A FULLY INTEGRATED MICROMACHINED TOROIDAL INDUCTOR WITH A NICKEL-IRON MAGNETIC CORE (THE SWITCHED DC/DC BOOST CONVERTER APPLICATION)

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ABSTRACT

A fully integrated inductor is realized on a silicon wafer by using a modified multilevel metallization technique to fabricate a wrapped coil wound around a 'bar' of high permeability magnetic material. In particular, efforts are made to minimize the coil resistance by using thick conductor lines and electroplated vias. An additional design constraint for this inductor is the use of a closed (i.e., toroidal) magnetic circuit, so that leakage flux and electromagnetic interference is minimized. In this structure, a 30 μm thick nickel-iron permalloy magnetic core is wrapped with 40 μm thick multilevel copper conductor lines, constructing a conventional toroidal inductor in planar shape. For an inductor size of 4 mm x 1.0 mm x 130 μm thickness having 20 turns of multilevel coils, the achieved inductance is approximately 0.2 μH at 1 Mhz, corresponding to a core permeability of approximately 500. The measured dc resistance of the conductor lines is approximately 0.3 ohms. By using the fabricated bar-type inductor, a switched DC/DC boost converter is demonstrated. The obtained maximum output voltage is approximately double an input voltage of 3 V at switching frequencies of 380-440 Khz and a duty cycle of 50%, showing good matching between calculated and measured voltage gains as well as demonstrating the usefulness of this new inductor.

INTRODUCTION

Recently the demands for new planar integrated inductors [1-3] which have high inductance and Q-factor have greatly increased for applications such as magnetic microactuators [4-8] and integrated micromagnetic power devices (such as a switched DC/DC converter). For example, integrated microactuators driven by electrostatic force usually require a drive voltage of several tens of volts or more; however, such voltages are often inconvenient to generate on-chip. A miniaturized DC/DC converter realized on chip has been considered as one of the available techniques to generate the voltages necessary for electrostatic actuation. Other non-micromachining applications such as distributed power supplies for multichip modules could also be addressed by such a miniaturized DC/DC converter. Unfortunately, integration of an inductive component has been the major obstacle in the fabrication of a fully integrated, miniaturized DC/DC converter. In this paper, a new planar toroidal inductive component (hereafter referred to as a 'bar-type' inductor), consisting of multilevel coils wrapped around a 'bar' of high permeability magnetic material, is realized on a silicon wafer using modified multilevel metal interconnection techniques. The bar-type inductive component is considered as one of the more promising inductive components for micromagnetic power device applications, since its geometrical characteristics can meet most of the required conditions of a basic inductive component for micromagnetic applications.

Researchers have previously attempted the fabrication of bar-type components. For example, to demonstrate the feasibility of a planar bar-type toroidal inductor, miniature coils of thin-gauge wire were manually wrapped around a thin-film bar of permalloy magnetic material [3]. It was verified from this structure that the introduction of a permalloy thin film increased the inductance value by a factor of 1000 when compared with an air core. Planar solenoid coils wrapped around an air core on a silicon substrate were fabricated by Kawahito [1] for application in highly sensitive magnetic sensors. However, this device was not designed to pass high currents and therefore is not suitable as an inductive component for micromagnetic actuators or magnetic power devices.

In this paper, a new structure with thick conductors and cores for high currents is adopted using a polyimide planarization technique and inserting a magnetic core bar instead of an air core. The proposed structure is shown in Figure 1. The metal interconnections which are used to construct the 'wrapping coils' include metal via contacts. These via contacts may limit the practical application of this component if they have a relatively high metal contact resistance which causes an increase of the coil resistance and correspondingly low Q-factor. In achieving a high inductance value, if more coil turns are required, more via contacts are added which increases the total coil resistance. To address this problem, we have used an electroplating technique to fabricate the conductor lines and the vias, as electroplated metal contacts usually have a relatively low metal contact resistance. If the resistance per via contact can be reduced to less than 0.1 milliohms using this electroplating technique, the restriction caused by the high via contact resistance will be removed [9].

To illustrate the utility of the integrated inductor, a switched DC/DC converter application is considered. Switched DC/DC converters are composed of inductive components and switching control circuits. In realizing an integrated DC/DC converter, integrated circuits for the switching function are already feasible, whereas few planar integrated inductive components are available as discussed earlier. Thus, the major obstacle in realizing an integrated switching DC/DC converter also comes from the feasibility of planar inductive components. Before implementing an actual integrated DC/DC switched converter, a simple hybrid construction of a switched DC/DC converter using the fabricated bar-type inductor is tested for feasibility using a bipolar transistor as the switching device and a diode as the complementary synchronized switch.

