Fabrication and assembly of one-dimensional semiconducting nanostructures and their applications to multi-functional devices

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One-dimensional (1D) semiconducting nanostructures have been extensively studied in the past few decades due to their excellent electrical, chemical and optical properties, which enable remarkable performance in various applications such as electronic/optoelectronic devices, chemical/biological sensors and energy harvesting. Since water pollution becomes as one of the most challenging global issues, photocatalytic degradation has received considerable attentions as an efficient water treatment technology with regard to removing organic contaminants. Upon receiving UV or sunlight irradiation with energy higher than their bandgap, semiconducting materials generate charge carriers such as electrons and holes that react with water and produce reactive species for decomposition. TiO$_2$ and ZnO are the most widely used photocatalysts because of their higher degradability and lower production cost. Especially, TiO$_2$ and ZnO nanostructures exhibit better degradability thanks to their low recombination of charge carriers and large active surface areas. However, the challenges like low utilization of sunlight (mainly responsive to UV light) and non-recyclability limit their large-scale use as photocatalysts. In this work, we tackle these limitations by developing a new immobilized photocatalytic system to improve their recyclability and investigating a novel semiconductor-semiconductor heterogeneous material to enhance their optical response in the visible region. First, ZnO nanowires (NWs) have been synthesized using a hydrothermal process and hybridized with silicon nanocrystals (SiNCs). This heterojunction lowers the ZnO bandgap (more active under visible light) and exhibits superior photodegradation performance under the visible and white light conditions compared to original ZnO NW photocatalysts. Second, we have developed a novel fabrication technique to create a vertically-aligned ZnO NW array on a polymer substrate with strong adhesion. The proposed two-step fabrication process allows the part of NWs to be embedded into the polymer matrix, securing the nanomaterials for harsh operating environments. A ZnO-NW/Polydimethylsiloxane (PDMS) film presents the unique immobilized photocatalytic system that can float on the water surface, targeting buoyant pollutants. In particular, crude oil has been used a model
pollutant for degradation experiment. A strong adhesion of ZnO NWs to the polymer substrate also enables two new implementations of the photocatalytic system including the application with high shear stresses and piezoelectrolysis. The latter application is particularly interesting as organic pollutants were degraded via mechanical vibration without resorting to light energy. Finally, this two-step synthesis technique combined with strain engineering allows us to create multifunctional soft micromotors, i.e., the ZnO-NWs/PDMS submillimeter 3D structures integrated with various nanomaterials (metal nanoparticle catalysts, magnetic nanoparticles, etc.). The micromotors possess multiple functionalities such as photocatalysis, piezoelectrolysis, locomotion/self-propulsion, and magnetic response. This level of multifunctionality integration on a single platform can be rarely found in the literature. In the end, an immobilized photocatalytic system with high surface areas, improved mass transfer, and easy recyclability has been developed, which can find its uses in biomedical and environmental applications. Apart from the photocatalytic applications, the research has also been oriented to address some technical challenges in deterministic assembly of the solution-processed 1D nanostructures for device integration. A methodology of rapidly and selectively creating 1D nanostructure array over a large area has been introduced using filtration guided assembly, producing an array of semiconducting single-walled carbon nanotube (SWNT) network pattern with sub-10-micron resolution over 20 cm² area within 10 minutes. The array uniformity and patter equality have been evaluated by measuring the electrical performance of the SWNT transistors built through the proposed technique.