Embedded Integrated Inductors With A Single Layer Magnetic Core: A Realistic Option

- Bridging the gap between discrete inductors and planar spiral inductors -

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Outline

I. Introduction

II. Analytical Models and Inductor Design

III. Fabrication of Integrated Inductors

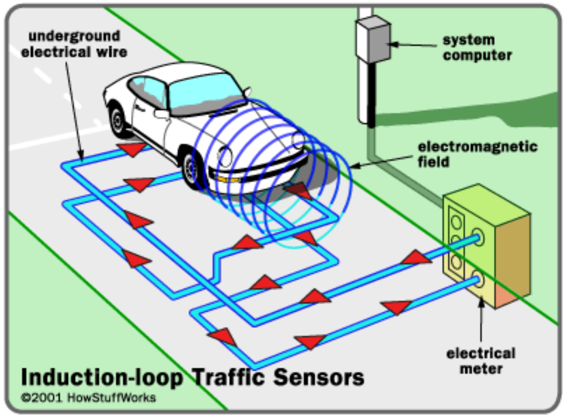
IV. Measurement of Fabricated Inductors

V. Analysis of Magnetic Inductors on Si

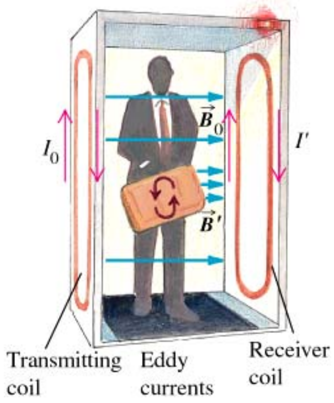
VI. Conclusion

Use of Inductors in Our Daily Lives

- Traffic light
- Red-light camera

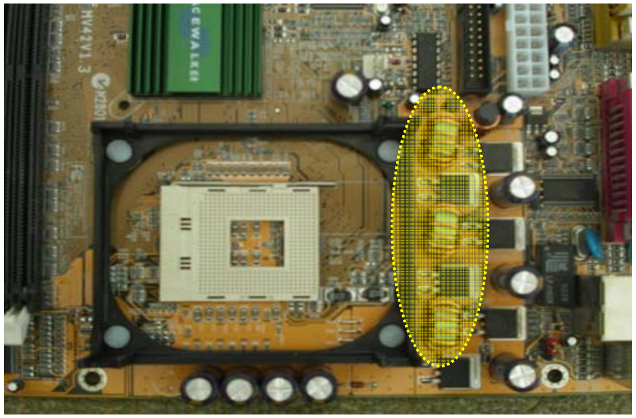


- Metal detector

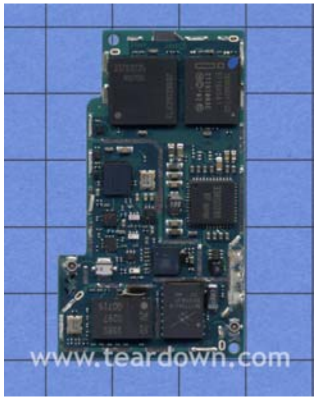


- RFID tag

- Voltage regulator module



- Cell phone



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Why Integrated Inductors?

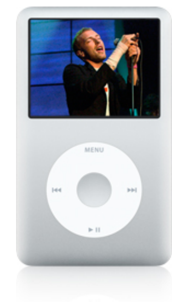
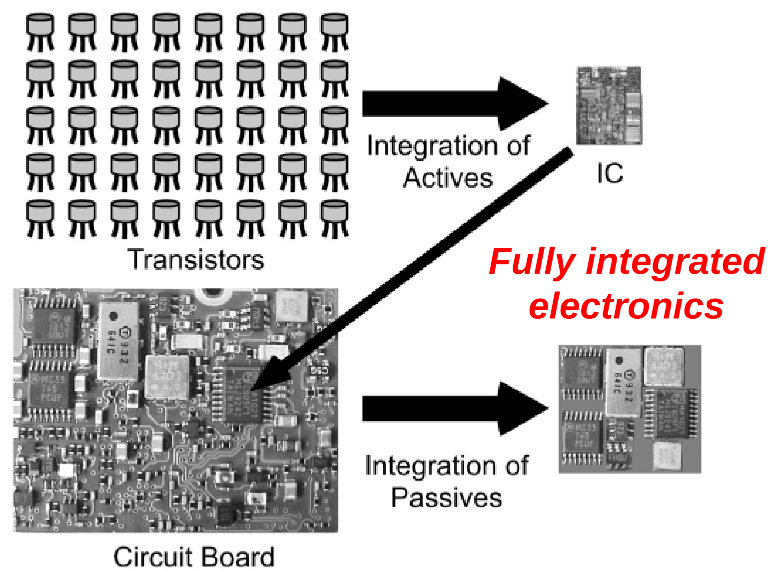


Table 1.1 Passive and IC count for portable consumer products [4]

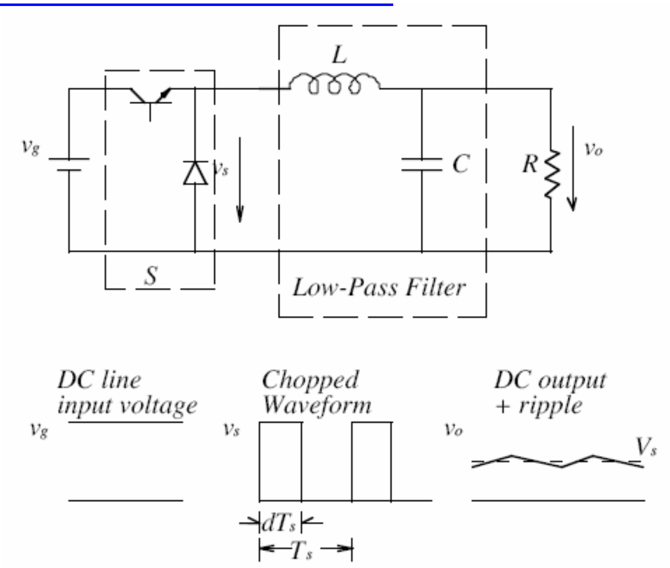
System	Total Passives	Total ICs	Ratio
	Cellular Phones		
Ericsson DH338 Digital	359	25	14:1
Ericsson E237 Analog	243	14	17:1
Philips PR93 Analog	283	11	25:1
Nokia 2110 Digital	432	21	20:1
Motorola Md 1.8 GHz	389	27	14:1
Casio PH-250	373	29	13:1
Motorola StarTAC	993	45	22:1
Matsushita NTT DOCOMO I	492	30	16:1
	Consumer Portable		
Motorola Tango Pager	437	15	29:1
Casio QV1O Digital Camera	489	17	29:1
1990 Sony Camcorder	1226	14	33:1
Sony Handy Cam DCR-PC7	1329	43	31:1
	Other Communication		
Motorola Pen Pager	142	3	47:1
Infotac Radio Modem	585	24	24:1
Data Race Fax-Modem	101	8	13:1
	PDA		
Sony Magic Link	538	74	7:1
	Computers		
Apple Portable Logic Board	184	24	8:1
Apple G4	457	42	11:1



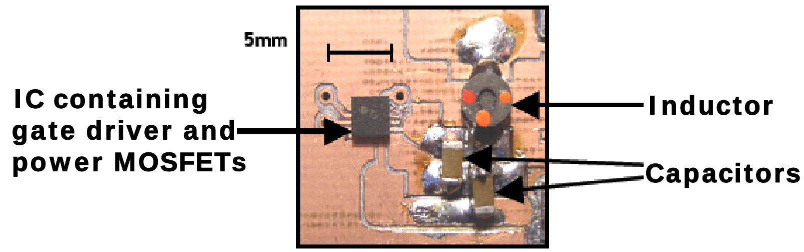
R.K. Ulrich and L.W. Schaper, "Integrated Passive Component Technology", 2003

Example: Power Management

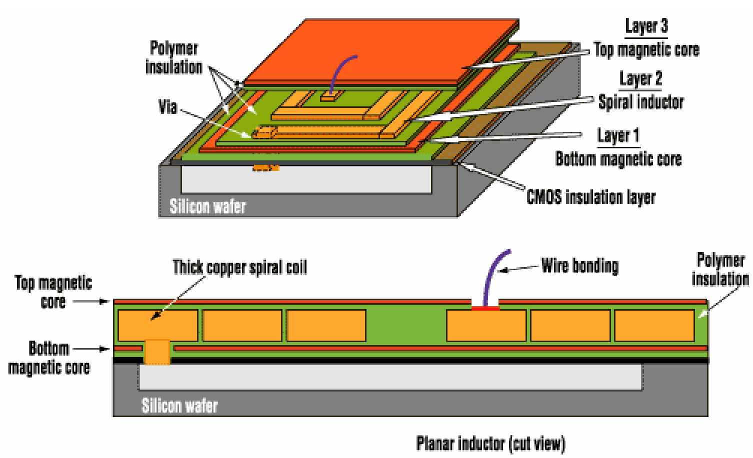
DC-DC converter



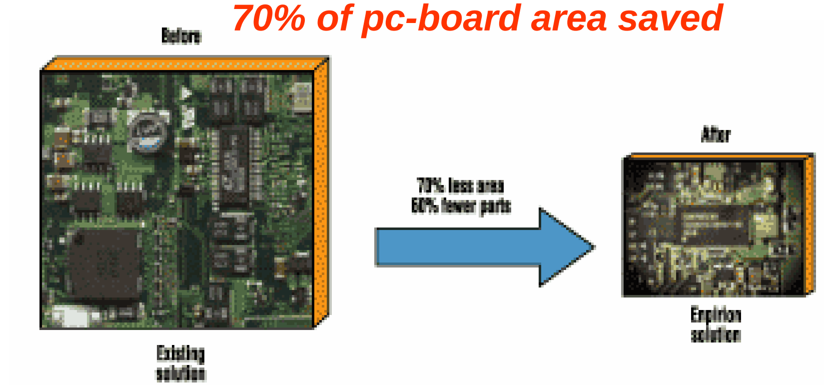
Passive components are discrete and occupy large areas



Enpirion EN5330 PSoC (Power-System-on-a-Chip) *

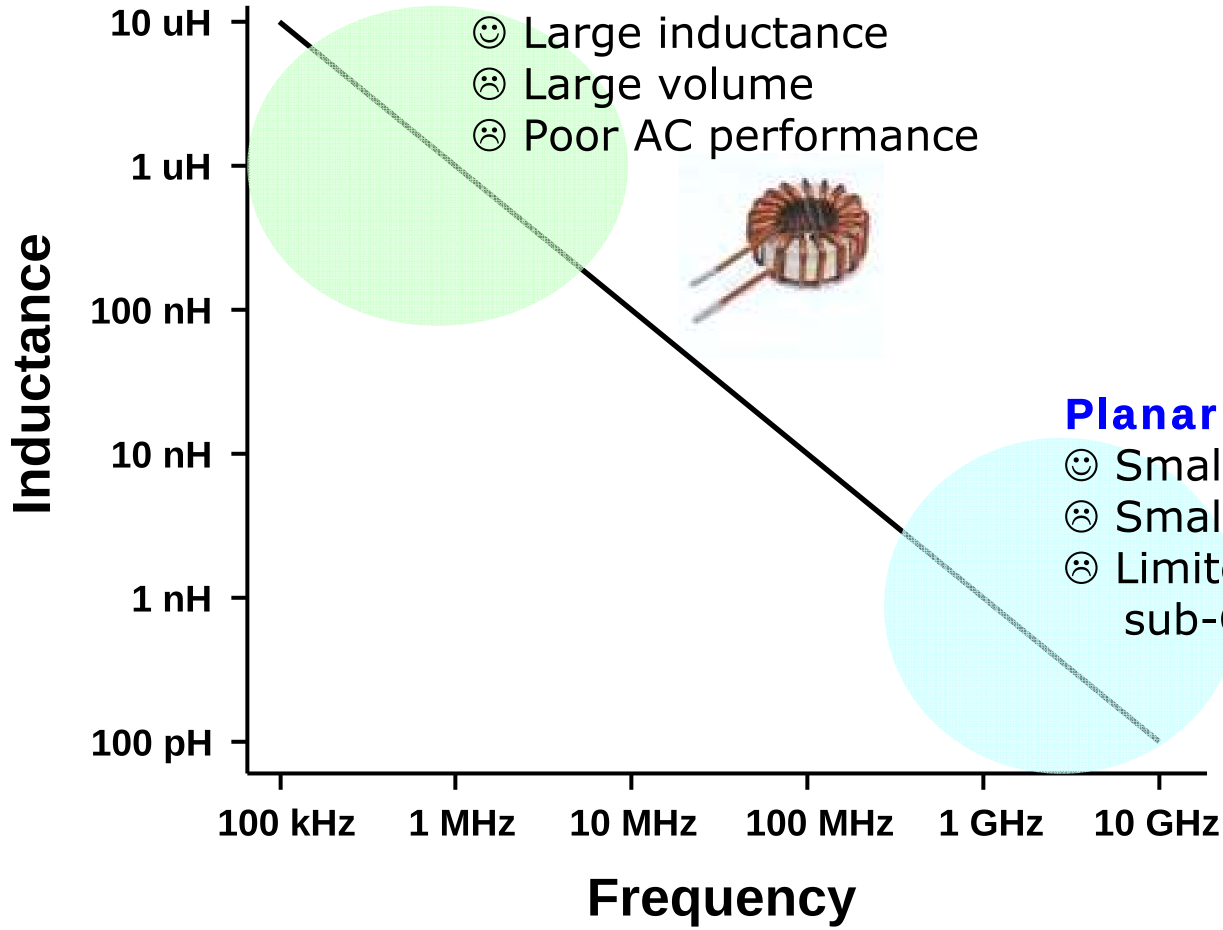


70% of pc-board area saved



** R. Allen, Electronic Design, May 2004*

Inductance Requirement for Power Management

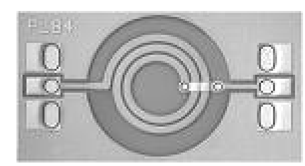


Discrete inductors

- ☺ Large inductance
- ☹ Large volume
- ☹ Poor AC performance

Planar spiral inductors

- ☺ Small area consumption
- ☹ Small inductance
- ☹ Limited performance in sub-GHz applications

