

Sub-picomolar dopamine sensing in aqueous electrolyte with surface-engineered MXene-gated organic transistors

Received: 16 February 2026

Accepted: 22 April 2026

Cite this article as: Genitoni, M., Baragau, I.-A., Sensi, M. *et al.* Sub-picomolar dopamine sensing in aqueous electrolyte with surface-engineered MXene-gated organic transistors. *npj 2D Mater Appl* (2026). <https://doi.org/10.1038/s41699-026-00703-3>

Matteo Genitoni, Ioan-Alexandru Baragau, Matteo Sensi, Dana Georgeta Popescu, George E. Stan, Petru Palade, Outman El Khouja, Sabina Alexandra Nicolae, Alice Lunghi, Pierpaolo Greco, Michele Bianchi & Fabio Biscarini

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

Sub-picomolar Dopamine Sensing in Aqueous Electrolyte with Surface-Engineered MXene-Gated Organic Transistors

Matteo Genitoni^{a,b}, Ioan-Alexandru Baragau^{c,*}, Matteo Sensi^d, Dana Georgeta Popescu^c, George E. Stan^c, Petru Palade^c, Outman El Khouja^c, Sabina Alexandra Nicolae^c, Alice Lunghi^e, Pierpaolo Greco^b, Michele Bianchi^{d,*}, Fabio Biscarini^{a,d}

^a Center for Translational Neurophysiology of Speech and Communication, Istituto Italiano di Tecnologia, Ferrara, 44121, Italy.

^b Department of Neuroscience and Rehabilitation, Università di Ferrara, Ferrara, 44121, Italy.

^c National Institute of Materials Physics, Măgurele, Ilfov, 077125, Romania.

^d Life Science Department, Università degli Studi di Modena e Reggio Emilia, Modena, 41125, Italy.

^e Department of Physics, Informatics and Mathematics, Università degli Studi di Modena e Reggio Emilia, Modena, 41125, Italy.

* correspondence to ioan.baragau@infim.ro and michele.bianchi@unimore.it

Abstract

Electrolyte-gated organic transistors (EGOTs) can be operated as sensors with high selectivity and an outstandingly low limit of detection. Their response to interfacial interactions occurs either by capacitive coupling between gate and channel or by faradaic reactions. In this work, we endow a high-affinity sensing response to EGOTs based on the PEDOT:PSS channel by functionalization of the gate electrode with $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes. MXene were synthesized in different conditions to tailor surface chemistry, while retaining a similar skeleton structure. The integration of MXene-based functionalization layers is shown to preserve the high transconductance in EGOT devices, while simultaneously tuning the switch-on voltage toward 0 V. This modulation enables a safe operational window in aqueous electrolytes, preventing unwanted electrochemical side reactions. We then demonstrated that EGOT with the surface-tailored MXene layers are sensitive to concentrations of the neurotransmitter dopamine down to sub-picomolar levels of detection. These unprecedented LODs indicate that modification of EGOTs gate with tailored or functionalized MXenes is a viable and versatile strategy to enhance sensitivity to relevant biomarkers.

Introduction

Biosensors transduce biological, chemical, and physical signals into measurable outputs, enabling real-time patient monitoring and biomarker-based diagnostics. This signal conversion capability makes them indispensable for personalised medicine and early disease detection¹. Among relevant biomarkers, dopamine (DA) is a critical neurotransmitter regulating reward pathways, memory, learning, attention, and motor control in the mammalian central nervous system². Extracellular DA concentrations in brain tissue range from nanomolar to sub-micromolar levels, and deviations from this narrow physiological window correlate with major pathological conditions, including depression, schizophrenia, psychosis, and Parkinson's disease (PD)³. For instance, halving the DA concentration in the caudate-putamen region correlates with the main pathogenic hallmark of PD⁴. Early interventions require analytical tools capable of detecting picomolar DA fluctuations before this critical tipping point. Current DA sensors predominantly rely on the electrochemical oxidation of DA to dopamine-o-quinone (DQ) at the electrode interface⁵. To date, state-of-the-art electrochemical detection strategies have focused on (bio)sensing platforms utilising Fast Scan Cyclic Voltammetry (FSCV) and Differential Pulse Voltammetry (DPV). While the selectivity against common physiological interferents - such as ascorbic acid (AA) and uric acid (UA) - has been significantly enhanced through surface modifications with conductive polymers⁶ and inorganic nanocomposites⁷, critical challenges persist. Specifically, electrochemical techniques often suffer from a progressive decline in electrode performance due to the degradation of the functionalized interface and significant biofouling during prolonged operation⁸. Furthermore, most existing platforms fail to achieve the picomolar-level sensitivity required for early-stage PD diagnostics and the monitoring of basal neurotransmitter fluctuations.

To overcome these limitations, organic electronics offer a promising route toward portable, cost-effective, and highly sensitive (bio)sensing platforms. Successful quantification of DA in the presence of its metabolites has been demonstrated using devices based on poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS)⁹. Unlike electrochemical sensors, the specificity of these devices arises from distinct kinetic timescales governed by non-covalent interactions between catecholamines and the active PEDOT:PSS surface, rather than direct oxidation of the analyte¹⁰. The robustness of this approach has been validated by transitioning from two- and three-terminal neuromorphic architectures designed for *in-vitro* sub-nanomolar detection¹¹ to high-performance applications for *in-vivo* DA monitoring¹². Among organic electronic devices, electrolyte-gated organic transistors (EGOTs) offer distinct advantages for biosensing: label-free detection, sub-1V operational window, and aqueous compatibility¹³. In EGOT devices, the gate bias is capacitively coupled to the organic semiconductor through the electrolyte, so that minute interfacial polarisation phenomena are

amplified and transduced into large variations in the transistor's electrical response, enabling ultra-low detection limits. Achieving high sensitivity and selectivity requires strategic/proper functionalization of the gate or channel with recognition moieties, including antibodies^{14,15}, oligonucleotide¹⁶, aptamers¹⁷, enzymes¹⁸ and conductive materials (rGO, PEDOT:PSS, CNTs)¹⁹.

EGOTs-based DA sensors can be classified according to the recognition mechanism occurring at the interface between the functional material and the target analyte. The first DA EGOT sensor, reported by Feng Yan's group²⁰, transduced the electrochemical oxidation of DA at the silicon gate electrode using a PEDOT:PSS channel, achieving tens-of-nanomolar detection. Over the years, different functionalization strategies have been explored to enhance the selectivity of DA recognition, including covalent bonds²¹, all-polymer PEDOT:PSS architectures⁹, Nafion/rGO-carbonised silk composites²², micropillars electrode arrays²³, and aptamer-functionalized gates²⁴. In the aforementioned cases, as well as with organic neuromorphic devices, sub-nanomolar level of DA detection was achieved.

Herein, we investigate the sensing performance of EGOTs toward DA by employing gate electrodes functionalized with MXenes, an emerging class of 2D transition metal carbides, nitrides, and carbonitrides²⁵. These materials are obtained through the selective etching of the 'A' element (Al, Ga, or Si) from the so-called MAX phase precursors ($M_{n+1}AX_n$). The extraction of the 'A' atoms, chemically bound to M atoms, generates unsaturated M sites which are partially saturated by different inorganic species in the reaction environment (like F^- , OH^- , O^{2-} , O_2^{2-}). This substitution introduces terminal functional groups, noted with T_x , to yield MXene, whose chemical formula is $M_{n+1}X_nT_x$. Currently, $Ti_3C_2T_x$ remains the most studied MXene due to its high electrochemically active surface area, excellent electrical conductivity, environmental stability, chemical and physical robustness, tunable surface chemistry and biocompatibility²⁶. Its surface functionality plays a crucial role in tailoring its electronic properties, thereby enabling its optimisation for a wide range of specific applications²⁷. Notably, the MXenes surface terminations act as effective anchor sites for the covalent binding of antibodies²⁸. In the context of sensing, MXenes were explored for developing electrochemical detection of dopamine (DA)²⁹ with a sub-nanomolar DA limit of detection (LOD). The rationale behind the development of MXene-EGOT sensors for DA detection relies on leveraging the rich surface chemistry of MXenes. The MXene surface features various terminal groups (e.g., -O, -F, -OH) that can engage in weak, non-covalent interactions - such as hydrogen bonding, electrostatic interactions, and π - π stacking - with the functional groups (hydroxyls and amines) and the aromatic ring of the DA molecule³⁰. Furthermore, beyond these weak interactions, the Ti atoms in the MXene framework can undergo a nucleophilic reaction with the nitrogen atom of primary amines to form strong Ti-N covalent bonds, as recently demonstrated³¹⁻³³.

However, the sub-nanomolar LOD of DA, which would be relevant to discriminate between physio- and pathological states, has not been attained yet via MXene-functionalized EGOTs. Only a few studies

involving the development of EGOT DA-sensors are available: Xu and coworkers achieved micromolar DA detection using ultrathin Ti_3C_2 FET devices³⁴, while Zhou *et al.* reached 50 nM LOD through MXene/Pt nanoparticles-functionalized gate in graphene transistors, thus positioning far above the desired sub-picomolar LOD³⁵.

Based on these premises, we present here a novel strategy to enhance EGOT's sensitivity towards DA sensing by leveraging surface-engineered $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes. To this end, three MXene samples with different surface chemistry were synthesised by thermal annealing of a common precursor phase in argon, hydrogen or ammonia gas fluxes. Even since its discovery, various methods for post-HF etching MXene surface chemistry modification have been developed³⁶. In this study, we are exploring a straightforward and effective heat treatment process to modify the surface chemistry of MXene by using diluted hydrogen as a main oxygen-related functional groups reducing agent and pure ammonia gas as a dual-action agent: reducing agent and nitrogen doping source. The MXene surface thermal annealing in pure hydrogen gas has been proven³⁷, and some studies showed the capacity of hydrogen to remove fluorine over the MXene surface³⁸. Thermal annealing of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene in pure ammonia gas flow has not been widely studied³⁹, most research focusing on annealing in other gases⁴⁰ (synthetic air, argon., nitrogen, etc), and some studies explored the N-doping through thermal decomposition of solid ammonium salts⁴¹; most of the related studies involving $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and $\text{NH}_3(\text{g})$ are focusing on ammonia sensing⁴². The effective modification of the MXenes was comprehensively investigated by Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS), X-ray Diffraction (XRD), High-Resolution X-ray Photoelectron Spectroscopy (HR-XPS), Fourier Transform Infrared (FTIR) and Raman spectroscopies. The surface-engineered MXenes were deposited on gold electrodes and characterised with cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). Finally, surface-tailored MXene-coated electrodes were integrated into EGOT devices to obtain DA sensors showing unprecedented sub-picomolar sensitivity.

Results

Synthesis and characterisation of surface-tailored multilayered MXenes

Wet chemical etching of a commercial Ti_3AlC_2 MAX phase with HF yielded the precursor phase HF-MX, which was subsequently annealed under different gas atmospheres (argon, 5% hydrogen in argon, and pure ammonia) to obtain three MXene samples, hereafter denoted as Ar-MX, H_2 -MX, and N-MX. The

formation of multilayered $\text{Ti}_3\text{C}_2\text{T}_x$ MXene was confirmed by multiple characterisation techniques, revealing substantial chemical and structural modifications of the parent MAX phase induced by the etching process. SEM-EDS analysis (**Figure 1A-C**, **Figure S1** and **Table S1**) shows the evolution from the dense MAX phase to the multilayered MXene structure, accompanied by a marked depletion of Al and an increase in C, O and F contents, whereas images of Ar-MX, H_2 -MX and N-MX samples show the typical layered morphology of MXene crystal domains, which remain largely preserved after annealing samples. No signs of thermal degradation or decomposition were observed following heat treatment at 400 °C under Ar, H_2 or NH_3 , indicating good structural stability under the selected conditions. EDS mapping further confirms a homogeneous distribution of Ti and C consistent with the $\text{Ti}_3\text{C}_2\text{T}_x$ composition, as well as a reduced oxygen content in H_2 -MX and N-MX compared to HF-MX. Effective etching of the MAX phase was additionally corroborated by XRD, Raman spectroscopy, XPS and FTIR analysis (**Figure S2-S5** and **Tables S2-S6**).

