Electronic Supplementary Material (ESI) for RSC Advances.

Supplementary Information

Effects of membrane thickness on the performance of ionic polymer-metal composite actuators

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Fabrication procedure of IPMC actuators

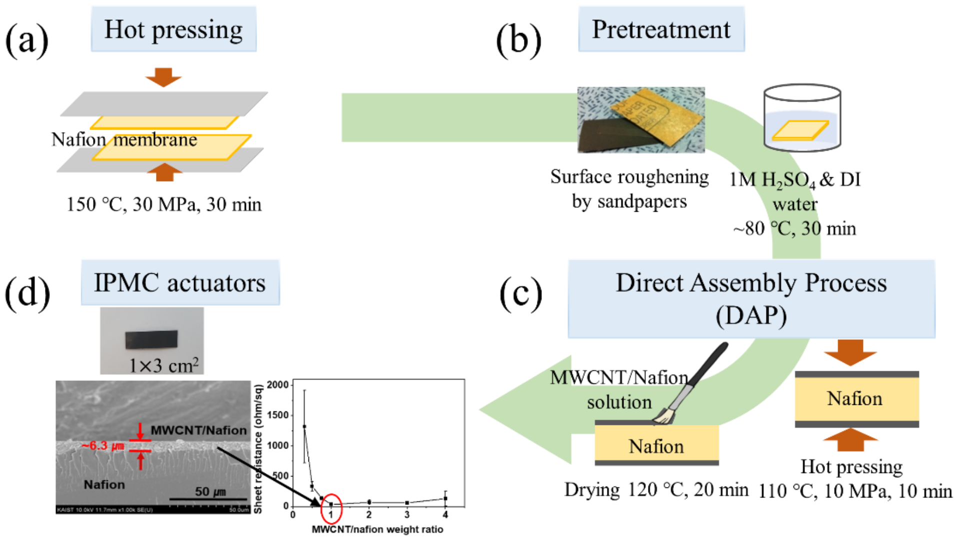

Figure S1. (a-c) Fabrication process of IPMC actuators with different thickness and (d) their cross-sectional images and resistances of electrode. They were fabricated under the weight ratio between Nafion and MWCNT of 1:1 for the lowest resistance.

AFM topography acquisition of Nafion membrane surface roughness and roughening treatment

We conducted additional experiments to analyze sub-micron scale changes in roughness and properties after a roughening process using sandpaper. Five Nafion membranes were prepared for measurement before and after the sandpaper treatment. We measured their topography using AFM (Atomic Force Microscopy) at 10 μm × 10 μm scales for each sample. Fig. S2 (a) show the surface images of the Nafion membrane before (left) and after (right) roughening, as measured by AFM. Fig. S2 (b) and (c) are scaled images to allow comparison. Root mean square (RMS) roughness values were calculated from the topography of the images measured by AFM. The average RMS roughness values are shown in Fig. S2 (d). We also performed an analysis of variance (ANOVA) test on the RMS roughness of the Nafion membrane after roughening to verify the reproducibility and repeatability of the roughening process as shown in Table S1. Except for the relationship between Sample # 1 and # 2 and between # 1 and # 5, the RMS roughness average was not significantly different between the five samples. Based on the results of the above experiments, we believe that the Nafion membrane roughening process using sandpaper shows some reproducibility and repeatability.

