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Supplementary Information

Transparent actuators and robots based on single-layer superaligned carbon nanotube sheet and polymer composites

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1. Transmittance spectra of the PET and BOPP film in the visible light wavelength region

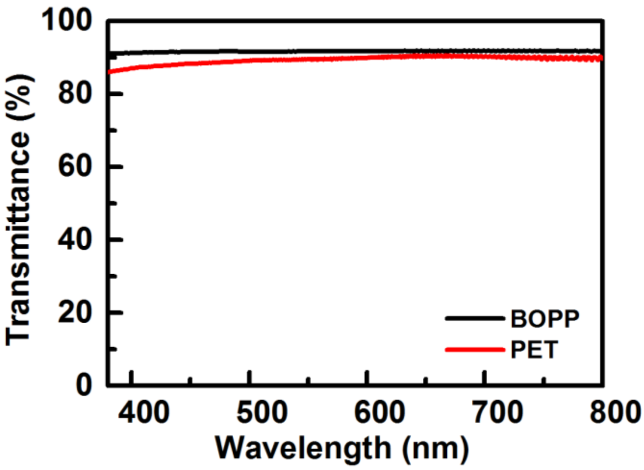

Fig. S1 Transmittance spectra of the PET and BOPP film in the visible light wavelength region.

2. SEM image showing the thickness of single-layer SACNT sheet coated with EVA in the trilayer actuator

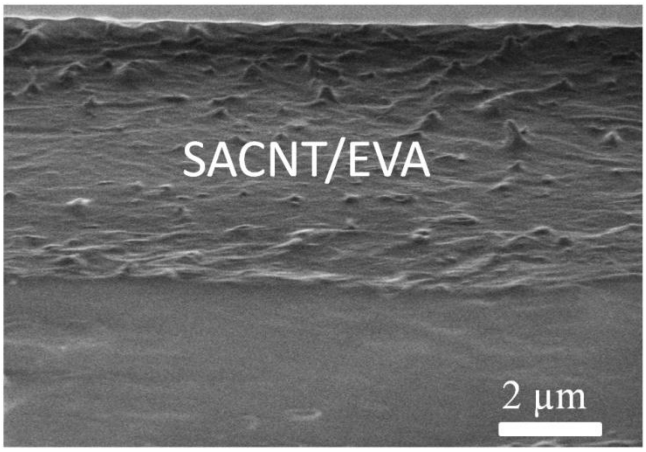

Fig. S2 SEM image showing the thickness of single-layer SACNT sheet coated with EVA in the trilayer actuator.

3. Calculation of curvature

The curvature of the SACNT/PET/BOPP actuator is defined as the reciprocal radius ($1/\rho$). As the bending angle is given by

$$\theta = \frac{L}{\rho} \ , \tag{1}$$

the curvature $1/\rho$ is deduced as

$$\frac{1}{\rho} = \frac{\theta}{L}. \tag{2}$$

Therefore, the curvature of the actuator can be calculated by achieving the bending angle and length of the actuator. The bending angle of the actuator is captured by using a digital camera.

4. Calculation of energy efficiency

The energy efficiency of the transparent actuator can be defined as the generated elastic energy density divided by the electrical energy density. As the SACNT layer is very thin, our trilayer structure can be approximated to a bilayer structure of PET/BOPP. Thus, the elastic energy density of our actuator can be calculated by using the following equation: [1]

$$W_1 = \frac{[E_3 t_3^2(3t_2+t_3)+E_2\, t_2^2\, (3t_3+t_2\,)][E_2^2 t_2^4+E_3^2 t_3^4+2E_2 E_3 t_2 t_3\left(2t_2^2+2t_3^4+3t_2 t_3\right)]}{36E_2 E_3 t_2^2 t_3^2(t_3+t_2)}(\frac{1}{\rho})^2 \tag{3}$$

where W_1 is the elastic energy density, $1/\rho$ is the curvature (0.41 cm^{-1}), t_2 and t_3 are the thickness of PET layer (80 μm) and BOPP layer (40 μm) respectively, E_2 and E_3 are the Young's modulus of PET layer and BOPP layer respectively. The Young's modulus of the PET layer and BOPP layer are 2.55 GPa and 1.10 GPa, which are measured by a material testing machine (Lloyd LR5k) with stretching rate of 0.5 mm min^{-1}.

The calculated elastic energy density is 3.4×10^4 J m^{-3}. Assuming the actuation time of 30 s, the total electrical energy density applied to the actuator is given by

$$W_2 = p \bullet \tau \tag{4}$$

where W_2 is the electrical energy density, p is the power density (14.37 mW mm^{-3}), τ is the actuation time (30 s).

The calculated electrical energy density is 4.3×10^8 J m^{-3}.

Hence, the energy efficiency η is given by

$$\eta = \frac{W_1}{W_2} \tag{5}$$

The energy efficiency η is then calculated to be 0.008%.

