

MICROELECTRODE ARRAYS FOR DROPLETRONIC CIRCUITS

Baptiste Tankwa¹, Jiaxin Zhu¹, Atila Shirin¹, Alain Aziz¹,
Yide Jiao¹, Antoine Remy¹, and Yujia Zhang¹

¹Laboratory for Bio-Iontronics (BION), Institute of Electrical and Micro Engineering, École Polytechnique Fédérale de Lausanne (EPFL); Lausanne, 1015, Switzerland

ABSTRACT

Iontronics is emerging as a promising approach for neuromorphic computing. Among various iontronic device architectures, researchers have used droplet assemblies to implement synaptomimetic functionalities. However, most reported devices rely on a two-droplet architecture. Here, we introduce microfabricated microelectrode arrays (MEAs) to enable a scalable droplet-based iontronic circuit, termed a droplet-based iontronic circuit. The MEAs are fabricated in the cleanroom using standard microelectromechanical systems (MEMS) techniques and consist of platinum tracks, a SiO₂ insulating layer, and an SU-8 confinement structure. The electrodes are characterized in phosphate-buffered saline (PBS), and surface wettability is assessed to ensure reliable operation. Moreover, electrochemical measurements in oil with droplet interface bilayers (DIBs) demonstrate favorable properties. Our platform represents a step toward achieving reservoir computing with arrays of droplet-based iontronic circuits.

KEYWORDS

MEAs, neuromorphics, dropletionics, iontronics

INTRODUCTION

The accelerating development of machine learning and large language models has driven an urgent need for energy-efficient computing hardware [1]. To address this challenge, researchers have looked to the human brain for inspiration. Brain-inspired computing seeks to replicate the remarkable efficiency of biological information processing. The brain contains trillions of synaptic connections, organized into a densely interconnected three-dimensional network, in which communication is mediated by ionic and chemical signaling. Computation occurs within this soft, aqueous, ionic environment. At synapses, information transfer is governed by the opening and closing of

membrane ion channels, which enable highly specific and efficient ionic transport (Fig. 1A). These channels play a central role in controlling ion transport and therefore serve as key inspirations for neuromorphic research [2, 3].

Significant progress has been made in developing neuromorphic devices based on inorganic materials that exploit nanoscale mechanisms, including interfacial redox reactions, thermally driven phase changes, and metal-ion or oxygen-vacancy percolation [3]. However, these devices do not operate in the biological, ionic language, which has motivated recent efforts to emulate neuronal membrane function using lipid-based structures [2]. Among these systems, the DIBs have emerged as promising platforms because they reproduce essential structural and functional features of synapses. A DIB forms when two aqueous droplets contact each other in a lipid-containing oil, allowing a lipid bilayer to self-assemble at the water-oil-water interface. Membrane proteins and ion channels can be inserted into the DIB (Fig. 1B), and their insertion can be modulated by applied voltages, producing hysteretic responses [3]. These behaviors enable memristive and memcapacitive dynamics suitable for reservoir computing, with reported energy consumption of less than 10 pJ per spike [2]. Despite these advantages, most DIB-based devices rely on interfacing two droplets with Ag/AgCl wires in connection with micromanipulators for recording and stimulation, a configuration that limits scalability and computational throughput.

Here, we introduce MEAs as a scalable platform for the assembly and electrical investigation of two-dimensional droplet networks. The MEAs are microfabricated on a glass wafer with platinum tracks insulated by a SiO_x layer, and droplets are spatially confined by a 200- μ m SU-8 structure. Our platform supports automated stimulation and recording of droplet networks, providing a robust, scalable architecture for droplet-based reservoir computing (Fig. 1C) [4–7].

