

# On-Chip Spiral Inductors with Patterned Ground Shields for Si-Based RF IC's

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## Abstract

This paper presents a novel on-chip inductor with a patterned ground shield inserted between the spiral inductor and the silicon substrate. Experimental results show that the ground shield effectively decouples the spiral inductor from the lossy silicon substrate. The new design improves the quality factor by 25% and reduces the substrate coupling between inductors up to 25 dB over those without the ground shields.

## Introduction

High quality on-chip inductors are essential to monolithic integration of RF circuits in silicon [1]. Degradation of the quality factor,  $Q$ , due to substrate effects has been studied [2]. In addition, the problem of signal coupling via the substrate in RF circuits has been reported [3]. As inductors occupy substantial area, it is critical to suppress the coupling between the inductors and the substrate. Physically, both problems stem from energy loss to the substrate as the electric field penetrates into the silicon, especially at above GHz frequencies. Therefore, an appropriate shielding technique can be the potential solution.

To reduce energy loss, the inductor's electric field must be terminated before reaching the silicon substrate. A conductive ground shield (GS) between the inductor and the substrate can achieve this effect. However, the image current induced by the magnetic field in the conductive ground shield will flow in a direction opposite to that of the current in the spiral. The negative self-inductance will then lead to a significant drop in the total inductance and hence  $Q$ . In this work, we have explored two alternative ground shields: (a) a resistive ground shield and (b) a patterned ground shield.

## Experimental

Fig. 1 shows the three types of inductors studied in this work: (a) no ground shield (NGS), (b) solid ground shield (SGS), and (c) patterned ground shield (PGS). Note that the slots in the PGS are orthogonal to the direction of current flow in the spiral. Such a pattern prevents the build up of image current. To study the effect of GS resistance, aluminum ( $64 \text{ m}\Omega/\square$ ) and polysilicon ( $12 \text{ }\Omega/\square$ ) were used. The polysilicon was chosen to be similar to that of MOSFET gates. The 8-nH inductors were fabricated on 10 to 20  $\Omega$ -cm silicon substrate with standard technology. Two-port S-parameters were measured using an HP8720B Network Analyzer and Cascade Microtech coplanar ground-signal-ground probes. The effectiveness of GS's for isolation was measured in terms of crosstalk between two electrically isolated inductors using the test structure shown in Fig. 2.

## Results and Discussion

### A. Improvement in $Q$

Fig. 3 and Fig. 4 show the effects of various GS's on  $Q$ . In

both figures, two sets of substrates, 11 and 19  $\Omega$ -cm, are included for comparison. In Fig. 3, the inductor with Al SGS has the lowest  $Q$  because of its lowest inductance. The conductive SGS allows the image current to flow and the negative mutual coupling between the spiral and SGS reduces the inductance from the designed 8 nH to 2 nH. The Al PGS successfully recovers most of the inductance, proving the effectiveness of the pattern. In Fig. 4, the 12- $\Omega/\square$  polysilicon SGS yields a  $Q$  similar to those of the NGS cases indicating that it is resistive enough to prevent most of the image current from flowing. Finally, the polysilicon PGS, which combines the appropriate sheet resistance and pattern, yields the most improvement in  $Q$  (25%) at the frequencies (1 to 2 GHz) of interest. The inclusion of a GS increases the inductor's parasitic capacitance which causes a reduction in the self-resonant frequency (i.e. when  $Q = 0$ ).

### B. Substrate Coupling Suppression

Substrate coupling between two adjacent inductors was measured by the transmission coefficient,  $S_{21}$ . Fig. 5 shows that the more conductive substrate has a stronger coupling due to its higher admittance. The peaks in  $|S_{21}|$  for the NGS cases correspond to the onset of significant penetration of the electric field into the silicon. In contrast, the inductors with polysilicon PGS's show improved isolation up to 25 dB at GHz frequencies.

### C. Other Advantages

The PGS's offer other benefits:

- Inductor behavior is independent of variations in substrate resistivity and type (e.g. bulk, epi and SOI).
- The inductor behavior is easier to model especially at different temperatures.
- The large silicon area under the inductor can potentially be used for device fabrication.
- For on-chip transformer, the stacking of two inductors separated by a PGS ensures that the primary coupling occurs in the magnetic field.

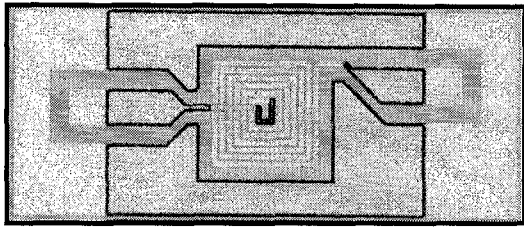
## Conclusions

A novel spiral inductor on silicon with a patterned ground shield has been presented. The effects of ground shield sheet resistance and pattern have been demonstrated. Measured results show that the new design improves  $Q$  and reduces the coupling between the inductors and the silicon substrate. Furthermore, the ground shield can be easily incorporated with no additional process steps.

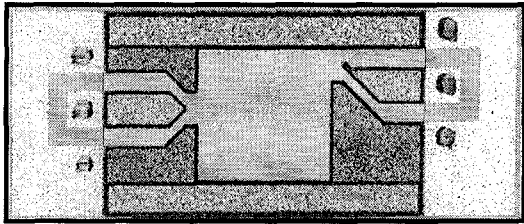
## References

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- [2] C. P. Yue, C. Ryu, J. Lau, T. H. Lee, and S. S. Wong, "A physical model for planar spiral inductors on silicon," *International Electron Devices Meeting Technical Digest*, pp. 155-158, 1996.

