We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

ZnO Nanostructures Synthesized by Chemical Solutions

Jose Alberto Alvarado Garcia, Zachary Garbe Neale,
Antonio Arce-Plaza, Avelino Cortes Santiago and
Hector Juarez Santiesteban

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.68278>

Abstract

Nanomaterials have been synthesized using several different techniques. Some of these techniques are sophisticated, expensive and need certain training before use. However, there are other highly efficient methods for preparing nanomaterials that are easy to work with and require no specialized equipment, making them relatively inexpensive routes for synthesis. The least expensive routes are those that are classified as solution-based techniques such as colloidal, sol-gel and microwave-assisted synthesis. The focus of this chapter is on a general description of each technique with recent advances in synthesis, doping processes and applications. Specifically, these processes are discussed in connection with the synthesis of ZnO compounds and its related nanomaterials.

Keywords: ZnO, synthesis, chemical solutions, nanostructures

1. Introduction

An important II–VI semiconductor is ZnO which has been well-studied and applied in a variety of applications. It has a band gap of 3.6 eV and large exciton binding energy of 60 meV. Nowadays this material is considered as one of the most important large band gap semiconductors due to its easy synthesis, stability at room temperature, eco-friendly properties, being a direct band gap material and fast mobility. This material exists in three different crystal phases such as zinc blende, cubic or rock salt and wurtzite or hexagonal. The first two phases are obtained only in certain well-controlled conditions such as certain pressures and

on specific substrates. However, the most common phase under ambient conditions is the wurtzite hexagonal crystal structure shown in **Figure 1**.

Another advantage of this compound is that it can be synthesized and deposited by employing different techniques. Slight variation in process conditions can result in different product morphologies and properties. Since the costs associated with research and industry is always an important consideration, it becomes necessary to use inexpensive and efficient methods to obtain the desired novel nanostructured materials with applications in different fields such as optoelectronics, solar cells, piezoelectric and sometimes in biological materials.

Sol-gel, colloidal solution and microwave-assisted synthesis are techniques that are still important in the synthesis of semiconductor nanomaterials. These techniques share some similar characteristics such as (i) they are relatively inexpensive; (ii) the efficiency of the synthesized materials is high; (iii) process parameters are easily controlled and (iv) these techniques are also well-studied. For these reasons, in this chapter we have focused on a review of these techniques, especially for the synthesis of ZnO, with emphasis on the recent advances in the synthesis of novel nanomaterials and its applications. A general overview of each process is also presented for ease of readability. The synthesized materials have been structurally characterized using X-ray diffraction (XRD) and scanning electron microscopy (SEM). **Figure 2** shows a representative XRD pattern of ZnO. XRD patterns of synthesized material can be compared to reference patterns to determine phase purity or if there is preferential crystal orientation. Most of the time, ZnO is obtained as a polycrystalline film or powder which can be identified by its numerous diffraction peaks at relative intensities. Depending on the processing conditions, single crystal or preferential growth can occur

Figure 1. Representation of ZnO wurtzite crystal structure (black and grey balls corresponds to Zn and Oxygen atoms).

in thin films that result in different relative peak intensities or missing peaks compared to the reference pattern. The 2-theta values of the (100), (002) and (101) lines in **Figure 2** of the hexagonal crystal planes are located at 31.770, 34.422 and 36.253° for wurtzite ZnO (Ref. JCPDS card # 36-1451).

Different processing parameters may result in different microscopic product morphologies of ZnO. From SEM, we can observe that this material could be obtained as nanoparticles

Figure 2. Typical XRD pattern of ZnO nanoparticles.

Figure 3. SEM image of ZnO nanoparticles obtained via colloidal synthesis. The scale bar is 500 nm.

(**Figure 3**), polycrystalline (**Figure 4**) and as a nanostructured thin film (**Figure 5**). All of these materials were synthesized under non-extreme conditions using colloidal synthesis to produce the source material. The crystal structure of these materials is the hexagonal wurtzite structure.

Figure 4. SEM image of polycrystalline ZnO thin film obtained through vacuum evaporation process, colloidal nanoparticles as source were used. The scale bar is 500 nm.

Figure 5. SEM ZnO nanostructures using colloidal nanoparticles as source. The scale bar is 500 nm.

2. Some techniques for synthesizing ZnO nanostructures and nanoparticles

2.1. Sol-gel

The sol-gel process encompasses a variety of precursors, solvents and additives. But in general, the basis of the sol-gel process includes some form of hydrolysis and condensation reactions. In the case of ZnO, usually a zinc salt such as zinc acetate is used with water or an alcohol as the solvent. An example of possible hydrolysis and condensation reactions for ZnO are shown in Eqs. (1) and (2), where Zn(OR)_2 is a soluble salt.

During the hydrolysis reaction, the soluble zinc precursor forms a zinc hydroxide intermediate that is able to condense with other intermediates to grow a zinc oxide inorganic polymer. The final product after drying has an amorphous structure and crystallization of ZnO particles require an annealing step. The morphology of the inorganic network can range from spherical nanoparticles to percolated gels and is highly dependent on the choice of precursors, water content, solute and solvent ratio, aging and additives. The sol-gel process has proven to be an inexpensive and relatively simple method of ZnO nanoparticle synthesis that is tailorable to produce unique nanostructures for different applications.

2.2. Colloidal solution

Colloidal synthesis is another well-known chemical solution method to obtain novel nanomaterials with different morphologies and sizes. All processing conditions involved in the system can be fixed to control nucleation and growth of the materials. The kind of interactions (physical and chemical) between particles include Vander Waals, electrostatic, Ostwald ripening and some other theoretical principles such as Derjaguin, Landau, Venvey and Overbeek theory (DLVO). These interactions can contribute to agglomeration and subsequently precipitation of the particles. Colloidal instability can be prevented through steric stabilization which usually requires a surfactant to maintain the colloidal suspension. Surfactants work in two ways: first, to prevent particulate interactions and second, to prevent the continuous nucleation and growth of particles.

2.3. Microwave-assisted synthesis

Microwave-assisted synthesis is a relatively recent technique that has been used for synthesis of nanomaterials. It has been considered as a promising approach to obtain novel nanomaterials in organic and inorganic fields. Additionally, microwave synthesis is considered as a green process and coheres perfectly to the principles formulated by Anastas et al. related to green chemistry [1].