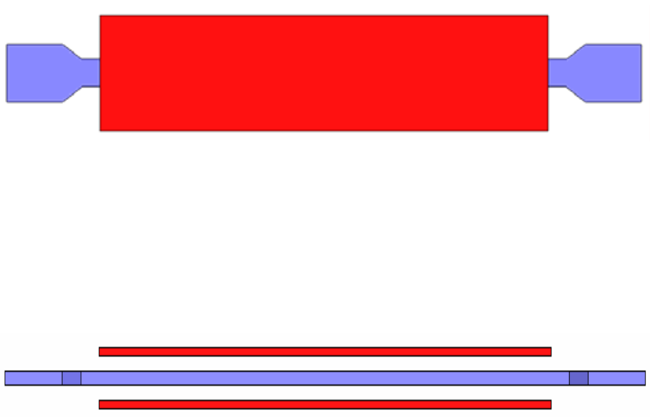


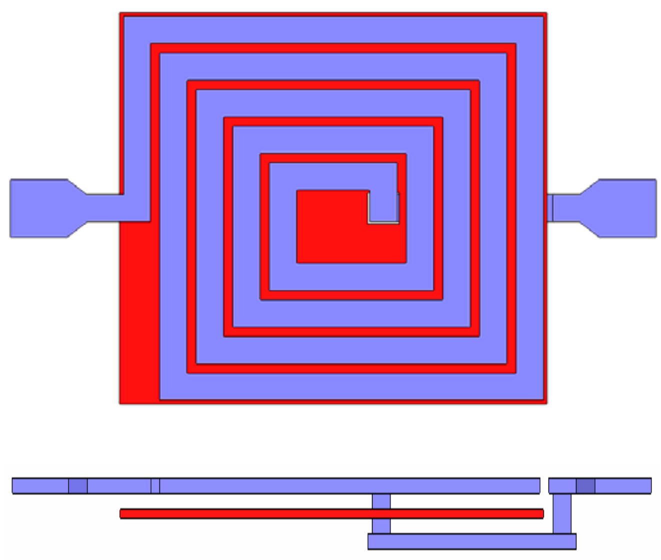
From A. Ghahary, Power Electronics Technology, Aug. 2004

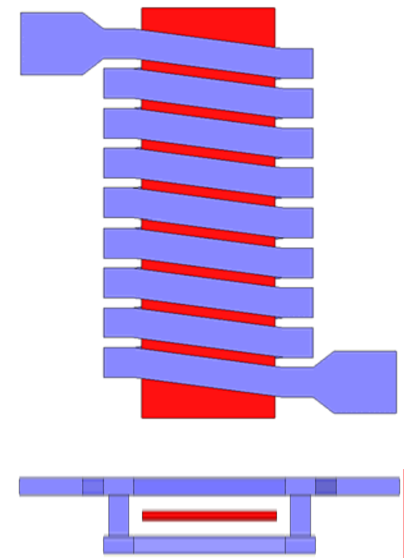
Schematics of Magnetic Inductor Designs

PWR SoC '08

Transmission line | **Spiral inductor** | **Solenoid inductor**







Transmission line

☺ Small resistance
☹ Small inductance
☹ Usually two magnetic layers needed

Spiral inductor

☺ Close to the planar spiral
☹ Limited inductance gain
😐 One or two magnetic layers

Solenoid inductor

☺ Magnetically efficient
☹ Relatively complex structure
☺ One magnetic layer

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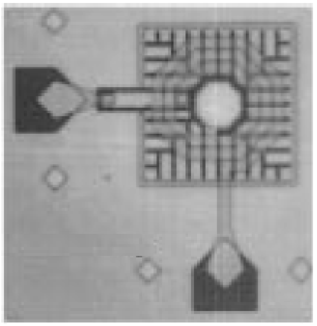
Brief Rev of Integrated Magnetic Inductors

	Inductor design	Core material	Substrate	L_{MI} (nH)	$\Delta L/L_{AC}$	R_{DC} (Ω)	Q_{Max}
Intel, Tyndall	Transmission line	$CoZrO_2$	Si	~3		0.014	
	Transmission line	CoTaZr	Si	~17	≥19		~3.8 @ 170MHz
	Spiral	CoTaZr	Si	47.9	0.65	59	~2.7 @ 1GHz
	Spiral	Ferrite	Si	1500		0.67	70 @ 5MHz
	Spiral	NiFe	Si	3200	1.3	5.9	1.3 @ 1MHz
Tohoku	Spiral	CoNbZr	Si	8.5~13.7	0.07~0.71	~5	3.05~11.8 @ 1GHz
	Spiral	FeHfN	Si	~4.8	0.30	~0.9	~10.2 @ 900MHz
	Solenoid	FeCoBSi	Si	45	10	~4	
CEA-LETI	Solenoid	NiFe	Si	~500	≥ 8.1	0.095	~20 @ 2MHz
	Solenoid	CoTaZr	Si	70.2	34	0.67	6.3 @ 26MHz
	Solenoid	CoTaZr	Si	48.4	32	0.67	6.5 @ 30MHz
	Spiral	Ferrite-polymer	Polyimide	1330		2.6	18.5 @ 10MHz
	Spiral	NiFe-based	Polyimide	5060		1.76	10.1 @ 1.4MHz
	Solenoid	$CoFeSiB/SiO_2$	MPS	5000		1.4	
	Solenoid	CoFeHfO	PCB	3.25	0.13	0.012	22 @ 250MHz

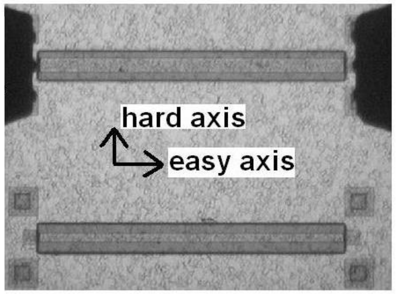
Taken from Lee et al, Embedded Inductors with Magnetic Cores, Book Chapter in press (Springer)

Magnetic Inductors from Stanford & Cowork



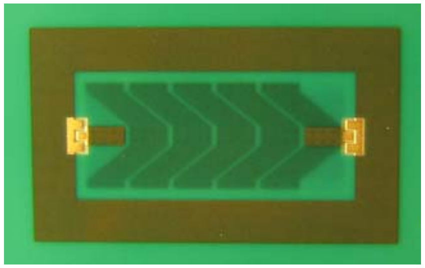
A.M. Crawford, et al.
IEEE Trans. Magn.
2002, p.3168-70

Planar spiral inductor with CoTaZr core, CMOS compatibility, Q ~ 2.7 @ 1 GHz



P. K. Amiri, et al.
Intermag 08, CV 01

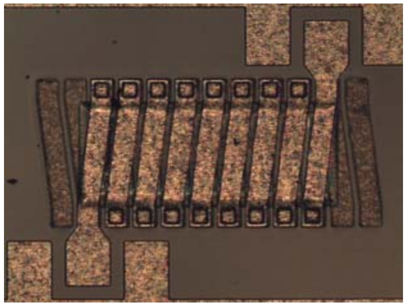
Planar transmission line inductor with CoTaZr core, Q = 6 @ 700 MHz



L. Li, D. W. Lee, et al.

IEEE Trans. Advanced Packaging (accepted 2008)

On-package solenoid inductor with CoFeHfO core, Q = 22 @ 200~300 MHz, R_{dc} ~ 10 mΩ



D. W. Lee, et al.
Intermag 08, AG 01 (invited)

Planar solenoid inductor with CoTaZr core, Inductance enhancement over air core = 34x Q>6 @ 26 MHz

II. Analytical Models and Inductor Design

I. Introduction

II. Analytical Models and Inductor Design

- Analytical models for key device properties
- Material selection
- Optimization of design parameters
- Inductor design concepts

III. Fabrication of Integrated Inductors

IV. Measurement of Fabricated Inductors

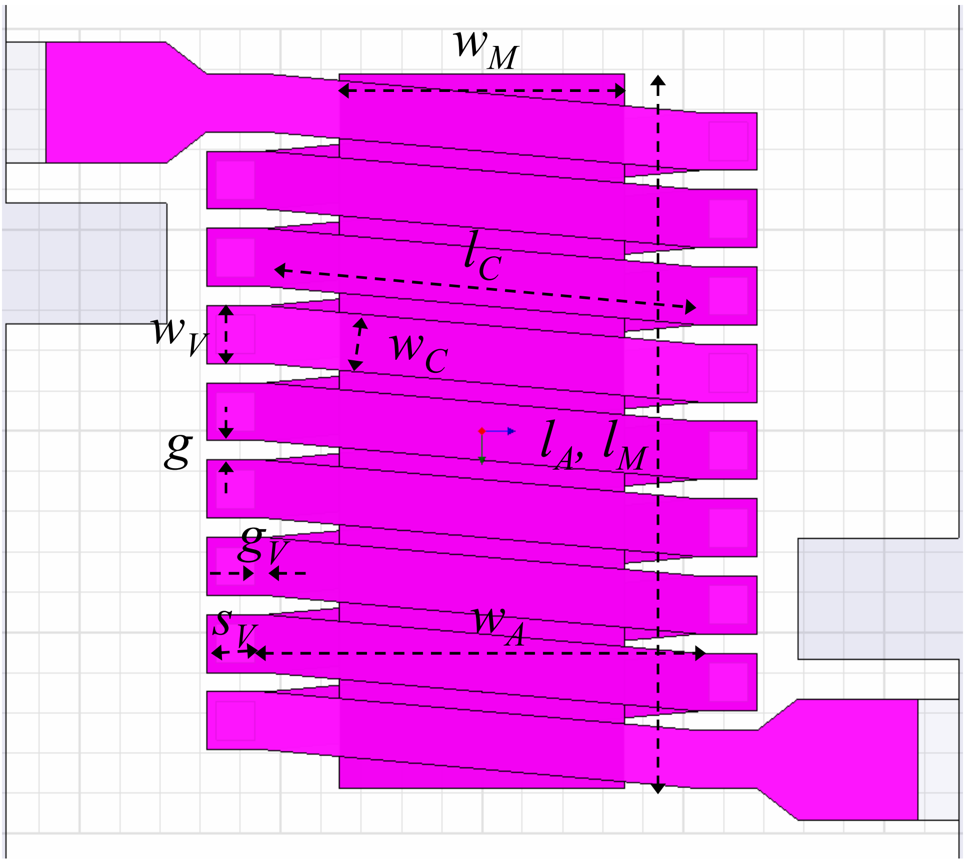
V. Analysis of Magnetic Inductors on Si

VI. Conclusion

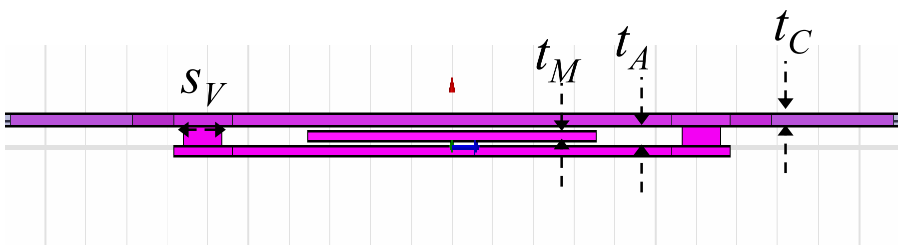
Schematics of Integrated Solenoid Inductor

- Solenoid inductor design was mainly considered in this work.

