Phase formation under conditions of self-organization of particle growth restrictions in the reaction system

Oksana V. Almjasheva[1,a], Vadim I. Popkov[2,b], Olga V. Proskurina[2,3,c], Victor V. Gusarov[2,d]

[1]St. Petersburg State Electrotechnical University "LETI", 197376 St. Petersburg, Russia
[2]Ioffe Institute, 194021 St. Petersburg, Russia
[3]St. Petersburg State Institute of Technology, 190013 St. Petersburg, Russia

[a]almjasheva@mail.ru, [b]vadim.i.popkov@mail.ioffe.ru, [c]proskurinaov@mail.ru, [d]victor.v.gusarov@gmail.com

Corresponding author: Olga V. Proskurina, proskurinaov@mail.ru

ABSTRACT   A systematic analysis of literature data concerning the influence of methods and conditions of synthesis on the possibility of self-organization of particle growth restrictions during chemical reactions of solid phase has been conducted. The prospects of using such methods to obtain nano-crystalline phases are shown. It is demonstrated that a disadvantage of such methods of synthesis is the risk of forming precursor phases instead of target products. To avoid such an outcome, several methods of synthesis are proposed. Based on the analysis of literature data, examples of the transformation of precursor nanoparticles into nanocrystals of target phases are classified and presented. A scheme that allows optimal combination of synthesis methods to obtain nano-crystalline particles of a given composition, structure, size, and shape is designed.

1.   Introduction

The production of crystalline particles with the smallest possible sizes can be achieved by two different mechanisms. First, it can result from thermodynamic processes related to the size of the critical phase embryo [1–4] and the crystal-chemical constraints determined by the minimum number of unit cell transformations for the formation of a stable crystalline structure of solid-phase particles [5]. Second, it can be caused by kinetic factors that condition the proportion of nucleation velocity to particle growth rate. In the latter case, it is possible to achieve minimum size particles by increasing the nucleation velocity and lowering the growth rate of new phase particles. Some aspects of increasing the rate of phase transformations were considered in [2, 6–13]. As examples of fast-flowing processes of formation of new phase crystalline particles, certain dehydration reactions under hydrothermal conditions [14–19], combustion reactions [20–30], as well as condensation of certain crystalline products from the gas phase [31–34], can be cited. It is crucial to highlight the processes whose high-speed results from the fact that the formation and growth of particles of a new phase is determined by the transfer of matter in the form of clusters with a large number of atoms [2, 35–42]. At the same time, in many cases obtaining nanoparticles in a fast-flowing process of phase formation is not possible. This is especially characteristic of the synthesis of crystalline phases of complex composition [43–56]. In these cases, it is possible to obtain nanoparticles of the synthesized phase with the smallest possible sizes by creating various kinds of restrictions for their growth. Particle growth restrictions may be thermodynamic (energetic) in nature, or they may be caused by kinetic factors. Conditions restricting the growth of particles of the new phase can be set before the start of the phase formation process or during the synthesis of a new phase. The first case involves physico-chemical processes in pre-created nanoreactors. The second case concerns self-organizing restrictions for the growth of nanoparticles during phase formation.

Different options for preliminary establishment of conditions under which mass transfer to particles of the forming phase would be restricted, that is, various types of nanoreactors were investigated in [57–68]. In these works, it was shown that the synthesis of nanoparticles in nanoreactors effectively restricts their growth and, in some cases, allows to control the morphology of the formed particles. As mentioned above, one of the options for restricting the growth of new phase particles is to conduct chemical processes in nanoreactors of diverse shapes, sizes, and compositions – such as dispersed, phase and chemical. Examples of such nanoreactors can be nanoscale and submicron pores in various materials [64, 65, 69–79], including channel pores in nanotubes [80–88], as well as various dispersed media such like microemulsions [89–91], and dispersions of nanoparticles in liquid media [92–95]. As an original nanoreactor, films

of nanoscale thickness applied, for example, by molecular layering (ML) [96–102], often called Atomic Layer Epitaxy (ALE) [103], or Atomic Layer Deposition (ALD) [104], to substrates of various compositions can be considered. Phase formation in such films or the interaction of their components with the substrate resulting in the formation of a new phase occurs with a natural restriction of the thickness of the obtained solid-phase product [105–111]. Interlayer spaces in compounds with a layered structure can also act as nanoreactors. An example of the use of interlayer spaces in hydrotalcites as nanoreactors is described in [57, 112–117]. Other heterogeneities in the structure of substances can also serve as nanoreactors – for example – cavities in polymers [118, 119]. A more complete description of various types of nanoreactors can be found in [57, 120–124], among other works.

A fundamentally different method for restricting particle growth rate is to increase the relaxation time of the process of mass transfer [6]:

$$\tau \sim D^{-1} \cdot (\Delta x)^2,$$

where D is the effective diffusion coefficient of the substance that determines the growth of particles, and Δx is the characteristic distance that the elementary components of the substance must overcome before they reach the growing particle. The latter value depends inversely on the concentration of the elementary components of the substance and the volume fraction of the particles formed in the reaction zone. Specific ways to reduce the rate of particle growth in this case may be to increase the viscosity of the reaction medium and to decrease the concentration of reagents.

Another principle of restricting the growth of particles of the synthesized phase is based on setting the conditions restricting their growth during the process of phase formation. To date, research in this area is fragmented. At the same time, the self-organization of growth restrictions of nanoparticles was observed during the formation of phases of different aggregate state, structure, chemical composition, and for nanocrystals with different morphology.

Recently, much attention has been paid to the study of the possibilities of obtaining oxide (including the production of oxyhydroxide and hydroxide) nanocrystals with a different range of variation in shape and size [11, 14, 16, 84, 125–137], including with the smallest possible crystal sizes [5]. Such interest is determined by the fact that their structure [20, 138–140] and functional properties [139, 141–147] may depend on the dimensional parameters of nanocrystals. In this regard, it is of interest to conduct a systematic analysis of the possibilities of self-organization of restrictions on the growth of particles of the forming crystalline phases. This work is devoted to this topic.

2. Nanoparticle growth restrictions occurring during the process of their formation

All types of restrictions on the growth of nanoparticles formed during their formation and presented in this paper can be conditionally divided into eight groups. The categorization depends on the physico-chemical reasons for the emergence of these restrictions as well as the methods of their formation.

The first group of restrictions on the growth of nanoparticles includes cases when the very structure of nanoparticles does not allow to increase its size continuously in certain or all directions by sequentially attaching atoms (molecules) to it. Usually, structures with a high degree of bond covalence act as such nanoparticles. The most well-known representatives of such nanostructures are carbon fullerenes, the sizes of which vary discretely depending on the number of carbon atoms in the structure from the smallest possible to the largest known to date [148–150]. It should be noted that there is a large group of similar nanostructures like buckyballs [151–153], with a very different chemical composition, including oxide buckyballs [154–160]. Analogically, the potential to increase the diameter of carbon nanotubes [161, 162] and nanotubes of other compounds [163–167] is restricted. Graphene particles, their derivatives, and morphological analogues with finite thickness are also close to the described group of nanoparticles. This variant of restricting the growth of nanoparticles can be referred to as restrictions resulting from their non-translational structure in one or more directions (Fig. 1).

The second group of restrictions on the growth of nanoparticles during their synthesis is characteristic, in particular, of nano-switches. This group is associated with the energy disadvantage of their folding following an increase in the diameter (decrease in curvature) of the nano-switch [168–173]. It is noteworthy that to date, there are only a small number of structures that differ in chemical composition and morphology (cylinders and cones) [174, 175]. The type of restrictions on the growth of nanoparticles in one or two directions that are similar in physico-chemical characteristics is associated with large differences in the values of the specific surface energy of the crystal faces. This leads to the redistribution of matter between the crystal faces during their growth and the formation of rod-shaped or lamellar morphology particles and, under certain conditions, to the formation of nanorods [19, 176–179] and nanoplates [180–183]. The described variants of self-organization of particle growth restrictions in certain directions during their formation can be classified as energy or, in generic terms, thermodynamic restrictions (Fig. 1).

Another type of nanoparticle growth restriction, which can occur during phase formation, is determined by the small magnitude of the driving force of the growth of nanoparticle size and is initiated by the high rate of nucleation [184–186]. In this case, the substance of the original composition is quickly exhausted for the almost simultaneous formation of the embryos of a new phase. The size of the forming particles in this case turns out to be close to the size of the critical embryo. Consequently, all the formed particles turn out to be similar in size. The transfer of matter from one particle to another in a system consisting of nanoparticles of almost the same size cannot be fast. This is because the driving force of the mass transfer process consists in the difference in the values of the specific surface energy, which in this specific case equals nearly zero. This type of restrictions on the growth of nanoparticles that occurred during the process of their
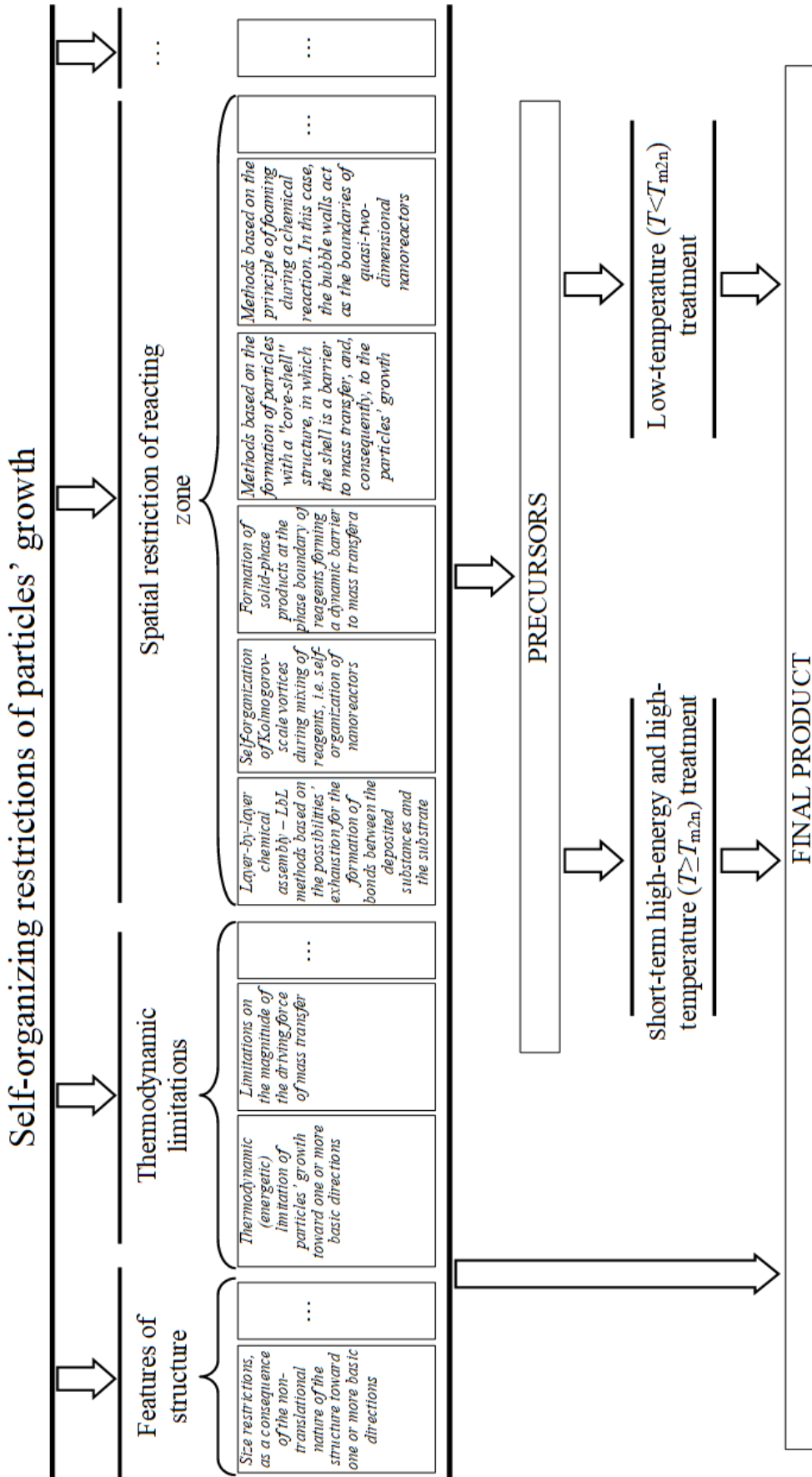
FIG. 1. Synthesis of solid phase particles over limited growth: principles and methods

formation can be classified as restrictions caused by minimizing the driving force of the mass transfer process. Some variant of this type of restriction of particle growth can be considered the case of the existence of very small particles whose specific surface energy decreases with a decrease in their size [187–193], as a result of which these particles may be in a state close to indifferent equilibrium with respect to each other. In particular, according to [194, 195], the specific surface energy of small particles is proportional to their diameter:

$$\sigma = \alpha \cdot d,$$

where $d < d_0$ is the diameter of small particles, and $\alpha = \sigma/d_0$ (Fig. 2a). In this case, in the particle size range $0 < d_i < d_0$ (Fig. 2) the expression for the value of the Gibbs energy of their formation, attributed to the unit volume, will have the following form:

$$\frac{\Delta G_i}{V_i} = \Delta g_V + \sigma_i \cdot \frac{S_i}{V_i},$$

ΔG_i is the Gibbs energy of the formation of the i-th particle, Δg_V is the volume specific Gibbs energy of the formation of the phase and, finally, S_i and V_i stand for the surface area and volume of the i-th particle. Consequently, taking into account the above dependence $\sigma(d)$, for an isometric particle, we obtain $\Delta G_i/V_i = \mathrm{const}$ for all particles i whose size d_i lies in the interval $(0, d_0)$. In this case, none of these particles has a thermodynamic preference over other particles in the size range $(0, d_0)$.

