Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Effects of Thermal Annealing on The Morphology and Structural Characteristics of Zinc Oxide Nanopowders for Triboelectric Nanogenerator Applications

Dayana Kamaruzaman[1,2], Mohamad Hafiz Mamat[1,3,*], Nurul Izzati Kamal Ariffin[1], A Shamsul Rahimi A Subki[1,4], Mohd Hanapiah Abdullah[5], Norfarariyanti Parimon[6], Muhamad Kamil Yaakob[7], Mohd Firdaus Malek[3] , Itreesh Basha Shameem Banu[8], Nagamalai Vasimalai[8], Suriani Abu Bakar[9], Azmi Mohamed[9], Mohd Khairul Ahmad[10], Mohamad Rusop Mahmood[1,3]

[1] NANO-ElecTronic Centre (NET), School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[2] School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Terengganu, Kampus Dungun, 23000 Dungun, Terengganu, Malaysia
[3] NANO-SciTech Lab (NST), Centre for Functional Materials and Nanotechnology, Institute of Science (IOS), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[4] Faculty of Electrical and Electronics Engineering Technology, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[5] Centre for Electrical Engineering Studies, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia
[6] Faculty of Engineering, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
[7] Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[8] School of Physical and Chemical Sciences, B.S. Abdur Rahman Crescent Institute of Science & Technology, Vandalur, Chennai 600 048, India
[9] Nanotechnology Research Centre, Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, 35900 Tanjung Malim, Malaysia
[10] Microelectronic and Nanotechnology-Shamsuddin Research Centre, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Malaysia

ARTICLE INFO

Article history:
Received 5 April 2022
Received in revised form 15 July 2022
Accepted 28 July 2022
Available online 24 August 2022

ABSTRACT

The influence of thermal annealing on the surface morphologies and structural characteristics of zinc oxide (ZnO) nanopowders synthesized via the solution immersion method for triboelectric nanogenerator applications is reported in this paper. The ZnO nanopowders were thermally treated at different temperatures of annealing in the ranges between 300°C to 700°C for 1 hour, and their surface morphologies and structural properties were studied using field emission scanning electron microscopy (FESEM) and X-ray diffraction (XRD) analysis. The ZnO nanopowders have a polycrystalline, hexagonal wurtzite structure and are composed of ZnO nanoparticles and hexagonal nanorods. ZnO based tribolectric nanogenerators were fabricated with these nanopowders and their performance was assessed in terms of the output voltage. It is found that the ZnO based triboelectric nanogenerator fabricated with ZnO nanopowders annealed at 500°C has superior performance compared with the other nanogenerators, with an average output voltage of 1.95 V. This corresponds to a fourfold increase in output voltage relative to that of the ZnO based triboelectric nanogenerator fabricated with as-deposited ZnO nanopowders. In conclusion, thermal annealing significantly influences particle size and

---

[*] *Corresponding author.*
E-mail address: mhmamat@uitm.edu.my

https://doi.org/10.37934/arfmts.99.1.1727

Keywords:
Triboelectricity; nanogenerator; zinc oxide; immersion

crystallinity of ZnO nanopowders, which in turn, influences the output voltage of ZnO based triboelectric nanogenerators.

1. Introduction

With advancements in information technology (Internet of Things, big data) and telecommunications (fifth generation (5G) technology), electronics are becoming smaller and smaller, hence increasing the demand for clean, sustainable, and reliable power sources [1,2]. Metal oxide nanostructures have attracted a great deal of interest owing to their superior and unique properties, which make them appropriate for advanced technological applications, including sensors, solar cells, batteries, and nanogenerators [3-11]. Nanogenerators have gained a significant amount of attention over the past two decades, as this device can generate electricity without the usage of batteries by harvesting mechanical energy from the surrounding environment [12,13]. Associated with the high demand for clean and affordable energy, a low cost, a facile synthesis, and excellent triboelectric nanogenerator (TENG) performance are required. The research community has taken a keen interest in it because of their potential as a clean, highly efficient, and sustainable power source. Typically, zinc oxide (ZnO), lead zirconium titanate (PZT), barium titanate ($BaTiO_3$), Polyvinylidene Fluoride Polymer Film (PVDF) and polydimethylsiloxane (PDMS) are utilized to fabricate [14-18]. ZnO has excellent potential compared with other materials because it possesses a direct wide band gap (3.37eV), capability to grow various nanostructures, ease of synthesis, environmental friendliness and piezoelectric properties [19-24]. ZnO is one of the metal oxides extensively studied for many applications ranging from electronics, energy conversion or storage, textile, nanofluids, and medical applications which make it appropriate for many applications [25-30].

Several common techniques including chemical vapour deposition (CVD), pulsed laser deposition (PLD), hydrothermal, magnetron sputtering and sol-gel techniques, have been utilized to produce high-quality ZnO nanostructures [31-37]. All these methods depend on the properly controlled synthesis parameters for the high-quality growth of ZnO nanostructures. To fulfill the rising demands for flexible, scalable, and low-temperature device production, a simple solution immersion method through low temperature chemical reaction can be appropriately adopted. However, it has been reported that the growth of ZnO nanostructures at low temperatures (<100°C) produces issues with the stability, dispersion and crystalline structures control of ZnO nanoparticles in aqueous solution bath due to the low kinetics or total suppression of the chemical reactions [38,39]. This could be a significant problem for the output performance of nanogenerators. The synthesis of ZnO nanostructures relies on both the growth and the thermal annealing processes. Thermal annealing is a widely used technique to apply energy to the material and improve the crystalline quality by reducing the defects in the material [40-42]. Some comparative studies on the effects of annealing temperature on the properties of ZnO nanostructures are reported. For example, the work of Malek *et al.,* [43] discovered that thermal annealing in the range 300°C to 600°C greatly influenced the surface and structural properties of ZnO nanoparticles prepared by sonicated sol-gel dip coating technique, whereas Sahdan *et al.,* [44] found the surface morphology of ZnO nanostructures deposited using chemical vapor deposition (CVD) could be significantly affected by the annealing temperature ranging between 100-300°C. Hence, thermal annealing is a crucial component in determining the surface morphologies and structural properties of ZnO nanostructures [45]. Meanwhile, the output performance of ZnO based TENG has significant influences by the structural as well as surface morphology properties of the material. This factor facilitates the charge transfer mechanism by relating to the surface charge density. A larger specific surface area can significantly enhance the charge transfer density after contact and separation process, resulting in a higher current [46].

