

Supplementary information

Strain amplification from within: Harnessing programmable intrinsic resonance in dielectric elastomers driven by space charge mechanism

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Table S1. The schematic of the splines and devices.

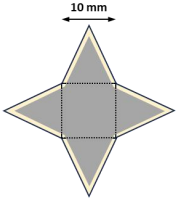
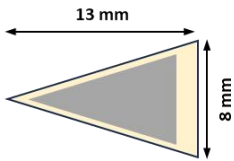
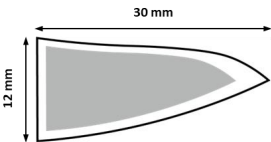
Position	Schematic	Film Size (mm)	Electrode Size (mm)
Default actuators		$15 \times 4 \times 0.3$	12×3.6
Figure 4d		$30 \times 30 \times 0.3$	27×27
Figure 4a, 4b		$13 \times 8 \times 0.3$	10×7
Figure 4f Movie S1		$30 \times 12 \times 0.3$ (Single)	25×11

Table S2. Quantitative comparison of representative SC-DE and bending-type DE actuators.

List	Electric field	Actuation amplitude	Resonance-amplified amplitude	Actuation frequency range	External frame Required	Reference
1	1 V/ μm	80°	150° at 16 Hz	30 Hz	No	This work
SC-DE systems						
2	8 V/ μm	30°	/	/	No	Chinese. J. Polym. Sci. 2026, 44, 1457
3	8 V/ μm	30°	/	/	No	Adv. Mater. 2024, 36, 2313078
4	6 V/ μm	32°	70° at 10 Hz	10 Hz	No	Adv. Mater. 2022, 34, 2206393
Traditional DE systems with bending actuation						
5	22 V/ μm	46°	/	1-10 Hz	Yes	Sci. Adv. 2022, 8, eabm6200
6	35 V/ μm	60°	/	/	Yes	Adv. Funct. Mater. 2024, 34, 2406710
7	40 V/ μm	20°	/	0-10 Hz	No	ACS Mater. Lett. 2025, 7, 2002
8	18 V/ μm	99°	/	0-1 Hz	Yes	Chem. Eng. J. 2025, 520, 165877
9	125 V/ μm	84.5°	/	0-15 Hz	Yes	Small 2026, 22, e10346
10	12.6 V/ μm	44.7°	/	/	Yes	J. Mater. Chem. A. 2023, 11, 14159
11	14 V/ μm	23.31°	/	0-8 Hz	Yes	ACS Appl. Polym. Mater. 2024, 6, 6667
12	30 V/ μm	40°	/	0-50 Hz	No	ACS Appl. Electron. Mater. 2022, 12, 4042
13	109 V/ μm	81.4°	/	0-1 Hz	Yes	Appl. Phys. Lett. 2017, 110, 182906
14	~100 V/ μm	60°	180° at 3 Hz	3-5 Hz	Yes	Meccanica 2015, 50, 2815-2824

“/” indicates not reported. For references where the electric field was not directly reported, the listed value is the nominal field estimated from the reported voltage and dielectric layer thickness.

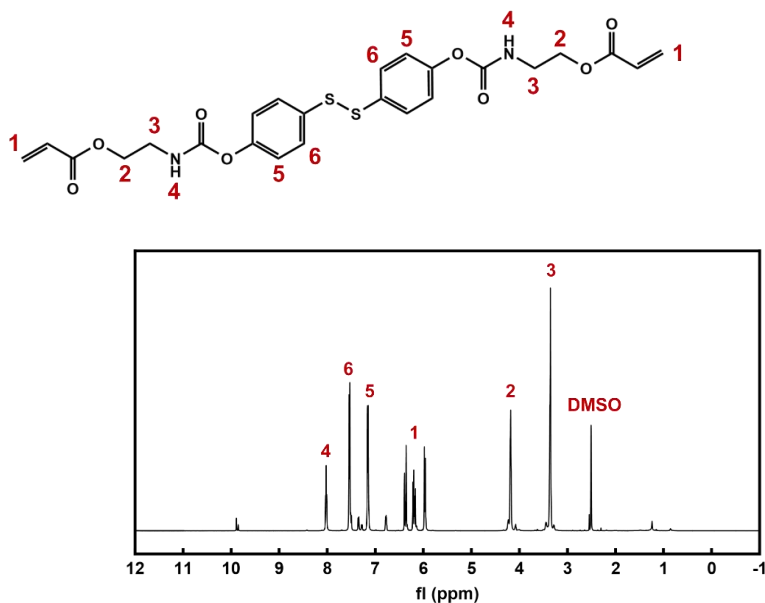


Figure S1. Molecular structure and ^1H -NMR spectrum of TDPDA. Peak 3 is slightly higher because of the H_2O absorbed by $\text{DMSO}-d_6$.