Often a domestic microwave is used and the synthesis is carried out in solvent-free solutions. This technique allows for rapid and homogeneous heating of the system since energy is transmitted directly through molecular vibrations. The short heating ramp time of microwave synthesis allows for better control of particle size distribution compared to conventional

heating. On the contrary, the extremely high heating rate of microwave-assisted synthesis may cause the boiling point of the solution to increase by a few degree Celsius. Additionally, the microwave susceptibility will vary between different materials and temperatures.

The microwave energy is generated by a magnetron that transforms electrical energy into a strong magnetic field. The electromagnetic energy interacts with the solution, vibrating the molecules and giving sufficient activation energy to the system for chemical reactions to take place in seconds or minutes.

The reaction rate during microwave synthesis can be explained through the Arrhenius equation [Eq. (3)] as follows:

$$K = A e^{-\Delta G/RT} \quad (3)$$

where K is the rate constant, T is the absolute temperature (in Kelvin), A is the pre-exponential factor, a constant for each chemical reaction that defines the rate due to frequency of collisions in the correct orientation, ΔG is the activation energy for the reaction (in Joules) and R is the universal gas constant. Thus, the two parameters affecting the kinetics of a particular chemical reaction are temperature and activation energy.

Bilecka et al. reported that nanoparticle growth can be described using four thermodynamic parameters related to the Arrhenius equation through activation energy [2]. These variables are the activation energies for precursor solvation, monomer formation, nucleation and crystal growth. As with colloidal synthesis, nucleation and growth in microwave synthesis are governed by Ostwald ripening.

3. Synthesis of ZnO nanostructures and nanoparticles via chemical solutions: recent advances

Sol-gel, colloidal and microwave-assisted synthesis are effective techniques to efficiently obtain novel ZnO nanostructures. These techniques are relatively inexpensive and do not require sophisticated laboratory equipment. Additionally, slight variations in precursors or process parameters can produce different morphologies that can be applied in different technological fields.

3.1. Process, materials and precursors

The precursors used in these synthesis routes usually start with a basic salt of Zn, a solvent and a catalyser such as temperature. The Zn precursor must be soluble in the selected solvent such that it can provide the necessary Zn ions to produce ZnO particles. Other reagents may be added in order to substitutionally dope ZnO with metal cations such as Fe, Cu, Co and Ba. Additionally, surfactants may be added to maintain colloidal stability of the product or influence the morphology of the growing particles.

Different precursors used in sol-gel and colloidal techniques from recent publications have been summarized in **Tables 1** and **2**, respectively. The readers are asked to consult the relevant publications for details of these processes.

Precursor	Solvent	Stabilizing agent	Reference	Technique
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	CH_3OH , $\text{C}_2\text{H}_5\text{OH}$, $\text{C}_3\text{H}_7\text{OH}$, $\text{C}_3\text{H}_7\text{OH}$, $\text{C}_4\text{H}_9\text{OH}$	$(\text{CH}_2\text{CH}_2\text{OH})_2\text{NH}$, $\text{N}(\text{CH}_2\text{CH}_2\text{OH})_3$	Pourshaban et al. [3]	Sol-gel
$\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}/\text{CuCl}$	2-methoxyethanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Joshi et al. [4]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Ba}(\text{NO}_3)_2$	2-methoxyethanol	$(\text{CH}_2\text{CH}_2\text{OH})_2\text{NH}/\text{DEA}$	Kasar et al. [5]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $(\text{NH}_4)_2\text{CO}_3$, $\text{Fe}(\text{NO}_3)_3$	Distilled water/ethylene glycol	–	Bahari et al. [7]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Mn}(\text{CH}_3\text{CO}_2)_2 \cdot 4\text{H}_2\text{O}$	Isopropyl alcohol	Urea	Kumar et al. [6]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{C}_2\text{H}_3\text{LiO}_2$	$\text{C}_2\text{H}_5\text{OH}$	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Boudjouan et al. [8]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, CaCl_2	CH_3OH , $\text{C}_2\text{H}_5\text{OH}$	–	Slama et al. [9]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $(\text{CH}_3\text{COO})_2\cdot\text{Co} \cdot 4\text{H}_2\text{O}$	CH_3OH	Mono ethanolamine $(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Dhruvash et al. [10]	Sol-gel
$\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$	$\text{C}_2\text{H}_5\text{OH}$	–	Singh et al. [21]	Sol-gel
$\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}/\text{KOH}$	CH_3OH	–	Kim et al. [22]	Sol-gel
$\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$	2-methoxyethanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Tabassum et al. [11]	Sol-gel
$\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}/\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}/\text{AgNO}_3$	$\text{C}_2\text{H}_5\text{OH}$	Diethanolamine (DEA)	Khan et al [12]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, NaCl	$\text{CH}_3\text{OCH}_2\text{CH}_2\text{OH}$	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Zhou et al. [30]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	Isopropyl alcohol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Chebil et al. [23]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Cu}(\text{CH}_3\text{COO})_2$		Diethanolamine (DEA)	Agarwal et al. [14]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	2-methoxyethanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Haarindraprasad et al. [24]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	Dimethyl formamide	Diethanolamine (DEA)	Bhunia et al. [25]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{C}_2\text{H}_7\text{NO}_2$	Distilled water/glacial acetic acid	–	Para et al. [26]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Ga}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$	2-methoxyethanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Wang et al [27]	Sol-gel
$[\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}]$	2-methoxyethanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Alfaro et al. [28]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, LiOH , graphene	$\text{C}_2\text{H}_5\text{OH}/\text{EtOH}$	–	Li et al. [29]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Mg}(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$, $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	Isopropyl alcohol	Diethanolamine (DEA)	Das et al. [13]	Sol-gel

