Mesocrystals—Ordered Nanoparticle Superstructures

By Rui-Qi Song and Helmut Cölfen*

Mesocrystals are 3D ordered nanoparticle superstructures, often with internal porosity, which receive much recent research interest. While more and more mesocrystal systems are found in biomineralization or synthesized, their potential as material still needs to be explored. It needs to be revealed, which new chemical and physical properties arise from the mesocrystal structure, or how they change by the ordered aggregation of nanoparticles to fully exploit the promising potential of mesocrystals. Also, the mechanisms for mesocrystal synthesis need to be explored to adapt it to a wide class of materials. The last three years have seen remarkable progress, which is summarized here. Also potential future directions of this research field are discussed. This shows the importance of mesocrystals not only for the field of materials research and allows the application of mesocrystals in advanced materials synthesis or property improvement of existing materials. It also outlines attractive research directions in this field.

1. Introduction

Mesocrystals are experiencing rapidly increasing attention of chemists and physicists in the last years. In particular for materials chemists, mesocrystals offer unique new opportunities for materials design due to their mesoscopic structure. The notation “mesocrystal” is an abbreviation for a mesoscopically structured crystal, which is an ordered superstructure of crystals with mesoscopic size (1–1000 nm). Often, the crystalline subunits are in perfect 3D mutual order resulting in the difficulty to distinguish a mesocrystal from a single crystal as the mesocrystal shows an identical scattering pattern and behavior in polarized light to a single crystal. Therefore, it is difficult to define the border between a single and mesocrystalline substance. Practically this can be done by the coherence length in scattering because single crystals usually exhibit coherence lengths >100 nm while mesocrystals typically have smaller ones. Another possibility to distinguish a mesocrystal from a single crystal is microscope images, which show subunits with mesoscopic size for a mesocrystal. The analytical challenge to correctly identify a

mesocrystal with perfect mutual order of its subunits becomes obvious.

The scattering and light polarization properties of mesocrystals are the reason, why mesocrystals were synthesized already many decades ago, but were not recognized as such and were usually interpreted as single crystals. This makes literature research for mesocrystals a difficult task. Available early reports on mesocrystals were summarized in [1]. However, in the last three years, a rapidly increasing number of mesocrystal systems have been reported due to increased analytical capabilities and the introduction of the mesocrystal and mesoscale organization concepts.^[2,3] These concepts highlight nonclassical crystallization as a nanoparticle-based crystallization pathway toward single crystals besides the classical atom/ion/molecule-based

mechanism. This includes the oriented aggregation mechanism of nanoparticles toward single crystals pioneered by Penn and Banfield 10 years ago^[4–6] or grain growth after grain rotation and coalescence in a polycrystalline material.^[7] Nonclassical crystallization has been discussed and reviewed in several recent overviews^[1,2,8–14] and the basic characteristics are known. However, while the mechanism of oriented attachment has been revealed, mesocrystals can form by various mechanisms and consequently, relatively little is yet known about the processes leading to mesocrystal formation. In addition, the number of known mesocrystal systems has much increased spanning from biominerals to functional materials. The fact that mesocrystals are found for biominerals, which are evolutionary highly optimized materials, shows that obviously, nonclassical crystallization is an advantageous crystallization pathway, which is worth to apply for the synthesis of advanced materials with improved properties. Also, mesocrystals were shown to be intermediates between a classical single crystal and a polycrystal without mutual orientation of its subunits and an extended view on crystallization with a continuous structural transition between single and polycrystal arises.^[15] Making the building units of a 3D-aligned mesocrystal smaller via clusters to ions will be the transition of a mesocrystal to a single crystal. On the other hand, if the mutual order of the nanocrystals is continuously brought out of crystallographic register until mutual order is lost, the mesocrystal will transform to an unoriented polycrystal (see also Fig. 5).^[15] These are just two examples and we therefore try to catch this exciting development and progress by reporting on mesocrystals in the literature between 2006 and 2008 to close the gap to the initial overviews.^[2,12]

[*] Dr. H. Cölfen, R.-Q. Song
Max-Planck-Institute of Colloids and Interfaces, Colloid Chemistry,
Research Campus Golm
Am Mühlenberg, D-14424 Potsdam (Germany)
E-mail: Coelfen@mpikg.mpg.de

2. Mesocrystal Formation Mechanisms

Several different mechanisms were reported for the formation of mesocrystals in the recent years and it is likely, that further mechanisms will follow in the future. With the present knowledge base in the literature, we can think of four basic mechanisms to form a mesocrystal, which are displayed in Figure 1. Combinations of these mechanisms are also possible.

2.1. Nanoparticle Alignment by an Organic Matrix

An obvious mechanism for mesocrystal formation would be to fill compartments with crystalline matter oriented by a structured organic matrix or align nanoparticles along an organic matrix (Fig. 1a). The nanoparticles could either be generated first and then attach to the organic matrix and get oriented or they could alternatively directly nucleate on the organic matrix, which could serve as a heterogenous nucleation site. Numerous examples of highly ordered macromolecular structures are especially known for biomacromolecules so that this mechanism can be considered to be especially relevant in biomineralization processes. Indeed, a matrix-mediated nanoparticle growth on a fibrous organic matrix was for instance suggested for the growth of corals.^[16] A highly oriented matrix which can be used for the purpose of nanoparticle alignment to a mesocrystal is chitin, which is for example found in the organic matrix of nacre. In an elegant work Kato and coworkers demonstrated that a peptide CAP-1 from a crayfish with a chitin binding motif, a phosphoserine unit for promoting the initial formation of amorphous CaCO_3 (ACC) and an acidic binding domain for CaCO_3 led to a mesocrystal film after nucleation of ACC, crystallization and nanoparticle alignment on a film composed of parallel α -chitin microfibrils.^[17] Here, calcite nanoparticles were aligned along the chitin fibrils. Alignment along an ordered chitin matrix can even work with less sophisticated molecules compared to CAP-1 like simple poly-(acrylic acid) (PAA).^[18] Here, a modified chitin phenylcarbamate was used to form a nematic liquid crystal. After conversion to a gel film, stretching, cleavage of the carbamoyl groups and drying, a chitin film with the chains elongated parallel to the direction of elongation was formed. Rod-like calcite mesocrystals were formed in a CaCO_3 crystallization essay elongated with the *c*-axis parallel to the direction of film elongation. It is assumed that PAA molecules bind to the oriented chitin backbone and thus facilitate oriented nucleation and the growth of calcite.

Related to nanoparticle alignment along fibers is the mesocrystal formation in a gel matrix, which can also lead to the orientation of the formed nanocrystallites (e.g., the fluorapatite mesocrystals in a gelatin gel matrix, see Section 5.1.2). It should be noted that gels are also discussed in biomineralization processes such as for example the silk hydrogel in the formation of nacre.^[19] Nacre aragonite tablets are known to be mesocrystals.^[20]

2.2. Ordering by Physical Fields

In the majority of known cases, mesocrystals form nanoparticles in solution, which aggregate and arrange in crystallographic

Helmut Cölfen studied Chemistry at the Gerhard-Mercator University Duisburg, Germany and completed his Ph.D. on Analytical Ultracentrifugation of gels in 1993. He then went to the National Centre for Macromolecular Hydrodynamics at the University of Nottingham, England to work on the solution characteriza-

tion of complex biopolymers as well as their interactions and superstructures. In 1995 he joined the Max-Planck-Institute of Colloids and Interfaces where he is currently leading the projects "Biomimetic Mineralization" and "Fractionating Colloid Analytics." After his habilitation in 2001, he was employed as senior scientist and head of the analytical service in the colloid chemistry department. Since 2004, he is private docent at the university of Potsdam. His current research is focused on nonclassical crystallization, prenucleation clusters, and additive controlled crystallization as well as Analytical Ultracentrifugation.

Rui-Qi Song is a postdoc associate at the Colloid Chemistry Department of the Max Planck Institute of Colloids and Interfaces. She received her Ph.D. in Physical Chemistry from the Chinese Academy of Sciences in 2002. After five years as a research fellow at Sun Yat-Sen University, she joined Helmut Cölfen's group in 2007. Her research involves

design and synthesis of new organic-inorganic hybrid materials, particularly using block copolymer driven crystallization through nanoparticle self-assembly.

order—even without any additives (Fig. 1b). This mechanism for mesocrystal formation heavily relies on particle interaction forces as well as on external forces, which have recently been reviewed for the formation of higher order nanoparticle structures.^[21]

The ordering physical fields/forces like electric,^[22,23] magnetic,^[24] or dipole fields^[23] as well as polarization forces have to be anisotropic to allow for an ordering of the nanoparticle units. The nanoparticles in turn also have to be anisotropic with respect to their interaction potentials so that an ordering can take place. Such anisotropy could for example be oppositely charged counter faces of a crystal, a magnetic or dipole moment along one nanocrystal axis or differences in the polarizability along different crystallographic directions. The anisotropy could already be present in the nanocrystal itself or be induced by face selective additive adsorption.

Figure 1. The four principal possibilities to explain the 3D mutual alignment of nanoparticles to a mesocrystal. a) Alignment of nanoparticles by an oriented organic matrix b) nanoparticle alignment by physical fields or mutual alignment of identical crystal faces. The arrows indicate the mutual alignment by physical fields or the faces. c) Epitaxial growth of a nanoparticle employing a mineral bridge connecting the two nanoparticles and d) nanoparticle alignment by spatial constraints. Upon growth of anisotropic nanoparticles in a constrained environment, the particles will align throughout growth according to the space restrictions as indicated by the open drawn particle in the arrangement of already grown particles in the lower image of (d). Please note that the building units are shown to be monodisperse for the sake of clarity. This is not always the case in real systems. Also, the mutual order is not necessarily that of the shown crystallographic register.

In an impressive work, Kniep and coworkers could show intrinsic electric field lines around a fluorapatite-gelatin mesocrystal by electron holography pointing out the importance of the organic component, which represents aligned dipoles in this case.^[23] These dipoles of aligned triple helical protein fibers on the nanometer scale can build up a macroscopic dipole if they are aligned along the mesocrystal *c*-axis. This showed for the first time the direct correlation between intrinsic electric fields and the self-organized growth of fluorapatite mesocrystals. Indeed, external electric fields can be used to create 2D and 3D mesocrystals as demonstrated for CdS nanorods^[22] and for large areas of several square micrometers if monodisperse CdSe/CdS nanorods were used.^[25] However, drying of the solution was also used here and it cannot be clearly separated which effect on the alignment is caused by the electric field and which by capillary forces generated by bringing the particles into close proximity by solvent evaporation. Nevertheless, as CdS has a permanent dipole moment, the electric field will have an ordering role. However, this is not fully sufficient to always lead to mesocrystals. For dipolar CdSe, the ordering effect of the electric field was demonstrated but no orientation was observed upon simple drying since the ligands on the nanoparticles can collapse onto the substrate rather than interact with those on another nanoparticle.^[26] Also ordering to a smectic superstructure by parallel arrangement of CdSe nanorods was observed.^[27] In such cases, the interaction forces between the nanoparticles have to be optimized. Russell and coworkers achieved this goal by orienting CdSe nanorods in an electric field and which froze in this orientation upon solvent evaporation by strong, nonfavorable polymer–ligand interactions leading to a 2D mesocrystal after removal of the electric field.^[28] Even without electric field, ordering is possible if surfactants with three or four alkane chains were used for the stabilization of CdS which facilitate corraling by hydrocarbon interaction.^[29] Above a critical particle concentration, simple drying led to 2D mesocrystals.

Besides electric fields, magnetic fields can be applied as external force for the orientation of nanocrystals to mesocrystals.

This was demonstrated for oleic acid stabilized maghemite in toluene^[30] and oleic acid stabilized cobalt nanocrystals in nonane^[31] by drying a droplet of the dispersion in a magnetic field perpendicular to the substrate. Large area (10 μm) mesocrystals with more than 10^6 nanocubes as well as 3D mesocrystals could be produced by this simple procedure.^[30] In addition, it was found that the strength of the magnetic field as well as the concentration of the nanoparticles in dispersion could determine the aspect ratio of rod shaped mesocrystals.^[31] This shows that the magnetic field assisted formation of mesocrystals from magnetic nanoparticles is controlled by the relative strength of the interplay of van der Waals interaction, steric repulsion and directional dipolar interactions between the nanoparticles supported by the external magnetic field. It was also demonstrated that the alignment of the nanocrystals in the mesocrystal is clearly advantageous for the physical properties. The cobalt mesocrystal showed a four times higher magnetic coercivity compared to unoriented nanoparticles.^[31]

Controlled rotation of a sample in a strong magnetic field with nonconstant velocity can also induce alignment along the magnetization axes for nanoparticles >10–100 nm and thus 3D mesocrystal formation as demonstrated for L-alanine, which itself is not magnetic.^[32]

Nanoparticles with dipole or magnetic moments will create local dipole/magnetic fields and can mutually attract each other in crystallographic register. The same is true for anisotropic particle polarization, where particle surfaces with equal polarizability attract each other by directed van der Waals forces.^[33] This concept requires the nucleation of a large number of nanoparticles of about the same size with the requirement of anisotropy along at least one crystallographic axis. This anisotropy can also be inherent to the crystal system as was observed for the case of amino acid crystals^[34,35] or might be induced by selective polyelectrolyte adsorption to expose highly charged faces simultaneously with their oppositely charged counterface.^[36] Amino acids are an ideal system for the study of mesocrystal formation since simple pH variation can vary the crystallization path between classical and nonclassical crystallization, the supersaturation, and crystallization speed as demonstrated for DL-alanine.^[34] Indeed, very recently, mesocrystals were also observed for the same system by precipitation in water–alcohol systems.^[35]

2.3. Interparticle Forces

Rapidly formed amorphous precursor structures are important in nonclassical reaction channels. As demonstrated for DL-alanine by conductivity experiments and light scattering, molecular supersaturation releases quite rapidly in the second and sub-second region,^[34] where the alanine precipitates toward metastable, presumably amorphous nanoparticles, or liquid droplets. These amorphous structures represent the real source of matter throughout crystallization. The number and size of amorphous intermediates is adjusted by their colloidal stability, i.e., there are

just as many particles or surface area as the system can support by its composition and stabilizer content. Additional material does not create new particles, but leads to particle growth in accordance to the LaMer growth mechanism.^[37] The amorphous nanoparticles or liquid precursors then partly crystallize and grow via colloidal aggregation due to crystallization. We assume that this phenomenon holds true for all crystallization processes with high material transfer, but it is especially pronounced for strongly interacting nanocrystals.

In later stages, the conditions determine the fate of the crystallization event, and three different possibilities can be differentiated for the amino acid model case:

- (i) When the concentration of amorphous intermediates is high enough and the growth by molecules low, the nucleated structures grow by addition of further colloidal building blocks. For that, the crystalline nucleus attracts a noncrystallized intermediate and restructures it after attachment in an epitaxial fashion.^[2,3] Once such a particle crystallizes, the polarization abilities within the structure sum up in a coherent fashion, the Hamaker constant and the related surface energy is increasing, and this crystal nucleus will attract other particles in a directional fashion, mostly in the direction of maximal polarizability.^[33] For dipolar structures, this is a self-accelerating process, because the larger the dipolar crystal, the stronger its attraction along the tips to attract further colloids.
- (ii) At higher temperatures and deviating pH values, the molecular solubility is high enough to make classical crystallization via a molecule-by-molecule addition the dominant crystallization channel. The molecular crystallization rate toward crystals is higher than that toward mesocrystals, and single crystals are formed.
- (iii) Too much undercooling or quenching the system too deep into the thermodynamic instability limits the lifetime of the amino acid mesocrystals. Although lower molecular solubility and a higher number of colloidal precursor particles in principle are even more supportive for a mesostructure process, the forces driving the recrystallization of the mesocrystal to a single crystal are also higher, thus making the mesocrystals short-living intermediate objects, only. The nanostructures must also possess a low interface tension toward the mother liquor, a mandatory prerequisite for their existence. Higher interface energy leads to high colloidal attraction, rapid flow-out of the separation layer, and crystallographic fusion toward an apparent single crystal.

These considerations show that a temporary stabilization of the nanoparticles is crucial for the nanoparticle orientation to a mesocrystal by interaction forces to maintain that the system is able find the point of minimal energy on its energy landscape. This means that thermal energy has to be able to populate all possible states. Such mutual adjustment is usually enabled in the secondary minimum of the Deryagin–Landau–Verwey–Overbeek (DLVO) potential, where the energy fine structure is of the order of thermal energy kT and the structure is organized, but still liquid.

If the stabilization is too strong, the nanoparticles will repel each other keeping them in solution as stable nanoparticles. On the other hand, if the stabilization is too weak, colliding

nanoparticles will stick to each other as their potential is in the primary minimum of the DLVO potential and they cannot change their mutual orientation anymore. A “correction mode” for nanoparticle orientation is therefore important where a feedback loop between nanoparticle orientation and resulting nanoparticle interaction potentials allows finding the energy minimum resulting from the mutual nanoparticle orientation.

One such example for balancing colloidal interactions preserving mobility is that of reverse microemulsions for nanoparticle synthesis. The nanoparticles are synthesized after fusion of micelles containing the reactants and are temporarily stabilized in the organic solvent against immediate single crystal formation or uncontrolled aggregation by the surfactant. Hydrophobic interactions between the surfactant tails occur and can drive the self assembly process of the nanoparticles, minimizing the surface energy of the surfactant phase. An example for the successful application of this mesocrystal formation strategy is the synthesis of CaMoO_4 mesocrystals in a *n*-octane/cetyltrimethylammonium bromide (CTAB)/*n*-butanol system^[38] by adjusting the hydrophilic-hydrophobic balance.

Beside physical fields with longer range, there are also forces upon particle contact. Already two identical crystal faces can orient each other when brought in close contact, as was observed in the process of oriented aggregation.^[4–6] The principal attractive force between two objects is the van der Waals attraction, which can lead to aggregation of particles. If there is a short range repulsive force like a hydration or surfactant layer, the nanoparticles can still rotate/translate in the aggregate until they come into a position where two identical (or complementary) crystal faces are in register to each other. These faces can mutually fuse as the atomic landscape of these faces is exactly complemented by the other nanoparticle surface. Release of surface hydration water or attached surfactant molecules can yield an additional entropic driving force besides the energy gain through elimination of two high energy surfaces. This would transform the mesocrystal into a single crystal. An alignment of a mesocrystal by crystallographic lock in was recently demonstrated for self similar CaCO_3 mesocrystals, which were obtained in presence of an anionic poly(styrene-*alt*-maleic acid) copolymer.^[39] Figure 2 shows the self similar crystals, which are composed from alignment of equally shaped anisotropic nanoparticles in crystallographic register.

The negative copolymer adsorbs on the triangular charged {001} faces and is responsible for their stabilization and expression in the morphology of the primary nanoparticles. The side faces, however, are neutral and no polymer adsorbs on them. If nanoparticles approach each other, they cannot fuse at {001} due to the polymer protection and will therefore align side by side, where the unprotected {011} faces will lead to mutual nanoparticle orientation and crystallographic lock in. However, there are many voids and pores in this self similar structure and the nanoparticle subunits are still clearly recognizable (Fig. 2d, f). This still shows the mesoscale structure although the nanoparticle building units are crystallographically connected.

2.4. Mineral Bridges

Another possibility for the 3D nanoparticle alignment in crystallographic register is the crystallographic connection

Figure 2. SEM images of self similar mesocrystals obtained in the presence of a polystyrene–maleic acid copolymer. a) Overall product morphology; b–d) High magnification SEM images showing the basal faces of elongated microparticles; e, f) SEM images showing the lateral faces along *c* axis; (g) a modeled calcite morphology of a combination of {001} and {011} forms constructed by the Cerius² software. Gray lines and face indices are those at the back. Reproduced with permission from [39]. Copyright 2008, Wiley-VCH.

between the nanoparticles by so-called mineral bridges (Fig. 1c). This concept was first used to explain the mutual *c*-axis orientation of aragonite tablets in nacre, and some experimental evidence for the mineral bridges could be given.^[40] An assembly of mineral bridge connected crystals is in fact also a single crystal. Thus, this concept is the most straightforward one among the mesocrystal formation mechanisms to explain the mutual crystallographic orientation of the nanocrystals.

