High-Performance Magnetically Actuated Mxene-Based Microelectrodes for Neural Interfacing

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Introduction

- Epineural interfaces are crucial for translating neural activities into signals that can drive external devices. They also stimulate neural tissue for neuropathy treatment, offering promising avenues for neuroprosthetics and rehabilitation devices.
- Achieving efficient and reliable epineural nerve-electrode interfaces is complex due to issues in electrode conformity and the adhesion between tissue and electrode materials.[1]
- While the integration of electronics has been achieved on magnetic elastomer substrates, soft robotic substrates have yet to demonstrate their advantages in neurological interface applications.[2]
- **Approach**: A new integration strategy that introduces a Mxene($Ti_3C_2T_x$)-PEDOT:PSS (MxP) composite into a magnetically actuated elastomer (PDMS/Fe_3O_4), aiming to bolster both mechanical and electrical properties for epineural interfacing.

- **Objective**: To determine the feasibility of robustly integrating a Mxene-PEDOT:PSS (MxP) composite into a magnetic elastomer for neurological interfacing

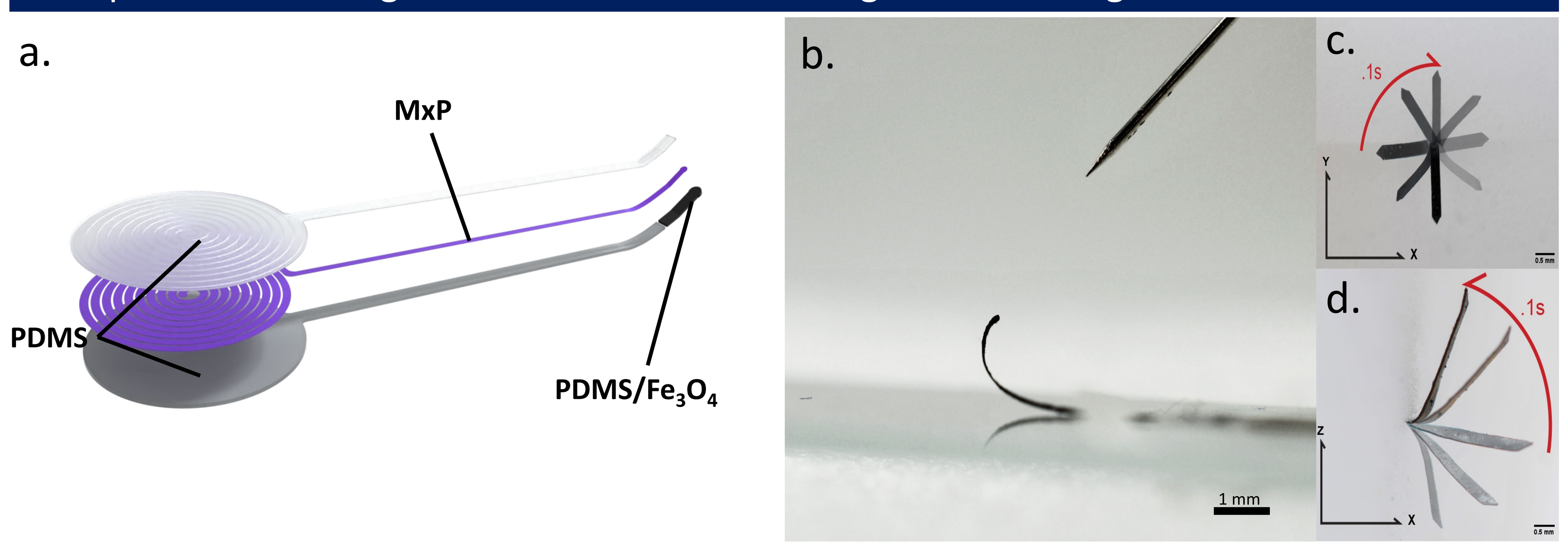

Figure 1. Kinetic analysis and microstructural transformation of magnetic MxP electrode. **(a)** Schematic illustration of magnetic MxP electrode, highlighting its layered structure. **(b)** Close-up photograph depicting the electrodes actuation in response to a magnetized sewing needle. **(c)** Top-down time-lapse sequence showing electrodes rapid actuation within .1 seconds, with directional arrows indicating movement. **(d)** Side view time-lapse sequence showing electrodes rapid actuation within .1 seconds, with directional arrows indicating movement.

