

# Depositing Pt nanoparticles on crumpled $\text{Ti}_3\text{C}_2\text{T}_x$ for enhanced electrochemical sensing

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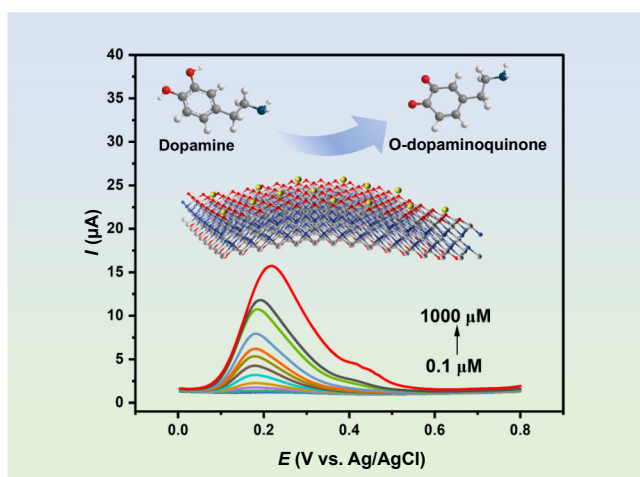
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**ABSTRACT:** Dopamine plays a crucial role in regulating various brain functions, making the development of highly sensitive detection methods and precise quantitative analysis techniques of great significance. However, realizing highly selective and sensitive detection of dopamine in complex biological environments remains a challenge. Here, we prepared three-dimensional (3D) crumpled  $\text{Ti}_3\text{C}_2\text{T}_x$  structures loaded with Pt nanoparticles ( $\text{Pt}/\text{Na-Ti}_3\text{C}_2\text{T}_x$ ) by wet chemical reduction and ion intercalation. The synergistic coupling between Pt nanoparticles and MXene support facilitates efficient electron transfer between dopamine and the electrode surface, thereby improving the sensing performance of dopamine. Furthermore, this wrinkled structure not only enhances the specific surface area by inhibiting the stacking of layered  $\text{Ti}_3\text{C}_2\text{T}_x$  nanosheets, but also effectively prevents the agglomeration of nanoparticles. The experimental results showed that  $\text{Pt}/\text{Na-Ti}_3\text{C}_2\text{T}_x$  possessed a wide linear range (0.1–100  $\mu\text{M}$ ), a low detection limit (0.029  $\mu\text{M}$ ), and a high sensitivity (0.556  $\mu\text{A} \cdot \mu\text{M}^{-1} \cdot \text{cm}^{-2}$ ). This work proposes an innovative strategy for achieving highly sensitive dopamine detection while advancing the utilization of MXene-based nanocomposites in electrochemical sensor development.

**KEYWORDS:** MXenes, dopamine sensors, nanoparticles, crumpled structure



## 1 Introduction

Dopamine (DA) has a variety of key roles in the brain as an important neurotransmitter in the central nervous system and other parts of the body<sup>1–3</sup>. In addition, abnormal dopamine levels and functions are closely associated with a variety of neurological and psychiatric disorders, such as Parkinson's disease, Alzheimer's disease, and schizophrenia<sup>4–6</sup>. Therefore, realizing the accurate detection of dopamine is crucial for the effective diagnosis, prevention, and therapeutic management of these disorders. Currently, the main techniques used for the detection of dopamine

include colorimetric assay<sup>7</sup>, chromatography<sup>8</sup>, chemiluminescence<sup>9</sup>, etc., which often require complex and expensive equipment or long detection time. In contrast, electrochemical sensing analysis has been widely used in the field of dopamine detection due to its advantages of low detection cost and simple operation. Current conventional sensing materials used for the detection of dopamine mainly include metal and metal oxide nanomaterials, carbon nanotubes, graphene, and reduced graphene oxide<sup>10–12</sup>. However, the conventional dopamine electrochemical sensor still suffers from a narrow detection range, low sensitivity and detection limit, and poor selectivity, which is not able to satisfy the needs for detection in extreme environments<sup>13</sup>. Therefore, there is an urgent need to develop a dopamine sensing material with high performance and specific selectivity.

In recent years, two-dimensional (2D) transition metal carbides/nitrides (MXenes) have demonstrated remarkable advantages in electrochemical sensing applications due to their unique physicochemical properties, including outstanding

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electrochemical activity, exceptional electrical conductivity, and abundant surface functional groups<sup>14–16</sup>. Compared with conventional two-dimensional materials, MXene has demonstrated remarkable advantages in electrochemical sensing applications due to its exceptional electrical conductivity and abundant catalytically active sites. Notably, the superior biocompatibility of MXene makes it an ideal material for constructing high-performance biosensing platforms, a characteristic that has been validated in the detection of various biomarkers<sup>17, 18</sup>. Traditionally, achieving direct electron transfer (DET) of enzymes and proteins has posed significant challenges because their redox-active centers are deeply embedded within the molecular structures<sup>19</sup>. MXene effectively immobilizes proteins and enzymes on its surface, making it a great substrate for DET that results in lower detection limits as well as increased sensitivity and selectivity. However, the strong van der Waals forces between neighboring MXene nanosheets and the hydrogen-bonding networks created by surface functional groups cause spontaneous self-stacking. This process not only reduces specific surface area but also drastically decreases interlayer spacing, eventually compromising both structural stability and charge transport capabilities<sup>20, 21</sup>.

