

# An approach to durable PVDF cantilevers with highly conducting PEDOT/PSS (DMSO) electrodes

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Received 21 September 2004; received in revised form 2 March 2005; accepted 3 March 2005

Available online 28 March 2005

## Abstract

Bimorph cantilevers were fabricated using the piezoelectric polymer [poly(vinylidene fluoride), PVDF,  $\beta$  phase] for the active layers and the highly conducting polymer [poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate), PEDOT/PSS] treated with a dimethyl sulfoxide (DMSO) solvent for the electrodes. The PVDF films were modified so as to have high adhesion at the interface between the PVDF and the PEDOT/PSS (DMSO) film by using an ion-assisted-reaction (IAR) method. A diffusion barrier was formed on the PEDOT/PSS (DMSO) surface after the IAR treatment. The barrier on the IAR treated electrode prevented the epoxy from penetrating into the PEDOT/PSS (DMSO) film, while the adhesive penetrated into the untreated electrode. In order to confirm the penetration of the epoxy adhesive into the IAR treated PEDOT/PSS (DMSO), X-ray photoelectron spectroscopy (XPS) spectra and scanning electron microscopy (SEM) images were analyzed. The surface resistance of the IAR treated electrodes was measured with a 4-point probe. The tip displacement of the cantilevers was measured at a resonance frequency, and the deformation of the PVDF film with the IAR treated PEDOT/PSS (DMSO) electrodes was found to be higher than that with PEDOT/PSS or inorganic electrodes at the same input voltages. The cantilevers made with indium tin oxide (ITO) or platinum (Pt) electrodes became damaged after operating the devices at a high frequency or a high input power. The PVDF cantilevers made with the PEDOT/PSS (DMSO) electrodes were found to be electrically and mechanically durable when operating at both high input voltage and high frequency.

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**Keywords:** Piezoelectric polymer; Conducting polymer; Bimorph actuator; Surface modification; Diffusion barrier

## 1. Introduction

Electro active polymers (EAP) have been used in many fields, such as artificial muscles, vibration and noise control systems, actuators and sensors for robots, acoustic transducers, medical imaging systems, and pumps and valves, and so on [1–4]. Piezoelectric polymers in the EAP materials have been investigated for use in various applications, such as sensors and actuators, because of their flexibility, easy processing, light weight, and low cost. The

electrical polarization in the piezoelectric materials varies in response to mechanical stress and vice versa. The short cyclic periods and fatigue phenomenon arising from the crack growth of piezoelectric ceramics are major problems [5,6]. The mechanical and electrical degradation of the ceramics are caused by an alternating electric field, and these problems limit their performance. Piezoelectric polymers can withstand a large dimensional change without suffering from fatigue. Poly(vinylidene fluoride) [PVDF,  $(\text{CH}_2\text{CF}_2)_n$ ] shows higher piezoelectric activity than other piezoelectric polymers, whose piezoelectric phenomenon was first reported by Kawai in 1969 [7]. The direction of polarization of the semi-crystalline PVDF is normal to the surface of the film. In recent years, a great deal of effort has been made

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to improve the piezoelectric performance of these polymers [8,9]. The PVDF surface needs to be modified because the hydrophobic surface exhibits poor adhesion with other materials [10]. In this study, the ion-assisted-reaction (IAR) method is used for the purpose of surface modification. The electrodes in piezoelectric polymer devices play an important role in the case of high power and high frequency systems, because of the high potential for large deformation or electrode breakdown of in these devices. In a previous study, it was demonstrated that acoustic devices with poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate) [PEDOT/PSS (DMSO)] electrodes operated in stable manner without damages at high power, and exhibited an increased efficiency and an extended lifetime [11]. In this study, we fabricated a durable bimorph type cantilever using IAR treated PEDOT/PSS (DMSO) for the electrodes and PVDF for the active layers.

## 2. Experimental

PEDOT/PSS (Bayer AG, Baytron P) solution was used in this experimental. The weight ratio of PEDOT to PSS was 1:1.6. In order to obtain highly conducting PEDOT/PSS samples, dimethyl sulfoxide (DMSO) was added to the Baytron P solution at a volume ratio of 4:1 (PEDOT/PSS:DMSO) and stirred for 8 h at room temperature (RT) [12]. The modified PEDOT/PSS (DMSO) solution was screen-printed on the PVDF ( $\beta$  phase, 45  $\mu\text{m}$  in thickness, Kureha, Japan) films. Before screen-printing, the surface of the PVDF was modified using the IAR method [13]. A cold hollow cathode type ion source for the IAR treatment was used for the surface modification. The energy of the irradiating argon ions and the rate of blowing oxygen gas was 1 keV and 14 standard cubic centimeters per minute (sccm), respectively. The ion dose of argon varied from  $5 \times 10^{14}$  to  $5 \times 10^{16}$  ions/cm<sup>2</sup>. The base pressure inside the chamber was  $2.5 \times 10^{-5}$  Torr, and the working pressure was  $1.0 \times 10^{-4}$  Torr during the IAR treatment. After screen-printing the PEDOT/PSS (DMSO) solution on the IAR treated PVDF films, the solution was dried for 10 h at RT. The composite films were also modified by the same IAR process. The thickness of the PEDOT/PSS (DMSO) films was measured to be 2500 Å from the cross-sectional scanning electron microscopy (SEM, JEOL JSM-5200) image. The samples were coated with 50 Å thick gold prior to SEM imaging. For the cross-sectional SEM imaging, the samples were tore after dipping into liquid nitrogen during 10 s.

