Optimizing Three-Dimensional Microelectrode Geometries For Neurostimulation

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Abstract

Neuromodulation, a closed-loop therapy that combines the recording and stimulation of neurons using implanted electrodes, is widely considered the future of care for many neurological diseases including epilepsy and Parkinson's. Existing neuromodulation therapies, however, are limited by planar macro electrodes with low selectivity [1]. To address this limitation, a major research milestone is to develop microelectrodes capable of delivering precise stimulation to specific neuronal ensembles. Three-dimensional (3D) microelectrodes which protrude from the substrate surface by several microns have shown promising advantages over planar macro electrodes. These 3D structures demonstrate closer contact with neurons and more localized electric fields for more precise stimulation [1]. This work investigates the electrochemistry of 3D microelectrode geometries via safe current distribution and electric field localization for increased selectivity in stimulation therapies. The performance of cylindrical, conical, and rounded geometries, both individually and in combinational designs, are investigated. The Electric Currents interface of the COMSOL Multiphysics® AC/DC Module is typically used to simulate current densities in stimulation microelectrodes, however it does not consider Faradaic reactions. Faradaic current remains a key factor in the safety of stimulation therapeutics, as irreversible electrochemical reactions will result in a changing chemical environment which can damage both the tissue and electrode [2]. In addition, microelectrode geometries influence both impedance and current density distribution [3], both factors in stimulation safety and efficacy. Of the modelling studies that do simulate Faradaic reactions, most focus on planar microelectrodes [4]. This work addresses this concern by utilizing the Electroanalysis interface of the COMSOL® Electrochemistry Module to simulate the distribution of faradaic current throughout 3D microelectrodes. Simulations identify geometries that concentrate faradaic current in a localized area and minimize current throughout the rest of the microelectrode to increase neural selectivity. Results are evaluated to assess the safety of these Faradaic current distributions with respect to current density magnitudes. The outcomes of this work suggest optimal 3D microelectrode geometries for increasing the safety and precision of chronic neuromodulation treatments to improve patient outcomes.

Reference

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[2] Merrill, D., Bikson M. and Jefferys J., “Electrical stimulation of excitable tissue: design of efficacious and safe protocols,” Journal of Neuroscience Methods, vol. 141, no. 2, p. 171, Feb. 2005, doi: 10.1016/j.jneumeth.2004.10.020.

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Figures used in the abstract

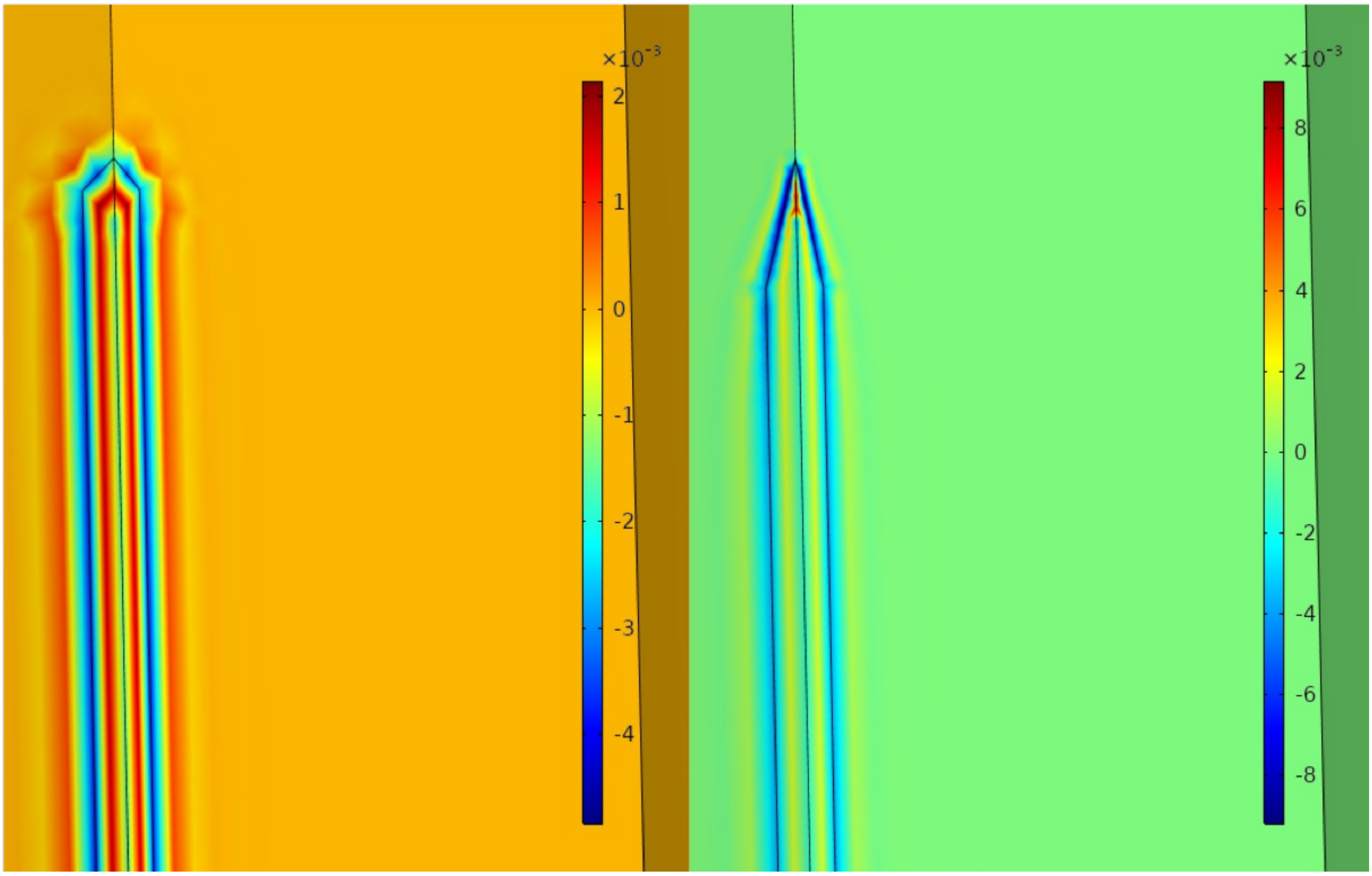

Figure 1 : Redox species concentrations (mol/m3) around 3D microelectrodes for Faradaic stimulation