

Electromagnetic Coupling Effects in RFCMOS Circuits

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Abstract: The electromagnetic isolation and coupling characteristics of basic structures, namely metal pads, spiral inductors, and spiral-transistors, implemented in a core-logic CMOS process are evaluated and modeled. The models provide design guidelines on the isolation characteristics of guard-rings and shield layers for RF cross-talk suppression between circuit blocks. The importance of electromagnetic coupling to layout interconnects is demonstrated.

I. INTRODUCTION

Integration of RF transceiver circuits in core CMOS process is actively pursued [1] in an effort to increase functionality and reduce cost. In mixed mode Logic-RF IC's digital switching noise coupled through the substrate, as well as electromagnetic coupling (EMC) between RF circuit blocks is a concern, and several papers have reported these effects [2, 3]. However, solutions have been proposed like the use of deep trenches [2], or the use of SOI substrate [4], which are not compatible with standard CMOS.

In this work, the measured and modeled RF interaction characteristics of basic structures, namely metal pads, spiral inductors, and spiral-transistors, implemented in a core-logic CMOS process are evaluated. Furthermore, the effects of shielding layers (P+ diffusion) and guard rings are presented. These simple test structures give insight in the coupling mechanisms and allow the derivation of guidelines to reduce EMC effects.

The experimental evaluation was conducted on a standard 0.25 μ m, 4-level Metal, logic-CMOS process on 10 Ω .cm p-type bulk wafers. The process features standard twin-wells and Shallow Trench Isolation.

II. PADS CAPACITIVE COUPLING

The simplest EM couplings to the substrate are due to capacitive interaction of metal pads or metal

interconnects and injection by well ties and pn diffusions. Fig.1 shows the metal pad-to-pad structures and the measured magnitude of coupling S_{21} versus frequency. The pad spacing and size are 100 μ m and 100 μ m x 100 μ m, respectively. The metal pad is coupled to the substrate capacitively. These effects can be well modeled by the equivalent circuit shown in Fig.2, where C_o 's are the ILD capacitances, R_p , C_p are the substrate resistance and capacitance to ground, and R_c , C_c are the substrate lateral coupling resistance and capacitance, respectively. The guard ring and the P+ grounded layer underneath the pad modify the substrate resistances R_p . In Fig.1, using different metal stacks varied the ILD capacitance effect. Using a P+ grounded shield underneath the pad or a P+ guard ring are the most effective ways to suppress coupling. At 2GHz, ~-17dB reduction in S_{21} is achieved by the P+ grounded shield layer, as compared with the non-shielded pad. As the model shows, the guard ring and shielding layers act reducing EMC by shorting out the substrate resistances R_p . The extracted R_p values are 50 Ω , 12 Ω and 5 Ω for the reference, the P+ guard ring and the P+ grounded shield, respectively.

III. SPIRAL-TO-SPIRAL COUPLING

Planar spiral inductors occupy a large Si area and are widely used in RF circuits. The EMC of planar spiral inductors must be modeled to determine the effect on gain and reverse isolation of amplifiers [3], as well as between large signal circuit blocks (output amp) and sensitive Low-Noise Amplifiers (LNA).

The spiral coupling was studied using the patterns in Fig.3. The spiral inductors are 100 μ m separated and have a length of 3810 μ m, $L=6.3$ nH, with metal width and spacing of 15 μ m and 5 μ m, respectively. The isolation effects of (1) a grounded P+ diffusion-top metal barrier in between the inductors and (2) Salicided P+ grounded shield underneath one of the

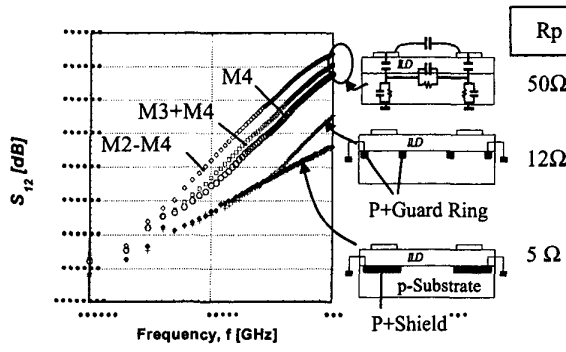


Fig.1: EM coupling S_{12} between metal pads and the effect of guard rings and P+ grounded shields. The extracted substrate resistances R_p are indicated.

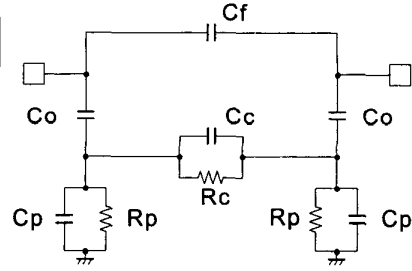


Fig.2: Equivalent circuit model for metal pad structures in Fig.1. The guard rings and P+ shield layers affect the substrate resistances R_{p1} , R_{p2} and R_c .

