NEW MICROMACHINED INDUCTORS ON SILICON SUBSTRATES

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Abstract – Microinductors with two layer vertically stacked spiral-type copper conductor lines and permalloy core have been fabricated, characterized, and compared using micromachining techniques. In this research, micromachined inductors with vertically laminated magnetic alloy cores are found to have better high frequency characteristics such as high inductance, high quality factor, and low ac resistance resulting in low magnetic core losses at high frequencies, than non-laminated types.

Index Terms – micromachined, inductors, vertically stacked, permalloy, laminated, high frequency characteristics

I. INTRODUCTION

Many integrated inductors with electroplated permalloy cores have been developed, but their high frequency characteristics were poor due to their low inductance, low quality value, and high ac resistance. Micromachined inductors that have low resistance and high values of inductance and Q-factor are useful in many applications such as miniaturized sensors, actuators, filters, switched power converters, multichip modules, and electronic systems [1-2]. In particular, the use of these devices is necessary to miniaturize DC/DC converters used as power supplies in communications, military/aerospace applications, and computer/peripheral or other portable devices. Miniaturized DC/DC converters using micromachined inductors have many potential advantages such as high frequency operation, efficiency, quality, low cost, and low power losses [3]. At high switching frequencies, miniaturized surface-mount magnetic components may be able to be replaced by micromachined inductors [4].

These micromachined magnetic devices should be designed to have a completely closed magnetic circuit to minimize leakage flux, since leakage flux does not contribute to the total inductance of the devices and can cause interference with other integrated circuitry on the same substrate. Our approach is to fabricate these required inductive components using low-temperature micromachining techniques in order to enable low-cost, fully integrated versions of these power converter devices and electronic systems. High frequency characteristics are also improved using a laminated magnetic core.

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In this research, a single solid permalloy magnetic core is vertically broken into several pieces using micromachining techniques for achieving high inductance, high quality values, and low magnetic core losses at high frequencies. These broken magnetic cores have rectangular shapes and insulation between them is made of thin polyimide films. Proposed micromachined inductors have a closed magnetic core that is comprised of a bottom, two sides, center, and top magnetic cores for constructing a closed magnetic circuit (Fig. 2(h)). The center magnetic core surrounded by a two layer vertically stacked spiral-type copper coils is broken into several pieces. These micromachined inductors are fabricated on silicon substrates compatible with CMOS processing.

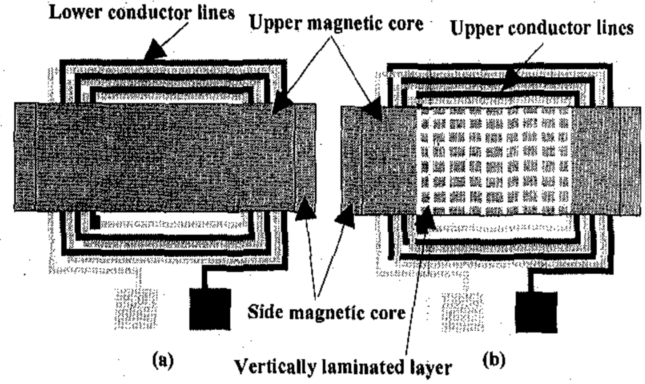

Fig. 1. A schematic drawing of top view of proposed new micromachined inductors with two layer vertically stacked coils and a closed magnetic core: (a) center core is composed of a single rectangular shaped core; (b) center core is composed of a large number of vertically laminated rectangular shaped cores

II. DESIGN AND MODELING

All of the designs investigated are modifications of traditional planar spiral windings along with electroplated metallic alloy cores. Spiral –type inductors are commonly used because of their simple geometries and easy fabrication sequences. However, these devices usually require large areas in order to achieve high inductance and high quality factor because of the area required for multiple conductor turns. To avoid this problem, conductor lines can be stacked vertically, and each layer of conductor line can be connected using vias. The vertically stacked spiral-type coils will also increase the mutual inductance and total inductance by keeping the turns close to the core and reducing gaps between the windings. Fig. 1 shows a schematic drawing of a top view of the proposed new micromachined inductors with two layer vertically stacked coils and a closed magnetic core. At high frequencies, thick and wide magnetic cores are not desirable due to their low resistivity and skin effect. The low resistivity increases the magnetic core losses and the skin effect decreases the effective cross-sectional area of the magnetic core at high frequencies. Thus, the thick and wide magnetic core is broken into several pieces as shown in Fig. 1(b) to increase the resistivity of magnetic core and to reduce the skin effects.