Precursor	Solvent	Stabilizing agent	Reference	Technique
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	1-butanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Demes et al. [31]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$	Ethanol and chelating with glycerin	Acetic acid	Kose et al. [32]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Li}(\text{CH}_3\text{-COO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Co}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$	$(\text{C}_2\text{H}_5\text{OH})$	$(\text{C}_2\text{H}_6\text{O}_2)$	Bashir et al. [15]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	Ethanol ($\text{C}_2\text{H}_5\text{OH}$)	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Ayana et al. [33]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Cu}(\text{CO}_2\text{CH}_3)_2 \cdot \text{H}_2\text{O}$	Ethanol ($\text{C}_2\text{H}_5\text{OH}$)	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Wang et al. [16]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, NaOH	2-Propanol	–	Zimmermann et al. [34]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	Acetone	TEA	Efafi et al. [35]	Sol-gel
Zinc nitrate hexa hydrate/ Na-CMC	Deionized water		Muthukrishnan et al [36].	Sol-gel
$\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ / $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$, NaOH	Deionized water	PEG-6000	Liu et al. [37]	Sol-gel
$\text{Ti}(\text{OCH}(\text{CH}_3)_2)_4$, $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$	Isopropyl alcohol	–	Boro et al. [38]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, NH_4VO_3	$\text{CH}_3\text{OH}/\text{MeOH}$	–	Slama et al. [17]	Sol-gel
ZnCl_2 , FeCl_3 , NH_4Ac , $\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	$\text{C}_2\text{H}_6\text{O}_2$		Rabbani et al. [39]	Sol-gel
$(\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O})/\text{TiO}_2$	Isopropyl alcohol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Marimuthu et al. [40]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	Double distilled water	$[\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}]$	Birajdar et al. [18]	Sol-gel
$\text{Zn}(\text{NO}_3)_2$, citric acid and tetraethoxysilane	Ethanol ($\text{C}_2\text{H}_5\text{OH}$)	–	Sivakami et al. [41]	Sol-gel
Isopropyl orthotitanate (TTIP), zinc nitrate tetra hydrate	Ethanol ($\text{C}_2\text{H}_5\text{OH}$)	Diethanolamine (DEA)	Moradi et al. [42]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	2-Methoxyethanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Ocaya et al. [43]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$, CoCl_2		Polyvinyl alcohol	Verma et al. [19]	Sol-gel
$[\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}]/\text{Ga}(\text{NO}_3)_3$, gelatin	Distilled water	–	Khorsand Zak et al. [20]	Sol-gel
$\text{Zn}(\text{CH}_3\text{OO})_2 \cdot 2\text{H}_2\text{O}$	Distilled water/ethanol	$(\text{CH}_2(\text{OH})\cdot\text{CH}_2\cdot\text{NH}_2)$	Kiani et al. [44]	Sol-gel

Table 1. Precursors and solvents used in the synthesis of ZnO by the sol-gel process.

Precursor	Solvent	Stabilizing agent	Reference	Technique
Zn(CH ₃ OO) ₂ 2H ₂ O, sulfo propyl methacrylatepotassium	Ethylene glycol	–	Liua et al. [45]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O	Distilled water	Poly(vinyl alcohol) (PVA)	Nagvenkar et al. [46]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O, LiOH·H ₂ O	Ethanol (C ₂ H ₅ OH)	–	Yuan et al. [47]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O, tetraalkylammonium hydroxide	DMSO	NEt ₄ OH	Panasiuk et al. [48]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O	Ethanol	Triethylamine, diethylamine	Gupta et al. [49]	Colloidal
(Zn(NO ₃) ₂ 6H ₂ O), NaOH	Distilled water	1-Thioglycerol (TG) and 2 mercaptoethanol (ME)	Hodlur et al. [50]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O	Deionized water	Hexamethyl netetramine	Guo et al. [56]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O, KOH	Methanol	–	Rahman [51]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O, KOH	Methanol	PVP	Gutul et al. [52]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O, KOH	Ethanol	3-aminopropyltriethoxysilane	Moghaddam et al. [53]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O, NaOH	Ethyl alcohol	–	Liu et al. [54]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O	Diethylene glycol.	–	Xie et al. [60]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O	Ethanol	LiOH	Verma et al. [61]	Colloidal
Zn(CH ₃ OO) ₂ 2H ₂ O, NaOH	2-propanol	–	Moghaddam et al. [64]	Microwave
GO, Zn(NO ₃) ₂ NaOH	Deionized water	–	Tian et al. [65]	Microwave
Zn(CH ₃ OO) ₂ 2H ₂ O, NaOH	Distilled water	Guanidinium carbonate, acetyl acetone,	Hamedani et al. [66]	Microwave
Zinc hydroxide	Distilled water	Cetyltrimethylammonium bromide	Rai et al. [67]	Microwave
Zn(CH ₃ OO) ₂ 2H ₂ O, NaOH, NH ₄ OH	Dieonized water	–	Yanga et al. [69]	Microwave
(Zn(NO ₃) ₂ ·6H ₂ O), hydrazine hydrate	Distilled water	–	Krishnakumar et al. [70]	Microwave
ZnSO ₄ ·7H ₂ O, GO, NaOH	Distilled water	–	Lua et al. [71]	Microwave
Zn(CH ₃ OO) ₂ 2H ₂ O	Deionized water	–	Zhu et al. [72]	Microwave

Precursor	Solvent	Stabilizing agent	Reference	Technique
ZnSO ₄ , NaOH	Deionized water	–	Liu et al. [73]	Microwave
Zn(NO ₃) ₂	Deionized water	–	Rassaeia et al. [74]	Microwave
Zinc oxide, ammonium hydroxide	Deionized water	–	Lu et al. [75]	Microwave
ZnSO ₄ , NaOH	Deionized water	–	Limaye et al. [76]	Microwave
Zinc acetylacetonate monohydrate	Water	Ethoxyethanol, ethoxyethanol, and n-butoxyethanol	Schneider et al. [77]	Microwave

Table 2. Precursors and solvents used in the synthesis of ZnO by colloidal/microwave synthesis.

3.2. Recent studies and applications

Various morphologies of ZnO can be obtained from the sol-gel process including nanorods [3], inhomogeneous films [4, 5], inhomogeneous nanoparticles [6] and nanocomposites [7].

