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A class of micromachined magnetic resonator for high-frequency magnetic sensor applications

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A class of *LC* resonators for micromagnetic sensor devices is reported, which is fabricated by means of the microelectromechanical system (MEMS) technique. The micro-*LC* resonator consists of a solenoidal microinductor with a bundle of soft magnetic microwire cores and a capacitor connected in parallel to the microinductor. The core magnetic material is a tiny glass-coated $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire fabricated by a glass-coated melt-spinning technique. The solenoidal microinductors fabricated by the MEMS technique were 500–1000 μm in length with 10–20 turns. The changes of inductance as a function of external magnetic field in microinductors with appropriately annealed microwire cores were varied as much as 370%. Because the permeability of ultrasoft magnetic microwire is changing rapidly as a function of external magnetic field, the inductance ratio as well as magnetoimpedance ratio (MIR) in a *LC* resonator is varied accordingly as a function of external magnetic field. The MIR curves can be tuned very precisely to obtain maximum sensitivity. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2163840]

I. INTRODUCTION

The aim of this study is finding microsized magnetic sensors with great sensitivity. These micromagnetic sensors can be well equipped with portable communication devices such as cellular phones, global positioning systems (GPS), industrial devices, etc. Recently a magnetic sensor utilizing the changes of permeability of the core material located in a solenoidal inductor as a function of external magnetic field, called the permeability ratio (PR) sensor, has been studied intensively.[1] Since the high-frequency sources are easily available nowadays in communication electronics such as personal computers (PCs), cellular phones, GPS, etc., the recent research objective for the PR sensor is aimed at achieving a very highly sensitive micromagnetic sensor device operating at very high-frequency region (VHF–UHF).

On the other hand, the microelectromechanical systems (MEMS) have been emerging since around 1960s in the field of silicon sensors, and are found in many applications. Such applications of MEMS range from automotive, electronics, defense, and medical areas to communications areas.[2,3] It may be inevitable to adapt the MEMS technology into the highly sensitive magnetic sensor system to make micrometer-sized magnetic sensor devices.

In this study we introduce a class of *LC* resonators consisting of a microinductor fabricated by means of the MEMS technique with a bundle of soft magnetic microwire cores and a capacitor connected in parallel to the microinductor to form a *LC* circuit. The solenoidal microinductors fabricated by the MEMS technique were 500–1000 μm in length with 10–20 turns. The glass-coated $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire used in this study was known to be one of softest magnetic materials in this class.

Because the permeability of the microwire changes as a function of external magnetic field, the inductance *L* of the microinductor can change according to the 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 the operating frequencies to get maximum sensitivity. The magnetoimpedance of the prototype micromagnetic sensor device was also investigated.

II. EXPERIMENT

The UV-lithography, electroplating and molding (LIGA) process is a cost-effective process utilizing standard ultraviolet (UV) lithography with UV-sensitive resists to form thick polymer molds, and the electroplating technique to build three–dimensional (3D) micromachined metallic MEMS. For low-cost MEMS fabrication, the UV-LIGA process is available with a 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 a lower resolution and a lower aspect ratio compared to the LIGA process. In this work, the negative photoresist SU-8 was used to develop the UV-LIGA process for fabricating polymeric or metallic mold inserts.

The fabrication of the high-aspect ratio inductor utilizes the UV-LIGA surface micromachining technique, which includes the spin coating of the photoresist, UV light exposure,

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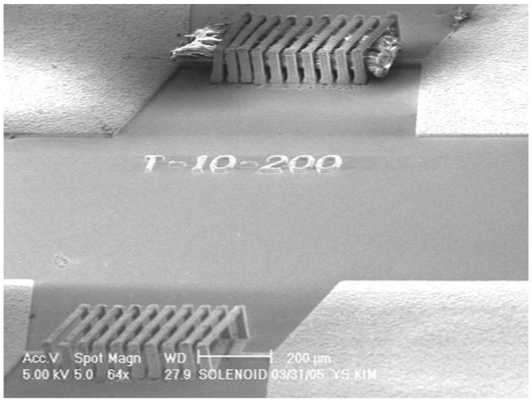

FIG. 1. Set of microinductors with and without microwires as a core.

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

A 10 μm thick of SU8 PR was spin coated onto the wafer and UV patterned after developing, and then copper electroplating was carried out to form the bottom conductors. The second layer of SU8 (75 μm in thickness) for creating the 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 SU8 layer was spun, patterned, and electroplated to form the top conductors. SU8 mold layers were removed by using a reactive ion etcher (RIE) with a 20% CF_4+80% O_2 plasma, and the seed layers were removed by wet etch process.

