Л.Н. Гумилев атындағы Еуразия ұлттық университетінің ХАБАРШЫСЫ.
ISSN: 2616-6836. eISSN: 2663-1296

ФИЗИКА СЕРИЯСЫ/ PHYSICS SERIES / СЕРИЯ ФИЗИКА

IRSTI: 29.19.31; 29.19.16;
Scientific article

https://doi.org/10.32523/2616-6836-2025-153-4-41-51

Electrospinning-assisted fabrication of ZnO nanostructures

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Abstract. The present study focuses on the synthesis of ZnO nanostructures via an electrospinning-assisted technique, followed by calcination under carefully controlled thermal conditions. The electrospinning process resulted in the formation of continuous, uniform, and bead-free polymeric precursor fibers, with a noticeable reduction in average fiber diameter. This clearly demonstrates the influence of electrospinning parameters, such as applied voltage, solution concentration, and flow rate, on the resulting fiber morphology. Subsequent calcination not only removed the polymeric matrix but also induced the crystallization of ZnO, transforming the fibrous structure into well-defined nanoparticles. The crystallite size of the obtained ZnO was strongly dependent on the calcination temperature, with the smallest crystallites achieved under optimized thermal treatment, thereby offering a route to fine-tune the nanostructure dimensions. Elemental analysis by energy-dispersive X-ray spectroscopy (EDS) confirmed the exclusive presence of zinc and oxygen, verifying the high purity and compositional integrity of the synthesized material. Furthermore, X-ray diffraction (XRD) analysis revealed sharp and intense diffraction peaks corresponding solely to the hexagonal wurtzite phase of ZnO, with no evidence of secondary phases or impurities. These results collectively demonstrate that electrospinning, coupled with controlled calcination, provides a robust, cost-effective, and scalable approach for producing high-quality ZnO nanostructures with desirable structural and compositional features. Such nanostructures hold significant promise for diverse applications, including gas sensing.

Keywords: ZnO nanoparticles, electrospinning, calcination, nanostructured materials, polymeric matrix, crystallite size, hexagonal wurtzite

Received 22.09.2025. Revised 14.11.2025. Accepted 26.11.2025. Available online 25.12.2025.

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Introduction

Zinc oxide (ZnO) is a n-type semiconductor material that is suitable for a wide range of applications, including gas sensors, photocatalysts, solar cells, and optoelectronic devices. It has a high exciton binding energy of 60 meV and a wide bandgap of 3.37 eV [1]. Its significance in advanced functional materials has been further enhanced by its distinctive characteristics, including biocompatibility, nontoxicity, and high chemical stability [2]. Electrospinning has emerged as a straightforward, cost-effective, and highly controllable method for the production of one-dimensional (1D) nanofibers with high aspect ratios and large surface area-to-volume ratios, among the numerous synthesis techniques for ZnO nanostructures [3]. Applications such as gas sensing and catalysis are particularly advantageous due to the substantial enhancement of active surface sites by these structural features. A high-voltage electric field is applied to a polymer solution containing a Zn precursor during the electrospinning process, which results in the formation of continuous nanofibers. These fibers can be calcined to eliminate the polymer matrix and crystalize ZnO. Electrospinning provides superior control over fiber morphology, alignment, and porosity in comparison to other fabrication techniques, such as hydrothermal or sol-gel [4]. Furthermore, this method facilitates the incorporation of dopants or composite materials, which enables the final ZnO nanofibers to possess tunable physical and chemical properties. Consequently, electrospinning has emerged as the preferred method for the production of ZnO-based nanostructures for energy-related applications and advanced sensing [5].

The research offers the investigation of the nanosized ZnO via electrospinning method and subsequent calcination. Influencing factors, namely, calcination temperature, collector-to-tip distance, and voltage, are determined to control the particle size of ZnO.

