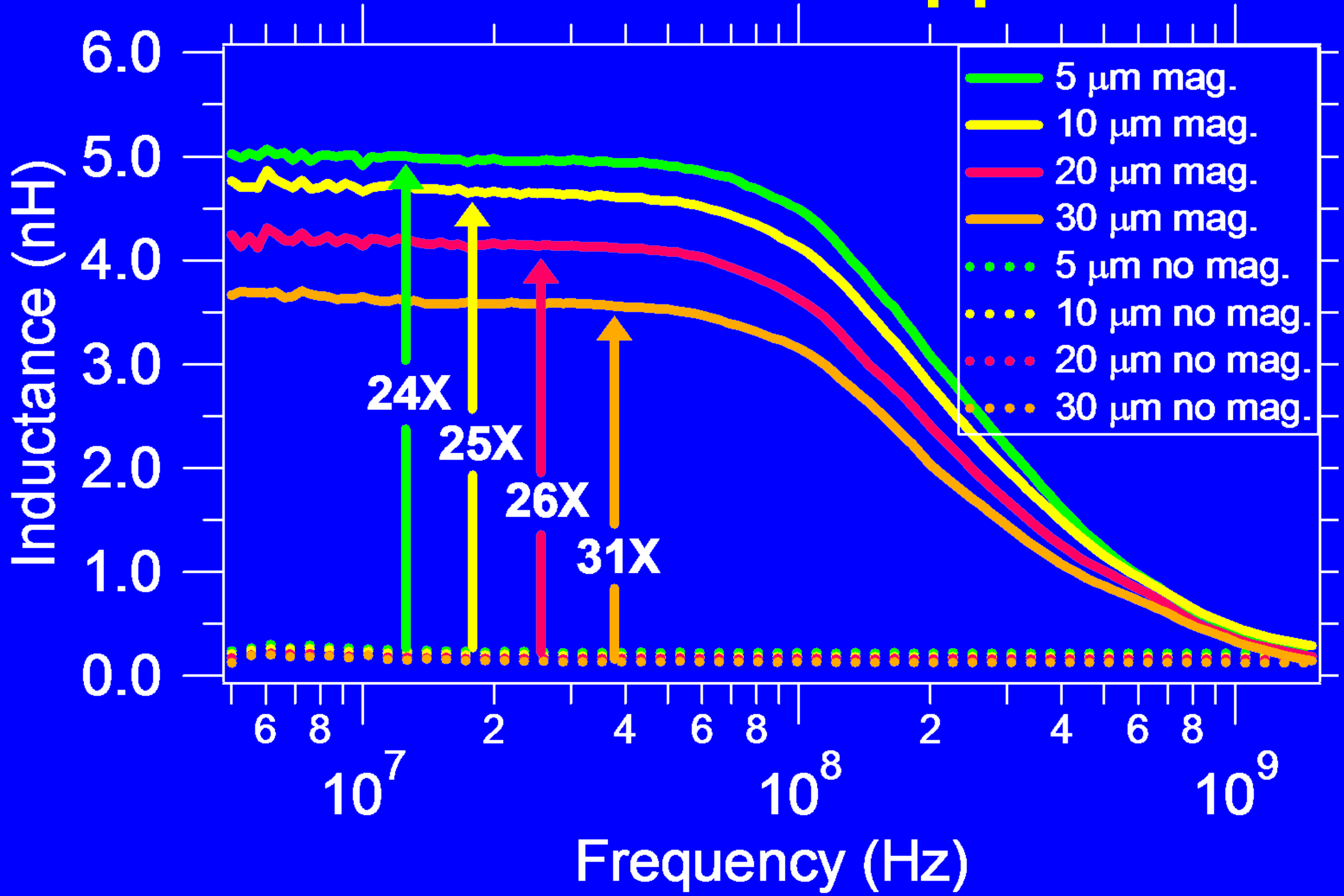


90 nm 7-level Metal CMOS Process

Cross-Sectional Image of Inductor



Stripe Inductors With Thick Copper

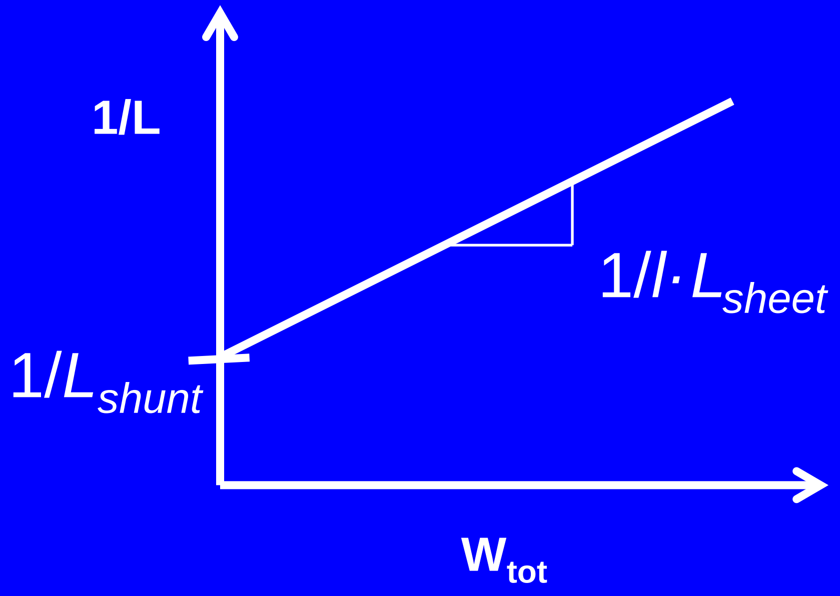


