

Research Article

Growth of ZnO Nanorod Arrays on Flexible Substrates: Effect of Precursor Solution Concentration

Fei Tong,¹ Kyusang Kim,¹ Yaqi Wang,¹ Resham Thapa,¹ Yogesh Sharma,¹ Aaron Modic,¹ Ayayi Claude Ahyi,¹ Tamara Issacs-Smith,¹ John Williams,¹ Hosang Ahn,² Hyejin Park,² Dong-Joo Kim,² Sungkoo Lee,³ Eunhee Lim,³ Kyeong K. Lee,³ and Minseo Park¹

¹Physics Department, Auburn University, Auburn, AL 36849, USA

²Materials Research and Education Center, Department of Mechanical Engineering, Auburn University, Auburn, AL 36849, USA

³Department of Eco and Functional Materials, Korea Institute of Industrial Technology, Cheonan, Choongnam 331-825, Republic of Korea

Correspondence should be addressed to Minseo Park, park@physics.auburn.edu

Received 7 May 2012; Accepted 11 June 2012

Academic Editors: A. Bendavid, P. Kumbhakar, A. Portavoce, A. Sorrentino, and C. Wang

Copyright © 2012 Fei Tong et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

We report a low-temperature aqueous solution growth of uniformly aligned ZnO nanorod arrays on flexible substrates. The substrate is Indium Tin Oxide (ITO) film coated on polyethylene terephthalate (PET). Solutions with five different concentrations of the precursors with equimolar Zinc Nitrate and Hexamethylenetetramine (HMT) in distilled water were prepared to systematically study the effect of precursor solution concentration on the structural and optical properties of ZnO nanorods. It was concluded that the precursor concentration have great influence on the morphology, crystal quality, and optical property of ZnO nanorods. The diameter, density, and orientation of the nanorods are dependent on the precursor solution concentration. X-ray diffraction and micro-Raman spectroscopy showed that the ZnO nanorods with the highest concentration of 50 mM were highly aligned and have the highest level of surface coverage. It was also found that the diameter and length of the nanorods increases upon increasing precursor solution concentration. This is the first systematic investigation of studying the effect of precursor solution concentration on the quality of ZnO nanorods grown on ITO/PET substrates by low-temperature solution method. We believe that our work will contribute to the realization of flexible organic-inorganic hybrid solar cell based on ZnO nanorods and conjugated polymer.

1. Introduction

Zinc oxide (ZnO) is a semiconductor with a wide direct band gap of 3.37 eV and a large exciton binding energy of 60 meV, which makes the material useful for optoelectronic application [1, 2]. Nanostructures of ZnO such as ZnO nanorods and nanowires have received increased attention due to their excellent electrical and optical properties [3]. Due to the high surface-to-volume ratio provided by the one-dimensional (1D) nanostructure, ZnO nanorod arrays are considered suitable to the application for hybrid photovoltaic devices [4–7]. In the past few years, ZnO nanorods have been synthesized *via* various physical and chemical methods including vapor phase synthesis [8–10], metalorganic chemical vapor deposition (MOCVD) [11–13], and solution-based synthesis

[14–17]. Among these routes, solution-based method has the advantages of simplicity, low costs, low growth temperature, and easy coating of large surfaces. Intensive research has been focused on the solution growth process of ZnO nanorods on ITO-coated glass substrates. Guo et al. [18] have systematically studied the effect of processing conditions such as pretreatment of the substrates, growth temperature, deposition time, and the concentration of the precursors on the morphology and alignment ordering of ZnO nanorod arrays during solution process.

Aiming at overcoming the problems endemic to organic solar cells, researchers worldwide have turned their attention to organic/inorganic hybrid solar cells. An example of such a hybrid solar cell is the one with ZnO nanorod arrays coated on ITO-coated glass substrates and they found that nanorods

play an important role in improving electron transport speed [4–7]. In addition, it will be an innovation to build plastic hybrid solar cells [19] consisting of ZnO nanorods and conjugated polymer on ITO/PET substrates since plastic materials are cheap, lightweight, bendable, and suitable to large-scale roll-to-roll manufacturing. To synthesize ZnO nanorods on plastic substrate, low-temperature solution-based process is highly suitable. Recently, Kim et al. [20] have reported the fabrication of flexible dye-sensitized solar cells by synthesizing ZnO NRs on ITO-coated PET substrates. Hu et al. [21] have studied density, adhesion, and electrochromic performance of ZnO nanorod arrays on the ITO-coated flexible substrates. However, the growth conditions such as growth temperature, concentration of the precursor, time duration concerning the solution growth of ZnO nanorods on ITO-coated PET substrates have not been systematically investigated.

