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A new class of *LC*-resonator for micro-magnetic sensor application

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Abstract

A new class of *LC*-resonators for micro-magnetic sensor device was invented and fabricated by means of micro-electromechanical system (MEMS) technique. The micro-*LC*-resonator consists of a solenoidal micro-inductor with a bundle of soft magnetic micro-wire cores and a capacitor connected in parallel to the micro-inductor. The core magnetic material is a tiny glass-coated $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ micro-wire fabricated by a glass-coated melt spinning technique. The core materials were annealed at various temperatures 150, 200, 250, and 300 °C for 1 h in a vacuum to improve soft magnetic properties. The solenoidal micro-inductors fabricated by MEMS technique were 500–1000 μm in length with 10–20 turns. The changes of inductance as a function of external magnetic field in micro-inductors with properly annealed micro-wire cores were varied as much as 370%, since the permeability of ultrasoft magnetic micro-wire changes rapidly as a function of external magnetic field. The inductance ratio as well as magnetoimpedance ratio (MIR) in an *LC*-resonator was varied drastically as a function of external magnetic field. The MIR curves can be tuned very precisely to obtain maximum sensitivity.

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Keywords: MEMS; Micro-inductor; Magnetoimpedance; Micro-wires; *LC*-resonator; Magnetic sensors

1. Introduction

Recently, magnetic sensor utilizing the changes in permeability of core material located in a solenoidal inductor as a function of external magnetic field, called as PR (permeability ratio) sensor, has been studied intensively [1]. The recent research object for PR sensor is aiming at very high-sensitivity micro-magnetic sensor device operating at very high frequency. Since the high-frequency sources are easily available now-a-days in communication electronics, such as PCs, cellular phones, GPS, etc., it might be expected that the micro-inductor with micro-wire core could well be adapted to these electronics, being profitable due to good characteristics at high frequency in nature.

On the other hand, the advanced integrated circuit (IC) technologies and the consumer electronics markets have been growing very rapidly. The market is forecasting the further-reduced minimum feature size and fabrication cost, while increasing density of devices in the applications of the IC technologies. Tremendous efforts have been made to improve the process yield, functionality, and reliability of IC technology-based products. In contrast to the remarkable prosperity in the IC technologies and their markets, the micro-electromechanical systems (MEMS) have been emerging since around 1960s in the field of silicon sensors, and have blossomed into many applications. Such applications of MEMS range from automotive, electronics, defence, medical areas, to communications areas [2,3]. It may be inevitable to adapt the MEMS technology into the high-sensitivity magnetic sensor system to make micron-sized magnetic sensor device. In this study, we introduce a new class of *LC*-resonator consisting of a micro-inductor fabricated by means of MEMS technique with a bundle of soft magnetic micro-wire cores and a capacitor connected in parallel to the micro-inductor.

Since the permeability of micro-wire is changing as a function of external magnetic field, the inductance L of micro-inductor can change drastically according to the

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external magnetic field. Therefore, the resonance frequency of this *LC*-resonator can be sensitively shifted as the external magnetic field changes. The impedance of the *LC*-resonator can be adjusted by changing operating frequencies to get maximum sensitivity. The characteristics of the prototype micro-magnetic sensor device were also investigated.

2. Experimental

UV-LIGA process is a cost-effective process utilizing standard ultraviolet (UV) lithography with UV-sensitive resists to form thick polymer molds, and electroplating technique to build 3D micro-machined metallic MEMS. For low-cost MEMS fabrication, UV-LIGA process is available with photosensitive polyimide, a positive photoresist with high viscosity and high transparency, and an epoxy-based negative photoresist SU-8 [4,5] with the compensation of lower resolution and lower aspect ratio compared to the LIGA process. In this work, the negative photoresist SU-8 was used to develop UV-LIGA process for fabricating polymeric or metallic mold inserts. The process sequence is shown in Fig. 1.

The fabrication of the high-aspect-ratio inductor utilizes UV-LIGA surface-micro-machining technique, which includes the spin coating of photoresist, UV light exposure, and metal electroplating.

A 700 μm thick 3 in diameter Pyrex glass wafer with high resistvity ($\rho \approx 10^{10}\,\Omega$/cm) and low dielectric constant ($\varepsilon_r \approx 4.6$) was used as the substrate. Three seed layers consisting of chromium(~15 nm)/copper(~100 nm)/chromium(~10 nm) were evaporated onto the wafer.

