Integrated On-Chip Inductors using Magnetic Films

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&

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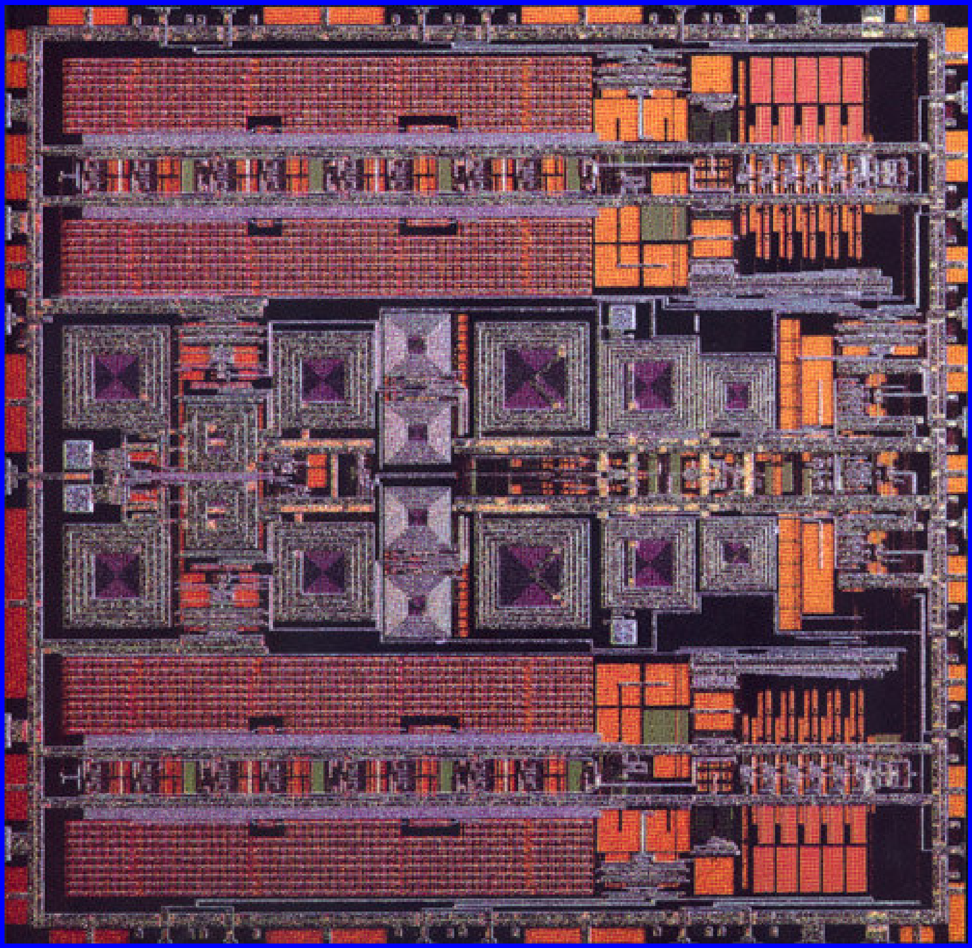
Outline

- **Magnetic material properties**
  - Magnetic hysteresis loops
  - Complex permeability spectra
  - Magnetic anisotropy
- **Inductor measurements**
  - Structure cross sections
  - Inductance measurements
  - Sheet and shunt inductance
- **Measurement analysis and modeling**
  - Eddy current and skin effect
  - Time constant and Quality factor
  - Effectiveness of laminations

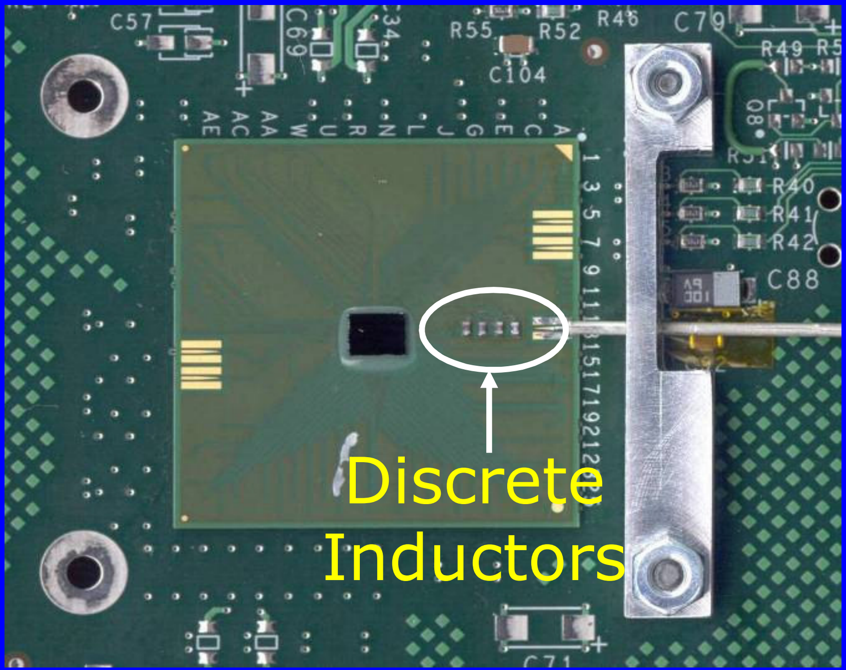
RF CMOS Integrated Circuit

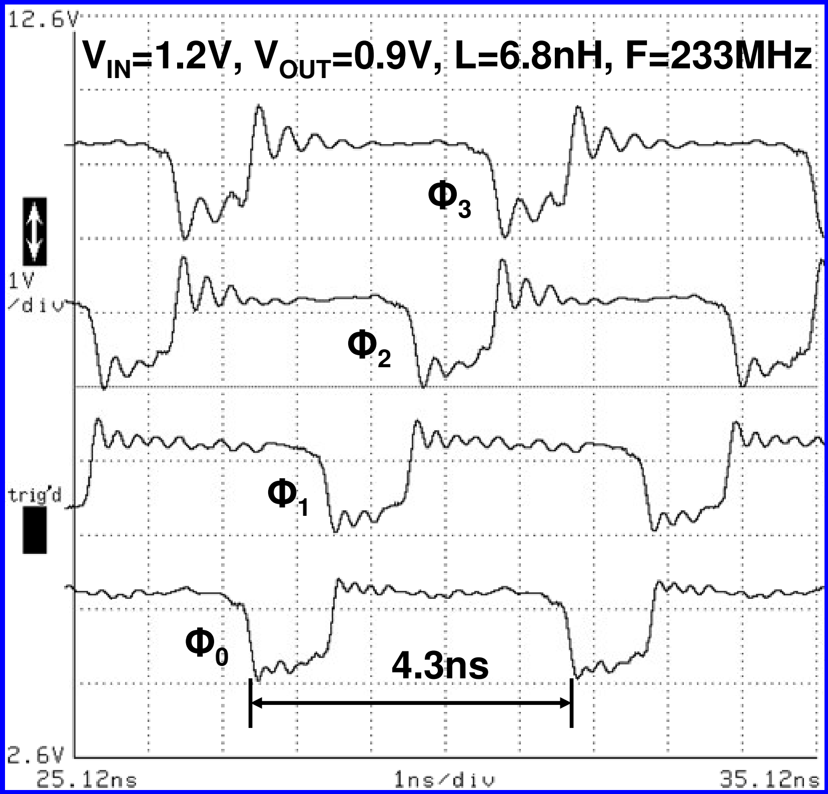


Inductors make up 24% of this chip

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

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

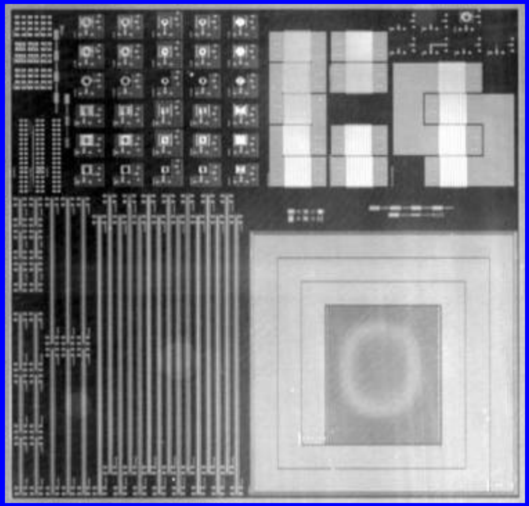
	[3]	[4]	[5]	[6]	[7]	Pavo-1
Year	1996	1999	2000	2002	2002	**2004**
Tech [µm]	n/a	0.25	n/a	0.25	n/a	**0.09**
# phases	1	1	1	1	1	**4**
V_{IN} [V]	4	3	4	2.5	3.6	**1.2**
V_{OUT} [V]	3.3	2	3	1.4	2.7	**0.9**
f [MHz]	1.6	0.5	3	0.75	1.8	**233**
Eff. [%]	85	94	83.3	95	80	**83.2**
L_{TOT} [µH]	3	10	1	15.2	1	**0.0017**
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

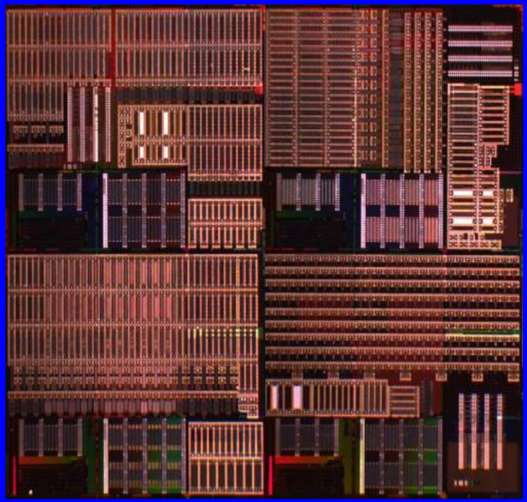
Inductor Test Chips

Circa 1997~2000



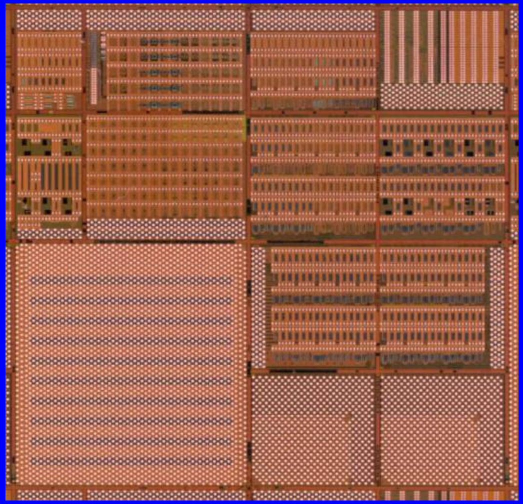
- **Thin Aluminum**
- **Thin CoZrTa**
- **GHz response demonstrated**