The dependence of the Gibbs energy on the particle size can be represented as

$$\Delta G = \Delta g_V \cdot d^3 + k_f \cdot \sigma \cdot d^2 = \begin{cases} d < d_0: & \Delta g_V \cdot d^3 + k_f \cdot \alpha \cdot d^3; \\ d \geq d_0: & \Delta g_V \cdot d^3 + k_f \cdot \sigma_0 \cdot d^2, \end{cases}$$

where k_f is a coefficient depending on the shape of the particles.

For the case

$$k_f \cdot \alpha < |\Delta g_V|,$$

$$\sigma = \alpha \cdot d_0 : d_{cr} = \frac{2}{3}\left(\frac{k_f \cdot \alpha}{|\Delta g_V|}\right) \cdot d_0$$

the calculated value of the size of the critical nucleus is $d_{cr} < 2/3 d_0$ (Fig. 2b (I)), i.e. critical nucleus does not exist.

For the case

$$k_f \cdot \alpha > |\Delta g_V|,$$

$$\sigma = \alpha \cdot d_0 : d_{cr} = \frac{2}{3}\left(\frac{k_f \cdot \alpha}{|\Delta g_V|}\right) \cdot d_0$$

the calculated value of the size of the critical nucleus is $d_{cr} \geq d_0$ (Fig. 2b (II)).

Another type of restrictions on the growth of nanostructures is implemented within the framework of a group of methods that can be designated as methods of Layered Chemical Assembly [196]. To some extent, the term Layer-by-Layer (LbL) synthesis [196–200] is synonymous with the designation of this group of methods. Historically, the first method in this group of methods is the Molecular Layering (ML) method proposed by V. B. Aleskovsky and S. I. Koltsov [96, 99–102, 201]. In literature, this method is also referred to as Atomic Layer Epitaxy (ALE) [103] and Atomic Layer Deposition (ALD) [104]. Ideologically close to the ML is the ionic layer deposition method suggested by V.P. Tolstoy and co-authors [202]. Subsequently, this method was developed in the works of many authors [203–206]. In literature, this method is also found under terms such as Successive Ionic Layer Deposition (SILD) [207] and Successive Ionic Layer Adsorption (SILAR) [200]. The self-organization of restraining the growth of the thickness of nanolayers on the surface of a solid when using LbL methods is based on the exhaustion of the possibilities for the formation of chemical bonds between the active centers on the surface that self-organize during synthesis. These centers include landing pads and atoms (atomic groups), or ions deposited from mobile media either gaseous or liquid, with sequential (cyclic) introduction of reagents of different composition into the reaction system. The most precise synthesis of planar nanostructures by the ML method occurs in cases of formation of substances with a predominantly covalent nature of the bond. It should be noted that by changing the temperature of the ML process within a certain range, the composition, structure, and thickness of the film can be varied within this method by changing the number of active centers self-organizing in the ML process on the surface of the solid. As a consequence, the density of filling the surface layer with molecules deposited on the surface can be altered [105–108, 208]. In addition, the filling of the surface layer can also be influenced by the steric effect, which is more characteristic of organic compounds [209–211].

The described method of restricting the growth of film thickness, which is determined by the self-organization of the size of the reaction space in the direction perpendicular to the surface of the solid (Fig. 3), differs in its physico-chemical characteristics from those discussed above. The self-organization of restricting the growth of the film during its formation by LbL methods is not associated with a change in the magnitude of the driving force of the chemical interaction of reagents, as was the case in the cases described earlier. Instead, it is determined by the exhaustion of the possibility of interaction of components due to the corresponding self-organization of the reaction medium during the deposition of a substance on the surface of the solid. Thus, this type of restriction on the growth of particle sizes of the formed phases
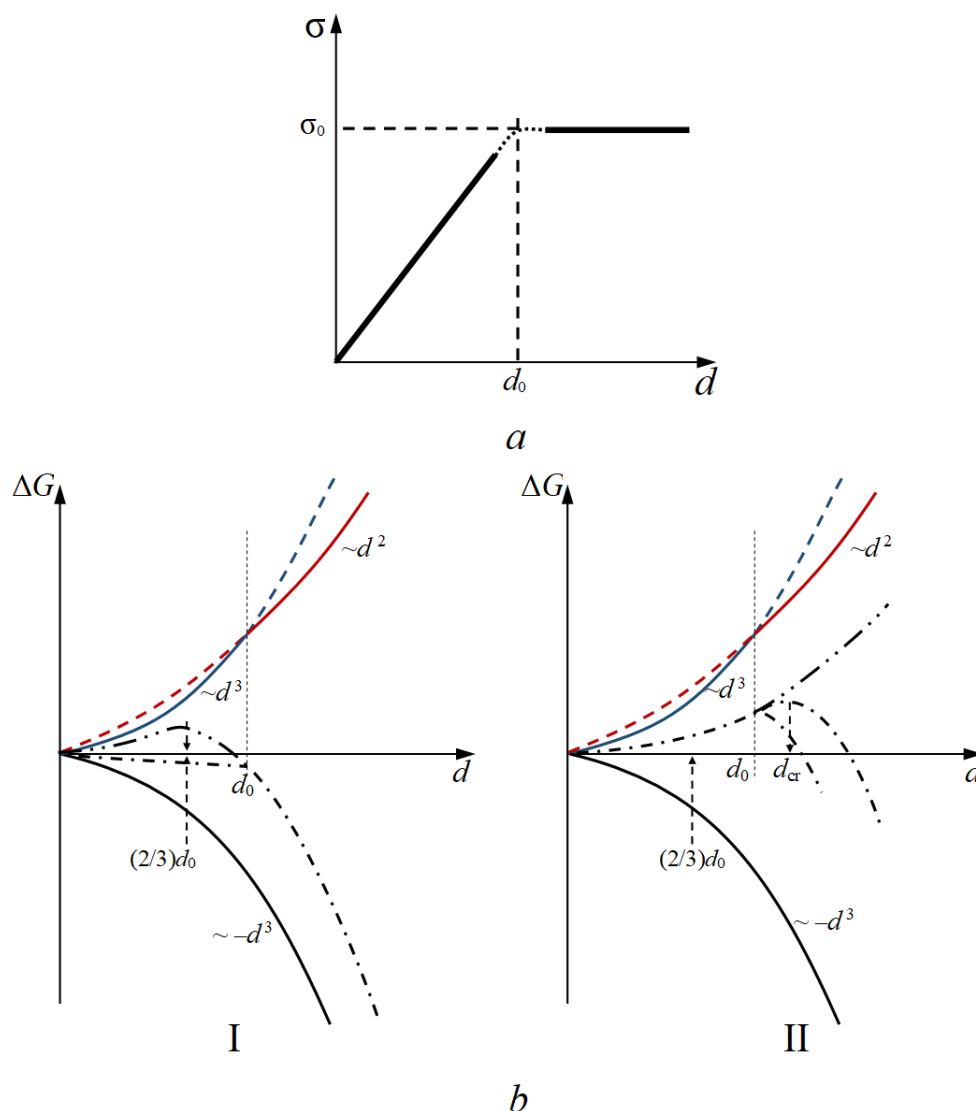
FIG. 2. Dependence of the surface energy (σ) on the particle size (d) (a); critical particle size (d_{cr}) of the formed phases (b)

introduces the next group of self-organizing constraints in the synthesis process. This class of self-organizing constraints will be based on a decrease in the possibilities for mass transfer of reagents into the reaction zone during the synthesis of nanostructures due to self-organization during the phase formation of spatially limited reaction zones (Fig. 1).

A promising direction in the organization of the synthesis of nanoparticles may be the use of intensive mixing of flows of liquid-phase reagents, in which vortices of the Kolmogorov scale are formed [212–214]. In this case, the synthesis takes place inside these vortices, and the mass transfer between the vortices is much less intense. This means that in this case, the vortices that self-organize during the mixing of reagents, in which phase formation occurs, can be considered as self-organizing nanoreactors (Fig. 1). In the works [176, 215–219] it was shown that such a method of mixing of reagents that exists, for instance, in microreactors with colliding jets [220–227], allows to synthesize nanoparticles with the smallest possible sizes under these conditions of chemical reactions. One disadvantage of the method based on the self-organization of spatial restrictions when mixing reagent solutions is, as a rule, the narrow temperature range at which solutions can be mixed. In some cases, these temperature values are not sufficient to form the final product. For example, when mixing aqueous solutions of reagents, intermediate hydroxides or amorphous forms of the substance are often created [20, 43, 142, 189, 228–232], and not the final product in the form of nanocrystalline oxide nanoparticles. That means that some nanoscale precursors are formed. In such cases, additional heat treatment is required, in which the particle size of the final product can significantly increase – as was observed during the formation of crystals of the phase with the structure of perovskite in the system Bi_2O_3–Fe_2O_3 [233–236].

Due to the need to achieve higher temperatures for the formation of oxide nanocrystals than is possible in the case of mixing aqueous solutions of components at atmospheric pressure, it is potentially possible to mix reagents dissolved in liquids that have higher boiling points. Another way to achieve higher temperatures is to increase the pressure in the
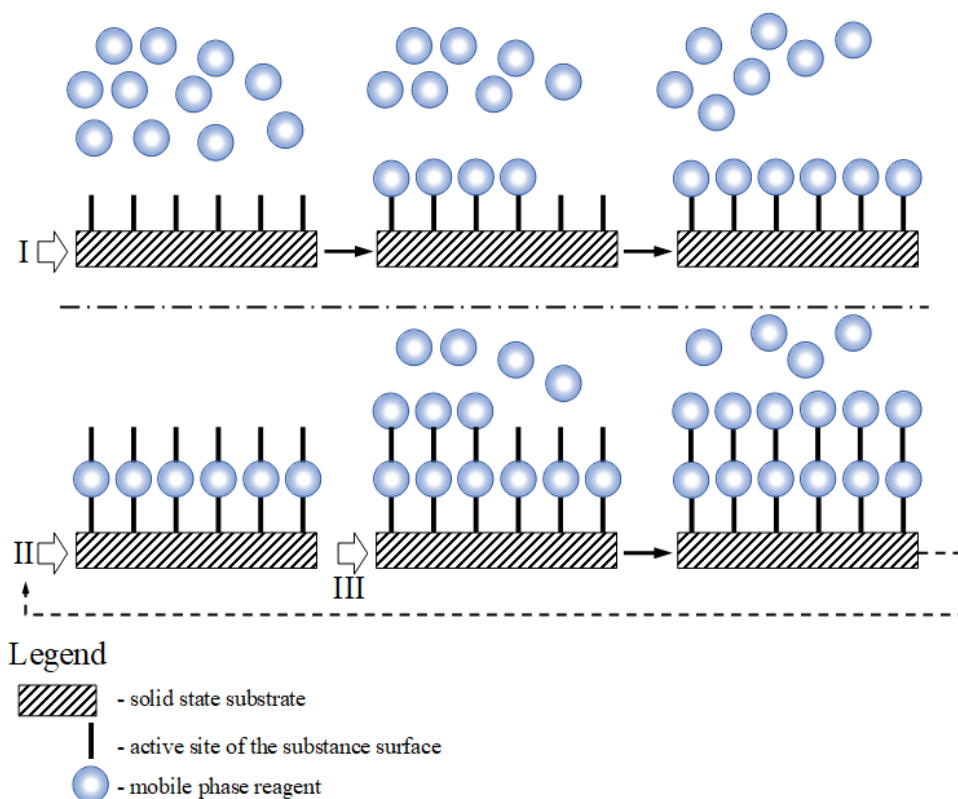
Legend

▨ - solid state substrate

▮ - active site of the substance surface

⬤ - mobile phase reagent

I – The cycle of mobile phase reagents' interaction with active centers on the surface of a solid-phase base;

II – Cycle of active centers' formation on the precipitated reagent;

III – Repeat of I-st cycle.

FIG. 3. Formation scheme of films with adjustable thickness by LbL methods

reactor to move into the field of hydrothermal synthesis. Naturally, the hydrodynamic conditions for the formation of vortices of the Kolmogorov scale change. Their boundaries acted as self-organizing spatial restrictions for mass transfer of reagents in the process of phase formation. At the same time, the transition to other reaction media in terms of chemical composition and other conditions of synthesis in terms of temperature and pressure, although it complicates in many cases the hardware design of the process, may expand the possibilities for self-organization of spatial restrictions in the reaction system.

It should be noted that when mixing reagents in the form of liquid solutions, in addition to vortex formation, other alternatives for self-organization of spatial restrictions for mass transfer of components to the particles of the resulting phase are possible. In particular, such a limitation may be the solid-phase product itself, which is formed at the contact boundary of reagent solutions (Fig. 1). The effectiveness of such a barrier for mass transfer of reagents in some cases leads to a situation where even with the usual form of introduction of one of the reagents – drops of a solution – nanocrystalline products can be obtained if two conditions are met. First, rapid nucleation is ensured at the interface of the reagents. Second, the particles formed during the new phase are quickly removed from the reaction zone, thereby ensuring the possibility of further nucleation process on the contact boundary of liquid-phase reagents [230, 234, 235, 237–240]. In the case described above, the layer of solid-phase reaction products itself acts as a self-organizing spatial restriction for the mass transfer of components from the liquid phase to the reaction zone. For the synthesis of nanoparticles with the smallest possible sizes under conditions of these spatial constraints being formed, it is important to organize a large contact surface of reagents and the rapid removal of interaction products from the reaction zone. It was shown in [241] that one of such possibilities is to carry out synthesis in apparatuses with swirling flows of reagent solutions.