III. Fabrication

Silicon dioxide (0.5 μm in thickness) and a seed layer (Cr/Cu/Ti) was deposited on a silicon substrate and polyimide (Dupont PI-2611) was then coated on the seed layer to build electroplating molds for the bottom magnetic core (see Fig. 2(a)). The plating molds were formed using plasma O_2 etch (see Fig. 2(b)). The electroplating molds were then filled with permalloy ($Ni_{80\%}$-$Fe_{20\%}$) using standard electroplating techniques (see Fig. 2(c)). Two coats of polyimide on top of the plated magnetic core were spun and hard-cured for insulation between the copper coils and magnetic core (see Fig. 2(c)). A seed layer (Cr/Cu/Ti) was then deposited and plating molds were formed using thick photoresist for lower spiral-type conductor lines (see Figs. 2(c) and 2(d)). The electroplating molds were then filled with electroplated copper (see Fig. 2(d). After removing the photoresist and seed layer, polyimide was then coated on top of the copper conductor lines and cured at 300 °C for 1 hour (see Fig. 2(d).

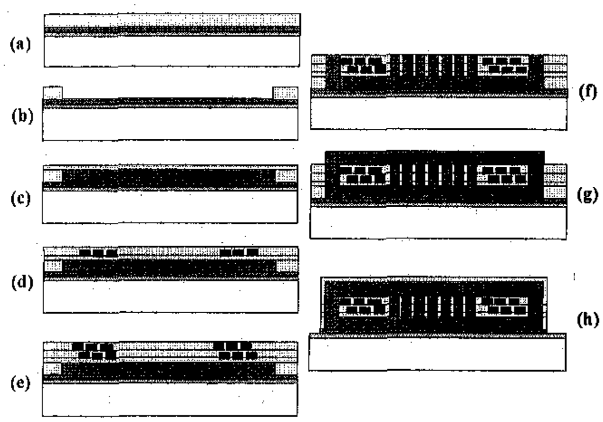

Fig. 2. Fabrication sequences of the new micromachined inductors on a silicon substrate: (a) silicon dioxide, seed layer, and polyimide deposition; (b) formation of polyimide molds for bottom magnetic core; (c) plating of bottom magnetic core and coating of polyimide; (d) formation of spiral-type lower conductor lines and coating of polyimide; (e) formation of vias and spiral-type upper conductor lines and coating of polyimide; (f) formation of side and center magnetic cores using electroplating; (g) formation of upper magnetic core; (h) selectively removal of polyimide using plasma etcher and seed layer using wet-etching solutions.

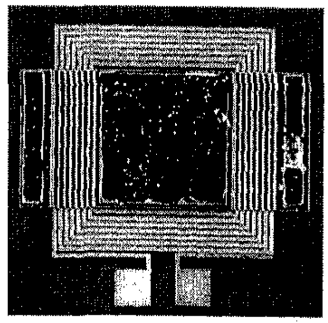

Fig. 3. A top view of A-type micromachined inductor with two layer vertically stacked coils on the silicon substrate.

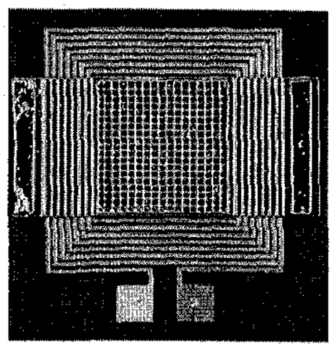

Fig. 4. A top view of C-type micromachined inductor with two layer vertically stacked coils on the silicon substrate.

Via molds were formed using plasma etch and a seed layer was then deposited using DC sputtering (see Fig. 2(e). Thick photoresist was coated on top of the seed layer and patterned to form electroplating molds for the upper spiral-type conductor lines (see Fig. 2(e). The plating molds were then filled with plated copper. The photoresist molds were then removed and the seed layer was wet-etched. Polyimide was then coated and cured for insulation between the upper copper coils and a top magnetic core (see Fig. 2(e).

Aluminum was deposited on top of the cured polyimide and patterned to form electroplating molds for side and center magnetic cores (see Fig. 2(f). The plating molds were formed using plasma O_2 etch. The electroplating molds were then filled with plated permalloy and a seed layer was then deposited on top of the plated permalloy core (see Fig. 2(f). Thick photoresist was coated on top of the seed layer and patterned to form the upper magnetic core (see Fig. 2(g). The plating molds were again filled with plated permalloy (see Fig. 2(g). After removing the photoresist molds, the seed layer was wet-etched (see Fig. 2(g). Polyimide was spun, cured, and selectively dry-etched to open bonding pads (see Fig. 2(h). The bottom seed layer was wet-etched and samples were tested. Figs. 3 and 4 show photomicrographs of fabricated new micromachined inductors on the silicon substrate.

