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Advanced Nanostructured Materials and Architectural Design for High-Performance Electrochemical Energy Storage Devices

S. Smart materials for nanoelectronics – nanophotonics

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Abstract

The global imperative for sustainable and efficient energy systems has accelerated the demand for next-generation electrochemical energy storage devices, such as asymmetric supercapacitors and advanced batteries. Meeting these performance demands requires the development of novel electrode materials with high electroactive surface areas, outstanding structural integrity, and exceptional cycling stability. This work highlights recent breakthroughs in synthetic engineering and architectural optimization across polymeric, carbon-based, and composite material frameworks to address these challenges. We have synthesized a novel in situ template-assisted synthesis strategy utilizing dynamic, self-decomposing templates to fabricate hollow polypyrrole nanoparticles. This concurrent template formation and localized polymer encapsulation yield unique hollow frameworks with a 30% structural contraction, giving rise to an exceptionally high surface area morphology. When integrated into asymmetric electrochemical capacitors, these soft-polymer configurations deliver remarkable capacitance profiles and outstanding durability, retaining over 104% of their initial capacitance across 15,000 continuous cycles. Further we have performed structural tailoring using sustainable and porous carbon-based matrices. By exploiting optimized physical and chemical engineering principles, highly porous carbon frameworks can be tuned to deliver fast mass transport and superior ion accessibility. These structures effectively mitigate the severe volume expansions typically experienced by active electrodes during prolonged charging and discharging cycles. Collectively, these multifaceted synthesis strategies offer critical insights into material design, pointing toward commercial-scale realization of flexible and robust energy storage technologies.

