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3D integrated coreless microtransformer processed by femtosecond laser micro/nano fabrication

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Abstract

Electronic and information hardware is developing in the direction of lightweight products, miniaturization, and integration. The transformer is still the most effective solution for signal isolation and power transfer. In response to the key problems of microtransformer fabrication, this paper presents a hybrid method for fabricating micro/nano structures via femtosecond laser wet etch technology and liquid metal microinjection. This research aims to develop a new method of creating an integrated microtransformer, offering an effective solution for the fabrication of widely applicable 3D integrated complex structures. The embedded 3D microtransformer can be easily integrated with other microelectrical, mechanical, and optical systems, with potential applications in MEMS, sensors and lab-on-chips.

Keywords: microtransformer, femtosecond laser, galinstan

(Some figures may appear in colour only in the online journal)

1. Introduction

With continued developments in electronic and information technology, electronic and information hardware is developing in the direction of lightweight products, miniaturization, and integration. The demand for functional and technical unit devices required in a single device has also increased exponentially. As a typical metal microdevice, the microtransformer has been widely used in integrated circuits and microelectronics. Microtransformers are mainly applied in portable electronic products such as mobile phones, notebooks, and e-paper. With the advancement of miniaturized portable products, the demand for on-chip efficient power supplies is increasing almost daily. The transformer is still the most effective solution for signal isolation and power transfer. Therefore, a great deal of research [1–3] is still being conducted to address the issue of miniaturizing high power-density and efficient transformers for on-chip power supplies.

In terms of the miniaturization process of transformers, the comparison data shows that the working frequency of the transformer with a magnetic core is lower. The size of transformers with a magnetic core is larger, and the processing steps are relatively difficult [4–8]. In contrast, coreless microtransformers are easier to miniaturize, highly integrated, and perform better in the high-frequency field. At present, the majority of planar microtransformers in the research arena are fabricated by the MEME process [6, 9–11] or the LIGA process [12–15]. These processes are complex, and the fabrication time is long. The coils exhibit low inductance and quality, and the magnetic field distribution is uneven, which limits the application range of such microtransformers. The three-dimensional microtransformer possesses the advantages of uniform magnetic field distribution, small size, and high conversion ratio, but the preparation of the three-dimensional microtransformer still poses a technical problem.

In our previous studies [16–18], we proposed the fabrication of complex 3D microcoils in fused silica using femtosecond laser wet etch (FLWE) technology and a metal microsolidification process. This single-microcoil fabrication method provides new ideas for and solutions to the processing problems inherent in the realization of workable miniaturized 3D microtransformers in fused silica.

In this paper, we use a liquid metal called galinstan instead of the gallium metal used in our previous work, owing to the fact that gallium metal is prone to fuse when high current loaded. Experimental results show that when the galinstan is heated to 100 °C, the microcoil structure still guarantees current conduction, ensuring the stability and reliability of the chip. In addition, the galinstan also has better fluidity, and can effectively solve the problem of gallium metal blocking in the microsolidifying process. The application of galinstan improves the success rate of chip preparation and the electrothermal performance of the chip.

In accordance with the performance and application requirements of the microtransformer, the structural design and parameter optimization are constantly adjusted to increase the voltage conversion ratio of the transformer. The fabrication of multi-structure microtransformers realizes three-dimensional integration in space, and improves the integration degree of devices. This greatly reduces the microtransformer size, and renders the electrical signal detection faster and more effective. Based on this approach, it will be possible for the miniaturized microtransformer to be integrated with other microfluidic devices.

In this paper, on the basis of improvements in the femtosecond laser wet etch technology and the liquid metal injection processing, two kinds of miniaturized transformers are achieved. We design two coreless transformer models, a solenoid microtransformer and a toroidal microtransformer, and test the performance and parameters of both. The most important aspect of this development is that the test results show that the microtransformer displays ultrafast response speeds and good capability for the transformation of high-frequency electrical signals. What is more, we also fabricate a turns-adjustable microtransformer, which enables more flexible control of the microtransformer signal.