In this investigation, we have synthesized ZnO nanorods on flexible ITO substrates by a solution-based approach under different precursor solution concentrations while time duration and temperature were fixed at 2 h and 85°C, respectively. The aqueous solution contains equimolar of zinc nitrate and hexamethylenetetramine (HMT), which are the main chemicals used by many research groups [16, 17, 22] in solution growth of ZnO nanorods. One of the major merits of this aqueous solution method is the use of distilled water instead of using alcohol as the solvent, since water is more inexpensive and environmentally friendly [23]. The influence of the precursor solution concentration on the growth of the ZnO nanorods on ITO-coated PET substrates was systematically investigated for the first time. We have demonstrated that the morphology, crystalline, and optical property of ZnO nanorods on ITO-coated PET substrates can be controlled by adjusting the concentration of the aqueous chemical solution.

2. Experiment

Flexible-indium-tin-oxide (ITO)-coated PET substrates were purchased from Delta Technologies. The substrates have a multi-layered films composed of $\text{In}_2\text{O}_3/\text{Au}/\text{Ag}$ sputtered on an optical grade polyethylene terephthalate (PET) film (0.2 mm). The sheet resistance of the coated ITO is 4–10 Ω square⁻¹. The substrates were cut into 1 inch \times 1 inch pieces. Prior to the growth of the ZnO nanorods, the ITO-coated PET substrates were cleaned sequentially by ultrasonic agitation in a detergent solution, acetone, isopropanol alcohol, and distilled water for 5 min, followed by nitrogen blow drying.

The zinc oxide nanorods were prepared by a two-step process which was similar to the procedure reported in the literature [17, 18]. In the first step, ZnO seed layer with an approximate thickness of 40 nm were radio-frequency (RF) sputtered on the flexible ITO substrates. In the second step, an aqueous solution which contains zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, Crystalline/Certified, Fisher Chemical, F.W. = 297.49), and the same mole of hexamethylenetetramine (HMT, Sigma-Aldrich, M.W. = 140.19) in 400 mL

TABLE 1: The average diameter, length, and aspect ratio (length/diameter) of ZnO nanorods on flexible ITO/PET substrates under different solution concentrations.

Solution con. (mM/L)	50	37.5	25	18.75	12.5
Average diameter (nm)	397.4	265.8	251.1	225	173.6
Average length (nm)	1200	950	830	750	600
Aspect ratio (Len./Dia.)	3.02	3.57	3.31	3.33	3.46

distilled water mixture was prepared in a beaker and was stirred for 10 min at room temperature. Subsequently, as-prepared substrates were immersed into the aqueous solution which was then transferred to an isothermal hot water bath (IsoTemp 202 Water Bath, Fisher Scientific). The solution synthesis process of ZnO nanorods was conducted at 85°C for 2 hours. The temperature of the water was elevated to 85°C before dipping the aqueous solution into the hot water bath. After 2 hours of solution growth, the substrates were rinsed with distilled water for several times and then dried in air at room temperature.

Five different concentrations (50 mM, 37.5 mM, 25 mM, 18.75 mM, and 12.5 mM) solutions of the Zinc Nitrate Hexahydrate and HMT in distilled water were prepared. The as-prepared ITO/PET substrates with the dense ZnO seed layers were suspended horizontally upside-down in a beaker which contains the aqueous solution of equimolar of Zinc Nitrate Hexahydrate and HMT. The ITO side of the sample was facing down and the distance between the sample and the bottom of the beaker is about 1 cm.