Methods

EIS Characterization:

- Submerged MxP electrode in phosphate-buffered saline (PBS) with AgCl reference and Platinum Counter electrodes.
- Conducted impedance measurements from 0.1 to 10^6 Hz using a potentiostat.

Fatigue Test:

- Created fatigue test samples with magnetic substrate, laser-cut into 2mm x 3mm rectangles.
- Affixed graphene tape to sample ends; connected to a 2V source.

In Vitro Phantom Spinal Cord:

- Utilized 3D-printed mold to cast gelatin-based phantom spinal cord; ensured standardization.
- Positioned phantom in vertebral model within PBS bath for testing.
- Inserted stainless steel electrodes at both ends of phantom; connected to PowerLab for voltage monitoring.
- Assessed MxP electrode's voltage output over 10 seconds with/without magnetic field.

Results

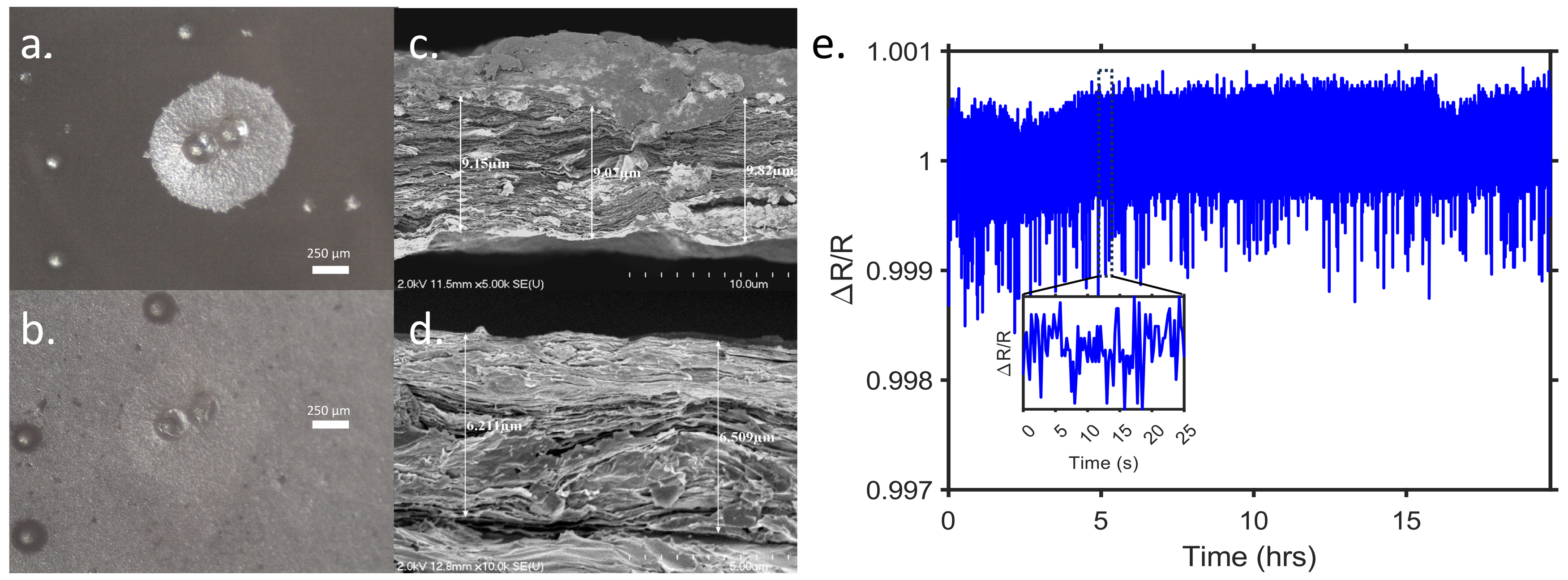

Figure 2. Enhanced Conductivity and Maintained Fatigue Resistance in Annealed MxP. (a-b) Progressive visualization of the MxP annealing process. **(c)** Scanning Electron Microscope (SEM) image of MxP before annealing. **(d)** SEM image showcasing the microstructural changes in MxP post-annealing. **(e)** Resistance measurements over 8,000 bending cycles (0–90°) at a frequency of 530 cycles/hr, demonstrating no significant variation in electrical resistance from start to end (p=0.64).

