Supporting Information

Electrical Energy Generated by Silicones Filled with Nanospring-Carbon-Nanotubes

Y. J. Lee,†[a,b] P. Caspari,†[c,d] D. M. Opris,[c] F. A. Nüesch,[c,d] S. Ham,[a,e] J.-H. Kim,[a,b] S.-R. Kim,[f] B.-K. Ju,[b] and W. K. Choi*[a,e]*

[a]Center for Opto-Electronic Materials and Devices, Post-Silicon Semiconductor Institute, Korea Institute of Science and Technology, Hwarangro 14 gil 5, Sungbuk Gu, Seoul 02792, Korea

[b]Department of Electronic, Electrical, and Computer Engineering, College of Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea

[c]Laboratory for functional polymers, Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf. Switzerland

[d]École Polytechnique Fédérale de Lausanne (EPFL), Institut des matériaux, Station 12, CH 1015, Lausanne, Switzerland

[e]Department of Nanomaterials and Nano Science, Korea University of Science and Technology (KUST), 217 Gajeong-ro Yuseong-gu, Daejeon 34113, Korea

[f]Department of Polymer Engineering, Korea National University of Transportation, 50 Daehak-ro, Chungjusi, Chungbuk 27469, Korea

Y.J.Lee and P. Caspari contributed equally to this work.

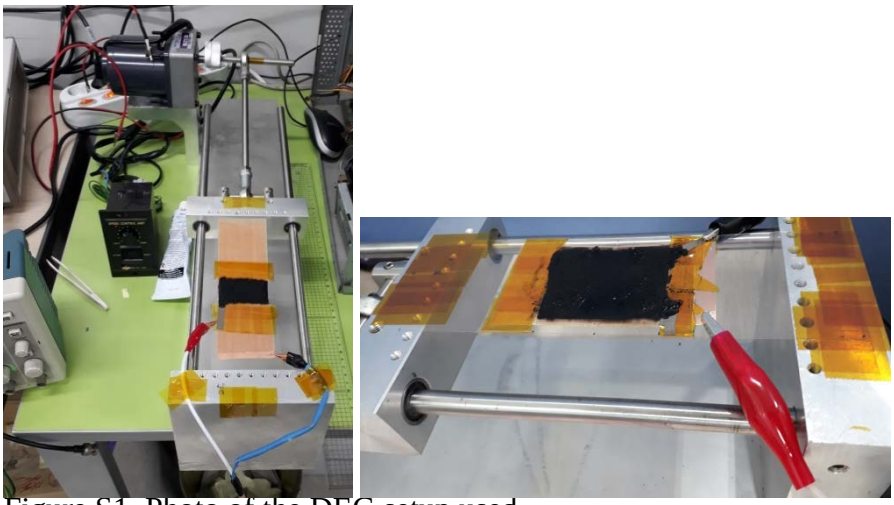


Figure S1. Photo of the DEG setup used.

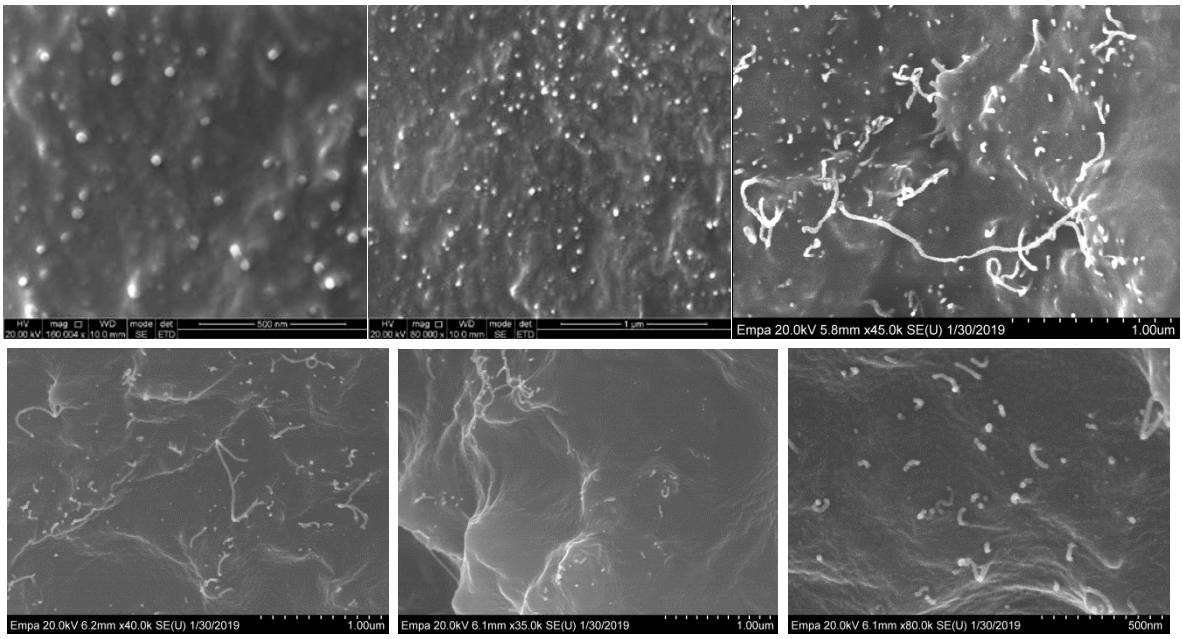


Figure S2. SEM images of the cross-section of **PDMS-CN-CNT** (top) and of **P3-Cl-CNT** (bottom) thin film elastomers.

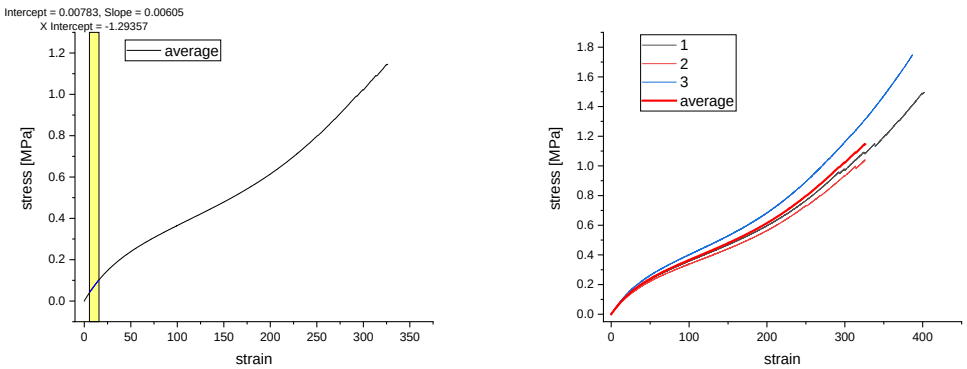


Figure S3. Tensile tests of **PDMS**. Three independent tests were performed.

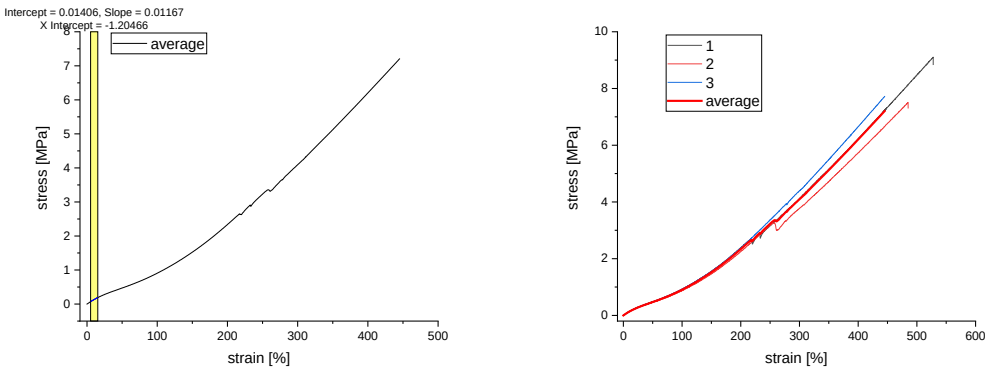


Figure S4. Tensile tests of **Elastosil®Film**. Three independent tests were performed.

