



Supporting Information

for *Small*, DOI: 10.1002/smll.202105857

Ionically Active MXene Nanopore Actuators

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Table S1. List of nanopores used in this study.

Pore name	Membrane	Pore projection area (nm²)	Figure
A	Ti ₃ C ₂ T _x	32	1d, S7d
B	Ti ₃ C ₂ T _x	21	2a, 2c, S6
C	Ti ₃ C ₂ T _x	6.7	2b
D	Ti ₃ C ₂ T _x	18	S1a, S4b
E	Ti ₃ C ₂ T _x	16.6	S1b
F	Ti ₃ C ₂ T _x	28.26	S2, S7b
G	Ti ₃ C ₂ T _x	51	S3
H	Ti ₃ C ₂ T _x	16.4	S4a
I	Ti ₃ C ₂ T _x	16	S7a, S7c
J	Ti ₃ C ₂ T _x	30	Table S2
K	Ti ₃ C ₂ T _x	17.5	S8
L	Ti ₂ CT _x	22.2	S9
M	Ti ₂ CT _x	42.2	S9
N	Ti ₂ CT _x	33.4	S9
O	SiN _x	51.5	S10
P	SiN _x	86.5	S10

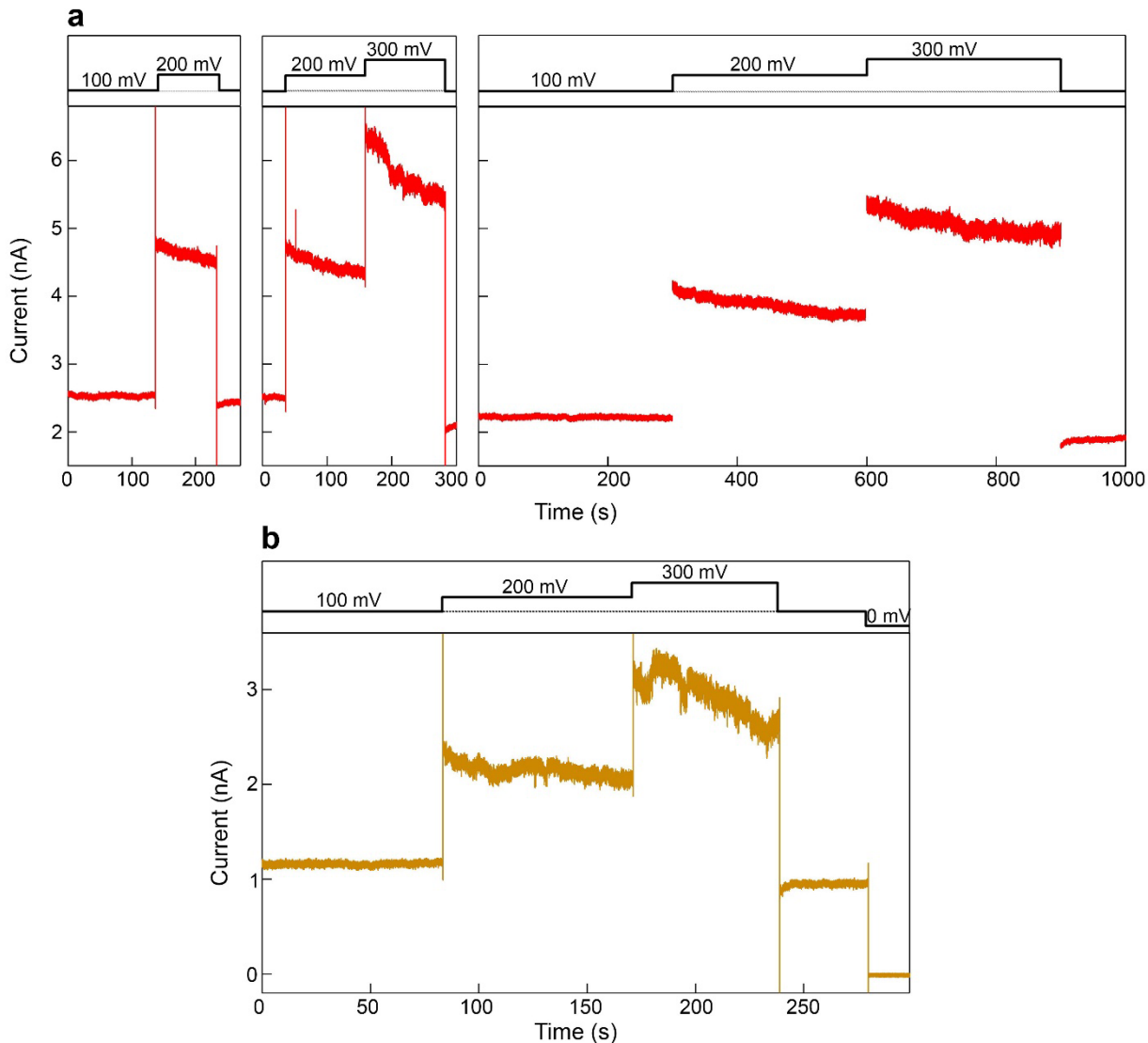


