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Design and Fabrication of a MEMS 3D Micro-transformer for Low Frequency Applications

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ABSTRACT

This study presents the fabrication of a 3D micro-transformer using MEMS technology in 10-600 kHz frequency range. The fabrication processes is developed for high-performance and low-cost realization with respect to planner design. The coil winding and the magnetic cores were fabricated by electro-deposition using copper and Ni/Fe Permalloy materials, respectively. In step-up configuration, the micro-transformer achieved 73.75% efficiency. The inductance achieved was 90 and 164 μH for primary and secondary coils, respectively. Characterization results and fabrication process of the fabricated transformer (2560×1240 μm) on alumina ceramic substrate are presented.

Key words: Micro-Nano electromechanical systems, MEMS fabrication, 3D, micro-transformer, micro-coil

INTRODUCTION

Micro-transformer is a type of magnetic device capable of transforming voltage, as well as current between primary and secondary coils in presence of a magnetic core that concentrate magnetic flux for higher efficiency (Moazenzadeh *et al.*, 2013). The differences between a regular size transformer and micro-transformer lies in the dimensions and the fabrication method (Huang *et al.*, 2013) in addition to the lower capacity. The main two types of the micro-transformers are planner and 3D structure (Del Vecchio *et al.*, 2010). Generally, miniaturized transformers that use MEMS techniques have many potential advantages these advantages include, a low-power consumption, low-cost, high-efficiency, high Q-factor and high frequency operation (Yunas *et al.*, 2009a). Therefore, there has been a large drive on the realization of 3D MEMS micro-transformers on a chip which can be fully integrated with other electronic circuits such as, DC/DC converters, signal isolators, RF ICs, portable devices and mobile power delivery applications etc. The current mainstream of planner transformer coils has small inductance values, a low Q factor and that consume relatively large area (Yunas *et al.*, 2009b). It is possible to achieve high inductance value, high Q-factor relatively in small areas by concentrating the magnetic flux inside the magnetic core with a high permeability coil wound around it that provides an advantage of 3D micro-transformers over planner type.

MATERIALS AND METHODS

Micro-transformer design description: Figure 1 shows the design structure of 3D MEMS micro-transformer. The micro-transformer consists of a primary and secondary coils wound around a magnetic core (Kang *et al.*, 2009), the input and output terminals and an insulation layer between the core and the coils. Both coils can be chosen alternatively as primary or secondary coil. The magnetic core is excited periodically by a sine wave that induces an electromagnetic field propagate through the core and induce a voltage in the secondary coil. Both coils are rectangular in shape and composed of bottom pads, vias on each side of the pads and top coil pads. Each bottom pad, vias and top pad form a single turn. The primary coil consists of 10 turns, while the secondary coil consist of 18 turns to form the ideal transformation ratio of 1.8. The insulation layer provides mechanical support for hanging coil pads in the layer in addition to the magnetic core itself. The rectangular shaped core was designed for a closed magnetic flux path in order to reduce the magnetic flux leakage. Copper (Cu) is used for the electroplated coils due to its high electrical conductivity, availability and low price (Yunas *et al.*, 2008). The magnetic core is fabricated using electro-deposition techniques using Ni-Fe ferromagnetic Permalloy material. The Ni-Fe Permalloy is used due to its simplicity in the MEMS fabrication process, good magnetic properties for low frequencies applications. This material also has high relative permeability and stability against variations (Mohan *et al.*, 1999; Park and Allen, 1996; Raman *et al.*, 1982). Due to the miniature size of the transformer, the transformer was magnetically shielded during the test phase in order to eliminate the presence of any external magnetic field that will affect the input/output transformation ratio. A patterned hard cured AZ 4620 photoresist was used to insulate and isolate the core from the two coils and provide a mechanical support for the hanging part of the magnetic core. Figure 2 and 3 shows the micro-transformers cross-sectional and top views respectively. The design parameters of the MEMS micro-transformer, corresponding dimensional notation of each component with unit range are presented in Table 1.