The structural effects of cation doping on ZnO nanoparticles was investigated in several studies. When doped with lithium, it was found that the concentration of Li^+ ion substitution for Zn^{2+} directly affected the XRD intensity of the (002) plane, but did not affect the grain size or crystallinity of the nanoparticles [8]. When ZnO was doped with Ca^{2+} ions, the average particle size was increased to 40–90 nm which could be attributed to the larger ionic radius of Ca^{2+} that substituted for Zn^{2+} ion sites [9]. Likewise, the average grain size reduced when a small radius ion is substituted for Zn^{2+} (0.74 Å) in the hexagonal wurtzite structure such as Co^{2+} (0.58 Å) [10]. Doping with Al^{3+} ions also showed the same tendency in reducing particle size, however, impurity phases such as Al_2O_3 and ZnAl_2O_4 were also observed [11]. Additionally, co-doping of ZnO with Ag^+ and Al^{3+} ions showed the formation of crystal defects due to the difference in ionic radius between Ag^+ , Al^{3+} and Zn^{2+} . Crystallinity improved proportionally with increased Ag^+ doping concentration, however, lattice defects and dislocations increased with Al^{3+} substitution [12]. Further dopant studies also demonstrated that limited dopant precursor solubility provoked a random distribution of dopant throughout the product [13]. Most research about doping ZnO has resulted in improved optical and electrical properties due to improved morphology or intrinsic material properties [14–20].

Synthesis of ZnO of different morphologies without doping is also important to consider since product morphology alone can affect device properties. Without any dopant ZnO can be obtained under normal laboratory conditions with well-aligned nanorods, agglomerated nanoparticles and inhomogeneous thin films composed of nanoparticles, quantum dots, nano-wires, spheres or nano-cubes [21–44].

Colloidal synthesis technique can be utilized to obtain nanocomposites of ZnO and other materials. Nano-sheets of poly (styrene-methyl methacrylate-sulfopropyl methacrylate potassium)/ZnO nanocomposites were obtained by Liua et al. [45]. Dissolving ZnO in other materials can result in a great combination and co-application of materials such as ZnO/PVA (Polyvinyl alcohol) [46]. The same process was done to produce ZnO/ TiO_2 multilayer thin films [47]. This technique allows obtaining well size-controlled nanoparticles such as those reported with use of dimethyl sulfoxide, but the author reports that the solvent and post-annealing treatment are also important factors in the crystallization process and average particle size [48].

Several authors have reported that the product morphology can be altered between flakes, hexagons, particles and flower-like morphologies by adding different surfactant material [49]. Agglomeration of ZnO nanoparticles was reduced by adding capping agents to different thiol molecules during synthesis [50]. It was demonstrated that the colloidal stability of nanoparticles can be maintained after dispersion in monoethanolamine (MEA). Also, hybrid structures can be obtained through this method like ZnO-Au reported recently [51]. Dispersion of nanomaterials could also be maintained through an additive such as poly (N-vinylpyrrolidone) which has been shown to maintain colloidal stability for more than a couple of months [52]. In the same way agglomeration of ZnO quantum dots can be prevented through a capping

agent such as 3-aminopropyltriethoxysilane in order to maintain their quantum properties [53]. Stabilization of the colloidal particles ensures that particle size and shape does not change with time allowing for more repetitive results for each batch of material. Stable colloidal solutions have also been used to grow novel nanostructures on several kinds of unique substrates such as wood that can allow for new ecological applications in future [54–63].

Colloidal and sol-gel processing are both chemical techniques that can be used to easily obtain different nanomaterials; similarly, microwave-assisted synthesis can obtain similar products but has been explored very little. In microwave-assisted synthesis, most reactions take place in a short amount of time and have resulted in the synthesis of good ZnO nanostructures. The technique has obtained spherical nanoparticles that are stable in solution for up to 50 days, and can be deposited several times on a substrate without any change in its morphology. Similarly, it is possible to obtain composites such as ZnO-nanoparticles on reduced graphene oxide. Also, the morphology is highly dependent on the complexing agent where the reaction takes place or if a dopant is added, such as that reported for obtaining ZnO nanoflowers, nanorods and nanoparticles. Additionally, a research group has confirmed the formation of flower-like to rod-like nanostructures by changing the system temperature. Other works have also reported about dumbbell-shaped nanoparticles, nano-flowers, graphene-ZnO nanocomposites, straw-bundle, chrysanthemum and nanorod-based microspheres obtained under certain temperature conditions. [2, 64–78].

4. Conclusions and future directions

The techniques listed in the above paragraphs remain as the most important chemical solution-based routes to synthesize ZnO. Within the same processing method, a variety of material morphologies and properties can be obtained by subtle changes in temperature, additives, dopants or other parameters. There has been a wide range of organic and inorganic particles that have been synthesized and applied in different fields through these techniques. Investigating the effects of processing conditions on ZnO nanoparticles is still a hot topic in current research for their applications in optoelectronic and solar cell devices.

Author details

Jose Alberto Alvarado Garcia^{1*}, Zachary Garbe Neale¹, Antonio Arce-Plaza², Avelino Cortes Santiago³ and Hector Juarez Santiesteban⁴

*Address all correspondence to: jalvarado@cinvestav.mx

¹ Department of Materials Science and Engineering University of Washington, Seattle, WA, USA

² School of Engineering and Architecture, Zacatenco Campus, National Polytechnic Institute (ESIAZ-IPN), Mexico City, Mexico

³ Faculty of chemical sciences, Benemeritous Autonomous University of Puebla, Puebla, Mexico

⁴ Semiconductor Devices Research Center, Benemeritous Autonomous University of Puebla, Puebla, Mexico

