HIGH Q SPIRAL-TYPE MICROINDUCTORS ON SILICON SUBSTRATES

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Abstract - Although integrated microinductors are in high demand for high frequency applications, their usefulness is limited due to their poor performance (e.g., low Q-factor, low inductance, and high parasitics). To expand the range of applicability of integrated microinductors at high frequencies, their electrical characteristics, especially quality factor and inductance, must be improved. In this research, integrated spiral-type microinductors suspended above the silicon substrate using surface micromachining and electroplating techniques are investigated. The silicon substrate used has resistivity ranging from 3 ~7 ohms-cm and thickness ranging from 330 μm ~ 430 μm. These fabricated inductors have inductance ranging from 10~25 nH and Quality factor ranging from 14 ~ 18.

Index Terms – spiral-type, high Q inductor, silicon, micromachining, integrated, suspended, electroplating

I. INTRODUCTION

Although a silicon semiconductor substrate is desirable to fabricate integrated passive elements for low cost integrated systems operating in intermediate and high frequency regime, the use of silicon is limited due to its high resistive and dielectric losses. The high parasitic effects of the substrates are also obstacles for fabricating integrated planar passive elements with high performance characteristics. Thus, much research has been performed to improve the characteristics of integrated inductors by reducing parasitics and losses from the substrate. Air gap spiral inductor structures have been fabricated using glass microbump bonding (GMBB) to reduce losses and parasitic capacitance [1]. The parasitic capacitance can be minimized due to the presence of the air gap, thereby enhancing the resonant frequency. A suspended inductor on a silicon substrate for RF amplifier applications was fabricated in [2]; the losses of the silicon substrate were reduced by selectively etching out the silicon under the integrated inductor. Transistor-integrated suspended spiral inductors have been fabricated using air-bridge technologies, these devices have a typical air gap of 3 μm between the conductor lines and the substrates [3].

In this research, surface-micromachined suspended air core spiral inductors on a highly conductive silicon substrate are designed, fabricated, and characterized. The surface micomachining technology is also compatible with the CMOS process. The proposed inductors have spiral geometry with an air core and a large air gap (60μm height) between the coils and the substrate (to reduce substrate parasitics), and thick, highly conductive electroplated copper conductor lines (to increase the quality factor). Various inductor geometries are also investigated by designing and fabricating several inductors with differing core areas and numbers of turns.

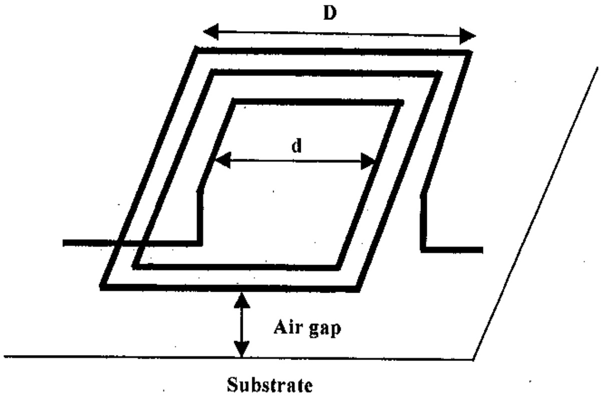

Figure 1. A schematic drawing of a proposed spiral inductor with a large air gap

II. DESIGN AND MODELING

At frequencies on the order of a hundred MHz and above, it is usually necessary to use air (or dielectric) cores in inductors due to the magnetic losses associated with many magnetic core materials at these frequencies. Thus, the quality factor and SRF (Self Resonant Frequency) of the integrated microinductor is strongly dependent upon the coil windings and stray capacitance between windings and substrate. The resistivity of the conductor should be low to obtain a high Q-factor by reducing the resistive loss of coils at very high frequencies. Thickness of conductor lines much in excess of several skin depths at the frequency of interest will not greatly reduce the conductor resistance or increase the Q-factor of integrated inductor. The integrated spiral inductor has a large air gap between the conductor lines and the substrate. The air gap is maintained by plated thick copper metal supports that allow the air gap to be large compared with traditional air bridge approaches, thus reducing the stray capacitance from the

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substrate. Thick (e.g., electrodeposited) conductor lines (i.e., several skin depths) are also necessary to increase the cross-sectional area of the conductor and to reduce the conductor resistance. Rectangular shaped conductor is desirable to increase the effective cross-sectional area of the conductor.