The Literature review

In the past decade, electrospinning has been predominantly employed to produce nanoparticles from precursor solution containing natural and synthetic polymers with addition of metal salts. However, it has also been employed to produce ceramics, such as ZnO materials. For example, Liu et al. synthesized ZnO nanoparticles through electrospinning, followed by calcination, and analyzed their morphology, elementary composition, and crystal structure. There, it was specified that the resulted ZnO has a mesoporous nanofibrous structure which possess a single phase with favorable crystallinity [6]. Ultra-thin fibers of ZnO were prepared using electrospinning techniques, with poly(vinyl acetate) and zinc acetate as precursors. Characterization methods included thermogravimetric analysis, scanning electron microscopy, Fourier-transfer infrared, and X-ray diffraction [7]. The morphology and optical properties of zinc oxide fibres with diameters in the nanometre to micrometre range are reported by Viswanathamurthi. The PVA/zinc acetate organic/inorganic hybridnanofiberss were successfully prepared by electrospinning. Pure ZnO fibres were obtained by high-temperature calcination of the obtained fibers. Synthesised ZnO has a band gap of 3.13 eV and can be applied in different applications [8]. Electrospun ZnO was deposited on a glass substrate from zinc acetate dihydrate with polyvinyl acetate p olymer and annealed in the presence of oxygen until

organic molecules were decomposed. Characterisation results state that the mean fibre width was found to be 260 nm, and fibre thickness was measured at 460 nm. XRD patterns show that ZnO has a hexagonal wurtzite structure, and the material band gap for this electrospun ZnO fibre was found to be 3.28 eV. In summary, the n-type electrospun ZnO can be fabricated via facile electrospinning methods [9].

The methodology

PVP and ZnAc dihydrate were used as used precursors. 10 wt% solution of PVP in ethanol was made and stirred at room temperature for 5 h. Electrospinning was conducted at voltages of 14 kV and tip-to-collector distances of 10 cm. Nanofibers were collected on aluminum foil, which was then calcined in air at 600, 700 and 800 ℃ for 2 h to determine optimal sintering temperature. Selected parameters were applied to investigate the influence of on ZnO (Figure1). Scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD) were employed to conduct a comprehensive analysis of the morphological and structural characteristics of the synthesized materials.