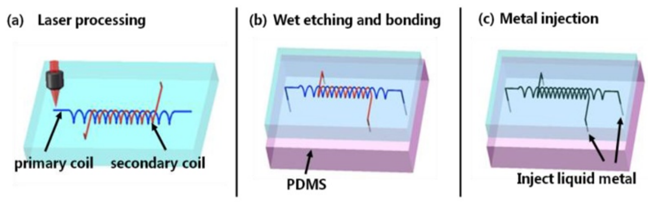

Figure 1. Schematic diagram of the fabrication process.

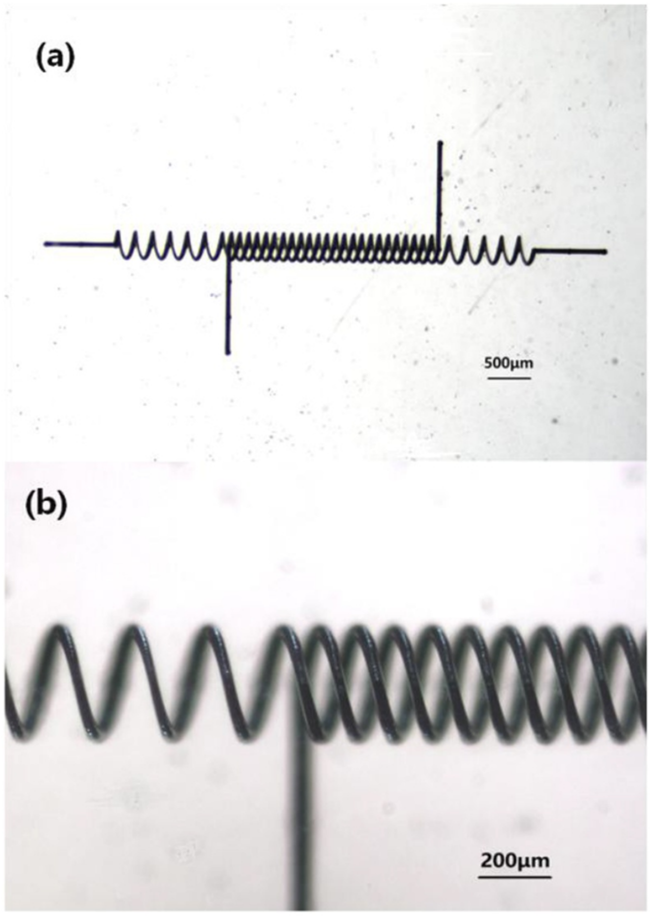

Figure 2. (a) Optical microscope image of microtransformer. (b) Locally enlarged image of microtransformer.

2. Experiment

The fabrication of a microtransformer is an integrated manufacturing process. The microtransformer manufacturing process includes two steps: the production of 3D microchannels, and the injection of metal galinstan into the channels in the fused silica (figure 1). Firstly, the microchannel structure for metal injection is prepared. Then galinstan is injected into microchannel structure to form metal microcoils.

The femtosecond laser micromachining system is used to fabricate the microchannels via a femtosecond laser source (wavelength: 1030 nm, pulse duration: 130 fs, repetition rate: 10 kHz), a microscope objective (NA = 0.9, 100×), a programmable three-axis stage (H101 A ProScan II Upright Stage; Prior Scientific), a charge-coupled device camera, and a laser beam control system. The microchannel was fabricated embedded in a fused-silica substrate (1.0 cm × 1.0 cm × 1 mm). The channel was laser-etched by moving the 3D stage along the pattern path at a speed of 100 μm s^{-1}. The laser power was adjusted from 40 mW to 60 mW by a computer-controlled attenuator with temporal modulation of the power compensation. Instead of linearly polarized laser light, circularly polarized laser light is used in the manufacture of complex 3D microchannels with a high etching rate [19, 20]. The geometry of the channel, the height, and the pitch circle diameter of the helix can all be controlled by computer.

