Three-dimensional Silicon Mesostructures for Biointerfaces

Si-based materials exhibit biocompatibility, biodegradability as well as a spectrum of important electrical, optical, thermal and mechanical properties, leading to their potential applications in biophysical or biomedical research. However, existing forms of silicon materials have been primarily focused on bulky crystals, two-dimensional (2D) nano-membranes, and one-dimensional (1D) nanowires. Si with 3D mesoscale features has become an emerging class of materials with potentially unique physical properties. Previous efforts in this area have been impeded by challenges in traditional chemical synthesis and/or micro-fabrication techniques to precisely construct the 3D mesostructures. We are seeking new opportunities in this field by incorporating new design elements to prepare various forms of 3D Si mesostructures. In the following paragraphs, I am going to present two major projects along this direction. Both projects represent our ongoing efforts to extend the materials and application library of Si-based systems for biological interfaces.

Project 1. Atomic gold–enabled 3D lithography for silicon mesostructures

During natural biomaterial nucleation and growth, trace amount of interfacial organic additives play important roles in determining the biomaterial structures and functions. Taking inspiration from these natural processes, we developed an iterative gold (Au)-based deposition-diffusion-incorporation by intentionally introducing pressure modulation cycles during a chemical vapor deposition (CVD) growth of Si nanowires. After wet chemical etching, two distinct types of skeleton-like mesostructured Si spicules were identified with defined motifs, pronounced curvature, anisotropy and gradient. We demonstrated a new mechanism in which atomic Au forms a dynamic chemical resist layer for 3D mesoscale lithography of Si. This mechanism is fundamentally different from previous reports or practices involving Au film-based etch masks. The anisotropic mesoscale texture, reminiscent of natural systems (*e.g.,* bee's stingers), enabled significantly enhanced interfacial interactions between mesostructured Si spicules and extracellular matrix materials (i.e. synthetic collagen hydrogel). The enhanced bio-interfaces promised future applications for adhesive bioelectronics, where mechanically robust interfaces are desired for efficient signal transductions between bioelectronic devices and biological tissues.

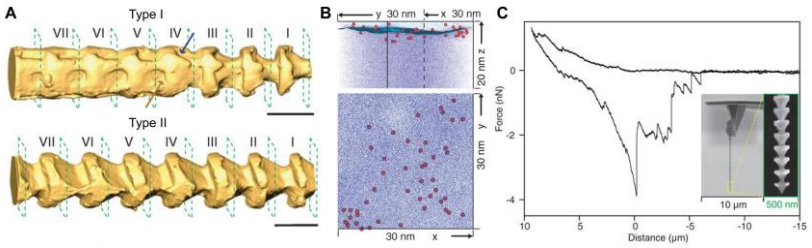

Fig. 1. Mesostructured Si spicules. (**A**) Scanning transmission electron microscopy (STEM) tomography of two types of spicules, both displaying pronounced curvature, anisotropy and gradient. The blue and brown arrows mark two distinct concave features. The letters and dashed lines mark individual segments. Scale bars, 200 nm. (**B**) Reconstructed 3D atom probe tomography (APT) dataset shows isolated Au atoms enriched at Si/SiO_2 interface. Si/SiO_2 interface (5 at.% O isosurface, cyan), Si (blue dots, 50%), Au (red dots, 100%), and O (cyan dots, 50%). (**C**) Representative force curves show strong mesoscale interfacial interaction with collagen hydrogel. Insets display the spicule-based AFM probe at different magnifications.

Project 2. Heterogeneous silicon mesostructures for lipid-supported bioelectric interfaces

Beyond creating quasi-3D mesostructures along 1D substrates, we extended our synthetic systems to truly 3D and spongy mesostructured particles. Ordered and uni-directionally aligned fibril-based framework is a fundamental layout in many natural biomaterials (*e.g.,* bones) which

shows modulative impacts on cellular systems. We used ordered mesoporous silica as a nano-casting template to create the 3D mesostructured Si via CVD growth with hexagonal organization of aligned nanowire bundles. The as-synthesized material displayed an amorphous framework on the atomic scale with multi-scale porosities on the mesoscale. The structural heterogeneity of the material induced a size-dependent chemical heterogeneity and both led to unique physical properties of the material. First of all, the mesostructured Si had significantly lower mechanical rigidity comparing to solid single crystalline Si and yielded minimal invasiveness to single cells. Additionally, the mesostructured Si displayed pronounced photothermal efficacy and was exploited to establish a remotely controlled lipid-supported bioelectric interface. We further demonstrated a dynamic hybrid Si/cell system by achieving non-genetic optical modulation of cellular electrophysiology dynamics. This work suggests that amorphous Si, a less exploited material in biomedical research, could serve as a building block in establishing functional biointerfaces and as a new bio-orthogonal and dynamic component for future synthetic biology.

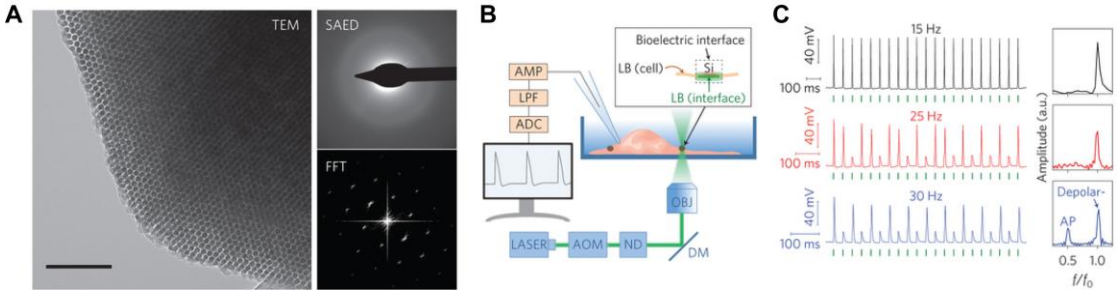

Fig. 2. Mesostructured Si for lipid-supported bioelectric interfaces. (**A**) Transmission electron microscopy (TEM) image (left) and its fast Fourier transform (FFT) diffractogram (lower right) indicate the hexagonal packing of Si nanowires (left panel). Selected area electron diffraction (SAED) pattern shows an amorphous atomic structure (upper right). Scale bar, 100 nm. (**B**) Experimental set-up used to elicit action potentials in dorsal root ganglia (DRG) neurons by illuminating a single Si particle attached to a cell. Neurons were patch clamped in the current-clamp whole-cell mode. AOM, acousto-optic modulator; ND, neutral density filters; DM, dichroic mirror; OBJ, microscope objective; AMP, amplifier; LPF, low-pass filter; ADC, analog-to-digital converter. Inset shows that a portion of the cell membrane functions as a built-in bioelectric interface. (**C**) Representative membrane potential recordings of a DRG neuron exposed to trains of laser pulses at different frequencies, with corresponding FFTs (right). f and f_0 are output and input frequencies, respectively. Green bars indicate when laser pulses were delivered.