Figure S1. Actuation property of nanopores in few-layer MXene membranes due to Li^+ and Na^+ (de)intercalation. (a) Current trace of nanopore D demonstrating that by increasing voltage, the nanopore conductance value decreases. By going back to lower voltage values (~ 100 mV) again, the conductance recovers. This behavior could happen repeatedly as the second and third traces show. Buffer: 0.4 M LiCl, 10 mM Tris pH 7.5. (b) Current trace of nanopore E showing voltage-gated actuation property of the MXene nanopore due to (de)intercalation of Na^+ ions. Buffer: 0.4 M NaCl, 10 mM Tris, pH 7.5.

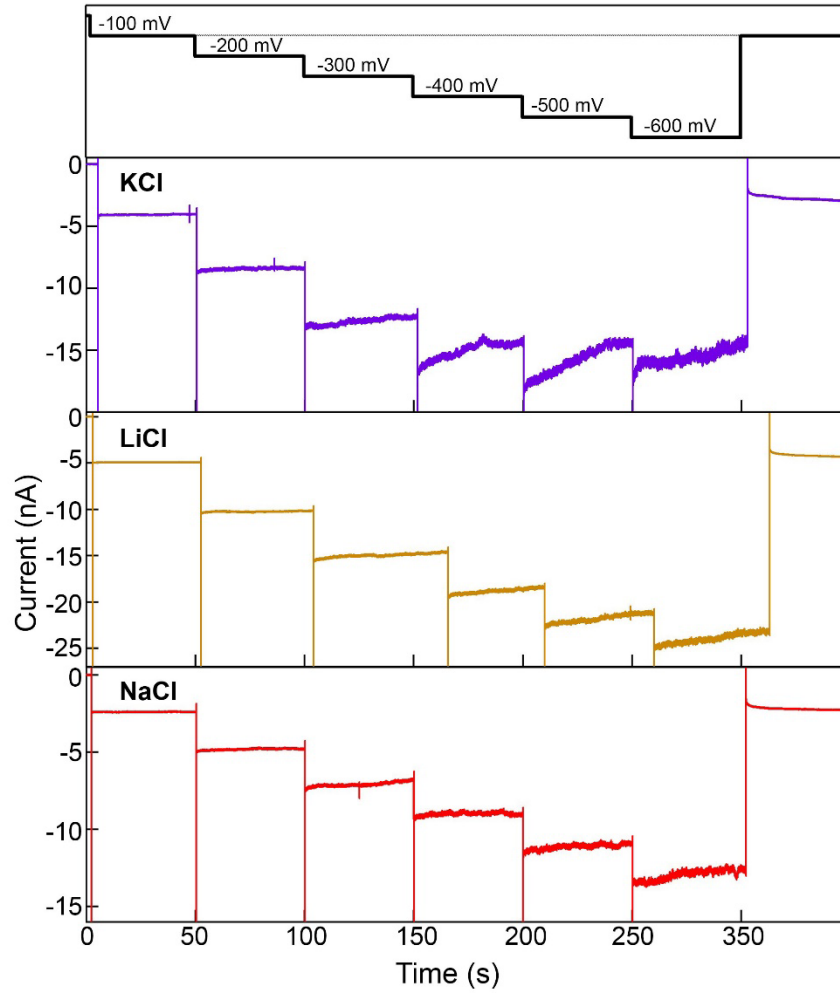


Figure S2. Actuation property of nanopore F in a few-layer MXene membrane tested with three different cations: potassium (purple), sodium (yellow), and lithium (red). Buffers: 1 M KCl, 10 mM Tris pH 7.5, 1 M NaCl, 10 mM Tris pH 7.5, 1 M LiCl, 10 mM Tris pH 7.5.