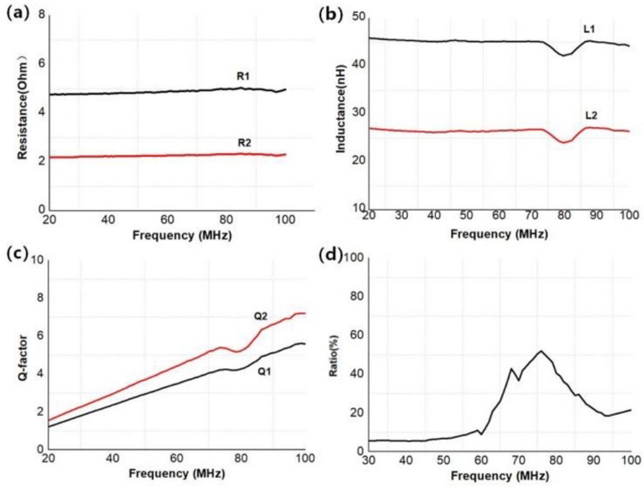

Figure 3. (a)–(d) The relationship of resistance value, inductance value, quality factor and voltage conversion ratio of the coil with frequency, respectively.

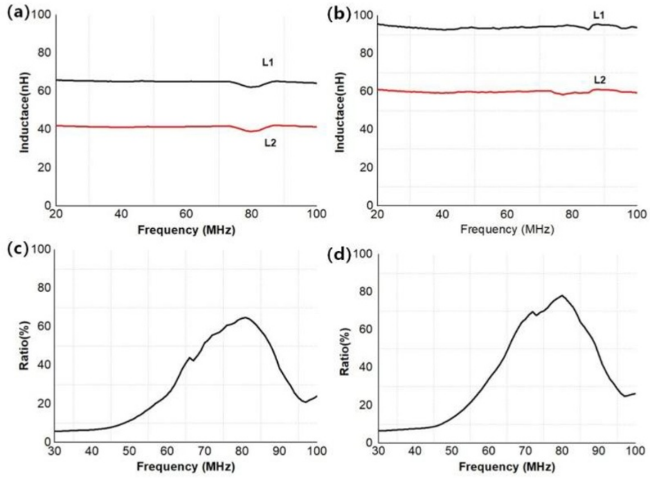

Figure 4. (a), (c) The relationship of inductance value and voltage conversion ratio of the coil with frequency (R = 200). (b), (d) The relationship of inductance value and voltage conversion ratio of the coil with frequency (R = 250).

Secondly, we used two-step wet etch. The sample was immersed in an ultrasound-assisted solution of 5% hydrofluoric acid (HF) for 1 h. We call this process pre-etching. This allows the entire femtosecond laser-irradiated pattern to have sufficient, but not intense, contact with the HF. The sample was then placed into another solution of 10% HF for about 2 h, thereby obtaining a hollow spiral channel with a dimension of 40 μm. With this approach, it is possible to improve the uniformity and smoothness of the microchannel inner wall to reduce the flow resistance of liquid materials [21].

To create the connector for the injection process, the fused-silica sample was placed on a prepared polydimethylsiloxane (PDMS) film. We optimally treated the PDMS substrate and the silica chip with oxygen plasma for 80 s, before bonding them together under room temperature conditions. Finally, two syringe needles were inserted into the PDMS film at the entrance of the channel, to connect all the channels. Next, the galinstan was injected into the manufactured helical microchannel to achieve conductive microcoils. In this process, liquid galinstan is injected at one side of the coil by a syringe pump at a low speed, while, being sucked out by a suction pump at another point. Thus, the entire PCR microfluidic chip is integrated.

3. Result and discussion

3.1. Solenoid microtransformer

Figure 2 shows an optical micrograph of the microtransformer. The microtransformer consists of two staggered coils, consisting of 24 turns of primary coil and 12 turns of secondary coil. The ideal voltage conversion ratio is 2:1. The microchannel diameter is about 40 μm and the radius of the microcoil is 150 μm. The lengths of the primary coil and the secondary coil are 4800 μm and 2400 μm, respectively.

The inductance and resistance of the microtransformer is measured by an impedance analyzer (Agilent, 4294 A), and the voltage ratio is measured by digital phosphor oscilloscope (Tektronix, DPO 3012). We measured the inductances of the microtransformer, finding that the average is 45.1nH for the primary coil, and 26.5nH for the secondary coil. In terms of the resistance of the microtansformer, the average is 4.81 Ω in the primary coil, and 2.13 Ω in the secondary coil. The relationship of resistance value *R*, inductance value *L*, quality factor *Q,* and voltage conversion ratio *k* of the coil with frequency is shown in figure 3. The relationship between quality factor *Q* of the primary or secondary coil, inductance *L,* and resistance *R* is shown in equation (1):