The XRD patterns of Ar-MX, H_2 -MX and N-MX (**Figure 1D**) show a strong reduction in the 002 peak intensity compared to the MAX phase, together with a slight shift toward lower angles for H_2 -MX and N-MX (**Table S2**), indicating a small increase in the interlayer spacing from 19.29 Å to 19.55 Å and 19.59 Å, respectively. The 002 peak broadening observed in all samples suggests reduced crystallite size and increased structural disorder induced by HF etching and subsequent annealing. Notably, H_2 -MX and N-MX samples, treated under reductive conditions, exhibit an additional peak at $\sim 13.9^\circ$, corresponding to an interlayer distance of ~ 6.36 Å. This value is smaller than that expected for Ti_3C_2 (~ 9.8 Å), likely associated with the formation of $\text{Ti}_3\text{C}_2\text{T}_x$ quantum dots resulting from the cleaning of oxidized or corroded surface/structure⁴³. Overall, despite these differences, Ar-MX, H_2 -MX, and N-MX display comparable microstructural features, indicating that the annealing doesn't significantly alter the core structure of the Ti_3C_2 layers.

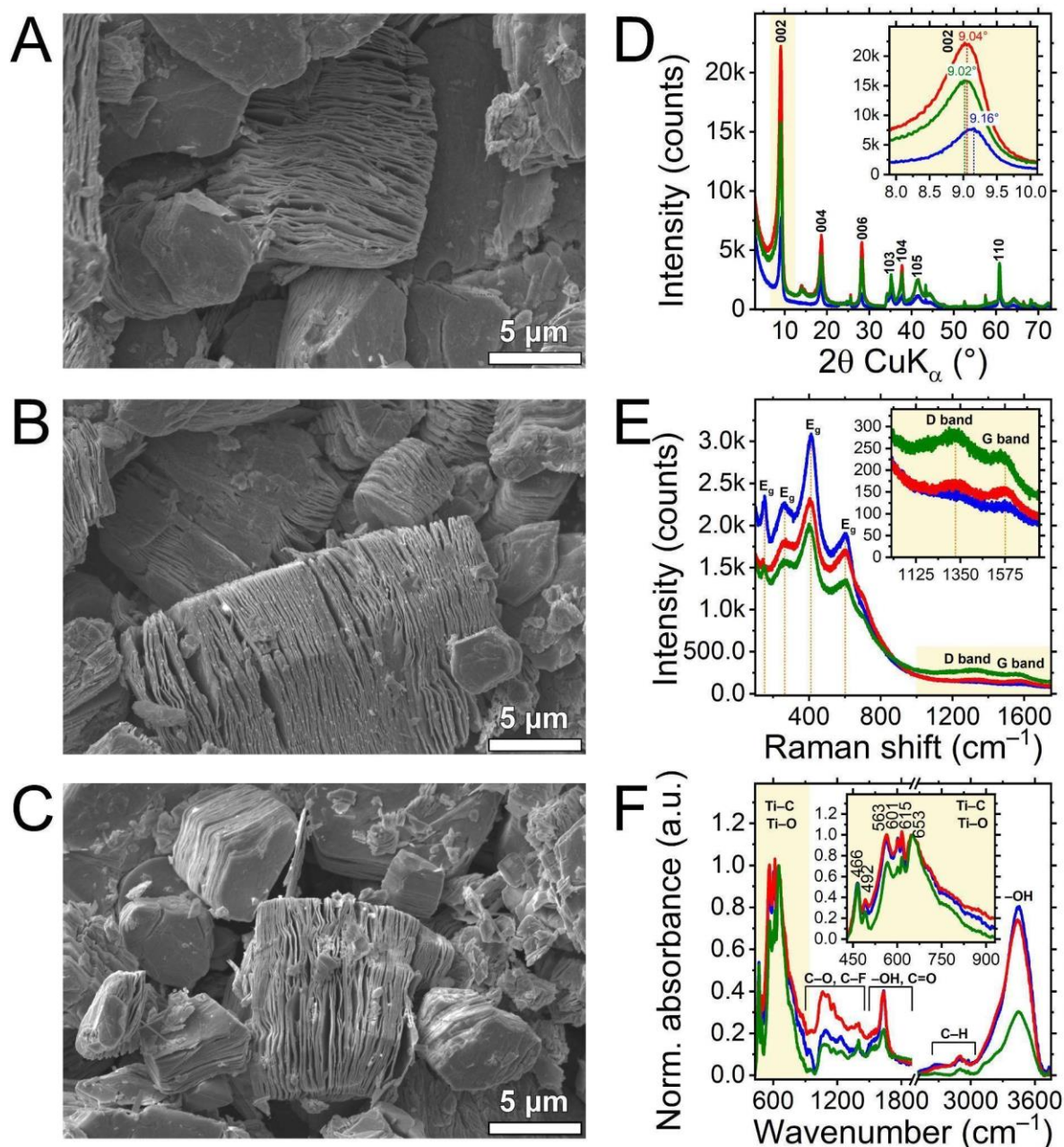


Figure 1: Morphological and structural characterisation of surface-tailored MXenes. SEM images of Ar-MX (A), H₂-MX (B) and N-MX (C) samples. (D) XRD patterns (with 002 peak region zoomed in the inset). (E) Raman spectra (with D and G bands region zoomed in the inset). (F) FTIR spectra (with the fingerprint region zoomed in the inset) for Ar-MX (blue), H₂-MX (red) and N-MX (green) samples.

The Raman spectra (**Figure 1E**) show a decrease in the relative intensity of the band at ~154.38 cm⁻¹ characteristic of Ti-O (C-Ti-O/TiO₂), compared to the other modes in the characteristic “flake” and “T_x”

regions (**Figure S3** and **Table S3**)⁴⁴. In the HF-MX samples, this peak at $\sim 154.2\text{ cm}^{-1}$ is the most intense, indicating a consistent oxidation degree of the Ti_3C_2 layers⁴⁵. In contrast, the Ar-MX sample exhibits a splitting of the E_g mode in two peaks at $\sim 143.8\text{ cm}^{-1}$, attributed to C–Ti–OH, and at $\sim 1519\text{ cm}^{-1}$, associated with C–Ti–O (TiO_2), reflecting thermally induced modifications of surface terminations. A complete suppression of the C–Ti–O (TiO_2) contribution is observed in the H_2 -MX sample, which displays a single E_g peak at $\sim 143.3\text{ cm}^{-1}$, characteristic of a less oxidized MXene surface. Besides, the N-MX spectrum contains both E_g components ($\sim 143.49\text{ cm}^{-1}$ and $\sim 151.57\text{ cm}^{-1}$), suggesting that NH_3 is less effective than H_2 in reducing surface oxides on $\text{Ti}_3\text{C}_2\text{T}_x$. Finally, the number of defects in the carbon network of Ti_3C_2 layers in the Ar-MX sample slightly decreases; the I_D/I_G ratio is 1.17 ± 0.06 , whereas in HF-MX it is 1.20 ± 0.04 . The H_2 -MX sample has the lowest I_D/I_G ratio (1.11 ± 0.14), confirming that the reductive environment has decreased the number of defects in the carbon lattice, too, while the N-MX sample has not achieved any major change with an I_D/I_G ratio of 1.19 ± 0.03 (similar to the HF-MX sample).

The FTIR spectra of the MX samples (**Figure 1F** and **Figure S4**) exhibit, in their fingerprint region, the characteristic IR absorption bands of MXene backbone: $\sim 466\text{--}467\text{ cm}^{-1}$ (Ti–C bending); $\sim 490\text{--}492\text{ cm}^{-1}$ (C--C vibrations); $\sim 562\text{--}654\text{ cm}^{-1}$ (various Ti–O and C–Ti–O vibrations), $\sim 772\text{--}786\text{ cm}^{-1}$ (Ti–F vibrations), $\sim 859\text{--}878\text{ cm}^{-1}$ (Al–O bending vibrations), $\sim 942\text{--}964\text{ cm}^{-1}$ (Ti–OH bending), $\sim 1048\text{--}1063\text{ cm}^{-1}$ (C–O stretching), $\sim 1088\text{--}1109\text{ cm}^{-1}$ (C–F stretching), $\sim 1161\text{--}1165\text{ cm}^{-1}$ (C–O stretching), and $\sim 1234\text{--}1236\text{ cm}^{-1}$ (C–O–C stretching; Ti–O–C bridging)⁴⁶. Among the investigated thermal treatments, annealing in anhydrous ammonia proved to be the most effective, as evidenced by the substantial attenuation of the Al–O bending vibration band at $\sim 859\text{--}878\text{ cm}^{-1}$. The functional groups region (**Figure 1F** and **Figure S4**) is dominated by the broad bending ($\sim 1631\text{--}1635\text{ cm}^{-1}$) and stretching ($\sim 3100\text{--}3700\text{ cm}^{-1}$) vibrational modes of adsorbed water molecules⁴⁷. These molecules are predominantly strongly hydrogen-bonded to the MX surface, particularly in HF-MX, and to a progressively lesser extent in Ar-MX, H_2 -MX, and N-MX. A complete assignment of the IR absorption bands is provided in **Table S4**.

Overall, SEM, XRD, Raman, and FTIR analyses revealed pronounced changes during the transformation from the MAX phase to HF-MX, followed by successful surface modification upon annealing to yield Ar-MX, H_2 -MX, and N-MX samples. Notably, this work introduces a surface-engineering strategy for MXenes based on a 5% H_2/Ar gas mixture, which is safer than pure H_2 and enables effective reduction of oxygen-containing surface terminations while minimizing secondary oxidation during annealing and allowing the rapid removal of highly volatile species from the reaction zone. In addition, this study was carried out on multilayered $\text{Ti}_3\text{C}_2\text{T}_x$ MXene particles annealed at 400°C for 3 h under NH_3 flow, differing from previous reports in terms of processing conditions⁴⁸, MXene morphology and surface-stabilization approach³⁹.

Although no significant differences in the core structure of the MXene were detected between the three annealed samples, XPS revealed pronounced differences in surface chemistry among the Ar-MX, H₂-MX and N-MX samples (**Figure 2**, **Figure S5**, **Table 1**, and **Table S5 and S6**). The Ar-MX sample shows an overall increase in carbon content with a slight decrease in oxygen and fluorine, changes that can be attributed solely to the thermal effects (Table S5). In this sample, most oxygen-related terminations (C-Ti-O, C-Ti-(OH)_x, and C=O) are significantly reduced, while Ti-O (TiO₂) and C-OH species exhibit a slight increase (Table S4). When compared to H₂-MX and N-MX, Ar-MX presents the lowest titanium concentration on the surface, while H₂-MX and N-MX display lower carbon and slightly higher oxygen content (even when compared to HF-MX).