Top view



Cross-section view



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Key Device Properties

- Inductance L ↑
- Resistance R ↓
- Quality factor Q ↑ $$Q = 2\pi \frac{Energy\ stored}{Power\ dissipation \cdot T} = \frac{\omega L}{R}$$
- Device area ↓
- Useful bandwidth ↑

Inductance of Magnetic Inductor L_{MC}

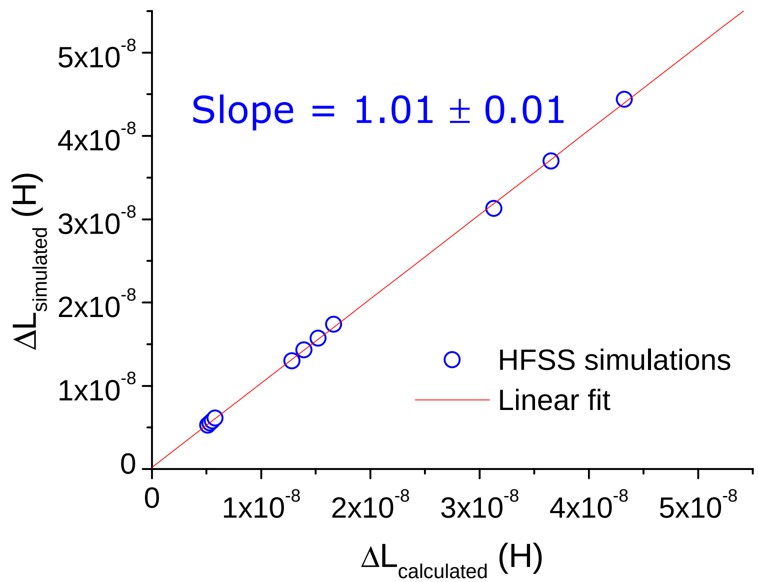
Inductance of magnetic inductor L_{MC}:

$$L_{MC} = L_{AC} + \Delta L$$

where $$\Delta L = \frac{\mu_0 \mu_r N^2 w_M t_M}{l_M [1 + N_d(\mu_r - 1)]} = \frac{\mu_0 \mu_{eff} N^2 w_M t_M}{l_M}$$

N_d = Demagnetizing factor of rectangular prism

$$\mu_{eff} \equiv \frac{\mu_r}{1 + N_d(\mu_r - 1)}$$



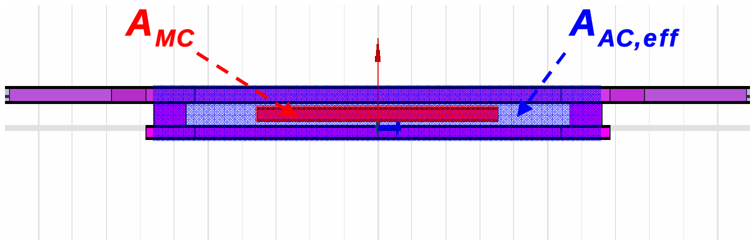
- For a finite-sized magnetic core, there is a demagnetizing field inside the magnetic core, which effectively reduces μ_r.

- Demagnetizing field is not uniform inside the magnetic core, and the numerical solutions should be used for $\mu_r > 1$.*

Inductance enhancement:

$$\frac{\Delta L}{L_{AC}} = \frac{L_{MC} - L_{AC}}{L_{AC}} \approx \mu_{eff} \frac{A_{MC}}{A_{AC,eff}}$$

Much less than μ_r but still significant



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* D.-X. Chen et al., IEEE Trans. Magn., 41, 2077 (2005)

Resistance of Magnetic Inductor R_{MC}

Resistance of magnetic inductor R_{MC}:

- From the classical electromagnetism:*

Magnetic contribution to the energy stored $E_{Magnetic} = \frac{1}{2}\iiint \mu' |H^2| dV$

Magnetic power loss $P_{Magnetic} = \iiint \omega\mu'' |H^2| dV$

$$P_{Magnetic} \approx 2\omega\left(\frac{\mu''}{\mu'}\right)E_{Magnetic}$$

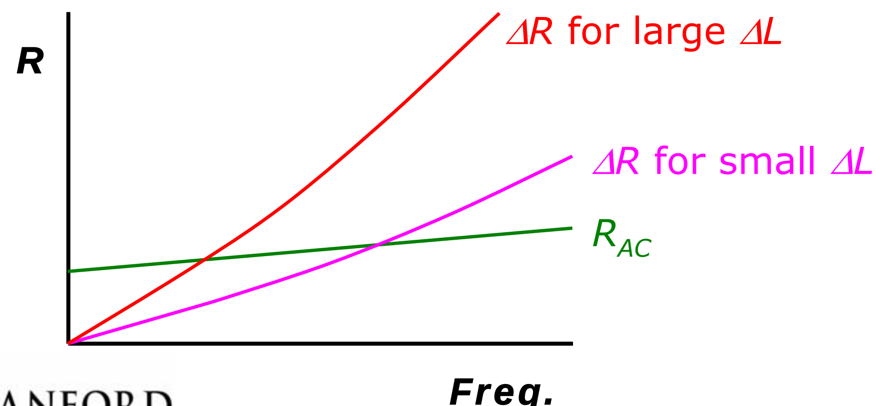
- Representing in terms of the device properties:

$P_{Magnetic} = (R_{MC} - R_{AC})I^2 = \Delta R I^2$ where $\Delta R \equiv R_{MC} - R_{AC}$

$E_{Magnetic} = E_{Magnetic\ inductor} - E_{Air\ core\ inductor} = \frac{1}{2}L_{MC}I^2 - \frac{1}{2}L_{AC}I^2 = \frac{1}{2}\Delta L I^2$

$$\Delta R = \omega\left(\frac{\mu''}{\mu'}\right)\Delta L$$

$$\therefore R_{MC} = R_{AC} + \Delta R = R_{AC} + \omega\left(\frac{\mu''}{\mu'}\right)\Delta L$$



- Both ω and (μ″/μ′) increase with frequency. Hence ΔR becomes significant as the frequency increases.
- The more inductance enhancement we obtain by using a magnetic core, the more resistive losses we introduce at high frequencies.

* *R.F. Harrington, "Time-Harmonic Electromagnetic Fields", 1961*

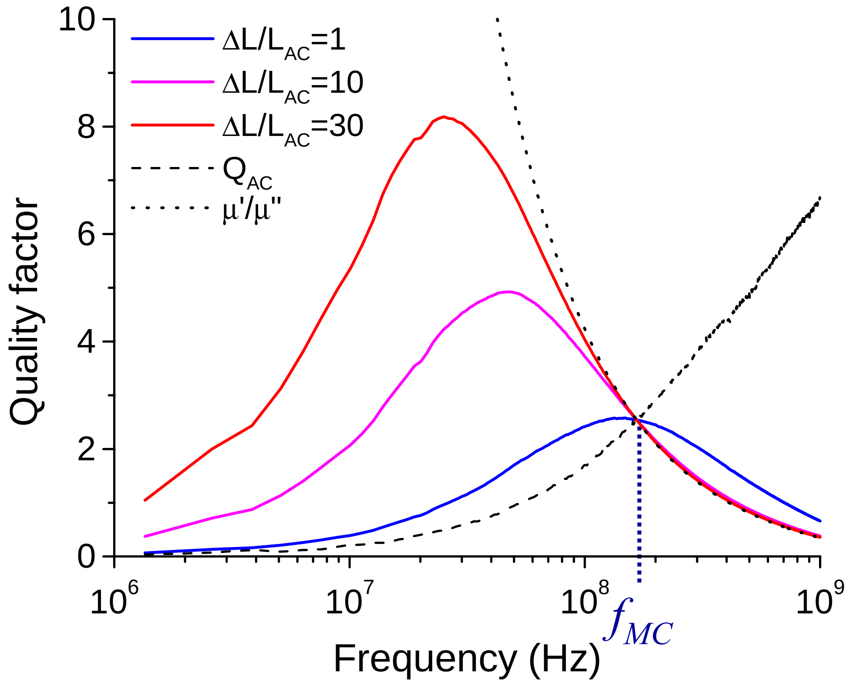
Quality factor Q

Quality factor of air core inductor Q_{AC}:

$$Q_{AC} = \omega \frac{L_{AC}}{R_{AC}}$$

Quality factor of magnetic inductor Q_{MC}:

$$Q_{MC} = \omega \frac{L_{MC}}{R_{MC}} = \omega \frac{L_{AC} + \Delta L}{R_{AC} + \omega \left(\frac{\mu''}{\mu'} \right) \Delta L}$$



- $\Delta L << L_{AC}$ → $Q_{MC} \sim Q_{AC}$ at low frequencies
- $\Delta L >> L_{AC}$ → $Q_{MC} \sim \mu'/\mu''$ at high frequencies
- f_{MC} can be considered as the useful bandwidth of the magnetic inductor.

Material Selection

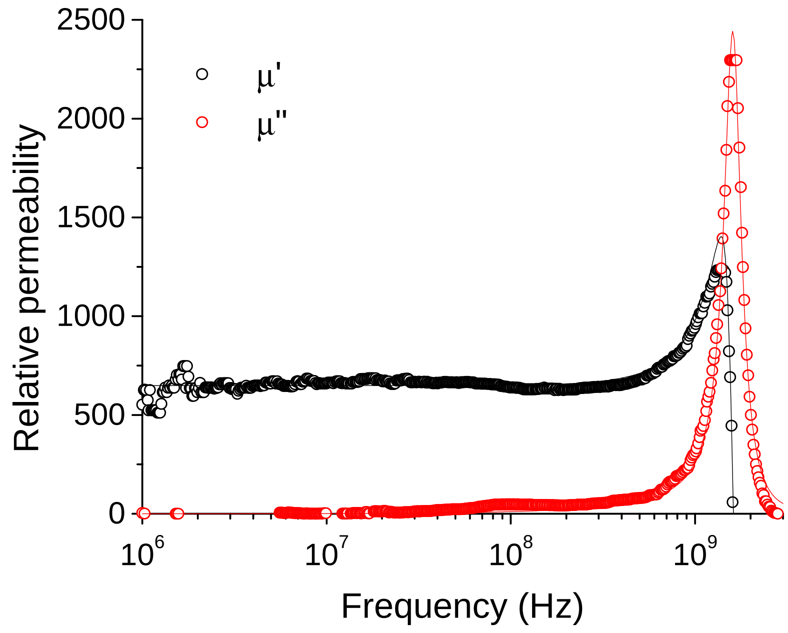
Conductor: Copper due to its low electrical resistivity

Magnetic core:

- Desirable properties:
  - High permeability
  - Soft magnetic material (low coercivity)
  - High resistivity
  - High ferromagnetic resonance (FMR) frequency

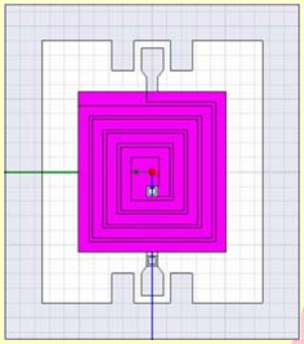
- Amorphous $Co_{90}Ta_5Zr_5$ (at. %) alloy:
  - $\mu' \sim 600$
  - $H_c < 1$ Oe
  - $\rho \sim 108$ μΩ-cm
  - $f_{FMR} \sim 1.5$ GHz

0.2 μm CoTaZr magnetic film



Inductor Designs

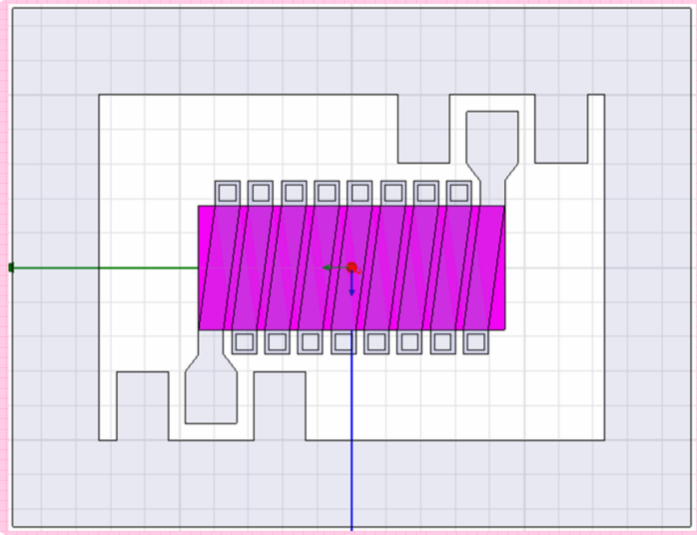
"Spiral"



N = 4.5

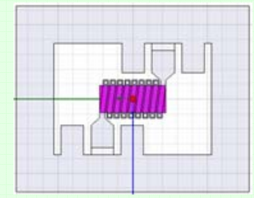
Planar spiral inductor
with or without magnetic plane

"Standard"



N = 4.5, 8.5, 17.5

"Scale-down"

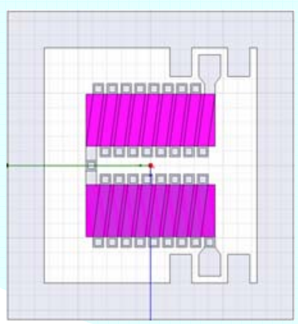


N = 4.5, 8.5, 17.5

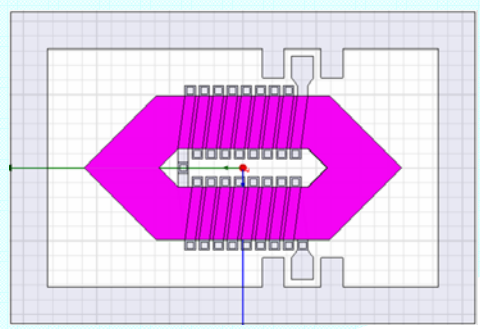
Solenoid inductor with lateral parameters scaled down by a factor of 2 while maintaining vertical parameters unchanged

Solenoid inductor with different magnetic core arrangement or shape

"Series"



"Closed core"



N = 4.5, 8.5, 17.5

III. Fabrication of Integrated Inductors

I. Introduction

II. Analytical Models and Inductor Design

III. Fabrication of Integrated Inductors

- Fabrication steps
- Images of fabricated inductor devices
- Magnetic properties of processed magnetic core

