Self-Deformable Flexible MEMS Tweezer Composed of Poly(Vinylidene Fluoride)/Ionic Liquid Gel for Electrical Measurements and Soft Gripping

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Abstract—We present a self-deformable flexible tweezer capable of simultaneous mechanical handling and electrical measurements. The tweezer has a soft cantilever with the dimensions 2 mm × 8 mm × 75-100 µm, and undergoes self-deformation. The device is shown to be successfully capable of detecting electrical signals by gently touching the surface and grasping a spherical bead. The device demonstrated the lowest working voltage (1.5 VDC), force suitable for soft gripping, and curvature radius of 2 mm, that was one of the smallest values compared to that of similar state-of-the-art devices. The device was fabricated using a unique and highly reliable process that was specifically developed to produce flexible cantilevers with novel ionic polymer-metal composites (IPMCs). The materials used were poly(vinylidene fluoride-co-trifluoroethylene) (PVDF-TrFE) and an ionic liquid (IL). The PVDF-TrFE/IL gel was prepared using acetone as the solvent and the gel was coated with silver nanowires as the electrodes. The actuator with a length of 8 mm and containing 50 wt% IL yielded the largest bending displacement of 7 mm and minimum curvature radius of 2 mm at 1.5 VDC.

Index Terms—Electrical detection, flexible actuator, ionic liquid, PVDF-TrFE, self-deformable cantilever, silver nanowire, soft gripping.

I. INTRODUCTION

MICROGRIPPERS are expected to be the next-generation devices for various applications such as manipulation, assembly, or pick-and-place tasks by grabbing the microobjects [1]. Different methods of their actuations have been studied such as piezoelectric [2]–[4], electrostatic [5], [6], electrothermal [4], [7], [8] and ionic polymer-metal composite (IPMC) [9]–[12] actuators. Jain et al. (2014) [2] designed the three degree-of-freedom-based microgripper with piezoelectric actuator for microassembly. It involved conducting sequential pick-and-place of a micro pin in a hole driven by robust control of the applied voltage. Jaiswal et al. (2017) [3] fabricated the piezoelectric microwezer with the flexible SU-8 end effector to measure the stiffness of spherical cells. Its force sensing by optical observation of the deflection of the actuator enables wide measurement of the forces ranging from less than one hundred nN to one mN. The main advantages of the piezoelectric grippers are small displacement...
of micro/nano scale, fast response of micro/nano-range second, precise control, and large gripping force [2]. The electrostatic actuator integrated in the microgrippers is also driven by voltage as a comb-drive mechanism. The electrostatic grippers sometimes grab soft materials such as a polystyrene sphere (Chen et al. (2009) [5]) or lilium pollen (Piriyanont and Moheimani (2015) [6]). To avoid the damage to the targets, the former electrostatic microtweezer has the piezoresistive sensors on the side wall of the actuator and the latter microgripper has electrothermal force sensors with the feedback control. The electrostatic microgrippers have advantages that the sensors are easily integrated in the grippers with micro-electromechanical system (MEMS) technology, they are capable of grasping objects from a wide dimension range in μm scale, and they are operated stably even in ambient or vacuum environments [5]. The electrothermal microgrippers are often used to manipulate soft materials because of their flexibility, large deformation, strong recovery force, low operating voltage, and compact structure [7]. Zhang et al. (2012) [7] designed the electrothermal SU-8 microgripper with a jaw for a large gripping scope. This gripper grasps the biological objects of different sizes such as a micro blood vessel and cyanobacteria cells for micromanipulation. The electrothermal microgripper is also integrated with the piezoresistive built-in force sensor in its jaw to firmly hold objects such as a glass sphere (Duc et al. (2008) [8]). Moreover, Rakotondrabe and Ivan (2011) [4] designed the microgripper composed of an actuator operated by electrothermal and piezoelectric effects for micromanipositioning. It works as a combination of the thermal actuation (coarse positioning) and piezoelectric effect (fine positioning), demonstrating the high range and resolution of a pick-and-place task of a polystyrene sphere. Finally, IPMC is a voltage-driven electroactive polymer, which has recently drawn attraction mainly for its high flexibility and large deformation at low operating voltage [9]. The handling targets of the IPMC tweezers are of various sizes and stiffness such as micropin [10], nut and ping-pong ball [9], fish egg [11], hydrogel and solder ball [12]. The IPMC microgripper is suitable for both industrial operations and bio-micromanipulation tasks [12].