In order to be able to fully utilize the electrochemical potential of MXene, several methods have been investigated to prevent and mitigate the nanosheet stacking problem<sup>22–24</sup>. The most commonly used method is to introduce intercalators to increase the interlayer distance of nanosheets and reduce the tendency of stacking, which in turn increases their effective surface area and improves their performance<sup>25</sup>. Extensive research has been conducted on diverse nanomaterial spacers, including but not limited to metal oxides, carbon-based materials, and one-dimensional nanostructures. However, the introduction of these nanomaterial spacers inevitably leads to intricate fabrication processes and diminished conductive properties, posing substantial obstacles for real implementation. Notably, constructing crumpled structures or assembling two-dimensional nanosheets into three-dimensional (3D) macroscopic structures is another effective way to prevent MXene nanosheets from re-stacking and aggregation, which leads to increased conductivity and improved electrochemical properties<sup>26, 27</sup>. Owing to the rich variety of surface terminations (e.g., –O, –F, and –OH) introduced during selective etching, MXenes exhibit remarkable colloidal stability in aqueous media<sup>26</sup>. This characteristic facilitates their assembly into three-dimensional frameworks using various solution-phase strategies, including self-assembly and template-directed approaches. Compared to conventional 2D layered structures, 3D interconnected MXene networks demonstrate dual advantages: They not only significantly enhance surface utilization efficiency and expose more electrochemically active sites, but also fully retain the intrinsic properties of 2D MXene nanosheets, including high electrical conductivity and rich surface reactivity.

On the other hand, to further enhance the catalytic activity of MXene toward DA molecules, various metallic nanomaterials such as palladium (Pd), platinum (Pt), and gold (Au) have been employed for its modification<sup>28</sup>. Among these, platinum nanomaterials have emerged as particularly promising candidates for developing advanced electrochemical sensors, owing to their exceptional combination of physicochemical properties. The interaction between Pt nanoparticles and the MXene support can change the electrical structure of active sites, boosting electron transport and increasing the composite material's electrocatalytic activity<sup>29, 30</sup>. However, the practical application of Pt in

electrochemical sensing is limited by its high cost and limited natural abundance<sup>31</sup>. One viable strategy to address this issue involves reducing the size of Pt nanoparticles through optimized synthesis methods, which increases the proportion of surface atoms and consequently improves the utilization efficiency of Pt. Therefore, in this study, we selected Pt nanoparticles composited with MXene to achieve highly efficient detection of DA molecules.

In this work, we designed composites of Pt nanoparticles with Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> for DA detection. And the Pt nanoparticles were uniformly anchored on the Na<sup>+</sup>-pre-inserted 3D crumpled Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> (Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>) structure. The more stable and active specific surface area of the Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> structure not only provides more reaction sites and improves the electrochemical performance, but also prevents the agglomeration of Pt nanoparticles during the reaction process and improves the structural stability. The Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>-modified glassy carbon electrode (GCE) was employed for highly sensitive dopamine detection, with cyclic voltammetry (CV) and differential pulse voltammetry (DPV) serving as the primary characterization techniques. The sensor demonstrated high selectivity for dopamine against interferents, as well as excellent long-term stability and reproducibility.

## 2 Results and discussion

The fabrication procedure of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> hybrid material is shown in Fig. 1a. The 2D few-layer Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> was formed by selectively etching off the Al layer with HF generated by LiF/HCl mixing and then stripping it by ultrasonication<sup>32</sup>. After the rapid addition of sodium borohydride, Na<sup>+</sup> would interact strongly with the –OH functional group on the surface and would spontaneously get embedded between the Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> layers due to the electrostatic interactions, causing the reassembly of the Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> nanosheet structure to form 3D crumpled Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> (Supplementary Fig. S1)<sup>33, 34</sup>. In addition, ion exchange was performed during the intercalation process, replacing Li<sup>+</sup> with Na<sup>+</sup> of larger hydration radius, and the layer spacing of the Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> nanosheets was also increased<sup>35–37</sup>. Finally, H<sub>2</sub>PtCl<sub>6</sub> solution was added to the solution to nucleate on the Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> structure by electrostatic adsorption. This was further reduced by calcination in an Ar atmosphere to form uniformly loaded Pt nanoparticles (denoted as Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> structure), thus providing effective active sites for the catalytic reaction.