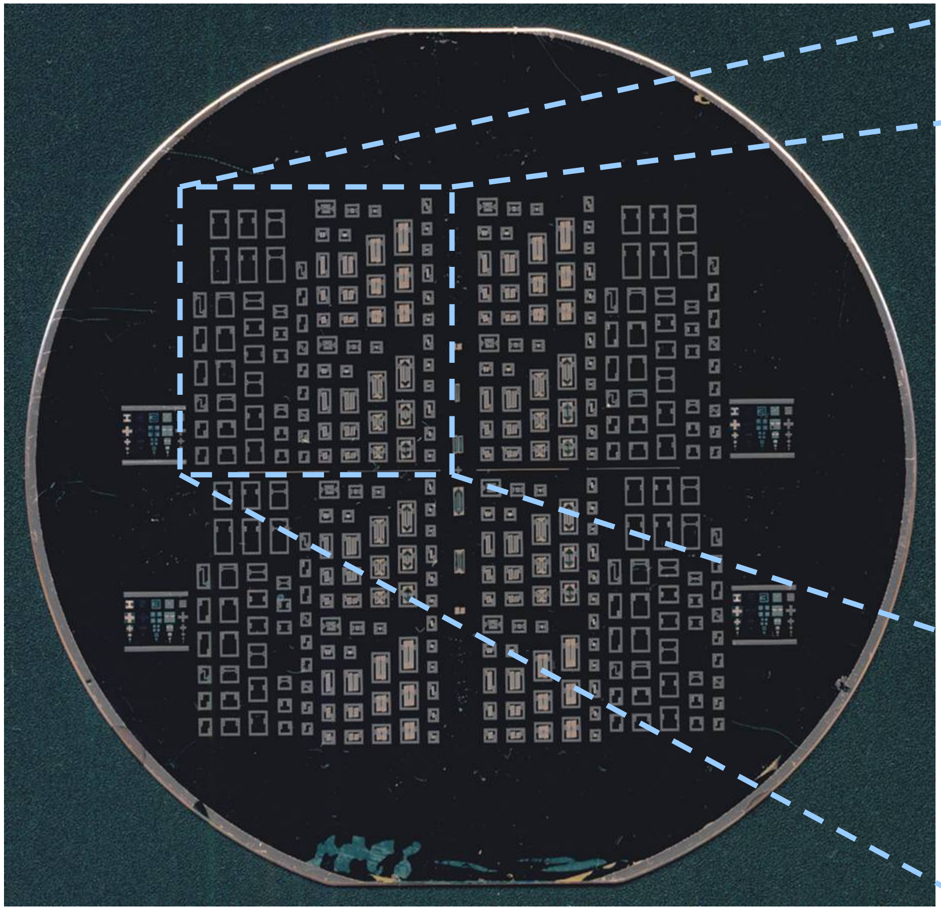
IV. Measurement of Fabricated Inductors

V. Analysis of Magnetic Inductors on Si

VI. Conclusion

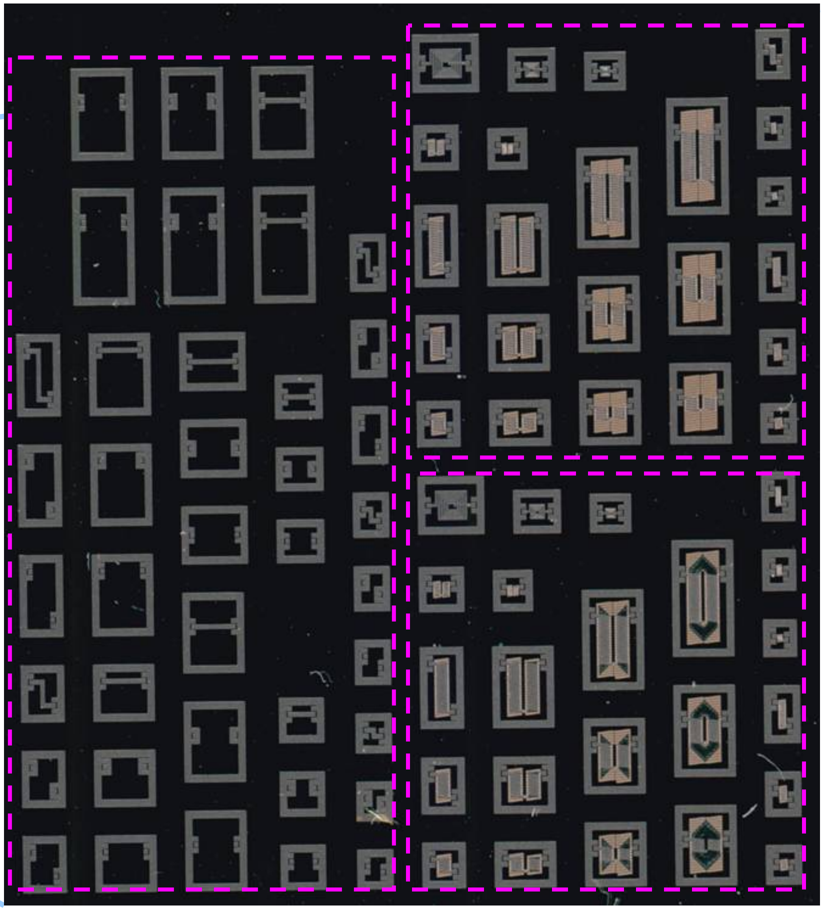
Image of Fabricated Wafer

Wafer (4”-dia.) map



Die map

“Air core inductors”



“De-embedding structures”

“Magnetic inductors”

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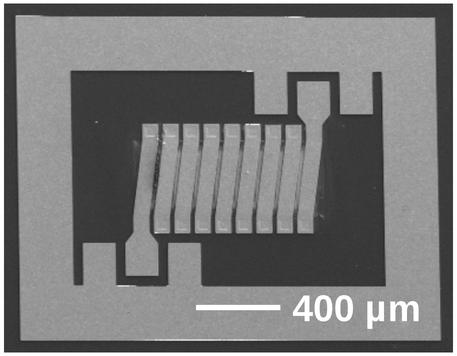
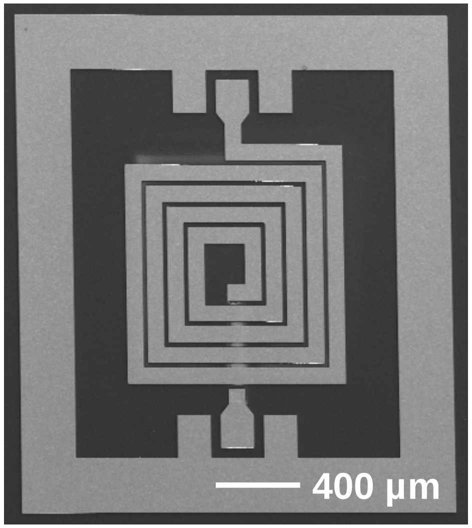
SEM Images of Fabricated Inductor Devices

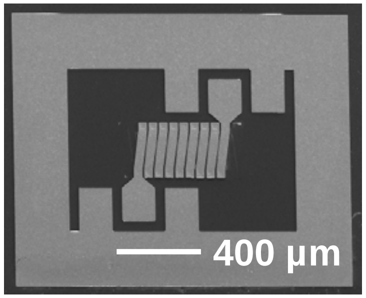
"Standard"



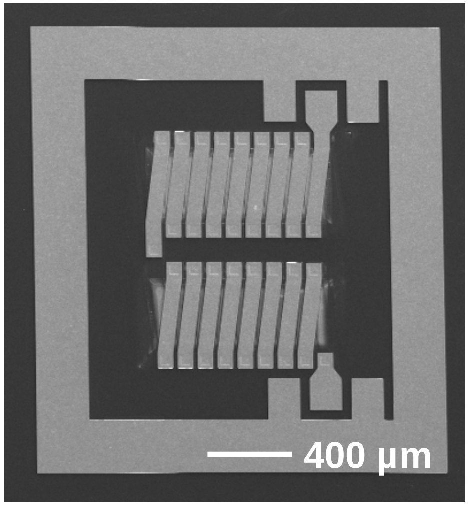
"Spiral"



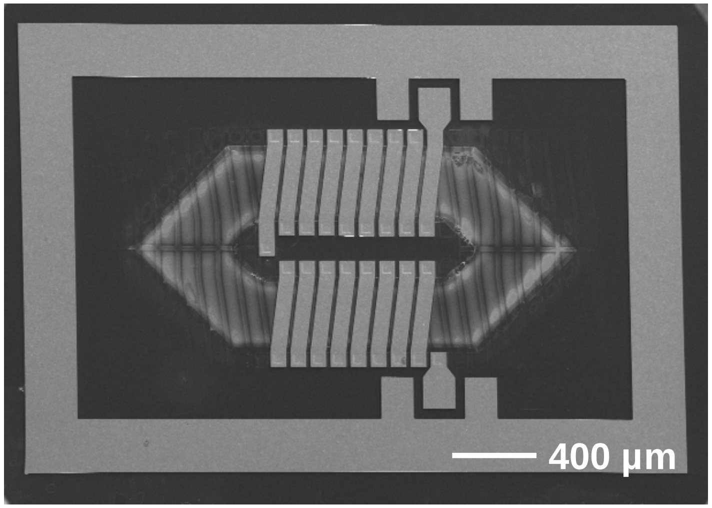
"Scale-down"



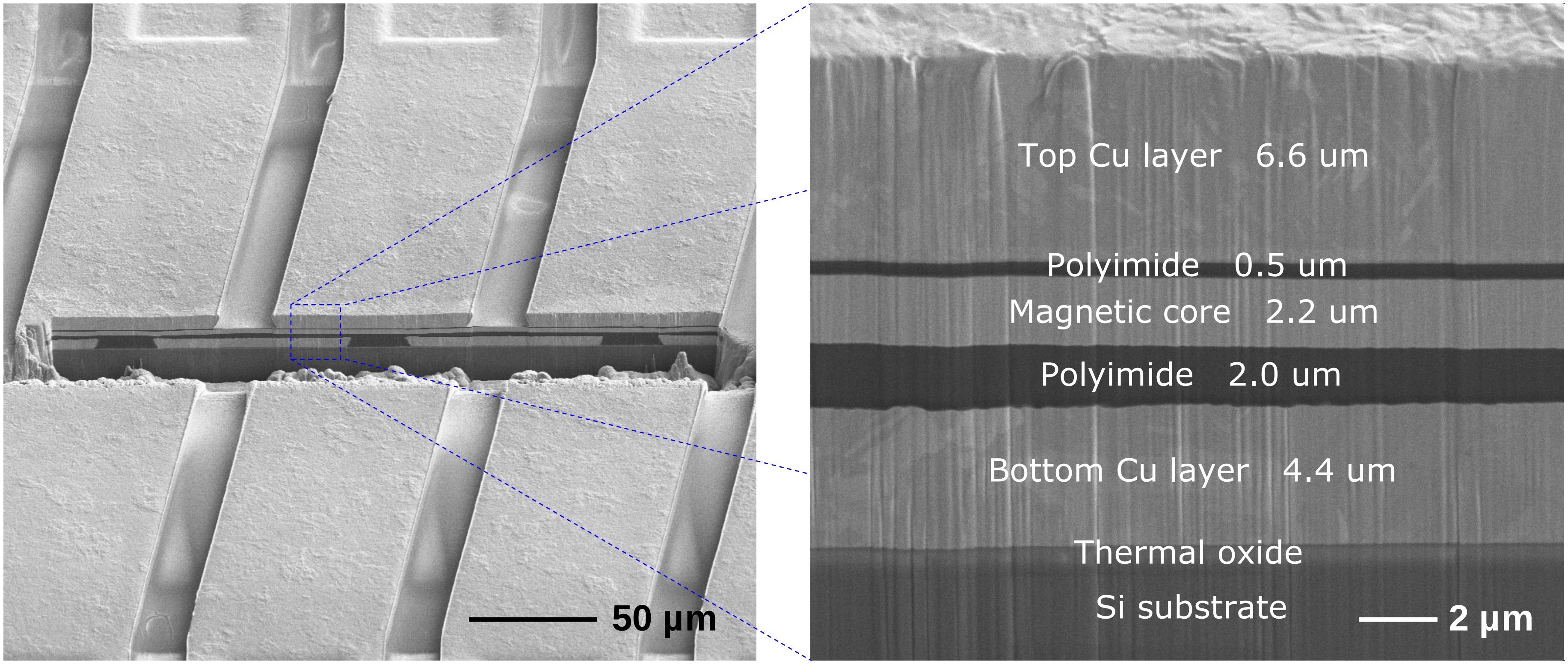
"Series"



"Closed core"



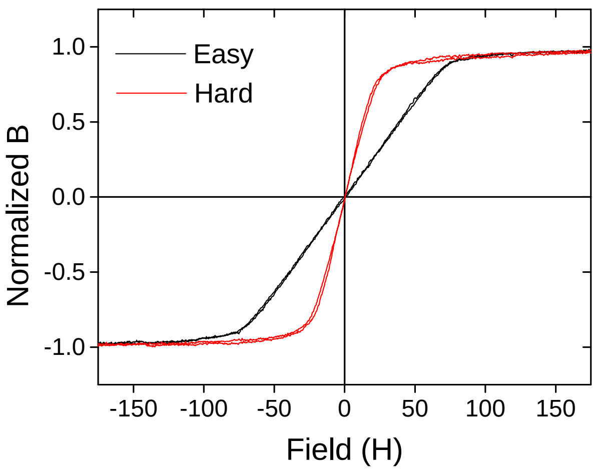
FIB Cross-section Images of Fabricated Inductors

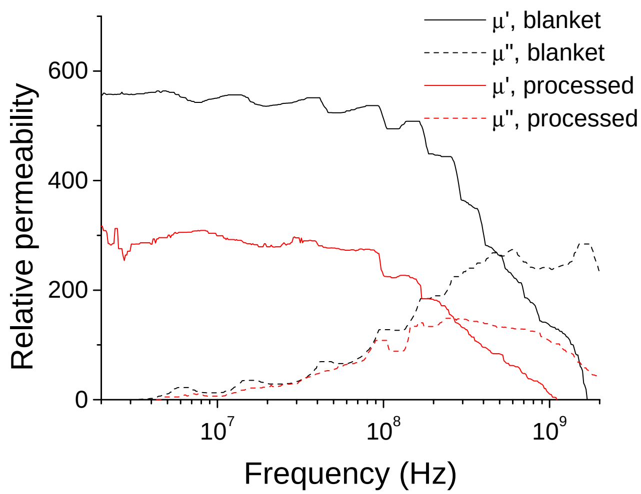


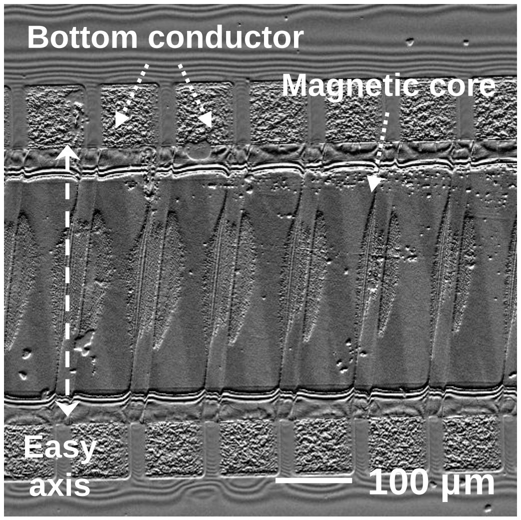
- FIB images confirm the successful fabrication of multi-layered inductor devices.
- The successful polyimide planarization is also confirmed, resulting in the continuous magnetic core layer.