Circa 2001~2005



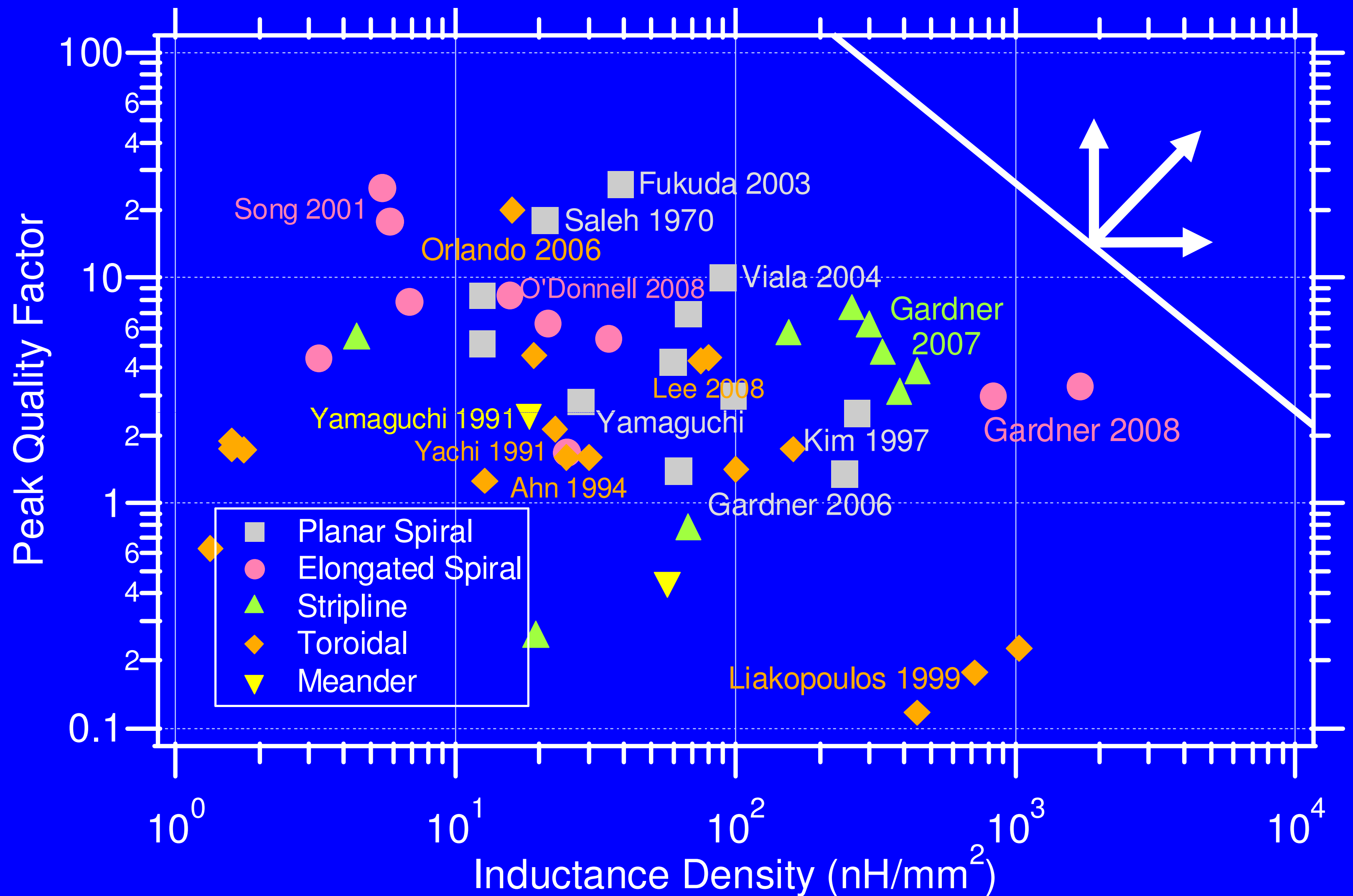
- **Thick Aluminum**
- **Thick CoZrTa**
- **High inductance demonstration**

Circa 2005~2008



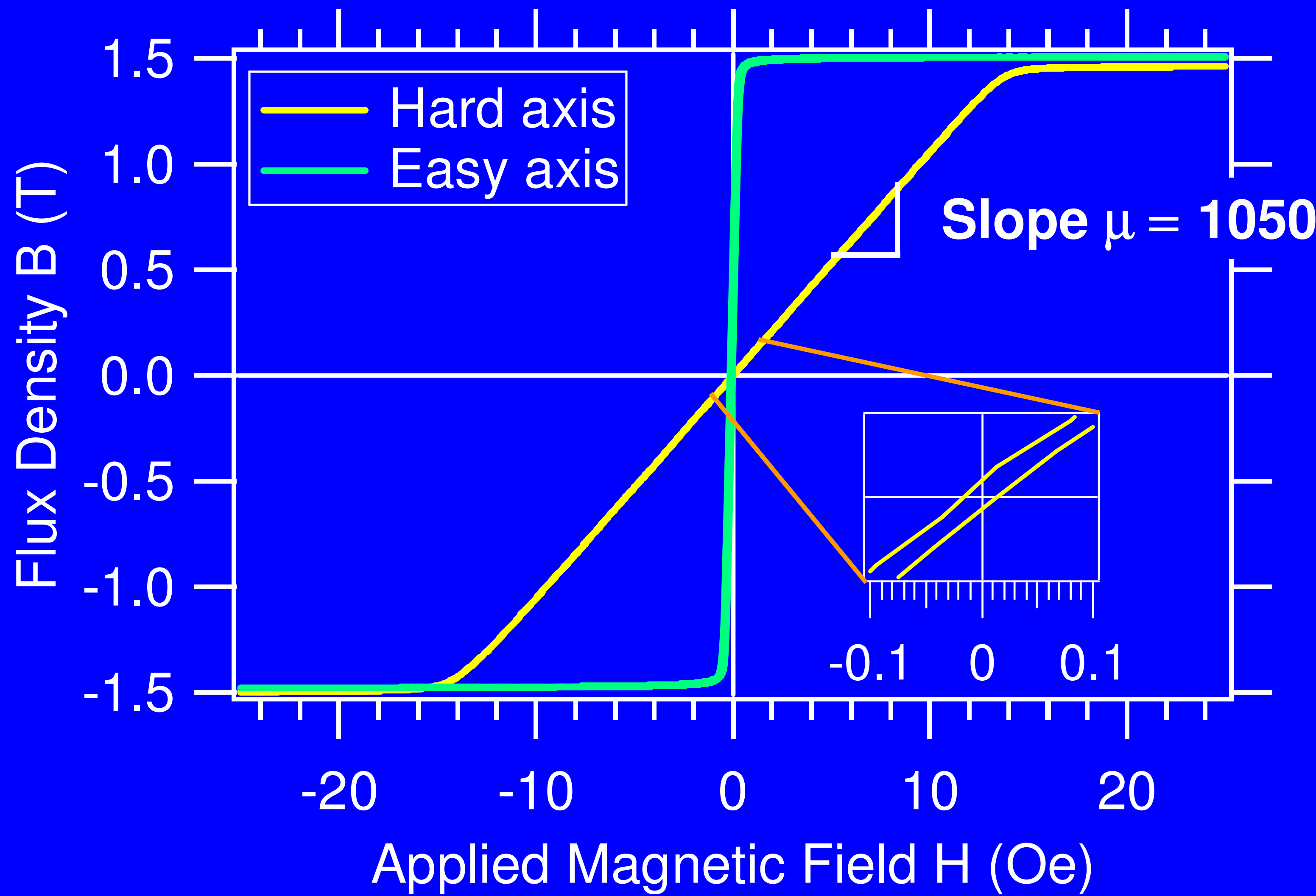
- **Thick Cu/Polyimide**
- **Thick Lam. CoZrTa**
- **High Q inductors demonstrated**

Inductance Densities vs. Q-Factor from the Literature



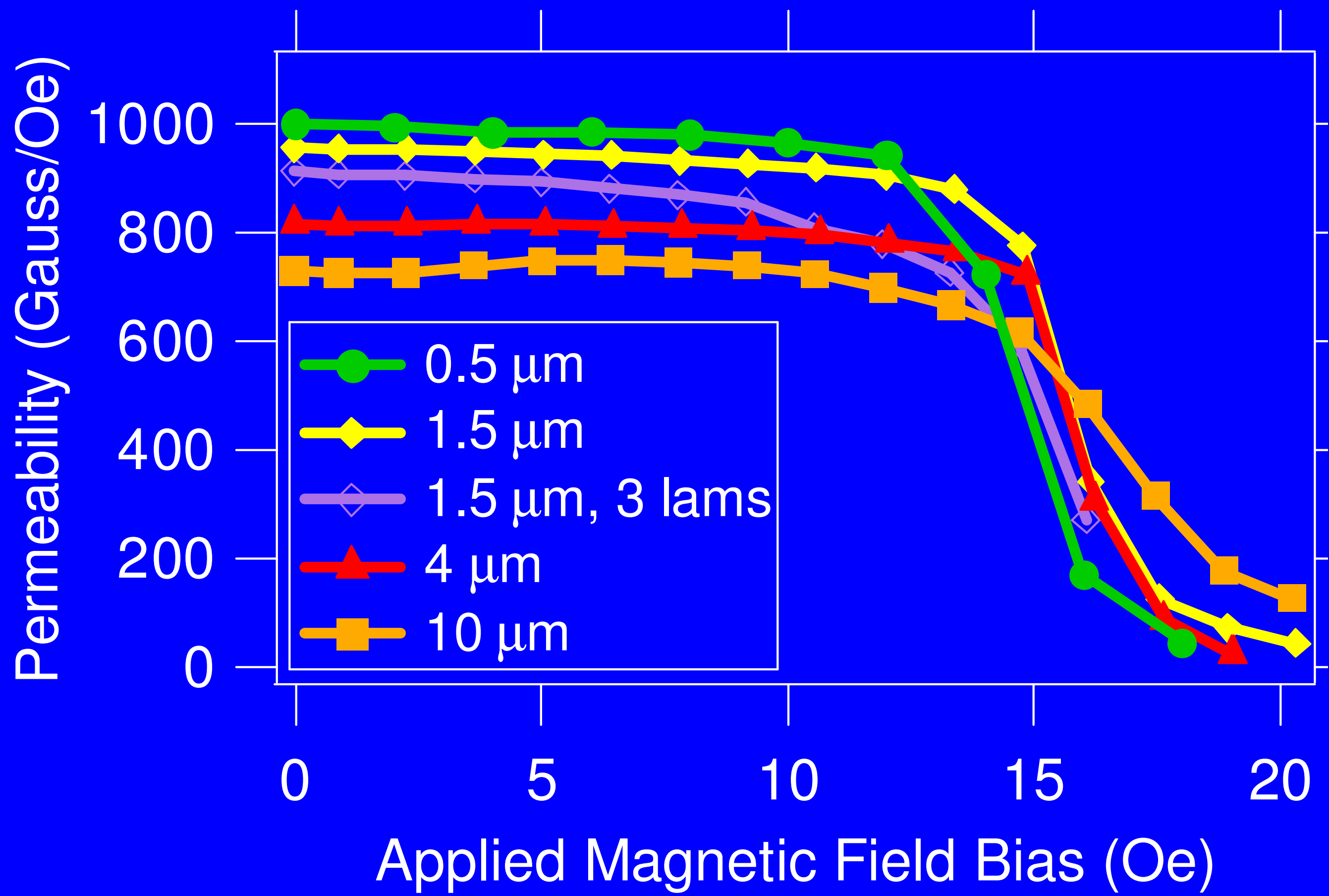
Gardner, Jamieson, et.al. IEEE Trans. Magnetics, 45, pp. 4760, 2009.