References

- [1] Anastas PT, Warner JC. Green Chemistry: Theory and Practice. New York: Oxford University Press; 1998. p. 152
- [2] Bilecka I, Elser P, Niederberger M. Kinetic and thermodynamic aspects in the microwave-assisted synthesis of ZnO nanoparticles in benzyl alcohol. *ACS Nano*. 2009;**3**(2):467-477. DOI: 10.1021/nn800842b
- [3] Pourshaban E, Abdizadeh H, Reza Golobostanfard M. A close correlation between nucleation sites, growth and final properties of ZnO nanorod arrays: Sol-gel assisted chemical bath deposition process. *Ceramics International*. 2016;**42**:14721-14729. DOI: <http://dx.doi.org/10.1016/j.ceramint.2016.06.098>
- [4] Joshi K, Rawat M, Gautam SK, Singh RG, Ramola RC. Band gap widening and narrowing in Cu-doped ZnO thin films. *Journal of Alloys and Compounds*. 2016;**680**:252-258. DOI: <http://dx.doi.org/10.1016/j.jallcom.2016.04.093>
- [5] Kasar CK, Sonawane US, Bange JP, Patil DS. Blue luminescence from Ba_{0.05}Zn_{0.95}O nanostructure. *Journal of Materials Science*. 2016;**27**:8126-8130. DOI: 10.1007/s10854-016-4814-9
- [6] Kumar P, Singh BK, Pal BN, Pandey PC. Correlation between structural, optical and magnetic properties of Mn-doped ZnO. *Applied Physics A*. 2016;**122**(8):122-740. DOI: 10.1007/s00339-016-0265-7
- [7] Bahari A, Roeinfard M, Ramzannezhad A. Characteristics of Fe₃O₄/ZnO nanocomposite as a possible gate dielectric of nanoscale transistors in the field of cyborg. *Journal of Materials Science: Materials in Electronics*. 2016;**27**:9363-9369. DOI: 10.1007/s10854-016-4978-3
- [8] F. Boudjouan, A. Chelouche, T. Touam, D. Djouadi, R. Mahiou, G. Chadeyron, A. Fischer, A. Boudrioua. Doping effect investigation of Li-doped nanostructured ZnO thin films prepared by sol-gel process. *Journal of Materials Science: Materials in Electronics*. 2016;**27**:8040-8046. DOI: 10.1007/s10854-016-4800-2
- [9] Slama R, Ghoul JEl, Omri K, Houas A, Mir L El, Launay F. Effect of Ca-doping on microstructure and photocatalytic activity of ZnO nanoparticles synthesized by sol gel method. *Journal of Materials Science: Materials in Electronics*. 2016;**27**:7939-7946. DOI: 10.1007/s10854-016-4786-9
- [10] Dhruvash, Shishodia PK. Effect of cobalt doping on ZnO thin films deposited by sol-gel method. *Thin Solid Films*. 2016;**612**:55-60. DOI: <http://dx.doi.org/10.1016/j.tsf.2016.05.028>
- [11] Tabassum S, Yamasue E, Okumura H, Ishihara KN. Electrical stability of Al-doped ZnO transparent electrode prepared by sol-gel method. *Applied Surface Science*. 2016;**377**:355-360. DOI: <http://dx.doi.org/10.1016/j.apsusc.2016.03.133>
- [12] Khan F, Ho Baek S, Hyun Kim J. Enhanced charge transport properties of Ag and Al co-doped ZnO. *Journal of Alloys and Compounds*. 2016;**682**:232-237. DOI: <http://dx.doi.org/10.1016/j.jallcom.2016.04.292>

- [13] Das A, Guha Roy P., Dutta A, Sen S, Pramanik P, Das D, Banerjee A, Bhattacharyya A. Mg and Al co-doping of ZnO thin films: Effect on ultraviolet photoconductivity. *Materials Science in Semiconductor Processing*. 2016;**54**:36-41. DOI: <http://dx.doi.org/10.1016/j.mssp.2016.06.018>
- [14] Agarwal L, Singh BK, Tripathi S, Chakrabarti P. Fabrication and characterization of Pd/Cu doped ZnO/Si and Ni/Cu doped ZnO/Si Schottky diodes. *Thin Solid Films*. 2016;**612**:259-266. DOI: <http://dx.doi.org/10.1016/j.tsf.2016.06.027>
- [15] Bashir MI, Ali K, Sarfraz AK, Mirza IM. Room temperature synthesis and multiferroic response of Li co-doped (Zn, Co)O nanocrystallites. *Journal of Alloys and Compounds*. 2016;**684**:151-161. DOI: <http://dx.doi.org/10.1016/j.jallcom.2016.04.019>
- [16] Wang M, Ji J, Luo S, Jiang L, Ma J, Xie X, Ping Y, Ge J. Sol-gel-derived ZnO/Cu/ZnO multilayer thin films and their optical and electrical properties. *Materials Science in Semiconductor Processing*. 2016;**51**:55-59. DOI: <http://dx.doi.org/10.1016/j.mssp.2016.04.020>
- [17] Slama R, El Ghouli J, Ghiloufi I, Omri K, El Mir L, Houas A. Synthesis and physico-chemical studies of vanadium doped zinc oxide nanoparticles and its photocatalysis. *Journal of Materials Science: Materials in Electronics*. 2016;**27**:8146-8153. DOI: 10.1007/s10854-016-4817-6
- [18] Birajdar SD, Khirade PP, Bhagwat VR, Humbe AV, Jadhav KM. Synthesis, structural, morphological, optical and magnetic properties of $\text{Zn}_{1-x}\text{Co}_x\text{O}$ ($0 \leq x \leq 0.36$) nanoparticles synthesized by sol-gel auto combustion method. *Journal of Alloys and Compounds*. 2016;**683**:513e526. DOI: <http://dx.doi.org/10.1016/j.jallcom.2016.05.043>
- [19] Verma KC, Bhatia R, Kumar S, Kotnala RK. Vacancies driven magnetic ordering in ZnO nanoparticles due to low concentrated Co ions. *Materials Research Express*. 2016;**3**:076103. DOI: doi:10.1088/2053-1591/3/7/076103
- [20] Khorsand Zak A, Suhail Abd Aziz N, Manaf Hashim A, Kordi F. XPS and UV-vis studies of Ga-doped zinc oxide nanoparticles synthesized by gelatin based sol-gel approach. *Ceramics International*. 2016;**42**:13605-13611. DOI: <http://dx.doi.org/10.1016/j.ceramint.2016.05.155>
- [21] Singh M, Yusuf Mulla M, Vittoria Santacroce M, Magliulo M, Di Franco C, Manoli K, Altamura D, Giannini C, Cioffi N, Palazzo G, Scamarcio G, Torsi L. Effect of the gate metal work function on water-gated ZnO thin-film transistor performance. *Journal of Physics D: Applied Physics*. 2016;**49**:275101. DOI: doi:10.1088/0022-3727/49/27/275101
- [22] Kim OS, Kang BH, Lee JS, Lee SW, Cha SH, Lee JW, Kim SW, Kim SH, Kang SW. Efficient quantum dots light-emitting devices using polyvinyl pyrrolidone-capped ZnO nanoparticles with enhanced charge transport. *IEEE Electron Device Letters*. 2016;**37**(8):1022-1024. DOI: 10.1109/LED.2016.2578304
- [23] Chebil W, Boukadhaba MA, Fouzri A. Epitaxial growth of ZnO on quartz substrate by sol-gel spincoating method. *Superlattices and Microstructures*. 2016;**95**:48-55. DOI: <http://dx.doi.org/10.1016/j.spmi.2016.04.033>

