Mesocrystals for photocatalysis: a comprehensive review on synthesis engineering and functional modifications

Shaodong Sun,*a Xiaojing Yu,*a Qing Yang,a Zhimao Yangb and Shuhua Liang*a

Mesocrystals are a new class of superstructures that are generally made of crystallographically highly ordered nanoparticles and could function as intermediates in a non-classical particle-mediated aggregation process. In the past decades, extensive research interest has been focused on the structural and morphogenetic aspects, as well as the growth mechanisms, of mesocrystals. Unique physicochemical properties including high surface area and ordered porosity provide new opportunities for potential applications. In particular, the oriented interfaces in mesocrystals are considered to be beneficial for effective photogenerated charge transfer, which is a promising photocatalytic candidate for promoting charge carrier separation. Only recently, remarkable advances have been reported with a special focus on TiO2 mesocrystal photocatalysts. However, there is still no comprehensive overview on various mesocrystal photocatalysts and their functional modifications. In this review, different kinds of mesocrystal photocatalysts, such as TiO2 (anatase), TiO2 (rutile), ZnO, CuO, Ta2O5, BiVO4, BaZrO3, SrTiO3, NaTaO3, Nb2O7(OH), Ir2O3-x(OH)y, and AgIn(WO4)2, are highlighted based on the synthesis engineering, functional modifications (including hybridization and doping), and typical structure-related photocatalytic mechanisms. Several current challenges and crucial issues of mesocrystal-based photocatalysts that need to be addressed in future studies are also given.

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1. Introduction

Photocatalysis is a promising pathway to resolve the problems of energy depletion and environmental pollution via the photocatalytic conversion of solar light into chemical energy.1–4 Currently, the low utilization of visible light and short lifetimes of photogenerated charge carriers are two bottlenecks that limit the practical applications of photocatalysts.5–7 Therefore, improvements in the visible-light response and effective separation of photogenerated charge carriers for photocatalysts have garnered increased attention. Generally, the enhanced performances for single-component photocatalytic materials can be achieved by morphology-control or facet-control strategies. For example, a surface heterojunction can be constructed within a single anatase TiO2 polyhedron with coexposed (001) and (101) facets, which facilitates the transfer of photogenerated electrons and holes on the (101) and (001) facets, respectively, yielding better activity through the optimal ratio of the exposed (101) and (001) facets.8 However, the recombination of photogenerated charge carriers cannot be effectively restrained due to the lack of an energy barrier for charge separation, and mass migration is only occurring on the surfaces.9 Therefore, it is imperative to reasonably design and synthesize novel architectures for efficient interparticle or interfacial charge transfer, which can provide a significant breakthrough in optimizing single-component photocatalytic materials.

Mesocrystals are a new class of superstructures, which are generally made of crystallographically highly ordered nanoparticles and could function as intermediates in a nonclassical particle-mediated aggregation process.9–13 It should be noted that a mesocrystal is the definition of a superstructure and not a formation mechanism, which displays a selected area electron diffraction (SAED) pattern similar to a single crystal or a quasi-single crystal, resulting in the enhancement of charge migration than that in traditional polycrystalline materials. Moreover, as compared to conventional single crystals, mesocrystals possess nanoscale subunits, anisotropic shapes, rough surfaces, or order porosity, which exhibit high specific surface areas and offer more active sites for photocatalytic reactions. Consequently, these features provide new opportunities for potential photocatalytic applications.

In the past decades, extensive research interest has been focused on the structural and morphogenetic aspects, as well as the growth mechanisms of mesocrystals. A number of reviews on the formation mechanisms have been published, mainly including nanoparticle-oriented aggregation along an ordered organic matrix by spatial constraints and the assistance of external physical fields (such as electronic, magnetic, and optical fields).14–25 In 2016, remarkable advances were reported, particularly focusing on the use of TiO2 mesocrystal photocatalysts.26 However, there is still no comprehensive overview on the photocatalytic applications of various metal oxide mesocrystals and their functional modification forms so far.

In this review, we mainly summarize the important progresses made in the development of photocatalysis-oriented mesocrystals in various species, including single-metallic oxides (such as TiO2 (anatase), TiO2 (rutile), ZnO, CuO, Ta2O5) and multimetallic oxides (such as BiVO4, BaZrO3, SrTiO3, NaTaO3, Nb2O5(OH), In2O3–x(OH)y, and AgIn(WO4)2) (Scheme 1). We start with the systematic review of the synthesis strategies and principles for enhanced performances of different...
mesocrystal photocatalysts. Next, the functional modifications (including hybridization and doping) for the construction of mesocrystal-based photocatalysts and structure-related photocatalytic mechanisms are presented. Finally, the current challenges and the crucial issues of mesocrystal-based photocatalysts that need to be addressed in future studies are mentioned.

2. Mesocrystal photocatalysts

Although a series of semiconductors with good structure–performance relationships have been investigated for improving the low quantum efficiency in photocatalysis, the existence of charge recombinations at the surface or inside the volume cannot be effectively avoided. With the development of a new class of porous metal oxide materials with uses ranging from catalysis to energy storage and conversion, highly ordered mesocrystal superstructures could limit the recombination of electron–hole pairs due to the anisotropic electron flow along the interparticles; therefore, the fast and efficient collection of photogenerated charge carriers on catalytic sites can be achieved by the dominant surface of mesocrystals. Therefore, understanding the synthesis strategies and corresponding formation mechanisms of typical single-component mesocrystal photocatalysts is significant for the controllable design of novel versatile mesocrystal-based composites. In this section, we mainly introduce the synthesis methods and photocatalytic mechanisms involving mesocrystal photocatalysts (Table 1), including TiO2 (anatase), TiO2 (rutile), ZnO, CuO, Ta2O5, BiVO4, BaZrO3, SrTiO3, NaTaO3, Nb2O5(OH), In2O3(OH)H, and AgIn(WO4)2. Initially, certain concepts involving the growth and formation mechanism of mesocrystals will be listed and explained. Topotactic transformation is a kind of structural transition in solid materials that enables structural transitions without losing the crystalline symmetry of the parental phase.27,28 Kirkendall effect is a kind of manifestation that induces void structures; due to the different diffusion rates between two species at an elevated temperature, movement can be induced at the interface between a diffusion couple.29,30 Oriented attachment is a nonclassical crystal growth model, where the nanocrystals align along a certain crystallographic direction in order to minimize their interfacial energy.31,32 Ostwald ripening process is a direct matter-relocation approach, which is defined as the “dissolution of small crystals or sol particles and the redeposition of the dissolved species on the surfaces of larger crystals or sol particles.”33,34

2.1 Binary oxide mesocrystals

2.1.1 TiO2 mesocrystals. Titanium dioxide (TiO2) is one of the most promising photocatalysts due to its strong redox ability, high chemical stability, low toxicity, and low cost. Among the existing mesocrystal photocatalysts, the development of TiO2 mesocrystals has been attracting increased attention; therefore, the appearance and morphology details of TiO2 mesocrystals are abundantly available as compared to others, including ellipsoids, spheres, polyhedra, nanosheets, and nanorods.35–43,46–52,59,63,65 In this subsection, we initially summarize the synthesis strategies of the different above-mentioned species. Thereafter, versatile applications in photocatalytic hydrogen evolution and organics degradation, as well as the corresponding structure-related photocatalytic mechanisms, are discussed by using typical examples.

Three-dimensional (3D) architectures. It is well known that both external morphology and internal structure of a photocatalyst are very significant with regard to photocatalytic activity. With regard to the widely investigated TiO2 photocatalysts, its large crystallite size facilitates electron–hole separation; a large specific surface area can provide more reaction sites and large exposure of highly active facets are conducive toward high reaction activity on the reaction sites. All the above three advantages are necessary to obtain a good photocatalytic ability.35 However, it is difficult for an integrated structure to satisfy all the above three requirements until the development of mesocrystal photocatalysts. In particular, hierarchical 3D TiO2 mesocrystals could not only improve the relationship between crystallite size and specific surface area, but also offer a large number of high active (001) facets.

Polyhedral TiO2 mesocrystals. The typical synthesis strategy for TiO2 mesocrystals comprising nanocrystals with exposed (001) facets involves the topotactic transformation of NH4TiOF3 mesocrystals at high annealing temperatures, which was first discovered by O’Brien’s group in 2008.36 However, the experimental procedures were relatively complicated and could not be scaled up for practical applications. Therefore, it is necessary to develop a one-pot facile synthesis method to prepare TiO2 mesocrystals exposed with high active facets. Majima and coworkers have obtained plate-like TiO2 mesocrystals by annealing a thin layer of precursor solution containing TiF4, NH4F, and NH4NO3 on a silicon wafer. Evidently, the nonporous intermediate NH4TiOF3 precursor was first formed following the combination reactions from the mixtures of Ti4+, F−, NH4+, and H2O at low temperatures (<200 °C). As the annealing process required higher temperatures (>300 °C), the as-synthesized NH4TiOF3 precursor would be topotactically
### Table 1: Mesocrystal photocatalysts and their properties

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transformed into porous anatase TiO₂ mesocrystals with dominant (001) facets. It should be noted that the gaps or holes are generated owing to nanocrystal diffusion and recrystallization during the removal of large amounts of N, H, and F atoms from the crystal lattice structure; therefore, the amount of NH₄F is significant for the morphology-controlled synthesis of TiO₂ mesocrystals (Fig. 1).²⁶

The TiO₂ mesocrystals assembled with highly ordered alignment of anatase nanocrystals (size: 40 nm) can display porous structures with pore diameters of several nanometers (surface area: >90 m² g⁻¹), resulting in remarkably long-lifetime charges, higher photoconductivity and photocatalytic hydrogen evolution, as well as degradation of 4-chlorophenol and Cr⁶⁺ in the aqueous phase.²⁷ In this case, it was observed that TiO₂ mesocrystals exposed with different facet ratios exhibited different reactivity orders during photooxidation, i.e., (001) > (101), and photoreduction, i.e., (101) > (001), under UV-light irradiation. Interestingly, the authors have confirmed that the (001) facets were preferable during molecular adsorption and photogenerated electron injection from the photoexcited dyes (eosin Y and Ruthenizer 470) to the conduction band (CB) of TiO₂ under visible-light irradiation, whereas the (101) facets were beneficial for the collection of photogenerated electrons because of the directional electron flow. These findings emphasized that the concept of crystal-facet-dependent photocatalytic reactions can be extended to mesocrystal systems.

Fig. 1   (a) Schematic illustration of the synthesis of differently shaped TiO₂ mesocrystals. SEM images of different TiO₂ mesocrystals prepared with x (molar ratio of NH₄F) = 0 (b), 46 (c), 116 (d), and 232 (e). Insets display the corresponding high-magnification SEM images. It can be found that the thickness size of the as-synthesized particles gradually reduced along with an increase in the amount of NH₄F. Adapted with permission from ref. 26. Copyright 2016 Elsevier.

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Based on the above synthesis route, Zhou and coworkers have developed TiO$_2$ mesocrystals largely exposed with (001) facets through the topotactic annealing of NH$_4$TiOF$_3$ mesocrystals at 800 °C synthesized by [NH$_4$]$_2$TiF$_6$ and NH$_4$OH without the need for extremely toxic HF treatments. In this case, the specific structure of the TiO$_2$ mesocrystal with a large crystallite size, high specific surface area, and additional numbers of active (001) facets can greatly enhance the photocatalytic activity, whereas lower or higher processing temperatures (e.g., 700 °C and 900 °C, respectively) would damage the microstructure, and therefore, deteriorate the photocatalytic activity. In addition, these particles have good photochemical stability and much larger size than commercial P25, which suggests that they can be easily removed from the liquid-phase system by centrifugation and reused.

