

# 1 **Enhanced stability of electrochemical performance of few-layer black** 2 **phosphorus electrodes by noncovalent adsorption of 1,4-diamine-9,10-** 3 **anthraquinone**

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Paweł Jakóbczyk<sup>1\*</sup>, Anna Dettlaff<sup>2</sup>, Grzegorz Skowierzak<sup>3</sup>, Tadeusz Ossowski<sup>3</sup>, Jacek Ryl<sup>4</sup>, Robert Bogdanowicz<sup>1</sup>

<sup>1</sup>*Department of Metrology and Optoelectronics, Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, Gabriela Narutowicza 11/12, 80-233 Gdańsk, Poland*

<sup>2</sup>*Department of Energy Conversion and Storage, Faculty of Chemistry, Gdańsk University of Technology, Gabriela Narutowicza 11/12, 80-233 Gdańsk, Poland*

<sup>3</sup>*Department of Analytical Chemistry, Faculty of Chemistry, University of Gdańsk, 63 Wita Stwosza St., 80-952 Gdańsk, Poland*

<sup>4</sup>*Institute of Nanotechnology and Materials Engineering, Faculty of Applied Physics and Mathematics, Gdańsk University of Technology, Gabriela Narutowicza 11/12, 80-233 Gdańsk, Poland*

5 \* Corresponding author.

6 E-mail address: [pawel.jakobczyk@pg.edu.pl](mailto:pawel.jakobczyk@pg.edu.pl) (P. Jakóbczyk).

7

## 8 **Abstract**

9 In this paper, the novel noncovalent functionalisation strategy of few-layer black phosphorus  
10 by 1,4-diamine-9,10-anthraquinone electrode was proposed and studied. The degradation of  
11 few-layer black phosphorus under exposure to oxygen and water is a significant obstacle to its  
12 use as an electroanalytical electrode. The anthraquinone compound adsorbed at black  
13 phosphorus flakes results in improved prevention of the phosphorus surface against degradation  
14 and electrode decomposition. Furthermore, a large concentration of amino group present in 1,4-  
15 diamine-9,10-anthraquinone enhances the electrochemical performance of electrode revealed  
16 by a faster rate of heterogeneous electron transfer observed in cyclic voltammetry studies. The  
17 designed electrode exhibits stable redox peaks over 100 cycles with separation between the  
18 peaks of  $79 \pm 2$  mV and the formal redox potential reaching  $257 \pm 3$  mV. The differential pulse  
19 voltammetry was utilised for the detection of ascorbic acid, revealing a limit of detection equal  
20 to 3.29 ppm (18.68  $\mu$ M) and a limit of quantification of 9.98 ppm (56.66  $\mu$ M). The linear range  
21 of 1-20 ppm was achieved, allowing for the detection of ascorbic acid in real conditions. Thus,

1 anthraquinone-modified few-layer black phosphorus may be an attractive novel electrode  
2 material for sensitive electroanalytical applications.

3 **Keywords:** few-layer black phosphorus, 1,4-diamine-9,10-anthraquinone, noncovalent  
4 functionalisation, electrochemical properties, electrochemical sensor

5

## 6 **1. Introduction**

7 During the last decade, 2D nanomaterials such as transition metal dichalcogenides or graphene  
8 have been explored extensively as promising materials for future electronics applications. In  
9 2014, the family of 2D materials was expanded by a new member, phosphorene, a monolayer  
10 of black phosphorus - BP (phosphorus allotrope). The phosphorene forms a puckered  
11 honeycomb structure in which each phosphorus atom is covalently bonded to 3 nearest  
12 neighbours. Similar to graphene and graphite, the BP monolayers are interconnected in black  
13 phosphorus by van der Waals interactions. Hence, the bulk black phosphorus can be exfoliated  
14 down to a single or few layers using chemical or physical forces. Recently, the BP nanosheets  
15 can be fabricated via electrochemical exfoliation [1,2], ball-milling [3], chemical vapour  
16 deposition [4] or ultrasonic liquid phase exfoliation [5–7].

17 Only a few papers describe the electrochemical properties of phosphorus. Hermes & Scholz  
18 described the electrochemical properties of white phosphorus [8]. The electrochemical  
19 oxidation layered black phosphorus in different pH has been studied [9]. Dettlaff et al.[7]  
20 investigated electrochemical stability of few-layer black phosphorene fabricated in different  
21 ultrasonic horn power using voltammetry and impedance technique. Properties of phosphorene  
22 like a large surface make it suitable for sensors and catalysis. In order to obtain the required  
23 electrochemical properties and stability under ambient conditions, it is subjected to various  
24 modifications [10]. BP exhibits anisotropic electrochemical properties, thanks to which the  
25 electron transfer is much faster at the edge sites than at the base plane [9]. This strategy was  
26 used to build electrochemical sensors. Faster charge transfer [11], higher adsorption [12],



1 improved conductivity [13,14], protection against degradation [15], defects [16] are the  
2 directions of changes in the properties of phosphorene that can be observed in the literature.

3 Research on phosphorene-based sensors has included: electrochemical sensors [14,17],  
4 electrochemical biosensors (enzyme electrodes [18,19], electrochemical aptasensors [20],  
5 electrochemical immunosensors [21,22], mixed aptamer immunosensors [23]),  
6 electrochemiluminescence [24,25].

7 The major hurdle for phosphorene in processing and application as the sensor is its fast  
8 oxidation and degradation in ambient conditions. Simultaneous dispositions of light, oxygen,  
9 and water cause the ageing process [7,26–28]. In order to enhance the ambient stability of  
10 phosphorene, its surface can be chemically modified. In particular, the phosphorene has been  
11 covalently functionalised by diazonium salt [29], azide [30], nucleophilic reagents [31], and  
12 noncovalently by poly-L-lysine [18], anthraquinone [32], and surface encapsulation [33].