As shown in Figs. 1b–1d and Supplementary Fig. S3, the images of scanning electron microscopy (SEM) and transmission electron microscopy (TEM) showed that the MXene nanosheets appeared curved and wrinkled, indicating the formation of a 3D crumpled skeleton of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>, while highly dispersed Pt nanoparticles were uniformly loaded on the 3D crumpled Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>. In addition, Pt precursor with uniform particle size and uniform distribution can be clearly observed in the high-resolution TEM (HRTEM) images (Fig. 1e), and their lattice spacing was measured to be 0.221 nm, which corresponds to the (111) crystal plane of Pt. In addition, the homologous element mapping image of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> (Fig. 1g) also confirms the uniform distribution of Pt nanoparticles on MXene. However, the SEM images (Supplementary Fig. S2) revealed that the Pt/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> composites, which were not treated with Na<sup>+</sup> ion intercalation at the same ratio of chloroplatinic acid, exhibited distinct stacking and agglomeration. This is a significant factor that contributes to the degradation of their electrochemical properties. The Pt contents in Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> and Pt-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> were calculated from inductively coupled plasma atomic emission

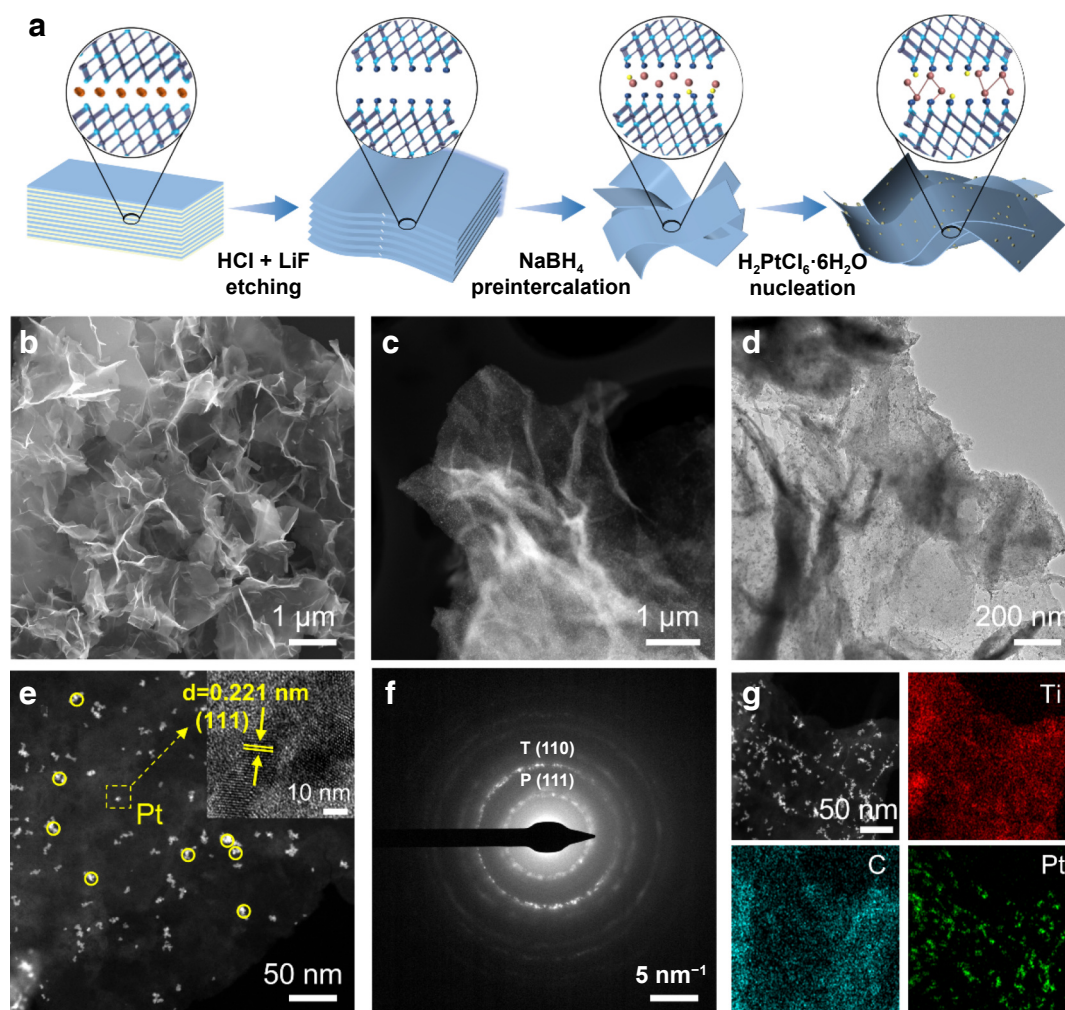


**Fig. 1.** Schematic representation diagram and microstructure characterization of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>. **a**, Fabrication process of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> composites. **b**, SEM image. **c–e**, TEM (**c**, **d**) and HRTEM (**e**) images. **f**, SAED patterns of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> nanocomposite. T and P denote Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> and Pt, respectively. **g**, High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) micrograph and corresponding elemental distribution profiles.