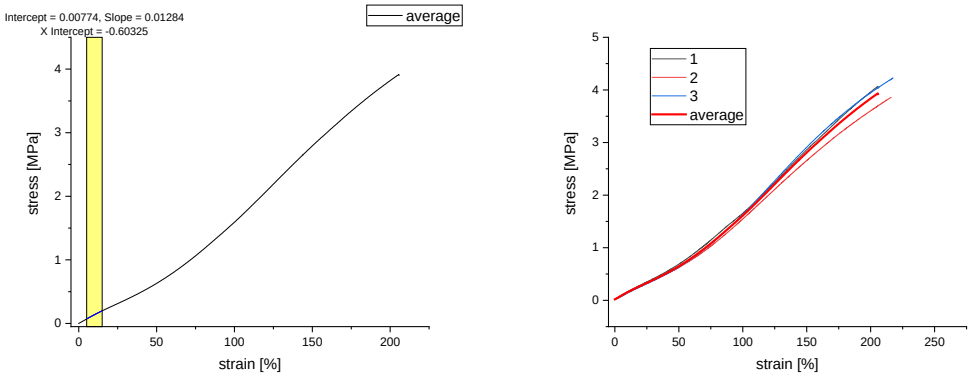


Figure S5. Tensile tests of **PDMS-CN**. Three independent tests were performed.

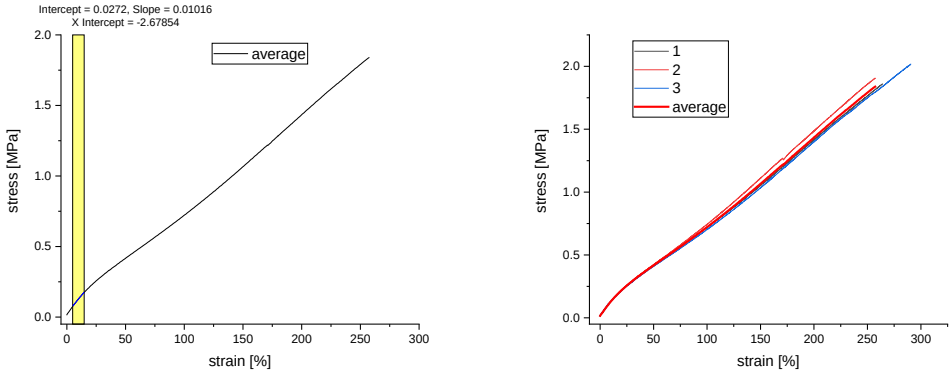


Figure S6. Tensile tests of **PDMS-CN-CNT**. Three independent tests were performed.

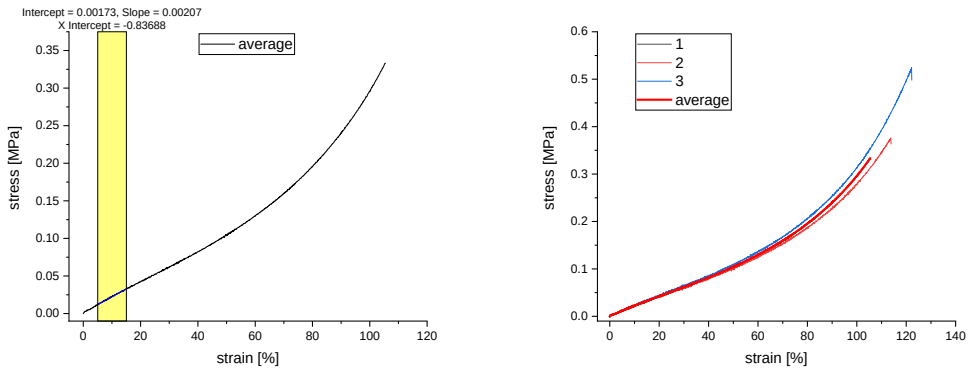


Figure S7. Tensile tests of **P3-Cl**. Three independent tests were performed.

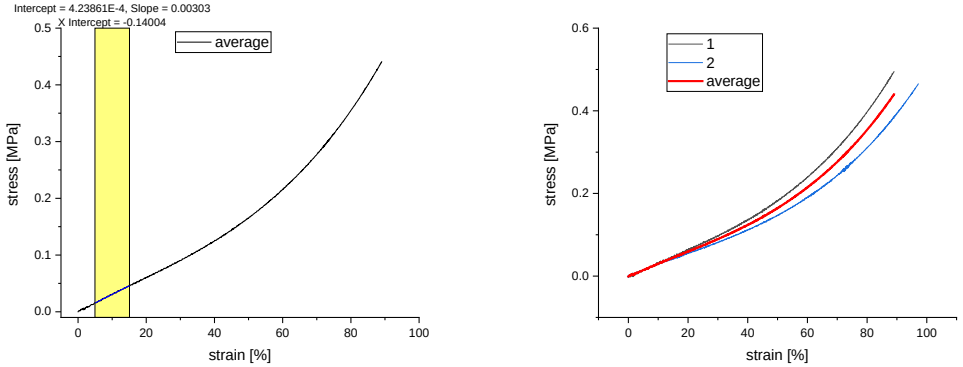


Figure S8. Tensile tests of **P3-Cl-CNT**. Two independent tests were performed.