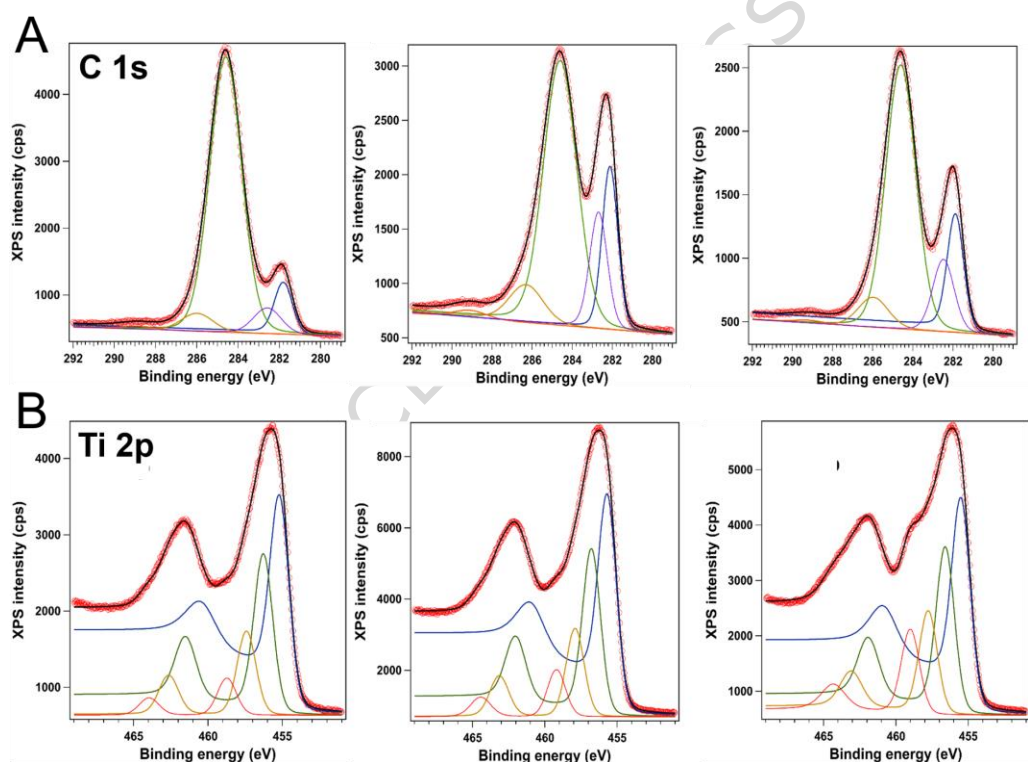


Figure 2: XPS surface chemistry characterisation of surface-engineered MXenes. (A) C 1s spectra, (B) Ti 2p spectra for Ar-MX (left), H₂-MX (middle) and N-MX (right) samples.

Table 1: XPS and EDS elemental composition of Ar-MX, H₂-MX, and N-MX samples.

Sample	XPS elemental composition (%)					
	C1s	O1s	N1s	F1s	Al2p	Ti2p
Ar-MX	58.88	12.60	/	8.81	1.86	17.85
H ₂ -MX	36.41	17.44	/	14.31	3.18	28.67
N-MX	34.00	18.48	4.74	11.74	4.10	26.93
	EDS elemental composition (%)					
	C	O	N	F	Al	Ti
Ar-MX	21.41	21.92	/	16.92	4.62	35.05
H ₂ -MX	17.29	21.68	/	17.20	4.62	39.21
N-MX	16.41	23.75	4.29	13.69	5.70	36.79

Notably, H₂-MX exhibits the strongest reduction, with C-Ti-O, C-Ti-(OH)_x, and C=O concentrations reduced by approximately 50% relative to the pristine HF-MX (see O 1s in **Table S6**), complete removal of Ti(III)-F species (which are converted into C-Ti-O bonds, see Ti 2p in **Table S6**), and enrichment in C-OH functionalities. Both H₂-MX and N-MX show a substantial decrease in C-Ti(OH/F)_x species and a corresponding increase in Ti-C-Ti bonds, indicating partial restoration of the Ti₃C₂ lattice and improved electronic characteristics. Consistent elemental trends are also observed by EDS (**Table 1** and **Table S1** and **S3**), albeit with different relative proportions due to the distinct probing depth of XPS and EDS. Finally, the N-MX sample has been successfully doped with nitrogen (4.47 at%), with nitrogen predominantly incorporated as Ti-N species, along with minor contributions from -C≡N and/or pyrrolic-N, and graphitic-N functionalities. Taken together, these results indicate that thermal annealing under different gas atmospheres mainly affects surface terminations without substantially altering the intrinsic -C-Ti-C- framework of the MXene.

Functionalization of the gate electrode with the surface-tailored MXenes

To develop an ultra-sensitive DA sensor, the Au gate electrode of the EGOT devices was functionalized with Ar-MX, H₂-MX and N-MX. Electrochemical methods were employed to both assess the functionalization procedure and to evaluate the effect of the different surface modifications on the MXene structures. Taking advantage of the hydrophilic nature and highly negative zeta potential of MXenes⁴⁹, stable DMSO dispersions of Ar-MX, H₂-MX and N-MX were prepared and drop-cast on the gate electrodes. Extensive surface coverage was achieved through the deposition of randomly oriented MXene multilayer grains, as evidenced by SEM images of the functionalized gate electrode (**Figure 3A, B**).

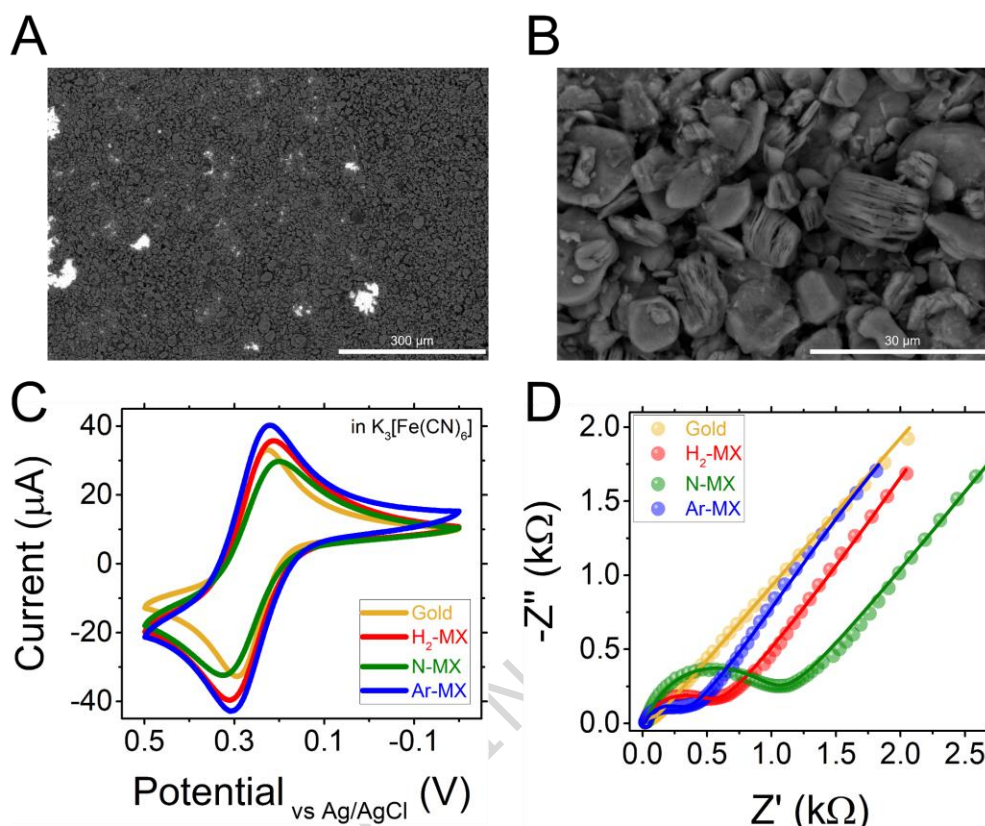


Figure 3: Functionalization of gold electrodes with surface-engineered MXenes. (A) Low and (B) high magnification SEM images of Au gate electrodes covered with surface-engineered MXenes. (C) CVs of the Au and Au/MXenes electrodes, recorded in the $K_3[Fe(CN)_6]$ redox probe, scan rate 100 mV/s. (D) EIS Nyquist plots of the Au and Au/MXenes electrodes, recorded in the $K_3[Fe(CN)_6]$ redox probe, $E = 260$ mV vs Ag/AgCl.

The MXene functionalization strategy was investigated with cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS), using $[Fe(CN)_6]^{3-/4-}$ as a redox probe.

As shown in **Figure 3C**, the oxidation peak progressively shifts towards more negative potentials following the sequence $N-MX > H_2-MX > Ar-MX \approx Au$. The H_2-MX and $Ar-MX$ functionalized electrodes display a broader current envelope in the CV plots compared to bare gold. In contrast, the $N-MX$ electrode exhibits a reduced peak current, even lower than that of unmodified gate electrodes, suggesting that the ammonia-assisted heat treatment adversely affects the faradaic electrochemical performance, likely due to a decrease in film electrical conductivity⁵⁰. This hypothesis is supported by the EIS data (**Figure 3D**). The Nyquist plots were fitted using the modified equivalent circuit proposed by Anjum *et al.*, for MXene-functionalized electrodes⁵¹ (Figure 3D, inset), while a standard Randles circuit was employed for bare

gold electrode. The resulting best-fit parameters, summarised in **Table S7**, further confirm the effectiveness of the surface modification process. The charge transfer resistance (R_{ct}) increases significantly from $\sim 55 \Omega$ (bare Au) to $\sim 254 \Omega$ (Ar-MX), $\sim 254 \Omega$ (H₂-MX), and $\sim 602 \Omega$ (N-MX). This trend is consistent with the highly negative surface charge of MXenes⁵², which induces electrostatic repulsion toward anionic $[\text{Fe}(\text{CN})_6]^{3-/4-}$ probe. Regarding the interfacial properties, the double-layer capacitance (C_1) is highest for H₂-MX ($4.30 \pm 0.67 \mu\text{F}$), decreases for Ar-MX ($1.02 \pm 0.09 \mu\text{F}$), and reaches the lowest value for N-MX ($0.53 \pm 0.03 \mu\text{F}$). The elevated C_1 observed for H₂-MX is consistent with its HR-XPS analysis (Table S6), which reveals the highest relative abundance of polar C-OH functional groups (45.78%), resulting in a more hydrophilic and thus electrostatically active surface.

Characterisation of EGOT devices with MXene-functionalized gate

The MXene-coated gate electrodes were integrated in an EGOT-based architecture, acting as sensitive probes for DA detection. **Figure 4A** shows the schematic representation of top-gated EGOT configuration, in which the gate electrode was positioned directly above the source and the drain interdigitated electrodes (IDEs), connected by a thin-film of poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) channel. The device is assembled by bridging the gate electrode and the IDEs with the buffer solution, as reported in **Figure 4B**.