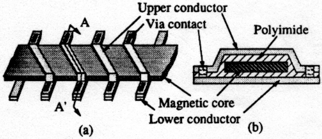

Figure 1. Schematic diagram of the planar bar-type inductive component: (a) schematic view (b) A-A' cut view.

DESIGN

As shown in Figure 1, the bar-type inductive component is composed of a magnetic core bar and multilevel metal interconnections, whose geometry has a similar structure to a conventional 'wrapped' inductor except for its planar shape. Thus, its design and modeling are straightforward. In order to accomplish the 'wrapping' function of the conductor coils on a planar surface, the patterned lower conductor lines are interconnected to the upper conductor lines through metal vias. To compose a closed magnetic circuit between the coils and the magnetic cores, the magnetic core bar is placed on the top of the lower conductor lines after the lower conductor lines are patterned and insulated, and then the coils are completed, wrapping around the magnetic cores and constructing an interlinkage with the magnetic cores.

A planar inductive component should achieve an inductance value as high as possible, while keeping the conductor resistance low in order to achieve a high Q-factor and to reduce coil-based heat loss. In this structure, the achievable inductance values depend on both the number of coil turns as well as the reluctance of the magnetic core bar, where the reluctance is determined from the dimensions and the permeability of the core bar.

The major difficulty in realizing this structure in a planar shape is due to fabrication constraints. In designing this structure, the fabrication difficulties to be encountered in actual process should be considered first; the structure should be subsequently designed to minimize these fabrication obstacles.

Among several obstacles encountered in fabricating this inductive component, the major difficulty comes from the fabrication of thick wrapping coils which have a low conductor resistance. Electroplating is a favorable technique for deposition of the thick metal conductor, but electroplating usually requires a plating seed layer which must be removed after completing the fabrication of the structure. Consequently, the seed layer used for the lower conductor lines should remain to serve as the plating seed layer for the via and the upper conductor plating until the component fabrication is completed. The seed layer must then be removed, or all of the coils will be shorted together. Unfortunately, the seed layer is now difficult to remove, as it is at the bottom of the structure. Simple blanket etching to expose the seed layer will not work as the magnetic core bar placed on the top of the lower conductors serves as a mask to prevent complete exposure of the seed layer. To solve this problem, a mesh-type seed layer as depicted in Figure 2 can be used. This mesh layer can serve as the electroplating seed layer for the conductor lines and vias until the fabrication is completed. When the fabrication of this component is finished, the edges of the mesh seed layer can be exposed using a blanket plasma etch and then removed, ensuring the electrical isolation of the coils.

Another difficulty in the fabrication comes from the need to fabricate a thick magnetic core bar (for low magnetic reluctance) which should be placed on the top of the insulated lower conductor lines. The relatively high aspect ratio of the magnetic core causes a serious difficulty in patterning the conductor vias and the upper conductor lines, due to poor planarization of the surface. If a cavity is made to contain the magnetic bar so that the magnetic bar is recessed, planarization of the surface for subsequent processing can be achieved. Thus, a cavity to contain the magnetic core bar is introduced in an insulated layer using a dry etching technique.

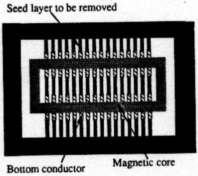

Figure 2. Mesh-type seed layer which is to be removed upon completion of fabrication after serving as a plating seed layer.

FABRICATION

A brief fabrication process of this component is shown in Figure 3. The process was started with an oxidized (0.6 μm) 2-inch <100> silicon wafer as a substrate. Onto this substrate, chromium (500 Å) / copper (2000 Å) / chromium (700 Å) layers were deposited using electron-beam evaporation to form an electroplating seed layer. This seed layer was patterned to form a conductor network to be removed after serving as the seed layer for the conductor plating. Polyimide (Dupont PI-2611) was then spun on the wafer to build electroplating molds for the bottom magnetic cores. Four coats were cast to obtain a 40 μm thick polyimide film. After the deposition of all coats, the polyimide was cured at 350 °C for 1 hour in nitrogen, yielding an after-cure thickness of 40 μm. Molds for lower conductor lines 40 μm in thickness were etched in this polyimide using an O_2 (100%) plasma etch and an aluminum hard mask until the chrome/copper/chrome seed layer was exposed. The electroplating forms were then filled with plated copper using standard copper electroplating techniques [9].