- [24] Haarindraprasad R, Hashim U, Gopinath SCB, Perumal V, Liu WW, Balakrishnan SR. Fabrication of interdigitated high-performance zinc oxide nanowire modified electrodes for glucose sensing. *Analytica Chimica Acta*. 2016;**925**:70-81. DOI: <http://dx.doi.org/10.1016/j.aca.2016.04.030>
- [25] Bhunia R, Das S, Dalui S, Hussain S, Paul R, Kumar Pal RBA. Flexible nano-ZnO/polyvinylidene difluoride piezoelectric composite films as energy harvester. *Applied Physics A*. 2016;**122**:122-637. DOI: [10.1007/s00339-016-0161-1](http://dx.doi.org/10.1007/s00339-016-0161-1)
- [26] Ahmad Para T, Ahmad Reshi H, Pillai S, Shelke V. Grain size disposed structural, optical and polarization tuning in ZnO. *Applied Physics A*. 2016;**122**:122-730. DOI: [10.1007/s00339-016-0256-8](http://dx.doi.org/10.1007/s00339-016-0256-8)
- [27] Wang H, Sun Y, Fang L, Wang L, Chang B, Sun X, Ye L. Growth and characterization of high transmittance GZO films prepared by sol-gel method. *Thin Solid Films*. 2016;**615**:19-24. DOI: <http://dx.doi.org/10.1016/j.tsf.2016.06.048>
- [28] Alfaro Cruz MR, Hernandez-Como N, Mejia I, Ortega-Zarzosa G, Martinez-Castañon G-A, Quevedo-Lopez MA. Impact of the annealing atmosphere in the electrical and optical properties of ZnO thin films. *Journal of Sol-Gel Science and Technology*. 2016;**79**:184-189. DOI: [10.1007/s10971-016-4035-y](http://dx.doi.org/10.1007/s10971-016-4035-y)
- [29] Li H, Wei Y, Zhang Y, Zhang C, Wang G, Zhao Y, Yin F, Bakenov Z. In situ sol-gel synthesis of ultrafine ZnO nanocrystals anchored on graphene as anode material for lithium-ion batteries. *Ceramics International*. 2016;**42**:12371-12377. DOI: <http://dx.doi.org/10.1016/j.ceramint.2016.05.010>
- [30] Zhou M, Zhang D, Zhai X, Gao Z, Zhang W, Wang C. Preparation of biomorphic porous zinc oxide by wood template method. *Ceramics International*. 2016;**42**:10704-10710. DOI: <http://dx.doi.org/10.1016/j.ceramint.2016.03.188>
- [31] Demes T, TERNON C, Riassetto D, Roussel H, Rapenne L, Gélard I, Jimenez C, Stambouli V, Langlet M. New insights in the structural and morphological properties of sol-gel deposited ZnO multilayer films. *Journal of Physics and Chemistry of Solids*. 2016;**95**:43-55. DOI: <http://dx.doi.org/10.1016/j.jpcs.2016.03.017>
- [32] Kose H, Dombaycioglu S, Osman Aydın A, Akbulut H. Production and characterization of free-standing ZnO/SnO₂/MWCNT ternary nanocomposite Li-ion battery anode. *International Journal of Hydrogen Energy*. 2016;**41**:9924-9932. DOI: <http://dx.doi.org/10.1016/j.ijhydene.2016.03.202>
- [33] Gemechu Ayana D, Ceccato R, Collini C, Lorenzelli L, Prusakova V, Dirè S. Sol-gel derived oriented multilayer ZnO thin films with memristive response. *Thin Solid Films*. 2016;**615**:427-436. DOI: <http://dx.doi.org/10.1016/j.tsf.2016.07.025>
- [34] Zimmermann LM, Baldissera P, Bechtold IH. Stability of ZnO quantum dots tuned by controlled addition of ethylene glycol during their growth. *Materials Research Express*. 2016;**3**:075018. DOI: [10.1088/2053-1591/3/7/075018](http://dx.doi.org/10.1088/2053-1591/3/7/075018)

- [35] Efafi B, Majles Ara MH, Mousavi SS. Strong blue emission from ZnO nanocrystals synthesized in acetone-based solvent. *Journal of Luminescence*. 2016;**178**:384-387. DOI: <http://dx.doi.org/10.1016/j.jlumin.2016.06.026>
- [36] Muthukrishnan K, Vanaraja M, Boomadevi S, Kumar Karn R, Singh V, Singh PK, Pandiyan K. Studies on acetone sensing characteristics of ZnO thin film prepared by sol-gel dip. *Journal of Alloys and Compounds*. 2016;**673**:138-143. DOI: <http://dx.doi.org/10.1016/j.jallcom.2016.02.222>
- [37] Ting Liu T, Hua Wang M, Ping Zhang H. Synthesis and characterization of ZnO/Bi₂O₃ core/shell nanoparticles by the sol-gel method. *Journal of Electronic Materials*. 2016;**45**(8): 4412-4417. DOI: 10.1007/s11664-016-4568-4
- [38] Boro B, Rajbongshi BM, Samdarshi SK. Synthesis and fabrication of TiO₂-ZnO nanocomposite based solid state dye sensitized solar cell. *Journal of Materials Science: Materials in Electronics*. 2016;**27**:9929-9940. DOI: 10.1007/s10854-016-5062-8
- [39] Rabbani M, Heidari-Golafzani M, Rahimi R. Synthesis of TCPP/ZnFe₂O₄@ZnO nano-hollow sphere composite for degradation of methylene blue and 4-nitrophenol under visible light. *Materials Chemistry and Physics*. 2016;**179**:35-41. DOI: <http://dx.doi.org/10.1016/j.matchemphys.2016.05.005>
- [40] Marimuthu T, Anandhan N, Thangamuthu R, Mummoorthi M, Ravi G. Synthesis of ZnO nanowire arrays on ZnO-TiO₂ mixed oxide seed layer for dye sensitized solar cell applications. *Journal of Alloys and Compounds*. 2016;**677**:211-218. DOI: <http://dx.doi.org/10.1016/j.jallcom.2016.03.219>
- [41] Sivakami R, Thiagarajan P. The effect of citric acid on morphology and photoluminescence properties of white light emitting ZnO-SiO₂ nanocomposites. *Photonics and Nanostructures—Fundamentals and Applications*. 2016;**20**:31-40. DOI: <http://dx.doi.org/10.1016/j.photonics.2016.03.003>
- [42] Moradi S, Aberoomand-Azar P, Raeis-Farshid S, Abedini-Khorrami S, Hadi Givianrad M. The effect of different molar ratios of ZnO on characterization and photocatalytic activity of TiO₂/ZnO nanocomposite. *Journal of Saudi Chemical Society*. 2012;**20**:373-378. DOI: <http://dx.doi.org/10.1016/j.jscs.2012.08.002>
- [43] Ocaya RO, Al-Ghamdi A, El-Tantawy F, Farooq WA, Yakuphanoglu F. Thermal sensor based zinc oxide diode for low temperature applications. *Journal of Alloys and Compounds*. 2016;**674**:277-288. DOI: <http://dx.doi.org/10.1016/j.jallcom.2016.02.267>
- [44] Kiani A, Dastafkan K. Zinc oxide nanocubes as a destructive nanoadsorbent for the neutralization chemistry of 2-chloroethyl phenyl sulfide: A sulfur mustard simulant. *Journal of Colloid and Interface Science*. 2016;**478**:271-279. DOI: <http://dx.doi.org/10.1016/j.jcis.2016.06.025>
- [45] Liua J, Hub ZY, Penga Y, Huanga HW, Lia Y, Wua M, Keb XX, Van Tendeloob G, Su BL. 2D ZnO mesoporous single-crystal nanosheets with exposed {0001} polar facets for the depollution of cationic dye molecules by highly selective adsorption and