A self-organizing barrier for mass transfer and, consequently, for particle growth can be surface layers that differ in their composition and structure from the volume of particles during the formation of "core-shell" structures (Fig. 1). Similar self-organizing structures during the formation of nanoparticles based on phases of variable composition were described in [242–245]. It should be noted that in these works, a noticeable decrease in the size of particles was experimentally shown precisely in the case of their formation as a "core-shell". This is due to the difficulty of transferring matter

from one particle to another through a self-organized barrier that emerges during their formation as a surface layer of a different composition and structure – or a shell.

Another variant of self-organization of particle growth restriction is associated with the formation of foam during a chemical reaction. In cases where the layer of foam bubble walls in which phase formation occurs is thin, it can be considered as a quasi-two-dimensional microreactor or, at least, a nanoreactor. An example of such phase formation can be the synthesis of oxide nanoparticles obtained by the method of "solution combustion" [23, 25, 28, 29, 246–254] under a certain regime of this process [255, 256]. Such a "solution combustion" mode can be considered as an independent method of obtaining nanoparticles or as the method of "foam combustion" schematically depicted in Fig. 4. The effect of the self-organization of quasi-two-dimensional thin layers as quasi-two-dimensional nanoreactors upon the production of nanoparticles by the "foam combustion" method of the reduction of particle growth rate is associated with the walls (boundaries) of the layers blocking of the transfer of matter to the formed particles (Fig. 4).
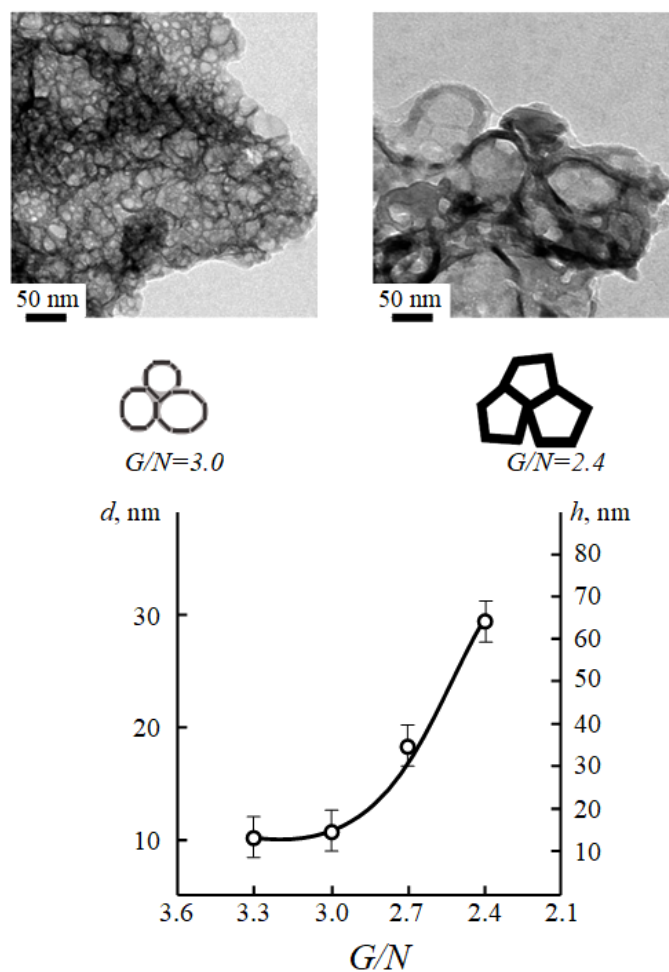

FIG. 4. Scheme of the particles growth restriction during their formation by the method of "foam combustion". Dependence of the $YFeO_3$ crystallite size (d) on the thickness of the bubbles' walls (h) formed during "foam combustion" (fuel-glycine, oxidizer-yttrium and iron (III) nitrates) at different glycine-nitrate ratios (G/N)

It should be emphasized that the effect of foaming on the course of chemical reactions was noted in different phase formation processes [20, 257–260]. Indicative in this regard is the self-oscillating process of foaming liquid during the decomposition of formic acid described in [260]. The self-oscillation of foaming is caused by an increase in the rate and reaction of decomposition of formic acid at the interface of the liquid and gaseous phases. This leads to an increase in the rate of foaming until it reaches exhaustion in the reaction zone of the reagent. Subsequently, the foam disappears, and the process starts from the initial state. Summarizing the considered cases of the influence of foaming on chemical reactions, it can be concluded that by conducting the synthesis process in a thin layer self-organizing during the chemical interaction of components at the interface of bulk phases, one can expect both an increase in the rate of chemical reactions and a decrease in the size of the particles formed due to the restricting of the mass transfer process by the boundaries of this layer (quasi-two-dimensional nanoreactor). As it was shown in [105, 106], the effects described above are also characteristic of some solid-phase reactions.

3.   Multistage phase formation processes and combination of crystal growth restrictions

In some cases, one or more high-temperature operations are required to form the final product [43, 230, 234, 235, 261–263]. This is the case for example when the goal of synthesis is to obtain oxide nanoparticles and at the initial stage soft chemistry methods are used to form hydroxide nanoparticles that are stable at temperatures of soft chemical synthesis. Another similar example may be the formation of oxide nanoparticles by the "foam combustion" method in cases where the temperature-time regime of the combustion of reagents leads to the formation of an amorphous phase instead of the target product, like oxide nanocrystals of a given composition and structure, and additional processing of the precursor material is required [8, 20, 255, 264–266]. A common feature of these and other similar situations is that the conditions of synthesis with self-organizing restrictions for particle growth, primarily its temperature-time regime, do not allow the formation of the target product in one stage. Since to obtain small particles, it is necessary to reduce the influence of the mass transfer process as well as the temperature and duration of synthesis (Fig. 1), situations when additional higher temperature and longer stages are required for the formation of the target product are frequent.

An increase in the temperature of synthesis always leads to an increase in the diffusion rate, which means that it increases the growth rate of particles of the reaction product. The effect of increasing the mass transfer rate on particle growth can be reduced either by shortening the duration of heat treatment, or by spatial separation of precursor particles, or by both. Reducing the duration of heat treatment without reducing the effectiveness of obtaining the target product – nanoparticles of a given composition and structure – is possible by means of radiation and laser heating [267–273]. An example of a technology that combines short duration of heat treatment with spatial separation of precursor particles, is spray pyrolysis [274–280]. Other approaches that implement short-term high-intensity energy effects on materials are also being developed and those include processing in electron flows, radiation stimulation of processes in solid phases [281–284], processing in low-temperature plasma [285–287], and more.

The methods listed above can also be used as independent ways for obtaining nanoparticles, but their significant disadvantage is, as a rule, that they cannot be used for synthesizing nanoparticles of compounds of complex composition. Soft chemistry methods are devoid of this disadvantage. Therefore, it is promising to combine methods of soft chemistry, including in conditions of self-organization of particle growth restrictions in the reaction zone, with methods of short-term high-energy processing of precursors obtained at the first stage.

It should be noted that the high-energy effect on precursors is not the only method of transformation into the final product and, in particular, into nanocrystalline oxides from hydroxide nanoparticles. For example, methods for obtaining oxides from the corresponding hydroxides by varying the partial pressure of water in the reaction space appear to be promising in this area. The selection of the pressure (P) and temperature (T) values necessary for the dehydration of hydroxides can be carried out either according to experimental data on the stability diagrams of hydroxide phases [288, 289], or according to thermodynamic calculations [290]. When selecting (P, T)-conditions for the production of oxides within the framework of these methods, it should be taken into account that the temperature should not exceed some critical values to not critically activate mass transfer processes in the reaction system. As it was shown in [6], the melting point of non-autonomous phases (T_{m2n}) can act as such a temperature limitation [291–293]. At $T < T_{m2n}$ mass transfer cannot ensure rapid particle growth and, consequently, there are no firm restrictions on the duration of precursor treatment. In this regard, the value of T_{m2n} is a boundary that divides all phases into high-temperature $T > T_{m2n}$, processes that proceed with a high rate of transfer of matter between grains and low-temperature processes $T < T_{m2n}$ [6, 291, 294–299].

Precursors formed at the first stage of synthesis are not limited to hydroxides and, consequently, the choice of conditions for the formation of nanoparticles of the target product should be based on the analysis of the chemical stability of the corresponding precursor phases. As for hydroxides, such an analysis can be conducted on the basis of appropriate experimental data or by thermodynamic calculations.

The described approaches to the transformation of precursor nanoparticles into nanocrystalline target products can be supplemented by other methods based for example on mechanochemical effects [300–306]. However, since the systematic consideration of such methods is not the purpose of this work, it only provides a schematic representation of the possibility of combining various methods of restricting crystal growth using multistage processes of synthesis of nanocrystalline phases (Fig. 1).

4.   Conclusion

Analysis of literature data has shown the prospects of synthesis methods in which particle growth restrictions are formed during the synthesis process itself. The disadvantage of many of such methods consisting in the fact that nanoparticles of precursor phases are formed instead of target products can be compensated by combining several different methods of synthesis. Based on the analysis of literature data, examples of the transformation of precursor nanoparticles into nanocrystals of target phases are classified and presented. A scheme that allows optimal combination of synthesis methods to obtain nano-crystalline particles of a given composition, structure, size, shape, is designed.

References

[1] Kuni F.M., Rusanov A.I. The homogeneous nucleation theory and the fluctuation of the center of mass of a drop. *Physics Letters A*, 1969, **29** (6), P. 337–338.

[2] Almjasheva O.V., Gusarov V.V. Metastable clusters and aggregative nucleation mechanism. *Nanosystems: Physics, Chemistry, Mathematics*, 2014, **5** (3), P. 405–417.

[3] Shi R., Heo T.W., Wood B.C., Wang Y. Critical nuclei at hetero-phase interfaces. *Acta Materialia*, 2020, **200** (6201), P. 510–525.

[4] Keesee R.G. Nucleation and Particle Formation in the Upper Atmosphere. *J. of Geophysical Research*, 1989, **94** (D12), P. 14683–14692.

[5] Almyasheva O.V., Lomanova N.A., et al. The minimal size of oxide nanocrystals: phenomenological thermodynamic vs crystal-chemical approaches. *Nanosystems: Physics, Chemistry, Mathematics*, 2019, **10** (4), P. 428–437.

[6] Gusarov V.V. Fast Solid-Phase Chemical Reactions. *Russian J. of General Chemistry*, 1997, **67** (12), P. 1846–1851.

[7] Popkov V.I., Almjasheva O.V., Gusarov V.V. The investigation of the structure control possibility of nanocrystalline yttrium orthoferrite in its synthesis from amorphous powders. *Russian J. of Applied Chemistry*, 2014, **87**, P. 1417–1421.

[8] Popkov V.I., Almjasheva O.V., et al. The role of pre-nucleus states in formation of nanocrystalline yttrium orthoferrite. *Doklady Chemistry*, 2016, **471**, P. 356–359.

[9] Gusarov V.V., Almjasheva O.V. The role of non-autonomous state of matter in the formation of structure and properties of nanomaterials. Chapter 13 in the book *Nanomaterials: properties and promising applications*. Ed. A.B. Yaroslavtsev. Scientific World Publishing House, Moscow, 2014, P. 378–403. (in Russian)

[10] Kotov Yu.A., Azarkevich E.I., et al. Iron oxide nanopowders prepared by the electroexplosion of wire. *Inorganic Materials*, 2007, **43** (6), P. 633–637.

[11] Kotov Y.A. The electrical explosion of wire: A method for the synthesis of weakly aggregated nanopowders. *Nanotechnologies in Russia*, 2009, **4** (7–8), P. 415–424.

[12] Kotov Y.A., Samatov O.M., et al. Production and Characteristics of Composite Nanopowders Using a Fiber Ytterbium Laser. *Technical Physics*, 2011, **56** (5), P. 652–655.

[13] Ilyin A.P. Development of electroexplosive technology for obtaining nanopowders at the High Voltage Research Institute at Tomsk Polytechnic University. *Bulletin of the Tomsk Polytechnic University*, 2003, **306** (1), P. 133–139.

[14] Pozhidaeva O.V., Korytkova E.N., Romanov D.P., Gusarov V.V. Formation of ZrO_2 nanocrystals in hydrothermal media of various chemical compositions. *Russian J. of General Chemistry*, 2002, **72** (6), P. 849–853.

[15] Popkov V.I., Bachina A.K., et al. Synthesis, morphology and electrochemical properties of spherulite titania nanocrystals. *Ceramics International*, 2020, **56** (15), P. 24483–24487.

[16] Ivanov V.K., Polezhaeva O.S. Synthesis of ultrathin ceria nanoplates. *Russian J. of Inorganic Chemistry*, 2009, **54** (10), P. 1528–1530.

[17] Tyrsted C., Becker J., et al. In-Situ Synchrotron Radiation Study of Formation and Growth of Crystalline $Ce_xZr_{1-x}O_2$ Nanoparticles Synthesized in Supercritical Water. *Chemistry of Materials*, 2010, *22* (5), P. 1814–1820.

[18] Ivanov V.K., Kopitsa G.P., et al. Hydrothermal growth of ceria nanoparticles. *Russian J. of Inorganic Chemistry*, 2009, **54** (12), P. 1857–1861.

[19] Enikeeva M.O., Danilovich D.P., Proskurina O.V., Gusarov V.V. Formation of nanocrystals based on equimolar mixture of lanthanum and yttrium orthophosphates under microwave-assisted hydrothermal synthesis. *Nanosystems: Physics, Chemistry, Mathematics*, 2020, **11** (6), P. 705–715.

[20] Popkov V.I., Almjasheva O.V., et al. Effect of spatial constraints on the phase evolution of $YFeO_3$-based nanopowders under heat treatment of glycine-nitrate combustion products. *Ceramics International*, 2018, **44** (17), P. 20906–20912.

