Optimization of magnetic enhancement layers for high-frequency transmission line micro-inductors

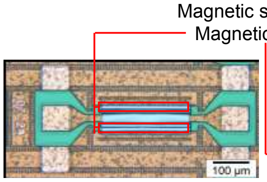
Brice Jamieson[a], Terence O'Donnell[a], Paul McCloskey[a],
D.S. Gardner[b], Saibal Roy[a]

[a]Microsystems Centre, Tyndall National Institute, Lee Maltings, Cork, Ireland
[b]Circuits Research Lab, Intel Labs, Hillsboro, OR, USA

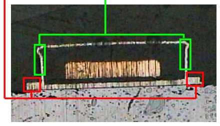
Background

- Miniaturization leading to increased consideration of integrated passives on-Si or in-package
- Soft ferromagnetic thin-films play a key part for inductance enhancement effects and low loss at high frequencies
  - Inductance enhancements of up to 28[i]
  - Current capacities of up to 10 A[ii]
- Ideal Magnetic thin-film will provide
  - High inductance enhancement
  - High saturation current
  - Low losses at high frequency (>100 MHz)

Devices to effectively close the core between the top and bottom magnetic layers are commonly used in transmission-line structures:



Fabricated transmission-line microinductor using uniaxial CoTaZr thin-film and magnetic vias



Cross-sectional view of a fabricated transmission-line inductor with a NiFe thin-film

- Develop a method to study the effects of various thin-film materials on integrated, high-frequency Transmission-line inductors
- Compare a set of measured ferromagnetic thin-films to determine the optimal parameters for operation in such an inductor
- Consider optimization for
  - Maximum Inductance Enhancement
  - Minimized Inductor Loss
  - Maximum Current-carrying capacity

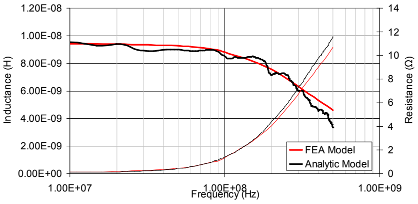
Objectives

- Inductance model based on series of reluctance elements to calculate inductance enhancement
- Resistance model based on $R_{DC}+R_{Winding}+R_{Core}$
- High-frequency complex permeability modelled using analytical equations[iv]

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

μ = relative permeability
μ_i = low-frequency permeability
δ = skin depth of thin-film
d = thin-film thickness

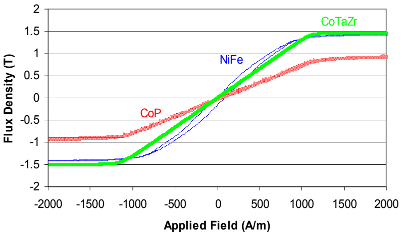
- Simulations show a good correlation with Finite-Element Analysis (FEA)



Comparison of analytic model with Finite-Element Analysis (FEA)

Three common materials for transmission-line micro-inductors were compared

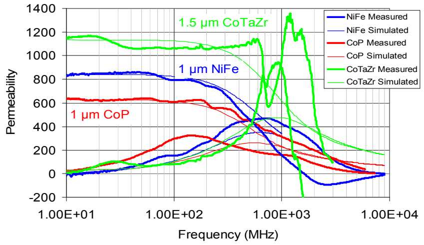
	Bs (T)	Hk (A/m)	Hc (Oe)	μ_{r0}	ρ (μΩ·cm)
CoP	0.94	1100	< 0.1	660	101
NiFe	1.43	800	5	850	40
CoTaZr	1.52	1000	< 0.1	1000	99



Hysteresis curves for three thin-film magnetic materials

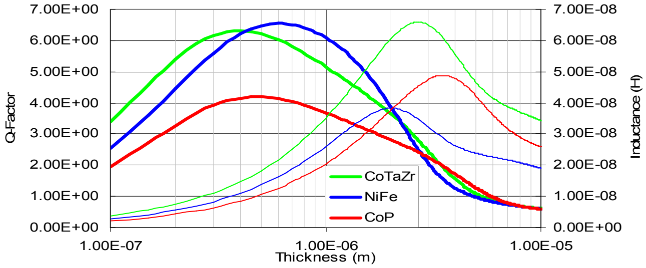
Sputtered materials (CoTaZr)
- good magnetic properties
- time-consuming to produce above a few μm

Electrodeposited materials (CoP, NiFe)
- Similar properties to sputtered materials
- Improved deposition rate



High-frequency complex permeability curves for selected magnetic materials and fit to theoretical model

Results



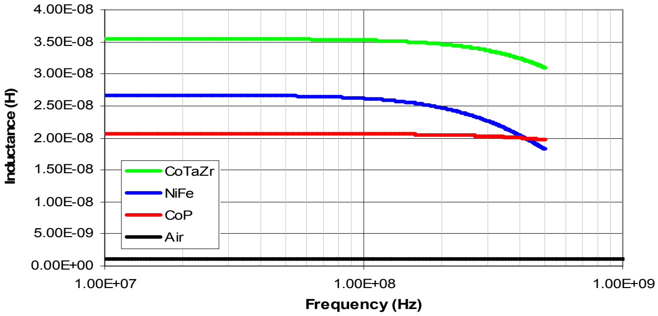
Q-factor and inductance peaks for a 5 x 10 μm conductor at 100 MHz

- The device Q-factor illustrates the relationship between inductance and resistance at a particular frequency and geometry

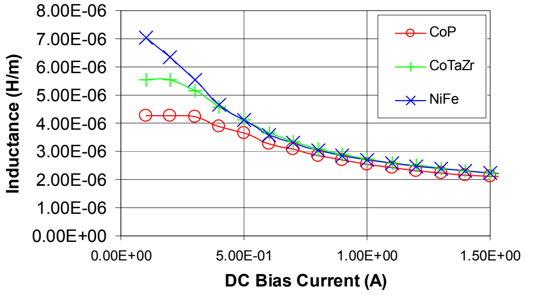
$$Q = \frac{j\omega L}{R}$$

Q = Q-F
ω = angular frequency
L = Inductance
R = Resistance

- Device Q-factor peaks can be seen for each material, indicating an optimal material thickness for a particular frequency, not shown in thin-film measurement
- Inductance enhancement at the Q-factor peak can be used to determine the material with the greatest inductance enhancement capability at a given frequency
- High-Bias current handling of a device is a function of anisotropy field, however initial bias is influenced by more than low-frequency permeability
- Inductance enhancement as a function of frequency directly related to relative permeability and resistivity, CoP shows inductance retention to a high frequency



Inductance enhancement as a function of frequency



Inductance enhancement as a function of DC bias field

Electroplated CoP shows promise for high-frequency transmission-line applications

Improved Resistivity (ρ) and Anisotropy field (H_k) could result in CoP performance greater than sputttered CoTaZr, with improved performance at high frequency and an increased deposition rate

References

[i] D.S. Gardner, G. Schrom, P. Hazucha, et al. "Integrated on-chip inductors using magnetic material", J. Appl. Phys. 103, 07E927-1 (2008)
[ii] Satish Prabhakaran et al., IEEE Trans. On Magnetics., 39, 3190 (2003)
[iii] D.S. Gardner, G. Schrom, P. Hazucha, et al. "Integrated on-chip inductors using magnetic material", J. Appl. Phys. 103, 07E927-1 (2008)
[iv] W.P. Jayasekara, J.A. Mabin, M.H. Kryder, IEEE T. Mag., **34**(4), 1438 (1998)

Acknowledgements: Intel Corporation Enterprise Ireland Tyndall National Institute