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Theoretical Insights into Growth Mechanisms of ZnO Nanorods

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ABSTRACT

Zinc oxide (ZnO) nanorods exhibit unique anisotropic growth behaviour influenced by surface energy variations, chemical potential gradients, and synthesis conditions. This study explores the fundamental thermodynamic and kinetic factors governing ZnO nanorod formation, focusing on surface energy minimization, Gibbs free energy stability, and Wulff construction-based morphology prediction. The role of chemical potential, supersaturation, and Ostwald ripening in directing anisotropic growth along the c-axis is also analyzed. Additionally, the hydrothermal synthesis of ZnO nanorods, the most often used synthesis process has also been used an example for understanding the whole ZnO nanorod formation process, highlighting the impact of reaction parameters such as temperature, pH, precursor concentration, and surfactant-mediated morphology control.

1. Introduction

In recent years, research on zinc oxide (ZnO) nanorods have attracted significant attention due to their extraordinary structural, electrical and optical properties, making them exceedingly suitable for various applications such as optoelectronics devices, gas sensing devices, energy harvesting devices etc. Due to wide-bandgap (3.37 eV) along with its high exciton binding energy (60 meV), ZnO can produce strong excitonic emission at room temperature, which make them useful candidate for use as ultraviolet (UV) photodetectors and light-emitting diodes (LEDs) [1] also. Furthermore, the one-dimensional (1D) morphology of ZnO nanorods provides enhanced charge transport, higher surface area, and improved light absorption, making them an ideal candidate for applications in dye-sensitized solar cells and photocatalysis [2, 3]. The synthesis of ZnO nanorods can be achieved through various techniques, including chemical vapor deposition (CVD) [4], hydrothermal growth [5], electrodeposition [6] etc. Among these, hydrothermal synthesis is particularly attractive due to its low-temperature operation, cost-effectiveness, and ability to produce vertically aligned nanorod arrays on diverse substrates. This method relies on the controlled dissolution and precipitation of ZnO precursors in an aqueous medium, where parameters such as precursor concentration, temperature, pH, and surfactant addition play a crucial role in determining the nanorod morphology and crystallinity [7].

Despite extensive research, several challenges persist in achieving precise control over ZnO nanorod growth and optimization of their properties for specific applications. Factors such as anisotropic surface energy, nucleation kinetics and growth mechanism uncertainties pose difficulties in developing a comprehensive theoretical framework [8]. Furthermore, computational modelling approaches, including density functional theory (DFT), molecular dynamics (MD), and phase-field simulations, have emerged as valuable tools in understanding the role of surface interactions, chemical potential variations, and diffusion kinetics in ZnO nanorod formation [9, 10]. In this paper we are trying to investigate the theoretical aspects of ZnO nanorod fabrication, with a particular focus on thermodynamic stability, surface energy anisotropy and kinetic growth factors.

2. Crystallographic Structure and Growth Behaviour of ZnO Nanorods

Normally, zinc oxide (ZnO) crystallizes in the wurtzite structure (Fig. 1), which belongs to the hexagonal crystal system with the space group $P6_3mc$ [11]. The structure consists of two interpenetrating hexagonal close-packed sublattices of Zn^{2+} and O^{2-} ions, where each Zn^{2+} ion is tetrahedrally coordinated by four O^{2-} ions, and vice versa [12]. This tetrahedral coordination leads to a non-centrosymmetric structure, which is responsible for the piezoelectric and pyroelectric properties of ZnO [13]. The anisotropic nature of the wurtzite structure significantly influences the growth morphology of ZnO nanostructures, particularly nanorods, where crystallographic orientation plays a crucial role in determining their shape and alignment [14].

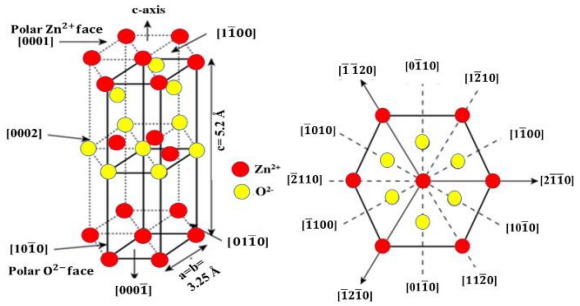

Fig. 1 (a) ZnO unit cell with wurtzite structure and (b) Various crystal planes of the ZnO wurtzite structure.

