Recent progress in molten salt synthesis of low-dimensional perovskite oxide nanostructures, structural characterization, properties, and functional applications: A review

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**A B S T R A C T**

Molten salt synthesis (MSS) method has advantages of the simplicity in the process equipment, versatile and large-scale synthesis, and friendly environment, which provides an excellent approach to synthesize high pure oxide powders with controllable compositions and morphologies. Among these oxides, perovskite oxides with a composition of ABO3 exhibit a broad spectrum of physical properties and functions (e.g. ferroelectric, piezoelectric, magnetic, photovoltaic and photocatalytic properties). The downscaling of the spatial geometry of perovskite oxides into nanometers result in novel properties that are different from the bulk and film counterparts. Recent interest in nanoscience and nanotechnology has led to great efforts focusing on the synthesis of low-dimensional perovskite oxide nanostructures (PONs) to better understand their novel physical properties at nanoscale. Therefore, the low-dimensional PONs such as perovskite nanoparticles, nanowires, nanorods, nanotubes, nanofibers, nanobelts, and two dimensional oxide nanostructures, play an important role in developing the next generation of oxide electronics. In the past few years, much effort has been made on the synthesis of PONs by MSS method and their structural characterizations. The functional applications of PONs are also explored in the fields of storage memory, energy harvesting, and solar energy conversion. This review summarizes the recent progress in the synthesis of low-dimensional PONs by MSS method and its modified ways. Their structural characterization and physical properties are also scrutinized. The potential applications of low-dimensional PONs in different fields such as data memory and storage, energy harvesting, solar energy conversion, are highlighted. Perspectives concerning the future research trends and challenges of low-dimensional PONs are also outlined.

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1. Introduction

MSS method is a simple, versatile, and environmental-friendly approach, which has been widely used to synthesize high purity and nanoscale inorganic oxides with controllable compositions and morphologies. In this approach, inorganic molten salt is served as the reaction medium to enhance the reaction rate and to reduce the reaction temperature of the reactant oxides. Thanks to the short diffusion distances and large mobilities of the reactant oxides in the molten salts, the whole solid-state reactions are easily carried out at moderate temperatures (600–800 °C) in a short soaking time (less one hour) [1,2]. Besides the low formation temperature, molten salts also promote to stabilize the specific morphology of the final products [1–3]. Furthermore, the morphology of the final products can be well controlled by adjusting the processing parameters (e.g. the types and quantities of the used molten salts, different reactant oxides, heating temperature and duration, and heating/cooling rates) in the MSS reactions [4–7]. Up to date, a wide range of inorganic oxide materials with tunable morphology has been synthesized by MSS method [8–11]. For examples, perovskite ceramic powders of BaTiO3 [12,13], BaZrO3 [14], SrTiO3 [15], Ca1−xSrxTiO3 [16,17], Pb(ZrTi)O3 [18], and lead-based relaxors with a A(B′B")O3 perovskite structure have been synthesized by the MSS method [1–19–21]. In addition, pristine BaTiO3 nanostructures (including nanowires) with diameters of 50–80 nm and aspect ratios from 1 to over 25, as well as single-crystalline SrTiO3 nanocubes with an average edge length of 80 nm have been synthesized [22]. The evolution of BaZrO3 particle morphology from predominantly cubes to

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a mixture of cubes and spheres and finally to solely spheres is also documented by increasing the annealing/reaction times at selected annealing temperatures [16,17]. Recently, the MSS method has been used to synthesize one-dimensional (1D) perovskite MTiO$_3$ (M = Pb, Ba, Sr elements) nanostrips by using the mixed chlorides (NaCl/KCl = 1:1) as molten salt media [23]. Generally, in the process of the MSS method, two fundamental reaction mechanisms are involved during the formation of the final products. The first one is all the reactant oxides are fully dissolved within the molten salt and they diffuse to react in a short time. One model example is the Bi$_2$WO$_6$ system [24], in which Bi$_2$WO$_6$ particles are formed through complete dissolution of the constituent oxides (WO$_3$ and Bi$_2$O$_3$) in an equimolar mixed KCl-NaCl chlorides heated at 650 °C for 1 h and complete reaction between WO$_3$ and Bi$_2$O$_3$. The second one is that some reactants are much more soluble within the molten salt than the other components, so they diffuse onto the surfaces of the other components and react with them, forming the final products with a similar morphology as the less soluble reactants. A model example is template-free fabrication of pure single-crystalline BaTiO$_3$ nanorods by MSS method at relatively high temperature and large ratios of the salt to the precursors [25]. Since barium oxide has higher solubility in the molten NaCl/KCl salts as compared with the titanium oxide, therefore, much amount of barium oxide is dissolved in the molten salt whereas the insoluble titanium oxide particles have a chance to reunite into rods-like particles in the molten salt environment, acting as templates for further growth. As a consequence, the dissolved barium oxide particles can diffuse to the surfaces of rod-like titanium oxide and react with it in situ to form BaTiO$_3$ rod-like nanostructure. Here, the relative dissolution is a key factor in the reaction process, and the morphology of the less soluble reactants is finally inherited during the formation of final products. During the particle growth stage, the total surface areas are reduced, thus, finally the surfaces with high energy disappear, and the morphology of the final product is composed of the crystallographic planes with lowest surface energy, reaching the equilibrium state. Details about the fundamental reaction mechanisms of MSS reactions can be found in the previous reviews [1,5,26].

The main processing stages of the MSS method for synthesis of perovskite oxide powders are schematically illustrated in Fig. 1. At stage I, the reactant oxides and/or other appropriate precursors corresponding to the desired compound are mixed with either the desired salts (e.g., NaCl, KCl) or an eutectic mixture of the salts (e.g., NaCl - KCl, NaOH - KOH, NaNO$_3$ - KN0$_3$, Na$_2$SO$_4$ - K$_2$SO$_4$, Li$_2$SO$_4$-Na$_2$SO$_4$). At stage II, the mixture is heated at a temperature above the melting point of the salt medium to form a molten flux. At this temperature, precursor molecules disperse, dissociate, rearrange, and then diffuse rapidly throughout the salt. At stage III, the product particles start to nucleate and grow up via the solution-precipitation process. The characteristics of the product powder are controlled by selecting the temperature and duration of the heating. The reacted mass is cooled to room temperature and washed with an appropriate solvent (water usually used) to remove the salt. The complex perovskite oxide powders can be obtained after drying, and they have several unique characteristics as compared to those obtained by other methods such as solid-state reactions [27,28], combustion synthesis [29,30], and sol-gel method [31,32]. Such unique features are determined mainly by the chemical and crystallographic constraints given by the salts [33,34], which are especially distinguishable in the case of strongly anisotropic perovskite oxides. It is believed that the features are related to the surface and interface energies between the constituents and the salts, resulting in a tendency to minimize the energies by forming a specific morphology. The environments during the development of the morphology of perovskite oxides can be controlled by the selected salts. Therefore, the selection of the molten salts is critical in obtaining desirable powder characteristics.