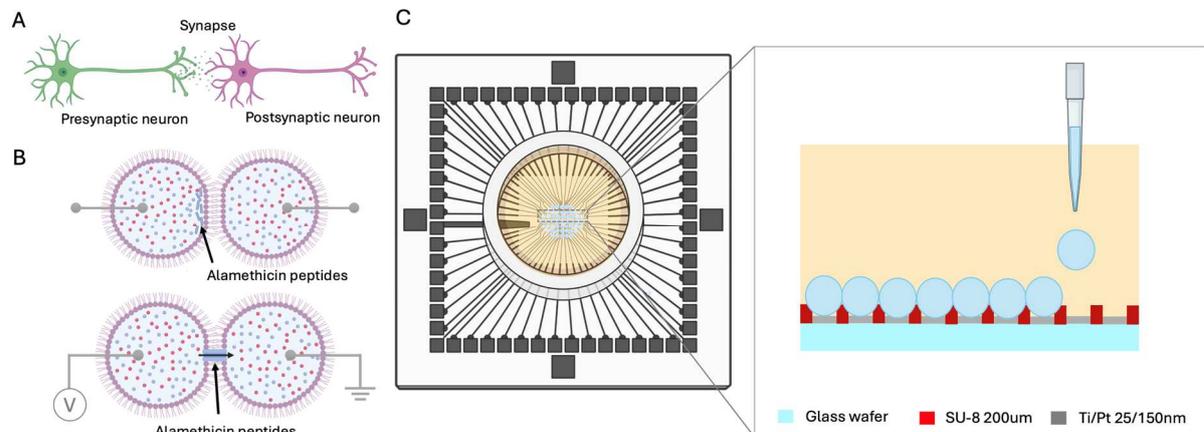


Figure 1: MEAs for dropletionics circuits. (A) Schematic illustration of a neuron synapse and (B) a droplet pair with voltage-responsive peptides. (C) Schematic illustration of the MEA platform for scaling dropletionics circuits.

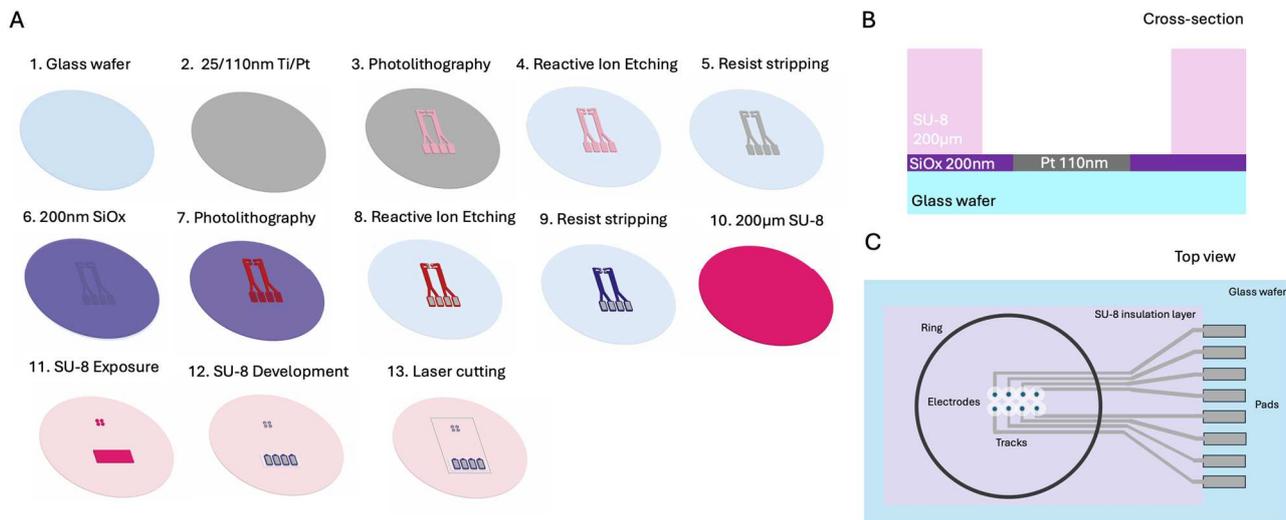


Figure 2: Microfabrication of the MEAs. (A) The process flow. (B) Cross-section of the device. (C) Top view of the MEA.