According to Oaki et al., the formation of a mesocrystal with mineral bridges starts with the formation of nanocrystals.^[41] After polymer adsorption onto the nanoparticle surface, its further growth is quenched. In this stage, mineral bridges can nucleate at the defect sites within the growth inhibition layer on the nanocrystal, and a new nanocrystal is growing on the mineral bridge. Its growth is again quenched by the polymer, new mineral bridges form and the process is sequentially repeated until the mesocrystal is built up (Fig. 1c). Such growth scenario is especially relevant for mesocrystal formation within an amorphous precursor phase, which is often observed for biominerals. Although the mineral bridge concept can easily explain the crystallographic orientation of the nanocrystals in a mesocrystal, mineral bridges are very hard to detect with an electron microscope in a microtome thin cut and have to be assumed to be only a few nanometer in diameter. Nevertheless, these bridges could be observed in some cases^[41–43] and the regions between the nanocrystals were shown to be stainable with a dye.^[41]

If a mesocrystal grows via mineral bridges as proposed above, the kinetics of mesocrystal formation should be rather slow as compared to free crystallization, which disagrees with the fast mesocrystal formation, which is often observed. However, there are certainly also slower mesocrystal growth scenarios as, e.g., in biominerals.

It is also possible that mineral bridges form after the alignment of the nanoparticles in crystallographic register and act as fixation of the mesocrystal structure. Local dissolution on a nanoparticle surface can lead to a local supersaturation in the space between two nanoparticles and the nucleation of a mineral bridge. Whether the mineral bridges form before or after the nanoparticle alignment into crystallographic register is still unclear and would require a demanding, time dependent investigation of mineral bridge formation.

2.5. Space Constraints and Self-Similar Growth

The fourth possibility for the formation of a mesocrystal would be a simple geometric argument as outlined in Figure 1d. When crystalline nanoparticles grow and these nanoparticles are not spherical in shape, simple entropic arguments (known from the Onsager theory of liquid crystallinity) can explain their alignment in a constrained reaction environment upon particle growth, as shown in Figure 1d for the open drawn particle. The particles first crystallize into a relatively disordered and loose structure of crystalline nanoparticles. Upon further growth in a confined reaction space, they cross the critical volume fraction to form a lyotropic liquid crystal, and the structures have to align mutually. The higher the volume fraction, the higher is the entropic force driving the order parameter, and the more regular is the packing. This argument for mesocrystal formation just requires the presence of a constrained reaction environment with a constant influx of reactants.

The constrained reaction environment can be a pre-formed cavity (such as a vesicle or gel), but can also be generated by the mutual attraction of first crystallizing particles to generate a packing for the alignment of further growing nanoparticles as outlined in Figure 1d. This mechanism is universal to all crystalline systems as long as the primary nanoparticle building units are sufficiently anisotropic in shape. It is obvious that in this scenario short range repulsive forces are also needed to allow for sufficient fluidity and the ability to re-arrange the nanoparticles in the aggregate so that re-structuring toward the final mesocrystal becomes possible. In this reaction scenario, all intermediate states would however be liquid and consequently rather hard to isolate.

Related to this growth scenario is self similar growth of a mesocrystal where the shape of the nanocrystals defines their oriented packing due to some elementary connection rules.^[44] For instance the construction of the mesocrystal can be provided by geometric packing of the building units, which mutually orient by edge to edge or face to face contacts. The driving force for the geometrical alignment is the minimization of the interface mismatch energy by forming a coherent interface and reducing the exposed surface area while edge sharing is promoted by

reduction of the amount of dangling unsaturated bonds along the edge, which have an inherently high chemical energy. Such self similar growth was demonstrated for the spontaneous self assembly of ca. 5 μm sized octahedral silica crystals on glass surfaces.^[45] Another example is the formation of 2D mesocrystals by drying of a dispersion on a smooth substrate covered with highly oriented pyrolytic graphite, which facilitates very slow drying, necessary to allow nanoparticles to optimize their attachment position onto the growing mesocrystal.^[46] Here, the hexagonal faceting of the CdS nanorods along the *c*-axis leads to shape induced ordering into a mesocrystal with mismatch of the units of 6°.^[46]

However, the self-similar alignment mechanism relies on a defined size and shape of the nanoparticle building units and is therefore certainly no common mechanism for mesocrystal formation.

Also, capillary forces can be responsible for nanoparticle alignment as shown in Figure 1d when a small space between the nanoparticles forms. Such a capillary, if not mechanically stabilized, tends to close. The two faces of the nanoparticles attract each other, and the liquid film in between rapidly flows out also over larger distances. A nanostructure in random orientation will find in its neighborhood different cleft sizes and therefore different pressures, which all will pull onto the particle thus creating a torque, until all local pressures are balanced. This is usually obtained in the oriented state, i.e., rod-like particles will usually oriented in parallel due to the minimization of capillary forces, but more complicated orientation patterns can be obtained by capillarity, too.

Capillary forces which occur upon drying of droplets containing nanoparticles were identified to be responsible for the rapid annealing toward large and very well organized arrays of magnetite nanocubes in situations as outlined in Figure 1d. Small octahedral magnetite crystals were found to arrange into a perfect super lattice driven by capillary forces.^[44] The magnetic interaction was found to play a minor role in this case, while balancing colloidal forces, here attractive van der Waals forces and repulsive steric interactions, were provided by appropriate choice of stabilizer molecules (which also prevent uncontrolled aggregation). The potential energy can be minimized by contact between the nanoparticles being largest for a face to face contact, thus also making the mutual distance minimal, which is the driving force for the mesocrystal formation. A similar evaporation technique was reported for the formation of mesocrystals from cubic Pt nanoparticles leading to a mesocrystal superlattice.^[47]

2.6. Topotactic Reactions

Once a mesocrystal is formed, it can be transformed to a mesocrystal of another mineral system by topotactic conversion under favorable conditions. The term topotaxy (Greek; "topos" = "space" and "taxis" = "in ordered manner") describes all solid state reactions that lead to a material with crystal orientations, which are correlated with crystal orientations in the initial product. This opens up a new route to chemically different mesocrystals from a mesocrystal precursor structure. One remarkable example is NH_4TiOF_3 mesocrystals which were

prepared in presence of nonionic poly(ethylene oxide) Brij 58 surfactant.^[48,49] Already the preparation of this mesocrystal species is remarkable, since the surfactant participates in the chemical reaction for the synthesis of NH_4TiOF_3 with the poly(ethylene oxide) moiety as Lewis base and oxygen donor interacting with metal centers. This produces a viscous amorphous phase with high surfactant concentration.^[48] Afterwards, in a second stage, aggregation occurs with cooperative reorganization of organic and inorganic compounds building up a larger hybrid particle. In a third step, crystallization occurs and the surfactant may act as a matrix for the oriented crystallization of the mineral nanoparticles and mesocrystal formation since it has affinity to the {001} faces of NH_4TiOF_3 . It is remarkable that the surfactant fulfills multiple roles in this example and shows, that the basic mechanisms in Figure 1 can be too simplified. Extended stirring was shown to disrupt the mesocrystal formation and to lead to aggregates composed of only small mesocrystal subunits.^[49] This shows that the self organization of the nanoparticles into crystallographic register is a sensitive process requiring delicate force balance. Temperature variation also allowed for shape control of the primary nanoparticles and the mesocrystals.^[49] This shows that transport effects can play a role in the formation of mesocrystals.

These mesocrystals can be converted to anatase TiO_2 mesocrystals by topotactic conversion by either washing the NH_4TiOF_3 mesocrystals with aqueous H_2BO_3 or sintering at 450 °C in air. For both methods, the surfactant in the NH_4TiOF_3 mesocrystals was almost completely removed. This is schematically shown in Figure 3.

TiO_2 has a greater atom density than NH_4TiOF_3 in *c*-direction, while the Ti-atom positions are similar in [001] for both systems. Thus shrinkage occurs on topotactic conversion, while the overall crystal orientation is conserved as shown in Figure 4.^[48] This can be attributed to the special structure of a mesocrystal consisting of individual nanoparticles. However, it was not commented why the TiO_2 nanoparticles are kept apart in the mesocrystal since the surfactant was removed in the conversion reaction.^[48,49] This is attributed to low surface energies of the TiO_2 faces resulting in a low driving force for oriented aggregation. This impressive example shows the potential, which topotactic conversions can have. For example, it circumvents problems associated with the conversion of amorphous metal oxide precursor phases to mesostructured materials.

A number of systems are known which can be converted by topotactic transformation and the application range is certainly not restricted to metal oxides. Another elegant example is the topotactic reaction of dicalcium phosphate dihydrate (DCPD) to dicalcium phosphate (DCP) by dehydration and further conversion to hydroxyapatite (HAP) by rapid DCP hydrolysis with NaOH solution.^[50] As already discussed in Section 5.1, a gel can be advantageously applied for the synthesis of mesocrystals because a high supersaturation can be maintained without the rapid mixing of the mineral forming ions. Using this strategy, the precipitation of calcium phosphate in a gelatin gel was found to lead to DCPD with ca. 2% gelatin incorporated in a hydrated layer parallel to the (010) plane. Dehydration of the DCPD to DCP at 60 °C in air kept the macroscopic crystal morphology but led to a dramatically different laminated microstructure.^[50] The laminated DCP architecture was found to consist of rectangular

Figure 3. Illustration of the oriented transformation of NH_4TiOF_3 mesocrystal to anatase TiO_2 mesocrystal. The selected area electron diffraction (SAED) images show the single crystal diffraction behavior of both systems. Reproduced with permission from [49]. Copyright 2008, American Chemical Society.

mesocrystal units (2–5 μm in length and 100–200 nm width), which themselves were composed of DCP nanoparticles with a size of ca. 50 nm mutually crystallographically oriented along the [100] and [001] directions.^[50] Therefore, the described mesocrystal exhibits hierarchical organization. FTIR investigations suggested that the nanocrystals are covered by gelatin and that the hierarchical structure is organic–inorganic in nature.

Gelatin plays a dual role in the structure formation process:

- (i) It provides a gel matrix for the formation of gelatin incorporated DCPD precursor crystals. These crystals grow slowly under inclusion of gelatin molecules due to a specific gelatin interaction and rapid mixing of the ions is prevented by the gel matrix.
- (ii) Gelatin assists and promotes the phase transition of DCPD to DCP by dehydration at 60 °C, and the specific interaction with the {100} and {001} DCPD faces restricts the DCP growth during the phase transition. This leads to lattice structures with rectangular units mainly exhibiting {010} faces and the emergence of a hierarchical structure.

Rapid hydrolysis of the DCP structure to HAP at 95 °C and pH 13.6 preserves the delicate hierarchical architecture as the conversion can be carried out in a topotactic way. The fast growing HAP *c*-axis was parallel to the surface of the formed nanoplate units (ca. 20 nm size), which make up the hierarchical mesocrystal structure. The structural details are, however, smaller due to the smaller HAP building units.

In the HAP case, the topotactic conversion is successful because the size of the nanocrystals making up the mesocrystal structure in educt and product is similar and the lattice angle of the laminated structure remains unchanged. The gelatin inclusions in the hierarchical crystals are important for the formation of the hierarchical mesocrystal structure as a similar HAP structure cannot be obtained when performing the same reaction cycle on commercial DCPD crystals. This remarkable reaction sequence shows that topotactic reactions can be used advantageously to produce hierarchically organized mesocrystal structures by simple chemical reactions.

2.7. Combined Mechanisms

It is possible that features of more than one of the four possibilities for mesocrystal formation in Figure 1 are observed. This is nicely illustrated for the example of $(\text{NH}_4)_3\text{PW}_{12}\text{O}_{40}$ mesocrystals, which finally form so-called sponge crystals.^[42] The cubic $(\text{NH}_4)_3\text{PW}_{12}\text{O}_{40}$ first forms rounded mesostructures from ca. 6 nm nanocrystallites, which then slowly transforms to a dodecahedral shape of a

mesocrystal with rough surfaces and single crystal scattering behavior. The mutual reorientation of the nanoparticles in close proximity can occur when two equivalent nanocrystal faces re-orient themselves into mutual crystallographic order. The nature of the short range repulsive forces in this example is not yet revealed but they must be temporarily present, as otherwise, crystallographic fusion of the oriented nanoparticles would immediately occur. Simultaneously, the total Brunauer–Emmett–Teller (BET) surface area decreases, which also indicates crystallographic fusion of the nanoparticles in the mesocrystal. From these data, three important conclusions can be drawn:

- (i) The nanoparticle building units in a mesocrystal are initially not connected, although they are already in crystallographic register.
- (ii) Mineral bridges form in this case after the primary nanoparticles mutually aligned into crystallographic register.
- (iii) The primary nanoparticles fuse together and the mesocrystal transforms into a porous single crystal either by formation of mineral bridges or mineral necks between two nanoparticles.

Figure 4. Schematic illustration of the formation process of $(\text{NH}_4)_3\text{PW}_{12}\text{O}_{40}$ mesocrystals. Reproduced with permission from [42]. Copyright 2006, Springer.

Figure 5. Microtome thin cut of BaSO_4 mesocrystals obtained in presence of a structure directing double hydrophilic block copolymer. The arrows indicate that the elongated nanoparticles splay outwards. The two dark elongated zones are a cutting artifact. Reproduced with permission from [51]. Copyright 2000, American Chemical Society.

Crystallographic fusion of nanoparticles rather than a dissolution–recrystallization mechanism can be concluded from the final porous nature of the single crystalline domains, which would not occur upon redissolution–reprecipitation in the absence of a porogen.

The whole mesocrystal formation process is schematically shown in Figure 4.

The question now arises, why mineral bridges form between two crystallographically aligned crystal faces in proximity of only a few nm, and if this is a general or necessary step in mesocrystal formation. Excess material entrapped between the two adjacent nanocrystals or incompletely crystallized planes can locally recrystallize to form the mineral bridge. If one assumes a hydration layer or an additive layer (in the above case, an urea layer would be possible), local small imperfections in the layer would provide a possible nucleation spot for the formation of the mineral bridge, which grows on expense of the surrounding ions in weak binding situations toward the next particle, which is already crystallographically aligned. There, the mineral bridge can epitaxially fuse with the respective face of the nanoparticle in close proximity—pushing a hydration or additive layer aside if present. In that way, the mineral bridges fix the porous mesocrystal structure. Obviously size, extent, but even the occurrence of mineral bridges at all depends on the solubility of the mineral, the amount of included material, and the strength of the binding of the surface stabilizers.

In addition to the mineral bridge formation, crystallographic fusion of two adjacent faces can also occur in the same mesocrystal

as indicated by the decrease in surface area. This implies that the repulsive force in form of a hydration/additive layer can be too small to prevent the fusion of the mesocrystal primary building units to a single crystalline domain when “flowing out” of the liquid membrane occurs, which is driven by the high capillary pressures. This latter mechanism is in agreement with the fact that mesocrystals are rarely observed, unless strongly surface active additives are applied to permanently fix their primary building units and allow their observation on a larger time scale.

We therefore assume the existence of three different scenarios for the aligned nanoparticles depending on the nanoparticle surface energies:

- (i) nanocrystals with high surface energies and interaction potentials will undergo oriented attachment and crystallographic fusion, as the flow out of the liquid separation layers can be quite fast;
- (ii) for surface energies in the intermediary region or medium-effective stabilizers, mineral bridges can form and fix the aligned nanoparticles toward a porous hybrid superstructure; or
- (iii) binding of the surface layer is too strong or immobilized (such as for glassy amorphous surface layers) so that the aligned situation is thermodynamically or kinetically stable. In this case, the nanoparticles stay aligned, but separated and do not form a joint crystalline system.

The above discussion of mesocrystal formation mechanisms based on the so far reported literature examples shows that

observation of a mesocrystal, at least as an intermediate, highly relies on a counterplay between long range attractive and short range repulsive forces. A considerable number of forces exists which can be of influence in a mesocrystal formation process and therefore, the so far reported mesocrystal formation mechanisms can largely differ from each other, especially in view of the possible combination of basic mechanisms shown in or if a subsequent topotactical conversion to a chemically different mesocrystal is carried out.

We want to emphasize that the mutual order between nanocrystals in a mesocrystal must not necessarily be that of the crystallographic register as drawn for reasons of simplicity in Figure 1. As has recently been shown, there exists a continuous transition between a single crystal and a mesocrystal with nanoparticles in mutual 3D crystallographic register and a polycrystal without any mutual orientation of its subunits.^[15] For example, Figure 5 shows a microtome thin cut through a BaSO₄ mesocrystal, which shows nanoparticle orientation splaying outwards just as if they were oriented along field lines. These nanoparticles are not in 3D crystallographic register but still show mutual order and thus satisfy the definition of a mesocrystal. The scattering pattern of such mesocrystal would show arcs instead of a spot pattern.

3. Mesocrystals in Bio- and Biomimetic Mineralization

Biomaterials are commonly considered to be archetypes for future advanced materials design. Insofar, these complex mineral systems are intensely investigated. An important recent finding is that several Biomaterials turned out to be mesocrystals like sea urchin spines,^[41,52,53] sponge spicules,^[54] foraminifera,^[41] nacre,^[20,41,55–58] calcite prisms in mussel shells,^[59] corals,^[41] or egg shells^[41] as summarized by Oaki et al.^[41] and for calcareous sponge spicules by Sethman and Worheide.^[60] Due to the complexity of biomaterial systems and the difficulty to observe structure formation starting on the nanoscale in living systems, not much is known yet about the formation mechanisms of mesocrystals in biomaterials. It seems likely that amorphous precursor material is deposited at an early growth stage^[54] possibly via vesicle carriers. Indeed, amorphous precursor phases were detected in a number of biomaterials.^[61] If this is the case, then it is hard to imagine, how a mesocrystal can form in an amorphous phase by oriented aggregation of nanoparticle subunits via an oriented aggregation process. This process would require nanoparticle mobility and the possibility of error correction in the aggregation process. One solution would be grain rotation of adjacent nanocrystallites, which were nucleated in the amorphous precursor phase.^[7] Another possible solution to this problem is offered by Oaki et al. who suggest that mineral bridges connect the individual nanoparticles (see Section 2).^[41,52] Although in their original concept, a polymeric mortar is suggested between the nanobricks, this concept could explain the mutual crystallographic alignment of the nanoparticles in mesocrystals and does furthermore not require a number of preformed particles which mutually align into crystallographic register. It is sufficient that one nanoparticle grows in an amorphous precursor phase until it is stopped from growth by

occluded macromolecules or other impurities in the amorphous precursor phase as suggested for the example of nacre from the observation of an amorphous surface layer.^[62] However, the exact formation mechanism of a mesocrystal still remains to be explored for biomaterials. An organic matrix certainly plays a role as demonstrated for the formation of a calcite mesocrystal film on a chitin matrix in presence of a peptide isolated from a crayfish exoskeleton.^[17]

Up to now, also not much is known about the possible function of biomaterial mesocrystal structures although it seems likely that the organic–inorganic mesocrystal structure of a biomaterial can improve its mechanical properties. Compared to a single crystal with cleavage planes, which makes it very brittle, the polycrystalline mesocrystal structure with soft regions between the single crystalline nanoparticle building units can make the hybrid material superior to its constituents. The brittle crystals can add mechanical strength and hardness to the system while the soft polymeric or amorphous phase is deformable and adds elasticity. A very prominent and much investigated example for such material combination is nacre, where aragonite platelets are interspaced with polymeric layers. The 3000-fold fracture toughness of nacre was explained by energy dissipation by the polymeric layers. However, it has been shown, that also the mesocrystal structure of a single aragonite platelet is important for fracture energy dissipation by nanograin rotation.^[56] An adhesive biopolymer spacing between the crystalline nanograins in the aragonite mesocrystal was suggested to facilitate grain rotation upon mechanical deformation making the aragonite platelets ductile resulting in deformability.^[56,63] Such observation makes much sense from the viewpoint that nacre, spines and spicules are protective elements of the organism, which need a very good mechanical performance. However, it cannot be generalized that a mesocrystal structure is generally the way to achieve superior mechanical performance as the example of an eggshell shows, which the chick must be able to break. Therefore, the reason why a mesocrystal structure is chosen for some biomaterials is not yet clear for all organisms.

