Fabrication of Straight Stainless-steel Micro-coils for the Use of Biodevice Components

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Abstract: Fabrication method of straight micro-coils of stainless steel was investigated for applying the coils to bio-measurements. As a non-magnetizable material, SUS304 stainless steel pipes with outer and inner diameters of 100 and 60 μm were used. Specimen pipes coated with positive resist films were exposed to a violet laser beam, and helical resist patterns were delineated. The pipes masked by the helical patterns were wetly etched in electrolytic etchant composed of sodium chloride, ammonium chloride, and boric acid. As a result, micro-coils with almost homogeneous widths were successfully fabricated. The calculated spring constant was in favourable a range of 0.7-2.4 N/mm. The new micro-coil fabrication method is feasible for the use of bio-device components.

1 INTRODUCTION

Various micro-fabrication methods have been developed for realizing new bio-devices. Combination of lithography and etching is one of the representative methods. Because fine patterns with complicated shapes are easily formed on flat substrates, various micro-fluidic devices, cell arrays to separate bio-materials, electrodes of bio-sensors are fabricated using the technology.

On the other hand, any methods had hardly been developed to form patterns onto fine cylindrical wires or pipes with diameters of 50-500 μm. Recently, however, laser-scan lithography to delineate arbitrary patterns onto cylindrical surfaces of fine wires or pipes with diameters of less than 100 μm was developed (Horiuchi and Sasaki, 2012). As an application of the new method, precise micro-coils were successfully fabricated by etching the pipes using the helical resist patterns as masking materials (Horiuchi et al., 2011). Micro-coils were also fabricated by electroplating nickel into helical space patterns formed on a fine core wire, and pulling the wire off afterwards (Horiuchi et al., 2011).

Because nickel micro-coils fabricated by these methods had appropriate rigidity and flexibility as micro-springs, they were practically applied to the springs packed in fine electrical probe pins of semiconductor integrated-circuit testers.

In addition to this application, finely patterned cylindrical parts will be very useful for developing new bio-devices. For this reason, accuracies of the patterning and etching are evaluated here, and it is tried to fabricate stainless steel micro-coils durable for bio-environments. From view points of cost, strength and durability, stainless steel is superior to nickel. Relationship between the spring constant and the coil parameters are also clarified.

2 NEEDS OF CYLINDRICAL BIODEVICE COMPONENTS

As important bio-devices, fine electrical probes arrayed in two-dimensional matrixes are conveniently used to pick up electrical signal flows on the surfaces of living organs or dermis, as shown in Fig. 1. For example, bipolar electrodes arranged in a 10×12 matrix with an inter-electrode distance of 1 mm were used to detect the signal propagation on the atrium surface of a rabbit (Honjo et al., 2003); (Honjo et al., 2003). Besides, a 10×10 electrode array was used for chemo-sensing of cancer cells (Liu et al., 2009). Although rigid electrode pins were also used, electrode pins with built-in coil springs or electrode pins coupled with coil-springs are preferable, as shown in Fig. 2, because the electrode pins should be softly pressed to bio-tissues with bumpy surfaces. In addition, to arrange electrode

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pins densely in an array, straight coil springs with a small diameter are favourable.

In addition, micro-coils are also useful for detecting various bio-signals in local narrow areas. For this use, various types of sensing coils were proposed (Ramadan et al., 2006).

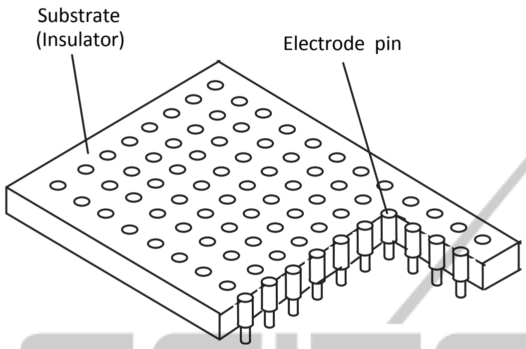

Figure 1: Schematic figure of an electrode array. Diameters and array size are deformed in the figure.

