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Carbon Nanofiber/PEDOT Based Macro-porous Composite For High Performance Multifunctional Neural Microelectrode

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Brain study methods mainly rely on neurochemical detection and electrophysiology, respectively to study the molecular dynamics [1] and electrical activity [2] in the brain cellular environment. Since the brain functioning relies on careful orchestration of both neurotransmitter and neuroelectric activities, coupled monitoring of them holds great promise in elucidating the brain functioning mechanisms and its related diseases e.g. Parkinson's, epilepsy, etc [3]. Most of the conventional implantable neural interfacing technologies are comprised of noble metals on silicon/ polymer substrates. They suffer from inferior electrical properties, mechanical tissue-electrode mismatch, incompatible surface area, and low signal-to-noise ratio [4]. To address the need, researchers around the world are developing innovative soft materials with multimodal functionalities, especially the organic flexible materials such as conductive polymers and carbon allotropes, to fuel the next-generation multimodal neural electrode devices [5].

Here in this work, we present a new macro-porous, conductive, and stable nanocomposite, made up of carbon nanofibers (CNFs) and PEDOT polymer, coated on a flexible neural microelectrode array (Fig. 1A-B). A fully controlled one-shot electrodeposition strategy was developed using chronopotentiometry technique, to coat flexible Au-microelectrode surfaces with macro-porous CNF/PEDOT nanocomposite. The oxidized CNFs were used as a dopant and infused within the conductive PEDOT, electrochemically, in such a way that their excellent electronic, mechanical, chemical properties, and resulting combined performances can be exploited to yield better quality neural recordings, electrical stimulation and neurotransmitter detection. At first, CNFs were oxidized to be dispersible in water (unlike raw CNFs) by vortex and sonication. Later, CNF/PEDOT composite was deposited on Au-electrodes galvanostatically, resulted in a 3D porous and fibrous network (Fig. 1B-D). Then, CNF/PEDOT deposits were characterized through electrochemical impedance spectroscopy (EIS) and pulse current injection. The composite microelectrodes showed low impedance, $16 \pm 2 \text{ k}\Omega$ for a typical electrode area of $1250 \mu\text{m}^2$, at 1kHz (value corresponding to the neuron firing frequency) (Fig. 1E). Voltage transient responses were measured, at continuous 1ms-biphasic current pulses (cathodic first) in biologically relevant aCSF media, resulted in a charge-injection limit value of $7.6 \pm 1.3 \text{ mC/cm}^2$ (Fig. F). Among all reported organic nanostructured composite materials that were deposited on flexible metallic substrates, CNF/PEDOT displayed superior electrical properties and charge injection capabilities [5]. Next, the capability of CNF/PEDOT composite electrode for *in-vitro* Dopamine (DA) sensing was evaluated by chronoamperometry, at 130mV vs SCE (oxidation potential of DA). The current responses submitted to DA injections resulted in linear regression (Fig. 1G, $R^2 > 0.99$), with a high sensitivity of $13.4 \text{ pA/nM}\cdot\mu\text{m}^2$, compared to similar electrochemical sensors [6]. Overall, these electrodes displayed excellent electrical properties: low impedance ($16 \pm 2 \text{ M}\Omega\cdot\mu\text{m}^2$ at 1 kHz) and high charge

injection capabilities ($7.5 \pm 1.3 \text{ mC/cm}^2$) making them promising candidates for bidirectional electrophysiology, while being capable to detect neurotransmitters like dopamine. Finally, integrated upon flexible neural probes, these composite microelectrodes were tested *in-vivo* on mouse brain slices as recording and stimulating electrodes (Fig. 1H). They displayed excellent performances, being capable to record spontaneous activities of neurons (sharp wave-ripples and single unit action potentials) and allowed to stimulate electrically the brain slice tissues, to obtain safe and stable evoked potentials. The obtained results show a great prospect for CNF/PEDOT composites for developing next-generation microelectrodes for applications in neural therapies.

