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Analysis on Square and Circular Inductor for a High Q-Factor Inductor

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ABSTRACT

This paper presents the high-quality (Q) factor inductors using Silicon-on-sapphire (SOS) for the 10GHz to 20GHz frequency band. Inductors are designed on SOS because of their advantages, including high resistivity and low parasitic capacitance. This paper compares square and circular inductor topologies for high-quality (Q) factor inductors using HFSS software for the high-frequency band. Both inductors have been designed with the same width and thickness to make them comparable with each other. The comparison shows that a circular inductor achieves the highest Q-factor. Furthermore, the circular and square inductor's Q-factor, inductance, and resistance are analyzed. As a result, the circular inductor has the maximum Q-factor of 89.34 at 10.6GHz for 0.29nH, while the square inductor has obtained a maximum Q-factor of 80.72 at 10GHz for 0.40nH inductance.

Keywords: High Q-Factor Inductor, Silicon-on-Sapphire (SOS), HFSS Software

1. INTRODUCTION

The quality factor, Q, is one of the essential features of an inductor on a silicon substrate. The techniques utilized to improve the Q-factor of inductors on a Si substrate can be divided into four groups. These are based on trace layout, trace metal characteristics, a high resistivity substrate, and a substrate shield[1].

According to Shakshi Mishra et al., the curve length phenomena are introduced because the design has been adjusted based on the curve length, and it is a good combination for square and circular spiral inductors [2]. However, in 2018, K. Subramani et al. in which they described spiral inductors particularly, suffer from significant losses in the silicon substrate. Therefore, higher substrate resistivity can counter this main obstacle in restricting the Q-factor of spiral inductors [3]. Moreover, the Q-factor, which is a significant emphasis in the design of the spiral inductor, is affected by the geometry parameters of an inductor because the performance of a spiral inductor is determined by the number of windings, ring width, the gap between windings, and inner diameter [3].

Furthermore, inductance, Q-factor, and self-resonance frequency (SRF) are three significant figures of merit that characterize spiral inductors [4]. The width of a conductor (W), spacing between turns (S), the number of turns (n), outer diameter (Dout), and inner diameter (Din) are the specified physical characteristics that influence the inductance value and Q-factor of the inductor [4].

In an inductor analysis, B Murali et al. found that the inductor that split each turn into two half turns and placed in two distinct layers can improve the Q-factor and inductance [5]. Previous research also proposed a multi-layer spiral inductor whose Q-factor could improve at all frequencies compared to the planar spiral inductor [6].

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Conventionally, inductor design in HFSS software is Differential Series Stacked Inductor, which has a greater inductance value due to increased conductor length and a higher Q-factor due to lower series resistance than standard differential inductor [7].

2. INDUCTOR DESIGN

The square and circular inductors are designed using HFSS simulation software, illustrated in Figure 1. The process starts with developing the SOS substrate by depositing a 0.6µm thin silicon layer onto the sapphire (Al2O3). A high-resistivity sapphire substrate was used to minimise substrate losses and eddy currents. The next step in the design is to oxidize the silicon, which provides an insulating layer. After that, the passivation layer is deposited and retained beneath the inductor area to protect the internal semiconductor devices after the completion of metallization. The inductor was designed with a passivation layer of relative permittivity of 7.9 and thickness of 0.7µm. Finally, the first metal layer is deposited on the SOS substrate to form the underpass of the inductor, which connects the inductor with other active and passive components in the circuit.

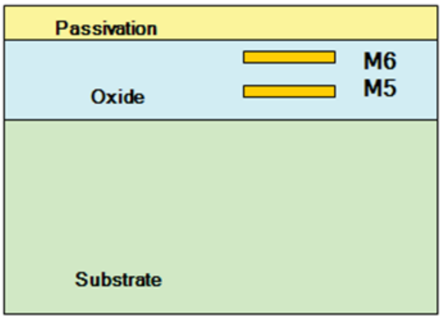
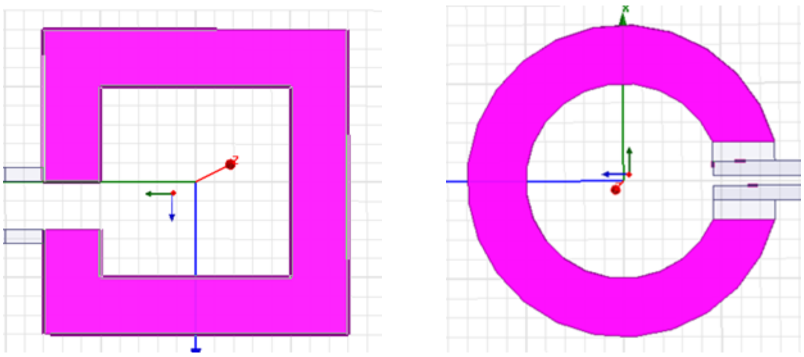


Figure 1. Design Process for the inductor

Figures 2 (a) and (b) show the complete design for circular and square inductors. Geometrical parameters such as the width of metal (W), the thickness of metal (T), and outer diameter (OD) are fixed for both inductors to analyse the Q-factor, inductance, and resistance. The width and thickness of inductors are fixed to 60µm and 15µm, respectively. The physical return path that connects the terminal called a ring must be created for the inductor [8].



