Hydrothermal growth optimization of vertically aligned ZnO nanowire arrays and their dye-sensitized solar cell performance under air/oxygen environments

Mahmoud Hezam, Ahmad Algarni, Hamid Ghaithan, Husain Alzahrani, Aqeel Alshehri, Abdulaziz Alfarhoud, Joselito Labis and Mohammad Alduraibi

1 King Abdullah Institute for Nanotechnology, King Saud University, Riyadh 11451, Saudi Arabia
2 Physics and Astronomy Department, College of Science, King Saud University, Riyadh 11451, Saudi Arabia
3 National Center for Nanotechnology and Semiconductors, King Abdulaziz City for Science and Technology (KACST), Riyadh 11421, Saudi Arabia

E-mail: mhezam@ksu.edu.sa and malduraibi@ksu.edu.sa

Keywords: Zinc Oxide, ZnO, nanowire array, hydrothermal, dye-sensitized solar cells, DSSCs

Abstract

In this work, the hydrothermal growth parameters of vertically aligned ZnO nanowire arrays on FTO substrates were optimized for best surface coverage and minimal stacking and entanglement between nanowires for dye-sensitized solar cell (DSSC) application. The concentration of seed layer solution was found to be essential in reducing the stacking effect of adjacent nanowires. The growth temperature study has revealed a remarkable existence of a temperature window in the range 90 °C–110 °C, beyond which the nanowire lengths start to decline. We attributed the nanowire length regression above 110 °C to the enhanced homogeneous nucleations in the growth solution. Nanowire entanglement started to be observable at ~100 °C for a growth duration of 2 h. DSSCs were fabricated using the grown ZnO nanowire arrays that are post-annealed under air and pure oxygen gas environments. Oxygen post-annealing resulted in a remarkable decrease in the open circuit voltage (VOC), which we attributed to the large impact of band bending.

1. Introduction

Zinc oxide (ZnO) is wide bandgap semiconductor (Eg = 3.4 eV) with excellent structural and optoelectronic properties, hence a promising material for a wide range of applications [1–4]. The wurtzite-type structure of ZnO exhibits a unique piezoelectric behavior, which find various applications, such as in surface acoustic wave (SAW) devices [5]. The high exciton binding energy (~60 meV) makes it favorable for UV optoelectronic applications (e.g., Light Emitting Diodes (LEDs) [6] and UV detectors [7]). On the other hand, the high electron mobility and the ability to achieve metal-like conductivities (by metallic doping), while preserving the visible light transparency, place ZnO as one of the well-known transparent conducting oxides [8]. Nanostructuring of ZnO has been explored to further provide new functionalities and charge transport enhancements in different solar cells technologies [9–12]. In DSSCs, vertically aligned ZnO nanowire arrays have been investigated and utilized as a mesoporous transport layer. This is because, first, they provide the large surface area necessary for efficient dye-loading. Secondly, they provide direct transport paths for photo-injected electrons into the FTO substrate, which, therefore, enhances the electron transport process. These advantages, in addition to the high electron mobility of ZnO (which is ~10 times higher than that of TiO2, which is traditionally used in DSSCs) makes vertically aligned ZnO nanowire arrays a promising material system to be explored as a transport layer in DSSCs [11, 12].

ZnO nanowire arrays can be prepared by several physical and chemical methods, such as, Chemical Vapor Deposition (CVD) [13], Metal-Organic CVD (MOCVD) [14], Pulsed Laser Deposition (PLD) [15],...
electrochemical deposition [16], and hydrothermal growth [17–20]. Among these methods, hydrothermal growth offers a low temperature, highly scalable and low-cost method, with the ability to grow nanostructures on various substrates including flexible substrates [17–21]. Hence, this method has been widely adopted for DSSC fabrication [11, 12, 22–27].

Post-annealing of ZnO nanowires can additionally result in the improved performance of DSSCs. For hydrothermally grown nanostructures, in general, post-annealing result in ‘burning’ of organic residuals brought upon during the nanowire growth, thus allowing more surface area to be available for dye-loading [28]. In addition, annealing can efficiently suppress defect traps that can form during the nanocrystal growth, thus resulting in better charge transport [29]. Post-annealing has been reported to provide a positive effect, in general. Although post-annealing at ∼ 300 °C–400 °C has been reported to enhance device efficiency [28, 29], increasing the annealing temperature to higher than 400 °C can, however, result in reduced light harvesting efficiencies [28]. In this regard, the effect of the annealing gas environment on DSSC performance has been less studied in the literature. Further exploration in this area would therefore elucidate this issue, as most studies were based on air annealing [22–27].

