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New Classes of *LC* Resonators for Magnetic Sensor Device Using a Glass-Coated Amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ Microwire

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New classes of *LC* resonators for micro magnetic sensor device were proposed and fabricated. The first type *LC* resonator (Type I) consists of a small piece of microwire and two cylindrical electrodes at the end of the microwire without direct contact to its ferromagnetic core. In type I resonator the ferromagnetic core of the microwire and cylindrical electrodes act as an inductor and two capacitors respectively to form a *LC* circuit. The second type *LC* resonator (Type II) consists of a solenoidal micro-inductor with a bundle of soft magnetic microwires as a core. The solenoidal micro-inductors fabricated by MEMS technique were 500~1,000 μm in length with 10~20 turns. A capacitor is connected in parallel to the micro-inductor to form a *LC* circuit. A tiny glass coated $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire was fabricated by a glass-coated melt spinning technique. A super-giant magneto-impedance effect was found in a type I resonator as much as 400,000% by precise tuning frequency at around 518.51 MHz. In type II resonator the changes of inductance as a function of external magnetic field in micro-inductors with properly annealed microwire cores were varied as much as 370%. The phase angle between current and voltage was also strongly dependent on the magnetic field. The drastic increments of magnetoimpedance at near the resonance frequency were observed in both types of *LC* resonators. Accordingly, the sudden change of the phase angle, as large as 180°C, evidenced the occurrence of the resonance at a given external magnetic field.

Key words : *LC* resonator, Magnetic sensor, Glass-coated microwire, Magnetoimpedance, Incremental permeability

1. Introduction

The aim of this study is finding a micro-sized magnetic sensors with great sensitivity. This micro magnetic sensors can be well-equipped with a portable communication devices such as cellular phone, GPS, industrial or military devices, etc. In this study we proposed and fabricated two new classes of *LC* resonators for micro magnetic sensor device. The first type *LC* resonator (Type I) consists of a small piece of microwire and two cylindrical electrodes at the end of the microwire without direct contact to its ferromagnetic core. In type I resonator the core ferromagnetic material of the microwire and cylindrical electrodes act as an inductor and two capacitors respectively to form a *LC* circuit. The second type *LC* resonator (Type II) consists of a solenoidal micro-inductor with a bundle of soft magnetic microwires as a core. 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 glass coated $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire was known to be one of softest materials in this class. Other soft magnetic microwire also can be a candidate for the *LC* resonator materials.

The type I resonator is a modified version of a magnetoimpedance (MI) sensor where the sensor material plays important role in *LC* resonance circuit. The MI phenomenon has a classical electromagnetic origin and is due to a simultaneous occurrence of the skin-effect and the changes of the transverse or circumferential permeability under the influence of an external dc-magnetic field applied along a magnetic element [1, 2]. As we increase the operating frequency to the VHF~UHF frequency regime, the skin depth due to high frequency ac current is becoming shorter and giving more beneficial to microwires [3]. Recently, it has been shown that this effect is of very large magnitude in tiny magnetic wires of

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a micrometer-diameter. One of difficult problems in MI sensor application in case of using a tiny glass coated microwire is peeling off its glass cover in order to connect the external circuit to the ferromagnetic core located at the center of microwire. Therefore we introduced two cylindrical electrodes at the end of the microwire without direct contact to its ferromagnetic core and without peeling off its glass cover [3].

The type II resonator consists of a solenoidal micro-inductor with a bundle of soft magnetic microwire cores. The solenoidal micro-inductors fabricated by MEMS technique were 500~1,000 μm in length with 10~20 turns. A capacitor is connected in parallel to the micro-inductor to form a *LC* circuit. Recently a magnetic sensor utilizing the changes of permeability of core material in a solenoidal inductor as a function of external magnetic field, called as PR (permeability ratio) sensor, has been studied intensively [4]. The recent research object for PR sensor is aiming at very high sensitive micro magnetic sensor device operating at very high frequency. The inductance *L* of micro-inductor can change drastically according to the external magnetic field. Therefore the resonance frequency of this *LC*-resonator can be sensitively shifted as an external magnetic field changes. The impedance of the *LC*-resonator can be adjusted by changing the operating frequencies to get maximum sensitivity. Since the high frequency sources are easily available nowadays in communication electronics such as PCs, cellular phones, GPS, etc. It might be expected that the micro-inductor with microwires core could well be adapted to these electronics, being profitable due to good characteristics at high frequency in nature. In this study we investigated the characteristics of the prototype micro magnetic sensor device.