Very recently, a fascinating mesocrystal architecture was reported for the red coral *Corallium Rubrum*.^[64] Mg-calcite fibers were found to be superstructures of aligned submicrometer particles and mesocrystalline fibers. However, each of the submicrometer building units itself is composed of aligned 2–5 nm nanoparticles—a mesocrystal. Therefore, this coral exhibits a hierarchical mesocrystal structure, which is a mesocrystal with mesocrystal building units. This first example demonstrates the assembly of hierarchical mesocrystal structures. The precise function of the hierarchical structure, however, is yet unknown.

HAP is another biomaterial, which was recently reported to form mesocrystals in tooth enamel-like structures^[65–68] and dentin remineralization^[69] suggesting a role of mesocrystals in calcium phosphate biomaterials too. The formation of mesocrystals with tooth enamel-like structure and *c*-axis orientation of their nanoparticle building blocks always involves the initial formation of amorphous calcium phosphate (ACP). This ACP phase was suggested to serve as mortar in a “bricks and mortar” model^[65,66] to cement the HAP nanoparticles once they have oriented into crystallographic register by control of biomolecules like amelogenin. Such control molecules for hierarchical assembly can be

Figure 6. Reorganization of HAP nanospheres in the presence of Gly. The previously formed colloidal aggregates were dissociated and the detached nanospheres were aligned into the linear chains A). ACP (white arrows) B) played the cementing role in the connections of the HAP nanoparticles. At this stage, the HAP nanospheres were not homogeneously oriented since their crystallographic directions were disordered. The evolution was associated with the phase transformation of calcium phosphates, and the newly crystallized HAP domains. The domains align and the nanocrystallites fuse to HAP single crystals (ca. 5 nm in width and 80 nm in length). C) These HAP single crystals serve as the building blocks for secondary assembly induced by Gly resulting in mesocrystals of enamel-like apatite, which were formed by the side-side assembly of the HAP needlelike crystals along their *c*-axes. Reproduced with permission from [66]. Copyright 2007, American Chemical Society.

simple amino acid molecules like glycine (Gly)^[66] or biomolecules like amelogenin, which can form self assembled structures in aqueous solution by themselves.^[66–68] ACP was found as a layer on a HAP core in 5 nm spheres, which subsequently form polycrystalline colloidal aggregates of ca. 30 nm.^[66] These aggregates deaggregate and reorganize to linear assemblies when dispersed in water containing Gly (Fig. 6a, b).

The crystallographic directions of the HAP particle cores in the linear ACP assembly are disordered. Upon ACP transformation to HAP, the HAP cores become aligned into crystallographic direction and form HAP single crystals ca. 5 nm wide and 80 nm long. It was argued that the ACP phase might have liquid character allowing for rotation of the HAP particles into crystallographic register.^[66] However, such liquid phase, if it exists, can be expected to be viscous slowing such diffusional processes down. Alternatively, ACP could simply dissolve in water and the HAP nanoparticles, which are in very close proximity of ca. 1 nm (Fig. 6b) then rotate into their crystallographic register. This would require an attractive force like van der Waals attraction and a weak repulsive force, which could be electrical charges. Finally, the HAP nanoparticles fuse to form the elongated single crystals, which themselves now serve as building units for the mesocrystals with enamel-like structure, which are observed after 2 months (Fig. 6c). This assembly could be accelerated to 3 days by amelogenin as modifier.^[66] An explanation for the ordered assembly of these nanoparticles was suggested by molecular modeling. The introduction of Gly raised the energy of the HAP (001) face greatly and reduced that of (100) slightly. Thus, HAP (001) faces became unstable in the Gly solutions and the ordered assembly along the *c*-axis was preferred to minimize the total interfacial energy of the assembly in the solutions.^[66]

Nancollas and coworkers have looked in more detail on the role of amelogenin in HAP mesocrystal formation in tooth enamel-like structures.^[67,68] They showed that amelogenin dramatically accelerates the nucleation of HAP by decreasing the induction time in a dose dependent manner, suggesting that in the presence of amelogenin as substrate, the charged COOH-terminal region

may be important in the specific apatite/protein binding. This promotes heterogeneous nucleation or binding of nucleation clusters.^[67,68] Furthermore, HAP attached amelogenin oligomers will reduce random Brownian motion-driven particle collisions and might promote attraction of such nanoparticle hybrids. Jiggling of nanoparticles in close proximity by Brownian motion may then allow for adjacent particles to rotate and find the low-energy configuration represented by a coherent particle–particle interface as described in the oriented attachment mechanism.^[4–6]

The protein ovalbumin was found to be a multifunctional ligand in CaCO_3 crystallization, and a multistep mineralization reaction was revealed applying small angle neutron scattering (SANS).^[70] This nicely shows the potential of macromolecules to control inorganic precipitation reactions. Mesocrystals were proposed as intermediates. However, as the mutual order between the nanoparticles building up the superstructure was not confirmed, it is not clear if these nanocrystal assemblies are mesocrystals in the meaning of their definition in Section 1. As mesocrystals are structural intermediates between single crystals and unoriented polycrystals,^[15] it may be difficult to reveal the mutual order, but nevertheless, this order is a requirement in a mesocrystal.

4. Mesocrystals from Functional Materials

Mesocrystals from functional materials are highly attractive due to the emergent properties of mesocrystalline materials, such as single crystal-like behavior, high crystallinity, high porosity and inner connection bridged by organic components and/or inorganic nanocrystals. Such property combinations in a single material are unrivalled compared to amorphous, polycrystalline, and single-crystalline materials. The role of mesocrystal structures for the mechanical improvement in biominerals was discussed before (Section 3). However, it is clear that a number of other desirable properties can be obtained with a mesocrystal architecture, which cannot be reached for the same material in amorphous or single crystalline form or as an unordered polycrystalline aggregate. For example, a material, which is catalytically active in its single crystalline phase can be very advantageously used in the form of a mesocrystal. It combines high crystallinity with small particle size, high surface area and high porosity of the mesocrystal as well as good handling since the mesocrystal has a size in the micrometer range. It can therefore be easily separated by conventional filtration or centrifugation. This is clearly advantageous over nanoparticles, which are much more difficult to separate or have potential toxicity problems. This is just one example to outline the new possibilities offered by the mesocrystal architecture toward advanced materials design.

It is therefore not surprising that the last three years have witnessed an emergence of mesocrystalline superstructures

being prepared for a wide range of functional materials. While the optimization of synthetic strategies to synthesize mesocrystalline materials has been reported by many groups, increasing effort is invested in the exploration of potential mesocrystal material applications. The progress has in turn led to an increasing understanding of the formation mechanism of mesocrystals. In this section, we survey mesocrystals synthesized from functional materials as diverse as amino acids, sodium ibuprofen, and many inorganic materials, with an emphasis on how the properties of these products can be altered by the mesocrystal architecture. The goal is to enhance performance or achieve new prospects in desired applications as diverse as reaction precursor and intermediate, catalytic, optical, electronic, drug, and drug delivery applications. We begin our survey with metal oxides because the largest number of mesocrystals (zinc oxide, magnetite, cerium oxide, tungsten oxide, and manganese oxide) has been produced for this family of materials. We then turn to mesocrystals from binary metal oxides (bismuth vanadate, bismuth tungstate, lead titanate, strontium titanate, potassium/sodium niobate, and calcium molybdenate) and other inorganic materials (lanthanide fluoride, copper oxalate, gallium phosphate, cadmium sulfide/selenide, lead sulfide, and silver). Finally mesocrystals made from organic molecules will be discussed. The potential applications enabled by these mesocrystals will also be briefly introduced.

4.1. Metal Oxide-Based Mesocrystals

4.1.1. Zinc Oxide (ZnO)

In terms of wide bandgap (3.37 eV at room temperature) and large exciton energy (60 meV), ZnO is a promising material for different purposes ranging from electronic, optic, piezoelectric, pyroelectric, photocatalysis, to chemical sensor applications. Also, ZnO has a great potential as a biodegradable and possibly biocompatible material suitable for medical and biological uses. Improved recognition of the role of polymers, surfactants, and ionic liquids (ILs) in crystallization has greatly advanced the popularity of using ZnO nanoparticles as building blocks for the fabrication of two and three-dimensional superstructures.

Because of its noncentrosymmetric structural anisotropy, ZnO single crystals normally grow along the [001] direction. One way in which the growth of ZnO crystals along the [001] direction may be suppressed is through the introduction of organic additives as stabilizing agent. The binding affinity of a stabilizing agent varies from one crystal face to another. The preferential adsorption of stabilizing agents on a particular face can thus hinder the growth of this face, thus providing a means for controlling the final shape of a crystal. Although it is well-documented that the introduction of stabilizing agents often leads to twinned crystal platelets or bicrystals with single crystalline structures,^[71] recent studies have shown this is not always the case. The presence of organic additives may also give rise to the formation of ZnO mesocrystals terminated with {001} faces. The high population of polar Zn-(001) planes in these products is potentially advantageous for applications in photocatalysis, such as H₂O₂ synthesis and phenol decomposition. There are two types of organic additives that can contribute to the stabilization of ZnO nanocrystallites and their

further aggregation to ZnO mesocrystals with stabilized {001} faces: surfactants and polymers.

For example, ZnO superstructures with sheet, platelet, and ring shapes, which demonstrate characteristics of mesocrystals, have been prepared by using CTAB as template.^[72] Taking advantage of micelle aggregation and phase transformation with temperature change, Lee and coworkers worked out a two-step self-organization process for the formation of these ZnO mesocrystalline superstructures. The key to producing ZnO mesocrystals is the formation of zinc hydroxyl double salt (Zn-HDS) mesocrystals as intermediate. Zn-HDS mesocrystals are formed by CTAB-modified self-assembly of Zn-HDS nanoparticles at room temperature. The SAED pattern taken from a single Zn-HDS sheet shows a single crystal-like diffraction with elongated spots. High-resolution transmission electron microscopy (HRTEM) image indicates that an individual Zn-HDS sheet is composed of hexagonal nanocrystals with a size of about 3 nm. The parallel lattice fringes of all these nanocrystals suggest a three-dimensional aggregation of nanoparticles aligned along the same crystallographic orientation with a slight mismatch, agreeing well with the highly ordered SAED pattern. The space between nanocrystals results in low contrast areas between the lattice-fringe-bearing regions. Notably, the decomposition temperature of Zn-HDS decreases to 50 from 130 °C of the bulk counterpart obtained without CTAB. CTAB plays a multiple role in the process, including widening the interlayer spacing of Zn-HDS, introducing defects and therefore resulting in decomposition at a significantly lower temperature, and acting as a soft template to mediate the transformation of Zn-HDS to ZnO. Zn-HDS undergoes a transformation of to ZnO hexagonal microsheets at 50 °C. The sheet is composed of hexagonal nanoplatelets sharing one common crystallographic orientation with edge dislocation. The inhibition of crystal growth along the [001] direction due to the adsorption of CTAB was proposed as a possible mechanism for the formation of sheet-like ZnO mesocrystals. When the reaction temperature was increased to 100 °C, ZnO mesocrystals with hexagonal platelet and ring morphologies were obtained. The platelet is composed of aligned ellipsoidal ZnO particles in a width of about 40 nm and a height about 80 nm. The nanoparticles share one common crystallographic orientation but retain free space between each other.

The organic additive can also be a functionalized polymer. Xu and coworkers prepared ZnO mesocrystal nanodisks in the presence of carboxyl modified polyacrylamide (PAM)-COOH.^[73] In an individual disk, there are two parts stacking to each other back-to-back. Scanning electron microscopy (SEM), SAED, and transmission electron microscopy (TEM) investigations indicate that each part consists of nanoparticle building blocks, demonstrating typical characteristics of mesocrystals. It is assumed that every disk is composed of dense polymer stabilized primary nanocrystals with the highest density of defects and the highest amount of occluded polymer at the center of the disk. Therefore, the central part of each disk has the largest tendency to dissolve.

More recently, Mo et al. prepared ZnO hollow microtubes by using poly[(acrylic acid)-co-(maleic acid)] sodium salt (PAMS) as template molecule.^[74] HRTEM investigation indicated that nanoplates growing along the [001] direction assemble layer-by-layer and form an individual tube. Embedded nanoplates

between other nanoplates imply the existence of many interstices in the microtubes. SAED pattern studies discovered a single crystal-like diffraction for individual tubes. It has been suggested that thermolysis of a zinc citrate-ethylenediamine complex and hydrothermal oxidation of zinc foil may produce nascent ZnO nanoclusters. ZnO nanoclusters and PAMS then spontaneously assemble into composite nanoclusters, which could further coagulate to multimers in order to minimize the total surface energy. Subsequently, mesocrystalline microtubes would be generated from the metastable composite multimer by Ostwald ripening. In this case, the driving force for the layer-by-layer self-assembly of the nanoplates into tubular mesocrystals is assigned to the oriented attachment and the strong dipole-dipole interaction induced by the polar surface of the nanoplates. Because the mesoscale interstices may allow small molecules to penetrate the tube wall, the tubular ZnO mesocrystals may have applications in drug transportation and as micro-reactors. After loading with noble metal nanoparticles, it could also be used as catalyst support.

Polymeric additives may play a more eminent role in directing the assembly of ZnO nanocrystallites into mesocrystalline aggregates and even exerting changes in optical properties. Despite noncentrosymmetric structural anisotropy, it is difficult to assemble ZnO nanocrystallites along the [001] direction into oriented aggregates with single crystal properties but spherical morphology. Relying on the presence of poly(vinylpyrrolidone) (PVP) in a mixture of *N,N*-dimethylformamide (DMF) and water, Zeng and coworkers obtained spherical ZnO mesocrystals from $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ using a solvothermal method.^[71] The diameter of the ZnO spheres varied from about 100 nm to several micrometers. Each sphere comprises two hemispheres with the (00-1) plane as a symmetric junction between the upper and lower parts. The ZnO spheres are indeed aggregates of nanocrystallites oriented along the [001] direction and are apparently porous (Fig. 7). The shape control was ascribed to the templating effect of PVP although the exact role of the polymer is not completely clear. PVP may also deactivate the primary ZnO nanocrystallites from rapid growth and even coordinate to the Zn^{2+} -rich (001) planes of ZnO crystals by carbonyl groups and thus prevent their further growth. In the process, DMF not only plays a role as reaction medium but also may produce $\text{NH}_2-(\text{CH}_3)_2^+$ by hydrolysis under solvothermal conditions. The positive ions could further stabilize the (00-1) planes of ZnO crystals during nucleation and twinning. Interestingly, a charge-transfer from the organic phase to the inorganic phase happens as revealed by X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR) measurements. The new donor energy levels created by the

Figure 7. a) UV-vis spectra of ZnO/PVP samples demonstrating the red shift of the ZnO/PVP sample. b) The $(\alpha E_{\text{photon}})^2$ versus E_{photon} plots based on the spectral data of (a). c) A schematic illustration for the crystallographically oriented ZnO nanocrystallites (shown as small white spheres; arrows indicate the [001]-direction of wurtzite ZnO), which are surrounded by PVP matrix material (indicated by gray color background) in a hemisphere. Reproduced with permission from [71]. Copyright 2007, American Chemical Society.

charge-transfer below the conduction band allows the absorption of smaller energy photons, leading to red shift of UV-absorption upon the presence of PVP in ZnO/PVP spheres (Fig. 7a).

The composite can be used as an *n*-type modifier doped ZnO mesocrystal. In addition, the porous structure of the composite makes it promising as a material in engineering ordered hexagonal closed-packing structures of spheres for photonic purposes. Composite thin films can further be made through self-assembly of these freestanding spheres by simple coating with the as-prepared suspensions. Additional modification is possible through removal of the PVP phase via thermal treatment and introducing new components to the interior spaces or exterior surfaces.

In addition to organic additives, the mesocrystalline assembly of ZnO nanocrystallites can further be facilitated through the selection of the reaction medium. IL, ethanol, and acetonitrile can all serve as the reaction medium to enable the mesoscale aggregation of nanocrystallites. Among the three options, ILs represent a unique reaction medium as it exhibits liquid crystal-like properties with ordered domains separated by internal interfaces. For example, an IL can serve as precursor, as reaction medium, and simultaneously as the template for the final product when components of the IL are appropriately chosen. Recently,

Taubert and coworkers reported the preparation of ZnO mesocrystals by using IL as solvent–reactant–template.^[75] Their work extends the role of IL in crystallization for the first time from morphology tuning to structural engineering combined with improvements in properties. As demonstrated in this case, hollow ZnO mesocrystals were produced in tetrabutylammonium hydroxide (TBAH) through the precipitation and aggregation of ZnO nanoparticles on the wall of the glass vessel under reflux at 100 °C. TEM and the single crystal-like SAED pattern of an individual crystal indicate that it is an ordered aggregate of a few single nanocrystals with a diameter of 10 to 50 nm. Similar to electric fields driving the growth of calcite mesocrystals in the presence of poly(styrene sulfonate) (PSS)^[36] and fluoroapatite mesocrystals in gelatin matrices,^[23,76] the intrinsic electric fields of the polar ZnO lattice is speculated to drive the assembly of primary nanoparticles to form ZnO mesocrystals in this case. Pores and channels in the crystals are observed with diameters of 3 to 10 nm. Compared to the commercial ZnO powder, ZnO mesocrystals grown in ILs possess a larger surface area of 34 m² g⁻¹. Amazingly, only green emission photoluminescence (PL) can be detected for an individual mesocrystal with size smaller than 5 μm under an excitation wavelength of 325 nm with a HeCd laser at room temperature (Fig. 8). The broad band appeared at around 2.2 eV ($\lambda = 560$ nm). No band-edge emission in the near UV around 3.3 eV (around 380 nm) can be observed from the PL spectrum measured for the mesocrystal. Decreasing the measurement temperature to 3.5 K can yield an emission band centered at 2.2 eV with an increased intensity and much smaller peak width. It is still the only detectable PL of the ZnO mesocrystal. No UV emission was observed. In general, the room temperature PL spectra of ZnO materials are characterized by both the UV emission and the green band emission. The green emission has been attributed to a deep-level emission, resulting from the recombination process of a photo-generated hole with an electron occupying the singly ionized oxygen vacancy in ZnO.^[77] The stronger the intensity of the green luminescence, the higher density of singly ionized oxygen vacancies is. Unlike the previously reported green emission ZnO nanostructures obtained via low-temperature fabrication processes, the presence of pores and channels in ZnO mesocrystals enables a predominant change in optical properties of the crystals. The hollow morphology and the high density of defects generated by nanocrystalline building blocks during aggregation are anticipated to be useful for catalysis.

