ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

Highly Stretchable, Global, and Distributed Local Strain Sensing Line Using GaInSn Electrodes for Wearable Electronics

Ryosuke Matsuzaki and Kosuke Tabayashi*

For identifying human or finger movement, it is necessary to sense subtle movements at multiple points, including the local strain and global deformation simultaneously; however, this has not yet been realized. Therefore, a highly stretchable, global, and distributed local strain sensing electrode made of GaInSn and polydimethylsiloxane is developed for wearable devices. To investigate the electrical properties of multiple sections of the GaInSn electrode when stretching, tensile, cyclic, and three-point-bending tests are performed. The results demonstrate that the electrode can withstand a strain up to 50% and has little hysteresis without any delay. Moreover, the distributed local strain and global strain can be simultaneously measured using just a single electrode line. Finally, a prototype of a data glove as an application of the strain sensing line is manufactured, and it is demonstrated that the folding state of fingers could be identified. The proposed technology may allow the creation of a lightweight master hand manipulator or 3D data entry device.

1. Introduction

A wide variety of electronic devices is now necessary in our daily life such as a cell phone, network equipment, and health-care equipment. By providing electronic devices with flexibility, it is possible to apply electronics to soft materials or curved surfaces, and many flexible electronics have been proposed, such as strain or pressure sensors[1–3] and flexible displays.[4,5] Although conventional flexible electronics using a thin film consisting of solid metals as an electrode have a high flexibility for bending deformation, microcracks or plastic deformation may occur owing to large in-plane deformation because of the film's inherent low failure-to-strain nature.[6,7]

More recently, stretchable electronics, which have an extremely high deformation capability in the in-plane direction in addition to out-of-plane flexibility, have attracted considerable attention.[8] The stretchable electronics or electrode can be applied to a complex, soft-shaped, or large deforming surface such as human body parts or bending and sliding structures such as robot arms.[8,9] To establish stretchable electronics, it is necessary to develop a stretchable electrode that can be embedded in the elastomer base. For example, stretchable electrodes utilizing carbon nanotubes (CNTs),[10,11] metal nanowires,[12] or metal ions[13] with an elastomer base have been proposed.

As a stretchable electrode, liquid metals, which are in the liquid state at room temperature, are highly attractive materials.[14] For the liquid metals of a stretchable electrode, a eutectic gallium–indium alloy (EGaIn) and GaInSn are often used because of their low toxicity and low melting point.[15,16] The composition of the constituent metals in EGaIn are 75% Ga and 25% In by weight and the melting point is 15.5 °C. For GaInSn, the composition is 68.5% Ga, 21.5% In, and 10% Sn by weight and the melting point is –19 °C. Because both of these materials are in the liquid state at room temperature, they have attracted attention as a replacement for highly toxic mercury.[15,16] **Table 1** summarizes the melting points and electrical conductivities of EGaIn and GaInSn.[17] By comparing GaInSn and EGaIn, it is found that the electrical conductivity is almost the same, but GaInSn has a lower melting point; thus, it can be in the liquid state at a lower temperature. The liquid metals have almost limitless deformability compared with solid metals. By using a liquid metal as the electrodes of a stretchable device, its mechanical properties are governed by the mechanical properties of the elastomeric substrate.[14] Therefore, extremely stretchable electronic devices are possible by using a high failure-to-strain elastomer for sealing liquid metals for application to stretchable wires[18] and interconnections.[19] For the high failure-to-strain elastomer, polydimethylsiloxane (PDMS) is often used because PDMS is a biomaterial and is highly stretchable without structural damage over 100% strain, which enables curved surfaces to be followed; therefore, PDMS can be applied to human-body sensing.[20,21] Moreover, liquid metals are not just for stretchable electrodes or wiring; functional stretchable devices using changes in the electrical properties due to stretching have been developed, such as a stretchable antenna that tunes the resonance frequency,[14,17] a capacitor and inductor that sense the applied strain,[22] strain-controlled diffraction of light,[23] and a device that senses pressure and strain.[24,25]

By using a combination of a low-toxicity and low-melting-point liquid metal and a biocompatible PDMS elastomer, various types of wearable electronics have been developed, such as sensor skin for intelligent robots[26] and a stretchable keyboard

Prof. R. Matsuzaki, K. Tabayashi
Department of Mechanical Engineering
Tokyo University of Science
2641 Yamazaki, Noda, Chiba 278-8510, Japan
E-mail: rmatsuza@rs.tus.ac.jp

DOI: 10.1002/adfm.201501396

Table 1. Properties of EGaIn and GaInSn.[17]

	Melting point [°C]	Electrical conductivity [10^6 S m^{-1}][30,31]
EGaIn	15.5	3.4
GaInSn	−19.0	3.5

interface as a wearable computer.[27] In particular, stretchable electrodes are suitable for sensing human movement, e.g., folding fingers, because of their high flexibility, stretchability, and compatibility with human movement. Therefore, research on sensing human folding movements has been carried out by using a liquid metal and an elastomer.[28,29] However, only one joint's movement was sensed in these studies, and multipoint sensing including global strain or distributed local strain has not yet been studied. For identifying human or finger movement, it is necessary to sense subtle movements at multiple points, including the local strain and global deformation simultaneously.

