Optics & Laser Technology 76 (2016) 29–32

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Three dimensional multilayer solenoid microcoils inside silica glass

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A R T I C L E I N F O

Article history:
Received 13 March 2015
Accepted 27 July 2015
Available online 4 August 2015

Keywords:
Femtosecond laser processing
Multilayers microcoils
3D solenoid microcoils
Silica glass

A B S T R A C T

Three dimensional (3D) solenoid microcoils could generate uniform magnetic field. Multilayer solenoid microcoils are highly pursued for strong magnetic field and high inductance in advanced magnetic microsystems. However, the fabrication of the 3D multilayer solenoid microcoils is still a challenging task. In this paper, 3D multilayer solenoid microcoils with uniform diameters and high aspect ratio were fabricated in silica glass. An alloy (Bi/In/Sn/Pb) with high melting point was chosen as the conductive metal to overcome the limitation of working temperature and improve the electrical property. The inductance of the three layers microcoils was measured, and the value is 77.71 nH at 100 kHz and 17.39 nH at 120 MHz. The quality factor was calculated, and it has a value of 5.02 at 120 MHz. This approach shows an improvement method to achieve complex 3D metal microstructures and electronic components, which could be widely integrated in advanced magnetic microsystems.

1. Introduction

Microcoils are widely used as the electric-magnetic devices in micro electromechanical systems (MEMS), micro-total analysis systems (μTAS) and Lab on a chip (LoC) [1–4]. For example, microcoils are used in nuclear magnetic resonance (NMR) and magnetic resonance images (MRI) systems, which can analysis the nucleic structure information and provide the images of the body for chemical applications and medical diagnosis [5–7]. As more practical applications in advanced magnetic microsystems, the stronger and more uniform magnetic field is pursued to keep a high performance, the demand of miniaturization and integration also increases. Although many studies have been reported for the fabrication of the microcoils, such as lithography, wire winding, electroplating and laser direct writing method [8–12], however, most of these works have focused on the single-layer and planar spiral-shaped microcoils.

The multilayer microcoils could increase the value of the inductance and enhance the magnetic field strength, which would improve the sensitivity and reduce the sample volume in the applications. The multilayer solenoid microcoils can generate stronger and more uniform magnetic field to meet the need of the advanced applications. Generally, ultraviolet photolithography is a conventional approach for fabricating microcoils, which was also improved to fabricate the multilayer microcoils [13,14]. However, the ultraviolet photolithography method requires the expensive equipments and masks with high resolution, complicated procedures, high cost, it is difficult to fabricate the 3D solenoid microcoils and provide a uniform magnetic field. The wire winding and electroplating method have been used for fabricating the multilayer microcoils [15,16]. But the integration in wire winding method and the turns in electroplating method need to be further improved, respectively; it is difficult to embed in the substrate and limit the miniaturization of devices.

Recently, a facile method based on femtosecond laser wet etch (FLWE) and microsolidics has been introduced to fabricate simple microcoils in two steps and under gentle conditions [17]. The extra access ports were introduced to make sure the simultaneity of the etching process and improve the uniformity of the microchannel. In the microsolidics process, the gallium was chosen as the conductive metal. However, the gallium with low melting point (29.76 °C) was easily melted and disconnected by the Joule heat, so the microwire has a low work temperature. Bi/In/Sn/Pb alloy is a kind of fusible metal alloy, which could be used as solder with various melting points (47 °C, 70 °C, 95 °C, 125 °C). In this work, we developed a femtosecond laser wet etch (FLWE) and microsolidics method to fabricate 3D multilayer solenoid microcoils in silica glass. The 3D multilayer solenoid microchannel has the different depth and length between the adjacent extra access ports. So the laser writing each layer with the different power and variable-speed scanning with different focus depth were used in FLWE to improve the uniformity of the microchannel with complex

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http://dx.doi.org/10.1016/j.optlastec.2015.07.020
0030-3992/

structures. As the features of the femtosecond laser processing inside the transparent material [18], the each layer of microchannel is independent without contact and insulated by the silica glass. In the microsolidics process, an alloy with high melting point is used to make the 3D electrical conductors, so the alloy microwire can reduce the impact of the Joule heat and overcome the limit of the low temperature. The alloy microwire can help the devices to get a higher working temperature. The inductance and resistance of the three layers microcoils was measured by an impedance analyzer. The multilayer microcoils with circle cross section could be applied for high performance electric-magnetic devices.