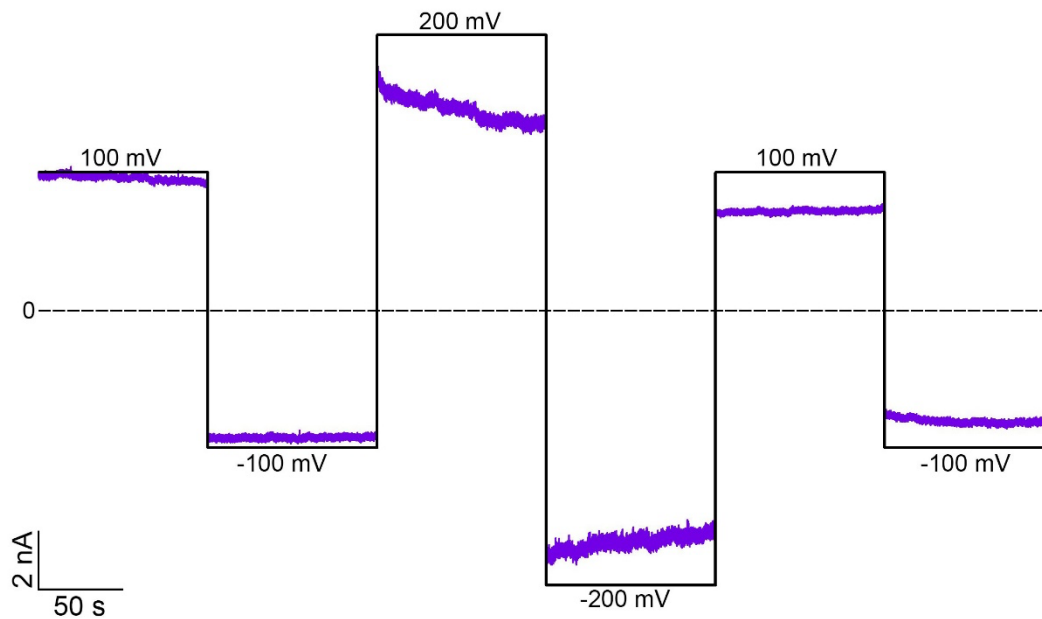


Figure S3. Current trace of nanopore G at positive and negative voltages. Buffer: 0.4 M KCl, 20 mM Tris, pH 7.5.

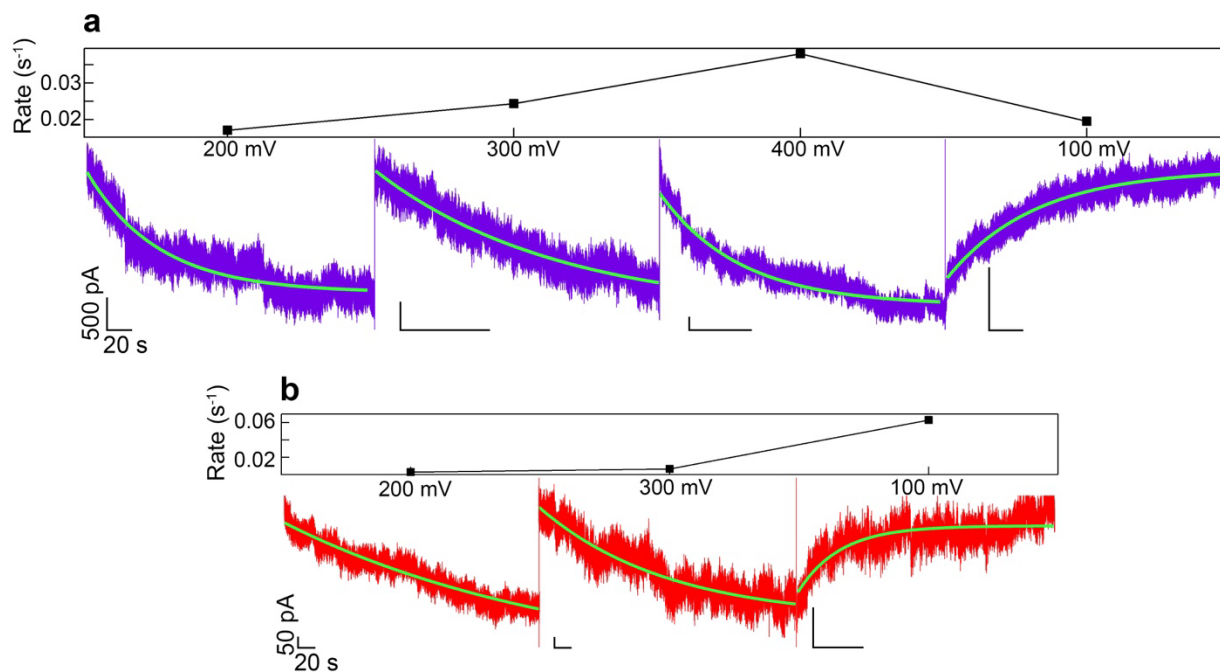


Figure S4. Rate of cation (de)intercalation between the MXene layers for nanopores H and D. (a) Single-exponential functions (green curves) fitted to the current trace of nanopore H. Buffer: 0.4 M KCl, 20 mM Tris, pH 7.5. (b) Single-exponential functions (green curve) fitted to the current trace of nanopore D. Buffer: 0.4 M LiCl, 20 mM Tris, pH 7.5.