Polyimide (PI-2611) was multi-spincoated and cured to construct a cavity of 40 μm in depth to contain the magnetic core. In order to achieve a smooth surface at the steep edge of the cavity which ensures the smooth connection of the plating seed layer, an additional polyimide layer (PI-2611) was spin-coated at 3000 rpm and hard-cured using the same conditions described above. The same seed layer (chrome/copper/chrome) used for the plating of the lower conductor lines was again deposited for magnetic core plating. Nickel (81%) / iron (19%) permalloy was then plated using standard electroplating techniques [11]. Upon completion of the electroplating, the chrome/copper/chrome seed layer was then removed using wet etching.

To insulate the core, additional polyimide was deposited in multiple coats (as described above). Via holes were then dry-etched through the polyimide layer using 100% oxygen plasma and an aluminum hard mask. Upon completion of the via etch, the aluminum hard mask was removed. Because the surface of the lower conductor strips was exposed to the oxygen plasma during dry etching, the surface of the copper was oxidized. To remove the oxide film, the exposed area of the lower conductors was etched in a sulfuric acid (2 %) solution for 10 seconds. Plating contact was then made to the seed layer of the lower conductors, and the metal vias were filled with plated copper using the copper electroplating bath and conditions described previously. Upon completion of the electroplating, a copper (2000 Å) / chromium (700 Å) layer was deposited again, and the copper plating mold was formed using 40 μm thick OCG Microelectronic Materials Probimide 349 photosensitive polyimide. The upper conductor lines were plated through the defined molds using the same plating conditions described above. After removing the photosensitive polyimide in a KOH based solution, the plating seed layer for the top conductors was wet etched.

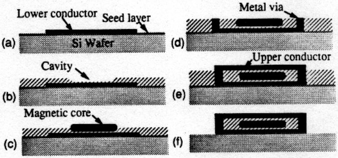

Figure 3. Fabrication steps of the bar-type inductive component: (a) patterning of bottom conductors; (b) dry etching of cavity to contain magnetic core; (c) magnetic core plating; (d) via conductor plating; (e) patterning of top conductors; (f) removal of seed layer.

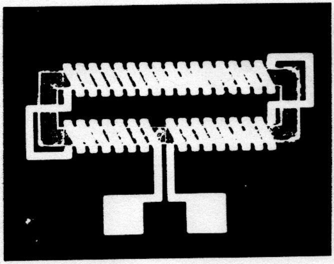

Figure 4. Photomicrograph of the fabricated bar-type inductor.

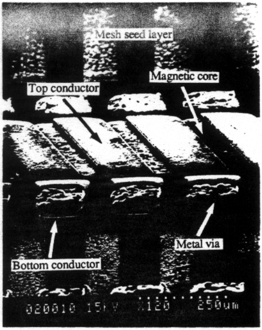

Figure 5. Scanning electron micrograph of a section of the fabricated bar-type inductor.

To electrically isolate the coils, the polyimide was optionally masked and etched to the bottom. The bottom mesh seed layer was then wet etched. Figure 4 shows the photomicrograph of the fully fabricated device. A scanning electron micrograph of the structure is shown in Figure 5, which was taken after dry-etching of the polyimide. At the completion of fabrication, samples were diced into chips for bonding and test.

THEORY

The calculation of the inductance value for the bar-type structure depicted in Figure 1 is very simple and more-or-less straightforward as reported earlier [3]. The inductance L of the bar-type inductor structure is expressed as:

$$L = \frac{\mu_0 \mu_r N^2 A_c}{\ell_c}, \tag{1}$$

where A_c is the cross-sectional area of the film magnetic core, ℓ_c is the length of the closed magnetic core, N is the coil turns, and μ_0 and μ_r are the permeability of the vacuum and the relative permeability of the magnetic core, respectively.

The Q factor of an inductor can be expressed as:

$$Q = \frac{\omega L}{R} = \frac{\omega \mu_0 \mu_r N A_c A_w}{2\rho W \ell_c}, \tag{2}$$

where A_w is the cross section area of the conductor, W is the width of the film magnetic core, and ρ is the conductivity of the conductor material.

From Equations 1 and 2, it is concluded that inductance and Q factor are linearly proportional to μ_r in the bar-type inductor. Thus, the introduction of thin film magnetic core in the integrated inductor should improve its feasibility for IC applications. Eddy current losses in the magnetic core as well as skin depth effect in the conductor are neglected in this calculation. This assumption is reasonable since bar-type inductors fabricated using IC technology are composed of cores and conductor lines whose thickness is in the order of several tens of microns.