2. Fabrication procedures

Silica glass with dimensions of $10 \times 10 \times 1$ mm^3 was used in the experiment. The femtosecond laser in the experiment outputs the pulses with wavelength of 800 nm, pulse duration of 50 fs, and repetition rate of 1 kHz. The laser beam was tightly focused by an objective lens (Nikon, $\times 100$, NA$=$0.90). The laser writing pattern in the sample was pre-designed by the computer. The pattern of multilayer solenoid microcoils was scanned by the laser, as shown in Fig. 1(a). In the etching process, the hydrofluoric (HF) acid solution with a concentration of 5% was used. The laser-irradiation materials have a higher selective etching rate than the un-irradiation regions. The modified materials were chemically etched out rapidly, and the multilayer microchannel with good uniformity formed gradually (Fig. 1(b)).

In the microsolidics process, a polydimethylsiloxane (PDMS) film was used to seal the extra access ports. In order to overcome the limitation of the work temperature, an alloy (Bi/In/Sn/Pb) with high melting point (95 °C) and good electrically conductive was chosen as the metallic conductors in this experiment. We put the microchannel devices and the alloy in the electrically heated drying oven; the temperature of the oven was 30 °C higher than the melting point of the alloy. The liquid alloy with high viscosity is difficult to flow in slim microchannel, so we applied a high positive pressure to squeeze the liquid metal at the inlet and a high negative pressure to suck at the outlet. The liquid metal was injected into the microchannel to achieve the conductor microwire. After the metal was cool and solidification, the 3D multilayer microcoils embedded in the silica glass were achieved. Then the inductance and resistance of three layers microcoils is measured by an impedance analyzer. The measure results demonstrate the electromagnetic property of the 3D multilayer microcoils.

3. Results and discussion

To successfully fabricate the multilayer microcoils in the microsystem, the insulation between the coil layers is a key challenge. Silica glass is an excellent insulation material, which can

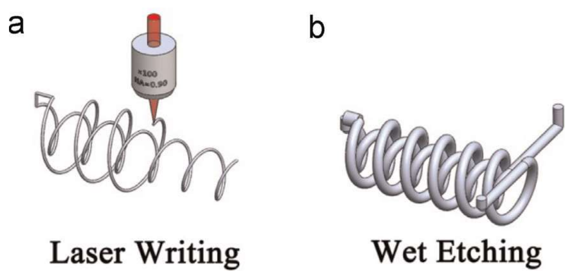

Fig. 1. Schematic of the two layers microchannel fabrication process. (a) Laser writing process. (b) Wet chemical etching process.

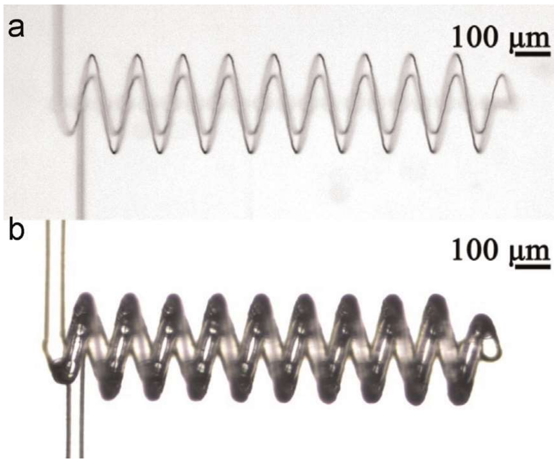

Fig. 2. The laser writing and the wet etching process. (a) Optical micrograph of the two layers solenoid line embedded in silica glass. (b) Optical micrograph of the two layers solenoid microchannel.

