Optimization of soft magnetic thin films structures in on-chip inductors for efficient power conversion in integrated voltage regulators

Hao Wu[1], Donald S. Gardner[2], and Hongbin Yu[1]

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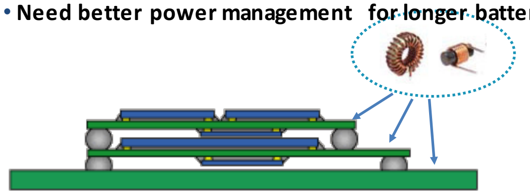
Motivation

Portable Electronics

- Need to integrate more functionalities into limited area
- Need better power management for longer battery life



System in Packages make by Package On Package

- Continued miniaturization at the system level:

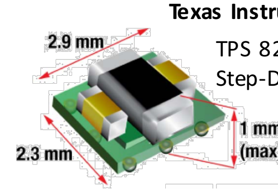
System Board Level	Package Level (SiP)	Chip Level (SoC)
• Power Control • Sensors • Analog/RF • **Passives**	• Inductors in package with magnetic cores	• Sub 100 µm size on-chip magnetic thin film inductors

- On-chip magnetic thin film inductors can benefit RF and power delivery applications:
  - High inductance density -> Reduces area
  - High quality factor -> Reduces loss
- Important magnetic material properties
  - High permeability, high resistivity, high FMR, CMOS compatibility
  - Material engineering required such as patterning and laminating

Different Strategies for Induction integration

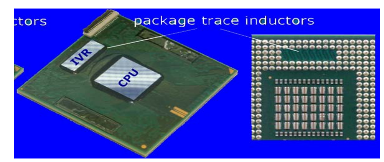
- Discrete inductor on mother board

Texas Instruments



TPS 82671 MicroSiP Step-Down Converter

- Inductor on/in package
  - Surface mount inductor
  - Air core inductor
    Large size & EMI

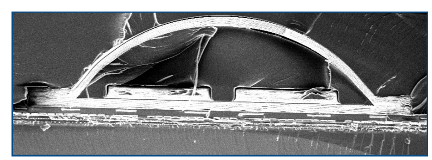


Intel Haswell

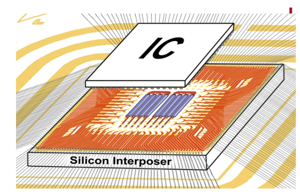
- Direct integration of magnetic core?
  Advantages: Smaller footprint; low height profile
  Challenges: material compatibility; thermal effect

Magnetic Materials

- Inductor on Si chip



Post CMOS: Intel



Si interposer: IBM/Columbia

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Materials Chnoice

- High saturation magnetization

$$L \approx \mu_0 \mu_r \frac{t_m}{2} \frac{l}{w} \qquad \mu \cong 4\pi M_s / H_k$$

- Controllable anisotropy

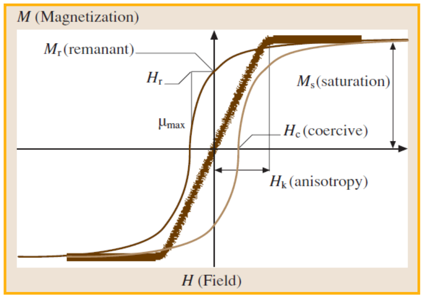
$$f_{FMR} \cong \gamma \sqrt{4\pi M_s H_k}$$

- High resistivity

$$f_{cutoff} = 4\rho / (\pi \mu_i d^2)$$

d, film thickness

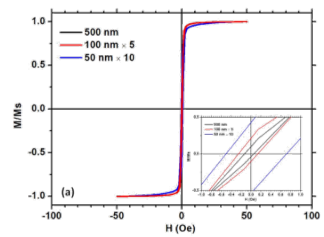
- Single domain state, for low magnetic loss
- Low magnetostriction to reduce the stress in fabrication

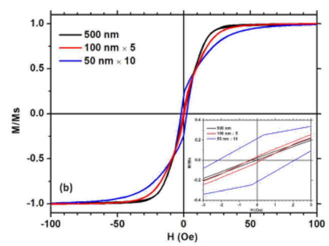


Thin Film Growth and Characterization

- DC magnetron sputter deposition: Co-4%Zr-4%Ta-8%B (at.%)
- Co oxide is used as insulation layer in laminated film.
- An external DC magnetic field was applied during deposition.
- B-H loop was measured by VSM.