13 Up to date, only Gusmão et al. [32] reported profitable phosphorene modification by  
14 anthraquinone for electrochemical application. Nevertheless, they applied plain anthraquinone  
15 targeting the application of that system to energy storage applications.

16 Rapid and cheap determination of vitamin C is still an area researched by scientists due to the  
17 great importance of ascorbic acid both for human life (in clinical samples) and applications in  
18 the pharmaceutical and food industries. Electrochemical techniques [34–36],  
19 spectrophotometry [37], spectrofluorometry [38], fluorescence [39,40], titration [41,42],  
20 electrophoresis [43] and high performance liquid chromatography (HPLC) [44,45] are common  
21 techniques used to detect ascorbic acid. The electrochemical sensors are the most commonly  
22 used by scientists to detect ascorbic acid due to its high sensitivity, low cost and simplicity [46].

23 A compound with a detection potential below the oxidation potential of phosphorus (0.65 V)  
24 [9] was selected for sensory experiment. Ascorbic acid meets this criterion. The detection of



1 any compound in the phosphorus oxidation potential could lead to an erroneous current  
2 response due to phosphorus oxidation.

3 This work has shown for the first time the noncovalent functionalisation of phosphorene with  
4 1,4-diamine-9,10-anthraquinone (1,4-DAAQ). Applied 1,4-DAAQ has amino moieties  
5 resulting in synergistic enhancement of electrochemical properties and delivering surface  
6 functional amino groups for further bio-oriented, electroanalytical applications (i.e. antigen or  
7 aptamer grafting). 1,4-DAAQ is adsorbed at few-layer black phosphorus (FLBP) and thus  
8 protects the phosphorus from rapid degradation under oxygen and water conditions resulting in  
9 enhanced stability of the designed electrode. The proposed modified FLBP was successfully  
10 used for ascorbic acid detection using differential pulse voltammetry (DPV).

## 11 **2. Experimental**

12

### 13 *2.1 Reagents*

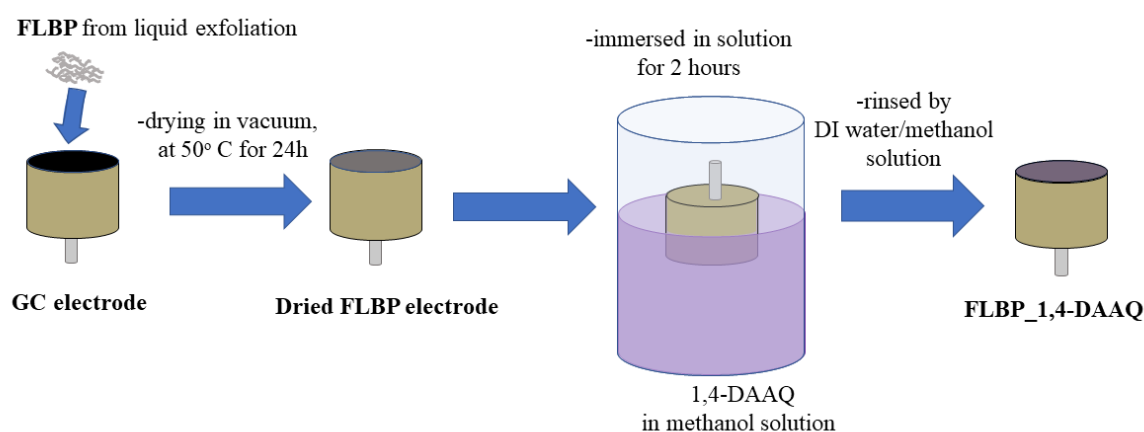
14 Black phosphorus (BP, >99.99%) was obtained from Smart Elements. 1-Methyl-2-  
15 pyrrolidinone (NMP), anhydrous, purity: 99.5%) was collected from Sigma Aldrich. 1,4-  
16 diamino-9,10-anthraquinone (1,4-DAAQ, >90%) was purchased from Fluka. Methanol  
17 (MeOH, 99%) was collected from Stanlab. The sodium sulfate (ACS reagent, purity  $\geq 99\%$ ,  
18 Aldrich), potassium hexacyanoferrate (III) (pure p. a., Chempur), and hydrochloric acid (35-  
19 38%, Chempur) aqueous solutions were prepared using demineralised water. The argon was  
20 collected from Air Liquid and was of the highest purity class. All reagents were used without  
21 further purification.

22

### 23 *2.2 Black Phosphorus Liquid Exfoliation and Functionalisation*

24 Pre-crushed BP (30 mg) was added to deoxygenated NMP solvent (7 ml). The process of liquid  
25 exfoliation was realised in an ice-cooled bath, at a temperature from 0 to 3 °C, under a stream

1 of argon using a horn probe ultrasonicator (Bandelin Sonopuls HD2200, 20 kHz). The  
2 sonication tip was set to a power of 40 W, and ON/OFF time equals 0.5/0.5 s. The mixture was  
3 sonicated in the ice bath (0-3°C) under a stream of argon. The sonication-aided exfoliation  
4 process took 4 hours. Afterwards, the resultant suspension was centrifuged at 11 000 rpm for  
5 15 min to remove the residual unexfoliated particles, yielding yellowish supernatant. The few-  
6 layer black phosphorus electrode (FLBP electrode) was made by applying the supernatant to a  
7 glassy carbon electrode and dried in a vacuum chamber at 60 Celsius degrees. Then the FLBP  
8 electrode was immersed in a 0.001 M 1,4-DAAQ solution in methanol: water mixture (volume  
9 ratio, 1:1) for 2 h.  
10 The next step was to wash the electrode with a solution of methanol and water (volume ratio,  
11 1: 1). The functionalised FLBP electrode with 1,4-DAAQ (FLBP\_1,4-DAAQ electrode) was  
12 used for electrochemical measurements. In Fig. 1, the scheme of FLBP noncovalent  
13 functionalisation using 1,4-DAAQ is shown.