Magnetic core shape affects permeability!

B-H loops	Permeability spectra	Kerr microscope image







- Magnetic test structures identical to the actual magnetic cores were included in the wafer layout and processed in parallel with the inductor fabrication.
- Magnetic measurements confirm that the magnetic core in the fabricated inductor maintains the desired soft magnetic properties.
- The permeability spectra of blanket film and processed magnetic core structures are not identical to each other.

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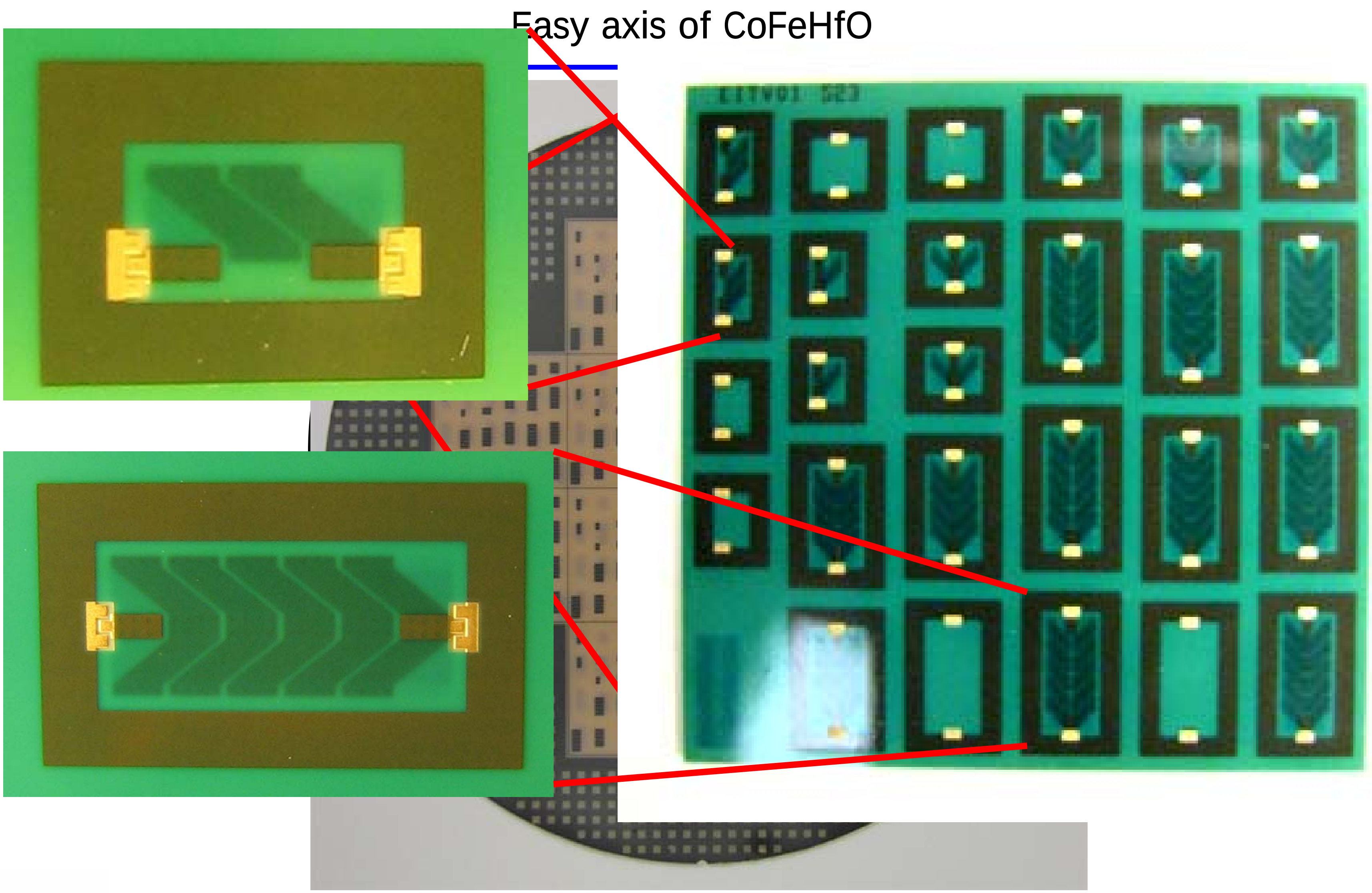
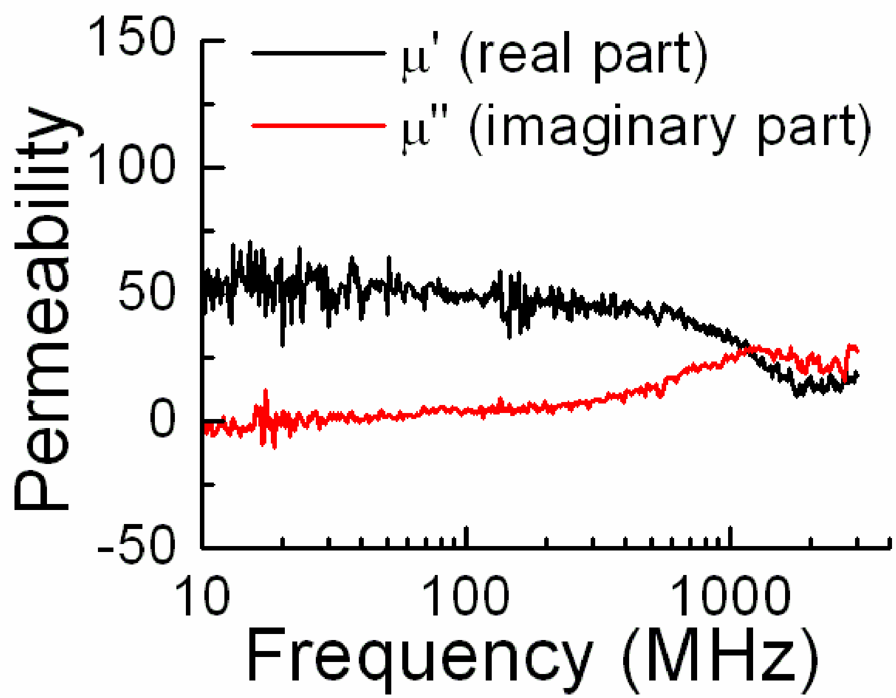
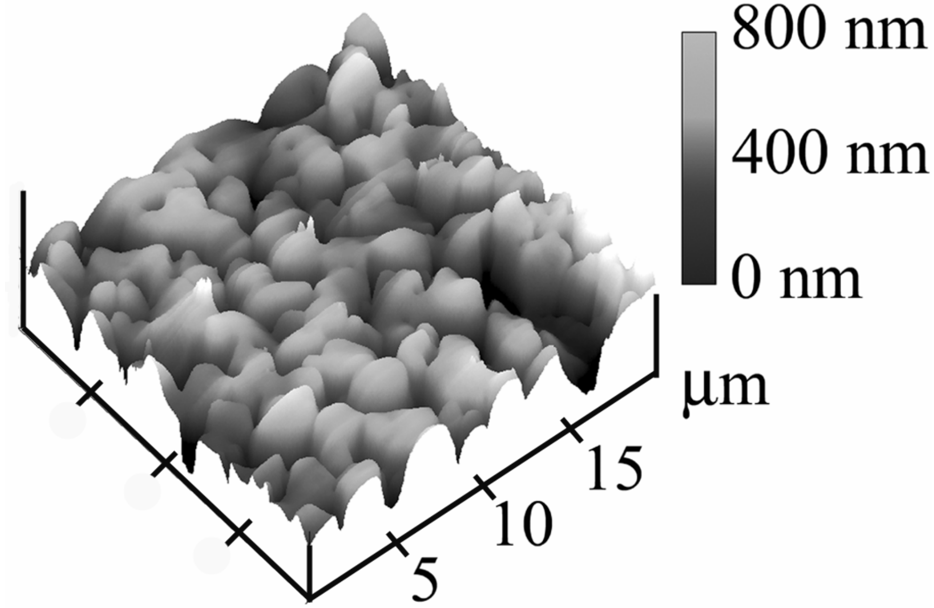
On-package Inductors on 8-inch Substrate



Surface roughness affects permeability!



Permeability spectra of patterned CoFeHfO bars on dielectric material



R_a=128.6 nm

Surface roughness of dielectric material

The rough surface of dielectric material degrades the magnetic properties of CoFeHfO deposited on it (even before patterning).

IV. Measurement of Fabricated Inductors

I. Introduction

II. Analytical Models and Inductor Design

III. Fabrication of Integrated Inductors

IV. Measurement of Fabricated Inductors

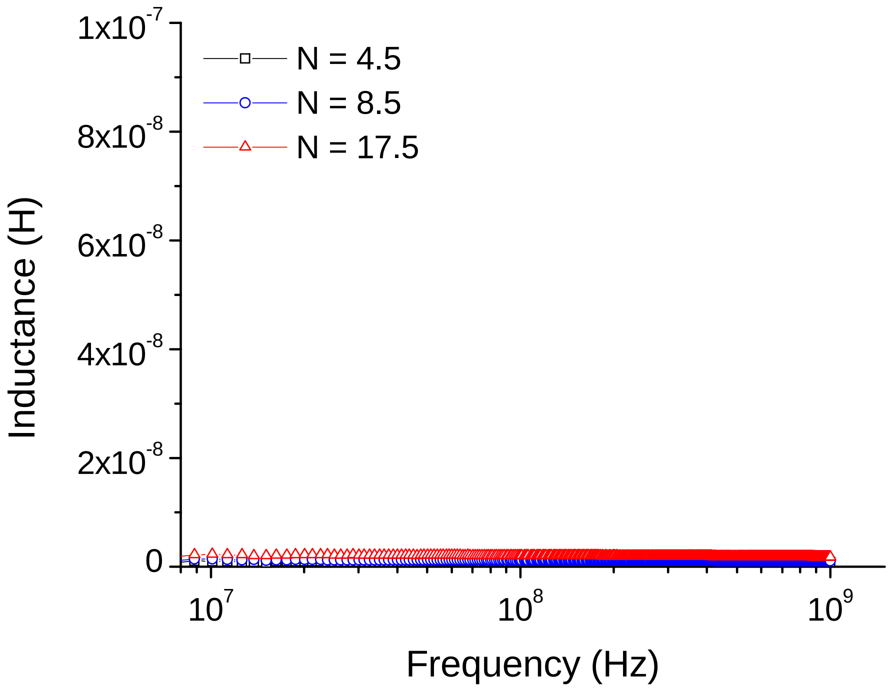
- Measurement method
- Circuit model of integrated inductor
- Measurement results of "Standard" inductors