Moreover, Leite and coworkers have proposed a kinetically controlled crystallization process by a nonaqueous sol-gel synthesis method to prepare anatase TiO$_2$ recrystallized mesocrystals, a chemical process based on the reaction of titanium(v) chloride with n-octanol. This is attributed to the oriented-attachment mechanism. During the oriented-attachment process, individual nanoparticles acting as primary building blocks could directly assemble with adjacent nanoparticles to yield a mesostructure with similar crystallographic orientation to minimize interfacial energy. The high-resolution transmission electron microscopy (HRTEM) analysis clearly revealed that the synthesized recrystallized anatase mesocrystals exhibited a truncated bipyramidal Wulff shape, indicating that its surface is dominated by (101) facets, which exhibited superior photoreactivity for rhodamine B degradation under visible-light irradiation as compared to commercial P25 as a benchmarking material.

Furthermore, nanothorn TiO$_2$ mesocrystals with dominant (101) facets displayed approximately 1.5 and 6 times higher photocatalytic hydrogen evolution activities than those of (001) facets and disordered nanocrystals, respectively, which can be attributed to the specific facet-induced charge separation and anisotropic electron flow. According to the single-particle photoluminescence measurements, Mott–Schottky analyses, and transient absorption measurements, efficient interfacial band alignment and charge separation were obtained, suggesting the contribution of the dominant (101) facet. This facet-induced anisotropic flow in the photocatalysis resulted in the realization of a photocatalyst that exhibited efficient charge separation and enhanced photocatalytic activity.

In addition, layered TiO$_2$ mesocrystals composed of nanosheets with exposed (001) facets were also successfully fabricated with the combination of hydrothermal treatments in the presence of (NH$_4$)$_2$TiF$_6$, H$_3$BO$_3$, and PrOH, followed by calcination treatments. A schematic illustration of the formation of layered TiO$_2$ is shown in Fig. 2. Initially, PrOH started to dissociate into PrO$^-$ under weak acidic conditions; then, both PrO$^-$ and BF$_4^-$ would preferentially bind to unsaturated Ti$^{4+}$ cations on the (001) facets of NH$_4$TiOF$_3$ nuclei to reduce their surface energies, leading to the formation of single-crystal NH$_4$TiOF$_3$ nanosheets with (001) facets. Subsequently, these NH$_4$TiOF$_3$ nanosheets with (001) facets capped with PrO$^-$ and BF$_4^-$ orderly assemble to block the tabular grains. Finally, NH$_4$TiOF$_3$ nanosheets were transformed into layered TiO$_2$ nanosheets after calcination treatment because of the removal of PrOH and the reduced volume from NH$_4$TiOF$_3$ to TiO$_2$. With regard to the photocatalytic activity, the as-prepared layered TiO$_2$ with (001) facet nanosheets exhibited excellent performance for the degradation of rhodamine B when compared with commercial P25, which can be ascribed to the synergetic effects between the layered structures and (001) facets. Similarly, anatase TiO$_2$ mesocrystals with exposed (001) facets have been successfully synthesized by a facile one-step solvothermal method using NH$_4$F as the structure regulator in a glacial acetic acid environment, which can be used in the photocatalytic decomposition of gaseous styrene.

It should be noted that the photocatalytic activity of polyhedral TiO$_2$ mesocrystals with controllable proportions of (101) and (001) facets is significant, so it is highly desirable to investigate the photocatalytic activities of TiO$_2$ mesocrystals with different (101)/(001) facet ratios. Fortunately, Zhao and coworkers have synthesized regular-shaped TiO$_2$ mesocrystals enclosed with different proportions of (001) and (101) facets by a simple approach in the presence of formic acid and titanium isopropoxide as the original reactants without any other additives and surfactants at 160 °C. Further, the control of the (101)/(001) ratio of TiO$_2$ mesocrystals was achieved by altering the solvothermal treatment periods. The TiO$_2$ mesocrystals enclosed by a high proportion of (101) facets showed higher photocatalytic activity for benzene destruction than those with a lower proportion, which was attributed to the synergistic effect of Ti$^{4+}$ and the proportion of (101) facets. In addition, the normalized photocatalytic activity of TiO$_2$ mesocrystals was better than that of nanocrystals as the proportion of (101) facets was equal, suggesting that the structural integrity played a key role in the photocatalytic activity.

Spindle-shaped TiO$_2$ mesocrystals. The formation of a spindle shape is common for metal oxide mesocrystals due to the oriented attachment of the nanoparticles. Based on earlier literature, it is found that spindle-shaped anatase TiO$_2$ mesocrystals can be facilely synthesized on a large scale through mesoscale assembly in titanium salt/acetic acid systems without any additives under solvothermal conditions. The acetic acid and solvothermal conditions are the key factors for the synthesis of spindle-shaped TiO$_2$ mesocrystals, whereas the type of titanium salt is adjustable, including tetrabutyl titanate, butyl titanate, titanium butoxide, and titanium tetrachloride.

For example, Qi and coworkers have demonstrated the first additive-free synthesis of porous anatase TiO$_2$ mesocrystals with a single-crystal-like SAED pattern by using tetrabutyl titanate as the titanium source and acetic acid as the solvent. A complex nanoparticle-assembly process was obtained, involving the slow release of soluble species from metastable solid tetrabutyl titanate precursors for the continuous formation of anatase building blocks, followed by the oriented aggregation of tiny anatase nanocrystals under the capping of the as-produced butyl acetate, finally leading to the formation of porous spindle-shaped mesocrystals after the removal of organic residuals by
calcination treatment. A schematic illustration of a tentative mechanism for the formation of porous anatase TiO$_2$ mesocrystals without additives is shown in Fig. 3a. Fig. 3b shows a typical transmission electron microscopy (TEM) image of a single spindle particle, indicating that the particle consists of nanosized subunits. Its SAED pattern exhibits diffraction spots corresponding to the (010) zone axis of the anatase-phase TiO$_2$, suggesting the possession of a “single-crystal-like” structure. Notably, it can be seen that the diffraction spots are slightly elongated, indicating that there is a small lattice mismatch between the boundaries of the nanoparticles, which is a typical characteristic of mesocrystals. The internal porosity of the particle is revealed by the TEM image taken on a microtomed sample (Fig. 3c). Lim and coworkers have synthesized spindle TiO$_2$ mesocrystals using a hydrothermal method in the presence of titanium butoxide/acidic acid/water system and investigated the effect of calcination temperature (100–800 °C) on their morphology, crystallinity, and photocatalytic activity. In this work, the authors have found that controlling the calcination temperature is an effective pathway to control the morphology, crystallinity, and photocatalytic activity of TiO$_2$ mesocrystals. The shape, dimension, and crystal structure of the TiO$_2$ mesocrystals have no appreciable changes as the calcination temperature increased to 300 °C, and the crystallinity can be improved by increasing the temperature. However, the mesocrystal characteristic began to disappear at 400 °C, and the specific surface area decreased with increasing temperature due to the reduced boundaries. Hence, the photocatalytic degradation of methylene blue for TiO$_2$ improved when the temperature increased to 300 °C owing to the enhanced crystallinity and elimination of byproducts; however, it became poor above 400 °C because of the decreased surface area. In addition, mesoporous anatase TiO$_2$ prepared by using butyl titanate as the Ti source and acetic acid as the solvent can be used toward inducing photocatalytic activity in the degradation of gaseous benzene.

Apart from the above solvothermal methods, the hard-template strategy has also been developed for the fabrication of porous TiO$_2$ mesocrystals. Zhao and coworkers have reported a facile evaporation-driven oriented assembly strategy to prepare olive-shaped mesoporous TiO$_2$ mesocrystals in an acidic tetrahydrofuran (THF)/pluronic F127/water/HCl/acetic acid/titanium tetrabutoxide mixed solution, which started with the liquid–liquid phase separation as the preferential evaporation of THF at 60 °C. Then, spindle-shaped TiO$_2$ particles assembled by pluronic F127/titania oligomer spherical micelles were generated at the liquid–liquid interface. Finally, 3D-open anisotropic spindle-like mesoporous TiO$_2$ mesocrystals were obtained by the continuous evaporation of residual THF and hydrolyzed solvents, which could drive the oriented attachment of both mesopore channels and flake-like nanocrystals from the initial spherical composite micelles along the free radial and restricted tangential directions. Dye-sensitized solar cells based on the above samples showed ultrahigh photoconversion efficiencies (beyond 11%), which were attributed to the intrinsic mesocrystal nature as well as high porosity.

Mesocrystalline TiO$_2$ assemblies. Although the studies on TiO$_2$ mesocrystal photocatalysts have been mainly concentrated on the structure/morphology and porosity control by the above-mentioned different synthesis techniques, the deep understanding the relationship between the oriented-attachment fashion and photocatalytic efficiency has been rarely investigated. Bian and coworkers have observed that TiO$_2$ mesocrystals...
showed largely enhanced photoconductivity and photocatalytic activities than those of polycrystalline materials because of the remarkably increased long-lifetime charges under illumination for TiO₂ mesocrystals. They have also synthesized hierarchical hollow microspheres with TiO₂ mesocrystal nanosheets as building blocks by an ultrasound-assisted aerosol-spray method followed by topotactic transformations. TiO₂ mesocrystal hollow hollow microspheres can largely enhance photocatalytic performances. Furthermore, they found, for the first time, that the presence of small misorientations had an obvious harmful effect on the charge transfer, and hence, largely suppressed the photocatalytic efficiencies, as shown in Fig. 4. The involved two typical TiO₂ spherical mesocrystals, one with oriented and the other with misoriented alignment, of secondary nanocrystals were prepared from a precursor containing TiOSO₄ and tert-butyl alcohol by thermal annealing and hydrothermal recrystallization processes, respectively. Therefore, this finding should be taken into account and avoided during the design and synthesis of semiconductor mesocrystal photocatalysts.

It is well known that the size effect is also significant for photocatalytic activity; therefore, the preparation of sub-100 nm mesocrystal-like porous assemblies is imperative. Tartaj and coworkers have developed an inverse microemulsion method for the synthesis of TiO₂ mesocrystalline assemblies with mesopores, and all the sizes ranged from 25 to 70 nm. These 25 nm nanostructures exhibited good electrochemical performance and good capability for photocatalytic degradation.

From the abovementioned results, it can be found that anatase TiO₂ mesocrystals can be synthesized by a facile process, whereas rutile TiO₂ mesocrystals for photocatalysis have been rarely reported. Jimmy C. Yu and coworkers have reported a simple and environmentally friendly approach for preparing photocatalytically active rutile TiO₂ mesocrystals by a microwave-assisted hydrothermal method involving titanium(IV) chloride as the only reactant. The as-synthesized one-dimensional (1D) rutile nanowires can easily assemble into three-dimensional (3D) hierarchical architectures without the help of surfactants or additives. Similarly, Wu and coworkers synthesized hollow TiO₂ microspheres assembled with rutile mesocrystal nanorods directly from a mixed aqueous solution of K₂TiO(C₂O₄)₂, H₂O₂, and HNO₃ at a low temperature of 80 °C, which displayed remarkable photocatalytic activity in photo-degrading rhodamine B solution under UV-light illumination.

