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Tactile microsensor elements prepared from arrayed superelastic carbon microcoils

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Superelastic carbon microcoils (SCMCs) with high elasticity and coiling chirality were prepared by the Ni-catalyzed pyrolysis of acetylene, and novel tactile microsensor elements using the SCMCs as the sensor material were prepared. The sensor elements with a very small size of $80\times80\times80\ \mu\text{m}^3$ showed a very high sensitivity of 0.3 mgf (1 Pa). It was found that the SCMC arraying in the matrix and the placement method on the electrodes dramatically affected the sensing properties. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2006209]

Recently, developing microelectromechanical system (MEMS) sensors that mimic the form and functionality of biological sensing systems has been attracting much interest. It is expected that artificial skin, which is manufactured by learning the structure of human skin, will be a type of potential tactile sensor. Micronization or miniaturization of such devices or sensors is one of the most important subjects for the application of the MEMS. Tactile sensors have usually been constructed based on the piezoresistive, piezoelectric, optical, capacitive, ultrasonic and conductive-based principles.

We have presented many articles about the preparation and properties of conventional carbon microcoils ("CCMCs," hereafter) with very regular-coiled forms having coil diameters of several micrometers and having fiber diameters of several hundred nanometers, and about various ceramic microcoils.[1–6] Furthermore, we obtained superelastic carbon microcoils ("SCMCs," hereafter), which have larger coil diameters than that of the CCMCs and can be extended up to 5–20 times compared to their original coil length.[7] Because the CCMCs or SCMCs have a particular coiling-chiral conformation and a three-dimensional (3D)-helical/spiral structure, these CMCs are a kind of novel micro/nano-material. To the best of our knowledge, until now, there have been no reports of micro/nano-sensor elements made from micro/nano-coils or micro/nano-springs.

Among the human skin's receptors, which can detect various stresses or stimuli, Meissnor's corpuscles are the most important receptors as tactile sensing receptors. Recently, tactile sensors with very high sensitivities and discrimination abilities have been requested for the development of safe medical instruments, such as catheters, endoscopes, forceps, etc. We have reported the initial study of preparing the novel tactile sensors using CCMCs and characterized their basic tactile sensing properties.[8]

In this study, the SCMCs were prepared by the Ni-catalyzed pyrolysis of acetylene at 700–800 °C. The detailed preparation procedures and conditions are described in Refs. 7 and 8. The representative as-grown SCMCs are shown in Fig. 1. The SCMCs have coil diameters in the range of 10–15 μm, while the CCMCs have coil diameters of 1–5 μm.[1–3] These SCMCs have a high elasticity and could be extended up to 5–10 times compared to their original coil length and contracted to the original coil length after releasing the load. The SCMCs were embedded in an elastic polysilicone resin matrix (Shin-Etsu, KE-103) at 5 wt % to produce a tactile sensor element of $10\times10\times1\ \text{mm}^3$ ("SCMCs sensor element" hereafter). Some stresses were vertically applied to the CMC sensor element using a free-hand manipulator, and the change (output) in the electrical parameters was measured at 200 KHz using an impedance analyzer (Agilent 54621) or an oscilloscope, in which the respective parameters were transformed into a dc voltage output. The applied load was measured using an electronic balance.

The *LCR* parameters of the sheet-like formed as-grown bulk SCMCs were obtained as a function of the extension and contraction. It was found that *L*, *C* and *R* parameters increased by 50 μH, 400 pF and 4.5 kΩ with their extension of 4 mm, respectively, and decreased to the original values after their contraction. The output of the $(L+C)$ and *R* pa-

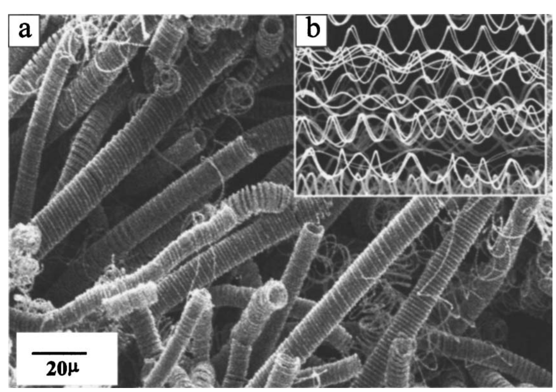

FIG. 1. As-grown scanning electron microscope images of superelastic carbon microcoils (SCMCs).