DEG Measurements at 33% strain

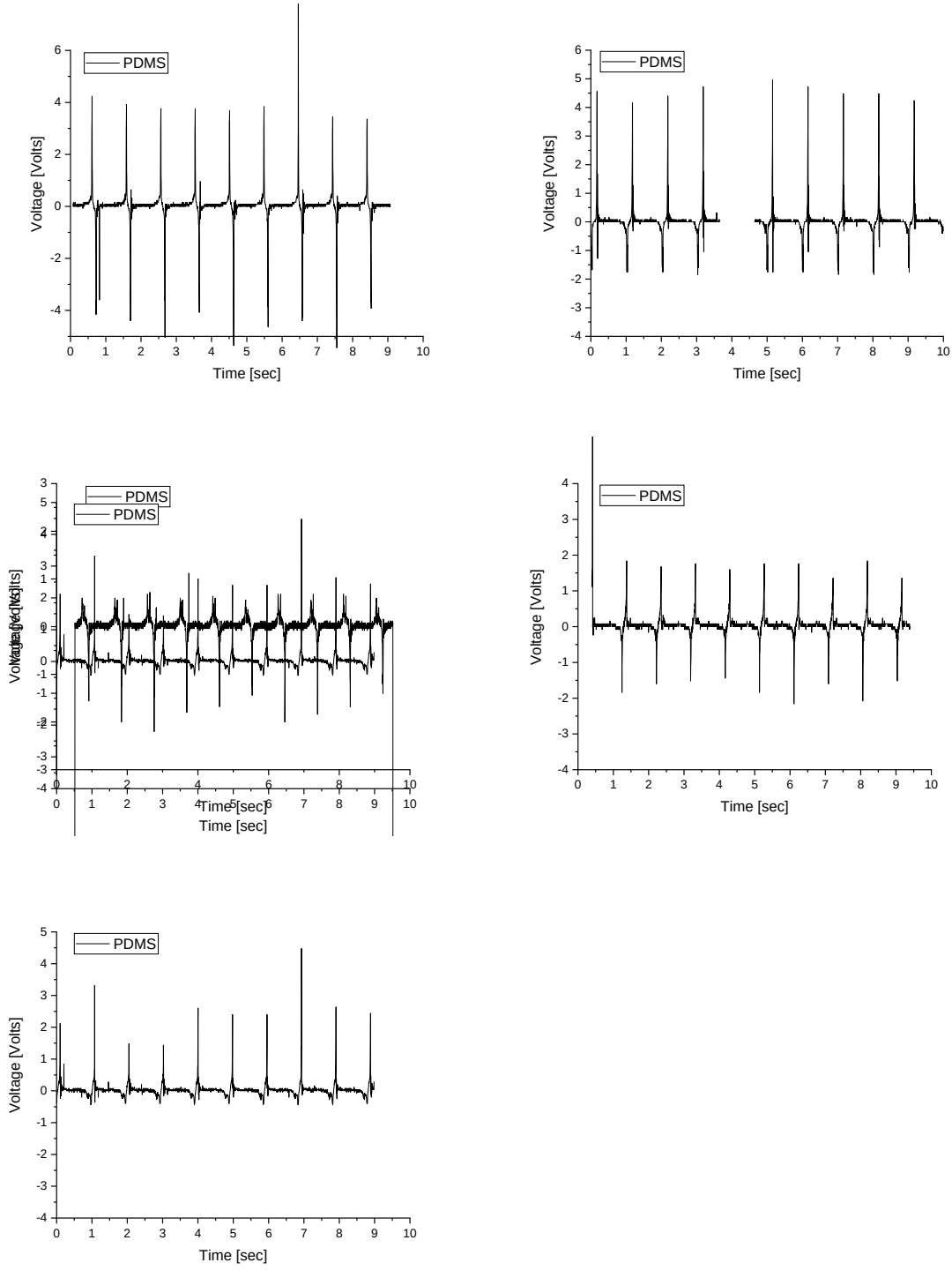


Figure S9. Output voltage of five different **PDMS** electret DEGs at 33% strain.

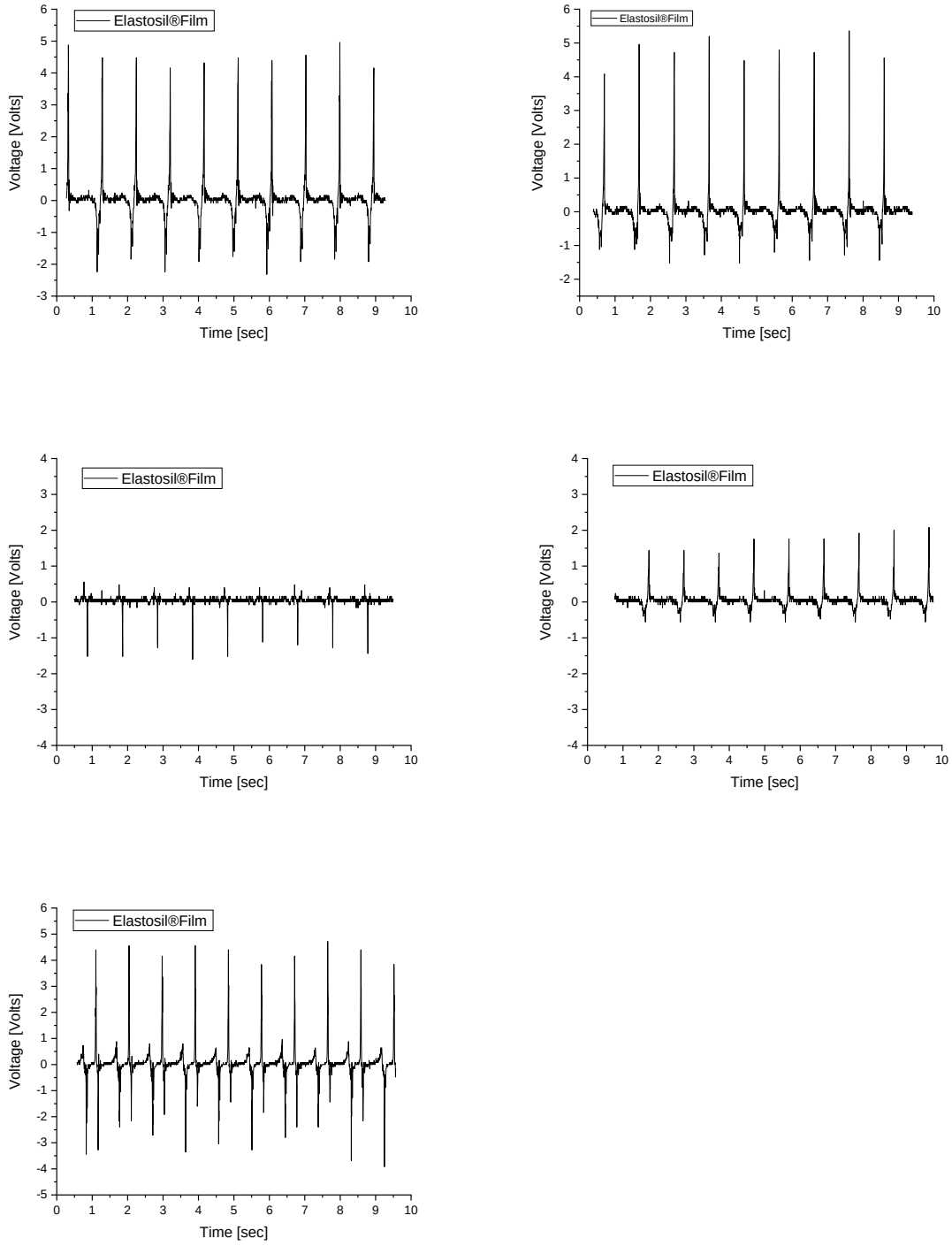


Figure S10. Output voltage of five different Elastosil®Film electret DEGs at 33% strain.