14  
15 **Fig. 1.** Scheme of the glassy carbon modification by few-layer black phosphorus and next noncovalent FLBP  
16 functionalisation using 1,4-diamino-9,10-anthraquinone.

17  
18 *2.3. Electrode characterisation*

19 X-ray photoelectron spectroscopy (XPS) analysis was carried out to determine changes in the  
20 chemical composition of functionalised FLBP electrodes and get information on the oxidation

1 of FLBP\_1,4-DAAQ and FLBP electrode surfaces. XPS measurements were performed using  
2 Escalab 250Xi spectroscope (ThermoFisher Scientific) using monochromatic Al K $\alpha$  X-ray  
3 source with a spot diameter of 200  $\mu$ m and pass energy 20 eV for high-resolution spectra. The  
4 adventitious carbon C1s peak at 284.6 eV was used for peak calibration.

5 The morphology and distribution of FLBP on the surface were characterised by scanning  
6 electron microscopy (SEM) and energy-dispersive X-ray (EDX) spectroscopy (Phenom XL  
7 instrument, Thermo Fisher Scientific). An accelerating voltage of 15 kV was used with a  
8 secondary electron detector (SED) working in high vacuum mode. The electrochemical studies  
9 were investigated by cyclic voltammetry (CV) and differential pulse voltammetry (DPV) in the  
10 three-electrode system using a potentiostat-galvanostat (VMP-300, BioLogic, France). The  
11 working electrode had a working area of 0.071 cm<sup>2</sup>, the counter electrode was a platinum wire,  
12 and the reference electrode was an AgCl-coated Ag wire in 3M KCl. CV measurements were  
13 carried out in 1 M HCl and in 0.5 M Na<sub>2</sub>SO<sub>4</sub> 5mM K<sub>3</sub>[Fe(CN)<sub>6</sub>], at a scan rate of 100 mV s<sup>-1</sup>  
14 for potential window and from 10 mV s<sup>-1</sup> to 700 mV s<sup>-1</sup> for redox probe tests. The optimisation  
15 of DPV parameters such as a pulse height, a pulse width, and scan rate was performed. The  
16 parameters influence on the peak current of ascorbic acid during DPV. The highest current of  
17 ascorbic acid was for potential height equals 60 mV and was considered as an optimum.  
18 However, the pulse width had no visible effect on the increase of the ascorbic acid peak current,  
19 therefore the value for which the peak shape was optimal was selected (70 ms). Next, the effect  
20 of the scan rate value, ranging from 2 to 50 mV s<sup>-1</sup> was analyzed. The highest ascorbic peak  
21 current was found at the 5 mV s<sup>-1</sup> scan rate value of 60 mV pulse height and 70 pulse width, so  
22 this value was used for subsequent studies. Moreover, the DPV measurements were performed  
23 in 0.1 M Na<sub>2</sub>SO<sub>4</sub> containing ascorbic acid with 1-20 ppm concentration.

24  
25



1 3. Results and discussion

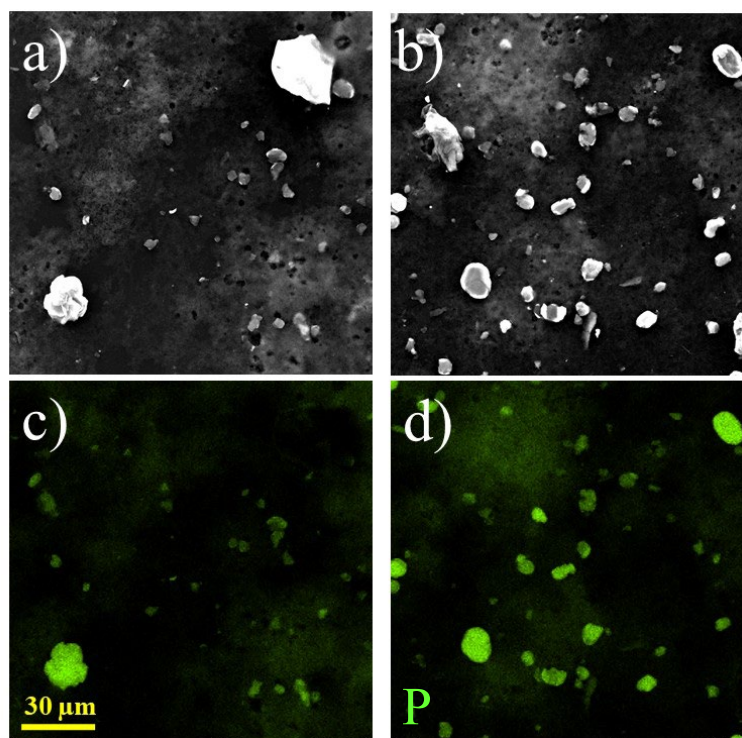
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3 3.1 Surface analysis of functionalised FLBP electrode

4

5 The layer of phosphorus particles on the glassy carbon electrode was confirmed by SEM and  
6 EDX images (Fig. 2). The deposited phosphorus layer is consisted from nano-size particles,  
7 below the resolution of SEM microscope, with a few agglomerates and residues of larger  
8 phosphorus particles, ranging in size from several to several dozen micrometres. The surface of  
9 the FLPB modified GC electrode (Fig. 2 a,c) and the modified GC electrode by FLBP and then  
10 functionalised by 1,4-DAAQ (Fig. 2 b,d) have a similar degree of coverage by phosphorus. The  
11 EDX images show that the FLBP, when functionalized by immersion in methanol: water (v / v,  
12 1: 1), does not detach from the glassy carbon surface due to functionalisation, but forms a  
13 structurally similar GC cover layer (FLBP\_1,4-DAAQ) to FLBP.