Taking the unique combination of slow reaction rates with the stabilizing effect of organic species into consideration, Niederberger and coworkers focused on nonaqueous sol–gel processes in organic solvents and found a method to allow the formation of ZnO mesocrystals specifically without the addition of water. The synthesis was carried out in anhydrous acetonitrile at 100 °C with zinc acetylacetonate as an oxygen-containing precursor.^[78] As acetonitrile is an oxygen-free solvent, the acetylacetonate ligand obviously serves as oxygen source by aminolysis for the formation of ZnO. The particle morphology includes spheres and well-faceted shapes with a size of 15–85 nm. HRTEM investigation of particles demonstrated an internal composite structure with defects and pores formed by fusion of a large number of nanocrystallites. Every particle shows single-crystal like diffracting behavior. Unfortunately, the lack of any functional character-

Figure 8. PL spectrum of hollow rods mineralized with 10 mg of zinc acetate/g of TBAH. a) Spectrum collected from an ensemble at room temperature, b) spectrum collected from one crystal at 3.5 K. Reproduced with permission from [75]. Copyright 2008, Wiley-VCH.

ization of the as-synthesized ZnO mesocrystals makes it impossible to compare their properties with those formed by aqueous methods.

An alternative way to gain control over the aggregation of primary ZnO nanocrystallites in a synthetic crystallization process was demonstrated by Chen and coworkers.^[79] Rather than using organic additives or IL and acetonitrile, they were able to prepare mesocrystalline ZnO disks from zinc acetate and hexamethylenetetramine by a solution reaction at 70 °C in excess ethanol. TEM studies revealed that the obtained circular disks are aggregates of ~20 nm ZnO nanoparticles and mesoporous. The circular disk morphology was ascribed to the integrated effect of the weak polarity of ethanol and the high pressure of ethanol vapor in the sealed flask during reaction. The former may promote the isotropic growth of ZnO, whereas the latter may inhibit it. Strong evidence that the aggregation could agree quite well with the definition of a mesocrystal was demonstrated by uniform crystallographic orientation of adjacent nanoparticles, observable misalignment among adjacent nanoparticles, and single-crystal scattering behavior of individual disks. Sintering the mesocrystalline ZnO disks by calcination at 800 °C then produced hollow ZnO pellets with interconnection. The pellet is aggregated by ~100 nm grains transformed from primary nanocrystals through melting and recrystallization. Capillary effects, which are produced due to the mesoporous structure of ZnO disks, play an important role in the formation of holes in the sintered pellets. As mesocrystalline ZnO disks and porous

ceramics possess relatively high surface area, they hold promise in sensor and catalysis applications.

4.1.2. Tungsten Oxide

In line with the effectiveness demonstrated by nonaqueous sol-gel processes in the formation of ZnO mesocrystals, WO₃ mesocrystalline nanoplatelets were synthesized simply by reacting tungsten chloride with benzyl alcohol (BA) at 100 °C.^[80] The alignment of primary nanocrystallites in the pseudo-single crystalline platelet is nearly perfect. In addition to SAED and HRTEM, Fourier analysis provides more detailed evidence for defects present in the superstructure, such as single dislocations as well as larger zones of misalignments of several planes. Niederberger and coworkers suggested that the formation of the two-dimensional arrangement of the WO₃ nanoparticles occurs by oriented attachment^[4,6] of primary crystallites. However, some of the oriented particles misaligned with respect to each other.

Upon the addition of deferoxamine to the tungsten chloride solution in BA, an organic-inorganic hybrid material with hexagonal mesostructure forms.^[80] The hybrid material consists of tungsten oxide single-crystalline nanowires grown along the [010] direction with a sheath of benzaldehyde and deferoxamine molecules. The interwire distance increases with reaction temperature, as a consequence of the increase in diameters of the nanowires from about 0.9 nm at 100 °C to 1.3 nm at 175 °C. Deferoxamine contains three hydroxamic acid groups which favor the formation of polynuclear complexes with the molar excess of tungsten relative to deferoxamine. It was assumed that the assembly of nanowires into mesostructures is driven by van der Waals interactions and the potential amide-amide interactions given by the deferoxamine molecules. The coordination of a large number of benzaldehyde molecules to Lewis acid sites on the tungsten oxide nanowire surface provides an additional factor for the stabilization of the overall structure by lowering the surface energy.

In addition to providing oxygen responsible for the formation of WO₃ through reduction to benzaldehyde, BA can also serve as a coordinating reaction medium as monodentate ligand. The combination of coordinating and solvent effects allows opportunities for an elegant control over WO₃ crystal growth in the nonaqueous sol-gel process solely by the complexation of BA solvent with additional ligands or changing the precursor. For example, upon the addition of 4-tert-butylcatechol in small amount, a lamellar organic-inorganic hybrid material with the interlamellar distance of 1.6 nm forms.^[81] Instead of platelets formed in pure BA solvent, only nanorods with diameters of 35–40 nm and length ranging from 50 to 800 nm were observed. Similar lamellar nanostructures were observed when pyrocatechol or nordihydroguaiaretic acid was added to BA. Based on their investigation of the ligand effects, Niederberger and coworkers proposed a model for the formation of lamellar nanostructures obtained in the BA-catechol solvents: BA molecules stabilize the exposed planar surfaces and space their assembly, whereas catechol groups bind preferentially on the high surface energy corners and edges of the nanoplatelets due to the strong binding of their bidentate ligands rather than intercalate between the lamellae. Moreover, switching from BA to 4-tert-butylbenzyl

Figure 9. Dependence of the tungsten oxide sensor signal on NO₂ concentration in humid air (50% r.h. at 25 °C) (operating temperature of the sensors: 225 °C. Reproduced with permission from [82]. Copyright 2006, Royal Society of Chemistry.

alcohol (4-tert-bBA) solvent can induce the self-organization of an organic-inorganic hybrid superstructure on two levels of hierarchy. The hybrid material demonstrates a ribbon-like morphology with diameter of 50 nm to 1 μm and length up to 10 μm. However, no lamellar mesostructure but a less ordered mesoscopic structure was observed with an increase in *d*-value of the first reflection in the XRD pattern from 1.6 to 2.2 nm. The polarization interaction of the crystalline building blocks, which may be stabilized by adsorption of 4-tert-bBA, was suggested as the driving force for the highly ordered assembly of nanoplatelets over a large length scale and the hierarchy of two levels.

Following the purpose of fabricating gas-sensor devices, tungsten isopropoxide was also used as precursor instead of tungsten chloride.^[82] WO₃ nanowires, which were synthesized from tungsten isopropoxide in BA, have a typical length in the range of 300–1000 nm and width between 20 and 100 nm. The XRD pattern demonstrates a mesoscopic structure with a *d*-value of the first reflection at 1.9 nm. The deposited WO₃ nanowire film fabricated by drop-coating and calcination is insensitive to CO in the concentration of 1–10 ppm but shows a high signal at a NO₂ concentration of 50 ppb (Fig. 9). This behavior was correlated with high surface area, good crystallinity, and porosity of the WO₃ mesocrystals, which provides good accessibility.

4.1.3. Manganese Oxide

Birnessite-type manganese oxide (BMO) nanoflakes have been synthesized in an aqueous solution containing PAA.^[83] The flakes are less than 100 nm in width and 10 nm in thickness. Each flake is made up of a mosaic structure of nanocrystals of 2–3 nm in size. To form the layered structure of BMO, sodium ions and/or water molecules intercalate between two-dimensional monolayers of edge-shared MnO₆ octahedra. Imai and Oaki suggested that PAA molecules coordinate to manganese species and/or interact with sodium, resulting in the control of crystal structure and morphology of the nanoflakes with mosaic interiors. They further demonstrated the synthesis of cobalt hydroxide nanoflakes with mosaic interiors by the same approach in the presence of poly(ethyleneimine). In the latter case, the formation of

mesocrystals depends on self-assembly of primary nanoparticles in a highly organized fashion. However, no isolated nanoparticles as the building blocks were observed in their study. The emergence of mosaic and oriented architecture can be attributed to inhibition and restarting of crystallization with the association of polymers. But the exact reason for the confinement of nanocrystals with a size of 2–3 nm is still unknown.

4.1.4. Cerium Oxide (CeO_2)

CeO_2 is an important component of automobile combustion catalysts for its role in oxygen storage and release. By using oleic acid as stabilizing agent, CeO_2 nanocubes bound by six {200} planes have been synthesized from $\text{Ce}(\text{NO}_3)_3$ through hydrolysis and oxidation in water/toluene. A bimodal size distribution was found for the nanocubes, especially at high concentration of $\text{Ce}(\text{NO}_3)_3$. The assembly of regular 2D patterns of nanosized particles with interparticle spacings is accomplished by the size increase in larger nanocubes with increasing the oleic acid/ $\text{Ce}(\text{NO}_3)_3$ molar ratio. For example, cubes as large as 50–100 nm in size can be obtained at the ratio of 10, whereas small-sized nanocubes are single crystals with an average size of about 4 nm. The large-sized nanocubes show single-crystalline nature together with the presence of pits, displacements, dislocations, and roughness, as evidenced by HRTEM and SAED investigations. More importantly, {200}-oriented monolayers of ceria nanocubes and even {200}-enclosed nanorods with length direction along [100] can be obtained by evaporating the nanoparticle solution in a mixed solvent of toluene and ethanol. Yang and Gao ascribed the former to 3D nanoparticle arrays and the latter could be due to oriented attachment-based anisotropic growth.^[84] The dipole–dipole interactions from the {200} faces may be the common driving force for the two scenarios. In this case, both the large-sized nanocubes and their 3D assemblies can be regarded as mesocrystals. Because of the dipole moment perpendicular to the {200} family, the {100} terminated surfaces of ceria are less stable, but more active than other facets as catalytic reaction sites. In view of the high density of {200} faces, oriented assemblies of CeO_2 nanocubes should be of significance in diverse applications ranging from catalysis to nanoparticle dopant-incorporated semiconductor devices and phosphors.

4.1.5. Colloidal Magnetite (Fe_3O_4) Nanocrystal Clusters

The synthesis of water soluble Fe_3O_4 nanocrystals with superparamagnetic properties, has been a popular subject of research in recent years due to their biocompatibility and stability under physiological conditions as targeting transporter in biomedical applications. Given their size as small as 10 nm, magnetite nanocrystals have a too low magnetization to be separated or controlled by a magnetic field. Increasing the size of Fe_3O_4 nanocrystals can increase their saturation magnetization, how-

ever, dispersion of Fe_3O_4 nanocrystals in water is troubled by the superparamagnetic–ferromagnetic transition at a domain size of ~ 30 nm for Fe_3O_4 .

In order to obtain increased magnetization while retaining the superparamagnetic properties of magnetite nanocrystals, a possible way would be to organize Fe_3O_4 nanocrystals as a mesocrystal. By using a high-temperature hydrolysis reaction starting from a mixture of FeCl_3 and PAA in diethylene glycol (DEG), Yin and coworkers developed a short cut to this goal.^[85] The as-obtained Fe_3O_4 nanoparticles are monodisperse mesocrystals with well-controlled size from ~ 30 to ~ 180 nm. Each mesocrystal is composed of ca. 6–10 nm nanocrystallites with the same crystal orientation. XRD measurement further evidenced that the primary nanocrystals do not grow significantly with increasing size of the mesocrystals when the rate of hydrolysis was improved with NaOH. A two-stage growth model, in which primary nanocrystals nucleate under supersaturation and then aggregate into mesocrystals, was suggested for the growth of the Fe_3O_4 mesocrystals. In this example, PAA plays a dual role. It can first stabilize Fe_3O_4 nanocrystals through the coordination between carboxylate groups and iron cations and via the uncoordinated carboxylate groups, PAA makes the crystals highly water-dispersible. Single-crystal like SAED diffraction patterns with slight misalignment were observed for individual mesocrystals. Most notably, the mesocrystal architecture appears to suppress the undesired superparamagnetic–ferromagnetic transition. As a consequence of this suppression, Fe_3O_4 nanocrystal clusters show superparamagnetic behavior at room temperature though their size exceeds 30 nm (Fig. 10) and their magnetization is much stronger than that of single Fe_3O_4 nanodots. The superparamagnetic properties, high magnetization, and high water dispersibility make colloidal Fe_3O_4 mesocrystals ideal candidates for drug delivery, bioseparation, and magnetic resonance imaging. This example shows impressively that a mesocrystal architecture can yield physical properties which would be impossible for the given particle size. Similar

Figure 10. Comparison of hysteresis loops of 53, 93, and 174 nm Fe_3O_4 colloidal nanocrystal clusters and a reference sample of 8 nm nanodots. Inset: magnetic moment μ per cluster (or dot) in a logarithmic plot. Reproduced with permission from [85]. Copyright 2007, Wiley-VCH.

considerations are certainly applicable to other materials with size dependent properties like quantum dots or metal nanoparticles.

4.2. Mesocrystals Based on Functional Binary Metal Oxides

4.2.1. Bismuth Vanadate (BiVO_4)

As a layered structured semiconductor, BiVO_4 , especially of monoclinic phase, shows activity for photocatalysis under visible light irradiation, such as water splitting and pollutant decomposition. Wang and coworkers prepared monoclinic BiVO_4 mesocrystals from $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$ and NH_4VO_3 by a facile additive-free aqueous reaction at 80°C .^[86] The morphology of BiVO_4 mesocrystals can be tuned by adjusting the pH value of the reaction solution. For example, mesocrystals obtained at pH 6.5 exhibit a flower-like morphology and are built up by rods in a well-organized manner. Each rod is composed of nanoparticles with a size of about 100 nm. SAED pattern and HRTEM image confirmed the single crystalline nature of the primary crystals. Morphology evolution indicated a three level growth model. Primary particles first grew into rod-like subunits along the [010] direction. Subunits then aggregate along eight $\langle 111 \rangle$ directions, leading to the formation of an octapod morphology. Subsequently, the well-defined flower-like mesocrystals form by a further growth of the rods along the [010] direction. Minimization of the total surface energy of disordered primary particles was suggested as the driving force for the self-assembly. Notably, mesocrystals can also exhibit an external morphology of cubic symmetry, formed by rods. This example demonstrates that the crystallization process of a mesocrystal may result in the formation of superstructures with an external morphology not related to the primary crystal structure, even in the absence of any additive. In a separate report, it was demonstrated that single crystalline monoclinic BiVO_4 microtubes, which were synthesized by reflux at 80°C , demonstrate a higher photocatalytic activity than that of monoclinic BiVO_4 synthesized by a high-temperature solid-state reaction.^[87] It is reasonable to expect a high catalytic activity of the as-synthesized monoclinic BiVO_4 mesocrystals due to their high surface area and single crystalline building units.

4.2.2. Bismuth Tungstate (Bi_2WO_6)

Like BiVO_4 , Bi_2WO_6 is also a photocatalyst responsive to visible light. Using a hydrothermal synthesis protocol and PSS as additive, Liu and Yu prepared Bi_2WO_6 flower-like assemblies with two level hierarchy at 180°C .^[88] The intermediate obtained after 2 h is aggregates of 10 nm nanoparticles with a common crystallographic orientation and voids. A 3D assembly obtained after 18 h is constructed by 2D mesocrystal layers with a size in the range of 2–3 μm . An individual layer consists of a large number of packed square-shaped nanoplates with an average side length of 50 nm and a thickness of less than 20 nm. Individual nanoplates show single crystal features and side-to-side crystallographic fusion of adjacent nanoplates. A bimodal mesoporous structures can be detected. One peak with mesopore size of 4 nm corresponds to the voids within a layer and another peak with mesopore size of 40 nm is understood as the interspace between stacked layers. In this case, PSS may stabilize amorphous

Figure 11. UV-visible diffuse reflectance spectra of Bi_2WO_6 flowers and leaves. Reproduced with permission from [88]. Copyright 2008, Academic Press Inc. Elsevier Science.

nanoparticles grown from the supersaturated solution and further induces their aggregation by surface binding, interparticle bridging, and depletion flocculation. The pendent chains of PSS adsorbed on the particles and the anisotropy of Bi_2WO_6 nanoplates could contribute together to the assembly from nanoplates to 2D layers. Yu and coworkers suggested hydrophobic interactions between PSS-adsorbed surfaces as the driving force for the layer-by-layer stacking of 2D layers to 3D structures at the last stage. This explanation is a result of failing to consider the charged character of PSS and charge interaction between PSS-adsorbed Bi_2WO_6 surfaces. In comparison with the absorption of Bi_2WO_6 leaf-like product obtained without the addition of any additives, Bi_2WO_6 mesocrystalline assemblies demonstrate a 30% enhancement of absorbance (Fig. 11), which may increase the photocatalytic activity of Bi_2WO_6 . Because of the stronger absorbance, Bi_2WO_6 mesocrystalline assemblies provide extended optical paths for multiple scattering. This example sheds light on the design of semiconductors with improved photo-reactivity and applications depending on the absorbance of photons.

4.2.3. Calcium Molybdate (CaMoO_4)

By using a microemulsion-mediated approach and the addition of CTAB, Qian and coworkers synthesized CaMoO_4 and SrMoO_4 mesocrystals with hollow structure in *n*-octane/*n*-butanol/water.^[38] SAED and HRTEM investigations of the flower-like architectures demonstrate mesocrystalline characteristics. The 3D mesocrystals are radial with “arms” about 2–3 μm in length. These arms are constructed by nanoparticles with size of about 150–300 nm. In this case, the growth of CaMoO_4 mesocrystals was speculated through a combined process of nucleation, aggregation, and ripening. At the nucleation stage, the microemulsion plays a key role in controlling the reaction rate and avoiding the crystallographic fusion of primary nanoparticles to a single crystal. The interaction of CTAB with the inorganic surface significantly influences shape and size of the primary nanopar-

ticles. As a result, nanoparticles were observed in 1 min. They are regarded as core-shell nanoparticles with an inorganic core and an organic surfactant shell. The hydrophobic interaction between surfactant molecules on the surface of these nanoparticles was suggested as the driving force for the assembly of CaMoO_4 mesocrystals at the aggregation stage. During the process, CTAB is inevitably included in the mesocrystals. Polydispersity and stacking defects of nanoparticles in the self-assembled structure are responsible for larger numbers of pores between the nanoparticles. At the third stage, the surfaces of CaMoO_4 mesocrystals turn scabbled owing to Ostwald ripening.

It is worth noting that the synthesized CaMoO_4 and SrMoO_4 mesocrystals are thermodynamically metastable. Changes in reaction temperature and reaction time could destroy the thermodynamic balance between individual nanoparticles which is obligate for the aggregation of nanoparticles to form mesocrystals. On the other hand, it was presumed that the interactions between nanoparticles in CaMoO_4 and SrMoO_4 mesocrystals may decrease with an increase in size. For example, at 160°C and by extending the reaction time from 6 to 24 h, a morphology evolution from CaMoO_4 mesocrystals 3D structures to nanoparticles with truncated octahedral morphology can be observed. A similarly morphology evolution was observed for SrMoO_4 mesocrystals at 160°C after 16 h. Further characterization by TEM is needed to evidence if the subsequent nanoparticles, which evolve from mesocrystals, are single-crystals. The optical properties of the CaMoO_4 mesocrystals show a strong green emission at 480 nm under excitation at 247 nm. The high crystallinity and complex structures could be of significance in luminescence applications.

4.2.4. Strontium Titanate (SrTiO_3)

Upon isotopic substitution, an external stress or doping, SrTiO_3 becomes ferroelectric at low temperature. SrTiO_3 mesocrystal particles with cubic morphology have been synthesized by precipitation from an aqueous gel suspension pre-formed by hydrolyzing TiOCl_2 .^[89] HRTEM and SAED investigations provide strong evidence that the formation of the mesocrystal particles is the result of epitaxial self-assembly of nanocrystals with diameter of 4–5 nm. In each particle, 10^4 – 10^6 nanocrystals aggregate in a highly oriented fashion, giving rise to the formation of a defective mesocrystalline structure with slight misorientations, dislocations, and pores. Dimples and creases can also be observed at the particle surface. In this case, the growth of the mesocrystal particles by the oriented aggregation of small nanocrystals is a spontaneous process and not induced by additives. Buscaglia and coworkers further demonstrated that the addition of sodium citrate can induce the formation of SrTiO_3 spheres with a narrow size distribution. Compared to SrTiO_3 cubic mesocrystals, the spheres show a more defective crystal structure. Nevertheless, the single-crystal like SAED pattern and oriented aggregates of primary nanocrystals with diameter of 4–5 nm were still observed as the typical mesocrystal features. SrTiO_3 mesocrystal particles are anticipated to provide a new strategy for the design of ferroelectric materials.