A 10 μm thick SU-8 PR was spin-coated onto the wafer and UV-patterned after developing, and then copper electroplating was carried out for forming the bottom conductors. Second layer of SU-8 (75 μm in thickness) for creating via structure was spun onto the first PR layer; it was then patterned and subsequently electroplated with copper to form via structures. The final 10 μm SU-8 layer was spun and pattered, and electroplated to form the top conductors.

SU-8 mold layers were removed by using reactive ion etcher (RIE) with 20% CF_4 + 80% O_2 plasma and the seed layers were removed by wet-etch process.

The solenoidal micro-inductors fabricated by MEMS technique were varied from 400 to 800 μm in length with 10–20 turns.

The core magnetic material is a tiny glass-coated amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ micro-wires fabricated by Taylor–Ulitosky method. The diameter was about 16 μm and the thickness of the insulating glass coating was about 5 μm. The core materials were annealed at various temperatures 150, 200, 250, and 300 °C for 1 h in vacuum to improve soft magnetic properties.

The inductance and impedance measurements were carried out by a network analyzer (Agilent, 8712ET, 0.3 MHz–1.3 GHz) and an impedance analyzer (HP4191A, 1 MHz–1 GHz), both connected to a computer-controlled data acquisition system. An external DC magnetic field, applied in an axial direction, was swept through the entire cycle between −300 and +300 Oe.

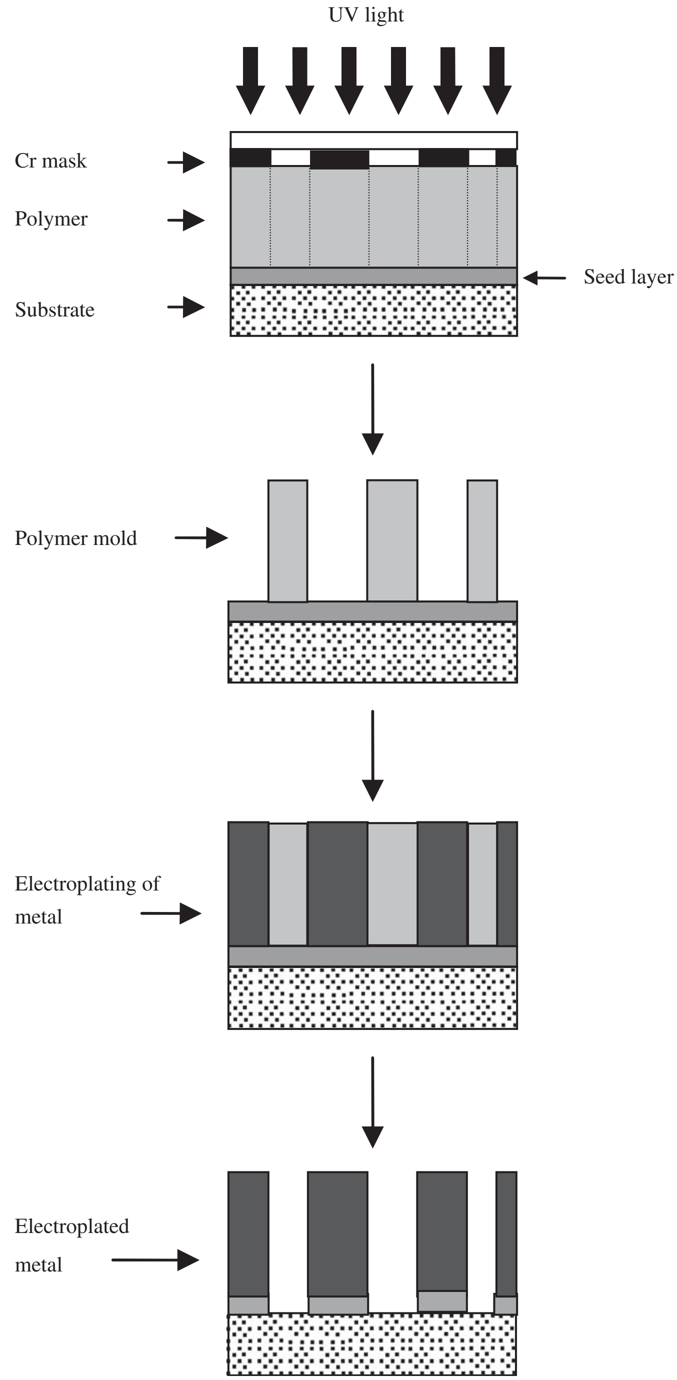

Fig. 1. A process sequence of the UV-LIGA technique.