**Two-dimensional (2D) architectures.** Thus far, the literature on 2D TiO₂ mesocrystals is not exhaustive. Pillai and coworkers have demonstrated anatase TiO₂ mesocrystals with exposed (001) facets and sheet-like morphologies by a facile halide-free low-temperature microwave-assisted sonochemical method, which exhibited good crystallinity, higher surface area, and excellent stability. In particular, sheet-like mesostructures played a crucial role in electron transport, which enabled faster charge transfer as confirmed by the enhanced photocurrent of 131 nA at 0 V bias. Therefore, this environmentally friendly synthesis strategy enabled 2D anatase mesocrystals to exhibit high energy facets, crystallinity, and low recombination rate of the photogenerated charge carriers, and therefore, resulted in improved photocatalytic activity. The effect of charge carriers on the photocatalytic activity was investigated in detail, and it followed the order: hydroxyl radicals > holes > electrons. Moreover, 2D rutile TiO₂ mesocrystals can also be prepared by the deposition route in the presence of glass substrates, and a titanium source (TiCl₃) facilitates this process at room temperature for several days. Rutile nanosheets with thickness of 10 nm and width of 200–600 nm consisted of oriented nanocrystals with size of 2–3 nm. The unit rutile nanocrystals were surrounded by a combination of (101) and (110) facets or (111) and (110) facets. In particular, a higher specific surface area was achieved on the rutile nanosheet with a mesocrystal interior, which displayed enhanced photocatalytic decomposition of an organic dye.

Using a hard template is an effective alternate strategy for the synthesis of porous TiO₂ nanosheets, which involved heterogeneous crystal nucleation and oriented growth within the templates. Hence, a series of mesoporous single-crystal-like structures, including anatase mesoporous TiO₂ nanosheets with dominant (001) facets and rutile mesoporous TiO₂ nanorods with tunable sizes, have been obtained in the presence of silica, titanium tetrachloride, titanium butoxide, hydrochloric acid, and hydrofluoric acid (Fig. 5). The resultant mesoporous TiO₂ single-crystal-like crystals displayed enhanced photocatalytic performances on hydrogen evolution and degradation of methyl orange owing to their enlarged surface area, single-crystal nature, and exposure of reactive crystal facets coupled with a 3D connected mesoporous architecture. It was observed that the (110) facets of rutile mesoporous TiO₂ can be essentially considered as reductive sites in the photoreduction reaction, while the (001) facets of anatase mesoporous TiO₂ exhibited oxidation sites in the oxidative process. However, the use of
a strong acid is not ecofriendly, so it is still a challenge to develop a new hard-template technology that can be used to fabricate mesoporous TiO$_2$ mesocrystals with tunable facets and crystalline phase.

**1D architectures.** 1D photocatalysts could trap solar light along their long axial direction and the simultaneous efficient carrier separation and collection in the nanometer-scale radial direction, resulting in the enhancement in the photocatalytic activity. Therefore, the synthesis of 1D TiO$_2$ mesocrystals has attracted considerable attention. Qi and coworkers reported excellent broadband and quasi-omnidirectional antirefection rutile TiO$_2$ nanorod arrays (Fig. 6), which were prepared by a simple hydrothermal treatment of Ti foils in the presence of tetrabutyl titanate and hydrochloric acid. In this case, the strong acid is not ecofriendly, so it is still a challenge to develop a new hard-template technology that can be used to fabricate mesoporous TiO$_2$ mesocrystals with tunable facets and crystalline phase.

**2.1.2 ZnO mesocrystals.** Zinc oxide (ZnO) is a well-known wide bandgap semiconductor, which has important applications in photocatalyses. A number of ZnO mesocrystals have been successfully prepared, including nanosheet-assembled mesocrystals, microspheres, rod-like bundles, and spindles. However, ZnO mesocrystals for photocatalysis have not been studied so far. Here, the structural and morphogenetic aspects of ZnO mesocrystals are initially summarized, and their photocatalytic applications are simultaneously discussed.

**Mesocrystalline ZnO assemblies.** Thus far, the most common morphology of a ZnO mesocrystal is 3D hierarchical architecture with mesocrystalline ZnO building blocks. The ZnO lattice has both polar surfaces, (0001) as well as (0001), and a nonpolar surface (1010), which differently interact with the surface-protecting surfactants or polymers. Generally, it is facile to obtain ZnO nanolites instead of nanorods because of the oriented attachment of ZnO nanoparticles with their nonpolar surfaces by protecting the polar surfaces, and mesocrystalline ZnO assembly with stacked nanoplate building blocks would be generated through the capping agent or intrinsic electrostatic field. Mou and coworkers have prepared a nacre-like hierarchical mesocrystal structure of ZnO in the presence of a mixture of gelatin/Zn(NO$_3$)$_2$–6H$_2$O/hexamethylenetetramine, where biopolymer gelatin containing many polar amino acids act as the surface-protecting agent for the polar surfaces of ZnO, finally resulting in the formation of micrometer-sized ZnO mesocrystals with hexagonal shapes resulting from the stacked
nanoplates. Similarly, Lee and coworkers have reported a facile, low-temperature synthesis approach in an aqueous solution for the synthesis of various ZnO mesocrystals (including platelets, rings, and ellipsoids) due to the oriented attachment of ZnO nanoparticles, where the surfactant cetyltrimethylammonium bromide (CTAB) played two critical roles, namely, shape control and micelles for the aggregation of nanoparticles with temperature changes. Typically, the samples were prepared by injecting an aqueous solution of ammonia into a Zn(NO$_3$)$_2$ solution in the presence of CTAB. CTAB-mediated zinc hydroxy double salt (zinc-HDS) mesocrystal sheets were synthesized at room temperature, and these Zn-HDS mesocrystal sheets can be decomposed into ZnO superstructure with rigid hexagonal morphology as the reaction temperature increased. Significantly, Wang and coworkers have demonstrated the fast and spontaneous room-temperature formation of ZnO mesocrystals constructed with nanosheet building blocks by the edge-sharing lateral attachment of 1D nanorods for the first time, which involved the phase transformation from two intermediate compounds, namely, ZnF(OH) and Zn(OH)$_2$. The epitaxial attachment of ZnO (1010) nanosheets led to the assembly of hierarchical mesocrystals, which was confirmed to be a geometrically ideal photocatalyst that was easily separable and recyclable. The superior efficiency of the UV and visible photocatalytic degradation of methylene blue can be ascribed to the maximized exposure of the reactive (1010) facets in the epitaxially assembled superstructures.

Furthermore, a hydrothermal strategy is an effective alternative for the synthesis of mesocrystalline ZnO assembly. For example, Xu and coworkers have prepared stable yellow ZnO microring mesocrystals with a relatively narrow bandgap ($E_g = 3.09$ eV) and visible-light response by the hydrothermal route in the presence of hexamethylenetetramine/HF/zinc acetate hydrate at 160 °C for 6 h. Raman and X-ray photoelectron spectroscopy spectra revealed that a large amount of oxygen vacancies existed in the yellow ZnO mesocrystals, resulting in the narrowing of the bandgap and an increase in the visible-light response of yellow ZnO. Further, the concentration of oxygen defects decreased with an increase in the annealing temperature in air. In addition, the electron paramagnetic resonance spectra confirmed that the yellow ZnO mesocrystals possessed abundant surface defects, leading to strong photoluminescence emission. Therefore, the yellow ZnO mesocrystals with highly ordered porous structures were found to be efficient for the photodecomposition of methyl blue under visible-light irradiation, which were favorable for directional transport and efficient charge carrier separation. It should be noted that these yellow ZnO microrings were very stable for at least one year. Moreover, various shaped ZnO architectures were synthesized through a simple hydrothermal route in the presence of a soft template as a structure-directing reagent. The flower-like hierarchical assembly was constructed with leaf-shaped mesocrystals that were composed of nanocrystals aligned along the (111) orientation, which displayed the highest photocatalytic activity when compared with the counterpart of nanocrystal ZnO, pencil-shaped mesocrystal ZnO, and plate-like mesocrystal ZnO. The improved photocatalytic activity could be attributed to not only the hierarchical structure, large specific surface area, and high crystallinity, but also the highly ordered mesostructured architecture.

Apart from the morphological architectures, defects engineering of photocatalysts is significant in determining the photocatalytic activity. Wang and coworkers have reported that the interface-defect-mediated photocatalytic activity of pompon-like ZnO mesocrystal photocatalyst could be synthesized via a hydrothermal approach in the presence of sodium citrate without any other organic templates. The as-prepared pompon-like ZnO assemblies were composed of mesocrystal nanosheets with exposed high energy (002) facets having high crystallinity. Here the defects were located at the interfaces among the nanocrystals in the ZnO mesocrystals, playing a key role in the photocatalytic degradation of organic pollutants (such as methylene blue and 2,4,6-trichlorophenol) than that of interstitial zinc vacancies in bulk.

Electrodeposition can also be used to synthesize ZnO mesocrystals. Lin and coworkers first developed an effective supercritical CO$_2$ (sc-CO$_2$) emulsion-assisted electrochemical strategy for the cathodic deposition of ZnO mesocrystals. The deposition process involved the formation of primary nanocrystals possessing high surface energy, followed by the oriented attachment of primary nanocrystals along an energetically favorable orientation to generate ZnO mesocrystals. Because of the highly oriented crystallinity of mesocrystals, the as-deposited ZnO mesocrystals exhibited remarkable near-band-edge emissions at room temperature and substantially long exciton lifetime, which can limit the nonradiative charge recombination to extend the exciton decay dynamics. Hence, these ZnO mesocrystals exhibited largely enhanced photocatalytic properties toward photoelectrochemical water oxidation, which was attributed to the advantageous structural characteristics of mesocrystals, including high crystallinity and abundant porosity.

Mesocrystalline ZnO microspheres. As mentioned above, the dipole-induced electrostatic interactions between the building units can act as the aligning force for the formation of ZnO mesocrystals. However, the dipole-field-induced assembly along the c-axis forming anisotropic ZnO superstructures has been less investigated. Liu and coworkers have demonstrated the direct evidences for a unique core–shell-structured ZnO mesocrystal microsphere constructed by densely packed nanoplatelets by a low-temperature, polymer-mediated, one-pot hydrothermal route in the presence of a water-soluble polymer poly(sodium-4-styrenesulfonate). These nanoplatelet-based core–shell mesocrystal ZnO microsphere formed via a nonclassical crystallization process, which involved the synergistic effects of the electric fields of the core and the dipole–dipole interaction between the nanoplatelets on the shell. The calculation based on a dipole model confirms the dipole-field-driven mechanism forming apple-like structures and mesocrystals, as shown in Fig. 7. Significantly, green light can stimulate terahertz emissions from these core–shell mesocrystal ZnO microspheres.

Mesocrystalline ZnO bundles. Similar to the formation of TiO$_2$ mesocrystals, the topotactic transformation of precursor
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Inherited the rod-like morphology of Zn(OH)2 into having unique mesostructural morphology. Then, the catalytic activities with respect to the photodegradation of nanoparticles, ZnO mesocrystals exhibited decent photomance, as shown in Fig. 8b. In comparison with individual ZnO temperature played a crucial role in the photocatalytic perfor-

Like ZnO mesocrystals is shown in Fig. 8a. The annealing schematic representation of the formation mechanism of rod-

spheres. Inset is the corresponding schematic illustration. Adapted with permission from ref. 78. Copyright 2011 Nature Publishing Group.