Magnetic Hysteresis Loops for CoZrTa



Coercivity < 0.02 Oe minimizing hysteretic losses.

Permeability vs. Applied Magnetic Field



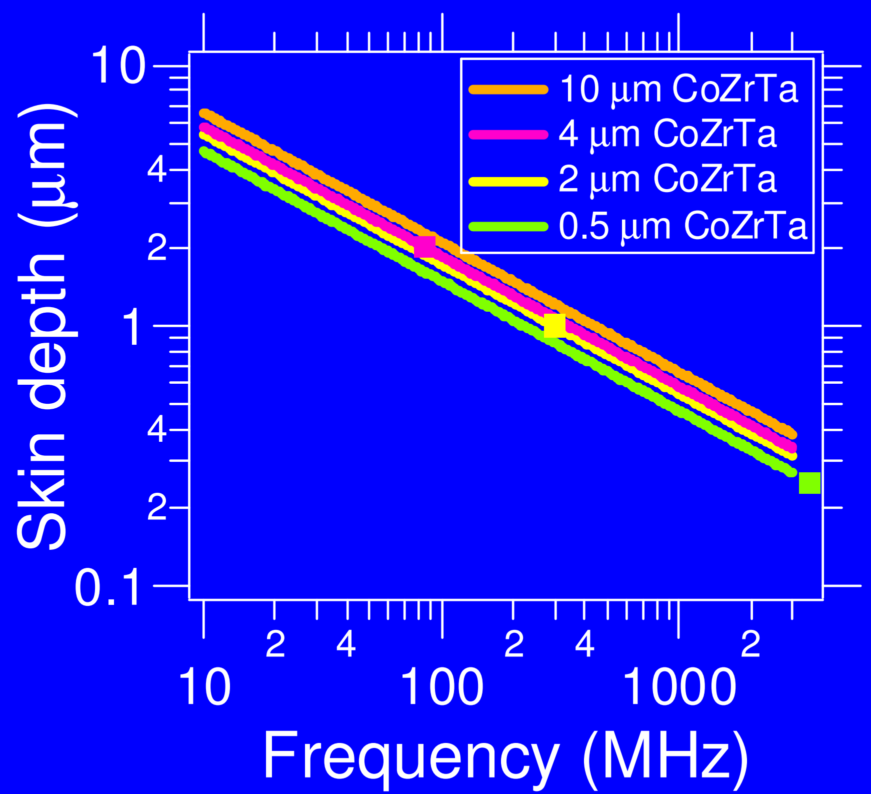
Magnetic anisotropy H_k has two components:

- **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

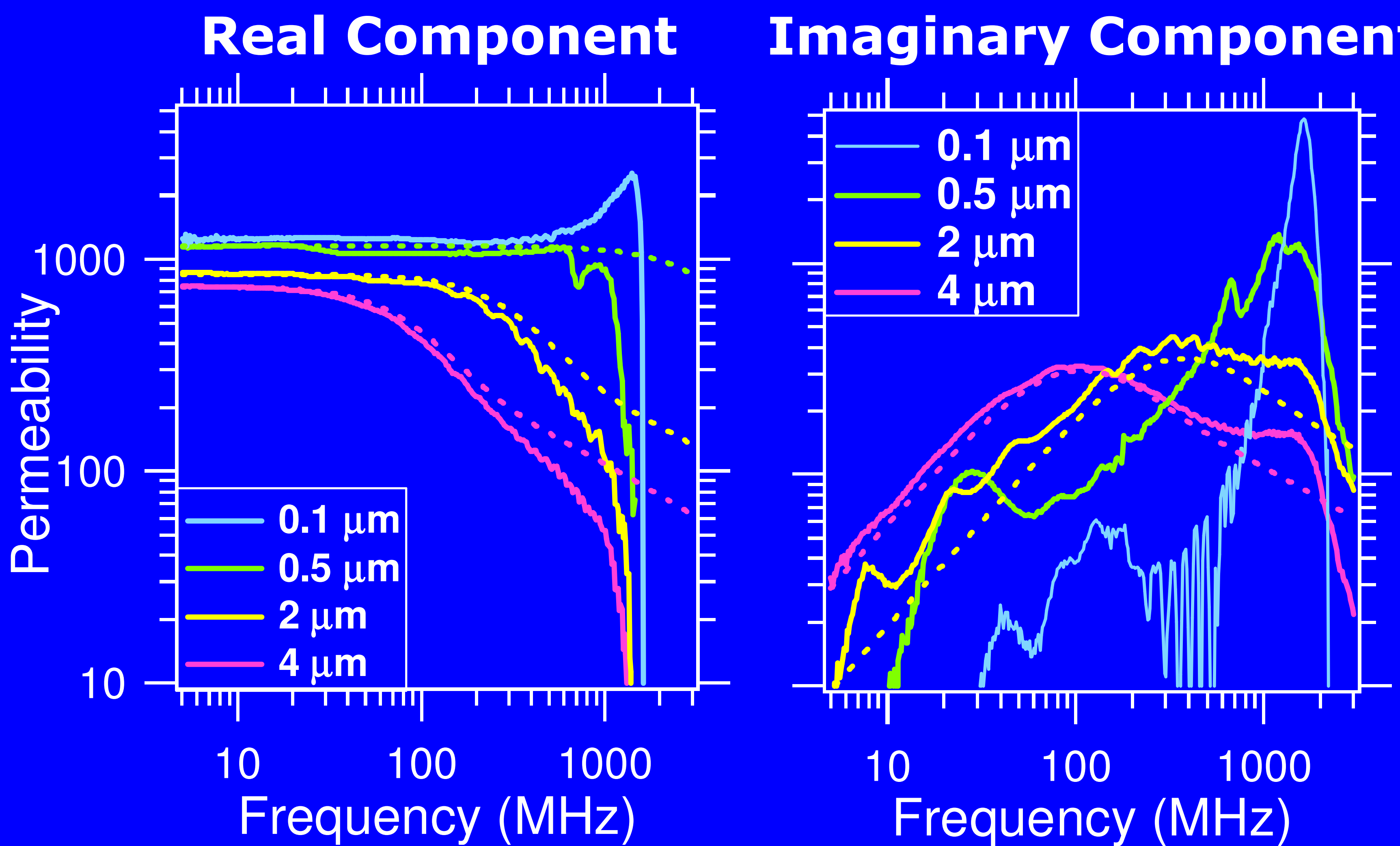


$$\mu = \mu_i \frac{2\delta}{(1+j)d} \tanh\frac{(1+j)d}{2\delta}$$

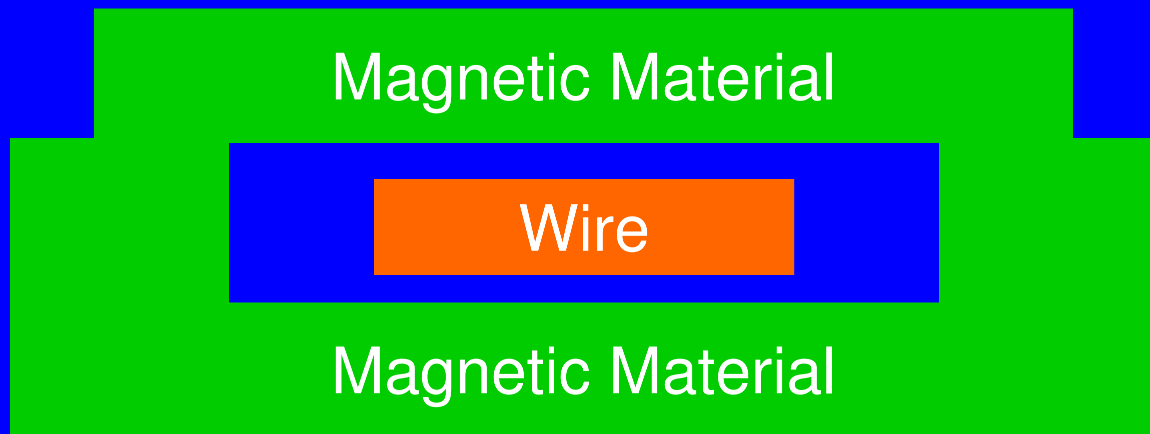
High resistivity materials are needed to reduce the eddy currents and increase the skin depth.