Nanostructured oxide materials exhibit novel phenomena because of the size effects that appear during the downscaling of the spatial geometry of oxide materials. Compared with the bulk counterparts, nanostructured oxide materials possess some specific surfaces and have lots of surface atoms and higher levels of surface energy. Up to date, nanostructured oxide materials including zero-dimensional (0D), 1D, and two-dimensional (2D) oxide nanostructures, have attracted much attention due to their unique geometries and novel properties, which make them as key building blocks to construct various oxide nanodevices [35–37]. However, it is found that the synthesis of 1D or 2D oxide nanostructures by the traditional MSS method is much difficult due to the nature of equiaxial growth for the oxide particles. To achieve the anisotropic growth of oxide particles in MSS process, selection of suitable templates with specific morphology is crucial to promote the process [39–41]. The template method is an efficient and mild way to prepare pure 1D or 2D oxide nanostructures with controllable morphology at moderate reaction conditions [40–42].

Among the inorganic oxides, perovskite oxides with a composition of ABO$_3$ are one of the most important functional materials due to their rich physical properties (e.g. dielectric, ferroelectric, piezoelectric, magnetic, multiferroic properties) [35]. Generally, in the ABO$_3$ perovskite structure A-site is occupied by alkaline earth ions or rare-earth ions, and B-site is occupied by transition metal ions. Many physical properties of perovskite oxides are resulted from B-site cations while tuned by A-site cations [43,44]. Over the past few years, many low-dimensional PONs (e.g. nanoparticles, nanowires, nanorods, nanotubes, nanofibers, nanobelts, and 2D-nanostructures) have been synthesized by MSS method. Their process-structure-property relations are intensively investigated.

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Fig. 2. Structural characterizations of the as-prepared BaZrO$_3$ nanoparticles with cubic or spherical morphology synthesized by MSS method. SEM images of BaZrO$_3$ nanoparticles with (a) cubic and (b) spherical morphology. (c) and (d) XRD and EDS patterns of the BaZrO$_3$ nanoparticles, respectively. The lower pattern in panel (c) corresponds to a database standard (JCPDS 06-0399) for the cubic phase of BaZrO$_3$. The carbon peak in (d) originates from the conductive carbon tape. (e) and (f) TEM, HRTEM, and SAED pattern (inset) of a cubic BaZrO$_3$ nanoparticle. (g) and (h) TEM, HRTEM, and SAED pattern (inset) of a spherical BaZrO$_3$ nanoparticle. Reproduced with permission [48]. Copyright 2007, American Chemical Society.

Fig. 3. XRD patterns of the BaTiO$_3$ nanoparticles synthesized by MSS method in (a) NaOH-KOH and (b) NaCl-KCl based salt systems under different temperatures. (c) and (d) The corresponding TEM images of the BaTiO$_3$ nanoparticles synthesized in different molten salt systems. Reproduced with permission [67]. Copyright 2010, Gordon and Breach Publishing.

The functional applications of PONs are also explored in the fields of storage memory, energy harvesting, and solar energy conversion. This review summarizes the recent advances and progress in the molten salt synthesis of PONs. The structural characterization, physical properties, and potential applications of low-dimensional PONs in the fields of storage memory, energy harvesting, and solar energy conversion, are also addressed. The prospects and
Fig. 4. SEM images of the KNbO₃ nanomaterials synthesized with different precursors. (a) KNb₃O₈ nanowires, (b) H₃ONb₃O₈ nanorods, and (c) Nb₂O₅ nanowires. Reproduced with permission [69]. Copyright 2009, American Chemical Society.

Fig. 5. XRD patterns of the KNbO₃ nanomaterials synthesized with different precursors: (a) KNb₃O₈ nanowires, (b) H₃ONb₃O₈ nanorods, and (c) Nb₂O₅ nanowires. (d) TEM image of a single KNbO₃ nanorod synthesized with the precursor of Nb₂O₅ nanowires and its corresponding SEAD pattern (inset). Reproduced with permission [69]. Copyright 2009, American Chemical Society.
challenges of future researches of low-dimensional PONs are also outlined.

2. Low-dimensional PONs synthesized by MSS

2.1. Perovskite oxide nanoparticles

Perovskite oxide nanoparticles exhibit some special physical properties that are ascribed to the surface effect, small size effect, quantum confinement effect, and etc. [45,46]. Up to date, many perovskite oxide nanoparticles are synthesized by MSS method. For example, Yang et al. [47] reported the perovskite SrFeO3 nanoparticles synthesized by MSS method. They investigated systematically the effects of processing parameters of MSS method (e.g. types of metal precursors, salt medium, annealing temperature, oxidizing properties of the melt salts) on the structural characteristics of the final products (e.g. phase compositions, crystallite sizes, and morphology). It was found that the formation of the perovskite SrFeO3 phase was mainly dependent upon the nature of the metal precursors and the used salt medium. Metal nitrates were found to be the suitable precursors and NaN3-NKNO3 eutectic with Na2O2 was the suitable salt medium for the synthesis of pure perovskite SrFeO3 nanoparticles. Li et al. [15] also synthesized cubic phase SrTiO3 nanoparticles by MSS method, where the eutectic NaCl - KCl molten salts were used as reaction medium, TiO2 and Sr(NO3)2 were used as the reactant powders. The results demonstrated that the sizes of the as-synthesized SrTiO3 nanoparticles were controlled the types of TiO3 precursors, indicating that the formation of SrTiO3 nanoparticles in the NaCl - KCl molten salts was mainly controlled via a template formation mechanism. Zhou et al. [48] reported the synthesis of single-crystalline perovskite BaZrO3 nanoparticles with cubic or spherical morphology by MSS method, where BaC2O4 and ZrO2 were used as precursors, and NaOH - KOH was used as the molten salt. Recently, single-phase perovskite Pb(Fex0.5 Nb0.5)O3 (PFN) [49], Ca1−xSr2TiO3 (0 ≤ x ≤ 1) nanoparticles [16], and multiferroic BiFeO3 nanoparticles [50–54] have been synthesized via MSS method. In order to understand the reaction mechanism in MSS reactions, the growth behavior of lead zirconate titanate (PZT) nanoparticles in MSS process was investigated by Bortolani and Dorey [55]. They found that lead was first dissolved in the molten salts and then reacted with insoluble TiO2 to form an intermediate phase of PbTiO3, and then the zirconium diffused into and reacted with PbTiO3 to form PZT nanoparticles. The diffusion of zirconium through the PbTiO3 follows a rate-limiting law, and simultaneously, the particle coarsening takes place based on a challenge to create small particles where two low solubility phases are present. Besides the ferroelectric perovskite nanoparticles, magnetic perovskite nanoparticles such as La0.7Sr0.3MnO3, (LSMO) (x = 0.18 − 0.37) with a rhombohedral perovskite structure, are also synthesized by MSS method [56]. The synthesized LSMO nanoparticles with mean size of ~50 nm have a lower magnetization and reduced Curie temperature as compared with their bulk counterpart.