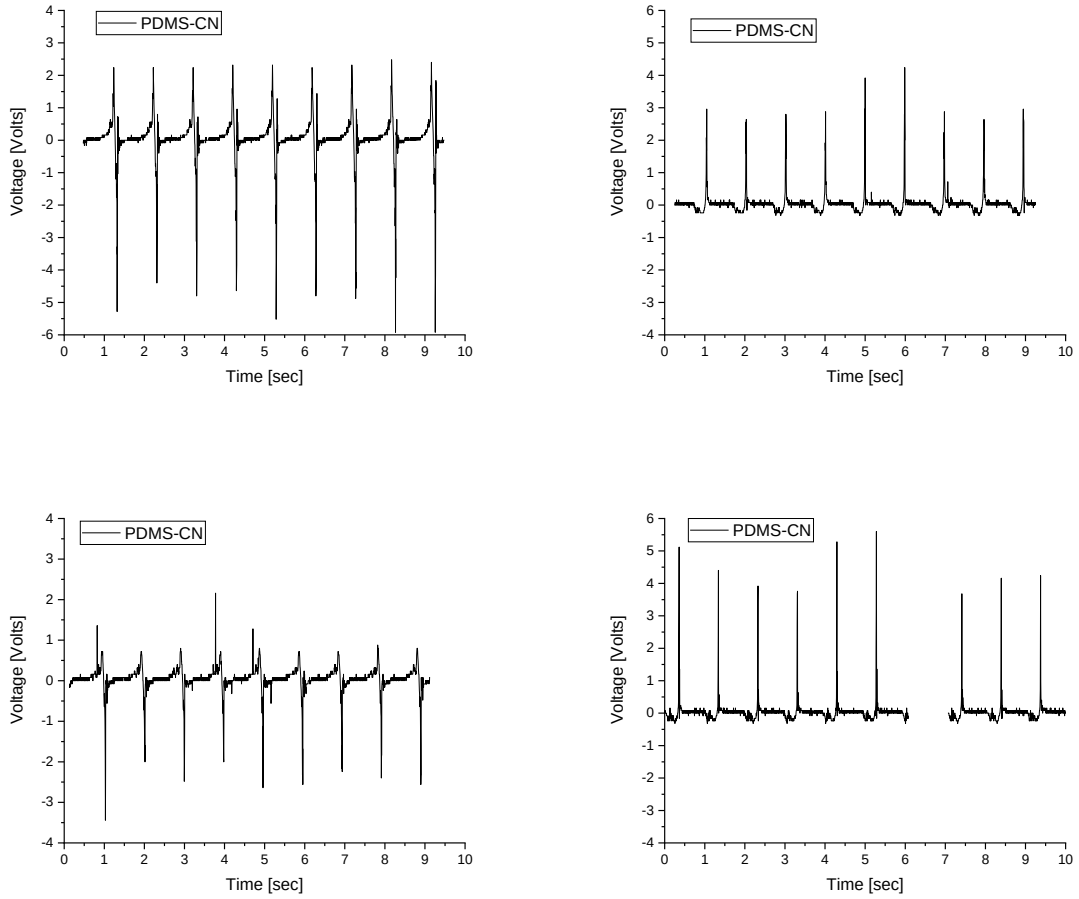


Figure S11. Output voltage of four different **PDMS-CN** electret DEGs at 33% strain.

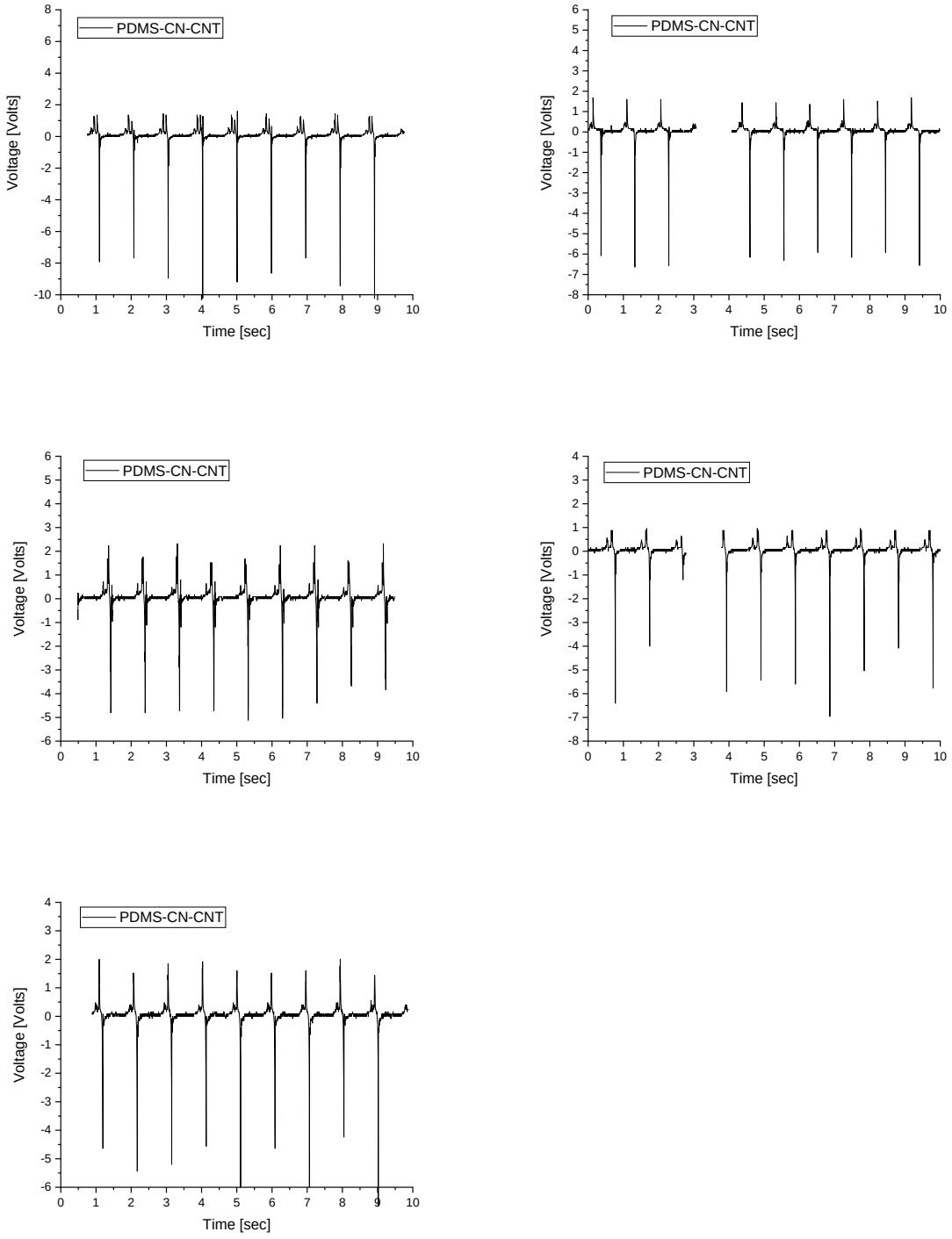


Figure S12. Output voltage of five different **PDMS-CN-CNT** electret DEGs at 33% strain.

