Using Two-dimensional (2D) Materials to Enhance the Performance of Electrochemical Energy Storage and Conversion Devices

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Two-dimensional (2D) materials consist of single layers of atoms and have a number of key features for electrochemical charge storage and conversion including quantum confinement in two dimensions, significant available surface area, and distinct local structures (*e.g.* surface states, edge sites). In addition to graphene which has been significantly investigated, 2D forms of transition metal oxides provide significant potential advantages for enhanced electrochemical energy storage and conversion devices including batteries, supercapacitors, sensors, fuel cells, and electrolyzers.

Iron oxide nanosheets were investigated to provide low-cost cathode materials for lithium-ion batteries. Iron oxide (FeO_x) nanomaterials were synthesized using a solution-phase process and then exposed to different temperature/atmosphere treatments. The structure was determined using transmission electron microscopy (TEM), scanning electron microscopy (SEM), x-ray diffraction and Raman spectroscopy. The improved Li-ion electrochemical capacities, cycling, and rate capabilities of the iron oxide nanosheets compared with nanoparticles is attributed to the combination of the two-dimensional form of the material which facilities a surface-based Li-ion charge storage process.

Vanadium pentoxide (V_2O_5) has a layered structure, and nanostructures have shown high capacities within lithium-ion batteries, the low magnesium-ion diffusion within the structure of highly crystalline V_2O_5 leads to poor performance in magnesium-ion batteries. Our work has shown an effective approach to increase the interlayer spacing of V_2O_5 nanosheets by incorporating poly(ethylene oxide) (PEO) between the layers. Inserting PEO in the V_2O_5 lattice was shown by x-ray diffraction to increase the interlayer distance. Magnesium-ion storage capability of interlayer expanded-V_2O_5-PEO nanocomposites was investigated using cyclic voltammetry and constant current charge-discharge methods. Based on the electrochemical analysis, interlayer expanded V_2O_5-PEO showed the highest specific capacity, with a 5-fold enhancement in specific capacity over pure V_2O_5 nanosheets. This novel method to expand the interlayer spacing of the lattice structure provides an effective way to enhance magnesium-ion storage in layered metal oxides.

Two-dimensional materials also have significant potential for use as electrocatalysts. Toward this end, we developed a transformative direction of using carbon-free two-dimensional nanostructures as oxygen reduction electrocatalysts rather than conventional carbon-supported nanoparticles. Two-dimensional Ni_xPt_y nanoframes that consist of a highly catalytically active Ni-Pt alloy phase integrated within a carbon-free metallic support structure were developed. Through controlled temperature/atmosphere treatments of Pt-decorated $Ni(OH)_2$ nanosheets, the high surface area 2D framework is maintained in the nanoframe structure. Our results show that Ni_xPt_y nanoframes provide significantly higher activities compared with conventional Pt/C catalysts.

Biosketch

Dr. Rhodes' research involves studying the structure and properties of electrochemical materials, and he has contributed to the research and development of advanced materials for batteries, supercapacitors, fuel cells, electrosynthesis of hydrogen peroxide, and solar hydrogen production. Dr. Rhodes received a B.A. in Chemistry in 1992 from Texas A&M University and received his Ph.D. in Physical Chemistry in 2001 from the University of Oklahoma. Subsequent to his doctoral work, Dr. Rhodes held an Office of Naval Research–MURI postdoctoral appointment at UCLA in the Department of Materials Science and Engineering and a joint appointment as a contractor at the U. S. Naval Research Laboratory in the Surface Chemistry Branch. Following his postdoc, Dr. Rhodes spent nine years in a private company, Lynntech, Inc., where he developed and commercialized advanced technologies. Dr. Rhodes accomplishments include numerous published articles in peer-reviewed journals, an issued patent, and numerous presentations at international meetings. Dr. Rhodes has served as Principal Investigator (PI) on grants and contracts from the National Science Foundation, Department of Energy, Department of Defense, and National Aeronautics and Space Administration. In addition to his research experience, Dr. Rhodes has experience in technology development and commercialization, and his research has resulted in two products that were purchased by private companies.