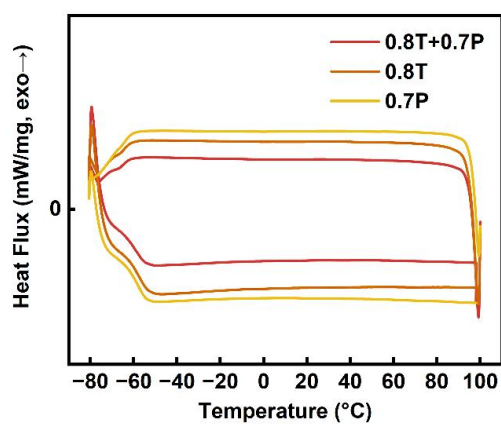


Figure S2. DSC heating curves of representative formula.

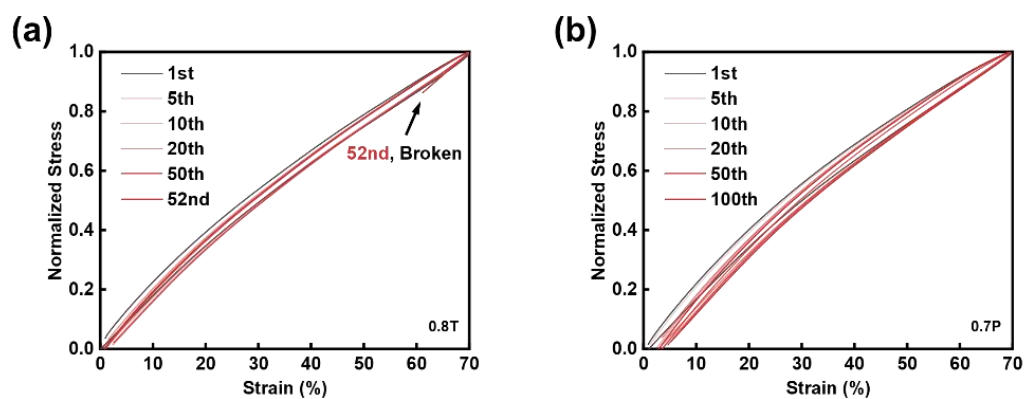


Figure S3. Repeated stretching test (100 times) curves. a) 0.8T. b) 0.7P.