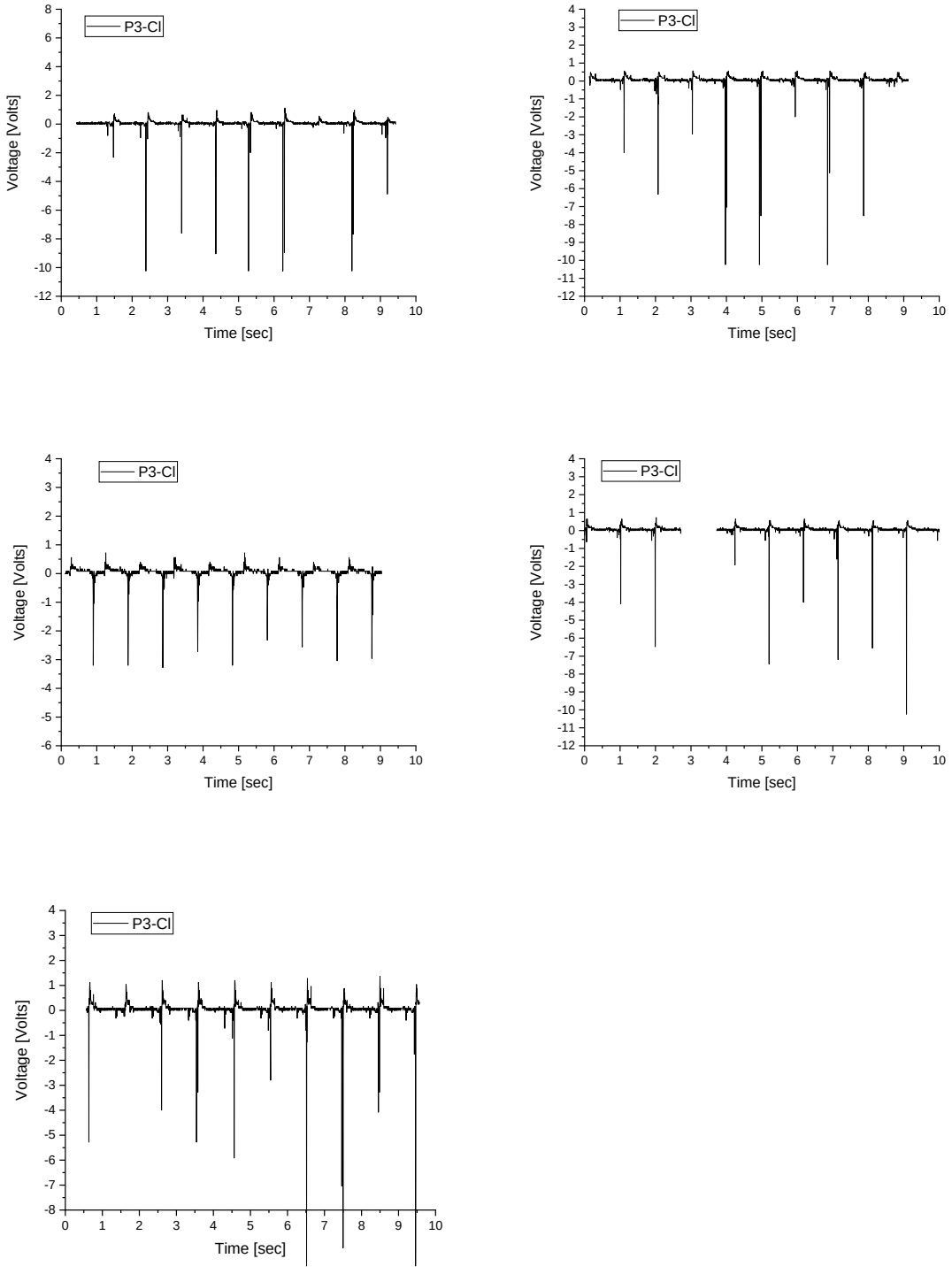


Figure S13. Output voltage of five different **P3-Cl** electret DEGs at 33% strain.

DEG measurements at 66% strain

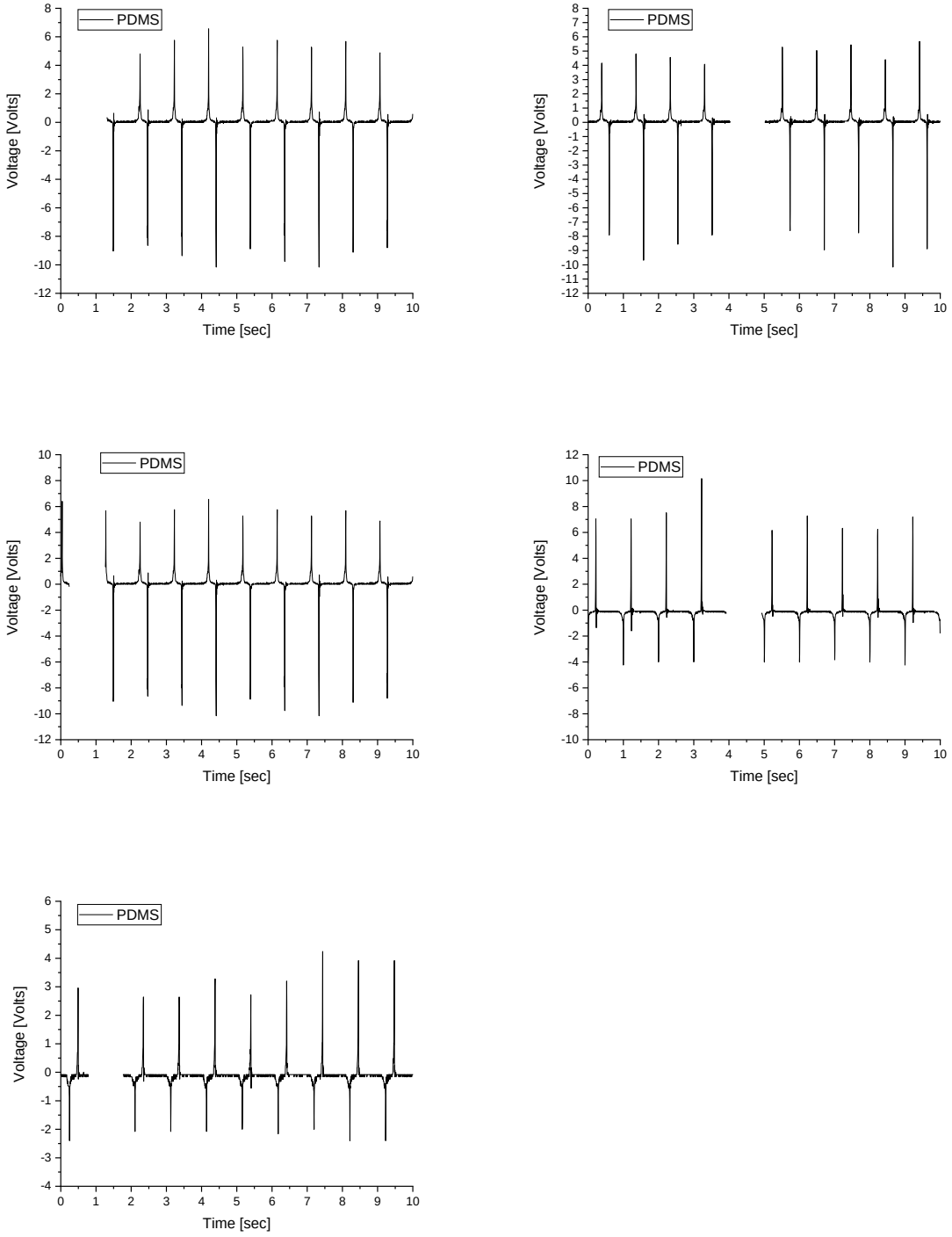


Figure S14. Output voltage of five different **PDMS** electret DEGs at 66% strain.