14



15

1 **Fig. 2.** SEM micro-images of electrode surfaces: (a) FLBP, (b) FLBP\_1,4-DAAQ, (c,d) EDX mapping of  
2 phosphorus.

3

4 The XPS spectra recorded in the core-level binding energy range of the P 2p signal allow us to  
5 assess the oxidation state of phosphorous. It can be seen in Figures 3a and 3b that spectra for  
6 both FLBP and FLBP\_1,4-DAAQ have well-defined P 2p doublets, with the primary P 2p<sub>3/2</sub>  
7 component located at 129.8 eV and P 2p<sub>1/2</sub> shifted by +0.5 eV, and ascribed to the P-P bonds.

8 Furthermore, the broad signal occurring ca. 134.1 eV usually is associated with phosphates or  
9 phosphorous hydroxides, in line with our previous work and other literature sources [21,22].

10 This is typical of black phosphorus, which easily oxidises under atmospheric conditions.

11 Notably, the peak intensity decreases significantly in the case of the FLBP\_1,4-DAAQ sample  
12 (Fig. 3b), suggesting that it is less prone to spontaneous surface oxidation. This negligible

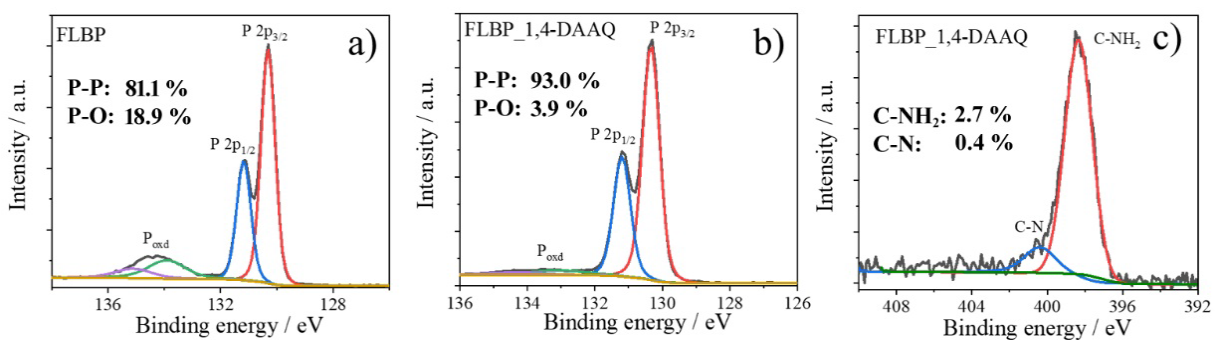
13 oxidation is caused by noncovalent interactions, mainly due to van der Waals forces. It was  
14 already noted in the literature that the noncovalent interaction significantly stabilises BP and

15 prevents its oxidation and degradation [32,47]. Finally, the FLBP\_1,4-DAAQ sample XPS

16 spectra in the N 1s peak binding energy range (Fig. 3c) may be deconvoluted using two peaks  
17 at 398.2 and 400.5 eV and characteristic of C-NH<sub>2</sub> and C-N bonds, respectively [48]. The first

18 of the two is dominant in the recorded spectra, testifying the successful functionalisation of

19 FLBP using 1,4-diamine-9,10-anthraquinone.



20

21 **Fig. 3.** High-resolution XPS of the P 2p core level for (a) FLBP, and (b) FLBP\_1,4-DAAQ. N 1s XPS spectrum  
22 of the FLBP\_1,4-DAAQ (c).



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2  
3

### 3.2 Electrochemical properties of FLBP and FLBP\_1,4-DAAQ

4 Functionalisation of the few-layer black phosphorus resulted not only in protection against  
5 oxidation but also change the electrochemical properties. Figure 4a shows the cyclic  
6 voltammetric behaviour of glassy carbon electrode (GC), modified glassy carbon electrode by  
7 few-layer black phosphorus (FLBP), and functionalised FLBP (FLBP\_1,4-DAAQ) in acid  
8 media (1 M HCl). During cyclic voltammetry (Figure 4a) the oxidation of the pristine FLBP  
9 [7,9] and FLBP\_1,4-DAAQ at 0.65 V is observed. The oxidation peak of phosphorus for  
10 FLBP\_1,4-DAAQ is visible but lower than for the pristine phosphorene, which may be due to  
11 partial coverage by 1,4-diamine-9,10-anthraquinone and a smaller oxidisable surface. In the  
12 following cycles, the peak from FLBP oxidation decreases. Peaks from 1,4-diamine-9,10-  
13 anthraquinone shown on the CV curve are attributed to the well-known 2 protons, 2 electrons  
14 quinone redox interconversion in acid media [32]. The presence of these peaks confirms the  
15 presence of anthraquinone derivatives on the surface of FLBP.