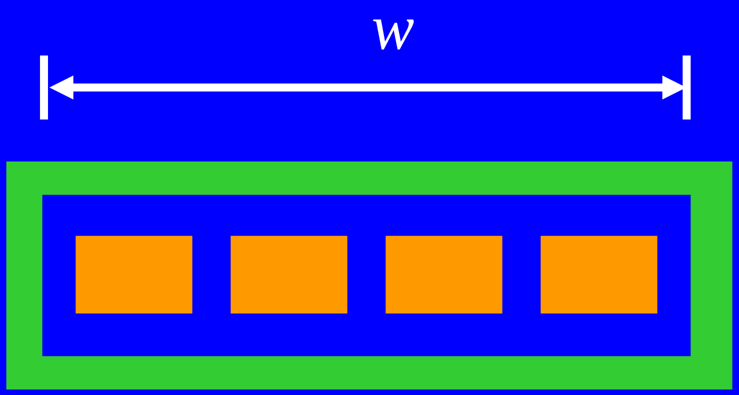
Inductance increases by up to over 30×

Inductance Modeling of Rectangular Line

$$L \approx \mu_0 \mu_r \frac{t_m}{2}\left(\frac{l}{w}\right)$$

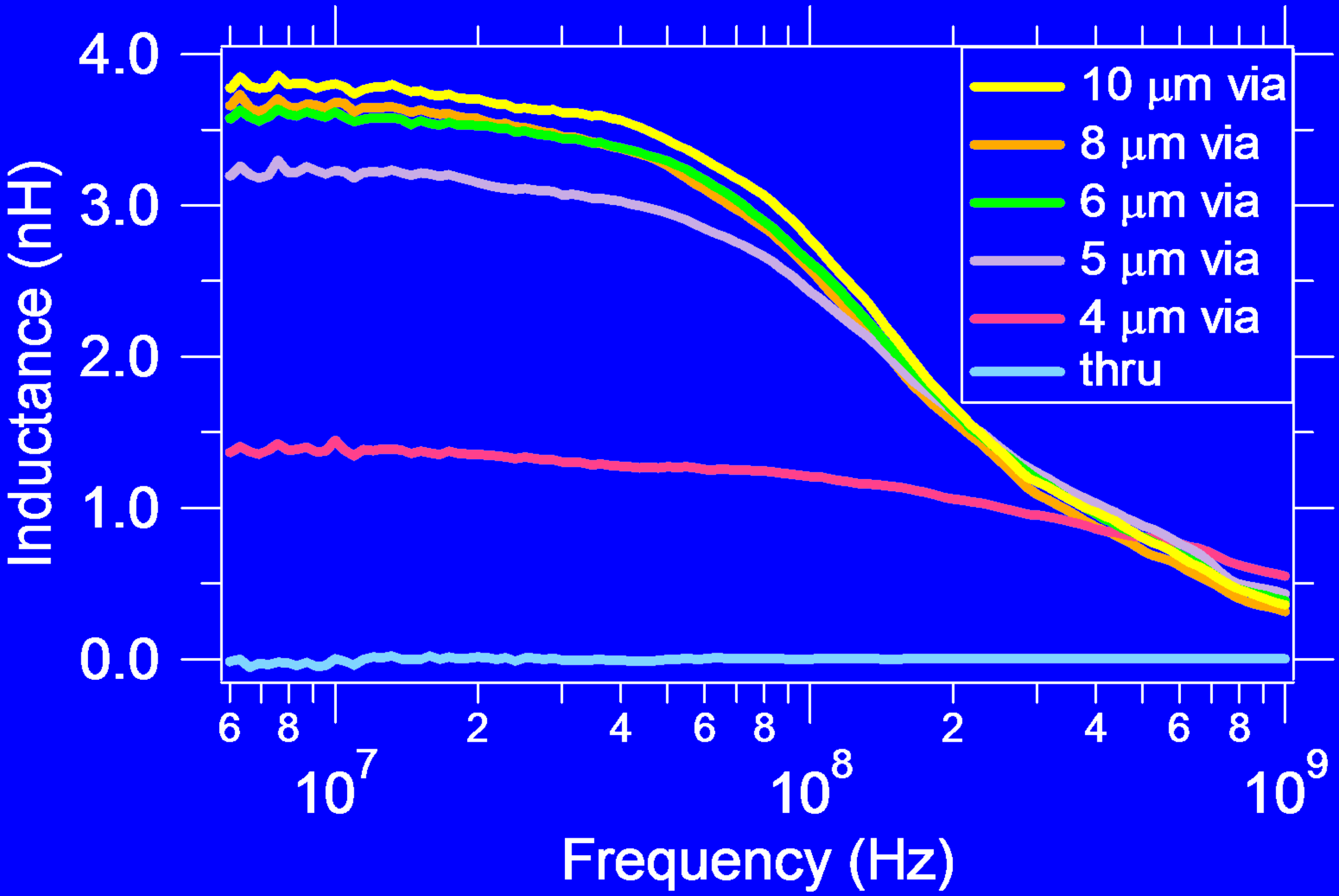