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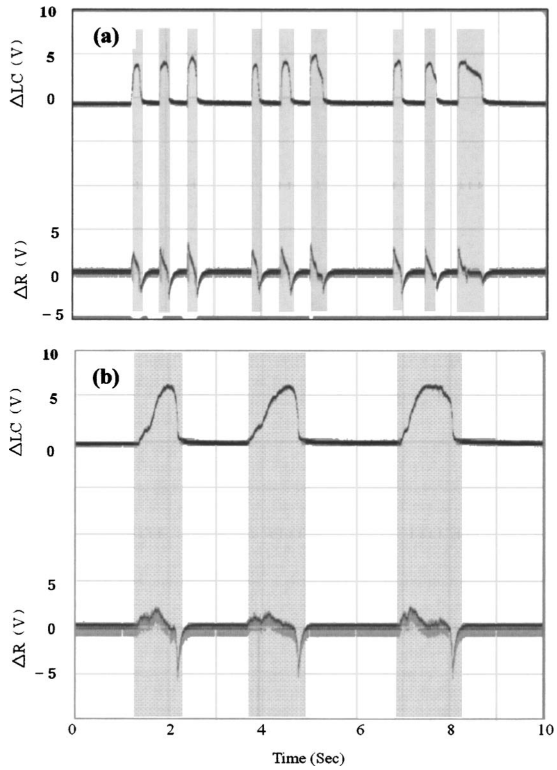

FIG. 2. Change in $(L+C)$ and R parameters of SCMC (5 wt %)/polysilicone sensor element under applied stresses. Size of sensor element: $10\times10\times1$ mm^3; separation of electrode: 2.5 mm. (a) Sticking by a needle; (b) touching by a soft brush.

rameters of the SCMCs sensor elements under various applied stresses was measured, It was found that different stresses, i.e., pressing by a finger, sticking by a needle, grabbing by tweezers, etc., could be detected as different wave forms. Figure 2 shows the output (V) of the $(L+C)$ and R parameters of the SCMC sensor elements under various applied stresses. In Fig. 2(a), the shaded parts indicate the moments at which a needle was applied for several tens of ms, and in Fig. 2(b), the shaded parts indicate the moments during which a soft brush touched the surface of the SCMC sensor element. It can be seen that very sharp output peaks can be obtained when the SCMC sensor element was touched by a needle. The response time was on a millisecond order. This performance is far better than conventional tactile sensors. When the SCMC sensor element was touched by a soft brush, broad signals were observed. That is, different applied stresses produced different wave form patterns and intensities. Continuously applied stresses for 24 s resulted in a continuous and a constant strength in the output lines. In other words, the type of applied stresses could be discriminated by the different wave form patterns. Some instabilities in the output form and the strength can be seen in Fig. 2. These instabilities may be caused by the various loaded weights, speeds and duration times which were caused by the manual treatment of the manipulators.

For determining the limit of the tactile sensitivities, a small weight, less than 200 mgf, was vertically applied to the SCMC sensor element ($10\times10\times2$ mm^3). Figure 3 shows the obtained output of the C parameter. It can be seen that the C parameter changed by about 50 pF when a load as small as 1 mgf was applied, and with an increase in the load, the output increased. It was found that the relationship between

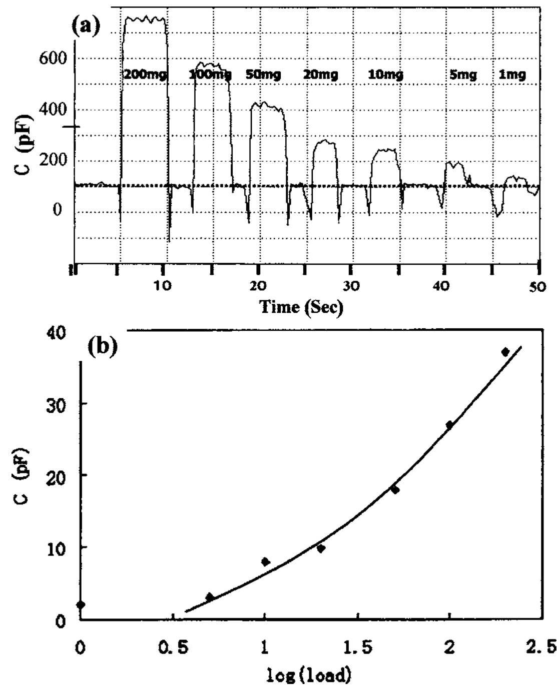

FIG. 3. (a) Change in C parameter while applying small loads of about 1 gf and (b) relationship between C and log (load).

