Materials Science and Engineering Dissertation Defense

Smart Electrochemical Sensors via Additive Manufacturing and Graphene Interfaces for Portable and Selective Detection

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Abstract

Additive manufacturing has emerged as a versatile and rapidly advancing platform for the fabrication of electrochemical sensors, offering unparalleled design flexibility, rapid prototyping, minimal waste, and cost efficiency. Despite these advantages, conventional 3D-printed electrodes often suffer from limited electrochemical activity, suboptimal material conductivity, and reproducibility challenges, which hinder their adoption in real-world applications. This dissertation presents an integrated framework that combines material innovation, advanced surface engineering, and modular device architecture to overcome these limitations and enable high-performance, portable sensing systems. Conductive electrodes were fabricated via fused deposition modeling (FDM) and subsequently enhanced through approaches such as reduced graphene oxide coating and copper-driven laser graphitization, which markedly improved surface conductivity, catalytic activity, and electrochemical capacitance. Comprehensive characterization using scanning electron microscopy, Raman spectroscopy, X-ray photoelectron spectroscopy, contact angle analysis, and electrochemical measurements demonstrated that these modifications yielded up to sixtyfold increases in hydrogen peroxide sensitivity, enabled near-Nernstian responses for ion detection, reduced potential drift, and optimized response time and detection limits. A modular sensor platform with replaceable working electrodes was developed, allowing straightforward customization of solid-contact layers using graphene, reduced graphene oxide, and graphene oxide, thereby enabling precise tuning of capacitance, hydrophobicity, and sensing performance for diverse analytes. Integration with portable smartphone-based potentiostat further allowed real-time, on-site detection, and field trials confirmed reliable measurements of hydrogen peroxide and potassium ions in complex matrices such as agricultural soils. Collectively, this work delivers a scalable, customizable, and reproducible strategy for manufacturing next-generation 3D-printed electrochemical sensors. By bridging additive manufacturing with tailored materials engineering and modular design, it establishes a foundation for versatile analytical platforms with broad potential in environmental monitoring, precision agriculture, healthcare diagnostics, and other point-of-need applications, paving the way for wider deployment of high-performance 3D-printed sensing technologies.

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