V. Permeability of CoTaZr Magnetic Cores

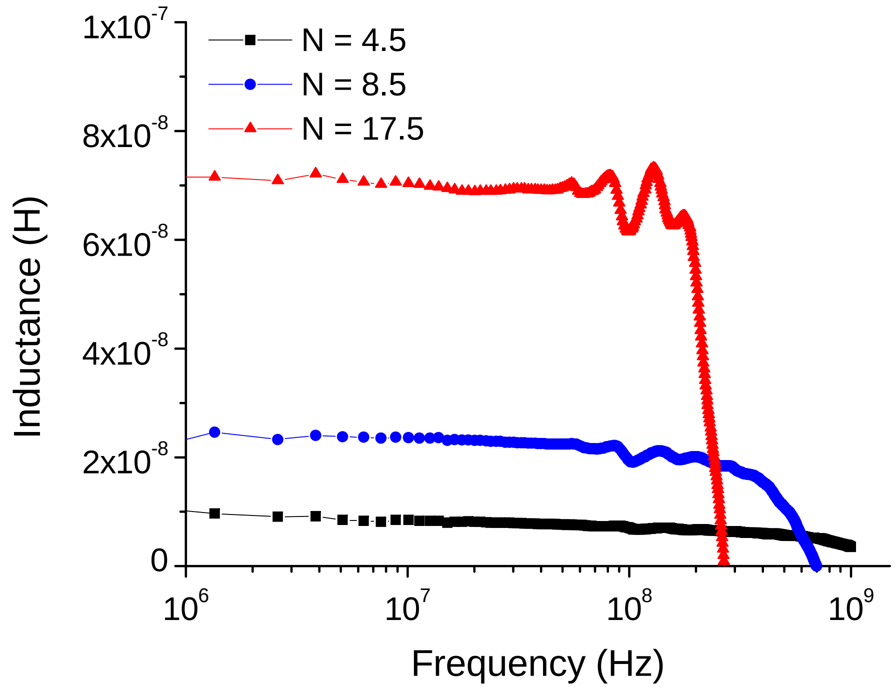
VI. Conclusion

Device Properties of "Standard" Inductors - *L*

Air core inductors



Magnetic inductors

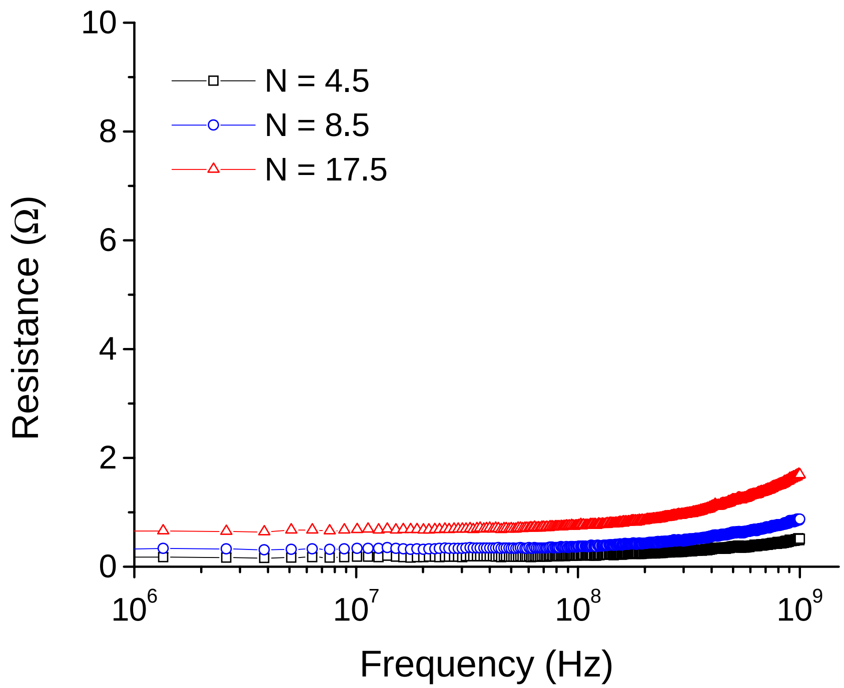


- With the use of magnetic core, inductance is 70.2 nH for N = 17.5, and the inductance enhancement is as high as 34×.

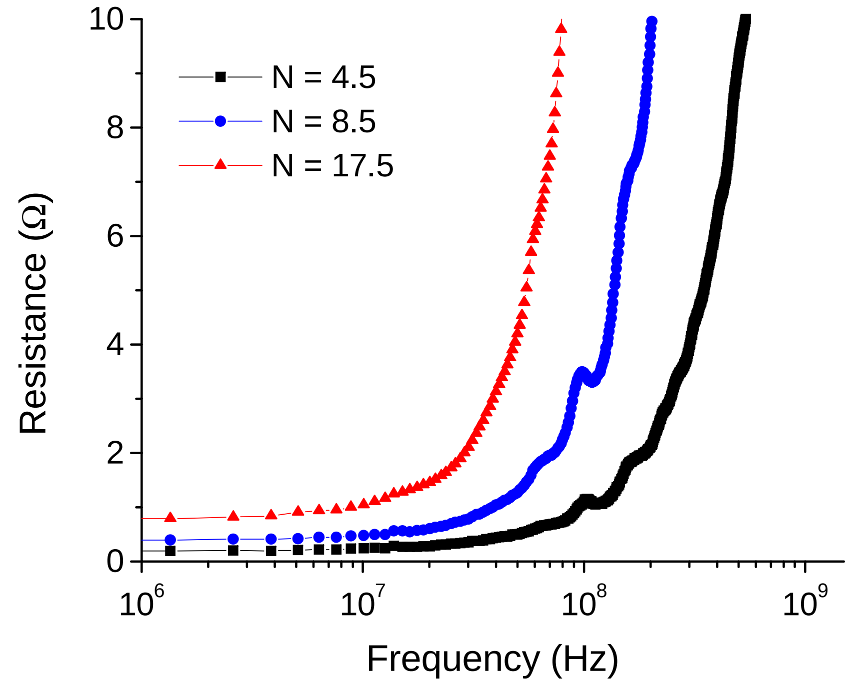
- The device area for N = 17.5 is 0.88 mm^2, corresponding to an inductance density of 80 nH/mm^2.

Device Properties of "Standard" Inductors - *R*

Air core inductors



Magnetic inductors



- Resistance at low frequencies is less than 1 Ω.
- Resistance of magnetic inductors increases greatly at high frequencies due to the magnetic power losses.

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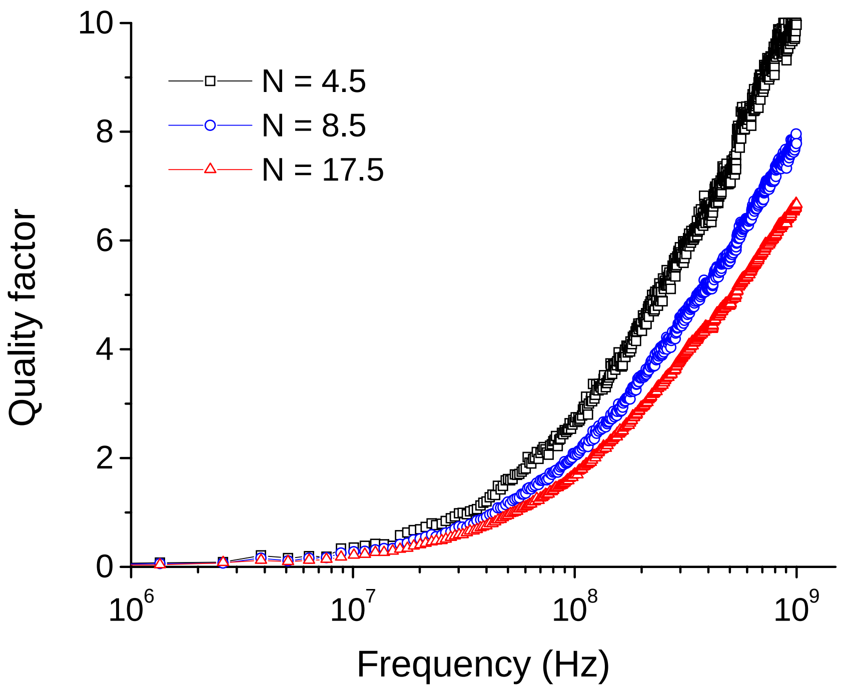
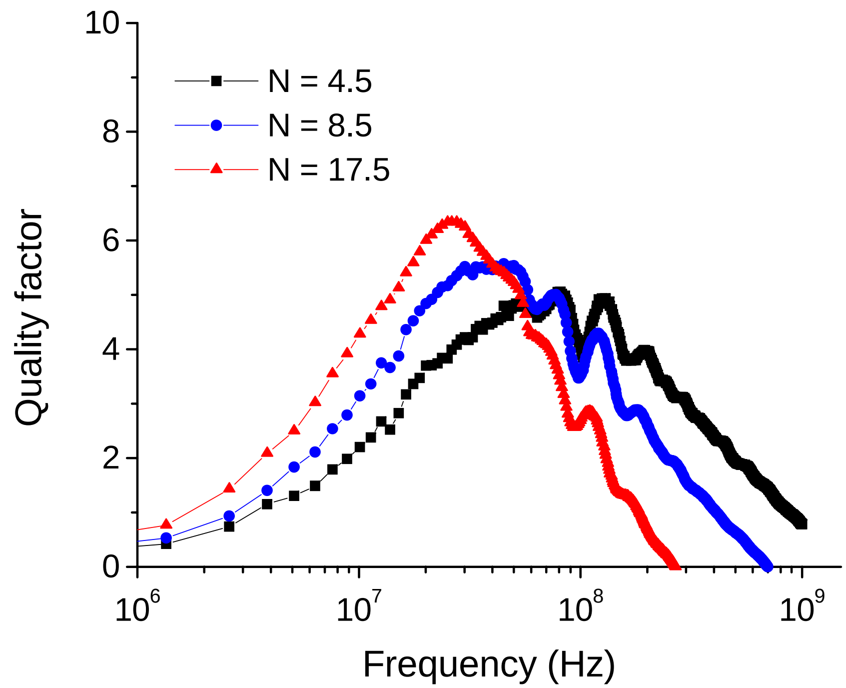
Device Properties of "Standard" Inductors - *Q*

Air core inductors



Magnetic inductors



- Quality factor of magnetic inductor is above 6 at 20 MHz for *N* = 17.5, and the enhancement over air core is well above 10×. However, it starts to decrease as the frequency increases due to the magnetic power losses.

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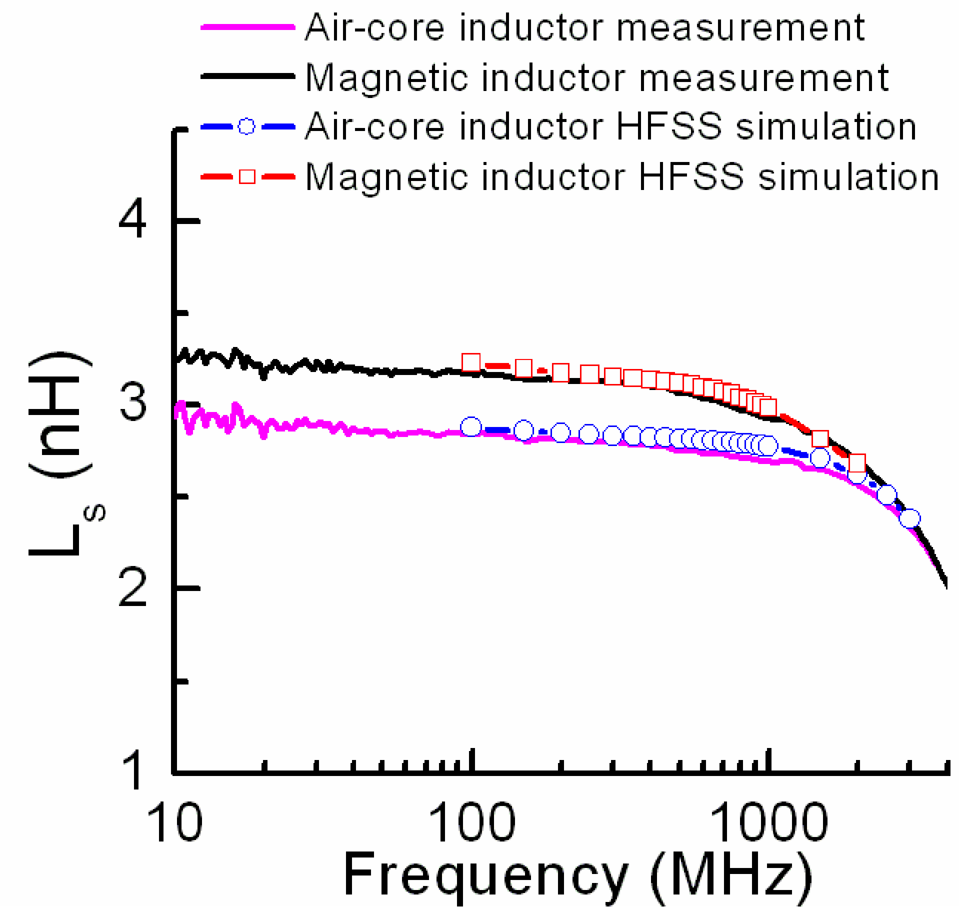
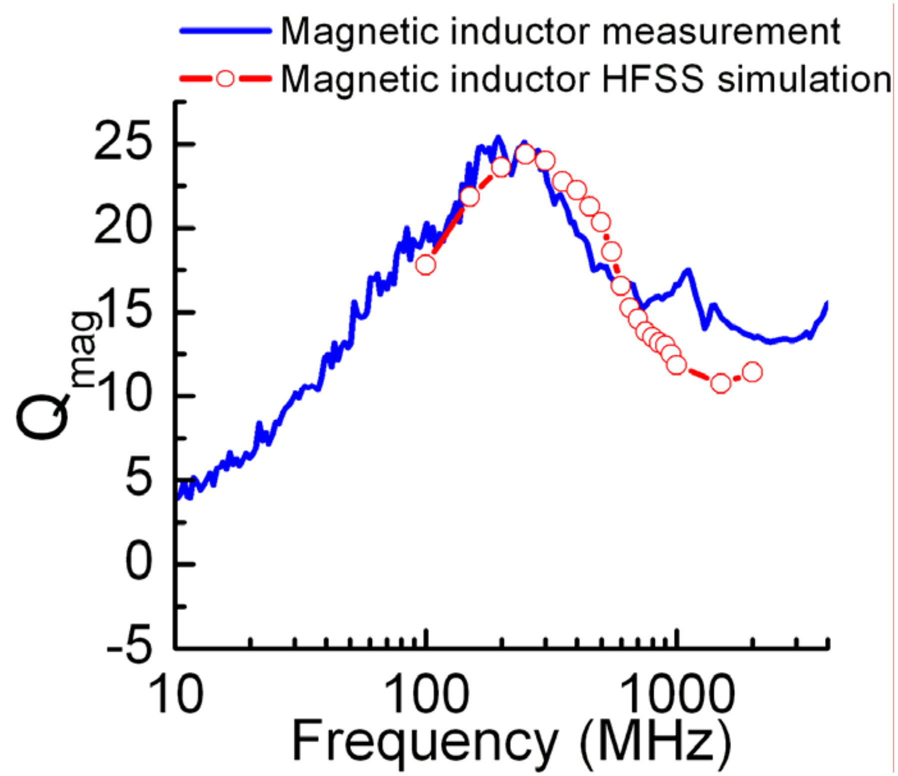
Five-Turn Magnetic Inductor on Package