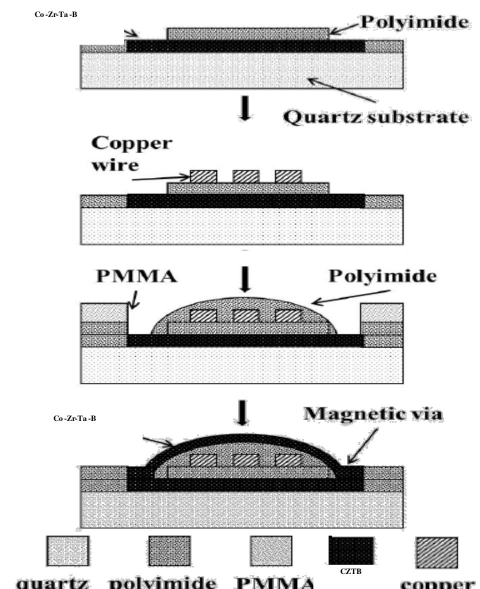
	Ni-Fe	Co-Zr-Ta	Co-Zr-Ta-B
μ	<650	1000	**1070**
ρ	20 μΩ·cm	100 μΩ·cm	**115 μΩ·cm**
FMR	640 MHz	1.4GHZ	**1.6GHz**

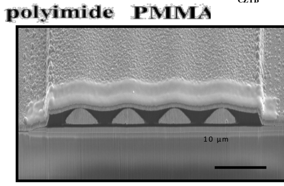




Inductor Fabrication

1. Deposit bottom-layer magnetic thin film
2. Spin 2 μm thick polyimide film as insulation layer
3. Deposit 2μm thick Cu layer and another polyimide insulation layer
4. Define magnetic via followed by O_2 plasma etching
5. Sputter top-layer magnetic material film and Cu layer





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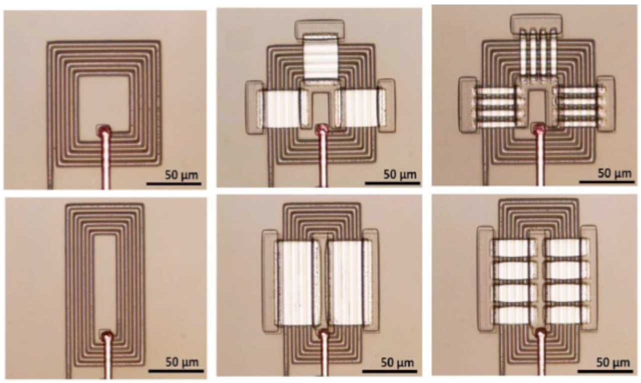
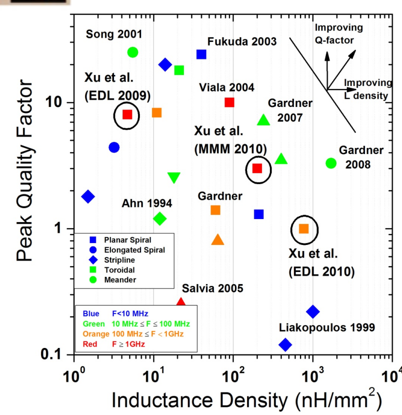
Inductor Performance