Since the output performance of ZnO base TENG varies depending on the surface morphologies of nanostructures, it is essential to explore the surface morphology and structural properties of ZnO utilizing a simple solution immersion method for ZnO based TENG applications. In this work, the surface morphologies and structural characteristics of ZnO nanopowders induced by thermal annealing were studied. The ZnO nanopowders were synthesized by the immersion method. Furthermore, six ZnO based TENG were fabricated with these nanopowders to evaluate the nanogenerator performance in terms of output voltage.

2. Methodology

The solution immersion method was used to synthesize the ZnO nanopowders. Zinc nitrate hexahydrate ($Zn(NO_3)_2{\cdot}6H_2O$), hexamethylenetetramine (HMT, $C_6H_{12}N_4$), and deionized (DI) water were used as the starting materials to synthesize the ZnO nanopowders. An ultrasonic water bath was used to sonicate the ZnO solution. Following this, the ZnO solution was poured into Schott bottles, which were then immersed in a 95°C water bath for 4 hours. The synthesized ZnO nanopowders were then filtered and dried.

The ZnO nanopowders were annealed at various temperatures (300°C, 400°C, 500°C, 600°C and 700°C), where the samples were placed in a furnace box for 1 hour. Next, the surface morphologies of the prepared ZnO nanopowders were examined using a field emission scanning electron microscope (FESEM, JOEL JSM-6320F) at 5kV accelerating voltage, while the structural properties of ZnO nanopowders were assessed using an X-ray diffraction (XRD, PANalytical X'Pert PRO) with Cu K-alpha radiation corresponding to an X-ray wavelength of 1.54 Å. The X-ray diffractograms were recorded at a diffraction angle (2θ) of 20°–90°.

To fabricate the ZnO based triboelectric nanogenerators, each of the ZnO nanostructured powders was mixed with polystyrene and toluene solution to form the ZnO layer. The bottom triboelectric layer consisted of ZnO layer and silver (Ag) electrode. Using thermal evaporation, the Ag electrode was deposited onto the ZnO layer. The upper triboelectric layer consisted of aluminium (Al) foil as the electrode and Kapton tape as the dielectric layer. A total of six ZnO tribolelectric nanogenerators was fabricated — one was prepared using the as-deposited ZnO nanopowder while the others were prepared using ZnO nanopowders annealed at different temperatures. The basic structure of the ZnO triboelectric nanogenerators fabricated in this work is illustrated in Figure 1. The output voltage values of the ZnO triboelectric nanogenerators in response to repetitive finger tapping were recorded using an oscilloscope (Model: RTC 1002, Rohde & Schwarz USA Inc., USA).

Fig. 1. Basic structure of the ZnO tribolelectric nanogenerators fabricated in this work

3. Results

3.1 Surface Morphology

Figure 2(a)-(f) show the surface morphologies of as-deposited ZnO nanopowder and ZnO nanopowders annealed at various temperatures. It can be observed that there is a random growth of ZnO nanoparticles and hexagonal nanorods for all samples. The particle size distributions for all samples were determined using ImageJ software, and the results are shown in Figure 2(g) to Figure 2(l). The average diameters for all ZnO nanopowders are summarized in Table 1. The as-deposited ZnO nanopowder has an average diameter of 345nm. The average diameter of the ZnO nanopowder increases from 408nm to 451nm when the annealing temperature is raised from 300°C to 400°C. This can be due to thermal expansion, in which the kinetic energy of the atoms increases as the annealing temperature rises [47]. But the average diameter of the ZnO nanopowder decreases to 367nm at 500°C and 359nm at 600°C. Atoms with sufficient thermal energy can move, resulting in the rearrangement of the atoms in the crystalline structure. Thus, ZnO nanoparticles notice a decrease in diameter. It is suggested that the crystalline quality enhances as the atoms are free to move to a more favourable position [44]. At 700°C, the atoms move closer together and consequently, the ZnO nanoparticles merge with the adjacent ZnO nanoparticles to form larger nanoparticles which is known as agglomeration. Agglomeration of the ZnO nanoparticles during thermal annealing may be due to the high surface energy of the nanoparticles Thus, it can be concluded that the annealing temperatures have an impact on the ZnO nanopowder's average diameter.