The MXene-EGOT device was operated in the linear regime with a source-drain voltage (V_{DS}) of -0.2 V, while sweeping the gate-source (V_{GS}) potential from -0.5 to 0.7 V. Once reaching the stabilization (see the Methods section for the details), the typical transfer characteristics of the devices featuring surface-tailored MXenes appears as reported in **Figure 4C**. Unlike functionalization with antibodies grafted onto organic self-assembled monolayers (SAMs), which typically causes a one-order-of-magnitude current reduction due to the Au surface passivation, the MXene functionalization layer induces only a minimal decrease in the I_{DS} current, with respect to not-functionalized (bare) gold electrode (Figure 4C). The three surface-tailored MXenes do not show any significant difference in the on state of the device, whereas in the off state (*viz.*, at $V_{GS} = +0.7 \text{ V}$), the H₂-MX device exhibits a significantly higher off-current (poor switching) compared to the Ar-MX and N-MX devices, which both switch off the device effectively. We extracted the transconductance (g_m) as the first derivative of the transfer curve (**Figure 4D**), which describes the ability of the device to amplify a small voltage variation (e.g., interaction of the target molecule with the functionalized gate) in a large current difference. Interestingly, the maximum of the transconductance was very close for gate electrodes functionalised with N-MX and Ar-MX, while it was lower for the H₂-MX functionalized electrodes. Notably, all the MXenes functionalized electrodes shifted the voltage of the maximum of transconductance closer to 0 V compared to bare gold gate electrodes, which is a key point for physiological applications. Given that MXene layers are known to undergo

oxidation at anodic potentials⁵¹, we monitored the evolution of their surface chemistry during gate voltage sweeping using XPS. To this end, surface-tailored MXenes were cast on Au foils, and their high-resolution XPS spectra (C 1s and Ti 2p) were compared before and after electrochemical cycling (**Figure S6**). The results indicate that the spectra in both regions remain qualitatively similar, confirming that the overall MXene chemical framework is preserved without the formation of entirely new chemical species. Nevertheless, the Ti 2p spectra reveal a clear redistribution of the relative peak contributions after cycling: the oxidized TiO_2 (Ti^{4+}) component increases with the corresponding decrease in the reduced Ti species (Ti-C and Ti^{3+}) (**Table S8**). This partial surface oxidation, driven by the gate sweeping, is particularly pronounced for the $\text{H}_2\text{-MX}$ sample. We hypothesize that the growth of this insulating oxide layer reduces the effective capacitance of the $\text{H}_2\text{-MX}$ electrode, thereby lowering both the on/off ratio and the peak transconductance of the $\text{H}_2\text{-MX}$ -based EGOT device.

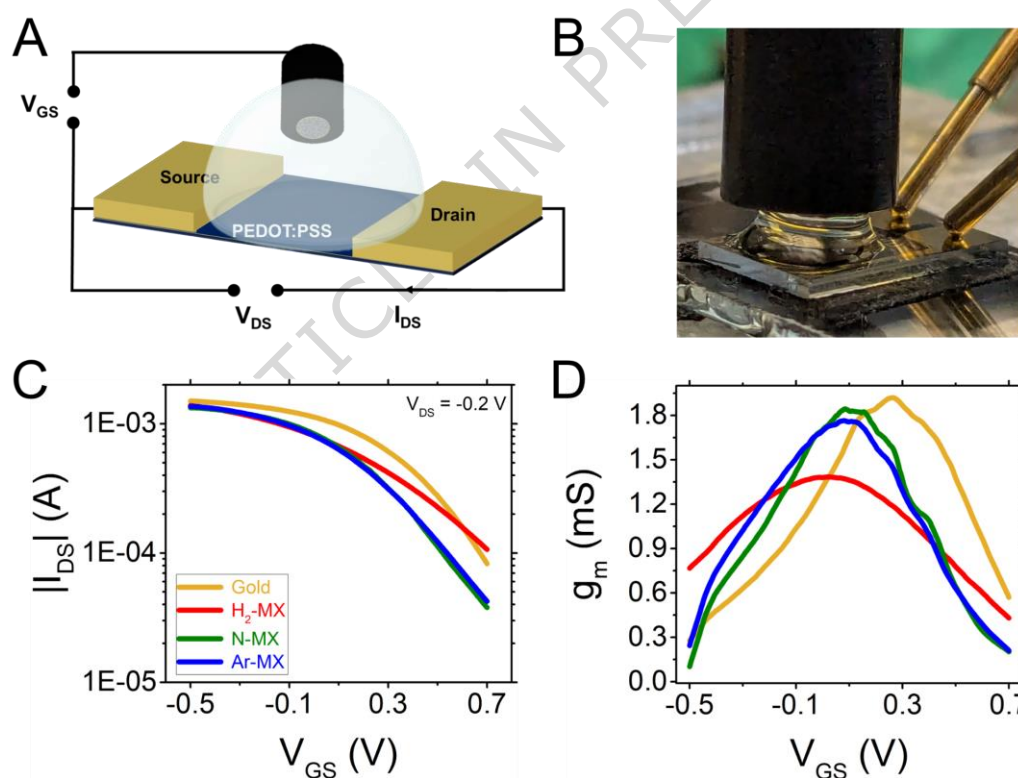


Figure 4: Architecture and electrical characterisation of the MXene-functionalized EGOT device. (A) Scheme of the EGOT device; (B) Layout of the MXene-EGOT DA sensor; (C) Representative transfer curves recorded with gold (yellow), $\text{H}_2\text{-MX}$ (red), N-MX (green), Ar-MX (blue) electrode; (D) corresponding transconductance (viz., first derivative of I_{DS} vs V_{GS}). $V_{DS} = -0.2$ V, 50 mM PB electrolyte.

Sensing of Dopamine with the MXene-functionalized EGOT device

The sensing capability of the MXene-functionalized EGOTs toward DA was evaluated by recording transfer characteristics under increasing DA concentrations to establish a dose-response profile. For all three MXene variants, a monotonic decrease in I_{DS} was observed in the saturation regime (**Figure 5A-C**) as a function of analyte concentration. These results suggest that DA molecules - positively charged at the physiological pH of 7.4 ($pK_{a_{DA}} = 8.9$) - interact with the MXene layer, effectively shifting the gate potential toward more positive values. This behavior is consistent with previous reports on the electrostatic gating effect of primary amines^{19,21}. Mechanistically, this interaction promotes cation injection into (or hinders anion extraction from) the PEDOT:PSS channel, leading to a depletion of hole carriers and a subsequent reduction in I_{DS} .

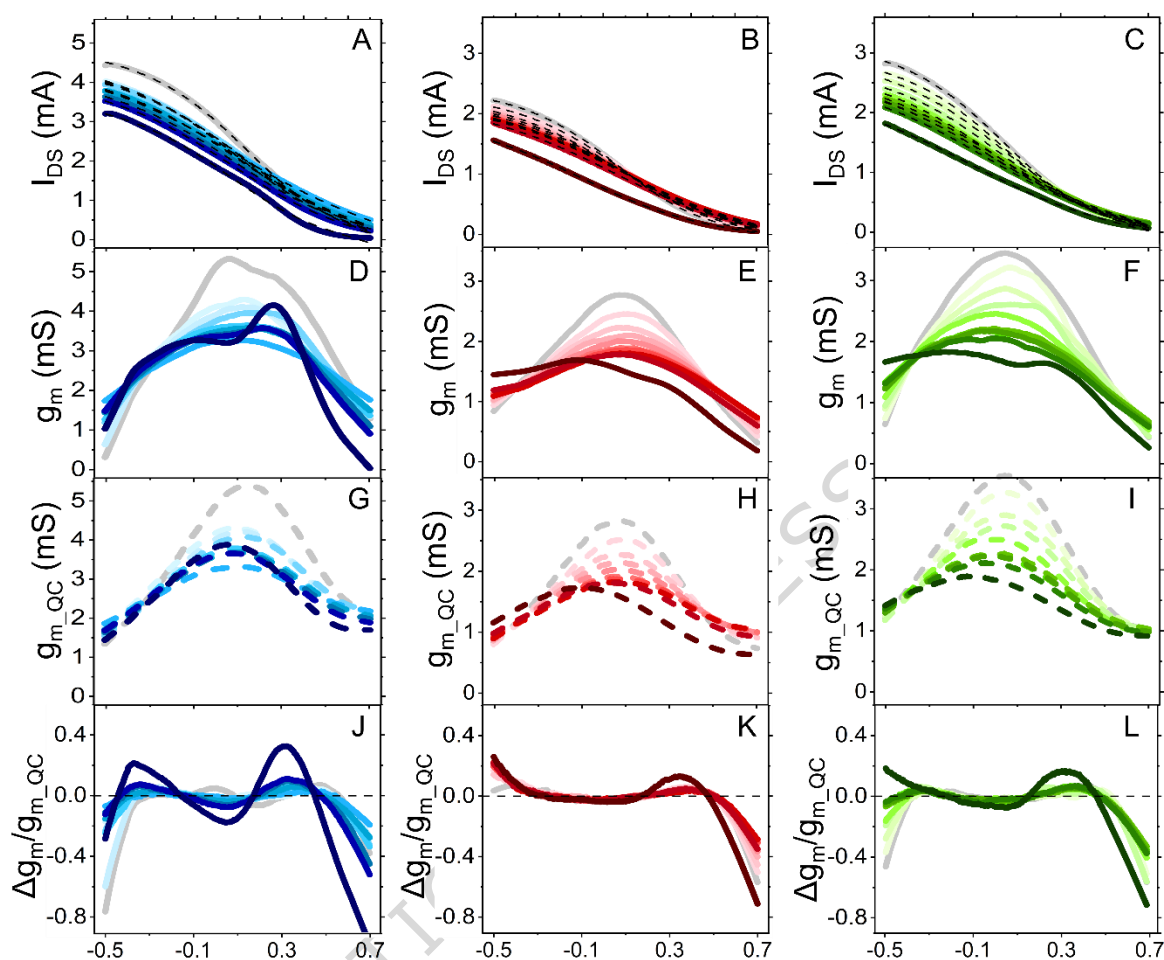


Figure 5: Electrical characterisation in the presence of Dopamine. Representative EGOT transfer curves for Ar-MX electrode (blue curves, A), H₂-MX electrode (red curves, B), N-MX electrode (green curves, C). Black dashed lines are the best fit curves obtained using eq 18 in Zanotti et al.⁵³. (D-F) The experimental transconductance (g_m) profile for the three surface-tailored MXene samples. (G-I) The transconductance profile obtained as the first derivative of the transfer characteristics best fit curves, modelled with eq. 18 reported in Zanotti et al.⁵³ (J-L) Differences between the experimental and the modelled transconductance profiles, normalised for the modelled g_m profiles. Grey profiles represent 50 mM PB in the absence of DA. The increasing color intensity of the curves corresponds to increasing DA concentrations (from 100 fM to 10 μ M).

Analysis of the gate currents (I_{GS} , **Figure S7**) revealed no faradaic peaks for the MXene-modified electrodes at sub-micromolar DA concentrations, confirming that the sensing mechanism in this regime is governed by non-faradaic interactions. Conversely, at concentrations exceeding 1 μ M, the positive gate potential triggers the electrooxidation of DA to dopamine-o-quinone (DQ). This transition is

evidenced by a voltammetric peak centered at $V_{GS} \approx 0.3$ V, which was particularly pronounced for Ar-MX. In this micromolar range, DA oxidation promotes a substantial change in channel conductance via the electrochemical reduction of PEDOT⁺ to PEDOT⁰ within the transistor channel⁵⁴. EGOTs operate as multiparametric devices, allowing the sensing event to be monitored through various figures of merit, including the switch-on voltage (V_T) and the transconductance (g_m). As shown in **Figure 5D-F**, all three surface-tailored MXenes exhibit a decrease in transconductance peak with increasing DA concentration. To further elucidate the device response, transfer curves were fitted using the unified analytical model recently proposed by Zanotti *et al.*⁵³. The experimental I_{DS} vs V_{GS} data were modelled using equation 18 from the cited work; the resulting best-fit curves (dashed lines, Figure 5A-C) and their numerical derivatives (**Figure 5G-I**) show excellent agreement with experimental data in the capacitive regime. Finally, the normalised difference between the experimental and modelled transconductance ($\Delta g_m/g_{m_{QC}}$) highlights the impact of the faradaic contribution. The peak at $V_{GS} \approx 0.3$ V, prominent at 10 μ M DA in **Figure 5J-L**, serves as a clear indicator of the transition from electrostatic gating to redox-active sensing, as previously pointed out⁵⁴. To quantitatively assess the sensor performance, the relative signal response was plotted against the DA concentration.