- photocatalytic decomposition. *Applied Catalysis B: Environmental*. 2016;**181**:138-145. DOI: <http://dx.doi.org/10.1016/j.apcatb.2015.07.054>
- [46] Nagvenkar AP, Deokar A, Perelshteina I, Gedanken A. A one-step sonochemical synthesis of stable ZnO–PVA nanocolloid as a potential biocidal agent. *Journal of Materials Chemistry B*. 2016;**4**:2124. DOI: 10.1039/c6tb00033a
- [47] Yuan S, Mu J, Mao R, Li Y, Zhang Q, Wang H. All-Nanoparticle Self-assembly ZnO/TiO₂ Heterojunction Thin Films with Remarkably Enhanced Photoelectrochemical Activity. *ACS Applied Materials & Interfaces*. 2014;**6**:5719–5725. DOI: dx.doi.org/10.1021/am500314n
- [48] Panasiuk YV, Raevskaya OE, Stroyuk OL, Kuchmiy SY, Dzhagan VM, Hietschold M, Zahn DRT. Colloidal ZnO nanocrystals in dimethylsulfoxide: A new synthesis, optical, photo- and electroluminescent properties. *Nanotechnology*. 2014;**25**:075601. DOI: 10.1088/0957-4484/25/7/075601
- [49] Gupta A, Srivastava A, Bahadur L, Amalnerkar DP, Chauhan R. Comparison of physical and electrochemical properties of ZnO prepared via different surfactant-assisted precipitation routes. *Applied Nanoscience*. 2015;**5**:787-794. DOI: 10.1007/s13204-014-0379-1
- [50] Hodlur RM, Rabinal MK, Mohamed Ikram I. Influence of dipole moment of capping molecules on the optoelectronic properties of ZnO nanoparticles. *Journal of Luminescence*. 2014;**149**:317-324. DOI: <http://dx.doi.org/10.1016/j.jlumin.2014.01.055>
- [51] Rahman DS, Kumar Ghosh S. Manipulating electron transfer in hybrid ZnO–Au nanostructures: Size of gold matters. *Journal of Physical Chemistry*. 2016;**120**:14906–14917. DOI: 10.1021/acs.jpcc.6b03551
- [52] Gutul T, Rusu E, Condur N, Ursaki V, Goncarencu E, Vlazan P. Preparation of poly(N-vinylpyrrolidone)-stabilized ZnO colloid nanoparticles. *Beilstein Journal of Nanotechnology*. 2014;**5**:402-406. DOI: [doi:10.3762/bjnano.5.47](http://dx.doi.org/10.3762/bjnano.5.47)
- [53] Moghaddam E, Youzbashi AA, Kazemzadeh A, Eshraghi MJ. Preparation of surface-modified ZnO quantum dots through an ultrasound assisted sol-gel process. *Applied Surface Science*. 2015;**346**:111-114. DOI: <http://dx.doi.org/10.1016/j.apsusc.2015.03.207>
- [54] Liu Y, Fu Y, Yu H, Liu Y. Process of in situ forming well-aligned Zinc Oxide nanorod arrays on wood substrate using a two-step bottom-up method. *Journal of Colloid and Interface Science*. 2013;**407**:116-121. DOI: <http://dx.doi.org/10.1016/j.jcis.2013.06.043>
- [55] Jhaveri JH, Murthy ZVP. A comprehensive review on anti-fouling nanocomposite membranes for pressure driven membrane separation processes. *Desalination*. 2016;**379**:137-154. DOI: <http://dx.doi.org/10.1016/j.desal.2015.11.009>
- [56] Guo D, Sato K, Hibino S, Takeuchi T, Bessho H, Kato K. Low-temperature preparation of transparent conductive Al-doped ZnO thin films by a novel solgel method. *Journal of Materials Science*. 2014;**4**:4722-4734. DOI: 10.1007/s10853-014-8172-9