The contact angles of de-ionized water and formamide to the PEDOT/PSS (DMSO) were measured using a contact angle goniometer (Tantec-CAM Micro). The contact angles were measured at 5 s and averaged value was taken from three different points on the IAR treated samples. The surface energy of the samples was calculated from two contact angle measurements [14], which consisted of the polar energy and the dispersion energy.

The surface configuration of the IAR treated PEDOT/PSS (DMSO) was analyzed using SEM. In order to confirm the chemical bonds on the IAR treated PEDOT/PSS (DMSO) surface, XPS (PHI 5700 ESCA) spectra were analyzed. An Al K $\alpha$  monochromatic X-ray source ( $h\nu = 1486.6$  eV) was used, and the pass energy of the analyzer was fixed at 23.5 eV.

The epoxy adhesive (Araldite standard, Ciba-Geigy Corp.) was screen-printed on the pristine and IAR treated PEDOT/PSS (DMSO) films, and dried for 1 h at 70 °C. The thickness of the epoxy was 40  $\mu\text{m}$ . After peeling off the PVDF film from the PEDOT/PSS (DMSO) film, the XPS spectra and the SEM images of the PEDOT/PSS (DMSO) surface were analyzed. The surface resistance of the PEDOT/PSS (DMSO) films was measured with a 4-point probe (SD-520, NAGY) after screen-printing the epoxy on the films.

All polymer based bimorph cantilevers were fabricated with two PVDF active layers, and the PEDOT/PSS (DMSO) or PEDOT/PSS was coated on both sides of each active layer (Fig. 1). Two poled PVDF films ( $12 \times 35$  mm<sup>2</sup>) were bonded with their directions of polarization parallel to each other. The length of the cantilever from the free end to the clamped position was 30 mm. The strips of PVDF in a series bimorph were connected to the voltage source in series, and that in a parallel bimorph were individually connected to the voltage sources. The bimorph caused bending deformation, because two PVDF films produce extension or contraction under an external AC electric field. Three different cantilevers with PEDOT/PSS (DMSO) electrodes were fabricated using high and low conducting electrodes, with and without the IAR treatment. The inner electrodes of the cantilevers were modified through the IAR process, whereas the outer electrodes were not modified. PVDF cantilevers with inorganic ITO and Pt electrodes were also fabricated, and these electrodes were deposited using the ion-beam sputtering method [15]. 2500 Å thick Pt and ITO electrodes were deposited on the IAR treated PVDF films. The working pressure and the base pressure were maintained to be  $3.5 \times 10^{-5}$  and  $5 \times 10^{-6}$  Torr, respectively. The ion beam potential of the argon was 1 keV, and the deposition rate of the target materials was 0.5 Å/s. The tip displacement of the cantilevers was measured using 0.05 mm scale vernier calipers. In order to define the resonance fre-

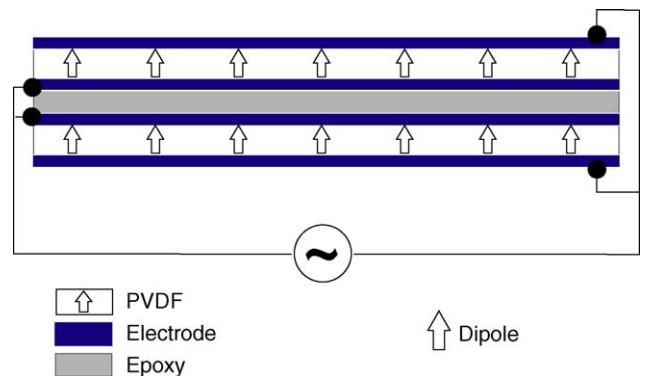


Fig. 1. Schematic diagram of the parallel type bimorph cantilever.

Table 1

The variation of the contact angle and the surface energy of the PEDOT/PSS (DMSO) film modified by 1 keV Ar ion irradiation with O<sub>2</sub> gas flow (14 sccm)

	Pristine	IAR treated PEDOT/PSS (DMSO) (ions/cm <sup>2</sup> )				
		$5 \times 10^{14}$	$1 \times 10^{15}$	$5 \times 10^{15}$	$1 \times 10^{16}$	$5 \times 10^{16}$
Contact angle (water/formamide) (°)	78/74	50/33	44/21	35/7	21/5	19/4
Surface energy (mJ/m <sup>2</sup> )	31	51	56	62	68	69
Polar energy (mJ/m <sup>2</sup> )	27	26	28	35	48	50
Dispersion energy (mJ/m <sup>2</sup> )	4	25	28	27	20	19

quency, the displacement of the devices was measured from 10 Hz to 1 MHz (inset in the Fig. 6b). The frequency showing peak displacement of the device is resonance frequency. Maximum displacement of the device was appeared at 1st mode resonance frequency. The vibration mode of the device in side view at 1st and 2nd resonance frequency was  $1/4$  and  $3/4 \lambda$  (wavelength) of standing wave, respectively.