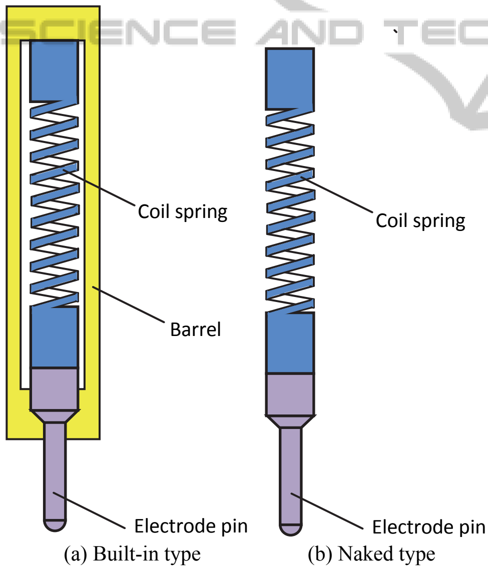

Figure 2: Schematic figures of electrode pins for the use of bio-sensing.

In such electrical measurement use, the micro-coils should not be magnetisable, because induced magnetic fields cause measurement errors. From this point of view, coil-springs of non-magnetisable materials are preferred.

On the other hand, micro-coils are also applied to realize special magnetic actuators for biomedical use. For example, actuators of micro-manipulator and tweezers were presented (Barbic, 2002).

For the biomedical use, materials not becoming rusty are very favourable in general, and strength and durability for the repeating use are required frequently. Considering these conditions, non-magnetisable stainless steels are one of the most appropriate materials.

3 FABRICATION METHOD OF STAINLESS MICRO-COILS

3.1 Fabrication Process

Micro-coils were fabricated by the process shown in Fig. 3. SUS304 stainless steel pipes with outer and inner diameters of 100 and 60 μm and length of 50 mm were prepared as specimens.

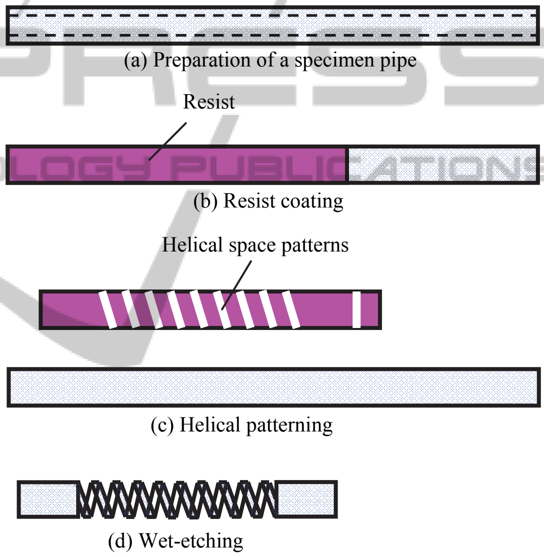

Figure 3: Micro-coil fabrication process.

They were coated with films of positive resist PMER P LA900PM (Tokyo Ohka Kogyo) by the dipping method. Using laser scan lithography, helical coil patterns were delineated on the specimen pipes. The patterned pipes were wetly etched in an electrolytic etchant applying appropriate voltage. Because the specimens were masked by the helical resist patterns, they were etched into coils.

3.2 Laser Scan Lithography

Patterning principle of the laser-scan lithography onto fine pipes is shown in Fig. 4. As a source, semiconductor violet laser with a wavelength of 408 nm was used. Nominal output power of the laser was 15 mW. The ejected laser light beam was reshaped using a pinhole with a diameter of 500 μm. The outlet of the pinhole was projected onto a specimen pipe using the projection optics being composed of a 10X object lens and 2X imaging lens. Accordingly, the laser spot size on the specimen was approximately 25 µm. The specimen pipes and wires were held and guided using a specially prepared half vacuum chuck with a V-shape guide, as shown in Fig. 5. The pipes were chucked at three separate linear chucking vacuum ports. Because the specimens were guided by the V-shape walls of the chuck, the irradiated position of the laser beam was maintained always constant, even if the specimens were moved and rotated along the guide, or slightly curved by nature before they were chucked.

Although the delineated pattern widths depended on the laser beam spot size, they were considerably adjusted by changing the scanning speed.