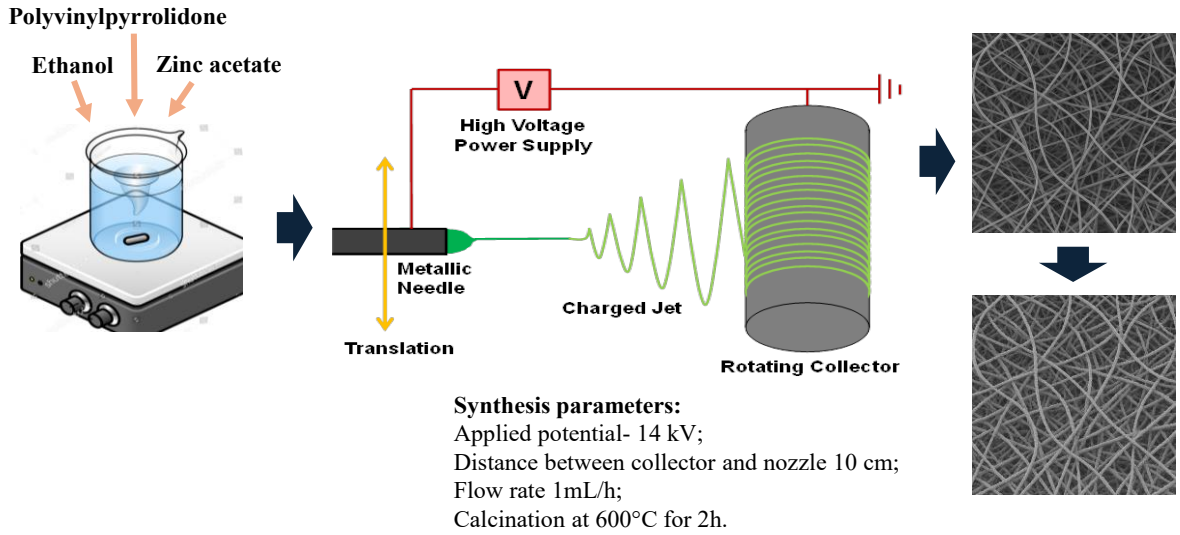


Figure 1 – Schematic illustration of synthesis procedure

Findings and Discussion

Effective electrospinning conditions were demonstrated by the formation of uniform, bead-free fibers across the samples, as indicated by SEM observations Figure 2a. The increased electrostatic force exerted on the polymer fluid at higher voltages, which enables the fiber to undergo greater stretching and elongation during electrospinning, resulting in a finer fiber morphology. In the same vein, the electric field intensity is increased by a shorter collector distance, which in turn promotes fiber thinning and uniform deposition [10]. The obtained fibers were effectively converted into ZnO particles with well-defined morphologies after

calcination Figure 2b. The crystallinity and particle size of ZnO are significantly influenced by thermal treatment. We observed a direct correlation between the calcination temperature and the size of the ZnO particles [7], [11]. Specifically, higher temperatures encourage grain growth and coalescence, while lower temperatures favour the formation of finer particles. In particular, the optimized electrospinning parameters are 14 kV voltage, 10 cm tip-to-collector distance, and 600 °C calcination resulted in ZnO particles with an average size of approximately 52 nm.

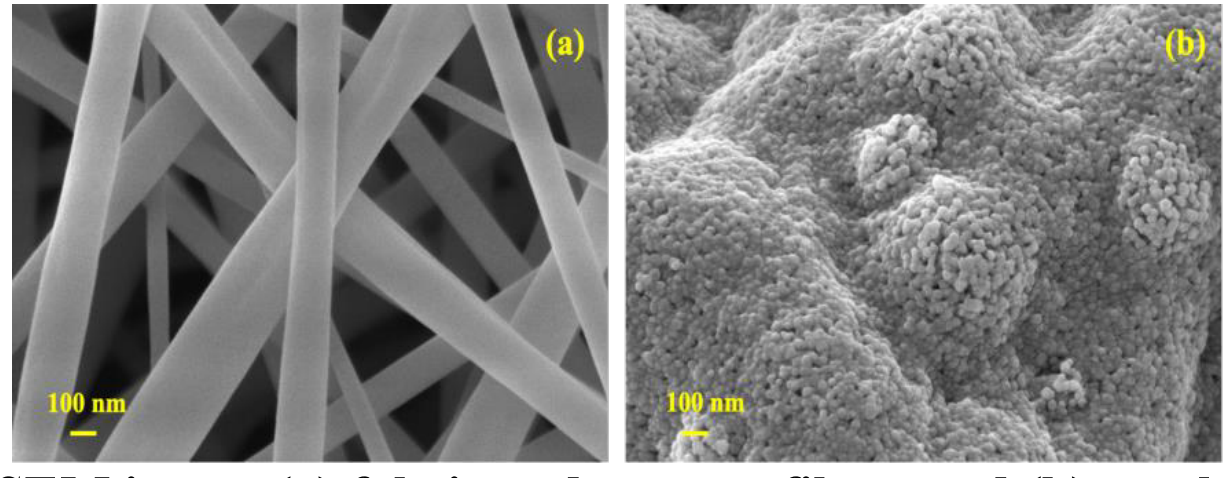
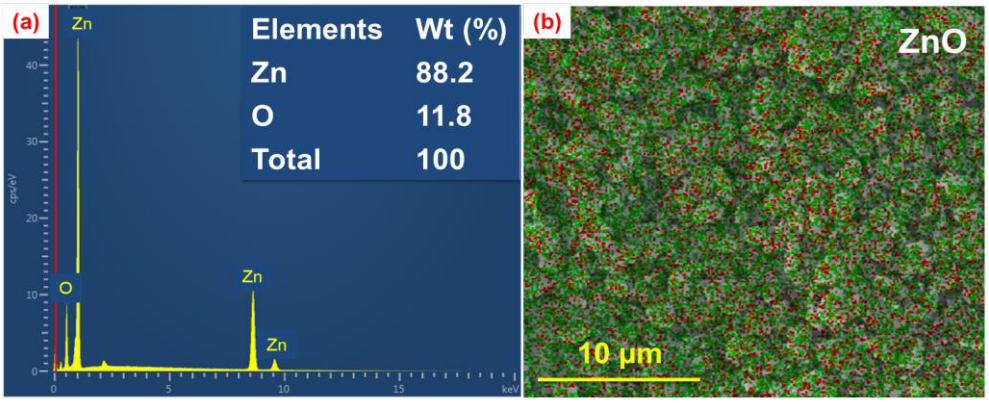


