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Metallization Proximity Studies for Copper Spiral Inductors on Silicon

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Abstract—The impacts of metallization proximity for copper spiral inductors on silicon have been investigated in this paper. Performance of the spiral inductor versus area consumption tradeoff with respect to its core diameter is evaluated quantitatively for the first time. Effects of the inductor's proximate grounded metallization on its overall inductive performance are also analyzed.

Index Terms—Core diameter, eddy-current and series resistance, inductance, quality factor, spiral inductor.

I. INTRODUCTION

THE STRONG growing demands for low-cost RF integrated circuits (ICs) have motivated surging research interest in silicon-based on-chip spiral inductors [1]–[6]. To exploit the full capabilities offered by these monolithic inductors, critical design constraints imposed by the matured silicon technology must be identified and carefully characterized so that accurate inductor models can be developed efficiently. The area occupied by the inductor, which is yet to be quantitatively addressed in the literature, is one such important design constraints. This refers to the design considerations of the inductor's core diameter as well as the proximity of its surrounding metallization.

Most circuit designers will agree that the on-chip spiral inductor is the largest silicon area-consuming device in an integrated circuit meant for radio frequencies operation. In general, the number of spiral inductors employed and their individual sizes predominantly determine the overall chip area of the circuit. Although designing inductors with small core diameter allow cost effective use of the silicon real estate, their performances are believed to suffer inevitably. Hence, in this paper, we will attempt to set up appropriate experiments and together with carefully designed test structures, investigate the performance versus area consumption tradeoffs for inductors with different core diameters and closeness of surrounding grounded metal conductors.

II. TEST STRUCTURES AND EXPERIMENTAL SETUP

To investigate the performance of inductors with different core diameters, very often, spiral inductor test structures are designed with a fixed number of turns and different core diameters.

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The typical quality factor and inductance versus frequency plots for such experimental setup are illustrated in Fig. 1.

From these quality factor plots, it is not possible to conclude which inductor has the best performance since all 3 inductors have completely different inductance values. Therefore, to have a fair common baseline for comparison, the inductor test structures must have similar inductance values with only very small differences from each other. This can be achieved by maintaining the same total conductor length for inductors with different core diameters. Fig. 2 shows the layout of the circular and square inductor test structures with a constant conductor length of 1500 μm . These inductors are designed with core diameters of 25, 50, 100, and 150 μm . They all have constant metal conductor width of 8 μm , their metal-to-metal spacing is 2 μm and the minimum distance between the spiral coils and surrounding grounded metal conductor is 50 μm .

For the second experiment, test structures illustrated in Fig. 3 are used to examine the effects of having grounded metallization close to the spiral inductor. Grounded metal conductors are fabricated at distances starting from 10 to 90 μm in steps of 10 μm , away from the spiral of the inductors to quantify the inductive degradation due to proximate grounded metal lines. 4-turn circular spiral inductors having core diameter of 75 μm , conductor width and metal-to-metal spacing of 8 and 2 μm , respectively, are used for this particular test setup. The inductors used in all the experiments of this paper are fabricated using the current 0.13- μm copper back-end of line process. The spirals of the inductors are constructed using the topmost metal with a thickness of 0.6 μm . 0.5- μm -thick copper lines are used as underpasses to contact the center of the spirals. The dielectric thickness between the spiral and substrate is about 5.0 μm , and the substrate has a sheet resistance of about 8 ohm/sq.

On-wafer device measurements have been carried out using Agilent 8510C Vector Network Analyzer and Cascade Microtech Air Coplanar GSG probes. Two-port S -parameters of the fabricated inductors are measured over the frequency range from 50 MHz to 10.05 GHz. Reverse side of the wafer has been polished to ensure that the substrate is grounded through the testing chuck. Substrate taps near the spiral are included in all ground pads of the 6-pad GSG configuration to ensure that the substrate is indeed effectively grounded. To facilitate the de-embedding process of the open test pad pattern without the inductor, open calibration structures are fabricated close to the devices.

