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EDITED AND REVIEWED BY
Nicola Maria Pugno,
University of Trento, Italy

*CORRESPONDENCE
Tierui Zhang,
✉ tierui@mail.ipc.ac.cn

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Grand challenges for colloidal materials and interfaces: perceiving the whole from small

Run Shi¹ and Tierui Zhang^{1,2*}

¹Key Laboratory of Photochemical Conversion and Optoelectronic Materials, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China, ²Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing, China

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Colloidal materials and interfaces are popular interdisciplinary fields involving the intersection of physics, chemistry, biology, and other disciplines. The particle size of the structural units of colloidal materials is at the mesoscale, giving colloidal materials unique properties between molecular and macroscopic materials, such as high specific surface area, quantum size effects, and interfacial interactions (Xia et al., 2000). Among these, interfacial phenomena are particularly important in colloidal materials, as the properties of interfaces significantly influence the stability, assembly behavior, and functional performance of colloidal particles. Therefore, the core of this field lies in studying the preparation, structure, and properties of colloids, as well as their interactions at various interfaces.

The development of colloidal materials has a long history, spanning from the Lycurgus Cup made in the fourth century, to the synthesis of colloidal “ruby” gold in 1857, and to the 2023 Nobel Prize in Chemistry for the discovery and synthesis of nanoparticles called quantum dots, covering over a thousand years. The foundational work of colloidal science began in the mid-20th century. In 1950, Victor La Mer and Robert Dinegar developed a theory and process for producing monodisperse hydrosols, which allowed for the controlled production of colloids with uniform particle sizes (LaMer and Dinegar, 1950). This was a pivotal moment, laying the foundation for the future development of nanotechnology and materials science.

Over the decades, the synthesis of colloidal materials has made significant progress, utilizing techniques such as sol-gel processes, hydrothermal synthesis, ultrasonic exfoliation, and chemical vapor deposition to achieve high-quality nanoparticles with controllable sizes and morphologies (Yin and Alivisatos, 2005). These advancements have not only greatly expanded the material database but enhanced the scalability of production for practical applications.

In recent years, research has shifted focus to the synthesis and applications of colloidal materials with unique optical, electronic, and catalytic properties. Among them, colloids with plasmonic effects (Au, Ag, Cu, etc.), which have high extinction coefficients and significant local field enhancement effects, are essential components of optics-related materials and devices (Linic et al., 2011). Thanks to breakthroughs in nanomaterial synthesis, plasmonic nanomaterials of various dimensions, morphologies, and compositions have been synthesized. Notably, the synthesis of chiral plasmonic colloidal metallic materials and the proposal of the periodic table of plasmonic colloidal materials are considered significant milestones in the development of colloidal materials (Lee et al., 2018; Tan et al., 2011), making colloidal material synthesis techniques and their applications in specialized optics and synthetic chemistry increasingly important.

Furthermore, semiconductor nanocrystals, quantum dots, and gels are also key research directions in colloidal materials and interfaces (Reiss et al., 2009). When the size of

semiconductor colloidal materials approaches or is smaller than the exciton radius, the separation and migration dynamics of their excited-state carriers exhibit fundamental differences compared to bulk materials, leading to a series of novel photophysical and photochemical properties such as excitation blue shift, quantum blinking, and directional electron migration (Efros and Nesbitt, 2016; Yoffe, 2002; Zhu et al., 2013). The latest advancements in colloidal photocatalytic materials have garnered widespread attention due to their unique properties and potential applications in environmental remediation, energy conversion, and special functionalities.

Semiconductor colloidal materials possess high surface area and tunable optical properties, making them ideal candidates for photocatalytic materials (Wu and Lian, 2016). Taking chalcogenide semiconductor quantum dots as an example, thanks to their unique visible light absorption behaviors and quantum confinement effects, they have been star materials in photocatalysis since their first synthesis in 1981 (Kalyanasundaram et al., 1981; Xu et al., 2016). Their outstanding advantage lies in their tunable band alignments and charge transfer behaviors for enhanced photocatalytic activity under visible light, addressing the limitations of traditional wide bandgap photocatalysts. Furthermore, incorporating plasmonic nanoparticles with semiconductor colloids has been proven to enhance light harvesting and charge separation efficiency, thereby further boosting photocatalytic performance (Wu et al., 2015). Moreover, sub-nanomaterials, as an emerging class of colloidal materials, exhibit properties distinct from traditional nanomaterials, showcasing fascinating prospects in energy conversion, and have developed into an important branch of colloidal materials (Lu and Wang, 2022).

Using colloidal materials as structural units, a variety of self-assembled superstructures (superlattices, superparticles, monolayers, etc.) can be formed through various self-assembly driving forces, including electrostatic interactions, hydrophilic-hydrophobic interactions, external field effects, ligand interactions, and entropy, opening new avenues for creating advanced materials with customized functions (Dong et al., 2010). In recent years, reversible, chiral, low-dimensional, and hierarchical self-assemblies based on colloidal building blocks have been extensively studied (Kundu et al., 2015; Lv et al., 2022). The as synthesized colloidal assemblies exhibit novel properties and functions compared to colloidal monomers and bulk materials, providing an important material foundation for the development of advanced functional materials and high-performance devices in areas such as bionics, solar energy conversion, drug delivery, heat conduction, and display (Yuan et al., 2024).

There are still several challenges in the field of colloidal materials and interfaces that require breakthroughs. First, the existing synthesis processes for colloidal materials are generally very complex, with high levels of synthesis difficulty and significant costs associated with raw materials and processing, which severely limit the commercialization of colloidal materials. In addition, colloidal materials chemically synthesized in solutions often exhibit a wide size and morphology distribution, and the uniformity of the materials is typically suboptimal, posing challenges for applications in advanced electronic devices. Furthermore, most colloidal materials lack stability. Under various optical, electrical, and thermal conditions, the surface and internal chemical composition

of colloidal materials are prone to changes, and irreversible agglomeration between colloidal particles can easily occur, leading to deactivation.

Achieving precise control over the size, morphology, and structure of colloids, as well as ensuring their stability in complex and harsh environments, are key focuses of current and future research. Additionally, the large-scale preparation processes for colloidal materials still require further optimization. Ensuring that large-scale synthesis can produce samples consistent with small-batch synthesis, while reducing costs and increasing yield, is another challenge that must be addressed for practical applications. At the same time, the microscopic mechanisms underlying interfacial phenomena in colloidal systems have not been fully elucidated, limiting the in-depth understanding and optimization of their performance.

As an important class of functional materials, colloidal materials are highly versatile. In the future, with the deepening of fundamental research and continuous technological breakthroughs, this field is expected to achieve more innovative results, providing new solutions to global challenges such as energy, environment, and health.

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