

Transient Graphene-Based Aptasensor on a Cellulose Substrate for Toxin Detection

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Summary:

We report a transient aptasensor for food toxin detection based on screen printed interdigitated electrodes (IDEs) fabricated using graphene ink printed on cellulose substrate. The aptamer is covalently-functionalized to provide selective biorecognition of the target food toxins on this transient platform. Electrochemical impedance spectroscopy reveals concentration-dependent impedance features, driven by interfacial modification due to the aptamer-toxin binding at the electrode surface. Compared to conventional single working and counter electrode configuration, the IDE electrode configuration enables a clear differentiation between the target concentrations in the high frequency range. The materials and fabrication process ensure eco-friendly and compatible device with low-cost, scalable manufacturing. This approach supports the development of sustainable biosensing technologies for rapid food safety screening adaptable for point of care (POC) detection system.

Keywords: Transient biosensor, graphene-carbon transducer, interdigitated electrodes, aptasensor, high frequency impedance spectroscopy

Background, Motivation and Objective

Impedimetric biosensors use EIS to detect biorecognition-induced changes at the electrode–electrolyte interface. In conventional single large-area electrodes, the response is dominated by double-layer capacitance and charge-transfer resistance, mainly at low frequencies. However, low-frequency operation can reduce stability and limit POC integration, motivating faster and more robust readout strategies.

Here we propose an interdigitated electrode (IDE) transducer made of printed graphene on a cellulose substrate. Compared with single-electrode designs, IDEs provide higher sensitivity to surface binding and support measurements at higher frequency and the use of an optimized single-frequency readout for rapid target detection of various concentrations.[1,2]

In parallel, the field is shifting toward transient and more sustainable electronics to reduce e-waste. Cellulose substrates and printable carbon-based functional inks provide a scalable and eco-responsible route to disposable devices. This approach is particularly relevant for food safety screening, where single-use sensors are intended at low-cost and easy field deployment. Foodborne toxins remain a persistent risk in

supply chains, posing a significant for public health threat, motivating the development of sensors for point-of-need food safety analysis beyond immunoassays and chromatography. Mycotoxin, such as Ochratoxin A (OTA), produced by fungal contamination of staple food, poses a severe long-term threat to human health and requires a sensor for point-of-use detection.[3]

We report on an OTA aptasensor based on interdigitated graphene electrode printed on cellulose substrate. The sensor exhibits concentration-dependent impedance signature compatible with high-frequency readout on a transient platform.

Description of the New Method

The sensor consists of interdigitated working and counter electrodes (WE–CE) (Fig. 1). The IDEs were fabricated by screen printing a graphene-carbon ink onto a cellulose substrate followed by curing. The electrode surface was functionalized by OTA-specific aptamer via covalent link to form the recognition layer. Upon binding of OTA, the aptamer layer undergoes conformational modifying their structure and leading to measurable changes in the electrical interfacial properties.

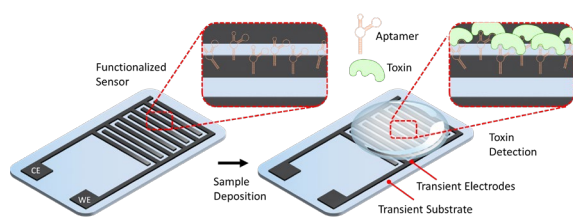


Fig. 1. Schematic representation of the sensor's IDE configuration functionalized with aptamers and its interaction with the toxin, resulting in impedance change due to conformational rearrangement.

Device performance was assessed by Electrochemical Impedance Spectroscopy (EIS), analyzing both Nyquist and Bode spectra over a broad frequency range (0.1 Hz to 500 kHz). The data were fitted with an equivalent-circuit model to extract interfacial electrical properties linked to surface modification and target capture. Measurements were performed for both graphene/aptamer functionalized electrode and bare electrode as a control before and after exposure to OTA at relevant concentrations of 0.1 nM, 1 nM, and 10 nM.