16 In the next step, fabricated electrodes were investigated versus the ferricyanide/ferrocyanide  
17 redox system to investigate the electron transfer behaviour (Figure 4b). Before the  
18 functionalisation process of FLBP electrode, one can notice the influence of the partially  
19 oxidized surface of the phosphorene on worse charge transfer resulting in a higher peak  
20 separation value ( $\Delta E_p=167 \pm 8$  mV) compared to the  $\Delta E_p$  equal to  $132 \pm 4$  mV for GC and the  
21 lowest  $\Delta E_p$  after functionalization of FLBP ( $\Delta E_p=80 \pm 3$  mV). Thanks to noncovalent  
22 modification of the FLBP, the electrode exhibited enhanced electrochemical properties (Figure  
23 4b). The surface analysis made with XPS presents that the FLBP has a higher proportion of  
24 oxygen than FLBP\_1,4-DAAQ (Fig. 3a). The differences in electrochemical properties are  
25 influenced by surface termination. Studies on the impact of boron-doped diamond (BDD)



1 termination by Granger and Swain [49] on the  $[\text{Fe}(\text{CN})_6]^{3-/4-}$  redox couple reaction show that  
2 after surface oxidation of BDD electrode the peak to peak potential separation increases for the  
3 ferricyanide/ferrocyanide reaction. After the hydrogen plasma treatment of BDD and the  
4 termination change to hydrogen,  $\Delta E$  returns to the original value and shows the effect of  
5 termination on  $\Delta E$  values. The oxygen causes deterioration of kinetic parameters. In this study,  
6 the absence of  $\text{PO}_x$  groups at the surface of FLBP\_1,4-DAAQ as proven by XPS (Fig. 3b),  
7 cause decrease of  $\Delta E_p$ . The presence of  $-\text{NH}_2$  groups derived from 1,4-DAAQ, which was  
8 confirmed electrochemically (Fig. 4b), promote charge transfer between the solution of  
9  $\text{K}_3[\text{Fe}(\text{CN})_6]$  and the functionalised electrode [11,50]. No deterioration can be seen in the course  
10 of subsequent cycles (Fig. 4c), so there is also no formation of irreversible adsorbates of  
11  $[\text{Fe}(\text{CN})_6]^{3-/4-}$  as it occurs at the platinum surface [49].

12 From the CV curves recorded in redox system it is also feasible to determine the electrode  
13 reaction kinetics [51]. Hence, it is possible to measure the reaction of electron transfer through  
14 the modified and unmodified FLBP electrodes. The estimated electrochemical parameters are  
15 gathered in Table 1. As can be seen, higher peak current densities of oxidation ( $j_{p,ox}$ ) and  
16 reduction ( $j_{p,red}$ ) of redox mediator are promoted on the FLBP\_1,4-DAAQ electrode. The values  
17 of  $j_{p,ox}$  are equal to  $0.88 \pm 0.03 \text{ mA cm}^{-2}$  and  $0.57 \text{ mA cm}^{-2}$  for FLBP\_1,4-DAAQ and FLBP,  
18 respectively, which follows from lower electrode resistance and easier charge transfer which  
19 can also be related to the presence of 1,4-diamine-9,10-anthraquinone on the electrode surface  
20 [11].

21 The heterogeneous electron transfer  $k^o$  for FLBP and FLBP\_1,4-DAAQ were calculated using  
22 Eq. (1) according to the Nicholson method [52,53].

23

$$k^o = \psi \cdot \sqrt{\frac{\pi \cdot D \cdot \nu \cdot F \cdot n}{R \cdot T}} \quad (1)$$

1 where  $\psi$  is a kinetic parameter,  $D$  corresponds to the diffusion coefficient ( $7.6 \cdot 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ )  
 2 [54,55],  $v$  is the scan rate,  $n$  reflects the number of electrons,  $R$  is the molar gas constant,  $T$  is  
 3 the temperature.

4 **Table 1.** Comparison of electrochemical parameters of FLBP-based electrode estimated for  
 5  $100 \text{ mV s}^{-1}$  scan rate.

	FLBP_1,4-DAAQ	FLBP
$E_{p,ox} / \text{mV}$	$297 \pm 5$	$332 \pm 7$
$j_{p,ox} / \text{mA cm}^{-2}$	$0.88 \pm 0.03$	$0.57 \pm 0.07$
$E_{p,red} / \text{mV}$	$217 \pm 4$	$165 \pm 6$
$j_{p,red} / \text{mA cm}^{-2}$	$0.93 \pm 0.04$	$0.63 \pm 0.06$
$j_{p,red} / j_{p,ox}$	1.06	1.11
$\Delta E_p / \text{mV}$	$80 \pm 3$	$167 \pm 8$
$E_f / \text{mV}$	$257 \pm 6$	$249 \pm 9$
$\Lambda$	2.36	0.35
$\Psi$	1.33	0.20
$k^o / \text{cm s}^{-1}$	$1.29 \cdot 10^{-2}$	$1.88 \cdot 10^{-3}$

6 \*assumption: charge transfer coefficient  $\alpha = 0.5$

7

8 FLBP\_1,4-DAAQ shows a faster rate of heterogeneous electron transfer compared to the layer  
 9 without functionalisation ( $1.29 \cdot 10^{-2} \text{ cm s}^{-1}$  and  $1.88 \cdot 10^{-3} \text{ cm s}^{-1}$ , respectively), which indicates  
 10 better electron transfer of the layer than the bare FLBP.