Table 1
Average diameter of the as-deposited ZnO nanopowder and ZnO nanopowders at various annealing temperatures

Samples	Average diameter (nm)
As-deposited ZnO nanopowder	345
ZnO nanopowder annealed at 300°C	408
ZnO nanopowder annealed at 400°C	451
ZnO nanopowder annealed at 500°C	367
ZnO nanopowder annealed at 600°C	359
ZnO nanopowder annealed at 700°C	418

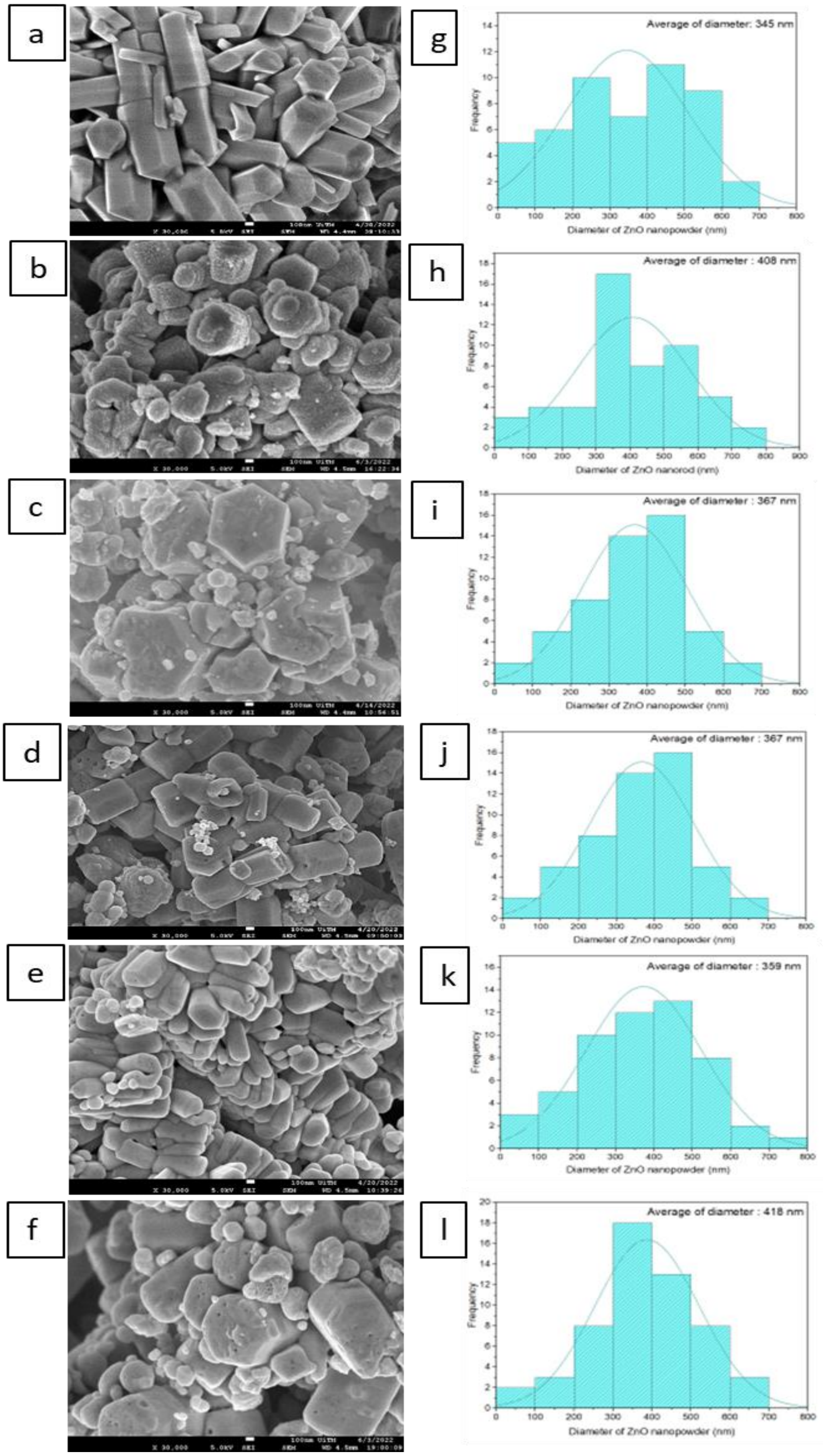

Fig. 1. FESEM images of the (a) as-deposited ZnO nanopowder and ZnO nanopowders at different annealing temperatures (b) 300°C, (c) 400°C, (d) 500°C, (e) 600°C, and (f) 700°C. Particle size distributions of the (g) as-deposited ZnO nanopowder and ZnO nanopowders at different annealing temperatures (h) 300°C, (i) 40 °C, (j) 500°C, (k) 600°C, and (l) 700°C

3.2 Structural Properties

The X-ray diffractograms and crystalline orientation of the as-deposited and thermally annealed ZnO nanopowders are shown in Figure 3. The diffraction peaks of all ZnO nanopowders match well with those of the JCPDS card no. 075-1526, indicating that the ZnO nanopowders have a polycrystalline, hexagonal wurtzite structure. For each sample, three significant ZnO diffraction peaks correspond to the (100), (002), and (101) planes were observed. The (102), (110), (103), (200), (112), (201), (004), and (202) planes correspond to the remaining diffraction peaks. The other diffraction peaks correspond to the (102), (110), (103), (200), (112), (201), (004), and (202) planes. There are no diffraction peaks of noticeable impurities in Figure 3, indicating the high purity of ZnO nanopowders synthesized by the solution immersion method. All the ZnO nanopowders have the same structure, with almost no impurities. The as-deposited ZnO nanopowder has weak diffraction peaks, indicating poor crystalline quality. It is evident that the diffraction peak intensities of the as-deposited ZnO nanopowder increase with the annealing temperature treatment. With an increase in temperature, the high intensity of the diffraction peak suggests an increase in the crystallinity of the ZnO nanopowder [40]. The good crystallinity of the produced ZnO nanopowders is indicated by the strong diffraction peaks.

