Monolithic High-Performance Three-Dimensional Coil Inductors for Wireless Communication Applications

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Abstract

An on-chip three-dimensional RF coil inductor is proposed as a key component to implement monolithic wireless transceivers. The device achieves a substantially superior performance compared to conventional spiral inductors, and is amenable to monolithic integration in a standard IC process due to its low thermal budget. Experimental devices fabricated on a standard silicon substrate (10 Ω-cm) achieve a 2.6 nH inductance with a peak quality-factor (Q) of 13 at 900 MHz. The Q-factor is limited by a lossy adhesive used in the fabrication. In a modified process without adhesive in the coil area, a 4.8 nH inductor achieves a peak Q-value of 30 at 1 GHz. High-Q 8 nH and 13.8 nH inductors have also been fabricated.

Introduction

Increasing demands for wireless communications motivate a growing interest in low-cost, monolithic personal communication transceivers. High-performance RF inductors are the key components for implementing critical building blocks such as low-noise RF voltage-controlled oscillators (VCOs), low-loss impedance matching networks, passive filters, and inductive loads for power amplifiers. Critical parameters include inductance value, quality factor, and self-resonant frequency. Many cellular communication systems such as AMPS and GSM operate around 1 GHz and require inductance values on the order of 5 nH, Q of at least 10, and a self-resonant frequency well in excess of the operating frequency. However, such high-performance inductors are not available in current silicon IC technology. Therefore, the integration of these devices has become the key task for realizing monolithic wireless transceivers.

Conventional aluminum spiral inductors fabricated on standard silicon substrates achieve Q-factors around 3 at 1 GHz [1, 2]. Two issues contribute to the limited quality factor: eddy currents in the substrate and metal resistive losses. The first problem can be addressed in part by removing the silicon substrate underneath the inductor, leading to a Q-value around 5 reported in [3]. Reference [4] reports a Q close to 10 at 1 GHz through using copper traces on a sapphire substrate. While improving the Q-value, sapphire substrates are incompatible with standard IC processes.

In this paper, a new solution based on a three-dimensional (3-D) coil inductor is proposed. The 3-D microstructure minimizes the device capacitive coupling to the substrate and eddy current loss. Thick copper traces reduce the series resistance thus ensuring a high Q. Because of the low processing temperature, the inductor can be fabricated on top of wafers with completed electronics without affecting the characteristics of active devices. This is particularly crucial in RF applications where the availability of the most recent IC technology is a critical competitive advantage.

Monolithic Three-Dimensional Coil Inductor

Figure 1 shows the schematic top and cross-sectional views of a 3-D two-turn coil inductor. The device consists of