Figure 2 – SEM image (a) fabricated as spun fibers and (b) synthesized ZnO

The successful formation of ZnO was further validated by the Energy Dispersive X-ray Spectroscopy (EDS) analysis (Figure 3), which confirmed the presence of zinc (Zn) and oxygen (O) elements in their respective stoichiometric concentrations (Figure 3c and Figure 3d). The EDS spectra reveal that the synthesised material is of high purity, as there are no detectable impurity peaks. This suggests that the electrospinning and subsequent calcination procedure did not introduce other elements into the structure. The peaks corresponding to Zn and O are both strong and distinct. The formation of a well-ordered ZnO crystal lattice is also facilitated by the near-stoichiometric Zn:O ratio, which is crucial for the preservation of stable electronic properties and the improvement of the performance of ZnO-based devices, such as gas sensors [12], [13].



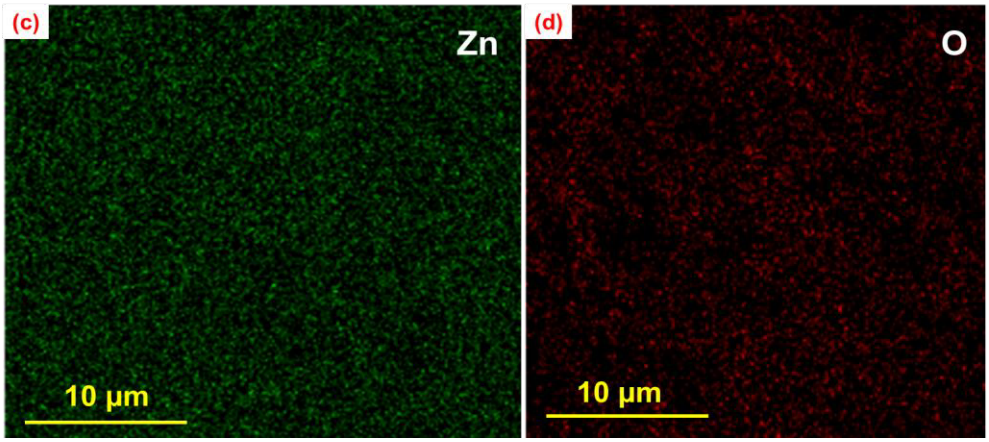


Figure 3 – EDS mapping of ZnO particles

The calcined samples exhibited a single-phase wurtzite structure of ZnO, as confirmed by X-ray Diffraction (XRD) analysis (Figure 4), without any detectable secondary phases or impurities. The hexagonal wurtzite crystalline structure is confirmed by the diffraction peaks observed at characteristic 2θ values, which correspond to the (100), (002), and (101) planes. The successful formation of phase-pure ZnO and the complete decomposition of the polymer matrix during calcination are indicated by the absence of additional peaks [1], [14], [15]. Therefore, among different calcining temperature 600 °C was determined as an optimal, as it produces clear, sharp, and intense diffraction peaks, indicating high crystallinity and phase purity of the material. At higher temperatures (700-800°C), a decrease in peak broadening is observed.