[21] Zaboeva E.A., Izotova S.G., Popkov V.I. Glycine-nitrate combustion synthesis of $CeFeO_3$-based nanocrystalline powders. *Russian J. of Applied Chemistry*, 2016, **89**, P. 1228–1236.

[22] Simagina V.I., Komova O.V., et al. Study of Copper-Iron Mixed Oxide with Cubic Spinel Structure, Synthesized by the Combustion Method. *Russian J. of Applied Chemistry*, 2019, **92**, P. 20–30.

[23] Ostroushko A.A., Russkikh O.V. Oxide material synthesis by combustion of organicinorganic Compositions. *Nanosystems: Physics, Chemistry, Mathematics*, 2017, **8** (4), P. 476–502.

[24] Khaliullin Sh.M., Zhuravlev V.D., et al. Thermal characteristics, gassing in solution combustion synthesis and conductivity of CaZrO3. *Int. J. of Self-Propagating High-Temperature Synthesis*, 2015, **24** (2), P. 83–88.

[25] Varma A., Mukasyan A.S., Rogachev A.S., Manukyan K.V. Solution Combustion Synthesis of Nanoscale Materials. *Chemical Reviews*, 2016, **116**, P. 14493–14586.

[26] Manukyan K.V., Cross A., et al. Solution Combustion Synthesis of Nano-Crystalline Metallic Materials: Mechanistic Studies. *J. of Physical Chemistry C*, 2013, **117**, P. 24417–24427.

[27] Trusov G.V., Tarasov A.B., et al. Spray Solution Combustion Synthesis of Metallic Hollow Microspheres. *J. of Physical Chemistry C*, 2016, **120**, P. 7165–7171.

[28] Khaliullin S.M., Zhuravlev V.D., Bamburov V.G. Solution-combustion synthesis of oxide nanoparticles from nitrate solutions containing glycine and urea: Thermodynamic aspects. *Int. J. of Self-Propagating High-Temperature Synthesis*, 2016, **25** (3), P. 139–148.

[29] Li F.T., Ran J., Jaroniec M., Qiao S.Z. Solution combustion synthesis of metal oxide nanomaterials for energy storage and conversion. *Nanoscale*, 2015, **7** (42), P. 17590–17610.

[30] Saukhimov A.A., Hobosyan M.A., et al. Solution-combustion synthesis and magnetodielectric properties of nanostructured rare earth ferrites. *Int. J. of Self-Propagating High-Temperature Synthesis*, 2015, **24** (2), P. 63–71.

[31] Sun L., Yuan G., Gao L., Yang J., Chhowalla M., Gharahcheshmeh M.H., Gleason K.K., Choi Y.S., Hong B.H., Liu Z. Chemical vapour deposition. *Nature Reviews Methods Primers*, 2021, **1** (1), P. 5.

[32] Cai Z., Liu B., Zou X., Cheng H.M. Chemical vapor deposition growth and applications of two-dimensional materials and their heterostructures. *Chemical Reviews*, 2018, **118**, P. 6091–6133.

[33] Martínez L., Mayoral A., et al. Core@shell, Au@TiO_x nanoparticles by gas phase synthesis. *Nanoscale*, 2017, **9**, P. 6463–6470.

[34] Deepak N., Carolan P., et al. Tunable nanoscale structural disorder in Aurivillius phase, $n = 3$ $Bi_4Ti_3O_{12}$ thin films and their role in the transformation to $n = 4$, $Bi_5Ti_3FeO_{15}$ phase. *J. of Materials Chemistry C*, 2015, **3** (22), P. 5727–5732.

[35] Yau S.-T., Vekilov P.G. Quasi-planar nucleus structure in apoferritin crystallization. *Nature*, 2000, **406** (6795), P. 494–497.

[36] Ivanov V.K., Fedorov P.P., Baranchikov A.Ye., Osiko V.V. Oriented attachment of particles: 100 years of investigations of non-classical crystal growth. *Russian Chemical Reviews*, 2014, **83** (12), P. 1204–1222.

[37] Fedorov P., Mayakova M., et al. Preparation of "NaREF₄" phases from the sodium nitrate melt. *J. of Fluorine Chemistry*, 2019, **218**, P. 69–75.

[38] Fedorov P.P., Ivanov V.K., Osiko V.V. Basic features and crystal-growth scenarios based on the mechanism of oriented attachment growth of nanoparticles. *Doklady Physics*, 2015, **60** (11), P. 483–485.

[39] Penn R.L., Banfield J.F. Oriented attachment and growth, twinning, polytypism, and formation of metastable phases: Insights from nanocrystalline TiO$_2$. *American Mineralogist*, 1998, **83** (9–10), P. 1077–1082.

[40] Penn R.L., Banfield J.F. Imperfect oriented attachment: Dislocation generation in defect-free nanocrystals. *Science*, 1998, **281**, P. 969–971.

[41] Fedorov P.P., Maslov V.A., et al. Flintstone as a nanocomposite material for photonics. *Nanosystems: Physics, Chemistry, Mathematics*, 2018, **9** (5), P. 603–608.

[42] Lin Q., Wang X., Li J., Han Y. Oriented aggregation of silver particles in gel solutions. *Colloids and Surfaces A*, 2018, **555**, P. 161–169.

[43] Lomanova N.A., Tomkovich M.V., et al. Formation of Bi$_{m+1}$Fe$_{m-3}$Ti$_3$O$_{3m+3}$ (m = 4–9) nanocrystals upon thermal decomposition of coprecipitated hydroxides. *Russian J. of Inorganic Chemistry*, 2021, **66** (5), P. 755–764.

[44] Lomakin M.S., Proskurina O.V., et al. Hydrothermal Synthesis, Phase Formation and Crystal Chemistry of the Pyrochlore/Bi$_2$WO$_6$ and Pyrochlore/α-Fe$_2$O$_3$ Composites in the Bi$_2$O$_3$–Fe$_2$O$_3$-WO$_3$ System. *J. of Solid State Chemistry*, 2020, **282**, P. 121064.

[45] Lomakin M.S., Proskurina O.V., Gusarov V.V. Influence of hydrothermal synthesis conditions on the composition of the pyrochlore phase in the Bi$_2$O$_3$–Fe$_2$O$_3$–WO$_3$ system. *Nanosystems: Physics, Chemistry, Mathematics*, 2020, **11** (2), P. 246–251.

[46] Kostyukhina E.M., Kustova A.L., Kustov L.M. One-step hydrothermal microwave-assisted synthesis of LaFeO$_3$ nanoparticles. *Ceramics International*, 2019, **45** (11), P. 14384–14388.

[47] Denisova L.T., Molokeev M.S., et al. Synthesis, Crystal Structure, and Thermal Properties of Substituted Titanates Bi$_2$Pr$_2$Ti$_3$O$_{12}$ and Bi$_2$Nd$_2$Ti$_3$O$_{12}$. *Physics of the Solid State*, 2021, **63** (8), P. 1159–1164.

[48] Zhuk N.A., Sekushin N.A., et al. Dielectric properties, Mössbauer study, ESR spectra of Bi$_2$FeTa$_2$O$_{9.5}$ with pyrochlore structure. *J. of Alloys and Compounds*, 2022, **903**, P. 163928.

[49] Matsukevich I., Kulak A., et al. Comparison of different methods for Li$_2$MTi$_3$O$_8$ (M – Co, Cu, Zn) synthesis. *J. of Chemical Technology & Biotechnology*, 2021, **97** (4), P. 1021–1026.

[50] Tugova E.A. A comparative analysis of the formation processes of Ruddlesden-Popper phases in the La$_2$O$_3$–SrO–M$_2$O$_3$ (M = Al, Fe) systems. *Glass Physics and Chemistry*, 2009, **35** (4), P. 416–422.

[51] Klyndyuk A.I., Tugova E.A., et al. Formation of solid solutions of multiferroics in the Bi$_2$O$_3$–Nd$_2$O$_3$–Fe$_2$O$_3$ system. *Russian J. of General Chemistry*, 2016, **86** (10), P. 2282–2287.

[52] Karami M., Masoudpanah S.M., Rezaie H.R. Solution combustion synthesis of hierarchical porous LiFePO$_4$ powders as cathode materials for lithium-ion batteries. *Advanced Powder Technology*, 2021, **32** (6), P. 1935–1942.

[53] Alhaji A., Taherian M.H., Ghorbani S., Sharifnia S.A. Development of synthesis and granulation process of MgAl$_2$O$_4$ powder for the fabrication of transparent ceramic. *Optical Materials*, 2019, **98**, P. 109440.

[54] Zhang Y., Bu A., et al. Rapid synthesis of Y3Al5O12 powders via plasma electrolysis. *Ceramics International*, 2021, **47** (21), P. 30147–30155.

[55] Opuchovic O., Beganskiene A., Kareiva A. Sol–gel derived Tb$_3$Fe$_5$O$_{12}$ and Y$_3$Fe$_5$O$_{12}$ garnets: Synthesis, phase purity, micro-structure and improved design of morphology. *J. of Alloys and Compounds*, 2015, **647**, P. 189–197.

[56] Klyndyuk A.I., Chizhova E.A., et al. Thermoelectric Multiphase Ceramics Based on Layered Calcium Cobaltite, as Synthesized Using Two-Stage Sintering. *Glass Physics and Chemistry*, 2020, **46**, P. 562–569.

[57] Tretyakov Yu.D., Lukashin A.V., Eliseev A.A. Synthesis of functional nanocomposites based on solid-phase nanoreactors. *Russian Chemical Reviews*, 2004, **73** (9), P. 899–921.

[58] Petrosko S. H., Johnson R., White H., Mirkin C.A. Nanoreactors: small spaces, big implications in chemistry. *J. of the American Chemical Society*, 2016, **138**, P. 7443–7445.

[59] Swisher J.H., Jibril L., Petrosko S.H., Mirkin C.A. Nanoreactors for particle synthesis. *Nature Reviews Materials*, 2022, **7**.

[60] Eliseev A.A., Falaleev N.S., et al. Size-dependent structure relations between nanotube and encapsulated nanocrystal. *Nano Letters*, 2017, **17**, P. 805–810.

[61] Eliseev A.A., Kharlamova M.V., et al. Preparation and properties of single-walled nanotubes filled with inorganic compounds. *Russian Chemical Reviews*, 2009, **78** (9), P. 833–854.

[62] Yashina L.V., Eliseev A.A., et al. Growth and Characterization of One-Dimensional SnTe Crystals within the Single-Walled Carbon Nanotube Channels. *The J. of Physical Chemistry C*, 2011, **115** (9), P. 3578–3586.

[63] Naberezhnov A.A., Stukova E.V., et al. Effects Associated with Confined Geometry in Nanocomposites Based on Mesoporous 2D-SBA-15 and 3D-SBA-15 Matrices Containing Sodium Nitrite Nanoparticles. *Technical Physics*, 2019, **64** (12), P. 1866–1871.

[64] Alekseeva O.A., Naberezhnov A.A., et al. Temperature range broadening of the ferroelectric phase in KNO$_3$ nanoparticles embedded in the pores of the nanoporous Al$_2$O$_3$ matrix. *Ferroelectrics*, 2021, **574** (1), P. 8–15.

[65] Bronstein L.M., Sidorov S.N., Valetsky P.M. Nanostructured polymeric systems as nanoreactors for nanoparticle formation. *Russian Chemical Reviews*, 2004, **73** (5), P. 501–515.

[66] Maslennikova T.P., Korytkova E.N., Kuznetsova O.M., Pivovarova L.N. Thermochemical modification of Mg$_3$Si$_2$O$_5$(OH)$_4$ hydrosilicate nanotubes by silver nitrate solutions. *Glass Physics and Chemistry*, 2016, **42** (3). P. 288–294.

[67] Maslennikova, T.P., Korytkova, E.N. Influence of synthesis of physicochemical parameters on growth of Ni$_3$Si$_2$O$_5$(OH)$_4$ nanotubes and their filling with solutions of hydroxides and chlorides of alkaline metals. *Glass Physics and Chemistry*,2013, **39**, P. 67–72.

[68] Maslennikova T.P., Gatina E.N. Modification of Mg$_3$Si$_2$O$_5$(OH)$_4$ nanotubes by magnetite nanoparticles. *Glass Physics and Chemistry*, 2017, **43** (3), P. 257–262.

[69] Molz E., Wong Apollo P.Y., Chan M.H.W., Beamish J.R. Freezing and melting of fluids in porous glasses. *Physical Review B*, 1993, **48** (9), P. 5741–5750.

[70] Saridakis E., Chayen N.E., Sear R.P. Experiment and theory for heterogeneous nucleation of protein crystals in a porous medium. *Proceedings of the National Academy of Sciences of the United States of America*, 2006, **103** (3), P. 597–601.

[71] Page A.J., Sear R.P. Heterogeneous Nucleation in and out of Pores. *Physical Review Letters*, 2006, **97**, 065701.

[72] Nanev C., Govada L., Chayen N.E. Theoretical and experimental investigation of protein crystal nucleation in pores and crevices. *International Union of Crystallography*, 2021, **8** (2), P. 270–280.

[73] Zalineeva A., Serov A., et al. Self-supported PdxBi catalysts for the electrooxidation of glycerol in alkaline media. *J. of the American Chemical Society*, 2014, **136** (10), P. 3937–3945.

[74] Kharlamova M.V., Sapoletova N.A., Eliseev A.A., Lukashin A.V. Magnetic properties of γ-iron oxide nanoparticles in a mesoporous silica matrix. *J. of Experimental and Theoretical Physics Letters*, 2007, **85** (9), P. 439–443.