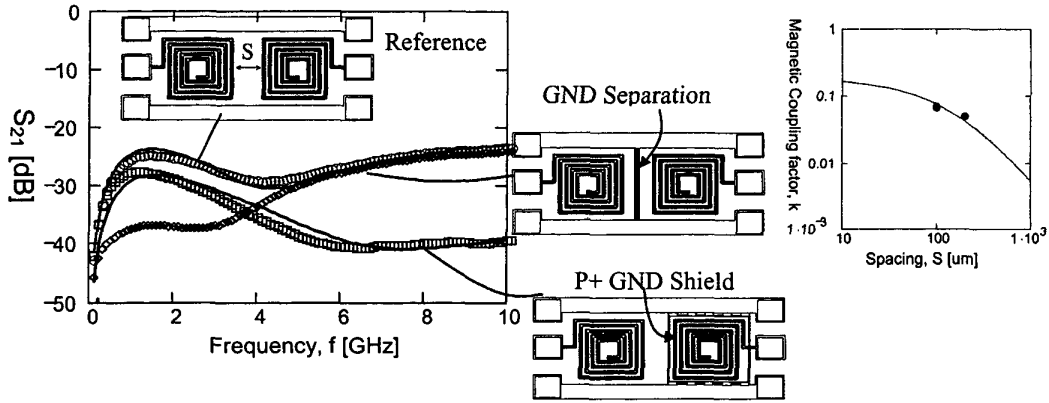


Fig.3: Measured (symbols) and model calculated (lines) magnetic coupling k and S_{21} for EM coupling between planar spiral inductors on bulk-Si 10Ω.cm p-substrate. The spirals spacing is $S=100\mu\text{m}$. The GND separation is a P+ grounded diffusion-Top metal barrier between the spirals. The P+GND shield is a salicided P+ diffusion layer underneath the right-side spiral.

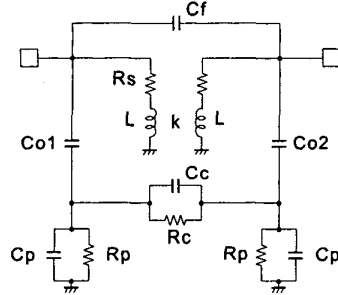


Fig.4: Equivalent circuit for Spiral-to-Spiral coupling.

Table I: Model Parameters Extracted for Spirals Coupling

Parameter	Unit	Reference	GND Separation	P+GND Shield
L	nH	6.3	←	←
Rs	Ω	8	←	←
k		0.07	0.015	0.04
Rp1	Ω	29	28	25
Rp2	Ω	29	28	3
Cp	fF	200	←	←
Rc	Ω	73	110	73
Cc	fF	10	1	10
Co	fF	320	←	←
Cf	fF	20	←	←

inductors were evaluated to gain insight into the coupling mechanisms. Fig.4 shows the proposed circuit model to analyze the EMC. In Fig.3, the measured (symbols) and calculated (lines) frequency response of S_{21} for the three structures, and the magnetic coupling factor k for the reference pair of spirals are reported. Good agreement is observed between the model results and measurements. The model parameters are summarized in Table I. A maximum S_{21} of ~ 25 dB is observed at 1.5 GHz for the reference pattern. At low frequencies, magnetic coupling (k) dominates spiral isolation. The grounded P+ diffusion-top metal separation effectively reduces S_{21} to ~ 37 dB at 1.5GHz. At high frequencies, the substrate coupling resistance (R_c) is dominant, however, a grounded shield underneath the spiral completely shorts out the coupling to $S_{21} = -40$ dB.

From the model and the experimental results, the effectiveness of each structure can be assessed.

IV. SPIRAL-TO-TRANSISTOR COUPLING

Due to its large area, the spiral inductor can couple significant EM energy not only to other spirals but also to sensitive transistors. Fig.5 shows the new test structure proposed to evaluate this effect. This structure is used to emulate the situation that might arise, for example, in the interference between the transmitter and receiver paths of a RF transceiver. Fig.6 illustrates the measured S_{21} at the transistor's drain terminal, and with bias current as parameter. The general shape of S_{12} -vs- f is similar to that for the spiral-spiral coupling structure. An equivalent circuit is proposed in the Fig.7.