As discussed above, various targets from hard metal pins and plastic spheres to vulnerable organisms are manipulated by the microgripper actuated by different mechanisms [2]–[12]. It is necessary to analyze the gripped objects in the industrial, material, and biological manipulation, especially fragile materials with unknown characteristics, because simultaneous manipulation and observation allows for more efficient verification of their electrical properties. Therefore, the microtweezer should grip a vulnerable target slowly and gently, not give unnecessary stimuli, and observe it electrically with close contact. Our attempts to observe a three-dimensional (3D) delicate object while it is gripped led us to propose an active flexible tweezer device, as shown in Fig. 1. This device, equipped with a self-deformable flexible cantilever, is capable of gripping a 3D target of even spherical structures with minimum force to closely perform adequate electrical measurements. An example of the proposed tweezer demonstrating gripping and electrical observation is an organism [1]. Microelectrode array-type two-dimensional (2D) devices are commonly used to detect electrical responses from organisms [13], [14]. However, a major disadvantage of these devices is their planar structure, that is, their inability to adhere to cellular tissues of the organisms, which are essentially 3D structures. Moreover, owing to their passivity, these devices can only detect the response from those parts of organism which are in their contact. Our active flexible tweezer can overcome these problems because the device can fix gently and adhere closely to the spherical organism and non-invasively measure electrical signals from the target.

The flexible cantilever of the tweezer in Fig. 1 was realized based on an IPMC actuator. Our suggested use of this actuator was motivated by its excellent suitability as an active device for gripping vulnerable objects as a result of its high flexibility, biocompatibility, huge strain, good conductivity, and low operating voltage without heating compared with other actuators [9]. An IPMC actuator is composed of polymers and mobile ions (cations and anions) and is equipped with electrodes. Theories that have been proposed to explain the deformation of IPMCs when voltage is applied are based on the size difference [15], the diffusion speed of ions [16], or the one-directional movement of ions [17]. In all these studies, the actuators deflected to one side when voltage was applied. The polymer is the main component of an IPMC actuator and various polymers, such as Nafion [9]–[12] or poly(vinylidene fluoride) (PVDF) [15], [18], have been used in this regard. IPMC actuators based on PVDF or its co-polymers and ionic liquids (ILs) as the source of mobile ions have a large strain of a few % at operating voltages below 10 V [15], [18]–[22]. PVDF and its co-polymers are ferroelectric and piezoelectric materials with a low Young’s modulus (∼500 MPa) [21]. Ionic liquids are salts that maintain their fluid state across a wide range of temperatures and are characterized by low vapor pressure, incombustibility, and good conductivity [15]. Among the IPMCs configured with PVDF co-polymers and an IL, the IPMC actuator (composed of poly(vinylidene fluoride-co-trifluoroethylene) (PVDF-TrFE) and 1-ethyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide (EMIMTFSI) as the IL) is known to have the largest displacement of 3.5 mm for an actuator length of 10 mm at 100 mHz and 5.0 Vpp [21].

These advantages prompted our decision to base the actuator on PVDF-TrFE/EMIMTFSI ionic gel composites with the ultimate aim of realizing a self-deformable flexible tweezer.
The co-polymer, PVDF-TrFE (PIEZOTECH ® FC25), conserved and used in a glove box under a nitrogen atmosphere. Purchased from the Tokyo Chemical Industry (Japan) and was stored and used in a glove box under a nitrogen atmosphere. Particularly, we previously reported an actuator based on this novel “ionic gel.” This actuator delivered a displacement of 7 mm, which was 88 % of the total length of the actuator, at 1.5 V (V DC) [1]. This actuator had one of the highest normalized strains among state-of-the-art IPMC actuators at the lowest operating voltage. The tweezer fabricated with this ionic gel actuator could also detect electrical signals in contact with the Au target electrode. However, the actuator had two major drawbacks: a low manufacturing yield of 33 % and low deformation speed of 2.3 mm/min. Moreover, although the actuator succeeded in detecting an electrical signal, we were unable to demonstrate that the tweezer performed the manipulation and gripping action satisfactorily.