In the present study, a novel highly stretchable, global, and distributed local strain sensing electrode for wearable electronics has been developed using a combination of GaInSn and PDMS. We investigated the electrical resistance of multiple sections of a single stretchable electrode line during stretching and compared it with theoretical values. By utilizing the distribution of an electrical property of the liquid-metal electrode during stretching, it is possible to detect human movement at multiple locations in detail using a single sensing line and to identify human body movement more easily. The biggest advance from previous strain sensors using liquid metal is that it is possible to measure changes in bending of multiple positions by a single sensing line with the proposed sensor, which is highly demanded for identifying the human body or finger movement. Finally, we demonstrated the development of a data glove as an application of stretchable, global, and distributed local strain sensing electrode for wearable electronics. If these technologies become a reality, a very lightweight and simple data glove may be realized for a more precise and simple master hand (finger) of a master/slave manipulator for remote handling or a data entry device for 3D movement.

2. Results and Discussion

2.1. GaInSn Stretchable Electrode

The manufacturing process of the stretchable electrode using GaInSn and PDMS is described in this section. First, the electrode pattern was created with a photoresist using a photolithography technique on a glass-fiber-reinforced plastic (GFRP) plate, as shown in **Figure 1**a. Then, uncured liquid-state PDMS was poured onto the photoresist electrode pattern and the PDMS was cured by the application of heat. By separating the PDMS sheet from the GFRP plate, the electrode pattern was transferred to the PDMS. GaInSn was poured onto the PDMS electrode pattern and another flat PDMS sheet was adhered to seal the GaInSn, as shown in Figure 1b. It should be noted that because GaInSn has a high wettability on PDMS, it is easy to spread GaInSn along the concave line on the PDMS substrate. Conductive electrodes were attached to the PDMS cover using adhesive bonding for connection to an external device. Figure 1c shows the configuration of the manufactured stretchable electrode. Using this stretchable GaInSn electrode, tensile and three-point-bending tests were performed to investigate the electrical properties when stretching. Finally, we developed a data glove for sensing the folding of multiple finger joints on the basis of the electrical properties of the GaInSn electrode.

2.2. Tensile Tests

To investigate the electrical properties of the GaInSn electrode during stretching, tensile tests of the GaInSn electrode were performed. **Figure 2**a shows the specimen configuration, where GFRP tabs were attached to the edge of the GaInSn electrode.

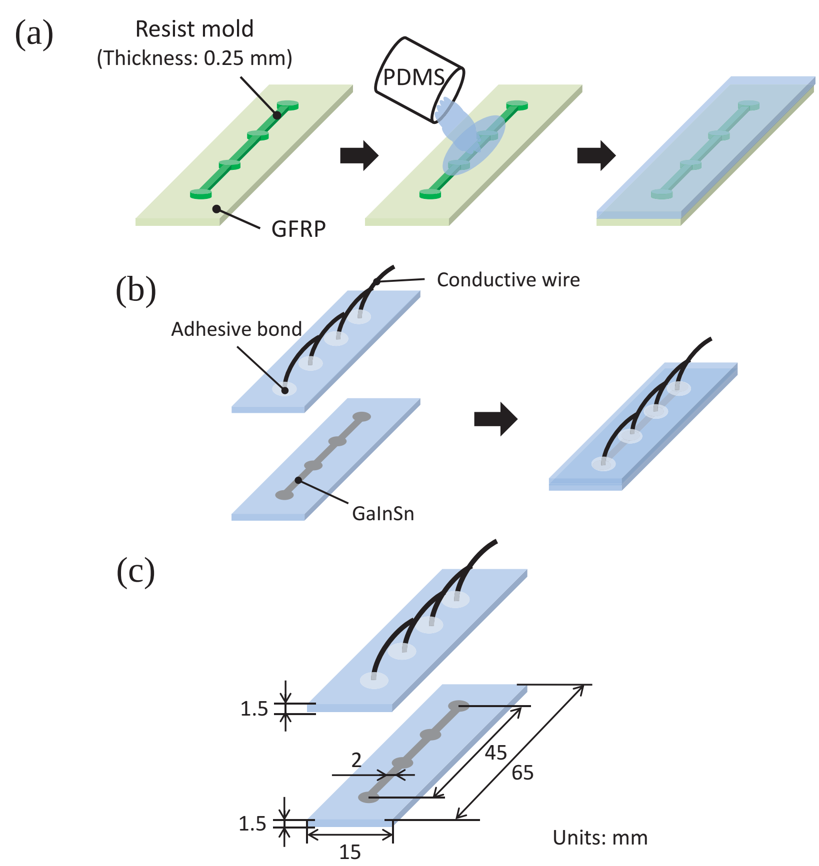

Figure 1. Fabrication process and dimensions of the GaInSn stretchable electrodes. a) Fabrication method for the patterned electrode sheet. b) Adhesion of two PDMS sheets. c) Dimensions of the GaInSn stretchable electrode.