$$Q = \frac{2\pi fL}{\mathrm{R}}. \tag{1}$$

During the test, sinusoidal voltage U_1 was loaded on both ends of the primary coil of the microtransformer, and the secondary coil generated induced voltage. The induced voltage generated under ideal conditions is U_2. In the actual measurement, the voltage at both ends of the secondary coil is U'_2. The voltage conversion ratio of the microtransformer is shown in equation (2):

$$k = \frac{U2'}{U2}. \tag{2}$$

The test results in figure 3(d) indicate that the conversion ratio of the microtransformer is in the frequency band from 20 MHz to 100 MHz, and the maximum conversion ratio is 50%. These results did not meet expectations, due to the low mutual inductance of the primary and secondary coils of the microtransformer. Therefore, in order to further improve the conversion ratio of the microtransformer, mutual inductance

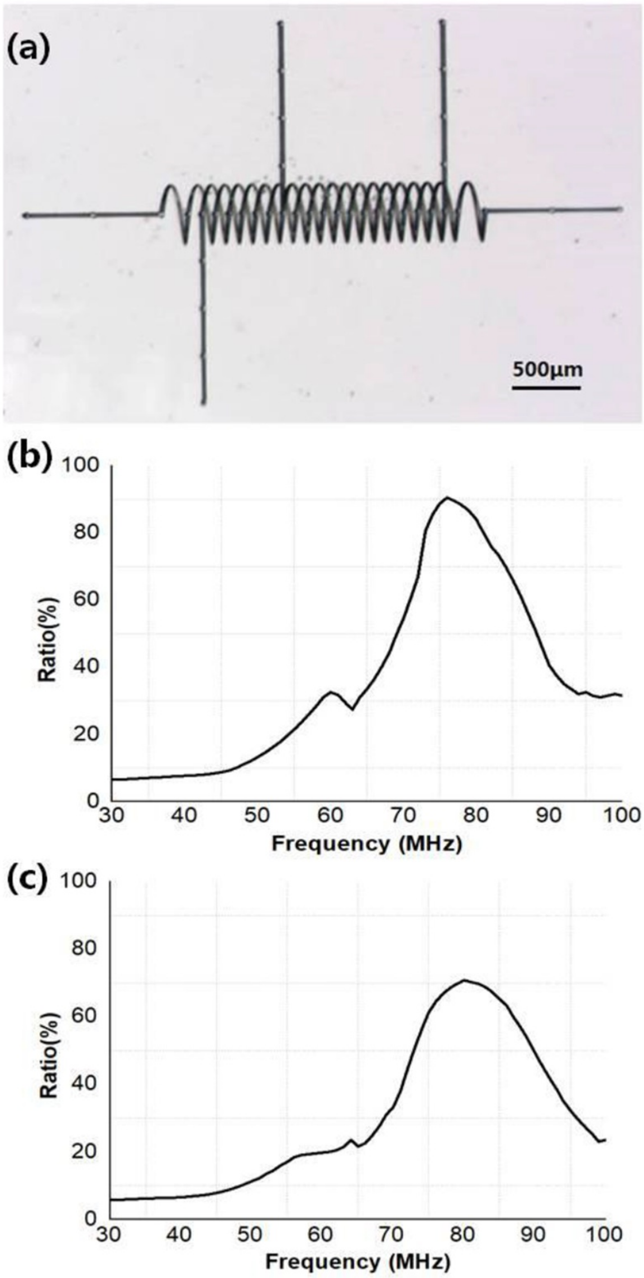

Figure 5. (a) Optical microscope image of fabricated microtransformer. (b) The relationship of voltage conversion ratio of the coil with frequency (ratios = 2:1). (c) The relationship of voltage conversion ratio of the coil with frequency (ratios = 4:1).

of primary and secondary coils can be improved by increasing the radius diameter of the coil.

In this way, the coil radius of the microtransformer is increased from 150 μm to 200 μm and 250 μm, as shown in figure 4. With the increase in the coil radius of the microtransformer, the mutual inductance of the coil is also increased after testing, and the conversion ratio of the microtransformer is also greatly improved, increasing from 50% to 65% and 78%, respectively. The overall performance of the microtransformer has thus been further improved.