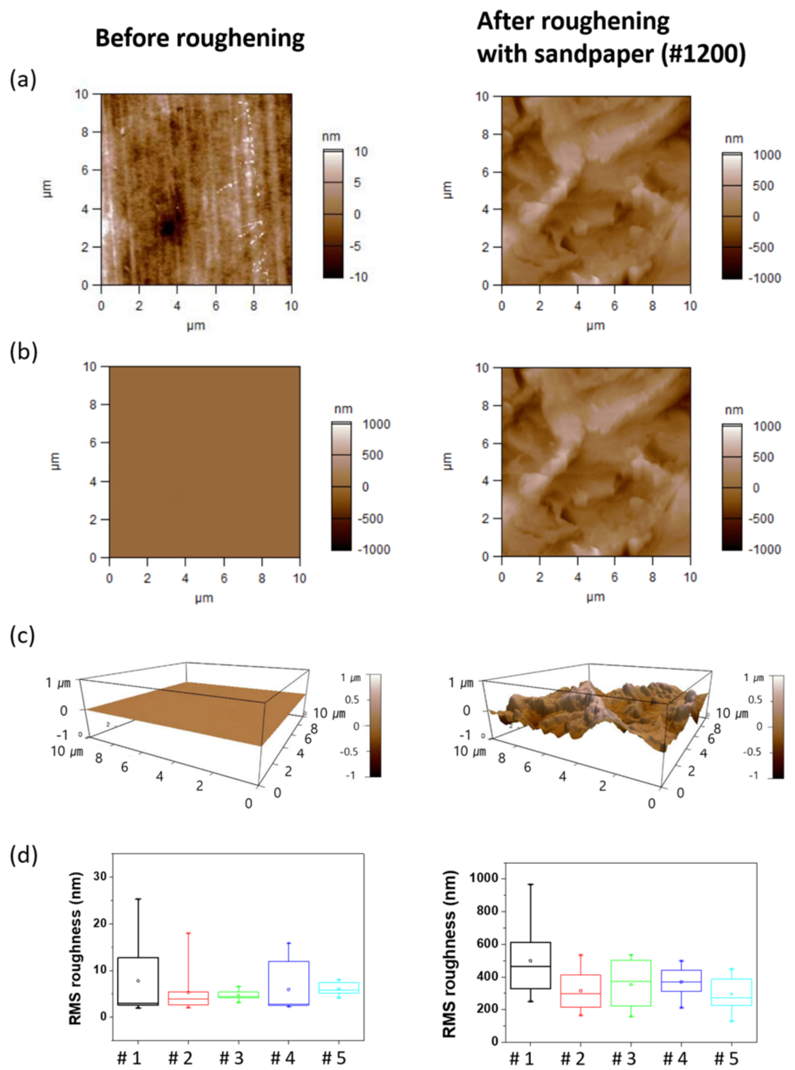

Figure S2. (a) AFM topography images of Nafion membrane before (left) and after (right) roughening treatment, (b) images after marching scales and (c) 3D images, (d) the average RMS roughness value before and after Nafion membrane roughening using sandpaper (#1200). The number on the x-axis represents the sample number, and the average value was calculated by measuring 10 data for each sample.

Table S1. One-way ANOVA (analysis of variance) test of the reproducibility and repeatability of surface roughness after the Nafion membrane roughening using sandpaper (#1200)

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
#2 #1	-184.6354	61.74141	4.22915	0.03468	0.05	1	-360.071	-9.20014
#3 #1	-147.2942	61.74141	3.37384	0.13802	0.05	0	-322.729	28.14106
#3 #2	37.3412	61.74141	0.85532	0.97362	0.05	0	-138.094	212.7765
#4 #1	-130.1493	61.74141	2.98113	0.23462	0.05	0	-305.585	45.28596
#4 #2	54.4861	61.74141	1.24803	0.90187	0.05	0	-120.949	229.9214
#4 #3	17.1449	61.74141	0.39271	0.99865	0.05	0	-158.29	192.5802
#5 #1	-203.9862	61.74141	4.67239	0.01533	0.05	1	-379.421	-28.5509
#5 #2	-19.3508	61.74141	0.44324	0.99783	0.05	0	-194.786	156.0845
#5 #3	-56.692	61.74141	1.29855	0.88839	0.05	0	-232.127	118.7433
#5 #4	-73.8369	61.74141	1.69127	0.75365	0.05	0	-249.272	101.5984

Experimental setup used to measure actuation properties

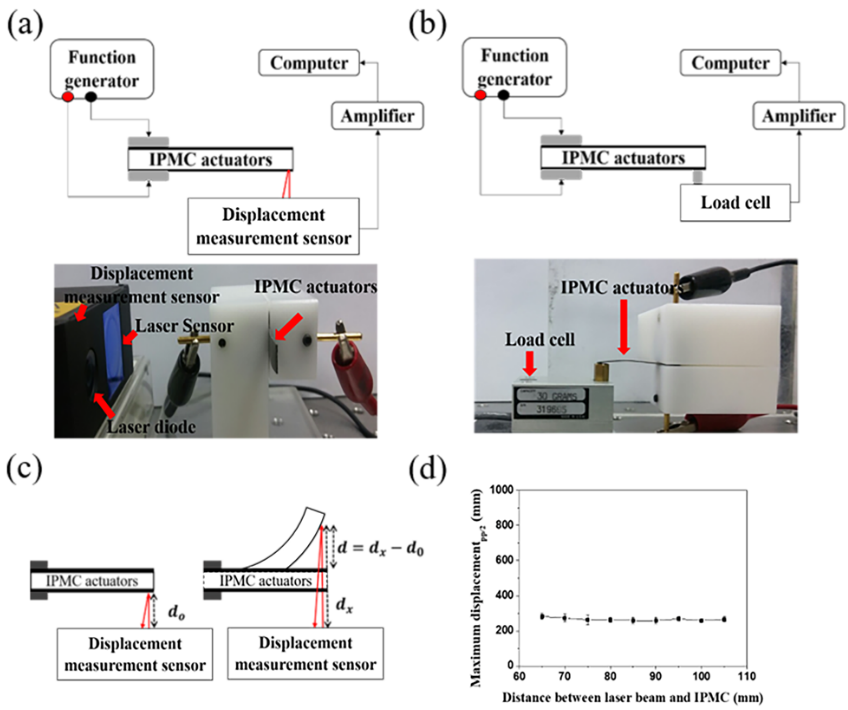

Figure S3. Schematic illustration of the experimental setup for measuring (a) displacement and (b) tip force of IPMC actuators. (c) Schematic diagram illustrating how the operational displacement of the IPMC actuator was measured using the displacement measurement sensor, and the resultant value was calculated. The displacement value (*d*) was defined by the difference between the measured value (d_x) during operation and the initial value (d_0), i.e. $d = d_x - d_0$. While the IPMC actuators were operated by applying the voltage through the function generator, the displacement was measured by displacement measurement sensor and the tip force was measured by load cell at the end of IPMC actuators. (d) Plot of maximum displacement of IPMC actuator at an ac voltage of 3 V, 0.5 Hz as a function of the distance between laser point and IPMC actuator (d_0).