2.2. Perovskite oxide 1D nanostructures (nanowires, nanorods, and nanotubes)

1D PONs include nanowires, nanotubes, nanorods, nanoribbons, and etc., which are not only used as the building blocks for constructing future nanodevices, but also provide with the possibilities for fundamentally investigating the intrinsic size effects of physical properties [36–38]. For instance, perovskite ferroelectric oxide nanowires have excellent piezoelectric properties, and this enables them used as active cantilevers in micro-electromechanical and nanoelectromechanical systems. Deng et al. [23] first reported on the general surface-free synthesis of MFeO3 (M = Pb, Ba, Sr) perovskite nanostrips by MSS method. The nanostrips had a width of ~200 nm, thickness of 20–50 nm, and length up to tens of micrometers. Giant dielectric copper calcium titanate (CaCu3Ti4O12) perovskite nanorods were also synthesized by MSS method [57], indicating that single-crystalline quaternary perovskite nanostructures can be formed. Besides perovskite oxide nanowires, perovskite nanotubes are also synthesized by MSS method. Wang et al. [58] also reported on the synthesis of single-crystalline LaFeO3 nanotubes by co-precipitation followed by MSS method. In this process, La(NO3)3 and Fe(NO3)3·9H2O were first added drop-wise to the co-precipitation reagent of NaOH and NP10, and then the precipitates of Fe(OH)3 and La(OH)3 were mixed with NaI and the mixture was annealed at 680 °C for 2.5 h. Finally, tube-like LaFeO3 nanostructures with a diameter of 40–200 nm and length up to 3 μm were obtained. Lead-free (KNa)NbO3 (KNN) single-crystalline nanorods with a high piezoelectric coefficient were also obtained by MSS method [59,60]. Their diameters were in the range from 200 nm to 700 nm with a length from 10 μm to 20 μm. Similarly, perovskite cubic phase of BaTiO3 nanowires with different diameters and aspect ratios were also synthesized by MSS method [25,61]. Recently, much longer (up to 80 μm) single-crystalline perovskite BaTiO3 nanowires with a tetragonal phase structure have also been synthesized [62]. They exhibit uniform cylindrical structure with diameters in the range of 100 nm to 1 μm.

2.3. Perovskite oxide 2D nanostructures

2D materials are described as the materials having a few nanometers or less in the thickness direction. Therefore, electrons can move freely in the two-dimensional plane normal to the thickness direction, however, their motion is limited in the thickness direction and governed by quantum mechanics. Typical 2D materials include quantum wells, nanoplates and nanofilms, and graphene. As one typical example of 2D materials, graphene has received much attention due to its fascinating electronic, magnetic, optical, and mechanical properties [63]. Recently, the focused point has switched to the low-dimensional PONs because of their unusual electron transport and magnetic properties, which are invaluable for developing multi-functional microelectronic, magnetic, and spintronic devices based on 2D PONs. However, it is not easy to fabricate 2D PONS due to the equiaxed growth nature.

of perovskite oxides. The MSS method provides an approach to obtain the 2D PONs [64–66]. For instance, Su et al. [64] fabricated the micrometer-sized (001)-oriented BaTiO$_3$ (BT) platelets with a diameter of 10–20 μm and thickness of 0.5–1.0 μm by a modified two-step MSS method. Plate-like NaNbO$_3$ with high aspect ratio (the ratio of length to thickness from 15:1 to 50:1) was synthesized by Zhang et al. via topochemical MSS method [65]. In this process, plate-like bismuth layered perovskite Bi$_{2.5}$Na$_3.5$Nb$_5$O$_{18}$ precursors were first synthesized by MSS method at 1100 °C with molten NaCl salt as reaction medium, and then they reacted with the complementary reactant Na$_2$CO$_3$ in NaCl flux at 950 °C. During the transformation of plate-like Bi$_{2.5}$Na$_3.5$Nb$_5$O$_{18}$ particles into the plate-like perovskite KNaNbO$_3$ particles, the morphology of the Bi$_{2.5}$Na$_3.5$Nb$_5$O$_{18}$ precursors was inherited. The transformation mechanism of the above reaction can be expressed as follows [65]:

$$\text{Bi}_{2.5}\text{Na}_{3.5}\text{Nb}_{5}\text{O}_{18} + \text{Na}_2\text{CO}_3 \rightarrow \text{KNaNbO}_3 + \text{Bi}_2\text{O}_3 + \text{CO}_2$$ (1)

Similarly, needle-like or plate-like KNbO$_3$ (KN) and K$_{1.5}$Na$_3$NbO$_3$ (KNN) nanostructures with high aspect ratios were also synthesized, which grew with preferred orientation along the [011] or [100] directions through a dissolution - precipitation mechanism [66]. It is expected that with the development of oxide electronics, more and more 2D PONs will be synthesized by MSS method and its improved ways.

3. Structural characterization of low-dimensional PONs synthesized by MSS method

3.1. Introduction

The structural characterizations of low-dimensional PONs are conducted to investigate their crystal structures, chemical compositions, and morphologies. The crystal structures are usually characterized by X-ray diffraction (XRD), Raman spectrum, Fourier transformed infrared spectroscopy, transmission electron microscopy (TEM), high-resolution TEM (HRTEM), and selected area electron diffraction (SAED). The chemical compositions are usually examined by energy dispersive X-ray detector (EDX), electronic energy loss spectroscopy (EELS), and X-ray photoelectron spectroscopy (XPS). The morphologies are usually characterized by atomic force microscopy (AFM), scanning electron microscopy (SEM) and TEM. In this section, the structural characterizations of low-dimensional PONs are described to provide a brief review of the microstructures of low-dimensional PONs synthesized by MSS method.