l = line length
w = line width
t_m = magnetic film thickness
μ_r = relative dc permeability





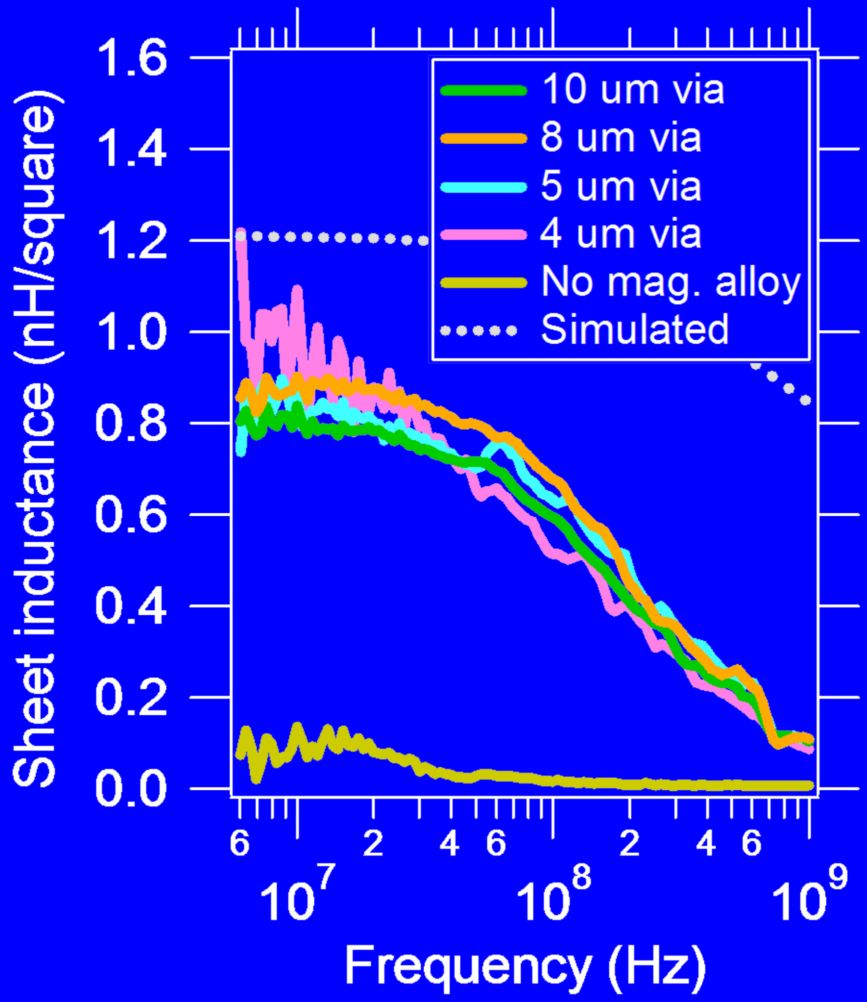
Eqn. from V. Korenivski and R. B. van Dover, JAP, v. 82 (10), 1997