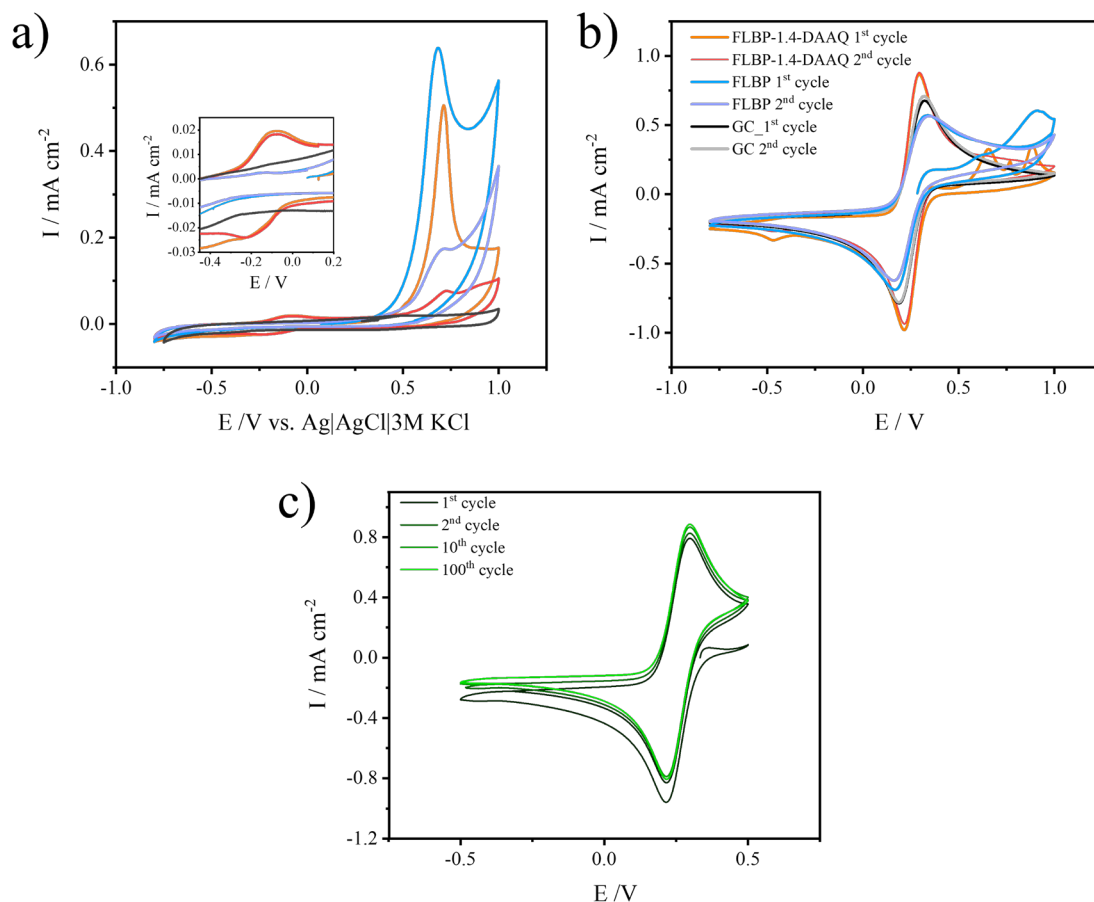
11 Furthermore, the value of the half potential,  $E_{p/2}$ , for electrochemically reversible reaction  
 12 should be equal to 56.5 mV and the  $j_{p,red} / j_{p,ox}$  ratio is 1 [54]. In our case, for the FLBP\_1,4-  
 13 DAAQ electrode the values are slightly higher  $E_{p/2} = 58 \text{ mV}$  and  $j_{p,red} / j_{p,ox} = 1.06$ , which suggest  
 14 a electrochemically quasi-reversible nature of electrode process. In order to confirm the quasi-  
 15 reversible reaction the Matsuda and Ayabe  $\Lambda$  parameter was calculated using Eq. (2) [54,56].

$$16 \quad \Lambda = k^o \cdot \sqrt{\frac{R \cdot T}{F \cdot D \cdot v \cdot n}} \quad (2)$$

1 The estimated  $\Lambda$  values are equal to 0.35 and 2.36 for FLBP and FLBP\_1,4-DAAQ,  
2 respectively. For both electrodes, the value of Matsuda and Ayabe parameter is in the quasi-  
3 reversible zone ( $15 > \Lambda > 10^{-3}$ ) [56], which indicate quasi-reversible redox reactions of  
4  $[\text{Fe}(\text{CN})_6]^{3-/4-}$  pair for scan rate of  $100 \text{ mV s}^{-1}$ . Thus, both mass transport and charge transfer  
5 influence the electrode reaction [54,56,57]. However, the parameters calculated for  
6 functionalised electrode show more facile electrode kinetics and are closer to the values  
7 corresponding to reversible reactions. Other parameters also suggest a quasi-reversible reaction.  
8 The kinetic parameter  $\psi$  for FLBP it is much lower and amounts to only 0.2 ( $\psi = 0.001$  refers  
9 to a totally irreversible reaction [52]). The previously calculated HET is also in a region  
10 classified as quasi-reversible, i.e. in the range from  $0.095 \text{ cm s}^{-1}$  to  $6.32 \cdot 10^{-6} \text{ cm s}^{-1}$  ( $T = 298 \text{ K}$ ,  
11  $v = 0.1 \text{ V s}^{-1}$ ,  $D = 7.6 \cdot 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ , and  $\alpha = 0.5$ ) [54,56].

12 Characterisation of electrochemical processes in terms of electrode stability was performed by  
13 100 cycles (Figure 4c) in the ferricyanide/ferrocyanide redox system in a basic electrolyte  
14 solution ( $0.5 \text{ M Na}_2\text{SO}_4$ ) below the phosphorus oxidation potential. The  $[\text{Fe}(\text{CN})_6]^{3-/4-}$  has a  
15 similar interaction with the surface as ascorbic acid [49,50], in both cases there is outer sphere  
16 electron transfer, therefore the stability of the system is shown for the  $[\text{Fe}(\text{CN})_6]^{3-/4-}$  redox  
17 system. Current response after 100 cycles slightly increased (7.4%). The separation between  
18 the peaks ( $\Delta E_p$ ) after 100 cycles is stable at  $79 \pm 2 \text{ mV}$ , while the formal redox potential ( $E_f$ )  
19 was  $257 \pm 3 \text{ mV}$ . The stability of the electrode operation can also be observed after the slight  
20 variation of the peak currents after the initial cycle. The ideal reversible electrochemical  
21 behaviour demonstrates the strong adsorption of 1,4-DAAQ on the electrode surface.