spectrometry (ICP-AES) results to be 3.9% and 1.6%, respectively. The selected area electron diffraction (SAED) pattern (Fig. 1f) clearly shows the polycrystalline structure of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> composites, and the diffraction rings represent the (100) and (110) faces of Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> and (111), (220), (420), and (422) faces of Pt, respectively.

The Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> and its composites were characterized by X-ray diffraction (XRD). As shown in Fig. 2a, the displacement of the (002) peak to a lower angle and the elimination of the strongest diffraction peak at 39° (2θ) indicate that the Al layer was removed and the Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> crystal structure has been formed<sup>30, 38, 39</sup>. Following Na<sup>+</sup> pretreatment, the (002) diffraction peak shifted from 2θ = 6.5° to 5.4° with concomitant peak broadening, indicating an expansion of interlayer spacing and reduced crystallinity. By using Bragg's law (Eq. (1)), we calculated that the corresponding interlayer spacing increased from 1.34 to 1.65 nm, indicating significant expansion between the nanosheet layers due to the insertion of Na<sup>+</sup>.

$$n\lambda = 2d\sin\theta \quad (1)$$

X-ray photoelectron spectroscopy (XPS) allows an in-depth analysis of the elemental composition and structure of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>, and the spectra were charge-corrected to adjust and

harmonize the peak positions by using the C 1s peak at 284.6 eV as a reference. The Ti 2p of the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> composite, shown in Fig. 2b, displays several double peaks with peaks at 454.9, 456.7, and 458.9 eV, which correspond to Ti–C, Ti(II), and Ti–O bonds, respectively. In the deconvoluted C 1s spectrum of Fig. 2c, the peaks located at 281.6, 284.8, 286.5, and 288.8 eV are attributed to Ti–C, C–C, C–O, and C=O bonds, respectively. The O 1s peaks at 530.1, 531.7, and 532.8 eV correspond to Ti–O, Ti–O–Pt, and Ti–OH bonds, respectively, indicating the successful formation of oxygen vacancies and abundant hydroxyl (–OH) groups on the MXene nanosheet surface (Supplementary Fig. S4). Additionally, Pt nanoparticles were uniformly deposited on the MXene substrate. As shown in the Fig. 2d, the Pt 4f spectrum of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> had two peaks located at 71.2 and 74.5 eV. The shift of the peaks of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> towards the high binding energy region suggests that the Pt has been effectively attached to Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>.

To verify the electrochemical behavior of the composites, CV was employed to characterize the redox response of 1 mM DA at various functionalized electrodes. Fig. 3a presents the CV curves of the modified electrodes employing different sensing materials recorded at a scan rate of 0.1 mV·s<sup>–1</sup> within the potential window of –0.2 to 0.8 V. Among them, the bare GCE showed a weak CV