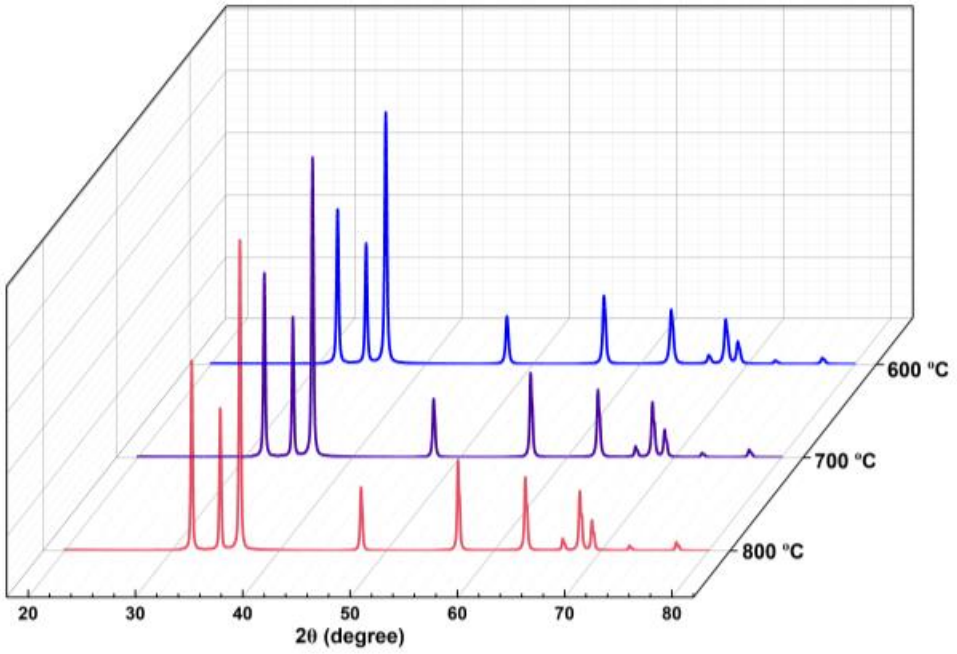


Figure 4 – XRD pattern of obtained ZnO nanoparticles

Conclusion

This research successfully synthesizes and controls ZnO nanoparticle size through electrospinning and calcination. Optimal synthetic conditions were reached for applied voltage, electrostatic distance, and calcining temperature. Optimal synthetic conditions under which uniform ZnO nanoparticles of 52 nm diameters in average could be achieved. This synthetic method allows morphology to be precisely controlled, and ZnO can be made compatible with sensor and electronic applications.

Funding
This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP23489498), PI: Natalya Khan.

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authorship contribution statement
A. Rakhmanova and **A. Jaldybayev** performed all the experiments, analyzed the data obtained and wrote the manuscript. Supervision, conceptualization, and revision were carried out by **N. Khan, G. Yergaliuly, B. Soltabayev,** and **A. Mentbayev**a All authors have reviewed and approved the final manuscript.

References

1. A. Rakhmanova et al., Nanofibrous ZnO-loaded PVA/PEDOT:PSS for selective and enhanced ammonia detection, Sensors and Actuators B: Chemical 426, (2025), DOI: https://doi.org/10.1016/j.snb.2024.137022.

2. M.A. Franco, P.P. Conti, R. S. Andre, and D. S. Correa, A review on chemiresistive ZnO gas sensors, Sensors and Actuators Reports 4, (2022), DOI: https://doi.org/10.1016/j.snr.2022.100100

3. J. Yin et al., Enhanced mechanical performances and high-conductivity of rGO/PEDOT:PSS/PVA composite fiber films via electrospinning strategy, Colloids and Surfaces A: Physicochemical and Engineering Aspects 643, (2022), DOI: https://doi.org/10.1016/j.colsurfa.2022.128791

4. E. Ghafari, Y. Feng, Y. Liu, I. Ferguson, and N. Lu, Investigating process-structure relations of ZnO nanofiber via electrospinning method, Composites Part B: Engineering 116, (2017), DOI: https://doi.org/10.1016/j.compositesb.2017.02.026.