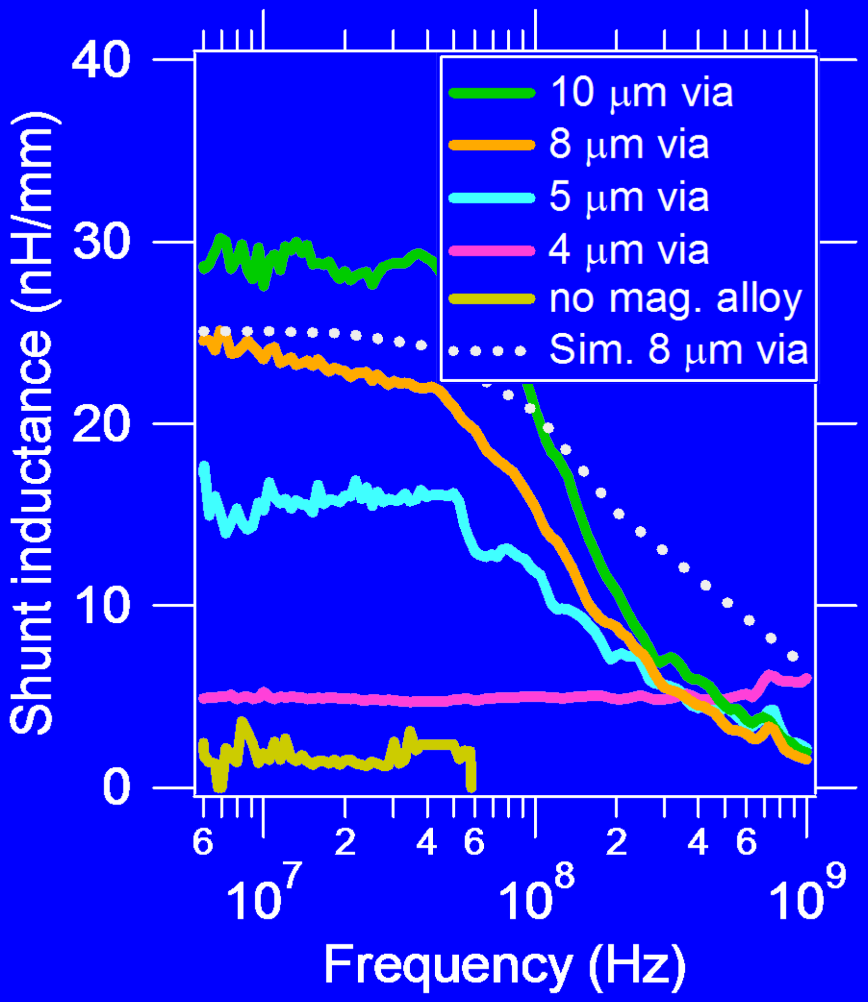
Magnetic Via Widths



Inductance increases with via width, but the change becomes diminishingly small.