insulate the different coil layers. Due to the femtosecond laser processing features, the multilayer solenoid line was written without any intersection and insulated by silica glass. Fig. 2 shows that the two layers solenoid microchannel embedded in the silica glass was fabricated by the femtosecond laser wet etching method. In the laser-irradiation process, the inner layer solenoid line was written firstly and the outer layer solenoid line was written subsequently with the contrary winding way. The number of turns of each layer is 10 and the length of the two layers solenoid is 1200 μm. The coil radius of the inner layer and the outer layer are 75 μm and 125 μm, respectively. The pitch of solenoid is 60 μm. The uniformity of the microchannel in the silica glass is the main challenge for the FLWE method, which is pursued by many groups [19,20]. In our previous work, to overcome the limitation of the length-diameter ratio and achieve the good uniformity of the microchannel, the extra access ports were introduced [21]. The perpendicular lines were written by femtosecond laser to connect the top of every turns with the sample surface. The modified materials have a higher selective etching rate in the wet etching process. The modified materials in the perpendicular line were solved rapidly and the extra access ports gradually form and get large. Hence, the fresh HF solution can flow into the solenoid line through the extra access ports to guarantee continuous reaction. In the wet etching process, the simultaneous etch can greatly improve the uniformity of the microchannel [17]. To guarantee the simultaneity etching in all parts of microchannle, extra access ports with moderate distance between adjacent ones were introduced in the every turn of the solenoid line. The limitation of the length-diameter ratio of the microchannel is overcome and the multilayer microchannel with good uniformity and high aspect ratio is achieved in the experiment, as shown in Fig. 2(b). The surface of the microchannel is smooth [22]. To reduce the impact of the extra access ports on the microcoils performance, the length of the extra access ports should be as short as possible, so the solenoid line is written closer to the surface of the silica glass. After the etching process, the extra access ports can be polished away by polishing machine.

At the basis of the fabrication two layers microchannel, the three layers solenoid microchannel could be also fabricated by the similar method. As shown in Fig. 3(a), the inner layer solenoid line was written firstly, the middle layer solenoid line was written subsequently with the contrary winding way and the outer layer with the same winding way of the inner layer last. The number of turns of three layers is 30 and the length of the three layers solenoid is 1800 μm. The radiuses of the three layers are 60 μm,

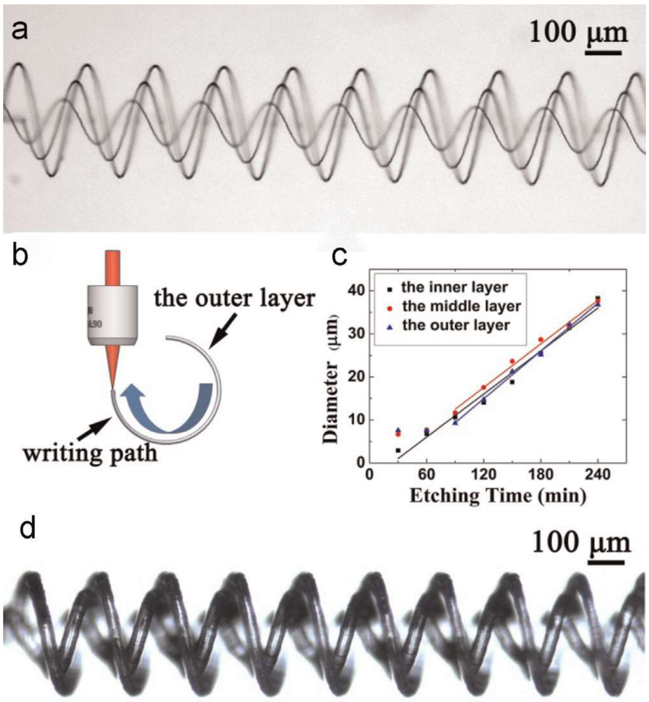

Fig. 3. The fabrication process of three layers solenoid microchannel. (a) Optical micrograph of the three layers solenoid line embedded in fused silica. (b) Laser writing the outer layer with the varying speed. (c) Comparison of diameters of the three layers microchannel under different laser power. (d) Optical micrograph of the three layers solenoid microchannel.