A conventional, non-isolated, switched DC/DC boost converter [10] is shown in Figure 6, which has a single transistor switch configuration. By using a 'flyback' inductor L, the magnetic energy stored in the inductor's magnetic field is converted to dc

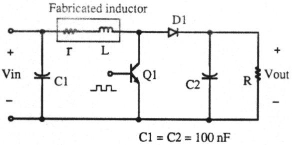

Figure 6. Circuit diagram of the conventional switched DC/DC boost converter.

voltage when switching operations take place. At the switching operation, the duty cycle D is defined as the ratio of the switch-on time interval to the total switching interval T. In this converter, the output voltage is controlled by controlling the duty cycle of the switch bipolar transistor T_{rs}. The theoretical voltage conversion gain is expressed as

$$\frac{V_0}{V_i} = \frac{1}{1-D}, \tag{3}$$

where V_i and V_0 are the input voltage and the output voltage respectively.

EXPERIMENTAL RESULTS

For an inductor size of 4 mm x 1.0 mm x 130 μm thickness having 20 coil turns, the achieved inductance is approximately 0.2 μH at 1 Mhz, corresponding to a core permeability of approximately 500. The variation of the measured inductance with frequency is shown in Figure 7.

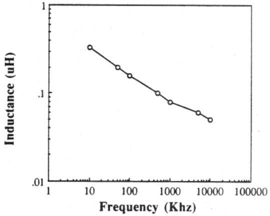

Figure 7. Measured inductance of the fabricated inductor as a function of excitation frequency.

The measured dc resistance of the conductor lines is approximately 0.3 ohms. This agrees well with a value of 0.29 ohms obtained from the inductor geometry (neglecting via resistance) and bulk values of copper conductivity [9]. Although the individual via contact resistance was not measured, the excellent agreement between measured and calculated total resistance indicates that the via resistance is negligibly small. Thus, the electroplated via technique avoids the high via resistance problem.

To find the circuit parameters of the inductor, an equivalent circuit is assumed that a stray capacitance is in parallel with the series connection of the inductance and the internal resistance. The resistance and stray capacitance of the inductor are derived from the measured impedance and phase as a function of frequency using equivalent circuit analysis. From this analysis, the stray capacitance is shown to be in the pF region, and also shown to have a negligibly small effect over the frequency ranges used. The effect of the inductance falloff at higher frequencies shown in Figure 7 is due almost entirely to the dependence of the permeability of the iron-nickel core on frequency, and has been confirmed using other test structures.

In constructing the actual DC/DC converter, simulation runs using the measured component values were performed using PSpice. Appropriate circuits were then constructed on a breadboard using the fabricated inductive component as well as components described in Figure 6. A bar-type inductor with a 0.2 μH inductance and an internal resistance of 0.3 ohm is sufficient to boost an input signal of 3V. The plot of output voltage variation as a function of load resistance at switching frequencies of 380-440 Khz and a duty cycle of 50 % obtained from the breadboarded circuit is shown in Figure 8. The obtained maximum output voltage is approximately double the input voltage at switching frequencies of 380-440 Khz. When the duty cycle is changed from 20 % to 60 %, the measured and the calculated voltage gains increase as shown in Figure 9.

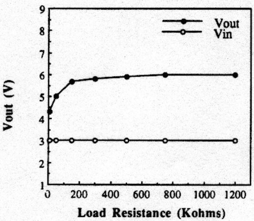

Figure 8. Output voltage of the switched DC/DC converter as a function of load resistance (R in Figure 6). The excitation frequency ranges between 380-440 Khz at the duty cycle of 50%. The input voltage is 3 volts.

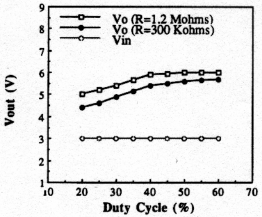

Figure 9. Variation of output voltage when the duty cycle of the switching pulse is varied between 20 % and 60 %.

CONCLUSION

A new planar bar-type inductive component is realized using micromachining and multilevel metal fabrication techniques. Since this inductive component has favorable magnetic characteristics as well as electrical properties, it is potentially very useful as a basic inductive component in applications for magnetic microsensors, microactuators, and micromagnetic power devices such as a DC/DC converter.

For an inductor size of 4 mm x 1.0 mm x 130 μm thickness having 20 coil turns, the achieved inductance is approximately 0.2 μH at 1 Mhz, corresponding to a core permeability of approximately 500. The measured dc resistance of the conductor lines in this inductor is approximately 0.3 ohms.

An application of this device as a flyback inductor in a DC/DC converter is presented. Using a conventional switched DC/DC boost converter circuit and the bar-type inductive component fabricated in this work, obtained maximum output voltage was about 2 times the input voltage at an input voltage of 3V and switching frequencies of 380-440 Khz. As the inductor presented here can potentially be integrated onto a chip or module, full DC/DC converter integration can be envisaged.

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