The solenoidal microinductors fabricated by the MEMS technique were varied from 500 to 1000 μm in length with 10–20 turns. The core magnetic material are tiny glass-coated amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwires fabricated by the Taylor-Ulitovskiy method.[6] 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 a vacuum to improve the 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.

III. RESULTS AND DISCUSSION

The fabricated microinductors on a Pyrex glass wafer by the MEMS technique are shown in Fig. 1. Each wafer consists of 48 air core microinductors with different dimensions. However, each set of four microinductors in a wafer has identical dimensions. We cut out each set of identical microinductors by the laser cutting technique. A bundle of microwires was inserted into two microinductors among four microinductors in a set as a core magnetic material. Microinductors with and without microwires in a set are shown in Fig. 1. We inserted five microwires into a microinductor as shown in Fig. 1 (upper). After connecting leads to the microinductors in a set to an external integrated circuit (IC) terminal socket, the inductor sets were molded to reinforce the mechanical structure with an epoxy.

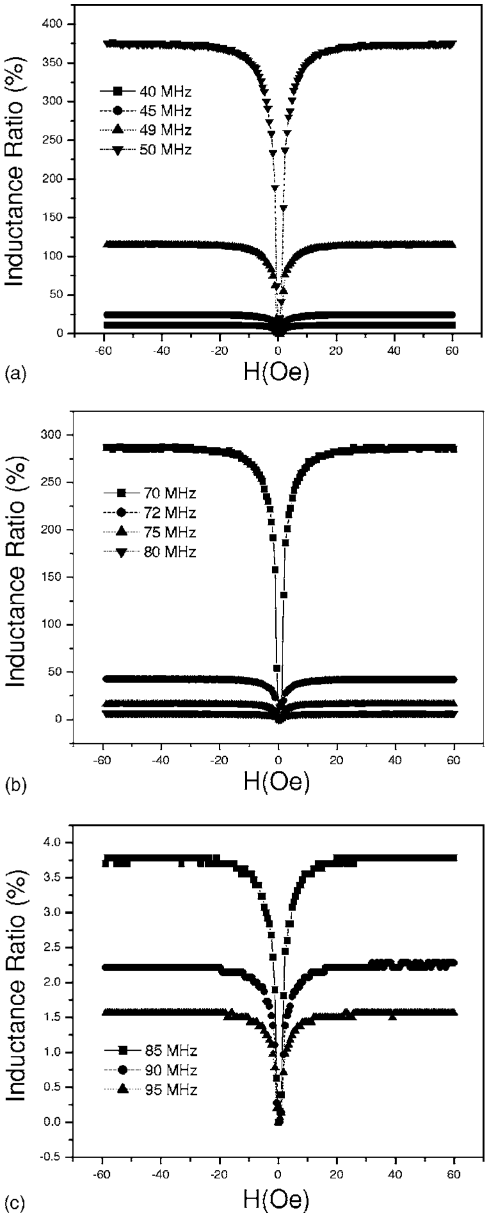

FIG. 2. Inductance ratio as a function of external magnetic field for microinductors with ten turns, 200 μm in width, 75 μm in height, and 500 μm in length.

The changes of inductance, called the inductance ratio (%), as a function of external magnetic field in the microinductors with annealed microwire cores at 150 °C for 1 h were varied as much as 370%. Since the incremental permeability of ultrasoft magnetic microwires is changing rapidly as a function of external 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 for microinductors with ten turns, 200 μm in width,

