

## Materials Science

Special Topic: Hollow Multishelled Structure

**Hollow multishelled structure: Progress and prospects for next-generation energy and biomedical applications**

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Hollow structures have long served as a cornerstone of advanced materials innovation, linking nanoscale structural engineering to macroscopic functional performance. As a representative platform, hollow multishelled structure (HoMS) consists of no fewer than two shells with isolated quasi-enclosed internal cavities, forming an intriguing mesoscopic system. HoMS not only retains the merits of a single-shelled hollow structure, but including large specific surface area, low density and high loading capacity. More significantly, they possess multiple adjustable shells and multiple adjustable inner cavities. Typically constructed from assembled nanoparticles, the shells of HoMS are interconnected via channels, gases, liquid or other cores, endowing them with a cell-like hierarchical architecture. Notably, their distinctive temporal-spatial ordering property renders HoMS irreplaceable in pivotal applications, including catalytic reactions, sustained drug delivery, and energy storage [1–3].

Since research interest in HoMS began in 2004, the unique structure has evolved over more than two decades to date. In pioneering research work, Wang's group developed a universal sequential templating approach (STA) in 2009 [4]. Furthermore, we have revealed the physical essence of concentration waves underlying HoMS formation, enabling the precise synthesis of HoMS with highly complex compositions and morphologies under mild conditions via rationally designed sequential templates [5]. This groundbreaking advance in synthetic methodology has garnered widespread global recognition from the scientific community, with numerous research groups adopting this strategy and recognizing HoMS as highly promising materials for diverse applications. Nevertheless, it remains to be explored regarding cutting-edge scientific concepts and phenomena in this field. We hope that HoMS will provide profound insights into the future development of materials science, boosting the prosperous advancement of catalysis, biomedicine, and energy storage in the context of carbon neutrality.

To highlight the state-of-the-art advances and transformative potential of hollow multishelled structures, we have organized this special topic on hollow multishelled structure in *National Science Open*. This collection features six high-quality reviews and original research articles, spanning controllable synthetic

methodologies, confined interfacial modulation, and pioneering applications in metal-air batteries, sodium-ion batteries, electrocatalysis, photothermal antibacterial therapy, amorphous framework materials and solar-driven uranium extraction. Collectively, these contributions reflect the latest progress of HoMS from rational structural design to practical translation, providing new insights for the development of next-generation multifunctional materials.

Innovations in synthetic methodologies serve as a fundamental driving force for the continuous advancement of HoMS. Zhang *et al.* [6] developed a versatile synthetic etching strategy for fabricating hollow and yolk-shell amorphous zeolitic imidazolate framework (ZIF) colloids. Using tannic acid as both etchant and surface protectant, the authors achieved selective interior etching while preserving the external morphology of precursors. This approach successfully extends the synthetic scope of HoMS to amorphous metal-organic frameworks (MOFs), which exhibit enhanced mechanical robustness and processability relative to their crystalline counterparts. This breakthrough resolves long-standing bottlenecks in the structural modulation of amorphous hollow nanostructures.

Catalysis and energy conversion represent the most extensively explored fields for HoMS. Son *et al.* [7] presented an insightful review that redefines hollow nanostructures beyond mere surface area maximization. They emphasize that HoMS actively regulates local concentrations of reactants, products and intermediates through cavity confinement. Such mass transport engineering significantly boosts electrocatalytic kinetics, selectivity and stability in reactions including water splitting, CO<sub>2</sub> reduction and nitrate reduction. This paradigm shift from “structure for activity” to “structure for microenvironment” establishes a theoretical basis for the rational design of HoMS-based electrocatalysts.

In energy storage, metal-air batteries (MABs) deliver ultrahigh energy density yet suffer from severe interfacial instability. Shang *et al.* [8] reviewed HoMS-enabled interfacial engineering for MABs, targeting multiphase interfacial failures including cathode pore clogging, anode dendrite growth and corrosion, and separator degradation. They demonstrate that HoMS alleviates discharge product accumulation, homogenizes ionic flux, stabilizes solid-electrolyte interphases and maintains intact triple-phase boundaries. Meanwhile, Song *et al.* [9] summarized HoMS as a versatile platform for boosting sodium-ion battery (SIB) performance. HoMS effectively mitigates volume expansion, accelerates ion transport and enhances interfacial stability in both anode and cathode. Key challenges, including scalable synthesis and precise structural control, are also outlined. These studies provide clear guidance for designing durable, high-safety HoMS-based batteries and promote their industrial translation.

Remarkable progress has been achieved in the biomedical applications of HoMS, particularly in antibacterial therapy. Kang *et al.* [10] systematically reviewed hollow-structured photothermal nanoplatfoms for the treatment of bacterial infections. Enabled by multishell-induced light scattering, HoMS architectures facilitate efficient photothermal conversion, support high-capacity drug loading and enable integrated synergistic therapies including photothermal, chemodynamic, gas and photodynamic modalities. These integrated strategies achieve effective elimination of drug-resistant bacteria and biofilms with favorable biocompatibility. This work further expands HoMS applications from energy systems to precision biomedicine and underscores the universal structural superiority of hierarchical hollow nanostructures.

In a recent innovative study, Shabbir *et al.* [11] reported a photothermal strategy for efficient uranium extraction from seawater using Ta<sub>2</sub>O<sub>5</sub>/C HoMS anchored on amidoxime-functionalized fibers. The HoMS enables efficient solar-to-thermal conversion and localized heating, which accelerates uranyl ion diffusion.

This system increases adsorption capacity by 27% compared with dark conditions and retains over 91% of its capacity after seven consecutive adsorption/desorption cycles. This approach provides a sustainable, scalable route for solar-driven uranium recovery to support the long-term supply of nuclear fuel.

This special topic reflects the vibrant innovation of HoMS as a frontier materials platform. We believe these studies will inspire further cutting-edge research on hierarchical hollow structures and drive fundamental breakthroughs and practical applications across energy, biomedicine and environmental science. Finally, we sincerely thank all authors, reviewers and editorial staff for their invaluable contributions to this special topic.

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