Surface Micromachined Solenoid On-Si and On-Glass Inductors for RF Applications

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***Abstract*—RF performance of surface micromachined solenoid on-chip inductors fabricated on a standard silicon substrate (10 $\Omega\cdot$ cm) has been investigated and the results are compared with the same inductors on glass. The solenoid inductor on Si with a 15-μm thick insulating layer achieves peak quality ($Q-$) factor of 16.7 at 2.4 GHz with inductance of 2.67 nH. This peak Q-factor is about two-thirds of that of the same inductor fabricated on glass. The highest performance has been obtained from the narrowest-pitched on-glass inductor, which shows inductance of 2.3 nH, peak Q-factor of 25.1 at 8.4 GHz, and spatial inductance density of 30 nH/mm^2. Both on-Si and on-glass inductors have been modeled by lumped circuits, and the geometrical dependence of the inductance and Q-factor have been investigated as well.**

***Index Terms*— High Q, integrated inductor, micromachining, on-chip solenoid inductor, RF MEMS.**

I. Introduction

An on-chip inductor is the last passive monolithic component that still needs active research for the improvement of its performance such as accurate inductance with small device area, high-quality (Q-) factor, and high peak-Q frequency. Although discrete inductors are fabricated as a solenoid type, on-chip inductors are usually fabricated as planar types such as meander or commonly spiral type since the three-dimensional (3-D) structure of the solenoid is difficult to realize by the conventional integrated circuits (IC) technology. For high-performance on-Si spiral inductors, reduction of substrate loss and metal resistance have been the key areas for improvement. For reducing the substrate loss, various methods have been reported such as use of a high resistivity substrate [1], etching the substrate underneath inductors [2], or insulating the inductors from the substrate using a thick polyimide [3], an oxidized porous silicon (OPS) layer [4], and high-dose proton beams [5]. For reducing the metal resistance, thick gold metallization [1], multiple metal layers in parallel [6], or copper metallization [7] have been reported.

Recently, solenoid on-chip inductors have been proposed as an alternative solution for high-performance inductors using 3-D laser lithography [8] or several micromachining technologies [9]–[11] to minimize both parasitic capacitive coupling to the substrate and inductor area. In our previous works, we proposed a novel method for fabricating monolithic solenoid inductors using simple surface micromachining [10] and investigated the RF performance of the solenoid inductors fabricated only on glass [11].

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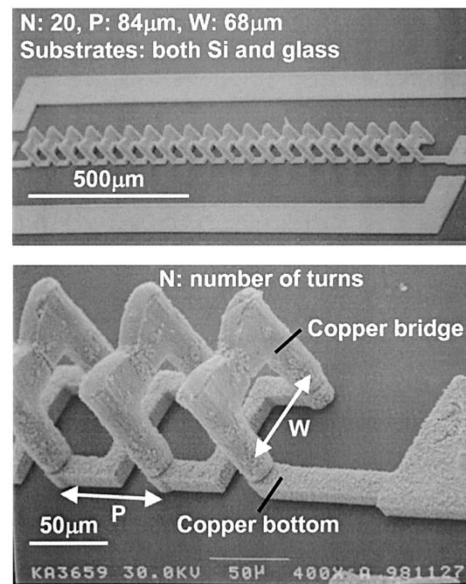

Fig. 1. SEM photographs of the fabricated 20-turn, all-copper solenoid inductor (upper: overview, lower: magnified view).

In this letter, we newly report experimental results for the "on-Si" inductors, which are of more practical importance, as well as on-glass inductors. Also, performance of on-glass inductors has been improved by a slight modification of the structural design, and geometrical dependence of the inductance and Q-factor are substantially presented as well.

II. Design and Fabrication

We have changed the solenoid design from the previous inclined top and bottom conductor type [11] to the parallel type (Fig. 1) to reduce the parasitic capacitance between the top and bottom conductor lines. The bottom conductor has 10 μm thickness, 14 μm width, and the top conductor has 30 μm thickness and 18 μm width, respectively. The center-to-center height of the solenoid inductor is 70 μm. We have fabricated solenoid inductors on both Si and glass wafers for separating the inductor-only performance and the substrate effect. The solenoid inductors have been monolithically fabricated using only simply-modified conventional lithography and well-established copper electroplating at a low process temperature below 120 °C. The fabrication steps in detail were reported previously [10], [11].

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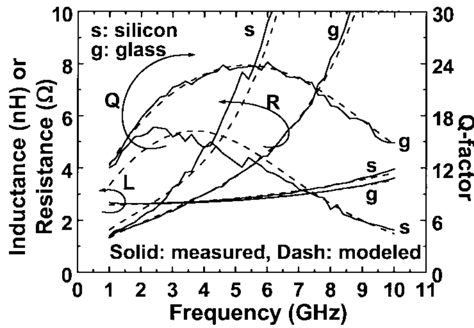
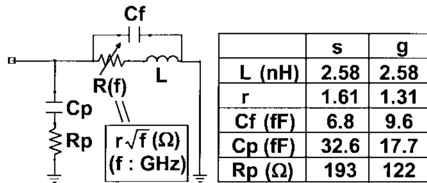


(a)



	s	g
L (nH)	2.58	2.58
r	1.61	1.31
Cf (fF)	6.8	9.6
Cp (fF)	32.6	17.7
Rp (Ω)	193	122