the C parameter and applied load was not linear, but logarithmic, as shown in Fig. 3(b), but the reason for this is not yet known. The L and R parameters also experienced a similar change. That is, the sensitivity of the SCMC sensor element was about 0.3 mgf, which is equivalent to about 1 Pa; this value is about 300–1000 times greater when compared to conventional tactile sensors.

Very thin CMC sensor elements with different arraying of the SCMCs in the matrix were manufactured with a size of $2\times2\times0.1$ mm^3; (1) The SCMCs were uniformly dispersed in the matrix and not arrayed (random-SCMCs sensor); (2) The SCMCs were vertically arrayed by slightly extending the matrix (Set A) or parallel (Set B) to the direction of the electrodes as shown in Fig. 4 (arrayed-SCMCs sensor). A load of ~0.5 gf was applied to the sensor element using a wood rod with a diameter of 2 mm. For the random-SCMC elements, the output of the $(L+C)$ parameter was about 1 V, although the R parameter output was about 0.2 V, as shown in Fig. 5. When the slightly extended SCMCs were embedded in the matrix, the SCMCs were partly arrayed in the vertical direction to the electrodes, and the R parameter output increased to about 2 V. However, when the arraying

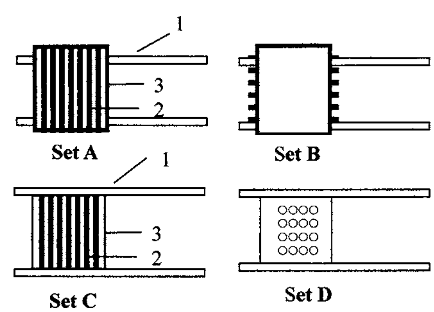

FIG. 4. Placement patterns of SCMC sensor elements on the electrodes. (1) Electrode, (2) coil array, (3) sensor element. Sets A and B: a sensor element is placed on the electrodes; Sets C and D: a sensor element is placed between two electrodes.

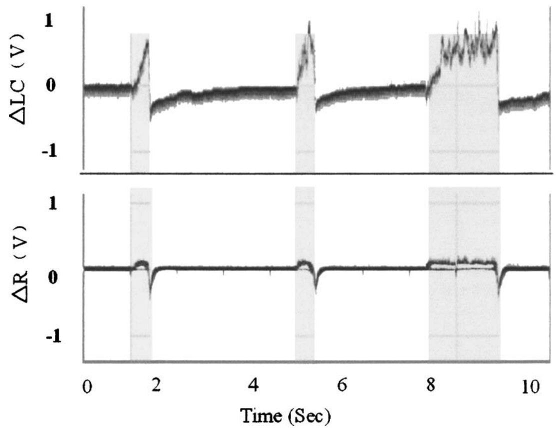

FIG. 5. Change in $(L+C)$ and R parameters of thin sensor element with randomly oriented CMCs. Sensor element size: $10\times10\times0.1$ mm^3; applied load: 0.5 gf; separation of the electrode: 1 mm.

direction of the SCMCs was parallel to the electrodes, no output was observed. This result indicates that by arraying the SCMCs vertical to the electrodes, the SCMCs act as conductive microsprings between the two electrodes.