### 3. Results and discussion

The de-ionized water contact angle to the PEDOT/PSS (DMSO) film rapidly changes because the polymer is water soluble. The contact angle of the PEDOT/PSS (DMSO) film decreased from 78 to 15° after 10 s. After the IAR treatment on the polymer film, the contact angle of the film retained its initial value after 1 min. The water and formamide contact angles to the PEDOT/PSS (DMSO) films decreased with increasing ion dose (Table 1). A remarkable decrease in water contact angle was observed as the ion dose increased from  $5 \times 10^{14}$  to  $1 \times 10^{16}$  ions/cm<sup>2</sup>. The contact angles of water and formamide of the sample at an ion dose of  $1 \times 10^{16}$  ions/cm<sup>2</sup> were 21 and 5°, respectively. The IAR

modification on the polymer at ion doses of greater than  $1 \times 10^{16}$  ions/cm<sup>2</sup> did not cause the contact angle of the substrates to be lowered any further.

The surface energy of the PEDOT/PSS (DMSO) was calculated from the contact angles, and the surface energy of the pristine PEDOT/PSS (DMSO) film was found to be 27 mJ/m<sup>2</sup>. As expected from the measured contact angles, the surface energy of the PEDOT/PSS (DMSO) film increased up to a maximum of 69 mJ/m<sup>2</sup> at an ion dose of  $5 \times 10^{16}$  ions/cm<sup>2</sup>. The polar energy was highly increased after the IAR treatment, while the change of dispersion energy was small (Table 1). The dispersion energy decreased at ion doses of greater than  $1 \times 10^{15}$  ion/cm<sup>2</sup>, even though the ion dose increased. The surface energy of the sample was saturated at ion doses of greater than  $1 \times 10^{16}$  ion/cm<sup>2</sup>. The IAR treatment on the surface of the PEDOT/PSS (DMSO) film is no longer effective at ion doses of greater than  $1 \times 10^{16}$  ion/cm<sup>2</sup>.

SEM images of the IAR treated PEDOT/PSS (DMSO) surfaces were analyzed (Fig. 2). The surface images of the IAR treated PEDOT/PSS (DMSO) films at low ion doses were very similar to that of the pristine PEDOT/PSS (DMSO) surface. The surface of the IAR treated sample has the

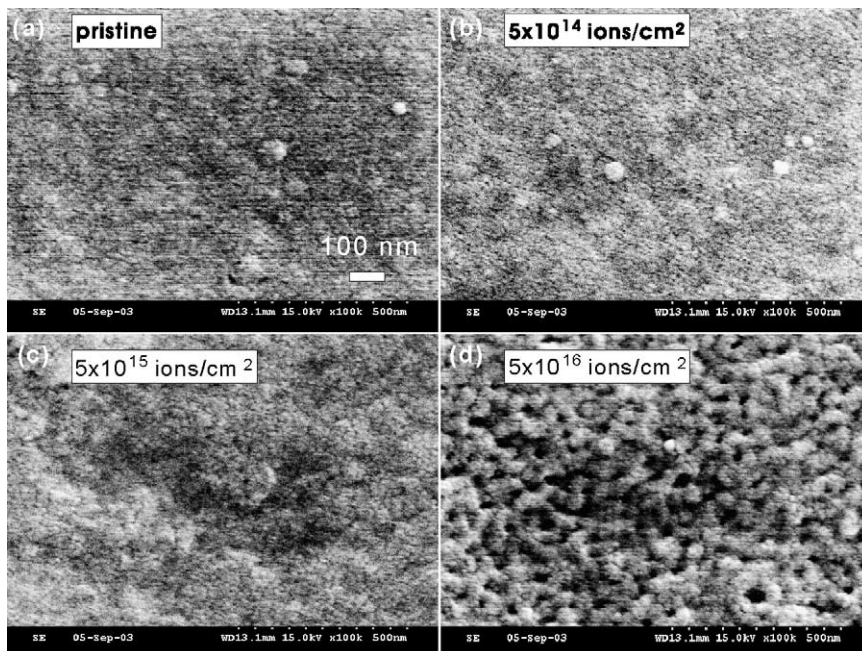


Fig. 2. SEM images of the pristine and IAR treated PEDOT/PSS (DMSO) with various ion dose.

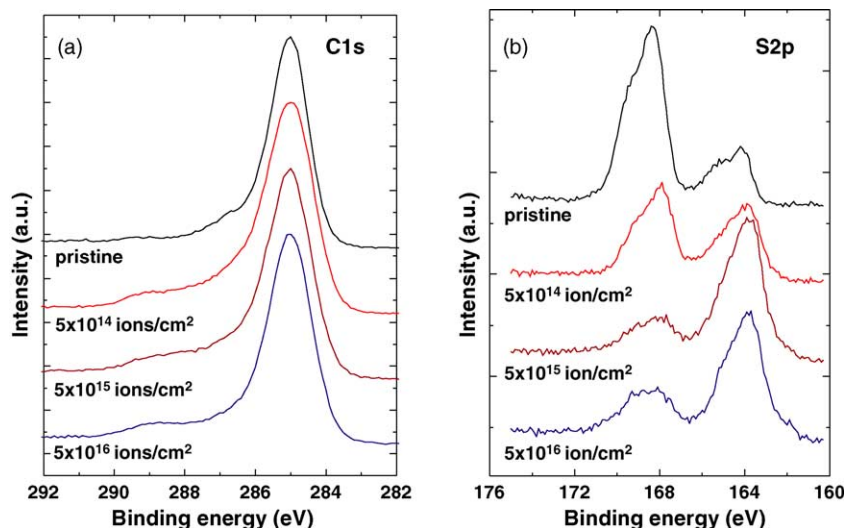


Fig. 3. Comparison of (a) C1s and (b) S2p core level spectra of the pristine and IAR treated PEDOT/PSS (DMSO) films with various ion doses in an  $O_2$  environment.

appearance of a porous structure at a high ion dose of  $5 \times 10^{16}$  ion/cm<sup>2</sup> (Fig. 2d).