Fabricated inductor has Small size, high inductance density

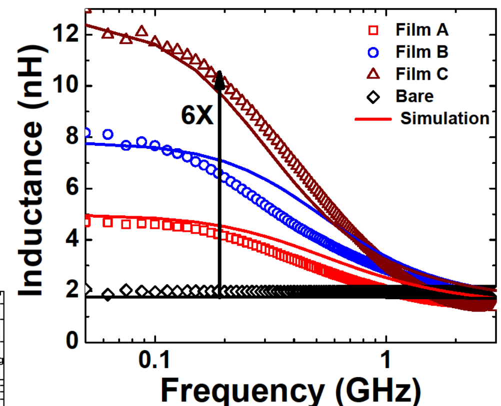


n	Area μm^2	W x T x S μm^3	L/bare nH	L/NiFe nH	Gain of L	L density nH/mm^2
2	40x40	1.5x1.0x1.5	0.21	0.5	2.4X	313
3	40x40	1.5x1.0x1.5	0.33	0.9	2.7X	563
3	62x62	1.5x1.0x1.5	0.78	1.8	2.3X	468
4	62x62	1.5x1.0x1.5	1.2	3.2	2.7X	832
5	62x62	1.5x1.0x1.5	1.5	5.1	3.4X	1327
4	130x130	5.0x2.0x2.5	1.8	6.7	3.7X	396
4	130x100	5.0x2.0x2.5	1.7	7.3	4.3X	562
4	160x100	5.0x2.0x2.5	2.05	12.3	6X	769
Ref.		Mag Mat.			Gain of L	L density nH/mm^2
[1]	320x50	CoZrTa	0.11	3.6	31X	1700@40MHz
[5]	340x200	Ferrite	0.9	2.3	1.6X	20@4GHz
[6]	60x120	NiFe	0.5	1	2X	138@5GHz
[7]	380x380	CoNbZr	8	13.9	0.7X	111.1@2GHz



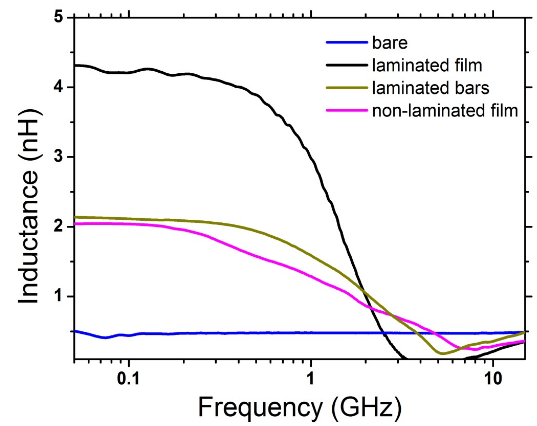
Mtaerials Comparison: NiFe vs CoZrTaB

Ni-Fe



Wei Xu, et al., IEEE EDL 32, 69 (2011).

Co-Zr-Ta-B



Hao Wu, *et al.*,, IEEE Trans. Magn (2012).

Higher resistivity CoZrTaB leads to higher frequency response to GHz range

Magnetic Core Inductors Fabricated on Organic Substrates

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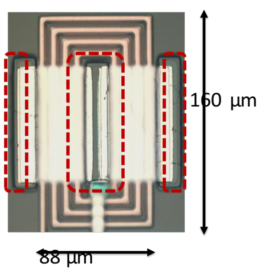
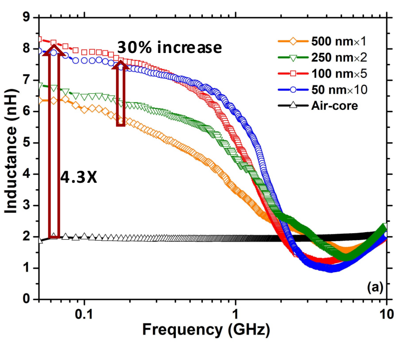
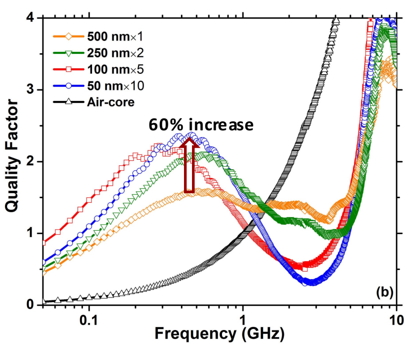
Improving Inductor Performance

Lamination Effect

- **4-turn rectangular spiral inductors**
  - W: 88 µm, L:160 µm
  - Laminations can suppress eddy current loss in the conductive magnetic films and skin depth effect resulting in better frequency response.