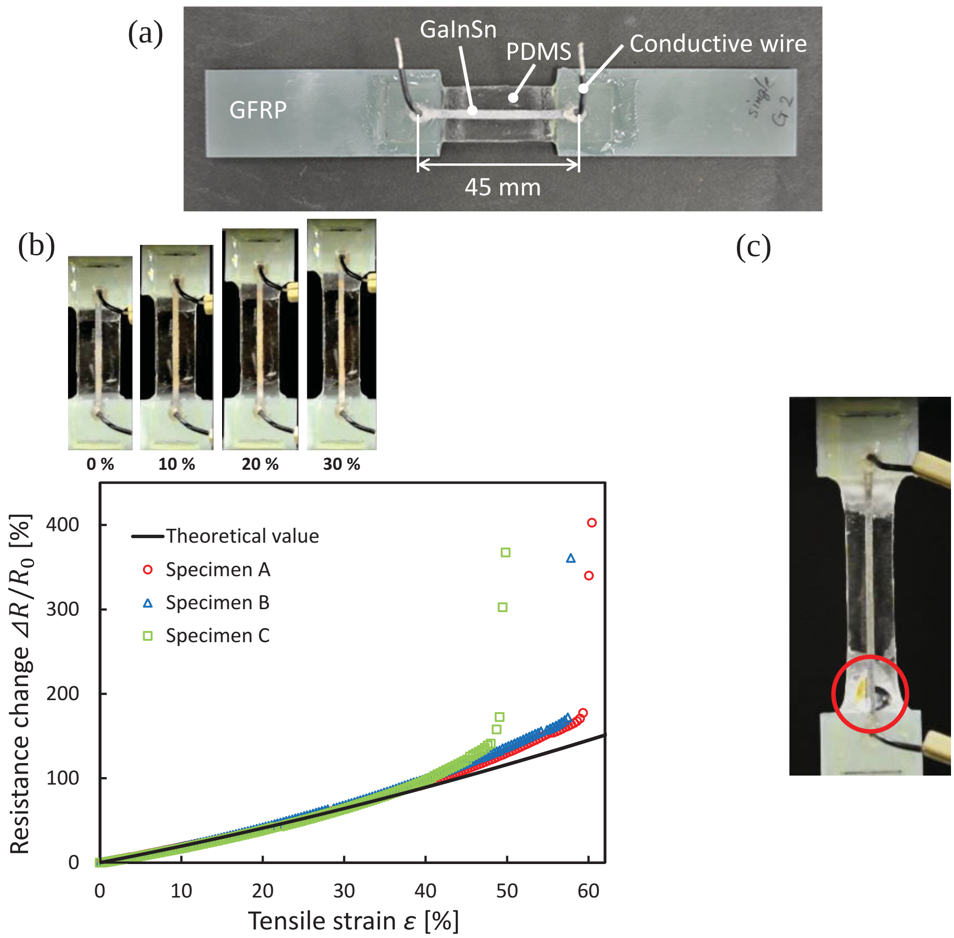

Figure 2. Tensile tests of the GaInSn stretchable electrodes. a) Specimen configuration. b) Relationship between the tensile strain and the electrical resistance change. c) Breaking point of the electrodes. The red circle indicates the leakage point of GaInSn. The theoretical value is given by Equation (1).

Figure 2b shows the experimental results of the tensile tests. The solid line indicates the theoretical value given by

$$\frac{\Delta R}{R_0} = \left(\varepsilon^2 + 2\varepsilon\right)\frac{R_0 - 2R_C}{R_0} \tag{1}$$

where R_0 is the initial measured electrical resistance, R_C is the contact resistance, and ε is the strain of the stretchable electrode (see the Supporting Information for the derivation). The pictures in Figure 2b show the appearance of the GaInSn electrodes corresponding to 0%, 10%, 20%, and 30% strain from left to right. From Figure 2b, the electrical resistance change agrees with the theoretical resistance change up to 50%–60% strain; after this, the electrical resistance change has a higher value than the theoretical value. By observing the specimen at the separation point from the theoretical curve, the leakage of GaInSn was observed, as shown in Figure 2c. Because of the loss of GaInSn, the electrical resistance change increases compared to the theoretical value. Because two PDMS sheets are attached to seal the GaInSn in the present study, the separation of these two PDMS sheets and the leakage of GaInSn occurred during stretching. Therefore, it was found that the electrode can withstand up to 50% strain, and its electrical resistance agrees with theory, which means that the strain can be calculated from the electrical resistance change using the electrode configuration.

Figure 3 shows the cyclic test results. We performed 20 cycles from 0% strain to a maximum strain of 30%. The dashed line indicates the theoretical line given by Equation (1). This figure corresponds to the first six cycles of the 20 test cycles. From the figure, the electrical resistance increases and decreases linearly corresponding to the strain and has its maximum values at the maximum strain (30%), whereas the electrical resistance decreases linearly to the initial value when the strain is at its initial value (0%). Therefore, it was demonstrated from the cyclic tests that the change in the electrical resistance corresponds to the change in the strain without delay and there is little hysteresis in the electrical resistance change. In addition, we did not observe any drastic electrical resistance change or failure of the GaInSn electrode after 20 cycles.