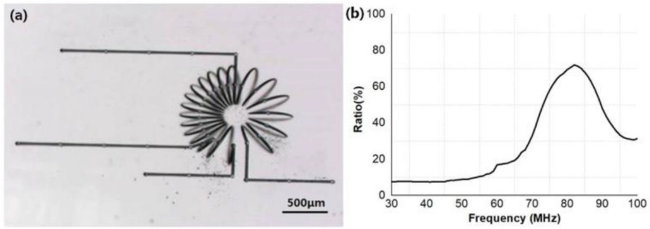

Figure 6. (a) Optical microscope image of fabricated microtransformer. (b) The relationship of voltage conversion ratio of the coil with frequency.

3.2. Variable voltage ratio transformer

On this basis, in order to realize a flexible and adjustable voltage transformer ratio, and expand the application range of the microtransformer, we designed a microtransformer with an adjustable voltage transformer ratio. Figure 5 shows the adjustable micro-transformer, with coil radius R = 250 m, comprising 12 primary turns, and 9 secondary turns. The secondary coil can be used as a whole or in two parts, 6 and 3, respectively. The transformer can achieve three transformer ratios of 4:1, 2:1 and 4:3.

Following preparation of the variable voltage ratio transformer, the performance of the microtransformer was tested. Coil ratios of 12:3 and 12:6 were selected for test purposes, and the ideal voltage ratio was 4:1 and 2:1. In the test, the primary coil was connected with a sinusoidal voltage signal of 4 V, and the test results are shown in figures 5(b) and (c). According to the test results, when the coil ratio of the adjustable transformer is 12:3, the voltage conversion ratio of the microtransformer reaches 90%, and the actual voltage ratio is about 4.4:1, which is close to the ideal transformer ratio. When the coil ratio of the adjustable transformer is 12:6, the maximum voltage conversion ratio of microtransformer is 70%, and the actual voltage ratio is 2.85:1. Taking into consideration resistance loss, magnetic leakage, and other factors, the test results demonstrate that the voltage ratio is adjustable.

3.3. Toroidal microtransformer

The toroidal microtransformer refers to the transformer whose induction coil is distributed in a circular manner. The toroidal microtransformer has prominent advantages, such as smaller size, small magnetic flux leakage, no high-frequency electromagnetic radiation, and strong anti-interference capability. The toroidal microtransformer is fabricated as shown in figure 6(a), in which the primary coil and the secondary coil are both 14 turns, and the coil radius is 250 μm. Similarly to the processes above, the performance of these microtransformers was also tested. A sinusoidal voltage of 7 V was applied at both ends of the primary coil. Figure 6(b) shows the conversion ratio of the toroidal microtransformer. According to the test results, the ratio of the toroidal microtransformer reaches 72%, and the performance compares favourably with other microfabricated transformers reported in the literature [5, 10–13, 15], as shown in table 1; in addition, the size of our microtransformer is smaller.

Table 1. Measured parameters compared with values reported in the literature.

	R_{dc} (Ω)	L (μH)	Freq. (MHz)	Type	Size (mm^2)	Ratio
[5]	2	0.046	125	Square spiral	2.25	78%
[10]	0.48	0.4	1–20	Racetrack	24	72%
[11]	1.22	0.27	10–30	Racetrack	3	78%
[12]	66	0.06	10–100	Circular spiral	0.5	N/A
[13]	N/A	0.053	20–50	Circular spiral	4.8	N/A
[15]	1.1	1.8	7–11	solenoid	4	N/A
Present work	4.81	45.1	75–90	Solenoid/Toroid	2.86	78%

4. Conclusions

In this paper, we have reported several types of coreless microtransformers inside fused silica chips, fabricated by a process involving enhanced femtosecond laser wet etching and liquid metal injection technology. The maximum ratio of the microtransformer is 78%. This approach is simple to process, and is capable of preparing three-dimensional devices without the need for complex mask etching and other associated processes. The size of the microtransformer is smaller. This work provides a potential route to realizing high quality 3D microcoils and 3D microtransformers inside fused silica glass, and would be beneficial for developing the miniaturization of highly integrated microactuators and microsensors. Although it is not easy to integrate into traditional electronic circuit systems, these microtransformers are anticipated to integrate well with other microfluidic devices.

Acknowledgments

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