In this study, we developed a new fabrication process for our ionic gel using the same materials from the previous actuator to improve its production yield and deformation properties. The new ionic gel has deformation properties superior to those of the former gel under the same electrical conditions. The latest actuator was similarly mounted on a tweezer device to detect electrical signals and to perform the grasping motion. The generated force of the actuator was estimated when the tweezer was gripping the target. Consequently, the tweezer with our PVDF-TrFE/EMIMTFSI gel actuator with the AgNWs electrode as the cantilever was confirmed to be capable of gripping the spherical target and detecting electrode signals for manipulating 3D targets such as organisms and detecting their signals.

II. FABRICATION OF IONIC GEL TWEEZER

A. Materials

The ionic gel, EMIMTFSI, with a purity of 98.0 %, was purchased from the Tokyo Chemical Industry (Japan) and was stored and used in a glove box under a nitrogen atmosphere. The co-polymer, PVDF-TrFE (PIEZOTECH® FC25), contained 25 mol% trifluoroethylene (TrFE) and was obtained from Arkema Piezotech (France). For the solvent, we used acetone with a purity of 99.5 % obtained from Kanto Chemical Holdings (Japan). The PVDF-TrFE and acetone were maintained at 25 % humidity in an atmospheric environment. The electrode was fabricated using an aqueous suspension of 5 mg/mL silver nanowires (AgNWs), purchased from Merck (Germany). The suspension was maintained at atmospheric pressure in the refrigerator (2-6 °C).

B. Fabrication of PVDF-TrFE/EMIMTFSI Ionic Gel Composites

Three PVDF-TrFE/EMIMTFSI ionic gel membranes were prepared by changing the weight ratio of PVDF-TrFE as 30, 50, and 70 wt% of the total weight of the ionic gel. The weight of PVDF-TrFE was 150 mg or 300 mg. Therefore, six ionic gel membranes were fabricated and denoted 30a, 30b, 50a, 50b, 70a, and 70b, where “30,” “50,” and “70” indicates the weight ratio of PVDF-TrFE/EMIMTFSI, and “a” and “b” indicate 150 mg or 300 mg PVDF-TrFE, respectively. The ionic gel was fabricated as follows: 150 or 300 mg PVDF-TrFE powder was placed in a glass bottle with acetone and 5 wt% of the polymer solution. This solution was magnetically stirred on a hotplate at 50 °C for approximately 24 h. After stirring, an appropriate quantity of EMIMTFSI was added to the liquid. The PVDF-TrFE/EMIMTFSI in acetone was agitated at 50 °C for 24 h. This solution was spread in a Petri dish of φ 80 mm × 17 mm with a BEMCOT® lid, and dried at room temperature (25 °C) for 24 h to allow the acetone to evaporate.

The aforementioned procedure yielded four of the six ionic gel membranes (30b, 50a, 50b, and 70b). The other two films (30a and 70a) were destroyed owing to their thinness when peeled from the dish. The four membranes were coated with AgNWs to form the electrode.

C. Coating of Silver Nanowire Electrode

The electrode of the actuator consisted of a coating of AgNWs. We developed two methods to form the electrode: “single-layer ionic gel (SLIG)” and “sandwich ionic gel (SWIG).” A coating of AgNWs was applied to the 30b, 50a, 50b, and 70b films to form the SLIG, and only 50b was used to form the SWIG. First, a syringe was used to drop an aqueous suspension of AgNWs on one side of the ionic gel membranes in the Petri dish. This film was heated on a hotplate at 100 °C for 15 min and allowed to cool at 25 °C for 5 min. The SLIG was formed by peeling off the membrane coated with the electrode, after which the membrane was turned over to apply a coating of AgNWs on the other side of the ionic gel to form the second electrode. The film was dried as before to produce the SLIG membrane, and a cross-sectional view thereof is shown in Fig. 2 on the left. The SWIG membrane was obtained by attaching two films coated with AgNWs on one side via their ionic gel surfaces, as shown in Fig. 2 on the right, followed by heating at 100 °C on the hotplate for 10 min.