Table S2. Rates of conductance changes for 6 MXene nanopores tested in the KCl buffer. Current traces were fitted to single exponential function: $I = I_0 e^{\frac{-t}{\tau}}$

Pore name	Rate at ± 200 mV (s⁻¹)	Rate @ ± 300 mV (s⁻¹)	Rate @ ± 400 mV (s⁻¹)	Rate @ ± 100 mV (s⁻¹)
<i>B</i>	0.076	0.133	0.17	0.067
<i>H</i>	0.0171	0.0244	0.038	0.0196
<i>F</i>	0.082	0.0137	0.0538	0.0431
<i>G</i>	0.011	-	-	0.049
<i>J</i>	0.0127	-	-	0.0267
<i>I</i>	0.0141	-	-	0.0264

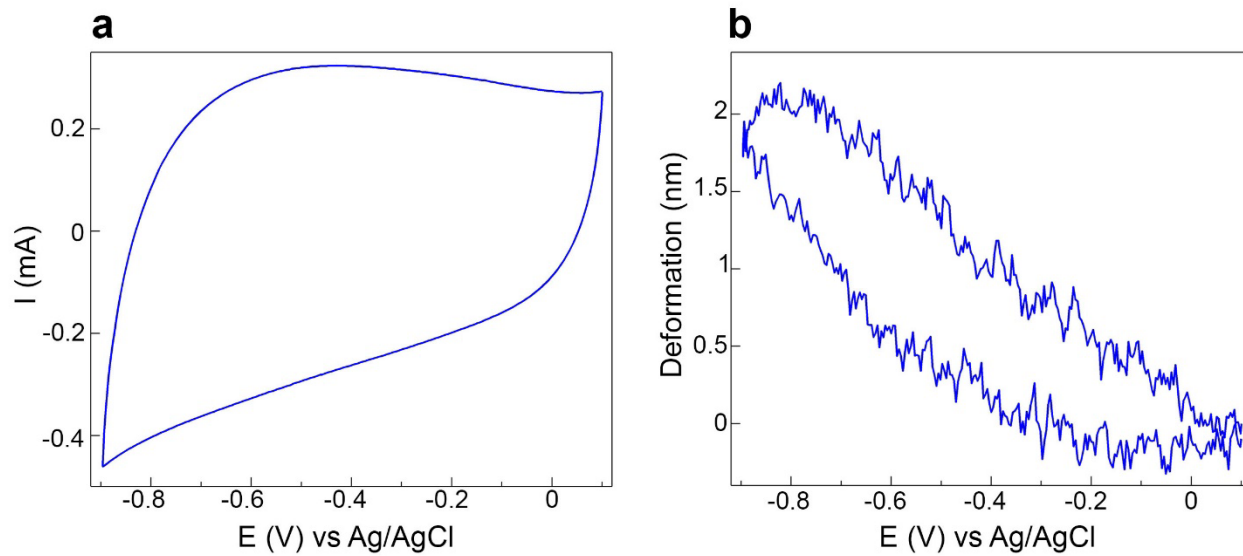


Figure S5. AFM dilatometry experiment of a deformation in a 16-layer MXene membrane. (a) CV and (b) deformation of a 16-layer MXene film in 0.5 M Li₂SO₄ at 1 V/s.