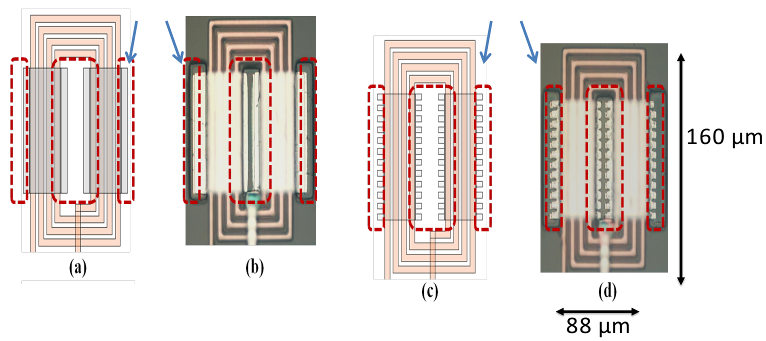


Hao Wu, Shirong Zhao, Donald S. Gardner, and Hongbin Yu, '*Improved High Frequency Response and Quality Factor of On-Chip Ferromagnetic Thin Film Inductors by Laminating and Patterning Co-Zr-Ta-B Films*', **IEEE Trans. Magn.**, 49, 4176 (2013

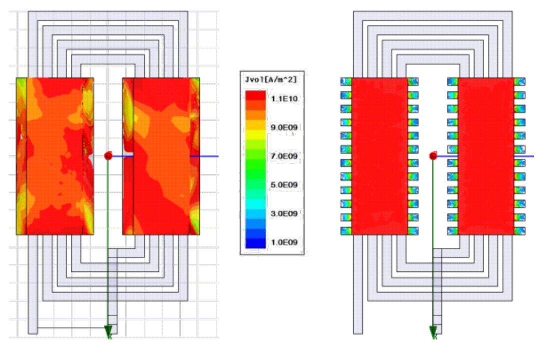
Finger-shaped Via

- **Finger-shaped magnetic via:** W: 5 µm, L: 4 µm × 13

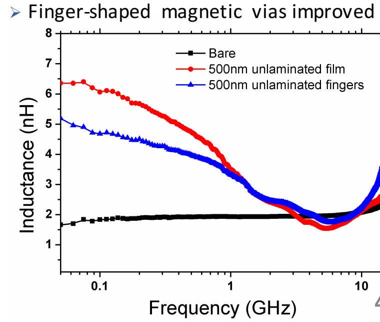
Regular Magnetic Vias **Finger-shaped Magnetic Vias**



HFSS 3D EM Simulations at 1GHz



- With Co-Zr-Ta-B film, a maximum 3.5X inductance increase and a 3.9X increase in the Q-factor at 1 GHz were achieved.
- Finger-shaped magnetic vias improved Q by >30%.



Hao Wu, *et al.*,, IEEE Transactions on Magnetics (2012).