- [57] Koushkia E, Farzaneha A, Majles Arab MH. Modeling absorption spectrum and saturation intensity of ZnO nano-colloid. *Optik*. 2014;**125**:220-223. DOI: <http://dx.doi.org/10.1016/j.ijleo.2013.06.007>
- [58] Senthil Kumar K, Chandramohan S, Natarajan P. Photophysics and photochemistry of phenosafranine adsorbed on the surface of ZnO loaded nanoporous materials. *Dyes and Pigments*. 2014;**109**:206-213. DOI: <http://dx.doi.org/10.1016/j.dyepig.2014.05.008>
- [59] Gwaka GH, Leeb WJ, Paekb SM, Oha JM. Physico-chemical changes of ZnO nanoparticles with different size and surface chemistry under physiological pH conditions. *Colloids and Surfaces B: Biointerfaces*. 2015;**127**:137-142. DOI: <http://dx.doi.org/10.1016/j.colsurfb.2015.01.021>
- [60] Xie J, Wang H, Duan M. QCM chemical sensor based on ZnO colloid spheres for the alcohols. *Sensors and Actuators B*. 2014;**203**:239-244. DOI: <http://dx.doi.org/10.1016/j.snb.2014.06.119>
- [61] Verma SD, Sharma SN, Kharkwal A, Bhagavannarayana G, Kumara M, Nath Singha S, Kumar Singha P, Sazad Mehdibb S, Husain M. Role of nanocrystalline ZnO coating on the stability of porous silicon formed on textured (100) Si. *Applied Surface Science*. 2013;**285**p:564-571. DOI: <http://dx.doi.org/10.1016/j.apsusc.2013.08.094>
- [62] Lin W, Haderlein M, Walter J, Peukert W, Segets D. Spectra library: An assumption-free in situ method to access the kinetics of catechols binding to colloidal ZnO quantum dots. *Angewandte Chemie International Edition*. 2016;**55**:932-935. DOI: 10.1002/anie.201508252
- [63] Zhang G, Morikawa H, Chen Y. Synthesis of ZnO nanoparticles in aqueous solution and their antibacterial activities. *Japanese Journal of Applied Physics*. 2014;**53**:06JG07. DOI: <http://dx.doi.org/10.7567/JJAP.53.06JG07>
- [64] Moghaddam FM, Saeidian H. Controlled microwave-assisted synthesis of ZnO nanopowder and its catalytic activity for O-acylation of alcohol and phenol. *Materials Science and Engineering B*. 2007;**139**:265-269. DOI: 10.1016/j.mseb.2007.03.002
- [65] Tian L, Pan L, Liu X, Lu T, Zhu G, Sun Z. Enhanced photocatalytic degradation of methylene blue by ZnO-reduced graphene oxide composite synthesized via microwave-assisted reaction. *Journal of Alloys and Compounds*. 2011;**509**:10086-10091. DOI: 10.1016/j.jallcom.2011.08.045
- [66] Hamedania NF, Mahjouba AR, Ali Khodadadib A, Mortazavi Y. Microwave assisted fast synthesis of various ZnO morphologies for selective detection of CO, CH₄ and ethanol. *Sensors and Actuators B*. 2011;**156**:737-742. DOI: 10.1016/j.snb.2011.02.028
- [67] Rai P, Song HM, Kim Yun-Su, Song MK, Oh PR, Yoon JM, Yu YT. Microwave assisted hydrothermal synthesis of single crystalline ZnO nanorods for gas sensor application. *Materials Letters*. 2012;**68**:90-93. DOI: 10.1016/j.matlet.2011.10.029
- [68] Kim YJ, Varma RS. Microwave-assisted preparation of cyclic ureas from diamines in the presence of ZnO. *Tetrahedron Letters*. 2004;**45**:7205-7208. DOI: 10.1016/j.tetlet.2004.08.042

- [69] Yanga LY, Donga SY, Suna JH, Fenga JL, Wua QH, Sun S-P. Microwave-assisted preparation, characterization and photocatalytic properties of a dumbbell-shaped ZnO photocatalyst. *Journal of Hazardous Materials*. 2010;**179**:438-443. DOI: 10.1016/j.jhazmat.2010.03.023
- [70] Krishnakumar T, Jayaprakash R, Pinna N, Singh VN, Mehta BR, Phani AR. Microwave-assisted synthesis and characterization of flower shaped zinc oxide nanostructures. *Materials Letters*. 2009;**63**:242-245. DOI: 10.1016/j.matlet.2008.10.008
- [71] Lua T, Pana L, Li H, Zhua G, Lva T, Liua X, Suna Z, Chenb T, Chuab DHC. Microwave-assisted synthesis of graphene–ZnO nanocomposite for electrochemical supercapacitors. *Journal of Alloys and Compounds*. 2011;**509**:5488-5492. DOI: 10.1016/j.jallcom.2011.02.136
- [72] Zhu P, Zhang J, Wu Z, Zhang Z. Microwave-assisted synthesis of various ZnO hierarchical nanostructures: Effects of heating parameters of microwave oven. *Crystal Growth & Design*. 2008;**8**(9): 3148-3153. DOI: 10.1021/cg0704504
- [73] Xinjuan Liu, Likun Pan, Tian Lv, Ting Lu, Guang Zhu, Zhuo Sun and Changqing Sun. Microwave[M5]-assisted synthesis of ZnO–graphene composite for photocatalytic reduction of Cr(VI). *Catalysis Science & Technology* 2011;**1**:1189-1193. DOI: 10.1039/c1cy00109d
- [74] Rassaeia L, Jabera R, Flowera SE, Edlera KJ, Comptonb RG, Jamesa TD, Marken F. Microwave-electrochemical formation of colloidal zinc oxide at fluorine doped tin oxide electrodes. *Electrochimica Acta*. 2010;**55**:7909-7915. DOI: 10.1016/j.electacta.2010.01.068
- [75] Lu CH, wang WJH, Godbole SV. Microwave-hydrothermal synthesis and photoluminescence characteristics of zinc oxide powders. *Journal of Materials Research*. 2005;**20**(2):464. DOI: 10.1557/JMR.2005.0067
- [76] Limaye MV, Singh S, Das R, Poddar P, Kulkarni SK. Room temperature ferromagnetism in undoped and Fe doped ZnO nanorods: Microwave-assisted synthesis. *Journal of Solid State Chemistry*. 2011;**184**:391-400. DOI: 10.1016/j.jssc.2010.11.008
- [77] Schneider JJ, Hoffmann RC, Engstler J, Klyszcz A, Erdem E, Jakes P, Eichel RA, Bauermann LP, Bill J. Synthesis, characterization, defect chemistry, and FET properties of microwave-derived nanoscaled zinc oxide. *Chemistry of Materials*. 2010;**22**:2203-2212. DOI: 10.1021/cm902300q
- [78] Guo Y, Wang H, He C, Qiu L, Cao X. Uniform carbon-coated ZnO nanorods: Microwave-assisted preparation, cytotoxicity, and photocatalytic activity. *Langmuir*. 2009;**25**(8):4678-4684. DOI: 10.1021/la803530h