5. F. Li, T. Zhang, X. Gao, R. Wang, and B. Li, Coaxial electrospinning heterojunction SnO_2/Au-doped In_2O_3 core-shell nanofibers for acetone gas sensor, Sensors and Actuators B: Chemical 252, (2017), DOI: https://doi.org/10.1016/j.snb.2017.06.077.

6. H. Liu, J. Yang, J. Liang, Y. Huang, and C. Tang, ZnO nanofiber and nanoparticle synthesized through electrospinning and their photocatalytic activity under visible light, Journal of the American Ceramic Society 91, 1287–1291 (2008), DOI: https://doi.org/10.1111/j.1551-2916.2008.02299.x.

7. H. Wu and W. Pan, Preparation of zinc oxide nanofibers by electrospinning, Journal of the American Ceramic Society 89, (2006), DOI: https://doi.org/10.1111/j.1551-2916.2005.00735.x.

8. P. Viswanathamurthi, N. Bhattarai, H. Y. Kim, and D. R. Lee, The photoluminescence properties of zinc oxide nanofibres prepared by electrospinning, Nanotechnology 15, (2004), DOI: https://doi.org/10.1088/0957-4484/15/3/015.

9. H. S. Bolarinwa et al., Determination of optical parameters of zinc oxide nanofibre deposited by electrospinning technique, Journal of Taibah University for Science 11, 1245–1258 (2017), DOI: https://doi.org/10.1016/j.jtusci.2017.01.004.

10. M. Wasim, A. Sabir, M. Shafiq, and T. Jamil, Electrospinning: A fiber fabrication technique for water purification, in Nanoscale Materials in Water Purification, (Elsevier, 2019), DOI: https://doi.org/10.1016/B978-0-12-813926-4.00016-1.

11. S. X. Wang, C. C. Yap, J. He, C. Chen, S. Y. Wong, and X. Li, Electrospinning: A facile technique for fabricating functional nanofibers for environmental applications, Nano Today Reviews 11, (2016), DOI: https://doi.org/10.1515/ntrev-2015-0065.

12. M. Kumar and P. Kumari, P(VDF-TrFE)/ZnO nanocomposite synthesized by electrospinning: effect of ZnO nanofiller on physical, mechanical, thermal, rheological and piezoelectric properties, Polymer Bulletin 80, (2023), DOI: https://doi.org/10.1007/s00289-022-04275-2.

13. A. Baji and Y.-W. Mai, Engineering ceramic fiber nanostructures through polymer-mediated electrospinning, in Ceramic Nanocomposites, (Springer, Cham, 2017), pp. 3–30, DOI: https://doi.org/10.1007/978-3-319-57003-7_1.

14. G. Hitkari, S. Singh, and G. Pandey, Structural, optical and photocatalytic study of ZnO and ZnO–ZnS synthesized by chemical method, Nano-Structures and Nano-Objects 12, (2017), DOI: https://doi.org/10.1016/j.nanoso.2017.08.007.