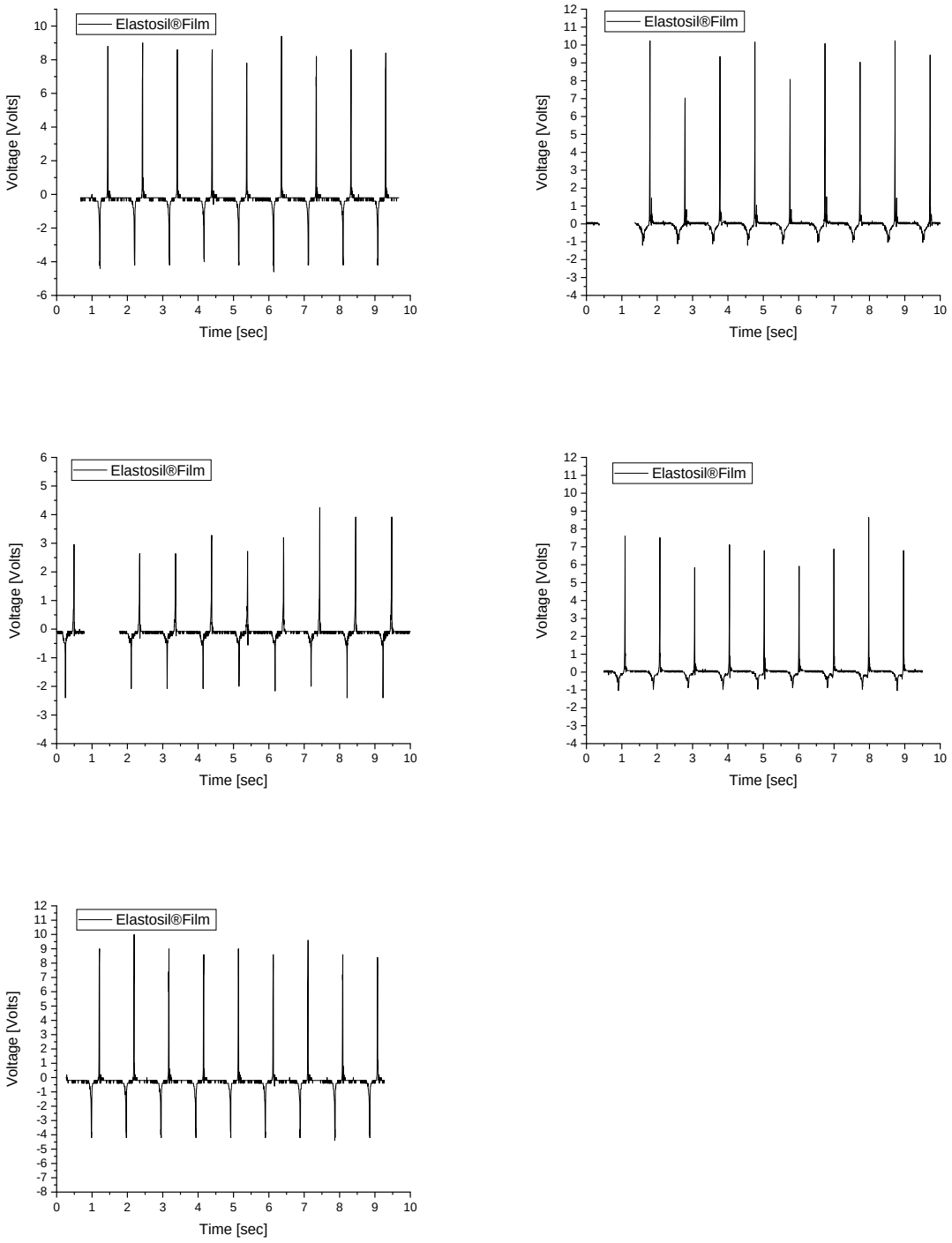


Figure S15. Output voltage of five different **Elastosil®Film** electret DEGs at 66% strain

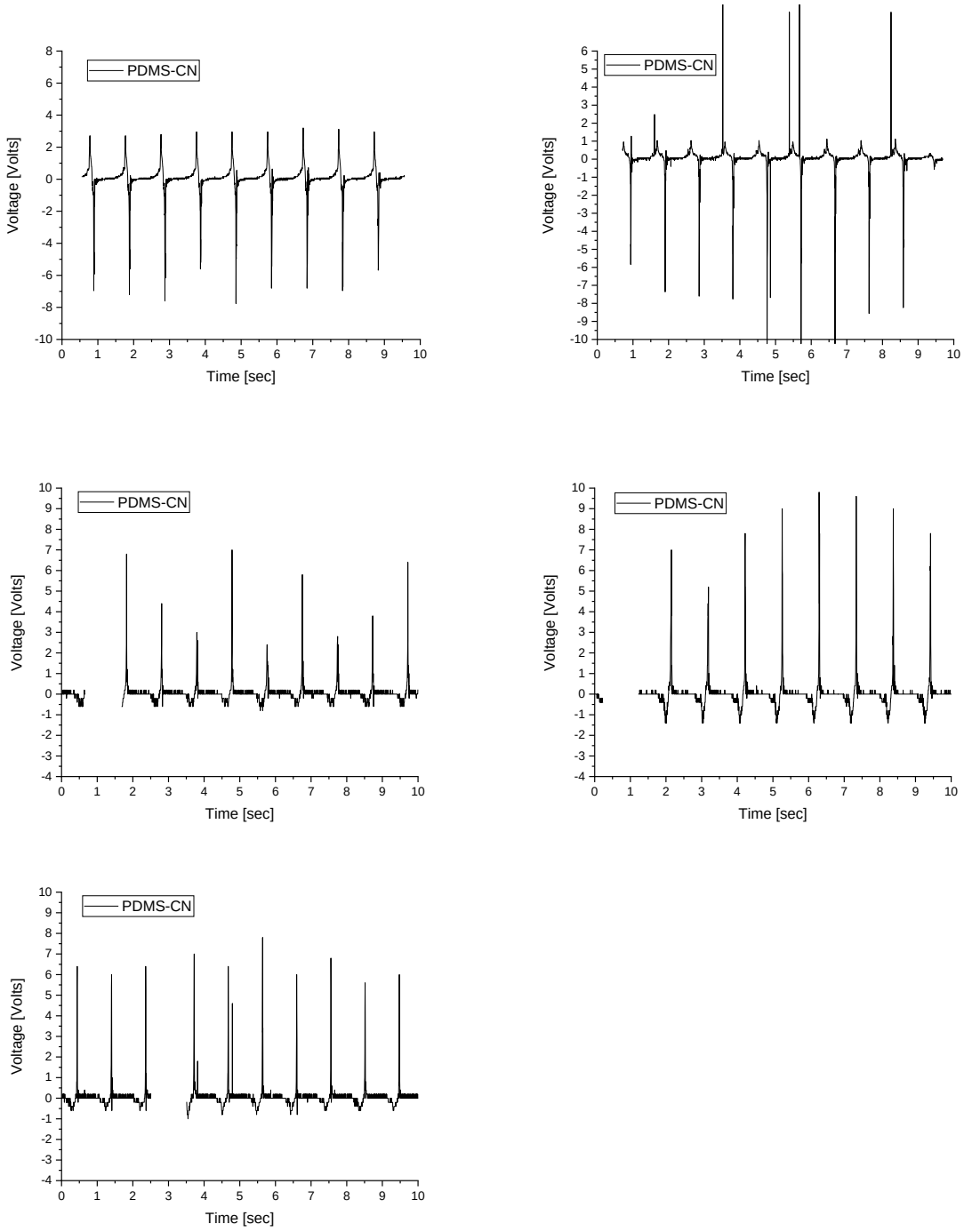


Figure S16. Output voltage of five different **PDMS-CN** electret-DEGs at 66% strain.