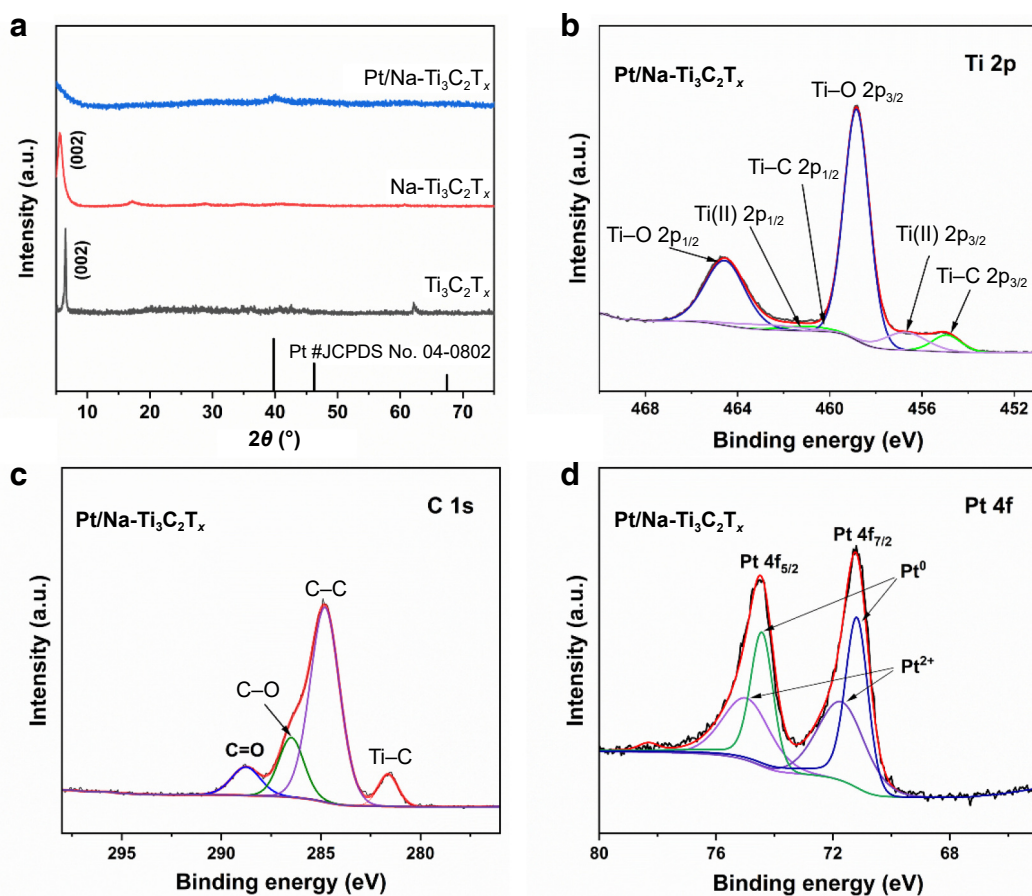


**Fig. 2.** Structure characterization. **a**, XRD pattern of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>, Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>, and Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>. **b–d**, High-resolution XPS spectra of Ti 2p (**b**), C 1s (**c**), and Pt 4f (**d**) for Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> hybrid.

response, while after modification with Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> and Pt-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>, both showed a better CV response. Importantly, the peak current of the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> modified electrode was significantly higher compared to the unmodified GCE. The enhanced peak current can be attributed to the three-dimensional crumpled architecture of the material, which exposes a higher density of catalytically active sites for DA adsorption. The interfacial charge transfer properties of various functionalized electrodes were systematically investigated through electrochemical impedance spectroscopy (EIS) analysis. Fig. 3b presents the Nyquist plots of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE, Pt-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE, and Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE, with the equivalent circuit models in the inset. The Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE electrode displays a larger semicircle diameter, while the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE electrode shows the smallest diameter. This result demonstrates that the 3D crumpled structure significantly enhances the electrochemical properties and charge transfer rate of the sensing materials. Through impedance fitting analysis, the  $R_{ct}$  of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE (87.5 Ω), Pt-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE (102.4 Ω), and Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE (163.9 Ω) can be estimated. The results show that Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE exhibits excellent electron transfer capability.

Fig. 3c presents the CV curves of the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE electrode for 200 μM DA at different scan rates (10–100 mV·s<sup>-1</sup>), where a marked enhancement in anodic peak current ( $I_{pa}$ ) was observed with increasing scan rate. Meanwhile, the oxidation peak potential shifted gradually in the positive direction, possibly due to changes in the reaction kinetics<sup>40</sup>. In addition, the  $I_{pa}$  value showed a linear relationship with the square root of the oxidation rate, with

a linear correlation value of 0.9896, indicating that this is a diffusion-controlled process<sup>41,42</sup>.

The response of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE to different concentrations of DA was evaluated using DPV under optimal experimental conditions. The results revealed (Fig. 3d) that the peak current showed a good linear relationship with the concentration in the range of 0.1–1000 μM assay, and the peak current increased with the increase of DA concentration. Based on the DPV test results, the calibration graph was plotted in the inset with the linear correlation equation

$$I_{pa} (\mu A) = 0.055C_{DA} (\mu M) + 1.161$$

$$(R^2 = 0.995, 0.1 \mu M \leq C \leq 100 \mu M) \quad (2)$$

$$I_{pa} (\mu A) = 0.012C_{DA} (\mu M) + 4.048$$

$$(R^2 = 0.991, 100 \mu M \leq C \leq 1000 \mu M) \quad (3)$$

The data indicate that the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE sensor has excellent detection of DA with a linear detection range of 0.1–1000 μM. In addition, the sensitivity of the sensor can be estimated to be 0.556 and 0.328 μA·μM<sup>-1</sup>·cm<sup>-2</sup> for 0.1–100 and 100–1000 μM, respectively, with a detection limit of ~0.029 μM. The sensitivity was determined by the equation: sensitivity =  $S/A_{eff}$ , where  $A_{eff}$  represents the electroactive surface area of the modified electrode (0.0512 cm<sup>2</sup>), derived from the data in Supplementary Fig. S5, and the limit of detection (LOD) was determined by the equation: LOD = 3.3( $S_b/S$ )<sup>43</sup>, where  $S_b$  is the relative standard deviation (RSD)