CoZrTa → ρ = 100 µΩ-cm

Permeability Spectra of CoZrTa



Inductance Modeling of Wire with Magnetic Material

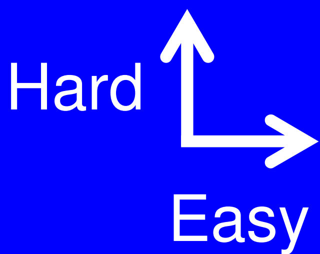


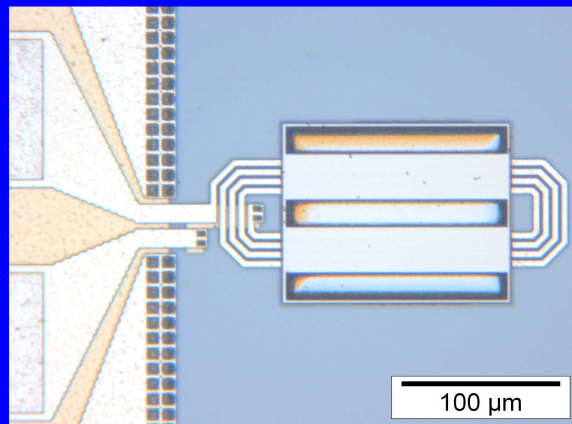
Maximum Increase in Inductance

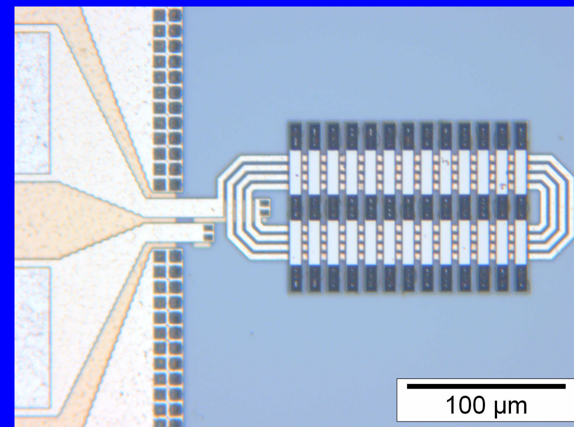
1 layer magnetic film → $\leq 2 \times$

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

Spiral and Transmission Line Inductors

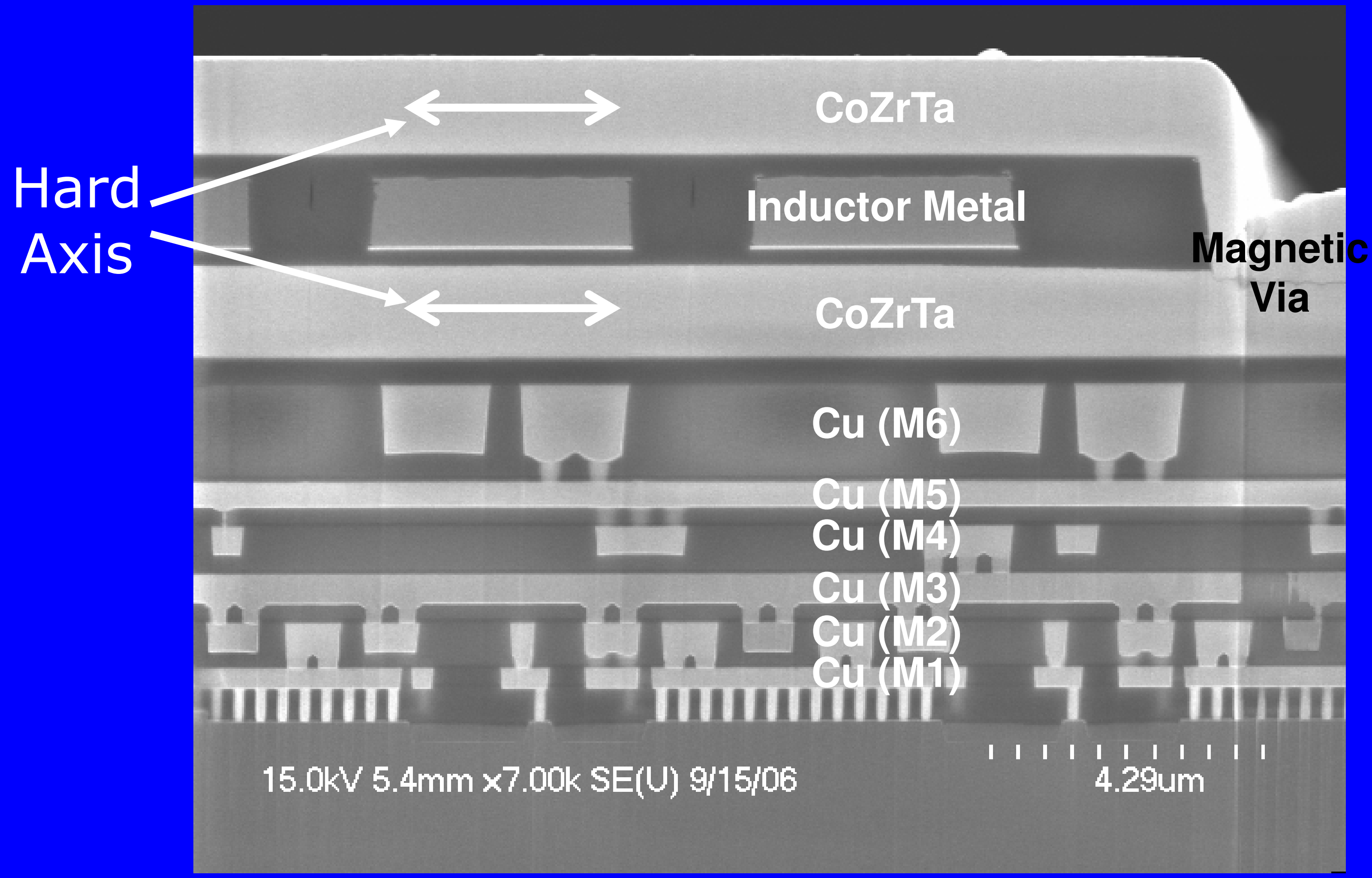




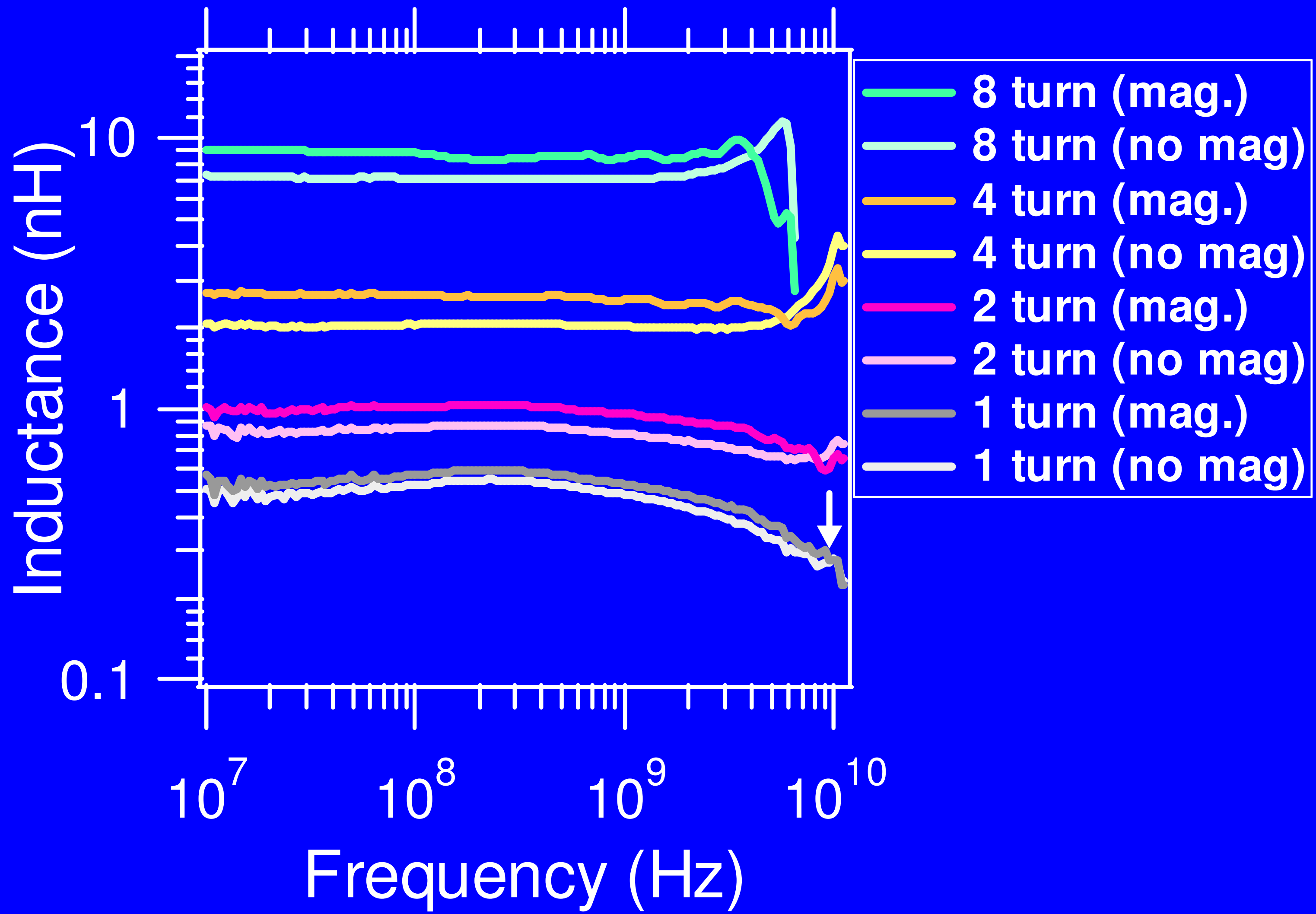


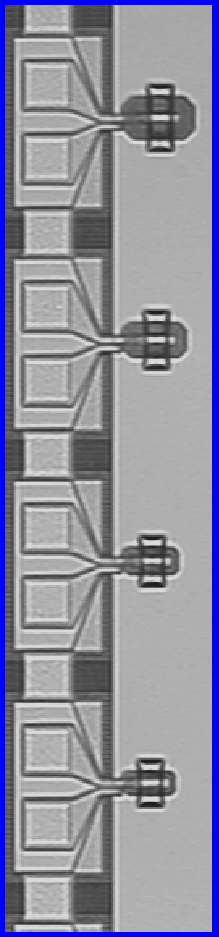
Structures take advantage of the uniaxial magnetic anisotropy.