As-grown ZnO nanorods were studied using scanning electron microscopy (SEM), X-ray diffraction (XRD), micro-Raman spectroscopy, and photoluminescence spectroscopy. Field emission-scanning microscope (FE-SEM, JEOL JSM-7000F) was used to observe the morphology of the ZnO nanorods on ITO flexible substrates. Bruker D8 X-ray Diffractometer was used to characterize the crystalline quality of the ZnO nanorods on ITO-coated PET substrates. Room temperature PL spectra were collected using the 325 nm line (20 mW) from a continuous-wave He-Cd laser (Kimmon Electric). Room temperature Micro-Raman spectroscopy was conducted using the 441.563 nm line (80 mW) from He-Cd laser. Back-scattering geometry was employed for micro-Raman scattering experiment, and the polarization state of the scattered light was not analyzed.

3. Results and Discussion

After the growth of the ZnO nanorods, scanning electron microscopy was used to study the morphology of the ZnO nanorod arrays. Figure 1 shows the SEM images of ZnO nanorods grown with five different solution concentrations, respectively. As shown in the figure, arrays of ZnO nanorods with hexagonal shapes were successfully formed under various solution concentrations. Based on the SEM images, average values of the length, diameter, and aspect ratio of the nanorods are summarized in Table 1 and are plotted in Figure 2 as a function of solution concentration. It was found