2.3. Global and Distributed Local Strain Sensing

By mounting multiple conductive wires to a single line of the stretchable electrode, multiple points of strain and the global

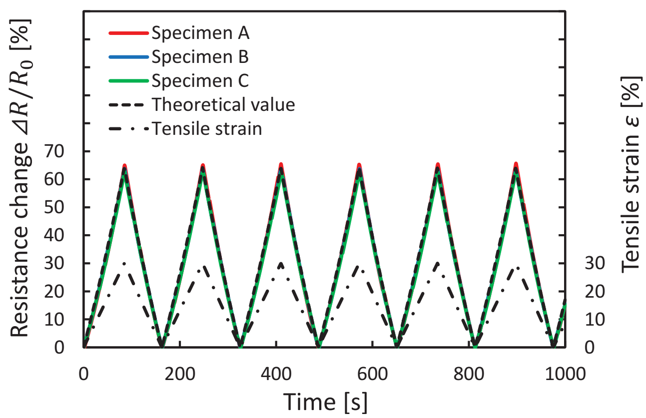

Figure 3. Electrical resistance change of the GaInSn stretchable electrodes over time under cyclic loading of tensile strain. This figure shows six cycles of the 20-cycle tests. The theoretical value is given by Equation (1).

and distributed local strains can be measured simultaneously. To verify global and distributed local strain sensing, we performed three-point-bending tests by attaching a GaInSn electrode to the surface of a GFRP rectangular plate. Four conductive wires were attached at regular intervals to the GaInSn electrode. Three-point-bending tests were performed by loading the center of the GFRP plate, where the side on which the GaInSn electrode was attached was facing downward. **Figure 4**a,b shows the specimen configuration and measurement sections for the electrical resistance, respectively. We measured the electrical resistance of three sections of the specimen: the center-section electrical resistance R_b, side-section electrical resistance R_a, and edge-to-edge global electrical resistance R_{all}. **Figure 5**a shows a schematic view of the three-point-bending tests and the pictures of deflections of 0 and 5 mm are shown in Figure 5b,c, respectively. Figure 5d shows the relationship between the electrical resistance change ratio at each measuring section and the deflection at the span center. Each line indicates a theoretical curve for R_b, R_a, and R_{all} given by

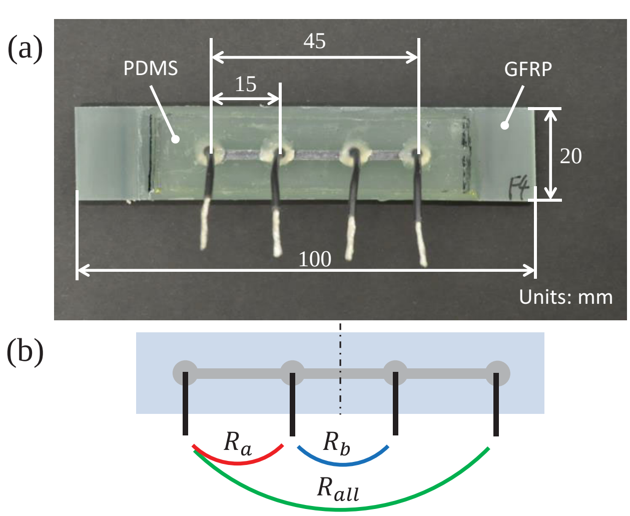

Figure 4. a) GaInSn stretchable electrode specimen for the three-point-bending tests. b) Measurement sections of the GaInSn electrodes.

$$\frac{\Delta R}{R_0} = \left\{ \frac{24h'}{l^3}(b+a)y + \frac{1}{3}\left(\frac{24h'}{l^3}\right)^2 (b^2+ab+a^2)y^2 \right\} \frac{R_0 - 2R_C}{R_0} \tag{2}$$

where h' is the half thickness of the GFRP plate and l is the span length (see the Supporting Information for the derivation of Equation (2)). Here, the measurement section is denoted by the interval [a, b], where the origin is set at the left supporting point. From beam theory, the bending modulus was calculated as E = 24.3 GPa, whereas the bending strain at the span center during bending tests is shown in Figure 5e. It should be noted that the bending strain was not very large, even though a large deflection occurred in the case of bending. From Figure 5d, it was demonstrated that the electrical resistances at multiple locations including the local and global distance were simultaneously measured using a single stretchable line by mounting multiple conductive wires, and these electrical resistances are in agreement with the theoretical values.

2.4. Data Glove Validation

To validate the application of a stretchable strain sensing line using a GaInSn electrode as a wearable sensor, we manufactured a prototype of a data glove for sensing the movements of multiple finger joints. **Figure 6**a,b shows the data glove based on a rubber glove to which GaInSn electrodes are attached at fixed measurement intervals of 15 mm for sensing the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MP) joints of the forefinger (see Figure 6c for a reference of each joint part). We wore this data glove on the right hand and measured the electrical resistance change when grasping various objects. **Figure 7** shows a) a pen and two different circular cylinders with diameters of b) 30 mm and c) 75 mm as the objects of measurement.