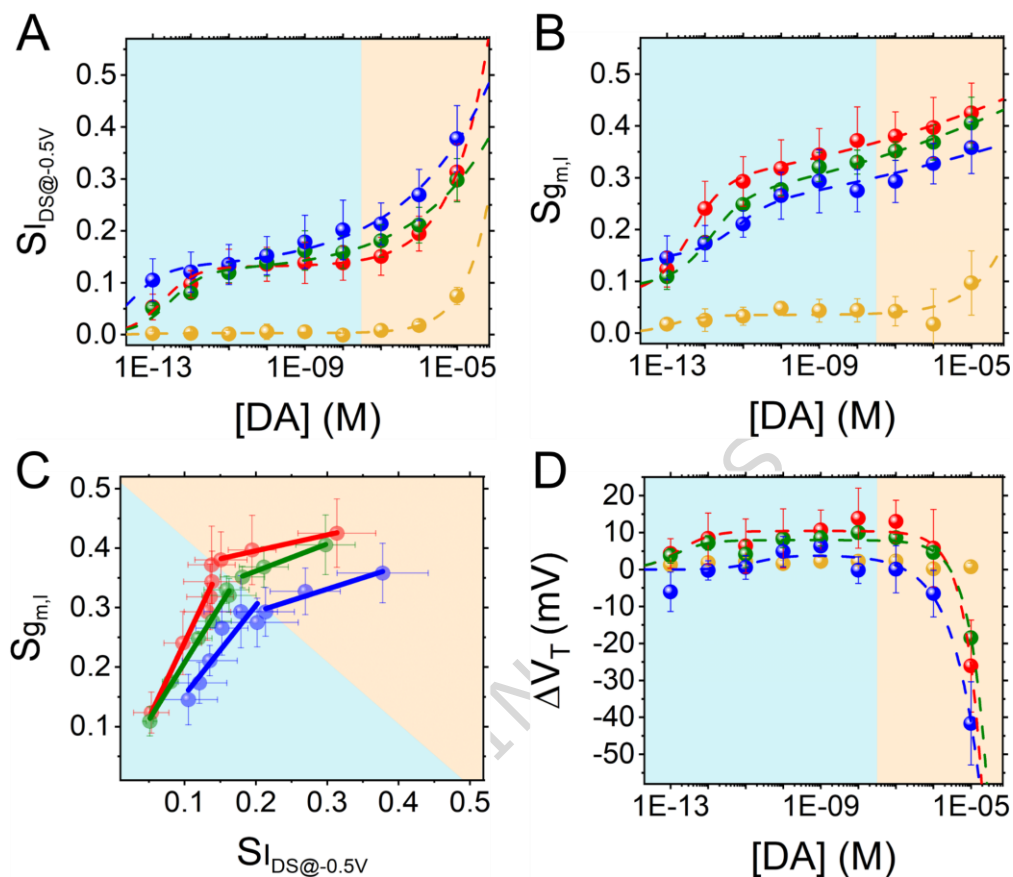


Figure 6: Dopamine sensing. (A-B) Semilog plot of the current signal $S_{I_{DS}}$ calculated at $V_{GS} = -0.5$ V and of the linear transconductance signal $S_{g_{m,l}}$ vs $[DA]$. (C) Correlation plot of the normalized I_{DS} change ($S_{I_{DS@-0.5V}}$), against the normalized $g_{m,l}$ ($S_{g_{m,l}}$) for each DA concentration. The two distinct sensing regimes are identified with the linear fit reported as guide-for-the eye. (D) Semilog plot of the ΔV_T vs $[Dopamine]$. In all the plots, we use blue dots for the Ar-MX electrode, red dots for the H_2 -MX electrode and green dots for the N-MX electrode. The error bars are the standard error of the mean. The dashed lines are the result of the fitting with Equation 1. The blue and orange areas define the two different sensing regimes.

For all the investigated MXenes, the I_{DS} at $V_{GS} = -0.5$ V decreased upon exposure to increasing DA concentrations. Defining the response as the relative current variation ($S_{I_{DS}}$, see Materials and Methods for further details), a monotonic increase in signal magnitude was observed across the entire concentration range (**Figure 6A**). The dose-response curves increase monotonically within the $[DA]$ investigated: i) a rapid signal increase at low concentration (10 pM for H_2 -MX and N-MX, 1 pM for Ar-MX), ii) a plateau or a region of slower increase (up to 100 nM) and iii) a second, sharp signal rise at concentrations exceeding 100 nM.

In EGOT-based (bio)sensor literature, this biphasic behavior hints at the concomitant presence of two distinct interaction mechanisms taking place at the gate/electrolyte interface and is described with multilayer adsorption model⁵⁵.

Here, the $S_{IDS@-0.5V}$ vs [DA] dose-response profile was fitted using an ad hoc two-term empirical model (Equation 1), which accounts for the dual interaction mechanism:

$$S_{IDS} = S_{max} \frac{K_a [DA]}{1 + K_a [DA]} + \left(\frac{[DA]}{C_0} \right)^n \quad (\text{Equation 1})$$

The first term acts as a Langmuir-like isotherm, describing the high-affinity, capacitive interactions-of DA with the functionalized MXene surface. These interactions are likely driven by the formation of Ti-N covalent bonds, π - π interactions, hydrogen bonding and van der Waals forces as recently pointed out^{34,35}. This process dominates in the low concentration regime (blue background), saturating at a maximum signal S_{max} , and is defined by the apparent association constant K_a . The second term accounts for the dominant interaction above 100 nM (orange background). Here, C_0 represents an upper limit of detection¹¹, and n is the characteristic growth exponent. We hypothesise that this secondary signal rise stems from the electrooxidation of DA to DQ and subsequent partial polydopamine electrodeposition.

Based on the Equation 1 fitting curves and according to the IUPAC definition⁵⁶, we calculated a limit of detection (LOD) as low as 0.30 fM (95% C.I. 0.09 – 0.87 fM) for Ar-MX, 1.03 fM (95% C.I. 0.66 – 1.69 fM) for H₂-MX and 0.89 fM (95% C.I. 0.35 – 3.06 fM) for N-MX (see Methods section for further details). These values are several orders of magnitude lower than those previously reported in the literature for MXene-based EGOT devices for dopamine detection^{34,35}. As recently demonstrated⁵⁷, the achievement of such an ultra-low LOD can be primarily ascribed to the high K_a extracted from the binding model and reported in **Table S9**.

The hypothesis of the concomitant presence of two distinct interaction mechanisms is strongly corroborated by our control experiment. The non-functionalized, bare Au electrode (yellow dots in Figure 6A) showed a negligible response at low concentrations, confirming that the high-affinity binding is driven by the MXene functionalization. However, the current extracted from the bare Au electrode exhibits an increase at 10 μ M, supporting the idea that the high-concentration mechanism is related to DA electrooxidation.

To isolate the (bio)sensor current response related to MXene-DA affinity from the background DA-PEDOT interactions, we extracted an intrinsic dose-response curve. This was calculated by taking the difference between the current signal obtained for each sample and the signal from the control gate experiments (bare gold) at the same DA concentration. This difference (ΔS_{IDS}) represents the genuine interaction between DA and the MXenes (**Figure S8A**). To assess the influence of the MXene surface

terminations, we calculated the sensitivity as the numerical derivative of this response ($d\Delta S_{IDS}/d[DA]$) versus $[DA]$ (**Figure S8B**). The analysis of the sensitivity reveals distinct optimal sensing ranges for the surface-tailored MXenes.

Specifically, H₂-MX exhibits a sharp peak in sensitivity in the sub-picomolar range ($\approx 10^{-13}$ M), alongside a steep increase in sensitivity at higher concentrations (approaching 10^{-5} M). N-MX displays a broader sensitivity peak in the picomolar range (10^{-13} to 10^{-11} M), making it advantageous for measurements requiring high sensitivity over this intermediate concentration interval. Meanwhile, Ar-MX exhibits its peak low-concentration sensitivity at the lower limit of the tested range ($< 10^{-13}$ M) and consistently maintains the highest absolute signal variation across most of the concentration spectrum (Figure S8A).

To further investigate the impact of MXene surface chemistry on the device performance, we leveraged the multiparametric nature of the EGOT response by fitting the experimental transfer curves with our unified analytical model⁵³, as shown in Figure 5.

In particular, we extracted the following parameters, that can be correlated with the variation of analyte concentration: V_T (switch-on voltage), σ (energy disorder of the density of states (DOS) of the organic semiconductor), $g_{m,l}$ (linear transconductance) and the parameter α ($\alpha = 2e^2dn_{max}/C_{DL}\sigma$, which describes the ratio of the areal charge densities).

The relative variation of the linear transconductance ($S_{g_{m,l}}$) displays a monotonic trend for all three surface-tailored MXenes (**Figure 6B**). Since $g_{m,l}$ variations in EGOTs are ascribed to the change in interfacial capacitance⁵⁸, this trend can be confidently attributed to the electrostatic interaction between the MXene layer and DA.

In the low-concentration range (from 10^{-13} to 10^{-7} M) the sensor exhibits a steep response driven by high-affinity, capacitive interactions, which is well described by the Langmuir isotherm (blue background). At concentrations above 100 nM (orange background), electrochemical interactions between the MXene and DA begin to emerge, resulting in a reduced sensitivity of the $S_{g_{m,l}}$ signal. To quantitatively describe the capacitive specific-interaction between the analyte and MXenes, we fitted the monotonic behavior of $S_{g_{m,l}}$ dose-calibration curve with equation 1. H₂-MX exhibits the highest affinity constant ($K_a = 2.3 \pm 0.6 \times 10^{12}$), followed by the K_a obtained for N-MX ($K_a = 6.6 \pm 2.1 \times 10^{11}$) and Ar-MX ($K_a = 1.3 \pm 1.2 \times 10^{11}$). These differences suggest that surface terminations play a pivotal role in the interface kinetics. The strong capacitive interactions observed for H₂-MX might be ascribed to the high concentration of oxidized titanium species on its surface after cycling at positive V_{GS} (Figure S6 and Table S8), as TiO₂ is known to exhibit a high affinity for enediol ligands⁵⁹.