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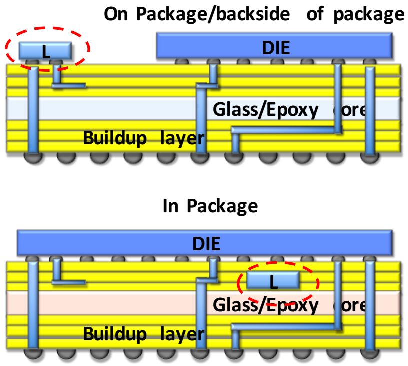
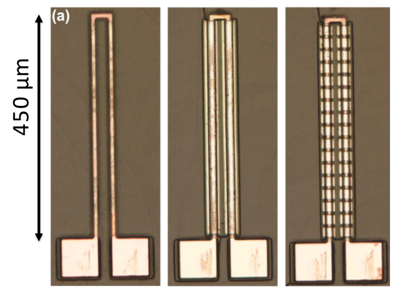
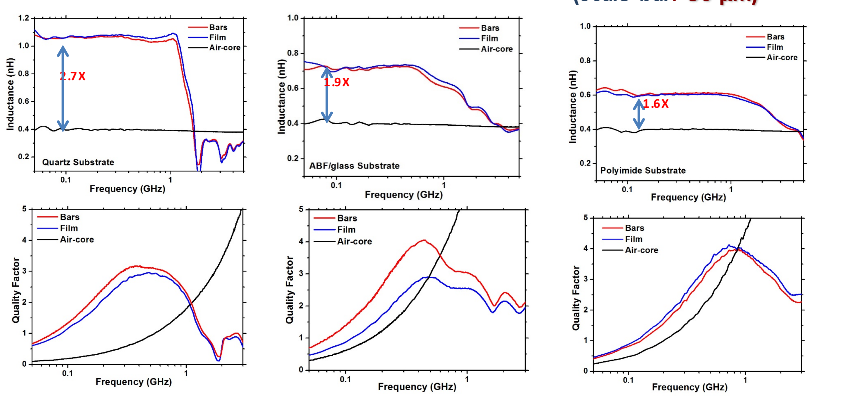
Inductors Fabricated on Package substrate





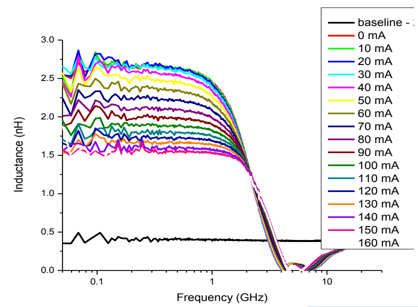
Fabricated inductors on ABF/glass substrate (scale bar: 80 µm)

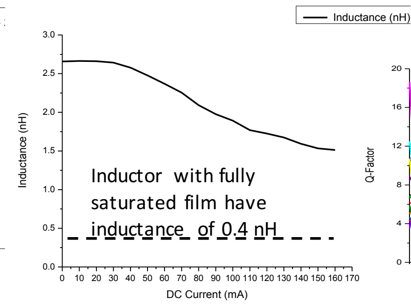


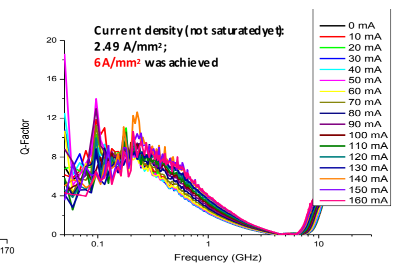
Quartz ABF Polyimide

Hao Wu, et al., Integration of Magnetic Materials into Package RF and Power Inductors on Organic Substrates for System in Package (SiP) Applications', IEEE Electronic Components and Technology Conference, Orlando, FL, May 2014

DC Current Bias







Acknowledgements

Donald Gardner, Wei Xu, Tawab Dastigir.
US National Science Foundation, Intel, Semiconductor Research Corporation, ASU Connection One.

Publications

- ✓ M. Khdour, H. Wu and H. Yu, "High DC Current Density On-Chip Strip-Line Inductors Integrated With Magnetic Film," in **IEEE Transactions on Magnetics**, vol. 52, no. 7, pp. 1-4, July 2016. doi: 10.1109/TMAG.2016.2542864.
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- ✓ Hao Wu, Donald S. Gardner, Shirong Zhao, Hai Huang, and Hongbin Yu 'Control of magnetic flux and eddy currents in magnetic films for on-chip radio frequency inductors: Role of the magnetic vias'**, J. Appl. Phys**. 115, 17E719 (2014).
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