Fig. 7 (a) SEM image of ZnO apple-like structures. Adapted with permission from ref. 78. Copyright 2011 Nature Publishing Group. Inset shows the corresponding schematic illustration and a typical particle. Adapted with permission from ref. 77. Copyright 2009 American Chemical Society. (b) SEM images of the ZnO mesocrystal micro-
spheres. Inset is the corresponding schematic illustration. Adapted with permission from ref. 78. Copyright 2011 Nature Publishing Group.

Mesocrystalline ZnO spindles. Although the shape-controlled synthesis of ZnO mesocrystals has been achieved by the various abovementioned synthesis methods, the invariable residual organic additives attached to the surfaces of the mesocrystals at high annealing temperatures is also suitable for the synthesis of ZnO mesocrystals. For example, Guo and coworkers have reported a simple and scalable wet-chemical route combined with a facile post-annealing process to produce rod-like ZnO mesocrystals with L(+)-tartaric acid (TA) as the orientation inducer. In this synthesis process, the authors proposed that the mild acidic characteristics and unique molecular structure of TA is important in assembling Zn(OH)2–TA into having unique mesostructural morphology. Then, the mesocrystals composed of ZnO nanoparticles were generated after being annealed in air at certain temperatures, which inherited the rod-like morphology of Zn(OH)2–TA composites. A schematic representation of the formation mechanism of rod-like ZnO mesocrystals is shown in Fig. 8a. The annealing temperature played a crucial role in the photocatalytic performance, as shown in Fig. 8b. In comparison with individual ZnO nanoparticles, ZnO mesocrystals exhibited decent photocatalytic activities with respect to the photodegradation of methyl orange and photoreduction of Cr6+.

Mesocrystalline ZnO spindles. Although the shape-controlled synthesis of ZnO mesocrystals has been achieved by the various abovementioned synthesis methods, the invariable residual organic additives attached to the surfaces of the building blocks resulted in unfortunate problems in their practical applications. Furthermore, the additive-assisted preparation approach not only increased the cost, but also made it more difficult for large-scale synthesis. Hence, it is still a challenge for us to develop new strategies to prepare well-defined ZnO mesocrystals with building blocks as surfactant free as possible. In our previous work, unusual designated tailoring on the zone-axis preferential construction of surfactant-free ZnO mesocrystals with different shapes and sizes was successfully achieved by an additive-free complex-preflow solution method. The controllable synthesis of ZnO mesocrystals was essentially determined by the characteristic of [Zn(OH)4]2− precursors, and an oriented nanoparticle aggregation with tailored sizes and shapes can be generated with different concentrations of reactants at high reaction temperatures. For example, spindle-like ZnO mesocrystals with controllable sizes (along the c-axis direction) were prepared by adjusting the concentration of hydroxyl ions, and peanut-like ZnO mesocrystals with tunable sizes (along the c-axis direction) and shapes (perpendicular c-axis direction) were synthesized by tailoring the concentration of zinc ions (Fig. 9). The investigation assumes significance in the bottom-up assembly of controllable ordering structures, and it offers a new opportunity to understand the growth mechanism and fundamental significance of zone-axis preferential construction of ZnO mesocrystals. Further, it might provide a green approach to design novel surfactant-free metal oxide mesocrystals with well-defined shapes. Dong and coworkers have developed an ultrafast antisolvent method for the synthesis of spindle-like ZnO mesocrystals. A deep eutectic solvent, generated by simply mixing and heating urea and choline chloride at 70 °C, can act as the anti-solvent to trigger the ultrafast formation of ZnO mesocrystals. The as-prepared spindle-like ZnO mesocrystals possessed mesoporous and near-single-crystalline building blocks.

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Mesocrystalline ZnO spindles. Although the shape-controlled synthesis of ZnO mesocrystals has been achieved by the various abovementioned synthesis methods, the invariable residual organic additives attached to the surfaces of the building blocks resulted in unfortunate problems in their practical applications. Furthermore, the additive-assisted preparation approach not only increased the cost, but also made it more difficult for large-scale synthesis. Hence, it is still a challenge for us to develop new strategies to prepare well-defined ZnO mesocrystals with building blocks as surfactant free as possible. In our previous work, unusual designated tailoring on the zone-axis preferential construction of surfactant-free ZnO mesocrystals with different shapes and sizes was successfully achieved by an additive-free complex-preflow solution method. The controllable synthesis of ZnO mesocrystals was essentially determined by the characteristic of [Zn(OH)4]2− precursors, and an oriented nanoparticle aggregation with tailored sizes and shapes can be generated with different concentrations of reactants at high reaction temperatures. For example, spindle-like ZnO mesocrystals with controllable sizes (along the c-axis direction) were prepared by adjusting the concentration of hydroxyl ions, and peanut-like ZnO mesocrystals with tunable sizes (along the c-axis direction) and shapes (perpendicular c-axis direction) were synthesized by tailoring the concentration of zinc ions (Fig. 9). The investigation assumes significance in the bottom-up assembly of controllable ordering structures, and it offers a new opportunity to understand the growth mechanism and fundamental significance of zone-axis preferential construction of ZnO mesocrystals. Further, it might provide a green approach to design novel surfactant-free metal oxide mesocrystals with well-defined shapes. Dong and coworkers have developed an ultrafast antisolvent method for the synthesis of spindle-like ZnO mesocrystals. A deep eutectic solvent, generated by simply mixing and heating urea and choline chloride at 70 °C, can act as the anti-solvent to trigger the ultrafast formation of ZnO mesocrystals. The as-prepared spindle-like ZnO mesocrystals possessed mesoporous and near-single-crystalline building blocks.
characteristic with high specific surface areas, leading to excellent photocatalytic activity toward the photodegradation of methylene blue.

2.1.3 CuO mesocrystals. As a p-type semiconductor with a narrow bandgap varying between 1.2–1.8 eV, CuO has been extensively studied as a photocatalyst or cocatalyst in the past. Various kinds of CuO architectures, including the ordered aggregation of nano-subunits into CuO mesocrystals has been reported. However, similar to the above TiO$_2$ and ZnO mesocrystals, the synthesis of CuO mesocrystals often involves nanocrystal building blocks sharing the same crystallographic orientations with interspersed organic additives. For example, a dandelion-like CuO mesocrystals assembly of rhombic nanoribbons was fabricated by the solvent hydrothermal route in the presence of ethanol. 3D ellipsoidal CuO mesocrystals composed of a hundred 1D nanoparticles were prepared by a simple solution oxidative route with the assistance of formamide. 2D CuO mesoplates have been synthesized by using a mild solution in the presence of tetrabutylammonium hydroxide. Therefore, it is still a challenge to employ additive-free strategies to prepare well-defined CuO mesocrystals with surfactant-free building blocks. In our previous report, based on the synthesis principle of ZnO spindle mesocrystals, we have further developed the green synthesis of ordered-aggregation-driven growth from surfactant-free 1D CuO nano-subunits into dimension-controlled mesostructures (3D mesospindles and 2D mesoplates) by an additive-free complex-precursor solution route. The formation of CuO mesocrystals was determined by the characteristic of [Cu(OH)$_4$]$^{2-}$ precursors, and the oriented aggregation of nanoparticles with well-defined shapes in different dimensions was achieved in different concentrations of reactants at higher reaction temperatures. The 3D “layer-by-layer” growth of mesostructural CuO spindles was successfully prepared in low concentrations of reagents, while the 2D “shoulder-by-shoulder” growth of mesostructural CuO plates was synthesized in high concentrations of reagents. In addition, we further demonstrated that such CuO mesocrystals could serve as a potential photocatalyst for the degradation of rhodamine B under visible-light irradiation in the presence of hydroxide water. The results indicated that 3D mesostructural CuO spindles exhibited higher adsorption and photocatalytic degradation of rhodamine B than that for 2D mesostructural CuO plates (Fig. 10).

2.1.4 Ta$_2$O$_5$ mesocrystals. As a typical wide bandgap semiconductor, Ta$_2$O$_5$ has a higher CB minimum (CBM) than TiO$_2$, which is an obvious advantage for photocatalysis because it potentially provides a strong driving force for water splitting. Therefore, the construction of superstructured Ta$_2$O$_5$ mesocrystal nanosheets is highly desirable for exploring efficient and stabilized photocatalysis. In 2018, a study on the synthesis of Ta$_2$O$_5$ mesocrystals has been reported, in which mesocrystalline Ta$_2$O$_5$ nanosheets were successfully prepared through the decomposition of mesocrystalline (NH$_4$)$_6$Ta$_2$O$_5$F$_6$ nanorods by annealing treatment for the first time, as shown in Fig. 11. The as-synthesized mesocrystalline Ta$_2$O$_5$ nanosheets exhibited remarkable visible-light absorption, owing to the formation of oxygen vacancy defects in the mesocrystalline nanosheets.
oxidizing ability of mesocrystalline Ta₂O₅. These mesocrystal-
line superstructures contributed toward the generation of long
lifetime photoinduced carriers and effective conductive path-
ways for photocatalytic hydrogen production.

2.2 Ternary oxide mesocrystals

2.2.1 BiVO₄ mesocrystals. As an ideal semiconductor for
photocatalytic oxygen evolution, bismuth vanadate (BiVO₄) has
received much research interest due to its appropriate valence
band (VB) edge, narrow bandgap for visible-light absorption,
low cost, and good stability.⁹⁵,⁹⁶ However, its low charge trans-
portation efficiency generally results in a very high electron-
hole recombination rate before the electrons and holes reach
the interfaces.⁹⁷ Hence, the actual water oxidation efficiency of
BiVO₄ is always much lower than the theoretical value.⁹⁸,⁹⁹
Therefore, it is imperative to develop suitable methods to
enhance the charge transportation efficiency of BiVO₄. In 2016,
BiVO₄ mesoporous single crystals were successfully prepared,
for the first time, by a one-pot hydrothermal method using
acidified BiVO₄ precursor solution pre-impregnated with silica
as the template.⁹⁵ The authors proposed a double-diffusion
mechanism to illustrate the formation of mesoporous BiVO₄
single crystals (Fig. 12a). Initially, the diffusion of acid from
the silica interior to the bulk solution triggered the nucleation of
BiVO₄ at the interior surface of the silica template. Subse-
quently, the diffusions of Bi³⁺ and VO₄³⁻ ions from the bulk
solution to the silica template interior resulted in the growth of
BiVO₄ nuclei into single crystals containing the silica template.
Finally, mesocrystalline BiVO₄ mesoporous single crystals were
formed based on an oriented attachment and Ostwald ripening
mechanism. When compared with BiVO₄ bulk single crystals,
mesoporous BiVO₄ single crystals exhibited obvious light
absorption enhancement in both UV- and visible-light regions,
which was attributed to the fact that the inner pores acted as
light scattering centers to localize and capture the incident
light. Notably, the absorption edge of mesoporous BiVO₄ single
crystals exhibited a distinct blue-shift when compared with that
of BiVO₄ bulk single crystals (Fig. 12b), owing to the contribu-
tion of Bi to the VB induced by local structure distortion and
quantum size effect. As for mesoporous BiVO₄ single crystals,
the highly crystalline structure was beneficial to the transfer of
photogenerated charge carriers in the interior. Further, the
mesoporous structure not only promoted the interface transfer
of charge carriers, but also reduced the carrier transfer distance
in the matrix. As a result, the photocatalytic oxygen evolution
rate over mesoporous BiVO₄ single crystals was improved nearly
10 times than that over bulk single crystals (Fig. 12c).

