Extended Abstracts of the 2002 International Conference on Solid State Devices and Materials, Nagoya, 2002, pp. 650-651

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Equivalent circuit analysis of RF integrated inductors with/without ferromagnetic material

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1. Introduction

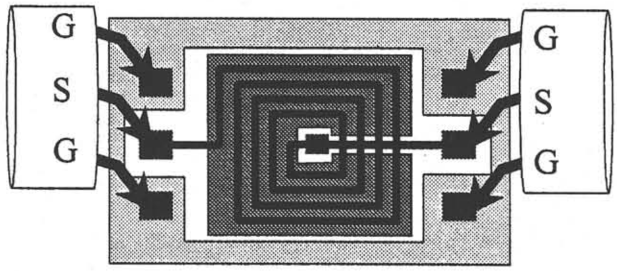
Many efforts have been undergoing to improve the quality factor, Q, and to miniaturize the size of RF integrated inductors fabricated on a Si wafer. Equivalent circuit analysis and electromagnetic field simulation are very often used to design and analyze the inductors. These techniques are required further improvements to deal with the brand-new ferromagnetic RF integrated inductors as well as to extend the frequency range beyond 10GHz.

This paper deals with the detailed procedure to extract the π-type equivalent circuit parameters of RF integrated spiral inductors with/without ferromagnetic material, followed by the discussion on the effectiveness of FEM simulation up over 10GHz.

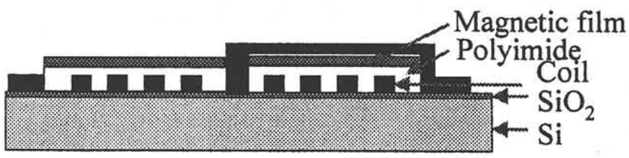
2. Structure and design

Fig. 1 shows the structure of the fabricated RF integrated inductor. The substrate was 600 μm-thick (100) oriented n-type Si with resistivity of higher than 500 Ωcm. The coil is made of a 2.6 μm thick Cu with width w_c=12 μm and spacing d_c= 10 μm. The outer size of the spiral is 393x393 μm^2.

In the case of the ferromagnetic inductor, a 0.1μm thick amorphous $Co_{85}Nb_{12}Zr_3$ (at%) soft ferromagnetic film was sputter deposited on top of the spiral with the 3.2 μm thick spun-coat polyimide layer in between. The hard axis of magnetization of the ferromagnetic film was along the vertical direction in Fig. 1(a). Narrow slits to shift the ferromagnetic resonance frequency were applied perpendicularly to the hard axis.



(a) Top view with GSG type wafer probes.



(b) Cross sectional view.

Fig. 1 Structure of 2-port type RF integrated magnetic thin-film inductor.

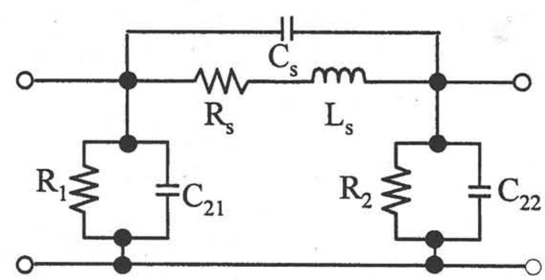


Fig. 2 Equivalent circuit of the air core inductor.

2. Equivalent Circuit Analysis

Air Core Spiral

Fig. 2 shows the known equivalent circuit structure of the RF integrated air-core inductor. The main inductance, L_s, is in series with the resistance, R_s, representing the wiring loss of the coil portion. This leg is in parallel with the line-to-line parasitic capacitance, C_s,, which includes the capacitance between the coil and the lead-out line. The capacitances, C_1 and C_2, lie between the coil and the doped-Si layer. Then the grounding parasitics are shown by C_{21}, C_{22}, R_1 and R_2.

Each component of the S-parameters, s_{11}, s_{21}, s_{12} and s_{22}, was measured by a network analyzer and a wafer probe. The S-parameters were once converted into Y-parameters. If the drive frequency is low enough to neglect the line-to-line capacitance, C_s, the Y-parameters can simply be converted into the equivalent circuit parameters with the one-to-one correlation to the S-parameters [5].