AFM indentation

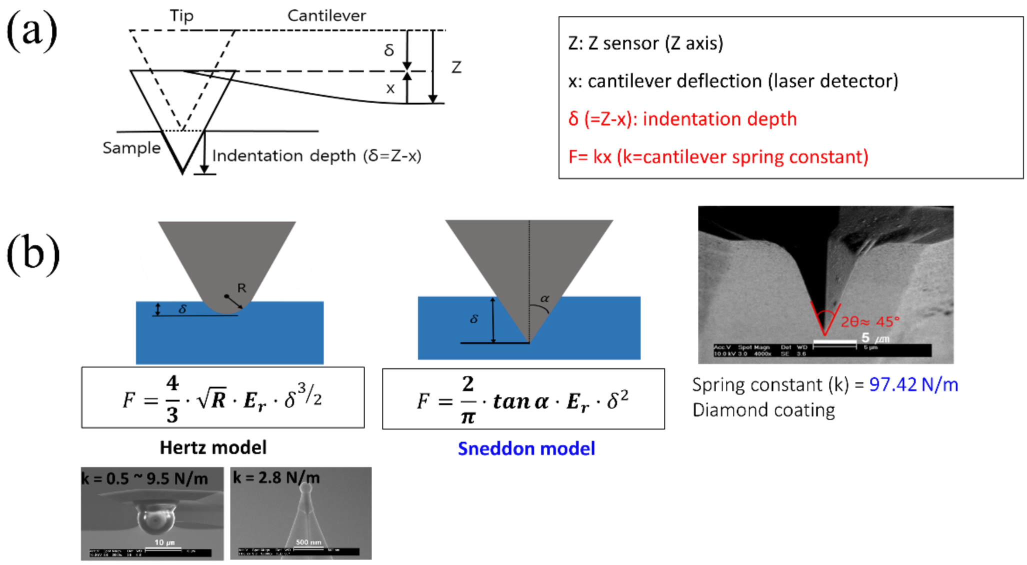

Figure S4. (a) Schematic of nano indentation using AFM. (b) Two models (Hertz and Sneddon) of indentation calculation method for AFM tips with different shape. The indentation depth (δ) was calculated from the Z sensor value (Z) and the cantilever diffraction value (x) measured at the AFM, and the force (F) was calculated from the measured spring constant value of the cantilever[1-4]. In this experiment, Sneddon model, which is used for sharp tip, is applied to calculate the elastic modulus.

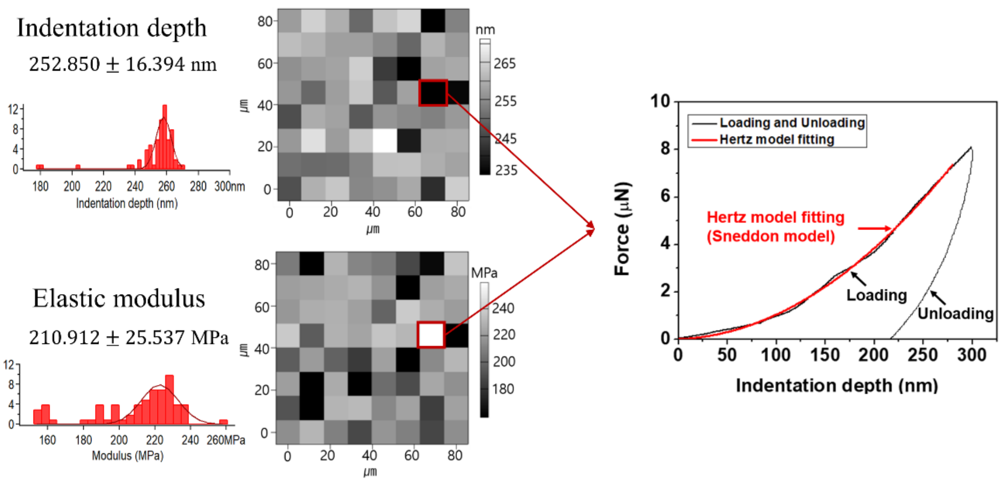

Figure S5. Results of elastic modulus calculated by force-distance (f-d) curve obtained by AFM indentation. The elastic modulus values were derived through the Hertz model fitting of the f-d curve at each point (64 points) over 80×80 μm^2 area.

Notes and references

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