3. Surface Energy and Anisotropic Growth of ZnO Nanorod

Surface energy (γ) represents the excess energy present at the surface of a material compared to its bulk phase. This phenomenon arises due to the unsaturated coordination of surface atoms, resulting in instability and a natural tendency for the system to minimize its surface area [15]. Mathematically, surface energy is expressed as, $\gamma = \Delta G/A$, where: γ is the surface energy (J/m^2), ΔG is the free energy change associated with creating a new surface and A is the surface area of the newly created interface [15]. Surface energy plays a critical role in dictating the growth dynamics and morphology of ZnO nanostructures too. Crystallographic planes with higher surface energies exhibit greater reactivity, thereby facilitating anisotropic growth as they evolve at a faster rate to lower their overall energy [16]. ZnO exhibits anisotropic growth due to the variation in surface energies among different crystallographic planes. Due to hexagonal crystal symmetry theoretically ZnO crystals can possess an

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infinite number of possible crystallographic planes based on different Miller indices. However, the most critical planes influencing ZnO nanorod growth include the (0001) Zn-terminated c-plane, the $(000\bar{1})$ O-terminated c-plane, the $(10\bar{1}0)$ m-plane, and the $(11\bar{2}0)$ a-plane [12] The approximate order of surface energies for ZnO wurtzite planes [17] is,

$$\gamma_{(0001} > \gamma_{(000\bar{1})} > \gamma_{(10\bar{1}0)} > \gamma_{(11\bar{2}0)}$$

Thus the (0001) i.e., the Zn-terminated plane has the highest surface energy the $(000\bar{1})$ O-terminated plane has slightly lower surface energy than (0001). But, the $(10\bar{1}0)$ plane and the $(11\bar{2}0)$ planes have lowest surface energies. So, the (0001) plane or the Zn-terminated plane is highly polar and chemically reactive, making it the preferred site for anisotropic growth [18]. Conversely, the $(000\bar{1})$ oxygen-terminated plane, while also polar, exhibits different surface reactivity, impacting growth kinetics and surface morphology. In contrast, the $(10\bar{1}0)$ and $(11\bar{2}0)$ planes are non-polar and possess relatively lower surface energy, contributing to lateral stability during nanorod formation [18]. That is why during synthesis, ZnO nanorods predominantly grow along the c-axis due to the strong dipole interactions in the polar (0001) plane, which accelerates vertical elongation. The $(10\bar{1}0)$ and $(11\bar{2}0)$ non-polar planes are less reactive thus help to regulate lateral expansion, thereby ensuring high-aspect-ratio growth and well-aligned ZnO nanorod arrays [19]. The $(000\bar{1})$ oxygen-terminated plane, being less reactive, balances overall growth kinetics, influencing the aspect ratio and surface stability of ZnO nanorods [16]. Overall, the interplay between these crystallographic planes dictates the final morphology, size, and orientation of ZnO nanorods, making them highly suitable for applications in optoelectronics, sensors, piezoelectric devices, and energy harvesting technologies. Understanding these growth dynamics provides valuable insights into the controlled synthesis of ZnO nanorods with tailored properties for advanced nanotechnology applications.

4. Effects of Thermodynamic Stability on Growth Direction

The thermodynamic stability of ZnO nanostructures can also be explained by the energy minimization principle. The fundamental statement of the principle is that a crystal tends to adopt a shape that minimizes its total free energy. In nanostructure growth, this involves reducing the overall surface energy by favouring the formation of lower-energy facets. In ZnO nanorod also the growth should be driven by the balance between surface energy, strain energy, and external conditions such as temperature and chemical environment [20]. Further the stability of a ZnO nanostructure is determined by its Gibbs free energy, given by, G=H–TS, where; H is the enthalpy, T is the absolute temperature, S is the entropy [21]. By the principle during ZnO growth, the structure with lower Gibbs free energy must become more stable. Thus, high-energy surfaces tend to grow rapidly to reduce their excess energy, while low-energy surfaces are more stable and persist in the final morphology.