2. Experiment

Glass-coated amorphous microwires of nominal composition $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ were fabricated using the Taylor-Ulitosky method. The diameter of the metallic core of the sample, measured in an optical microscope, was about 16 μm and the thickness of the insulating glass coating was equal to ~5 μm. The samples were annealed for 1 hour in vacuum at various temperatures in the range of 100~400 °C in order to settle the optimum annealing conditions to achieve the best magnetic softness by reducing residual internal stress.

The type I *LC*-resonator consisted of the microwire and two cylindrical electrodes at the end of the microwire without the direct contact to its ferromagnetic core. The length of wire was about 15 mm and the width of the electrodes was about 2 mm, respectively. The electrodes play a role of capacitors in the *LC*-resonance circuit. MI measurements were carried out along the sample axis under a dc longitudinal applied magnetic field. The frequency of the ac current was varied from 1 MHz to 1 GHz.

The external dc field, applied by a solenoid, was swept through the entire cycle equally divided by 800 intervals from −120 Oe to 120 Oe. The magneto-impedance ratio (MIR) can be defined as $MIR(H) = \Delta Z/Z(H_{max}) = 1 - |Z(H)/Z(H_{max})|$, where H_{max} is an external magnetic field sufficient for saturating the magnetoimpedance. In the present experiment H_{max}=120 Oe. This equation was applied to calculate the magnetoimpedance ratio, MIR, using the data obtained in the experiment.

For type II *LC* resonator we utilized MEMS technology to make micro-inductors. The UV-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 3-D micromachined metallic MEMS. For low-cost MEMS fabrication, the 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 [5, 6] 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 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 photoresist, UV light exposure, and metal electroplating. A 700 μm thick 3" diameter Pyrex glass wafer with high resistvity ($\rho \approx 10^{10}$ Ω/cm) and low dielectric constant ($\varepsilon_r \approx 4.6$) was used as a substrate. Three seed layers consisting of chromium (~15 nm)/copper (~100 nm)/cromium (~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. Second layer of SU8 (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 SU8 layer was spun, patterned, and electroplated to form the top conductors. SU8 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 400~800 μm in length with

10~20 turns.

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 Oe and +300 Oe.

3. Results and Discussion

3.1. Type I *LC* resonator

It was found that the sample annealed at 180 °C displayed best magnetic softness and, therefore this wire-specimen was used in the experiment. Fig. 1 shows the MIR curves calculated using the experimental data obtained at different frequencies and plotted as a function of the external axial dc-field. As can be clearly seen in Fig. 1, the maximum value of MIR increases drastically with an increase of the frequency up to 518 MHz. This is mainly due to a decrease of the penetration depth, the value of which is, at the frequencies used in the experiment, smaller than 1 μm as estimated. The dominating contribution to the effective permeability comes either from the rotation of magnetization or from the domain wall motion [7]. In general, depending on the frequency, three main mechanisms of the giant-MI (GMI) effect can be distinguished, namely: (i) at relatively low frequencies the changes of the impedance are entirely ascribed to the magneto-inductive effect arising from the circular magnetization processes, (ii) at high frequencies, the skin effect becomes dominant because of the large permeability, and (iii) at very high frequencies, a motion of domain walls is totally damped and the permeability rapidly decreases until the resonance phenomena are reached [8]. Because of the frequencies of the ac-current flowing along the wire-sample are very high, the obtained experimental dependencies of GMI can be interpreted in accordance with the case (iii), where the domain walls are immovable. Therefore, the MIR curves obtained at below 400 MHz can be understood considering the above case. At frequencies above 400 MHz, a dramatic increase of the MIR value is observed, owing to the occurrence of the resonance. At very high frequency range, the sample behaves like a *RLC*-electric circuit, where *R* is its resistance, *L* the inductance and *C* the capacitance. Therefore, the resonance frequency of the sample can be given by well-known expression

$$\omega_r(\omega, H) = \frac{1}{\sqrt{L(\omega, H)C}} \tag{1}$$

where ω is the angular frequency of the ac-current flowing along the wire-sample.