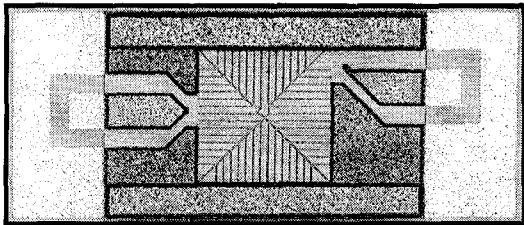
[3] M. Pfost, H. Rein, and T. Holzwarth, "Modeling substrate effects in the design of high speed Si-bipolar IC's," *IEEE Journal of Solid-State Circuits*, vol. 31, no. 10, pp. 1493-1501, Oct. 1996.



(a) Spiral Inductor with No Ground Shield (NGS)



(b) Solid Ground Shield (SGS) (spiral not shown)



(c) Patterned Ground Shield (PGS) (spiral not shown)

Fig. 1 The three types of inductors studied in this work. Each spiral was fabricated using  $2\ \mu\text{m}$  thick top layer aluminum. A  $1\ \mu\text{m}$  thick underpass was used to contact the center of the spiral. The spiral and the ground shield are separated by  $5.2\text{-}\mu\text{m}$  of oxide. The ground shield is separated from the silicon substrate by  $0.4\text{-}\mu\text{m}$  of oxide.

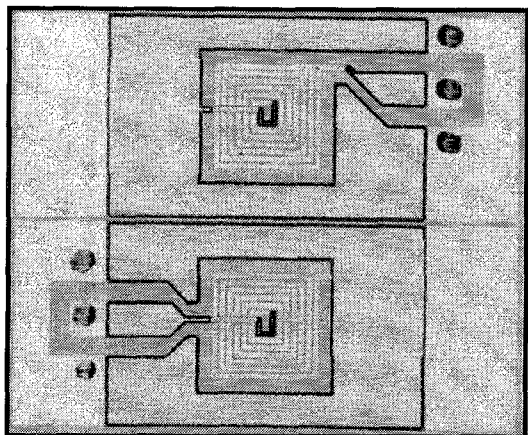


Fig. 2 A two-port test structure for substrate coupling between two adjacent inductors. Each inductor has one end grounded. The ground rings surrounding the inductors are not connected.

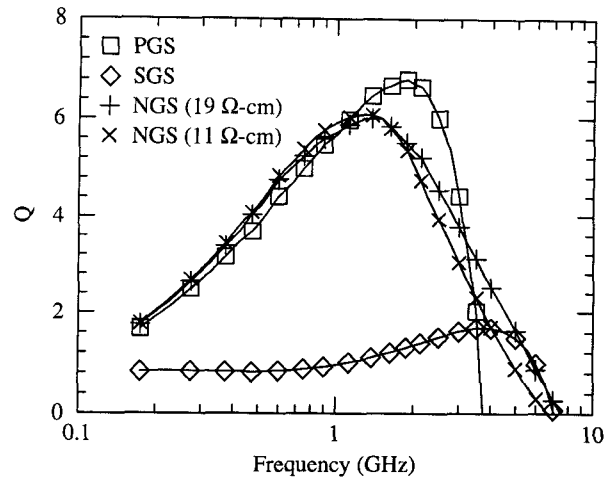


Fig. 3 Effect of aluminum ground shields on Q.

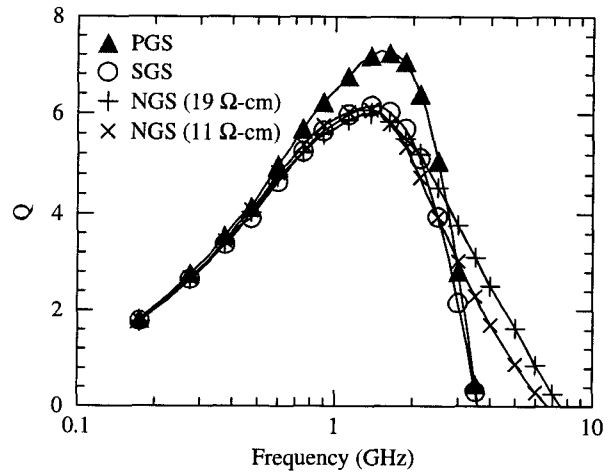


Fig. 4 Effect of polysilicon ground shields on Q.

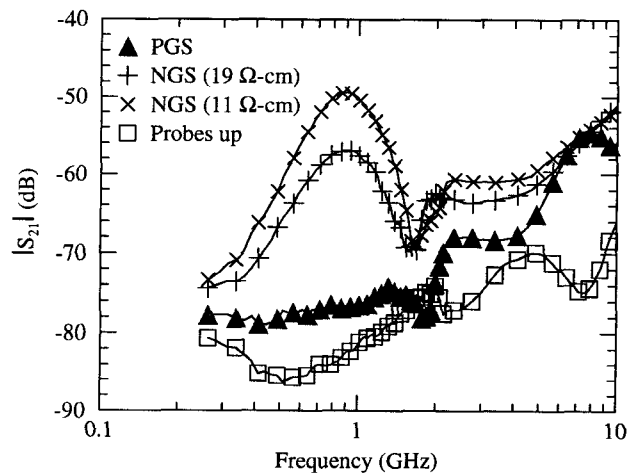


Fig. 5 Effect of polysilicon PGS on substrate coupling between two adjacent inductors. The "Probes up" data represents the intrinsic noise floor of the testing setup.