[75] Gorozhankin D.F., Eliseev A.A., et al. Synthesis and Properties of Iron Oxide Nanoparticles in the Matrix of Mesoporous Silica. *Doklady Chemistry*, 2004, **396** (4–6), P. 132–135.

[76] Eliseev A.A., Gorozhankin D.F., et al. Preparation of strontium hexaferrite nanowires in the mesoporous silica matrix MCM-41. *J. of Magnetism and Magnetic Materials*, 2005, **290** (l), P. 106–109.

[77] Burova L.I., Petukhov D.I., et al. Preparation and properties of ZnO nanoparticles in the mesoporous silica matrix. *Superlattices and Microstructures*, 2006, **39** (1–4), P. 257–266.

[78] Sokolov M.R., Enakieva Y.Yu., et al. Intercalation of Porphyrin-Based SURMOF in Layered Eu(III) Hydroxide: An Approach Toward Symbimetic Hybrid Materials. *Advanced Functional Materials*, 2020, **30** (27), 2000681.

[79] Yapryntsev A.D., Baranchikov A.E., Ivanov V.K. Layered rare-earth hydroxides: a new family of anion-exchangeable layered inorganic materials. *Russian Chemical Reviews*, 2020, **89** (6), P. 629–666.

[80] Takaiwa D., Hatano I., Koga K, Tanakathe H. Phase diagram of water in carbon nanotubes. *Proceeding of the National Academy Sciences of the United States of America*, 2008, **105** (1), P. 39–43.

[81] Findenegg G.H., Jähnert S., Akcakayiran D., Schreiber A. Freezing and melting of water confined in silica nanopores. *Chem. Phys. Chem.*, 2008, **9** (18), P. 2651–2659.

[82] Ghernysheva M.V., Kiseleva E.A., et al. Synthesis and invenstigation of of nanocrystals inside channels of single-walled carbon nanotubes. *Int. Sci. J. for Alternative Energy and Ecology*, 2008, **57** (1), P. 22–29. (In Russian)

[83] Kharlamova M.V., Kramberger C. Applications of Filled Single-Walled Carbon Nanotubes: Progress, Challenges, and Perspectives. *Nanomaterials*, 2021, **11** (11), 2863.

[84] Rempel A.A., Valeeva A.A., Vokhmintsev A.S., Weinstein I.A. Titanium dioxide nanotubes: synthesis, structure, properties and applications. *Russian Chemical Reviews*, 2021, **90** (11). P. 1397–1414.

[85] Latysheva E.N., Pirozerskii A.L., et al. Polymorphism of Ga–In Alloys in Nanoconfinement Conditions. *Physics of the Solid State*, 2015, **57**, P. 131–135.

[86] Riboni F., Nguyen N.T., So S., Schmuki P. Aligned metal oxide nanotube arrays: key-aspects of anodic TiO_2 nanotube formation and properties. *Nanoscale Horizons*, 2016, **1** (6), P. 445–466.

[87] Li G., Fu C., et al. Giant Raman Response to the Encapsulation of Sulfur in Narrow Diameter Single-Walled Carbon Nanotubes. *J. of the American Chemical Society*, 2016, 138 (1), P. 40–43.

[88] Monet G., Paineau E., et al. Solid wetting-layers in inorganic nano-reactors: the water in imogolite nanotube case. *Nanoscale Advances*, 2020, 2 (5), P. 1869–1877.

[89] Vafakish B., Wilson, L.D. A Review on Recent Progress of Glycan-Based Surfactant Micelles as Nanoreactor Systems for Chemical Synthesis Applications. *Polysaccharides*, 2021, **2** (1), P. 168–186.

[90] Porras M., Martínez A., et al. Ceramic particles obtained using W/O nano-emulsions as reaction media. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2005, **270–271**, P. 189–194.

[91] Hada R. A Novel Synthesis Process for Making Nickel Oxide Nanoparticles. *Int. Research J. of Pure and Applied Chemistry*, 2013, **3**, P. 111–117.

[92] Al'myasheva O.V., Gusarov V.V. Nucleation in media in which nanoparticles of another phase are distributed. *Doklady Physical Chemistry*, 2009, **424**, P. 43–45.

[93] He Z., Alexandridis P. Nanoparticles in ionic liquids: interactions and organization. *Physical Chemistry Chemical Physics*, 2015, **17**, P. 18238–18261.

[94] Hammond O., Mudring A.-V. Ionic Liquids and Deep Eutectics as a Transformative Platform for the Synthesis of Nanomaterials. *Chemical Communications*, 2022, **58**, P. 3865–3892.

[95] Sergievskaya A., Chauvin A., Konstantinidis S. Sputtering onto liquids: a critical review. *Beilstein J. of Nanotechnology*, 2022, **13**, P. 10–53.

[96] Kol'tsov S.I., Aleskovskii V.B. Effect of degree of dehydration of silica gel on mechanism of hydrolysis of adsorbed titanium tetrachloride. *Russian J. of Physical Chemistry*, 1968, **42** (5), P. 630–632.

[97] Aleskovskii V.B. Chemistry and technology of solids. *J. of Applied Chemistry of the USSR*, 1974, **47** (10), P. 2207–2217.

[98] Malygin A.A. Molecular Layering Nanotechnology. *Nanotechnologies in Russia (Rossiiskie Nanotekhnologii)*, 2007, **2** (3–4). P. 87–100. (In Russian)

[99] Malygin A.A., Drozd V.E., et al. Aleskovskii's "Framework" Hypothesis to the Method of Molecular Layering/Atomic Layer Deposition. *Chemical Vapor Deposition*, 2015, **21**, P. 216–240.

[100] Sosnov E.A., Malkov A.A., Malygin A.A. Nanotechnology of Molecular Layering in Production of Inorganic and Hybrid Materials for Various Functional Purposes (a Review): I. History of the Development of the Molecular Layering Method. *Russian J. of Applied Chemistry*, 2021, **94** (8), P. 1022–1037.

[101] Sosnov E.A., Malkov A.A., Malygin A.A. Nanotechnology of Molecular Layering in Production of Inorganic and Hybrid Materials for Various Functional Purposes: II. Molecular Layering Technology and Prospects for Its Commercialization and Development in the XXI Century. *Russian J. of Applied Chemistry*, 2021, **94** (9), P. 1189–1215.

[102] Malygin A.A. Molecular Layering Technology and Some of its Applications. *Russian J. of Applied Chemistry*, 1996, **69** (10) P. 1419–1426.

[103] Goodman C.H.L., Pessa M.V. Atomic layer epitaxy. *J. of Applied Physics*, 1986, **60**, R65.

[104] George S.M. Atomic layer deposition: An overview. *Chemical Review*, 2010, **110** (1), P. 111–131.

[105] Gusarov V.V., Malkov A.A., Ishutina Zh.N., Malygin A.A. Phase formation in a nanosize silicon oxide film on the surface of aluminum oxide. *Technical Physics Letters*, 1998, **24** (1), P. 1–3.

[106] Gusarov V.V., Ishutina Z.N., Malkov A.A., Malygin A.A. Peculiarities of the solid-phase chemical reaction in formation of mullite in the nanosize film composition. *Doklady Akademii Nauk*, 1997, **357** (2), P. 203–205. (In Russian)

[107] Gusarov V.V., Malkov A.A., Malygin A.A., Suvorov S.A. Generation of aluminum titanate in compositions with high-level of space and structural conjugation of components. *Zhurnal Obshchei Khimii*, 1994, **64** (4), P. 554–557. (In Russian)

[108] Smirnova Zh.N., Gusarov V.V., et al. High-Speed Synthesis of Mullite. *Zhurnal Obshchei Khimii*, 1995, **65** (2), P. 199–204. (In Russian)

[109] Ramazanov S., Sobola D.S., et al. Surface Modification and Enhancement of Ferromagnetism in $BiFeO_3$ Nanofilms Deposited on HOPG. *Nanomaterials*, 2020, **10** (10), P. 1990.

[110] Orudzhev F., Ramazanov S., et al. Atomic Layer Deposition of Mixed-Layered Aurivillius Phase on TiO_2 Nanotubes: Synthesis, Characterization and Photoelectrocatalytic Properties. *Nanomaterials*, 2020, **10** (11), P. 2183.

[111] Koshtyal Y., Nazarov D., et al. Atomic Layer Deposition of NiO to Produce Active Material for Thin-Film Lithium-Ion Batteries. *Coatings*, 2019, **9** (5), P. 301.

[112] Lukashin A.V., Eliseev A.A., et al. Synthesis of PbS/S Nanostructures through. *Doklady Chemistry*, 2002, **383** (4–6), P. 93–96.

[113] Lukashin A.V., Vertegel A.A., et al. Chemical Design of Magnetic Nanocomposites Based on Layered Double Hydroxides. *J. of Nanoparticle Research*, 2003, **5**, P. 455–464.

[114] Nikiforov M.P., Chernysheva M.V., et al. Synthesis of Iron-Containing Oxide Nanocomposites from LDH Precursors. *Doklady Chemistry*, 2003, **391** (1–3). P. 173–176.

[115] Lukashin A.V., Vyacheslavov A.S., Vertegel A.A., Tret'yakov Yu.D. Synthesis of PbS/LDH Nanocomposites with the Use of the Method of Reversible Delamination of LDHs. *Doklady Chemistry*, 2002, **385** (1–3), P. 178–181.

[116] Parida K., Satpathy M., Mohapatra L. Incorporation of Fe^{3+} into Mg/Al layered double hydroxide framework: Effects on textural properties and photocatalytic activity for H_2 generation. *J. of Materials Chemistry*, 2012, **22**, P. 7350–7357.

[117] Boumeriame H., Da Silva E.S., et al. Layered double hydroxide (LDH)-based materials: A mini-review on strategies to improve the performance for photocatalytic water splitting. *J. of Energy Chemistry*, 2022, **64**, P. 406–431.

[118] Voropaeva D.Yu., Novikova S.A., Yaroslavtsev A.B. Polymer electrolytes for metal-ion batteries. *Russian Chemical Reviews*, 2020, **89** (10), P. 1132–1155.

[119] Ushakov N.M., Yurkov G.Yu., et al. Nanocomposites based on the cerium oxide nanoparticles and polyethylene matrix: Syntheses and properties. *Acta Materialia*, 2008, **56** (10), P. 2336–2343.

[120] De Martino M.T., Abdelmohsen L.K.E.A., Rutjes F.P.J.T., van Hest J.C.M. Nanoreactors for green catalysis. *Beilstein J. of Organic Chemistry*, 2018, **14**, P. 716–733.

[121] Vriezema D.M., Aragonès M.C., et al. Self-Assembled Nanoreactors. *Chemical Reviews*, 2005, **105**, P. 1445–1489.

[122] Syah R., Zahar M., Kianfar E. Nanoreactors: properties, applications and characterization. *Int. J. of Chemical Reactor Engineering*, 2021, **19** (10), P. 981–1007.

[123] Kaur M., Singh B. A Brief Review of Construction, Working and Applications of Nanoreactors. *Chemical Sciences J.*, 2018, **09** (03), 1000192.

[124] Volodin A.M., Bedilo A.F., Vedyagin A.A., Stoyanovskii V.O. Synthesis of Nanocrystalline Oxide Ceramic Materials: a Carbon Nanoreactor Concept. *JOJ Material Science*, 2017, **3** (4), P. 555617.

[125] Ryabochkina P.A., Egorysheva A.V., et al. Synthesis and photoluminescence properties of novel $LaGa_{0.5}Sb_{1.5}O_6$: Eu^{3+}, Dy^{3+}, Tb^{3+} and $BiGeSbO_6$: Eu^{3+}, Dy^{3+}, Tb^{3+} phosphors. *J. of Alloys and Compounds*, 2021, **886**, P. 161175.

[126] Proskurina O.V., Tomkovich M.V., et al. Formation of Nanocrystalline $BiFeO_3$ under Hydrothermal Conditions. *Russian J. of General Chemistry*, 2017, **87** (11), P. 2507–2515.

[127] Wang C., Cui Z., et al. Theoretical and experimental studies on the size- and morphology-dependent thermodynamics of nanoparticle electrodes. *Thermochimica Acta*, 2022, **708**, P. 179140.

[128] Bugrov A.N., Almjasheva O.V. Effect of hydrothermal synthesis conditions on the morphology of ZrO_2 nanoparticles. *Nanosystems: Physics, Chemistry, Mathematics*, 2013, **4** (6), P. 810–815.

[129] Gopinath S., Mayakannan M., Vetrivel S. Structural, optical, morphological properties of silver doped cobalt oxide nanoparticles by microwave irradiation method. *Ceramics International*, 2022, **48** (5), P. 6103–6115.

[130] Svinolupova A.S., Lomakin M.S., Kirillova S.A., Almjasheva O.V. Formation of Bi_2WO_6 nanocrystals under conditions of hydrothermal treatment. *Nanosystems: Physics, Chemistry, Mathematics,* 2020, **11** (3), P. 338–344.

[131] Sukhdev A., Challa M., et al. Synthesis, phase transformation, and morphology of hausmannite Mn_3O_4 nanoparticles: photocatalytic and antibacterial investigations. *Heliyon*, 2020, **6** (1), P. e03245.

[132] Rozenberg B.A., Tenne R. Polymer-assisted fabrication of nanoparticles and nanocomposites. *Progress in Polymer Science*, 2008, **33** (1), P. 40–112.

[133] Kostyukhin E.M., Kustov L.M. Microwave-assisted synthesis of magnetite nanoparticles possessing superior magnetic properties. *Mendeleev Communications*, 2018, **28** (5), P. 559–561.

[134] Golyeva E.V., Kolesnikov I.E., et al. Effect of synthesis conditions on structural, morphological and luminescence properties of $MgAl_2O_4$:Eu^{3+} nanopowders. *J. of Luminescence*, 2018, **194**, P. 387–393.