![Fig. 7](image-url) (a) TEM image of the as-prepared K$_0.5$Bi$_{0.5}$TiO$_3$ nanowires with random orientation. (b) XRD pattern of the corresponding nanowires. (c) TEM image of a single K$_0.5$Bi$_{0.5}$TiO$_3$ nanowire. (d) SAED pattern taken from an individual nanowire. (e) High-resolution TEM image of a single K$_0.5$Bi$_{0.5}$TiO$_3$ nanowire. Reproduced with permission [71]. Copyright 2007, The American Institute of Physics.
Fig. 8. (a) TEM image and (b) EDS spectrum of the BaMnO₃ nanorods synthesized by MSS method at 200 °C for 120 h. (c) TEM image of a single BaMnO₃ nanorod and (d) its diffraction pattern, and (e) HRTEM image taken from the square box marked in Fig. c. Reproduced with permission [72]. Copyright 2006, The American Chemical Society.
3.2. Perovskite oxide nanoparticles

Zhou et al. [48] reported the microstructural characterizations of single-crystalline perovskite BaZrO₃ nanoparticles with cubic and spherical morphologies synthesized by MSS method. The results including the SEM images, XRD and EDS patterns, TEM and HRTEM images, are shown in Fig. 2. As it can be seen that the lattice fringes in the HRTEM images and the SAED patterns (Fig. (f)–(h)) clearly reveal the single-crystalline nature of the BaZrO₃ particles. The XRD pattern (Fig. 2(c)) demonstrated that the BaZrO₃ particles crystallized in a cubic phase with a lattice constant of $a = 0.4183$ nm, which was in good agreement with literature data ($a = 0.4181$ nm, JCPDS no. 06-0399). Sahoo and Mazumder [67] reported the microstructural evolutions of perovskite BaTiO₃ nanoparticles during their formation process in MSS reaction. The XRD patterns revealed that pure perovskite BaTiO₃ phase appeared at 175 °C in the NaOH - KOH based-salt system (Fig. 3(a)), whereas pure perovskite BaTiO₃ phase appeared at much higher temperature (e.g. 700 °C) in the NaCl - KCl based-salt system (Fig. 3(b)). That demonstrates that the selection of different molten salt systems play an important role in affecting the formation temperature of perovskite phase [68]. TEM images demonstrated that the average particle size of the BaTiO₃ particles synthesized in the NaOH - KOH based-salt system was about 70–100 nm with cube shape (Fig. 3(c)), whereas in the NaCl - KCl based-salt system the BaTiO₃ particles exhibited cube shape mixed with some irregular shaped ones (Fig. 3(d)).

3.3. Perovskite oxide 1D nanostructures (nanowires, nanorods and nanotubes)

In spite of the effectiveness of MSS method for perovskite oxide nanoparticles, the reliable synthesis of 1D PONs is restricted to only a few types of perovskite oxides such as niobates [69,70], titanates [21,23,71], as well as some manganate systems [72,73]. Li et al. [69] reported on the perovskite niobate ANbO₃ (A=K, Na, or Na/K) nanorods, which were prepared by topochemical MSS method, where the Nb₂O₅ nanorods were used as precursors. They found that only KNbO₃ nanoparticles rather than nanorods were obtained as either KNbO₃ nanowires or H₃ONbO₃ nanorods were used as precursors, indicating the morphologies of the precursors are not inherited. That was confirmed by the SEM images (Fig. 4). On the contrary, when the Nb₂O₅ nanorods were used as the precursors, their morphology were inherited, thus, the rods of KNbO₃ were obtained, as shown in Fig. 4(c). The above results show that suitable selection of the template (1D Nb₂O₅ precursor) is crucial for the formation of perovskite KNbO₃ nanowires because during the molten flux reaction the layer-structured rod-like precursors (e.g. KNbO₃ or H₃ONbO₃) are easily disrupted by the transport of alkali ions, and thus, their initial rod-like morphology is not able to be inherited. By contrast, Nb₂O₅ precursors maintain a more compact and stable crystal structure, which can easily accommodate the alkali ions without destroying its initial rod-like morphology, therefore, perovskite KNbO₃ nanorods were formed by inheriting the rod-like morphology of the Nb₂O₅ precursors. XRD patterns (Fig. 5(a)-(c)) demonstrated that all the synthesized KNbO₃ nanorods crystallized in an orthorhombic structure (JCPDS 71-946). Their growth direction was along the [011] direction, as marked by an arrow in Fig. 5(d). By using a modified multi-step MSS procedure, Wong’s group synthesized potassium and sodium niobate nanorods and LiNbO₃ nanowires [70]. Recently, much effort has been made to synthesize 1D MTO₃ (M=Pb, Ba, Sr) perovskites due to their promising applications in oxide microelectronics. Dong et al. [23] first reported on the general synthesis of MTO₃ nanotips (M=Pb, Ba, Sr) by a surfactant-free approach in non-aqueous molten salt media. The as-synthesized MTO₃ nanotips had a width of 50–200 nm, a thickness of 20–50 nm, and a length up to tens of micrometers. They all grew in the [001] direction. In this MSS process, the corresponding metal oxalate (barium oxalate, stron-
tium oxalate and lead oxalate) and TiO$_2$ were used as precursors in a NaCl - KCl flux. It was found that high reaction temperature, long reaction time as well as small-sized TiO$_2$ precursors were benefit for growing the titanate nanostrips. The possible growth mechanism of the MTIO$_3$ nanostrips can be expressed in the following reaction [23]:

$$MC_2O_4(s) + TiO_2 \xrightarrow{NaNCl-KCl flux} MTIO_3 + CO_2 (g)$$ (2)