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Электроспиннинг әдісі арқылы ZnO наноқұрылымдарын алу

Аңдатпа. Бұл зерттеу қатаң бақыланатын термиялық жағдайда кейінгі қыздырумен бірге ZnO наноқұрылымдарын электроспиннинг әдісі арқылы синтездеуге арналған. Электроспиннинг процесі кезінде үздіксіз, біртекті және «түйіршіксіз» полимерлі прекурсорлы талшықтар алынып, олардың орташа диаметрінің айтарлықтай азаюы байқалды. Бұл қолданылған кернеу, ерітінді концентрациясы және берілу жылдамдығы сияқты электроспиннинг параметрлерінің талшық морфологиясының қалыптасуына ықпалын айқын көрсетеді. Кейінгі қыздыру тек полимерлі матрицаны жойып қана қоймай, сонымен қатар ZnO кристалдануын бастады, нәтижесінде талшықты құрылым жақсы қалыптасқан нанобөлшектерге айналды. Алынған

ZnO кристаллиттерінің өлшемі қыздыру температурасына айтарлықтай тәуелді болды: ең кіші мәндер оңтайлы термиялық режимде байқалды, бұл наноқұрылымдардың өлшемін дәл реттеуге мүмкіндік береді. Элементтік талдау (EDS) тек мырыш пен оттегінің болуын растады, бұл синтезделген материалдың жоғары тазалығын және құрамдық тұтастығын дәлелдейді. Сонымен қатар рентгеноструктуралық талдау (XRD) тек ZnO-ның гексагоналды вюрцит фазасына сәйкес келетін айқын әрі қарқынды дифракциялық шыңдарды көрсетті, бөгде фазалар мен қоспалардың ешқандай белгісі табылған жоқ. Жинақталған нәтижелер электроспиннинг пен бақыланатын қыздыруды біріктіру арқылы ZnO наноқұрылымдарын қажетті құрылымдық және құрамдық сипаттамаларымен алудың сенімді, үнемді және ауқымды тәсіл екенін дәлелдейді. Мұндай наноқұрылымдар әртүрлі қолданбаларда, соның ішінде газға сезімтал сенсорларда үлкен әлеуетке ие.

Түйін сөздер: ZnO нанобөлшектері, электроспиннинг, қыздыру (кальцинация), наноқұрылымды материалдар, полимерлі матрица, кристаллит өлшемі, гексагоналды вюрцит.

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Электропрядение как метод получения наноструктур ZnO

Аннотация. Настоящее исследование посвящено синтезу наноструктур ZnO методом электропрядения с последующим прокаливанием при тщательно контролируемых термических условиях. В процессе электропрядения удалось получить непрерывные, однородные и свободные от дефектов типа «бусин» полимерные прекурсорные волокна, при этом наблюдалось заметное уменьшение среднего диаметра волокон. Это наглядно демонстрирует влияние параметров электропрядения, таких как приложенное напряжение, концентрация раствора и скорость подачи, на формирование морфологии волокон. Последующее прокаливание не только удалило полимерную матрицу, но и инициировало кристаллизацию ZnO, трансформировав волокнистую структуру в хорошо сформированные наночастицы. Размер кристаллитов полученного ZnO сильно зависел от температуры прокаливания: минимальные значения достигались при оптимальном термическом режиме, что открывает возможность точной настройки размеров наноструктур. Элементный анализ методом энергодисперсионной рентгеновской спектроскопии (EDS) подтвердил присутствие исключительно цинка и кислорода, что свидетельствует о высокой чистоте и целостности состава синтезированного материала. Дополнительно рентгеноструктурный анализ (XRD) показал резкие и интенсивные дифракционные пики, соответствующие исключительно гексагональной вюрцитной фазе ZnO, без признаков вторичных

фаз или примесей. Совокупность полученных результатов доказывает, что электроформование в сочетании с контролируемым прокаливанием представляет собой надёжный, экономичный и масштабируемый подход к получению высококачественных наноструктур ZnO с требуемыми структурными и композиционными характеристиками. Такие наноструктуры обладают значительным потенциалом для различных применений, включая газочувствительные сенсоры.

Ключевые слова: наночастицы ZnO, электропрядение, прокаливание, наноструктурные материалы, полимерная матрица, размер кристаллитов, гексагональный вюрцит.

References

1. A. Rakhmanova et al., Nanofibrous ZnO-loaded PVA/PEDOT:PSS for selective and enhanced ammonia detection, Sensors and Actuators B: Chemical 426, (2025), DOI: https://doi.org/10.1016/j.snb.2024.137022.