Fabrication process of the micro-transformer: The summary of the process flow of fabricating the micro-transformer that is performed on an alumina ceramic substrate is shown in Fig. 4. Firstly,
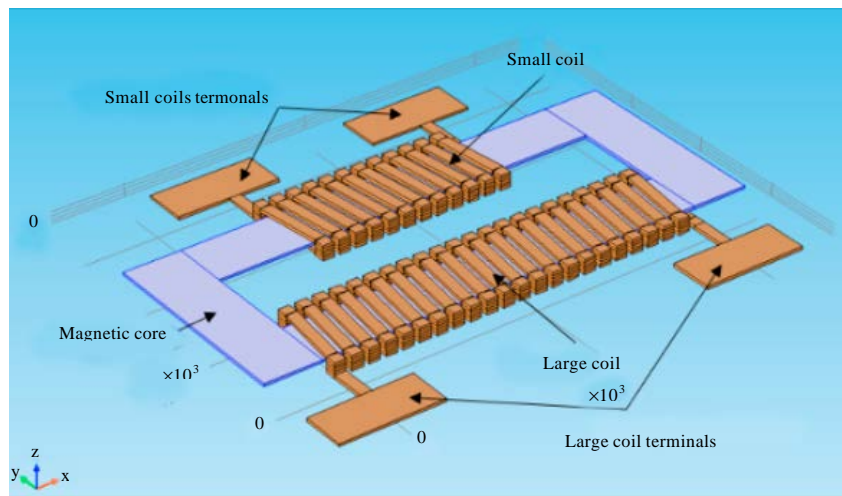
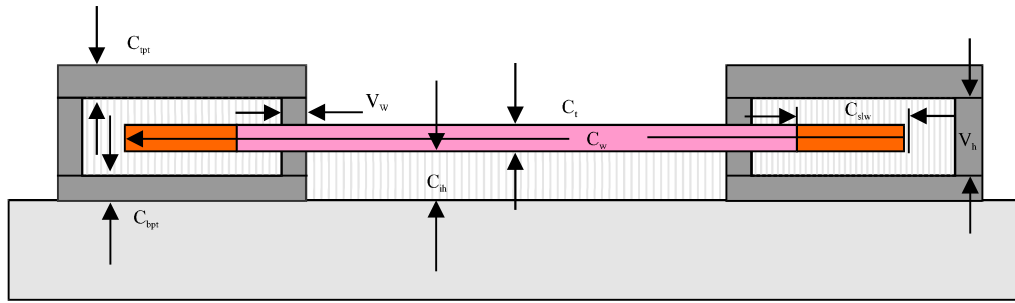

Fig. 1: 3D MEMS micro-transformer design structure

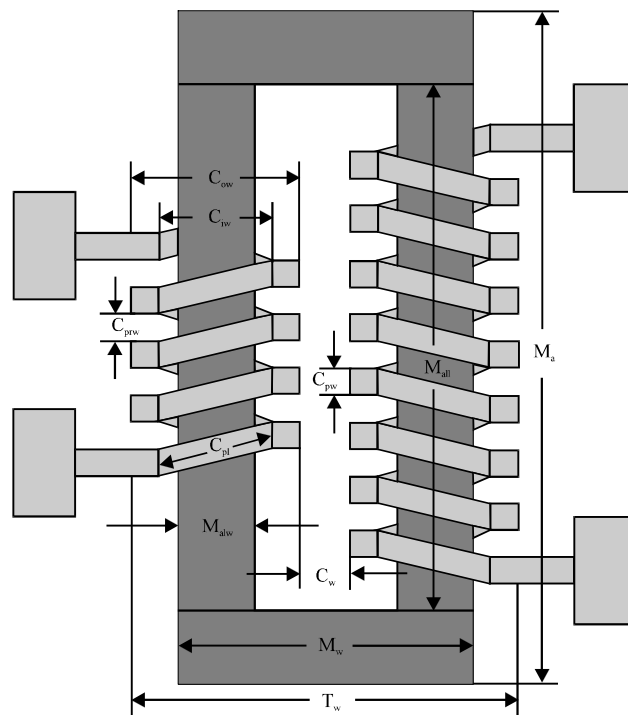Fig. 2: Cross-section view of the micro-transformer