X-ray photoelectron spectroscopy (XPS) spectra analysis was carried out to confirm the changes in the chemical bonds on the IAR treated PEDOT/PSS (DMSO) films. All of the spectra were referenced to the C(1s) level which was set to 285.0 eV. The spectrum of the pristine PEDOT/PSS (DMSO) shows two main features, a strong peak at 285.0 eV and a shoulder at 286.5 eV (Fig. 3a). The high binding energy peak originated from the saturated and  $\pi$ -conjugated carbon atoms in the PEDOT and the PSS chains. The shoulder peak at 286.6 eV corresponds to  $-C-O-C-$  bonds in the PEDOT chains [16]. The XPS spectrum of the PEDOT/PSS (DMSO) surface is similar to that of the PEDOT/PSS surface, because the structure of the PEDOT/PSS is not changed after adding the solvent [12]. New chemical bonds were detected on the PEDOT/PSS (DMSO) surface after IAR treatment (Fig. 3a). The shoulder at the higher binding energy originated from the newly generated chemical bonds containing oxygen caused by surface modification. The different binding energies of the oxidized carbons corresponding to the  $-C-O-C-$ ,  $-C=O$ , and  $-O-(C=O)-$  were 286.6, 287.9, and 289.0 eV, respectively.

A remarkable increment of the  $-C=O$  bonds were observed on the IAR treated olefinic polymer at a low ion dose [17]. The number of oxygen atoms doubly bonded to the carbon atoms at a low ion dose decreased upon further ion irradiation. In the case of the PEDOT/PSS (DMSO) films, a peak corresponding to the carbonyl groups also appeared at a low ion dose, but slightly decreased in intensity with increasing ion dose. A peak corresponding to the carboxylate groups was observed at 289.0 eV on the IAR treated PEDOT/PSS (DMSO), while this peak was not observed on the olefinic polymer. The surface phenomena of the IAR treated polymer were explained in a previous study [18]. The energetic argon

ions make the polymer surface unstable and, consequently, new chemical bonds were produced from the chemical reaction between the unstable surface and the blown reactive oxygen gases. The hydrophilic functional groups created by the IAR treatment usually play an important role in the adhesion between the surface modified samples and other materials [17,18]. The hydrophilic groups containing oxygen can attract water, and also prevent water from penetrating into the PEDOT/PSS (DMSO) film (Table 1).

The S(2p) core level spectra of the IAR treated PEDOT/PSS (DMSO) were obtained (Fig. 3b). The sulfur atom gives rise to a spin-split doublet,  $S(2p_{1/2,3/2})$ , having energy difference (1.18 eV) in the S(2p) core level spectrum. The S(2p) spectra show two main peaks corresponding to the sulfur atoms in the PEDOT and the PSS chains, respectively. The peaks near 164.7 and 169.0 eV were attributed to the sulfur atoms in the PEDOT and the PSS chains, respectively. The high binding energy peak of the pristine sample corresponding to the sulfur in the PSS chains was stronger than that in the PEDOT chains (Fig. 3b). The high binding energy peaks near 169.0 eV include two kinds of sulfur peaks, namely the ionic ( $PSS^-Na^+$ ) and neutral ( $PSSH$ ) peaks. The two low binding energy peaks at 164.2 and 165.3 eV correspond to a spin-split doublet of sulfur atoms. Greczynski et al. [16] described the reduction of the sulfur atoms in the PSS chains on the surface of the HCl treated PEDOT/PSS samples after heat treatment. The sulfur atoms in the PSS chains were easily attacked and decomposed by the HCl after heat treatment, because the PSS chains mainly existed on the PEDOT/PSS surface. A similar phenomenon was observed on the IAR treated PEDOT/PSS (DMSO) surface. The low binding energy peak of the sulfur atoms from the PEDOT chains was increased after the IAR surface modification, while the high binding energy peak from the PSS decreased. Both the ionic and neutral sulfur peaks in the PSS chains were reduced after the

IAR treatment. The atomic concentration of sulfur on the PEDOT/PSS (DMSO) surface was 6.2%, while that on the IAR treated polymer surface was 4.5%. The quantitative ratio of the sulfur atoms in the PSS chains to that in the PEDOT chains decreased from 4:1 to 1:3.2 after surface modification with an ion dose of  $5 \times 10^{15}$  ions/cm<sup>2</sup>. The decrease of peak intensity resulted from the sputtered sulfur atoms caused by the IAR process. The IAR treatment on the PEDOT/PSS (DMSO) film at a high ion dose resulted in a change in the surface configuration, as well as the reduction of the sulfur atoms in the PSS chains. The decrease of sulfur atoms in the PSS chain on the film surface do a small contribution to the conductivity of PEDOT/PSS (DMSO) film, because DMSO polar solvent does a major role in increasing conductivity of the film [12].