4.2.5. Ferroelectric Lead Titanate (PbTiO_3)

By hydrothermal treatment of an amorphous PbTiO_3 precursor, a 3–6 μm thick mesocrystal layer with a varying degree of porosity

has been grown on PbTiO_3 or SrTiO_3 substrates in the presence of sodium dodecylbenzenesulfonate (SDBS) as surfactant.^[90] The lower part of the mesocrystal layer is relatively porous, the middle part more dense, and the surface part consists of nanorods growing along the polar [001] direction. The PbTiO_3 rods with tetragonal phase have a square cross-section of 35–400 nm and length up to 5 μm . SEM and TEM studies demonstrate evidence for the construction of PbTiO_3 mesocrystals from smaller rods by loose mutual attachment. Einarsrud and coworkers proposed a two-step-model for the growth of mesocrystal arrays of ferroelectric PbTiO_3 nanorods: an epitaxial layer first forms on the substrate by ion-by-ion growth, followed by the self-assembly of nanocrystals into a mesocrystal layer. The mesocrystal layer can further ripen into arrays of single crystalline nanorods via redissolution–reprecipitation. In this case, the key to control the growth of the in-plane array on substrates, is the similar crystal lattice of PbTiO_3 or SrTiO_3 . For example, when Al_2O_3 was used as the substrate, no layers covering the substrate surface were observed due to crystal lattice mismatch. In addition, polycrystalline PbTiO_3 nanorods or nanotubes, which are fabricated on nanoporous alumina or track-etched polycarbonate by a template-assisted method, tend to stick together after the removal of the templates. The main advantages of PbTiO_3 mesocrystals include single crystal properties of the product, no required template, and the elimination of the template-removal step after the fabrication. PbTiO_3 nanorod arrays are expected to be applicable in studies of nanoscale ferroelectricity.

4.2.6. $(\text{K}, \text{Na})\text{NbO}_3$ -based Mesocrystals

$(\text{K}, \text{Na})\text{NbO}_3$ (KNN)-based lead-free ceramics are environment-friendly piezoelectric materials. They possess a higher Curie temperature and better piezoelectric properties compared to BiTiO_3 .^[91] Owing to the strong dependence of ferroelectric properties on grain size and compositional aspects for piezoelectric ceramics, grain control is very important for property optimization. Recently, Zhen and Li reported a unique abnormal grain growth (AGG) phenomenon they found both in pure KNN and $(\text{Li}_{0.04}\text{K}_{0.44}\text{Na}_{0.52})(\text{Nb}_{0.85}\text{Ta}_{0.15})\text{O}_3$ (LKNNT) piezoelectric ceramics.^[91] At a relatively low sintering temperature (1060°C for KNN and 1100°C for LKNNT), a homogeneous microstructure with grain size of 100 nm–1 μm was observed. When the sintering temperature was increased only by a range of 10 – 20°C , a small part of the grains grew up to 2–3 μm in size due to grain coarsening, while most grains retained their original shapes and sizes. Then, when the sintering temperature was increased to 1100°C for KNN and 1120°C for LKNNT, coarse grains with sizes larger than 10 μm appeared. The core region of the structure is composed of highly parallel nanosized subgrains, whereas the shell region consists of larger subgrains in a similar self-assembled fashion. The whole coarse grains behave like a single crystal with small misorientation. The formation of coarse grains with a core-shell structure in KNN-based ceramics is different from the core-shell grain structure in BaTiO_3 -based ceramics,^[92–94] which results from the concentration gradients of additives. A transformation of the nano-building-block to a typical core-shell grain structure similar to mesocrystal formation via self-assembly was observed both in pure KNN and LKNNT systems. A liquid phase, which was found at high temperature

($\geq 1100^\circ\text{C}$)-sintered KNN system due to the volatilization of alkali metal oxides, was suggested to serve as surfactant during the process. The liquid phase could contribute to sintering by accelerating particle redistribution because of the enhanced mobility and improving the final sample density by capillary forces. As the sintering temperature was increased to 1080°C for KNN and 1110°C for LKNNT, due to the liquid phase-mediated interactions, the formation of self-assembled aggregation clusters of nanosized grains was observed. However, only a further $10\text{--}20^\circ\text{C}$ increase in sintering temperature can induce a grain growth transformation. As a result of the classical grain growth, self-assembled aggregation clusters of nanosized grains finally turned to core-shell structures observed in both systems. Following the occurrence of the unique AGG with the formation of mesocrystals with a core-shell structure, KNN systems show the highest densities and the highest dielectric constants along with the lowest dielectric losses compared to counterparts sintered at relatively low temperature. But their piezoelectric coefficient d_{33} decreases. A further study on the relationship between their piezoelectric properties and mesocrystal intermediates will be of interest to improve the properties of lead-free piezoelectric ceramic materials by structural control.

4.3. Mesocrystals of Other Functional Inorganic Materials

4.3.1. Cerium Fluoride (CeF_3)

Lanthanide (Ln) fluoride attracted much attention because of its higher luminescence quantum efficiency compared to oxides. Very recently, Li and coworkers synthesized LnF_3 and Ln-doped LnF_3 nanocrystals by an IL-based “all-in-one” route. ILs applied in the study include 1-octyl-3-methylimidazolium hexafluorophosphate (OmimPF_6), 1-octyl-3-methylimidazolium tetrafluoroborate (OmimBF_4), and 1-butyl-3-methylimidazolium hexafluorophosphate (BmimPF_6).^[95] These ILs serve as reaction media, templates as well as fluoride source through hydrolysis with the hydration water molecules of the metal precursors, similar to TBAH in the study of ZnO mesocrystals.^[75] The formation of LnF_3 nanocrystals with 3D structures was suggested as a result of nanoparticle aggregation through a nonclassical crystallization process. Both TEM image and single-crystal like SAED pattern of CeF_3 nanocrystals obtained in OmimPF_6 suggested the typical mesocrystal character, even if no mesocrystal structure has been claimed by Li and coworkers in their report.^[95] However, a proof is still missing to ascertain whether the other LnF_3 also possess mesocrystal character. The effect of doped ions varies with the components. With the addition of Tb^{3+} , CeF_3 nanodisks transformed to donut-shaped nanostructures with larger size. However doped ions have no effect on the morphology and size of LaF_3 nanocrystals. The uniformity of CeF_3 nanocrystals was also influenced by the anions of the ILs. Contrasted to those synthesized in OmimPF_6 , the uniformity of CeF_3 nanocrystals synthesized in OmimBF_4 decreases. Due to the effect of anions, Tb-doped CeF_3 nanocrystals, which were synthesized in different ILs, show quite different luminescence properties. In contrast to the excitation spectra of Tb^{3+} -doped CeF_3 nanocrystals synthesized in OmimBF_4 , that of Tb^{3+} -doped CeF_3 nanocrystals

synthesized in OmimBF_6 exhibit a red shift. For Tb^{3+} -doped CeF_3 nanocrystals prepared in OmimPF_6 , the emission intensity of Tb^{3+} is much lower than that of Ce^{3+} , opposite to the case of the crystals synthesized in OmimPF_4 . These interesting luminescence properties provide new options for redox luminescent switches.

4.3.2. Copper Oxalate

By using hydroxyl-methylpropylcellulose (HPMC) as additive, Bowen and coworkers synthesized copper oxalate mesocrystals.^[96] They proposed a brick-by-brick model for the formation of mesocrystals by the organization of nanoparticles. The roles of HPMC in the process include face selective adsorption and multiple influences on nucleation, nanocrystal growth, as well as aggregation. In a follow-up report of the systematic study on copper oxalate precipitation at moderate supersaturations, they further put forward a core-shell growth model.^[97] A large number of primary nanoparticles can form initially in the supersaturated solution. These particles favor random agglomeration toward a poorly ordered core. On the other hand, subsequent ordered attachment of crystallites at decreasing nanoparticle concentrations leads to the formation of an inner shell with well-aligned nanocrystals with a size of $50\text{--}70\text{ nm}$. SEM and TEM studies support the co-existence of two regimes of aggregation. Particle evolution over 2 weeks demonstrated formation of an outer shell of larger well-cemented crystallites through ripening. The outer shell eliminates the possibility of the appearance of facets with high surface energy, which can be observed in the earlier stages of growth. The core-shell growth mechanism supplements the initially proposed brick-by-brick model very well. Copper oxalate mesocrystals can be transformed to copper or copper oxides without losing the ordered structure.^[98]

4.3.3. Gallium Phosphate (GaPO_4)

As a material developed primarily for the design of high temperature sensors, GaPO_4 is a piezoelectric material of much greater high-temperature frequency stability than quartz sensors. By using a hydrothermal synthesis approach and an amphiphilic triblock copolymer $[(\text{EO})_{106}(\text{PO})_{70}(\text{EO})_{106}]\text{-OH}$ (F127), as surfactant template, Yang et al. prepared GaPO_4 mesocrystals.^[99] The product shows rod morphology. Inter-spaces among nanoparticles are discernable in TEM images, indicating porosity inside the crystals as is typical for mesocrystals. The typical pore size distribution, which was derived from the adsorption branch by Barrett-Joyner-Halenda (BJH) model, ranges from 1.0 to 3.5 nm with a major distribution peak centered at 2.5 nm and an average surface area of $37\text{ m}^2\text{ g}^{-1}$. The product shows ordered structures at the mesoscopic scale. In the small-angle X-ray diffraction spectrum, two diffraction peaks, d_{100} (7.35 nm) and d_{110} (4.9 nm) of the face centered cubic space group, were attributed to the lowered symmetry of the crystal or different orientations of the mesophase domains. On the other hand, the product exhibits a short-range order at the atomic level as a mixed structure of cubic and orthorhombic phases of GaPO_4 . TEM studies revealed that the rods are assembled by a large number of nanoparticles. The triblock copolymer F127 appears to fulfill a critical templating and structure-directing role in the assembly process. At elevated temperature and concentrations higher than the critical micelle

concentration, block copolymer micelles are formed with a hydrophilic (EO)₁₀₆ corona and hydrophobic (PO)₇₀ core. The interaction between Ga³⁺ ions and the active nucleophilic O-sites of (PO)₇₀ fractions is strong enough to chelate and transport Ga³⁺ from the aqueous phase into the hydrophobic core of the micelle as confined environment for the growth of nanoparticles. It was proposed that the interaction between (EO)₁₀₆ fractions could be responsible for the creation of inter-spaces among nanoparticles. In addition to the structure-directing effect of F127, pH is another potential factor in determining the porosity, structure, and size of the final mesocrystals. At high pH (>12.54), rod-shaped GaPO₄ mesocrystals decompose into colloidal nanoparticles. What effect orients the nanoparticles to a mesocrystal is still unknown. The obtained GaPO₄ mesocrystals have the unique advantage of high porosity (pore volume of 60 mm³ g⁻¹). After the removal of the organic template by calcination under mild conditions to keep the high surface area, the resulting GaPO₄ may find potential use as a new high-temperature sensor material.

4.3.4. Mesocrystals Formed by CdS/CdSe Nanorods

CdS and CdSe nanorods provide an example to study the effect of shape on ordered assemblies of nanocrystals and their chemical and physical properties for practical applications in terms of the ability to transport charges along the long axis. Manna and coworkers developed a seeded-growth approach for the synthesis of core-shell CdSe/CdS nanorods with a high homogeneity in shape.^[25] The approach is flexible and the product morphology can be easily tuned by various parameters, such as the diameter of seeds, reaction temperature, and the ratio between precursors and seeds. The resulting CdSe/CdS nanorods can undergo evaporation-mediated self-assembly to form long-range assemblies on substrates or toluene-water interface. For example, when a drop of nanorod solution was deposited on the carbon support film of TEM grids, the formation of mainly lateral alignment and few areas of vertical alignment were observed under TEM. When the process was carried out on the surface of water, larger areas of vertical assembly of nanorods were achieved. This kind of superlattice with oriented alignment can be regarded as mesocrystal formed by the self-assembly of nanocrystals under rapid drying. In addition to substrates or interfaces, an external electric field was also found to have an important influence on the evaporation-mediated self-assembly of core-shell CdSe/CdS nanorods^[25] and CdSe nanorods into

Figure 12. PL from different types of nanorod assemblies. PL spectra of regions of laterally, vertically aligned, and disordered nanorods with aspect ratio = 10 are marked by the open circles. The Gaussian fits of the data shown by solid green lines give 2.06, 2.07, and 2.09 eV as energy peak position for disordered ensemble, vertical arrays, and lateral arrays, respectively. The PL spectra were normalized with respect to their amplitude and shifted vertically for clarity. The insets show corresponding images of the laser backscattering (BS) and PL intensity of regions consisting of disordered, vertically, and laterally aligned nanorod arrays recorded with the confocal setup, and representative TEM images taken from the respective regions (various regions of self-assembled vertically and laterally aligned nanorods were mapped by inspecting the substrate under low magnification TEM). Large areas of vertically aligned nanorods (with respect to the substrate) were observed that could also be spotted under the confocal microscope. The bright areas in the BS images originate from the nanorod ensembles. Reproduced with permission from [25]. Copyright 2007, American Chemical Society.

mesocrystals.^[22] The core-shell CdSe/CdS nanorods are highly fluorescent and exhibit a linearly polarized emission, which was proposed to reach a maximum in the plane perpendicular to the dipole and a minimum in the direction of the nanorod long axis. As a result, regions of vertically oriented rods show almost no linearly polarized emission and a slight red-shift was observed in their PL spectrum with respect to that of areas of disordered alignment (Fig. 12). PL emission collected from areas of

ribbon-like assemblies is much stronger, accompanied by a blue-shift up to 30 meV compared to that of areas of disordered alignment.

Although theoretically predicted and experimentally observed, the need for the corraling of 1D semiconductor nanostructures without an external direction-controlling force is increasing for use as light-emitting diodes. A monolayer of CdS nanorod-bundled polarizer with a thickness in the order of nanometers and area in the order of micrometers could help to meet this demand. In an aim to fabricate arrays of self-bundled CdS, Chou and coworkers considered the possibility of resorting to the direction-controlling effect of a surfactant. Upon capping CdS with tri-*n*-octylphosphine (TOP) and tetradecylphosphonic acid (TDPA), they obtained 2D self-bundled CdS nanorods with an area as large as $2.0 \mu\text{m}^2$.^[29] TEM studies revealed self-assemblies of CdS nanorods with outer edges of leaning bundles and an inner part of hexagonal packing perpendicular to the substrate. Evaporation-induced corraling of nanorods normal to the substrate, might serve as a nucleation site. Then neighboring nanorods assembled in the same direction. In the self-assembly process, intrinsic properties of CdS, nanorod concentration, and the hydrocarbon chains of the surfactants between adjacent CdS rods play important roles. When hexadecylamine was added to replace a large amount of TOP, only randomly packed bundles were observed. In comparison to the dominant defect emission of CdS nanorods in toluene solution, the bundled arrays exhibit nearly defect free optical emission, implying an enhanced electron transport between nanorods.

4.3.5. Mesocrystals Formed by PbS Nanocrystals

PbS is a semiconductor material with a narrow band gap energy and large exciton Bohr radius (18 nm). Yang and coworkers reported the alignment of PbS truncated octahedron nanocrystals to form a mesocrystal structure by using a CTAB-mediated hydrothermal method.^[100] PbS nanocrystals have an average diameter of 180 nm and are enclosed by eight {111} and six {100}. Significantly, the resulting nanocrystals were found to spontaneously aggregate into a mesocrystal structure with orientational ordering by sharing the {100} faces and aligning {111} faces along the same orientation. Compared to {111}, {100} facets have a higher surface energy. As a result, the total surface energy of the single crystal like aggregate is minimized. In this case, dipolar interactions are the most probable reason for the self-assembly process. It was proposed that nanocrystals are driven to attach to the end of the growth patterns when they have the largest dipole moment along the [100] axis. Additionally, CTAB can selectively stabilize {111} as a capping agent. The formation of PbS mesocrystals by the self-assembly of nanocrystals provides a supplemental proof of mesocrystal formation mechanisms as proposed in Section 2. It could find potential applications because of their well-defined symmetries. For example, Raman spectra of the patterns show an unusual peak at 190 cm^{-1} , corresponding to a Raman shift of the surface phonon mode possibly due to the regular symmetry of the patterns. Under higher laser power, a Raman peak at 966 cm^{-1} was clearly observed, indicating that the product is sensitive to laser irradiation and can be photodegraded at much higher power.

4.3.6. Mesocrystals Formed by Ag Nanocubes

Self-assembly of Ag nanoparticles into well-defined structures is of growing interest for surface-enhanced Raman scattering applications.^[101] In a recent study, Xia and coworkers demonstrated the self-assembly of Ag nanocubes into controlled structures, by functionalizing their side faces with hydrophobic and hydrophilic self-assembled monolayers (SAMs).^[102] When one side of each cube was modified with a hydrophobic, octadecanethiol (ODT) SAM and all others are modified with a hydrophilic, mercaptohexadecanoic acid (MHA) SAM, dimers are formed from the cubes. When two opposing faces of each cube were functionalized with ODT and the other four faces with MHA, cubes assembled in the form of linear chains. When functionalized in an inverse manner that four sides were modified with ODT and the other two were modified with MHA, cubes tended to form 2D sheets with a typical length of 500 nm. These structures are similar to the result obtained by computer simulations for nanocubes with strong face-to-face interactions. When all surfaces of each nanocube were modified by ODT, cubes underwent a 3D aggregation and reached a plateau with 10 to 12 nanocubes along the edge. The cubic nature of the final structures suggests that a mutual alignment of Ag nanocubes occurred equally in all three dimensions. The 3D aggregates of Ag nanocubes can be regarded as mesocrystals. Compared to the nanocube-assembled CeO_2 mesocrystals,^[84] the hydrophobic force-driven self-assembly of Ag nanocube aggregates in this case is more versatile and may be adaptable to other mesocrystal systems.

4.4. Mesocrystals Based on Functional Organic Molecules

Classical organic crystals are molecular crystals. Until recently, the mesoscale assembly of ordered nanoparticle aggregates was not anticipated for organic molecules. With a reasonable understanding of the formation mechanisms of the observed inorganic mesocrystals, some pioneering research activities have led to extend research on mesocrystals into the organic realm. These activities demonstrate that mesocrystals can be constructed from nanoscale building blocks consisting organic molecules by mesoscopic assembly. Apart from anisotropic polarizability encoded in the organic crystals, chirality, dipole moment, and hydrophilic-hydrophobic interactions provide additional parameters for the control of the bottom-up assembly of nanoparticles to form organic mesocrystals. Currently, the research on mesocrystals based on functional organic molecules is still in its infancy. Thanks to the intermolecular interactions in organic materials, such as hydrogen bonds, π - π stacking, and van der Waals contacts, it can be expected that organic mesocrystals would exhibit optical and electronic properties fundamentally different from those of inorganic mesocrystals.

4.4.1. Alanine Mesocrystals

The first organic mesocrystals were synthesized from DL-alanine supersaturated aqueous solutions in the presence of a chiral double hydrophilic block copolymer poly(ethylene glycol)-*block*-poly(ethylene imine)-S-isobutyric acid (PEG₄₇₀₀-PEI₁₂₀₀-S-iBAC).^[103] SEM and XRD characterization indicated the orientation

of nanocrystal platelets within a mesocrystal. Although the selected polymer is able to differentiate D- and L-alanine, the obtained mesocrystal for DL-alanine was found to be the racemate. The formation of DL-alanine mesocrystals was interpreted by the adsorption of charged butyric acid blocks onto the high energy (001) face of DL-alanine. The resulting inhibition of crystal growth along the *c*-axis produced platelet-like crystals with a dipole moment along the same direction. Subsequently, platelets stack along the *c*-axis under dipole–dipole attraction, leading to the formation of mesocrystals. The polar aligned structure makes the system a promising candidate for organic piezoelectricity.