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



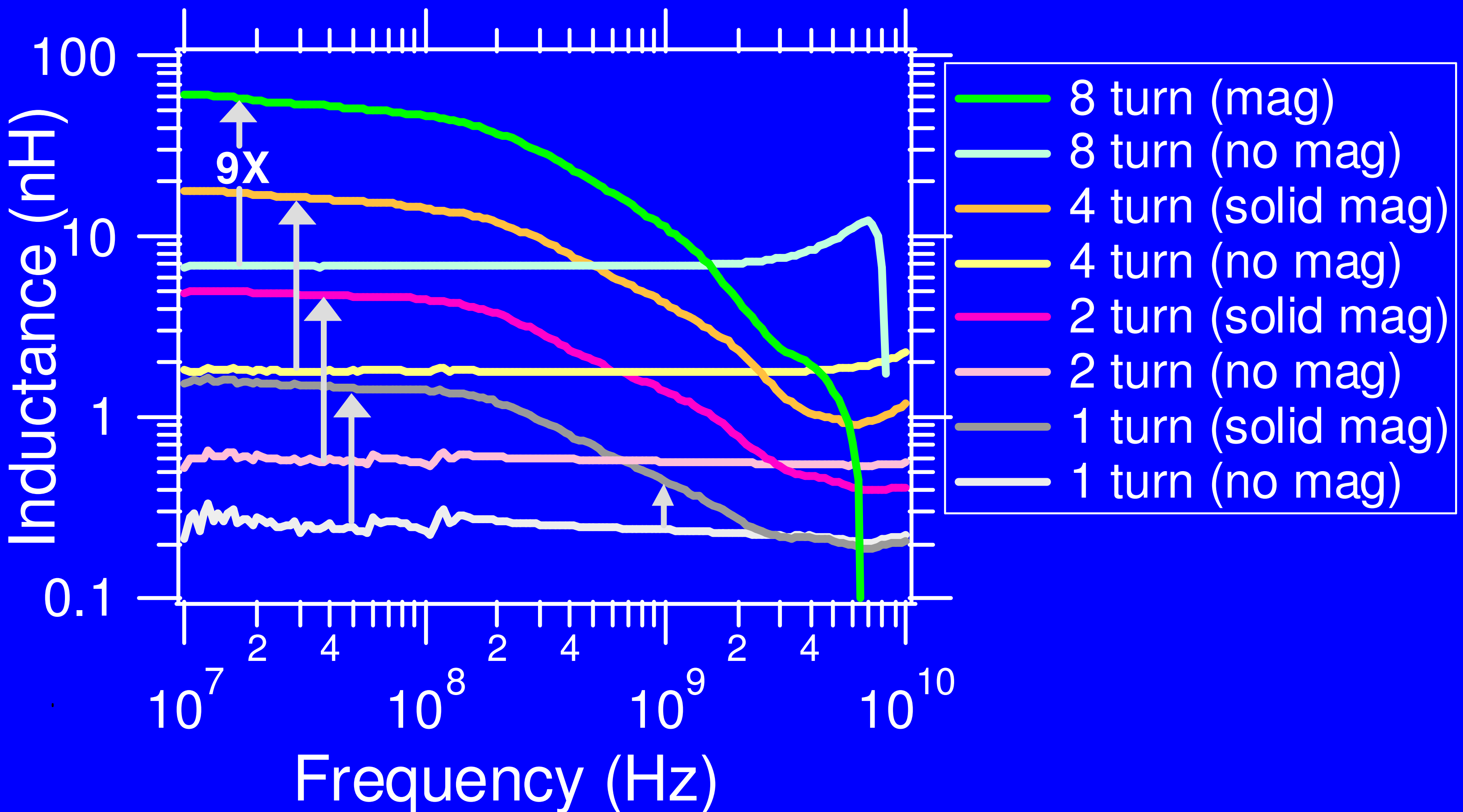
Spiral Inductors with <u>Single</u> Magnetic Layer





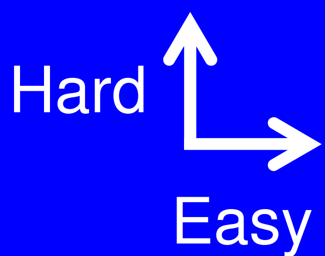
Increase in inductance is small (10~30% at up to 9.8 GHz)

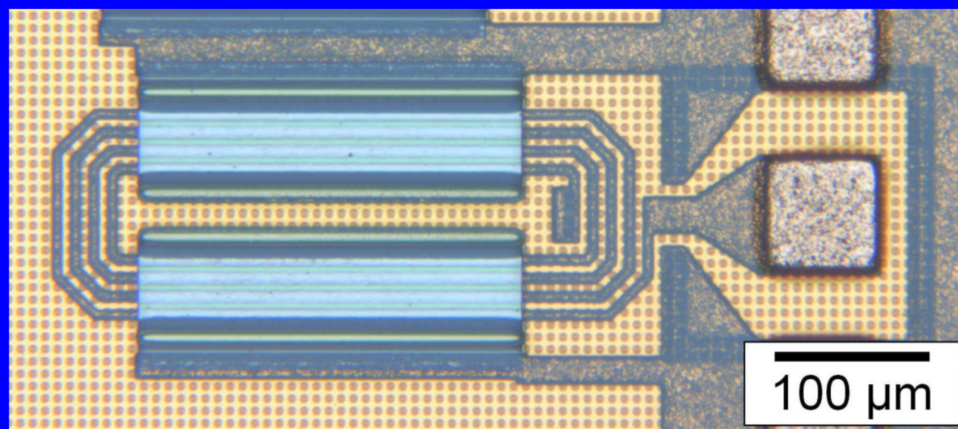
Spiral Inductors with Two Magnetic Layers

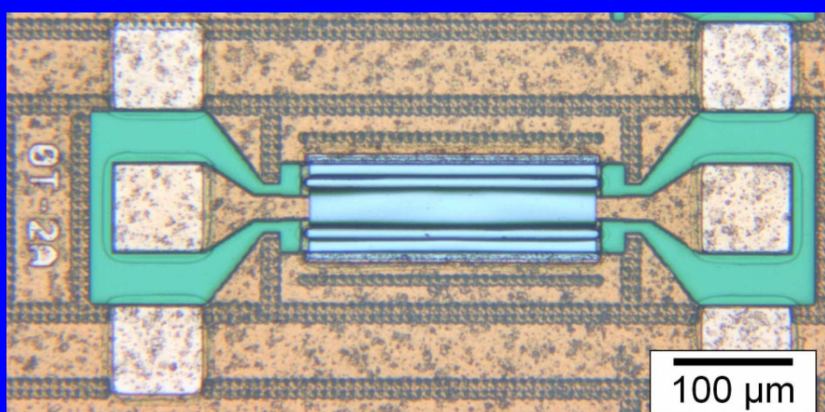


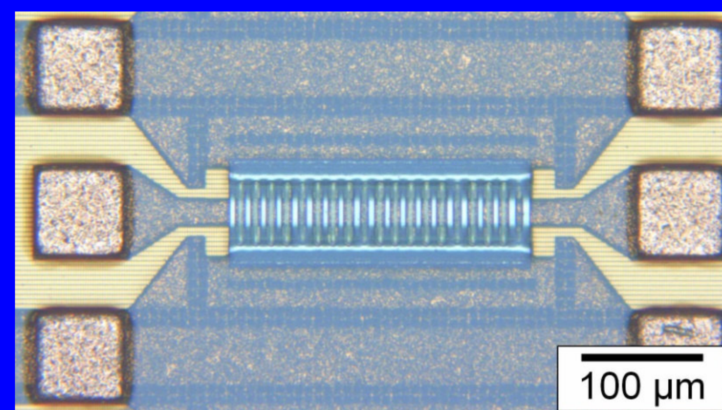
Inductance increases by 9 ×

Spiral and Stripe Inductors Using 5um thick Copper







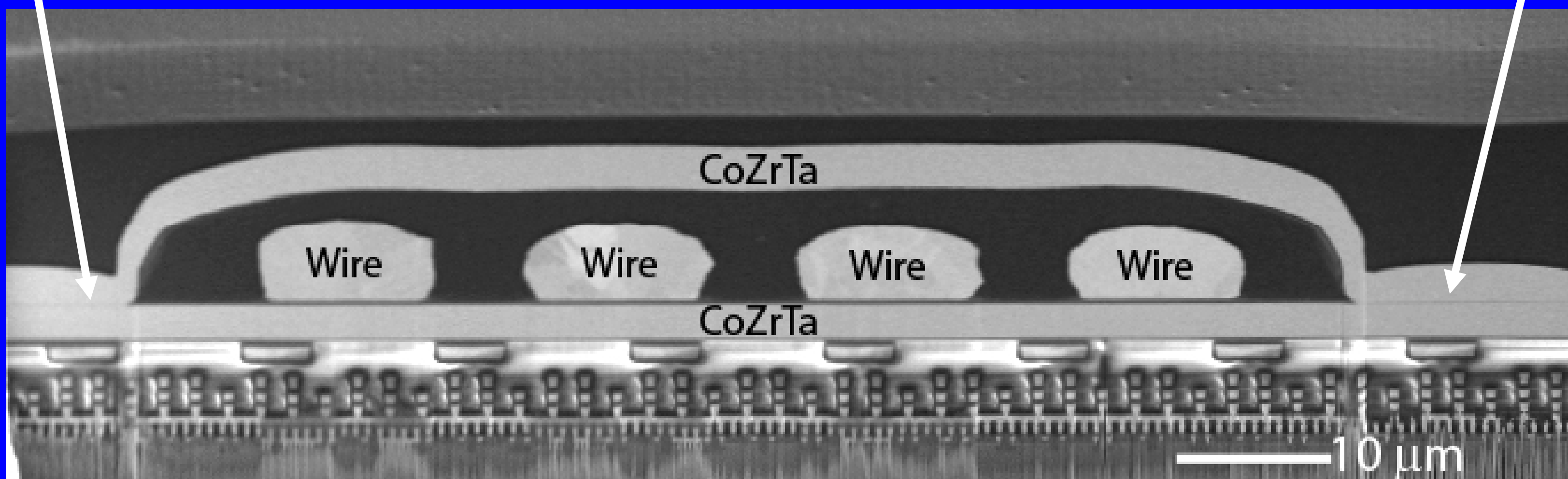


Structures take advantage of the uniaxial magnetic anisotropy.

