ABSTRACT

As diabetes has become more prevalent, there is an urgent need for the development of transdermal drug delivery systems that are biocompatible, can deliver drugs painlessly, are easy to use. There is also an urgent need of development of a highly sensitive detection system that can rapidly detect diabetes and its complications with reliable results. In this work, the fabrication, characterization, and application of all-carbon hollow microneedles and electrodes are addressed. The microneedles were fabricated using UV photolithography and carbon microelectromechanical (C-MEMS) process. A hollow cylindrical structure with 190µm outer diameter, 90µm inner diameter, and a height of 550µm of SU8 was chosen. These SU8 microneedles were converted into an all-carbon, i.e., viz. carbon microelectromechanical systems (C-MEMS) based process, which showed an overall shrinkage rate of 43%. These all-carbon microneedles showed mechanically robust structures with a high hardness of 5.5 GPa and a Young's modulus of 42 GPa, enabling painless and infection-free transdermal drug delivery. The flow rates of deionized (DI) water and ethanol through microneedles were found to be 111.66 µL/min and 134.28 µL/min, respectively, at a pressure of 10kPa. Preclinical testing was conducted to assess the biocompatibility and mechanical strength of all-carbon microneedles in Whister rats. The results confirmed no inflammation and effective skin penetration, with no breakage or lumen clogging. For diabetes and complication detection systems, all-carbon solid micropillar array design was fabricated, which yielded better results than coplanar electrodes for enhanced electrochemical detection of glucose and oxidative stress-induced H_2O_2, and systemic inflammation. The solid all-carbon micropillar electrodes, with a 1.4 × enhanced surface area over coplanar electrodes, were functionalized with glucose oxidase (GOx)/chitosan for highly sensitive glucose detection in real diabetic blood samples that can be used as a gluco test strip, and exhibiting a sensitivity of 9.85 $\mu A \cdot mM^{-1}$ with a low detection limit of 5.56 µM. Additionally, CeO_2 nanoparticle-functionalized electrodes demonstrated non-enzymatic detection of oxidative stress-induced hydrogen peroxide (H_2O_2), a key biomarker, with sensitivity of -3.84$\mu A \cdot mM^{-1}$ and LOD of 1.02µM, and high selectivity. Therefore, all-carbon hollow microneedles facilitated controllable drug flow rates and mechanical resilience showing successful biocompatibility in skin, while the micropillar array electrodes offered enhanced surface area and reproducibility for reliable glucose and oxidative stress induced H_2O_2 and systemic inflammation detection. The developed sensors showed minimal interference from common bioanalytes and correlate well with commercial devices in clinical sample analysis. Overall, this research advances the fabrication of all-carbon microstructures for drug delivery and sensing capabilities, offering promising avenues for next-generation diabetes management with scalable, minimally invasive, and high-performance cost-effective therapeutic devices. Future work includes fabrication of applicators for controlled drug dosing and expanding sensor functionalities for broader healthcare applications.

Keywords- *All-carbon Microneedles, all-carbon micropillar-electrodes, photolithography, C-MEMS, transdermal drug delivery, electrochemical sensing*

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