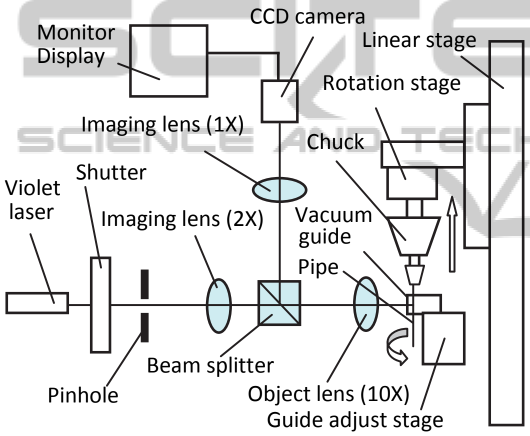

Figure 4: Principle of laser-scan exposure system.

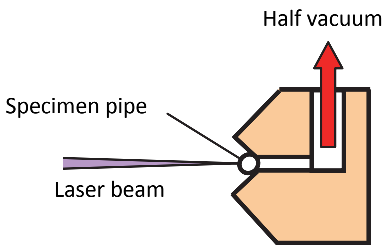

Figure 5: Principle of half-vacuum support guide.

3.3 Electrolytic Etching

Etching was performed holding the pipe specimen vertically in an etchant bottle, and placing an aluminium cylindrical cathode surrounding the specimen. The specimen pipe was used as an anode, as shown in Fig. 6. As an etchant, mixture of water, sodium chloride (NaCl), ammonium chloride, and boric acid was used. The etchant was heated on a hotplate, and the temperature was kept at 40-60ºC.

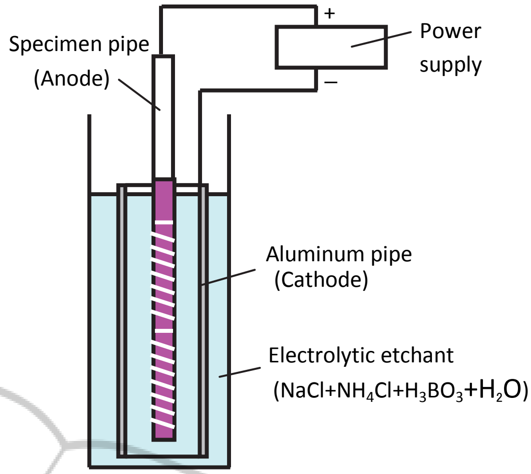

Figure 6: Schematic figure of dissociation etching.

4 FABRICATION OF MICRO-COILS AND EVALUATION

Micro-coils with a pitch of 150 µm, turn number of 20, and the length of 3 mm were fabricated, and the accuracy was evaluated. In the lithography process, the resist was coated in 4 µm thick, and the delineation speed was set at 50 µm/s. The etching time was determined by monitoring the electrolytic etching voltage, and was approximately 40 s. The resist patterns were removed after etching the specimens by dipping them in the resist remover.

Figs. 7 and 8 show a patterned pipe and a fabricated micro-coil. Space pattern widths along the coil were almost constant, as shown in Fig. 9, and the width variation was within ±1 µm for the mean width of 15.5 µm. The error was almost equal to the measurement error.

Resist patterns should have perpendicular sidewalls to obtain the aimed widths stably with good repeatability. From this point of view, the resist patterns had favourite cross sections, as shown in Fig. 10. This superiority probably comes from the use of half-vacuum chuck and a fact that the exposure beam spot size is kept always constant.

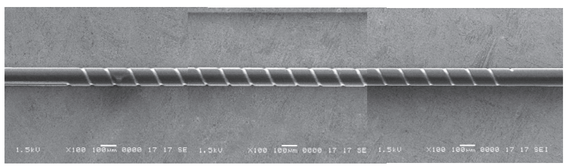

Figure 7: Helical pattern delineated on a specimen pipe.

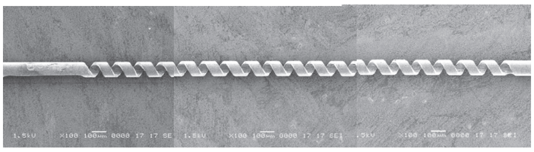

Figure 8: Micro-coil fabricated by electrolytic etching.