In this work, we study the effect of air/O2 post-annealing of vertically aligned ZnO nanowire arrays on the Power Conversion Efficiency (PCE) performance of DSSCs. For this purpose, we first performed a thorough optimization of different nanowire growth parameters. More importantly, since entanglement between vertically aligned ZnO nanowires starts to dominate with increasing the nanowire lengths, we have reduced the nanowire length to ∼ 400 nm. The optimized grown nanowire array films have exhibited uniform coverage with non-entangled adjacent nanowires. This property is deemed important in ensuring uniform dye-loading with non-entangled adjacent nanowires. This property is deemed important in ensuring uniform dye-loading among samples, as this would allow a fair and objective comparison among them. Remarkably, in spite of the short nanowire lengths considered in this study, our DSSC devices still exhibit excellent PCEs as compared to other devices reported in the literature.

2. Experimental procedure

2.1. Growth of ZnO Nanowire arrays

In the growth of ZnO nanowire arrays, we followed the Green et al method [18], that is widely adopted in the literature. Briefly, zinc acetate is dissolved in ethanol, and the precursor solution is simply drop-casted on an FTO slide. The film thickness, as well as the coverage, can be adequately controlled by increasing the precursor concentration and/or by drop-casting multiple drops. To compare the results, we have chosen four consecutive drops as a basis for the minimum thickness under a specified concentration, which we call a cycle. The zinc acetate precursor concentration was first varied over a molar range between 2.5 to 100 mM using one cycle (i.e., 4 drops) for each concentration. The seed layer is, then, heated at 350 °C for 30 min. This heating step is necessary to prevent the seed layer from dissolving into the growth solution [18], and to promote better vertical alignment of the grown nanowires [30]. The nanowire growth was then performed inside the 25 mM aqueous growth solution having 1:1 zinc nitrate/HMTA molar ratio at 90 °C for two hours. A Teflon cell was especially designed for this purpose, in which the FTO slide can be placed upside down, facing the growth solution inside an autoclavable laboratory glass bottle. Based on the resulting morphologies, a seed layer precursor of 10 mM was, thereafter, chosen to study the effect of number of cycles (i.e., 1, 2, 3 and 4 cycles) on the nanowire growth. The optimum growth conditions (namely, seed layer: 10 mM, 2 cycles, growth solution: 25 mM for both zinc nitrate dehydrate and HMTA, 2 h) were then fixed and the growth temperature was varied from 70 to 130 °C.

2.2. Materials characterization

The morphologies of the nanowire samples were investigated using the JEOL 7600 Field Emission Scanning Electron Microscope (FE-SEM, Japan), while it crystallinity was studied using the PANalytical MPD x-Ray Diffractometer (XRD, the Netherland) using Cu Kα x-ray anode (λ = 1.54 Å). The morphological dimensions of the grown nanowires (i.e., diameter and length) were analyzed from the FE-SEM images using ImageJ software, where ∼ 30 nanowire images were used for each measurement.

2.3. DSSC fabrication and characterization

Several samples that were grown at 90 °C were then prepared and post-annealed under different annealing environments for DSSC device application. The fabricated ZnO nanowire array electrodes were first immersed in the dye solution (0.5 mM N719 dye solution in ethanol) for one hour. The Pt counter electrode was prepared by drop-casting 10 mM ethanol solution of H2PtCl6·6H2O, and then heating at 400 °C for 30 min. The two electrodes were then fixed face-to-face and the electrolyte (Dyesol HPLSE) was then introduced between the two electrodes by capillary action, with a thin insulating polymeric spacer placed between the two electrodes. A
simplified schematic for the resulting layout of the final DSSC device is shown in figure S1 (available online at stacks.iop.org/MRX/8/105501/mmedia) (Supplementary Information).