Figure 8 shows the experimental results of the application of stretchable, global, and distributed local strain sensing electrodes to the data glove. The initial electrical resistance R_0 corresponds to the open-palm state. From the experimental results, the largest deformation joint varies depending on the object grasped and the finger states can be identified by measuring the electrical resistance of multiple sections. For the two different diameters of the circular cylinders, each electrical resistance is higher for the 30 mm diameter cylinder than the 75 mm diameter cylinder, especially for the PIP and DIP joints. For the small-diameter object, the finger joints fold more tightly, and the strains at the PIP and DIP joints have very large values, which result in a large electrical resistance change. In addition, the 30 mm diameter cylinder has the largest electrical resistance change from the global electrical resistance change ratio results. It should be noted that this global electrical resistance is not just the summation of the resistances of the DIP, PIP, and MP joint sections, but it includes the interval between each section of the DIP, PIP, and MP joints.

In the present study, a comparison of the MP joint and the global electrical resistance is the easiest way to identify the finger states: a high MP resistance and low global resistance

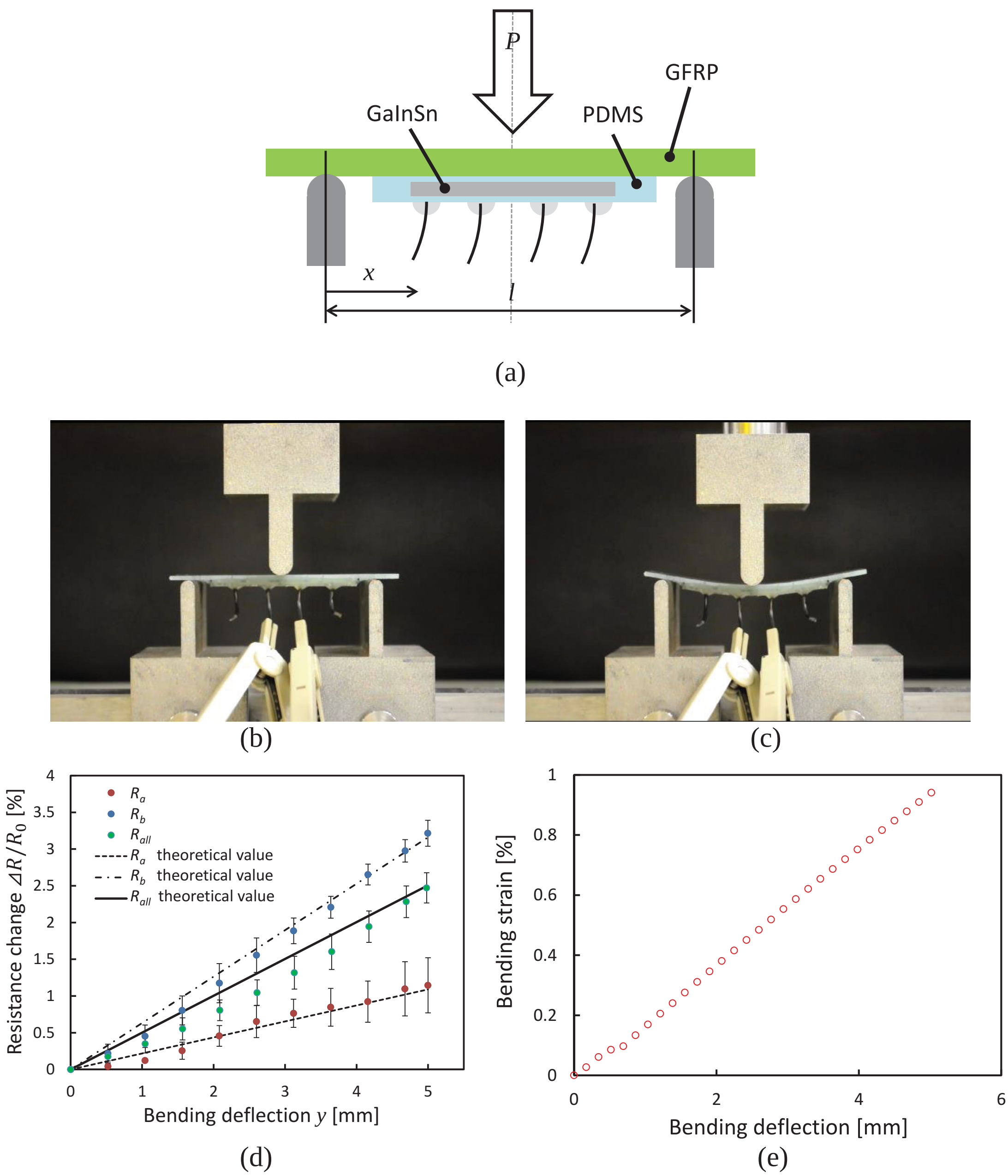

Figure 5. Three-point-bending tests of the GFRP with a GaInSn electrode. a) Schematic view of the three-point-bending tests of the GaInSn electrode attached to the GFRP plate. b) Picture at a bending deflection of $y = 0$ mm. c) Picture at bending deflection of $y = 5$ mm. d) Relationship between the bending deflection and the changes in the resistances of the GaInSn electrode, R_a, R_b, and R_{all}. e) Relationship between the bending deflection and the bending strain at the span center.

indicates that the pen is grasped, a low MP resistance and high global resistance means that the 30 mm diameter cylinder is grasped, and a low MP resistance and low global resistance means that the 75 mm diameter cylinder is grasped. As for the grasping behavior, the global resistance is the most robust (output ratio between cylinder 1 and cylinder 2) parameter because the global resistance represents the overall finger-grasping configuration, whereas the some joint (especially the DIP joint) does not always vary during grasping behaviors. From the data-glove demonstration, finger joint movement or a hand state can be identified by using a simple sensing line with a GaInSn electrode with multiple measurement points. This implies that the data glove can be used as a very lightweight master finger of a master/slave manipulator or a data entry device for 3D movement.