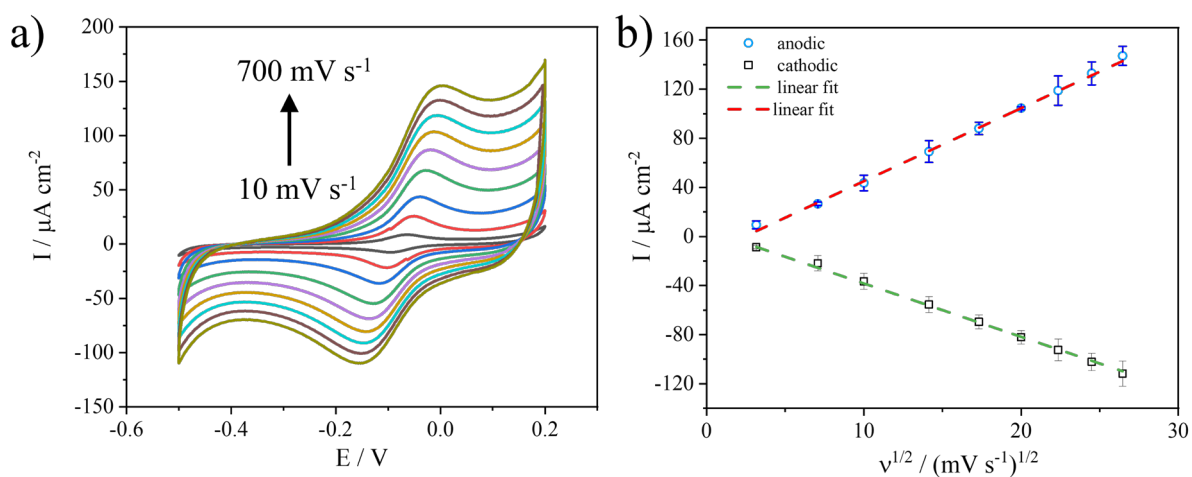




1  
 2 **Fig. 4.** CVs obtained for a) GC, FLBP, FLBP\_1,4-DAAQ electrode in 1M HCl; b) GC, FLBP, FLBP\_1,4-DAAQ  
 3 electrode in 1 mM  $K_3[Fe(CN)_6]$  in 0.5  $Na_2SO_4$ ; c) FLBP\_1,4-DAAQ electrode in 1 mM  $K_3[Fe(CN)_6]$  in 0.5  
 4  $Na_2SO_4$ ; vs. Ag/AgCl in 3M KCl. Scan rate: 100  $mV s^{-1}$ .

5  
 6 On the basis of the shape of the voltammograms, the limiting factor of the process could be  
 7 predicted. The bell-type shape of curves corresponds to an adsorption wave or a draw-out type  
 8 corresponding to a diffusional-type wave. Figure 5a displays the draw-out waves, but their  
 9 shape is strongly affected by chemical interactions with reaction intermediates and solvent  
 10 molecules, e.g., partially surface oxidised phosphorene and residuals of NMP from FLBP  
 11 fabrication step, 1,4-DAAQ adsorption. When redox species in solution are partially adsorbed  
 12 to the surface, the electrode process is far from predictable shape typical for adsorption due to  
 13 the very high concentration in the adsorbed state. However, according to the literature, a draw-  
 14 out-shaped wave also could be observed for the adsorbed control reaction [58]. Deviations of  
 15 the curves may be attributed to electrostatic effects incurred by neighbouring charged species

1 [59]. The capacitive nature of the current response complicates the determination of ongoing  
 2 processes. The curve's character could interfere with the diffusion process. Due to the  
 3 mentioned elements, it is challenging to determine the nature of the processes taking place on  
 4 the electrode. However, the curve shows the dependence characteristic for diffusion (linear  
 5 dependence of the peak currents on the square root of the scan rate) (Fig. 5b). As can be seen,  
 6 the cathodic and anodic peak currents increased with the sweep rate. Moreover, there is an  
 7 asymmetry between the oxidation and reduction peaks, which demonstrated a more complex  
 8 electrode process related as previously mentioned interactions with NMP residuals.



9  
 10 **Fig. 5.** Cyclic voltammograms of a) FLBP\_1,4-DAAQ electrode in 1M HCl at scan rates from 10 to 700  $\text{mV s}^{-1}$ .  
 11 The linear variation of the Faradaic process of b) FLBP\_1,4-DAAQ electrode, the dependence of the peak  
 12 current of the electrode process on the square root of the scan rate.

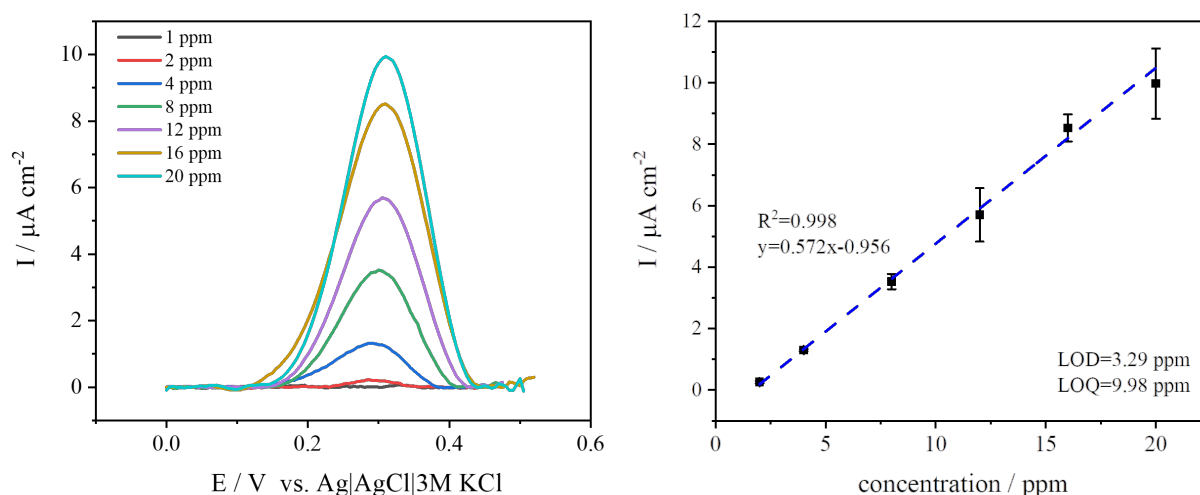
### 13 3.3 Detection of ascorbic acid on the FLBP\_1,4-DAAQ electrode