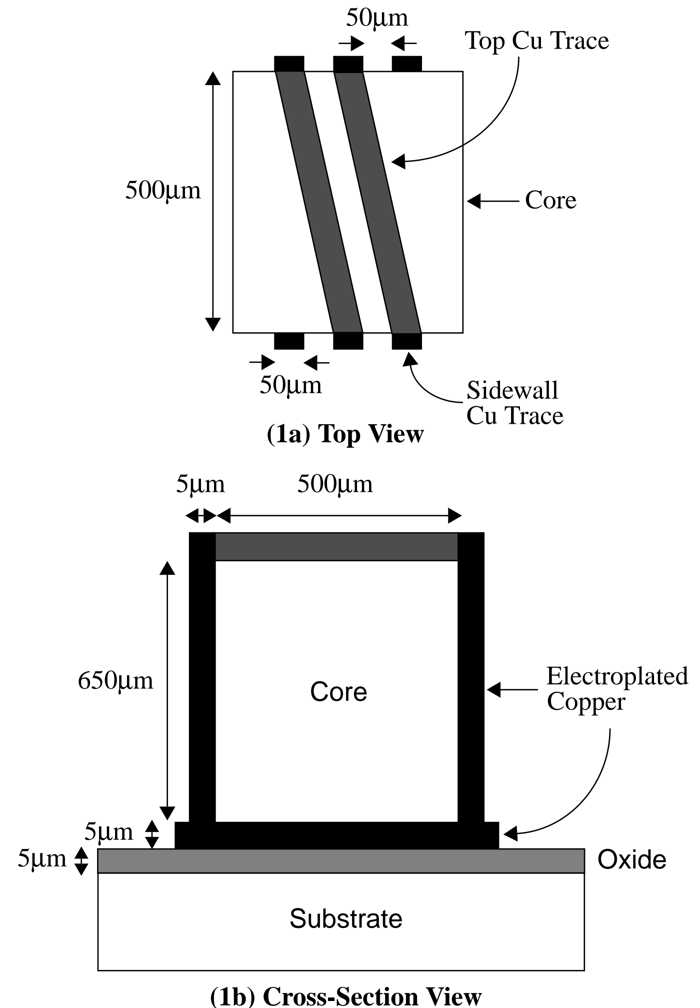

Figure 1. 3-D Coil Inductor

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5 μm-thick copper traces electroplated around an insulating core with a 650 μm by 500 μm cross-section. Compared to spiral inductors, this geometry minimizes the coil area which is in close proximity to the substrate and hence the eddy current loss, resulting in a maximized Q-factor and self-resonant frequency of the device.

Copper is selected as the interconnect metal because of its low sheet resistance, critical for achieving a high Q-factor. The skin depth at 1 GHz determines the optimal metal thickness of 5 μm. The 50 μm metal width represents a compromise between the interconnect resistance and capacitance to the substrate. A 50 μm line spacing is used in this conservative design to avoid processing difficulties.

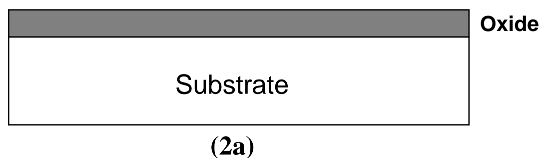
Alumina is used as the core material because of its negligible loss tangent at high frequencies [5], a key parameter to ensure a high Q-factor. The core width of 500 μm is found experimentally to be the minimum that avoids tilting during attachment to the bottom copper traces. Its height is limited by the thickness of a commercially available alumina sheet.

A typical RF transceiver employs inductances on the order of 5 nH. For the current fabrication, devices with one, two, and four turns are designed to achieve 5 nH, 8.5 nH, and 13.5 nH, respectively.

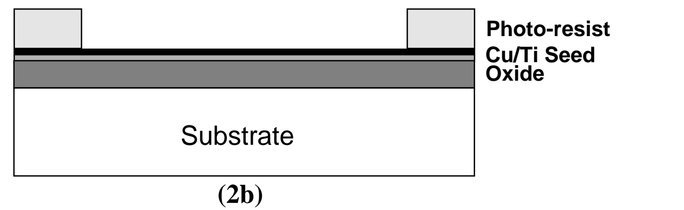
Fabrication Process

Figure 2 illustrates the process flow. First, the wafers are passivated with 5 μm or 10 μm low-temperature oxide (Fig. 2a). Then the bottom traces of the inductors are fabricated. For this purpose, a 500 Å titanium and 3000 Å copper seed layer are sputtered and then covered by an 8 μm thick electroplated resist. The electroplating method is chosen because it can conformally deposit a thick resist on a complex surface such as an inductor core. The patterns of the bottom metal traces are transferred photolithographically (Fig. 2b). This step is followed by selective electroplating of the 5 μm copper traces. To prevent oxidation, the copper is passivated with two 1000 Å layers of electrolytic nickel and gold (Fig. 2c). Finally the photoresist and copper/titanium seed layer are removed with a wet etch, leaving the bottom metal traces of the inductor on the substrate (Fig. 2d).

The core of the inductor is formed from an alumina sheet. The sheet is first covered with a 75 μm thick electrically insulating thermoplastic adhesive film and then diced into 500 μm wide strips. A 2% width accuracy has been achieved by using a thin diamond grit blade on a commercial dicing saw. The strips are then centered on the bottom copper traces and baked for 30 seconds at 170 °C to cure the adhesive (Fig. 2e).