XPS C1s core level spectra of the PEDOT/PSS (DMSO) surface after detaching the PVDF film from the screen-printed film were analyzed (Fig. 4). The surface energy of the IAR treated sample with an ion dose of  $1 \times 10^{15}$  ions/cm<sup>2</sup> was 56 mJ/m<sup>2</sup>. The surface spectrum of the IAR treated sample shows two main features, a strong peak at 285.0 eV and a shoulder at 286.6 eV, as is also the case in the reference PEDOT/PSS (DMSO) sample. The C1s spectrum of the IAR treated PEDOT/PSS (DMSO) was very similar to that of the reference sample. In the pristine PEDOT/PSS (DMSO) film without the IAR treatment, an increment of the XPS signal at 286.6 eV was observed. This increased shoulder peak resulted from the penetration of epoxy containing the chemical structure of  $-C-O-C-$  into the film. The increment in the concentration of the epoxy in the PEDOT/PSS (DMSO) film caused the increase in the resistance of the PEDOT/PSS (DMSO) film.

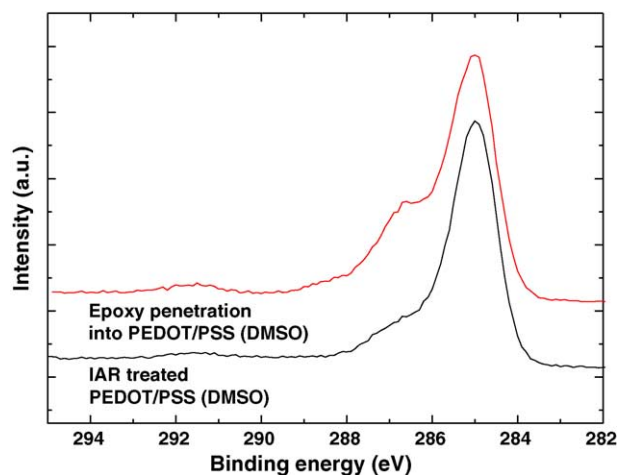


Fig. 4. Comparison of C1s core level spectra of the pristine and IAR treated PEDOT/PSS (DMSO) films with an ion dose of  $5 \times 10^{15}$  ions/cm<sup>2</sup> in an O<sub>2</sub> environment after peeling off the PVDF from the PEDOT/PSS (DMSO) film.

SEM images of the surface and cross section of the pristine PEDOT/PSS (DMSO) film, with and without the IAR treatment were demonstrated (Fig. 5). The penetrated epoxy from the opposite surface was observed on the surface of the pristine sample (Fig. 5a). The interface between the epoxy and the pristine PEDOT/PSS (DMSO) film was not clear, as shown in the cross sectional image (Fig. 5c), since both epoxy and PEDOT/PSS (DMSO) coexist at the interface. In the case of the IAR treated sample, epoxy was not observed on the PEDOT/PSS (DMSO) surface (Fig. 5b). A clear interface between the epoxy and PEDOT/PSS (DMSO) film was observed after IAR treatment (Fig. 5d). This result implies

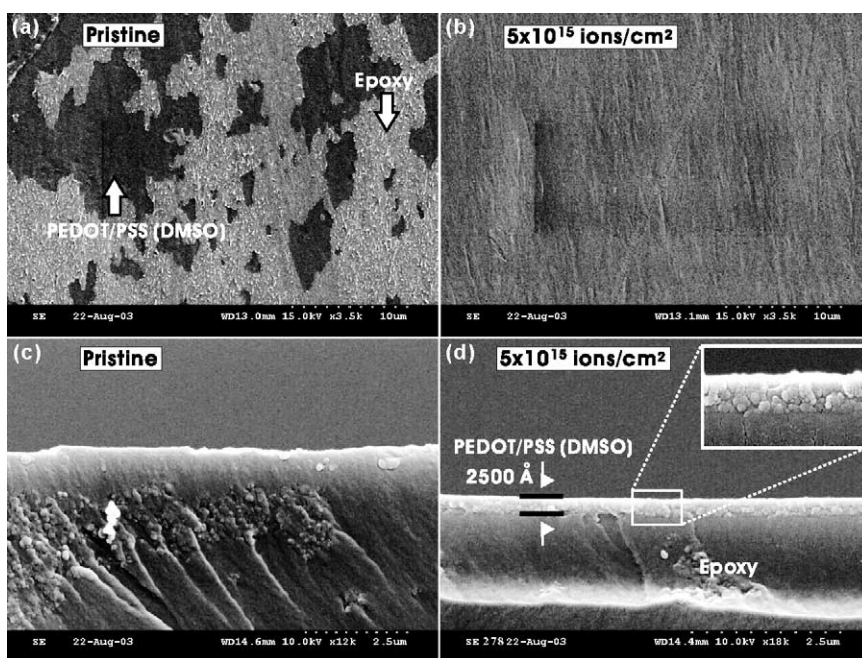


Fig. 5. SEM images of the surface of (a) the pristine and (b) the IAR treated sample with an ion dose of  $5 \times 10^{15}$  ions/cm<sup>2</sup> in an O<sub>2</sub> environment, and cross sectional images of (c) the pristine and (d) the IAR treated samples. Inset: magnification of the interface.