IV. Experimental Results and Discussions

The initial relative permeability and saturation flux density of the plated permalloy film was 1100 and 0.9 Tesla respectively. The fabricated micromachined inductors have been measured using Wayne Kerr 3245 precision inductance analyzer. The process yield of the micromachined inductors was approximately 90 %. Table I shows the different geometries of the fabricated micromachined inductors. Fig. 5 shows inductance and ac resistance of the fabricated micromachined inductors on the silicon substrate. As shown in Fig. 5, the C-type inductor with 342 pieces of vertically laminated magnetic cores has better high frequency characteristics than other type inductors. The C-type inductor has the highest inductance and the lowest ac resistance at high frequencies, while the A-type inductor has the lowest inductance and highest ac resistance. Fig. 6 shows a comparison of inductance and ac resistance of B-type inductors by varying the number of coil windings. As shown in Fig. 6, the inductance increases as a number of windings increases, but the inductance sharply decreases due to the skin effects and the decreasing of permeability as frequency increases. As predicted, ac resistance slightly increases up to several hundred kHz, while it is sharply increased above several hundred kHz due to the magnetic core losses at high frequencies. The fabricated micromachined inductors have very high inductance in the range of 4 ~ 6 μH. The silicon substrate used has 3 ~ 7 ohms-cm in resistivity and 331 μm ~ 431 μm in thickness.

TABLE I. Designed parameters of fabricated micromachined inductors : these inductors have 14 windings of copper conductor lines and the cross-sectional area of the conductor is 40 μm x 10 μm.

Type	Dimension of bottom and top core (mm)	Dimension and number of center core (mm)	Dimension of side core (mm)
A	3.55 x 1.6 x 0.01	(1.5 x 1.5) x 1	0.2 x 1.5 x 0.06
B	3.55 x 1.6 x 0.01	(0.22 x 1.5) x 6	0.2 x 1.5 x 0.06
C	3.55 x 1.6 x 0.01	(0.05 x 0.04) x 342	0.2 x 1.5 x 0.06

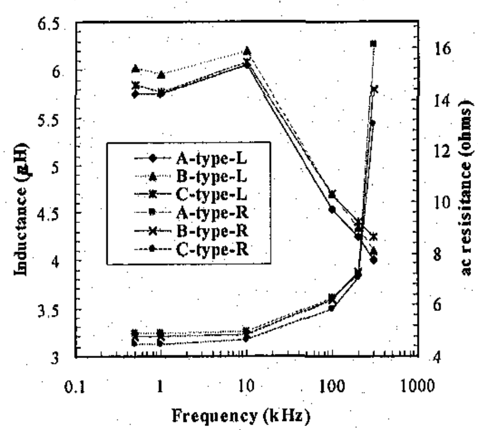

Fig. 5. Comparison of inductance and ac resistance of the fabricated micromachined inductors.

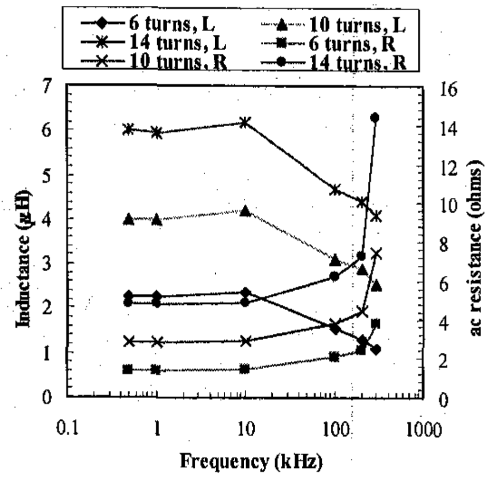

Fig. 6. Comparison of inductance and ac resistance of the fabricated B-type micromachined inductors by changing the number of turns.

V. Conslusions

Fully integrated micromachined inductors with two layer verically stacked spiral-type coils and different geometries of magnetic cores have been fabricated and tested on a silicon substrate. In the comparison of these micromachined inductors, the inductors with laminated center cores that are omposed of a large number of small pieces have much better high frequency characteristics than other type devices. Only low temperature processes have been used in fabrication, and the fabrication sequences are compatible with organic packaging and CMOS processing. These micromachined inductors have potential applications as integrated passives for multichip modules, compact electronic systems, integrated miniaturized DC/DC power converters and filters, and micromagnetic sensors and actuators integrated with the package.

Acknowledgment

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