[135] Lomanova N.A., Tomkovich M.V., Osipov A.V., Ugolkov V.L. Synthesis of Nanocrystalline Materials Based on the Bi_2O_3–TiO_2 System. *Russian J. of General Chemistry*, 2019, **89**, P. 2075–2081.

[136] Bugrov A.N., Smyslov R.Yu., et al. Phosphors with different morphology, formed under hydrothermal conditions on the basis of ZrO_2:Eu^{3+} nanocrystallites. *Nanosystems: Physics, Chemistry, Mathematics*, 2019, **10** (6), P. 654–665.

[137] Kurdyukov D.A., Feoktistov N.A., et al. Template Synthesis of Monodisperse Submicrometer Spherical Nanoporous Silicon Particles. *Semiconductors*, 2019, **53**, P. 1048–1053.

[138] Almjasheva O.V. Formation and structural transformations of nanoparticles in the TiO_2–H_2O system. *Nanosystems: Physics, Chemistry, Mathematics*, 2016, **7** (6), P. 1031–1049.

[139] Popkov V.I., Almjasheva O.V., et al. Crystallization Behavior and Morphological Features of $YFeO_3$ Nanocrystallites Obtained by Glycine-Nitrate Combustion. *Nanosystems: Physics, Chemistry, Mathematics*, 2015, **6** (6), P. 866–874.

[140] Tajiri T., Terashita N., et al. Size dependences of crystal structure and magnetic properties of $DyMnO_3$ nanoparticles. *J. of Magnetism and Magnetic Materials*, 2013, **345**, P. 288–293.

[141] Lomanova N.A., Panchuk V.V., et al. Bismuth orthoferrite nanocrystals: magnetic characteristics and size effects. *Ferroelectrics*, 2020, **569** (1), P. 240–250.

[142] Popkov V.I., Almjasheva O.V., et al. Magnetic properties of $YFeO_3$ nanocrystals obtained by different soft-chemical methods. *J. of Materials Science: Materials in Electronics*, 2017, **28** (10), P. 7163–7170.

[143] Manukyan A., Elsukova A., et al. Structure and size dependence of the magnetic properties of Ni@C nanocomposites. *J. of Magnetism and Magnetic Materials*, 2018, **467**, P. 150–159.

[144] Tian Z., Zhu C., et al. Size dependence of structure and magnetic properties of $CoCr_2O_4$ nanoparticles synthesized by hydrothermal technique. *J. of Magnetism and Magnetic Materials*, 2015, **377**, P. 176–182.

[145] Farbod M., Dehbidi V.K., Shoushtari M.Z. Size dependence of optical and magnetic properties of nickel oxide nanoparticles fabricated by electric arc discharge method. *Ceramics International*, 2017, **43** (16), P. 13670–13676.

[146] Murakami N., Kawakami S., Tsubota T., Ohno T. Dependence of photocatalytic activity on particle size of a shape-controlled anatase titanium(IV) oxide nanocrystal. *J. of Molecular Catalysis A: Chemical*, 2012, **358**, P. 106–111.

[147] Li L., Gao H., et al. Comparative investigation on synthesis, morphological tailoring and photocatalytic activities of $Bi_2O_2CO_3$ nanostructures. *Colloids and Surfaces A Physicochemical and Engineering Aspects*, 2022, **644**, P. 128758.

[148] Kroto H.W., Heath J.R., O'Brien S.C., Curl R.F. C60: Buckminsterfullerene. *Nature*, 1985, **318**, P. 162–163.

[149] Kratschmer W., Lamb L.D., Fostiropoulos K., Huffman D.R. Solid C60: a new form of carbon. *Nature*, 1990, **347** (6291), P. 354–358.

[150] Dunk P., Niwa H., et al. Large fullerenes in mass spectra. *Molecular Physics*, 2015, **113** (15), P. 1–3.

[151] Müller A., Shah S.Q.N., et al. Archimedean Synthesis and Magic Numbers: "Sizing" Giant Molybdenum-Oxide-Based Molecular Spheres of the Keplerate Type. *Angewandte Chemie International Edition*, 1999, **38** (21), P. 3238–3241.

[152] Müller A., Krickemeyer E., et al. Organizational Forms of Matter: An Inorganic Super Fullerene and Keplerate Based on Molybdenum Oxide. *Angewandte Chemie International Edition*, 1998, **37** (24), P. 3359–3363.

[153] Ostroushko A.A., Gagarin I.D., Danilova I.G., Gette I.F. The use of nanocluster polyoxometalates in the bioactive substance delivery systems. *Nanosystems: Physics, Chemistry, Mathematics*, 2019, **10** (3), P. 318–349.

[154] Müller A., Gouzerh P. From linking of metal-oxide building blocks in a dynamic library to giant clusters with unique properties and towards adaptive chemistry. *Chemical Society Reviews*, 2012, **41** (22), P. 7431–7463.

[155] Awada M., Floquet S., et al. Synthesis and Characterizations of Keplerate Nanocapsules Incorporating L- and D-Tartrate Ligands. *J. of Cluster Science*, 2017, **28** (2), P. 799–812.

[156] Ostroushko A.A., Tonkushina M.O., et al. Stability of the $Mo_{72}Fe_{30}$ polyoxometalate buckyball in solution. *Russian J. of Inorganic Chemistry*, 2012, **57** (9), P. 1210–1213.

[157] Qiao Z.-A., Zhang P., et al. Lab-in-a-Shell: Encapsulating Metal Clusters for Size Sieving Catalysis. *J. of the American Chemical Society*, 2014, **136** (32), P. 11260–11263.

[158] Hervieu M., Mellène B., et al. The route to fullerenoid oxides. *Nature Materials*, 2004, **3**, P. 269–273.

[159] Lebedev O.I., Bals S., et al. Mixed $(Sr_{1-x}Ca_x)_{33}Bi_{24}Al_{48}O_{141}$ fullerenoids: the defect structure analysed by (S)TEM techniques. *Int. J. of Materials Research*, 2006, **97** (7), P. 978–984.

[160] Boudin S., Mellenne B., et al. New Aluminate with a Tetrahedral Structure Closely Related to the C84 Fullerene. *Inorganic Chemistry*, 2004, **43** (19), P. 5954–5960.

[161] Iijima S. Helical microtubules of graphitic carbon. *Nature*, 1991, **354**, P. 56–58.

[162] Venkatesan S., Visvalingam B., et al. Effect of chemical vapor deposition parameters on the diameter of multi-walled carbon nanotubes. *International Nano Letters*, 2018, **8** (4), P. 297–308.

[163] Serra M., Arenal R., Tenne R. An overview of the recent advances in inorganic nanotubes. *Nanoscale*, 2019, **11** (17), P. 8073–8090.

[164] Zhang Y.J., Ideue T., et al. Enhanced intrinsic photovoltaic effect in tungsten disulfide nanotubes. *Nature*, 2019, **570** (7761), P. 349–353.

[165] Qin F., Shi W., et al. Superconductivity in a chiral nanotube. *Nature Communications*, 2017, 8 (1), P. 14465.

[166] Panchakarla L.S., Radovsky G., et al. Nanotubes from Misfit Layered Compounds: A New Family of Materials with Low Dimensionality. *J. of Physical Chemistry Letters*, 2014, **5** (21), P. 3724–3736.

[167] Polyakov A.Yu., Zak A., et al. Nanocomposites based on tubular and onion nanostructures of molybdenum and tungsten disulfides: inorganic design, functional properties and application. *Russian Chemical Reviews*, 2018, **87**, P. 251–271.

[168] Lourenco M.P., de Oliveira C., et al. Structural, Electronic, and Mechanical Properties of Single-Walled Chrysotile Nanotube Models. *J. of Physical Chemistry C*, 2012, **116**, P. 9405–9411.

[169] Guimaräes L., Enyashin, A.N., Seifert G., Duarte H.A. Structural, Electronic, and Mechanical Properties of Single-Walled Halloysite Nanotube Models. *J. of Physical Chemistry C*, 2010, **114**, P. 11358–11363.

[170] Krasilin A.A., Gusarov V.V. Energy Model of Bilayer Nanoplate Scrolling: Formation of Chrysotile Nanoscroll. *Russian J. of General Chemistry*, 2015, **85**, P. 2238–2241.

[171] Demichelis R., De La Pierre M., et al. Serpentine Polymorphism: A Quantitative Insight from First-Principles Calculations. *Cryst. Eng. Comm.*, 2016, **18**, P. 4412–4419.

[172] Krasilin A.A., Gusarov V.V. Energy model of radial growth of a nanotubular crystal. *Technical Physics Letters*, 2016, **42** (1), P. 55–58.

[173] Krasilin A.A., Nevedomsky V.N., Gusarov V.V. Comparative Energy Modeling of Multi-Walled $Mg_3Si_2O_5(OH)_4$ and $Ni_3Si_2O_5(OH)_4$ Nanoscrolls Growth. *J. of Physical Chemistry C*, 2017, **121** (22), P. 12495–12502.

[174] Krasilin A.A., Suprun A.M., Nevedomsky V.N., Gusarov V.V. Formation of conical $(Mg,Ni)_3Si_2O_5(OH)_4$ nanoscrolls. *Doklady Physical Chemistry*, 2015, **460** (2), P. 42–44.

[175] Krasilin A.A., Gusarov V.V. Redistribution of Mg and Ni cations in crystal lattice of conical nanotube with chrysotile structure. *Nanosystems: Physics, Chemistry, Mathematics*, 2017, **8** (5), P. 620–627.

[176] Proskurina O.V., Sivtsov E.V., et al. Formation of rhabdophane-structured lanthanum orthophosphate nanoparticles in an impinging-jets microreactor and rheological properties of sols based on them. *Nanosystems: Physics, Chemistry, Mathematics*, 2019, **10** (2), P. 206–214.

[177] Avdeeva A.V., Zang X., Muradova A.G., Yurtov E.V. Formation of Zinc-Oxide Nanorods by the Precipitation Method. *Semiconductors*, 2017, 51 (13), P. 1724–1727.

[178] Zaien M., Ahmed N.M., Hassan Z. Growth of cadmium oxide nanorods by vapor transport. *Chalcogenide Letters*, 2012, 9 (3), P. 115–119.

[179] Tokunaga T., Kawamoto T., et al. Growth and structure analysis of tungsten oxide nanorods using environmental TEM. *Nanoscale Research Letters*, 2012, **7** (1), P. 85.

[180] Ma M., Zhang Y., Guo Z., Gu N. Facile synthesis of ultrathin magnetic iron oxide nanoplates by Schikorr reaction. *Nanoscale Research Letters*, 2013, **8** (1), P. 16.

[181] Nguyen V.T., Nguyen H.S., et al. Tungsten Oxide Nanoplates: Facile Synthesis, Controllable Oxygen Deficiency and Photocatalytic Activity. *Communications in Physics*, 2020, **30** (4), P. 319.

[182] Krasilin A.A. Energy modeling of competition between tubular and platy morphologies of chrysotile and halloysite layers. *Clays and Clay Minerals*, 2020, **68**, P. 436–445.

[183] Krasilin A.A. The influence of edge specific surface energy on the direction of hydrosilicate layers scrolling. *Nanosystems: Physics, Chemistry, Mathematics*, 2021, **12** (5), P. 623–629.

[184] Antonov N.M., Popov I.Y., Gusarov V.V. Model of spinodal decomposition of phases under hyperbolic diffusion. *Physics of the Solid State*, 1999, **41** (5), P. 824–826.

[185] Jáger C., Tomán J.J., Erdélyi Z. Nanoparticle formation by spinodal decomposition in ion implanted samples. *J. of Alloys and Compounds*, 2022, P. 164781.

[186] Ahmadi R., Masoudi A., Hamid Reza Madaah Hosseini, Gu N. Kinetics of magnetite nanoparticles formation in a one step low temperature hydrothermal process. *Ceramics International*, 2013, **39** (5), P. 4999–5005.

[187] Tyrsted C., Becker J., et al. In-situ synchrotron radiation study of formation and growth of crystalline $Ce_xZr_{1-x}O_2$ nanoparticles synthesized in supercritical water. *Chemistry of Materials*, 2010, **22** (5), P. 1814–1820.

[188] Ivanov V.K., Polezhaeva O.S., et al. Microwave-hydrothermal synthesis of stable nanocrystalline ceria sols for biomedical uses. *Russian J. of Inorganic Chemistry*, 2010, **55** (1), P. 1–5.

[189] Kuznetsova V.A., Almjasheva O.V., Gusarov V.V. Influence of microwave and ultrasonic treatment on the formation of $CoFe_2O_4$ under hydrothermal conditions. *Glass Physics and Chemistry*, 2009, **35** (2), P. 205–209.

[190] Liu L., Wang S., et al. Supercritical hydrothermal synthesis of nano-ZrO_2: Influence of technological parameters and mechanism. *J. of Alloys and Compounds*, 2022, **898**, P. 162878.

[191] Bachina A.K., Almjasheva O.V., et al. Heat-stimulated crystallization and phase transformation of titania nanoparticles. *J. of Crystal Growth*, 2021, **576**, P. 126371.

[192] Escobedo-Morales A., Téllez-Flores D., et al. Green method for producing hierarchically assembled pristine porous ZnO nanoparticles with narrow particle size distribution. *Materials Chemistry and Physics*, 2015, **151**, P. 282–287.

[193] Ngoi K.H., Wong J.C., et al. Morphological structure details, size distributions and magnetic properties of iron oxide nanoparticles. *J. of Industrial and Engineering Chemistry*, 2021, **95**, P. 37–50.