The overall shape growth also can be explained by Wulff construction method. The Wulff construction is a fundamental method used to determine the equilibrium crystal shape by minimizing the total surface energy. It is based on the idea that a crystal will naturally adopt a shape that reduces its overall energy by favouring lower-energy facets [22, 23]. This principle is particularly useful in predicting the morphology of ZnO nanorods, as the wurtzite structure exhibits anisotropic surface energies across different planes. According to the Wulff theorem, the equilibrium shape of a nanostructure is determined by the relation, $\frac{h_i}{\gamma_i} = constant$, where: h_i is the perpendicular distance of a given facet from the crystal center, γ_i is the surface energy of that facet. In the case of ZnO, the Wulff construction predicts a hexagonal prism-like shape dominated by the low-energy $(10\bar{1}0)$ and the $(11\bar{2}0)$ facets, with the high-energy polar (0001) and $(000\bar{1})$ facets driving anisotropic growth along the c-axis. This also explains why ZnO commonly forms nanorods and nanowire structure.

5. Role of Chemical Potential and Supersaturation in Growth

The chemical potential (μ) of Zn and O species in solution or vapor phase plays a crucial role in ZnO nanostructure formation. The chemical potential determines the direction of a chemical reaction. Chemical potential is mostly influenced by factors such as surface energy, surface curvature, surface adsorption, and surface reactions [24]. Growth of crystals occurs when the chemical potential difference (Δμ) between the source and the growing crystal is sufficient to drive mass transport and deposition. The anisotropic growth of ZnO nanorods is also influenced by chemical potential gradients. The (0001) Zn-terminated plane, having high surface energy, exhibits a strong chemical potential gradient, leading to preferential growth along the [0001] c-axis. Supersaturation is another key factor in determining the growth mode and direction. The Supersaturation defined as,

$$S = \frac{C - C_{eq}}{C_{eq}}$$

where: C is the actual concentration of Zn and O species, C_{eq} is the equilibrium concentration [25]. At low supersaturation (μ close to equilibrium), nucleation is slow, favouring large, well-defined nanorods. At high supersaturation, rapid nucleation leads to many small particles, sometimes causing secondary growth or defects [26]. Thus, by controlling chemical potential and supersaturation through factors such as precursor concentration, temperature, and reaction time, ZnO nanostructure morphology can be tailored for specific applications in optoelectronics, sensing, and catalysis.

6. Kinetics of ZnO Nanorod Formation

The formation of ZnO nanorods is governed by the interplay between diffusion and mass transport of precursor species in solution or vapor. In solution-based synthesis (e.g., hydrothermal or sol-gel methods), Zn^{2+} and OH^- ions diffuse toward nucleation sites, where ZnO begins to crystallize [7]. The overall growth rate depends on Bulk diffusion of precursor species from the surrounding solution to the growing nanorod surface, Surface diffusion, where adatoms rearrange on the surface to form stable crystal structures and Convective transport, which can be influenced by temperature, stirring, and external fields. In a diffusion-limited regime, the slow transport of precursor species results in well-defined, uniform nanorods. Conversely, in a reaction-limited regime, rapid precursor consumption can lead to defects and irregular morphologies [27].

Nucleation is the first step in ZnO nanorod growth, where ZnO nanoparticles form from dissolved precursor species such as Zn^{2+} and OH^- ions. This process follows classical nucleation theory, which states that nucleation occurs when the free energy change (ΔG) due to the formation of a new phase becomes favourable. The Gibbs free energy change (ΔG) for forming a nucleus is given by,

$$\Delta G = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma$$

where r is the radius of the nucleus, ΔG_v is the volumetric free energy change, and γ is the surface energy [28]. It is noticeable that there exists a critical nucleus size (r_c) beyond which the nucleus is stable and continues to grow. If the nucleus is smaller than r_c, it dissolves back into solution. Normally nucleation can be both homogeneous nucleation, in which occurs uniformly throughout the solution without any external influence and heterogeneous nucleation which takes place on a substrate or seed particles, reducing the energy barrier for nucleation. This type of nucleation is commonly seen when ZnO nanorods are grown on precursor coated substrate [29]. Higher supersaturation (high Zn^{2+} and OH^- concentration) leads to rapid nucleation, forming a large number of small nuclei (Fig. 2). Lower supersaturation favours fewer, larger nuclei, leading to well-defined nanorods.