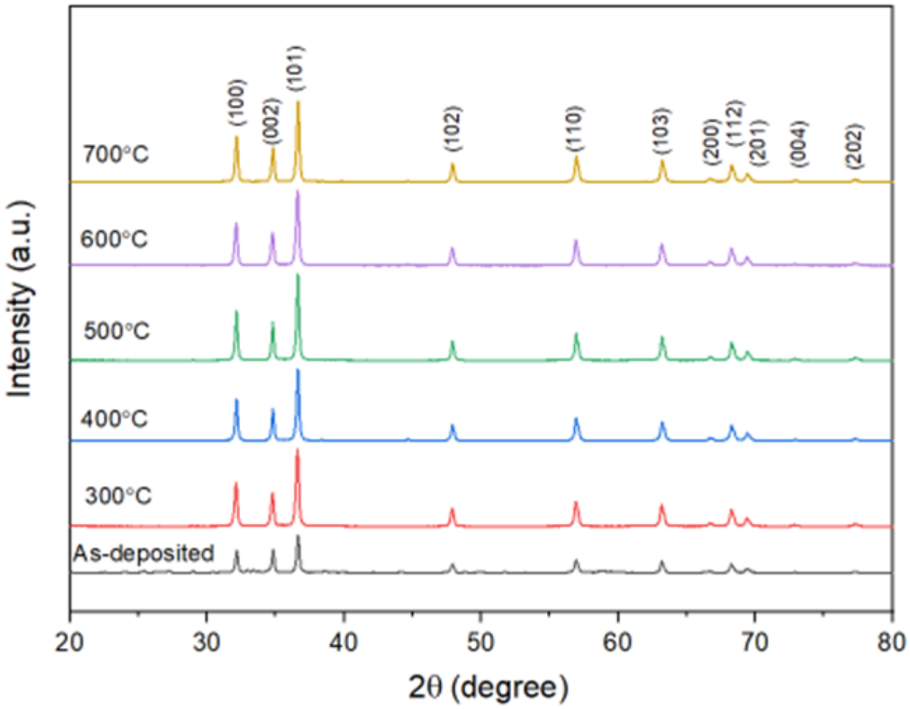

Fig. 3. X-ray diffractograms of the synthesized ZnO nanopowders annealed at various temperatures

3.3 Performance of the ZnO Based Triboelectric Nanogenerators

After examining the surface morphologies and structural characteristics of both as-deposited ZnO nanopowder and ZnO nanopowders annealed at 300°C, 400°C, 500°C, 600°C, and 700°C, ZnO based triboelectric nanogenerators were fabricated with these nanopowders and their performance was investigated. Figure 4(a)-(e) show the output voltage values of the ZnO based triboelectric nanogenerators. In general, the ZnO based triboelectric nanogenerators fabricated with thermally annealed ZnO nanopowders have a higher average output voltage compared with the ZnO triboelectric nanogenerator fabricated with as-deposited ZnO nanopowder, as shown in Table 2. It can be indicated that thermal annealing enhances the output voltage of the ZnO based tribolelectric nanogenerators, where the ZnO layer was synthesized by the solution immersion method.

