Supporting Information

Enhanced Performance of Pencil-Drawn Paper-based Electrodes by Laser-

Scribing Treatment

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S1. Graphite surface after the laser treatment



Figure S1. Photo of the graphite surface after the treatment using a CO_2 laser. The total painted area corresponds to a 4 cm x 4 cm square.

S2. Graphite film thickness

The working electrode was cleaved using liquid nitrogen, and its thickness was analyzed by SEM. Figure S2 shows the cross-section SEM image of the graphite film.



Figure S2. Cross-section SEM image of CO₂ laser-treated PDE.

S3. Raman single spectra

Raman spectroscopy provides a fingerprint of carbon materials since these have common characteristics in their Raman spectrum in the range of 800-2000 cm⁻¹, where the D and G bands are found¹. Both bands appear in PDE non-treated at 1352 and 1582 cm⁻¹, respectively. While in the CO₂ laser-treated PDE, the bands D and G are at 1347 and 1578 cm⁻¹. In the region of 2700 cm^{-1,} another band, called band 2D appears, and it is layers of graphene when there is only one layer this band layer, intense and thin. As the number of layers increases, this band becomes broad, and its intensity decreases². As we can see, the 2D band appears in 2715 cm⁻¹ in the PDE non-treated, and the PDE treated with CO₂ laser, and its profile is in agreement with the profile presented in the literature for graphite^{3,4}.



Figure S3. Raman spectra of (a) office paper, (b) non-treated PDE, and (c) CO_2 laser-treated PDE.

S4. XPS O1s spectra

O1s spectra, as shown in figure S6, demonstrate the oxygenated groups in office paper, CO_2 laser-treated, and nontreated PDEs. This data confirms the presence of the functional groups assigned using the C1s spectra. The peaks for each material were assigned as follows: C=O and C-O at 531.8 and 532.7 eV in office paper, C=O, and C-O/C-OH in graphite before and after laser-scribing treatment were at 531.9 and 533.3 eV and 531.9 and ~533 eV, respectively⁵. The amount of C=O and C-O/C-OH in graphite before laser treatment was 64.4% and 35.6%, respectively. There are no significant changes in these amounts (C = O: 64.5% and C-O / C-OH: 35.5%) on laser activation.



Figure S4. O1s XPS spectra of (a) office paper, (b) non-treated PDEs, and (c) CO₂ laser-treated PDEs.

Table S1a. Percentages of functional groups for the XPS C1s spectra for both non-treated and CO₂ laser-treated PDEs.

	Non-treated PDEs (%)	CO ₂ laser-treated PDEs (%)
Csp ²	~47	~51
Csp ³	30	~20
С-О/С-ОН	17	16
C=O	5.6	4.8
π - π^* transition	-	8.4

Table S1b. Percentages of functional groups for the XPS O1s spectra for both non-treated and CO₂ laser-treated PDEs.

	Non-treated PDEs (%)	CO ₂ laser-treated PDEs (%)
C=0	64	65
С-0/С-ОН	36	36

S5. Contact angle measurements

To characterize the wettability of the PDE surface as a function of the CO₂ laser treatment, we performed advancing (ACA) and receding (RCA) contact angle measurements (Figure S5). The ACA and RCA measurements involve measuring the largest and smallest angles at the liquid-surface interface, while increasing and decreasing the volume of liquid, respectively, within the hysteresis range (the difference between the ACA and the RCA)⁶. We observed that ACA and RCA angles for both laser-treated and non-treated PDEs were close (Table S2), indicating that there were no significant changes in surface wettability even after treatment.

Contact angle hysteresis is an essential property in the wettability of a surface since it is related to surface roughness and chemical heterogeneities, among other properties⁷. This parameter measures the mobility of a drop on a surface and, the greater the difference between ACA and RCA, the lower the mobility of a drop⁶. As we can notice, in the CO_2 laser-treated PDE, surface hysteresis is bigger (30.7°) than that in the non-treated PDE surface (19°).