The composite film comprising the polymer/IL with electrodes was cut into a rectangular form of 2 mm × 10 mm using a UV laser cutter (LPKF Protolaser U4). The thickness of the SLIG before and after placement of the electrodes was measured using an Olympus LEXT OLS5000 laser microscope. The thicknesses of the 30b, 50a, 50b, and 70b actuators after applying the coating to form the electrodes were 52.6,
analyze the VAC signal. In this mode, the voltage at a particular
respectively. The math mode of the oscilloscope was used to
produces an AC signal with 700 mV sinusoidal wave of 1 kHz.
GDS-2072A oscilloscope were used. The function generator,
a HIOKI DT4253 (a digital multimeter) ammeter,
measurements of the tweezer), a RIGOL DG4202 function
generator, a Hewlett-Packard E3640A was used as the DC
power supply and the movement of the actuator was recorded
by an iPhone camera. In Subsection III-D (the electrical
measurements of the tweezer), a RIGOL DG4202 function
generator, a HIOKI DT4253 (a digital multimeter) ammeter,
a 1.5 V alkaline battery DC power supply, and a GWinstek
GDS-2072A oscilloscope were used. The function generator
produces an AC signal with 700 mV sinusoidal wave of 1 kHz.
The capacitor and inductor settings were 10 pF and 47 mH,
respectively. The math mode of the oscilloscope was used to
analyze the VAC signal. In this mode, the voltage at a particular
frequency from the observed voltage can be detected using
fast Fourier transformation. Finally in Subsection III-E (the
motion of the tweezer in Subsection III-D
and III-E was recorded using an iPhone camera and a SONY
HDR-PJ680 video camera.

D. Measurement Equipment

The electrical equipment used for measuring the character-
istics of the ionic gel and tweezer are detailed in this
section. In Subsection III-A and III-F (the characteristics of
the actuator), a Hewlett-Packard E3640A was used as the DC
power supply and the movement of the actuator was recorded
by an iPhone camera. In Subsection III-D (the electrical
measurements of the tweezer), a RIGOL DG4202 function
generator, a HIOKI DT4253 (a digital multimeter) ammeter,
a 1.5 V alkaline battery DC power supply, and a GWinstek
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III. RESULTS AND DISCUSSION

A. Measurement of Deformation Characteristics in
Ionic Gel Actuator

A 2 mm × 2 mm section of the 2 mm × 10 mm SLIG
and SWIG actuators was fixed between a jig of copper tape
electrodes. Then, DC power, VDC was supplied to the actuator
in the forward and reverse directions for 3 min to observe
its bending motion. For the SLIG, the applied voltage was
changed from 0.5-3.0 VDC in increments of 0.5 VDC. For the
SWIG, the voltage was fixed at 1.5 VDC. The displacement
was measured in units of 1 mm using the graph sheet.

1) Deformation Properties of SLIG: The SLIG actuator
always bent to the anode side, which was positively charged,
as shown in Fig. 3 [1]. This was because the cations in IPMCs
based on EMIMTFSI diffused faster than the anions [16].
All four actuators detected electrical signals at their maximum
voltages owing to the destruction of the electric double layer
in the ionic gel. During conduction, the current across the
actuator suddenly increased to 3 A, which is the limit of the
voltage supply. We observed that membranes 30b and 70b
hardly deformed regardless of the direction of the applied
voltage, although 50a and 50b exhibited significant deforma-
tion [1]. Except for the voltage levels at which the actuators
conducted electricity, 50b exhibited the largest displacement
of 7 mm at +1.5 VDC and 5 mm at −1.5 VDC, in Fig. 3 [1].

2) Deformation Properties of SWIG: The 50b SWIG actu-
ator was displaced by 7 mm at +1.5 VDC and 6 mm at
−1.5 VDC in the direction of the anode, similar to the SLIG
(Fig. 4(a)). Moreover, the 50b SWIG could undergo deforma-
tion almost to the physical limit of the minimum 2 mm curva-
ture radius for a total length of 8 mm at 1.5 VDC (Fig. 4(b)).