Similarly, single-crystalline perovskite BaTiO$_3$ nanowires were also synthesized by MSS method [64]. As shown in Fig. 6(a), the BaTiO$_3$ nanowires had a width of 30–100 nm and length up to several micrometers. The enlarged TEM images collected from the tip points A and B (Fig. 6(b)-(c)) revealed that the tips of the nanowires exhibited triangle or circular arc morphologies. Fig. 6(d) was a representative HRTEM image taken from the tip of a BaTiO$_3$ nanowire with a triangle shape. Clearly, the two-dimensional lattice fringes with spacings of 0.4013 nm and 0.1795 nm are resolved, which correspond to the (100) and (210) lattice planes of the cubic BaTiO$_3$ nanoparticle, respectively. The SAED pattern taken from a single BaTiO$_3$ nanowire was shown as an inset in Fig. 6(c), which demonstrated the growth direction of the nanowire along [001] direction. Yang et al. [71] also fabricated single-crystalline $K_{0.5}Bi_{0.5}TiO_3$ nanowires by a large scale and facile molten salt synthetic method. Analytical grade $K_2CO_3$, $Bi_2O_3$ and TiO$_2$ were used as the starting materials, and KCl used as molten salt. A representative TEM and HRTEM image of the as-prepared ($K_{0.5}Bi_{0.5}$)TiO$_3$ nanowires (Fig. 7) reveal that the nanowires have a tetragonal perovskite structure with a diameter about 40 nm and lengths over 4 μm. The single-crystalline nature of the ($K_{0.5}Bi_{0.5}$)TiO$_3$ nanowires are also confirmed by the SAED pattern and the lattice fringes resolved in the HRTEM image. In addition, manganese perovskite oxide nanowires are also synthesized by MSS method. For example, Hu et al. [72, 73] reported on BaMnO$_3$ and Ba(Ti$_{0.5}$Mn$_{0.5}$)O$_3$ nanorods/nanowires synthesized under a mixed KOH and NaOH with a K/Na ratio of 48.5:51.5. The synthesis temperature was as low as 170 °C. Typical BaMnO$_3$ nanorods had a width of 50–100 nm, and their lengths were easily controlled by processing parameters of the MSS process (e.g. annealing temperature, soaking time). Fig. 8 demonstrated the TEM characterizations of the BaMnO$_3$ nanorods synthesized at 200 °C for 120 h. The SAED pattern and HRTEM (Fig. 8(d)-(e)) revealed the single-crystalline nature of the nanorods, which grew along the direction of [001]. The formation mechanism of perovskite BaMnO$_3$ nanorods is described as the following reactions [72]:

$$BaCl_2 + 2NaOH \rightarrow Ba(OH)_2 + 2NaCl$$ (3)
$$MnO_2 + 2NaOH \rightarrow Na_2MnO_3 + H_2O$$ (4)
$$Ba(OH)_2 + Na_2MnO_3 \rightarrow BaMnO_3 + 2NaOH$$ (5)

3.4. Perovskite oxide 2D nanostructures

Perovskite oxide 2D nanostructures such as perovskite oxide nanosheets, exhibit interesting optical and electrical properties due to the electron and phonon confinement, large-surface-to-volume ratios and tap density, high surface reaction activity, and high catalytic efficiency. They have promising applications in the fields of high-density memory and storage, solar cells, and photocatalysis. Recently, Arney et al. [74] reported the synthesis of rectangular platelet-like perovskite La$_2$Ti$_2$O$_7$ photocatalyst by MSS method, where the mixed Na$_2$SO$_4$-K$_2$SO$_4$ flux was used as molten salt and analytical grade TiO$_2$ and La$_2$O$_3$ oxides were used as the starting materials. SEM images revealed that rectangular platelet-like morphology was obtained with maximal dimensions of 500–5000 nm and thicknesses below 100 nm. The products with smaller sizes can be synthesized under larger molar ratio of molten salt to the starting oxides and the extent of aggregation is increased with increasing the reaction time. It is found that the exposed crystalite edges and the (010) and (001) crystal faces in the platelet-like perovskite La$_2$Ti$_2$O$_7$ sheets play a key role in enhancing their photocatalytic activities. Meanwhile, Liu et al. [75] reported micron-scale platelet-like BaTiO$_3$ particles with an average size of 5–10 μm and a thickness of 0.5 μm. Fig. 9 shows the SEM image of platelet-like BaTiO$_3$ particles heated at 1100 °C for 1 h, whereas the morphology of these platelets are still kept after high-temperature treatment. However, up to date perovskite oxide 2D nanostructures synthesized by MSS method are rarely reported, their researches and developments are still at the embryonic stage. Therefore, the integration of perovskite oxide 2D nanostructures into oxide micro-electronic devices faces great challenges. Much work lies ahead in this direction.

4. Physical characterizations of low-dimensional PONs synthesized by MSS method

4.1. Introduction

Perovskite oxides exhibit excellent ferroelectric, piezoelectric, pyroelectric, ferroelastic, and other unique physical properties such as ferromagnetism, magnetoresistance, and multiferroics [76–78]. Up to date, the most widely investigated perovskite oxides include BaTiO$_3$, PbTiO$_3$, SrTiO$_3$, Pb(Zr,Ti)O$_3$, (Ba,Sr)TiO$_3$, KTaO$_3$, and multi-ferroic oxides such as BiFeO$_3$ [79, 80]. Recent interest in nanoscience and nanotechnology has led to great efforts focusing on the synthesis of low-dimensional PONs to better understand their novel
physical properties at nanoscale. In this section, some important physical properties of low-dimensional PONs synthesized by MSS method, are addressed and discussed.

4.2. Electrical properties

Perovskite oxide nanocrystals and nanowires can be used to fabricate ferroelectric ceramics at low sintering temperatures, which exhibit highly uniform nanostructured texture and grain sizes. Recently, Liu et al. [81] prepared BiFeO$_3$ ceramics, which are made from the BiFeO$_3$ micro- and nano-crystals synthesized by MSS method in the NaCl – KCl salt system. They found the BiFeO$_3$ ceramics exhibiting relatively high dielectric constants (the maximal value ~250 measured @10$^4$ Hz and room temperature). The corresponding dielectric losses were in the range of 0.05–0.2, which were dependent upon the processing parameters of the MSS method. The effects of MSS processing parameters (e.g. annealing temperature, soaking time, and the molar ratio of the starting oxides to molten salts) on the dielectric properties of the BiFeO$_3$ ceramics are shown in Fig. 10. Thus, the dielectric properties of BiFeO$_3$ ceramics can be effectively controlled by adjusting the processing parameters of the MSS method. In another example, Zhao et al. [82] fabricated 0.67Pb(Mg$_{1/3}$Nb$_{2/3}$)$_2$O$_3$ – 0.33PbTiO$_3$ (0.67PMN–0.33PT) perovskite ceramics based on the corresponding ceramic powders synthesized by MSS method in sulphate and chloride molten salts. Large grain sizes and better electrical properties were observed in the 0.67PMN–0.33PT ceramics prepared in chloride molten salts in comparison with that prepared in sulphate molten salts. The maximal dielectric constant of the 0.67PMN–0.33PT ceramics was 29385, and its piezoelectric constant $d_{33}$ was about 660 pC/N. High-density NaNbO$_3$ piezoelectric ceramics with an orthorhombic structure were also prepared by MSS method [83]. Their ferroelectric properties before and after the polarization treatment are shown in Fig. 11, which are closely related to the polarization treatment. More specifically, the polarized specimens have smaller coercive electric field ($E_c$) than that of the un-polarized specimens, however, they have two times larger remanent polarization than that of the un-polarized specimens. The piezoelectric constant $d_{33}$ of the NaNbO$_3$ ceramics was evaluated to be 28 pC/N after aging for 24 h, which is comparable to the values reported previously [84,85]. Recently, the piezoelectric properties of an individual (K,Na)NbO$_3$ nanobar synthesized by MSS method, is also reported.
4.3. Magnetic properties