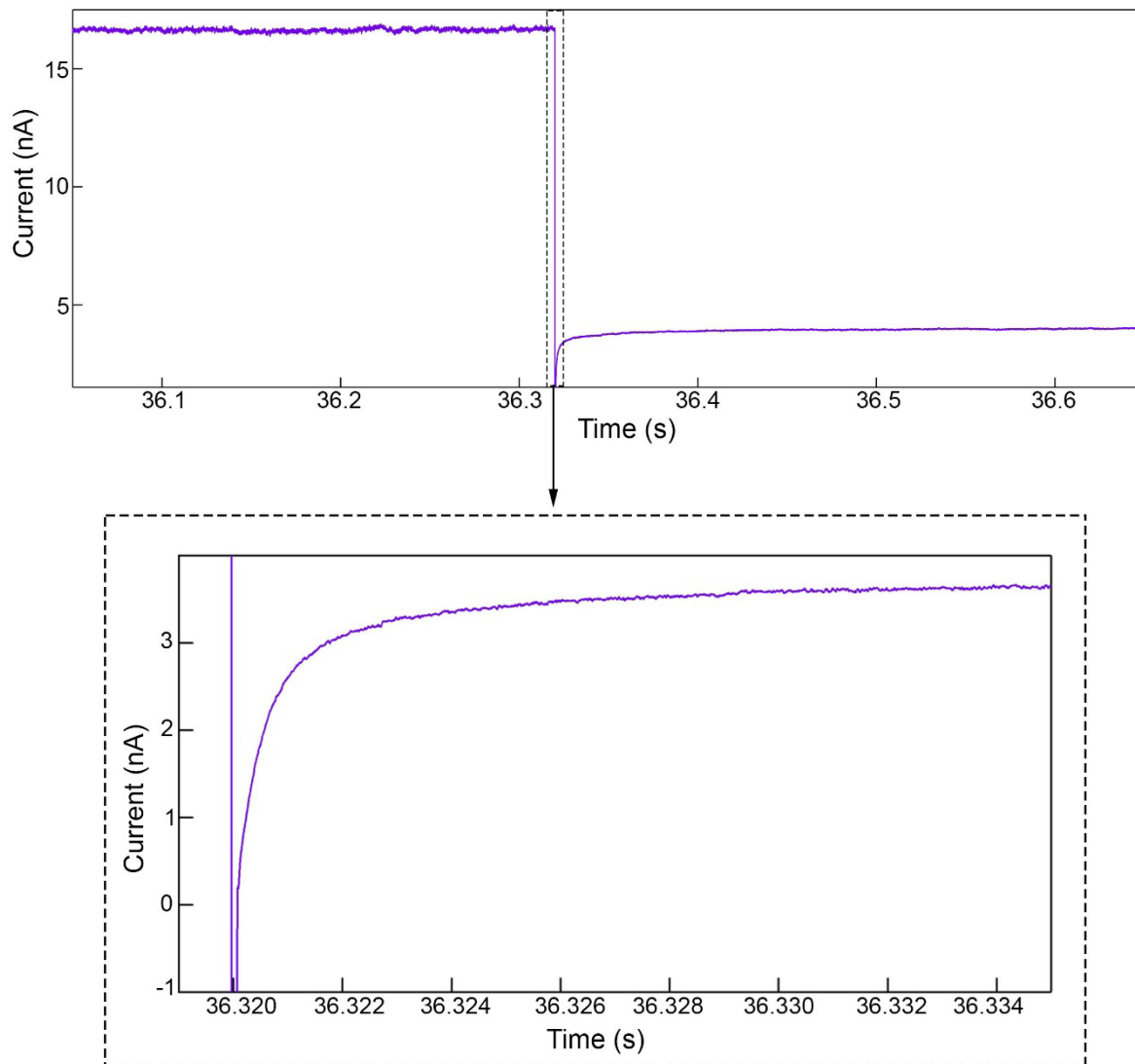


Figure S6. Capacitive response of nanopore B in millisecond timescale upon changing voltage from 400 mV to 100 mV. Buffer: 0.4 M KCl, 20 mM Tris, pH 7.5.