It is worth noting that the shape of MIR curves at very high frequency can be explained in terms of *LC*-resonance circuit and ordinary MI effect. However, a

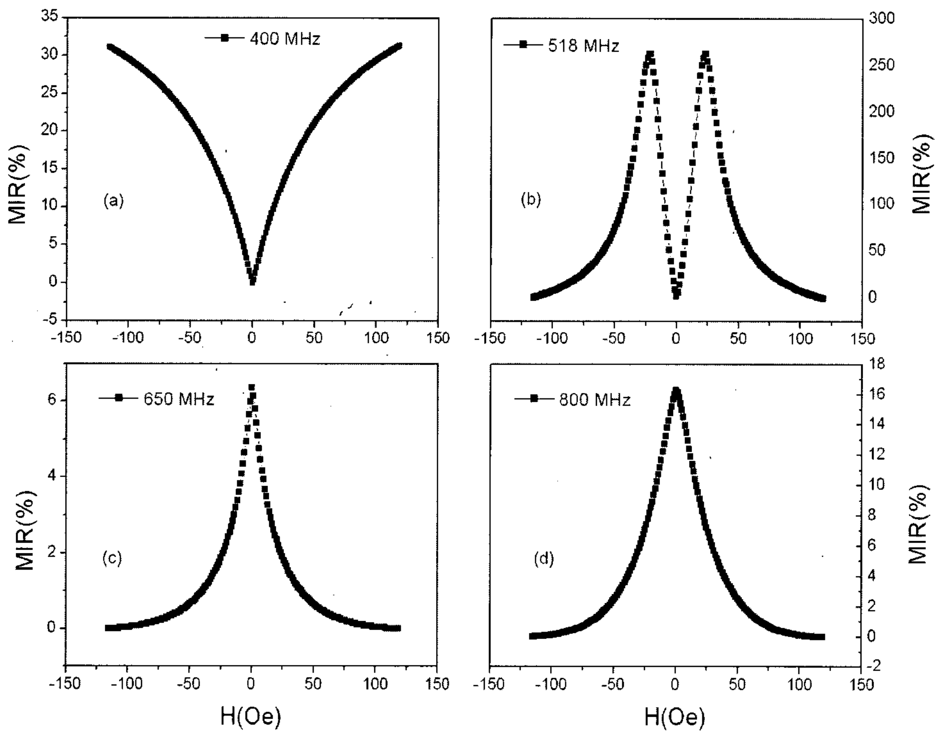

Fig. 1. MIR curves measured at various frequencies (a) 400 MHz, (b) 518 MHz, (c) 650 MHz, and (d) 800 MHz.

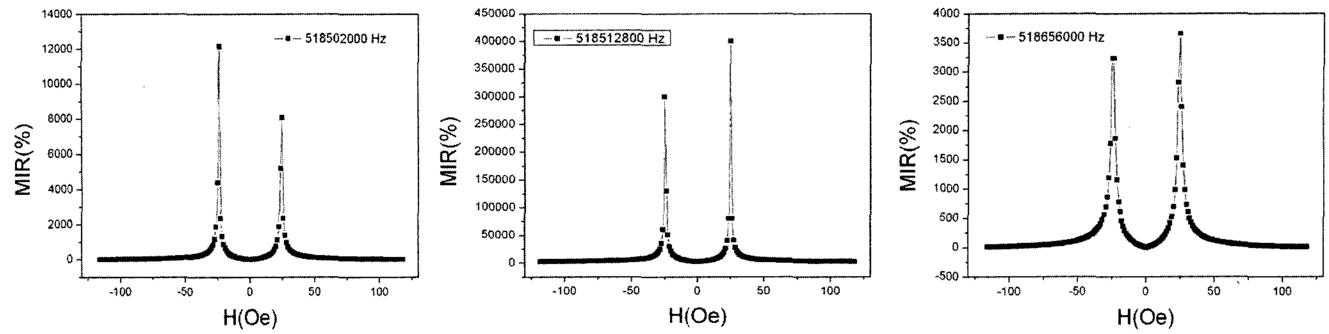

Fig. 2. MIR curve measured at 518,502,000 Hz, 518,512,800 Hz, and 518,656,000 Hz, respectively.

drastic increase of the ac-current takes place at the resonance frequency. This effect was not taken into account in the calculated experimental data of the impedance. The large current generates large circumferential magnetic ac-field in the wire-sample resulting in an increment of the circumferential permeability, μ_Φ. Therefore, a drastic rise of the magneto-impedance in the vicinity of the resonance frequency can be expected. This is clearly visible in the MIR-curve measured at 518 MHz (see Fig. 1).