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 15  
 16  
 17 The functionalised electrode (FLBP\_1,4-DAAQ) was used to determine ascorbic acid in 0.1 M  
 18  $\text{Na}_2\text{SO}_4$  solution. Differential pulse voltammetry (DPV) was applied as the detection method  
 19 due to excellent background suppression and higher sensitivity than the CV technique. The  
 20 FLBP\_1,4-DAAQ electrode, thanks to the use of 1,4-diamine-9,10-anthraquinone enhancing  
 21 electroanalytical properties, could be utilised for electrochemical detection.



1 Figure 6a exhibits the current response versus increasing ascorbic acid concentrations in the  
 2 range from 1 to 20 ppm. Figure 6b shows a linear calibration curve ( $R^2=0.998$ ) over the 1-20  
 3 ppm concentration range. The resulting linear dependence is characterised by a high value of  
 4 the slope coefficient ( $0.572 \mu\text{A cm}^{-2} \text{ ppm}^{-1}$ ), which proves the high sensitivity of the tested  
 5 electrode. The adsorbed 1,4-diamine-9,10-anthraquinone molecules are ascribed for improved  
 6 detection since they attract ascorbic acid molecules by the  $\pi$ - $\pi$  interactions. Additionally, the -  
 7  $\text{NH}_2$  groups of the adsorbed compound enhance the electron transfer in the electrode reaction.

8



9 **Fig. 6.** Detection of ascorbic acid: a) Differential pulse voltammograms of varying ascorbic acid concentrations in  
 10 0.1 M  $\text{Na}_2\text{SO}_4$  in the range from 1 ppm to 20.0 ppm; b) the linear fit of concentration vs peak current density of  
 11 FLBP\_1,4-DAAQ electrode.

12

13 To investigate the electrode-to-electrode reproducibility, five different electrodes were used to  
 14 determine 12 ppm ascorbic acid. The current responses for this electrochemical sensor offered  
 15 the reproducible responses with a 1.51% relative standard deviation (RSD), demonstrating good  
 16 reproducibility. The limit of detection (LOD) and the limit of quantification (LOQ) were  
 17 calculated using the method based on the equations containing the standard deviation ( $\sigma$ ) of the  
 18 estimated value (net signal), as is the slope of the calibration curve (s):  $\text{LOD} = 3.3 \sigma / s$ ,  $\text{LOQ}$   
 19  $= 10 \sigma / s$  [60]. The limit of detection was 3.29 ppm (18.68  $\mu\text{M}$ ), and the LOQ was 9.98 ppm  
 20 (56.66  $\mu\text{M}$ ) ascorbic acid. The linear range of 1-20 ppm was achieved, allowing for the

1 detection of ascorbic acid in real conditions. In this work, better values of sensitivity ( $0.572 \mu\text{A}$   
2  $\text{cm}^{-2} \text{ppm}^{-1}$ ) were obtained than Zhang et al., who modified glassy carbon electrodes using the  
3 poly(acid chrome blue K). Also, the limit of detection obtained with the FLBP\_1,4-DAAQ  
4 electrode is better than, e.g., polyaniline modified screen-printed carbon electrode [61]. There  
5 are also known electrodes with a lower LOD ( $0.05 \mu\text{M}$ ) in the literature, but they have a lower  
6 linear range and are expensive, e.g., gold nanoparticles modified electrode [62]. FLBP\_1,4-  
7 DAAQ electrode has properties that allow satisfactory detection of ascorbic acid over a wide  
8 range of concentrations.

9

## 10 **Conclusions**

11

12 The degradation of phosphorus under exposition conditions to oxygen and water is a significant  
13 obstacle to its use as sensors. The proposed functionalisation in this work with 1,4-diamine-  
14 9,10-anthraquinone enhanced the stability in ambient conditions of FLBP while improving  
15 charge transfer in redox reactions. Noncovalent functionalised FLBP electrodes show that 1,4-  
16 diamine-9,10-anthraquinone is anchored to FLBP and exhibits redox peaks that are stable over  
17 100 cycles. Moreover, the fabricated FLBP\_1,4-DAAQ electrode was used for the detection of  
18 ascorbic acid.

19 The developed electrochemical sensor combines a low detection limit with significant  
20 sensitivities and a wide linear concentration range for ascorbic acid detection. Other electrodes  
21 tend to have one of these advantages and become less useful. Thus, FLBP\_1,4-DAAQ may be  
22 an attractive novel electrode material for the sensitive detection of ascorbic acid.

23

24





## 1 Declaration of Competing Interest

2

3 The authors declare that there are no competing financial interests or personal relationships that  
4 could have appeared to influence the work reported in this paper.

5

## 6 Credit authorship contribution statement

7 **Paweł Jakóbczyk:** Conceptualisation, Formal analysis, Investigation, Writing – original draft,  
8 Writing – review & editing. **Anna Dettlaff:** Writing – review & editing. **Jacek Ryl:** Formal  
9 analysis, Writing review & editing. **Grzegorz Skowierzak:** Investigation. **Tadeusz Ossowski,**  
10 review & editing. **Robert Bogdanowicz:** Writing – review & editing, Funding acquisition.

11

## 12 Acknowledgements

13 This work was supported by the Polish National Science Centre [2016/22/E/ST7/00102].

14

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