frameworks and Pt precursors. Afterward, "we could not help but to test their ORR catalytic activities in fuel cells since we are an electrocatalysis-fuel cell group, and the experimental setup was already there," Liu says; "we were glad we did it."

The developed ORR catalysts were fabricated into fuel cell membrane electrodes for performance evaluation. The electrodes contained ultralow Pt loadings, approximately one tenth of those used in commercial electrodes, while still exhibiting excellent ORR catalytic activity. At an output voltage of 0.9 V, the highest mass activity (current generated per milligram of Pt) was 1.77 A/mg_{Pt}, which exceeds a 2025 target (0.44 A/mg_{Pt}) set by the US Department of Energy. The improved ORR catalytic activity was attributed to the synergistic catalysis between the Pt-Co nanoparticles and the Co, N-containing carbon support. Specifically, in addition to directly reducing O_2 to water over the Pt-Co nanoparticles, the N-coordinated cobalt ($Co\text{-}N_x\text{-}C_y$) sites on the substrate can also reduce O_2 to water and H_2O_2. The generated H_2O_2 then diffuses to the surface of nearby Pt-Co nanoparticles where it is eventually reduced to water.

Bao Yu Xia of Huazhong University of Science & Technology, China, says that the key deliverables of this work, "developing cost-effective and scalable approaches for some of the most promising ORR catalysts with ultralow Pt contents," as well as understanding their catalytic activities in fuel cells are vital to large-scale implementation of fuel cells. Xia was not involved in this study.

"This work brings out a new research direction and is far from complete," Liu says. The research group is investigating various issues to further enhance the performance of their catalysts, including the optimal distance between the Pt-Co nanoparticles and the $Co\text{-}N_x\text{-}C_y$ coordination sites, the influence of humidity on the synergistic catalysis, and the minimal Pt loading possible without sacrificing catalytic activity.

Tianyu Liu

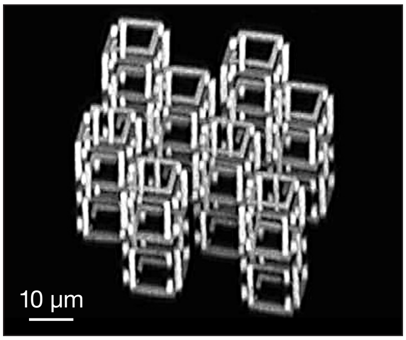
NANO FOCUS

Shrinkage leads to nanoscale resolution in 3D geometries and with a variety of materials

Optical metamaterials are structures that interact with light to challenge the laws of physics. They can exhibit a negative refractive index to be used in electromagnetic cloaks, for super-high resolution imaging, and for unusual color effects. To interact with electromagnetic waves, however, these materials have to possess dimensions comparable to the wavelengths, namely 100 nm and smaller. Such precision is enabled in state-of-the art two-dimensional (2D) nanofabrication but remains challenging in three-dimensional (3D) geometries.

The research team of Edward S. Boyden at the Massachusetts Institute of Technology has developed a unique approach to fabricate 3D patterns with nanoresolution. The process, called ImpFab for "implosion fabrication," was reported in a recent issue of *Science* (doi:10.1126/science.aau5119) and relies on the following principle. A porous hydrogel, typically a polyacrylate or a polyacrylamide, is swollen in an aqueous solution containing ions or organic molecules that readily diffuse through the pores and deposit at the surface of polymeric chains. Chemical reactions can occur, such as the growth of metallic nanoparticles from ionic suspension, directly within the hydrogel. After this internal coating, the composite is shrunk down, and then further solidified by sintering to create metallic structures.

Since hydrogels can be 3D-printed at the microscale, this principle can be easily coupled with 3D printing. Using hydrogels with controllable cross-linking density, the homogeneous shrinkage occurring after dehydration results in retention of the shape, but a decrease in dimensions. As a result, 3D patterns with complex shapes and resolutions of 50 nm could be fabricated in silver. These were found to exhibit an electrical conductivity only about 10 times less than that of bulk silver despite the high porosity (see Figure).



Fluorescence imaging of a silver nanostructure created with ImpFab. Credit: *Science*.

Shweta Agarwala, a researcher at the Singapore Centre for 3D Printing and leading innovator in additive manufacturing for electronics and biotechnology, says that "currently, direct-writing of nanostructures is possible using non-contact methods like inkjet and aerosol jet, but the resolution is limited to 10 μm. Moreover, these techniques are able to print in 2D plane only. This research of using sacrificial scaffolds to pattern desired structures and shrinking them to achieve 3D nanoscale objects is fascinating." Furthermore, Boyden emphasizes that "the contribution of the work is not just that we can achieve similar or better resolution, but rather that we have found a way to do the patterning of many different materials in a modular fashion to achieve any geometry." Indeed, the research team provides examples of patterning with fluorescent molecules, proteins and DNA, and several metals.

Daniel Oran and Samuel G. Rodriques, the lead authors of the article, are excited by the possibilities that the method offers to create and study optical metamaterials. "There is a huge need for a robust and efficient way of generating 3D nanoscale features out of a variety of materials. We are eager to find collaborators in any domain where the benefit of arbitrary 3D geometry is paramount to asking new scientific questions or creating devices that would otherwise be impossible or impractical to fabricate," Oran says.

Hortense Le Ferrand

https://doi.org/10.1557/mrs.2019.63 Published online by Cambridge University Press https://doi.org/10.1557/mrs.2019.63 Published online by Cambridge University Press