[194] Rusanov A.I. *Fazovye ravnovesiya i poverkhnostnye yavleniya (Phase Equilibria and Surface Phenomena)*, Leningrad: Khimiya, 1967, 388 p. (In Russian)

[195] Rusanov A.I. *Phasengleichgewichte und Grenzflächenerscheinungen*. Berlin: Akademie Verlag, 1978, 465 p.

[196] Tolstoy V.P. *Fundamentals of Ion Layering Nanotechnology. Tutorial*. SPbU, SPb, 2020, 142 p. (In Russian)

[197] Ermakov S.S., Nikolaev K.G., Tolstoy V.P. Novel electrochemical sensors with electrodes based on multilayers fabricated by layer-by-layer synthesis and their analytical potential. *Russian Chemical Reviews*, 2016, **85** (8), P. 880–900.

[198] Tolstoi V.P. New routes for the synthesis of nanocomposite layers of inorganic compounds by the layer-by-layer scheme. *Russian J. of General Chemistry*, 2009, **79** (12), P. 2578–2583.

[199] Mateos-Maroto A., Abelenda-Núñez I., et al. Polyelectrolyte Multilayers on Soft Colloidal Nanosurfaces: A New Life for the Layer-By-Layer Method. *Polymers (Basel)*, 2021, **13** (8), P. 1221.

[200] Richardson J.J., Björnmalm M., Caruso F. Technology-driven layer-by-layer assembly of nanofilms. *Science*, 2015, **348** (6233), P. 411.

[201] Ahvenniemi E., Akbashev A.R., et al. Review Article: Recommended reading list of early publications on atomic layer deposition—Outcome of the "Virtual Project on the History of ALD". *J. of Vacuum Science and Technology A*, 2017, **35** (1), P. 010801.

[202] Method of manganese dioxide synthesis, Patent. 1396600, Russia: 4 C 03 17/25 Tolstoy V.P., Bogdanova L.B., Mitykova G.V. N 4010248/31-33, Prior. 01.06.1986. Issue N 3, p. 114, 1988.

[203] Popkov V.I., Tolstoy V.P., Nevedomskiy V.N. Peroxide route to the synthesis of ultrafine CeO_2–Fe_2O_3 nanocomposite via successive ionic layer deposition. *Heliyon*, 2019, **5** (3), P. e01443.

[204] Tolstoi V.P. Synthesis of thin-layer structures by the ionic layer deposition method. *Russian Chemical Reviews*, 1993, **62** (3), P. 237–242.

[205] Tolstoy V.P., Altangerel B. A new "fluoride" synthesis route for successive ionic layer deposition of the $Zn_xZr(OH)_yF_z \cdot nH_2O$ nanolayers. *Materials Letters*, 2007, **53** (1), P. 123–125.

[206] Li Z., Xiong S.,et al. Role of Ag_2S coupling on enhancing the visible-light-induced catalytic property of TiO_2 nanorod arrays. *Scientific Reports*, 2016, P. 19754.

[207] Popkov V.I., Tolstoy V.P. Controllable wettability tuning of the stainless steel surface through successive ionic layer deposition of Zn–Fe layered double hydroxysulfate. *Surface and Coatings Technology*, 2021, **409**, P. 126914.

[208] Li X., Chen F., et al. Layer-by-layer synthesis of hollow spherical CeO_2 templated by carbon spheres. *J. of Porous Materials*, 2010, **17**, P. 297–303.

[209] Shekhah O. Layer-by-Layer Method for the Synthesis and Growth of Surface Mounted Metal-Organic Frameworks (SURMOFs). *Materials*, 2010, **3**, P. 1302–1315.

[210] Khajavian R., Ghani K. Fabrication of $[Cu_2(bdc)_2(bpy)]_n$ thin films using coordination modulation-assisted layer-by-layer growth. *Cryst. Eng. Comm.*, 2018, **20**, P. 1546–1552.

[211] Galkin V.I., Sayakhov R.D., Cherkasov R.A. Steric effects: the problem of their quantitative assessment and manifestation in the reactivity of organoelement compounds. *Russian Chemical Reviews*, 1991, **60** (8), P. 815–829.

[212] Teychené S., Rodríguez-Ruiz I., Ramamoorthy R.K. Reactive crystallization: From mixing to control of kinetics by additives. *Current Opinion in Colloid & Interface Science*, 2020, **46**, P. 1–19.

[213] Johnson B.K., Prud'homme R.K. Chemical Processing and Micromixing in Confined Impinging Jets. *AIChE J.*, 2003, **49** (9), P. 2264–2282.

[214] Erkoc E., Fonte C.P., et al. Numerical and experimental modeling of mixing of impinging jets radially injected into crossflow. *Chemical Engineering Research and Design*, 2016, **106**, P. 74–91.

[215] Abiev R.Sh., Almjasheva O.V., Popkov V.I., Proskurina O.V. Microreactor Synthesis of Nanosized Particles: The Role of Micromixing, Aggregation, and Separation Processes in Heterogeneous Nucleation. *Chemical Engineering Research and Design*, 2022, **178**, P. 73–94.

[216] Abiev R.S., Almyasheva O.V., Izotova S.G., Gusarov V.V. Synthesis of cobalt ferrite nanoparticles by means of confined impinging-jets reactors. *J. of Chemical Technology and Applications*, 2017, **1** (1), P. 7.

[217] Maki T., Takeda S., Muranaka Y., Mae K. Silver Nanoparticle Synthesis Using an Inkjet Mixing System. *Frontiers in Chemical Engineering*, 2021, **3**, P. 742322.

[218] Wu Y., Lu J., Yang Q. A Control System Design for Nanoparticle Manufacturing by Using Impinging-jet Micromixers. *Advanced Materials Research*, 2012, **528**, P. 3–9.

[219] Rivallin M., Benmami M., Kanaev A., Gaunand A. Sol–Gel reactor with rapid micromixing: modelling and measurements of titanium oxide nano-particle growth. *Chemical Engineering Research and Design*, 2005, **83**, P. 67–74.

[220] Abiev R.S. Impinging-Jets Micromixers and Microreactors: State of the Art and Prospects for Use in the Chemical Technology of Nanomaterials (Review). *Theoretical Foundations of Chemical Engineering*, 2020, **54** (6), P. 1131–1147.

[221] Abiev R.S., Proskurina O.V., Enikeeva M.O., Gusarov V.V. Effect of Hydrodynamic Conditions in an Impinging-Jet Microreactor on the Formation of Nanoparticles Based on Complex Oxides. *Theoretical Foundations of Chemical Engineering*, 2021, **55** (1), P. 12–29.

[222] Zhao C.-X., He L., Qiao S.Z., Middelberg A.P.J. Nanoparticle synthesis in microreactors. *Chemical Engineering Science*, 2011, **66** (7), P. 1463–1479.

[223] Barashok K.I., Panchuk V.V., et al. Formation of cobalt ferrite nanopowders in an impinging-jets microreactor. *Nanosystems: Physics, Chemistry, Mathematics*, 2021, **12** (3), P. 303–310.

[224] Zdravkov A.V., Kudryashova Y.S., Abiev R.S. Synthesis of Titanium Oxide Doped with Neodymium Oxide in a Confined Impinging-Jets Reactor. *Russian J. of General Chemistry*, 2020, **90** (9), P. 1677–1680.

[225] Kudryashova Y.S., Zdravkov A.V., Ugolkov V.L., Abiev R.S. Preparation of Photocatalizers Based on Titanium Dioxide Synthesized Using a Microreactor with Colliding Jets. *Glass Physics and Chemistry*, 2020, **46** (4), P. 335–340.

[226] Abiev R.Sh., Sirotkin A.A. Influence of Hydrodynamic Conditions on Micromixing in Microreactors with Free Impinging Jets. *Fluids*, 2020, **5** (4), P. 179.

[227] Ravi Kumar D.V., Prasad B.L.V., Kulkarni A.A. Impinging Jet Micromixer for Flow Synthesis of Nanocrystalline MgO: Role of Mixing/Impingement Zone. *J. of Industrial and Engineering Chemistry*, 2013, **52**, P. 17376.

[228] Proskurina O.V., Nogovitsin I.V., et al. Formation of $BiFeO_3$ Nanoparticles Using Impinging Jets Microreactor. *Russian J. of General Chemistry*, 2018, **88** (10), P. 2139–2143.

[229] Kudryashova Y.S., Zdravkov A.V., Abiev R.S. Synthesis of Yttrium–Aluminum Garnet Using a Microreactor with Impinging Jets. *Glass Physics and Chemistry*, 2021, **47** (3), P. 260–264.

[230] Sokolova A.N., Proskurina O.V., Danilovich D.P., Gusarov V.V. Photocatalytic properties of composites based on $Y_{1-x}Bi_xFeO_3$ ($0 \leq x \leq 0.15$) nanocrystalline solid solutions with a hexagonal structure. *Nanosystems: Physics, Chemistry, Mathematics*, 2022, **13** (1), P. 87–95.

[231] Lomakin M.S., Proskurina O.V., et al. Crystal structure and optical properties of the Bi-Fe-W-O pyrochlore phase synthesized via a hydrothermal method. *J. of Alloys and Compounds*, 2022, **889** (5), P. 161598.

[232] Vo Q.M., Mittova V.O., et al. Strontium doping as a means of influencing the characteristics of neodymium orthoferrite nanocrystals synthesized by co-precipitation method. *J. of Materials Science: Materials in Electronics*, 2021, **32**, P. 26944–26954.

[233] Gao T., Chen Z., et al. A review: Preparation of bismuth ferrite nanoparticles and its applications in visible-light induced photocatalyses. *Reviews on Advanced Materials Science*, 2012, **40** (2), P. 97–109.

[234] Proskurina O.V., Abiev R.S.,et al. Formation of nanocrystalline $BiFeO_3$ during heat treatment of hydroxides co-precipitated in an impinging-jets microreactor. *Chemical Engineering and Processing – Process Intensification*, 2019, **143**, P. 107598.

[235] Proskurina O.V., Sokolova A.N., et al. Role of Hydroxide Precipitation Conditions in the Formation of Nanocrystalline $BiFeO_3$. *Russian J. of Inorganic Chemistry*, 2021, **66** (2), P. 163–169.

[236] Chang Chien S.-W., Ng D.-Q., et al. Investigating the effects of various synthesis routes on morphological, optical, photoelectrochemical and photocatalytic properties of single-phase perovskite $BiFeO_3$. *J. of Physics and Chemistry of Solids*, 2022, **160**, P. 110342.

[237] Che D., Zhu X., et al. A facile aqueous strategy for the synthesis of high-brightness $LaPO_4$: Eu nanocrystals via controlling the nucleation and growth process. *J. of Luminescence*, 2014, **153**, P. 369–374.

[238] Nightingale A.M., de Mello J.C. Segmented Flow Reactors for Nanocrystal Synthesis. *Advanced Materials*, 2013, **25**, P. 1813–1821.

[239] Kawase M., Suzuki T., Miura K. Growth mechanism of lanthanum phosphate particles by continuous precipitation. *Chemical Engineering Science*, 2007, **62**, P. 4875–4879.

[240] Kawase M., Miura K. Fine particle synthesis by continuous precipitation using a tubular reactor. *Advanced Powder Technology*, 2007, **18** (6), P. 725–738.

[241] Abiev R.Sh., Zdravkov A.V., et al. Synthesis of Calcium Fluoride Nanoparticles in a Microreactor with Intensely Swirling Flows. *Russian J. of Inorganic Chemistry*, 2021, **66** (7), P. 1047–1052.

[242] Almjasheva O.V., Krasilin A.A., Gusarov V.V. Formation mechanism of core-shell nanocrystals obtained via dehydration of coprecipitated hydroxides at hydrothermal conditions. *Nanosystems: Physics, Chemistry, Mathematics*, 2018, **9** (4), P. 568–572.

[243] Smirnov A.V., Fedorov B.A., et al. Core-shell nanoparticles forming in the ZrO_2–Gd_2O_3–H_2O system under hydrothermal conditions. *Doklady Physical Chemistry*, 2014, **456** (1), P. 71–73.

[244] Almjasheva O.V., Smirnov A.V., et al. Structural features of ZrO_2–Y_2O_3 and ZrO_2–Gd_2O_3 nanoparticles formed under hydrothermal conditions. *Russian J. of General Chemistry*, 2014, **84** (5), P. 804–809.

[245] Malygin A.A., Malkov A.A., Sosnov A.A. Structural-dimensional effects and their application in the "core-nanoshell" systems synthesized by the molecular layering. *Russian Chemical Bulletin*, 2017, **66**, P. 1939–1962.

[246] Patil K.C., Aruna S.T., Mimani T. Combustion synthesis: an update. *Current Opinion in Solid State and Materials Science*, 2002, **6** (6), P. 507–512.

[247] Merzhanov A.G. Combustion and explosion processes in physical chemistry and technology of inorganic materials. *Russian Chemical Reviews*, 2003, **72** (4), P. 323–345.

[248] Sytschev A.E., Merzhanov A.G. Self-propagating high-temperature synthesis of nanomaterials. *Russian Chemical Reviews*, 2004, **73** (2), P. 157–170.

[249] Deshpande K., Mukasyan A., Varma A. Direct synthesis of iron oxide nanopowders by the combustion approach: Reaction mechanism and properties. *Chemistry of Materials*, 2004, **16** (24), P. 4896–4904.

[250] Mukasyan A.S., Epstein P., Dinka P. Solution combustion synthesis of nanomaterials. *Proceedings of the Combustion Institute*, 2007, **31**, P. 1789–1795.

[251] Aruna S.T., Mukasyan A.S. Combustion synthesis and nanomaterials. *Current Opinion in Solid State and Materials Science*, 2008, **12** (3–4), P. 44–50.