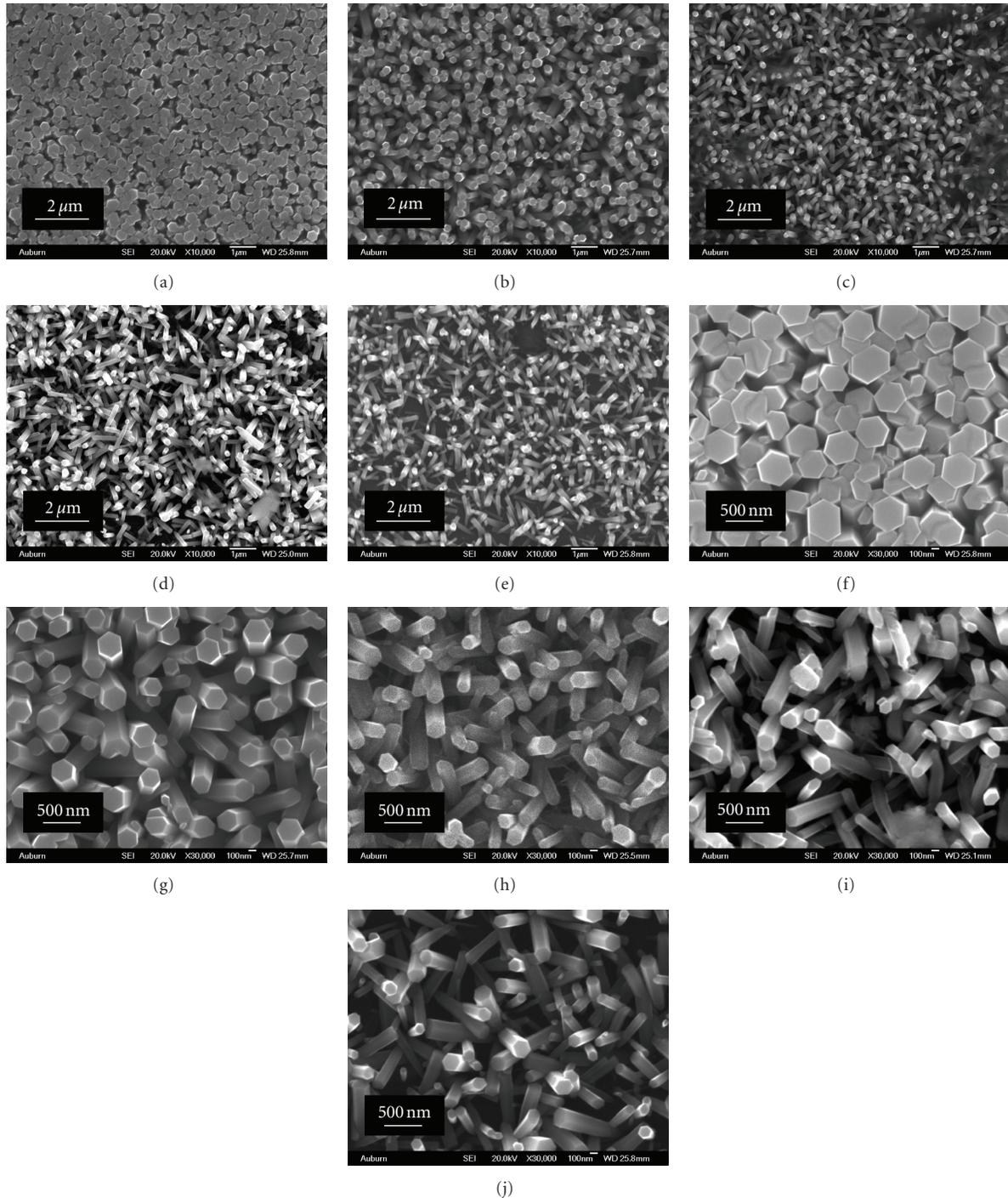


FIGURE 1: SEM images of ZnO nanorods synthesized on ITO/PET substrates under different solution concentrations: under lower magnification (scale bar $-2\ \mu\text{m}$): (a) 50 mM, (b) 37.5 mM, (c) 25 mM, (d) 18.75 mM, and (e) 12.5 mM; under higher magnification (scale bar $-500\ \text{nm}$): (f) 50 mM, (g) 37.5 mM, (h) 25 mM, (i) 18.75 mM, and (j) 12.5 mM.

that the diameter and length of the ZnO nanorod increases as the precursor solution concentration increases. The average diameter and length of the nanorod increased almost linearly from about 174 nm to 397 nm and from 600 nm to 1200 nm, respectively, upon increase of the solution concentration from 12.5 mM to 50 mM. It was found that the diameter, length, and density of the ZnO nanorods could be well

controlled by changing the solution concentration during growth. It also appears that the coverage of the nanorod array on the substrate increases as the precursor solution concentration increases. In addition, the nanorods grown with higher concentration precursor solution exhibited higher degree of alignment than the nanorods with lower concentration ones.