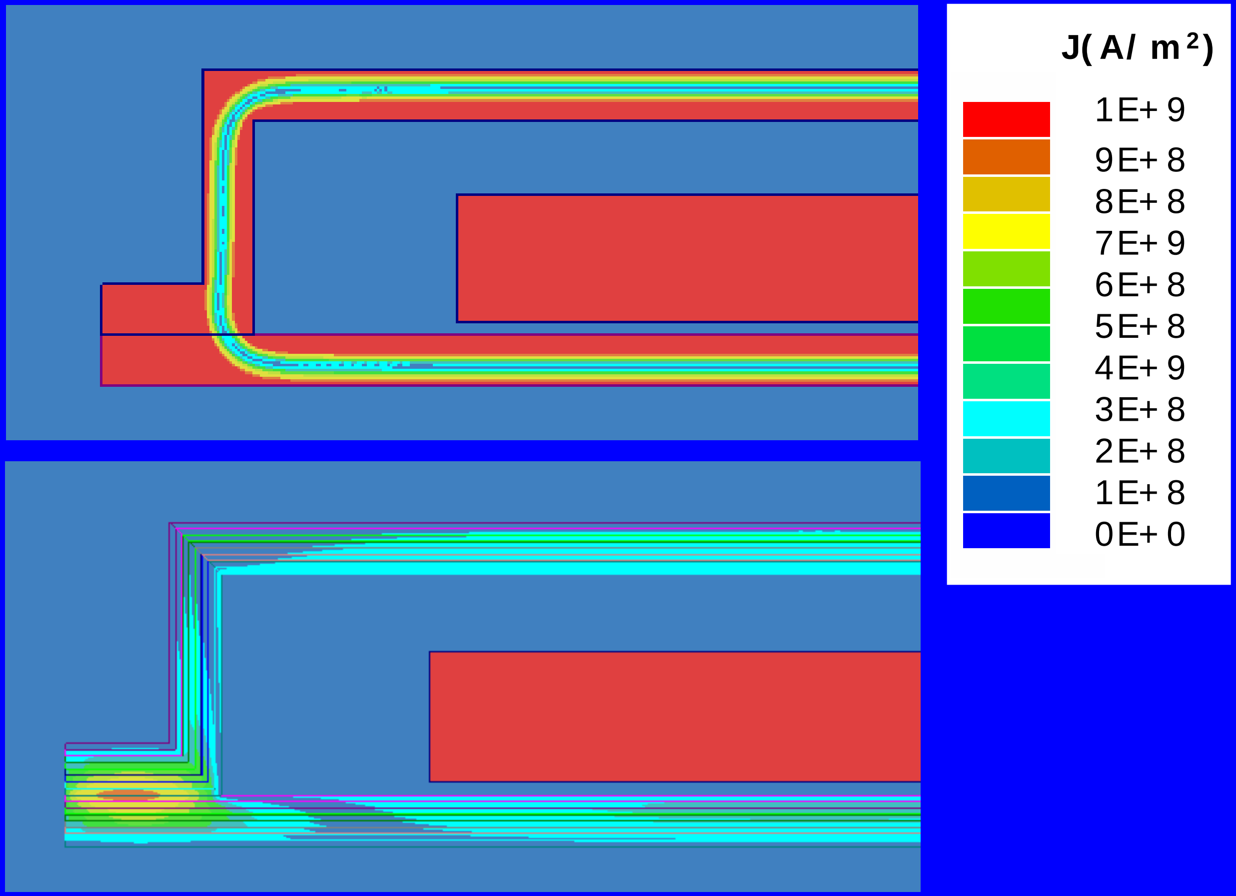
Sheet and Shunt Inductances





Sheet inductance is independent of the magnetic via width.
Shunt inductance increases with increasing via width.