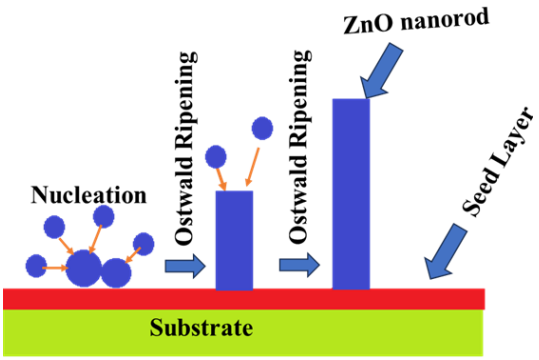

Fig. 2 Schematic diagram of ZnO nanorod growth via nucleation and Ostwald ripening

After nucleation, ZnO nanoparticles do not remain static and Ostwald ripening starts to occur. Ostwald ripening is the process where smaller, less stable nanoparticles dissolve and redeposit onto larger, more stable structures. This occurs because small particles have higher surface energy, making them thermodynamically less stable than larger ones.

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Consequently, Zn^{2+} ions dissolve from small ZnO particles, increasing their concentration in solution, while redeposition occurs onto larger ZnO structures with lower chemical potential [30]. As the growth along Zn-terminated (0001) plane and O-terminated $(11\bar{2}0)$ plane is preferred and both are along opposite c-axis direction growth along c-axis becomes rapid and rapid along c-axis hence large ZnO nanorods grow at the expense of smaller particles.

This process is governed by the Lifshitz-Slyozov-Wagner (LSW) theory, which describes the growth rate of larger particles over time,

$$r^3 - r_0{}^3 = kt$$

where r is the radius of a particle at time t, r_0 is the initial radius and k is a material-dependent constant [31,32]. This equation basically summarizes that with increasing value of time the final radius of particle increases, whereas the initial radius decreases.

7. Common Experimental Factors Influencing Nanorod Formation: With Emphasis on Hydrothermal Synthesis

Hydrothermal synthesis is one of the most widely used methods for fabricating ZnO nanorods due to its simplicity, cost-effectiveness, and ability to control nanostructure morphology. As it is the mostly used synthesis method of nanorod fabrication, I am considering hydrothermal synthesis to study the effects of different experimental factors on synthesis of ZnO nanorod. This process typically involves dissolving a zinc precursor, such as zinc nitrate $(Zn(NO_3)_2$ or zinc acetate $Zn(CH_3CO_2)_2$, in an aqueous solution with a hydroxide source like sodium hydroxide (NaOH) or hexamethylenetetramine (HMTA) [7, 33]. The solution is then heated in a sealed autoclave at moderate temperatures (typically 80–200 °C), for a long period of time upto ~24 hour promoting the nucleation and growth of ZnO nanorods. Key factors influencing hydrothermal growth include reaction temperature, time, precursor concentration and solution pH. Controlling these parameters enables precise tuning of nanorod dimensions, orientation, and density.

The pH of the solution directly affects the Zn^{2+} to OH^- ratio, influencing nucleation and growth kinetics. A higher pH promotes faster ZnO formation, leading to shorter and thicker nanorods, while a lower pH slows growth and results in more elongated structures. The ideal pH range for ZnO nanorod growth is typically between 9 and 12 [34, 35]. In case of temperature, a higher temperature (>150 °C) leads to acceleration of the reaction kinetics, increasing both nucleation and growth rates, thus resulting irregular shapes and secondary nucleation [35]. Researcher has found that well-defined nanorods forms at moderate temperatures (~90 °C) only [36]. The concentration of zinc and hydroxide precursors dictates the supersaturation level. At low precursor concentrations, fewer nuclei form, leading to longer and thinner nanorods. At high precursor concentrations, rapid nucleation results in shorter, densely packed nanorods [35].