In order to miniaturize the sensors, the SCMC sensor element with a 100 μm thickness was successively cut to obtain microelements of $100\times100\times100$ μm^3. It was observed that these microelements have the same sensitivity as that of the large $2\times2\times0.1$ mm^3 element. Furthermore, we prepared microelements of $80\times80\times80$ μm^3 by arraying about 50 SCMC pieces in a matrix as shown in Fig. 6. The arraying was carried out under a microscope (OLYMPUS, U-LH100-3). When the microsensors were placed between the two microelectrodes with the SCMCs arraying vertical to the planes of the electrodes (set C), and by applying a load as low as 2 mgf, strong outputs of the $(L+C)$ and R parameters were observed. However, when the microsensors were placed horizontally (set D), no output by the $(L+C)$ and R parameters was observed.

As a reference sensor element, commercial PAN-based carbon fibers ("CF" hereafter) were used in place of the SCMCs, and the CF-based sensor element was prepared using the same preparation procedure as that of the SCMCs. When this reference element was placed between the two electrodes with the fibers arraying vertical to the planes of the electrodes as shown in Fig. 4, set C, the R parameter output was much lower than that of the SCMCs, and no output of the $(L+C)$ parameter was observed. Accordingly, by micronization and arraying the SCMCs in the matrix, the SCMC sensor elements have potential applications as novel tactile sensors with high sensitivities for various applications in medical instruments, humanoid robot, etc.

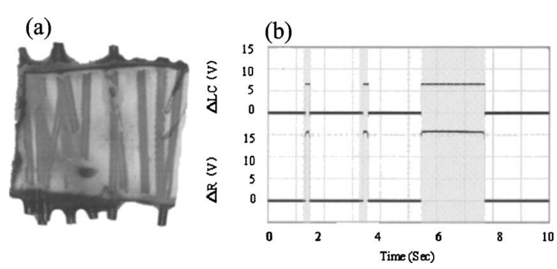

FIG. 6. (a) Arraying mode of SCMCs in sensor element and (b) change of $(L+C)$ and R parameters. Placement pattern of the element on the electrode was the same as Fig. 4, set C. Sensor element size: $80\times80\times80$ μm^3.

The SCMCs have electrical resistance, inductance and capacitance components which can be changed by the extension or contraction of the coils as already described. These parameters may be resonantly changed by the applied stresses. The different sensing modes for the conventional tactile or pressure sensors, such as the electrostatic capacitor type, piezoresistivity type, silicon oscillation type, or diaphragm type have already been reported. The conventional sensors with these sensing modes have a single mode type with a sensitivity as low as 1–10 KPa, and cannot discriminate different types of applied stresses. The very high sensitivities and discrimination abilities of the SCMC sensor elements may be caused by a hybrid *LCR* resonant oscillation. That is, the CMC sensor using the *LCR* hybrid resonance circuit is a novel-type tactile sensor.

In conclusion, superelastic carbon microcoils (SCMCs) were used as tactile sensor materials. It was found that the electrical *LCR* parameters of the bulk SCMCs increased with their extension and decreased with their contraction. It was found that the arraying of the SCMCs in the matrix resulted in a significant increase in the tactile sensitivity. A tactile microsensor element of $80\times80\times80$ μm^3, which is composed of SCMCs arraying in polysilicone, with a high sensing ability to an applied load of 0.3 mgf (1 Pa), was obtained.

[1]X. Chen and S. Motojima, J. Mater. Sci. **34**, 5519 (1999).
[2]X. Chen and W.-In Hwang, Mater. Tech. (Duebendorf, Switz.) **18**, 229 (2000).
[3]S. Motojima, H. Iwanaga, and V. K. Varadan, Hyomen Kagaku, **36**, 140 (1998).
[4]M. Fujii, M. Matsui, S. Motojima, and Y. Hishikawa, J. Cryst. Growth **237**, 1937 (2002).
[5]Y. Furuya, T. Hashishin, H. Iwanaga, S. Motojima, and Y. Hishikawa, Carbon **42**, 331 (2004).
[6]Y. Kato, N. Adachi, T. Okuda, T. Yoshida, S. Motojima, and T. Tsuda, Jpn. J. Appl. Phys., Part 1 **42**, 5035 (2003).
[7]X. Chen, S. Motojima, and H. Iwanaga, J. Cryst. Growth **237–239**, 1931 (2002).
[8]X. Chen, S. Yang, M. Hasegawa, K. Takeuchi, and S. Motojima, Proceedings of the International Conference on MEMS, NANO, and Smart Systems, 2004, pp. 486–490.