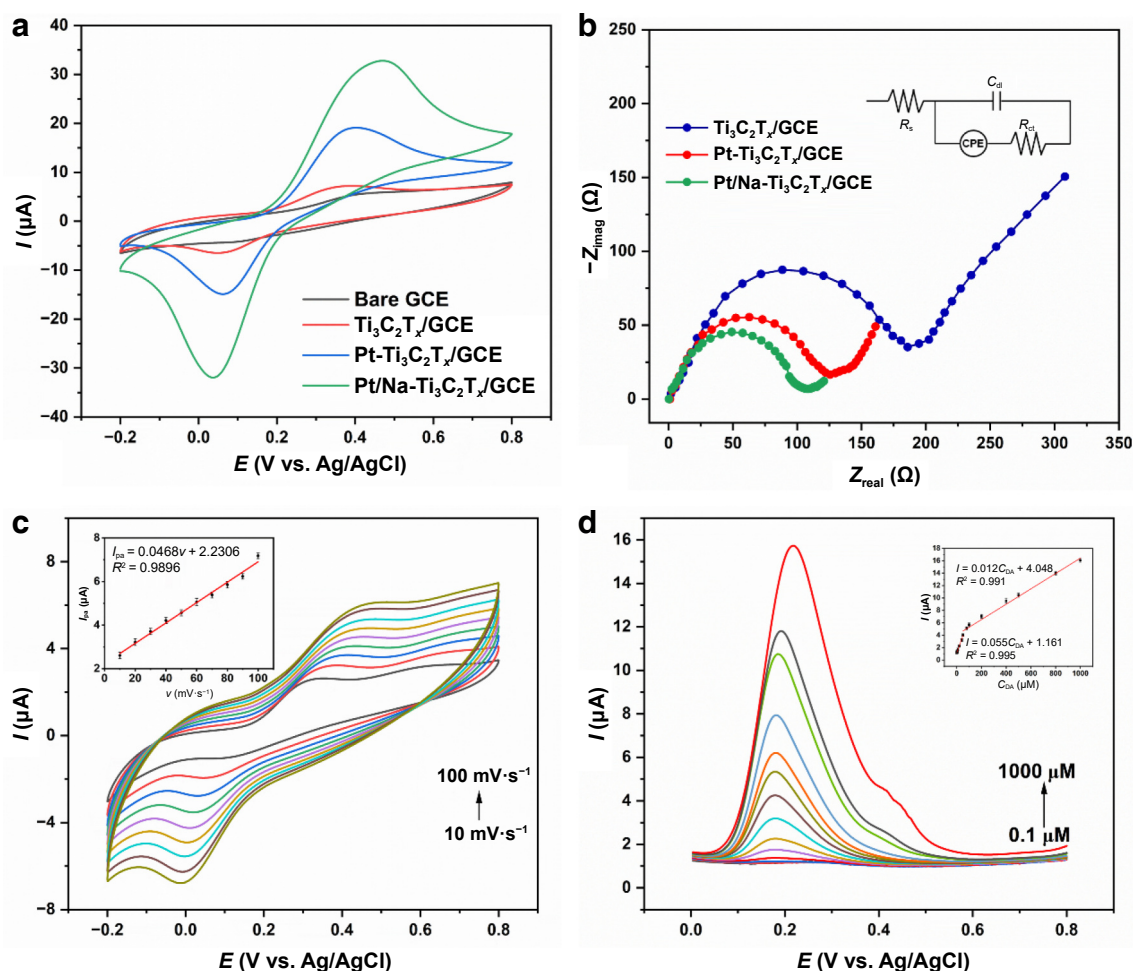


**Fig. 3. Electrochemical performance.** a, CV measurements were performed in 0.1 M PBS (pH 6.5) containing 1 mM DA at a scan rate of 0.1 V·s<sup>-1</sup>, comparing the electrochemical responses of bare GCE, Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE, Pt-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE, and Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE. b, The EIS Nyquist plots obtained from the modified electrodes. Supporting electrolyte: 0.1 M KCl containing 5 mM [Fe(CN)<sub>6</sub>]<sup>3-/4-</sup>. Frequency range: 0.1 Hz to 100 KHz. c, CVs of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE at various scan rates (10–100 mV·s<sup>-1</sup>) in 0.1 M PBS (pH 6.5) containing 200 μM DA and the  $I_{pa}$  vs.  $v$ . d, DPV-based quantitative detection of DA at Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE with linear concentration-response correlation.

of the response to the blank after seven passes, and  $S$  is the slope of the calibration curve described above.