5. Control experiment

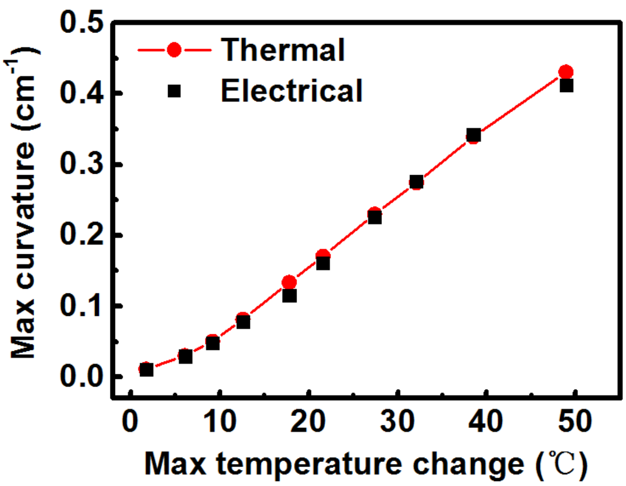

Fig. S3 Pure thermal actuation of the SACNT/PET/BOPP actuator. The measured maximum curvatures for the pure thermal actuation are in accordance with those measured from electrothermal actuation experiments for the same temperature change.

6. Modeling of the SACNT/PET and PET/BOPP composites

(1) Modeling of the SACNT/PET composite

We develop a model to analyze the bending performance of the SACNT/PET composite. Based on the bimetal thermostat equation of Timoshenko,[2] the curvature of the composite is given by

$$\frac{1}{\rho}=\frac{6(\alpha_2-\alpha_1)(T-T_0)(1+m)^2}{h(3(1+m)^2+(1+mn)(m^2+\frac{1}{mn}))}, \tag{6}$$

where h is the total thickness of the composite, T is the temperature, T_0 is the initial temperature, α_1 is the CTE of CNT (3 ppm K^{-1}), α_2 is the CTE of PET (38 ppm K^{-1}),

$$m=\frac{t_1}{t_2}, \tag{7}$$

t_1 and t_2 are the thickness of SACNT layer and PET layer (80 μm) respectively, and

$$n=\frac{E_1}{E_2}, \tag{8}$$

E_1 and E_2 are the Young's modulus of SACNT layer and PET layer respectively.

The SACNT layer is embedded in EVA resin and has a total thickness of 5 μm in the trilayer actuator. To simplify the modeling, we assumed that the thickness of SACNT layer t_1 is equivalent to a densified pure SACNT layer of ~50 nm.[3-4]

The Young's modulus of SACNT layer is given as a constant of 2.2 GPa.[5] The Young's modulus of the PET layer is 2.55 GPa.

(2) Modeling of the PET/BOPP composite

We develop another model to analyze the bending performance of the PET/BOPP composite. Based on the bimetal thermostat equation of Timoshenko,[2] the curvature of the composite is given by

$$\frac{1}{\rho}=\frac{6(\alpha_3-\alpha_2)(T-T_0)(1+m)^2}{h(3(1+m)^2+(1+mn)(m^2+\frac{1}{mn}))}, \tag{9}$$

where h is the total thickness of the composite, T is the temperature, T_0 is the initial temperature, α_2 is the CTE of PET (38 ppm K^{-1}), α_3 is the CTE of BOPP (137 ppm K^{-1}),

$$m = \frac{t_2}{t_3}, \tag{10}$$

t_2 and t_3 are the thickness of PET layer (80 μm) and BOPP layer (40 μm)respectively, and

$$n = \frac{E_2}{E_3}, \tag{11}$$

E_2 and E_3 are the Young's modulus of PET layer (2.55 GPa) and BOPP layer (1.10 GPa) respectively.

7. Repeatability test

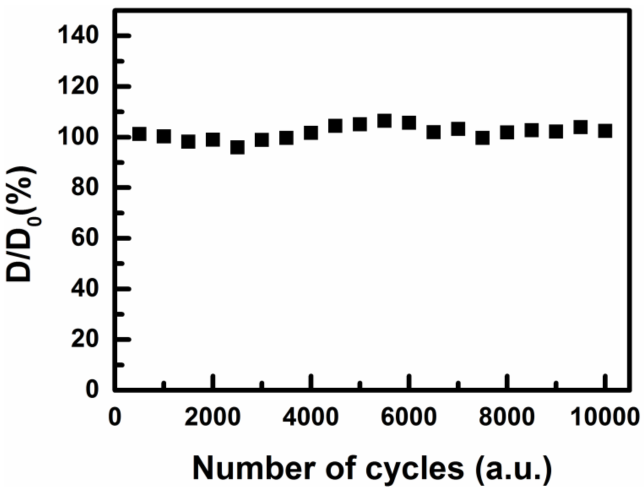

Fig. S4 Cycle life of the SACNT/PET/BOPP actuator with a 0.1 Hz square wave voltage (0 - 20 V) for 10,000 cycles. As the repeatability test takes a long time, using the digital camera to capture the bending angle and then calculating the curvature is not efficient. Hence, a laser displacement sensor was used to record the free-end displacement of the actuator, which could demonstrate the repeatability of the actuator as well. D_0 represents the initial displacement value.

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