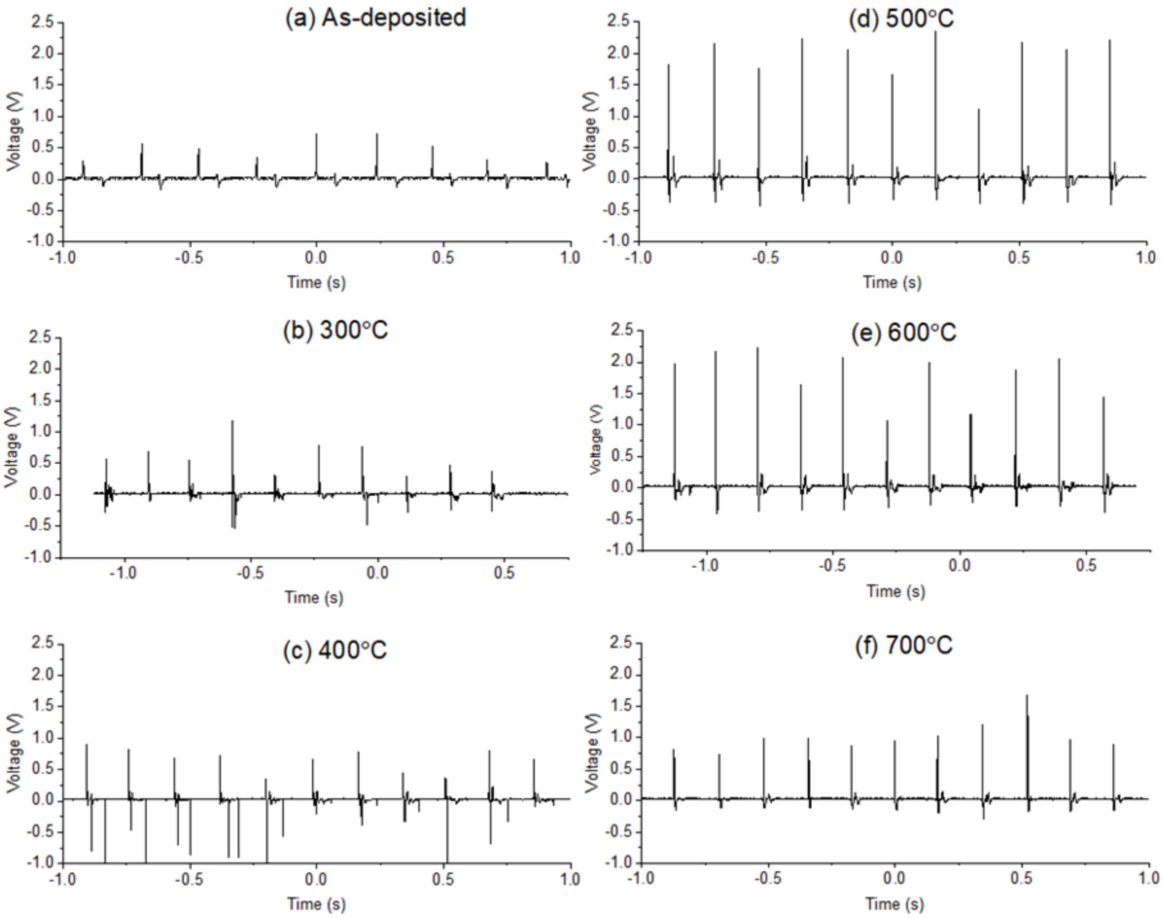

Fig. 4. Output voltage values of the ZnO based triboelectric nanogenerators fabricated with (a) as-deposited ZnO nanopowder and ZnO nanopowders at different annealing temperatures (b) 300°C, (c) 400°C, (d) 500°C, (e) 600°C, and (f) 700°C

Table 2
Average output voltage of the ZnO based triboelectric nanogenerators fabricated with different ZnO nanopowders

Samples	Average output voltage (V)
As-deposited ZnO nanopowder	0.47
ZnO nanopowder annealed at 300°C	0.59
ZnO nanopowder annealed at 400°C	0.61
ZnO nanopowder annealed at 500°C	1.95
ZnO nanopowder annealed at 600°C	1.71
ZnO nanopowder annealed at 700°C	0.99

Figure 4(a) shows that the average output voltage is 0.47 V for the ZnO based triboelectric nanogenerator fabricated with as-deposited ZnO nanopowder. Interestingly, increasing the thermal annealing temperature from 300°C to 500°C increases the average output voltage of the device to 1.95 V, which is roughly a fourfold increase over the average output voltage of the ZnO based triboelectric nanogenerator fabricated with as-deposited ZnO nanopowder. The ZnO based triboelectric nanogenerator fabricated with ZnO nanopowder annealed at 500°C shows superior performance compared with the other ZnO based triboelectric nanogenerators. This is possibly due to the enhanced surface charge associated with the small particle size and good crystallinity produced by thermal annealing [48]. The reduction in the average output voltage of the device as the thermal annealing temperature is raised to 700°C may be due to agglomeration of the ZnO nanopowder. The results indicate that the ZnO has adequate annealing energy at an annealing temperature of 500°C, resulting in the superior performance of the ZnO based triboelectric nanogenerator.

4. Conclusions

ZnO nanopowders were successfully synthesized by the solution immersion technique, which is an easy, cheap, and effective synthesis route. The surface morphologies and structural characteristics of the ZnO nanopowders were examined in relation to the impact of annealing temperature. The ZnO nanopowders are formed of ZnO nanoparticles and hexagonal nanorods, according to the FESEM images. The annealing temperature has been found to significantly impact the microstructure of ZnO. The X-ray diffractograms confirmed the presence of ZnO nanoparticles. It is found that thermal annealing produces the ZnO nanopowders with high crystallinity. ZnO based triboelectric nanogenerators were fabricated with the synthesized nanopowders, and it is found that the annealed ZnO nanogenerator have a higher output voltage than as-deposited ZnO nanogenerator. The ZnO based triboelectric nanogenerator fabricated with ZnO nanopowder annealed at 500°C shows superior performance compared with the other ZnO based triboelectric nanogenerators, with an average output voltage of 1.95 V. Thus, it can be concluded that the surface morphologies and structural characteristics of ZnO nanopowders are vital factors in determining the performance of ZnO-based triboelectric nanogenerators. The findings of this work provide insight into how annealing temperature affects the synthesized ZnO nanopowders, which in turn affects the performance of ZnO based triboelectric nanogenerators.

Acknowledgement

The authors acknowledge the Office of Deputy Vice Chancellor (Research and Innovation) UiTM Shah Alam (project no.: 600-RMC/KEPU 5/3(018/2021)) and UiTM Cawangan Terengganu (project no.: 600-TNCPI5/3/DDN (11)(001/2021)) for research funding.

References

[1] Raj, Abhi, and Dan Steingart. "Power sources for the internet of things." *Journal of the Electrochemical Society* 165, no. 8 (2018): B3130. https://doi.org/10.1149/2.0181808jes

[2] Richelli, Anna, Mohamed Salem, and Luigi Colalongo. "A Review of Fully Integrated and Embedded Power Converters for IoT." *Energies* 14, no. 17 (2021): 5419. https://doi.org/10.3390/en14175419

[3] Rasool, Asif, Santhosh Kumar, M. H. Mamat, C. Gopalakrishnan, and R. Amiruddin. "Analysis on different detection mechanisms involved in ZnO-based photodetector and photodiodes." *Journal of Materials Science: Materials in Electronics* 31, no. 9 (2020): 7100-7113. https://doi.org/10.1007/s10854-020-03280-3

[4] Fazli, F. I. M., M. K. Ahmad, C. F. Soon, N. Nafarizal, A. B. Suriani, A. Mohamed, M. H. Mamat, M. F. Malek, M. Shimomura, and K. Murakami. "Dye-sensitized solar Cell using pure anatase TiO_2 annealed at different temperatures." *Optik* 140 (2017): 1063-1068. https://doi.org/10.1016/j.ijleo.2017.04.027