2.2.2 BaZrO₃ mesocrystals. As a typical cubic perovskite
oxide, BaZrO₃ is a promising photocatalytic material for water
splitting.⁹⁶,⁹⁷ Generally, the presence of defects among the grain
boundaries can serve as trapping and recombination centers
between photoinduced electrons and holes, leading to
a decrease in the photocatalytic activity.⁹⁸,⁹⁹ Improving the
crystallinity is a possible measure to overcome this drawback.
Thus far, investigations on the direct correlation between the
crystallinity of BaZrO₃ mesocrystals (denoted as BZO-mc) and
photocatalytic activity is of significance for the construction of
highly efficient photocatalysts. However, engineering the crys-
tallinity of semiconductor mesocrystals is rare because the
structure of BaZrO₃ remains stable even at 1000 °C
(denoted as BZO-1000). Ye and coworkers have demonstrated
the direct evidence of the crystallinity effect of mesocrystals on
the photoconversion efficiency by using BaZrO₃ hollow nano-
ospheres as an ideal photocatalyst model (Fig. 13a–f).⁹⁹ The
authors found that the lower recombination rate of the photo-
generated charge carriers in the highly crystalline photocatalyst
was in favor of enhancing the photocatalytic activities,
including high photocatalytic hydrogen production and methyl
orange degradation. As shown in Fig. 13g and h, both the
hydrogen production rate and degradation rate of methyl
orange increased with the crystallinity of BZO-mc. This work
presents a better understanding of the actual crystallinity effect
on the photocatalytic performance of mesocrystal
photocatalysts.

2.2.3 NaTaO₃ mesocrystals. Perovskite sodium tantalate
(NaTaO₃) is the most efficient water-splitting catalyst reported
with a bandgap up to 4.01 eV.¹⁰¹ To optimize its photocatalytic
performance, several strategies were employed to alter the band
structure, phase structure, particle morphology, and size of
NaTaO₃. In particular, mesocrystalline NaTaO₃ nanoparticles
were confirmed for effectively improving the photocatalytic
activity.¹⁰² Cubic NaTaO₃ mesocrystals with sub-100 nm sizes
and high crystallinity were synthesized in a surfactant-free
environment by alkoxide-hydrolyzation-based rapid reaction.
The self-assembly of primary nanoparticles was controlled by
adjusting the concentration of reagents, and larger meso-
crystals with pores were prepared under higher concentrations.
The as-produced mesocrystalline NaTaO₃ exhibited a surface

Fig. 12 (a) Schematic illustration of the formation mechanism of
BiVO₄ mesoporous single crystals (MSCs). (b) UV-vis diffuse reflec-
tance spectra of BiVO₄ bulk single crystals (BSCs) (black line) and
BiVO₄ MSCs (red line). The inset shows the plots of (αhν)² versus
photon energy (hν) of the two samples. (c) Photocatalytic oxygen
evolution of BiVO₄ MSCs, BSCs, and nanoparticles. The transient
photocurrent and photocatalytic oxygen evolution were conducted
using a 300 W Xe lamp (420 nm cut-off filter) as the light source.
Adapted with permission from ref. 95. Copyright 2016 Royal Society
of Chemistry.
step structure and high surface area with abundant active sites for the improvement of charge separation and migration, which resulted in a photocatalytic hydrogen evolution rate as high as 3.106 mmol h$^{-1}$ g$^{-1}$, as shown in Fig. 14.

2.2.4 SrTiO$_3$ mesocrystals. As a typical cubic-perovskite-type multimetallic oxide with a bandgap of 3.2 eV, strontium titanate (SrTiO$_3$) is a promising photocatalyst to split water into hydrogen and oxygen and to degrade organic pollutants, because of its extraordinary physical and chemical properties such as excellent thermal stability, photocorrosion resistibility, and good structural stability. Consequently, the successful synthesis of mesocrystalline SrTiO$_3$ structures with high crystallinity would potentially improve its photocatalytic performance. Based on the previous literature, it can be found that the hydrothermal topotactic epitaxy of titanate was an effective strategy for the controllable synthesis of SrTiO$_3$ mesocrystals. For instance, Majima and coworkers have prepared a novel perovskite SrTiO$_3$ mesocrystal superstructure with well-defined orientation of assembled cubic nanocrystals induced by topotactic epitaxy from TiO$_2$ mesocrystals through a facile hydrothermal treatment. In this case, starting from sheet-like TiO$_2$ mesocrystals, which consisted of assembled anatase TiO$_2$ nanocrystals with dominant (001) facets, Sr$^{2+}$ ions from Sr(OH)$_2$ reacted with TiO$_2$ in an alkaline solution to generate an epitaxial overlayer of SrTiO$_3$ grains at the interface via the dissolution–precipitation process. During the nucleation and growth (12–24 h) stages, cubic SrTiO$_3$ nanocrystals with highly ordered orientation were formed, followed by an increase in crystallinity. Upon prolonging the hydrothermal time to 36 h, larger cubic crystals were generated onto the external surfaces of SrTiO$_3$ mesocrystals. A schematic shape evolution of the SrTiO$_3$ mesocrystals is shown in Fig. 15a. As shown in Fig. 15b, the typical TEM image indicates that the external surfaces of SrTiO$_3$ mesocrystals are covered with larger nanocubes (200 nm) rather than small nanocubes (30 nm) assembled inside the mesocrystals. The corresponding SAED patterns obtained near the center and edge (red circles) exhibit single-crystal-like spots, suggesting that SrTiO$_3$ mesocrystals are made of crystallographically aligned nanocrystals. It should be noted that the orientation of crystals is maintained during the epitaxial structural conversion and subsequent crystal growth, which is
obviously attributed to particle-to-particle interactions in the mesocrystal. According to the structural features of the above SrTiO$_3$ mesocrystals, the authors have proposed the photocatalytic mechanism and charge transfer process (Fig. 15c) in which the well-ordered architecture promoted the spatial charge separation throughout the long-distance electron transfer along the highly ordered adjacent nanocubes. Therefore, the photogenerated charge carriers were transported to the larger external nanocubes with active (100) facets, where hydrogen ions were reduced to generate hydrogen gas under UV-light irradiation. The morphology of the titanate precursors is significant in the controllable synthesis of SrTiO$_3$ mesocrystals. Kalyani and coworkers have prepared 1D rod-like SrTiO$_3$ mesocrystals through the hydrothermal crystallization from the suspensions of single-crystal anatase and hydrogen titanate nanowires, which further revealed the mechanism driving the mutual crystallographic alignment of nanocrystals in mesocrystals. In this synthesis, the lattice mismatch and defective state of the precursor surface might determine the degree of mutual crystallographic alignments of the subunits, namely, the larger lattice mismatch would result in a lower level of ordering.\footnote{106}

In addition, single-crystal-like mesoporous SrTiO$_3$ submicrometer spheres with large surface area and high crystallinity were successfully produced by a facile hydrothermal approach in the presence of tetrabutyl titanate/strontium nitrate/potassium hydroxide/polyvinyl alcohol (PVA) system.\footnote{107} The oriented aggregation of nanoparticles was proposed to be the dominant formation mechanism, which was accompanied by the ripening process. Typically, the pore density of the as-prepared SrTiO$_3$ spheres obviously increased as the PVA concentration increased, and the average pore size ranged from 4.5 to 16.1 nm. The photocatalytic degradation of rhodamine B with the as-produced mesocrystalline SrTiO$_3$ spheres was a function of PVA concentration and reaction time. The highest photocatalytic activity has been achieved in mesocrystalline SrTiO$_3$ synthesized at 200 °C for 6 h with a higher PVA concentration.

2.2.5 In$_2$O$_{3-x}$(OH)$_y$ mesocrystals. Although it has been demonstrated that mesocrystals with long lifetimes of photoexcited carriers can exhibit enhanced activity in liquid-phase photocatalytic dye degradation and water splitting, the photocatalytic performances of mesocrystalline superstructures toward gas-phase chemical reactions have not yet been investigated. He and coworkers presented the spatial separation of charge carriers in mesocrystalline In$_2$O$_{3-x}$(OH)$_y$ superstructures for enhanced gas-phase photocatalytic activity in 2016,\footnote{108} which were synthesized through a two-step process, including the synthesis of In(OH)$_3$ nanorods using InCl$_3$ and urea as the precursors without initially using any surfactant, followed by the transformation into bixbyte-structured indium oxide (Fig. 16a).

A typical nanorod exhibiting a nanoporous superstructure is shown in Fig. 16b. It has been demonstrated that interparticle charge transfer generated within the nanocrystal superstructure and the lifetime of photoinduced carriers was prolonged in In$_2$O$_{3-x}$(OH)$_y$ mesocrystals, which was in favor of the increase in the conversion rate of the gas-phase, light-assisted reverse water–gas shift reaction. Under solar-light illumination, photogenerated electrons from the VB would be excited into the CB of the semiconductor, leading to the formation of photogenerated holes in the VB. The photogenerated holes migrated into the surface hydroxide trap states, while the photogenerated electrons located in the CB might be captured in the oxygen vacancies. Notably, the mesocrystalline In$_2$O$_{3-x}$(OH)$_y$ nanorods were made up of close-contact nanocrystals, which would cause the spatial separation of the photoexcited carriers between the neighboring subunits, and the migration of holes between the neighboring nanocrystals has a lower probability than electron movement (Fig. 16c–e).

In addition, it is interesting to note the nanorod length dependence on the hydrogenation rate of carbon dioxide to carbon monoxide.

2.2.6 Nb$_2$O$_5$(OH) mesocrystals. Niobium oxide, such as Nb$_2$O$_5$(OH) mesocrystals, is a promising material for photochemical and photophysical devices. Betzler and coworkers have developed a template-free hydrothermal synthesis approach for preparing 3D hierarchical Nb$_2$O$_5$(OH) superstructures with perpendicularly aligned nanowire building blocks (Fig. 17).\footnote{109} The as-synthesized products were synthesized by the hydrothermal treatment of an aqueous Nb(iv) chloride solution at temperatures between 150 and 200 °C, and the morphologies can be tailored by adjusting the synthesis parameters including the pH value, temperature, and reaction time. Based on the time-dependent shape-evolution process, it can be found that mesocrystalline Nb$_2$O$_5$(OH) nanowire networks resulted from the transformation of amorphous hollow cubes with smooth surfaces under hydrothermal conditions. The obtained cubic superstructures with a bandgap of 3.2 eV possessed high photocatalytic degradation efficiency toward different organic dyes because of the periodic nanowire networks, large surface area, and high crystallinity.\footnote{109}

2.3 Quaternary mesocrystals

Thus far, quaternary metal oxide mesocrystals have been rarely reported. AgIn(WO$_4$)$_2$ is a typical example. Yu and coworkers have reported a facile and mild microwave-assisted route for synthesizing caterpillar-like AgIn(WO$_4$)$_2$ mesocrystals with tuned shapes in the presence of AgNO$_3$, In(NO$_3$)$_3$, and Na$_2$WO$_4$.\footnote{110} In this synthesis, microwaves might improve the nucleation and growth of AgIn(WO$_4$)$_2$ in the Ag/In/W/O system. Initially, small amorphous nanoparticles were generated and randomly assembled in an aggregative manner. Subsequently, these connected nanoparticles evolved into tiny olive-like core structures by the oriented-attachment process. Finally, outgrowths occurred on the surface of the core and produced caterpillar-like architectures under the oriented-attachment process accompanied by Ostwald ripening. It should be noted that the pH value played an important role in the phase formation and morphology evolution. These caterpillar-like AgIn(WO$_4$)$_2$ mesocrystals displayed selective photocatalytic properties for degrading organic dyes under UV- and visible-light irradiation. The rate constants for the degradation of
 eosin Y, rhodamine B, and methyl orange were 0.111, 0.044, and 0.0084 min\(^{-1}\), respectively, which clearly demonstrated that the photodegradation process of eosin Y was much faster than those of rhodamine B and methyl orange (Fig. 18). Moreover, the photoluminescence spectra of \(\text{AgIn(WO}_4\text{)}_2\) mesocrystals with different morphologies have been investigated by the above authors. It can be found that all the products displayed white emission in the visible region when excited by visible light with a wavelength of 460 nm because of the surface nanostructures of the outgrowths.