Current Density At 100 MHz

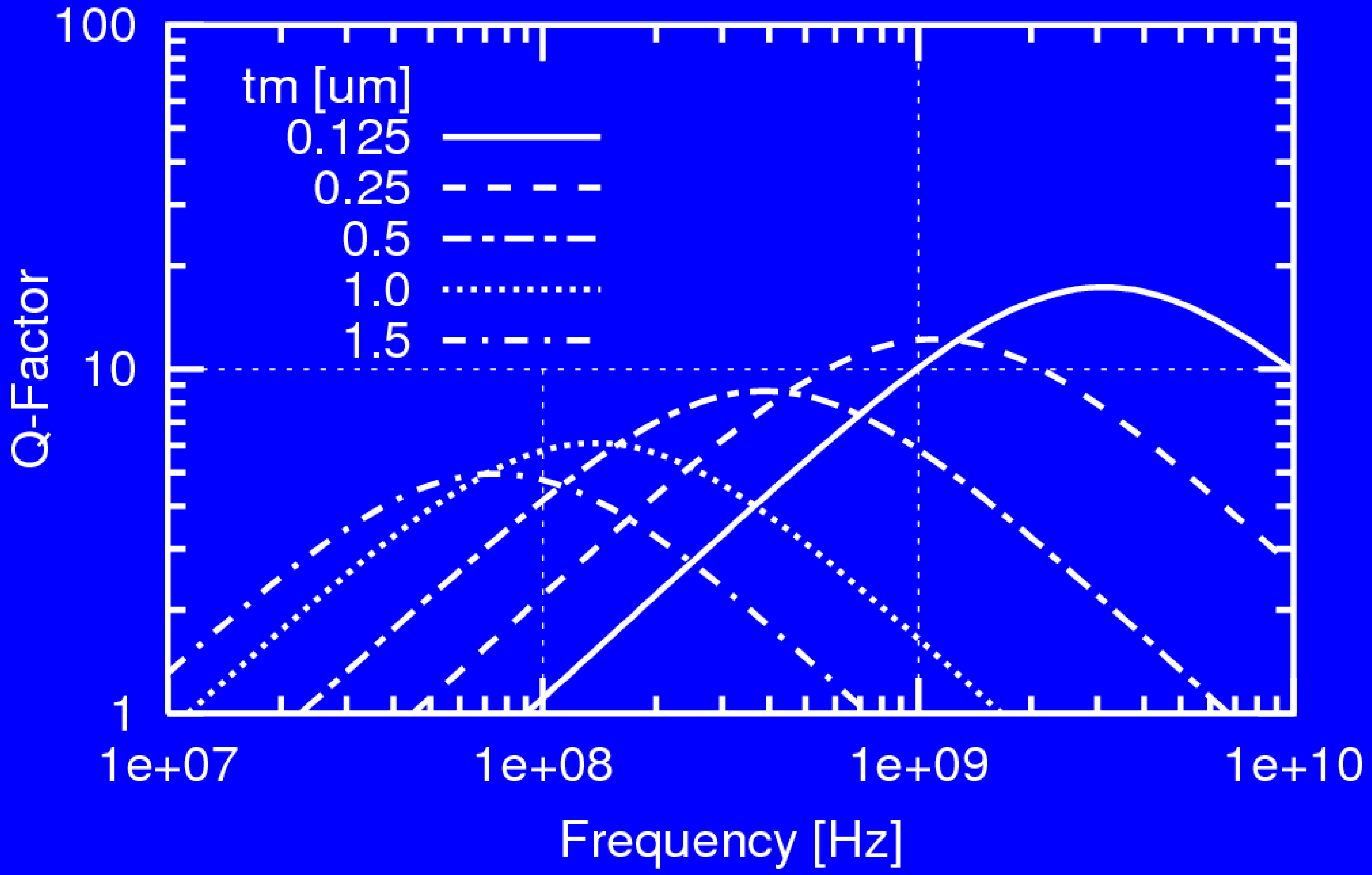


Unlaminated Cobalt alloy