105 μm and 150 μm, respectively. So the length of the laser scanning line between the adjacent extra access ports of each layer in the three layers solenoid line was is different. The length of the inner layer is shortest, and the length of the outer layer longest, which would result in the different diameter of the three layers microchannel with the same etching time and influence the uniformity of the microchannel. The diameter of the laser writing line can increase with the laser power [23], so we use the different power to write the three layers line, the inner layer line with 4.5 mW, the middle layer line with 6.5 mW and the outer layer line with 9 mW. The length of the outer layer line between the adjacent extra access ports is the longest, and the depth of the outer layer line is deepest in the fuse silica. When the laser was used to write the outer layer line, the laser power would be absorbed by the sample and the absorbed laser power increases with the depth, the laser was also scattered by the other two layers line, so the laser modified threshold increases and the volume of the modified materials decreases. Reducing the writing speed can increase the irradiation energy and the volume of the modified materials. To make sure the uniformity of the modified materials volume, the writing speed decreases with the depth by the computer control, as shown in Fig. 3(b). The Fig. 3(c) shows the diameters at the deepest point of each layers microchannel increase with the etching time. The inner layer is written by lowest laser power and the length of each turn is shortest, so the inner layer microchannel begins to etch and the diameter increases firstly. The outer layer is written by the highest laser power with variable-speed, the outer layer microchannel begins to etch last and the etch rate is the highest in the three layers. Then the diameter of the out layer microchannel increases rapidly to pursue the other two layers. Finally, the diameters of the each layers microchannel are almost uniformity. Fig. 3(d) shows the fabrication of three layers solenoid microchannel.

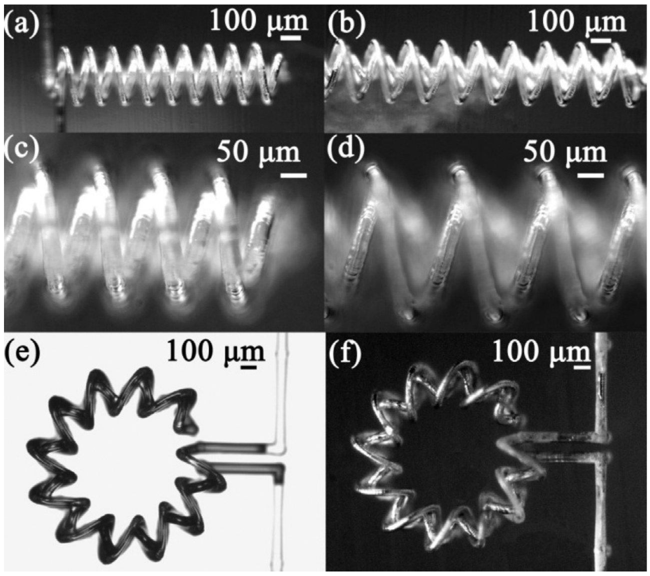

Fig. 4. (a) and (b) are optical micrograph of the two and three layers solenoid microcoils. (c) and (d) are optical micrograph of the enlarged images in the (a) and (b), respectively. (e) The two layers *O*-shaped micromicrochannel. (f) The two layers O-shaped microcoils.

The microsolidics method was developed to fabricate the metallic microstructures by injecting the liquid metal into the microchannels, allowing the metal to cool and solidify, and ultimately generating the solid metal structures [24]. In the previous work, the metal gallium was chosen as the metallic conductors, because of its low melting point (29.76 °C), which is easily injected the microchannel [17]. But the low melting point of the gallium limits the work temperature of the microcoils. In this paper, the alloy (Bi/In/Sn/Pb) with high melting point (95 °C) has better electrically conductive, which was chosen as the metallic conductors. In the microsolidics process, the temperature should be maintained above the melting point of the alloy to keep the alloy in the liquid state. As shown in Fig. 4(a–d), the liquid alloy was injected into the multilayer microchannels, and then multilayer microcoils were well fabricated. So the multilayer microcoils could work with high temperature and reduce the effect of Joule heat. The diameter of the microwire in the multilayer microcoils is about 38 ± 2 μm.