Perovskite manganites with a composition of $R_{1-x}A_xMnO_3$ ($R = \text{La and rare earths}$, $A = \text{Ca, Sr, Ba, etc.}$) exhibit complex interactions among the freedoms of spin, charge, orbital, and lattice degrees, leading to novel physical phenomena such as colossal magnetoresistance (CMR) effect, metal-insulator (M-I) transition, electronic phase separation [89–93]. At nanoscale the properties of perovskite manganites are quite different from their corresponding bulk counterparts. Numerous special physical characters such as surface spin glass behavior, high magnetic coercivity, and small remanent magnetization are reported in the low-dimensional PONs [94–97]. For instance, Kacenka et al. [56] found that the single-phase perovskite La$_{1.33}$Sr$_{0.67}$MnO$_3$ (LSMO, $x = 0.18$ – 0.37) nanoparticles synthesized by molten salt method, exhibited much lower remanent magnetization and Curie temperature in comparison with samples derived from a sol-gel process. Such anomalous behaviors could be partially ascribed to the presence of magnetically dead surface layer in the perovskite magnetic nanoparticles. In addition, neutron diffraction data collected from the as-prepared LSMO nanoparticles indicate that the anomalous behaviors of the LSMO nanoparticles is probably originated from an over-doped outer shell, which is resulted from both the surface oxygen chemisorption and an increased Sr concentration in the shell. Luo et al. [98] also found that the nanocrystalline La$_{0.7}$Sr$_{0.3}$MnO$_3$ particles synthesized by MSS method, exhibited an enhanced magnetoresistance (MR). Their temperature dependence of the MR ratio (defined as $(R_{\text{RT}} - R_{\text{ST}})/R_{\text{RT}}$) of the products and the resistance are shown in Fig. 13. As can be seen that the MR ratio of the samples annealed at 700 °C is much larger than that of the samples annealed at 500 and 600 °C, and the MR ratio reaches 1050% at 10 K for the samples annealed at 700 °C (Fig. 13(a)). This value is much higher than that of the LSMO samples annealed at 800 °C derived from the sol-gel process [99]. The enhanced MR effect is mainly ascribed to the enhanced spin polarized tunneling effect caused by the improved crystallinity of the nanosized LSMO grains [100,101]. In Fig. 13(b), it was observed that the resistivity of LSMO samples was increased as the annealed temperature was increased, which was due to the reduction of the LSMO particle size. Generally, as the particle size is decreased, the resistance between the grain boundary is increased, which is benefit for the spin polarized tunneling. It is known that the crystallization degree of the LSMO grains becomes improved with increasing the annealed temperature, resulting in the disappearance of surface spin-glass behavior. As a consequence, the blocking temperature ($T_q$) that corresponds to the super-paramagnetic transformation, moves towards higher temperature as the increasing annealed temperature, as marked by arrows in Fig. 13(c). The inset of Fig. 13(c) demonstrates that the magnetization is increased with increasing the annealed temperature whereas it is not saturated even at the external magnetic field up to 5T. Overall, the above results indicate that the surface crystallization degree of the manganese particles determines their spin-glass behavior and enhances the MR effect at low temperatures.

![Fig. 13. Plots of (a) MR ratio measured at 5T for LSMO calcined at different temperatures, and (b) their resistance (@ 0T and 5T) as a function of the temperature. (c) Temperature dependence of the ZFC and FC magnetizations (@ H = 200Oe) of the LSMO particles calcined at different temperatures. The inset shows typical M - H curves at 5K. Reproduced with permission [98]. Copyright 2003, Elsevier Ltd.]()
ical Eu$^{3+}$-emission, where the optical absorption bands from $^5D_0$ to $^7F_j$ ($j=0-5$) are clearly resolved. Three strong optical absorption bands are contributed from the $^5D_0 \rightarrow ^7F_{1,2,4}$ transitions can be seen, i.e. the dipole-dipole type and hypersensitive $^5D_0 \rightarrow ^7F_2$ (at least 3 peaks) dominate the magnetic type $^5D_0 \rightarrow ^7F_1$ transition (3 peaks). The structure of $^5D_0 \rightarrow ^7F_4$ transition is very complex and it demonstrates at least 8 bands. In addition, the forbidden transition from $^5D_0$ to $^7F_0$ was also observed, which was composed of at least 3 bands, implying that the Eu$^{3+}$ ions are located three different local sites in the Eu-doped LaAlO$_3$ nanocrystals. Generally, such non-degenerate transition is often used as a probe to detect structural information on the local crystallographic symmetry, number of sites and site distribution of Eu$^{3+}$ cations in the crystalline matrix. The excitation spectra shown in Fig. 14(b) are composed of one broad (FWHM ~ 50 nm) and intense band as well as less intense and narrow (FWHM ~ 7 nm) bands. The former one with maximum is located at around 325 nm that was ascribed to the $^1O_2 \rightarrow$ Eu$^{3+}$ charge transfer transition, while the latter narrow excitation bands are originated from the $f$-$f$ transitions of Eu$^{3+}$ ions. These bands can be assigned to the charge transfer transitions from $^7F_0$ to highest manifolds (e.g. $^7F_0 \rightarrow ^5G_7$, $^5L_4$ at 373–382 nm range, $^5F_0 \rightarrow ^5L_6$ at 393 nm, and $^7F_0 \rightarrow ^5D_3$, $^5D_2$, $^5D_1$ at 413, 463 and 520–540 nm), respectively. The PL spectra of the CaTiO$_3$ phosphors doped by Eu with different doping concentrations (i.e. 0, 2, 4, and 6 mol%) is shown in Fig. 15(a) [108]. As it can be seen, the PL intensity was increased with increasing the Eu-doped concentrations, and a maximum value was reached at the doping level of 6 mol%, yielding the highest PL red emission intensity. As the optimal Eu-doping level of 6 mol% is kept as a standard, the optical properties of the Eu-doped other perovskites such as SrTiO$_3$, BaTiO$_3$, and CaTiO$_3$ are comparatively investigated, details are shown in Fig. 15(b). Clearly, the expected Eu$^{3+}$-emission bands corresponding to the $f$-$f$ transitions, are observed for all of the examined perovskite titanate structures. Among them, the Eu-doped CaTiO$_3$ nanoparticles exhibit the highest intensity of the PL red emission [108].