Cross-Sectional Image of Inductor in 90 nm CMOS Process

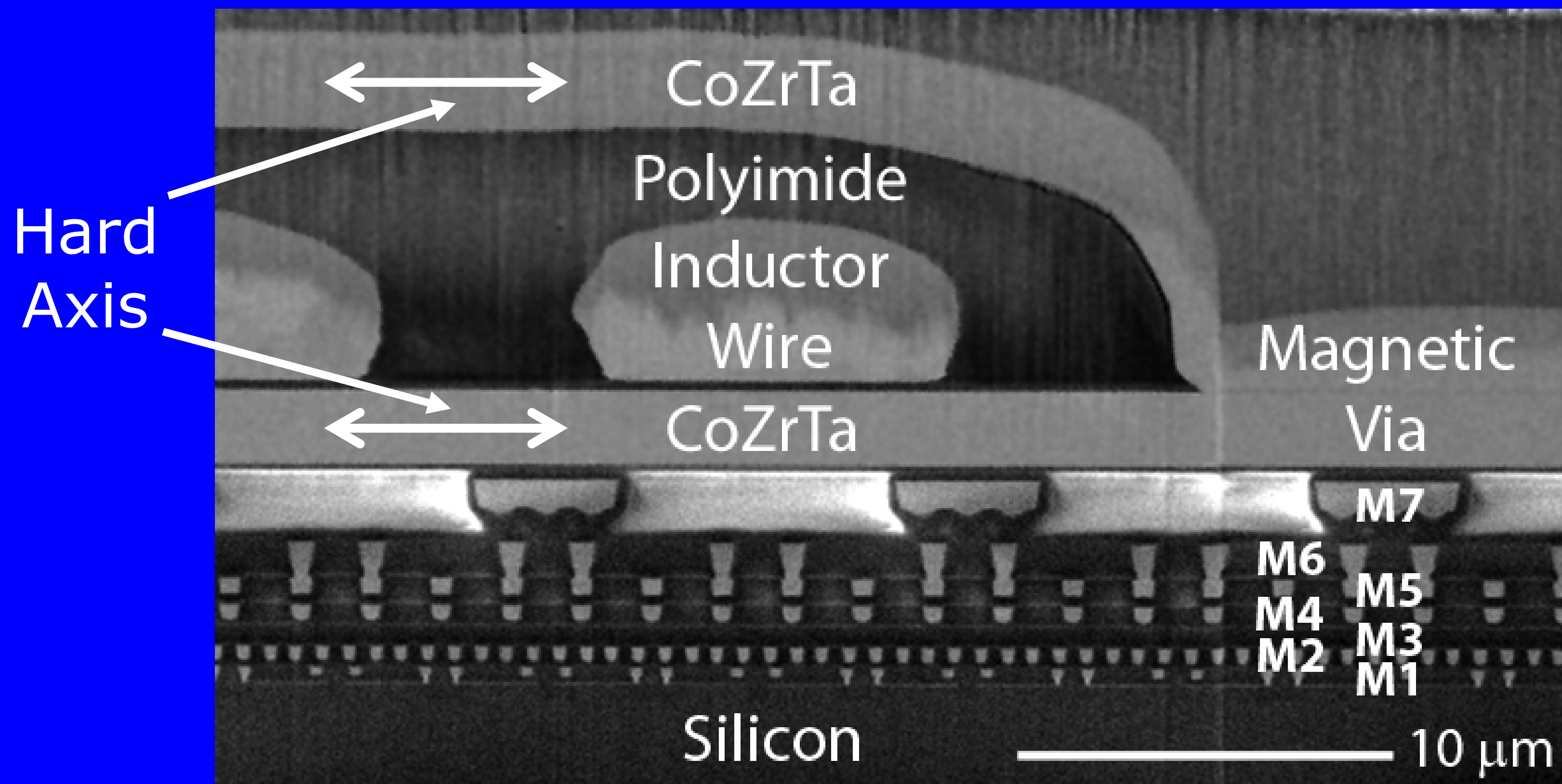
Magnetic Via

Magnetic Via

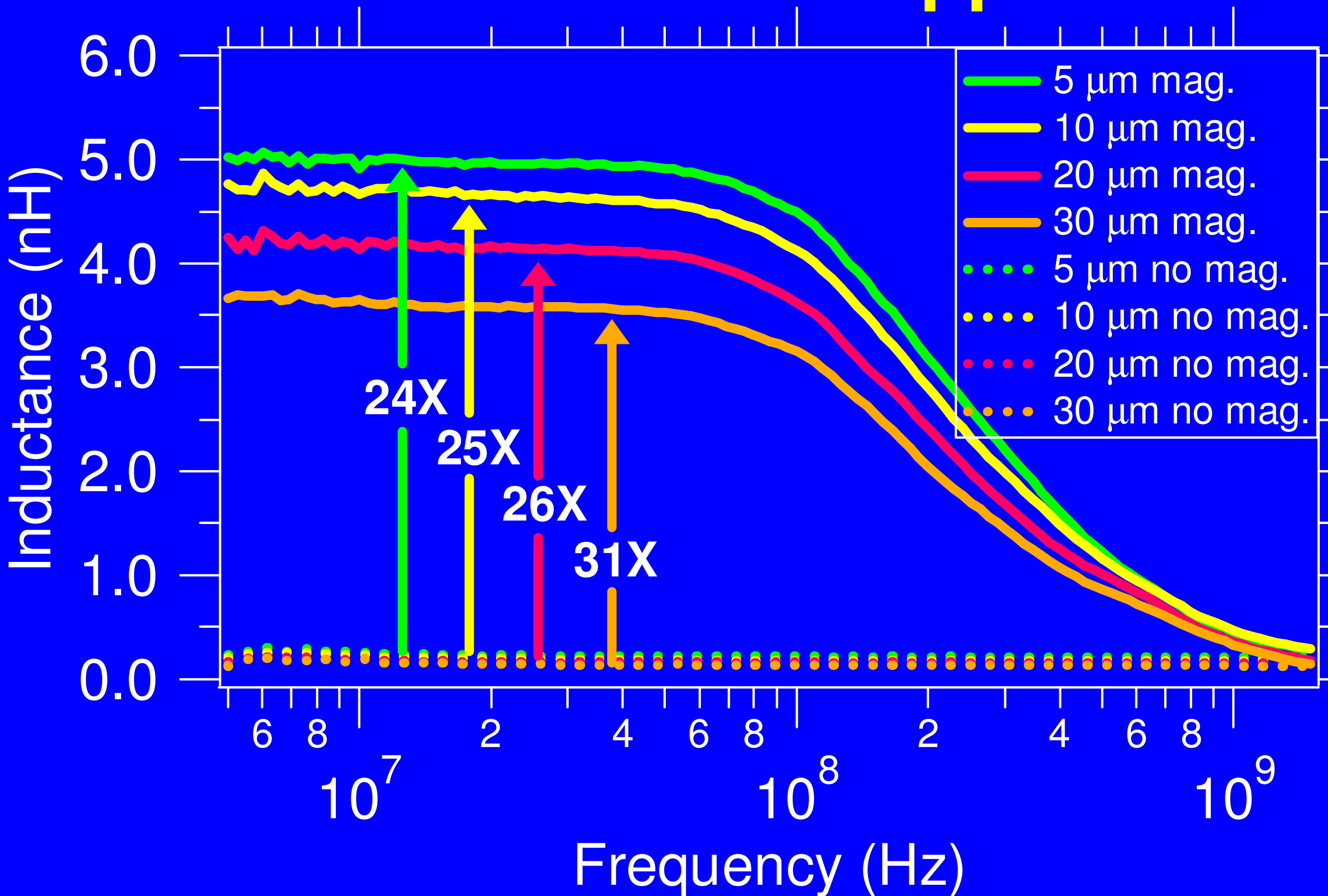


90 nm 7-level Metal CMOS Process

Cross-Sectional Image of Inductor



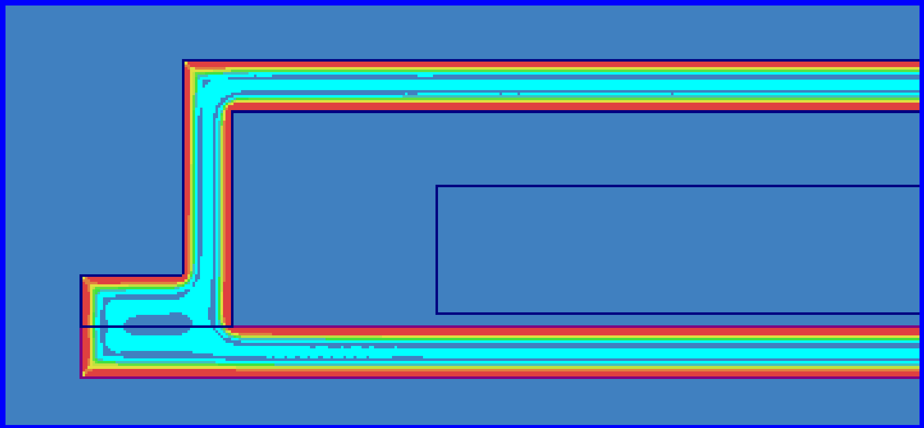
Stripe Inductors With Thick Copper



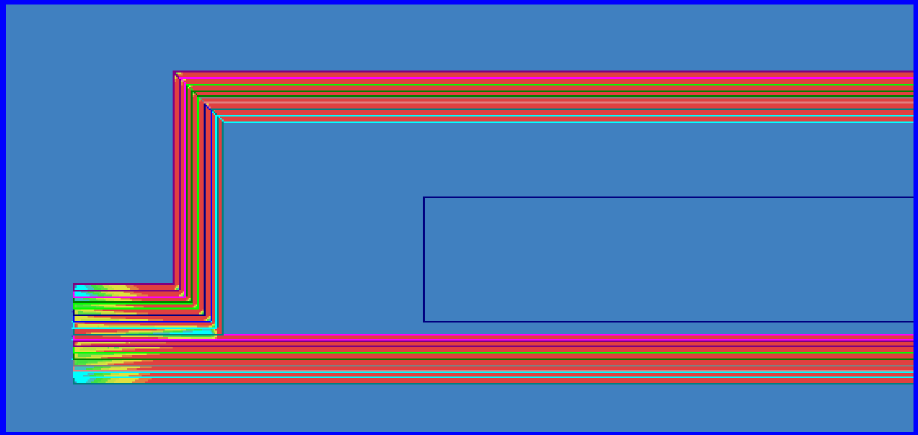
Inductance increases by up to over 30×

Magnetic Flux Density At 1GHz

Unlaminated Cobalt alloy



Laminated Cobalt alloy

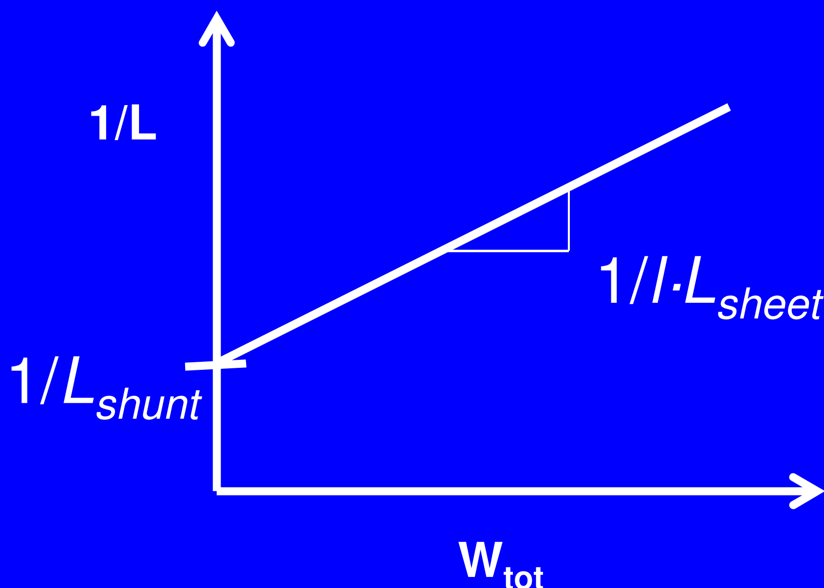


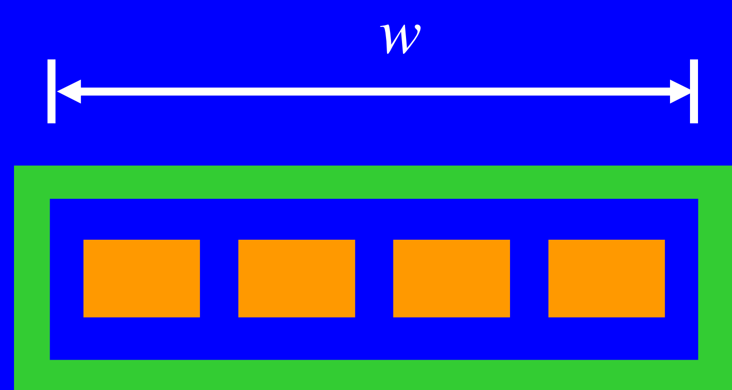
Skin-depth effect limits penetration of B-field.
Larger skin depth results in lower losses.