(2a)



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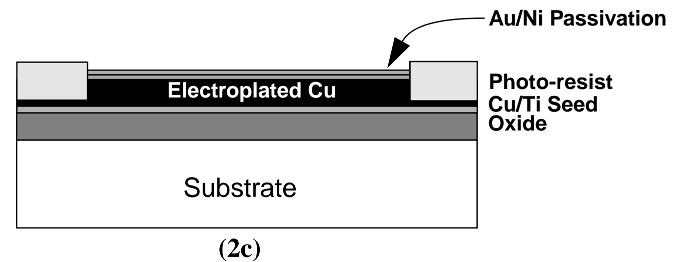

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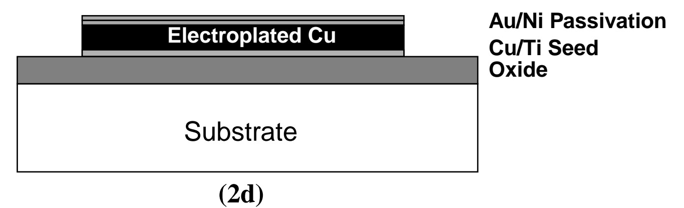

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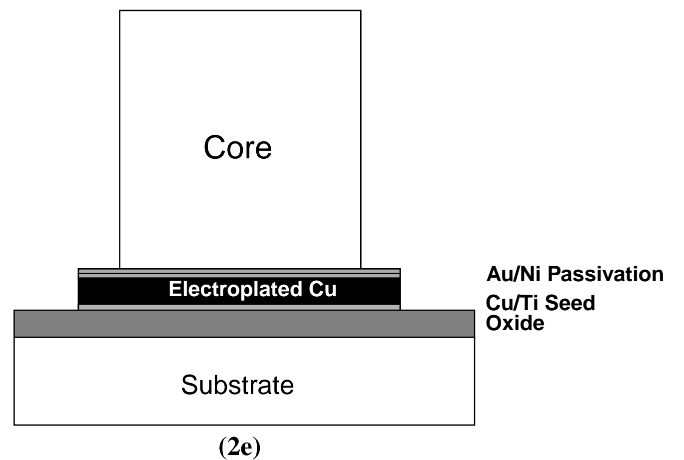

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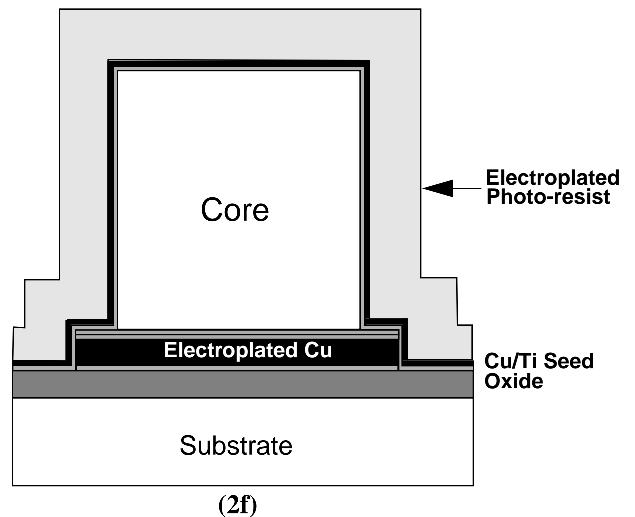

(2f)

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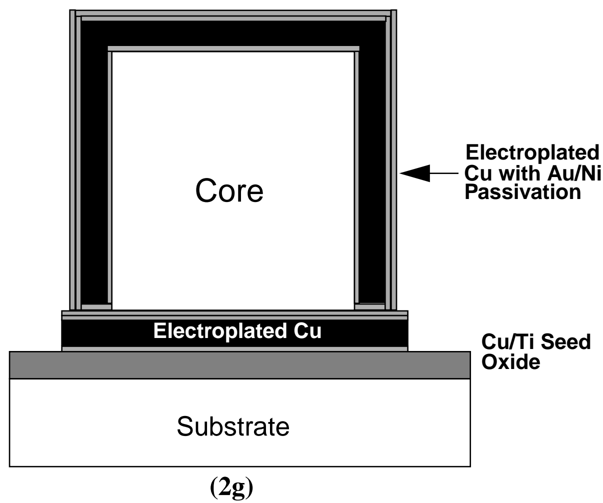