The I-V characteristics were measured using Zahner IM6 electrochemical workstation with a third party AM1.5G solar simulator (Lot-Oriel LS0106 Solar Simulator, ABA class). THALES software was used for the analysis of I-V curves. The area of each ZnO nanowire array electrode was estimated in order to correctly calculate the short circuit current density ($J_{sc}$). The post-annealing of grown ZnO nanowire array films were performed at 400 °C for 30 min under both air and oxygen environments. The post-annealing in air was performed using a programmable hotplate, whereas the post-annealing in oxygen environment was performed using a vacuum furnace (with base pressure maintained at $\sim 10^{-2}$ Pa) attached with a high-purity oxygen (99.999%) cylinder.

3. Results

3.1. Optimization of growth parameters

3.1.1. Concentration of seed layer solution

Figure 1 shows the SEM micrograph for the nanowires grown on seed layers with different zinc acetate concentrations. Lower magnification images are shown in figure S2 (Supplementary Information) to elucidate about the surface coverage. At 2.5 mM concentration, the nanowires have resulted to relatively thicker diameters compared to the other higher concentration samples, and are shown to grow adjacent and stacked to each other. This could possibly be explained by greater grain sizes of the seed layer at this concentration, hence thicker nanowires were grown. At 5 mM, the nanowire diameter has slightly decreased with the nanowires still stacking substantially. The smallest nanowires (in terms of its diameter) were achieved at 10 mM concentration along with good homogeneity of surface coverage, however at the expense of less areal density of the nanowires. At 25 mM concentration, the areal density has remarkably increased. At higher concentrations of 50 mM and 100 mM, the nanowire density, however, steeply declined, which remains to be clarified.

3.1.2. Number of cycles

Due to excellent surface coverage of the 10 mM concentration of the seed layer, and its small nanowire diameters, different number of cycles were, then, deposited using this concentration. The results are shown in

![Figure 1. Top-view SEM micrographs of vertically grown nanowires using zinc acetate seed layer solution of concentrations (a) 2.5 mM, (b) 5 mM, (c) 10 mM, (d) 25 mM, (e) 50 mM, and (f) 100 mM. The seed layer was deposited by drop-casting 4 consecutive drops (1 cycle) followed by heating at 350 °C. The nanowire growth was performed using 25 mM nitrate/HMTA concentration at 90 °C for 2 h. All scale bars correspond to 1 μm length.](image-url)
Interestingly, the 2-cycle growth yields a good surface coverage over the seed layer, while still preserving the non-stacking growth of the nanowires. Although, the 3-cycle growth has resulted in an even better surface coverage, however, some areas have bundled nanowires and they were stacked with each other. This can be attributed to higher morphological local variations of the seed layer film at 3 cycles, thus resulting in such nanowire bundles. At 4 cycles, the density of the nanowires was reduced. Actual observation at the seed layer areas below the nanowires reveals agglomerated grains. These agglomerated grains could have resulted from the increased quantity of the nanowires. It is also possible that the lateral growth of the seed layer grains is more efficient at 4-cycle growth, which might have resulted in less density of vertically grown nanowires.

For the device performance, as far as this study and grown methods used are concerned, the 2-cycle growth of 10 mM seeding solution has resulted in the optimized nanowire growth conditions that ensure excellent surface coverage, high areal density, and thin non-entangled and nono-stacking nanowires. Fulfilling all these conditions is vital in providing sufficient room for homogeneous dye-loading first, and to allow direct electron transport through single nanowires without other complications due to entangled or stacked nanowires. Moreover, it allows uniform light illumination on the grown nanowires when testing the device, especially with the shorter nanowire length.