2. M. A. Franco, P. P. Conti, R. S. Andre, and D. S. Correa, A review on chemiresistive ZnO gas sensors, Sensors and Actuators Reports 4, (2022), DOI: https://doi.org/10.1016/j.snr.2022.100100

3. J. Yin et al., Enhanced mechanical performances and high-conductivity of rGO/PEDOT:PSS/PVA composite fiber films via electrospinning strategy, Colloids and Surfaces A: Physicochemical and Engineering Aspects 643, (2022), DOI: https://doi.org/10.1016/j.colsurfa.2022.128791

4. E. Ghafari, Y. Feng, Y. Liu, I. Ferguson, and N. Lu, Investigating process-structure relations of ZnO nanofiber via electrospinning method, Composites Part B: Engineering 116, (2017), DOI: https://doi.org/10.1016/j.compositesb.2017.02.026.

5. F. Li, T. Zhang, X. Gao, R. Wang, and B. Li, Coaxial electrospinning heterojunction SnO_2/Au-doped In_2O_3 core-shell nanofibers for acetone gas sensor, Sensors and Actuators B: Chemical 252, (2017), DOI: https://doi.org/10.1016/j.snb.2017.06.077.

6. H. Liu, J. Yang, J. Liang, Y. Huang, and C. Tang, ZnO nanofiber and nanoparticle synthesized through electrospinning and their photocatalytic activity under visible light, Journal of the American Ceramic Society 91, 1287–1291 (2008), DOI: https://doi.org/10.1111/j.1551-2916.2008.02299.x.

7. H. Wu and W. Pan, Preparation of zinc oxide nanofibers by electrospinning, Journal of the American Ceramic Society 89, (2006), DOI: https://doi.org/10.1111/j.1551-2916.2005.00735.x.

8. P. Viswanathamurthi, N. Bhattarai, H. Y. Kim, and D. R. Lee, The photoluminescence properties of zinc oxide nanofibres prepared by electrospinning, Nanotechnology 15, (2004), DOI: https://doi.org/10.1088/0957-4484/15/3/015.

9. H. S. Bolarinwa et al., Determination of optical parameters of zinc oxide nanofibre deposited by electrospinning technique, Journal of Taibah University for Science 11, 1245–1258 (2017), DOI: https://doi.org/10.1016/j.jtusci.2017.01.004.

10. M. Wasim, A. Sabir, M. Shafiq, and T. Jamil, Electrospinning: A fiber fabrication technique for water purification, in Nanoscale Materials in Water Purification, (Elsevier, 2019), DOI: https://doi.org/10.1016/B978-0-12-813926-4.00016-1.

11. S. X. Wang, C. C. Yap, J. He, C. Chen, S. Y. Wong, and X. Li, Electrospinning: A facile technique for fabricating functional nanofibers for environmental applications, Nano Today Reviews 11, (2016), DOI: https://doi.org/10.1515/ntrev-2015-0065.

12. M. Kumar and P. Kumari, P(VDF-TrFE)/ZnO nanocomposite synthesized by electrospinning: effect of ZnO nanofiller on physical, mechanical, thermal, rheological and piezoelectric properties, Polymer Bulletin 80, (2023), DOI: https://doi.org/10.1007/s00289-022-04275-2.

13. A. Baji and Y.-W. Mai, Engineering ceramic fiber nanostructures through polymer-mediated electrospinning, in Ceramic Nanocomposites, (Springer, Cham, 2017), pp. 3–30, DOI: https://doi.org/10.1007/978-3-319-57003-7_1.

14. G. Hitkari, S. Singh, and G. Pandey, Structural, optical and photocatalytic study of ZnO and ZnO–ZnS synthesized by chemical method, Nano-Structures and Nano-Objects 12, (2017), DOI: https://doi.org/10.1016/j.nanoso.2017.08.007.

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