In particular, the sudden changes of MI at near the resonance frequency are extraordinary. The dramatic change of MIR values reached in the experiment as much as 12,000% at 518,502,000 Hz, 400,000% at 518,512,800 Hz, and 3,800% at 518,656,000 Hz, respectively as shown in Fig. 2. The best maximum value of MIR of 400,000% was observed by precise tuning frequency with 100 Hz resolution at the resonance frequency as shown in Fig. 2. Accordingly, the sudden change of the phase angle, as large as 180 °C, evidenced the occurrence of the resonance at a given intensity of the external dc- magnetic field as shown in Fig. 3. It should be mentioned that the super-giant MI effect can be observed by precise tuning frequency around the resonance frequency. Furthermore, this extraordinary change of MI cannot be explained in terms of LC-resonance only. Because the sharpness of resonance peaks varies periodically at around the resonance frequency. These phenomena could be explained in terms of a ferromagnetic resonance in an ultra-soft magnetic microwire.

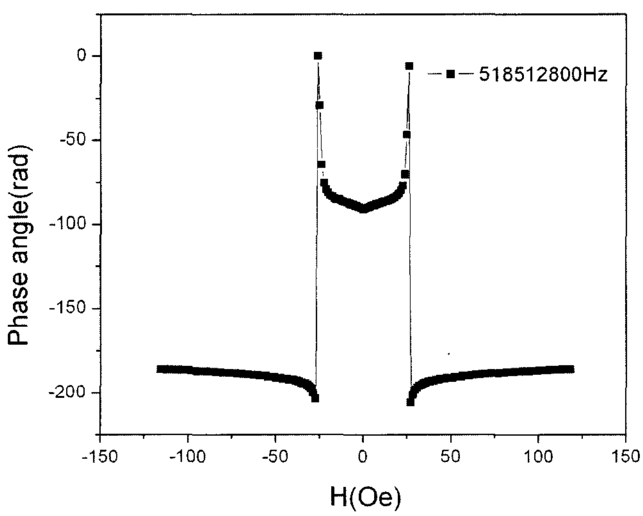

Fig. 3. Phase angle curve measured at 518,512,800 Hz.

3.2. Type II *LC* resonator

The micro-inductors on a Pyrex glass wafer was fabricated by MEMS technique. Each wafer consists of 48 air core micro-inductors with different dimensions. However, each set of 4 micro-inductors in a wafer has identical dimensions. We cut out each set of identical micro-inductors by the Laser cutting technique. Two micro-inductors among four micro-inductors in a set were inserted microwires as a core magnetic material. A micro-inductors with and without microwires in a set is shown

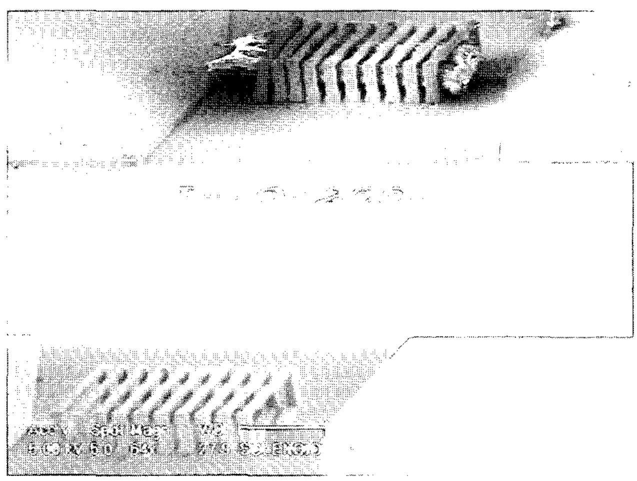

Fig. 4. Set of micro-inductors with and without microwires as a core magnetic materials.