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V. Analysis of Measurement Results

I. Introduction

II. Analytical Models and Inductor Design

III. Fabrication of Integrated Inductors

IV. Measurement of Fabricated Inductors

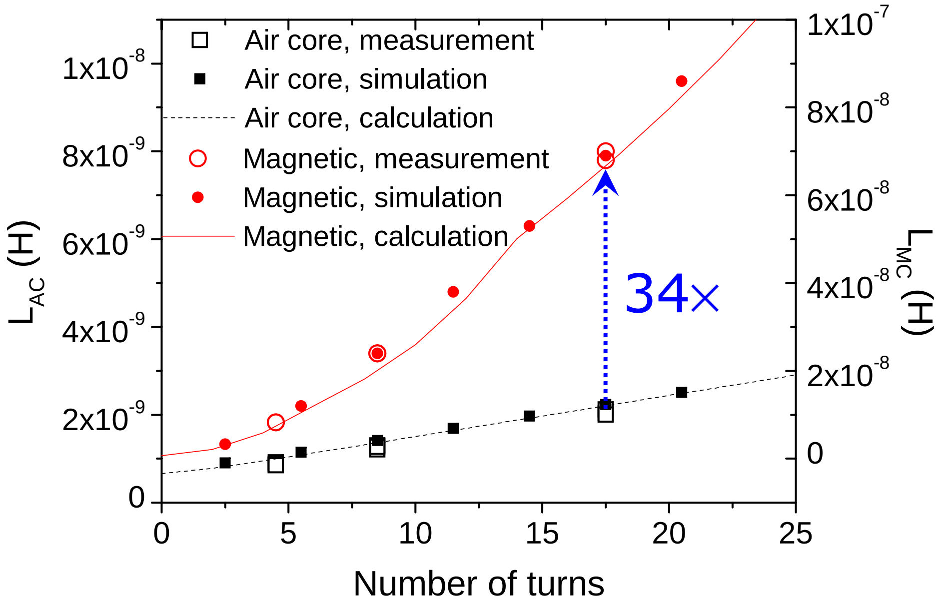
V. Analysis of Magnetic Inductors on Si

- Comparison with analytical models
- Effect of magnetic core shape
- Effect of scaling down

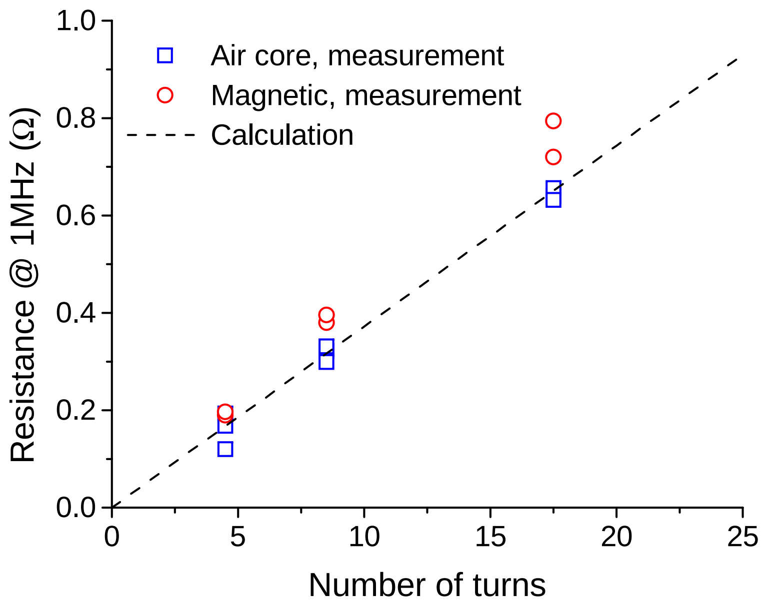
VI. Conclusion

Comparison with Analytical Models (I)

Inductance (@ 10 MHz)



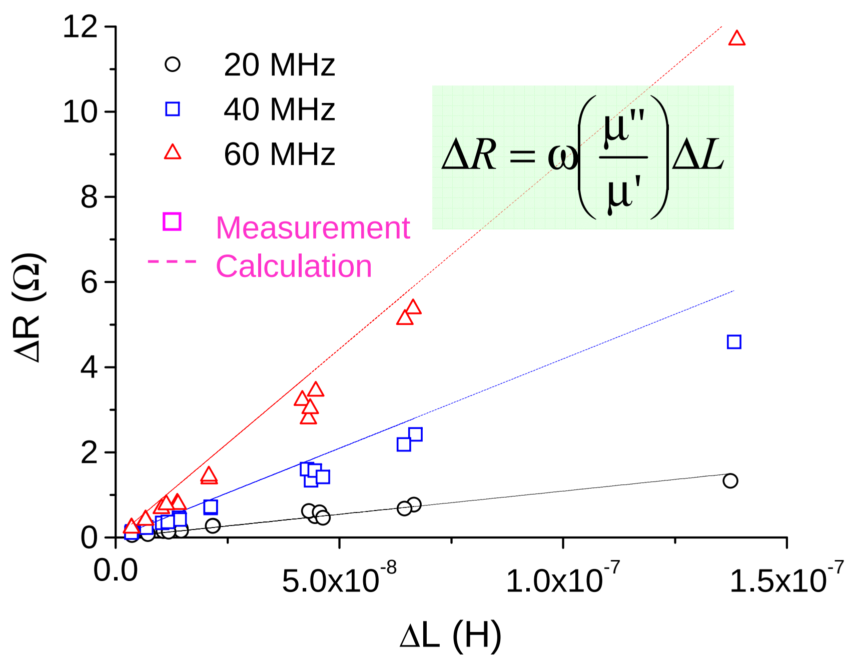
Coil resistance



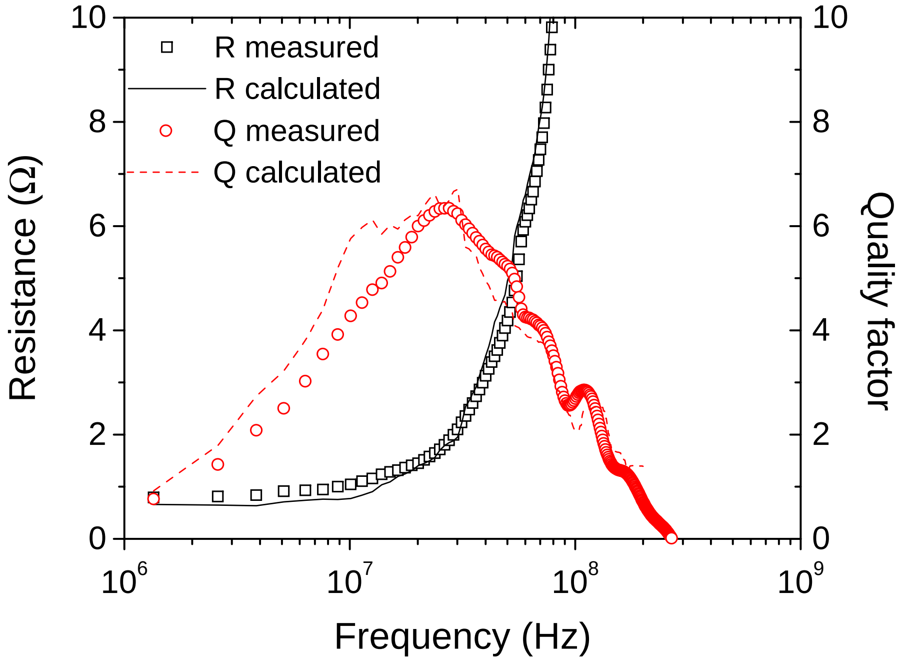
- The good agreements confirm that the analytic models can accurately describe the inductances of air core and magnetic inductors and their coil resistances.
- It indicates that the demagnetization effect plays a major role in determining the effective permeability of the magnetic inductors.
- The calculated inductance enhancement is about 30× for N = 17.5, which is very close to the observed enhancement of 34×.

Comparison with Analytical Models (II)

Trade-off between ΔL and ΔR



"Standard" with N = 17.5



- Permeability spectra of the processed magnetic core are used for the calculations of resistance and quality factor of the magnetic inductor.

- The excellent agreements between the calculation and measurement results directly confirm the validity of the proposed analytical models.

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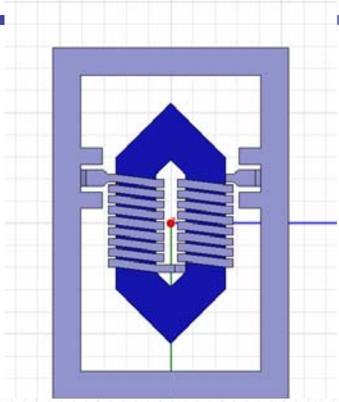
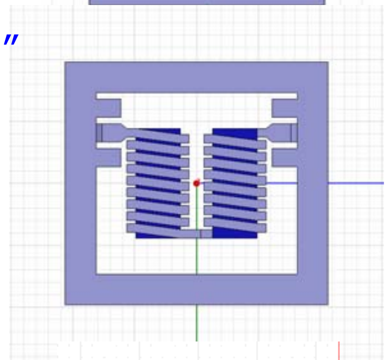
Effect of Magnetic Core Shape (I)

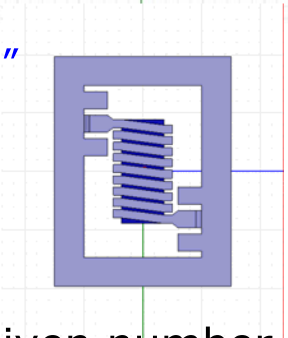
“Closed core”

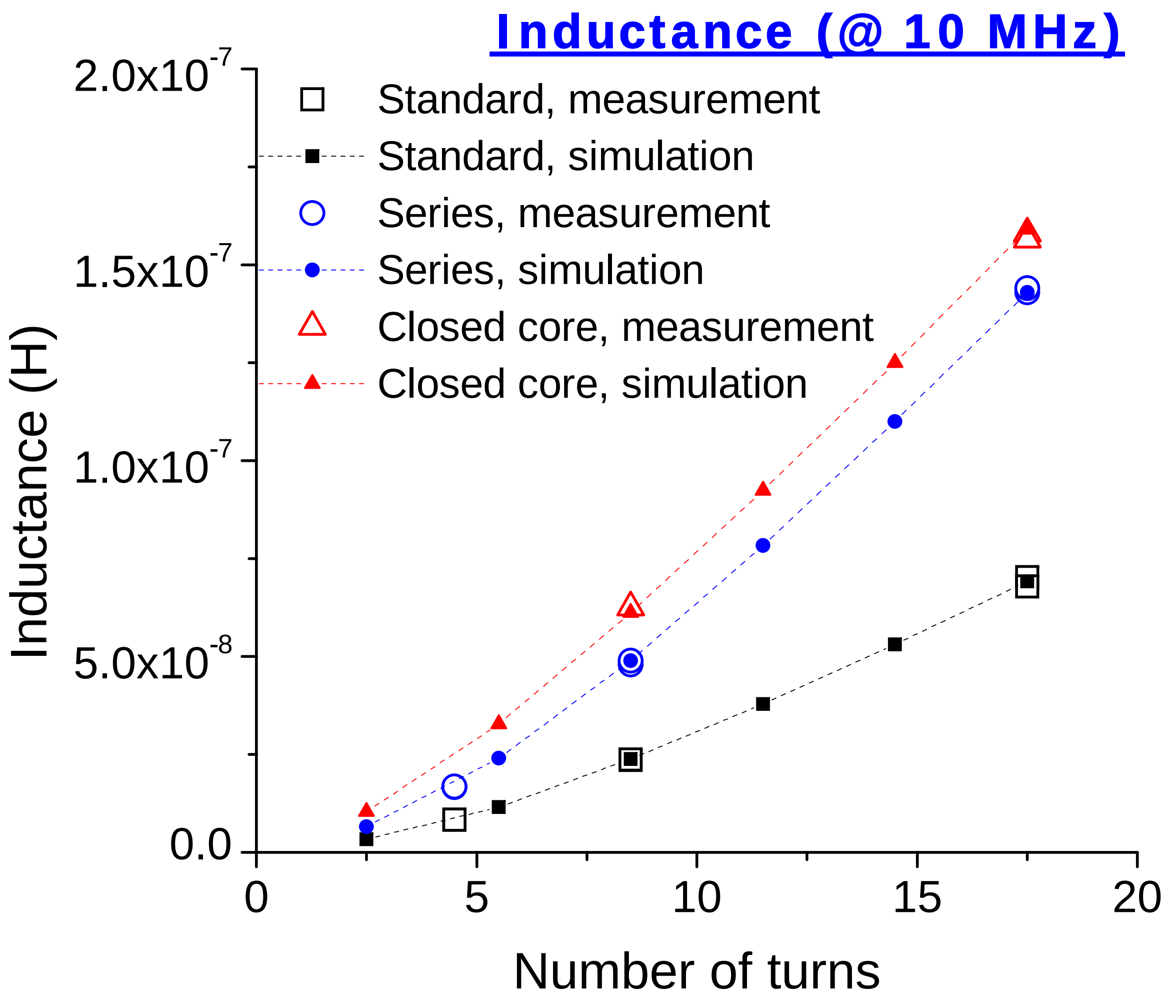


“Series”