3.1.3. Growth temperature

Figure 3 shows the top-view SEM images of the nanowires grown at different growth temperatures. Below 80 °C, no growth was observable during the 2 h growth duration. As the growth temperature increases, the growth kinetics are expected to be enhanced, resulting, as reported by many groups in the literature [23, 31–33], in faster growth rates in both lateral and vertical growth directions. Increasing the growth temperature has resulted in thicker and longer nanowires. Notably, after 110 °C (see figure 4), the growth along both directions has declined when the temperature is further increased. As most related literature usually reports growth temperature studies up to 100 °C only, probably driven by the boiling point of water, to the extent of our knowledge and to this date, there is no report on hydrothermal growth temperatures beyond 100 °C for vertically grown ZnO nanowires. A related result was, however, observed by Wijeratne et al who prepared ZnO nanowire powders using thermal alcoholysis of zinc acetylacetonate solutions with the growth declining with increasing growth temperature [34]. We explain this growth decline by the increased homogenous nucleation/growth events inside the growth solution are also taking place along with the additionally enhanced heterogeneous growth at the ZnO seed layer. These nucleation/growth events could have contributed to the consumption of the precursor ions in the solution, which will ultimately reduce the growth rate along both vertical and lateral directions.
Additionally, as can be seen in figure 3, the entanglement of adjacent nanowires starts to be observable at 100 °C, and it noticeably increases with increasing growth temperature. Together with other optimized parameters, the growth temperature at 90 °C, which gives a film thickness of ~ 400 nm was, therefore, chosen for the solar cell devices, as it is the highest temperature in this study that ensures excellent surface coverage with optimally thin non-stacking and non-entangled nanowires, and thus allowing both homogeneous dye loading and light illumination. This optimal morphology has also the advantage of offering direct transport channels for dye-injected electrons through single nanowires, with minimal probability for the photo-injected electrons to cross multiple nanowires during transport, thus allowing objective comparison between different samples.

Figure 3. Top-view SEM images of vertically aligned ZnO nanowires grown at different growth temperatures: (a) 80 °C, (b) 90 °C, (c) 100 °C, (d) 110 °C, (e) 120 °C, and (f) 130 °C. All scale bars correspond to 0.5 μm.

Figure 4. Plot of nanowire diameters and nanowire lengths with increasing growth temperature.

Figure 5 shows FE-SEM images of the FTO substrate, the seed layer and a cross-sectional image of the grown nanowires, both under the optimized conditions discussed above. The seed layer, figure 5(b), does not make a continuous layer on the FTO substrate; rather, it consists of small ZnO nanoparticles homogenously distributed over the FTO substrate.
The XRD pattern of the typical ZnO nanowire array electrode fabricated using the above growth parameters, along with XRD patterns of the optimized seed layer are shown in figure 6. As can be seen in the figure, all XRD patterns can be indexed with the ZnO wurtzite hexagonal structure (JCPDS card no. 36–1451). The seed layer showed small (100) and (101) peaks (asterisks are drawn above the peaks for clarity). ZnO usually grows along the [002] direction because of the high surface energy of the (001) facet. The growth along other directions is however not uncommon for ZnO, and many growth conditions can result in this alteration of growth direction, e.g. doping [35, 36], chemical environment [37], and growth temperature [38]. In addition, the possibility of
having (002)-oriented seed nanoparticles of smaller sizes and less quantity cannot be excluded, which would result in a smaller and wider (002) peak that is hard to be detected. We speculate that this is a possible scenario based on the subsequently preferred nanowire growth along the [002] direction, a point that still needs additional investigation. The ZnO nanowires are textured mainly along the [002] direction as can be seen in their XRD pattern. It can be noticed however that other powder diffraction peaks also appeared in the XRD pattern, despite the vertical alignment of the nanowires. This reflects the size of nanowire tilt resulting in such ‘pseudo-vertical’ alignment making the nanowires prone to entanglement if the length is further increased.

3.2. J-V characteristics
DSSC devices were fabricated using the optimized growth conditions obtained in this study. The ZnO nanowire array films were first annealed at 400 °C in the open air and second in a closed oxygen environment as detailed in the experimental part. A non-annealed sample was also studied for comparison. Figure 7 shows the J-V curves for all devices and table 1 presents their extracted J-V characteristics. Although the obtained power conversion efficiencies are relatively low, mainly because of the smaller thickness of the ZnO nanowire film of ∼400 nm, which is ∼30–40 times less compared to a standard DSSC device, however, due to the excellent surface coverage of our sample, our efficiency values are, remarkably excellent compared to other reports using ZnO nanowire films with small thicknesses. Table 2 summarizes the nanowire length/PCE comparison between different hydrothermally grown ZnO nanowire-based DSSCs as reported in the literature. Most notably, when the nanowire film thickness is taken into consideration, our results outperform even those with seed layers deposited using more advanced vacuum techniques, such as Pulsed Laser Deposition (PLD) and RF sputtering [22, 23].