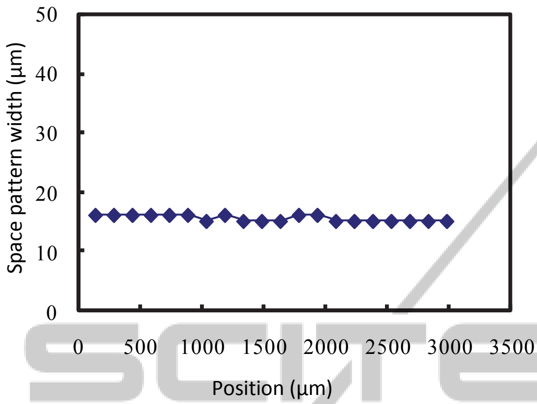

Figure 9: Width variation of space patterns along the specimen axis.

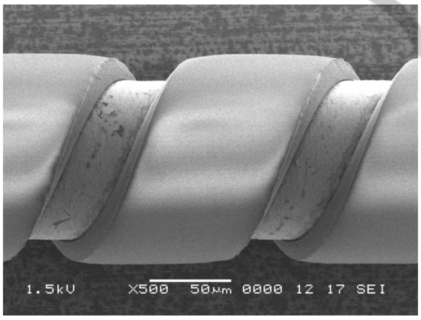

Figure 10: Sidewall profiles of a helical resist pattern.

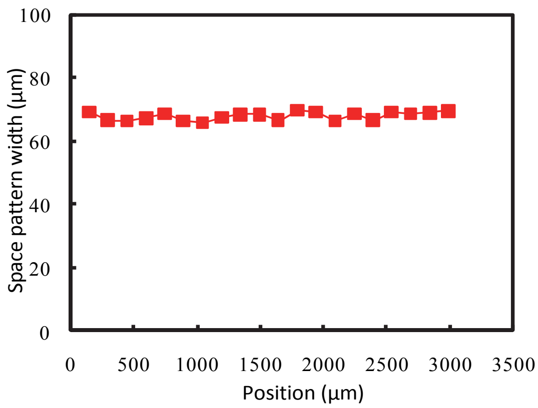

Figure 11: Space width variation of a fabricated coil.

Because the pipes were undercut during the etching, space widths of the fabricated coils were wider than the space pattern widths, as shown in Fig. 11. The width differences between the resist pattern and the coil were approximately equal to twice of the pipe thickness. However, the coil space widths were also almost homogeneous, and the deviation was ±2 μm for the mean width of 68 μm. Because the coil pitch was 150 μm, coil widths were approximately 82 μm. It was also verified that natural pipe parts were remained at both ends in arbitrary lengths, if necessary.

5 SPRING CHARACTERISTICS DEPENDENCE ON SIZES

Spring constant was calculated if micro-coils had appropriate rigidity or flexibility. Spring constant k was calculated by eq. (1) (Utoguchi et al., 1957).

$$k = \frac{P}{\delta} = \frac{G\beta b^3 h}{2\pi n R^3} \tag{1}$$

Here, P is the axial load [N], δ is the distortion [μm], G is the shearing modulus [N/mm^2], b is the thickness of the coil [μm], h is the width of the coil element [μm], n is the number, and R is the mean radius, as shown in Fig. 12. β is the constant dependent on the ratio of h/b, and calculated by eq. (2) (Shibahara, 1977).

$$\beta = \frac{1}{3}\left\{1 - \frac{192}{\pi^5}\frac{b}{h}\tanh\left(\frac{\pi}{2}\frac{h}{b}\right)\right\} \tag{2}$$

Since function tanh x is expressed by eq. (3), β is calculated, as shown in Fig.13.

$$\tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{3}$$

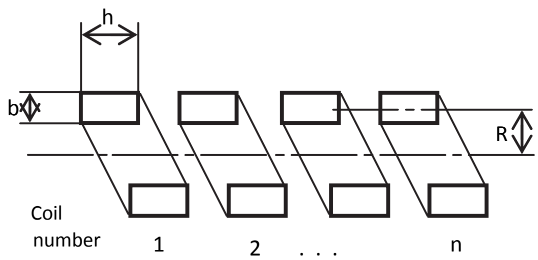

Figure 12: Size parameters of a micro-coil.

When material pipes with an outer diameter of 100 μm, k was calculated, as shown in Figs. 14 and 15. Because k is proportional to 3rd power of b, the rigidity largely changes depending on the pipe wall thickness.