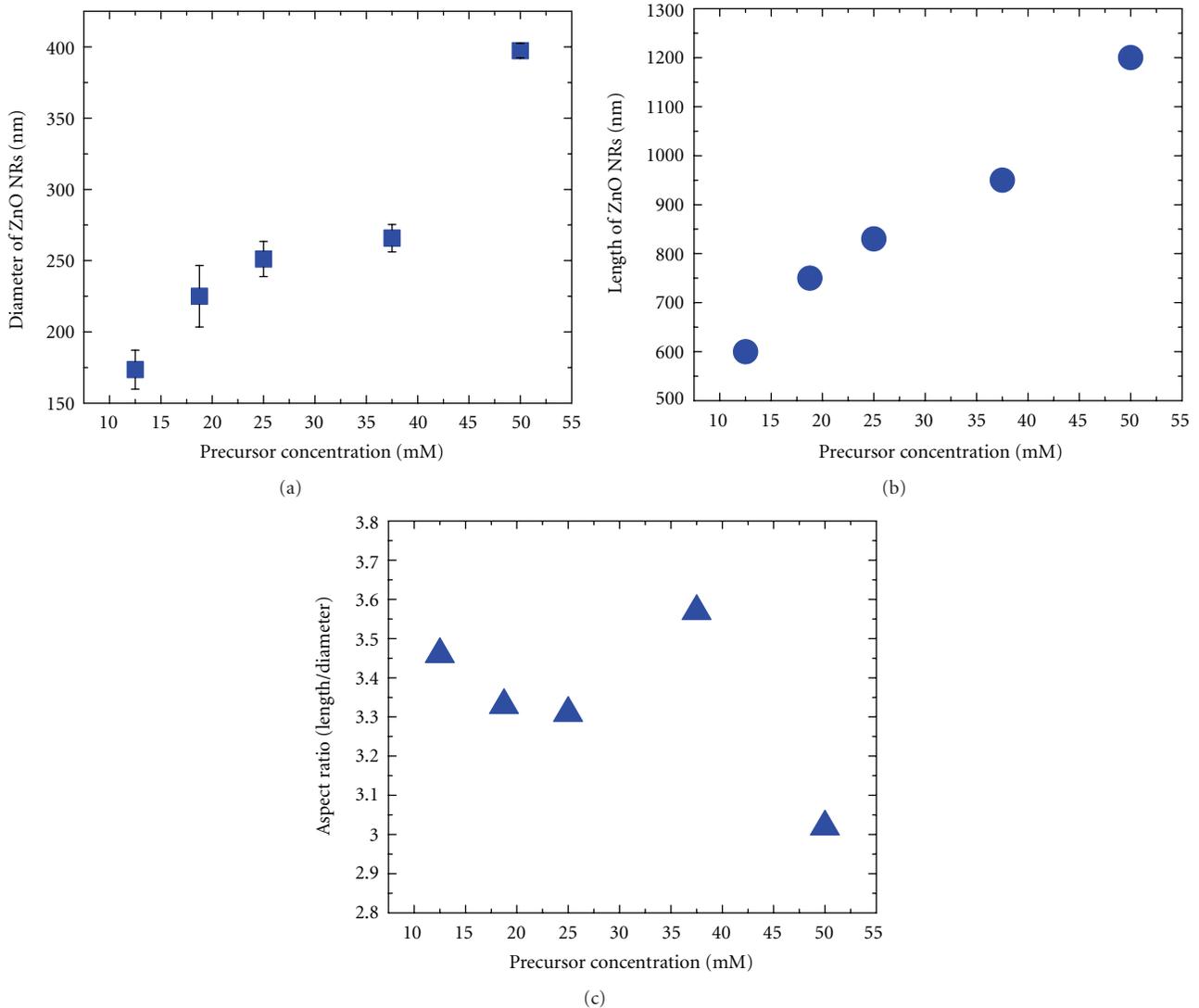


FIGURE 2: The plots of (a) average nanorod diameter, (b) average nanorod length, and (c) aspect ratio as a function of the solution concentration.

The XRD measurement was conducted to characterize the crystalline quality and orientation of the ZnO nanorods. Figure 3 shows the XRD patterns of ZnO nanorods grown under different solution concentrations on ITO/PET substrates. The XRD pattern of each sample was originated both from the ZnO nanorods and the ITO/PET substrates. The X-ray diffraction result is in agreement with the standard diffraction pattern of hexagonal phase ZnO wurtzite structure from the Joint Committee on Powder Diffraction Standards (JCPDS 36-1451) [24]. The diffraction peaks corresponding to the lattice planes (100), (002), (101), (102), (110), and (103) are indexed. In the case of the sample with the concentration of 50 mM, the sharp and distinct diffraction peak at $2\theta = 34.41^\circ$ due to ZnO (002) crystal plane shows the strongest intensity, indicating its strong *c*-axis orientation, and the nanorods are preferentially oriented perpendicularly to the substrate. The notable difference in the full-width at half-maximum (FWHM) strongly supports

our speculation that ZnO nanorod crystal promotes along the (001) direction [25]. It was observed that the relative intensity of the (002) diffraction peak with respect to other peaks decreases as the precursor concentration decreases, indicating that the orientation of the nanorods arrays becomes randomized. The XRD results are consistent to SEM data.

Photoluminescence measurement was employed to study the influence of precursor solution concentration on the optical property of the ZnO nanorods grown on ITO/PET substrates. Room temperature PL spectra from the ZnO nanorods grown under various precursor concentrations and from the bare ITO-coated PET substrate are shown in Figure 4. The PL spectra from the ZnO nanorods typically exhibit two bands: a strong and sharp peak at about 385 nm (3.22 eV, UV emission) and a broad band at around 530 nm (2.34 eV, visible emission). The former is a typical near band edge transition of intrinsic ZnO and is related to excitonic