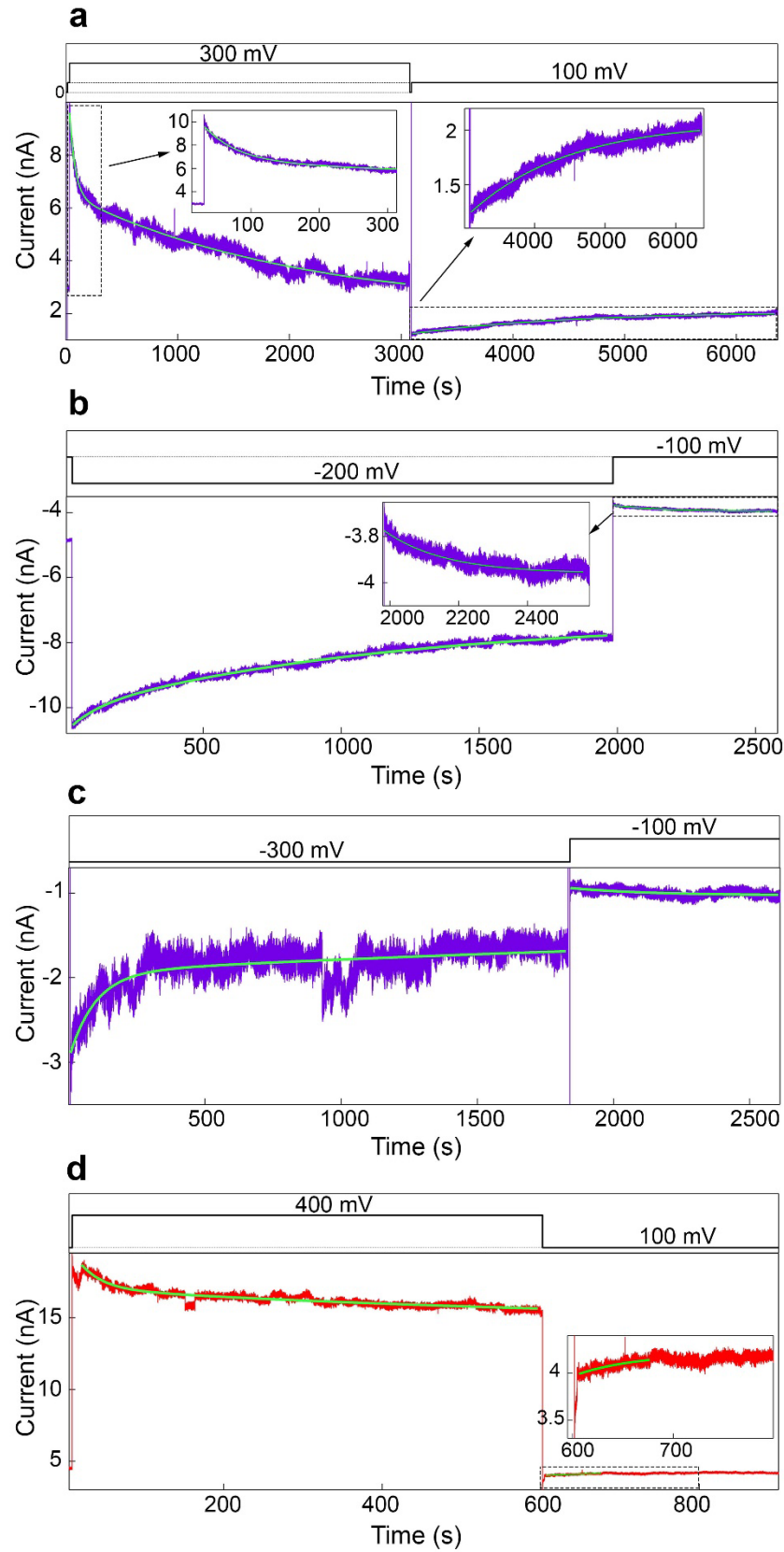


Figure S7. Current traces of MXene nanopores at $V > 200$ mV for up to ~3,000 seconds. (a) Current trace of the nanopore I at 300 mV for ~ 50 minutes. A double exponential function ($I = I_1 e^{\frac{-t}{\tau_1}} + I_2 e^{\frac{-t}{\tau_2}}$, green curve) was fitted to the trace with rates of $\tau_1^{-1} = 0.019 \text{ s}^{-1}$ and $\tau_2^{-1} = 0.0004 \text{ s}^{-1}$. This was followed by applying 100 mV for ~ 50 minutes. A single-exponential function was fitted to the trace with rate of 0.007 s^{-1} . Buffer: 1 M KCl, 10 mM Tris, pH 7.5 (b) Current trace of nanopore F at -200 mV for ~ 33 minutes. A double exponential function (green curve) was fitted to the trace with rates of $\tau_1^{-1} = 0.0096 \text{ s}^{-1}$ and $\tau_2^{-1} = 0.0008 \text{ s}^{-1}$. This was followed by applying 100 mV for ~ 10 minutes. A single-exponential function was fitted to the trace with rate of 0.0057 s^{-1} . Buffer: 1 M KCl, 10 mM Tris, pH 7.5. (c) Current trace of nanopore I at -300 mV for ~ 30 minutes. A double exponential function (green curve) was fitted to the trace with rates of $\tau_1^{-1} = 0.01 \text{ s}^{-1}$ and $\tau_2^{-1} = 0.0003 \text{ s}^{-1}$. This was followed by applying 100 mV for ~ 10 minutes. A single-exponential function was fitted to the trace with rate of 0.0034 s^{-1} . Buffer: 1 M KCl, 10 mM Tris, pH 7.5. (d) Current trace of nanopore A at 400 mV for ~ 10 minutes. A double exponential function (green curve) was fitted to the trace with rates of $\tau_1^{-1} = 0.035 \text{ s}^{-1}$ and $\tau_2^{-1} = 0.0014 \text{ s}^{-1}$. This was followed by applying 100 mV for ~ 5 minutes. A single-exponential function was fitted to the trace with rate of 0.016 s^{-1} . Buffer: 1 M LiCl, 10 mM Tris, pH 7.5.