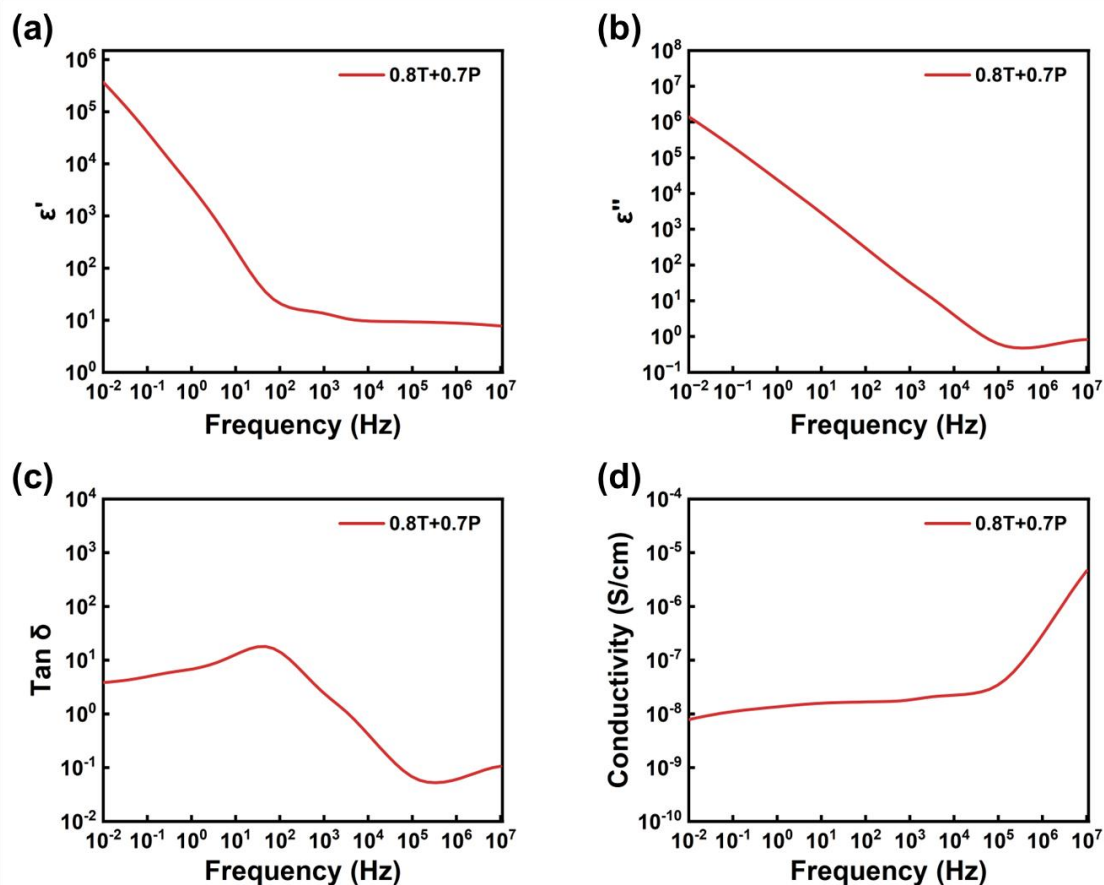


Figure S4. Dielectric properties. a) Relative permittivity. b) Imaginary permittivity. c) Loss factors. d) Conductivity.

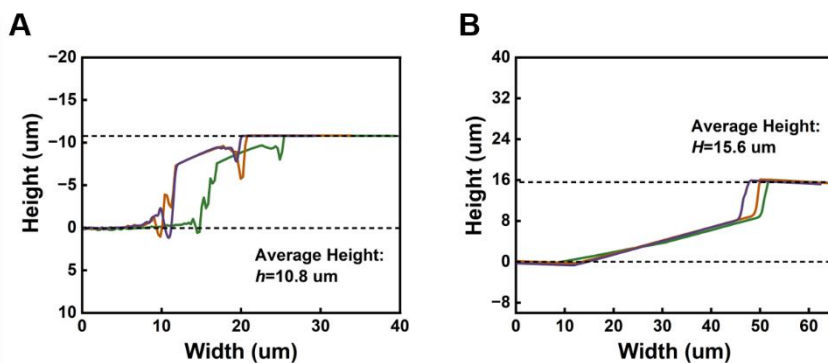


Figure S5: Thickness characterization of the CNT electrode. A. Height of the neat SC-DE film; B. Height of the SC-DE film coated with CNT electrodes on the top and bottom surfaces. The thickness of the CNT electrode therefore is about 2.4 μm .

The resonance frequency of the suspended CNT-coated SC-DE is calculated as follows:

To determine whether the experimentally observed resonance frequency is consistent with classical beam dynamics, the suspended SC-DE actuator was modeled as a symmetric CNT/SC-DE/CNT composite cantilever beam. The sample had a total length of 15 mm, of which approximately 3 mm was constrained by the clamp. The effective free length used in the calculation was therefore $L_{\text{eff}} = 12$ mm. The SC-DE film had a width $b = 4.0$ mm and a

thickness $h = 0.30$ mm. CNT electrodes were coated on both surfaces of the film, with an electrode-covered width $b_e = 3.6$ mm and an approximate thickness $t_e = 2.4$ μm for each electrode layer as characterized in Figure S5. The shear storage modulus of the neat SC-DE matrix in the relevant frequency range was approximately 40 kPa. Assuming that the elastomer is nearly incompressible, with a Poisson's ratio of approximately 0.5, the corresponding tensile storage modulus was estimated as: $E_s = 2(1+\nu) \times G_s \approx 3G = 120$ kPa. The density of the SC-DE matrix was approximated using a representative value for polyacrylate-based elastomers, $\rho = 1100$ kgm^{-3} .

For a first-order estimate, the density of the porous CNT network electrodes was taken as $\rho = 132.6$ kgm^{-3} , which is calculated based on reference 26. The first bending-mode resonance frequency of a clamped-free beam is given by $f_r = \frac{\beta_1^2}{2\pi L_{\text{eff}}^2} \sqrt{\frac{D_{\text{eff}}}{\mu_{\text{eff}}}}$, where $\beta_1 = 1.875$ is the first-mode coefficient, D_{eff} is the effective flexural rigidity of the composite beam, and μ_{eff} is its mass per unit length.