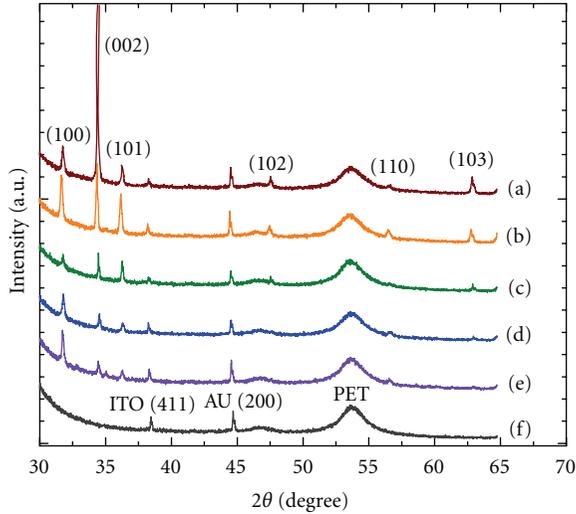


FIGURE 3: XRD patterns of ZnO nanorods grown on ITO/PET substrates under different solution concentrations: (a) 50 mM, (b) 37.5 mM, (c) 25 mM, (d) 18.75 mM, (e) 12.5 mM, and (f) bare ITO/PET substrates.

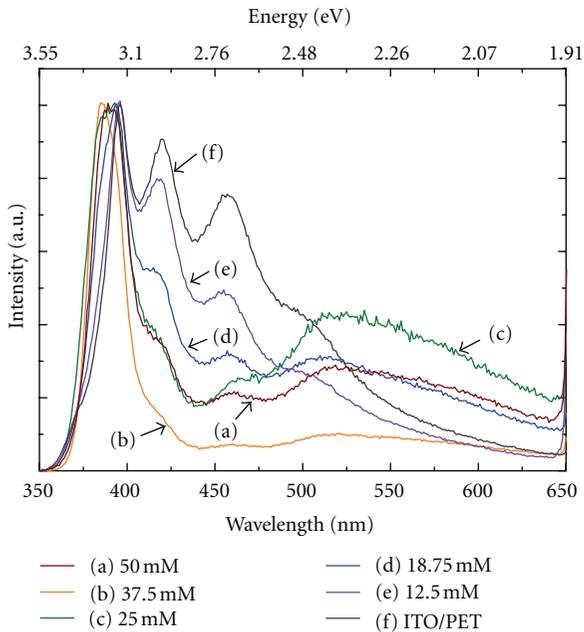


FIGURE 4: PL spectra of ZnO nanorods synthesized on ITO/PET substrates under different precursor concentrations: (a) 50 mM, (b) 37.5 mM, (c) 25 mM, (d) 18.75 mM, (e) 12.5 mM, and (f) bare ITO/PET substrates.

process [26–28]. The latter visible band is considered to be resulted from the impurities and/or structural defects such as singly ionized oxygen vacancies in ZnO [29, 30]. The PL spectra of the ZnO nanorods grown from the solution with the lowest precursor concentration of 12.5 mM were mainly dominated by peaks of the bare ITO/PET substrates, which indicate that the coverage of the ZnO nanorods on the ITO surface is substantially low. As can be seen from the PL

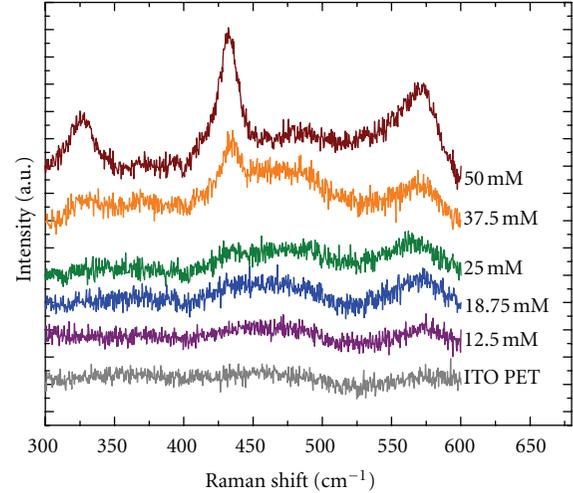


FIGURE 5: Raman scattering spectra of ZnO nanorods synthesized on ITO/PET substrates under different precursor concentrations: 50 mM, 37.5 mM, 25 mM, 18.75 mM, 12.5 mM and bare ITO/PET substrates.

spectra, the contribution from the ZnO becomes dominant as the precursor solution concentration increases.