3. Results and discussion

The fabricated micro-inductors on a Pyrex glass wafer by MEMS technique are shown in Figs. 2 and 3. Each wafer consists of 48 air-core micro-inductors with different dimensions. However, each set of 4 micro-inductors in a wafer has

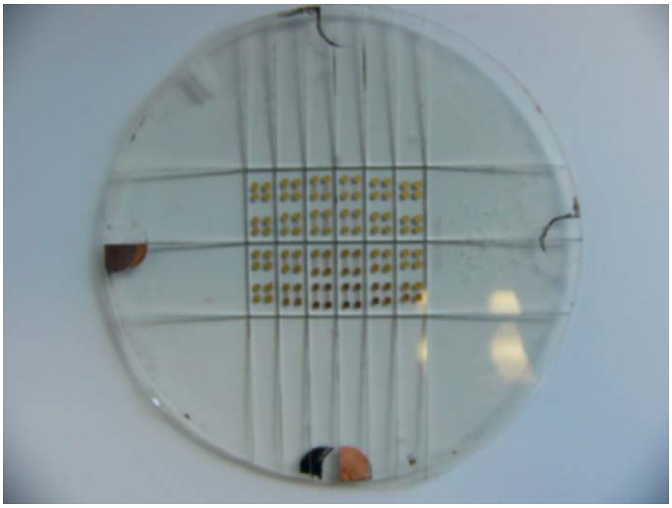

Fig. 2. Fabricated micro-inductors on a pyrex glass wafer by MEMS technique.

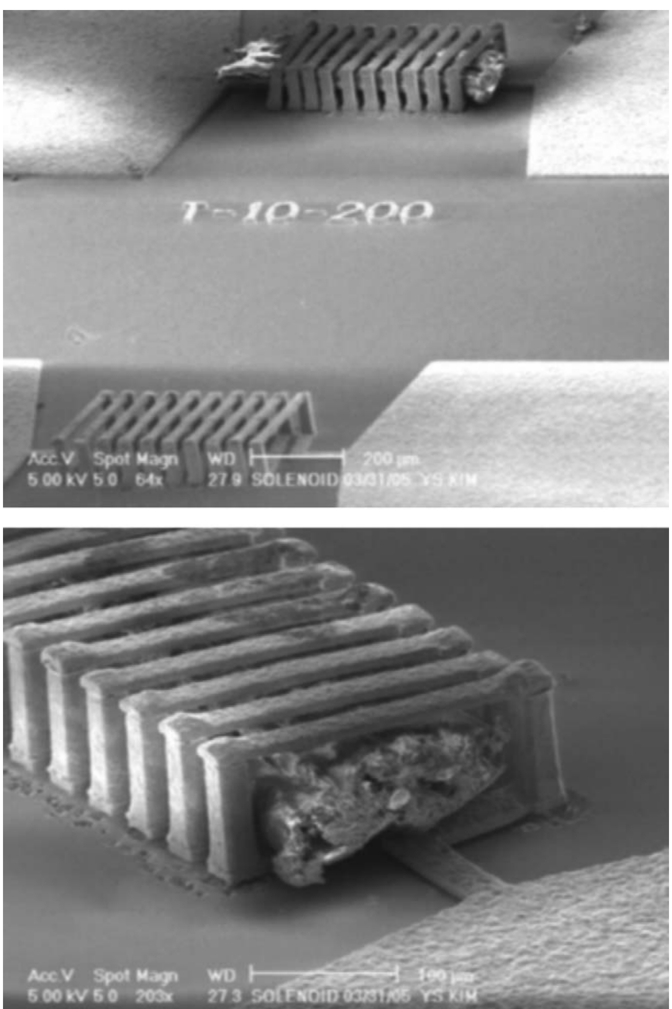

Fig. 3. Set of micro-inductors with and without micro-wires as a core (top); magnified photo of micro-inductors with 5 micro-wires core (bottom).

identical dimensions. We cut out each set of identical micro-inductors by laser cutting technique as shown in Fig. 2. Two micro-inductors among four in a set were inserted with micro-wires as a core material. Micro-inductors with and without micro-wires in a set are shown in Fig. 3.

We inserted 5 micro-wires into a micro-inductor as shown in Fig. 3 (bottom). After connecting leads to micro-inductors in a set to external IC terminal socket, the inductor sets was molded to reinforce mechanical strength by epoxy.

The changes of inductance as a function of external magnetic field in micro-inductors with annealed micro-wire cores at 150 °C for 1 h were varied as much as 370%. Since the incremental permeability of ultrasoft magnetic micro-wires is changing rapidly as a function of biased magnetic field, the resonance frequency, as well as inductance and impedance of the circuit can also change drastically.