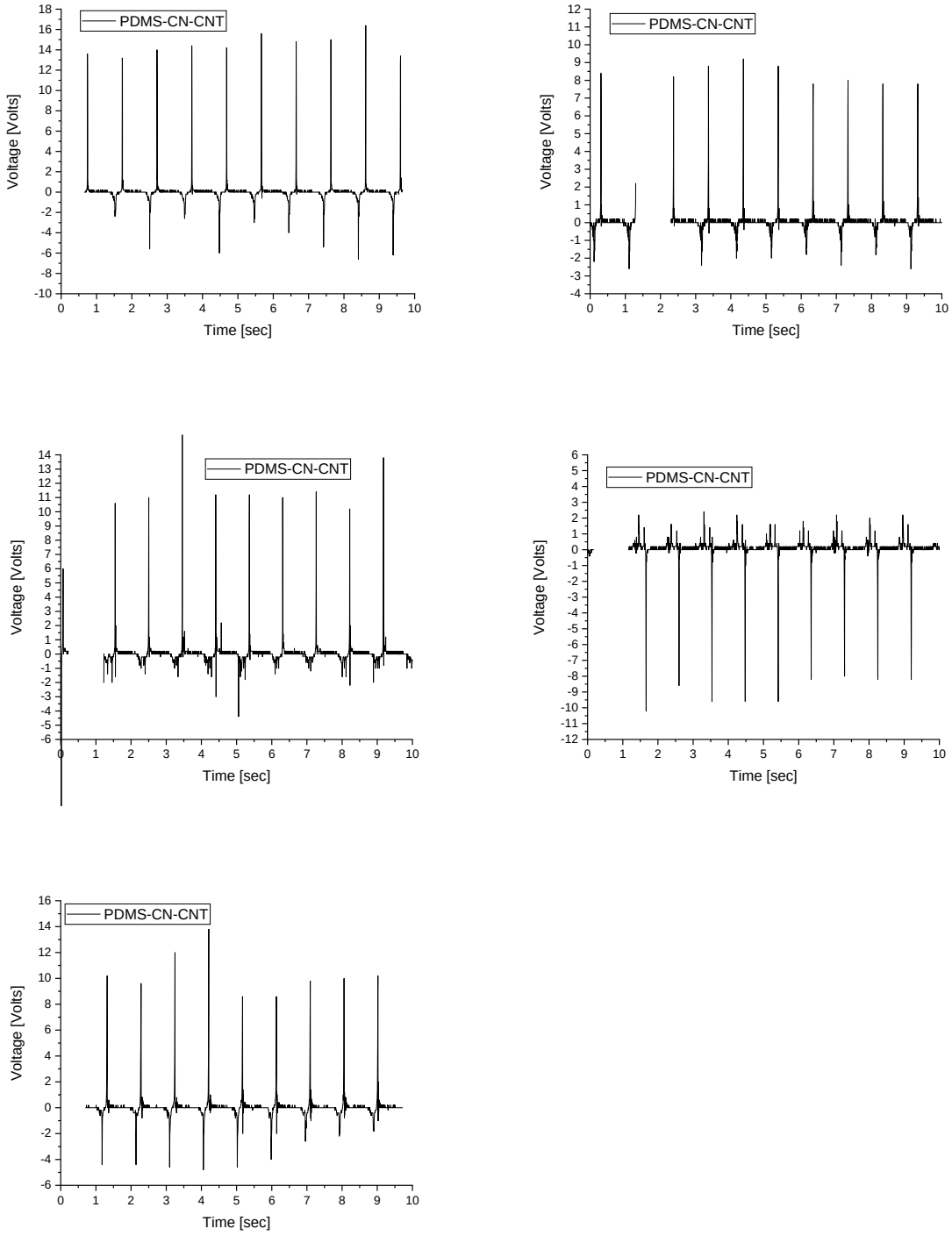


Figure S17. Output voltage of five different **PDMS-CN-CNT** electret DEGs at 66% strain.

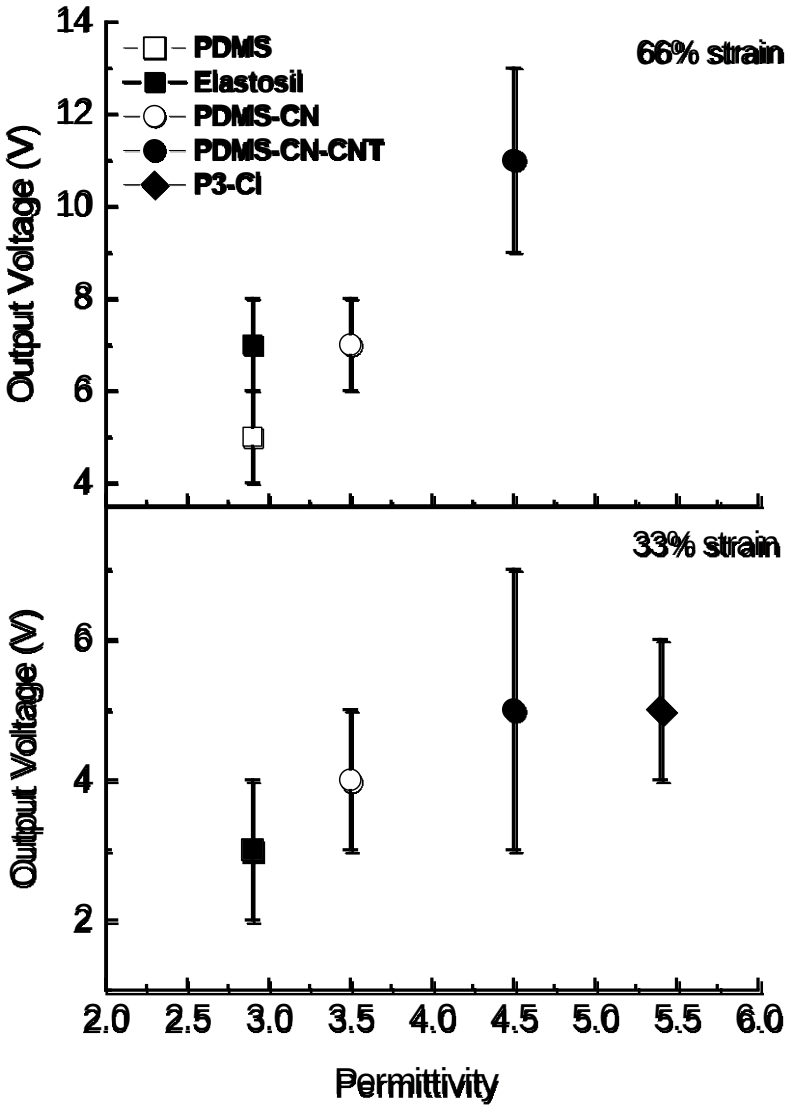


Figure 18. Average output voltage obtained from five different DEG *versus* permittivity ε' of the DE at 33% and at 66% strain. For the generators strained by 66%, a clear increase in the output voltage with the dielectric permittivity is seen.

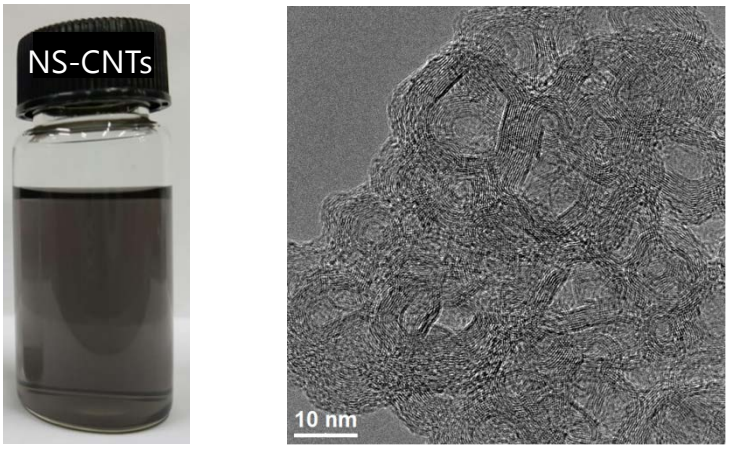
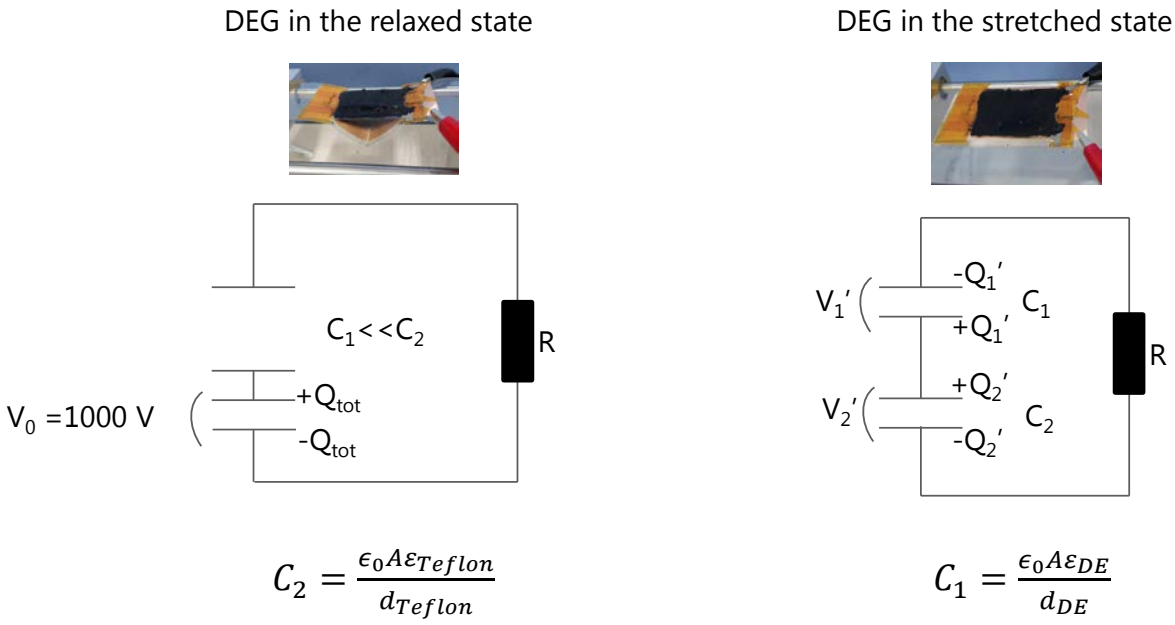


Figure S19. Photographs of a dispersion of NS-CNTs in DMF after standing for 1 month at room temperature (left) and high-resolution TEM images of the buckled NS-CNTs (right).