B. Performance Comparison of SLIG and SWIG

We compare the properties of 50b SLIG and 50b SWIG in
Table I. In total, 15 SLIG of 50b and 28 SWIG of 50b were
manufactured for validation of their yields. Both actuators
underwent a maximum displacement of 7 mm at 1.5 VDC
working voltage for a PVDF-TrFE:EMIMTFSI weight content
ratio of 300:300 mg (50b ionic gel). Meanwhile, SWIG
outperformed SLIG with its maximum deformation speed 4.6
times as high as that of SLIG. The reason for the superior performance of SWIG
compared with SLIG is the difference in the unevenness of
the electrode coating. During the AgNW coating process of
SLIG, the membrane with the electrode coating on one side
was turned over to apply the AgNW coating to the reverse
side. Membrane films coated with AgNWs on the reverse side
shrink and contain many wrinkles because of the surface
tension of the water in which the AgNWs are suspended and
the internal stress resulting from the difference in Young’s
modulus between the ionic gel and AgNWs. Therefore, the
electrode is printed unevenly on the reverse side such that
the electrical conductivity of the electrodes is considered to
be strongly influenced. However, the SWIG was fabricated by attaching the two membranes, each with an electrode coating on one side. This implies that the electrodes on both sides of the SWIG membrane were more uniform than those on SLIG because the SWIG membrane was not crumpled much by applying the electrode coating to only one side. As a result, SWIG would have higher electrical conductivity on the electrodes than SLIG, explaining the higher moving speed and yield of the former.

C. Performance Comparison of State-of-the-Art IPMCs

The 50b SWIG actuator with the largest 7 mm displacement and smallest 2.0 mm curvature radius at 1.5 V_DC was compared with the state-of-the-art IPMCs actuators produced from Nafion [9] or PVDF co-polymers [15], [18]–[22]. To appropriately evaluate the deformation, we employed the following equation, which is commonly used to compare the displacement of IPMC actuators [1], [9], [15], [18], [20], [21], [23].

$$\epsilon = \frac{2T}{L^2 + \delta^2} \left(= \frac{T}{R} \right)$$  \hspace{1cm} (1)

where \( \epsilon \), \( T \), \( \delta \), \( L \), and \( R \) are the normalized strain, thickness, displacement, deformed length projected on the unbent state, and curvature radius of the actuator, respectively. \( L \) is equal to the free length of the actuator when \( \delta \) is sufficiently small compared to \( R \). Now, \( \epsilon \) is proportional to the working voltage \( V_{DC} \) in consideration of the deformation principle. Therefore, in this study, the next figure-of-merit (FoM1) was defined for the evaluation.

$$FoM_1 = \frac{\epsilon}{V_{DC}} = \frac{T}{RV_{DC}}$$  \hspace{1cm} (2)

The largest values of \( \epsilon \) and \( \delta \) in these studies are cited. The values in Table II and Fig. 5 indicate that our ionic gel actuator had the largest FoM1 at the minimum working voltage of 1.5 V_DC. This huge FoM1 was a consequence of the combination of PVDF-TrFE and EMIMTFSI. This combination has the largest displacement of PVDF co-polymer IPMC actuators [21], and the electrode with the AgNWs offers higher flexibility than metal electrodes in sheet form.

