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Editorial

Nanomaterials: Bringing New Excitements to the Energy World

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Energy and materials have a continual and mutually enriching relationship. Certain historical periods have been categorized as Stone Age, Bronze Age, and Iron Age based on the prevalent materials used during those specific times. People used these materials to either conserve energy or create new energy forms. In the modern day society, materials for energy come in a near continuum: naturally occurring materials release energy through chemical or nuclear reactions, refractory metals and ceramics are being used in energy conversion systems, and functional materials are actively sought for energy storage and use. Materials enable the production of energy more efficiently or transformation of primary energy into more useful forms. Energy, in turn, has made possible the production of a broad range of materials for the society: from tailor-made fluids, to solid state devices, and to high temperature components. Increasing demand for energy, diminishing stocks of fossil fuels, and the public's desire to enhance environmental quality, particularly by reducing greenhouse gas emissions, all point to the need for improved materials. Nanomaterials advancements have brought new excitements to the energy world.

In the complex web of energy resource, production, storage, use, and efficiency, nanomaterials play a critical role as diverse and far-reaching as energy itself.

Energy production

New nanomaterials that increase the efficiency of energy conversion and lower its cost provide valuable flexibility in energy production. For example, in fossil fuel combustion and gas separation, nanomaterials can increase the energy conversion temperatures, separate gases with higher purities, and produce electricity with lower or no CO_2 emissions. These have been the frontier of nanomaterials research in turbine blade coatings, high temperature gas separation membranes, and even hot electrodes for magneto hydrodynamic energy conversion. In nuclear power plants, new nuclear fuels and claddings using nanomaterials would realize a new generation of safer and more efficient nuclear reactors. For example, cladding materials are exposed to simultaneous chemical and mechanical interactions with high neutron irradiation. Oxides (e.g., Y_2O_3, TiO_2) have been added into stainless steels to enhance their mechanical properties regarding irradiation-induced swelling, creep resistance, and strength degradation [1-3]. A 2-5 nm particle is enough to stop the grain boundary from slipping at elevated temperatures [4,5]. Extensive testing was done with Eurofer97, a variation of 7-9wt% Cr stainless steel, where the irradiated samples exhibit a high yield stress of ~1,400 MPa compared to the unirradiated samples at ~1,000 MPa [6].

Energy harvesting

Engineered thermoelectric and mechano electric nanomaterials can tap otherwise wasted energy and transform it into useful forms. Photovoltaic nanomaterials can convert solar energy into electricity or produce hydrogen fuel gas by splitting water. Enormous efforts have been devoted to expanding the application of TiO_2 nanotubes in energy conversion and storage, electro chromic devices, and sensors [7-9]. Among different approaches used to synthesize TiO_2 nanotubes, anodization of titanium foil is an easy method to achieve nanotubular TiO_2 with controlled morphologies. The diameters of anodic TiO_2 nanotubes are determined by the applied potential and range from 10 nm to 600 nm [10-12]. In recent years, ZnO piezoelectric nanostructures (such as nanowires and nanoribbons) have attracted great interest in generating electric energy to power nanosensors or nanoelectromechanical systems. One major advantage to use nanowires instead of bulk materials is the much higher strain that can be sustained by nanowires. For instance, the maximum strain for ZnO nanowires is ~7.7% [13]. While the maximum strain for bulk ZnO materials is ~0.2% [14]. Therefore, much higher output power can be expected from nanosized structures compared to their bulk forms. The higher flexibility and strain tolerance of nanostructures could also effectively reduce the risk of potential fracture or damage of the piezoelectric materials under high-frequency vibration conditions, and thus broaden their vibration frequency and amplitude range. Piezoelectric nanowires using ABO_3 materials can be good candidates for mechanical energy harvesting [15]. Static and dynamic analyses show that $BaTiO_3$ nanowires and $(Pb(Mg_{1/3}Nb_{2/3})O_3{-}xPbTiO_3)$ nanowires would ideally produce as high as 30,000 $W{\cdot}cm^{-3}$ and 11,800 $W{\cdot}cm^{-3}$ maximum output power density, respectively, assuming the entire space is filled by nanowires.

Energy storage

Materials store and deliver energy in the forms of batteries, supercapacitors, or fuels. High performance nanomaterials for storing hydrogen would enable more energy efficient vehicles and off-grid operation. It is these fascinating material behaviors and properties that give us the high hope of tackling the challenging renewable and sustainable energy use problems. In order to improve the energy density of super capacitors, the most promising approaches are either to use an electrode material with large specific capacitance or increase its working voltage by utilizing a hybrid super-capacitor system which consists of an activated carbon electrode and a battery electrode material (pseudo-capacitor material). The porous electrode often has

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nano-sized crystalline clusters in a nanopore size matrix. Different carbon formats have been used as electrodes in super-capacitors: activated carbons, carbon aerogels, carbon fibers, carbon nanotubes, and carbon onions. Of special interest has been the development of advanced carbons with specific capacitance significantly greater than the present values of 150-200 F·g^{-1} in aqueous electrolytes and 80-120 F·g^{-1}in organic electrolytes. Activated carbons possessing various physicochemical properties with well-developed surface areas as high as 3000 m^{2}g^{-1} have been produced and their electrochemical properties have been studied [16].

Energy use

Solid state lighting based on light emitting diodes (LEDs) is a promising technology for illumination applications due to its high energy efficiency, environmental benefits, reliable performance, and potential functionalities to lighting systems. LEDs can be made into submicron feature arrays for microelectronics even though the market is still in the formative stage. The chip arrays reduce the demand for thermal management while simplifying the design of directional luminaires. LED encapsulation is a critical technique since it provides physical, chemical, and mechanical protection and is able to improve the luminescence efficiency for LED chips. Two essential requirements for LED chip encapsulation are high optical transparency and high thermal stability. Current LED chip encapsulates are far from being desirable because they cannot satisfy these requirements simultaneously for either low light extraction efficiency (caused by low refractive index) or discoloration at elevated temperatures. One promising approach is to take advantages of the high refractive index and UV-light shielding effect of quantum dots such as ZnSe, as well as LED array patterning ability from lithography to fabricate quantum dot filled LED arrays. The refractive index is adjustable based on the volume percent of quantum dots and can be greatly enhanced compared to polymeric encapsulation (e.g., increase from ~1.5 to 1.89 with 30 vol% ZnSe loading). The visible transparency maintains even after long time aging at elevated temperature (e.g. 200°C). Quantum dot loaded polymeric matrix can also provide good UV-light shielding efficiency.

In summary, the issues associated with the harvesting, conversion, storage, and efficient use of energy are being actively studied. Underlying much of the potential advancements in energy are nanomaterials, which have greatly advanced at the fundamental understanding level in the last two decades. Annals of Material Science and Engineering will provide a great new platform for disseminating the new theories, applications, techniques, and tools from nanomaterials where they can be used as the primary vehicles to solve energy problems and enable energy technology innovations. It has the potential to transform landscapes of scientific understanding in energy by linking innovative nanomaterials with energy research and development in a uniquely multidisciplinary and interdisciplinary nature.

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