Integrated Hierarchical Surface Restructuring of Assembled Electrode Arrays for Next-Generation Neural Interfaces

Alexander Blagojevic, Wesley Roser, Wesley Seche, Shahram Amini, Pouya Tavousi, Sina Shahbazmohamadi

Neural interfacing devices rely on implantable electrode arrays to modulate neural activity to provide various clinical benefits. The continued development of these devices is dependent on further miniaturization and increasing the density of electrode arrays, to enable more conformal implantation and selective and targeted stimulation. However, miniaturization reduces the geometric-surface area of the electrode contacts, leading to prohibitively poor electrochemical performance.

One recent solution to this limitation is femtosecond laser Hierarchical Surface Restructuring (HSR™); a maskless, laser surface treatment technology that forms bioinspired hierarchical surface structures, on native electrode contacts, enhancing electrochemical performance by up to two orders of magnitude. HSR™ technology increases the electrochemically active area of an electrode independently of its geometric surface area, allowing electrodes to be manufactured smaller without compromising performance. Despite its potential, widespread adoption of HSR™ in medical device manufacturing has been limited by cost considerations and the inherent complexities of integrating new surface technologies into established production workflows

This work investigates the application of HSR™ to fully assembled Pt–10Ir paddle electrode arrays used for spinal cord stimulation, amongst other neural interfacing applications, and demonstrates, for the first time, its use as a stand-alone, post-fabrication surface modification technology compatible with existing device geometries and material constraints. This represents a significant advancement towards the manufacturing viability of the HSR™ platform, by demonstrating that the technology can be integrated seamlessly into existing production lines, without disruptive process changes.

Using stable fixturing, surface height mapping, and optional in-operando CO_2-snow-assisted processing, approximately 86% of each electrode contact was restructured, while maintaining the integrity of the surrounding soft polymer insulation. The resulting morphology, electrochemical performance, and processing efficiency were characterized, revealing substantial improvements in total charge storage capacity, specific capacitance, and impedance compared to unrestructured Pt-10Ir electrodes, while maintaining viable processing times.

To address the high material cost of platinum-based electrodes, this study also evaluates Reactive HSR™ (R-HSR™) applied to titanium-based electrode contacts for the construction of paddle electrode arrays, which are processed in a nitrogen rich environment. Electrodes produced using this approach exhibit total charge storage capacity and specific capacitance comparable to Pt-10Ir-based HSR™ electrodes. By combining hierarchical surface restructuring with lower cost, biocompatible materials such as titanium, the R-HSR™ platform provides a cost-effective alternative to Pt-10Ir for high performance, neural interfacing electrodes.

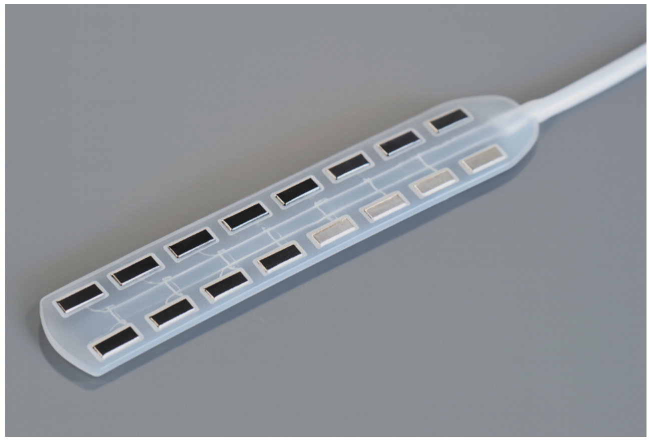

Figure 1: Photograph of a restructured Pt-10Ir paddle-type electrode array, with three sets of four channels restructured at different laser fluences. From left to right, top to bottom: 4x 8.63 J/cm², 4x 5.96 J/cm², 4x 3.86 J/cm², and 4x unrestructured.

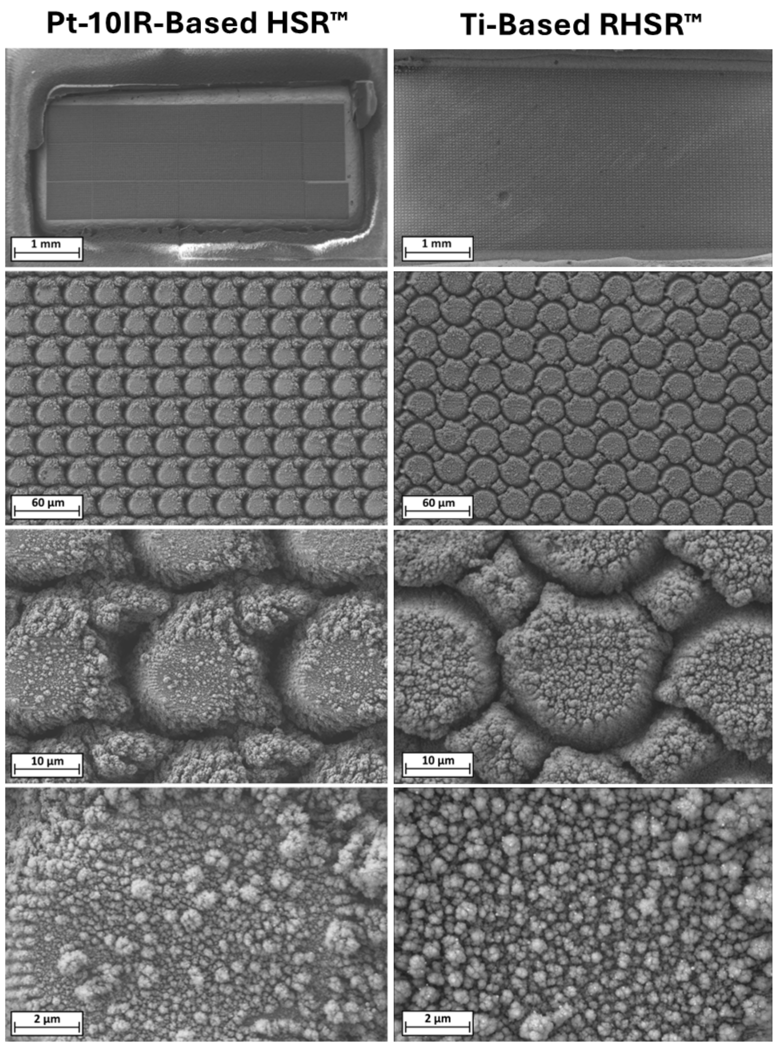

Figure 2: SEM micrographs the meso-, micro-, and nano-structures of paddle electrode contacts restructured using HSR™ and RHSR™, at magnifications of (top to bottom) 70x, 1kx, 5kx, 20kx to capture the hierarchical meso-, micro-, and nano-scale morphology. Note that due to electron beam distortion caused by charging of the insulation surrounding the electrode contact, the lower magnification micrographs of the RHSR™ electrode appear more zoomed in than the HSR™ counterpart.