D. Demonstration of Tweezer as Electrical Probe

We demonstrated the tweezer illustrated in Fig. 6 by using our self-deformable ionic gel actuator as an electrical probe. Previously, we used 50b SLIG as probe of the tweezer [1]. However, in this study, a 50b SWIG was applied for the probe to detect the electrical signal because the SWIG has superior properties than SLIG. The cantilever of the actuator was held in place between the jig, which was the fixed electrode supplying power to the actuator of the printed circuits. The jig was composed of two electrodes for operation: the negative electrode was a fixed bar supplied with DC and the positive electrode was connected to the AC supply and was equipped with a Cu signal electrode. The blue circuit was powered by applying DC to operate the cantilever, whereas AC was supplied to the red circuit. The circuits were electrically separated by a capacitor and an inductor. When V_DC was applied to the electrodes in the DC circuit, the cantilever was deformed until it made contact with the Cu signal electrode (“+1.5 V DC” applied situation and electrically “OFF” state of AC circuit). Because the red AC circuit conducted electricity as a result of the cantilever movement, V_AC was recorded by the oscilloscope (“+1.5 V DC” applied and “ON”). After the connection of the probe and electrode, the reverse V_DC was applied so that the cantilever was operated to the opposite direction (“−1.5 V DC” applied and “ON”). The AC circuit became open when the cantilever lost contact with the signal electrode (“−1.5 V DC” applied and “OFF”). The cantilever repeatedly made contact with and was released from the signal electrode six times consecutively, as shown in Fig. 7. The V_AC level was recorded six times for repetition of the electrical ON and OFF state of the AC circuit and the readings were...
averaged. The change in the $V_{\text{AC}}$ was recorded using a video camera.

Fig. 7 shows variation of the movement and voltage in the third instance of the repetition. In Fig. 7, the voltage was 0.5-3 mV from 0-60 seconds, when the cantilever was released from the signal electrode in the left “OFF” state of Fig. 7. From 60 to 85 seconds, the voltage suddenly increased to 13–17 mV, when the cantilever fully contacted the signal electrode in the middle electrical “ON” state. For 85–88 seconds, the voltage increased to 22 mV, because the DC circuit to move the cantilever (blue circuit in Fig. 6) became open for the change of the DC voltage from $+1.5 \text{ V}_{\text{DC}}$ to $-1.5 \text{ V}_{\text{DC}}$ and the AC current leaking through the inductor was supposed to flow into the red AC circuit. During 89–110 seconds, the voltage was 10–19 mV when the cantilever is “ON” state. However, the voltage was gradually decreasing during 100–110 seconds, because a part of the cantilever was leaving the electrode, as seen during 5–6 seconds of the supplementary movie. After 110 seconds, the voltage decreased greatly to 0.3–4 mV. This variation of the voltage means that the AC circuit became “OFF” when the cantilever was completely released from the electrode in Fig. 7. The results in Table III indicate that the observed signal voltage at 1 kHz averaged for six times at the time during which the cantilever was in contact with the Cu electrode (“ON” state) was more than 25 times as high as one when the cantilever was not making contact with the electrode (“OFF” state). These results confirmed that the cantilever based on our PVDF-TrFE/EMIMTFSI gel with an AgNW actuator was able to detect $V_{\text{AC}}$ by making contact with and released from the signal electrode for the detection of the signal. The contact voltage of 14 mV in the SWIG cantilever was approximately 10 times smaller than that in SLIG [1]. This is caused by the large surface resistance of AgNW electrode. The electrode resistance of the SLIG cantilever was calculated as approximately 500 kΩ [1]. However, the electrode resistance of the SWIG was measured by the digital multimeter as 7 MΩ, more than 10 times greater than that of SLIG. The AgNW electrode in SWIG is thought to deteriorate and lose conductivity due to reaction with ionic liquid or atmosphere during huge deformation.

### E. Demonstration of the Gripping Function of the Tweezer

We demonstrated the gripping function of the tweezer. The tweezer was composed of a 50b SWIG actuator, jig fixing actuator, and an immobile bar, as shown in Fig. 8. The jig was composed of an acrylic plate with a thickness of 3 mm and copper tape electrodes. As described in Subsection III-A, an area sized $2 \text{ mm} \times 2 \text{ mm} \times 10 \text{ mm}$ SWIG was fastened between the copper electrodes. The grasping target was a plastic sphere with a diameter of 5 mm to imitate an organism. Application of $\pm 1.5 \text{ V}_{\text{DC}}$ for 3 min resulted in the actuator making repeated contact with and then releasing the target sphere, as shown in Fig. 8. These experiments confirmed that the tweezer with our ionic gel was able to grip the bead imitating an organism.

