Supplementary Information for

Bioinspired nervous signal transmission system based on 2D laminar nanofluidic system: from electronics to ionics

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This PDF file includes:

  Supplementary information text
  Figures S1 to S10
  SI References
Supplementary Information Text

Materials and method

Preparation of the MXene membrane. Firstly, the initial multilayer MXene dispersion was synthesized from a solution of chemical treated MAX phase TiAlC$_2$ powders (SI Appendix, Figure S9), which uses a mixture of LiF/HCl as etching agents to selectively removed the Al component in raw materials. Secondly, a sonication procedure was conducted for continuous physical exfoliation. Then, a colloid solution of (~ 1mg/mL) few-layer MXene nanosheets can be obtained (SI Appendix, Figure S9). A classical vacuum filtration process would transform them into MXene nanofluidic membrane on a commercial polycarbonate membrane (PC, an average pore diameter of 200nm).

Preparation of the AC Ionic Nanofluidic Devices. Without detaching from the porous polycarbonate membrane, the MXene nanofluidic membrane was sealed in PDMS with a 6000 rpm spin-coating for 60 seconds and heated at 80°C for 90 minutes. A parallel experiment has been conducted in order to prove the independence of PC in our nanofluidic devices (SI Appendix, Figure S10). The PDMS sealed MXene membrane would be cut into rectangle strips of ~ 30mm × 6mm. Then the PDMS covered MXene nanofluidic was furtherly sealed in our PMMA containers (as shown in Fig. 1) with highly p-doped silicon chips placed on their corresponding positions. A pair of Ag/AgCl electrodes were chosen to record the ionic current with 0.1 M KCl solution under room temperature.

The Generation and Measurement of Alternating Ionic Signal. Alternating electronic signals were generated by a commercial Arbitrary Function Generator (Tektronix AFG1062) and its corresponding software (ArbExpress). A commercial dual-channel Source/Measure Unit (Keithley 2636B) was chosen to record the waveform of the external electrostatic potential on silicon chips and capture the ionic signal in the 2D laminar nanofluidic device. The time sequence between generated and measured signal was furtherly guaranteed by the synchronistic sampling of this dual-channel SMU.

Characterization. The XRD pattern was recorded in a 2θ range of 4-70° at room temperature on a D8 Focus Powder XRD (Bruker, Germany) with a Cu Kα radiation source (40kV, 40mA). For the Raman Spectroscopy measurement of MXene surface, we used inVia Reflex (Renishaw, UK) under the radiation of a 532 nm laser. FT-IR spectra of MXene powder was recorded with Excalibur 3100 (Varian, USA). SEM images were taken on S-4800 (HITACHI, Japan) at an accelerating voltage of 10 kV. X-ray photoelectron spectroscopy of MXene is recorded by ESCALAB 250Xi (ThermoFisher Scientific, USA). AFM image is captured by MultiMode 8 (Bruker, Germany), TEM image, and selected-area electron diffraction pattern is captured by JEM-2100F (JEOL, Japan).
Fig. S1. Electronic Circuitry Diagram of Source/Measure Unit (Red), Arbitrarily Function Generator (blue), and ionic nanofluidic device (green). In this diagram, the alternating nanofluidic device is represented with a symbol of inductance.
Fig. S2. Verification of the smoothing method (adjacent average). Both the initial (black) and smoothed (red) waveform of ionic signal feedback has been obtained under a 6V sine external electrostatic potential pulse. The local maxima of individual curves have been marked with the corresponding color. The expression of the adjacent average method was also obtained. $N$ is the length of the averaging window, $x_n$ is initial values and $\bar{x}_n$ is averaged values.
Fig. S3-1. The value of peaks and valleys at ±10 volts have been gathered with a statistic data-processing. The frequency of peak values has been fitted with a gaussian distribution with a reasonable determinant coefficient of 0.96. Additional necessary parameters of Gaussian function are presented in small squares with corresponding colors.
Fig. S3-2. The value of peaks and valleys at ±8 volts have been gathered with a statistic data-processing. The frequency of peak values has been fitted with a gaussian distribution with a reasonable determinant coefficient of 0.94. Additional necessary parameters of Gaussian function are presented in small squares with corresponding colors.

\[ y = y_0 + \frac{2}{\sqrt{\pi}} \cdot A \cdot e^{-2(x-x_0)^2} \]

\[ N=121, R^2=0.94 \]

- \[ x_{\text{negative}} = -2.89192 \times 10^{-6} \]
- \[ y_{\text{negative}} = -0.03391 \]
- \[ \sigma = 2.4548 \times 10^{-7} \]
- \[ A = 5.16704 \times 10^{-6} \]