Surfactants and structure-directing agents also can be employed for tailoring ZnO nanorod morphology by selectively adsorbing onto different crystallographic planes and modulating growth rates. Researcher has shown that common surfactants such as Polyethylene glycol (PEG) and Polyvinylpyrrolidone (PVP) polymers gets bounded preferentially to nonpolar facets, limiting lateral growth and promoting well-aligned nanorods [37, 38]. On the other hand, citrate ions get adsorb onto ZnO surfaces, influencing nucleation density and controlling rod diameter [39]. In the same time one of the mostly used surfactants CTAB (Cetyltrimethylammonium bromide) alters surface charge and affects the aspect ratio of nanorods [40]. Thus, by introducing surfactants, the overall shape and aspect ratio of ZnO nanorods can be finely controlled, allowing for application-specific optimization.

8. Conclusion

The growth of ZnO nanorods is governed by a complex interplay of thermodynamic stability, surface energy minimization, and kinetic factors. The wurtzite crystal structure of ZnO introduces anisotropic growth, where the high-energy (0001) Zn-terminated plane drives elongation along the c-axis, while lower-energy nonpolar facets stabilize lateral dimensions. Growth kinetics are influenced by diffusion, mass transport, nucleation dynamics, and Ostwald ripening, all of which can be fine-tuned by adjusting experimental parameters such as pH, temperature, precursor concentration, and surfactant use. Hydrothermal synthesis remains a widely used method due to its ability to produce well-defined nanorods under controlled conditions. Despite significant progress, theoretical modelling of ZnO nanorod formation still faces numerous challenges due to the complex interplay of thermodynamic, kinetic, and environmental factors. Accurately modelling the entire growth process, including ion adsorption, the influence of surfactants, and growth-modifying agents on different ZnO crystallographic planes, is particularly difficult due to the dynamic nature of chemical interactions. Traditional models, such as classical nucleation theory and the Lifshitz-Slyozov-Wagner (LSW) theory, often assume idealized conditions that fail to capture real experimental environments, especially since many synthesis processes operate under non-equilibrium conditions. This limitation makes it difficult to apply equilibrium-based models, such as Wulff construction, to all possible cases of ZnO nanorod growth. Another major challenge lies in representing the anisotropic growth behaviour of ZnO, which is influenced by crystallographic surface energies, chemical potential gradients, and precursor diffusion. Additionally, impurities, point defects, and lattice strain further complicate theoretical predictions, as they impact nucleation and growth kinetics in ways that are difficult to incorporate into computational models. The need for precise descriptions of surface interactions, including the role of surfactants, ligands, and seed layers, adds another layer of complexity. While atomistic simulations, such as density functional theory (DFT) and molecular dynamics (MD), offer valuable insights into these interactions, their high computational cost limits their application to large-scale predictions. On the other hand, continuum models like phase-field and finite element methods allow for larger-scale simulations but may oversimplify atomic-scale details.

References

[1] Ü. Özgür, Y.I. Alivov, C. Liu, A. Teke, M.A. Reshchikov, S. Doğan, V. Avrutin, S.J. Cho, H. Morkoç, A comprehensive review of ZnO materials and devices, J. Appl. Phys. 98(4) (2005) 041301.

[2] S.J. Pearton, D.P. Norton, K. Ip, Y.W. Heo, T. Steiner, Recent progress in processing and properties of ZnO, Superlattices Microstruct. 34 (2003) 3-32.

[3] X. Wang, J. Song, J. Liu, Z. L. Wang, Direct-current nanogenerator driven by ultrasonic waves, Sci. 316(5821) (2016) 102-105.

[4] F.S.S. Chien, C.R. Wang, Y.L. Chan, H.L. Lin, M.H. Chen, R.J. Wu, Fast-response ozone sensor with ZnO nanorods grown by chemical vapor deposition, Sens. Actuators B: Chem. 144(1) (2010) 120-125.

[5] Y. Lee, Y. Zhang, S.L.G. Ng, F.C. Kartawidjaja, J. Wang, Hydrothermal growth of vertical ZnO nanorods, J. Am. Ceram. Soc. 92(9) (2009) 1940-1945.