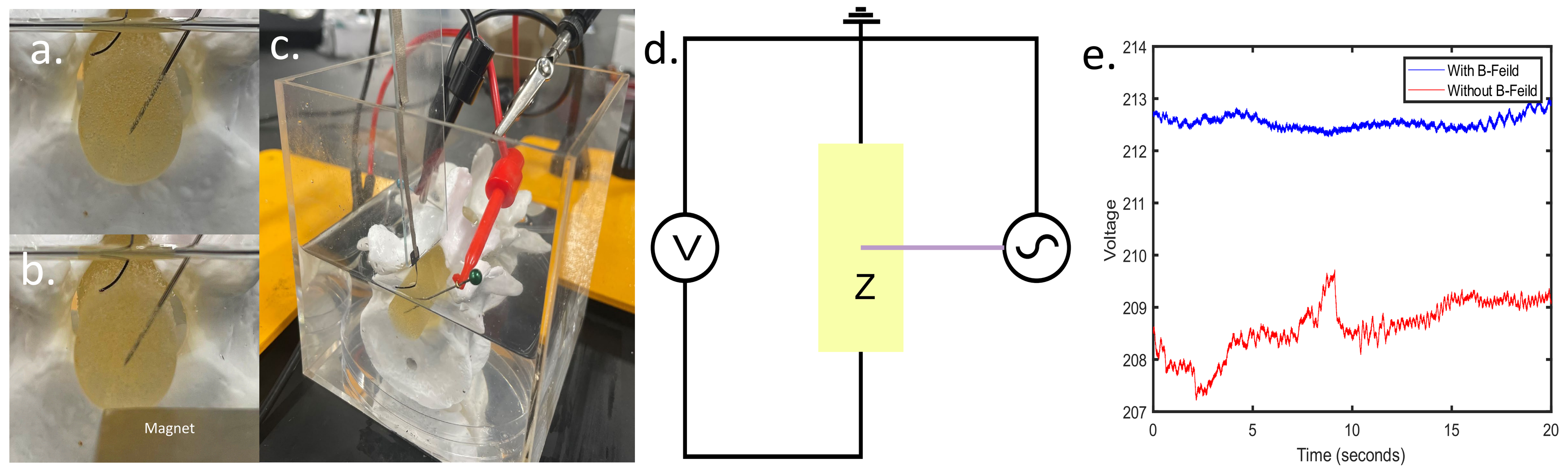

Figure 4. Improved In vitro stimulation of phantom spinal cord with application of magnetic actuation. **(a-b)** Sequential images depicting the epineural electrode's deflection towards a magnet, illustrating the magnetically induced actuation of the MxP composite electrode. **(c)** Experimental setup featuring the MxP composite electrode interfaced with a spinal cord phantom, positioned within a custom apparatus with model vertebrae to replicate the geometry biological environment. **(d)** Circuit schematic delineating the experimental arrangement: the purple segment represents the MxP electrode, while 'Z' indicates the spinal cord phantom, which is the subject of the stimulation tests. **(e)** Temporal voltage profiles of the spinal cord phantom, recorded with (blue) and without (red) an applied magnetic field, indicating the magnetic field's influence on the MxP electrode's performance.