The presence of two distinct interaction mechanisms is confirmed in the correlation plot $S_{g_{m,l}}$ vs $S_{IDS@-0.5V}$, reported in **Figure 6C**. For DA concentrations lower than 100 nM, the device operates in a sensing

regime dominated by the capacitive interaction between the MXene layer and DA molecules, leading to a more pronounced variation of $S_{g_{m,l}}$ than $S_{I_{DS@-0.5V}}$. This behavior is quantitatively confirmed by the slope of the linear fit from $S_{g_{m,l}}$ vs $S_{I_{DS@-0.5V}}$ correlation plot, which remains consistently greater than 1 for all surface-engineered MXene gates (H_2 -MX = 2.5 ± 0.3 , N-MX = 1.9 ± 0.1 , Ar-MX = 1.5 ± 0.3). The higher values observed for $S_{g_{m,l}}$ with the respect to $S_{I_{DS@-0.5V}}$ confirm that the high-affinity, capacitive interaction between MXenes and DA at low concentration can be successfully described by the $S_{g_{m,l}}$ trend. For DA concentrations exceeding 100 nM, a second sensing mechanism appears and $S_{I_{DS@-0.5V}}$ results higher than $S_{g_{m,l}}$, as confirmed by the slope of the linear fit which is lower than 1 for all the functionalized MXenes. Under this operational regime, the interaction between DA and MXene-EGOT sensor is reflected in a variation of the switch-on shift $\Delta V_T = V_T[DA] - V_{T,0}$ for the three surface-tailored MXenes (**Figure 6D**). ΔV_T slightly increases towards positive values for increasing [DA] concentrations, achieving its maximum positive value at 1 nM for Ar-MX and 10 nM for H_2 -MX and N-MX. The trend of the ΔV_T then clearly reverses, dropping to negative values (- 27 mV for H_2 -MX, - 19 mV for N-MX and - 42 mV for Ar-MX) at the 10 μ M DA concentration. Since the switch-on voltage V_T represents the gate voltage at which the semiconductor is in the flatband (or charge neutrality condition), it influences the initial doping level of the EGOTs by modulating the effective gate voltage $v = e(V_{GS} - V_T)/\sigma^{19,53}$ and therefore depends on the work function variations of the gate electrode and/or of the semiconductive channel. As discussed earlier, for low [DA], the interaction between DA and MXene leads to a variation of the interfacial capacitance and therefore of the $S_{g_{m,l}}$. This results in a modest V_T shift towards positive values, as reported elsewhere for capacitive DA sensing²¹. For [DA] > 100 nM a marked ΔV_T shift at negative values is observed for all the chemically-functionalized MXenes. This behavior could be ascribed to the electrooxidation of DA to DQ that takes place at the gate electrode (Figure S7) and results in a negative drift of ΔV_T , as previously demonstrated in the literature⁶⁰.

Discussion

In this work, we synthesised $Ti_3C_2T_x$ MXene and engineered its surface with an innovative process to obtain three distinct variants: Ar-MX, H_2 -MX and N-MX. These materials were comprehensively characterised by a suite of techniques, including HR-XPS, SEM-EDX, XRD, FTIR and Raman spectroscopy. The extensive characterisation revealed that, although the treatments induced only minor changes to the original core structure, they produced significant alterations in surface chemistry and functional group distribution. The integration of surface-tailored MXenes in PEDOT:PSS-based EGOTs shifts of maximum of transconductance at zero gate bias, which is a crucial aspect for translational organic bioelectronics.

The EGOT devices were then employed as sensors for DA detection over a wide concentration range, spanning from sub-picomolar to micromolar levels. Limits of detection (LOD) as low as 0.30 for Ar-MX, 1.03 fM for H₂-MX and 0.89 fM for N-MX were obtained. Within this sensing framework, two distinct sensing mechanisms were identified, depending on the DA concentration.

In the sub-nanomolar DA concentration range (blue background) the device response variation is primarily ascribed to the variation of the linear transconductance ($g_{m,l}$). Conversely, at micromolar DA concentration (orange background) the sensing mechanism is governed by the variation of ΔV_T . At low concentration a capacitive sensing mechanism could be hypothesized since the linear transconductance embodies the product of the charge mobility μ and the double layer capacitance⁵³. In EGOT-based (bio)sensor, the charge carrier mobility does not undergo sizable changes upon binding of the target analyte⁵⁸. Therefore, the variation of the linear transconductance can be mostly affected by the variation of the double layer capacitance. In contrast, at higher concentration a faradaic sensing mechanism prevails (as confirmed by the presence of a faradaic current in the I_{GS} profiles) and it is reflected in the variation of ΔV_T , with $Sg_{m,l}$ that remains almost constant.

In this work, we demonstrated that tailoring the MXene surface chemistry effectively tunes the response of the sensor across the tested DA concentration windows. Specifically, H₂-MX demonstrated superior performance for capacitive DA sensing at sub-picomolar concentrations, as evidenced by the high K_a extracted from $Sg_{m,l}$ dose curve. Conversely, Ar-MX promoted the faradaic mechanism at lower concentrations compared to the other MXenes, likely due to the presence of oxidized carbon functionalities and a reduced fluorine content on its surface. Lastly, N-MX demonstrated high sensitivity for capacitive DA sensing in the picomolar range, making it particularly suitable for physiological samples characterized by sub-nanomolar DA levels. Furthermore, the preservation of the nitrogen surface terminations under the operating potentials of PEDOT:PSS-based EGOTs paves the way for future applications, as these groups serve as ideal anchoring sites for the binding of specific target receptors.

Methods

Reagents

1X Phosphate buffered (PB) solution, monobasic and dibasic phosphate, Dopamine hydrochloride, H_2SO_4 , $\text{K}_3\text{Fe}(\text{CN})_6$, dimethylsulfoxide (DMSO) and 0.2% (3-glycidyloxypropyl)trimethoxysilane (GOPS) were purchased from Sigma–Aldrich (Germany), poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), PH1000 is produced by Ossila (UK). MAX phase Ti_3AlC_2 (200 mesh) was purchased from Carbon Ukraine Ltd., HF 40% solution and isopropanol from Fisher Chemical. Ar 5.0, 5% H_2 in Argon 5.0, and anhydrous NH_3 5.0 cylinders were purchased from Linde.

Synthesis of HF-MX ($\text{Ti}_3\text{C}_2\text{T}_x$)

A commercial MAX phase Ti_3AlC_2 (6 g) was slowly added under magnetic stirring (Teflon-coated magnetic stirrer) over a 27.7% HF solution (obtained by carefully adding 150 mL of 40% HF into 75 mL of deionised water), resulting in H_2 formation and release due to the reaction between HF and Al atoms inside MAX phase structure. After finishing the MAX phase, the reaction mixture was kept under constant stirring at room temperature for 24 hours. The reaction mixture was filtered on filter paper under vacuum and washed multiple times with DI water until a pH of 6-7 was reached. The HF-MXene $\text{Ti}_3\text{C}_2\text{T}_x$ solid was washed on the filter with 100mL of isopropanol, collected and vacuum dried at 100°C for 6 hours. The resulting HF-MX dried solid was stored in a glass vial under vacuum for further experiments and characterisation.

Synthesis and characterisation of Ar-MX, H_2 -MX and N-MX samples

Ar-MX, H_2 -MX and N-MX samples synthesis: 1 g of HF-MX was loaded into a quartz boat and transferred into a horizontal MIT OTF-1200X tubular furnace (with 8 inches heating zone and equipped with OD:25mm, ID:23mm and 1m length quartz tube); the system was sealed and a gas flow of 100mL/min of Ar 5.0, 5% H_2 in Argon 5.0 or NH_3 anhydrous gas 5.0 has started to flow inside the quartz tube. The heating was turned on with a heating rate of $5^\circ\text{C}/\text{min}$ until it reached 400°C , and after 3 hours the sample was cooled down with a cooling rate of $5^\circ\text{C}/\text{min}$, keeping an argon flow (H_2 or NH_3 flow off and switched to Ar 5.0 flow) on until MXene samples reached $20\text{--}25^\circ\text{C}$ (room temperature). The MXene samples were stored in a glass vial under vacuum for further testing and characterisation. The X-ray Diffraction (XRD) measurements were conducted with an Anton Paar XRDynamic 500 powder diffractometer equipped with a Primux 3000 X-ray source ($\text{CuK}\alpha_1$, $\lambda=1.5406\text{ \AA}$) operated at a 40 kV voltage and a 50 mA current. The patterns were recorded with a scan step of 0.02° and dwell times of $\sim 1.2\text{ s/step}$. The Raman spectra of all the MXene samples were recorded using a Horiba LabRAM HR Evolution Raman Spectrometer

equipped with a 633 nm laser. The Scanning Electron Microscopy (SEM) images of all MXene samples were recorded using a field emission scanning electron microscope (FESEM) Zeiss Gemini 500 equipped with an Energy Dispersive X-ray (EDX) detector from Bruker. The EDX measurements were used to reveal the chemical composition of the MXene samples. The MAX phase (Ti_3AlC_2) sample's SEM and EDS images were recorded using an EVO 50 XVP microscope from Zeiss, equipped with an energy-dispersive X-ray system (EDX) from Quanta Bruker 200. The X-ray Photoelectron Spectroscopy (XPS) spectra of Ar-MX, H_2 -MX, and N-MX samples were measured with a SPECS spectrometer equipped with a monochromatized Al K_α (1486.61 eV) anode radiation source operated at 250W 12.5 kV x 20 mA. The spectra were recorded at pressures lower than 2×10^{-9} mbar with 50 eV pass energy for surveys and 30 eV pass energy for high-resolution measurements. The XPS spectra of MAX phase (Ti_3AlC_2) and HF-MX ($\text{Ti}_3\text{C}_2\text{T}_x$) were recorded using a Kratos AXIS Ultra DLD system equipped with a hemispherical analyser with a reference intensity of over 50,000 counts per second (cps) and spectral resolution of 0.6 eV, using Al $K_{\alpha 1}$ (1486.74 eV) radiation produced by a monochromatized X-Ray source with a spot size of 0.7 mm. The operating power was 192 W (12 kV $\times$ 12 mA), and the spectra were recorded with 160 eV pass energy for surveys and 40 eV pass energy for high-resolution measurements, with Hybrid lens mode and slot aperture. Fourier Transform Infrared (FTIR) spectroscopy measurements were performed using a Jasco 6800-FV-BB spectrometer. Spectra were collected in transmission mode under vacuum in the 4000–400 cm^{-1} wavenumber range, with a spectral resolution of 4 cm^{-1} . Each spectrum represents the average of 128 accumulated scans. Vacuum conditions were applied to minimise atmospheric absorption from CO_2 and H_2O , thereby enhancing spectral accuracy and reproducibility. The samples were prepared by dispersing and diluting the material of interest in potassium bromide (KBr, Pike Technologies) at a ratio of approximately 1:400.

Fabrication of the EGOT device

ED-IDE1-Au interdigitated (IDE) source and drain electrodes were supplied by Micrux (Spain). The IDEs are made of gold on glass, showing 90 pairs of interdigitated gold electrodes, with a gap width of 10 μm , giving a ratio width/length (W/L) of 49000. The IDEs were cleaned by a three steps procedure to eliminate organic contaminations: i) ultrasonication in 2% Hellmanex detergent in distilled water, followed by rinsing with water and dry with N_2 flow; ii) ultrasonication in distilled water, followed by rinsing with water and dry with N_2 flow and iii) ultrasonication ethanol, followed by rinsing with ethanol and dry with N_2 flow. We prepared the PEDOT:PSS solution by adding 5% m/m DMSO and 0.2% GOPS. The solution was diluted in distilled water 1000 times and a drop of 10 μL was cast on the IDE. To evaporate the solvent and cure the semiconductor, we put the device in the oven at 120°C for 30 minutes.