3.3. Effect of annealing conditions on DSSC performance
The effect of the annealing conditions can be observed from figure 7 and table 1. It is worth mentioning that all growth parameters and DSSC fabrication steps were kept the same for all samples. It can be further noticed that annealing has resulted in a significant improvement in short circuit photocurrent density (J_sc), resulting in 67% and 74% enhancement, respectively, under oxygen and air environment. This could be explained by the improved crystalline quality of nanowires after annealing, resulting in less defect traps and recombination centers that usually hinder electron transport in non-annealed samples. The effect of annealing on the open circuit voltage (V_oc) was, however, more complicated. Remarkably, the devices fabricated under oxygen

Table 1. J-V characteristics of ZnO nanowire-based DSSCs with different annealing conditions.

| Annealing Conditions | V_oc (V) | J_sc (μA cm⁻²) | FF | V_max (V) | I_max (μA cm⁻²) | P_max (μW cm⁻²) | Efficiency (%) |
|----------------------|---------|----------------|----|-----------|----------------|----------------|---------------|
| Non-annealed         | 0.464   | 226.0          | 0.404 | 0.296 | 143.1 | 42.31 | 0.04          |
| Oxygen, 400 °C       | 0.418   | 377.4          | 0.434 | 0.269 | 255.06 | 68.58 | 0.07          |
| Air, 400 °C          | 0.552   | 393.9          | 0.453 | 0.363 | 271.68 | 98.58 | 0.10          |

Figure 7. J-V curves of DSSCs prepared using vertically aligned ZnO nanowires with optimized growth parameters under annealing environments: non-annealed (blue dashed line), post-annealed at 400 °C under air (red solid line) and oxygen (red dot-dashed line). The J-V characteristics are extracted in table 1.
environment have reproducibly lower $V_{OC}$ values. The oxygen-annealed device has a $V_{OC}$ of 0.418 V, which is lower than both the non-annealed and air-annealed samples. Annealing under oxygen environment can affect the photovoltaic behavior in two ways. First, oxygen annealing has been reported to improve the electron transport process, as it results in reduced concentration of oxygen vacancies that work as scattering centers against electron mobility. Therefore, oxygen annealing is reported to directly enhance the electron mobility in ZnO nanowires [39]. In our case, the improved electron mobility is reflected in the higher $J_{SC}$ for the oxygen annealed sample compared to the non-annealed one. The same reasoning holds for the air-annealed sample. In addition, the improved photocurrent of the air-annealed sample resulted in a remarkable enhancement of $V_{OC}$, as $V_{OC}$ is proportional to $J_{SC}$ by the equation:

$$V_{OC} = \frac{k_B T}{e} \ln \left( \frac{J_{SC}}{J_0} \right)$$

where $k_B$ is Boltzmann constant, $T$ is the temperature in Kelvin, $e$ is the electronic charge, $J_0$ is the reverse saturation current density in the dark. This is, however, not the case for the oxygen-annealed sample, suggesting the existence of an energy loss mechanism for photo-injected electrons during their journey towards the FTO substrate. Second, annealing under oxygen increases the concentration of O$_2$ molecules chemisorbed on the ZnO surface. Chemisorbed oxygen molecules are reported to cause an upward band bending at the ZnO surface [40–42]. This is schematically shown in figure 8. ZnO has a low dielectric constant, resulting in an efficient band bending effect [40]. This band bending can affect the electron transfer at two interfaces: the N719/ZnO interface and the ZnO/FTO interface. The latter interface, although can be severely affected by upward band bending, is not accessible to oxygen molecules in our vertically aligned ZnO nanowires case, leaving the N719/ZnO interface as the mainly affected one. From figure 8, the energy difference between the N719 lower unoccupied molecular orbital (LUMO) level and ZnO conduction band (CB) edge is 0.5 eV. Also, compared to the air-annealed device, the $V_{OC}$ reduction in the oxygen-annealed sample is 0.134 V. Therefore, a minimum upward band bending of 0.634 eV is necessary to explain the $V_{OC}$ value of the oxygen annealed sample. This value is well within band bending values typically reported for ZnO [40–43].

