Thick Au High-\(Q\) Inductor and Its Chip-on-Chip Bonding on an RF IC for Various Frequencies

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1. Introduction

Passive components on radio frequency integrated circuits (RF ICs), especially on-chip spiral inductors, should have high quality (high \(Q\)) for sophisticated wireless modules. There are many reports about the \(Q\) improvement of spiral inductors by using spiral winding optimization [1], low-resistivity metallization [2], patterned ground shielding [3], substrate engineering [4], and micro electromechanical systems (MEMS) technology [5].

As a new approach to high-\(Q\) inductors, we propose a method to fabricate on-chip spiral inductors by using multi-layer thick Au electroplating and chip-on-chip bonding. In the method, the inductor and IC chip are fabricated separately, and then assembled into a composite RF IC chip.

2. Thick Au Inductor and Its Integration on IC Chip

Figure 1 illustrates the concept of the proposed chip-on-chip composite chip with an inductor chip assembled on an RF IC chip. The inductor chip was turned upside down and then bonded to the RF IC chip. The cross-sectional view of the inductor chip is shown in Fig. 2. On a high-resistivity Si substrate with a dielectric layer, Au lower interconnections are formed by electroplating to a thickness above 2 \(\mu\)m, and then an SiO\(_2\) inter-layer is sputtered on the lower metal. The lower interconnection consists of Ti/Au/Ti layers. Then, Au upper spiral windings are electroplated. The thickness of the upper winding can be set to 30 \(\mu\)m at maximum. In this structure, a passivation layer above the spiral is not needed since Au is not oxidized.

Figure 3 shows the chip-on-chip assembly process flow. First, Au stud bumps are formed on the pads of an RF IC chip. The height of the bumps can be controlled and set to around 40 \(\mu\)m. Then, a thick Au electroplated inductor chip is aligned and pressed to the IC chip with chip heating. Figure 4 is an example of the fabricated composite RF IC chip.

3. Results and Discussion

Using the proposed process for thick Au inductors, we fabricated two types of inductors described below.

One is a 100- to 200-nH inductor for the frequency of around several hundred MHz. Figure 5 shows a plan view and cross-sectional image of a high-\(Q\) on-chip spiral inductor with an inductance of 100 nH. The thickness of the spiral is 30 \(\mu\)m, the line-and-space pitch is \(L/S = 10\mu\text{m}/10\mu\text{m}\). As shown in Fig. 6, the spiral has the maximum \(Q\) of 20 at 150 MHz. The \(Q\) of 20 with 100-nH inductance is mainly due to thick Au upper winding with optimized spiral layout design and can improve RF IC performance in several hundred MHz region.

The other is a 1- to 5-nH inductor for the frequency of around several GHz. Figure 7 shows the characteristics of a 3.5-turn spiral inductor with 10-\(\mu\)m-thick and 20-\(\mu\)m-width line, and 10-\(\mu\)m space. The width of the inductor was determined by an electro-magnetic simulation in the GHz region. The maximum \(Q\) of the inductor is 17 at 5 GHz. The data shows that the inductor can improve RF IC performance at around several GHz.

Table I summarizes the features of the inductors. The results confirm that the thick Au inductors show good performance for RF circuit operation at various frequencies below several hundred MHz and around several GHz.

We also investigated the reliability of the chip-on-chip composite IC chip. The shared stress of the bonded interface is high enough because of the tight binding of a Au inductor on Au bumps. The bonded interface of the chip and the wiring resistance through the bumps showed no degradation after a 100-cycle temperature cycle test. These results reveal that the reliability of the chip-on-chip composite RF IC chip is sufficient.

We then fabricated a wide-tunable-range voltage controlled oscillator (VCO) IC chip and assembled a thick Au inductor chip on it [6]. The VCO oscillates at a frequency of around 5 GHz, and has a phase noise of -100 dBc/Hz at 1 MHz offset due to the thick and wide Au winding and a 40-\(\mu\)m large air gap between the inductor and the pads on the IC chip.

4. Summary

We have developed a high-\(Q\) inductor fabrication technique consisting of multi-layer thick Au electroplating and chip-on-chip bonding. We fabricated two types of inductors optimized for use at frequencies below several hundred MHz and in several GHz range. The results confirm that the proposed inductor fabrication technique has advantages in various frequencies for RF ICs.
Acknowledgements
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References

Table I  Summary of the fabricated inductors.

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<tr>
<th>L</th>
<th>Area</th>
<th>Qmax</th>
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<tr>
<td>100 nH</td>
<td>900 µm sq.</td>
<td>20     (@ 150 MHz)</td>
</tr>
<tr>
<td>55 nH</td>
<td>700 µm sq.</td>
<td>17     (@ 180 MHz)</td>
</tr>
<tr>
<td>3.5 nH</td>
<td>290 µm sq.</td>
<td>17     (@ 5 GHz)</td>
</tr>
<tr>
<td>2.5 nH</td>
<td>240 µm sq.</td>
<td>20     (@ 5.5 GHz)</td>
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Fig. 1. Concept of the composite RF IC chip with a flip-chip assembled inductor chip.

Fig. 2. Cross-sectional view of the inductor chip.

Fig. 3. Process step for flip-chip assembly of the inductor chip on the RF IC chip.

Fig. 4. Fabricated composite RF IC chip with a flip-chip assembled inductor chip.

Fig. 5. (a) Plan view and (b) cross-sectional view of a 100-nH inductor.

Fig. 6. Q of the fabricated 100-nH inductor at frequencies below several hundreds MHz.

Fig. 7. Q of the fabricated 3.5-turn inductor in the GHz frequency region.