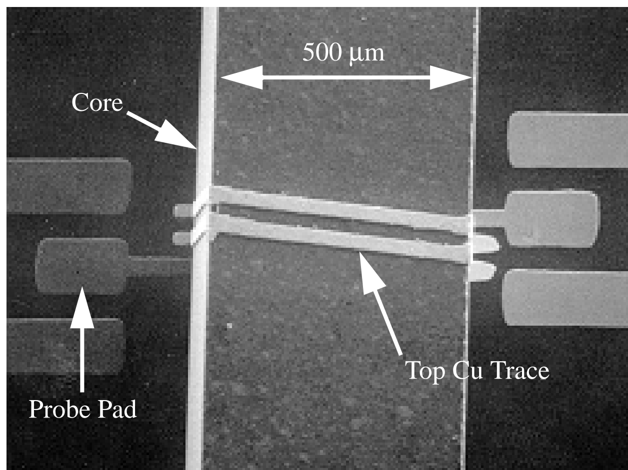
Figure 2. Fabrication Process Flow

To fabricate the copper traces on the side and the top of the alumina core, the same process as for the bottom traces is used (Fig. 2f). However, the resist is exposed with a three-dimensional maskless direct-write laser lithography tool [6]. After developing the laser-exposed resist, 5 µm thick copper traces are electroplated at the sides and on the top of the alumina core. The completed inductor coil is illustrated in Fig. 2g.

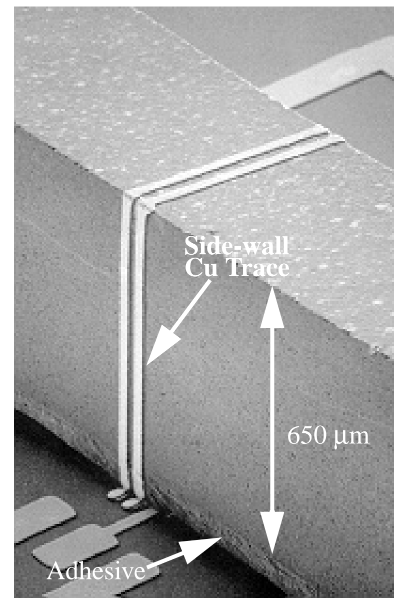
Experimental Results

Figure 3 shows an SEM of a two-turn inductor on a standard silicon wafer with a 5 µm oxide above the substrate. The coil area above the substrate is approximately 250 µm by 500 µm, comparable to that of a typical spiral inductor of the same value. The two-port S-parameters of the device are obtained with an HP8719 network analyzer. Figure 4 shows the measured Q and inductance value as a function of frequency after de-embedding the parasitics from the probe pads. The inductance is 2.6 nH with a peak Q of 13 around 900 MHz. This Q-value is substantially higher than previously published results. However, the inductance is lower than the simulated value of 8.5 nH. Loss in the adhesive at high frequencies is suspected as the reason. This interpretation would also explain the rapid decrease of Q for frequencies above 1 GHz. A higher inductance (3.9 nH) is measured for inductors fabricated on high-resistivity silicon substrate (1 kΩ-cm), but no improvement in Q at 1 GHz. Loss in the adhesive is again suspected as the reason.

Inductors recently fabricated with a modified process that does not use an adhesive inside the coil area achieve an improved performance. A two-turn inductor on a high-resistivity substrate achieves 8 nH inductance with a Q of 16 at 900 MHz. These results closely match the simulated values. Figure 5 presents an SEM of inductors with one and four turns. Measurement results for these devices are shown in Figures 6 and 7 and demonstrate a record Q of 30 at 1 GHz for the single turn device. The resonant frequencies for the devices are over 4 GHz, well above the operating frequency of interest.