Parasitics of the test structures are accurately de-embedded by subtracting Y -parameters of the open calibration structures from those test structures with the inductors [4]. Quality factor, Q , and inductance, L , of the spiral inductors are subsequently

Fig. 1. Quality factor and inductance plots for 3.5-turn circular inductors with different core diameters.

Fig. 2. Layout of the circular and square inductor test structures with similar total conductor length but different core diameters.

Fig. 3. Layout of circular inductors with different distance of proximate grounded conductors.

extracted from the resultant Y_{11} parameters after the de-embedding procedure. Their expressions are given as

$$Q = -\frac{\text{Imag}[Y_{11}]}{\text{Real}[Y_{11}]} \quad (1)$$

$$L = \frac{1}{\frac{\text{Imag}[Y_{11}]}{2\pi \times \text{Frequency}}} \quad (2)$$

The series resistances, R_{11} and R_{12} , of the inductors are extracted from the resultant Y_{11} and Y_{12} parameters and they can be evaluated using

$$R_{11} = \frac{1}{\text{Real}[Y_{11}]} \quad (3)$$

$$R_{12} = \frac{1}{\text{Real}[Y_{12}]} \quad (4)$$

Fig. 4. Quality factor and inductance plots for circular inductors with 1500- μm conductor length, but different core diameters.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Fig. 4 shows the quality factor and inductance plots for the four circular inductors with different core diameters. It can be seen that because these inductor test structures have identical total conductor length and width (i.e., same conductor area), their extracted inductance values are comparable. When the inductance values are examined closely, small variations of not more than 5.7% (0.19 nH) are observed even though the mutual coupling effects between the coils in these inductors are quite different. With that, meaningful conclusions on the performance of these inductors can therefore be drawn with respect to the sizes of their core diameters.

A significant improvement of more than 33% in quality factor is noted when the inductor's core diameter increases from 25 to 100 μm . This phenomenon has been observed for all the inductors displaying the same peak quality factor frequency of 2.9 GHz. Since all the extracted inductance values are very close to each other, the massive enhancement in quality factor can be said to be primarily due to the fact that the conductor eddy current generated in the inner turns gradually reduces when the inductor's core diameter increases. With reference to Fig. 5, the following paragraph will further discuss the formation and effects of the conductor eddy currents.

The circular inductor shown in Fig. 5 carries a current I_{spiral} , which flows in the direction as indicated, generating an associated magnetic field B_{spiral} , that has a maximum intensity at the center of the spiral. For the case of a large inductor with a very small core diameter, an enormous part of this magnetic field does not pass through the center of the spiral but rather through its inner turns. In accordance to Faraday and Lenz's laws, an

Fig. 5. Formation of conductor eddy currents.

electric field is magnetically induced in these inner turns, generating circular eddy currents, I_{eddy} , which flow in the direction opposing the original change in magnetic field. The magnitude of this induced electric field is proportional to the derivative of $B(t)$ with respect to time suggesting this effect to be very significant at high frequencies. Such eddy currents cause a nonuniform current flow in the inner turns of the spiral. On the inner side of the conductor for the inner turns, the inductor current, I_{spiral} and eddy current, I_{eddy} flow in the same direction. The outer side, however, has a very low current density because these two currents are in opposing directions. The magnitude of these eddy currents is comparable to the spiral current at high frequencies, thereby increasing the series resistance of the inductor, which will in turn reduce its quality factor [7].

Figs. 6 and 7 illustrate the series resistance plots of the circular inductors extracted from both the resultant Y_{11} and Y_{12} parameters respectively, after the pad de-embedding procedure.

Fig. 6. Quality factor and resistance (Y_{11} parameter extraction) plots for circular inductors with 1500-μm conductor length, but different core diameters.

Fig. 7. Quality factor and resistance (Y_{12} parameter extraction) plots for circular inductors with 1500-μm conductor length, but different core diameters.

Fig. 8. Peak quality factor versus inductor core diameter at 2.90 GHz and total area occupied by the inductors.

Both series resistance plots extracted from Y_{11} and Y_{12} parameters are shown in this paper because Y_{11} reflects the behavior of the whole inductor, which includes the substrate effects. Y_{12} parameter, on the contrary, does not take into account the effects of the silicon substrate.