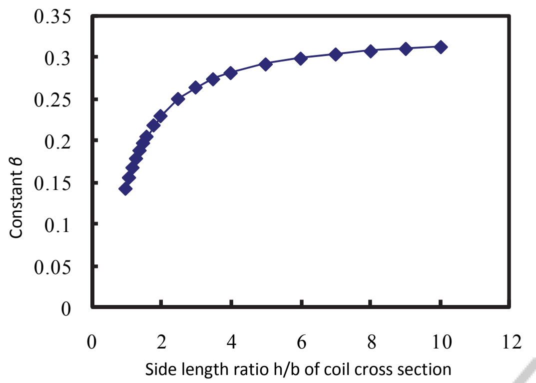

Figure 13: Constant β used for the calculation of spring constant.

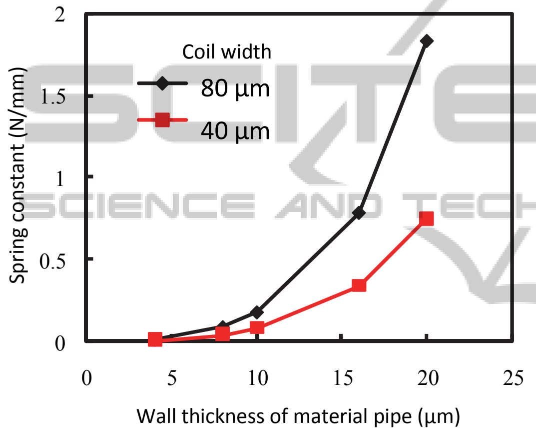

Figure 14: Spring constant dependence on wall thickness of material pipe.

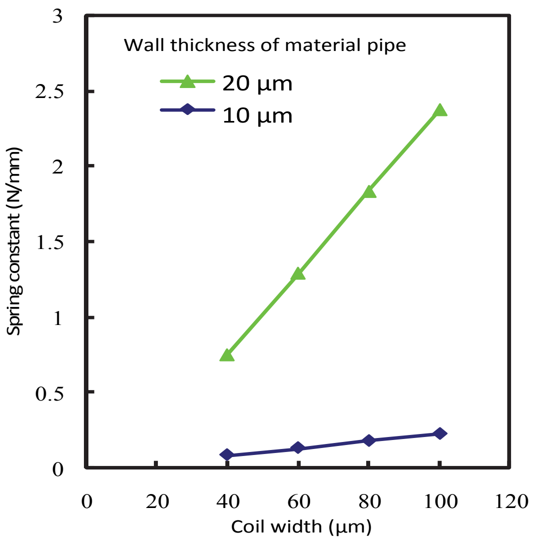

Figure 15: Spring constant dependence on coil width.

Calculated spring constant values were in a favourite range. However, perhaps it is felt apprehensive that the coils are slightly too stiff. This time, specimen pipes with a wall thickness of 20 µm were used. However, pipes with a wall thickness of 10 µm are also commercially available. Therefore, far flexible springs can also be fabricated, if necessary.

Because the wall thickness is strictly cared by the pipe maker, spring constant variation caused by the wall thickness dispersion is very small. This is a noteworthy advantage of this fabrication method.

On the other hand, k is simply proportional to the width h of the coil element. Because h is controllable by the scan exposure speed or the etching time, the spring constant can be finely adjustable by controlling h.

Required stiffness of the micro-coil spring depends on the application. Therefore, it is preferable that the spring constant can be easily changed in a wide range.

6 CONCLUSIONS

Micro-coil springs of SUS304 stainless steel were successfully fabricated by etching pipes masked by helical patterns. Despite of the scan exposure, resist patterns had good cross section profiles with perpendicular sidewalls, and pattern width fluctuation was small enough. This superiority probably depends on the use of half-vacuum specimen guide in the exposure system.

After the lithography, patterned pipes were finely etched in the electrolytic etchant. Pattern width variation in the longitudinal direction of the coil was less than ±2 µm. Because the spring constant is decided by the mean width of the coil, above width fluctuation is permissible.

It was clarified that the spring constant was in an expected range, and could be changed in considerably wide ranges by selecting appropriate shape parameters. The new stainless steel micro-coils will be applicable to various bio-devices.

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