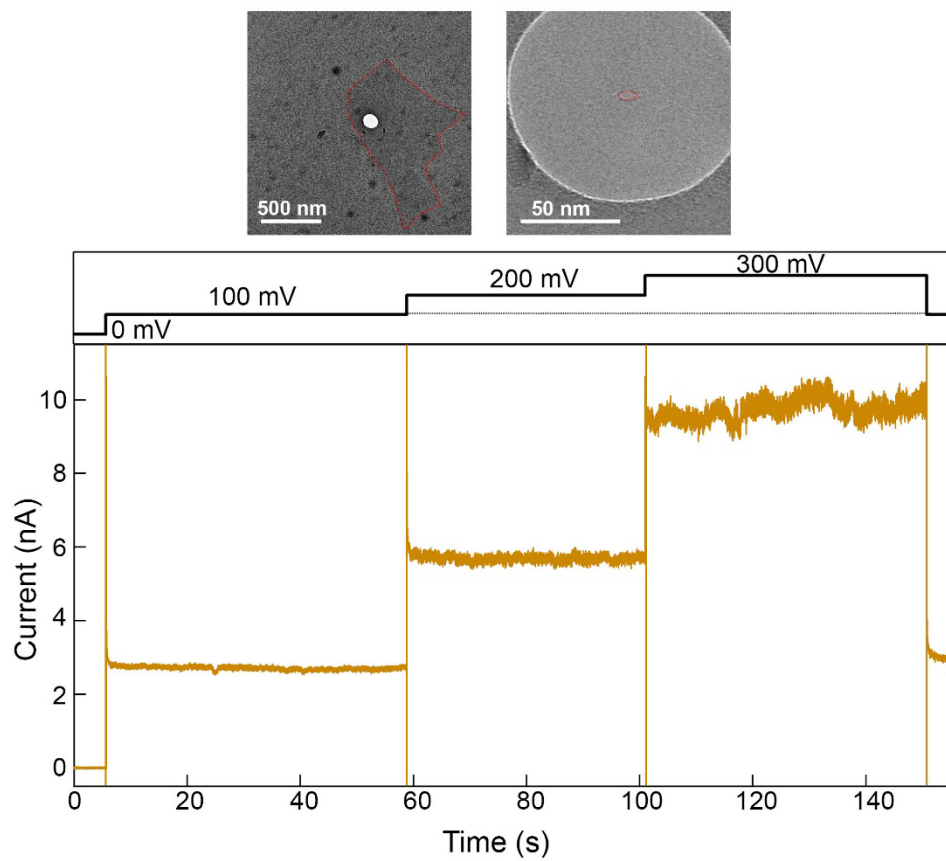


Figure S8. Current trace of nanopore K fabricated through monolayer MXene membrane showing no actuation behavior. TEM images of the monolayer MXene membrane and the fabricated nanopore are shown. Based on the contrast in the images, this pore might be a monolayer MXene pore.