[252] Martinson K.D., Kondrashkova I.S., Popkov V.I. Synthesis of $EuFeO_3$ nanocrystals by glycine-nitrate combustion method. *Russian J. of Applied Chemistry*, 2017, **90**, P. 1214–1218.

[253] Lomanova N.A., Tomkovich M.V., et al. Formation of $Bi_{1-x}Ca_xFeO_{3-\delta}$ Nanocrystals via Glycine-Nitrate Combustion. *Russian J. of General Chemistry*, 2019, **89**, P. 1843–1850.

[254] Tugova E.A., Karpov O.N. Glycine–nitrate combustion engineering of neodymium cobaltite nanocrystals. *Rare Metals*, 2021, **40**, P. 1778–1784.

[255] Martinson K.D., Ivanov V.A., et al. Facile combustion synthesis of $TbFeO_3$ nanocrystals with hexagonal and orthorhombic structure. *Nanosystems: Physics, Chemistry, Mathematics*, 2019, **10** (6), P. 694–700.

[256] Martinson K.D., Panteleev I.B., Shevchik A.P., Popkov V.I. Effect of the Red/Ox ratio on the structure and magnetic behavior of $Li_{0.5}Fe_{2.5}O_4$ nanocrystals synthesized by solution combustion approach. *Letters on Materials*, 2019, **9** (4), P. 475–479.

[257] Tretyakov Y.D., Oleinikov N.N., et al. Self-organization in physicovhemical systems: On the path to creating novel materials. *Inorganic Materials*, 1994, **30** (3), P. 277–290.

[258] Noyes R.M. Gas-Evolution Oscillators. 4. Characteristics of the Steady State for Gas Evolution. *J. of Physical Chemistry*, 1984, **88**, P. 2827–2833.

[259] Yang J., Sasaki T. Synthesis of CoOOH Hierarchically Hollow Spheres by Nanorod Self-Assembly through Bubble Templating. *Chemistry of Materials*, 2008, **20** (5), P. 2049–2056.

[260] Morgan J.S. The Periodic Ecolution of Carbon Monoxide. *J. of the Chemical Society, Transaction*, 1916, **109**, P. 274–283.

[261] Duyen P.T.H., Nguyen A.T. Optical and magnetic properties of orthoferrite $NdFeO_3$ nanomaterials synthesized by simple co-precipitation method. *Condensed Matter and Interphases*, 2021, **23** (4), P. 600–606.

[262] Rotermel M.V., Samigullina R.F., Ivanova I.V., Krasnenko T.I. Synthesis of the $Zn_{1.9}Cu_{0.1}SiO_4$ pigment via the sol–gel and coprecipitation methods. *J. of Sol-Gel Science and Technology*, 2021, **100**, P. 404–413.

[263] Kiseleva T.Yu., Uyangaa E., et al. Strucute, magnetic, and magnetocaloric properties of submicronic yttrium iron garnet particles. *J. of Structural Chemistry*, 2022, **63**, P. 26–36.

[264] Matrosova A.S., Kuz'menko N.K., et al. Synthesis of Nanosized Luminophores Gd_2O_3:Nd^{3+} by Polymer-Salt Method and Study of Their Main Characteristics. *Optics and Spectroscopy*, 2021, **129**, P. 662–669.

[265] Zhuravlev V.D., Dmitriev A.V., et al. Parameters of Glycine–Nitrate Synthesis of $NiCo_2O_4$ Spinel. *Russian J. of Inorganic Chemistry*, 2021, **66**, P. 1895–1903.

[266] Kondrat'eva O.N., Nikiforova G.E., Smirnova M.N., Pechkovskaya K.I. Synthesis and Thermophysical Properties of Ceramics Based on Magnesium Gallate. *Russian J. of Inorganic Chemistry*, 2021, **66**, P. 957–962.

[267] Sheindlin M.A., Kirillin A.V., Heyfetz L.M., Khodakov K.A. Fast automated-system for high-temperature (2500–6000-degrees-K) measurements of samples heated by laser-radiation. *High Temperature*, 1981, **19** (4), P. 620–627.

[268] Kirillin A.V., Kovalenko M.D., et al. Apparatus and methods for examining the properties of refractory substances at high-temperatures and pressures by stationary laser-heating. *High Temperature*, 1986, **24** (2), P. 286–290.

[269] Sheindlin M.A., Son E.E. Lasers in high-temperature energy materials. *Izvestiya RAS. Energy*, 2011, **5**, P. 88–103. (In Russian)

[270] Rivera-Chaverra M.J., Restrepo-Parra E., et al. Synthesis of Oxide Iron Nanoparticles Using Laser Ablation for Possible Hyperthermia Applications. *Nanomaterials*, 2020, **10** (11), P. 2099.

[271] Kim M., Osone S., et al. Synthesis of Nanoparticles by Laser Ablation: A Review. *Powder and Particle J.*, 2017, **34**, P. 80–90.

[272] Amendola V., Amans D., et al. Room-temperature laser synthesis in liquid of oxide, metal-oxide core-shells and doped oxide nanoparticles. *Chemistry – A European J.*, 2020, **26**, P. 9206–9242.

[273] Popova-Kuznetsova E., Tikhonowski G., et al. Laser-Ablative Synthesis of Isotope-Enriched Samarium Oxide Nanoparticles for Nuclear Nanomedicine. *Nanomaterials*, 2020, **10** (1), P. 69.

[274] Liu S., Moein Mohammadi M., Swihart M.T. Fundamentals and Recent Applications of Catalyst Synthesis Using Flame Aerosol Technology. *Chemical Engineering J.*, 2021, **405**, P. 126958.

[275] Nemade K.R., Waghuley S.A. Synthesis of MgO Nanoparticles by Solvent Mixed Spray Pyrolysis Technique for Optical Investigation. *Int. J. of Metals*, 2014, **5**, P. 389416.

[276] Santiago A.A.G., Tranquilin R.L., et al. Effect of temperature on ultrasonic spray pyrolysis method in zinc tungstate: The relationship between structural and optical properties. *Materials Chemistry and Physics*, 2021, **258**, P. 123991.

[277] Matsukevich I., Krutko N.P., et al. Effect of preparation method on physicochemical properties of nanostructured MgO powder. *Proceedings of the National Academy of Sciences of Belarus, Chemical Series*, 2018, **54** (3), P. 281–288.

[278] Ivanovskaya M.I., Tolstik A.I., Pan'kov V.V. Synthesis of $Zn_{0.5}Mn_{0.5}Fe_2O_4$ by low-temperature spray pyrolysis. *Inorganic Materials*, 2009, **45** (11), P. 1309–1313.

[279] Puzyrev I.S., Andreikov E.I., et al. Adsorption properties of mesoporous carbon synthesized by pyrolysis of zinc glycerolate. *Russian Chemical Bulletin*, 2021, **70** (5), P. 805–810.

[280] Melkozerova M.A., Ishchenko A.V., et al. Intrinsic Defects and their Influence on Optical Properties of $ALa_9(GeO_4)_6O_2$ (A = Li, Na, K, Rb, Cs) Oxyapatites prepared by Spray Pyrolysis. *J. of Alloys and Compounds*, 2020, **839**, P. 155609.

[281] Boldyrev V.V., Voronin A.P., et al. Radiation-Thermal Synthesis. Current Achievement and Outlook. *Solid State Ionics*, 1989, **36**, P. 1–6.

[282] Lyakhov N.Z., Boldyrev V.V., et al. Electron beam stimulated chemical reactions in solids. *Thermal Analysis*, 1995, **43**, P. 21–31.

[283] Ancharova U.V., Mikhailenko M.A., et al. Effect of irradiation with relativistic electrons on the synthesis kinetics of $Ni_{0.75}Zn_{0.25}Fe_2O_4$. *Vestnik NSU. Series: Physics*, 2013, **8** (4), P. 41–48. (In Russian)

[284] Stepanov V.A. Radiation-stimulated diffusion in solids. *Technical Physics*, 1998, **43** (8), P. 938–942.

[285] Kretusheva I.V., Mishin M.V., Aleksandrov S.E. Synthesis of silicon dioxide nanoparticles in low temperature atmospheric pressure plasma. *Russian J. of Applied Chemistry*, 2014, **87** (11), P. 1581–1586.

[286] Kim K.S., Kim T.H. Nanofabrication by thermal plasma jets: From nanoparticles to low-dimensional nanomaterials. *J. of Applied Physics*, 2019, **125** (7), P. 070901.

[287] Uschakov A.V., Karpov I.V., Lepeshev A.A., Petrov M.I. Plasma-chemical synthesis of copper oxide nanoparticles in a low-pressure arc discharge. *Vacuum*, 2016, **133**, P. 25–30.

[288] Toropov N.A., Barzakovskii V.P., Lapin V.V., Kurtseva N.N. *Handbook of Phase Diagrams of Silicate Systems. I. Binary Systems*. Second Revised Edition (Diagrammy Sostoyaniya Silikatnykh Sistem - Spravochnik), Nauka, Leningrad, 1969, 822 p. (In Russian)

[289] *Minerals: Phase Equilibrium Diagrams: Handbook*. Resp. ed. F.V. Chukhrov, Moscow, Nauka, 1974. Issue 1: Phase equilibria important for natural mineral formation. Resp. ed. F.V. Chukhrov, I.A. Ostrovsky, V.V. Lapin., 1974, 514 p. (In Russian)

[290] Belov G.V., Iorish V.S., Yungman V.S. Simulation of equilibrium states of thermodynamic systems using IVTANTERMO for Windows. *High Temperature*, 2000, **38**, P. 191–196.

[291] Gusarov V.V., Suvorov S.A. Melting-point of locally equilibrium surface phases in polycrystallibe systems based on a single volume phase. *J. of Applied Chemistry of the USSR*, 1990, **63** (8), P. 1560–1565.

[292] Gusarov V.V. The thermal effect of melting in polycrystalline systems. *Thermochimica Acta*, 1995, **256** (2), P. 467–472.

[293] Dash J.G. History of the search for continuous melting. *Reviews of Modern Physics*, 1999, **71** (5), P. 1737–1743.

[294] Gusarov V.V., Suvorov S.A. Transformation of Nonautonomous Phases and Densification of Polycrystalline Systems. *J. of Applied Chemistry of the USSR*, 1992, **65** (7), P. 1227–1235.

[295] Gusarov V.V., Suvorov S.A. Transformation and transport processes in polycrystalline systems and creep of materials. *J. of Applied Chemistry of the USSR*, 1992, **65** (10), P. 1961–1964.

[296] Gusarov V.V., Popov I.Yu. Flows in two-dimensional nonautonomous phases in polycrystalline systems. *Nuovo Cimento*, 1996, **18D** (7), P. 1834–1840.

[297] Gusarov V.V., Malkov A.A., Malygin A.A., Suvorov S.A. Thermally Activated Transformations of 2D Nonautonomous Phases and Contraction of Polycrystalline Oxide Materials. *Inorganic Materials*, 1995, **31** (3), P.320–323.

[298] Ishutina Zh.N., Gusarov V.V., et al. Phase Transformations in Nanosized γ-Al_2O_3-SiO_2-TiO_2 Compositions. *Russian J. of Inorganic Chemistry*, 1999, **44** (1), P. 12–14.

[299] Neiman A.Ya., Uvarov N.F., Pestereva N.N. Solid state surface and interface spreading: An experimental study. *Solid State Ionics*, 2007, **177** (39–40), P. 3361–3369.

[300] Boldyrev V.V. Mechanochemistry and mechanical activation of solids. *Russian Chemical Reviews*, 2006, **75** (3), P. 177–189.

[301] Grigorieva T., Korchagin M., Lyakhov N. Combinations of SHS and mechanochemical synthesis for nanopowder technologies. *Powder and Particle*, 2002, **20**, P. 144–158.

[302] Isupov V.P., Borodulina I.A., Gerasimov K.B., Bulina N.V. Effect of Mechanical Activation on Reaction between Boehmite and Lithium Carbonate. *Inorganic Materials*, 2020, **56**, P. 56–61.

[303] Eremina N.V., Isupov V.P. Mechanochemical synthesis of lithium pentaaluminate from lithium carbonate and boehmite. *Inorganic Materials*, 2020, **56** (5), P. 466–472.

[304] Avvakumov E., Senna M., Kosova N. *Soft Mechanochemical Synthesis: a Basis for New Chemical Technologies*. Boston/Dodrecht/ London: Kluwer Academic Publishers, 2001, 201 p.

[305] Avvakumov E.G., Pushnyakova V.A. Mechanochemical synthesis of complex oxides. *Khimicheskaya Tekhnologiya*, 2002, **5**, P. 6–17. (In Russian)

[306] Kolbanev I.V., Shlyakhtina A.V., et al. Room-temperature mechanochemical synthesis of RE molybdates: Impact of structural similarity and basicity of oxides. *J. of the American Ceramic Society*, 2021, **104**, P. 5698–5710.

Information about the authors:

Oksana V. Almjasheva – St. Petersburg State Electrotechnical University "LETI", 197376 St. Petersburg, Russia; ORCID 0000-0002-6132-4178; almjasheva@mail.ru

Vadim I. Popkov – Ioffe Institute, 194021 St. Petersburg, Russia; ORCID 0000-0002-8450-4278; vadim.i.popkov@mail.ioffe.ru

Olga V. Proskurina – Ioffe Institute, 194021 St. Petersburg, Russia; St. Petersburg State Institute of Technology, 190013 St. Petersburg, Russia; ORCID 0000-0002-2807-375X; proskurinaov@mail.ru

Victor V. Gusarov – Ioffe Institute, 194021 St. Petersburg, Russia; ORCID 0000-0003-4375-6388; victor.v.gusarov@gmail.com

Conflict of interest: the authors declare no conflict of interest.