### 4. Conclusions

In this study, vertically aligned ZnO nanowire arrays were successfully grown on FTO substrates with excellent and remarkable surface coverage. Different growth parameters were optimized for optimum surface coverage and uniform dye-loading along the nanowire length. The concentration of seed layer solution has an optimal concentration of ∼ 10–25 mM, above which the areal density of nanowires will start to steeply decline. Below this concentration, thicker nanowires are grown resulting in increased stacking of adjacent nanowires. The growth temperature had a significant effect on the nanowire morphology. Both nanowire length and diameter notably declined beyond a growth temperature window between 90 °C–110 °C. While this decline can be explained by temperature dependent growth kinetics below 90 °C, it is attributed to the enhanced homogeneous nucleation in the growth solution above 110 °C that result in faster consumption of precursor ions. It was observed that nanowire entanglement starts to observably take place at ∼ 100 °C. Therefore, a growth temperature of 90 °C was chosen to fabricate the DSSC devices for further study. The optimized nanowires were post-annealed at 400 °C under air and oxygen gas environments. It was observed that oxygen gas environment severely reduces the open-circuit voltage, which is attributed to the higher impact of band-bending effect in the oxygen-annealed sample.

| Ref. | Seed layer Coating Method | NW Growth Method | NW Film Thickness ($\mu$m) | Post-Annealing Temperature | PCE |
|------|--------------------------|-----------------|--------------------------|---------------------------|-----|
| [22] | PLD                      | Microwave-assisted hydrothermal | 3.4 $\mu$m | 450 °C | 0.35% |
| [23] | RF Sputtering            | Hydrothermal    | 2.5 $\mu$m | 450 °C | 0.13% |
| [24] | Dip Coating              | Hydrothermal    | 9.8 $\mu$m | 400 °C | 0.73% |
| [25] | Dip Coating              | Hydrothermal    | 5.5 $\mu$m | 400 °C | 0.45% |
| [26] | Drop casting             | Hydrothermal    | 1 $\mu$m | —      | 0.07% |
| [27] | Spin Coating             | Hydrothermal    | 0.75 $\mu$m | 400 °C | 0.13% |
| Our work | Drop Casting          | Hydrothermal    | 0.4 $\mu$m | 400 °C | 0.1% |

Table 2. Literature comparison of PCEs of DSSCs fabricated using hydrothermally grown ZnO nanowire arrays post-annealed in air.
Acknowledgments

This research was funded by the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Kingdom of Saudi Arabia, Award Number (12-ENE2829-02).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflicts of interest

The authors declare no conflict of interest.

ORCID iDs

Mahmoud Hezam https://orcid.org/0000-0003-2567-0441
Mohammad Alduraibi https://orcid.org/0000-0003-1790-4586

References

[1] Özgür Ü., Alivov Y I., Liu C., Teke A., Reshchikov M A., Doğan S., Avrutin V., Cho S J. and Morkö̧h 2005 A comprehensive review of ZnO materials and devices J. Appl. Phys. 98 041301
[2] Wang Z L 2004 Zinc oxide nanostructures: growth, properties and applications J. Phys. Condens. Matter 16 R829
[3] Theerthagiri J., Salla S., Senthil R A., Nithyadharseni P., Madankumar A., Arunachalam P., Maiyalagan T. and Kim H S 2019 A review on ZnO nanostructured materials: energy, environmental and biological applications Nanotechnology 30 392001
[4] Consonni V., Briscoe J., Kärber E., Li X and Cossuet T 2019 ZnO nanowires for solar cells: a comprehensive review Nanotechnology 30 362001
[5] Le A T, Ahmadipour M and Pung S Y 2020 A review on ZnO-based piezoelectric nanogenerators: synthesis, characterization techniques, performance enhancement and applications J. Alloys Compd. 844 156172
[6] Rahman F 2019 Zinc oxide light-emitting diodes: a review Opt. Eng. 58 10901
[7] Liu K., Sakurai M and Aono M 2010 ZnO-based ultraviolet photodetectors Sensors 10 8604–34

Figure 8. Energy level distribution of the FTO/ZnO/N719 system. The electron transport mechanism is depicted. Band bending caused by oxygen annealing makes an energy barrier across the dye/ZnO interface resulting in a reduced $V_{OC}$. 