Fig. 1 shows a schematic drawing of a proposed large suspend spiral-type microinductor. D and d are the outermost and innermost dimensions, respectively, as shown in Fig. 1, and N is the number of turns of the square shaped spiral-type inductor. Bryan found an empirical equation to calculate the inductance of a flat square spiral-type inductor based on these variables [4-5]:

$$L = 0.0241 aN^{(5/3)} \ln[8(a/c)] \qquad (1)$$

where:

$$a = \frac{D+d}{4}, c = \frac{D-d}{2} \qquad (2)$$

The above equation (1) predicts inductance in microhenries when dimensions are expressed in centimeters. The unloaded Q-value is found by taking the ratio of the imaginary part to the real part of the input impedance of the inductor (neglecting bonding pads and interconnect). High quality factor means that the inductor has the desirable properties of low dissipation and favorable frequency characteristics when utilized in filter circuits. The effects of the substrate on the SRF and Q-factor can be reduced by introducing a large air gap between the substrate and the spiral coils. In the spiral geometry, this approach can also reduce winding capacitance by spatially separating the spiral coils from the central return lead. This separation is obtained not by dielectric material but by the air, and the parasitic capacitance can be minimized.

III. FABRICATION

Silicon dioxide (approximately 0.8 μm in thickness) and seed layer (Cr/Cu/Ti) was deposited on the silicon substrate and polyimide (Dupont PI-2611) was then coated on top of seed layer to construct electroplating molds for posts, signal connection, test pads, and grounds.

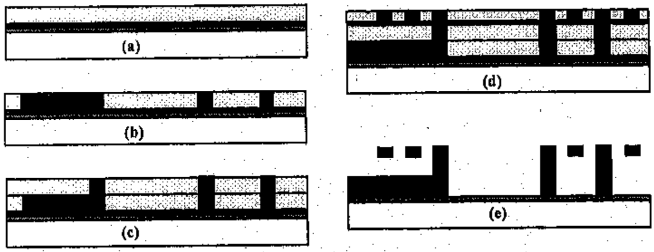

Figure 2. Fabrication sequences of the high Q microinductor: (a) dioxide, seed layer, and polyimide deposition; (b) formation of polyimide molds and electrodeposition (copper) for posts, signal connection, and test pads; (c) via formation; (d) formation of spiral type conductor lines using electroplating techniques; (e) removal of polyimide using plasma etcher and seed layer using wet-etching solutions.

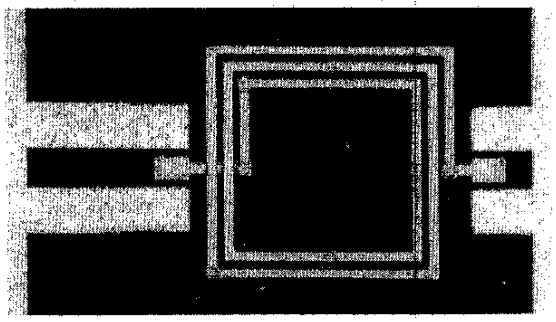

Fig. 3. A top view of the fabricated large suspended microinductor above the silicon substrate.

Fig. 4. A side view of the fabricated large suspended microinductor above the silicon substrate

Two coats were applied to obtain thick polyimide molds. The plating molds were formed using plasma O_2 etch. The electroplating molds were then filled with copper using standard electroplating techniques. Two coats of polyimide on top of the plated copper metal were spun and cured. Electroplating molds were formed for via connections between selected posts and spiral-type conductor lines. The plating molds were then filled with plated copper. A seed layer was then deposited, and thick photoresist was coated on the seed layer and patterned to form additional electroplating molds for building spiral-type conductor lines. The plating molds were again filled with plated copper. The photoresist molds were then removed and the seed layer wet-etched. Plasma etching using 95 % O_2 and 5 % CHF_3 was used to remove all polyimide on top of the substrate. After removing all polyimide, the bottom seed layer was wet-etched. Figures 3 and 4 show photomicrographs of the fabricated large suspended microinductor above the silicon substrate.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The fabricated air core spiral-type microinductors have been measured using an HP 8510C Network Analyzer, and CASCADE MICROTECH ground-signal-ground high frequency coplanar probes with 150 μm pitch size. The unloaded Q-factor was determined by dividing the imaginary