[5] Yoon, Chongsei, Swathi Ippili, Venkatraju Jella, Alphi Maria Thomas, Jang-Su Jung, Yire Han, Tae-Youl Yang, Soon-Gil Yoon, and Giwan Yoon. "Synergistic contribution of flexoelectricity and piezoelectricity towards a stretchable robust nanogenerator for wearable electronics." *Nano Energy* 91 (2022): 106691. https://doi.org/10.1016/j.nanoen.2021.106691

[6] Mamat, M. H., N. Parimon, A. S. Ismail, IB Shameem Banu, S. Sathik Basha, R. A. Rani, A. S. Zoolfakar et al. "Synthesis, structural and optical properties of mesostructured, X-doped NiO (x= Zn, Sn, Fe) nanoflake network films." *Materials Research Bulletin* 127 (2020): 110860. https://doi.org/10.1016/j.materresbull.2020.110860

[7] Thauer, E., G. S. Zakharova, E. I. Andreikov, V. Adam, S. A. Wegener, J-H. Nölke, L. Singer et al. "Novel synthesis and electrochemical investigations of ZnO/C composites for lithium-ion batteries." *Journal of Materials Science* 56, no. 23 (2021): 13227-13242. https://doi.org/10.1007/s10853-021-06125-4

[8] Yusoff, M. M., M. H. Mamat, M. F. Malek, A. B. Suriani, A. Mohamed, M. K. Ahmad, Salman AH Alrokayan, Haseeb A. Khan, and M. Rusop. "Growth of titanium dioxide nanorod arrays through the aqueous chemical route under a novel and facile low-cost method." *Materials Letters* 164 (2016): 294-298. https://doi.org/10.1016/j.matlet.2015.11.014

[9] Xiao, Yun, Haibin Wang, Fumiyasu Awai, Naoyuki Shibayama, Takaya Kubo, and Hiroshi Segawa. "Emission Spectroscopy Investigation of the Enhancement of Carrier Collection Efficiency in AgBiS2-Nanocrystal/ZnO-Nanowire Heterojunction Solar Cells." *ACS Applied Materials & Interfaces* 14, no. 5 (2022): 6994-7003. https://doi.org/10.1021/acsami.1c21762

[10] Ahmad, Mansoor, M. K. Ahmad, N. Nafarizal, C. F. Soon, N. M. A. N. Ismail, A. B. Suriani, A. Mohamed, and M. H. Mamat. "Effects of As, P and Sb on the output voltage generation of ZnO nanowires based nanogenerator: Mitigation of screening effect by using surface modified ZnO nanowires." *Vacuum* 202 (2022): 111130. https://doi.org/10.1016/j.vacuum.2022.111130

[11] Hamed, N. K. A., M. K. Ahmad, N. H. H. Hairom, A. B. Faridah, M. H. Mamat, A. Mohamed, A. B. Suriani et al. "Dependence of photocatalysis on electron trapping in Ag-doped flowerlike rutile-phase TiO_2 film by facile hydrothermal method." *Applied Surface Science* 534 (2020): 147571. https://doi.org/10.1016/j.apsusc.2020.147571

[12] Ding, Zhuyu, Ming Zou, Peng Yao, and Li Fan. "A triboelectric nanogenerator for mechanical energy harvesting and as self-powered pressure sensor." *Microelectronic Engineering* 257 (2022): 111725. https://doi.org/10.1016/j.mee.2022.111725

[13] Venu Gopal, V. R., and Susmita Kamila. "Effect of temperature on the morphology of ZnO nanoparticles: a comparative study." *Applied Nanoscience* 7, no. 3 (2017): 75-82. https://doi.org/10.1007/s13204-017-0553-3

[14] Batra, Kriti, Nidhi Sinha, and Binay Kumar. "Ba-doped ZnO nanorods: Efficient piezoelectric filler material for PDMS based flexible nanogenerator." *Vacuum* 191 (2021): 110385. https://doi.org/10.1016/j.vacuum.2021.110385

[15] Niu, Xushi, Wei Jia, Shuo Qian, Jie Zhu, Jing Zhang, Xiaojuan Hou, Jiliang Mu et al. "High-performance PZT-based stretchable piezoelectric nanogenerator." *ACS Sustainable Chemistry & Engineering* 7, no. 1 (2018): 979-985. https://doi.org/10.1021/acssuschemeng.8b04627

[16] Zhang, Renyun, and Håkan Olin. "Material choices for triboelectric nanogenerators: a critical review." *EcoMat* 2, no. 4 (2020): e12062. https://doi.org/10.1002/eom2.12062

[17] Zhou, Yihao, Weili Deng, Jing Xu, and Jun Chen. "Engineering materials at the nanoscale for triboelectric nanogenerators." *Cell Reports Physical Science* 1, no. 8 (2020): 100142. https://doi.org/10.1016/j.xcrp.2020.100142

[18] Nordin, Nur Fatihah, Kee Quen Lee, Hooi Siang Kang, and Nor' Azizi Othman. "Energy Harvesting of Daily Human Life Activities using a Self-Made Piezoelectric System." *Progress in Energy and Environment* 10 (2019): 1-5.