### F. Measurement of Gripping Force and Young’s Modulus of the SWIG Actuator

The gripping force of the tweezer during the grasping motion and Young’s modulus of the cantilever of the tweezer were assessed by measurement of the structural values of the 50b SWIG actuator. In this study, this was accomplished by developing a simple method using the formula for the deformation of the cantilever, thereby obviating the need for the use of measuring equipment, such as a force sensor.

#### 1) Estimation of the Gripping Force of the Tweezer:

The actuator was operated as a cantilever, as described in Subsection III-A. The tip of the cantilever of the actuator was set to touch one of the overhead projector (OHP) film, as shown in Fig. 9. When $1.5 \text{ V}_{\text{DC}}$ was applied to the electrode, the measuring cantilever imposed strain because the actuator underwent deformation to push the cantilever. This displacement was considered to be generated by the concentrated load at the free end as the pushing force of the actuator. Consequently, the displacement of the cantilever is given by (3):

$$d = \frac{wL^3}{3EI}$$
where \( d, w, l, E, \) and \( I \) are the displacement, concentrated load at the free end, free length, Young’s modulus (longitudinal elastic modulus), and moment of inertia of the OHP cantilever, respectively. Based on Fig. 9, because the concentrated load at the free end \( w \) was the same as the force \( F \) generated by the ionic gel, we could find the value of \( F \) by evaluating \( w \) with (3).

The OHP film was cut into 2 mm \( \times \) 10 mm \( \times \) 100 \( \mu \)m rectangular pieces to be used as the cantilever for the measurement. A section of the cantilever sized 2 mm \( \times \) 2 mm was fixed in the jig as shown in Fig. 9. Because the inertia of the film was determined by the 2 mm \( \times \) 100 \( \mu \)m rectangle, the moment of inertia \( I \) was calculated using (4).

\[
I = \frac{bh^3}{12} \tag{4}
\]

The values of the parameters in (3), (4) are provided in Table IV. The Young’s modulus \( E \) was acquired using the equation of the strain with another OHP cantilever of 2 mm \( \times \) 90 mm \( \times \) 100 \( \mu \)m rectangular form with its 2 mm \( \times \) 2 mm part fixed in the jig was set parallel to the ground and bending under its own weight. The moment of inertia \( I \) and Young’s modulus \( E \) were estimated with the formula (4) and (5), respectively, under a uniformly distributed load. The values used in the equations are shown in Table V. Consequently, the Young’s modulus of the SWIG was estimated as 0.3 MPa. The small Young’s modulus of the SWIG compared to 0.52 GPa of the OHP film was supposed to be due to the gel and flexible AgNW electrodes. It contributed to the large deformation of the SWIG actuator at the low operating voltage of 1.5 V\textsubscript{DC}.

G. Comparison of Gripping Performance With That of MEMS Tweezers

To confirm that the tweezer composed of our ionic gel had characteristics appropriate for gripping, the tweezer was compared with existing MEMS tweezers in terms of its gripping force and electrical characteristics. The targets were tweezers driven by voltage or current or composed of IPMC actuators.

1) Evaluation With Voltage-Driven MEMS Tweezers: The performance of our ionic gel tweezer is compared with that of comb-drive and piezoelectric tweezers [2], [4]–[6], as given in Table VI and Fig. 10. The comb-drive and piezoelectric actuators operate owing to electrostatic and piezoelectric effects, respectively, generated by the applied voltage. The FoM, FoM\textsubscript{2}, is defined as the gripping force normalized by
TABLE VI

PERFORMANCE COMPARISON WITH VOLTAGE-OPERATING TWEEZER

| Ref.   | How to work | $F$ (μN) | $V_{DC}$ (V) | $F_{oM_2}$ | Gripping Target |
|--------|--------------|----------|--------------|------------|-----------------|
| This Work | IPMCs (SWIG) | 63.3     | 1.5          | 29.5       | Beads          |
| [6] Comb-drive | 8.7        | 80       | 1.38 x 10^{-3} | Filled     |
| [5] Comb-drive | 350        | 75       | 1.88 x 10^{-2} | Polystyrene sphere |
| [4] Piezo-electric | 15 000    | 32       | 2.5          | Polystyrene sphere |
| [2] Piezo-electric | 201 000   | 60       | 84.6         | Nail        |

Fig. 11. Figure-of-merit 3 (FoM3) and power consumption.

the working voltage and maximum displacement at the tip of the actuator, and the expression for this is given in (6).

$$FoM_2 = \frac{F}{V_{DC}} \cdot \frac{x}{a}$$  \hspace{1cm} (6)

where $F$, $V_{DC}$, $x$, and $a$ are the gripping force, DC working voltage, maximum strain at the tip, and total length of the tweezer, respectively. As shown in Fig. 10, our tweezer has a large FoM2 at the lowest working voltage.