[6] B. Postels, A. Bakin, H.H. Wehmann, M. Suleiman, T. Weimann, P. Hinze, A. Waag, Electrodeposition of ZnO nanorods for device application, Appl. Phys. A, 91 (2008) 595-599.

[7] S. Baruah, J. Dutta, Hydrothermal growth of ZnO nanostructures, Sci. Technol. Adv. Mater. 10 (1) (2009) 013001.

[8] M. Ethayaraja, R. Bandyopadhyaya, Mechanism and modeling of nanorod formation from nanodots, Langmuir, 23(11) (2007) 6418-6423.

[9] L. Zhu, Y. Li, W. Zeng, Enhanced ethanol sensing and mechanism of Cr-doped ZnO nanorods: Experimental and computational study, Ceram. Int. 43(17) (2017) 14873-14879.

[10] M. Chakraborty, A. Ghosh, R. Thangavel, Experimental and theoretical investigations of structural and optical properties of copper doped ZnO nanorods, J. Sol-Gel Sci. Technol. 74 (2015) 756-764.

[11] N.H. Tiep, K.T.H. My, N.D. Lam, H.N. Nhat, N.T. Dang, D.T. Khan, L.V. ruong-Son, B.N. Yahya T.L. Phan, Structural, phonon vibrational, and catalytic properties of high-energy ground ZnO nanoparticles, J. Electron. Mater. 53(12), (2024) 7271-7281.

[12] R. Kumar, O. Al-Dossary, G. Kumar, A. Umar, Zinc oxide nanostructures for NO_2 gas–sensor applications: A review, Nanomicro. Lett. *7*(2015) 97-120.

[13] S. Goel, B. Kumar, A review on piezo-/ferro-electric properties of morphologically diverse ZnO nanostructures, J. Alloys Compd. 816 (2020) 152491.

[14] D. Tsivion, M. Schvartzman, R. Popovitz-Biro, E. Joselevich, Guided growth of horizontal ZnO nanowires with controlled orientations on flat and faceted sapphire surfaces, ACS Nano. 6(7) (2012) 6433-6445.

[15] Z.L. Wang, Zinc oxide nanostructures: growth, properties and applications, J. Phys. Condens. Matter. 16(25) (2004) R829.

[16] Q. Zhang, S.J. Liu, S.H. Yu, Recent advances in oriented attachment growth and synthesis of functional materials: concept, evidence, mechanism, and future, J. Mater. Chem. 19(2) (2009) 191-207.

[17] J. Zhang, Y. Zhang, K. Tse, B. Deng, H. Xu, J. Zhu, New approaches for calculating absolute surface energies of wurtzite (0001)/(0001): A study of ZnO and GaN, J. Appl. Phys. 119(20) (2016) 205302.

[18] T. Lim, P.S. Mirabedini, K. Jung, P.A. Greaney, A.A. Martinez-Morales, High-index crystal plane of ZnO nanopyramidal structures: Stabilization, growth, and improved photocatalytic performance, Appl. Surf. Sci. 536 (2021) 147326.

[19] V. Consonni, E. Sarigiannidou, E. Appert, A. Bocheux, S. Guillemin, F. Donatini, I.C. Robin, J. Kioseoglou, F. Robaut, Selective area growth of well-ordered ZnO nanowire arrays with controllable polarity, ACS Nano. 8(5) (2014) 4761-4770.

[20] S. Chen, Y. Yao, Elastic theory of nanomaterials based on surface-energy density, J. Appl. Mech. 81(12) (2014) 121002.

[21] W.D. Callister Jr, D.G. Rethwisch, Materials science and engineering: An introduction, 10th Ed., E-Book, John wiley & sons, NY, USA, 2020.

[22] G.X.X.V. Wulff, Xxv. Zur frage der geschwindigkeit des wachsthums und der auflösung der krystallflächen, Zeitschrift *für* Kristallographie-Cryst. Mater. 34(1-6) (1901) 449-530.

https://doi.org/10.30799/jnst.357.25100201

Cite this Article as: Manjit Borah, Theoretical insights into growth mechanisms of ZnO nanorods, J. Nanosci. Tech. 10(2) (2025) 995–998.