(3a) Top View



(3b) Side View

Figure 3. SEM of a Two-Turn Coil Inductor

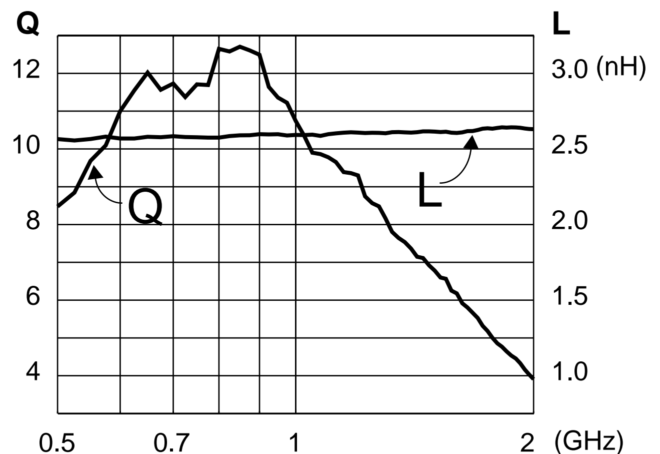


Figure 4. L and Q vs. Frequency for a Two-Turn Inductor

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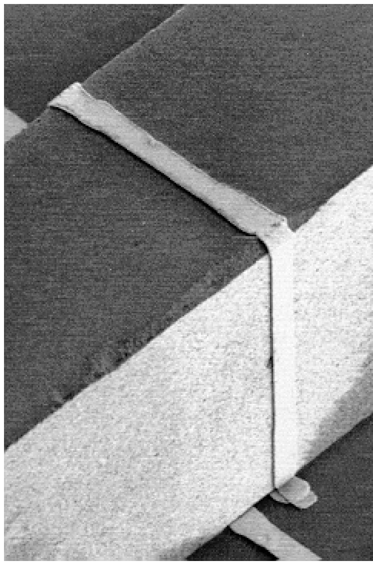
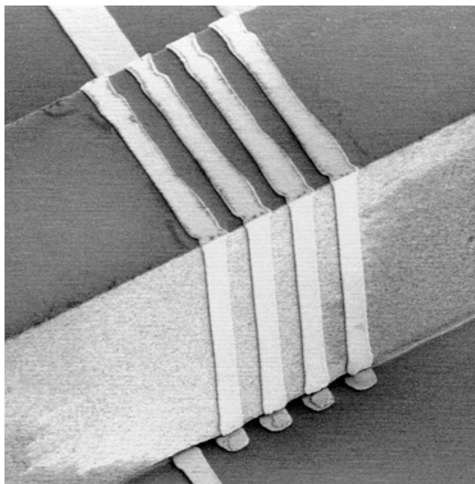


(5a) One-Turn Inductor



(5b) Four-Turn Inductor

Figure 5. SEM of Coil Inductors

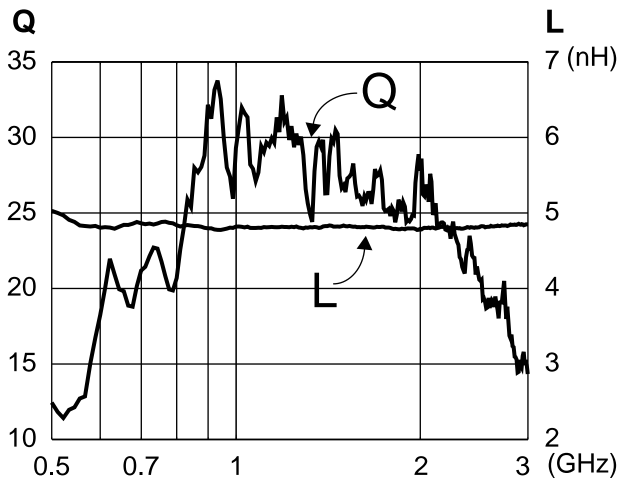


Figure 6. L and Q vs. Frequency for a One-Turn inductor

Figure 7. L and Q vs. Frequency for a Four-Turn Inductor

Conclusion

Compared to conventional aluminum spiral inductors, the proposed 3-D copper coil inductors achieve a substantially superior performance with Q-values up to 30 at 1 GHz. These elements are critical for reducing the off-chip component count, lowering power dissipation, and improving the performance of personal RF communication devices such as cellular phones. While initial devices have been fabricated on bare silicon wafers, all fabrication steps are compatible with standard IC technology, thus allowing monolithic integration of active devices with high-Q inductors.

Acknowledgment

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