Fig. 3: Top view of the schematic design with corresponding dimensions notation

a seed layer of titanium (Ti) (25 µm)/gold (Au) (75 µm) was deposited on an alumina ceramic wafer by sputtering. Using thick photoresist (AZ-4620) and traditional lithography, molds were prepared for the bottom conductors. Next copper lines were electroplated to form the primary and secondary coil pads. The thicknesses of the molds determine the thickness of the Cu conductors. Then the photoresist was stripped using acetone and the seed layer was etched using chemical wet etching. For the Au seed layer, a diluted aqua regia solution (3 HCL: 1 HNO_3: 2 H_2O) was used. For the Ti seed layer, 0.5% HF solution was used for the etching. A new photoresist layer was spun to form an insulation layer between the coil's pads and the magnetic core, this layer was hard cured for 1 h at 220°C. After that, a new layer of photoresist was spun to for a pattern vias seed layer. A seed layer was sputtered, followed by a new photoresist layer to form the vias molds. The coil vias were then electroplated, followed by the removal of the photoresist and the seed layer. A new layer of photo-resist was spun over the coil's pads and vias. A new seed layer was sputtered on the coil
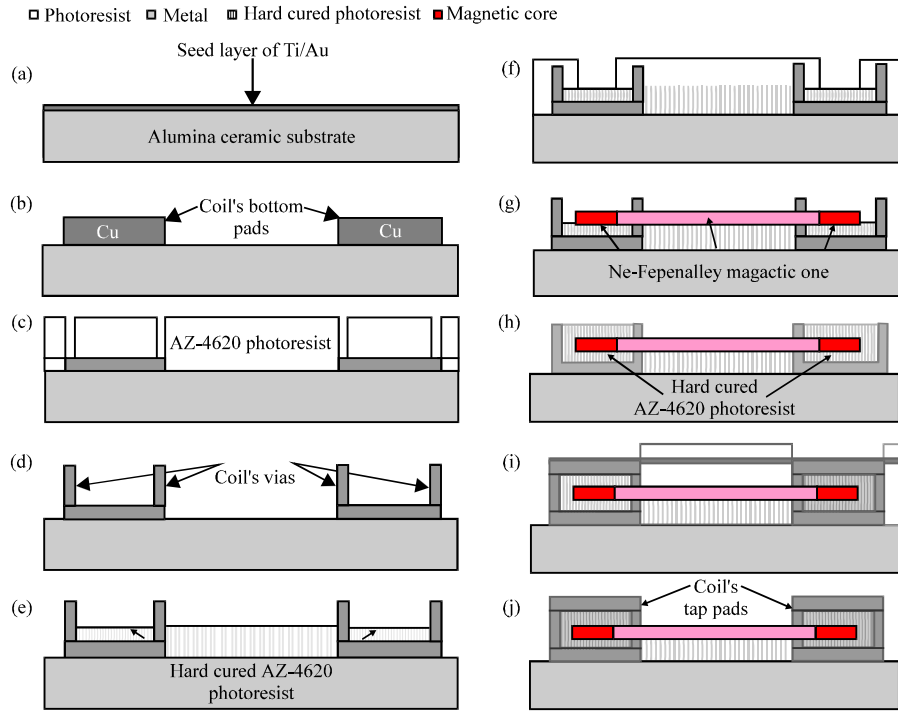
Fig. 4(a-j): Fabrication process steps of 3D micro-transformer (front view), (a) Sputtering a seed layer, (b) Electroplate coil's bottom pads, (c) Mold the vias holes, (d) Electroplate the coils vias, (e) Hard cure the AZ4620 photoresist, (f) Mold the Ni-Fe magnetic core, (g) Mold the Ni-Fe magnetic core, (h) Hard cure the AZ-4620 photoresist, (i) Electroplate the coil's top pads and (j) Remove the extra AZ-4620 photoresist using acetone