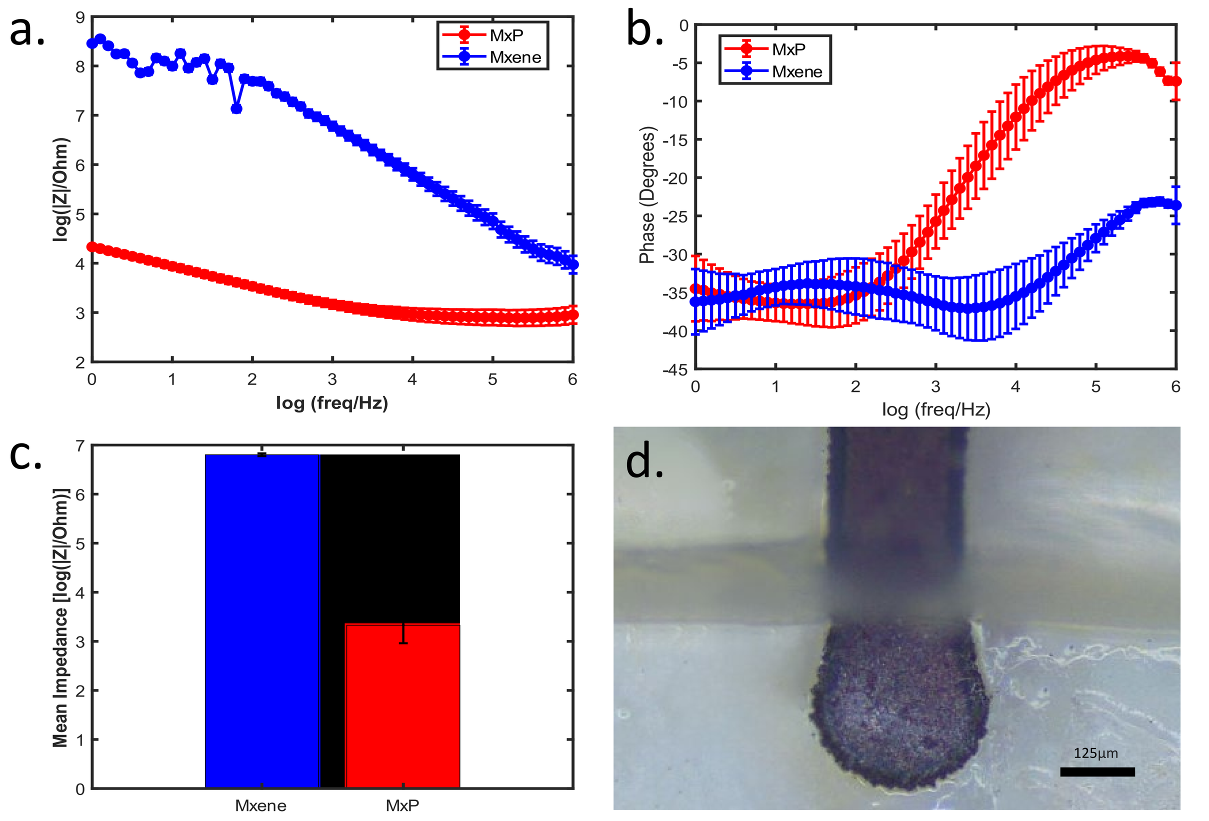

Figure 3. Enhanced electrochemical impedance spectroscopy (EIS) measurements with MxP. **(a)** Bode plot displaying the impedance magnitude and phase angle across a frequency range of 0.1 Hz to 1 MHz for six individual eletrodes. **(b)** Phase angle versus frequency plot derived from EIS data, illustrating the phase response characteristics. Measurements were replicated across six individual electrodes for both Mxene and MxP types to ensure statistical robustness. **(c)** Comparative analysis of the mean impedance at 1 kHz for six Mxene and six MxP electrodes, indicating a significant reduction in impedance for MxP ($p = 0.001$). **(d)** Microscopic image of the electrode geometry utilized in EIS assessments.

Discussion

- Unannealed vs. annealed MxP shows notable microstructure changes.
- Annealed samples denser with aligned fibrils, likely enhancing conductivity.
- Annealed MxP retains electrical properties after 8,000 bending cycles, which Demonstrates material robustness and suitability for dynamic use.
- MxP exhibits lower impedance than Mxene base, suggesting improved charge transfer, essential for epineural interfaces.
- MxP electrode reacts to magnets, potentially aiding adaptive neural interfacing.
- Magnetic fields modulate electrode performance, a new control method for stimulations.
- **Overall Implications:** The magnetic MxP composite holds promise for adaptive neuroprosthetics with its flexible, efficient, and magnetically responsive properties.

Conclusion

The study validates the Mxene-PEDOT:PSS (MxP) composite as a robust material for neuroprosthetic interfaces, with annealing significantly enhancing its microstructure and electrical properties. The overall electrode demonstrates sustained performance under mechanical stress and responsive behavior to magnetic fields, suggesting its utility for adaptive neural stimulation. These attributes indicate MxP's strong potential for advancing neuroprosthetic technology.

References

1. Liang, C. *et al.* Strategies for interface issues and challenges of neural electrodes. *Nanoscale* **14**, 3346–3366 (2022).
2. Qi, Z. *et al.* Reconfigurable Flexible Electronics Driven by Origami Magnetic Membranes. *Advanced Materials Technologies* **6**, 2001124 (2021).

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