

Soft and Stretchable Carbon Flower Sensors Detect Hormones and Neurotransmitters at High Sensitivity

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Summary:

Continuous monitoring of hormones, neurotransmitters, and metabolites in biofluids such as sweat and saliva holds great promise for personalized health. Yet, current sensor technologies lack the sensitivity, selectivity, and mechanical compliance needed for on-skin and real-life applications. We introduce carbon flowers, which are graphitic microparticles with flower-like morphology, as a novel electrochemical sensing material. These carbon flowers are synthesized through a bottom-up approach by polymerizing acrylonitrile and feature unique morphology with high conductivity and defect-rich structure. Fabricated via scalable spray-coating onto stretchable substrates, the sensors achieve nanomolar detection of serotonin, dopamine, melatonin, uric acid, estradiol, and ascorbic acid, outperforming state-of-the-art carbon materials. Simultaneous multi-analyte detection with excellent linearity ($R^2 > 0.97$) and robustness under physiological pH and salt conditions makes them promising for future wearable, real-time health monitoring.

Keywords: soft electronics, health monitoring, electrochemical sensor, multi-analyte detection, defective carbon

Background, Motivation and Objective

Sweat and saliva are biofluids rich in health information. They contain a plethora of hormones, neurotransmitters, and metabolites that reflect underlying physiological processes [1]. Monitoring such biomarkers continuously at the point-of-care could significantly advance personalized health, but suitable sensing technologies are missing. This is because current sensors lack the **sensitivity** to measure these biomarkers at physiological levels, the **selectivity** to measure individual biomarkers in the presence of other molecules, and the stability under real conditions. Finally, many sensors are **rigid and require highly complex fabrication**, unsuitable for low-cost on-skin applications, as desired for sweat sensing. We introduce carbon flower (CF) electrodes to address these challenges [2]. CFs have previously shown interesting capabilities in electrocatalysis applications [3, 4], but have never been explored in electrochemical sensing. We demonstrate the use of such carbon flowers as soft, stretchable electrodes for the detection of a multitude of biomarkers and biomarker mixtures.

Description of the New Method or System

Carbon flowers are synthesized *bottom-up* from acrylonitrile polymerization and converted to graphitic, hierarchical CFs via stabilization and carbonization [5]. This in-house synthesis

ensures controlled and uniform graphitic particles of $\sim 1 \mu\text{m}$ diameter. A key advantage of the CFs is their high defect density, accessible surface sites, and good conductivity, ideal for electrochemical sensing [2].

The CFs are dispersed in chloroform with a polymeric binder using ultrasonication and spray-coated onto stretchable substrates. Each device features patterned silver interconnects and eight electrodes ($2.5 \times 0.5 \text{ mm}$) connected to a flexible cable for signal readout (Fig. 1a,b).

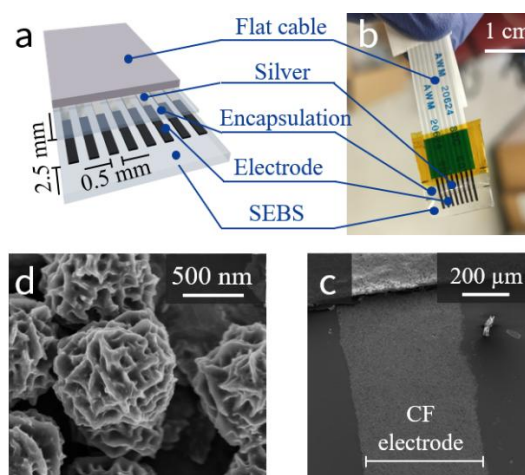


Fig. 1. (a) Sensor design. (b) Photograph of a sensor featuring 8 sensing electrodes on a flexible substrate. (c) SEM image of a carbon flower electrode. (d) SEM image of the carbon flowers.

The fabrication requires no cleanroom steps, enabling low-cost, scalable production of soft sensor arrays.

Results

A scanning electron microscopy (SEM) image of the carbon flower electrode with a zoom-in on the carbon flowers is shown in Fig. 1c,d. The particles exhibit a distinctive flower-like morphology with excellent uniformity in size; highly graphitic crystalline areas are revealed in XRD analysis, while Raman and XPS show high defect density and the presence of nitrogen sites stemming from the acrylonitrile precursor.