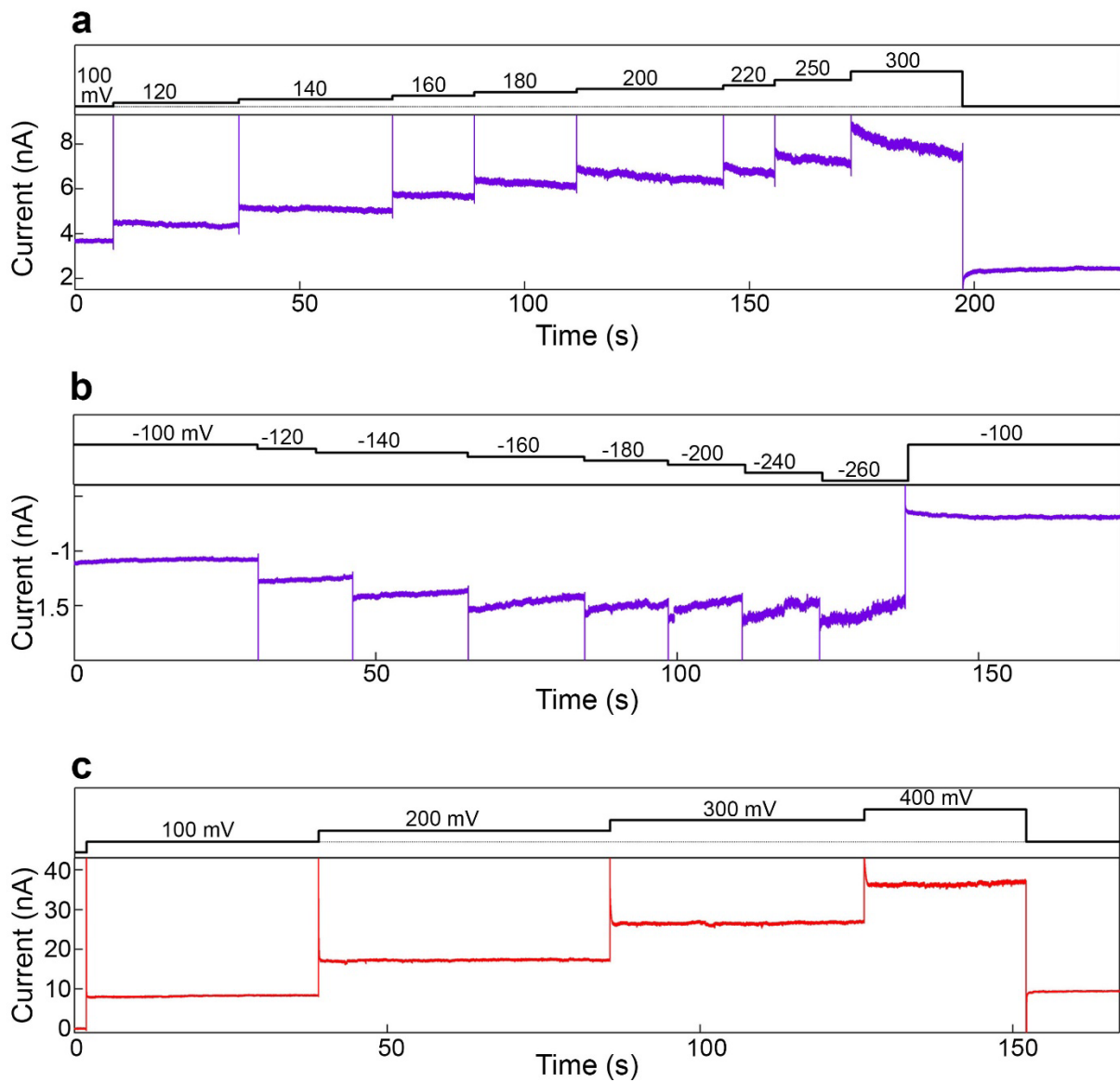


Figure S9. Current traces of Ti_2CT_x MXene nanopores. (a-b) Current traces of nanopores L and M showing voltage-gated actuation behavior. Buffer: 0.4 M KCl, 20 mM, Tris pH 7.5 (c) Current trace of nanopore N showing no actuation behavior at high voltages. Buffer: 2 M LiCl, 20 mM Tris, pH 7.5.

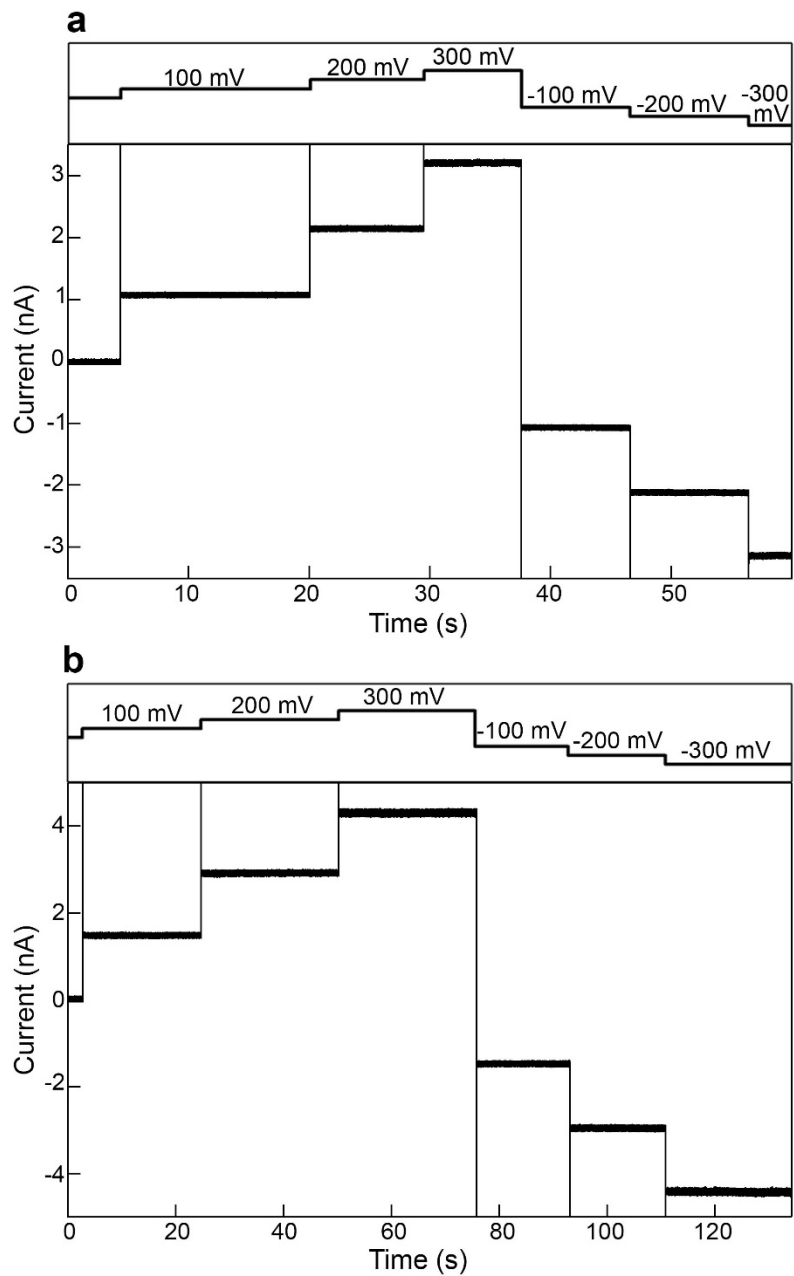


Figure S10. Current traces of SiN_x nanopores showing no voltage-gated actuation behavior. (a) nanopore Q and (b) nanopore P were fabricated through ~ 30 nm SiN_x free-standing membrane. Buffer: 0.4 M NaCl, 20 mM Tris, pH 7.5.