Based on the above overview, the synthesis strategies of diversified photocatalyst mesocrystals are an exciting direction to fabricate compounds with high activity. Further, it provides an opportunity to investigate structure-related photocatalytic performance relationship. However, it should be noted that a series of hybrid mesocrystal-based heterogeneous photocatalysts with well-controlled compositions, shapes, and sizes have been demonstrated in the field of photocatalysis along with rapid progresses in nanomaterials science and nanotechnology.

### 3 Functionally modified mesocrystal photocatalysts

Effectively understanding the correlations between the modified interfacial/electronic structures and improved photocatalytic performances is crucial for developing novel mesocrystal-based photocatalysts. Generally, the modifications of mesocrystal photocatalysts can be divided into two strategies: hybridization and doping. Hybridization is a general strategy for inducing unexpected physicochemical characteristics to improve the potential application of a single material, which is attributed to the synergistic effect between the active component and support. Therefore, mesocrystals acting as host components would offer a good chance to tune the interfacial property of hybrid mesocrystal-based micro/nanostructures for improving practical applications. Furthermore, an alternative strategy for improving the physicochemical properties is to dope heteroatoms into the mesocrystal to modify its electronic structure. However, a systematic review of mesocrystal-based architectures has not been reported so far. In this section, we will firstly summarize the significant advances in the development of different types of hybrid mesocrystal-based photocatalysts, such as hybrid semiconductor-mesocrystals, hybrid mesocrystal–metal nanostructures, and hybrid mesocrystal–carbon nanostructures. Next, doped mesocrystal photocatalysts will be introduced based on some typical examples.

#### 3.1 Hybridization

**3.1.1 Semiconductor–mesocrystals.** The controllable synthesis of heterogeneous semiconductor–mesocrystal composites is an exciting direction to pursue highly active photoelectric beacons, and it also provides a good opportunity to investigate the structure–performance relationship. Recently, considerable efforts have been employed to construct high-activity hybrid semiconductor–mesocrystals with various heterogeneous interfaces for photocatalysis. In this section, we will mainly summarize the enhanced photocatalytic mechanism of different mesocrystalline \(\text{TiO}_2\)/semiconductors according to previous reports because other composites have not been reported so far. The combination of \(\text{TiO}_2\) mesocrystals with photosensitizers can enhance the light-harvesting ability of \(\text{TiO}_2\) under solar-light irradiation, achieving visible photocatalysis. Bian and coworkers have presented, for the first time, novel \(\text{TiO}_2\) mesocrystals with exposed (001) facets synthesized from a simple solvothermal alcoholysis process, followed by modification with CdS quantum dots (narrow energy bandgap: \(\sim 2.4 \text{ eV}\)) through a facile ion-exchange treatment. The integration of mesoporous anatase \(\text{TiO}_2\) mesocrystals with exposed...
enhanced number of CdS/TiO2 heterojunctions can facilitate characteristics. In this system, it has been conformation capability, reactant molecule adsorption, and activation light-harvesting capacity, photoinduced charge carriers separation, as well as the large amount of oxygen vacancies, enhanced the surface area and exposed (001) facets with high surface energy, junctions; meanwhile, the mesoporous structure with high surface area and exposed (001) facets with high surface energy, as well as the large amount of oxygen vacancies, enhanced the light-harvesting capacity, photoinduced charge carriers separation capability, reactant molecule adsorption, and activation characteristics. In this system, it has been confirmed that the enhanced number of CdS/TiO2 heterojunctions can facilitate the transfer of photoinduced electrons from CdS to TiO2 and improve the separation of photoelectrons from holes (Fig. 19a). Moreover, the (001) facets exhibited higher surface energy, which favored the photoactivation of reactant molecules when compared with those for (101) facets. Furthermore, the (001) facets also exhibited strong interactions with CdS nanoparticles, which might optimize the photosensitizing effect of CdS and further accelerate the photoelectron transfer from CdS to TiO2 via heterojunctions. In addition, the (001) facets possessed more oxygen vacancies than the (101) facets, which would trap photogenerated electrons, and therefore, limit the recombination with holes.

The photocatalytic activity of graphitic carbon nitride (g-C3N4) was inhibited to lower efficiencies because of the fast recombinations of the photogenerated charge carriers. Majima and coworkers have synthesized g-C3N4 nanosheets/TiO2 mesocrystals metal-free composites to improve the charge separation. The photocatalytic hydrogen evolution experiments demonstrated that coupling g-C3N4 nanosheets with TiO2 mesocrystals exhibited the highest photocatalytic activity, which was 20 times larger than that of pristine g-C3N4 without any noble metal cocatalyst under visible-light irradiation (λ > 420 nm) and 7 times higher than that of g-C3N4/P25, suggesting the significance of the strong interface interactions between 2D g-C3N4 nanosheets and plate-like TiO2 mesocrystals. Significantly, femtosecond time-resolved diffuse reflectance (fs-TDR) spectra revealed that the migration of photogenerated charge carriers was promoted and their lifetimes were prolonged because of the tight interface between the g-C3N4 nanosheets and plate-like TiO2 mesocrystals. Consequently, the fs-TDR spectra indicated that TiO2 mesocrystals acted as an electron transfer channel to promote charge separation (Fig. 19b). Similarly, direct Z-scheme Ti3+ self-doped TiO2 mesocrystals/g-C3N4 composites were synthesized by a simple solvothermal method, which exhibited visible-light absorption and photocatalytic activity for hydrogen production. This direct Z-scheme

Fig. 17 (a) Schematic illustration of the hydrothermal growth of Nb3O7(OH) mesocrystals. (b) and (c) Low- and high-magnification SEM images, respectively. (d) TEM image of a fragment of one cube wall; the inset shows the corresponding SAED pattern. (e) Schematic drawing illustrating the crystal shape of the nanowires and crystallographic arrangement of the nanowires in the network. (f) HRTEM image of a T-shaped nanowire junction and schematic illustration showing the arrangement of the nanowires at the junction (inset). (g) HRTEM image of a nanowire crossing and schematic drawing of the junction (inset).

(h)–(j) Measurement of the photocatalytic degradation of three different dyes at three different pH values (pH 2 (■), pH 6 (●), and pH 10 (▲)). The kinetic rate constant can be determined from the curve obtained by plotting −ln(Ct/C0) versus the irradiation time t. The corresponding curves are shown in (h) for methylene blue, in (i) for rhodamine B, and in (j) for indigo carmine. Adapted with permission from ref. 109. Copyright 2014 Royal Society of Chemistry.

Fig. 18 (a) SEM image of caterpillar-like AgIn(WO4)2 mesocrystals. (b) TEM image of an individual caterpillar-like particle. (c) Corresponding SAED pattern. (d) Photocatalytic degradation of different organic dyes under 300 W Xe lamp irradiation with AgIn(WO4)2 mesocrystals. Adapted with permission from ref. 110. Copyright 2010 Royal Society of Chemistry.
photocatalytic mechanism is confirmed as follows (Fig. 19c).\textsuperscript{115} Under visible-light irradiation, the Ti\textsuperscript{3+}-doped TiO\textsubscript{2} mesocrystals and g-C\textsubscript{3}N\textsubscript{4} nanosheets easily excited the photo-generated carriers, and the photogenerated electrons from the VB of g-C\textsubscript{3}N\textsubscript{4} nanosheets had strong reduction potential when compared with the CB electrons of TiO\textsubscript{2}. They would react with water for hydrogen evolution, and the VB holes in Ti\textsuperscript{3+}-doped TiO\textsubscript{2} possessed strong oxidizing potential and could oxidize the sacrificial agents, but the VB holes of g-C\textsubscript{3}N\textsubscript{4} could not react with the sacrificial agents due to a lower oxidizing potential. In addition, the CB electrons of Ti\textsuperscript{3+}-doped TiO\textsubscript{2} mesocrystals would react with the generated VB holes of g-C\textsubscript{3}N\textsubscript{4} owing to the short charge-transfer distance, leading to an improvement in charge separation. In addition, Van and coworkers have demonstrated a self-assembled nanocomposite photoanode composed of an epitaxial BiVO\textsubscript{4} matrix embedded with WO\textsubscript{3} mesocrystals for visible-light-driven photoelectrochemical applications. In this system, the orientation of the crystal facets and interfaces offered a superior template to investigate the intimate contact between the two constituent phases, which revealed that the interfacial coupling of the mesocrystal and matrix enhanced the separation and migration of photo-generated carriers (Fig. 19d), leading to a largely improved photoelectrochemical activity when compared with their counterparts.\textsuperscript{116}

As an efficient oxygen-evolution cocatalyst, cobalt phosphate (CoPi) has been decorated onto TiO\textsubscript{2} mesocrystals for enhancing the photocatalytic water-splitting ability. For a CoPi/TiO\textsubscript{2} mesocrystal/Pt photocatalytic hydrogen evolution system, active Co III/IV species in CoPi, as well as holes in the VB of TiO\textsubscript{2}, can oxidize the probe dye of 3’-p-aminophenyl fluorescein and 3’-p-hydroxyphenyl fluorescein to produce fluorescein as the fluorescent product through O-dearylation reaction. During this reaction, the photogenerated holes in the VB of TiO\textsubscript{2} would transfer to the CoPi cocatalysts and get deposited onto the surface of the (001) facets upon UV-light irradiation. The photoexcited electrons in the CB of TiO\textsubscript{2} would preferentially transfer to the lamellar (101) facet to deposit Pt, finally limiting the recombination of charge carriers (Fig. 20).\textsuperscript{117} Moreover, Majima’s group has demonstrated that polyhedral TiO\textsubscript{2} mesocrystals packed with an exfoliated MoS\textsubscript{2} shell can exhibit promising reactive efficiency and good stability in photocatalytic hydrogen evolution, which is attributable to the anisotropic electron flow to achieve enhanced photocatalytic performance.\textsuperscript{118}

### 3.1.2 Metal–Mesocrystals

Mesocrystals with special surface structures can effectively stabilize the as-deposited metal nanoparticles, resulting in the formation of hybridization composites with good stability and improved charge separation. However, the controllable synthesis of hybrid metal–mesocrystal composites is still in its infancy. Consequently, it is necessary to summarize the advances in hybrid metal–mesocrystal composites.

