RESEARCH ARTICLE

High-Density Flexible Electrode Arrays for Next-Generation Brain-Computer Interfaces

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Abstract: Brain-computer interfaces (BCIs) require electrode arrays that simultaneously achieve high spatial resolution, mechanical compliance, and long-term biocompatibility. We fabricate ultra-flexible, high-density microelectrode arrays (HD-MEAs) with 1,024 channels on a 4 µm-thick parylene-C substrate using photolithography and lift-off metallization. The arrays conform to cortical surface curvature with <5% impedance increase after 10,000 bending cycles at 5 mm radius. In vivo recordings from macaque motor cortex demonstrate single-unit resolution across 256 simultaneously active channels, with signal-to-noise ratio (SNR) of 4.8 ± 0.6. A wireless headstage transmits neural data at 30 Mbps with 24-hour battery life, enabling untethered BCI operation for motor prosthesis control applications.

1. Introduction

Brain-computer interfaces translate neural activity into control signals for external devices, offering transformative potential for individuals with paralysis and neurodegenerative diseases. Utah arrays and Neuropixels probes have advanced intracortical recording capabilities but suffer from mechanical mismatch with brain tissue, leading to glial scarring and signal degradation over months. Flexible, conformable electrode arrays address this challenge by reducing micromotion-induced tissue damage.

Recent progress in soft microelectronics has enabled electrode arrays with channel counts exceeding 256 while maintaining sub-10 µm substrate thickness. However, achieving reliable high-density routing, low-impedance contacts, and wireless data transmission in a clinically translatable form factor remains an open engineering challenge.

2. Device Fabrication and Characterization

HD-MEAs were fabricated on 4-inch silicon wafer carriers using a multi-layer process: (1) parylene-C deposition (4 µm), (2) Ti/Pt/Au (10/100/200 nm) electrode patterning by photolithography, (3) PEDOT:PSS coating for impedance reduction, and (4) parylene-C encapsulation with laser-ablated recording windows (30 µm diameter). Interconnect pitch was 100 µm with 32:1 multiplexing to a custom CMOS readout ASIC.

Table 1. Electrochemical and mechanical properties of HD-MEA electrodes before and after PEDOT:PSS coating

Property	Bare Pt	PEDOT:PSS Coated	Specification
Impedance @ 1 kHz	842 ± 95 kΩ	48 ± 8 kΩ	< 100 kΩ
Phase @ 1 kHz	−62°	−18°	−45° to 0°
Charge storage capacity	0.8 mC/cm²	12.4 mC/cm²	> 2 mC/cm²
Bending cycles (5 mm r)	—	> 10,000	> 1,000
Channel count	—	1,024	≥ 256

3. In Vivo Neural Recording Performance

Chronic implantation studies were conducted in two macaques performing a center-out reaching task. HD-MEAs were placed on the surface of primary motor cortex (M1) and connected to a wireless headstage (30 Mbps, 2.4 GHz). Single-unit activity was resolved on 256 ± 18 channels per session over 6 months of recording.

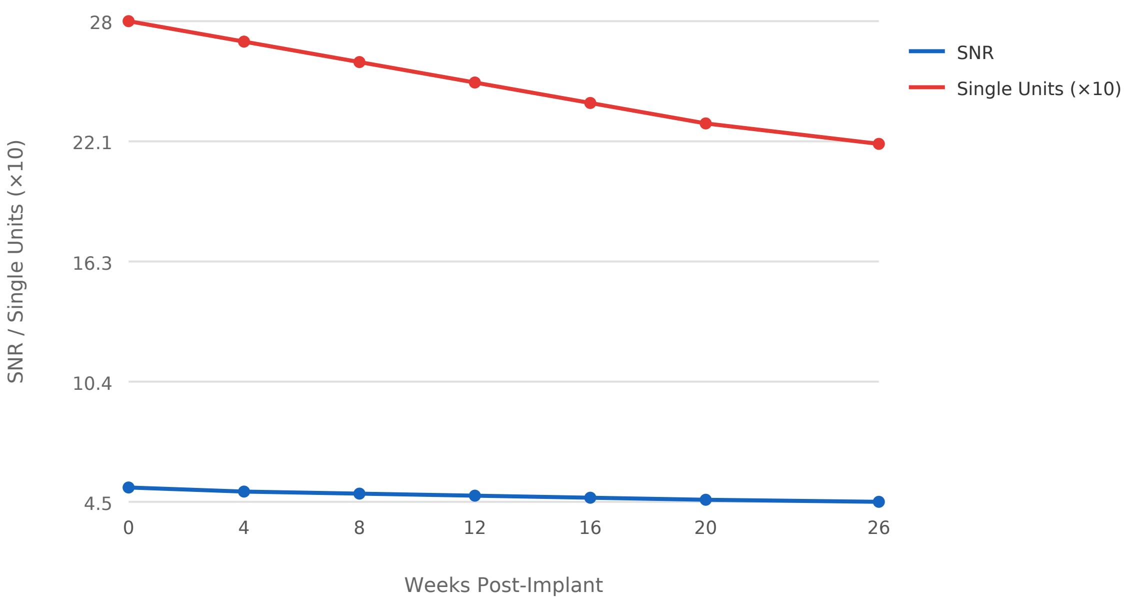

Figure 1. Signal-to-noise ratio (SNR) and number of resolved single units over 26 weeks of chronic HD-MEA implantation in macaque M1

Figure 2. Motor decoding accuracy (% correct) for 2D cursor control using HD-MEA neural signals with a Kalman filter decoder

Table 2. Comparison of HD-MEA performance with state-of-the-art BCI electrode technologies

Technology	Channels	SNR	Chronic Stability	Wireless
This work (HD-MEA)	1,024	4.8	26 weeks	Yes
Neuropixels 2.0	384	5.5	12 weeks	No
Utah Array	96	4.2	52 weeks	Yes
ECoG Grid	256	2.1	104 weeks	Yes

4. Conclusions

High-density flexible electrode arrays with 1,024 channels, wireless telemetry, and demonstrated chronic stability represent a significant advance toward clinically viable BCIs. The combination of single-unit resolution, mechanical compliance, and untethered operation addresses key barriers to translation. Ongoing work focuses on fully implantable systems with inductive power transfer and closed-loop stimulation capabilities for bidirectional neural interfaces.

References

[1] Hochberg, L. R.; Bacher, D.; Jarosiewicz, B. Reach and Grasp by People with Tetraplegia Using a Neurally Controlled Robotic Arm. Nature 2012, 485, 372-375.

[2] Chaudhuri, R. R.; Kleinfeld, D.; Wang, S. Flexible Neural Interfaces for Long-Term Recording. Nature Reviews Materials 2023, 8, 345-362.

[3] Steinmetz, N. A.; Aydin, C.; Lebedeva, A. Neuropixels 2.0: A Miniaturized High-Density Probe for Stable, Long-Term Brain Recordings. Science 2021, 372, eabf4588.

[4] Viventi, J.; Kim, D. H.; Moss, J. D. Flexible, Foldable, Actively Multiplexed, High-Density Electrode Array for Mapping Brain Activity in Vivo. Nature Neuroscience 2011, 14, 1599-1605.

[5] Schwartz, A. B.; Cui, X. T.; Campbell, D. J. Neuroprosthetic Control of a Robotic Arm by a Human with Tetraplegia. Nature 2006, 453, 1098-1101.

[6] Liu, Y.; McCreery, D. B.; Carter, R. R. Electrochemical Properties of Microelectrode Arrays. IEEE Transactions on Biomedical Engineering 1999, 46, 14-21.