EXPERIMENTAL METHODS

Interfacing with droplets is challenging because they could be mobile, prone to water evaporation, and require appropriate electrode materials for reliable signal recording. The MEAs are designed to interface with droplets ranging from 200 to 500 nL. With further microfabrication scaling, adapting the device to operate with droplets as small as 5–10 nL may be feasible. The MEAs consist of planar arrays of eight electrodes, each 50 µm in diameter, fabricated from a 110 nm layer of platinum (Fig. 3A). A glass substrate is chosen for its optical transparency, which facilitates droplet handling and enables microscopic analysis of samples. Surface wettability is a critical parameter for droplet interfacing. Previous studies have shown that hydrophilic electrode materials, such as poly(3,4-ethylenedioxythiophene): polystyrene sulfonate (PEDOT:PSS), can promote lipid bilayer formation on electrode surfaces [8–10]. To support this behavior, the metal tracks are insulated with a 200 nm SiO_x layer, which is hydrophilic (Fig. 3E). Platinum is also chosen for its hydrophilic nature and good conductivity.

Achieving precise droplet placement is essential for stable recordings. To address this, a 200 nm SU-8 confinement layer is patterned with holes of diameter matching the droplet diameter. These wells spatially confine the droplet, improving the stability of the DIBs. Each hole contains a single electrode smaller than the well diameter to prevent alignment-dependent variations in electrode impedance. While SU-8 is naturally hydrophobic (Fig. 3E), its surface chemistry can be modified to render it hydrophilic if required.

The microfabrication process follows standard MEMS techniques (Fig. 2A). First, a Ti/Pt metallization layer (25/110 nm) was deposited on a glass wafer via sputtering (Sputter AC 450, Alliance Concept). To define the metal tracks and electrodes, an 8 µm layer of photoresist (AZ10XT, MicroChemicals) was spin-coated and patterned using direct laser writing (MLA150, Heidelberg Instruments). The exposed Ti/Pt layer was then etched using Ar/BCl₃-based reactive ion etching (210IL, Corial).

After stripping the photoresist, a 200 nm SiO_x insulation layer was sputtered (Sputter AC 450, Alliance Concept), preceded by a 15 nm Ti adhesion layer. A second

photolithography step was performed using a 6 µm AZ10XT layer to pattern the insulation and open the contact pads and electrode sites. The Ti/SiO_x stack was selectively etched using CHF₃-based reactive ion etching (RIE) followed by a Cl₂-based RIE (210IL, Corial). Following resist stripping, a 200 nm SU-8 layer (GM1075, Gerseltec) was spin-coated and soft-baked. The SU-8 was then patterned using a mask aligner (Süss MJB4), post-exposure baked, and developed to form the confinement structures. The device outline was defined via laser micromachining (WS Turret, Optec Laser Systems). Finally, a well was bonded onto the MEA, and wires were soldered to the contact pads to allow connection to the electrochemical workstation (µStat-i 400, Metrohm).

EXPERIMENTAL RESULTS

To evaluate the functionality of the electrodes, electrochemical impedance measurements were performed using a two-electrode configuration over a frequency range of 0.1 to 1,000,000 Hz in PBS. Although the final device will operate in an oil-based environment, validating electrode performance in PBS is essential for ensuring fabrication quality using standard characterization methods. To demonstrate the suitability of this platform for DIB formation, DIBs were generated within SU-8 wells. A lipid solution composed of 50% silicone oil and 50% n-hexadecane containing 2 mg/mL 1,2-diphytanoyl-sn-glycero-3-phosphocholine and 1-palmitoyl-2-oleoyl-sn-glycero-3-phosphocholine (molar ratio 1:2) was injected into the MEA, and droplets were then dispensed into the wells to promote bilayer formation. The surface properties of the wells play a crucial role in enabling the formation of the DIBs. Further optimization of SU-8 surfaces, as well as improvements to the well geometry, could facilitate the DIB formation speed and stability.

Preliminary electrochemical measurements using cyclic voltammetry revealed measurable conductance across the DIBs over a voltage range of -200 to 200 mV. Droplets occasionally coalesced during a higher-voltage scan, yielding impedance values comparable to those obtained in PBS.