There are several factors, which can be identified to be important for the formation of the alanine mesocrystals. The polar character of the (001) and (00 $\bar{1}$) faces (one side amine, one side carboxyl groups) must be taken into consideration for the construction of the final superstructure as this creates a dipole moment along the *c*-axis. Besides, a sufficient supersaturation of alanine in the solution is generally required to create a huge number of initially amorphous and subsequently crystalline nanoparticles as building blocks for the assembly while molecular crystallization is suppressed.^[34] Opposite to the classical molecular crystallization mechanism dominating at pH values much different from the isoelectric point (IEP), DL-alanine mesocrystals with pores, rough surfaces, and rounded corners were found to form in cases of high supersaturation and low molecular solubility near the IEP.^[34] Single crystal XRD analysis evidenced the single crystalline feature of the DL-alanine mesocrystals. These mesocrystals, however, are kinetically unstable and transform to a compact single crystal by crystallographic fusion of the aligned building units^[104] according to the oriented attachment mechanism.^[6] SANS was able to resolve the transformation from a mesocrystal to a single crystal in a time resolved manner showing for the first time that indeed, mesocrystals can be kinetic intermediates in the formation of a single crystal,^[104] unless their fusion is prevented by polymer adsorption (for more details, see Section 6).

Similar to the growth of PEG₄₇₀₀-PEI₁₂₀₀-S-iBAC-mediated DL-alanine mesocrystals,^[103] the formation of kinetically unstable DL-alanine mesocrystals was understood as a result of alignment of nanoparticles along a specific crystallographic orientation. Given a high concentration of amorphous nanoparticles, once such a particle crystallizes, the nucleated structures grow by the addition of further colloidal building blocks along the *c*-axis direction. About 10⁶–10⁹ primary particles are required to compose one final mesostructured crystal.^[34]

More recently, Medina and Mastai have described racemic DL-alanine mesocrystals with a needlelike hollow morphology from supersaturated solutions in water/isopropyl alcohol.^[33] Raman scattering patterns indicate that the (210) face is crystalline and other faces are of poor crystallinity. It was assumed that the isopropanol-induced DL-alanine supersaturated solution may produce a large amount of DL-alanine nanocrystals and amorphous precipitate, both of which then assemble to form mesoscale crystals. Subsequently, amorphous species in the structure could evolve to crystalline phases through a dissolution–recrystallization process. The model deviates from the previously proposed mechanisms for the formation of DL-alanine mesocrystals.^[34,103] If the formation of the product is subjected to a mesocrystal growth, the alignment of nanoparticles can take

place via the inherent dipole moment or due to influences arising from the inherent polarizability of the DL-alanine and the increasing Hamaker constant with the aggregation of nanocrystals and amorphous species. It is of interest to see whether a highly ordered alignment of nanoparticles occurred in this case.^[34,103,104] A further structural investigation of such mesocrystals is needed to back up the suggested schematic.

4.4.2. Sodium Ibuprofen

In contrast to racemic ibuprofen, racemic sodium ibuprofen forms both γ -form as well as two polymorphic racemic compounds, α - and β -forms.^[105] Among the three crystal forms, γ is thermodynamically stable racemic conglomerate. The other two forms, which are enantiotropically related, are metastable monotropes of γ -form. And α is more stable at lower temperatures, whereas β is more stable at higher temperatures. Because of the industrial demand, it is important to understand the crystallization behavior of the chiral salt. Lee and Zhang prepared mesocrystals of racemic (R,S)-($\pm$)-sodium ibuprofen dihydrate from a supersaturated aqueous solution in the presence of sodium dodecyl sulfate (SDS).^[106] As a result of the ordered stacking of platelets, the racemic (R,S)-($\pm$)-sodium ibuprofen dihydrate crystalline platelets grown in the presence of SDS, appeared to be larger and thicker than those obtained without the addition of SDS. The resulting ibuprofen mesocrystals are a mixture of the racemic compounds in α - and β -form and the resolved conglomerate in γ -form. No SDS was detected in the final product. Birefringence-induced interference colors and the changes in the relative intensity of XRD peaks, suggest that these mesocrystals are highly anisotropic. The side-to-side hydrophobic interaction between the alkane tails of SDS and ibuprofen was proposed to mediate the formation of mesocrystals through the assembly of the nanosized platelets by oriented attachment. It is worth noting that the dissolution rate of ibuprofen mesocrystals is more rapid than that of their single crystalline counterpart prepared by the conventional crystallization method (Fig. 13). The formation of sodium ibuprofen mesocrystals has provided a new approach for engineering organic crystals and re-designing the dissolution characteristics of pharmaceuticals.

5. Other Mesocrystal Systems

5.1 Gel-Mediated Mesocrystals

5.1.1. Calcite Mesocrystals Formed in Hydrogels

Habit change is a usual event for crystal growth in gel media. The change is correlated with the diffusion restricted transportation of new building units toward the growing surface in the gel medium. In terms of the limited diffusion function, gels provide a simple approach to guiding crystallization to mesocrystals under high supersaturation. Grassmann et al. observed calcite octahedral mesocrystals grown in polyacrylamide gels.^[107] A growth model based on hierarchical aggregation of rhombohedral subunits was suggested for the formation of calcite mesocrystals. A morphogenesis change of calcite mesocrystal products from octahedral

Figure 13. Dissolution profiles of crystals of racemic (R,S)-(+/-)-sodium ibuprofen dihydrate in water at 37.5 °C: a) without milling (inverted triangle = SDS generated mesocrystals, and square = conventional crystals without SDS), and b) with milling (circle = SDS generated mesocrystals, and triangle = conventional crystals without SDS). Reproduced with permission from [106]. Copyright 2008, Springer/Plenum Publishers.

toward cubo-octahedral can be induced by modifying the neutral polyacrylamide gels with charged acrylamidopropanesulfonate groups.^[108] As to be presented in Section 5.1.2, charged groups of gelatin gels can interact with inorganic crystals, whereas polyacrylamide gels are inert and do not directly affect the crystallization. One question arising from these studies is which factors control changes in the morphology of polyacrylamide gel-generated calcite mesocrystals. As reported by Grassmann, the dense polyacrylamide gels-mediated calcite crystals were assembled from small rhombohedral calcite crystals and appeared as single crystal aggregates. The permeability through a homogeneous gel increases with decreasing crosslinker and polymer content. Subsequently, calcite crystals synthesized in a hydrogel with polymer content of 5% and pore size of 150 nm, appeared in the form of calcite cleavage rhombohedra. Relying on a double diffusion set-up, Helbig recently demonstrated that the morphology of crystals has a strong dependence on the polymer content of the hydrogels, in which the crystals grow.^[109] A gel with acrylamide content of 10% and pore size of 30 nm can produce calcite pseudo-octahedral mesocrystals.

Similar to biogenic calcite crystals with incorporated biomolecules,^[110] calcite single crystals can also be grown with the incorporation of hydrogel networks. Li and Estroff have described rhombohedral calcite single crystals grown in agarose hydrogels.^[111,112] There is a presence of agarose gel nanofibers through the crystals. The internal structure of these single crystals is full of pores with size of 60–364 nm with an average of 190 ± 82 nm. The high porosity suggests that possibility that an individual crystal is an assembly of nanocrystallites connected by mineral bridges, as illustrated in Figure 1c.

Extending their work on apatite–gelatin nanocomposite structures, Knip and coworkers more recently investigated the growth of calcite in gelatin gels.^[113] They dealt with otoconia-like calcite–gelatin composite particles obtained by a double diffusion method in gelatin gel matrices. Associated to the inclusion of gelatin (1.9–2.6 wt %), the particles possess a lower density (2.563 g cm^{-3}), compared to bulk calcite crystals with a density of 2.711 g cm^{-3} . Two different kinds of structures were found in the individual particles, a much denser one in the branch areas and a more porous one in the belly region. The branch area shows a

perfect periodic calcite SAED pattern, whereas the belly region consists of nanodomains in a mosaic arrangement and shows a reduced crystallinity. However, the overall crystallographic orientation of the two areas in the individual particles is identical, in agreement with the single crystal-like X-ray scattering properties of the particles. These observations have hinted at the underlying mesocrystal structure of the calcite–gelatin composite.

5.1.2. Fluorapatite–Gelatin Mesocrystals

Mimicking the formation of hierarchically structured functional materials such as bone and teeth from apatite and proteins, Knip and coworkers synthesized fluorapatite nanoaggregates with fractal growth in gelatin matrices by a double-diffusion method. The products were

identified as organic–inorganic composites with a gelatin content of 2.3%, the same amount as observed in mature tooth enamel. As revealed by TEM investigations, the composite consists of parallelly stacked elongated hexagonal-prismatic nanocomposite subunits oriented with their long axes parallel to the [001] direction, thereby giving rise to scattering properties similar to that of single crystals.^[114,115] The mesocrystalline state of this highly controlled nanocomposite superstructure has been ascertained in a previous review paper.^[2,3] The fractal morphogenesis of this nanocomposite involves the evolution from hexagonal prismatic mesocrystal seeds via dumbbell structures to spheres.

Studies on the effect of ions on morphogenesis further demonstrated that ion impregnation can exert a pre-structuring effect on gelatin matrices and thus influence form development.^[116] Intermediates obtained in a Liesegang band next to the calcium source show fan-like morphology, whereas fractal growth was observed for the intermediates obtained from both the band next to phosphate source and the middle band. Interestingly, fan-like morphologies are straight and hard, whereas fractal morphologies are bent and soft. Moreover, aggregates found in the middle band exhibited a mixture of both archetypes when the supply of calcium ions was faster than that of phosphate ions. On basis of molecular dynamic simulations, it was suggested that the ion impregnation could make the gelatin gels pre-structured prior to the composite formation. According to atomistic computer simulation analysis, phosphate ions can form two to three hydrogen bonds with hydroxyproline side-groups and partially also with amino groups, resulting in heavy bending of the applied (Gly–Pro–Hyp)₁₂ polypeptide model. Ionic binding of calcium ions to the oxygen atoms of the carbonyl groups of the polypeptide backbone and to the side chains of proline and hydroxyproline, could cause only marginal configurational change of the local structure of the protein fibers. Subsequently, the protein fibers of the band next to the calcium source would be stiffened by a large number of calcium ions before the nucleation of apatite starts.

Until recently, the fractal growth mechanism has been predominantly recognized as a splitting procedure that develops directly from the basal planes of the young seed.^[117,118] A recent finding, that the intrinsic pattern of gelatin microfibrils

embedded within the periodic matrix of the fluorapatite–gelatin nanocomposite is already present within a young composite seed with its perfect hexagonal-prismatic habit,^[76] provides an important evidence for the realization of the microfibril pattern with a high level of complexity in mature composite seeds.^[23] This would lead to a template situation as schematically presented in Figure 1a with the additional important feature that the gelatin triphelices are dipolar resulting in intrinsic electrical fields. Polar triplehelices provide nucleation sites for the oriented formation of nano-apatite. It favors the formation of fluorapatite–gelatin mesocrystals. By adding up all microscopic dipoles, a macroscopic electric dipole is formed, thus producing an intrinsic electrical field, which can organize neighboring polar macromolecules to form microfibrils along the direction of the developing electrical field. As a consequence, even the crystallographic orientation of small regions of the mature seed is consistent with periodicity of the nanostructured collective.

5.2. Polymer-Mediated CaCO₃ Mesocrystals

5.2.1. Double-Hydrophilic Block Copolymer Mediated Formation of Calcite Mesocrystals

As a versatile class of amphiphilic molecules, double-hydrophilic block copolymers (DBHCs) show a rapidly increasing importance as pigment stabilizers and crystal growth modifiers.^[119,120] This is due to the separation of binding and stabilizing moiety within one molecule and the possibility to design tailor made binding blocks for specific crystal surfaces. The first demonstration of the continuous structural transition for calcite particles from polycrystalline to mesocrystal to single crystal^[15] showed that using poly(ethylene oxide)-*b*-poly(4-styrenesulfonate) (PEO₂₂-PNaSt₄₉), a diblock copolymer comprising a nonionic PEO block and an anionic block comprising pendent aromatic sulfonate groups, allowed for the versatile growth in a unifying crystallization framework. The principle is DHBC-controlled aggregation of precursor subunits. The mode of aggregation varies with the supersaturation level from a low to a high degree of orientation. Growth of single crystals via classical ion-by-ion growth, mesocrystals resulting from particle-mediated oriented aggregation, and polycrystalline particles yielded by nonoriented aggregation are all possible within the framework. Thermogravimetric analyses (TGA) of calcite mesocrystals revealed a weight loss of 3.5% below 600 °C showing that the extent of copolymer incorporation in the mesocrystals is higher than in single crystals (2.0 wt %) and lower than that in polycrystalline particles (7.5 wt %).

5.2.2. Polyglycerol Mediated Formation of Calcite Mesocrystals

Hyperbranched polyglycerols have a high number of functional groups and good water-solubility. In a recent report, You and coworkers synthesized sulfate-based polyglycerols from pentaerythritol and glycidol by anionic ring-opening polymerization.^[121] They described that sulfate-based polyglycerols can serve as an effective modifier to control the morphology of calcite mesocrystals. Crystal shapes change with cations present in sulfate-based hyperbranched polyglycerols changing from H⁺,

Na⁺ to imidazolium. In the presence of Na, the resulting calcite crystals resemble a rounded Chinese lantern with rough surface with polymer inclusion of a relatively high level, as evidenced by TGA. The pivotal role played by the interaction between polyglycerols and surfaces of calcite primary particles in the process provides a driving force for the assembly. It was assumed that an assembly mechanism similar to calcite mesocrystals mediated by PSS^[36] or PEO₂₂-PNaSt₄₉^[15] is responsible for the morphogenesis. But the characterizations in the report lack the evidence to prove vital information on mutual orientation of nanosized building blocks.

5.2.3. Calcite Mesocrystals from Direct CO₂ Diffusion Method

A mesoscopic assembly process does not occur in an ion-by-ion manner, however, ionic strength and ionic species are still important variables in controlling crystallization to form mesocrystals. In particular for surfactant phases and microemulsion involved crystallization processes, phase equilibria and physical characteristics of the product can strongly depend on ionic species and ionic strength—especially if catanionic lyotropic phases are applied. To avoid influences related to the presence of spectator ions involved in the common CaCO₃ precipitation protocols and to better control the ionic strength and ionic species, a new crystallization setup was designed applying CO₂ vapor diffusion into a Ca(OH)₂ solution for the crystallization of calcium carbonate.^[122] Compared to other techniques for CaCO₃ crystallization, such as conventional gas diffusion method, Kitano process, double jet technique, double diffusion technique, constant composition method, and thermal or enzymatic decomposition of urea, the method has the advantage of avoiding the interference of ammonium or other extraneous ions, minimizing ionic strength and approaching a pH close to biological conditions at the end of the crystallization reaction. This method turned out to be useful for the growth of calcite mesocrystals. Morphologies of products obtained by using the setup and two polymeric additives agree well with the results obtained previously by the gas-diffusion method.^[36,123] The direct CO₂ diffusion method allows for further investigation of the driving forces for the oriented aggregation of nanoparticles toward mesocrystals, such as intrinsic electric fields, which are shielded by ions in solution.

5.2.4. Vaterite Mesocrystals

Thermodynamically, vaterite is the least stable phase of the three anhydrous polymorphs of calcium carbonate. However, vaterite can be stabilized by polymeric additives as demonstrated for vaterite hollow spheres which were found to be stable in aqueous solution even after 1 year.^[120] Therefore, even a metastable polymorph should be suitable for the synthesis of mesocrystals. By using a gas-diffusion method and an *N*-trimethylammonium derivative of hydroxyethyl cellulose as additive, vaterite mesocrystals with hexagonal morphology could be synthesized.^[124] Vaterite remained stable in aqueous solution for at least 2 weeks. The mesocrystals are uniform in size with diameters ranging from 5 to 10 μm. Hexagonal nanoparticles with sizes of 30–60 nm and sharp edges were identified as mesocrystal building units. TEM and SAED investigation revealed that each hexagonal plate consists of nanoparticles sharing the same crystallographic

orientation and diffracting as a single crystal with the expression of the {001} face. TEM measurements of products obtained at different growth stages further revealed that the vaterite hexagonal plates are formed by aggregation and phase transformation from amorphous nanoparticles. The stabilization and inhibition of the vaterite {001} faces is the consequence of attachment of the positively charged polymer on the negatively charged {001} face. Without polyelectrolyte stabilization, vaterite is unable to expose the high energy {001} faces which are composed of either carbonate or calcium ions in a hexagonal configuration. At low polymer concentration, the mesoscale assembly in three dimensions becomes obvious with the production of mesocrystals by multilayer stacking of small hexagonal plates along the [001] direction.

6. Mesocrystals as Intermediates in Single Crystal Formation

Due to their high inner surface and their usually crystallographically aligned building units, mesocrystals are metastable with respect to their transformation to single crystals by the process of oriented attachment.^[4–6] They can only get stabilized if additives or charge are used on the nanoparticle surfaces. This is possibly the reason why mesocrystals were only discovered rather recently although examples of mesocrystals can already be found in the literature of decades ago.^[1] It is an analytical challenge to detect mesocrystals if their nanoparticle building units are not stabilized because the crystallographic fusion of their building units may be a fast process—especially for systems with high lattice energies which provide a high driving force for oriented attachment of the building units. Therefore, the transformation of mesocrystal to single crystal should be especially difficult to observe for inorganic systems without stabilizing molecules. However, for an organic *D,L*-alanine mesocrystal, it was possible to observe the time dependence of this transition by SANS.^[104] For the mesocrystal, a Q^{-3} power law was observed, which is characteristic for aggregates with an inner surface. This power law gradually changed to a Q^{-4} dependence which is characteristic for compact particles. This first time resolved observation of a mesocrystal to single crystal transition is an important proof for the nonclassical crystallization pathway for single crystals via mesocrystal intermediates. It therefore seems likely that many more single crystal systems are formed via a mesocrystal intermediate, which may however be difficult to detect. Indeed, a mesocrystal to single crystal transition could also be observed for dendritic silver^[125] and silver plate crystals^[126] using time resolved TEM. Xie and coworkers could nicely capture the mesocrystal intermediates in the formation of prussian blue microparticles by a time resolved electron microscopy study as shown in Figure 14.^[127]

Figure 14a shows the forming mesocrystal in which local areas are already oriented in crystallographic register (Fig. 14b). The final cubic crystals (Fig. 14c) are single crystals as demonstrated

Figure 14. Time resolved electron microscopy study on the formation of Prussian blue single crystals via mesocrystal intermediates. a) SEM after 1.5 h b) Left: TEM after 1.5 h and corresponding SAED c) SEM after 2.5 h and d) enlarged SEM image showing surface defects on the microcubes. Images reproduced with permission from [127]. Copyright 2007, American Chemical Society.

by peak narrowing of the wide angle X-ray diffraction peaks (WAXSS) and a closer look at the crystal surface (Fig. 14d) shows that the growth defects clearly have a cubic substructure (arrow in Fig. 14d), demonstrating that the single crystal was assembled from the cubic nanoparticles via a mesocrystal aggregate. In addition, Figure 14c shows some nanoparticle building units resting on the surface of the microcrystal in the front. This example very illustratively demonstrates the nanoparticle assembly process to a mesocrystal and its fusion to a single crystal as drawn in the corresponding schematics,^[1,2] since in this example the building units are monodisperse. Other systems in which the time resolved mesocrystal to single crystal transition was observed include PbTiO_3 ^[128] or InOOH ^[129] where the transition to a single crystal is less documented and suggested to occur by dissolution–recrystallization of nanoparticle surfaces and/or removal of stabilizer molecules.^[89,129]

7. Analogy between Mesocrystals and Biopolymer Superstructures

It is remarkable that the structural levels found for biopolymers such as proteins or polysaccharides have similar features as the structural levels found in a mesocrystal. Both structures rely on self organization/structuration processes in a solvent and it is useful to consider analogies. Proteins have a primary sequence with secondary interaction patterns which control the folding up to the tertiary structure. By appropriately placed functionalities on the different sites, a quarternary superstructure can be adjusted by interactions between the tertiary structures. In that sense, crystalline nanoparticles with appropriate surface encoding are very similar to the tertiary protein nanostructures, and accordingly, superstructures are found, which rely on the functionality of the tertiary structures. An important lesson from the multilevel structure formation in biopolymers is the coding of the structural

organization process by chemical functionalities, which is for example the amino acid sequence in proteins. In analogy, mesocrystal formation can be coded by adsorption of appropriate additives on the surface of the nanoparticle building units.