- \[ x_{\text{positive}} = 2.95181 \times 10^{-6} \]
- \[ y_{\text{positive}} = -0.03391 \]
- \[ \sigma = 2.67233 \times 10^{-7} \]
- \[ A = 5.34322 \times 10^{-6} \]
**Fig. S3-3.** The value of peaks and valleys at ±6 volts have been gathered with a statistic data-processing. The frequency of peak values has been fitted with a gaussian distribution with a reasonable determinant coefficient of 0.99. Additional necessary parameters of Gaussian function are presented in small squares with corresponding colors.

\[ y = y_0 + \frac{2}{\sqrt{\pi}} A \cdot e^{-2(x-x_0)^2} \]

\[ N=61, R^2=0.99 \]

- \[ x_{\text{negative}} = -1.11221\times 10^{-6} \]
- \[ y_{\text{negative}} = 0.07545 \]
- \[ \omega = 8.76362\times 10^{-8} \]
- \[ A = 5.40203\times 10^{-6} \]

- \[ x_{\text{positive}} = 1.14987\times 10^{-6} \]
- \[ y_{\text{positive}} = 0.07545 \]
- \[ \omega = 1.20099\times 10^{-7} \]
- \[ A = 5.40466\times 10^{-6} \]
Fig. 3-4. The value of peaks and valleys at ±4 volts have been gathered with a statistic data-processing. The frequency of peak values has been fitted with a gaussian distribution with a reasonable determinant coefficient of 0.84. Additional necessary parameters of Gaussian function are presented in small squares with corresponding colors.
Fig. S3-5. The value of peaks and valleys at ±2 volts have been gathered with a statistic data-processing. The frequency of peak values has been fitted with a gaussian distribution with a reasonable determinant coefficient of 0.89. Additional necessary parameters of Gaussian function are presented in small squares with corresponding colors.
Fig. S4. The environmental tolerance of the alternating nanofluidic device was estimated with zeta-potential and parallel experiments under different pH conditions. Zeta potential of nanoparticles is measured by gold electrodes with a 0.2 mg/mL aqueous dispersed solution. The testing range of the pH value is from 3 to 11. The verification experiment of alternating ionic transport has been conducted at the pH condition of 3 (yellow), 7 (green) and 11 (purple).
**Fig. S5.** FT-IR Spectra of fresh MXene nanosheets powder with potassium bromide pellet technique.
**Fig. S6.** Surface Raman spectrum of MXene membrane with a 532nm excitation laser.
Fig. S7. X-ray photoelectron spectroscopy (XPS) scans (1-3). (A) X-ray photoelectron spectroscopy (XPS) scans of Ti$_3$AlC$_2$ and Ti$_3$C$_2$Tx. (B) High-resolution XPS spectra of F 1s. F 1s region is composed of F-C (689.9 eV) and F-Ti (684.9 eV). (C) High-resolution XPS spectra of Ti 2p. Ti 2p region is composed of Ti-C (454.9 eV), Ti (II) suboxide and/or hydroxide (455.7 eV), Ti (III) suboxide and/or hydroxide (456.7 eV) and TiO$_2$ (458.8 eV). (D) High-resolution XPS spectra of C 1s. C 1s region is composed of C-Ti (281.8 eV), C-C (284.5 eV), C-O (285.2 eV) and COOR (289.1 eV). (E) High-resolution XPS spectra of O 1s. O 1s region is composed of O-Ti (529.7 eV), O-TiOH (531.2 eV), O-C/OH (531.9 eV) and H$_2$O (532.6 eV).
Fig. S8. Amplitude modulated ionic signal transmission. A 1 Hz sine voltage function (blue) is used as the baseband signal. A 20Hz sine voltage function (red) is used as the carrier signal. The ionic current feedback (purple) triggered by the modulated electric stimulus is also presented.
Fig. S9. Morphological characteristics of MXene and its related substances during the preparation procedure. (A) SEM image of MXene on a porous anodized aluminum substrate. (B) AFM image of a single and double layer MXene showing thickness of ~1.5nm and ~3nm. (C) SEM image of accordion-like MXene powder. (D) SEM image of Ti$_3$AlC$_2$ MAX phase powder. (E) TEM image of MXene at high magnification. (F) Selected-area electron diffraction pattern indicates the high crystallinity of MXene nanosheet.
Fig. S10. A parallel experiment with only a PC porous membrane is sealed in the PMMA container with the identical signal input and acquisition system. (A) The input alternating electrostatic potential is a sine function with an amplitude of 10 volts. (B) The captured ionic current in the parallel experimental device that shows an extremely limited contribution compared with 2D MXene nanofluidic devices.
SI References

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