Because CNT electrodes were applied symmetrically to both surfaces, the neutral axis remains at the mid-plane of the SC-DE layer. The effective flexural rigidity can therefore be expressed as $D_{\text{eff}} = E'_s \frac{bh^3}{12} + 2E'_e \left[\frac{b_e t_e^3}{12} + b_e t_e \left(\frac{h+t_e}{2} \right)^2 \right]$, where E'_e is the effective Young's modulus of the CNT electrode. The first term in brackets represents the centroidal bending rigidity of an individual CNT layer, whereas the second term accounts for its displacement from the neutral axis through the parallel-axis theorem.

Because $t_e \ll h$, the term $b_e t_e^3/12$ is negligible relative to the parallel-axis contribution. Thus, the increase in flexural rigidity arises predominantly from the placement of the CNT electrodes near the outer surfaces of the composite beam.

The mass per unit length of the CNT-coated actuator is $\mu_{\text{eff}} = \rho_s b h + 2\rho_e b_e t_e$. Using the specified dimensions gives $\mu_{\text{eff}} = 1.323 \times 10^{-3}$ kgm^{-1} . The effective modulus of a flexible CNT network is substantially lower than the intrinsic modulus of an individual CNT because of network porosity, imperfect tube-to-tube load transfer, inter-tube sliding, and possible interfacial deformation. Based on the effective modulus reported for a compliant CNT network in Reference 30, the CNT electrode modulus was taken as $E'_e \approx 19$ MPa. Substitution into the composite-beam expression gives $D_{\text{eff}} = 8.67 \times 10^{-9}$ Nm^2 , the corresponding first bending-mode resonance frequency is $f_{\text{res}} \approx 9.95$ Hz

This calculated value is reasonably consistent with the experimentally observed resonance frequency of approximately 10 Hz, given the uncertainties associated with the effective free length, CNT-network modulus, electrode thickness, interfacial load transfer, and idealized clamped-free boundary condition.

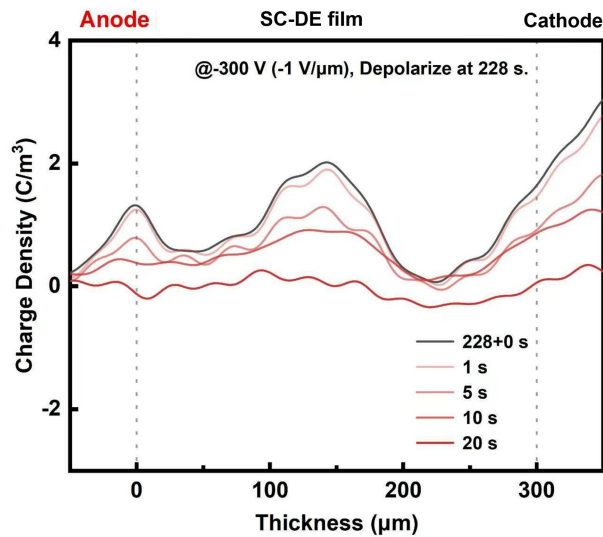


Figure S6. Temporal evolution of the charge density with the SC-DE film after depolarization (after polarizing for 228 s).

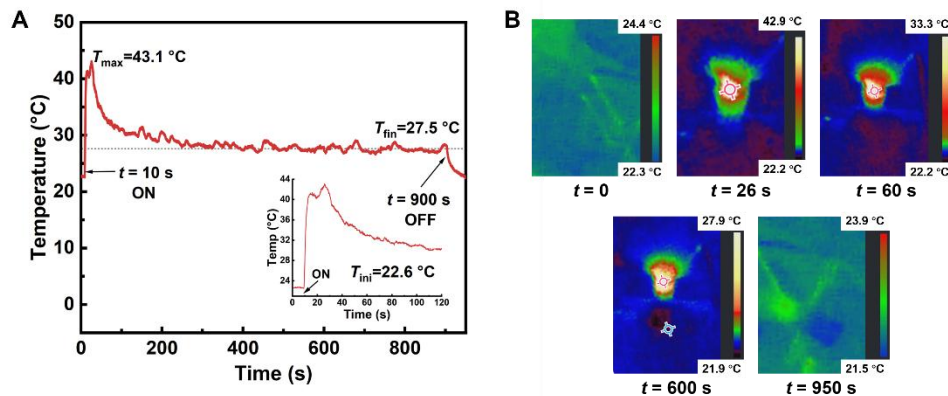


Figure S7: Temporal evolution of the sample's surface temperature during long-term actuation (3 V/ μm , 7 Hz, 1000 s). A. Temporal evolution of the surface temperature. B. Infrared camera images of the sample at different times.