The inductance ratio as a function of external magnetic field is shown in Fig. 4 for a micro-inductors with 10 turns, 200 μm width, 75 μm height and 500 μm length. One notes that the inductance ratios in the figure are just changes of inductance of micro-inductors in percentage between maximum and minimum values.

Therefore, the graph can be upside down depending upon choice of the minimum and maximum values of inductance. The maximum value of inductance ratio is about 370%.

The largest inductance ratio value can be obtained at optimal conditions for the design of solenoid and annealing micro-wires at certain frequency.

Fig. 5 shows the inductance ratio for micro-inductors with 20 turns, 200 μm width, 75 μm height and 1000 μm length. The maximum values are not as good as the previous one. The different size of solenoid will give totally different properties.

The reference inductance values at zero external magnetic field in Figs. 4 and 5 varied from 150 to 290 nH as a function of measuring frequencies from 10 to 100 MHz.

In order to construct a prototype sensor device, a capacitor of 300 pF is connected in parallel to the micro-inductor as shown in Figs. 2 and 3.

The resonance frequency as well as the current through the circuit is changing drastically according to the external magnetic field. The impedance vs. magnetic field curve was changing abruptly near the resonance frequency. The change of phase angle as much as 180° evidenced the occurrence of resonance. The resonance frequency can be tuned very precisely to obtain maximum sensitivity. Fig. 6 shows very large and sharp peaks obtained at 211.6 MHz. This frequency is almost double of the resonance frequency. The asymmetric shape in Fig. 6 is due to the low resolution at exact peak points in magnetic fields.

The magnetoimpedance ratio (MIR) for a micro-*LC*-resonator can be measured at various frequencies to find sharp peaks for maximum sensitivity. Even slight change in measuring frequencies can change MIR curves to totally different shapes, magnitudes, sensitivity, etc.