Figure 8. Energy level distribution of the FTO/ZnO/N719 system. The electron transport mechanism is depicted. Band bending caused by oxygen annealing makes an energy barrier across the dye/ZnO interface resulting in a reduced $V_{OC}$. 

9
[8] Chen Y 2018 Review of ZnO transparent conducting oxides for solar applications Proceedings of the IOP Conference Series: Materials Science and Engineering 423 12170

[9] Müller J, Schöpe G, Kluth O, Rech B, Ruske M, Trube J, Szytsza B, Jiang X and Bräuer G 2001 Upscaling of texture-etched zinc oxide substrates for silicon thin film solar cells Thin Solid Films 392 327–33

[10] Yan X, Venkataram S and Aberle A G 2013 Modified surface texturing of aluminium-doped zinc oxide (AZO) transparent conductive oxides for thin-film silicon solar cells Energy Procedia 33 157–65

[11] Baxter J B and Aydil E S 2005 Nanowire-based dye sensitized solar cells Appl. Phys. Lett. 86 053114

[12] Law M, Greene L E, Johnson C, Saykally R J and Yang P 2005 Nanowire dye sensitized solar cells Nat. Mater. 4 455–9

[13] Bae S Y, Seo H W and Park J 2004 Vertically aligned sulfur-doped ZnO nanowires synthesized via chemical vapor deposition J. Phys. Chem. B 108 5206–10

[14] Zeng Y J, Ye Z Z, Xu W Z, Zhu L P and Zhao B H 2005 Well-aligned ZnO nanowires grown on Si substrate via metal–organic chemical vapor deposition Appl. Surf. Sci. 250 280–3

[15] Labis J P, Al-Anazi A Q, Al-Brithen H A, Hezam M, Aldurahibi M A, Algarni A, Alharbi A A A, Al-Awadi A S, Khan A and El-Toni AM 2019 Zinc oxide nanostructures (nanoworms, nanoflowers, nanowalls, and nanorods) by pulsed laser ablation technique for gas-sensing application J. Am. Ceram. Soc. 102 4367–75

[16] Mora-Seró J J, Fabregat-Santiago F V, Denier B and Bisquer V 2016 Tena-Zaera R, Elias J and Lévy-Clément C 2006 Determination of carrier density of ZnO nanowires by electrochemical techniques Appl. Phys. Lett. 89 203117

[17] Greene L E, Law M, Goldberger J, Kim F, Johnson J C, Zhang Y, Saykally R J and Yang P 2003 Low-temperature wafer-scale production of ZnO nanowire arrays Angew. Chemie - Int. Ed 115 3139–42

[18] Greene L E, Law M, Tan D H, Montano M, Goldberger J, Somorjai G and Yang P 2005 General route to vertical ZnO nanowire arrays using textured ZnO seeds Nano Lett 7 1231–6

[19] Greene L E, Yuhas B D, Law M, Zitoun D and Yang P 2006 Solution-grown zinc oxide nanowires Inorg. Chem. 45 7355–43

[20] Ahmad M, Ahmad M K, Nafarizil N, Soon C, Suriani A B, Mohamed A and Mamat M H 2020 Adsorption effect of oxygen on ZnO Nanowires (100 nm) leading towards pronounced edge effects and voltage enhancement Mater. Res. Express 7 55004

[21] Maddah M, Unsworth C P and Plank N O 2018 V Selective growth of ZnO nanowires with varied aspect ratios on an individual substrate Mater. Res. Express 6 15905

[22] Liu L, Hong K, Ge X, Liu D and Xu M 2014 Controllable and rapid synthesis of long ZnO nanowire arrays for dye-sensitized solar cells J. Phys. Chem. C 118 15551–5

[23] Nayeri F D,SOLEIMANI E A and Salehi F 2013 Synthesis and characterization of ZnO nanowires grown on different seed layers: The application for dye-sensitized solar cells Solar. Energy 60 246–55

[24] Yang W, Wan F, Chen S and Jiang C 2009 Hydrothermal growth and application of ZnO nanowire films with ZnO and TiO2 buffer layers in dye-sensitized solar cells Nanoscale Res. Lett 4 1486