The Tohoku University group (TU) and The Tokyo Institute of Technology group (TIT) separately acquired the equivalent circuit parameters. TU used HP 8720D

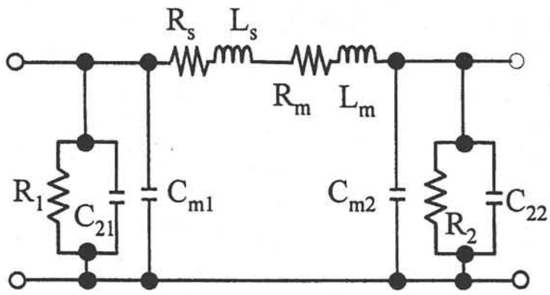


Fig. 3 Equivalent circuit of the magnetic thin-film inductor.

network analyzer and a wafer probe of GGB Industries, Inc., Model 40A GSG while TIT used Agilent 8720ES network analyzer and Cascade Microtech, Inc., ACO40-GSG type wafer probe. The extracted parameters were perfectly identical. For example, L_s=7.1nH, R_s=6.3Ω, R_1=2.0kΩ, C21=0.15pF, R2=2.7kΩ and C22=0.09pF are obtained for f=2GHz.

For the higher frequency analysis, the line-to-line capacitance, C_s, can be extracted as follows. Resonance frequency, f_{r1}, of L_s gives $f_{r1} = 1/2\pi\sqrt{L_s C_s}$. Then adjust L_s and C_s so that the resonance frequency of the input impedance, $Z_{in} = 50(1+s_{11})/(1-s_{11})$, best fits. Finally adjust R_s to fit the peak value of Z_{in}. This calculation lead to Cs=0.014pF.

Ferromagnetic Spiral Inductor

In Fig. 3, a simplified equivalent circuit of the on-top type RF ferromagnetic integrated inductor is shown. The main contribution of magnetic film is represented by the inductance, L_m, and the loss resistance, R_m, which are in series to the leg of the air-core inductance. C_{m1} and C_{m2} represent the parasitic capacitance between the magnetic film and the coil, and between the magnetic film and the ground plane. Assuming that the parameters, L_s, R_s, C_{21} and C_{22}, were equal to those of the air core spiral, the estimated increase of the inductance was 6.7% at 2GHz. It was also found that the magnetic film has enhanced the inductance up to 5GHz.

3. Electromagnetic field simulation

Measured s_{11} parameter for the air core spiral exhibited a minimum at 17.6GHz as shown in Fig. 4. This minimum cannot be explained by the equivalent circuit parameters because the reconstruction of the s_{11} value from the extracted equivalent circuit parameters did not work well as shown by the thin line. On the other hand, the 3D-FEM simulation (Ansoft HFSS, Ver. 8.0. 25.) well explained this minimum without the deembedding technique as shown by the dashed line, which clarified the wave shortening effect by the permittivity of Si.

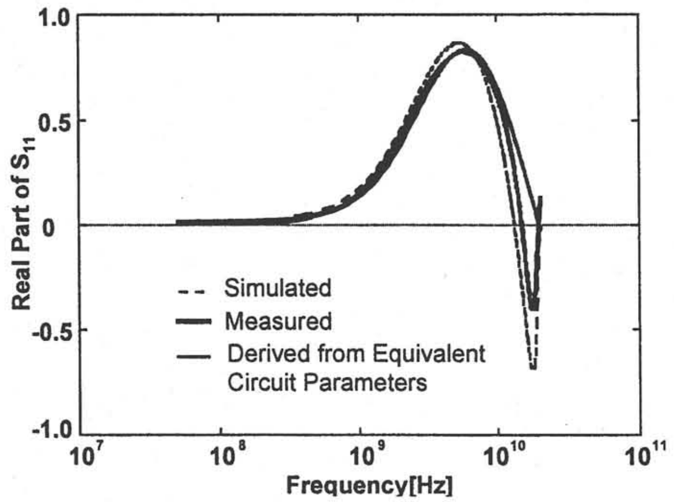


Fig. 4 Measured s_{11} parameter of the air core spiral.

Table I Effect of ferromagnetic material at 150MHz.

Device structure	Ls+Lm	Rs+Rm
Without ferromagnetic material	7.38 nH	3.84 Ω
With ferromagnetic material	8.19 nH	3.83 Ω

Ferromagnetic inductor was also applied for the 3D FEM simulation. Table I shows the simulated L_s+L_m and R_s+R_m values. The magnetic layer thickness is 0.1μm, width is 21μm, spacing is 1μm, resistivity is 120 μΩcm, real part of permeability along width direction is 1000 and along other directions is 1, and imaginary part is 0 in all direction, respectively. This simulation can be compared with low frequency measurements because the loss term of the permeability is neglected. At 150MHz, the measured inductance was 7.9nH, which is closely to the simulated value as shown in Table I.

4. Conclusions

Equivalent circuit analysis of RF integrated inductors with/without magnetic materials are demonstrated in the GHz frequency range. Effectiveness of FEM simulation is also demonstrated, which leads to optimum design of the inductors..

Acknowledgments

A part of this work is supported by the Grant-In-Aid for Scientific Research, No. 12305025 and No. 13025202.

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