It is well known that the Fermi level and electron-accepting states of noble metals are generally located at an energy level below the CB of TiO\textsubscript{2} semiconductors.\textsuperscript{1} Accordingly, with regard to a noble metal–TiO\textsubscript{2} system, the photogenerated electrons in the CB of TiO\textsubscript{2} will effectively migrate to the deposited metal nanoparticles under UV-light irradiation, while the photoexcited holes stay in the VB of TiO\textsubscript{2}, finally resulting in the
achievement of charge carrier separation. Moreover, the photoinduced electrons can transfer to TiO$_2$ under visible-light irradiation due to the localized surface plasmon resonance.\textsuperscript{110} Notably, TiO$_2$ mesocrystals provide good support for depositing noble metals to enhance the photocatalytic activity, because the highly ordered superstructure with high surface area can avoid the numerous interfacial defects, facilitate charge separation as well as transfer, and provide abundant reaction sites for photocatalytic reactions. Bian and coworkers have developed a facile photodeposition strategy to synthesize Au- or Pt-nanoparticle-loaded TiO$_2$ mesocrystals, and the transport and reaction dynamics of the photogenerated charge carriers in individual composite materials are investigated.\textsuperscript{119} Based on the single-molecule fluorescence spectroscopy measurements on a single composite particle, it has been found that most of the photoexcited electrons could transfer from the dominant (001) facet to the edge of TiO$_2$ mesocrystals in micrometer distances, and the photoreduction reactions mainly occurred at the lateral surfaces containing (101) facets. Therefore, this anisotropic electron flow in the superstructure considerably limited the electron recombinations with holes, leading to improved photocatalytic oxidation activity (Fig. 21a).\textsuperscript{119} More interestingly, TiO$_2$ mesocrystals composites with Au nanorods can be used for highly efficient visible-NIR-photocatalytic hydrogen production (Fig. 21b).\textsuperscript{119} Yan and coworkers have deposited Au nanoparticles selectively anchored on the (101) facet of polyhedral TiO$_2$ mesocrystals, which exhibited highly selective photocatalytic reduction of nitroarenes because of the plasmonic effect of Au nanoparticles, unique superstructure of TiO$_2$ mesocrystals, and highly strong interaction between Au and TiO$_2$ through the close Schottky heterointerface (Fig. 21c).\textsuperscript{112} In addition, the detailed electron–hole separation dynamics for visible-light- and UV-vis-induced catalytic mechanisms of Au/TiO$_2$ mesocrystals were discussed in detail by Wang and coworkers (Fig. 21d).\textsuperscript{123} Similarly, Ag/hematite mesocrystal composites can exhibit high photo-Fenton activity in the oxidation of rhodamine B, methyl orange, and glyphosate under visible-light irradiation.\textsuperscript{124} Apart from the abovementioned synthesis strategy, wet chemical impregnation method and ion exchange–reduction approach might be useful for the synthesis of metal–mesocrystal composites, but it has not been extensively studied so far.

### 3.1.3 Carbon–mesocrystals

Carbon nanomaterials, including carbon dots (CDs), graphene, and graphene oxide (GO), have been investigated as excellent supports for photocatalysis because of their outstanding thermal and chemical stabilities, high conductivities, and high specific surface areas. As for carbon–mesocrystals composites, the carbon supports/or active ingredients would serve as good electron acceptors that can promote the charge separation and migration in mesocrystal semiconductors. As a result, improved activities can be achieved for hybrid carbon–mesocrystals composites when compared with pristine mesocrystal semiconductors. In this subsection, we will briefly summarize the different types of hybrid carbon–mesocrystal photocatalysts.
CDs with a large number of active groups (including hydroxyl groups and carboxyl groups) have been widely applied in photocatalysis due to their excellent photoelectric properties, excellent water solubility, and suitable chemical reactivity. Hence, it is expected that the coupling of CDs with mesocrystals could inhibit photogenerated charge recombinations, leading to enriched photoelectrons. Bian and coworkers have demonstrated the enhanced photoreduction of Cr(VI) to Cr(III) by using CDs-coupled TiO2 mesocrystals, where CDs played the roles of electron collectors and active sites (Fig. 22a). Furthermore, the CDs coupled on TiO2 mesocrystals can facilitate photogenerated charge separation. In addition, the authors have found that the positive charges on the surface of CDs/TiO2 was in favor of the selective adsorption of Cr(VI) and rapid desorption of Cr(III), which obviously promotes the photocatalytic reduction of Cr(VI) and retention of photoreduction activity. Therefore, the photoreduction of Cr(VI) performance of the as-prepared CDs/TiO2 is about 5.4 times higher than that of pure TiO2 mesocrystals under UV-light illumination.127 Yan and coworkers have reported that CDs/TiO2 mesocrystal composites synthesized through a simple one-pot solvothermal method can exhibit effective photocatalytic activity in the degradation of methyl orange under visible-light irradiation.126

As an sp2-bonded carbon sheet with the thickness of a single atom, graphene has received much more attention owing to its large surface area, good flexibility, high electrical conductivity, and high chemical stability, which allows it to be an effective host support for the heterogeneous growth of the desired active guest materials because the surface functional groups, such as hydroxyl groups, act as favorable nucleation sites for guest materials.130 Moreover, graphene can decrease the recombinations of photogenerated electron–hole pairs, increasing the charge transfer rate of electrons and surface-adsorbed amount of chemical molecules through π–π interactions. Consequently, the integration of graphene and mesocrystal semiconductors is promising in the field of photocatalysis. For example, Yang and coworkers have employed a facile template-free solvothermal method for obtaining well-dispersed spindle-like anatase TiO2 mesocrystals anchored onto graphene nanosheets, which were synthesized by mixing GO with acetic acid under ultrasonication, followed by the dropwise addition of tetrabutyl titanate into the above suspension.128 The as-synthesized graphene/anatase TiO2 mesocrystals can considerably enhance the photocatalytic activity of TiO2 under visible-light irradiation.

As a graphene derivative with an edge-bearing oxygen functionality, GO provides the advantage of uniformly loading metal oxide nanoparticles on its surface through oxygen-containing groups as nucleation centers.139 Nonetheless, the poor electron migration ability of GO is undesirable in photocatalysis, which limits the charge transfer between the nanoparticles and GO. Decreasing the oxygen-containing groups was an effective approach to increase the charge transportation capacity of GO. Liu and coworkers have synthesized a pyrrolic nitrogen (N)-doped GO/Fe2O3 mesocrystal nanocomposite by a simple solvothermal route and optimizing the oxygen-containing groups on GO. The as-prepared N-doped GO/Fe2O3 mesocrystals can enhance the efficient separation of electron–hole pairs and promote the fast conversion of Fe(II) and Fe(III) in photo-Fenton synergistic reactions because of the excellent electroconductivity of pyrrolic-N-doped GO and a large specific surface area (Fig. 22b).128 The photodegradation rate of methyl blue increased by 1.5 times and the conversion rate of glyphosate increased by 2.3 times for the GO/Fe2O3 mesocrystals under visible-light irradiation as compared to bare Fe2O3 mesocrystals.

Besides the above CDs, GO, and graphene, amorphous carbon can be also used to improve the photocatalytic activity of mesocrystal photocatalysts. Wu and coworkers have found that
carbon-modified NaTaO₃ mesocrystal nanoparticles can be prepared by a one-step solvothermal method using TaCl₅ and NaOH as the starting materials and distilled water/ethylene glycol mixed solution as the reaction solvent in the presence of appropriate amounts of glucose.¹³¹ These carbon-modified NaTaO₃ mesocrystals exhibited excellent efficiency for continuous NO gas conversion under UV irradiation, short-wavelength visible light (>400 nm), and even long-wavelength visible light (>510 nm), which was considerably better than those of unmodified NaTaO₃ and commercial P₂₅ due to the large specific surface area, high crystallinity, and carbon-induced visible-light harvesting (Fig. 22c).¹³¹

The rapid emergence of novel carbon–mesocrystal heterogeneous nanostructures can provide a new opportunity to further understand the fundamental importance of mesocrystals as well as to improve their practical applicability. Notably, other carbon nanomaterials possessing unique physicochemical properties, such as carbon nanotubes (CNTs), C₆₀, polymer polypyrrole (PPy), and metal–organic frameworks (MOFs), should be decorated with mesocrystals in the future.

### 3.2 Doping

It is well known that doping is a well-demonstrated strategy for effectively enhancing the physicochemical properties by changing the electronic structure of semiconductors; therefore, studies on doped mesocrystals have attracted increased attention. Herein, we will discuss structure-related photocatalytic mechanisms based on some typical doped-mesocrystal photocatalyst examples. Table 2 summarizes the metal- and nonmetal-doped mesocrystal photocatalysts and their physicochemical properties, as well as their photocatalytic applications.

#### 3.2.1 Metal doping.

Generally, the introduction of metallic elements would intensify additional binding functions, which induces unique photocatalytic properties in the doped system by decreasing the bandgap and increasing the absorption of visible light.¹³²,¹³³ In order to import metal ions into the framework of mesocrystals, the corresponding soluble salt is always uniformly mixed with the mesocrystal precursors; therefore, metallic impurities get simultaneously doped into the mesocrystals.

An and coworkers have synthesized Sr²⁺-doped NaTaO₃ photocatalysts by solid-state and hydrothermal routes.¹³⁴ The as-synthesized NaTaO₃–SrSr₃₁/Ta₂₉₃O₉ solid solution was a Sr-rich shell covered with a Sr-poor core. This heteroepitaxial core–shell interface can induce surface reconstruction with regularly separated steps due to lattice mismatch. Therefore, the recombination of electron–hole pairs was limited in solid-solution photocatalysts. The steady-state photogenerated electrons increased by up to 180 times in the solid-solution photocatalysts under Hg–Xe lamp irradiation, in which both A sites and B sites of the perovskite-structured lattice were doped with Sr²⁺ (Fig. 23a). Surface reconstruction and enhanced electron population were absent in the A-site-doped photocatalysts.¹³⁴ In addition, a simple molten salt route without using any organic additives has been employed to prepare Sr²⁺-doped NaTaO₃ mesocrystals with high crystallinity and orientation-aggregated morphology, which exhibited excellent photocatalytic hydrogen generation activity because of their nanosteps, high porosity, and preferred oriented direction.¹³⁵

As for TiO₂ photocatalysts, Ti³⁺ self-doping can result in the visible-light response of TiO₂ materials without introducing recombination centers for the photogenerated charges.¹³⁶ Therefore, the achievement of Ti³⁺ self-doped anatase TiO₂ mesocrystals would be significant for the construction of an ideal photocatalyst. For instance, Zhao and coworkers have prepared spindle-like Ti³⁺ self-doped anatase TiO₂ mesocrystals through the calcination of pre-synthesized anatase TiO₂ mesocrystals in N₂ atmosphere.⁴⁹ However, volatile organic solvents and an expensive surfactant additive were inevitably utilized in this work. Hence, it is highly desirable to develop a simple, green synthesis strategy for fabricating Ti³⁺-doped TiO₂ mesocrystals. Recently, Tan and coworkers have reported a novel method for the growth of spindle-shaped anatase TiO₂ mesocrystals through the one-step hydrolysis reaction of TiCl₃ in the green and recyclable media, polyethylene glycol. Subsequently, Ti³⁺ sites can be easily generated in the anatase crystal lattice, leading to the formation of Ti³⁺ self-doped mesocrystals after being annealed in vacuum. These as-transformed Ti³⁺ self-doped anatase mesocrystals exhibited enhanced visible-light photocatalytic activity toward the removal of NO gas, which could be attributed to their intrinsic Ti³⁺ self-doping nature, as

<table>
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<tr>
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<td>F</td>
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well as high crystallinity and high porosity of the mesocristalline architecture. Moreover, Yu and coworkers have successfully prepared willow-leaf-like plasmonic Ti$^{3+}$-doped Au/Cl–TiO$_2$ mesocrystals by means of modified two-phase vapor hydrolysis and photoreduction methods. The as-prepared Ti$^{3+}$-doped Au/Cl–TiO$_2$ mesocrystals displayed higher visible-light harvesting and visible-light photocatalytic activity for hydrogen evolution, which was 208.70 times as high as that of P25 TiO$_2$ and 1.59 times as high as that of Ti$^{3+}$-doped TiO$_2$ mesocrystals. Therefore, the co-doping of TiO$_2$ mesocrystals might provide remarkably higher activity than that of single doping and bare TiO$_2$. Mesocrystalline Cr- and Sb-co-doped anatase TiO$_2$ nanoparticles with a solid solution characteristic were prepared by the hydrothermal aging of an aqueous solution containing titanium alkoxide, chromium acetylacetonate, antimony acetate, and triethanolamine as the stabilizer, which could improve the visible-light harvesting ability, thereby revealing high efficiency in the degradation of methyl orange dye under visible-light irradiation.