(a) (b)

Figure 2. (a)Square Inductor (b) Circular Inductor

3. INDUCTOR RESULT

This work focuses on the high Q-factor of inductors for square and circular inductors. Therefore, the effective quality factor, Qeff, in this work is simulated based on the given Equation (1), describing the degree to which an inductor deviates from an ideal component in microwave circuits where the inductors are operated much below the self-resonance frequency [1].

$$Qeff = \omega L/R \tag{1}$$

Where,
Q = Quality Factor
$\omega = 2\pi f$
R = Resistance

In this section, simulations have been done in three subsections for Q-factor, resistance, and inductance. The highest possible Q-factor and resonance frequency (fres) in the lowest possible area is ideal for a given inductance value. However, changing the width and the inner diameter of an inductor influences its area, making it impossible to establish a proper comparison. The following Equation (2) is the figure of merit of an inductor (FOM) is defined [9]. The proposed design aims to improve the performance of an inductor for wireless applications. Therefore, FOM could be a useful formula to see how effective the optimum size of the inductor is for an application.

$$FOM = \frac{L(nH).Q_{max}}{A(mm^2)} \tag{2}$$

3.1 Q-Factor of Inductor

The simulation of square and circular inductors was performed to see the difference of Q-factor between both inductors. The outer diameter of a circular and square inductor is fixed to 320μm. Figure 3 illustrates the Q-factor for both circular and square inductors.

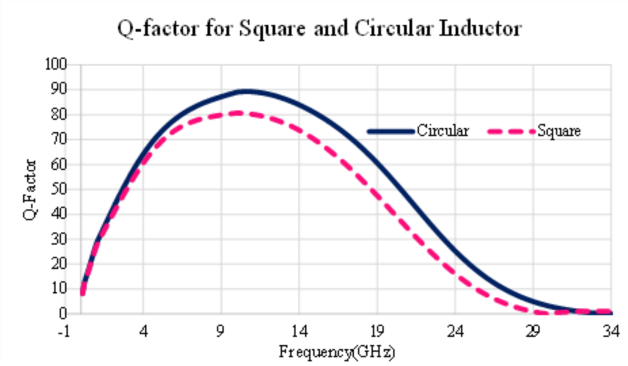


Figure 3. Q-factor for Square and Circular Inductor

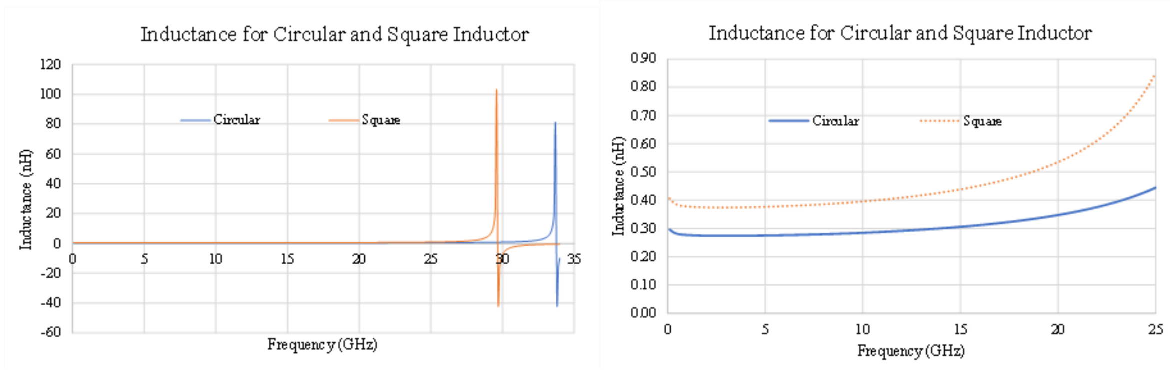
The graph shows that the circular inductor has the highest Q-Factor, with a Qmax of 89.34 at 10.6GHz, while a square inductor has a Qmax of 80.72 at 10GHz. Table 1 shows the results of Qmax for both inductors. The result shows that the inductor with circular topologies has increased the Q-factor by 10.13% compared to the square inductor. This matches previous research, stating that circular spiral inductors are most efficient since they require an infinite angle step [3]. Note that the inner diameter should be about 40% of the outer diameter as a guideline to design a high Q-factor inductor [10].

Table 1 Summary of Q-factor for circular and square inductor

Inductors	Frequency [GHz] @ Q_{max}	Q-factor
Circular	10.60	89.34
Square	10.00	80.72

3.2 Effect of Inductance

Figures 4 (a) and (b) reveal that the simulation result of inductor operation varies with frequency. Additional result for inductance at Qmax is tabulated in Table 2. The result shows that the inductance value for square topology at Qmax is 0.40nH, while circular is 0.29nH.