Table 1: Micro-transformer dimensional parameters

Parameters	Length (µm)
Core thickness (C_t)	7
Core width (C_w)	1020
Core side limb width (C_{slw})	240
Core insulation height (C_{ih})	24
Coil's top pads thickness (C_{tpt})	15
Coil's bottom pads thickness (C_{bpt})	15
Vias width (V_w)	60
Vias height (V_h)	25
Magnetic core width (M_w)	1020
Magnetic core side limb width (M_{slw})	240
Magnetic core side limb length (M_{sll})	2080
Magnetic core length (M_l)	2560
Coil's outer width (C_{ow})	480
Coil's inner width (C_{iw})	360
Coils separation (C_s)	300
Coil's pads width (C_{pw})	60
Coil's pads separation width (C_{psw})	50
Coil's pads length (C_{pl})	362
Transformer width (T_w)	1240

initial photoresist layer, followed by a second patterned photoresist layer to electroplate the ferrite magnetic core. A new layer of Ni-Fe Permalloy magnetic core with a 7 μm thickness was electroplated over the seed layer. The photoresist was then stripped and the seed layer was etched. A new layer of photoresist was again spun and hard cured to insulate the magnetic core from the vias and coil's top conductors. Then, a new photoresist layer was deposited and patterned to form the coil's top conductors. Afterward, the fourth seed layer was deposited and another patterned photoresist layer was deposited. The top-level conductor lines were electroplated, connecting the vias and thus concluding the coil and the micro-transformer fabrication. Finally, both of the photoresist and the seed layer were removed.

RESULTS

Figure 5a shows the microscope image of the fabricated MEMS micro-transformer (2560×1240 μm) that displays the magnetic core dimensions of (2560×1020 μm), coils lengths are 1980 μm for primary and 1160 μm for secondary coil and part of the wires connecting the transformer to its input and output terminals. Figure 5b is a 10X microscope image showing the coil's bottom pads, vias and the first layer of the hard cured AZ-4620 photoresist. Figure 6a shows the measurement values of the inductance for the coil with 18 and 10 turns consequently. The inductance value reaches as high as 164 μH for the large coil with N = 18 and 90 μH for the small coil with N = 10. Both coils had a very low DC resistance of 0.23 S and 0.12 S for the large and small coil consequently.

Inductance and reactance versus frequency: Agilent 4284A Precision LCR meter is used to measure inductance for the large (18 turns) and the small (10 turns) coils with respect to frequency range from 1 kHz to 1 MHz. Figure 6a shows the inductance versus frequency for a range starting from 1 kHz and ending at 1 MHz. The center of the optimum operating frequency is around the 10 kHz mark and gives an inductance of 58 μH for the large coil and 32 μH for the small one. Maximum inductance value achieved at 1 kHz frequency, 90 μH (small coil) and 164 μH (large coil). Inductance value for the both coils degrade gradually with the increment of the frequency, this is due to the nature of the magnetic core (80-20 Ni-Fe Permalloy) used in the
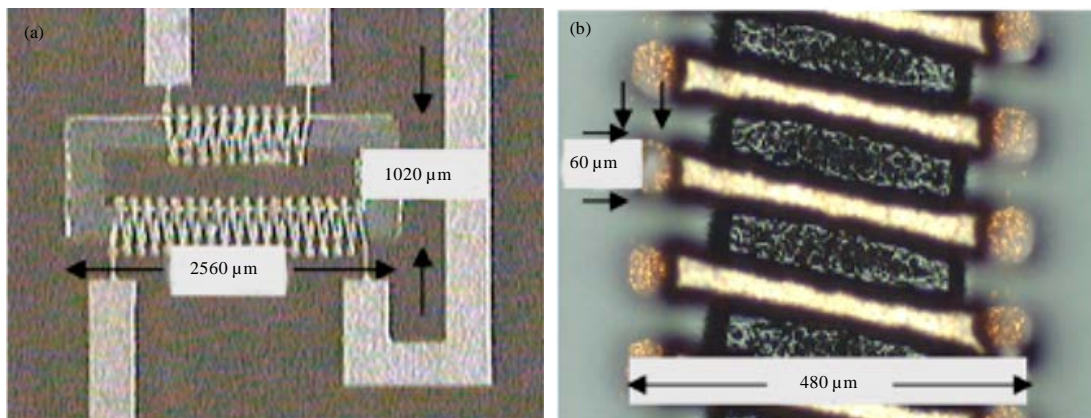