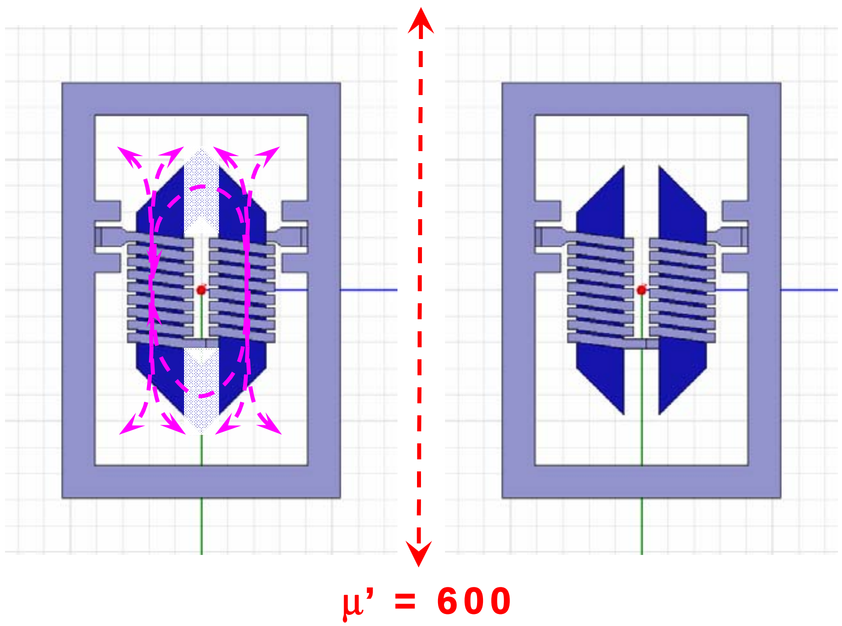
“Standard”

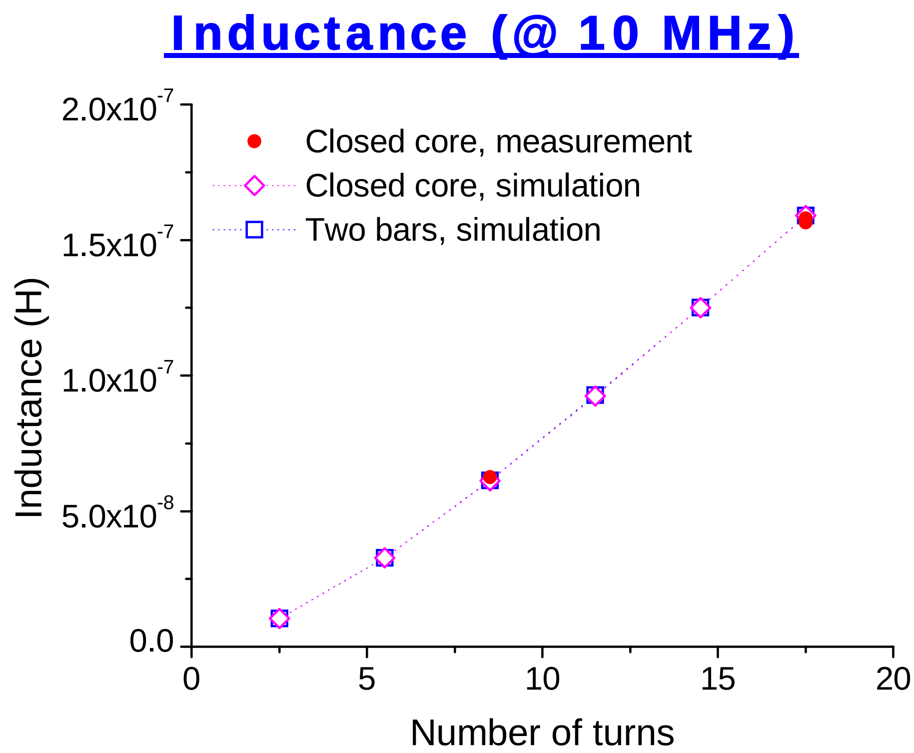




- For a given number of turns, the inductance of the “series” inductor is nearly doubled from those of the “standard” inductor, indicating that the “series” inductor can be viewed as two “standard” inductors connected in series.

Effect of Magnetic Core Shape (II)



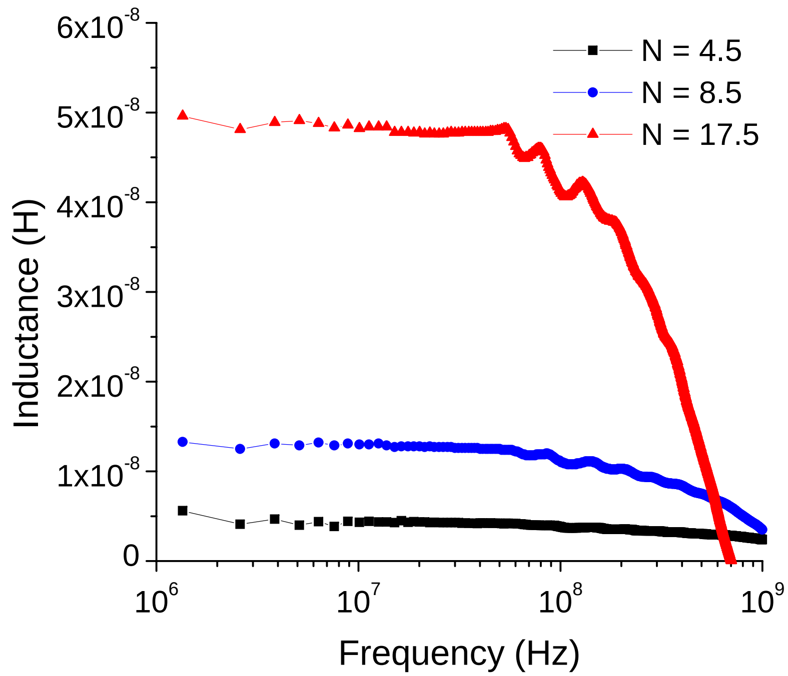


- Simulation results indicate that the effective shape of the closed magnetic core should be viewed as two parallel magnetic bars closed by two "bad" soft magnets.

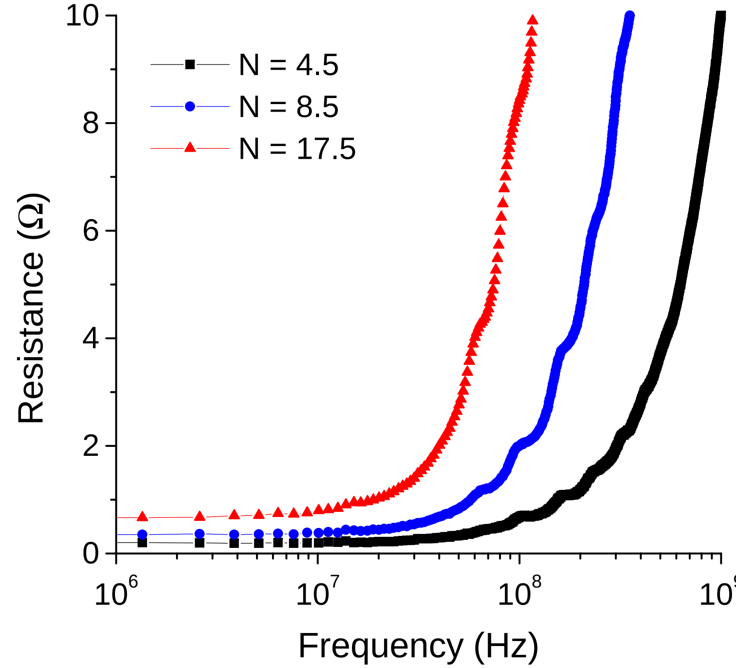
- Hence, the closed magnetic core is not effective in improving the magnetic flux closure significantly, and it can be explained by the tensor nature of permeability of the magnetic core.

Effect of Scaling Down

Inductance



Resistance



- Inductance is 48.4 nH at 10 MHz for N = 17.5, and the device area is reduced by a factor of four to 0.22 mm^2, resulting in the inductance density to 219 nH/mm^2.

- The coil resistance is not affected by the scale-down and is measured to be 0.57 Ω for N = 17.5 at 1 MHz.

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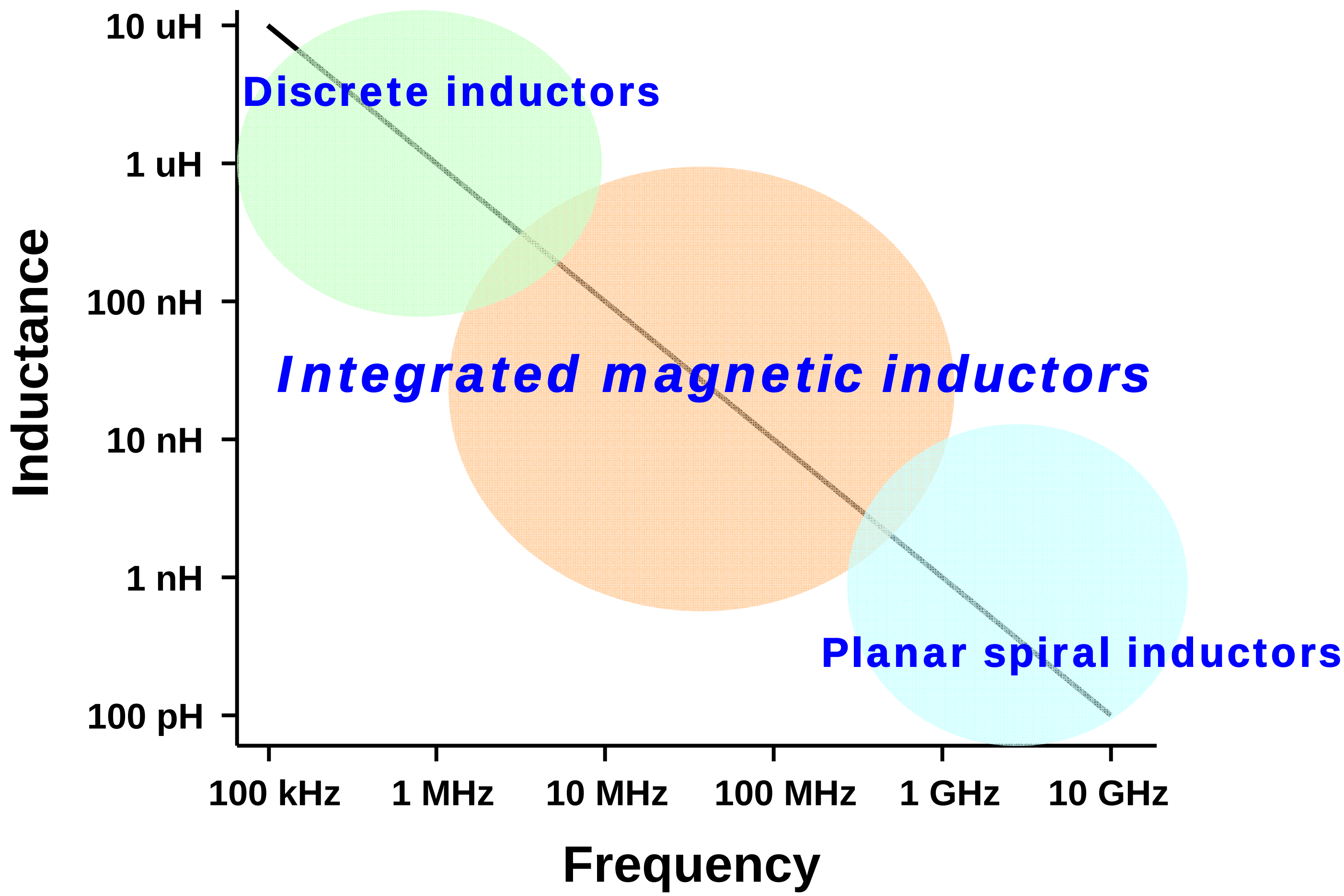
Bridging the Gap



Summary

- **High-performance integrated magnetic inductors were successfully designed and fabricated:**
  - For the coil resistance less than 1 Ω and the device area below 1 mm^2, the inductance as high as 70.4 nH was obtained on Si, corresponding to the inductance enhancement of 34× over the air core equivalent, and the inductance density reached 219nH/mm^2.
  - For DC resistance ~ 10 mΩ and device area of ~14 mm^2: Q ~ 25 at 200 MHz for magnetic inductor on package.
- **An analytical model can accurately describe the actual device properties**:
  - The fundamental trade-offs (ΔL vs ΔR) of the integrated magnetic inductors are well understood.
  - The inductor device properties can be further optimized (by materials or design) for a given application or frequency range.

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