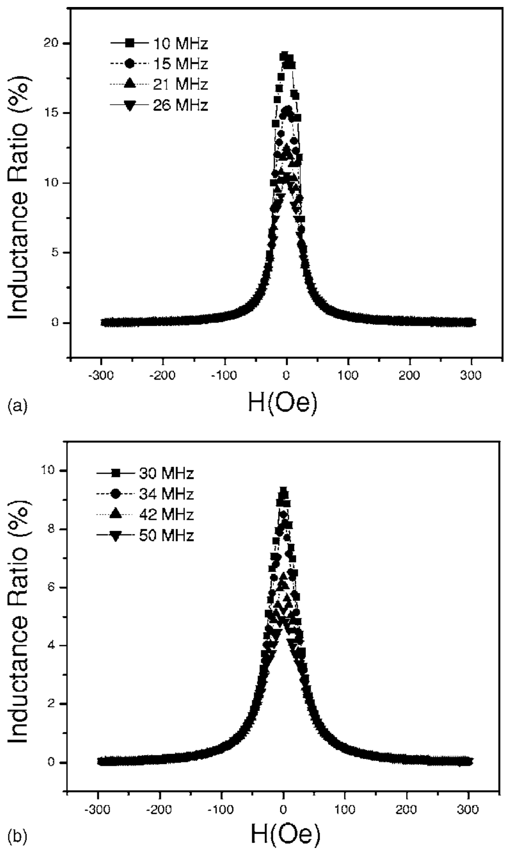

FIG. 3. Inductance ratio as a function of external magnetic field for microinductors with 20 turns, 200 μm in width, 75 μm in height, and 1000 μm in length.

75 μm in height, and 500 μm in length, is shown in Fig. 2. One notes that the inductance ratios in the figure are just changes of inductance of microinductors in percentage between maximum and minimum values. Therefore, the graph can be upside down depending upon choosing the minimum and maximum values of inductance. The largest inductance ratio value can be obtained at optimal conditions for the dimensions of solenoid and annealing microwires at chosen frequencies. The reference inductance values at zero external magnetic field in Fig. 2 varied from 290 to 150 nH as a function of measuring frequencies from 10 to 100 MHz.

Figure 3 shows the inductance ratio for microinductors with 20 turns, 200 μm in width, 75 μm in height, and 1000 μm in length. The maximum values are not as good as the previous one. The different size of the solenoid will give totally different specifications. Therefore the reference inductance or impedance value of each coil is not very important at this time for the primary investigation.

In order to construct a prototype sensor device, a capacitor of 300 pF is connected in parallel to the microinductor as shown in Fig. 1. A built-in capacitor in the micro-*LC* resonator could be included during the MEMS process for convenience.

The resonance frequency as well as the current through the circuit changes drastically according to the external magnetic field. The impedance versus magnetic field curve changes abruptly near the resonance frequency. The change of phase angle by as much as 180° proved the occurrence of resonance. The resonance frequency can be tuned very precisely to obtain maximum sensitivity.

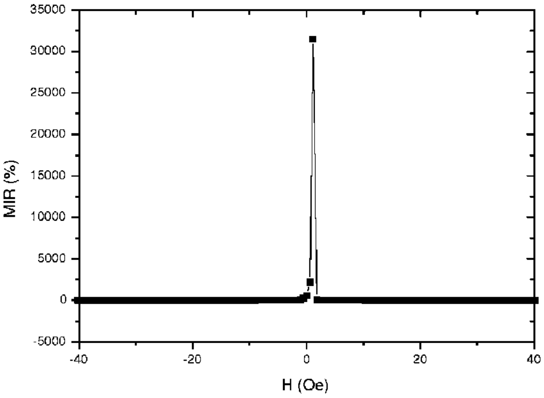

FIG. 4. Magnetoimpedance ratio curves for a micro-*LC* resonator measured at 105.8 MHz.

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 of measuring frequencies can change MIR curves to totally different shapes, magnitudes, sensitivity, etc.

Figure 4 shows very large and sharp peaks obtained at 105.8 MHz. The frequency is almost the resonance frequency. The MIR curves change very sensitively even with slight changes in the measuring frequencies. The very sensitive nature of the MIR curves near the resonance frequency with numerical simulations will be published elsewhere.

IV. CONCLUSIONS

A class of the prototype *LC* resonator consisted of a solenoidal microinductor with microwire cores and a capacitor connected in parallel to the microinductor is reported, which is fabricated by adapting the MEMS technique. The inductance ratio as well as MIR in a constructed *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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[1] Heebok Lee, Y. K. Kim, T. K. Kim, Y. H. Song, and S. C. Yu, J. Appl. Phys. **85**, 5429 (1999).
[2] G. T. A. Kovacs, *Micromachined Transducers Sourcebook*, 1st ed. (McGraw-Hill, New York, 1998).
[3] C. Hierold, Proc. IEEE **2000**, 1 (2000).
[4] K. Y. Lee, N. Labianca, S. A. Rishton, S. Zolgharnain, J. D. Gelorme, J. Shaw, and T. H.-P. Chang, J. Vac. Sci. Technol. B **13**, 3012 (1995) .
[5] Y. E. Chen, Y. K. Yoon, J. Laskar, and M. Allen, IEEE MTT-S Int. Microwave Symp. Dig. **2001**, 523.
[6] A. V. Ulitovskiy, Prib. Tekh. Eksp. **3**, 115 (1957)