4.5. Photocatalytic properties

Recently, perovskite oxide nanomaterials have received much attention in solar energy conversion due to their high conduction band gap position, high stability, solar absorption band gap. Especially, the controllable physicochemical properties enable them as energetic materials for catalysis. For example, BiFeO$_3$ nanowires and nanocubes exhibit photocatalytic abilities to produce O$_2$ under UV irradiation [109,110]. It is also found that BiFeO$_3$ nanoparticles coated with SrTiO$_3$ can produce H$_2$ under visible-light irradiation although the pure BiFeO$_3$ nanoparticles are not able to produce hydrogen [111]. Previous reports demonstrate that among the ABO$_3$-type perovskites, tantalates (e.g. NaTaO$_3$), titanates (e.g.
SrTiO$_3$ as well as niobates (e.g. KNbO$_3$, NaNbO$_3$) exhibit excellent hydrogen production under UV-light irradiation [112–114]. In addition, under UV-light irradiation perovskite NaTaO$_3$ and KTaO$_3$ nanomaterials also exhibit high photocatalytic activities for water splitting [113,115]. However, most perovskite oxide nanomaterials primarily absorb UV light due to their wide bandgap ($E_g$) (e.g. NaTaO$_3$: $E_g$ = 4.0 eV, KTaO$_3$: $E_g$ = 3.6 eV). Unfortunately, the UV light only accounts for 3.5% of the solar spectrum. On the contrary, the visible and near infrared (NIR) lights account for 48% and 44% of the solar spectrum, respectively. Therefore, to improve the water splitting efficiency under sunlight irradiation, the development of new perovskite oxide nanomaterials that are sensitive to UV, visible, and NIR lights at the same time become crucial issue [113]. It is also noticed that the small absorption coefficients of perovskite oxide nanomaterials further weakens their light harvesting capabilities. In addition, to realize efficient charge separation and migration, perovskite oxides nanostructures with small size and high crystallinity are also highly required because the small particle size provides higher diffusion length and electrons or holes can be easily transported to the catalyst surface for reaction. The high degree of crystalline structure also avoids electron’s trapping inside the particles.

In recent years, besides the ideal and the modified ABO$_3$-type perovskite oxides, numerous layered perovskite oxides are also reported to be used as photocatalysts. For instance, the (110)-layer structured perovskites such as $M_2$Nb$_2$O$_7$ ($M$ = Ca, Sr) and $R_2$Ti$_2$O$_7$ ($R$ = Y, La-Yb) exhibit the highest photocatalytic rates, and their quantum yields are reported to be as high as ~20–50% under UV irradiation [116,117]. In the past decade, the photocatalytic activities of $R_2$Ti$_2$O$_7$ for H$_2$ and/or O$_2$ have been studied as a function of the different rare-earth elements (i.e. $R$ = Y, La, Pr, Nd, Sm, Gd) [118–120], transition-metal dopants for its sensitization to visible light [121,122], as well as for the decomposition of organic pollutants [123,124]. Among the layer-structured $R_2$Ti$_2$O$_7$ perovskites, La$_2$Ti$_2$O$_7$ ($R$ = La) has received the most attention due to its high photocatalytic activity under sacrificial reagents or pure water. Recently, Arney et al. [74] reported the photocatalytic properties of perovskite platelet-like La$_2$Ti$_2$O$_7$ particles with thicknesses below 100 nm, which were synthesized by a modified MSS method. The photocatalytic properties of the platelet-like La$_2$Ti$_2$O$_7$ products measured under UV irradiation in aqueous methanol solutions were about 55–140 μmol H$_2$·h$^{-1}$·g$^{-1}$. Such photocatalytic rates are nearly two times higher than that of the La$_2$Ti$_2$O$_7$ powders prepared by solid-state reaction method. That is ascribed to the exposed crystalline edges in the platelet-like La$_2$Ti$_2$O$_7$ products and their (010) and (001) crystal faces play a key role in enhancing the photocatalytic activity. To extend the application of layer-structured La$_2$Ti$_2$O$_7$ perovskite into the visible-light region, doping approach with different metals (e.g. Ba, Sr, Ca, Cr, Fe and Rh) has been used [112,113,125,126]. Recently, Rh$^{3+}$-doped La$_2$Ti$_2$O$_7$ powders with a plate-like morphology (prepared by MSS method) were reported to exhibit photocatalytic activity for H$_2$ evolution under visible light irradiation up to 540 nm in an aqueous methanol solution [126]. The visible light activity was ascribed to the electron transition from the Rh$^{3+}$ donor states to the conduction band, and the oxidized Rh$^{4+}$ species went back to their original states by oxidation of CH$_3$OH. However, up to date the reported layered perovskites so far have wide band gaps, thus, to extend their photocatalytic performance into the visible light region band gap engineering is highly needed to shift their band gaps into visible light region, and even to the NIR region. As compared to the simple binary metal oxides with d$^0$, d$^{10}$, and f$^{6}$ metal ions (e.g. TiO$_2$, Nb$_2$O$_5$, WO$_3$, Ga$_2$O$_3$, and CeO$_2$), perovskite and perovskite related structures with three or more compositions, can provide a very wide platform to adjust their physicochemical properties by controlling the compositions and stoichiometry. To rationally design and synthesize perovskite oxide photocatalysts with the optimal photocatalytic activity, it is necessary to better understand the relationships between the compositions, structures and photocatalytic performance of perovskite oxide nanomaterials. In this direction, there is a long way to walk on before the commercialization of perovskite oxide nanomaterials.
5. Applications of low-dimensional PONs