[25] Xu C H and Wu J J 2007 Chemical bath deposition of ZnO nanowire-nanoparticle composite electrodes for use in dye-sensitized solar cells Nanotechnology 18 505706

[26] Baxter J B, Walker A M, Van Ommering K and Aydil E S 2006 Synthesis and characterization of ZnO nanowires and their integration into dye-sensitized solar cells Nanotechnology 17 S5304

[27] Bhattacharyya S R, Mallick Z and Gayen R N 2020 Vertically aligned Al-Doped ZnO nanowire arrays as efficient photoanode for dye-sensitized solar cells J. Electron. Mater. 49 3860–8

[28] Pandey P, Parra M R, Haque F Z and Kurchania R 2017 Effects of annealing temperature optimization on the efficiency of ZnO nanoparticles photoanode-based dye sensitized solar cells J. Mater. Sci., Mater. Electron. 28 1357–45

[29] Wahyuomo R A et al 2017 Effect of annealing on the sub-bandgap, defects and trapping states of ZnO nanostructures Chem. Phys. 483 112–21

[30] Barua S and Dutta J 2009 Effect of seeded substrates on hydrothermally grown ZnO nanorods J. Sol-Gel Sci. Technol 50 456

[31] Rachamim A R, Dalal S H, Paendler S M L, Swanwick M E, Flewitt A J and Milne W J 2009 Quantitative investigation of the factors affecting the hydrothermal growth of zinc oxide nanowires Proc. of the Materials Research Society Symp. Proc. 1174

[32] Chevalier-César, Capocchi-Gnambodoe M and Leprince-Wang Y 2014 Growth mechanism studies of ZnO nanowire arrays via hydrothermal method Appl. Phys. A Mater. Sci. Process (https://doi.org/10.1007/s00339-013-7908-8)

[33] Akagun M C, Kalay Y E and Unalan H E 2012 Hydrothermal zinc oxide nanowire growth using zinc acetate dihydrate salt J. Mater. Res. 27 1445–51

[34] Wijeratne K and Bandara J 2014 Aspect-ratio dependent electron transport and recombination in dye-sensitized solar cells fabricated with one-dimensional ZnO nanostructures Electrochim. Acta (https://doi.org/10.1016/j.electacta.2014.10.046)

[35] Goyal D J, Agache C, Takwale M G, Bhide V G, Mahammusi S and Kulkarni S K 1993 Dopant induced modifications in the physical properties of sprayed ZnO: In films J. Mater. Res. 8 1052–6

[36] Shirazi M, Dariani R S and Torogheidejad M R 2016 Influence of doping behavior of Al on nanostructure, morphology and optoelectronic properties of Al doped ZnO thin film grown on FTO substrate J. Mater. Sci., Mater. Electron. 27 10226–36

[37] Aizawa M, Ben, Litaier N, Chitourou R and Ammar S 2021 The influence of different stabilizers on properties of Sol–Gel Spin-coated zinc oxide films Brazilian J. Phys. 51 722–30

[38] Angappane S, Selvi N R and Kulkarni G U 2009 ZnO (101) films by pulsed reactive crossed-beam laser ablation Bull. Mater. Sci. 32 253–8

[39] Nguyen V H, Bellet D, Masenilli B and Muñoz-Rojas D 2018 Increasing the electron mobility of ZnO-based transparent conductive films deposited by open-air methods for enhanced sensing performance. ACS Appl. Nano Mater 1 6922–31

[40] Zhang Z and Yates J T Jr 2012 Band bending in semiconductor: chemical and physical consequences at surfaces and interfaces Chem. Rev. 112 5520–51

[41] J. J. Loskot, J. Sproles E S Jr and Gatos H C 1977 Quantitative study of the charge transfer in chemisorption; oxygen chemisorption on ZnO J. Appl. Phys. 48 5366–75

[42] Li M and Seebauer E G 2016 Defect engineering in semiconductor oxides: Control of ZnO surface potential via temperature and oxygen pressure AIChE J. 62 500–7

[43] Quintana M, Edvinsson T, Hagfeldt A and Boschloo G 2007 Comparison of dye-sensitized ZnO and TiO2 solar cells: studies of charge transport and carrier lifetime J. Phys. Chem. C 111 1035–41