3. Conclusion

For the development of wearable devices, the feasibility of a data glove was investigated using a stretchable, global, and

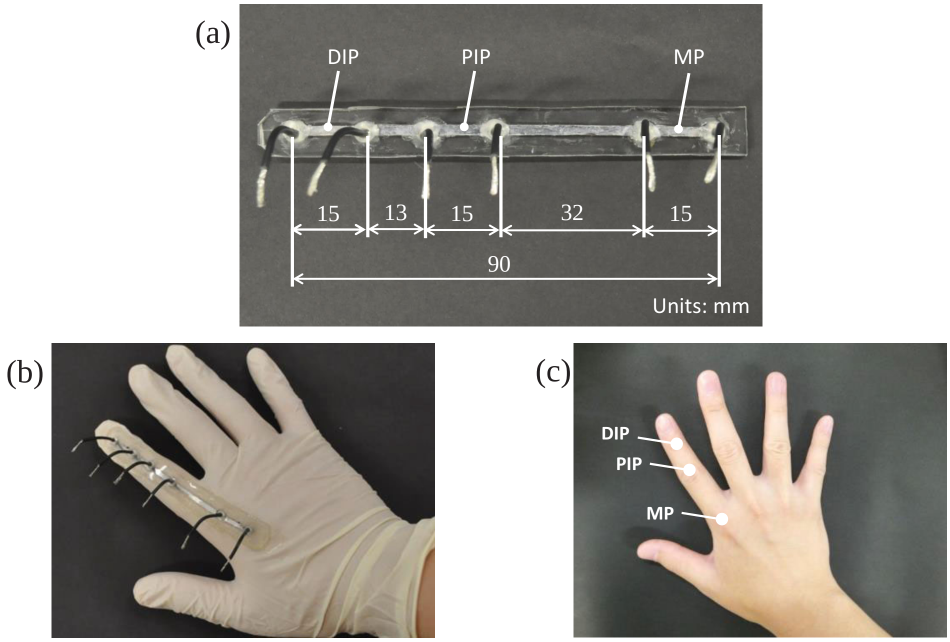

Figure 6. Application of a wearable sensor using a GaInSn stretchable electrode. a) GaInSn stretchable electrode for a data glove. b) A data glove using a GaInSn stretchable electrode. c) Names of the finger joints.

distributed local strain sensing line made of GaInSn and PDMS. Tensile, cyclic, and three-point-bending tests were performed to investigate the electrical properties of multiple sections of the GaInSn electrode when stretching. For the tensile tests, the electrode withstands a strain up to 50% and the leakage of GaInSn occurred owing to the separation of the PDMS sheets at this strain. From the cyclic tests, it was found that the electrical resistance of the stretchable electrode had no hysteresis and the change in the electrical resistance corresponded to the applied strain without a delay. From the three-point-bending tests, the distributed local strain in addition to the global strain can be simultaneously measured using just a single electrode line by setting multiple measurement points. These electrical resistance changes agreed well with the theoretical values. Finally, a prototype data glove was manufactured as an application of the strain sensing line with the GaInSn electrode and it was demonstrated that the folding state of the fingers could be identified by utilizing the electrical resistance change depending on object grasped. The proposed technology may be utilized to create an extremely lightweight manipulator and thus may broaden the use of a master hand manipulator or 3D data entry device.

4. Experimental Section

Manufacturing Process of the GaInSn Electrode: Stretchable electrodes were made from GaInSn and PDMS. The composition of the GaInSn was Ga: 68.5 wt%, In: 21.5 wt%, and Sn: 10 wt%. Ga, In, and Sn were placed in a polytetrafluoroethylene (PTFE) beaker (As One) and heated to 30 °C, at which Ga will melt, on a hot plate (CHP-170DN, As One). When all three metals became liquid, the metals were mixed with a stirring rod and cooled down to room temperature, thereby obtaining the liquid state of GaInSn. The electrode pattern was manufactured using a thick negative photoresist (THB-151N, JSR), as shown in Figure 1a. The photoresist was coated in three layers using a spin coater (MS-A150, Mikasa) at 1000 rpm for 20 s. Then, the photoresist was exposed to UV light (Ushio HB-25103BY-C, light source: Ushio UV lamp 250BY) for 3 min and developed using a developer (NMD-3 TMAH2.38%, Tokyo Ohka Kogyo) for 7 min. The liquid-state uncured PDMS (Silpot184, Dow Corning Toray, strain-to-failure: 160%[17] was poured onto the manufactured electrode pattern and cured for 2 h at 90 °C. By this process, a PDMS sheet was prepared with a transferred electrode pattern. Then, GaInSn was poured onto the manufactured pattern and another flat PDMS sheet was adhered using elastic adhesives (Super X No. 8008, Cemedine) to seal the GaInSn. A conductive wire for connection to an external device was attached to the top PDMS sheet using the same elastic adhesives.