The primary structure of the protein is its amino acid sequence, which has its analogon in the atoms/ions/molecules building up a crystal. The atom/ion radii define their packing in an atom/ionic crystal and the interaction between molecules the packing in a molecular crystal. The smallest regular unit in such a crystal is the unit cell, which corresponds to the secondary structure in biopolymers (α -helix, β -sheet, γ -turn). The interaction between several secondary structural elements of biopolymers defines the tertiary structure. In analogy, a number of unit cells build the nanocrystal with potentially unusual shape and interaction pattern, which is the primary building unit in a nonclassical crystallization process. These nanoparticles are often covered with additives in a site selective manner coding the further interaction. Finally, the interaction between several tertiary units of a biopolymer forms the quaternary structure, for instance the fibrils in the collagen example in Figure 15. The analogy in the nonclassical crystallization scenario is the mesocrystal, with an either self-determined morphology (this is the usual case) or a morphology determined by an external template, which is likely the case for some biominerals. The analogy between these structural levels as displayed in Figure 15 is striking and implies that concepts from polymer chemistry/

biophysical chemistry are useful to understand mesocrystal formation and other nonclassical crystallization reactions. In addition, the close similarity between the structural cascades from primary to quaternary structures can explain the “bio-like” appearance and morphologies of many crystals formed by a nonclassical crystallization pathway. The formation of biopolymer quaternary structures from several different molecules (e.g., the insulin tertiary structure is formed from chain A and B) implies that it should also be possible to form mesocrystals that consist of chemically different nanocrystals. So far, such mesocrystals were not yet reported and it is not known which requirements must be fulfilled by the nanoparticle building units to form such structures.

8. Conclusion and Outlook

Mesocrystals are ordered nanocrystal assemblies with a huge potential for the synthesis of advanced materials. They combine easy processability due to their typical micrometer size with the favorable properties of their nanoparticle building units and often, the organic–inorganic hybrid material character is the key to the improved properties as is observed in biominerals. Also, mesocrystals can adapt morphologies, which are not encoded in the crystal structure of the crystalline material they are made of.^[130] The fact that Nature applies the mesocrystal structure in at

Figure 15. The four structural levels in collagen as example for a biopolymer (left) and the corresponding structural levels in a hypothetical urea mesocrystal (right).

least some of its highly sophisticated biominerals shows that obviously, such construction principle is advantageous and thus favored by evolution (see Section 3). Indeed, first examples which were outlined in Section 4, show that the materials properties of functional mesocrystals are improved compared to their single crystalline counterparts. This is due to the high crystallinity, high porosity, subunit alignment, and organic/inorganic-inorganic hybrid material character of the mesocrystal, which have relevance for solubility, mechanical, catalytic, optical, electronic, magnetic, and sensing properties to name the most important ones.

It will be a challenge to transfer mesocrystals into applications because currently, their formation processes are often still too poorly understood and the applied highly effective organic additives for their stabilization are usually still too expensive for large scale applications. Nevertheless, existing materials properties can be expected from mesocrystals, which should be exploitable for the synthesis of advanced materials. One strategy, which can be deduced from biominerals as sea urchin skeletal elements or nacre is the brick and mortar principle. These mesocrystals exhibit improved mechanical properties due to the organization of the organic and inorganic building units in an appropriate manner. If such building principle could be transferred to a material like cement, a tough and fracture resistant hierarchically structured building material could result, which would serve for extraordinarily strong but lightweight constructions.

Current building materials are mainly limited by their compression strength, and a brick building cannot be much higher than 125 m. A similar calculation restricts concrete to about 500 m height, whereas wood—just judged from its mechanical properties and density, would allow a tower to be 1500 m high. This shows that a tough and lightweight material with hierarchical organization can improve the future construction possibilities of humankind significantly. The theoretical value of a fully oriented “concrete” mesocrystal might allow for a 15 km high building. It is obvious how such material could change the possibilities of architecture and therefore our daily world since concrete is the most applied material of human kind based on mass.

Other existing application areas for mesocrystals would be optics or electronics—particularly for metal or semiconductor mesocrystals. Nowadays, these materials are already available as defined nanoparticles but their controlled bottom up assembly to superstructures with defined nanoparticle orientations and spacings will create new electrical and optical properties due to mutual interactions of the nanoparticles within the mesocrystal. The defined self organization of these nanoparticles is not straightforward and a topic of active research (see Section 2.2). Tuning the organic–inorganic structure might result in optical or electrical band gaps, improved capacitors or other electronic devices, which are based on interfaces between conducting–nonconducting, semiconducting–conducting or semiconducting–nonconducting materials. Mesocrystals offer a potential toolbox for the modular design of such advanced electronic or optical materials once the self organization principles are understood as well as the possible choices of materials and their combinations.

These are just some speculations about the use of existing chemistry to generate materials with new properties due to the synergy of their constituents. The principle is however already omnipresent in nature. Nature’s building materials as such do

not have extraordinary mechanical properties. In fact, Nature has to apply the materials which are available like the brittle silica glass or the crack endangered CaCO_3 . Nevertheless, the key to the superior materials properties is the building principle of a composite structure controlled over several length scales which adds the remarkable strength and toughness to biominerals.^[131] Humankind has developed much better synthetic materials, and it is an interesting speculation to what height materials may climb up when a perfected starting component is combined with a perfected hierarchical structure. The much improved mechanical properties of a synthetic nacre mimic based on Al_2O_3 and a ductile chitosan polymer matrix compared to the original biomineral nacre, which is based on the mechanically worse CaCO_3 , already demonstrates what is possible if the biomineral design principle can be adapted to synthetic materials with improved mechanical properties of its constituents.^[132] Such result means that even a biomineral composite structure, which was evolutionary optimized over several hundred million years can be outperformed if the notoriously weak bioceramic components can be replaced by improved synthetic counterparts. Similar principles should apply to mesocrystals.

A mesocrystal architecture may even allow to realize physical properties, which would not exist for their single crystal counterparts. An impressing example is Fe_3O_4 mesocrystals, which suppress the undesired superparamagnetic–ferromagnetic transition, happening at room temperature for particles larger than 30 nm.^[85] Therefore, the mesocrystal retains the desired superparamagnetic behavior at room temperature although its size exceeds 30 nm. This combines the desired good magnetization of larger particles for alignment and separation with the superparamagnetism of small nanoparticles, which otherwise would have a too low magnetization. One can imagine that such principles should also apply for mesocrystals of other nanocrystals with size dependent properties like quantum dots or metal nanoparticles. This could lead to micron sized particles, which can be easily handled (separation, fabrication, etc.) but which nevertheless still have the properties of their nanoparticle building units or even improved properties through synergy effects.

It is interesting to note that up to now, the few examples which accessed the properties of mesocrystals, focused on physical properties (mainly mechanical, optical, and magnetic). However, the nanoparticle building units in a mesocrystal also have a chemical functionality. This is obvious for catalytic applications but furthermore, the possibility of topotactic transformations for mesocrystals (see Section 2.6) indicates, that the nanoparticle surfaces in a mesocrystal can be used as reactive surfaces. For example, one could think of catalyzed polymerizations inside a mesocrystal template but also, the surface could be changed by a chemical reaction like the passivation of toxic semiconductor surfaces or reduction of a metal salt to a metal film. There are numerous possibilities one could think of in terms of application of the chemical properties of a mesocrystal. But even if the nanoparticle surfaces cannot directly take part in a chemical reaction, the fact that chemical reactions in a confined space can lead to different reaction products can be advantageously employed. In this sense, highly porous mesocrystals like those of CaCO_3 ,^[39,133] which on the first sight have no improved properties could be used as porous and easily removable scaffold

providing confined reactors in the range of a few nanometers. Also, the voids between the nanoparticles in a mesocrystal can be used for the immobilization of small organic molecules like dyes but also drugs, suggesting mesocrystals as carrier systems in drug release applications.

If the structure of a mesocrystal made up from a single nanoparticle species can already lead to such improved properties, the improvement would be expected to be even much bigger and the obtainable physical and chemical property range much more diverse, if several nanoparticle species could be combined to a mesocrystal. That such strategy is possible was demonstrated for nearly spherical nanoparticles of a different size, which were combined to a binary superlattice.^[134] In this work, the formation of more than 15 binary superlattice structures was demonstrated using a combination of semiconductor, metal, and magnetic nanoparticle building blocks leading to a material with a tunable property combination from those of its constituents like a magnetic semiconductor and so forth. The applied nanoparticles were sterically stabilized but electrical charges determined the stoichiometry of the binary superlattice as well as the nanoparticle size which is in analogy to the formation of crystal lattices from ions. Entropic, van der Waals, steric and dipolar forces stabilize the different binary nanoparticle superlattices. Whether these superlattices are mesocrystals is not known as the mutual nanoparticle orientation was not determined. One could think of mesocrystal formation if for example dipole-dipole interactions lead to nanoparticle orientation in crystallographic register. However, as this is not yet known, we did not treat these fascinating superlattices in this report about mesocrystals. Nevertheless, this progress for colloidal crystals made up of spherical subunits implies what could be possible with nonspherical mesocrystal building blocks, which in addition have direction dependent chemical and physical properties. A whole class of new modular materials would become available not only with combinations of nanoparticle constituent properties but in addition the possibility to apply directionally different properties. Such a mesocrystal could for example show a high magnetization in the one direction but a high polarizability in another direction and so forth. If combinations of organic and inorganic nanoparticles to a mesocrystal could be realized, the property combinations could even be further enhanced. For example, the high extinction coefficients of organic dyes might be employed in improved dye sensitized solar cells with semiconductors like ZnO, which do not destroy the dyes. The order and tunable inter nanoparticle distance could be beneficial in this respect. Also, the combination of optical properties like fluorescence of organic nanocrystals and nanoparticle properties like magnetism could be beneficial for combined fluorescent, X-ray and tomography tracers, which could be guided by magnetic fields. However, an important requirement for binary superlattices is the availability of monodisperse nanoparticles with defined size and tunable surfaces. This is so far only partly realized for nonspherical semiconductors or magnetic nanoparticles and it is not yet clear whether a similar self organization of nonspherical nanoparticles would be possible rather than the self organization of each of the components to an individual mesocrystal.

This leads to a point which is critical for the development of mesocrystal structures for advanced materials. So far, only a few

formation mechanisms of mesocrystals are fully revealed. This is mainly an analytical issue as the observation of the whole mesocrystal formation process is truly challenging. One problem is their often only intermediate nature in the formation process of a single crystal (see Section 6). In most cases, the mesocrystal intermediate cannot be directly observed but can only be concluded from the final porous single crystal structure as observed for BaSO₄^[135] or (NH₄)₃PW₁₂O₄₀.^[42] A second analytical challenge is the multi step process of mesocrystal formation consisting at least of two elementary steps: (i) nanoparticle nucleation and (ii) mesocrystal assembly. Usually, there are more steps involved like the formation of amorphous precursors, the formation of mineral bridges between the nanoparticles in a mesocrystal or the crystallographic fusion of the crystallographically aligned nanocrystals to single crystalline domains. Therefore analysis of a mesocrystal growth scenario means to face the problem to analyze a time dependent process, which already starts from molecules and ions in solution and usually ends on the micron scale. The relevant particle size range spans 5 decades from 10⁻⁹–10⁻⁴ m, which is a challenge for a single analytical technique. However, the situation gets further complicated. According to very recent findings, the precursors to amorphous or crystalline structures are not necessarily critical crystal nuclei as assumed in classical nucleation theory^[136] but can be thermodynamically stable prenucleation clusters as observed for calcium carbonate,^[137,138] -phosphate,^[137] and -oxalate.^[137] The observation of such prenucleation clusters calls for demanding analytical techniques like cryo-TEM,^[138] analytical ultracentrifugation,^[137,138] or advanced titration.^[137] Even during the aggregation of clusters to amorphous but solid species, there appear to be liquid intermediates, which can transform to mesocrystals or single crystal—liquid hybrid particles exhibiting a soap film like texture or the typical minimal surfaces of liquids like the P-surface.^[139]

The corresponding time scales related to mesocrystal formation are even broader spanning from the sub-ms range for primary particle formation^[140,141] to many hours of structural ripening, as observed for the (NH₄)₃PW₁₂O₄₀ example.^[42] This spans at least about 8 decades in time (10⁻³–10⁵ s). With this in mind, it becomes clear that a combination of analytical techniques has to be applied, which consists of imaging techniques, kinetic techniques, techniques sensitive to dissolved species and analytical techniques sensitive to the structure of the mesocrystal.

This can be illustrated by the investigation of the growth mechanism of copper oxalate mesocrystal intermediates, which was revealed in an elegant way by a combination of a number analytical techniques for various time and length scales.^[97] The particle growth mechanism of this particular crystal with a mesocrystal intermediate can be described in four stages: (i) initial nucleation and growth of primary particles; (ii) rapid aggregation to give a core of randomly oriented primary particles or crystallites; (iii) a period of ordered attachment of crystallites giving an inner shell of well-aligned nanocrystals; (iv) a slow approach toward equilibrium with the solution where high-energy surfaces are eliminated and an outer shell of larger well-cemented crystallites envelopes the first-formed particles. The schematic diagram in Figure 16 shows that in this particular example, a time scale from the ms range up to 2 weeks and a

Figure 16. Schematic representation of the precipitation mechanism of copper oxalate formation from the initial stage to the final particle as a function of time with the applied analytical techniques for the different time and size regimes. Based on results in and redrawn from [97].

size range from nanocrystals to microcrystals had to be monitored.

The applied analytical techniques are shown in Figure 16 for the various stages of mesocrystal growth. In the present example, the results from eight different analytical techniques were combined to learn about the mesocrystal formation process. This example shows, why it is so demanding to reveal how a mesocrystal forms. Additionally, the quite considerable variety of already known mesocrystal formation mechanisms (see Section 2) makes it difficult to extract universally valid rules and mechanisms, which can then be theoretically described. However, theoretical description needs a solid basis of experimental observations of mesocrystal formation mechanisms, which is so far not yet completed. On the other hand, the nanoparticles, which are the building units of mesocrystals are at the limit of what can be modeled at the moment by molecular modeling approaches and modeling of mesocrystal formation will call for multi-scale modeling approaches.^[142] Therefore, predictions which kind of mesocrystal will form for a given system and certain experimental parameters are not yet possible at the moment.

The analogy of organic polymerization reactions (on the molecular scale) and oriented attachment (on the nanoscale) is an obvious point for nonclassical crystallization structures and was discussed in previous work.^[143,144] This analogy however might give a guideline how to progress in the field of mesocrystals, which is also an aggregation-based superstructure formation process. However, mesocrystal formation usually takes place in three dimensions and often, the nanoparticle surfaces are covered with additives, which complicates the theoretical treatment. However, different initiators/nucleators will result in different polymers/assemblies, and controlled/living polymerization reactions will result in monodisperse, uniform structures. The analogs to block copolymers are hetero-crystalline rods or binary core-shell hybrids, which opens access to materials with multifunctionality. It is obvious that principles from polymer physics/chemistry should be adaptable to mesocrystal formation too and possibly, such concepts will help to make mesocrystal formation predictable. However, we are now still very far away

from reaching this goal since the experimental data basis on mesocrystal formation mechanisms is still in its infancy.

On the other hand, learning from biology, also opens exciting opportunities and might help to understand the basis for mesocrystal formation. For instance, the “oriented attachment” of a set of spherical proteins to microtubuli is governed by a molecular cofactor, GTP, the conversion of which controls assembly and disassembly of the tubes. The mimic of this process might provide us with a tool to couple structure with chemical gradients as one base for artificial motility of colloidal objects. This is just one example as living systems are full of encoded intermolecular organization patterns which are worth to mimic.

Finally, analysis of the mesocrystal formation process in the absence of any biological entity might also demystify the formation of biominerals. Many reports in the biomineralization field how specific organisms control their mineral deposition are full of very complicated regulatory circuits, active vesicle structures or highly specific proteins controlling exactly one step in a complicated process chain. Whether this is really the case is doubtful as nature is efficient and will employ the most suitable/simple solution as evolutionary principle. This would be a spontaneous, physico-chemical reaction cascade rather than a demanding micromanagement of every step to reach a desired effect. Therefore, physical chemistry appears neglected in this field. On the other hand, mesocrystal formation has a lot in common with known biological structuration processes and one can state that there is certainly a lot of “biology” involved in such nonclassical crystallization processes. This is also found in the related field of the so called biomorphs. These are structures closely resembling morphologies of biominerals but are of purely synthetic origin and traditionally made from silica and BaCO_3 . Recently, a large part of the underlying mechanism was revealed to be based on a physicochemical principle of pH cycling between two coupled reactions.^[145]

Insofar, we appear to reveal part by part of a larger picture. Nonclassical crystallization^[1] has many facets, which so far may appear unrelated. However, the common underlying principle is controlled self organization. As this is a common principle in nature, we can further learn from natural organization schemes to take advantage of evolutionary optimization. This will help to transfer mesocrystal structures into the synthetic materials world. Already the existing first examples show that materials with improved properties compared to their single crystal analogues can be expected if they adapt a mesocrystal structure. Controlled engineering of mesocrystals should yield a modular set for materials synthesis with superior properties. It can be expected that mesocrystals will play an important role in the synthesis of many future advanced materials. The main question is only how fast the synthesis protocols and theoretical descriptions advance. We can hardly await these exiting developments.

Acknowledgements

We thank the Max-Planck-Society for financial support of our research.