Laminated Cobalt alloy

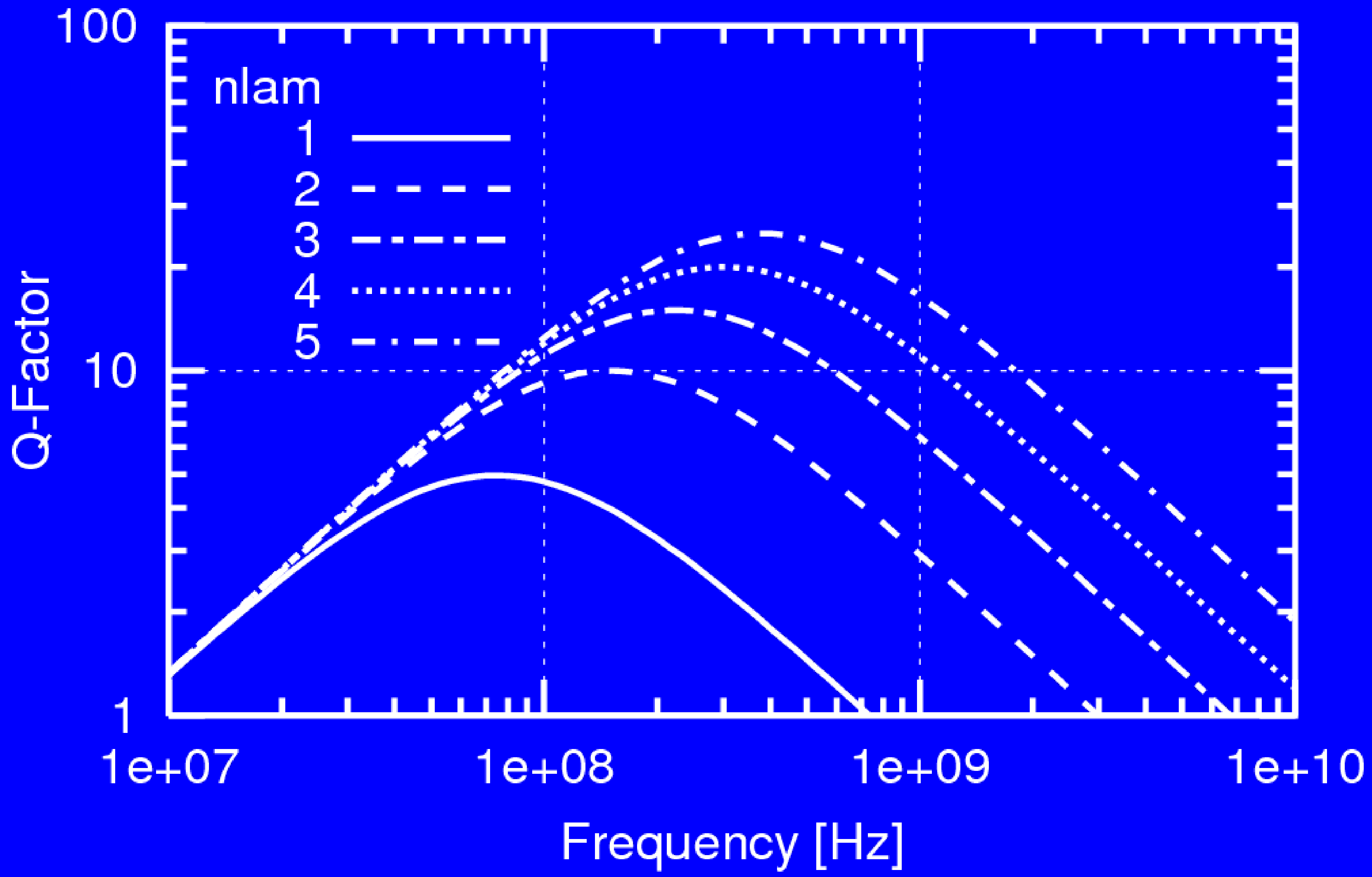
Eddy currents are reduced by laminations.