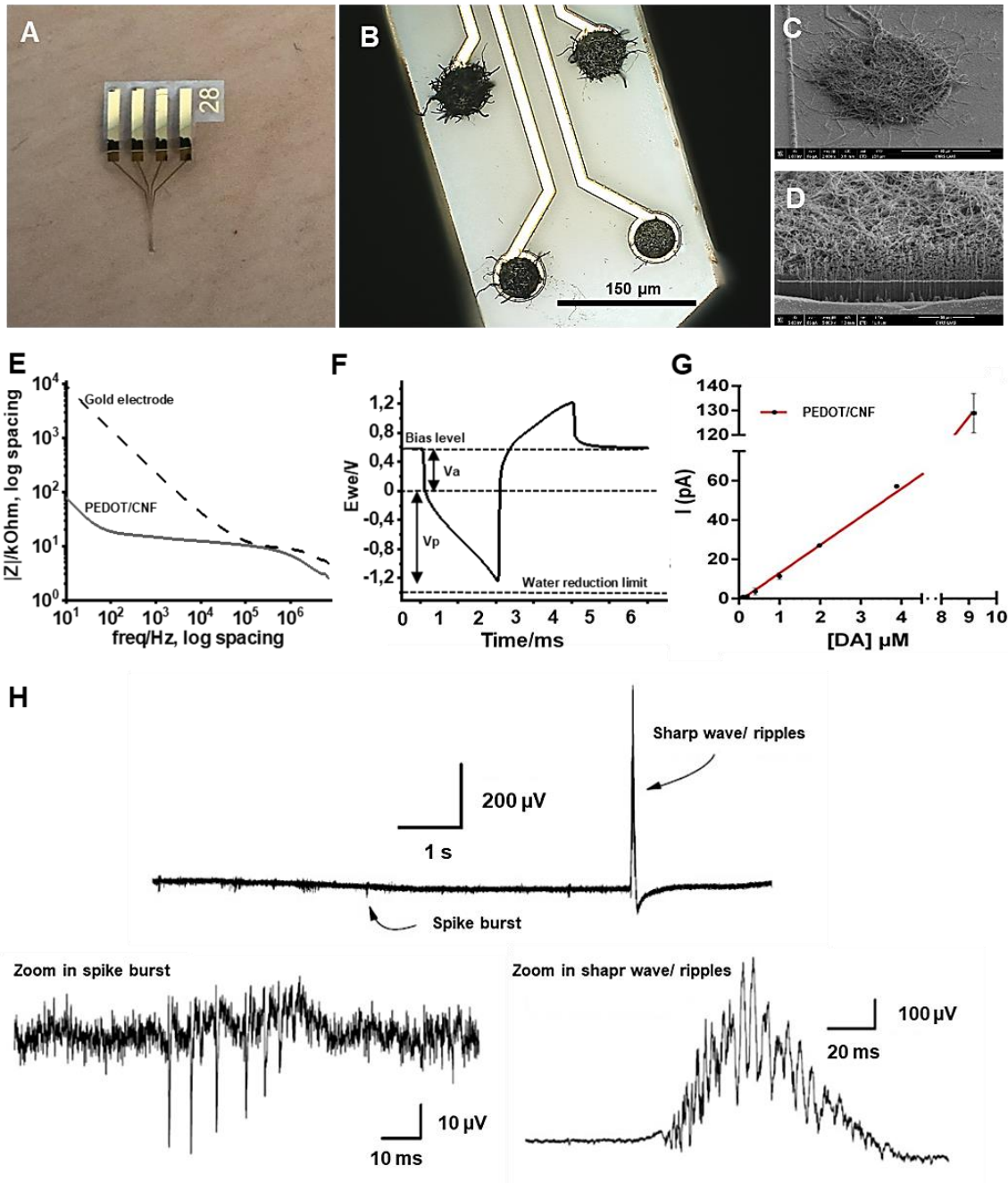


Figure 1. (A) Optical micrograph of flexible neural probe. (B) CNF/PEDOT deposition on 4 Au-microelectrodes of the implant. SEM images, (C) top view and (D) cross-sectional view of the composite electrode. (E) EIS measurement on modified

microelectrodes from 10 Hz to 7 MHz in aCSF at 0V Vs Ag/AgCl. (F) Voltage transient of a CNF/PEDOT microelectrode resulting from the injection of a biphasic current pulse (90 μ A with 1 ms pulse width). (G) Linear regression curve of CNF/PEDOT electrode current response at 130mV vs SCE to dopamine injections. (H) Electrophysiological recordings in the hippocampal region (CA1 and CA3) of a mouse brain slice, using flexible microelectrode array modified with CNF/PEDOT composite.

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