Tensile Tests: GaInSn electrodes were manufactured with two conductive wires connected to the electrode, and the electrode interval was set to 45 mm. GFRP tabs were adhered at both edges of the GaInSn electrode using elastic adhesives (Super X No. 8008, Cemedine), as shown in Figure 2a. By clamping the GFRP tabs, tensile tests were performed using a material testing machine (AGS-J, Shimadzu) under displacement control conditions at 10 mm min^{-1}. During the tensile tests, the electrical resistance was measured using an inductance-capacitance-resistance (LCR) meter (LCR Hi Tester 3522-50, Hioki) at 100 Hz by connecting measurement cables to the conductive wires of the GaInSn electrode. In addition, the appearance of the GaInSn electrode was recorded using a digital video camera and the changes in the appearance were checked after the tensile tests. In the cyclic tests, we set the maximum strain to 30% considering the failure strain obtained from the tensile tests and tests were performed for 20 cycles at 0%–30% strain. Three specimens were used in both the tensile and cyclic tests.

Three-Point-Bending Tests: Four conductive wires were connected to the GaInSn electrode at 15 mm intervals. The GaInSn electrodes were attached to the GFRP plate (thickness: 2 mm, 20 mm × 100 mm) using elastic adhesives (Super X No. 8008, Cemedine), as shown in Figure 5a. The three-point-bending tests were performed using a material testing

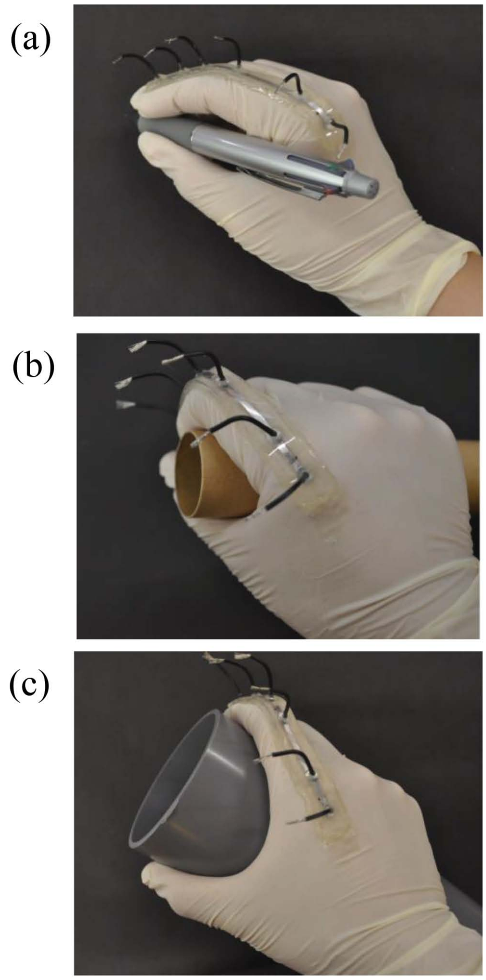

Figure 7. Measurement objects for validation of the data glove. a) Pen. b) Cylinder 1 (30 mm in diameter). c) Cylinder 2 (75 mm in diameter).

machine (AGS-J 10kN, Shimadzu) by applying a load at the center of the GFRP plate using a three-point-bending fixture. A schematic of the test is shown in Figure S3 (Supporting Information). The span length was 80 mm, and the indenter was displaced at a speed of 10 mm min^{-1} until the specimen center achieved a deflection of 5 mm. The electrical resistance change was measured using an LCR meter at 100 Hz and

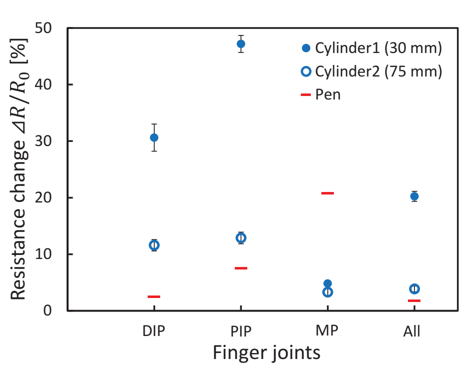

Figure 8. Relationship between the finger joints and the electrical resistance change when grasping cylinders and a pen while wearing a data glove.

the measurements were conducted using three specimens for each measurement section.