Functionalization of the gate electrode

Gold (Au) disc electrodes were cleaned with ultrasonication in ethanol for 10 minutes, dried with N₂ flow, polished with 0.05-micron alumina powder, rinsed abundantly with water and dried with N₂ flow. A 5 mg/mL MXene dispersion in dimethylsulfoxide (DMSO) was prepared and sonicated 10 minutes for six times. A further sonication step was performed by bubbling N₂ in the MXene dispersion for 15 minutes. The Au electrodes were functionalized by drop-casting 4 μ L of the 5 mg/mL MXene solution in DMSO on the gold surface. The Au-MXene electrodes were then cured by a two-step process at 50 °C for 30 minutes and 70 °C for further 30 minutes. The deposition and curing process was repeated two times.

Electrochemical characterisation

Electrochemical measurements were performed in a standard three-electrode electrochemical cell, filled with 5 mM K₃Fe(CN)₆, 1M KCl. The Au electrode was cleaned with alumina on a polish cloth and by CVs in H₂SO₄. The clean or covered with MXenes electrode was connected as a working electrode, in presence of a Pt counter electrode and an Ag/AgCl reference electrode. Cyclic voltammetry was recorded by applying a 100 mV/s scan rate, between -0.2 and 0.5 V, while electrochemical impedance spectroscopy was performed by applying a potential of -0.27 V, a frequency from 0.1 to 10⁵ Hz.

XPS measurements on functionalized electrodes

Silicon dies (1 cm²) coated with a thin layer of gold were functionalized with the three surface-tailored MXenes, following the procedure described above. Uncycled samples were characterized by XPS in their pristine state. Conversely, cycled samples were first operated as working electrodes in a two-electrode configuration, employing a gold wire as the counter electrode with 50 mM PB solution (pH 7.4) as electrolyte. The electrochemical cycling was performed using a Keysight B2912A Source/Measure Unit by sweeping the potential of the working electrode from -0.5 V to +0.7 V for 50 cycles. The XPS spectra of the functionalized electrodes were recorded using a Kratos AXIS Ultra DLD system equipped with a hemispherical analyser with a reference intensity of over 50,000 counts per second (cps) and spectral resolution of 0.6 eV, using Al K α 1 (1486.74 eV) radiation produced by a monochromatized X-Ray source with a spot size of 0.7 mm. The operating power was 192 W (12 kV $\times$ 12 mA), and the spectra were recorded with 160 eV pass energy for surveys and 40 eV pass energy for high-resolution measurements, with Hybrid lens mode and slot aperture.

Electrical measurements

The EGOTs were measured by means of a Keysight B2912A Source/Measure Unit. Transfer curves were measured by sweeping the V_{GS} between -0.5 to 0.7 V, applying a fixed $V_{DS} = -0.2$ V until achieving stability, meaning complete superimposition between five successive transfer curves.

Dopamine sensing experiments

Initially, the device was stabilised in a blank 50 mM PB solution (pH 7.4) by continuously cycling the gate bias between -0.5 V and +0.7 V for at least 60 minutes. The source-drain current (I_{DS}) was recorded at fixed V_{DS} of -0.2 V to extract the transfer curves. We considered a device stabilised when the ratio between the standard deviation ($\sigma_{I_{DS}}$) and the average value ($\langle I_{DS} \rangle$) of the current at $V_{GS} = -0.5$ V over the last 20 transfer curves was lower than 1.2%. Subsequently, the sensor was exposed to a wide dynamic range of DA concentrations, from 100 fM to 10 μ M. For each DA concentration, we measured the device current with the DA solution as electrolyte, until stabilization of the transfer curves. Then we rinsed the device and replaced the electrolyte with successive concentrations. For each DA concentration, we recorded at least 30 transfer curves; we considered a device stabilized when five consecutive transfer curves were perfectly superimposed, or alternatively, when $\frac{\sigma_{I_{DS}}}{\langle I_{DS} \rangle}$ was smaller than 0.2% at $V_{GS} = -0.5$ V.

The device response in terms of current is calculated as the normalized current modulation relative to the blank sample (*i.e.*, buffer solution without DA): $S_{IDS} = -(I_{DS,[DA]} - I_{DS,0})/I_{DS,0}$ where $I_{DS,[DA]}$ is the current at a specific V_{GS} and $I_{DS,0}$ is the baseline current measured at the same V_{GS} in the blank sample. The theoretical LOD was estimated on the basis of the transfer curve standard deviation of the blank samples (*viz.*, in the absence of DA). The LOD is defined as the concentration of analyte that corresponds to a signal of $S_0 \pm 3\sigma$, where S_0 is the signal of the blank (set to zero according to the definition of the signal), and σ is the standard deviation of the blank sample signal. Specifically, $\sigma = \delta I_0/I_0$, where δI_0 is the standard deviation of the source-drain current (at a specific V_{GS}) of the blank sample. For the three surface-tailored MXenes tested, the data reported are the average of three sensing experiments performed with independent devices.

Data availability

The primary data supporting the conclusions of this work are included in the main text and the Supplementary Information. Any additional data can be obtained from the authors upon reasonable request.

Acknowledgments

IAB, DGP, GS, PD, OEK, and SAN would like to acknowledge funding through the Core Programme of the National Institute of Materials Physics (NIMP), granted by the Romanian Authority for Research (RAR) through the Project PC3-PN23080303. All the photoemission experiments were performed by using the National Interest Setup “System of complex XPS/ESCA installations and research using synchrotron radiation”, funded by the RAR. MB and FB would like to acknowledge the “FAR2025PD” funding (Università degli Studi di Modena e Reggio Emilia, E93C25000400005) and the “HELP-AID” Project (Bando FIS3, Ministero dell’Università e della Ricerca, E53C25002440001), respectively, for supporting part of this work. IAB would like to thank Dr. Cristian Mihail Teodorescu for his insightful discussions, suggestions, and support during this study. Special thanks are also due for his continuous financial support during these years at NIMP, which made the development of valuable MXene research within the research group possible.

Author contributions

M.B. and M.S. developed the project idea. M.G. performed all the experiments related to electrical and electrochemical characterisation of the MXene electrodes and MXene-based EGOT sensors. M.G. and A.L. prepared Figures 3-6 and related Supporting information figures and wrote the related text. M.S. and P.G wrote and edited the main manuscript, participated in the experimental design and in the early stage of materials characterisation with electrical methods. M.B. and F.B. supervised the drafting of the UNIMORE part of the manuscript, as well as provided part of the funding to support this research.

IAB, SAN, and PP synthesised all the MX samples (including the HF etching of the MAX phase). OEK and SAN performed SEM and EDS measurements. DGP and IAB performed XPS measurements, providing reports and data interpretation. IAB performed XRD measurements and interpreted the data. SAN and IAB performed Raman analysis and interpreted the data. GS performed the FTIR measurements, processed and analysed the data and provided comments and data interpretation. IAB wrote and edited the NIMP part of the manuscript; GS and SAN assisted with writing, providing guidance and corrections. All the UNIMORE and NIMP authors have read, commented, revised and approved the manuscript.

Competing Interests

The authors declare no competing financial or non-financial interests.

References

1. Singh, I., Kumar, S. & Koh, J. Innovations in wearable biosensors: A pathway to 24/7 personalized healthcare. *Measurement: Journal of the International Measurement Confederation* vol. 254 at <https://doi.org/10.1016/j.measurement.2025.117938> (2025).
2. Atta, N. F., Galal, A., Abu-Attia, F. M. & Azab, S. M. Carbon Paste Gold Nanoparticles Sensor for the Selective Determination of Dopamine in Buffered Solutions. *J. Electrochem. Soc.* **157**, F116 (2010).
3. Speranza, L., Di Porzio, U., Viggiano, D., Donato, A. De & Volpicelli, F. Dopamine: The Neuromodulator of Long-Term Synaptic Plasticity, Reward and Movement Control. (2021).
4. Oertel, W. & Schulz, J. B. Current and experimental treatments of Parkinson disease: A guide for neuroscientists. *J. Neurochem.* **139**, 325–337 (2016).
5. Lakard, S., Pavel, I. A. & Lakard, B. Electrochemical biosensing of dopamine neurotransmitter: A review. *Biosensors* vol. 11 at <https://doi.org/10.3390/bios11060179> (2021).
6. Johnson, J. A. & Mark Wightman, R. Cyclic voltammetric measurements of neurotransmitters. *Electrochem. Soc. Interface* **26**, 53–57 (2017).
7. Joseph, X. B., Umesh, N. M., Wang, S. F. & Jesila, J. A. CoFe₂O₄supported g-C₃N₄nanocomposite for the sensitive electrochemical detection of dopamine. *New J. Chem.* **45**, 18131–18138 (2021).
8. He, C. *et al.* Microelectrode-Based Electrochemical Sensing Technology for in Vivo Detection of Dopamine: Recent Developments and Future Prospects. *Critical Reviews in Analytical Chemistry* vol. 52 544–554 at <https://doi.org/10.1080/10408347.2020.1811946> (2022).
9. Gualandi, I. *et al.* Selective detection of dopamine with an all PEDOT:PSS Organic Electrochemical Transistor. *Sci. Rep.* **6**, 1–10 (2016).
10. Giordani, M. *et al.* Neuromorphic Organic Devices that Specifically Discriminate Dopamine from Its Metabolites by Nonspecific Interactions. *Adv. Funct. Mater.* **30**, 1–13 (2020).
11. Giordani, M. *et al.* Specific Dopamine Sensing Based on Short-Term Plasticity Behavior of a Whole Organic Artificial Synapse. *ACS Sensors* **2**, 1756–1760 (2017).
12. Rondelli, F. *et al.* A Single Electrode Organic Neuromorphic Device for Dopamine Sensing in Vivo. *Adv. Electron. Mater.* **10**, (2024).
13. Torricelli, F. *et al.* Electrolyte-gated transistors for enhanced performance bioelectronics. *Nature Reviews Methods Primers* vol. 1 at (2021).
14. Genitoni, M. *et al.* Discrimination of Tryptophan Enantiomers at Sub-pm Level by Multiparametric Analysis of a Label-Free Organic Immunosensor. *Small Methods* **10**, (2025).