Figure S5. Advancing and receding contact angle measurements for (a, b) non-treated PDEs and (c, d) CO₂ laser-treated PDEs.

Table S2.	Advancing.	receding.	and hysteresis	contact angle	measurements of	of laser-treated	and non-trea	ted PDEs
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	Advancing (°)	Receding (°)	Hysteresis (°)
Non-treated PDEs	76.5 ± 2	57.5 ± 2	19
CO ₂ laser-treated PDEs	68.3 ± 6	37.6 ± 5	30.7

S6. Optimization of the CO₂ laser parameters in the graphite surface treatment

Figure S6A shows the variation of the resistance values of the graphite tracks painted on the paper surface concerning the percentage of power used. The graphite film's electrical resistance before the laser treatment was approximately 600 Ω , and as the percentages of power increased, their respective resistance values decreased. The mean values of electrical resistance for the CO₂ laser-treated graphite surface using the power percentages of 6.2, 6.4, and 6.6 were 379, 353, and 280 Ω , respectively. Thus, the 6.6% power was chosen to carry out the treatment of the graphite film and fabricate the PDEs.

The relationship between the laser scan rates and the electrochemical profile (separation between the oxidation peaks and potassium ferricyanide reduction) was evaluated. Figure S6B displays the peak-to-peak separation (an indication of improved electrochemical reversibility of the redox probe on the surface) for differents laser scan rates: 25, 38, and 45 mm s⁻¹, which were 177, 220 e 203 mV, respectively. As we can see, the lower laser scan rate promoted a more efficient treatment of the graphite surface. Therefore, the surface laser-treatment

conditions of the graphite film were as follows: 6.6% power and a laser scan rate of 25 mm s⁻¹. The height of the laser output to the paper platform (distance Z) used was 10mm, and it was kept constant during the experiments.



Figure S6. (A) Bar graph showing the relationship between the electrical resistance (measured in triplicate) in non-treated (**red bar**) and CO_2 laser-treated PDEs (**black bar**) using different powers and (**B**) Relationship between the separation of both oxidation and reduction peaks of K_3 [Fe(CN)₆] as a function of the CO_2 laser scan rate.

S7. Tafel analysis



Figure S7. A) CVs of a 5 mM [Fe(CN)₆]³⁻ solution with the non-treated PDE (**red line**) and CO₂ laser-treated PDE (**black line**); **B**) Mass transport corrected Tafel analysis; Regular Tafel analysis **C**) non treated and **D**) CO₂ laser-treated PDE, the analysis were performed in the CVs presented in fig. A; **E**) CVs of a 5 mM [Ru(NH)₆]³⁺ solution with the non-treated PDE (**red line**) and CO₂ laser-treated PDE (**black line**); **F**) Mass transport corrected Tafel analysis; Regular Tafel analysis **G**) non treated and **H**) CO₂ laser-treated PDE, the analysis was performed in the CVs presented in fig. E.

S8. CVs of FUR recorded in different carbon surfaces



Figure S8. CVs registered using different carbon electrodes: (a) non-treated PDE; (b) CO_2 laser-treated PDE; (c) commercial screen-printed carbon electrode and (d) commercial screen-printed graphene electrode in a solution of 1 mmol L⁻¹ FUR (solid line) in 0.1 mol L⁻¹ PBS (pH=6.8) (dashed line). Scan rate: 10 mV s⁻¹.

S9. Study of interfering species

Each set of measurements (I_{FUR} / I_{FUR} + Interferents) were carried out using a single PDE. Therefore, the percentages of variation of the FUR current signal after the addition of each interference were calculated, taking into account the FUR current signal (before the addition of the interferent species) in each device, thus being a relative value.



Figure S9. Current signal variation (duplicate measurements) of possible interfering species for FUR detection using CO₂ laser-treated PDE. The FUR/Interferent ratio was 1:2, and the measurements were performed using DPV in the optimized experimental conditions for FUR detection. Interferent species: ascorbic acid (AA), uric acid (UA), urea (UR), creatinine (CRE), and glucose (GLU).

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