Table 2

Surface resistance of the pristine, the IAR treated, and the epoxy penetrated PEDOT/PSS (DMSO) films

	Non treated PEDOT/PSS (DMSO)		IAR treated PEDOT/PSS (DMSO) (ions/cm <sup>2</sup> )				
	Reference	Pristine	$5 \times 10^{14}$	$1 \times 10^{15}$	$5 \times 10^{15}$	$1 \times 10^{16}$	$5 \times 10^{16}$
Surface resistance (k $\Omega$ /□)	1.3	70	2.7	1.9	1.4	2.8	3

that the hydrophilic groups on the IAR treated PEDOT/PSS (DMSO) films prevent the epoxy from penetrating into the films.

The penetration of the epoxy into the pristine PEDOT/PSS (DMSO) film gave rise to increase in the surface resistance (Table 2). The PVDF film was peeled from the pristine and IAR treated PEDOT/PSS (DMSO) films after dry of the screen-printed epoxy on the polymer film. The PVDF film was able to be peeled from the PEDOT/PSS (DMSO) film, because the adhesion strength between the adhesive and the IAR treated PEDOT/PSS (DMSO) film was stronger than that between the IAR treated PVDF and the PEDOT/PSS (DMSO) film. The surface resistance of the PEDOT/PSS (DMSO) sample before IAR treatment was 1.3 k $\Omega$ /□. The

surface resistance of the pristine PEDOT/PSS (DMSO) sample with screen-printed epoxy, which was not subjected to IAR treatment, increased up to 70 k $\Omega$ /□. The increased surface resistance of the film resulted from the penetration of the epoxy into the PEDOT/PSS (DMSO) film (Figs. 4 and 5). In the case of the IAR treated samples, no significant change in the surface resistance was observed (Table 2). The surface resistance of the IAR treated sample with an ion dose of  $5 \times 10^{15}$  ions/cm<sup>2</sup> was 1.4 k $\Omega$ /□.

Bimorphs are usually mounted as a cantilever and operate in the  $d_{31}$  mode. The maximum displacement of the cantilever was observed at the same resonance frequency of 27 Hz in all of the cantilevers made with either the PEDOT/PSS (DMSO) or the PEDOT/PSS electrodes (Fig. 6b). The thickness of the