Fig. 5(a-b): (a) Fabricated MEMS micro-transformer and (b) 10X microscope image showing coil's bottom pads, the first layer of the hard cured AZ-4620 photoresist and vias
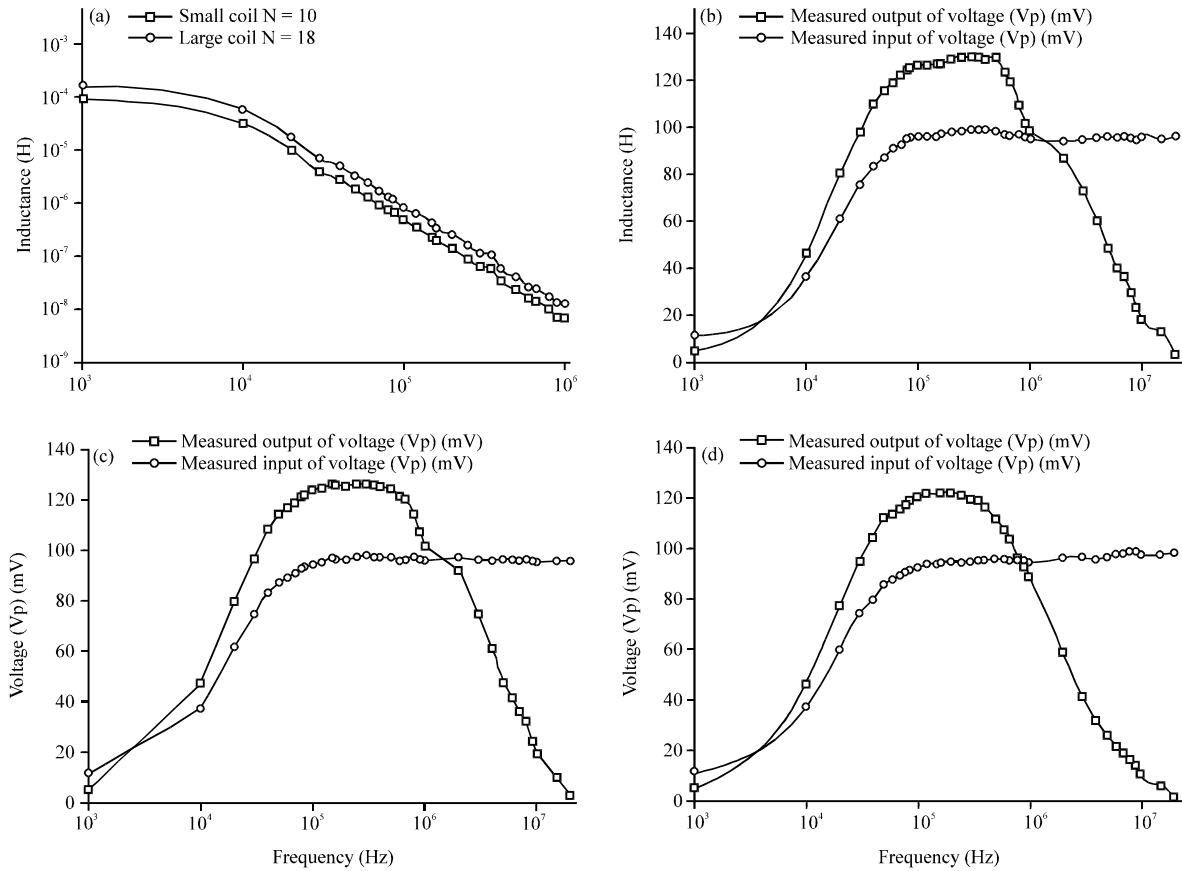
Fig. 6(a-d): (a) Inductance vs. frequency (b) Input and Output voltages vs. frequency (load = 1 kS) step-up (c) Input and Output voltages vs. frequency (load = 100 S) step-up (d) Input and Output voltages vs. frequency (load = 50 S) step-up

