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Institut de Recherche en Électrotechnique et Électronique de Nantes-Atlantique

Modeling of RF CMOS Passive Components: from electromagnetic interpretation

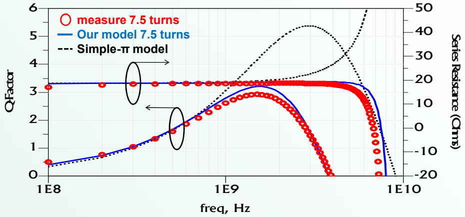
Siamak Salimy[1,3], Serge Toutain[1], Ahmed Rhallabi[2], Antoine Goullet[2], Fatiha Challali[2,3], Jean-Claude Saubat[3]
[1]IREENA, Fédération CNRS Atlanstic, Université de Nantes, Polytech'Nantes, La Chantrerie, 44306 Nantes
[2] IMN, Institut des Matériaux de Nantes, 2 rue de la Houssinière, 44322 Nantes
[3] MHS Electronics, 92 route de Gachet, La Chantrerie, 44306 Nantes
Siamak.Salimy@univ-nantes.fr

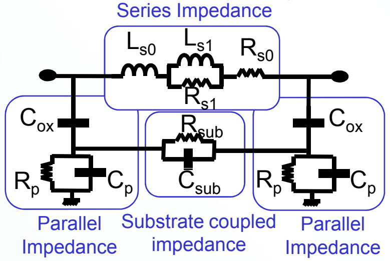
Introduction

- ❑ **An enhanced scalable compact model for on-chip RF CMOS spiral inductors is presented.**
- ❑ **By considering layout and technology parameters, the model elements are all expressed analytically and based on physical assumptions.**
- ❑ **The proposed approach provides simple physical and electrical interpretation for spiral inductors design.**
- ❑ **The model is suitable to be easily implemented in design kits by foundry**

Enhanced Simple- π network

The physical and analytical approaches is based on enhanced simple-π network to model spiral inductors. This network is introduced to model the frequency dependent behavior of CMOS spiral such as substrate coupling, skin and proximity effects, and decrease of equivalent series resistance.





❑ The inductance value is resulting from the contribution of both an overall inductance L_{s0} and a metal lines intrinsic inductance L_{s1} related to proximity effects.

❑ Series resistances R_{s0} represents the DC resistance of the metal line, and R_{s1} the resistance due to the skin effect.

❑ C_{ox} is considered as the capacitance between metal lines and silicon substrate.

❑ C_p capacitance resulting from the coupling capacitance between the spiral metal lines and the capacitance between strips and the bottom ground plane through the silicon substrate

❑ R_p resistance models the losses due to silicon substrate

❑ C_{sub} models the capacitance induced between the spiral underpass and the metal strip.

❑ R_{sub} is modeled as the equivalent resistor due to current flowing in the substrate under the spiral underpass region.

Model Parameters Calculation

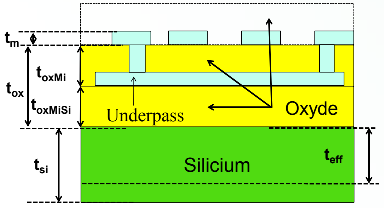
Series Impedance

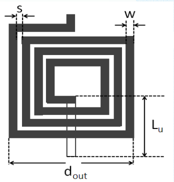
L_{s0} is evaluated by current sheet approximation, which considers the spiral to be symmetrical and traversed by currents of equivalent densities [i]

L_{s1} is calculated from the inductance of a single rectangular metal sheet with a reduced width w/2 [ii].

$$R_{s0} = \frac{\rho_m . L_g}{w . t_m} \qquad R_{s1} = \frac{\rho_m . L_g}{w}\left(\frac{1}{\delta(1-e^{-tm/\delta})} - \frac{1}{t_m}\right)$$

δ is the skin effect thickness, and ρ_m the metal sheet resistivity. L_g the total length of metal line





Parallel Impedance

$$C_{ox} = \frac{1}{2} L_g . \varepsilon_0 . \varepsilon_r . \left(\frac{w}{t_{ox}} + \frac{t_m}{s}\right) \qquad C_{shunt} = \frac{C_p . C_{ox}}{C_p + C_{ox}}$$