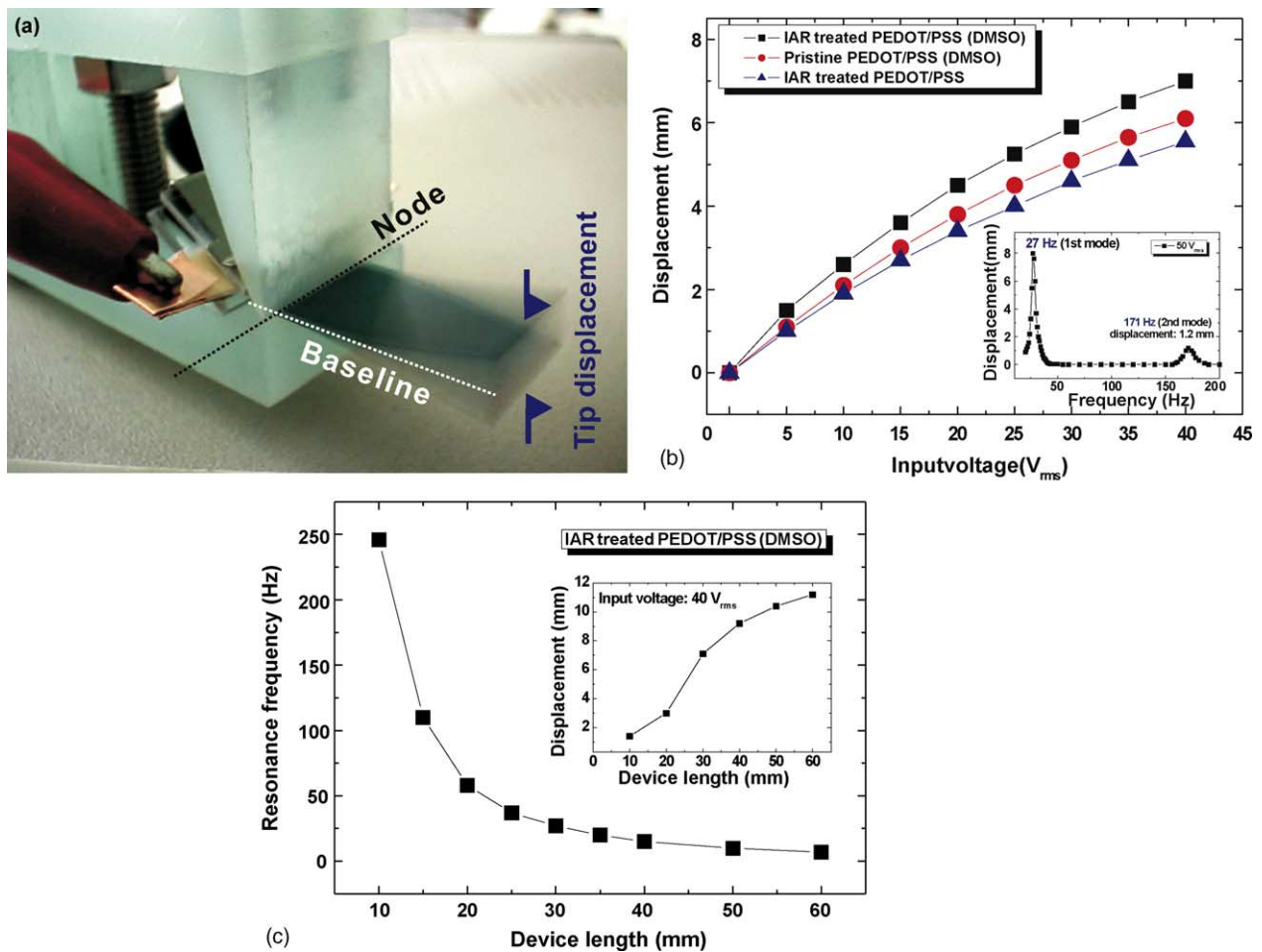


Fig. 6. (a) Photographs of the actuation of all polymer based cantilevers with representing the resonance frequency, (b) comparison of the displacement of the cantilevers made with the pristine, IAR treated PEDOT/PSS (DMSO), IAR treated PEDOT/PSS electrodes and (c) the resonance frequency as a function of the length of the bimorph cantilever made with the IAR treated PEDOT/PSS (DMSO) electrode.

epoxy in this device was  $40\ \mu\text{m}$ . The displacement of all the cantilevers increased with increasing input voltage. The displacements of the device made with the IAR treated PEDOT/PSS (DMSO) and the PEDOT/PSS electrodes were 7 and 5.5 mm, respectively, at an input voltage of  $40\ \text{V}_{\text{rms}}$ . The surface resistance of the IAR treated PEDOT/PSS inner electrode in the cantilever device was measured to be  $195\ \text{k}\Omega/\square$ . The device made with the pristine PEDOT/PSS (DMSO) electrodes underwent a lower displacement, because of the low conductivity of the inner electrodes caused by the epoxy penetration into the electrodes (Fig. 6b). The displacement of the device with pristine PEDOT/PSS (DMSO) electrodes was 6.1 mm at an input voltage of  $40\ \text{V}_{\text{rms}}$ . The displacement of the devices was dependent on the conductivity of the electrode. The epoxy thickness in the cantilever devices made with PEDOT/PSS (DMSO) electrodes had an effect on the tip displacement and resonance frequency. The resonance frequency and the displacement of the cantilever device ( $110\ \mu\text{m}$  thick epoxy) were 46 Hz and 5.3 mm at  $40\ \text{V}_{\text{rms}}$ , respectively. The epoxy thickness should be reduced for the high bending rate of the cantilever, because the epoxy acts

as a mechanical resistor in the device. The resonance frequency of the bimorph cantilever increased with decreasing device length (Fig. 6c). The resonance frequencies of the bimorph cantilevers with length of 60 and 10 mm were 7 and 246 Hz, respectively. The devices made with the IAR treated PEDOT/PSS (DMSO) electrodes operated in a stable manner during 1 h at 1 MHz and  $200\ \text{V}_{\text{rms}}$ .

The displacement of the cantilever tip for various electrodes is shown (Fig. 7a). The resonance frequencies of the devices with the PEDOT/PSS (DMSO), Pt, and ITO electrodes were 27, 31, and 34 Hz, respectively. The difference in the resonance frequencies of the devices may originate from the different stiffnesses of the electrodes. The tip displacements of the devices made with the PEDOT/PSS (DMSO) and Pt electrodes were 7.0 and 6.7 mm, respectively, at an input voltage of  $40\ \text{V}_{\text{rms}}$ . The surface resistance of the Pt and ITO electrode was measured to be 0.57 and  $4.3\ \Omega/\square$ , respectively. Even though the conductivity of the PEDOT/PSS (DMSO) electrodes was lower than that of the Pt electrodes, the displacement of the device made with the polymer electrodes was 0.3 mm higher than that with Pt electrodes at the