TABLE I. **Designed parameters of fabricated spiral-type air core inductors**

Type	Dimension of fabricated inductors (mm)	Width, thickness, and spacing of conductor lines (μm)	Core area (mm)	Number of turns
A	1.0 x 1.0	40 x 15 x 20	0.5 x 0.5	4.5
B	0.88 x 0.88	40 x 15 x 20	0.5 x 0.5	3.5
C	0.76 x 0.76	40 x 15 x 20	0.5 x 0.5	2.5
D	0.98 x 0.98	40 x 15 x 40	0.5 x 0.5	3.5

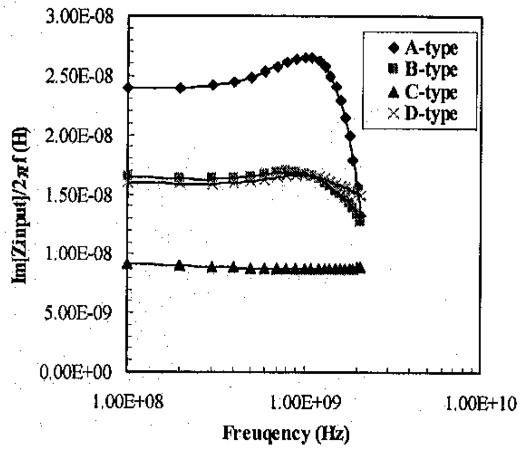

Fig. 5. Comparison of inductance of the fabricated large suspended microinductors above the silicon substrate.

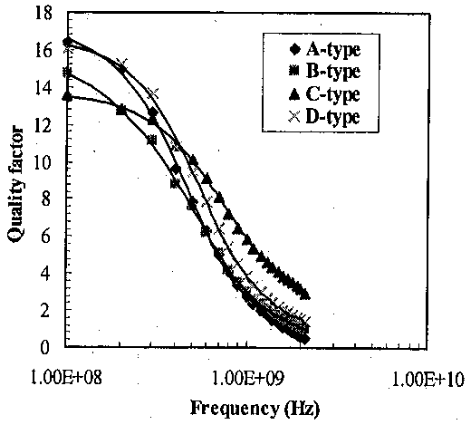

Fig. 6. Comparison of Q-value of the fabricated large suspended microinductors above the silicon substrate.

part by the real part (dissipated energy) of the input impedance, Z_{11}. Table I shows a list of the different geometries of the fabricated air core spiral-type inductors on silicon. These inductors have thick electroplated copper conductor lines and are suspended above the substrate by 60 μm air gaps. Figures 5 and 6 show inductance and quality factor of the fabricated inductors. As shown in Figure 5, as the number of turns is decreased, the inductance is decreased. Although A-type inductor has the largest inductance and Q-factor up to several hundred MHz of frequencies, its Q-factor is decreased as frequency increases. The inductance is constant and slightly increased, while the ac resistance of the inductor increase sharply as frequency increases. In other words, the real part of the input impedance is dominant to determine the Q-value as frequency increases. Thus, the inductor with short conductor lines has higher Q-value than the inductor with large conductor lines at higher frequencies shown in Figure 6 due to the reduced series resistance and stray capacitance. The calculated inductance using Equations 1 and 2 was slightly higher than the measured inductance. The measured inductances of A, B, C, D type inductors are 24.2 nH, 16.5 nH, 9.1 nH, and 16 nH, while the calculated inductances are 26 nH, 18 nH, 10.7 nH, and 17.3 nH respectively. These microinductors have inductance in the range of 9-25 nH and the quality factors in the range of 14-18 at a hundred MHz.

V. CONCLUSIONS

A large suspended spiral-type integrated microinductor has been proposed, fabricated, and characterized on a highly conductive silicon substrate using electroplating techniques and surface micromachining techniques. A 60 μm air gap was introduced between the spiral-type conductor lines and the substrate to achieve higher Q-value and self resonant frequency by reducing substrate loss and the parasitic capacitance from the substrate that is dominant in the total parasitic capacitance. The air gap was realized by supporting the spiral-type conductor lines using plated copper posts. Fabricated inductors with various geometries have been compared. As the number of turns is increased, the inductance, resistance, and parasitic capacitance are also increased. The increased resistance and parasitic capacitance reduce the Q-factor and the self resonant frequency. These high Q integrated inductors are useful for communications, signal processing, MMIC circuitry, and analog circuitry applications.

ACKNOWLEDGMENT

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