Finger Folding Tests Using a Data Glove: A GaInSn electrode was adhered to the rubber glove using elastic adhesives (Super X No. 8008, Cemedine) and the area surrounding the electrode was coated using the same elastic adhesives, preventing separation from the glove. The electrical resistance was measured for each section using the LCR meter at 100 Hz and measurements were conducted three times for each finger joint.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Received: April 7, 2015
Published online: May 7, 2015

[1] R. Matsuzaki, T. Keating, A. Todoroki, N. Hiraoka, *Sens. Actuators A* **2008**, *148*, 1.
[2] T. Someya, T. Sekitani, S. Iba, Y. Kato, H. Kawaguchi, T. Sakurai, *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 9966.
[3] R. Matsuzaki, A. Todoroki, *Sens. Actuators A* **2007**, *140*, 32.
[4] J. A. Rogers, Z. Bao, K. Baldwin, A. Dodabalapur, B. Crone, V. R. Raju, V. Kuck, H. Katz, K. Amundson, J. Ewing, P. Drzaic, *Proc. Natl. Acad. Sci. U.S.A.* **2001**, *98*, 4835.
[5] L. Zhou, A. Wanga, S.-C. Wu, J. Sun, S. Park, T. N. Jackson, *Appl. Phys. Lett.* **2006**, *88*, 083502.
[6] T. Li, Z. Suo, *Int. J. Solids Struct.* **2006**, *43*, 2351.
[7] S. P. Lacour, D. Chan, S. Wagner, T. Li, Z. Suo, *Appl. Phys. Lett.* **2006**, *88*, 204103.
[8] T. Sekitani, Y. Noguchi, K. Hata, T. Fukushima, T. Aida, T. Someya, *Science* **2008**, *321*, 1468.
[9] D. H. Kim, J. Song, W. M. Choi, H. S. Kim, R. H. Kim, Z. Liu, Y. Y. Huang, K. C. Hwang, Y. W. Zhang, J. A. Rogers, *Proc. Natl. Acad. Sci. U.S.A.* **2008**, *105*, 18675.
[10] T. Sekitani, H. Nakajima, H. Maeda, T. Fukushima, T. Aida, K. Hata, T. Someya, *Nat. Mater.* **2009**, *8*, 494.
[11] C.-X. Liu, J.-W. Choi, *IEEE Trans. Nanotechnol.* **2010**, *9*, 590.
[12] P. Lee, J. Lee, H. Lee, J. Yeo, S. Hong, K. H. Nam, D. Lee, S. S. Lee, S. H. Ko, *Adv. Mater.* **2012**, *24*, 3326.
[13] S. Rosset, M. Niklaus, P. Dubois, H. R. Shea, *Adv. Funct. Mater.* **2009**, *19*, 470.
[14] J.-H. So, J. Thelen, A. Qusba, G. J. Hayes, G. Lazzi, M. D. Dickey, *Adv. Funct. Mater.* **2009**, *19*, 3632.
[15] P. Surmann, H. Zeyat, *Anal. Bioanal. Chem.* **2005**, *383*, 1009.
[16] M. D. Dickey, R. C. Chiechi, R. J. Larsen, E. A. Weiss, D. A. Weitz, G. M. Whitesides, *Adv. Funct. Mater.* **2008**, *18*, 1097.
[17] M. Kubo, X. Li, C. Kim, M. Hashimoto, B. J. Wiley, D. Ham, G. M. Whitesides, *Adv. Mater.* **2010**, *22*, 2749.
[18] S. Zhu, J.-H. So, R. Mays, S. Desai, W. R. Barnes, B. Pourdeyhimi, M. D. Dickey, *Adv. Funct. Mater.* **2013**, *23*, 2308.
[19] H.-J. Kim, C. Son, B. Ziaie, *Appl. Phys. Lett.* **2008**, *92*, 011904.
[20] D. E. Hanson, M. Hawley, R. Houlton, K. Chitanvis, P. Rae, E. B. Orler, D. A. Wrobleski, *Polymer* **2005**, *46*, 10989.
[21] J. P. Heggers, N. Kossovsky, R. W. Parsons, M. C. Robson, R. P. Pelley, T. J. Raine, *Ann. Plast. Surg.* **1983**, *13*, 38.
[22] A. Fassler, C. Majidi, *Smart Mater. Struct.* **2013**, *22*, 055023.
[23] M. G. Mohammed, M. D. Dickey, *Sens. Actuators A* **2013**, *193*, 246.
[24] Y.-L. Park, B. Chen, R. J. Wood, *IEEE Sens. J.* **2012**, *12*, 2711.

[25] S. Liu, X. Sun, O. J. Hildreth, K. Rykaczewski, *Lab Chip* **2015**, *15*, 1376.
[26] H. Hu, K. Shaikh, C. Liu, "Super flexible sensor skin using liquid metal as interconnect," presented at *IEEE Sens. Conf.*, Atlanta, GA, October **2007**.
[27] R. K. Kramer, C. Majidi, R. J. Wood, "Wearable tactile keypad with stretchable artifical skin," presented at *IEEE Int. Conf. Robot. Autom.*, Shanghai, May **2011**.
[28] C. Majidi, R. Kramer, R. J. Wood, *Smart Mater. Struct.* **2011**, *20*, 105017.
[29] Y.-L. Park, B. Chen, D. Young, L. Stirling, R. J. Wood, E. G. Nagpal, "Bio-inspired active soft orthotic device for ankle foot pathologies," presented at *IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, San Francisco, CA, September **2011**.
[30] *CRC Handbook of Chemistry and Physics*, CRC Press, FL, USA **2009**.
[31] N. B. Morley, J. Burris, L. C. Cadwallader, M. D. Nornberg, *Rev. Sci. Instrum.* **2008**, *79*, 056107.