Nanowire-based composites for energy and the environment

Pu-Xian Gao

Multifunctional architectures are synthesized cost-effectively and efficiently.

Since the emergence of nanotechnology in the early 1990s, nanoparticle- and nanofiber-strengthened composite materials have improved structural components in buildings, bridges, and air- and spacecraft. However, chemical and functional characteristics of composite nanostructures are currently inadequate, despite the usefulness of such properties toward emerging energy and sustainability challenges. Such challenges otherwise lack low-cost and efficient solutions.

Homogeneous nanomaterials are generally nonfunctional. However, through either doping/alloying or interfacing/layering, improvement or functional multiplication of single-component nanomaterials is achievable. We are designing, fabricating, and using a new class of hierarchical, oxide-based nanowire composites. Our goals are to understand and advance UV-lighting technologies, solar absorption, emission control, and chemical sensing.

We are rationally designing and fabricating numerous oxide-based hierarchical nanostructures (such as nano-arrays) by integrating solution- and vapor-phase syntheses. These arrays include but are not limited to semiconducting oxide composite nanowires with tunable band structures and metal oxide/perovskite (spinel) composite nanowires (see Figure 1).

Toward efficient band-structure engineering at low cost, we developed a low-temperature (50–155°C) two-step sequential hydrothermal process for magnesium (Mg) alloying in zinc oxide (ZnO) nanowire arrays. Photoluminescence spectroscopy revealed enhanced and blue-shifted near-band-edge UV emission in the MgZnO arrays relative to ZnO arrays. These results proved that it is feasible to engineer band structures of semiconductor nanostructures through low-temperature solution routes without resorting to post-heat treatments, in contrast to conventional vapor-phase techniques. Advantages include low cost, large yield, environmental sustainability, and low reaction temperature.

Figure 1. (a) Top view, scanning-electron-microscopy (SEM) image, of solution-processed zinc magnesium oxide (ZnMgO)/(Zn,Mg)1.7SiO4 nanowires, after ambient thermal treatment. Zn: Zinc. Mg: Magnesium. O: Oxygen. Si: Silicon. (b) Transmission-electron-microscopy images of a single ZnMgO nanowire with an epitaxial shell of (Zn,Mg)1.7SiO4. (c) Top view, SEM image of zinc oxide (ZnO)/La2–xSrxCuO4 composite nanowire arrays. La: Lanthanum. Sr: Strontium. Cu: Copper. (d) Top view, SEM image of Zn2SnO4/Ag2O composite nanowire arrays. Sn: Tin. Ag: Silver.

We also developed post-thermal-treatment processes to further tune MgZnO nanowire composite band structures to meet opto-electronic application requirements. For instance, by ambient annealing, intrinsic near-band-edge (NBE) emission was intentionally quenched completely with red-shifted and enlarged defect-related visible bands. Structurally, an epitaxial shell of silicates on the MgZnO nanowire core was achieved through an ambient thermal-treatment process, which is key to NBE-emission quenching, while broadening and red shifting the visible optical bands. Upon vacuum thermal treatment, complete quenching of defect-related visible bands occurs, with enhanced and blue-shifted NBE emission. These unique thermal-treatment processes may be applied to tune optical bands of nanowire-based composites for ultra-efficient visible solar absorption and UV-lighting technologies.

Furthermore, we self-assembled metal oxide/perovskite (spinel) composite nanowire arrays, such as ZnO/(La,Sr)CoO3 and Ag2O/Zn2SnO4 (La: Lanthanum. Sr: Strontium. CoO3: Cobalt)
trioxide. AgO: Silver oxide. SnO$_4$: Tin tetroxide), using a combination of vapor- and solution-phase approaches. They exhibit reduced photocatalytic degradation relative to organic dyes, photoresponsive humidity-detection capacity, and unique reversible catalytic ambient-oxygen/ethanol-detection capacity. These demonstrations validate a new class of multifunctional nanowire-based composites as smart nanocatalysts for vehicle- and industry-emissions control, and chemical sensors for multiple transient chemical detection in combustors and power plants.

We are currently further developing nanowire-based composite technologies to address energy and environmental challenges. Solution-based routes and post-thermal-treatment processes are under investigation for band-structure engineering relevant to UV lighting and visible solar absorption. Spinel-based nanowire composites are under investigation toward development of multifunctional nanocatalysts and nanosensor arrays for environmental emissions control and monitoring.

This work was supported by the University of Connecticut, the Honda Research Institutes-USA, the United Technologies Research Center, the American Chemical Society’s Petroleum Research Fund, and the Department of Energy.

Author Information
Pu-Xian Gao
University of Connecticut
Storrs, CT

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