Low-dimensional PONs are of great attraction and show potential applications in different fields such as data memory storage, solar energy conversion, and so on. The ferroelectric random-access memories (FeRAM) are one of the main applications of low-dimensional PONs in data memory storage, which are superior to the electrically erasable and programmable read-only memories (EEPROM’s) and Flash memories in terms of write-access time and overall power consumption. Their operational principles are based on the reversible polarization of a perovskite ferroelectric materials used in nonvolatile memory, and the direction of polarization switching representing the binary ‘1’ and ‘0’ in data storage [127–130]. Since the density of FeRAM nonvolatile-memory can be increased thousands-fold by reading and writing in nanoparticle-based FeRAM, thus, low-dimensional PONs (e.g. nanowires [131,132], nanotubes [133–135], and nanoparticles [136–138]) have been widely investigated for potential application in storage memory. Owing to the high dielectric permittivity perovskite ferroelectric nanoparticles (e.g., BaTiO₃) can be also used as the dielectric layer for constructing multilayered ceramic capacitors (MLCCs). Besides the practical applications in the MLCCs, perovskite ferroelectric nanoparticles are also use as a filling dielectric material in the polymer-based nanocomposite structures [139,140], which have promising applications in the fields of dielectric energy storage, flexible thin-film dielectric capacitors [141–143], and flexible electrical energy generators [144]. For the applications of the potential energy harvesting from collective mechanical movements, piezoelectric oxide nanowires are investigated extensively [145–147]. For example, electrical energy collected from piezoelectric nanostructures has already been utilized effectively to power nanoelectronic devices [148] and sensors [149]. 1D perovskite piezoelectric nanostructures, especially piezoelectric oxide nanowires and rods, have mostly been used for piezotronics applications due to their large mechanical strain tolerance [145]. Particularly, vertically or horizontally aligned arrays of piezoelectric nanowires are in an ideal configuration for energy harvesting applications due to their enhanced anisotropic piezoresponse [148,149], Besides energy harvesting application, perovskite oxide nanowires are also used for fabricating humidity sensors. For example, Li et al. [25] reported the response time (humidification from 11% to 95% humidity) and recovery time (desiccation from 95% to 11% humidity) of the humidity sensors based on perovskite BaTiO₃ nanowires, which were about 14 and 20 s, respectively. Such fast response and recovery behaviors demonstrate that BaTiO₃ nanowires are suitable for high-performance
humidity sensors. Similarly, perovskite oxide nanotubes are also widely investigated as potential building blocks for gas sensors. Recently, Wang et al. [58] synthesized single-crystalline LaFeO$_3$ nanotubes with diameters of 40 – 200 nm and length up to 3 μm by a co-precipitation method followed by MSS. Gas sensors fabricated from the as-prepared LaFeO$_3$ nanotubes exhibit fast response characteristics (Fig. 16), and the detection limit of the sensors achieves 1 ppm Cl$_2$ at room temperature. These sensors also exhibit good selectivity and stability (Fig. 16(c)). The (110)-layered perovskite La$_4$Ti$_2$O$_7$ photocatalysts synthesized via MSS method also exhibit a promising prospect in the photocatalytic area [74]. Their photocatalytic rates are nearly two times larger than that of the counterpart prepared by the solid-state method. As compared with TiO$_2$ photocatalysts, perovskite oxide photocatalysts have their own unique features such as tunable compositions, crystalline and electronic/energy band structures, which in some cases lead to more effective photo-induced reduction and oxidation efficiencies. In addition to the photocatalytic properties, perovskite oxides also exhibit photovoltaic behavior, which has important applications in photovoltaic devices such as solar cells. The typical example is perovskite 1D BiFeO$_3$ nanostructures with band gap of 2.5 eV [109,150]. Fig. 17(a) is schematic illustration for the measurement setup of random BiFeO$_3$ nanofiber–based photovoltaic devices [151]. The I – V curves of BiFeO$_3$ nanofibers and nanowires under dark and illumination condition, are shown in Fig. 17(b) and (c), respectively [151,152]. It is found that much higher currents are generated under the illumination as compared with the dark condition, demonstrating the excellent photovoltaic behavior of 1D BiFeO$_3$ nanostructures. It is reported that the current density of BiFeO$_3$ nanofibers (~200 nm) in response to the applied voltage is about 1 mA/cm$^2$, which is 2 – 10 times larger than that of BiFeO$_3$ thin films [151]. The enhanced photovoltaic properties of BiFeO$_3$ nanofibers are ascribed to the free-standing nanofibers with ferroelectric domains to be switched easily and more photons trapped by nanofibers due to their geometric confinement. In addition, the depolarization field may be helpful for driving electrons and holes in opposite directions, hampering their combination and thus enhancing the photovoltaic performance [152]. To date, perovskite oxide photocatalysts exhibit much better activities in environmental remediation and solar fuel generation fields. It is believed that the applications of low-dimensional PONS in photocatalytic and photovoltaic devices have a bright future.

6. Conclusions

Over the past decade, many low-dimensional perovskite oxide nanostructures have been fabricated successfully by MSS method and its modified version. Extensive researches on the effects of different precursors, annealing temperature, soaking time, etc. in MSS method have been conducted in depth. Despite the recent tremendous progresses are very inspiring but there are still some issues for further researches. Apart from the common zero-dimensional nanoparticles, much more attention has been switched to 1D or 2D PONS and other special nanostructures. However, in the growth of 1D or 2D PONS by traditional MSS method, some problems are urgent to be solved. For instance, the growth mechanisms of low-dimensional PONS in MSS process are not well understood, and more improvements on synthesis of low-dimensional PONS with controllable morphologies, sizes and crystallinity, require further researches. In the applications of low-dimensional PONS in photocatalysis, the fundamental understanding of the photocatalysis process and the relationships between the compositions, structures and photocatalytic performance of low-dimensional PONS should be well understood. Therefore, ongoing and future efforts should pay attention to the bandgap engineering of perovskite oxide nanomaterials, making them sensitive to UV, visible, and NIR lights and enhancing their photocatalytic performance. Overall, we still have a relatively long journey to achieve this ambition. In this report, we provide a comprehensive review of the state-of-the-art research activities in the field of molten salt synthesis of PONS, microstructural characterization, physical properties, and potential applications in the fields of storage memory, energy harvesting, and solar energy conversion. This review will be a good tutorial material for non-expert readers for understanding molten salt synthesis of low-dimensional PONS. Also, it provides important updates to experts in these research areas. It is believed that low-dimensional PONS have important applications not only in the area of perovskite oxide nanoelectronics, but also in energy fields including solar energy and energy storage. Much work remains to be done in this area.

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