At low frequencies, the series resistances of the 4 circular inductors are similar since they have identical total conductor length. However, at high frequencies, both series resistances in Figs. 6 and 7 decrease as the core diameter increases. This suggests that the conductor eddy current effect has been reduced when a sufficiently large core diameter for the inductor is used, leading to an improvement in the quality factor.

Nevertheless, in Fig. 4, the quality factor improvement ceases to sustain when the core diameter is further increased to 150 μm . At the peak quality factor frequency of 2.9 GHz, the difference in quality factor between inductors with diameters of 100 μm and 150 μm is about 1.54%. This is observed because above 100 μm , smaller reductions in conductor eddy-current effects are no longer helpful as series resistance decreases in a much smaller magnitude (5.06%) when the diameter increases from 100 to 150 μm (See Fig. 7). In addition, as diameter increases, there is a 5.70% decrease in inductance, which is likely due to lesser mutual coupling effects between the coils for the inductor with 150- μm diameter. Overall, the decrease in series resistance has been offset by this small reduction in inductance. These results have shown that indeed, there is some important tradeoff in performance when deciding an appropriate inner diameter for these silicon-based on-chip inductors. The performance versus area-consumption tradeoff is finally summarized in Fig. 8, showing the peak quality factor versus core diameter plot at 2.90 GHz as well as the total area occupied by the inductors.

For the case of square inductors, the same conductor length (1500 μm), width (8 μm) and metal spacing (2 μm) have been used. Similar conductor eddy-current effects have been reduced when inductors are designed with large core diameters. Nevertheless, they generally exhibit poorer performance when compared to their circular counterparts because of the fact that the numerous sharp corners in square inductors introduce undesirable crowding series resistance, which degrades the quality factor of the inductor significantly. Even at low frequencies, it can be observed that square inductors have much higher series resistances compared to circular inductors.

All these results are shown in Fig. 9, which consolidates the performance comparison plots of the circular and square inductors with core diameters of 25 and 100 μm . Higher quality factor values for the circular and square inductors with 100 μm core diameter as compared to the ones with 25 μm could be attributed to the fact that the conductor eddy current is a more dominant performance degradation factor for inductors with small core diameter.

In the second part of the experiment, we focus on studying how the closeness of surrounding grounded metallization affects the performance of spiral inductors. The test structures used have already been summarized in Fig. 3. Fig. 10 compares the quality factor and inductance plots of the inductors with distance of the surrounding ground metal lines increasing progressively. Fig. 11 on the other hand compares the series resistance and provides an enlarged view of the quality factor for the same inductors.

The extracted inductances and series resistances for the inductors with different metallization distance are quite close with a maximum difference of 4.1% and 4.92%, respectively. The

Fig. 9. Quality factor and resistance (Y_{11} parameter extraction) plots for circular versus square inductors with 1500- μm conductor length but different core diameters.

Fig. 10. Quality factor and inductance plots for circular inductors with different closeness of surrounding grounded metallization.

quality factor, on the other hand, for a metallization proximity distance of 10 μm as opposed to that of 90 μm is calculated to

have an improvement of about 2%. From these results, it can be shown that grounded conductors only have small impact on

Fig. 11. Quality factor (enlarge view) and series resistance plots for circular inductors with different closeness of surrounding grounded metallization.

the overall performance of spiral inductors when the distance is fairly small ($>10 \mu\text{m}$).

IV. CONCLUSION

This paper has presented results of quantitative studies on the proximity of metal conductors for copper spiral inductors. It reveals the performance versus silicon area consumption tradeoffs for inductors with different core diameters. Significant improvement in quality factor has been achieved when an optimized large core diameter is used. More importantly, using a core diameter that is too large may not yield any further significant improvement in the quality factor, but only waste expensive chip area.

The effect of surrounding metallization closeness on the inductor's performance is also evaluated. A 2% improvement is observed when the surrounding metal distance to the spiral is increased from 10 to $90 \mu\text{m}$. This paper has suggested new test structures design techniques that might gives useful insights and hints to both device modeling engineers and RF ICs circuit designers, when they drive toward the goal of achieving optimal high-performance inductor design with cost effective use of silicon chip area.

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