[19] Ismail, A. S., M. H. Mamat, M. M. Yusoff, M. F. Malek, A. S. Zoolfakar, R. A. Rani, A. B. Suriani, A. Mohamed, M. K. Ahmad, and M. Rusop. "Enhanced humidity sensing performance using Sn-Doped ZnO nanorod Array/SnO_2 nanowire heteronetwork fabricated via two-step solution immersion." *Materials Letters* 210 (2018): 258-262. https://doi.org/10.1016/j.matlet.2017.09.040

[20] Mamat, M. H., N. N. Hafizah, and M. Rusop. "Fabrication of thin, dense and small-diameter zinc oxide nanorod array-based ultraviolet photoconductive sensors with high sensitivity by catalyst-free radio frequency magnetron sputtering." *Materials Letters* 93 (2013): 215-218. https://doi.org/10.1016/j.matlet.2012.11.105

[21] Goktas, Abdullah, Sait Modanlı, Ahmet Tumbul, and Ahmet Kilic. "Facile synthesis and characterization of ZnO, ZnO: Co, and ZnO/ZnO: Co nano rod-like homojunction thin films: Role of crystallite/grain size and microstrain in photocatalytic performance." *Journal of Alloys and Compounds* 893 (2022): 162334. https://doi.org/10.1016/j.jallcom.2021.162334

[22] Karthik, K. V., A. V. Raghu, Kakarla Raghava Reddy, R. Ravishankar, M. Sangeeta, Nagaraj P. Shetti, and Ch Venkata Reddy. "Green synthesis of Cu-doped ZnO nanoparticles and its application for the photocatalytic degradation of hazardous organic pollutants." *Chemosphere* 287 (2022): 132081. https://doi.org/10.1016/j.chemosphere.2021.132081

[23] Ismail, A. S., M. H. Mamat, ND Md Sin, M. F. Malek, A. S. Zoolfakar, A. B. Suriani, A. Mohamed, M. K. Ahmad, and M. Rusop. "Fabrication of hierarchical Sn-doped ZnO nanorod arrays through sonicated sol– gel immersion for room

temperature, resistive-type humidity sensor applications." *Ceramics International* 42, no. 8 (2016): 9785-9795. https://doi.org/10.1016/j.ceramint.2016.03.071

[24] Yoo, Kangeun, Wonseok Lee, Kyungnam Kang, Inhwan Kim, Daehun Kang, Dong Kyo Oh, Min Cheol Kim et al. "Low-temperature large-area fabrication of ZnO nanowires on flexible plastic substrates by solution-processible metal-seeded hydrothermal growth." *Nano Convergence* 7, no. 1 (2020): 1-10. https://doi.org/10.1186/s40580-020-00235-6

[25] Sahrudin, Intan Norshalina, Mohd Sharizal Abdul Aziz, Mohd Zulkifly Abdullah, and Mohd Arif Anuar Mohd Salleh. "Study on the addition of nanoparticles in the lead-free solder during reflow soldering via numerical simulation-a review." *CFD Letters* 12, no. 5 (2020): 111-119. https://doi.org/10.37934/cfdl.12.5.111119

[26] Kean, Tung Hao, and Nor Azwadi Che Sidik. "Thermal performance analysis of nanoparticles enhanced phase change material (NEPCM) in cold thermal energy storage (CTES)." *CFD Letters* 11, no. 4 (2019): 79-91.

[27] Walden, Ryan, Irthasa Aazem, Aswathy Babu, and Suresh C. Pillai. "Textile-Triboelectric nanogenerators (T-TENGs) for wearable energy harvesting devices." *Chemical Engineering Journal* 451 (2022): 138741. https://doi.org/10.1016/j.cej.2022.138741

[28] Ahmed, Waqar, Nor Azwadi Che Sidik, and Yutaka Asako. "Metal Oxide and Ethylene Glycol Based Well Stable Nanofluids for Mass Flow in Closed Conduit." *Journal of Advanced Research in Micro and Nano Engineering* 6, no. 1 (2021): 1-15.

[29] Mohammed, H. A., O. A. Alawi, and N. A. Che Sidik. "Mixed convective nanofluids flow in a channel having forward-facing step with baffle." *Journal of Advanced Research in Applied Mechanics* 24, no. 1 (2016): 1-21.

[30] Hamrayev, Hemra, Kamyar Shameli, and Mostafa Yusefi. "Preparation of zinc oxide nanoparticles and its cancer treatment effects: A review paper." *Journal of Advanced Research in Micro and Nano Engineering* 2, no. 1 (2020): 1-11.

[31] Narin, Polat, Ece Kutlu-Narin, Senem Kayral, Remziye Tulek, Sibel Gokden, Ali Teke, and Sefer Bora Lisesivdin. "Morphological and optical characterizations of different ZnO nanostructures grown by mist-CVD." *Journal of Luminescence* 251 (2022): 119158. https://doi.org/10.1016/j.jlumin.2022.119158

[32] Subki, A. S. R. A., Mohamad Hafiz bin Mamat, M. Z. Musa, M. H. Abdullah, Shameen Banu IB, N. Vasimalai, M. K. Ahmad et al. "Effects of Varying the Amount of Reduced Graphene Oxide Loading on the Humidity Sensing Performance of Zinc Oxide/Reduced Graphene Oxide Nanocomposites on Cellulose Filter Paper." *Journal of Alloys and Compounds* 926 (2022): 166728. https://doi.org/10.1016/j.jallcom.2022.166728

[33] Ahmadpour, Gholamreza, Mohammad Reza Nilforoushan, Behrooz Shayegh Boroujeny, Morteza Tayebi, and Seyed Mohammad Jesmani. "Effect of substrate surface treatment on the hydrothermal synthesis of zinc oxide nanostructures." *Ceramics International* 48, no. 2 (2022): 2323-2329. https://doi.org/10.1016/j.ceramint.2021.10.011