fabrication process that has a typical operating frequency range of 1-25 kHz. In addition, the eddy current, hysteresis losses and flux leakage effects due to the extremely small size of the transformer.

Output voltage versus frequency: The micro-transformer measured input and output voltage with respect to frequency. Figure 6b shows the measured input and output voltage across the primary and the secondary terminals with load resistor of 1 kS in step-up configuration, the micro-transformer achieved 73.75% efficiency at 50 kHz frequency range. Figure 6c shows the measured input and output voltage in step-up configuration with load resistor of 100 S. Figure 6d shows the measured input and output voltage in step-up configuration with load resistor of 50 S. The maximum transformation ratio efficiency in step-down configuration achieved is 63.24% at 10 kHz frequency with a load resistor of 100 S. The corresponding transformation ratio for step up and step down operation calculated are 13.27 and 0.351, respectively.

DISCUSSION

The fabricated 3D micro-transformer was designed targeting low frequency range applications. One potential application for example is integration with MEMS capacitive microphone. In

Table 2: Comparison with published micro-transformers

Reference	L_{max} (H)	R_{DC} (S)	F_{max} (MHz)
Current work (10 turns), 2015	90 µ	<1	0.6
Current work (18 turns), 2015	164 µ	<1	0.6
Mino *et al.* (1992)	800 n	7.7	40
Xu *et al.* (1998)	800 n	1.1	11
Rassel *et al.* (2003)	100 n	1.2	0.5
Wang *et al.* (2007)	400 n	0.48	20
Lu *et al.* (2008)	100 n	<1	300
Yunas *et al.* (2008)	35 n	23.7	60
Meyer *et al.* (2010)	500 n	10	125
Raimann *et al.* (2012)	370 n	2.6	100
Moazenzadeh *et al.* (2012) sample 1	372 n	3.93	40
Moazenzadeh *et al.* (2012) sample 2	199 n	2.81	40

comparison to other published research works, this 3D micro-transformer exhibits few advantages and disadvantages. All the recent research works surveyed from the published literature were found designed and fabricated to operate in high frequency range, i.e., above 1 MHz. In contrast, present 3D micro-transformer maximum operating frequency is only 600 kHz. This variation in the operating frequency range affects in making a straight comparison tremendously.

The inductance reported by Yunas *et al.* (2008), Rassel *et al.* (2003), Lu *et al.* (2008), Moazenzadeh *et al.* (2012), Raimann *et al.* (2012), Wang *et al.* (2007), Meyer *et al.* (2010), Mino *et al.* (1992) and Xu *et al.* (1998) are 35, 100, 100, 199, 370, 372, 400, 500 and 800 nH, respectively. While in this fabricated work the values achieved for the inductance were 90 and 164 µH for the 10 and 18 turns, respectively. Despite this large value, the inductance value will roll off gradually due to the magnetic core effect, reaching to the nH scale and by the increment of the frequency range as show in Fig. 6a. At the same time, the coil's resistance achieved was less than 1 S for both coils which is in consistence with other work presented in Table 2. This low resistance value is achieved by the usage of the bleached copper which was electroplated by the presence of sulfuric acid and the large cross sectional area for the wires that reaches up to 60×60 µm in most areas.

CONCLUSION

This study presented the fabrication of the MEMS 3D micro-transformer operating with high efficiency in the range of 10-600 kHz. The micro-transformer is characterized in terms of inductance versus frequency and input/output voltages versus frequency. For high frequency applications, a different magnetic core material can be used to operate properly with the desired and required values of frequencies.

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