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Tunable Mass Transport and Enhanced Electrochemical Performance of CO_2 Laser-Engraved Electrodes

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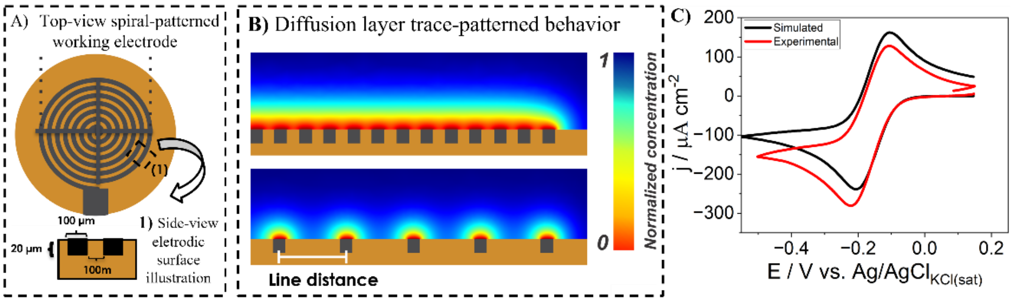
Over the past decade, laser engraving has emerged as a viable alternative for producing carbon-based electrodes. Laser engraving converts non-conductive carbon precursors into conductive surfaces, with performance depending on the processing parameters and the type of precursor material[1]. Untreated laser-engraved electrodes often exhibit suboptimal electrochemical responses, requiring post-treatment methods that increase costs, reduce reproducibility, and limit the widespread adoption of this technology[2]. To address these challenges, we developed a vectorized laser engraving protocol that precisely controls carbonization by patterning individual lines over substrates, eliminating heterogeneous carbonization and unpredictable charge transfer kinetics. Our proposed design, a spiral electrode (Fig. A), showed performance comparable to commercial electrodes, with differences in current density of approx.5%. This design enables the tuning of mass transport by adjusting the spiral line distance, facilitating the transition from radial to planar diffusion (Fig. B), as supported by numerical simulations (Fig. C). The electrode reached 95% electrochemical efficiency with just 50% of the surface engraved, effectively mimicking traditional disk electrodes. Proof-of-concept studies demonstrated improved sensitivity for environmental monitoring applications, and interdigitated electrode layouts proved the ability to customize electrochemical interfaces through vectorized engraving, supported by numerical simulations.



A) Spiral electrode with a crosshair engraved with vectorized mode. **B)** Simulated Diffusion layer profile for Spiral electrode at different line distances. **C)** Simulated and Experimental cyclic voltammogram (scan rate: 5 mV s; n=3) recorded with $[Ru(NH_3)_6]^{+3}$ (5.0 mmol L^{-1} in 0.5 mol L^{-1} KCl).

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References: [1] F. Silveri, F. Della Pelle, D. Compagnone, TrAC Trends in Analytical Chemistry 2025, 185, 118175. [2]D. M. de Farias, L. A. Pradela-Filho, I. V. S. Arantes, J. L. M. Gongoni, W. B. Veloso, G. N. Meloni, T. R. L. C. Paixão, ACS Appl Mater Interfaces 2023, 15, 56424.