- [1] H. Cölfen, M. Antonietti, *Mesocrystals and Nonclassical Crystallization*, John Wiley & Sons, New York 2008.
- [2] H. Cölfen, M. Antonietti, *Angew. Chem. Int. Ed.* **2005**, *44*, 5576.
- [3] H. Cölfen, S. Mann, *Angew. Chem. Int. Ed.* **2003**, *42*, 2350.
- [4] R. L. Penn, J. F. Banfield, *Am. Mineral.* **1998**, *83*, 1077.
- [5] R. L. Penn, J. F. Banfield, *Science* **1998**, *281*, 969.
- [6] R. L. Penn, J. F. Banfield, *Geochim. Cosmochim. Acta* **1999**, *63*, 1549.
- [7] D. Moldovan, V. Yamakov, D. Wolf, S. R. Phillpot, *Phys. Rev. Lett.* **2002**, *89*, 206101.
- [8] H. Cölfen, *Top. Curr. Chem.* **2007**, *271*, 1.
- [9] H. Cölfen, in: *Biomining: From Paleontology to Materials Science* (Eds: J. L. Arias, M. S. Fernandez), Editorial Universitaria, Universidad de Chile, Santiago **2007**, p. 515.
- [10] H. Imai, *Top. Curr. Chem.* **2007**, *270*, 43.
- [11] H. Imai, Y. Oaki, A. Kotachi, *Bull. Chem. Soc. Jpn.* **2006**, *79*, 1834.
- [12] M. Niederberger, H. Cölfen, *Phys. Chem. Chem. Phys.* **2006**, *8*, 3271.
- [13] Q. Zhang, S. J. Liu, S. H. Yu, *J. Mater. Chem.* **2009**, *19*, 191.
- [14] L. Zhou, P. O'Brien, *Small* **2008**, *4*, 1566.
- [15] A. N. Kulak, P. Iddon, Y. Li, S. P. Armes, H. Cölfen, O. Paris, R. M. Wilson, F. C. Meldrum, *J. Am. Chem. Soc.* **2007**, *129*, 3729.
- [16] J. P. Cuif, Y. Dauphin, *Biogeosciences* **2005**, *2*, 61.
- [17] A. Sugawara, T. Nishimura, Y. Yamamoto, H. Inoue, H. Nagasawa, T. Kato, *Angew. Chem. Int. Ed.* **2006**, *45*, 2876.
- [18] T. Nishimura, T. Ito, Y. Yamamoto, M. Yoshio, T. Kato, *Angew. Chem. Int. Ed.* **2008**, *47*, 2800.
- [19] L. Addadi, D. Joester, F. Nudelman, S. Weiner, *Chem. Eur. J.* **2006**, *12*, 981.
- [20] M. Rousseau, E. Lopez, P. Stempfle, M. Brendle, L. Franke, A. Guette, R. Naslain, X. Bourrat, *Biomaterials* **2005**, *26*, 6254.
- [21] Y. J. Min, M. Akbulut, K. Kristiansen, Y. Golan, J. Israelachvili, *Nat. Mater.* **2008**, *7*, 527.
- [22] K. M. Ryan, A. Mastroianni, K. A. Stancil, H. T. Liu, A. P. Alivisatos, *Nano Lett.* **2006**, *6*, 1479.
- [23] P. Simon, D. Zahn, H. Lichte, M. Knip, *Angew. Chem. Int. Ed.* **2006**, *45*, 1911.
- [24] S. Q. Li, C. Y. Wu, K. Sassa, S. Asai, *Mater. Sci. Eng. A* **2006**, *422*, 227.
- [25] L. Carbone, C. Nobile, M. De Giorgi, F. D. Sala, G. Morello, P. Pompa, M. Hytch, E. Snoeck, A. Fiore, I. R. Franchini, M. Nadasan, A. F. Silvestre, L. Chiodo, S. Kuder, R. Cingolani, R. Krahne, L. Manna, *Nano Lett.* **2007**, *7*, 2942.
- [26] L. S. Li, A. P. Alivisatos, *Phys. Rev. Lett.* **2003**, *90*, 097402.
- [27] C. Querner, M. D. Fischbein, P. A. Heiney, M. Drndic, *Adv. Mater.* **2008**, *20*, 2308.
- [28] S. Gupta, Q. L. Zhang, T. Emrick, T. P. Russell, *Nano Lett.* **2006**, *6*, 2066.
- [29] C. C. Kang, C. W. Lai, H. C. Peng, J. J. Shyue, P. T. Chou, *ACS Nano* **2008**, *2*, 750.
- [30] A. Ahnizay, Y. Sakamoto, L. Bergstrom, *Proc. Natl. Acad. Sci.* **2007**, *104*, 17570.
- [31] J. I. Park, Y. W. Jun, J. S. Choi, J. Cheon, *Chem. Commun.* **2007**, 5001.
- [32] T. Kimura, F. Kimura, M. Yoshino, *Langmuir* **2006**, *22*, 3464.
- [33] A. Taden, K. Landfester, M. Antonietti, *Langmuir* **2004**, *20*, 957.
- [34] Y. Ma, H. Cölfen, M. Antonietti, *J. Phys. Chem. B* **2006**, *110*, 10822.
- [35] D. D. Medina, Y. Mastai, *Cryst. Growth Des.* **2008**, *8*, 3646.
- [36] T. P. Wang, M. Antonietti, H. Cölfen, *Chem. Eur. J.* **2006**, *12*, 5722.
- [37] V. K. LaMer, R. H. Dinegar, *J. Am. Chem. Soc.* **1950**, *72*, 4847.
- [38] Q. Gong, X. F. Qian, X. D. Ma, Z. K. Zhu, *Cryst. Growth Des.* **2006**, *6*, 1821.
- [39] A. W. Xu, M. Antonietti, S. H. Yu, H. Cölfen, *Adv. Mater.* **2008**, *20*, 1333.
- [40] T. E. Schaffer, C. IonescuZanetti, R. Proksch, M. Fritz, D. A. Walters, N. Almqvist, C. M. Zaremba, A. M. Belcher, B. L. Smith, G. D. Stucky, D. E. Morse, P. K. Hansma, *Chem. Mater.* **1997**, *9*, 1731.
- [41] Y. Oaki, A. Kotachi, T. Miura, H. Imai, *Adv. Funct. Mater.* **2006**, *16*, 1633.
- [42] K. Inumaru, *Catal. Surv. Asia* **2006**, *10*, 151.
- [43] T. Miura, A. Kotachi, Y. Oaki, H. Imai, *Cryst. Growth Des.* **2006**, *6*, 612.
- [44] R. K. Zheng, H. Gu, B. Xu, K. K. Fung, X. X. Zhang, S. P. Ringer, *Adv. Mater.* **2006**, *18*, 2418.
- [45] Z. R. Tian, J. Liu, J. A. Voigt, B. McKenzie, H. Xu, *Angew. Chem. Int. Ed.* **2003**, *42*, 413.
- [46] S. Ahmed, K. M. Ryan, *Nano Lett.* **2007**, *7*, 2480.
- [47] J. Ren, R. D. Tilley, *J. Am. Chem. Soc.* **2007**, *129*, 3287.
- [48] L. Zhou, D. S. Boyle, P. O'Brien, *Chem. Commun.* **2007**, 144.
- [49] L. Zhou, D. S. Boyle, P. O'Brien, *J. Am. Chem. Soc.* **2008**, *130*, 1309.
- [50] K. Furuichi, Y. Oaki, H. Imai, *Chem. Mater.* **2006**, *18*, 229.
- [51] L. M. Qi, H. Cölfen, M. Antonietti, *Chem. Mater.* **2000**, *12*, 2392.
- [52] Y. Oaki, H. Imai, *Small* **2006**, *2*, 66.
- [53] I. Sethmann, A. Putnis, O. Grassmann, P. Lobmann, *Am. Mineral.* **2005**, *90*, 1213.
- [54] I. Sethmann, R. Hinrichs, G. Worheide, A. Putnis, *J. Inorg. Biochem.* **2006**, *100*, 88.
- [55] Y. Dauphin, *Paläontolog. Z.* **2001**, *75*, 113.
- [56] X. D. Li, W. C. Chang, Y. J. Chao, R. Z. Wang, M. Chang, *Nano Lett.* **2004**, *4*, 613.
- [57] Y. Oaki, H. Imai, *Angew. Chem. Int. Ed.* **2005**, *44*, 6571.
- [58] M. Rousseau, E. Lopez, A. Coute, G. Mascarel, D. C. Smith, R. Naslain, X. Bourrat, *J. Struct. Biol.* **2005**, *149*, 149.
- [59] Y. Dauphin, *J. Biol. Chem.* **2003**, *278*, 15168.
- [60] I. Sethmann, G. Worheide, *Micron* **2008**, *39*, 209.
- [61] S. Weiner, I. Sagi, L. Addadi, *Science* **2005**, *309*, 1027.
- [62] N. Nassif, N. Pinna, N. Gehrke, M. Antonietti, C. Jäger, H. Cölfen, *Proc. Natl. Acad. Sci.* **2005**, *102*, 12653.
- [63] X. D. Li, Z. H. Xu, R. Z. Wang, *Nano Lett.* **2006**, *6*, 2301.
- [64] D. Vielzeuf, J. Garrahou, A. Baronnet, O. Grauby, C. Marschal, *Am. Mineral.* **2008**, *93*, 1799.
- [65] Y. R. Cai, R. K. Tang, *J. Mater. Chem.* **2008**, *18*, 3775.
- [66] J. H. Tao, H. H. Pan, Y. W. Zeng, X. R. Xu, R. K. Tang, *J. Phys. Chem. B* **2007**, *111*, 13410.
- [67] L. J. Wang, X. Y. Guan, C. Du, J. Moradian-Oldak, G. H. Nancollas, *J. Phys. Chem. C* **2007**, *111*, 6398.
- [68] L. J. Wang, X. Y. Guan, H. Y. Yin, J. Moradian-Oldak, G. H. Nancollas, *J. Phys. Chem. C* **2008**, *112*, 5892.
- [69] F. R. Tay, D. H. Pashley, *Biomaterials* **2008**, *29*, 1127.
- [70] V. Pipich, M. Balz, S. E. Wolf, W. Tremel, D. Schwahn, *J. Am. Chem. Soc.* **2008**, *130*, 6879.
- [71] K. X. Yao, H. C. Zeng, *J. Phys. Chem. C* **2007**, *111*, 13301.
- [72] H. Tang, J. C. Chang, Y. Y. Shan, S. T. Lee, *J. Phys. Chem. B* **2008**, *112*, 4016.
- [73] Y. Peng, A. W. Xu, B. Deng, M. Antonietti, H. Cölfen, *J. Phys. Chem. B* **2006**, *110*, 2988.
- [74] M. S. Mo, S. H. Lim, Y. W. Mai, R. K. Zheng, S. P. Ringer, *Adv. Mater.* **2008**, *20*, 339.
- [75] Z. H. Li, A. Gessner, J. P. Richters, J. Kalden, T. Voss, C. Kubel, A. Taubert, *Adv. Mater.* **2008**, *20*, 1279.
- [76] R. Knip, P. Simon, *Angew. Chem. Int. Ed.* **2008**, *47*, 1405.
- [77] K. Vanheusden, W. L. Warren, C. H. Seager, D. R. Tallant, J. A. Voigt, B. E. Gnade, *J. Appl. Phys.* **1996**, *79*, 7983.
- [78] J. Buha, I. Djerdj, M. Niederberger, *Cryst. Growth Des.* **2007**, *7*, 113.
- [79] Z. J. Yan, K. Zhu, W. P. Chen, *Mater. Lett.* **2009**, *63*, 486.
- [80] J. Polleux, N. Pinna, M. Antonietti, M. Niederberger, *J. Am. Chem. Soc.* **2005**, *127*, 15595.
- [81] J. Polleux, M. Antonietti, M. Niederberger, *J. Mater. Chem.* **2006**, *16*, 3969.
- [82] J. Polleux, A. Gurlo, N. Barsan, M. Antonietti, M. Niederberger, *Angew. Chem. Int. Ed.* **2006**, *128*, 9330.
- [83] Y. Oaki, H. Imai, *J. Mater. Chem.* **2007**, *17*, 316.
- [84] S. W. Yang, L. Gao, *J. Am. Chem. Soc.* **2006**, *128*, 9330.
- [85] J. P. Ge, Y. X. Hu, M. Biasini, W. P. Beyermann, Y. D. Yin, *Angew. Chem. Int. Ed.* **2007**, *46*, 4342.
- [86] L. Zhou, W. Z. Wang, H. L. Xu, *Cryst. Growth Des.* **2008**, *8*, 728.
- [87] L. Zhou, W. Z. Wang, L. Zhang, H. L. Xu, W. Zhu, *J. Phys. Chem. C* **2007**, *111*, 13659.

- [88] S. W. Liu, J. G. Yu, *J. Solid State Chem.* **2008**, *181*, 1048.
- [89] V. R. Calderone, A. Testino, M. T. Buscaglia, M. Bassoli, C. Bottino, M. Viviani, V. Buscaglia, P. Nanni, *Chem. Mater.* **2006**, *18*, 1627.
- [90] P. M. Rorvik, A. Almlı, A. T. J. van Helvoort, R. Holmestad, T. Tybell, T. Grande, M. A. Einarsrud, *Nanotechnology* **2008**, *19*, 225605.
- [91] Y. H. Zhen, J. F. Li, *J. Am. Chem. Soc.* **2007**, *90*, 3496.
- [92] T. R. Armstrong, R. C. Buchanan, *J. Am. Ceram. Soc.* **1990**, *73*, 1268.
- [93] H. Chazono, H. Kishi, *J. Am. Ceram. Soc.* **2000**, *83*, 101.
- [94] H. Y. Lu, J. S. Bow, W. H. Deng, *J. Am. Ceram. Soc.* **1990**, *73*, 3562.
- [95] C. Zhang, J. Chen, Y. C. Zhou, D. Q. Li, *J. Phys. Chem. C* **2008**, *112*, 10083.
- [96] N. Jongen, P. Bowen, J. Lemaıtre, J. C. Valmalette, H. Hofmann, *J. Colloid Interface Sci.* **2000**, *226*, 189.
- [97] L. C. Soare, P. Bowen, J. Lemaıtre, H. Hofmann, *J. Phys. Chem. B* **2006**, *110*, 17763.
- [98] N. Jongen, H. Hofmann, P. Bowen, J. Lemaıtre, *J. Mater. Sci. Lett.* **2000**, *19*, 1073.
- [99] C. S. Yang, C. J. Chen, X. H. Lin, *New J. Chem.* **2007**, *31*, 363.
- [100] N. Wang, X. Cao, L. Guo, S. H. Yang, Z. Y. Wu, *ACS Nano* **2008**, *2*, 184.
- [101] Y. Xia, Y. J. Xiong, B. Lim, S. E. Skrabalak, *Angew. Chem. Int. Ed.* **2009**, *48*, 60.
- [102] M. Rycenga, J. M. McLellan, Y. Xia, *Adv. Mater.* **2008**, *20*, 2416.
- [103] S. Wohlrab, N. Pinna, M. Antonietti, H. Cölfen, *Chem. Eur. J.* **2005**, *11*, 2903.
- [104] D. Schwahn, Y. R. Ma, H. Cölfen, *J. Phys. Chem. C* **2007**, *111*, 3224.
- [105] G. G. Zhang, S. Y. L. Paspal, R. Suryanarayanan, D. J. W. Grant, *J. Pharm. Sci.* **2003**, *92*, 1356.
- [106] T. Lee, C. W. Zhang, *Pharm. Res.* **2008**, *25*, 1563.
- [107] O. Grassmann, R. B. Neder, A. Putnis, P. Lobmann, *Am. Mineral.* **2003**, *88*, 647.
- [108] O. Grassmann, P. Lobmann, *Chem. Eur. J.* **2003**, *9*, 1310.
- [109] U. Helbig, *J. Cryst. Growth* **2008**, *310*, 2863.
- [110] A. Berman, L. Addadi, S. Weiner, *Nature* **1988**, *331*, 546.
- [111] H. Y. Li, L. A. Estroff, *Crystengcomm* **2007**, *9*, 1153.
- [112] H. Y. Li, L. A. Estroff, *Adv. Mater.* **2009**, *21*, 470.
- [113] Y. X. Huang, J. Buder, R. Cardoso-Gil, Y. Prots, W. Carrillo-Cabrera, P. Simon, R. Knıep, *Angew. Chem. Int. Ed.* **2008**, *47*, 8280.
- [114] P. Simon, W. Carrillo-Cabrera, P. Formanek, C. Gobel, D. Geiger, R. Ramlau, H. Tlatlik, J. Buder, R. Knıep, *J. Mater. Chem.* **2004**, *14*, 2218.
- [115] P. Simon, U. Schwarz, R. Knıep, *J. Mater. Chem.* **2005**, *15*, 4992.
- [116] H. Tlatlik, P. Simon, A. Kawska, D. Zahn, R. Knıep, *Angew. Chem. Int. Ed.* **2006**, *45*, 1905.
- [117] S. Busch, U. Schwarz, R. Knıep, *Adv. Funct. Mater.* **2003**, *13*, 189.
- [118] R. Knıep, S. Busch, *Angew. Chem. Int. Ed.* **1996**, *35*, 2624.
- [119] H. Cölfen, *Macromol. Rapid Commun.* **2001**, *22*, 219.
- [120] H. Cölfen, M. Antonietti, *Langmuir* **1998**, *14*, 582.
- [121] G. T. Wang, L. L. Li, J. B. Lan, L. J. Chen, J. S. You, *J. Mater. Chem.* **2008**, *18*, 2789.
- [122] M. G. Page, H. Cölfen, *Cryst. Growth Des.* **2006**, *6*, 1915.
- [123] H. Cölfen, L. M. Qi, *Chem. Eur. J.* **2001**, *7*, 106.
- [124] A. W. Xu, M. Antonietti, H. Cölfen, Y. P. Fang, *Adv. Funct. Mater.* **2006**, *16*, 903.
- [125] J. X. Fang, B. J. Ding, X. P. Song, Y. Han, *Appl. Phys. Lett.* **2008**, *92*.
- [126] J. X. Fang, B. J. Ding, X. P. Song, *Appl. Phys. Lett.* **2007**, *91*, 083108.
- [127] X. J. Zheng, Q. Kuang, T. Xu, Z. Y. Jiang, S. H. Zhang, Z. X. Xie, R. B. Huang, L. S. Zheng, *J. Phys. Chem. C* **2007**, *111*, 4499.
- [128] G. Z. Wang, R. Saeterli, P. M. Rorvik, A. T. J. van Helvoort, R. Holmestad, T. Grande, M. A. Einarsrud, *Chem. Mater.* **2007**, *19*, 2213.
- [129] Z. B. Zhuang, Q. Peng, J. F. Liu, X. Wang, Y. D. Li, *Inorg. Chem.* **2007**, *46*, 5179.
- [130] F. C. Meldrum, H. Cölfen, *Chem. Rev.* **2008**, *108*, 4332.
- [131] J. Aizenberg, J. C. Weaver, M. S. Thanawala, V. C. Sundar, D. E. Morse, P. Fratzl, *Science* **2005**, *309*, 275.
- [132] L. J. Bonderer, A. R. Studart, L. J. Gauckler, *Science* **2008**, *319*, 1069.
- [133] T. X. Wang, H. Cölfen, M. Antonietti, *J. Am. Chem. Soc.* **2005**, *127*, 3246.
- [134] E. V. Shevchenko, D. V. Talapın, N. A. Kotov, S. O'Brien, C. B. Murray, *Nature* **2006**, *439*, 55.
- [135] B. Judat, M. Kind, *J. Colloid Interface Sci.* **2004**, *269*, 341.
- [136] F. C. Meldrum, R. P. Sear, *Science* **2008**, *322*, 1802.
- [137] D. Gebauer, A. Völkel, H. Cölfen, *Science* **2008**, *322*, 1819.
- [138] E. M. Pouget, P. H. H. Bomans, J. Goos, P. M. Frederik, G. de With, N. Sommerdijk, *Science* **2009**, *323*, 1555.
- [139] R. Q. Song, A. W. Xu, M. Antonietti, H. Cölfen, *Angew. Chem. Int. Ed.* **2009**, *48*, 395.
- [140] H. Haberkorn, D. Franke, T. Frechen, W. Goesele, J. Rieger, *J. Colloid Interface Sci.* **2003**, *259*, 112.
- [141] D. Pontoni, J. Bolze, N. Dingenouts, T. Narayanan, M. Ballauff, *J. Phys. Chem. B* **2003**, *107*, 5123.
- [142] A. M. Stoneham, J. H. Harding, *Nat. Mater.* **2003**, *2*, 77.
- [143] R. L. Penn, *J. Phys. Chem. B* **2004**, *108*, 12707.
- [144] C. Ribeiro, E. J. H. Lee, E. Longo, E. R. Leite, *ChemPhysChem* **2006**, *7*, 664.
- [145] J. M. Garcia-Ruiz, E. Melero-Garcia, S. T. Hyde, *Science* **2009**, *323*, 362.