Analytical Modeling of Q-Factor



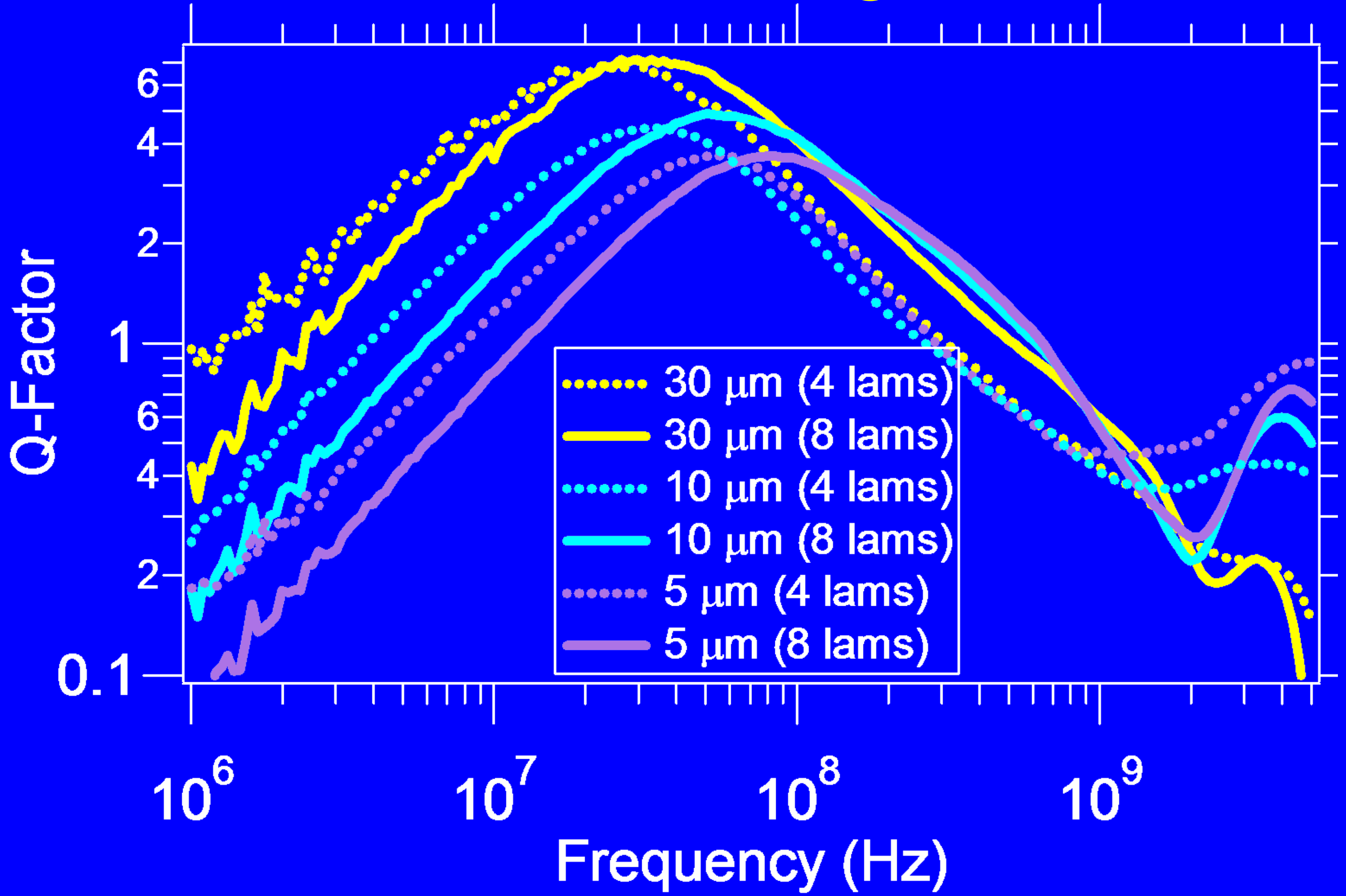
Thinner films give higher Q-factors, but lower inductance.

Analytical Modeling of Q-Factor



Laminations increase the Q-factor.

Quality Factor of Inductors With Laminated Magnetic Films



Peak quality factor is increased,
But quality factor at lower frequencies decreased.

Summary

- DC Voltage Converters
  - High-frequency buck converters
  - High inductance density needed
  - Low DC resistance important
- Magnetic materials
  - Complex permeability (real and imaginary)
  - Low hysteretic losses
  - CMOS compatibility (thermal, process compatibility)
- Inductors with magnetic material
  - Single films increase inductance by ≤30% up to 9.8 GHz
  - Magnetic vias – Sheet inductance vs. shunt inductance
  - 2 magnetic films increase inductance
    - Over 30× compared to air-core
    - 200 nH inductors possible (1,700 nH/mm^2)

For More Information

- IEEE Trans. Magnetics, **45**, pp. 4760, 2009.
- Journal of Applied Physics, **103**, pp. 07E927, Apr. 1, 2008.
- IEEE Trans. Magnetics, **43**, pp. 2615, 2007.
- IEEE PESC 2004 and IEEE VLSI Symp. 2004.
- APEC, Paper #SP1.4.2, p. 75, 2010.
- Intl. Electron Devices Meeting (IEDM), pp. 221-224, 2006.
- IEEE Intl. Interconnect Technology Conference, pp.101–103, 2001.