Electret DEG energy considerations:



$$C_2 = \frac{\epsilon_0 A \varepsilon_{Teflon}}{d_{Teflon}} \qquad C_1 = \frac{\epsilon_0 A \varepsilon_{DE}}{d_{DE}}$$

$$V_0 = 1000\,V\ (Electret\ surface\ potential)$$

$C_1 = \varepsilon_0 \varepsilon' \frac{A}{d}$ capacity of the DE when stratched

$$V'_1 = V'_2\ (Equilibrium\ of\ electric\ potential\ in\ the\ stretched\ state)$$

$$Q_{total} = C_2\, V_0 (Total\ amount\ of\ charges\ on\ the\ electret\ surface)$$

$$Q_{total} = Q'_1 + Q'_2$$

$$V'_1 = \frac{Q'_1}{C_1}$$

$$Q'_1 = \frac{Q_{tot}\, C_1}{C_1 + C_2}$$

$$E_{stretched} = \frac{1}{2} C_1 {V'_1}^2 + \frac{1}{2} C_2 V'^2_2 = \frac{1}{2} V'^2_1 (C_1 + C_2)$$

$$E_{open} = \frac{1}{2} C_2 V_0^2$$

$$\Delta E = E_{stretched} - E_{open} = \frac{1}{2} \left(((C_1 + C_2) V'^2_1) - (C_2 V_0^2) \right)$$

$$= -\frac{1}{2} V_0^2 \frac{C_1 C_2}{C_1 + C_2}$$

Theoretical values of ΔE for an electret device where the DE is strained at maximum.

Entry	ε′	s_{max} [%]	A[a]	d[b]	C_1 [nF]	Q'_1 [μC]	V'_1 [V]	ΔE [J]	E [V/μm]
PDMS	2.9	372	5cm × 14.2cm 0.0071 m^2	42.4	4.3	0.77	179.5	$-3.86\ 10^{-4}$	4.2
Elastosil	2.9	485	5cm × 17.6cm 0.0088 m^2	34.2	6.6	0.99	150.3	$-4.95\ 10^{-4}$	4.4
PDMS-CN	3.5	313	5cm × 12.4cm 0.0062 m^2	48.4	4.0	0.68	171.9	$-3.41\ 10^{-4}$	3.6
PDMS-CN-CNT	4.6	270	5cm × 11.1cm 0.0056 m^2	54.1	4.2	0.62	149.9	$-3.13\ 10^{-4}$	2.8
P3-Cl	5.3	114	5cm × 6.4cm 0.0032 m^2	93.5	1.6	0.34	209.2	$-1.69\ 10^{-4}$	2.2
P3-Cl-CNT	6.3	95	5cm × 5.85cm 0.0029 m^2	102.6	1.6	0.31	196.3	$-1.56\ 10^{-4}$	1.9

[a]the theoretical surface area of DE films (initial size of 5 cm × 3 cm) that were uniaxially stretched by s_{max}, [b]d= d_0/ (1+ s_{max}), where d represents the DE thickness after being stretched by s_{max}, C_1 represents the capacitance of the DE in the stretched state, Q'_1 is the charge on the stretched DE. *ΔE* represents the theoretical amount of energy harvested if the material was stretched at maximum. E represents the theoretical electric field in the DE calculated using V1' and d.

$$C_2 = \varepsilon_0 \varepsilon' \frac{A}{d} \ (\epsilon' = 2.1, d_{Teflon} = 140\ \mu m, A\ depends\ on\ the\ area\ of\ the\ DE)$$

$$V_2 = \frac{(Q_{total} - Q'_1)}{C_2}$$

Electret	Electret Area[a] [m^2]	C_2 [nF]	Q_{total} [μC]	V_2 [V]
PDMS	0.0071	0.94	0.94	179.8
Elastosil	0.0088	1.17	1.17	150.3
PDMS-CN	0.0062	0.82	0.82	171.9
PDMS-CN-CNT	0.0056	0.74	0.74	149.9
P3-Cl	0.0032	0.43	0.43	209.2
P3-Cl-CNT	0.0029	0.39	0.39	196.3

[a]To be able to calculate the maximum energy when the DE materials is stretched at maximum, electrets with different surface area has to be used.

Theoretical values of ΔE when the DE is stretched by 33%.

Entry	ε'	A[a]	d[b] [μm]	C_1 [nF]	Q'_1 [μC]	V'_1 [V]	ΔE [J]	E [V/μm]
PDMS	2.9	5cm × 4 cm 0.002 m^2	150.4	0.34	0.15	437.5	-7.48 10^{-5}	2.9
Elastosil	2.9	0.002 m^2	150.4	0.34	0.14	437.5	-7.48 10^{-5}	2.9
PDMS-CN	3.5	0.002 m^2	150.4	0.41	0.16	391.9	-8.08 10^{-5}	2.6
PDMS-CN-CNT	4.6	0.002 m^2	150.4	0.54	0.18	329.0	-8.92 10^{-5}	2.2
P3-Cl	5.3	0.002 m^2	150.4	0.62	0.19	298.5	-9.32 10^{-5}	2.0
P3-Cl-CNT	6.3	0.002 m^2	150.4	0.74	0.20	263.6	-9.79 10^{-5}	1.8

[a]the surface area of the electret used and of the DE films (5 cm × 3 cm) that were uniaxially stretched by 33%.

$$V_2 = \frac{(Q_{total} - Q'_1)}{C_2}$$

Electret	C_2 [nF]	Q_{total} [μC]	V_2 [V]
PDMS	0.27	0.27	437.5
Elastosil	0.27	0.27	437.5
PDMS-CN	0.27	0.27	391.9
PDMS-CN-CNT	0.27	0.27	329.0
P3-Cl	0.27	0.27	298.5
P3-Cl-CNT	0.27	0.27	263.6

Theoretical values at 66% DEG strain

Entry	ε'	A[a]	d[b] [μm]	C_1 [nF]	Q'_1 [μC]	V'_1 [V]	ΔE [J]	E [V/μm]
PDMS	2.9	5cm × 5 cm 0.0025 m^2	120.5	0.53	0.20	383.9 V	-1.02 10^{-4}	3.2
Elastosil	2.9	0.0025 m^2	120.5	0.53	0.20	383.9 V	-1.02 10^{-4}	3.2
PDMS-CN	3.5	0.0025 m^2	120.5	0.64	0.22	340.5 V	-1.10 10^{-4}	2.8
PDMS-CN-CNT	4.6	0.0025 m^2	120.5	0.84	0.24	282.1 V	-1.19 10^{-4}	2.3
P3-Cl	5.3	0.0025 m^2	120.5	0.97	0.25	254.3 V	-1.24 10^{-4}	2.1
P3-Cl-CNT	6.3	0.0025 m^2	120.5	1.15	0.26	222.9 V	-1.29 10^{-4}	1.9

[a]the surface area of the electret used and of the DE films (5 cm × 3 cm) that were uniaxially stretched by 66%.

$$V_2 = \frac{(Q_{total} - Q'_1)}{C_2}$$

Electret	C_2 [nF]	Q_{total} [μC]	V_2 [V]
PDMS	0.33	0.33	383.9

Elastosil	0.33	0.33	383.9
PDMS-CN	0.33	0.33	340.5
PDMS-CN-CNT	0.33	0.33	282.1
P3-Cl	0.33	0.33	254.3
P3-Cl-CNT	0.33	0.33	222.9