One of the greatest advantages of femtosecond laser wet etching method is flexibility. Through careful control of the laser writing path, various 3D structures could be fabricated on or in the samples [22,23]. The shapes of the microcoils can be altered flexibly and parameters can be controlled smartly. In this paper, the multilayer microcoils with complex shape could be also fabricated. As shown in Fig. 4(e) and (f), the O-shaped microcoils with two layers are smartly fabricated. The number of turns is 24 and the radius of the toroid is 400 μm. The radius of inner layer microcoils is 65 μm, and the radius of the out layer microcoils is 115 μm, which was wound with the contrary winding way and returned along the toroid, as shown in Fig. 4(f). The diameter of the microwire is about 35 ± 2 μm.

Fig. 5 shows the characteristic of inductance and resistance of the three layers solenoid microcoils as a function of frequency. As shown in Fig. 5(a), the inductance of the microcoils decreases with the frequency and has a value of 77.71 nH at 100 kHz. The inductance is stable up from 10 MHz to 120 MHz and the value decreases from 19.28 nH to 17.39 nH. The resistance is 2.06 Ω at 100 kHz. The resistance increases with the frequency and the values are 2.28 Ω at 10 MHz and 2.61 Ω at 120 MHz, respectively. Quality factor, *Q*, indicates the energy efficiency of the inductor

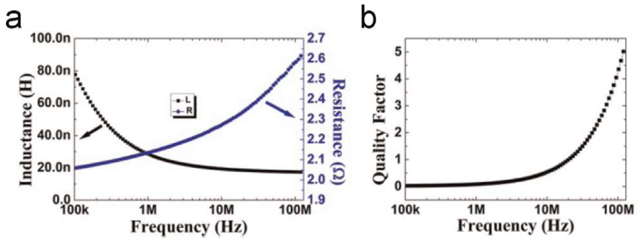

Fig. 5. Characteristic inductance and resistance for the three layers solenoid microcoils. (a) The inductance and resistance of the microcoils. (b) The quality factor of the microcoils.

device, which can be calculated by the equation: $Q = \omega\frac{L}{R}$, where ω is the frequency. Fig. 5(b) shows the calculated Q of the three layers solenoid microcoils. The quality factor increases with frequency and the maximal Q is 5.02 at 120 MHz. These results show that the electromagnetic properties of three layers microcoils such as inductance and quality factor are very close to the high-performance inductor with magnetic core [25]. But the size of the three layers microcoils is smaller, and it would probably do a better job for certain applications.

4. Conclusions

In conclusion, multilayer solenoid microcoils have been fabricated in silica glass by an improved femtosecond laser wet etching and microsolidics method. By carefully controlling the laser writing path, the multilayer solenoid microchannel with high uniformity could be flexibly fabricated. In the microsolidics method, an alloy (Bi/In/Sn/Pb) with high melting point was chosen as the conductive metal to achieve microwire. The alloy microwire has excellent electrical property and can overcome the impact of the Joule heat, so the devices get a higher working temperature and larger current. The complex microcoils could be smartly achieved and have more practical value. The inductance and resistance of the three layers microcoils were measured, which can show the electromagnetic property of the multilayer coil. The quality factor was also calculated and its maximum value is 5.02 at frequency of 120 MHz. This work provides a more flexible method in the geometry designs for multilayer microcoils, which can be widely used as radio frequency coil, 3D electronic circuits, low-power microfluidic heaters and temperature controllers, magnetic-field generators for NMR/MRI and microcoils for transformers.

Acknowledgments

This work is supported by the National Science Foundation of China under the Grant nos. 61275008, 61176113 and 51335008, the Special-funded programme on national key scientific instruments and equipment development of China under the Grant no. 2012YQ12004706.

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