Multicomponent Sb–Nb:TiO$_2$ mesocrystals have been synthesized by a microwave-assisted nonaqueous sol-gel method, with size of 25–35 nm and composed of crystallographically aligned Nb:TiO$_2$ subunits, embedded in a porous amorphous Sb-rich scaffold. The formation of Sb–Nb:TiO$_2$ mesocrystals is responsible for a particle-based assembly mechanism. In this process, the Sb scaffold acted as a nucleation site for the construction of Nb:TiO$_2$ subunits, which grew and rotated in a mutual crystallographic orientation. It then prevented the complete fusion of Nb:TiO$_2$ subunits, leading to the porosity of Sb–Nb:TiO$_2$ mesocrystals (Fig. 23b). When compared with undoped TiO$_2$, Sb–Nb:TiO$_2$ mesocrystals exhibited superior photocatalytic activity for the degradation of organic dyes under simulated solar or visible light, which can be attributed to the high crystallinity, abundant porosity, and additional exposed reactive surfaces.

In addition, magnetic recyclable mesocrystalline Zn-doped Fe$_3$O$_4$ hollow sub-microspheres were successfully prepared through a facile one-step solvothermal method and were used for fabricating efficient heterogeneous photo-Fenton catalysts. A possible growth mechanism of doped mesocrystalline hollow materials was proposed. Initially, Fe$_3$O$_4$ mesocrystals were assembled by oriented nanocrystals, and Zn-rich amorphous shells grew onto the surfaces. Subsequently, Zn element gradually diffused into Fe$_3$O$_4$ mesocrystals to generate Zn-doped Fe$_3$O$_4$ because of the Kirkendall effect by increasing the reaction time, in which a directional flow of zinc species at the Fe$_3$O$_4$ interfaces could result in the formation of voids in the products. Simultaneously, the inner solids would be dissolved, and the outer particles would grow larger due to the Ostwald ripening process, finally resulting in the formation of a hollow structure with a porous shell. The Zn-doped hollow Fe$_3$O$_4$ mesocrystals possessed high and stable photo-Fenton activity for the degradation of rhodamine B and cephalaxin under visible-light irradiation in the presence of H$_2$O$_2$ (Fig. 23c), and it could be easily separated and reused by an external magnetic field.

Fig. 23 (a) Crystal structure of NaTaO$_3$–SrS$_{1/3}$Ta$_{2/3}$O$_3$ solid solutions. Adapted with permission from ref. 134. Copyright 2015 American Chemical Society. (b) Schematic of the formation mechanism of Sb–mesoNb/TiO$_2$. Adapted with permission from ref. 140. Copyright 2017 American Chemical Society. (c) Schematic of the growth process for Zn-doped Fe$_3$O$_4$ hollow sub-microsphere mesocrystals and their photocatalytic activities. Adapted with permission from ref. 141. Copyright 2017 American Chemical Society. (d) Schematic illustration of a facile hydrothermal treatment synthesis process of N-doped TiO$_2$ mesocrystals and (N,F)-doped TiO$_2$ mesocrystals. Adapted with permission from ref. 150. Copyright 2016 Elsevier.
In brief, metal ions were extensively employed as dopants for mesocrystal photocatalysts. Generally, the introduction of metal ions can form new energy levels in the bandgap, optimize the visible-light response, and accelerate the separation of the electron–hole charges. Although many studies on transition metal-doped mesocrystals have been reported, non-metal doping is still in its infancy.

3.2.2 Non-metal doping. Thus far, non-metal-doped mesocrystals have mainly focused on TiO$_2$ mesocrystals. Previously, it has been confirmed that the substitution of an oxygen atom with a fluorine (F) atom can effectively improve the photocatalytic activity of TiO$_2$.

However, obtaining n-type F-doping in TiO$_2$ mesocrystals was still a challenge, until Majima and coworkers reported that an in situ F-doping of TiO$_2$ superstructures can be used for efficient visible-light-driven hydrogen generation. In this case, the details of crystal growth and dynamic structure evolution during the topotactic transformation from the initial intermediate NH$_4$TiOF$_4$ to HTiOF$_3$, TiOF$_3$, and F-doped TiO$_2$ mesocrystals were revealed. Further, F-doped TiO$_2$ mesocrystals synthesized at 500 °C can accelerate the electronic mobility for efficient visible-light-driven hydrogen production.

It has been demonstrated that N-doping is one of the most efficient avenues to generate N 2p in the localized mid-gap state, resulting in an increase in the thermal stability and decrease in recombination.

Therefore, it is necessary to integrate N- and F-doping into TiO$_2$ mesocrystals, which could combine the advantages of these single dopants for further optimizing the photocatalytic activity. With regard to synthesizing co-doped mesocrystals, only TiO$_2$ mesocrystals with N- and F-co-doping have been studied thus far. Topochemical transformation is an effective method for the synthesis of (N,F)-co-doped TiO$_2$ (NFT) mesocrystals exposed with (001) facets. The distribution of two dopants in NFT strongly depended on the annealing temperature. It was found that NFT (500 °C) displayed the highest photocatalytic efficiency from Cr(v) to Cr(III) because of the highest concentration of N with the surface modification from F coupling.

Similarly, Majima and coworkers have found that N-doped TiO$_2$ mesocrystals can be synthesized by a facile hydrothermal treatment with triethanolamine, while F-doped TiO$_2$ mesocrystals were easily formed by a simple stirring of TiO$_2$ mesocrystals with NaF at room temperature. Therefore, (N,F)-co-doped TiO$_2$ mesocrystals were prepared by a two-step post-modification process. A schematic illustration of the preparation of N-doped and (N,F)-co-doped TiO$_2$ mesocrystals is shown in Fig. 23d.

In this system, it was seen that doping has no effect on the crystal structure of TiO$_2$ mesocrystals, and the plate-like structure and high surface area can be retained. These (N,F)-co-doped TiO$_2$ mesocrystals displayed high photocatalytic activities for the degradation of rhodamine B and 4-nitrophenol under visible-light irradiation, which was attributed to the synergistic effect of N- and F-doping. The introduction of heterogeneous N atoms enhanced visible-light absorption, resulting in a decrease in the bandgap energy by adjusting the concentration of N, while F increased the production of hydroxyl radicals, adsorption, and charge separation efficiency. Therefore, TiO$_2$ mesocrystals with N- and F-co-doping provided a particular interest in promising visible-light-driven photocatalytic efficiency and allowed us to devote the effect on developing new materials as a photocatalyst.

4. Conclusions and perspective

Mesocrystal photocatalysts with tunable crystalline phases, sizes, and morphologies have been widely studied owing to crystallographically highly ordered superstructures for photogenerated charge transfer and separation, high surface area, and ordered porosity as compared to corresponding single crystal and polycrystalline nanomaterials. Herein, a comprehensive review on the synthesis strategies and growth mechanisms, morphological diversities, functional modifications including hybridization and doping, and current applications, as well as the corresponding structure-related photocatalytic mechanisms, have been summarized for different types of mesocrystal photocatalysts, such as TiO$_2$ (anatase), TiO$_2$ (rutile), ZnO, CuO, Ta$_2$O$_5$, BiVO$_4$, BaZrO$_3$, SrTiO$_3$, NaTaO$_3$, Nb$_2$O$_5$(OH)$_2$, In$_2$O$_3$ (OH)$_2$, and AgIn(WO$_4$)$_2$. Recent advances in designated tailoring of various kinds of mesocrystals provides a promising approach for the rational design and construction of high-performance photocatalysts, as well as the enrichment of their surface atomic/or electronic and interfacial properties. Although extensive investigations and significant achievements made during the past decades, as discussed in this review article, there is still a long way ahead before mesocrystal photocatalysts can be comprehensively understood and satisfactorily used in industrialization. In order to achieve this, we have numerous tasks to particularly investigate in the future.

With regard to the synthesis of novel mesocrystal photocatalysts, an important task is to promote the synthesis of mesostructural architecture with desired crystallographic facets, particularly high-index facets. The selection of suitable capping agents for constructing targeted mesostructures based on computer-assisted surface energy variations might considerably promote the synthesis of targeted mesocrystalline photocatalysts. With regard to popular TiO$_2$ mesocrystals, the literature mainly focuses on the anatase phase with diverse architectures, whereas studies involving the rutile phase are still in their infancy. Moreover, the size-controlled synthesis of polyhedral TiO$_2$, particularly ultrathin monodisperse nanoparticles (size < 100 nm), is an urgent task. Notably, the as-reported polyhedral TiO$_2$ mesocrystal photocatalysts generally exhibited low-index (001) and (101) facets, which strongly restrained investigations on facet-dependent properties. Therefore, considerable efforts should be further expended to explore the synthesis of novel polyhedral TiO$_2$ mesocrystals exposed with controllable-index facets for uncovering the relationship between surface structures and performances.

Apart from TiO$_2$, it is urgently necessary to focus more attention on enriching the structural and morphogenetic aspects, as well as formation mechanisms, of other mesocrystals, which are beneficial toward tuning the size, morphology, crystalline phase, monodispersity, surface atomic arrangement, and intrinsic electronic structure. Significantly, the surfactant-free, large-scale controllable synthesis of low-
dimensional mesocrystalline architectures is still a challenge for all the current mesocrystal species because the general growth mechanism is still uncertain.

In order to optimize the performances of mesocrystal photocatalysts, functional modifications, including doping and hybridization, should be thoroughly explored. For the doped mesocrystal photocatalysts, the current literature concentrates mainly on metal doping, studies have not focused on morphology- or sized-controlled syntheses of doped ones. Moreover, non-metal doping should also be taken into consideration because it is a promising research avenue. In addition, the co-doping and selective doping of heteroatoms for synergistically optimizing the electronic structures is still a formidable challenge. As a result, the development of doped precursors for annealing or transformation might be an effective strategy to achieve the controllable synthesis of doped mesocrystals. For mesocrystal-based hybridized photocatalysts, decorating active components with controllable structures on specific sites of mesocrystals should attract extensive attention, and revealing the relationship between facet-dependent interfacial and photocatalytic activities is still a primary target. Significantly, it is imperative to focus more efforts toward the synthesis of multicomponent mesocrystals (including hetero- or hetero-phase junctions) for exploring novel photocatalysts. Notably, the theoretical calculations involving the electronic structures of doped mesocrystals and interfacial structures of hybridization architectures should be investigated for the actual cognition of photocatalytic mechanisms.

To summarize, the comprehensive and in-depth review on the synthesis engineering and functional modifications (including doping and hybridization), as well as their corresponding structure-related enhanced photocatalytic mechanisms, can facilitate the development of new mesocrystal-based photocatalysts.

Conflicts of interest

There are no conflicts to declare.

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Notes and references