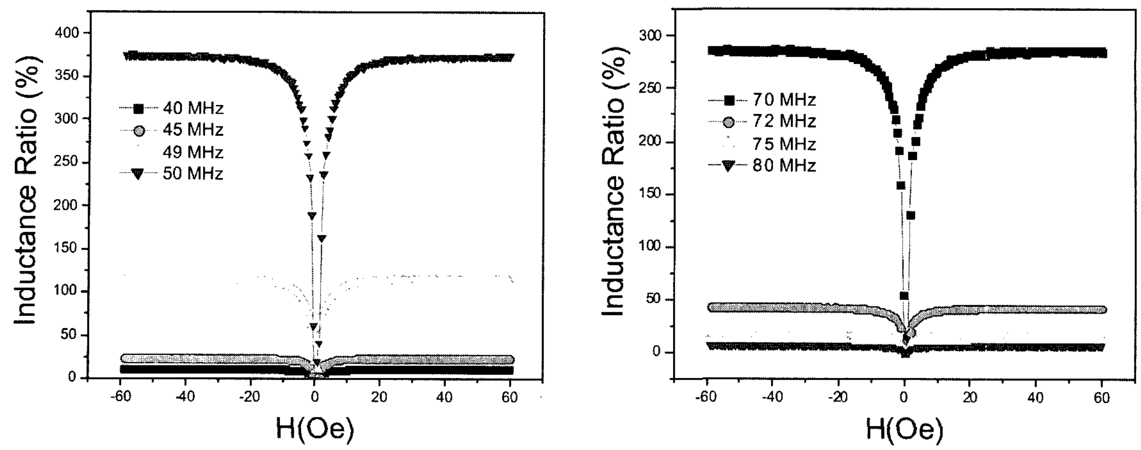

Fig. 5. Inductance ratio as a function of external magnetic field for micro-inductors with 10 turns, 200 μm in width, 75 μm in height, and 500 μm in length.

in Fig. 4. We inserted 5 microwires into a micro-inductor. After connecting leads to micro-inductors in a set to external IC terminal socket, the inductor sets was molded to reinforce mechanical structure with an Epoxy.

The changes of inductance, called as inductance ratio (%), as a function of external magnetic field in micro-inductors with annealed microwire cores at 150 °C for 1 hour were varied as much as 370%. Since the incremental permeability of ultra soft magnetic microwires 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 for a micro-inductors with 10 turns, 200 μm in width, 75 μm in height, and 500 μm in length, is shown in Fig. 5. The largest inductance ratio value can be obtained at optimal conditions for the dimensions of solenoid and annealing microwires at chosen frequencies as much as 350%. The different size of solenoid will give totally different specifications.

In order to construct a prototype sensor device a capacitor of 300 pF is connected in parallel to the micro-inductor. 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 is changing drastically according to the external magnetic field. The impedance vs. magnetic field curve was changing abruptly at near the resonance frequency. The change of phase angle as much as 180 degree evidenced the occurrence of resonance. The resonance frequency can be tuned very precisely to obtain maximum sensitivity.

The magneto-impedance 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 6 shows very large and sharp peaks obtained at 105.8 MHz and 211.6 MHz. These frequencies are almost

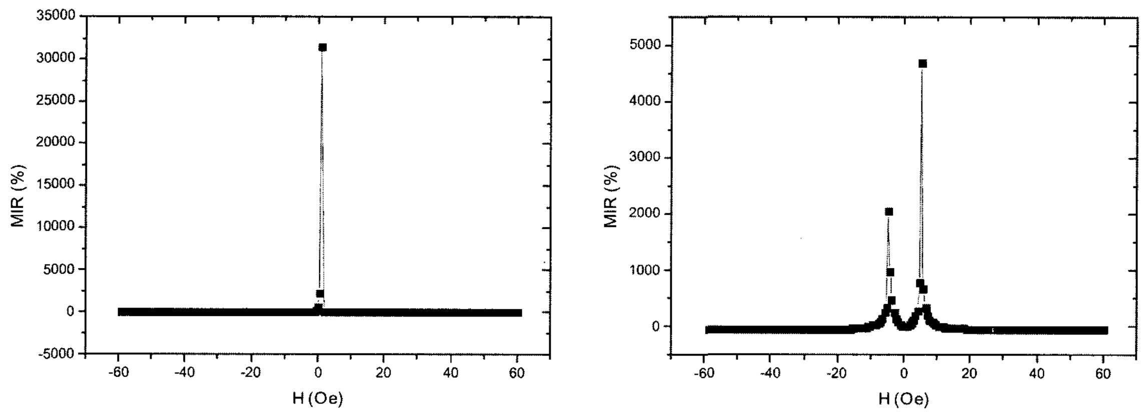

Fig. 6. Magnetoimpedance ratio curves for a micro-*LC* resonator measured at 105.8 MHz and 211.6 MHz.

single and double of the resonance frequency, respectively. The MIR curves are changing very sensitively even with slight changes of measuring frequencies. The details of the changes of MIR curves and numerical simulations with slight changes of measuring frequencies will be published elsewhere.

4. Conclusions

In this work, we developed new classes of *LC* resonators, namely the type I and type II *LC* resonators, using amorphous $Co_{83.2}B_{3.3}Si_{5.9}Mn_{7.6}$ microwire in a very high frequency range from 100 MHz up to 1 GHz.

For the type I *LC* resonator cylindrical electrodes at the end of microwire to form a *LC* circuit were introduced. The maximum value of MIR reached in the experiment equals 400,000% at the frequency of around 518.51 MHz.

For type II *LC* resonator a solenoidal micro-inductor fabricated by utilizing MEMS technique with microwire cores and a capacitor connected in parallel to the micro-inductor were introduced. 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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