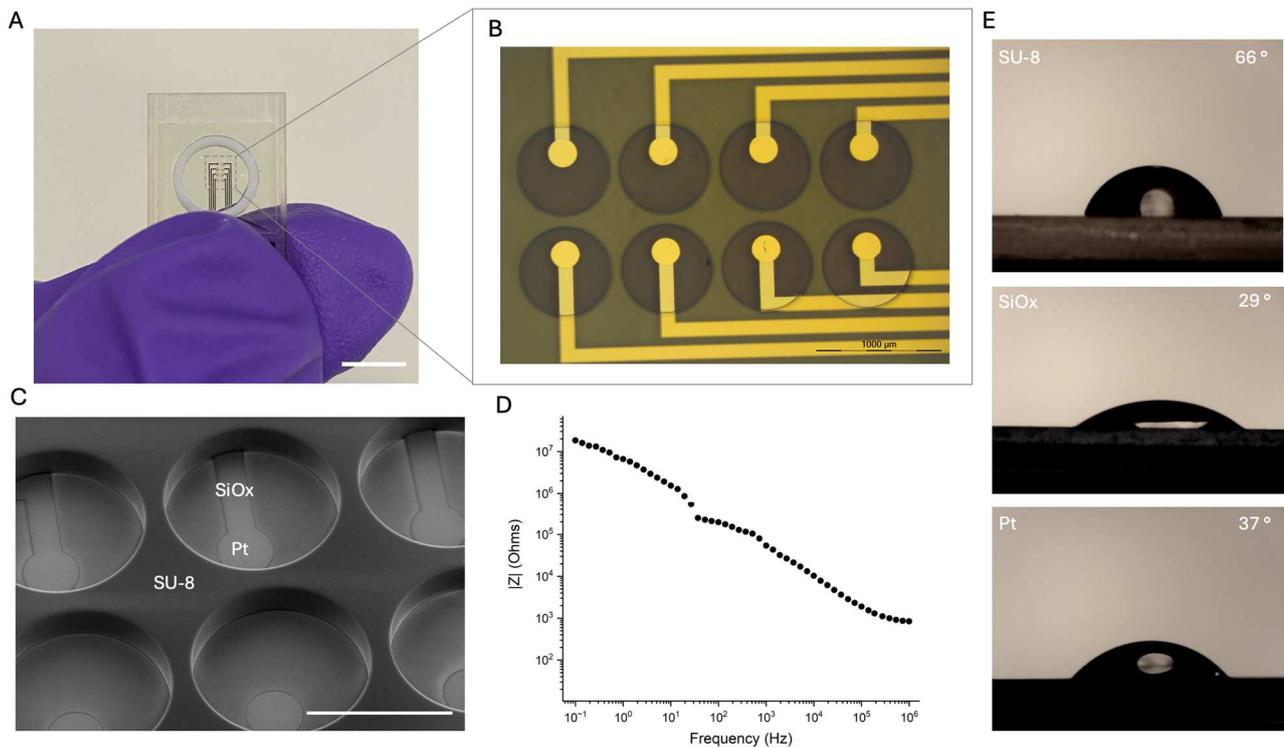


Figure 3: Characterization of the MEAs. (A) Photograph of the MEA platform (scale bar: 6mm). (B) Optical micrograph of the MEA after SU-8 development. (C) SEM image of the electrode surfaces (scale bar: 500 μm). (D) Average impedance spectrum ($n = 8$). (E) Contact angle measurements of deionized water droplets on SU-8, SiO_x, and Pt surfaces, respectively.

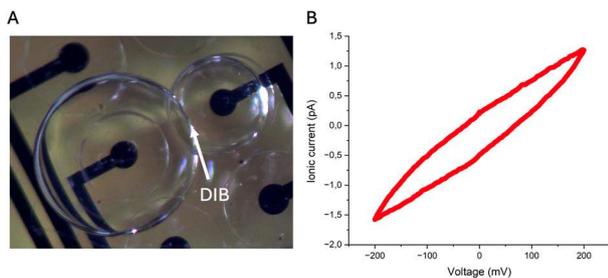


Figure 4: DIB measurements. (A) Optical microscope image of the droplet interface bilayer. (B) Cyclic voltammetry was recorded at MEA electrodes holding a DIB (scan rate: 50 mV/s).

CONCLUSION

In this work, we developed an MEA platform to enable scalable dropletic circuits. By integrating platinum electrodes with a hydrophilic SiO_x insulation layer and SU-8 confinement wells, the platform ensures reliable droplet positioning and robust electrochemical performance. Cyclic voltammetry measurements confirm that the system effectively interfaces with the DIBs. These advances establish a scalable route toward neuromorphic computing based on soft, aqueous, iontronic systems.

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CONTACT

*Yujia Zhang, Email: yujia.zhang@epfl.ch;