Inductance Modeling of Rectangular Line

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

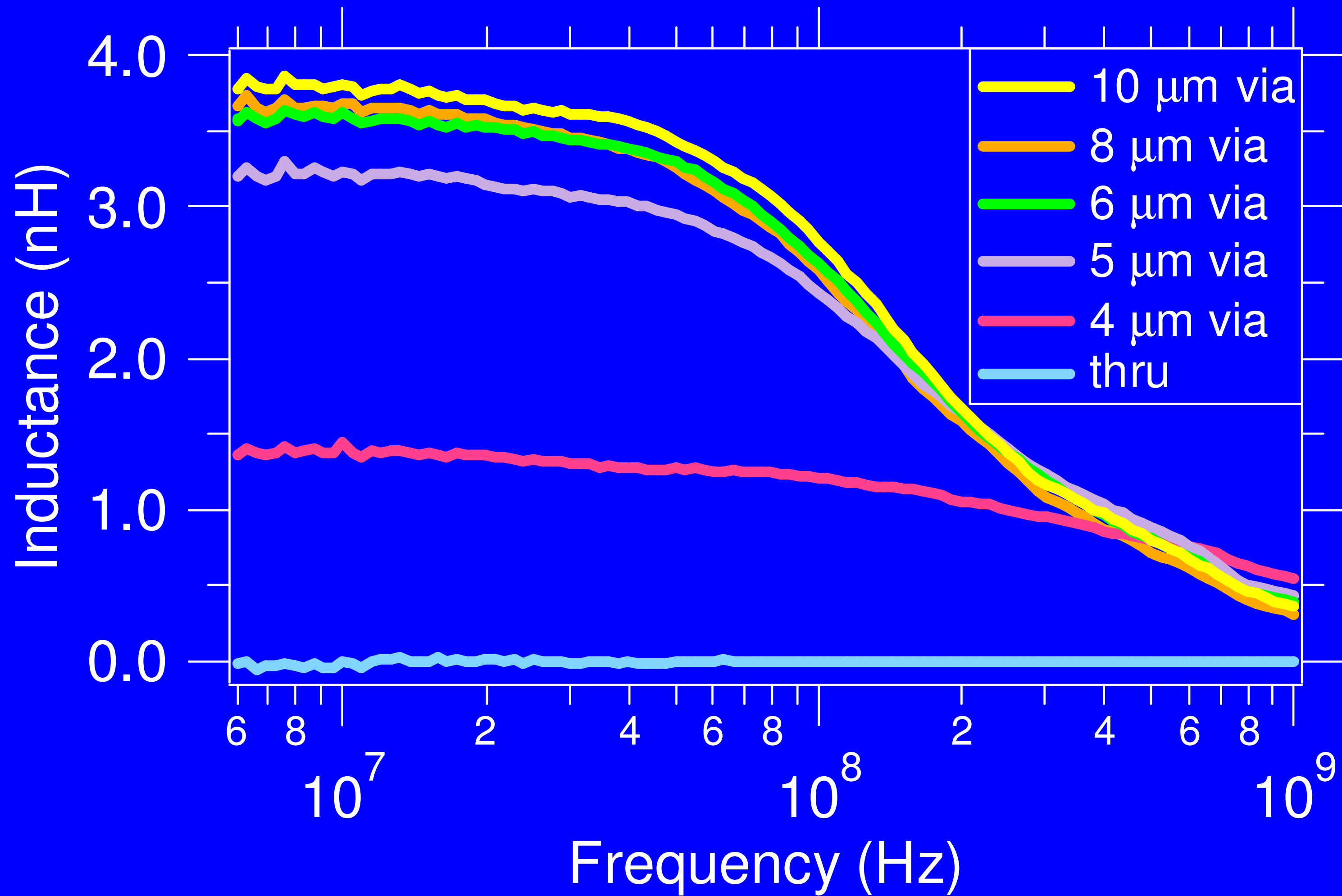
l = line length
w = line width
t_m = magnetic film thickness
μ_r = relative dc permeability





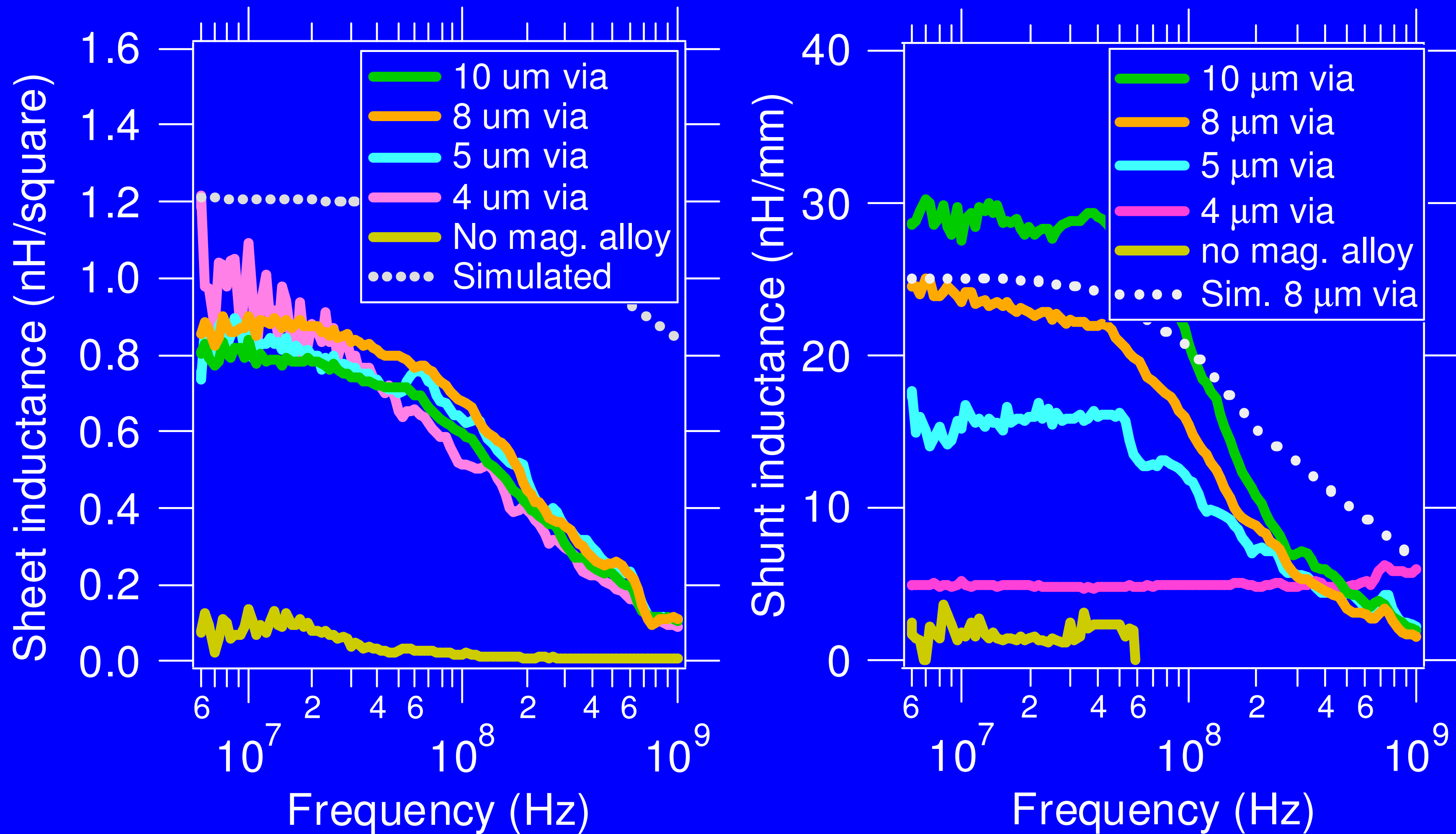
Eqn. from V. Korenivski and R. B. van Dover, JAP, v. 82 (10), 1997