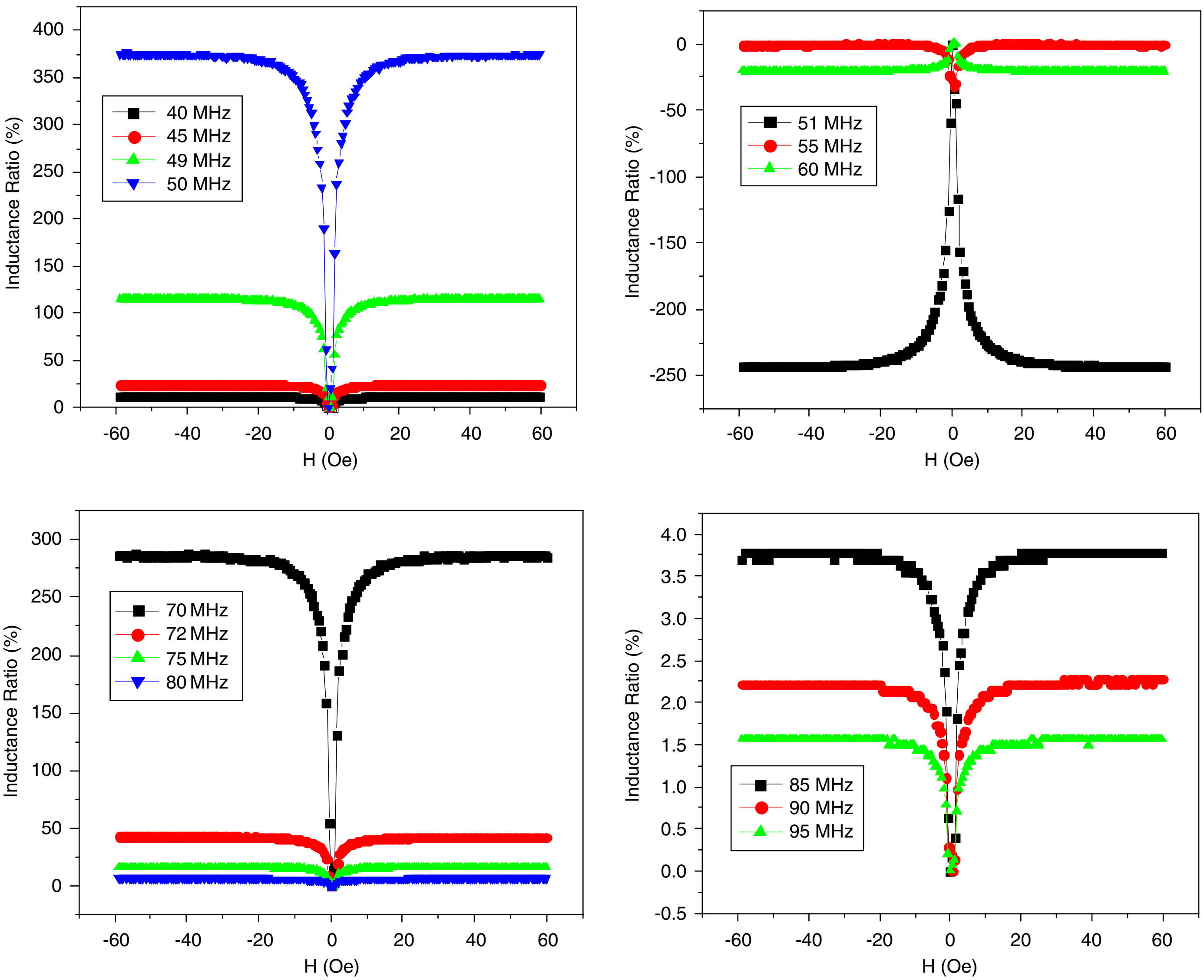

Fig. 4. Inductance ratio as a function of external magnetic field for micro-inductors with 10 turns, 200 μm width, 75 μm height, and 500 μm length.

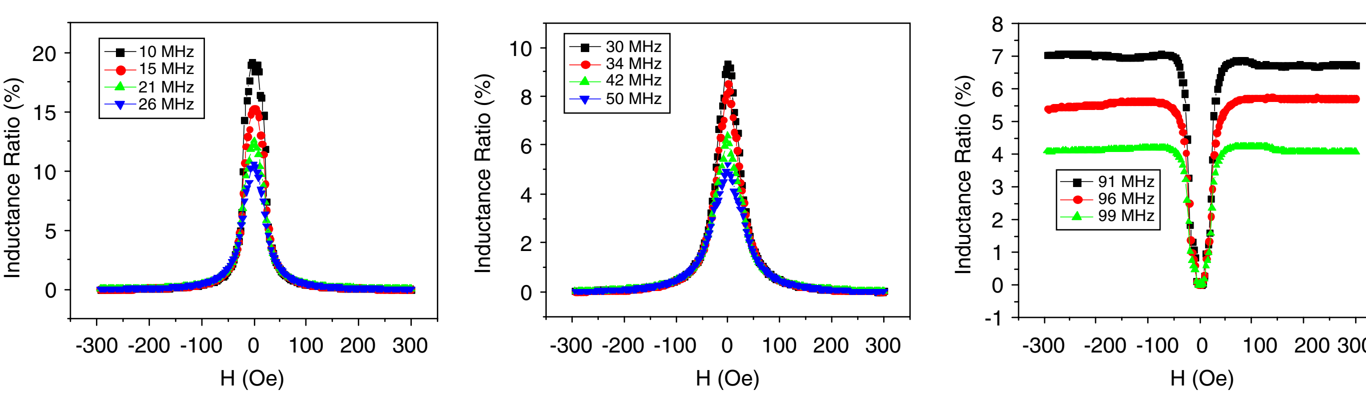

Fig. 5. Inductance ratio as a function of external magnetic field for micro-inductors with 20 turns, 200 μm width, 75 μm height, and 1000 μm length.

4. Conclusions

A new class of *LC*-resonator consisting of a solenoidal micro-inductor with micro-wire cores, and a capacitor connected in parallel to the micro-inductor, was invented and fabricated by adapting MEMS technique. The inductance ratio as well as MIR in a constructed *LC*-resonator was varied drastically as a function of external

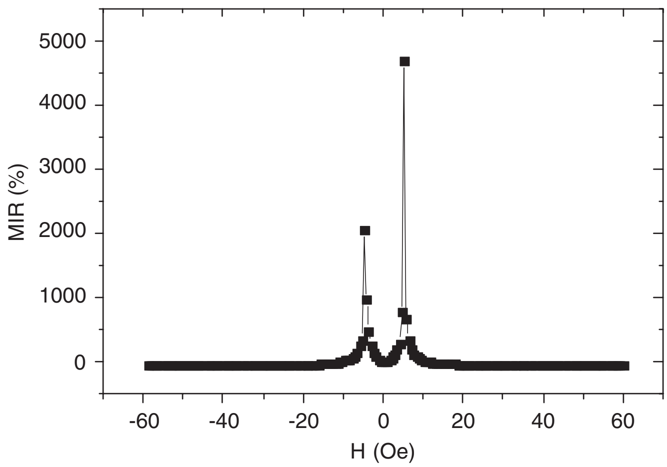

Fig. 6. Magnetoimpedance ratio for a micro-*LC*-resonator measured at 211.6 MHz.

magnetic field. The MIR curves can be tuned very precisely to obtain maximum sensitivity.

Acknowledgments

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