[34] Mamat, M. H., M. F. Malek, N. N. Hafizah, M. N. Asiah, A. B. Suriani, A. Mohamed, N. Nafarizal, M. K. Ahmad, and M. Rusop. "Effect of oxygen flow rate on the ultraviolet sensing properties of zinc oxide nanocolumn arrays grown by radio frequency magnetron sputtering." *Ceramics International* 42, no. 3 (2016): 4107-4119. https://doi.org/10.1016/j.ceramint.2015.11.083

[35] Singh, Jai, and Amit Srivastava. "Morphological evolution and its correlation with optical and field emission properties in pulsed laser deposited ZnO nanostructures." *Materials Science in Semiconductor Processing* 138 (2022): 106282. https://doi.org/10.1016/j.mssp.2021.106282

[36] Mamat, M. H., A. S. Ismail, N. Parimon, N. Vasimalai, M. H. Abdullah, M. F. Malek, M. K. Yaakob et al. "Heterojunction of SnO_2 nanosheet/arrayed ZnO nanorods for humidity sensing." *Materials Chemistry and Physics* 288 (2022): 126436. https://doi.org/10.1016/j.matchemphys.2022.126436

[37] Khudiar, Shahad S., Uday M. Nayef, Falah A-H. Mutlak, and Sarah K. Abdulridha. "Characterization of NO_2 gas sensing for ZnO nanostructure grown hydrothermally on porous silicon." *Optik* 249 (2022): 168300. https://doi.org/10.1016/j.ijleo.2021.168300

[38] Morales, Carlos, Dietmar Leinen, Adolfo del Campo, José Ramón Ares, Carlos Sánchez, Jan Ingo Flege, Alejandro Gutiérrez, Pilar Prieto, and Leonardo Soriano. "Growth and characterization of ZnO thin films at low temperatures: From room temperature to− 120 °C." *Journal of Alloys and Compounds* 884 (2021): 161056. https://doi.org/10.1016/j.jallcom.2021.161056

[39] Shaba, Elijah Yanda, John Olusanya Jacob, Jimoh Oladejo Tijani, and Mohammed Abubakar Tanko Suleiman. "A critical review of synthesis parameters affecting the properties of zinc oxide nanoparticle and its application in wastewater treatment." *Applied Water Science* 11, no. 2 (2021): 1-41. https://doi.org/10.1007/s13201-021-01370-z

[40] Kumar, Nitin, Bhawana Joshi, and K. Asokan. "The effects of thermal annealing on the structural and electrical properties of zinc tin oxide thin films for transparent conducting electrode applications." *Physica B: Condensed Matter* 558 (2019): 5-9. https://doi.org/10.1016/j.physb.2019.01.016

[41] Akhir, Rabiatuladawiyah Md, Wan Marhaini Wan Harrum, Irmaizatussyehdany Buniyamin, M. Rusop, and Zuraida Khusaimi. "Enhanced structural and morphological properties of ZnO nanorods using plant extract-assisted solution immersion method." *Materials Today: Proceedings* 48 (2022): 1855-1860. https://doi.org/10.1016/j.matpr.2021.09.205

[42] Mamat, Mohamad Hafiz, Mohd Izzudin Che Khalin, Nik Noor Hafizah Nik Mohammad, Zuraida Khusaimi, Nor Diyana Md Sin, Shafinaz Sobihana Shariffudin, Musa Mohamed Zahidi, and Mohamad Rusop Mahmood. "Effects of annealing environments on the solution-grown, aligned aluminium-doped zinc oxide nanorod-array-based ultraviolet photoconductive sensor." *Journal of Nanomaterials* 2012 (2012): 189279. https://doi.org/10.1155/2012/189279

[43] Malek, M. F., M. H. Mamat, M. Z. Musa, Z. Khusaimi, M. Z. Sahdan, A. B. Suriani, A. Ishak, I. Saurdi, S. A. Rahman, and M. Rusop. "Thermal annealing-induced formation of ZnO nanoparticles: Minimum strain and stress ameliorate preferred c-axis orientation and crystal-growth properties." *Journal of Alloys and Compounds* 610 (2014): 575-588. https://doi.org/10.1016/j.jallcom.2014.05.036

[44] Sahdan, M. Zainizan, M. Hafiz Mamat, M. Salina, Zuraida Khusaimi, Uzer M. Noor, and Mohamad Rusop. "Heat treatment effects on the surface morphology and optical properties of ZnO nanostructures." *Physica Status Solidi C* 7, no. 9 (2010): 2286-2289. https://doi.org/10.1002/pssc.200983722

[45] Kim, Dong Wook, Ju Hyun Lee, Jin Kon Kim, and Unyong Jeong. "Material aspects of triboelectric energy generation and sensors." *NPG Asia Materials* 12, no. 1 (2020): 1-17. https://doi.org/10.1038/s41427-019-0176-0

[46] Lyu, Yang, and Yi Wang. "Output Optimization of Biodegradable Triboelectric Nanogenerators." *Nano Energy* (2022): 107811. https://doi.org/10.1016/j.nanoen.2022.107811

[47] Eswar, K. A., J. Rouhi, H. F. Husairi, M. Rusop, and S. Abdullah. "Annealing heat treatment of ZnO nanoparticles grown on porous Si substrate using spin-coating method." *Advances in Materials Science and Engineering* 2014 (2014). https://doi.org/10.1155/2014/796759

[48] Lu, Cun Xin, Chang Bao Han, Guang Qin Gu, Jian Chen, Zhi Wei Yang, Tao Jiang, Chuan He, and Zhong Lin Wang. "Temperature effect on performance of triboelectric nanogenerator." *Advanced Engineering Materials* 19, no. 12 (2017): 1700275. https://doi.org/10.1002/adem.201700275