In order to explore the effect of pH on the electrochemical response of DA, the CV response at several different pH values was tested and the peak current was recorded (Fig. 4a). According to Fig. 4b, the  $I_{pa}$  value first increased and then decreased, and the peak value appeared at pH = 6.5, therefore, pH = 6.5 was chosen for the subsequent experiments. In addition, the oxidation peak potential ( $E_{pa}$ ) decreased in a gradient with increasing pH (Fig. 4c), and the linear relationship between the two was expressed using the regression equation shown below

$$E_{pa} \text{ (V)} = 0.8447 - 0.0652\text{pH} \quad (R^2 = 0.9803) \quad (4)$$

For a given range of pH values, the slope is -65 mV per pH, close to the -59 mV per pH in the Nernst equation<sup>44</sup>. Thus, it can be concluded that DA involves an equal number of protons and electrons involved in the oxidation process<sup>43,45</sup>.

Interference studies are a critical part of sensor performance testing, and it is crucial to be able to ensure accurate detection of the target when multiple similar electroactive substances are present. To systematically assess the sensor's selectivity, under the same

experimental conditions, scans were performed to obtain DPV response curves for 200 μM DA when coexisting with equal concentrations of various interferents, including uric acid (UA), glucose (Glu), ascorbic acid (AA), epinephrine, K<sup>+</sup>, Na<sup>+</sup>, and Ca<sup>2+</sup>. As shown in Fig. 5a, these results demonstrate remarkable DA signal preservation, confirming the sensor's exceptional selectivity in complex biological matrices. Furthermore, the relative error of the peak DA current caused is within 5%, confirming the excellent performance of Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE sensor in selective DA detection (Supplementary Fig. S6). The excellent selectivity of the sensor can be attributed to the electronegative MXene preferentially adsorbing DA through electrostatic interactions, while effectively repelling negatively charged interfering substances<sup>46</sup>.

Fig. 5b shows CV testing for DA detection with five distinct Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE electrodes to assess sensor repeatability. The results show a RSD of only 2.4% in the  $I_{pa}$  responses, validating the sensor's high reproducibility. In addition, to check the repeatability of the sensor, five consecutive CV responses were recorded with the same Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE in 0.1 M phosphate buffered saline (PBS) solution in 200 μM DA, and almost identical results were obtained from the five runs, with the relative standard deviation RSD of the calculated peak currents being 0.32%, confirming its excellent

repeatability (Fig. 5c). To investigate the stability of the sensor, the prepared Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE sensor was stored at room temperature for 14 days. The peak current was measured daily by recording DPV curves against 200  $\mu$ M DA under consistent experimental conditions during this period. Fig. 5d shows the results of the stability test. After 14 days of storage at room temperature, the peak current remained at 92.4% of the initial value, and the sensor remained intact. This demonstrates the excellent stability of the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE sensor.

To verify the sensor's detection reliability in biological applications, DA levels in serum samples were quantified employing the standard addition method. According to the previous literature, the serum was diluted 10 times, then different concentrations of DA standard solution were added, and the

samples were tested three times in parallel by DPV. The DA concentration was determined using the calibration curve, and the recovery rate was calculated by comparing the measured value with the standard concentration. As shown in Table 1, the sensor demonstrated excellent recovery rates ranging from 96.4% to 102.4%, indicating that the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE electrode exhibits promising potential for practical sample detection applications.

### 3 Conclusions

In this work, we developed a high-performance electrochemical sensor for the detection of DA by loading Pt nanoparticles into 3D crumpled Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>. The larger active specific surface area exhibited by the Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> composite not only enhances the stability of

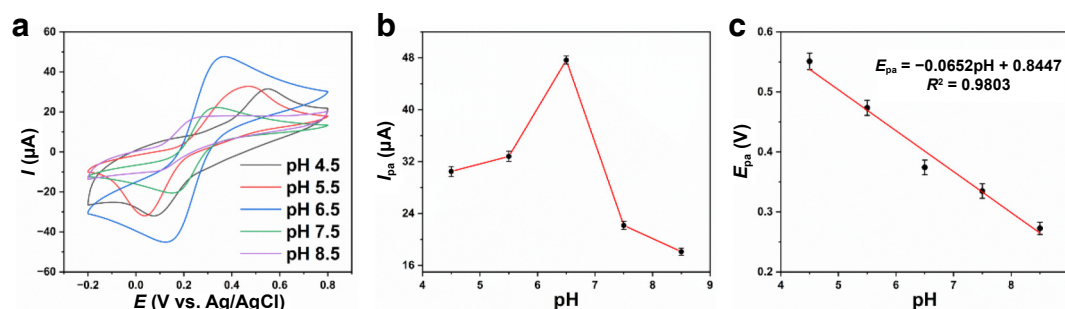


Fig. 4. a, Electrochemical behavior of 200  $\mu$ M DA at varied pH values (4.5–8.5). b, The relationship between  $I_{pa}$  and pH. c, Linear relationship between  $E_{pa}$  and pH.