Magnetic Via Widths



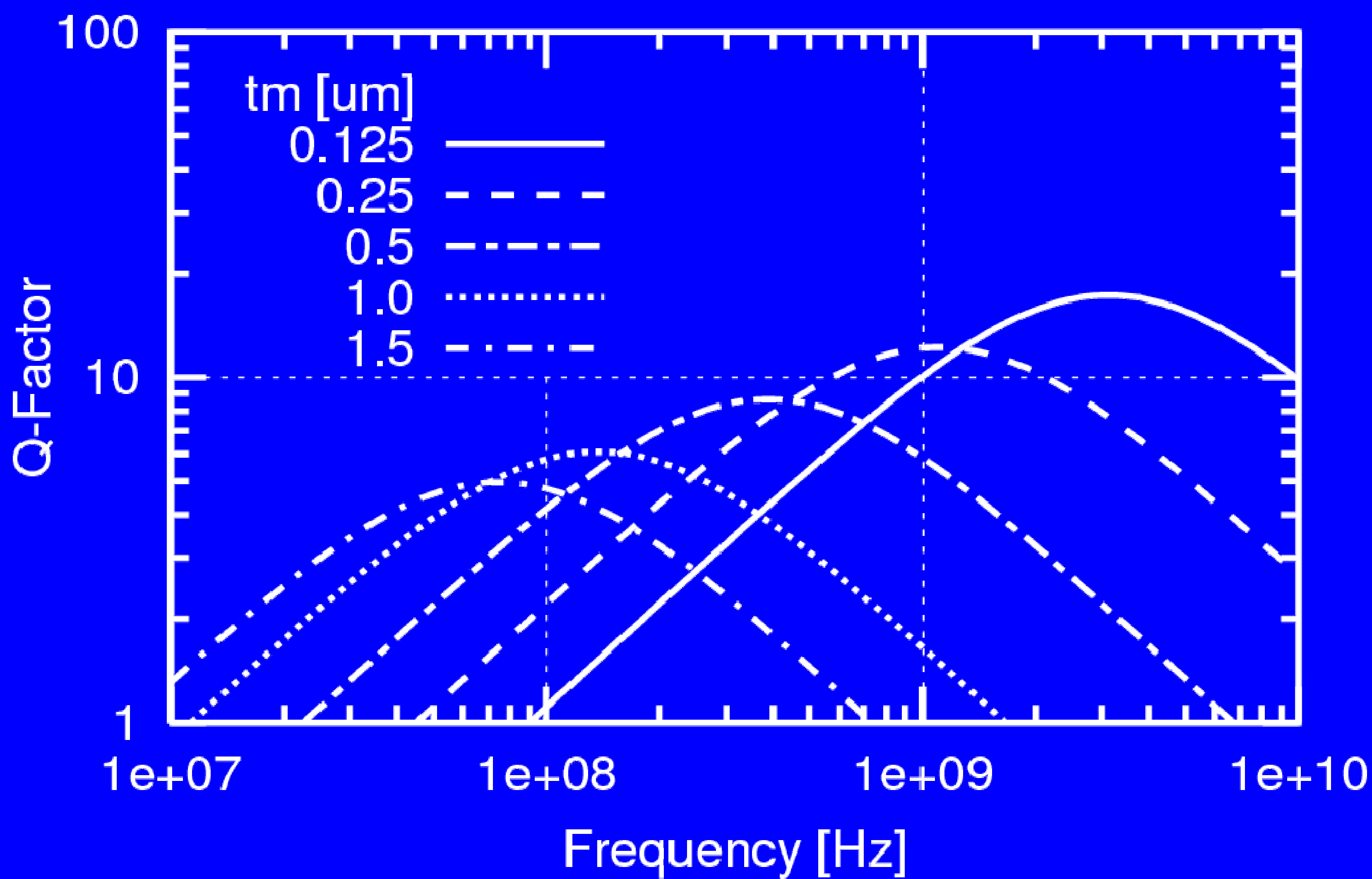
Inductance increases with via width, but the change becomes diminishingly small.

Sheet and Shunt Inductances



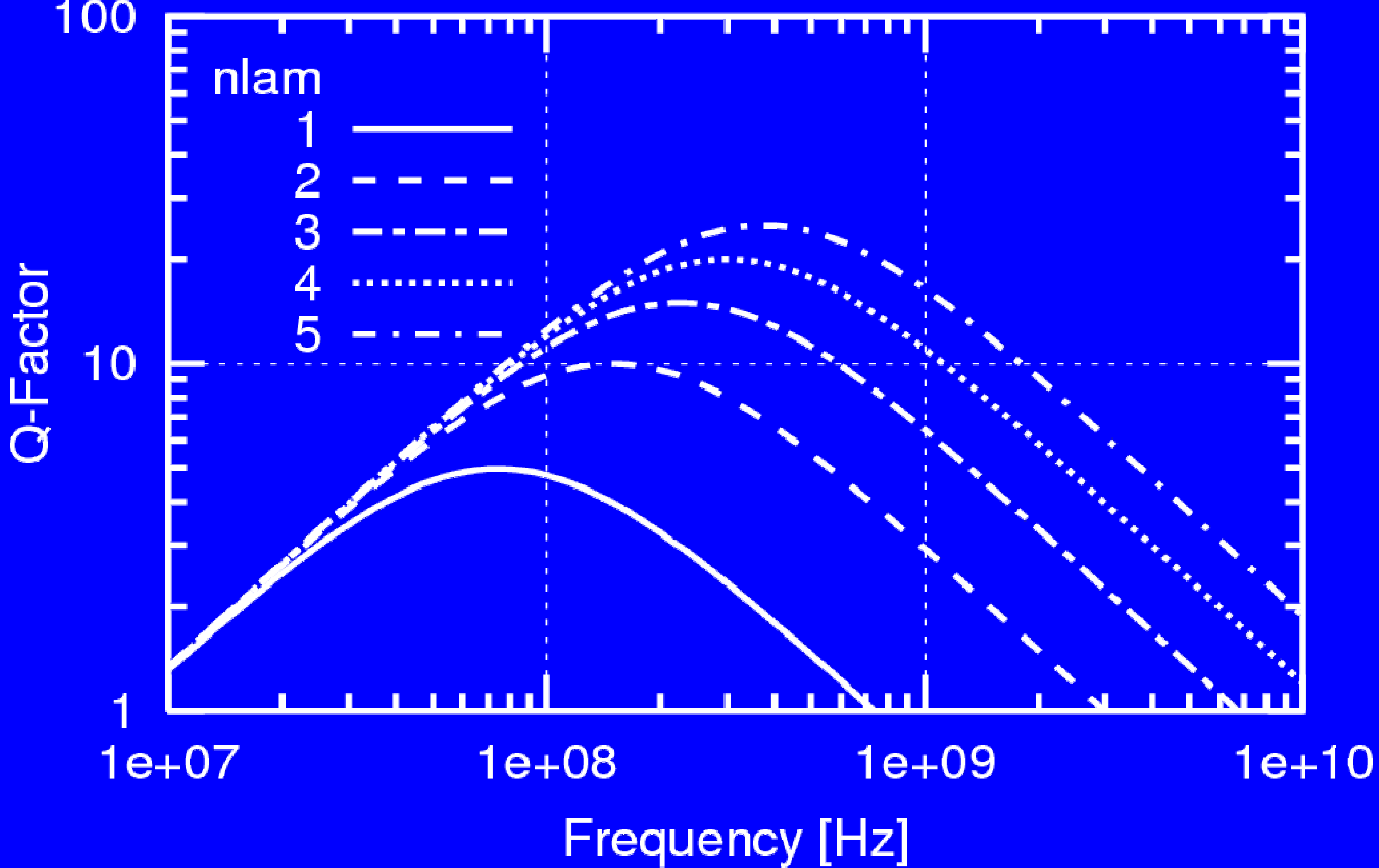
Sheet inductance is independent of the magnetic via width.
Shunt inductance increases with increasing via width.

Analytical Modeling of Q-Factor



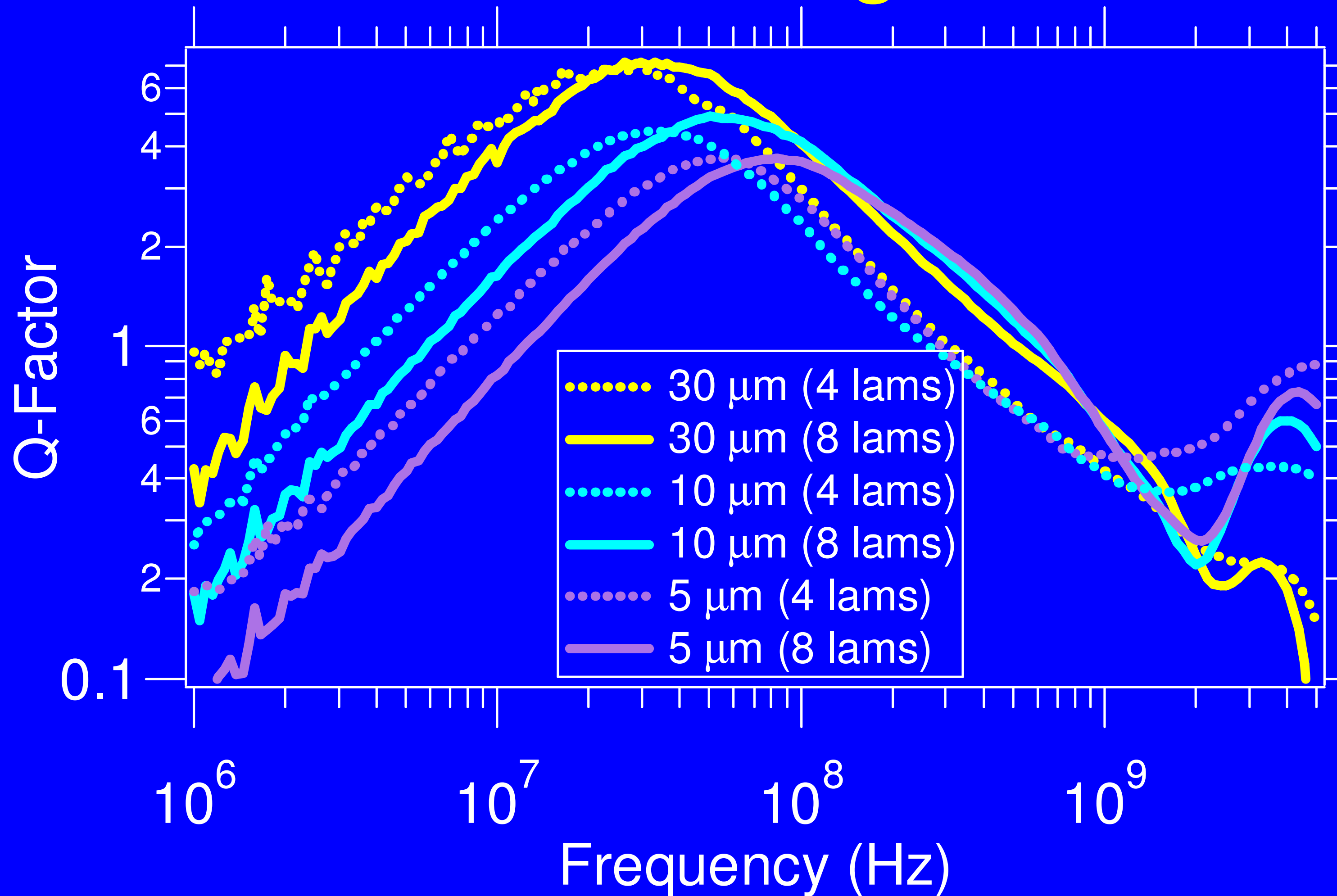
Thinner films give higher Q-factors, but lower inductance.

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

- Magnetic materials
  - Permeability
    - Complex spectra (real and imaginary)
    - Need small coercivity
  - CMOS compatibility (thermal, process compatibility)
- Inductors
  - Single films increase inductance by ≤30% up to 9.8 GHz
  - 2 magnetic films increase inductance
    - up to over 30× compared to air-core
    - Over 200 nH inductors possible (1,700 nH/mm^2)
  - Sheet inductance vs. shunt inductance
  - Effectiveness of laminated structures
  - Time constants and quality factors
    - Measurements, simulations, and analytical models

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.