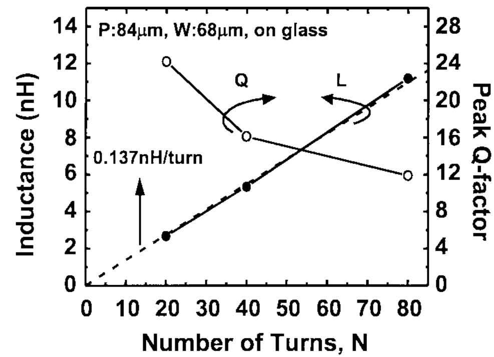
(b)

Fig. 2. Comparison of inductor performances of the two identical on-Si and on-glass solenoid inductors shown in Fig. 1. (a) Measured and modeled RF characteristics and (b) equivalent lumped-circuit model and parameters. The equivalent circuit parameters are extracted by EEsof Libra simulator. Substrates: s (silicon) 540-μm thick p-type Si (10–23 $\Omega\cdot$ cm)/1-μm thick thermal oxide/14-μm thick hard-cured photoresist, and g (glass) 560-μm thick Corning #7740 glass.

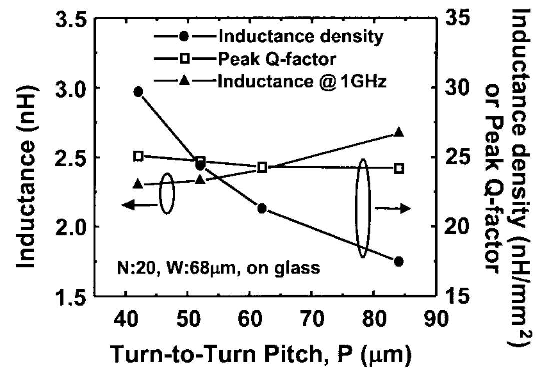
III. Results and Discussion

Fig. 1 shows a 20-turn, all-copper solenoid inductor fabricated on both Si and glass substrates. The one-port S-parameters of the fabricated inductors were obtained from their two-port S-parameters which were measured in RF band (1–10 GHz) by Wiltron 360B vector network analyzer and Cascade on-wafer probes. Fig. 2 compares the performances of two identical on-Si and on-glass inductors shown in Fig. 1. The measured and modeled RF characteristics, the equivalent lumped-circuit model and parameters are also shown in Fig. 2. For the on-Si inductor, the pad-parasitics on the Si wafer were de-embedded using the dummy pattern, which has only pad patterns. The de-embedded on-Si inductor exhibits inductance of 2.67 nH and peak Q-factor of 16.7 at peak-Q frequency of 2.4 GHz. The on-glass inductor shows same inductance and larger peak Q-factor of 24.2 at 6 GHz, which also indicate substantial improvement over the results reported earlier (2.5 nH, peak Q-factor of 19 at 5.5 GHz, [11]). Based on the Greenhouse's equation [12] applied to the micro-scale solenoid structure [13], the calculated inductance value was 2.53 nH (6% error). Other measured inductance values (2.67–11.2 nH) were within 10% of the calculated values. By comparing the equivalent circuit parameters in Fig. 2, it can be easily understood that the inferior Q-factor performance of the on-Si inductor originates from the relatively large increase in the parasitic capacitance to the substrate.

Fig. 3 shows the geometrical dependence of the inductance and peak Q-factor of the on-glass inductors. Unlike spiral inductors, Fig. 3(a) exhibits a good linear relationship between inductance and the number of turns (0.137 nH/turn). Meanwhile, the on-silicon inductors have shown 0.136 nH/turn.



(a)



(b)

Fig. 3. Geometrical dependence of the inductance and peak Q-factor of the solenoid on-glass inductors (a) number-of-turns (N) variation and (b) turn-to-turn pitch (P) variation. All the inductance values are obtained at 1 GHz and the height of all solenoid inductors is 70 μm.

It should be noted that this linear relationship is very important and advantageous in designing accurate inductance and this cannot be obtained from spiral inductors. Fig. 3(b) shows the effect of the turn-to-turn pitch on the inductor performance. We have obtained spatial inductance density as high as 30 nH/mm^2 from the on-glass inductor with narrowest pitch of 42 μm, and the inductor also shows highest peak Q-factor of 25.1 at 8.4 GHz with inductance of 2.3 nH. The on-silicon inductors have shown the same pitch-to-inductance relationship within 2% difference in inductance values from those of the on-glass inductors. It should be noted that a narrower pitch is favorable for smaller device area, higher peak Q-factor and higher peak-Q frequency in spite of a little decrease in inductance. Also, we have observed that inductance relates to the inductor width simply by a first-order. Solenoid inductors with more than 68 μm in width were fabricated using dummy posts [11].

IV. Conclusions

RF performance of surface micromachined solenoid on-chip inductors fabricated on both Si and glass substrates has been investigated. The fabricated on-Si and on-glass inductors show high peak Q-factors of up to 16.7 and 25.1 at GHz ranges, respectively and they are well modeled by lumped circuits. The solenoid on-chip inductors fabricated here have many desirable aspects, such as high performance even on a Si substrate,

linear relationships between inductance and the number of turns, scaling merits by reducing the turn-to-turn pitch, and high-current capability by thick metallization. These solenoid on-chip inductors can be used for various RF applications such as RF power amplifiers requiring high-current inductor loads, various RF filters and voltage-controlled oscillators (VCO's).

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