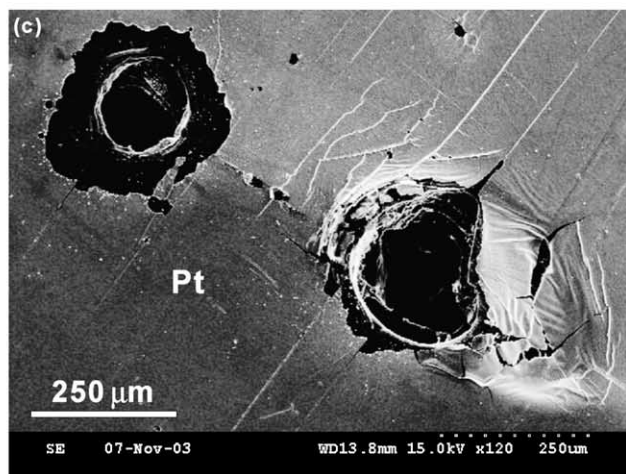
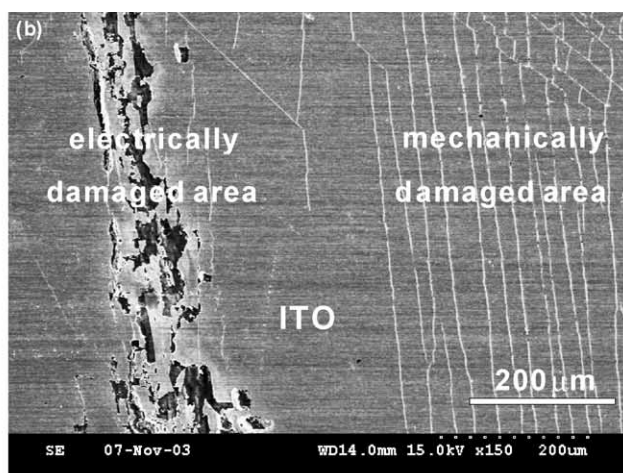
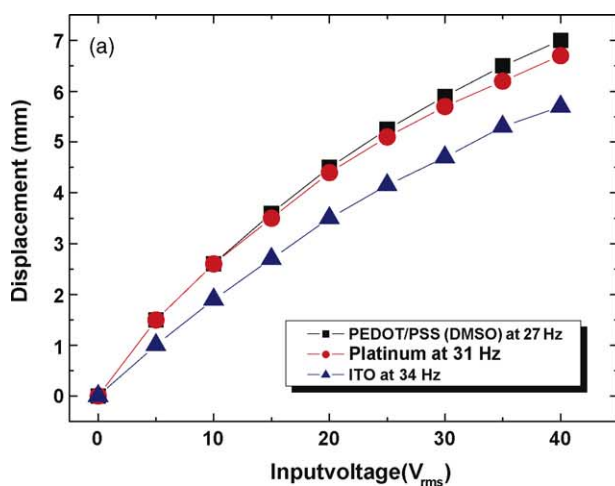


Fig. 7. (a) Displacement of the cantilever made with ITO, Pt, and IAR treated PEDOT/PSS (DMSO) electrodes and SEM images of the electrically or mechanically damaged (b) ITO and (c) Pt electrode.

same input voltage of  $40 V_{\text{rms}}$ . The cantilever made with the ITO electrodes became damaged after operating the device at 213 Hz and  $200 V_{\text{rms}}$  in several seconds (Fig. 7b). The conductive ITO electrode became an insulator ( $>600 \text{ k}\Omega/\square$ ) following the electrical and mechanical damage caused by the high voltage. The mechanically induced cracks might have resulted from the stiffness of the ITO electrode [19]. Electric charges concentrate on the mechanically cracked area, and electric field increases around the damaged area. Electrode damage is induced by the locally increased electric field, and propagates along the mechanically damaged track. A similar phenomenon was observed in an acoustic device made with the ITO electrode, after operating the device at high power, as described in our previous work [11]. The ITO could not withstand at the high voltage, and the growth of cracks in the ITO film was observed across the electrode, resulting in it becoming an insulator. An electrode breakdown phenomenon was observed after operating the device made with Pt electrodes at 33 kHz and  $200 V_{\text{rms}}$  in several seconds. The Pt electrodes were still metallic ( $0.57 \Omega/\square$ ), but cylindrical hole of  $200 \mu\text{m}$  in diameter appeared in the device. Mechanical cracks caused by the vibration and holes caused by the melting of the PVDF at high input power were both observed in the devices made with the Pt electrodes, and this resulted in the disappearance of the piezoelectric property of the PVDF. The electrical and mechanical properties of the electrode materials should be considered, in order to produce a high displacement (Figs. 6 and 7).

#### 4. Conclusions

The surface energy of the PEDOT/PSS (DMSO) was  $62 \text{ mJ/m}^2$  at an ion dose of  $5 \times 10^{15} \text{ ions/cm}^2$ . A change in the surface configuration of the PEDOT/PSS (DMSO) film was observed at a high ion dose of  $5 \times 10^{16} \text{ ion/cm}^2$ . A diffusion barrier was formed on the PEDOT/PSS (DMSO) film after the IAR treatment. The hydrophilic groups,  $-\text{C}-\text{O}-\text{C}-$ ,  $-\text{C}=\text{O}$ , and  $-\text{O}-(\text{C}=\text{O})-$ , on the IAR treated surface prevented the epoxy from penetrating into the PEDOT/PSS (DMSO) film. The surface resistance of the IAR treated PEDOT/PSS (DMSO) film was almost the same as that of the reference film. The cantilever made with inorganic electrodes such as Pt or ITO was easily damaged due to the high deformation and high input voltage, while that made with the PEDOT/PSS (DMSO) electrodes operated in a stable manner. The devices with the IAR treated PEDOT/PSS (DMSO) electrodes produced a higher deformation than that made with the pristine electrodes. The displacement of the devices made with the IAR treated PEDOT/PSS (DMSO) electrodes was  $7 \text{ mm}$  at an input voltage of  $40 V_{\text{rms}}$  and a resonance frequency of 27 Hz. The use of highly conducting PEDOT/PSS (DMSO) electrode is desirable in the piezoelectric polymer devices. In order to increase the displacement and decrease the operating voltage of the cantilever devices, a highly conducting polymer electrode without adhesive

and a high performance piezoelectric polymer are needed. In a future study, the mechanical property and the generator effect of the bimorph cantilever devices will be investigated.

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