15. Sensi, M. *et al.* Reduced Graphene Oxide Electrolyte-Gated Transistor Immunosensor with Highly Selective Multiparametric Detection of Anti-Drug Antibodies. *Adv. Mater.* **35**, (2023).
16. Selvaraj, M. *et al.* Label free detection of miRNA-21 with electrolyte gated organic field effect transistors (EGOFETs). *Biosens. Bioelectron.* **182**, (2021).
17. Berto, M. *et al.* EGOFET Peptide Aptasensor for Label-Free Detection of Inflammatory Cytokines in.pdf. *Adv. Biosyst.* **2**, (2018).
18. Demuru, S. *et al.* All-Inkjet-Printed Graphene-Gated Organic Electrochemical Transistors on Polymeric Foil as Highly Sensitive Enzymatic Biosensors. *ACS Appl. Nano Mater.* **5**, 1664–1673 (2022).
19. Sergi, I. *et al.* Dual-compartment-gate organic transistors for monitoring biogenic amines from food. *Biosens. Bioelectron.* **271**, (2025).
20. Tang, H., Lin, P., Chan, H. L. W. & Yan, F. Highly sensitive dopamine biosensors based on organic electrochemical transistors. *Biosens. Bioelectron.* **26**, 4559–4563 (2011).
21. Casalini, S., Leonardi, F., Cramer, T. & Biscarini, F. Organic field-effect transistor for label-free dopamine sensing. *Org. Electron.* **14**, 156–163 (2013).
22. Ji, W. *et al.* Carbonized silk fabric-based flexible organic electrochemical transistors for highly sensitive and selective dopamine detection. *Sensors Actuators, B Chem.* **304**, (2020).
23. Zhou, X. *et al.* Self-Assembly of 3D-Printed Multiscale Micropillar-Based Organic Electrochemical Transistors for Ultrasensitive Dopamine Sensing. *ACS Nano* **19**, 39615–39627 (2025).
24. Soliman, I. & Gunathilake, C. Aptamer-enhanced organic electrochemical transistors for ultra-sensitive dopamine detection. *Next Mater.* **3**, (2024).
25. Naguib, M. *et al.* Two-dimensional nanocrystals produced by exfoliation of Ti 3AlC 2. *Adv. Mater.* **23**, 4248–4253 (2011).
26. Lunghi, A. *et al.* MXene-Based Conductive Micropatterned Composites Promote Myogenic Differentiation of Muscle Cells. *Small Struct.* **7**, (2026).
27. Hart, J. L. *et al.* Control of MXenes' electronic properties through termination and intercalation. *Nat. Commun.* **10**, (2019).
28. Barman, S. C. *et al.* Antibody-functionalized MXene-based electrochemical biosensor for point-of-care detection of vitamin D deficiency. *Commun. Mater.* **6**, (2025).
29. Ankitha, M., Shabana, N., Mohan Arjun, A., Muhsin, P. & Abdul Rasheed, P. Ultrasensitive electrochemical detection of dopamine from human serum samples by Nb₂CTx-MoS₂ hetero structures. *Microchem. J.* **187**, 108424 (2023).
30. Wang, H. *et al.* In situ polymerized Ti₃C₂Tx/PDA electrode with superior areal capacitance for supercapacitors. *J. Alloys Compd.* **778**, 858–865 (2019).

31. Boota, M. *et al.* Interaction of Polar and Nonpolar Polyfluorenes with Layers of Two-Dimensional Titanium Carbide (MXene): Intercalation and Pseudocapacitance. *Chem. Mater.* **29**, 2731–2738 (2017).
32. Chen, C. *et al.* Effect of glycine functionalization of 2D titanium carbide (MXene) on charge storage. *J. Mater. Chem. A* **6**, 4617–4622 (2018).
33. Boota, M. *et al.* Probing Molecular Interactions at MXene-Organic Heterointerfaces. *Chem. Mater.* **32**, 7884–7894 (2020).
34. Xu, B. *et al.* Ultrathin MXene-Micropattern-Based Field-Effect Transistor for Probing Neural Activity. *Adv. Mater.* **28**, 3333–3339 (2016).
35. Zhou, R. *et al.* High-performance Pt/Ti₃C₂T_x MXene based graphene electrochemical transistor for selective detection of dopamine. *Anal. Chim. Acta* **1201**, (2022).
36. Saha, D., Dalmieda, J. & Patel, V. Surface-Modified MXenes: Simulation to Potential Applications. *ACS Applied Electronic Materials* vol. 5 2933–2955 at <https://doi.org/10.1021/acsaelm.3c00076> (2023).
37. Zhang, K. *et al.* Enhancing the magnetism of 2D carbide MXene Ti₃C₂T_x by H₂ annealing. *Carbon N. Y.* **157**, 90–96 (2020).
38. Schied, M. *et al.* Reactivity of Ti₃C₂T_x MXene with Atomic Hydrogen: Tuning of Surface Terminations by Halogen Removal and Reversible O to OH Conversion. *Chem. Mater.* **36**, 11905–11919 (2024).
39. Ahmadian, Z., Mohammadi, S., Mortazavi, Y. & Khodadadi, A. A. Stable N-doped Ti₃C₂T_x gas sensors for recoverable detection of ammonia at room temperature. *Ceram. Int.* **49**, 38635–38643 (2023).
40. Gao, J. *et al.* Thermal Stability of MXene: Current Status and Future Perspectives. *Small* vol. 21 at <https://doi.org/10.1002/sml.202505881> (2025).
41. Cai, M. *et al.* Nitrogen-doped Ti₃C₂T_x MXene prepared by thermal decomposition of ammonium salts and its application in flexible quasi-solid-state supercapacitor. *Chem. Eng. J.* **458**, 141338 (2023).
42. Yadav, P. *et al.* Development of high-performance NH₃ gas sensor through novel MoSe₂/PANI/Ti₃C₂T_x composite for medical diagnosis and industrial applications. *npj 2D Mater. Appl.* **9**, (2025).
43. Liu, J. *et al.* Ti₃C₂T_x MXene Quantum Dots with Surface-Terminated Groups (-F , -OH , = O , -Cl) for Ultrafast Photonics. 1–13 (2022).
44. Sarycheva, A. & Gogotsi, Y. Raman Spectroscopy Analysis of the Structure and Surface Chemistry of Ti₃C₂T_x MXene. *Chem. Mater.* **32**, 3480–3488 (2020).

45. Adomaviciute-Grabusove, S. *et al.* Monitoring Ti₃C₂Tx MXene Degradation Pathways Using Raman Spectroscopy. *ACS Nano* **18**, 13184–13195 (2024).
46. Parker, T. *et al.* Fourier-Transform Infrared Spectral Library of MXenes. *Chem. Mater.* **36**, 8437–8446 (2024).
47. Li, Y. *et al.* Facile preparation of in situ coated Ti₃C₂Tx/Ni_{0.5}Zn_{0.5}Fe₂O₄ composites and their electromagnetic performance. *RSC Adv.* **7**, 24698–24708 (2017).
48. Wen, Y. *et al.* Nitrogen-doped Ti₃C₂Tx MXene electrodes for high-performance supercapacitors. *Nano Energy* **38**, 368–376 (2017).
49. Maleski, K., Mochalin, V. N. & Gogotsi, Y. Dispersions of Two-Dimensional Titanium Carbide MXene in Organic Solvents. *Chem. Mater.* **29**, 1632–1640 (2017).
50. Guo, T. *et al.* Tailoring Surface Chemistry of Ti₃C₂N_x MXene for Superior H⁺, Li⁺, and Na⁺ Storage via Molten Salt-Derived N-Termination. *Small* **21**, (2025).
51. Anjum, N. *et al.* Electrochemical Impedance Analysis of Ti₃C₂Tx MXene for Pseudocapacitive Charge Storage. *J. Compos. Sci.* **9**, 1–21 (2025).
52. Rozmysłowska-Wojciechowska, A. *et al.* Engineering of 2D Ti₃C₂ MXene surface charge and its influence on biological properties. *Materials* vol. 13 at <https://doi.org/10.3390/ma13102347> (2020).
53. Zanotti, R. *et al.* Charge Carrier Density in Organic Semiconductors Modulates the Effective Capacitance: A Unified View of Electrolyte Gated Organic Transistors. *Adv. Mater.* **36**, (2024).
54. Keene, S. T. *et al.* A biohybrid synapse with neurotransmitter-mediated plasticity. *Nat. Mater.* **19**, 969–973 (2020).
55. Swenson, H. & Stadie, N. P. Langmuir's Theory of Adsorption: A Centennial Review. *Langmuir* **35**, 5409–5426 (2019).
56. McNaught, A. D. & Wilkinson, A. *IUPAC Compendium of Chemical Terminology*. (Oxford, 1997).
57. Sakata, T. Signal transduction interfaces for field-effect transistor-based biosensors. *Commun. Chem.* **7**, 1–14 (2024).
58. Parkula, V. *et al.* Harnessing selectivity and sensitivity in electronic biosensing: A Novel Lab-on-Chip Multigate Organic Transistor. *Anal. Chem.* **92**, 9330–9337 (2020).
59. Rajh, T. *et al.* Surface restructuring of nanoparticles: An efficient route for ligand-metal oxide crosstalk. *J. Phys. Chem. B* **106**, 10543–10552 (2002).
60. Mariani, F. *et al.* Needle-type organic electrochemical transistor for spatially resolved detection of dopamine. *Microchim. Acta* **187**, (2020).

Figure legends

Figure 1: Morphological and structural characterisation of surface-tailored MXenes. SEM images of Ar-MX (A), H₂-MX (B) and N-MX (C) samples. (D) XRD patterns (with 002 peak region zoomed in the inset). (E) Raman spectra (with D and G bands region zoomed in the inset). (F) FTIR spectra (with the fingerprint region zoomed in the inset) for Ar-MX (blue), H₂-MX (red) and N-MX (green) samples.

Figure 2: XPS surface chemistry characterisation of surface-engineered MXenes. (A) C 1s spectra, (B) Ti 2p spectra for Ar-MX (left), H₂-MX (middle) and N-MX (right) samples.

Figure 3: Functionalization of gold electrodes with surface-engineered MXenes. (A) Low and (B) high magnification SEM images of Au gate electrodes covered with surface-engineered MXenes. (C) CVs of the Au and Au/MXenes electrodes, recorded in the K₃[Fe(CN)₆] redox probe, scan rate 100 mV/s. (D) EIS Nyquist plots of the Au and Au/MXenes electrodes, recorded in the K₃[Fe(CN)₆] redox probe, E = 260 mV vs Ag/AgCl.

Figure 4: Architecture and electrical characterisation of the MXene-functionalized EGOT device. (A) Scheme of the EGOT device; (B) Layout of the MXene-EGOT DA sensor; (C) Representative transfer curves recorded with gold (yellow), H₂-MX (red), N-MX (green), Ar-MX (blue) electrode; (D) corresponding transconductance (viz., first derivative of I_{DS} vs V_{GS}). $V_{DS} = -0.2$ V, 50 mM PB electrolyte.

Figure 5: Electrical characterisation in the presence of Dopamine. Representative EGOT transfer curves for Ar-MX electrode (blue curves, A), H₂-MX electrode (red curves, B), N-MX electrode (green curves, C). Black dashed lines are the best fit curves obtained using eq 18 in Zanotti et al.⁵³. (D-F) The experimental transconductance (g_m) profile for the three surface-tailored MXene samples. (G-I) The transconductance profile obtained as the first derivative of the transfer characteristics best fit curves, modelled with eq. 18 reported in Zanotti et al.⁵³ (J-L) Differences between the experimental and the modelled transconductance profiles, normalised for the modelled g_m profiles. Grey profiles represent 50 mM PB in the absence of DA. The increasing color intensity of the curves corresponds to increasing DA concentrations (from 100 fM to 10 μ M).

Figure 6: Dopamine sensing. (A-B) Semilog plot of the current signal $S_{I_{DS}}$ calculated at $V_{GS} = -0.5$ V and of the linear transconductance signal $S_{g_{m,l}}$ vs [DA]. (C) Correlation plot of the normalized I_{DS} change ($S_{I_{DS@-0.5V}}$), against the normalized $g_{m,l}$ ($S_{g_{m,l}}$) for each DA concentration. The two distinct sensing regimes are identified with the linear fit reported as guide-for-the eye. (D) Semilog plot of the ΔV_T vs [Dopamine]. In all the plots, we use blue dots for the Ar-MX electrode, red dots for the H₂-MX electrode and green dots for the N-MX electrode. The error bars are the standard error of the mean. The dashed lines are the

result of the fitting with Equation 1. The blue and orange areas define the two different sensing regimes.

Table 1: XPS and EDS elemental composition of Ar-MX, H₂-MX, and N-MX samples.

ARTICLE IN PRESS