The magnetic coupling between the spiral and the layout parasitics of the transistor, especially the gate bias interconnect line, can be studied using the equivalent circuit model. When the substrate coupling is neglected ($R_p=0$, $C_c=0$, $R_c \rightarrow \infty$),

$$\begin{aligned} |S_{21}(\omega)| &\cong 2 g_m M \omega & \omega \rightarrow 0, \\ |S_{21}(\omega)| &\cong \frac{2 g_m M}{\omega^3 L_1 L_2 C_g (C_o + C_{gd})} & \omega \rightarrow \infty \end{aligned} \quad (1)$$

where L_1 , L_2 and $M = k \sqrt{L_1 L_2}$ are the spiral inductor, gate line parasitic inductance, and the mutual inductance, respectively, and g_m is the

transistor transconductance. The coupling coefficient is $k \sim 0.05$ as estimated from layout. At low frequencies, the S_{21} increases due to the magnetic coupling, and the amplification action of the transistor. As frequency increases S_{21} decreases since the gate capacitance of the transistor, C_g , shorts the coupling to ground. As a result of the two behaviors described by (1), a peak is seen in the S_{21} characteristic. At further high frequencies, the substrate-coupling path becomes dominant. The substrate capacitively and resistively couples the interference to the interconnect lines, the back gate of the transistor, and the drain-substrate capacitance of the transistor.

These results clearly show how the transistor action amplifies the coupled interference which results in $S_{21} \sim 20$ dB at 1.5GHz, i.e. stronger effect than in the passive spiral-spiral coupling of Fig.3. When the transistor is OFF ($I_d=0$ mA curve), the capacitive coupling to the substrate (C_o , C_{db}) and transmission through the substrate (R_c , C_c) are similar to the effect reported in Fig.1 for the metal pads EMC. This test structure demonstrates the importance of modeling EMC effects between passive components; interconnect lines, and active circuits.

V. CONCLUSION

Characterization and analysis of the EMC effects of basic structures (metal pads, spiral-spiral and spiral-to-transistor), implemented on a standard logic CMOS process on p-type bulk wafers, were described. Compared with previous reports, a comprehensive equivalent circuit modeling was introduced and validated with measured data. The effect and effectiveness of different guard rings, and P+ grounded shield layers were also studied. From these results, it is observed that not only the substrate, but also the electromagnetic coupling to layout interconnect must be considered in the characterization and minimization of EMC at radio frequencies.

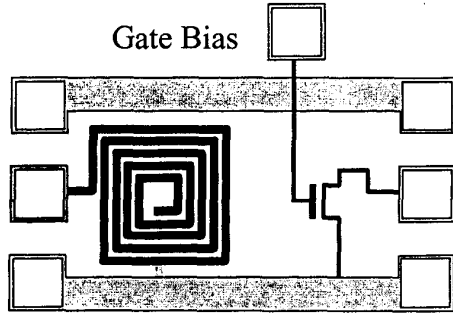


Fig.5: Test pattern to evaluate Spiral-Transistor EM coupling. Transistor: $L=0.25\mu\text{m}$, $W=60$ fingers $\times$ $5\mu\text{m}$.

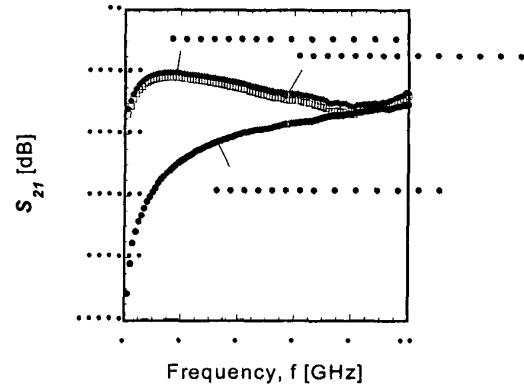


Fig.6: Measured coupling S_{21} of the Spiral-Transistor structure at different bias conditions.

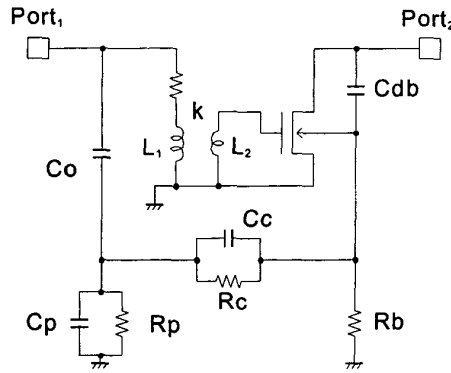


Fig.7: Proposed equivalent circuit of the Spiral-Transistor coupling.

L_1 : Planar spiral inductance, L_2 : parasitic inductance of the gate bias line, k : magnetic coupling factor, R_b : Transistor equivalent body resistance, C_{db} : transistor drain-substrate junction capacitance. C_o : Spiral to substrate (ILD) capacitance, R_p , C_p : substrate resistance and capacitance to ground, respectively, R_c , C_c : substrate coupling resistance and capacitance, respectively.

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