Results

The graphene-carbon IDE aptasensor exhibits a concentration-dependent impedance signature upon toxin exposure at concentrations of 0.1 nM, 1 nM, and 10 nM, relative to the aptamer-functionalized electrode measured in toxin-free solution (0 nM control). This demonstrates effective toxin sensing on the transient cellulose platform. As shown in Fig. 2, the Nyquist spectra show a high variation at high frequency range with increasing toxin concentration. The Bode magnitude plot shows clear impedance change after OTA binding across a wide frequency range, 500 kHz to 1 kHz. In parallel, a sensor based on a single-electrode layout exhibited a markedly smaller response at high-frequency, indicating that the interdigitated configuration enhances signal transduction at elevated frequencies.

The sensor displays a linear-log dependence of impedance magnitude on analyte concentration (Fig.2). Sensitivities of $626 \pm 22 \text{ } \Omega/\text{dec}$, $641 \pm 48 \text{ } \Omega/\text{dec}$, $615 \pm 13 \text{ } \Omega/\text{dec}$ and $550 \pm 15 \text{ } \Omega/\text{dec}$ were derived at 1 kHz, 10 kHz, 100 kHz and 500 kHz, respectively. These results demonstrate the good response at high frequency of our toxin aptasensor on cellulose enabled by using interdigitated graphene-carbon electrodes. The limit of detection and selectivity are under evaluation and will be presented at the conference.

To support interpretation of the sensing mechanism, the impedance spectra were fitted with an equivalent circuit consisting of a solution resistance in series with two interfacial time constants including resistance of charge transfer

and capacitance. These two contributions arise from electrical parameters variation of the graphene electrode interface and the aptamer-modified recognition layer. The fitted capacitance and resistance values show consistent increase with toxin concentration, demonstrating progressive surface modification and blocking effects following aptamer-toxin recognition.

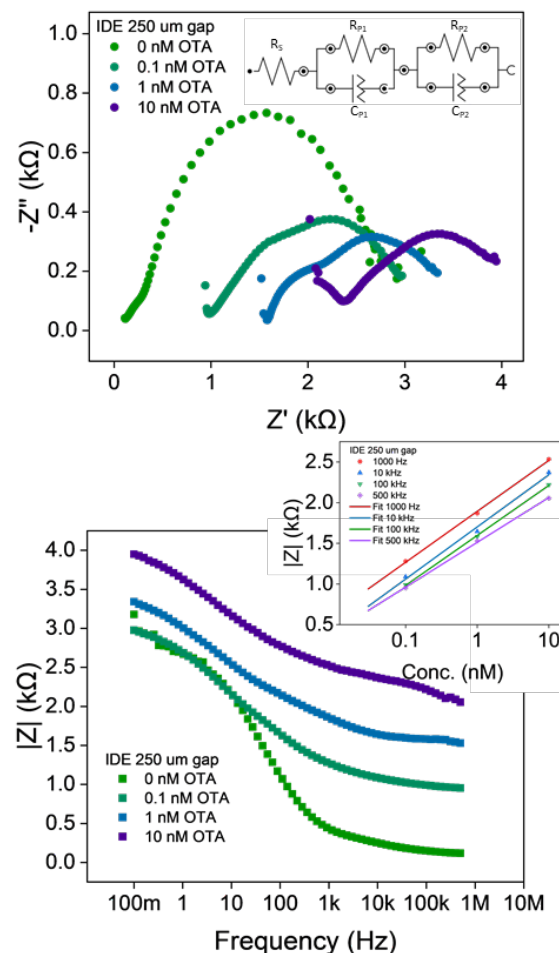


Fig. 2. Impedance characterization of IDE aptasensor. (Top) Nyquist plots showing concentration-dependent changes in the impedance spectra. (Bottom) Impedance magnitude as a function of frequency, highlighting clear separation between concentrations from 500 kHz to 1 kHz.

References

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