2) Evaluation With Current-Driven MEMS Tweezers: The subjects that were compared were tweezers composed of electrothermal actuators [7], [8] (Table VII). The figure-of-merit FoM3 is FoM2 in Subsubsection III-G.1 and is based on the maximum power consumption $P$ instead of $V_{DC}$ (6). This is because the electrothermal actuators deform as a result of joule heat, which was supposed to be the main power consumption of the devices. FoM3 is expressed as follows:

$$FoM_3 = \frac{F}{P} \times \frac{d}{L}$$  \hspace{1cm} (7)

As shown in Fig. 11, our tweezer yielded the maximum FoM3 for the lowest power consumption.

3) Evaluation With IPMCs Tweezers: Finally, in Table VIII we compared our ionic gel tweezer with tweezers based on IPMC actuators [9]–[12]. All the previous IPMC tweezers contained Nafion as the polymer, whereas the polymer in our actuator was PVDF-TrFE in the SWIG structure. The figure-of-merit, FoM4, is defined as follows:

$$FoM_4 = F \times FoM_1$$  \hspace{1cm} (8)

where $F$ is the gripping force of the actuator and $FoM_1$ is the same variable as in (2). We focused on the group of tweezers designed to grip either organisms or tender targets, with single-digit values for FoM4 in Fig. 12 because our tweezer is designed to grasp vulnerable materials in addition to hard ones gently. As shown in Fig. 12, our tweezer proved to have the highest FoM4 at the lowest working voltage among the grippers intended to grasp soft materials.

4) Verification of the Gripping Force of the Ionic Gel Tweezer: To confirm that the estimated gripping force 63.3 μN was appropriate for grasping objects softly, we re-examined the generated force and gripping targets in Fig. 10–12 and Table VI–VIII. The gripping force of the tweezers with a non-living rigid substance was almost four or five
orders of magnitude of \( \mu N \) [2], [4], [9], [10]. Meanwhile, those that grasped organisms (pollen [6], blood vessels [7], fish eggs [11]), soft material (hydrogel [12], polystyrene sphere [5]) or even hard objects (solder sphere [12]) had a gripping force of no more than two orders of \( \mu N \). The calculated force of our tweezer based on 50b SWIG was 63.3 \( \mu N \) of two orders. Therefore, our device with high FoMs had an appropriate force for minimally invasive gripping to gently enclose the various targets.

IV. CONCLUSION

We realized a self-deformable flexible tweezer capable of gently gripping mm-scale targets and detecting their electrical signals. The self-deformable cantilever in the device was fabricated based on a PVDF-TrFE/EMIMTFSI ionic gel actuator with an electrode consisting of AgNWs using acetone as the solvent. We established a highly reliable manufacturing method with an 89% yield. Our ionic gel actuator, which contained EMIMTFSI in a weight ratio of 50 wt%, produced the largest displacement of 7 mm for 88% of the total length of the actuator and the minimum curvature radius of 2 mm at the operating voltage of 1.5 VDC. The flexible cantilever in the tweezer composed of the actuator was proven to detect a sinusoidal signal of 700 mV, at 1 kHz, by deforming itself, the first such example in the world. Simultaneously, the tweezer could grip and release a 5 mm sphere using a gripping force determined to be 63.3 \( \mu N \), which is appropriate for gripping organisms softly. In the future, we plan to enhance the durability of the ionic gel actuator by improving the electrodes, develop a microfabrication process to separate the electrodes intended for detection from those intended for actuator operation, and demonstrate the gripping of and detection of electrical signals generated by real organisms.

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