Most importantly, carbon flower sensors detect a variety of biomarkers, including dopamine, ascorbic acid, uric acid, serotonin, estradiol, and melatonin. The square wave voltammetry (SWV) detection of serotonin and melatonin is shown exemplarily in Fig. 2. The limits of detection (LOD) of 1 nM surpass state-of-the-art carbon-based sensors. We attribute the high sensitivity to the unique morphology of the CFs, in combination with high conductivity and a highly defective structure. Notably, the carbon flower sensors can be used for repetitive measurements and are robust to changes in salt and pH [2].

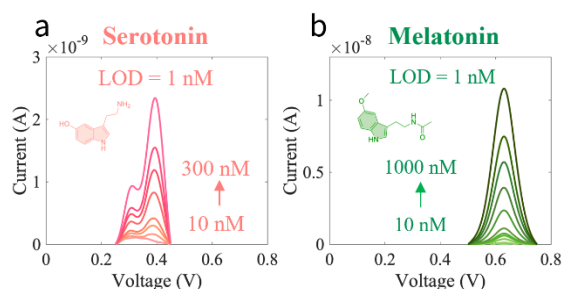


Fig. 2. SWV detection of (a) 10–300 nM serotonin and (b) 10–1000 nM melatonin

In addition, distinct oxidation peaks permit concurrent detection of biomarkers in mixtures. Fig. 3a shows the simultaneous detection of serotonin and estradiol, indicating that the oxidation peaks are clearly separated and allow for the selective detection of either molecule. This is possible also when testing the three biomarkers serotonin, estradiol, and melatonin in mixture (Fig. 3b): despite the increased complexity, the individual molecules remain clearly separable, and calibration curves in mixtures closely match single-analyte measurements ($R^2 > 0.97$). Yet, limitations arise when increasing mixture complexity further, e.g. through addition of ascorbic acid, which overlaps with serotonin. Combining the intrinsic selectivity shown here with sensor arrays or Nafion coatings could overcome this limitation and further advance multi-analyte sensing.

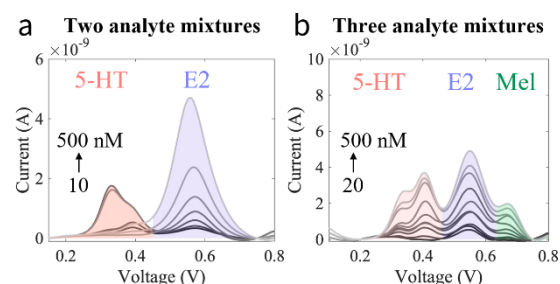


Fig. 3. (a) Simultaneous detection of 50–100 nM serotonin (5-HT) and 10–100 nM estradiol (E2). (b) Simultaneous detection of 20–500 nM serotonin, estradiol, and melatonin (Mel).

Conclusion

Carbon flower electrodes enable soft, stretchable electrochemical sensors with superior sensitivity, achieving nanomolar detection of serotonin, melatonin, estradiol, dopamine, uric acid, and ascorbic acid. Their scalable, cleanroom-free fabrication on stretchable substrates, combined with robust multi-analyte discrimination under physiological conditions, makes them a compelling platform for continuous wearable health monitoring.

References

- [1] D. Sim, M. C. Brothers, J. M. Slocik, A. E. Islam, B. Maruyama, C. C. Grigsby, R. R. Naik, S. S. Kim, Biomarkers and Detection Platforms for Human Health and Performance Monitoring: A Review, *Advanced Science* 9, 7, 2104426 (2022). doi: 10.1002/advs.202104426
- [2] I. C. Weber et al., Sensitive Hormone and Neurotransmitter Detection with Carbon Flower Electrodes, *Advanced Functional Materials* e28595 (2026). doi: 10.1002/adfm.202528595.
- [3] H. Gong, L. Wei, S. Chen, Z. Chen, T. F. Jaramillo, Z. Bao, Carbon flowers as electrocatalysts for the reduction of oxygen to hydrogen peroxide, *Nano Research* 16, 9, 11556–11563 (2023). doi: 10.1007/s12274-023-5903-8
- [4] S. Chen, H. Gong, B. Dindoruk, J. He, Z. Bao, Dense Carbon Nanoflower Pellets for Methane Storage, *ACS Applied Nano Materials* 3 (8), 8278–8285 (2020). doi: 10.1021/acsnano.0c01700.
- [5] K. Parkatzidis, D. U. Patino, Y. Shi, K.-J. Hsu, I. Weber, H. S. Wang, Z. Bao, Polyacrylonitrile Flower-Like Particles with Tunable Size and Morphology via Scalable Oxygen-Tolerant Polymerization, *ACS Nano* 20, 5, 4455–4469 (2026). doi: 10.1021/acsnano.5c19392.