The total shunt capacitance Cp is calculated by a conformal mapping approach on a bi-layer substrate for coplanar lines with length Lg/2

$$R_p = \frac{R_t . t_{eff}}{{d_{out}}^2}$$

Rt is the transverse p.u.l resistance of silicon substrate

$$t_{eff} = \mathrm{Re}\left\{\frac{1-j}{2}\delta_{si}\tanh\left[(1+j)\frac{t_{si}}{\delta_{si}}\right]\right\}$$

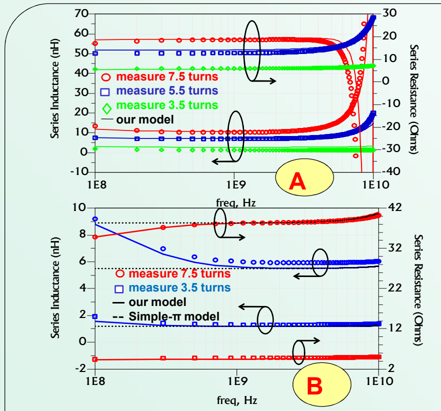
teff is the effective silicon thickness due to the eddy current generated in the substrate which operating as a virtual ground plane

Subrate Coupled Impedance

$$C_{sub} = w . \varepsilon_0 . \varepsilon_{ox} . \left(\frac{n_{co} . w}{t_{oxMi}} + \frac{L_u}{t_{oxMiSi}}\right) \qquad R_{sub} = \frac{\rho_{si} . L_u}{w . t_{eff}}$$

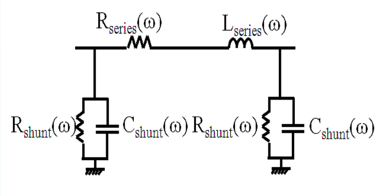
ρsi is the silicon resistivity and nco the number of cross over

Model Validation



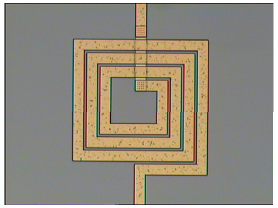
Measured and modeled (this work and previous development [iii]) series inductance and resistance

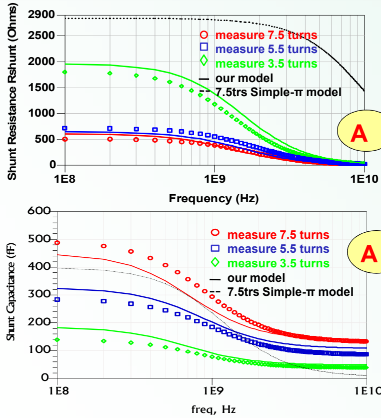
To characterize the frequency response of the measured spirals, four frequency dependent elements are considered. The circuit is composed of the equivalent series inductance **$L_{series}(\omega)$** and resistance **$R_{series}(\omega)$** on the one hand, and equivalent shunt resistance **$R_{shunt}(\omega)$** and capacitance **$C_{shunt}(\omega)$** on the other hand.



Set A of tested inductors:
7.5-turns spiral, d_{out}=300 μm
5.5 –turns, d_{out}=280 μm
3.5 –turns, d_{out}=160μm
w=12μm, s=4μm

Set B of tested inductors:
7.5 turns (w=3μm, s=2.5μm and dout=145μm),
3.5-turns (w=12μm, s=2.5μm and dout=145μm).





Comparison of measured and modeled (this work and previous development [iii]) of shunt resistance and shunt capacitance of 3.5, 5.5 and 7.5 turns CMOS spiral inductors.

This extended model improves the previous scalable physical and analytical based models by considering the proximity effects and the decrease of the equivalent series resistance due to substrate coupling. This approach can be applied well for the modeling of MIM capacitors and thin film resistors

References: [i] E. B. Rosa, "Calculation of the self-inductances of single-layer coils,"*Bull. Bureau Standards,* vol. 2, no. 2, pp. 161–187, 1906.
[ii] W. Gao, Z. Yu "Scalable compact circuit model and synthesis for RF CMOS spiral inductors", *IEEE Trans. on Microwave Theory & Tech.*, Vol. 54, pp. 1055- 1064, Mar. 2006.
[iii] C. P. Yue and S. S. Wong, "Physical modeling of spiral inductors on silicon," *IEEE Trans. Electron Devices*, vol. 47, no. 3, pp. 560–568, Mar. 2000