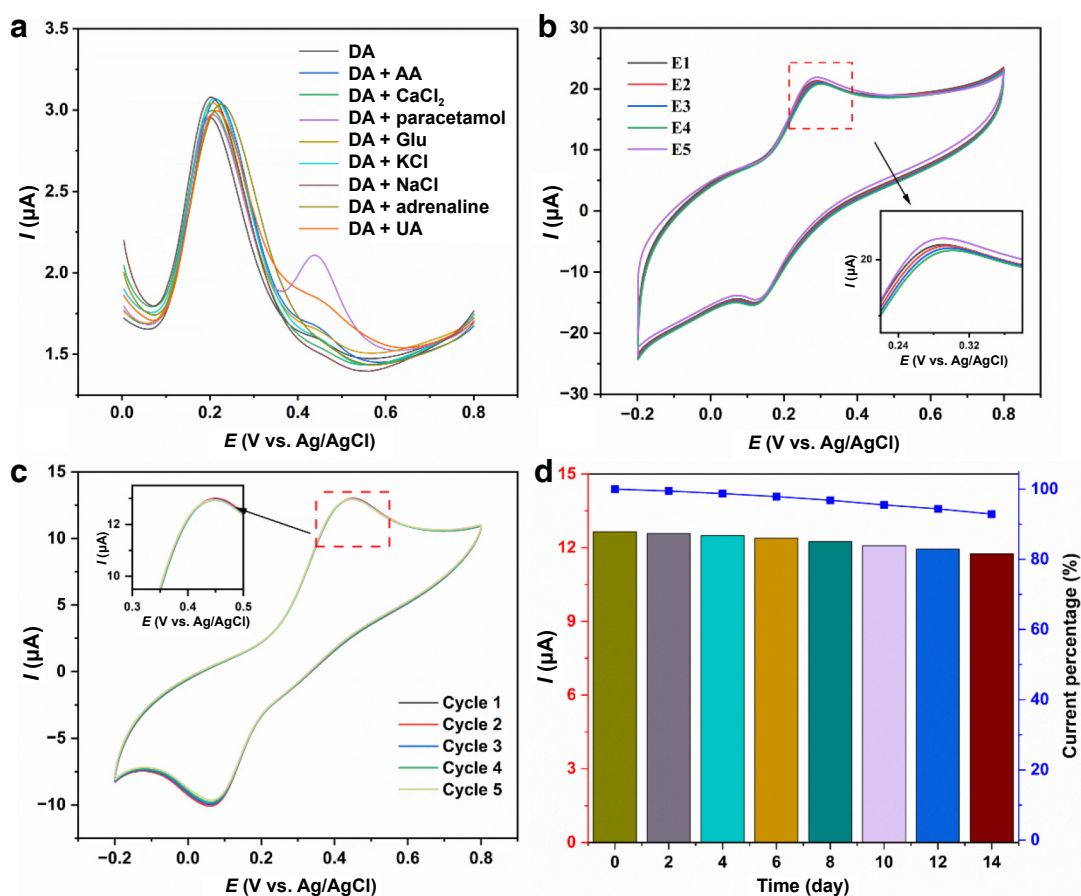


Fig. 5. a, The DPVs of different substances on Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE in 0.1 M PBS. b, Reproducibility. c, Repeatability. d, Stability investigations, oxidation peak current on the same Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE at different storage time.

Table 1 DA analysis in real serum samples using Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE

|   | Added (μM) | Founded (μM) | Recovery (%) | RSD (%) |
|---|------------|--------------|--------------|---------|
| 1 | 0          | 0            | —            | —       |
| 2 | 20         | 19.27        | 96.4         | 2.17    |
| 3 | 40         | 41.43        | 103.6        | 2.86    |
| 4 | 80         | 78.54        | 98.2         | 2.31    |
| 5 | 100        | 102.35       | 102.4        | 2.45    |

the structure effectively mitigating the agglomeration of the nanoparticles, but also further enhances the rate of electron transfer, and greatly enhances the electrochemical performance of the sensor. The sensor demonstrated excellent sensitivity and superior performance in dopamine detection. The Pt/Na-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/GCE effectively distinguished DA from other biomolecules and interfering substances. Overall, this work presents a new strategy for dopamine detection, with the developed nanocomposites show great promise for electrocatalytic and sensor-related applications.

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## Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Supplementary Information. Additional data related to this paper may be requested from the corresponding author upon request.

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## Author contributions

H. Q. C. and B. W. Z. conceived the project. H. Q. C., T. S. C., and S. D. G. conducted the experiments. R. Y. and S. D. G. contributed to the STEM characterization. H. Q. C., T. S. C., and B. W. Z. wrote the manuscript. B. W. Z. and F. Z. X. supervised this project. All authors discussed and commented on the manuscript.

## Competing interests

The authors have no competing interests to declare that are relevant to this article.

## Use of AI statement

None.

## Additional information

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