[23] G.D. Barmparis, Z. Lodziana, N. Lopez, I.N. Remediakis, Nanoparticle shapes by using Wulff constructions and first-principles calculations, Beilstein J. Nanotechnol. 6(1) (2015) 361-368.
[24] G. Ouyang, C.X. Wang, G.W. Yang, Surface energy of nanostructural materials with negative curvature and related size effects, Chem. Rev. 109(9) (2009) 4221-4247.
[25] J. Zhang, H. Li, Q. Kuang, Z. Xie, Toward rationally designing surface structures of micro-and nanocrystallites: role of supersaturation, Acc. Chem. Res. 51(11) (2018) 2880-2887.
[26] J. Wang, S. Hou, L. Zhang, J. Chen, L. Xiang, Ultra-rapid formation of ZnO hierarchical structures from dilution-induced supersaturated solutions, Cryst. Eng. Comm. 16(30) (2014) 7115-7123.
[27] G. Cao, D. Liu, Template-based synthesis of nanorod, nanowire, and nanotube arrays, Adv. Colloid Inter. Sci. 136(1-2) (2008) 45-64.
[28] R. Rajasekaran, K.V. Rajendiran, R.M. Kumar, R. Jayavel, R. Dhanasekaran, P. Ramasamy, Investigation on the nucleation kinetics of zinc thiourea chloride (ZTC) single crystals, Mater. Chem. Phys. 82(2) (2003) 273-280.
[29] B. Weintraub, Y. Deng, Z.L. Wang, Position-controlled seedless growth of ZnO nanorod arrays on a polymer substrate via wet chemical synthesis, J. Phys. Chem. C. 111(28) (2007) 10162-10165.
[30] Z. Zhou, Y. Deng, Kinetics study of ZnO nanorod growth in solution, J. Phys. Chem. C. 113(46) (2009) 19853-19858.
[31] I.M. Lifshitz, V.V. Slyozov, The kinetics of precipitation from supersaturated solid solutions, J. Phys. Chem. Solids. 19(1-2) (1961) 35-50.
[32] K. Biswas, B. Das, C.N.R. Rao, Growth kinetics of ZnO nanorods: Capping-dependent mechanism and other interesting features, J. Phys. Chem. C. 112(7) (2008) 2404-2411.
[33] P.K. Aspoukeh, A.A. Barzinjy, S.M. Hamad, Synthesis, properties and uses of ZnO nanorods: a mini review, Int. Nano Lett. 12(2) (2022) 153-168.
[34] S. Baruah, J. Dutta, pH-dependent growth of zinc oxide nanorods, J. Cryst. Growth 311(8) (2009) 2549-2554.
[35] G. Amin, M.H. Asif, A. Zainelabdin, S. Zaman, O. Nur, M. Willander, Influence of pH, precursor concentration, growth time, and temperature on the morphology of ZnO nanostructures grown by the hydrothermal method, J. Nanomater. 2011(1) (2011) 269692.
[36] J.K. Tsai, T.H. Meen, T.C. Wu, Y.D. Lai, Y.K. He, Morphology and optical properties of ZnO microrods grown by high-temperature hydrothermal method, Microelectron. Eng. 148 (2015) 55-58.
[37] S.O. Aisida, A. Batool, F.M. Khan, L. Rahman, A. Mahmood, I. Ahmad, T.K. Zhao, M. Maaza, F.I. Ezema, Calcination induced PEG-Ni-ZnO nanorod composite and its biomedical applications, Mater. Chem. Phys. *255* (2020) 123603.
[38] M.R. Parra, F.Z. Haque, Structural and optical properties of poly-vinylpyrrolidone modified ZnO nanorods synthesized through simple hydrothermal process, Optik 125(17) (2014) 4629-4632.
[39] S. Cho, J.W. Jang, S.H. Jung, B.R. Lee, E. Oh, K.H. Lee, Precursor effects of citric acid and citrates on ZnO crystal formation, Langmuir, 25(6) (2009) 3825-3831.
[40] X. M. Sun, X. Chen, Z.X. Deng, Y.D. Li, A CTAB-assisted hydrothermal orientation growth of ZnO nanorods, Mater. Chem. Phys.78(1) (2003) 99-104.

https://doi.org/10.30799/jnst.357.25100201

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