(a) (b)

Figure 4. Inductance for Square and Circular Inductor

The functional operational region for the inductor is from 0 to 27GHz, as shown in Figure 4 (a), whereas after 27GHz, the inductance value changes when frequency increases, and in other frequencies, the inductance values become negative and behave like capacitive. Moreover, the useful frequency range of the inductor and Self-Resonant Frequency (SRF) marks the point where the inductor turns capacitive, and obviously, the larger the capacitive range, the lower the SRF and Q-factor of the inductor [11]. Therefore, the inductor's SRF and Q-factor decrease as the capacitive range increase.

Table 2 Summary of inductance for circular and square inductor

Inductor	Frequency (GHz) @ Q_{max}	Inductance (nH)
Circular	10.60	0.29
Square	10.00	0.40

The inductance value for inductor also has affected by the impact of magnetic energy storage in an electrical circuit, where it is represented by an inductance L, which is described in terms of magnetic flux ψ, and by derivation of inductance L. Theoretically, inductance can be derived in the term of the area by [12] in Equation (3).

$$L = \mu_0 \, nNA \tag{3}$$

Where,
L = Self-Inductance
μ_0 = Absolute Magnetic Permeability
n = Number of turns of solenoid per Length of Solenoid
A = Area of the Solenoid

The relationship between inductance and area is strictly proportional, according to Equation (3). Therefore, the higher the inductor area, the wider the inductor, resulting in a high number value of inductance. But in the circular inductor, the shortest length inductor has been designed to reduce the resistance [11]. Furthermore, by optimizing the width, resistance can be further minimized [11]. Figure 4(b) shows that the inductance value decrease as the length increase.

3.3 Resistance of Inductor

Figure 5 shows the simulated results of the circular and square inductor on resistance. Additional result for resistance at Qmax is tabulated in Table 3. The resistance of both inductors was calculated by rearranging the Equation (1). The result demonstrates that the circular inductor has lower resistance than the square inductor, by the percentage difference calculated for both inductors is 36.01%. The reason is that the entire length of the conductor strip in the coil is precisely proportional to the resistance, as stated by Equation (2) [9]. On the other hand, the square inductor has the edge indicating the current direction enhances current crowding and near the edges of the inductor, causing an increase in line resistance. But the circular form inductor has less resistive loss than the other shapes, leading to a high-Q- factor due to the lack of sharp points [12].

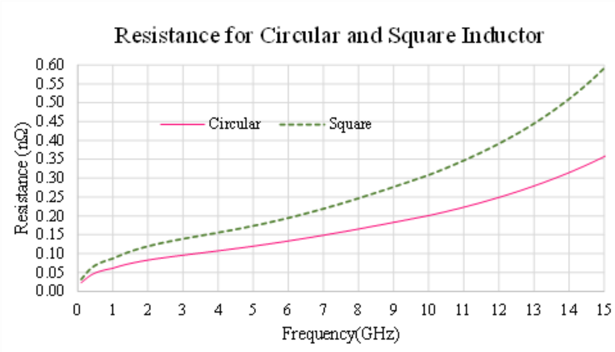


Figure 5. Effect of Square and Circular Inductor to the Resistance

Table 3 Summary of resistance value for circular and square inductor

Inductor	Frequency (GHz) @ Qmax	Resistance (nΩ)
Circular	10.60	0.214
Square	10.00	0.308

4. CONCLUSION

Table 4 shows the summary of the simulation result for both inductors from this work. In comparison, a circular inductor from this work has a high Q-factor compared with the square inductor.

Table 4 Summary of comparison result between square and circular inductor

Parameters	Square	Circular
Width, W(um)	60	60
Thickness, T (um)	15	15
Outer Diameter (um)	320	320
Qmax	80.72 @ 10GHz	89.34 @ 10.6GHz
L (nH) @ Qmax	0.40	0.287
Q @ 12GHz	78.86	88.33
L (nH) @ 12GHz	0.41	0.29

R (nΩ) @ Qmax / 12GHz	0.31 / 0.39	0.21 / 0.25

Moreover, Table 5 shows the comparison between the previous work with this work. The Q-factor from this work is higher when compared to previous work as it is proved that circular topology inductors with appropriate design offer the highest Q-factor.

Table 5 Summary of comparison of previous and current work

Parameters	**[2]**	**[4]**	**[13]**	**Current Work**
Type	Circular Inductor	Circular Inductor	Circular Inductor	Circular Inductor
Qmax @ Hz	16.749 @ 44GHz	≈ 30 @ ≈1000MHz	42.8 @ 26.56GHz	89.34 @ 10.6GHz
Metal Width	4μm	-	20μm	60 μm Cu
Metal Thickness (μm)	-	-	20μm	15μm Cu
Outer Diameter/inner diameter	-	5mil to 10mil of inner diameter	200μm/40μm	320μm of outer diameter
L(nH)	13.5	≈ 16nH for 5turns of circular spiral inductor	0.61nH	0.21

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