Micro-Raman spectroscopy was used to further analyze the quality of the ZnO nanorods. Wurtzite form of ZnO belongs to the space group C_{6v}^4 with two formula units per primitive cell [31]. Group theory predicts the following optical modes at the Γ point of the Brillouin zone: $A_1 + E_1 + 2E_2 + 2B_1$. Among these modes, A_1 , E_1 and $2E_2$ modes are Raman active, $2B_1$ modes are silent, and A_1 and E_1 modes are infrared active. Both A_1 and E_1 modes split into transverse optical (TO) and longitudinal optical (LO) phonons [32]. Figure 5 shows the room temperature micro-Raman spectra (after baseline subtraction) collected from the five samples that were grown under different precursor concentrations and from the bare ITO/PET substrate. Lorentzian functions were employed to fit the Raman spectra in the region between 300 and 600 cm^{-1} . The observed peaks at about 438 and 586 cm^{-1} are assigned to be $E_2^{(2)}$ (high-frequency E_2 mode) and Quasi-LO (QLO), respectively, [33–35]. The peak at 329 cm^{-1} results from the multiple phonon scattering processes [36]. As can be seen from Figure 5, the intensities of the ZnO Raman peak become higher as the precursor concentration increases, which indicate the increase in the crystal quality of the nanorods and/or the increase in the coverage of the nanorod arrays on the substrate. The Raman scattering result is in agreement with the X-ray and photoluminescence analyses.

4. Summary and Conclusion

In summary, we have systematically studied the effect of precursor solution concentration on the materials quality, orientation, and optical property of the ZnO nanorods grown on flexible ITO/PET substrates. Our investigation demonstrates that the morphology, crystal orientation, and optical

property of ZnO nanorods grown on ITO/PET substrates can be tailored by changing the concentration of the precursor solution. By tuning the precursor concentration, we can grow nanorods with different morphology, crystal quality, and orientation. X-ray diffraction and micro-Raman spectroscopy showed that the ZnO nanorods with the highest concentration of 50 mM were highly aligned and have the highest level of surface coverage. It was also found that the diameter and the length of the nanorods increase upon increasing precursor solution concentration. To the best of our knowledge, this is the first systematic investigation of studying the effect of precursor solution concentration on quality of ZnO nanorods grown on ITO/PET substrates by low-temperature solution method. We strongly believe that our work will contribute to the realization of flexible organic-inorganic hybrid solar cell based on ZnO nanorods and polymer.

Acknowledgment

This work was supported by Korea Institute of Industrial Technology (KITECH).

References

- [1] A. Ohtomo, M. Kawasaki, Y. Sakurai et al., "Room temperature ultraviolet laser emission from ZnO nanocrystal thin films grown by laser MBE," *Materials Science and Engineering B*, vol. 54, no. 1-2, pp. 24–28, 1998.
- [2] M. Godlewski, E. Guziewicz, K. Kopalko et al., "Zinc oxide for electronic, photovoltaic and optoelectronic applications," *Low Temperature Physics*, vol. 37, no. 3, Article ID 009103LTP, pp. 235–240, 2011.
- [3] G. C. Yi, C. R. Wang, and W. I. Park, "ZnO nanorods: synthesis, characterization and applications," *Semiconductor Science and Technology*, vol. 20, no. 4, pp. S22–S34, 2005.
- [4] K. Takanezawa, K. Hirota, Q. S. Wei, K. Tajima, and K. Hashimoto, "Efficient charge collection with ZnO nanorod array in hybrid photovoltaic devices," *Journal of Physical Chemistry C*, vol. 111, no. 19, pp. 7218–7223, 2007.
- [5] P. Ravirajan, A. M. Peiró, M. K. Nazeeruddin et al., "Hybrid polymer/zinc oxide photovoltaic devices with vertically oriented ZnO nanorods and an amphiphilic molecular interface layer," *Journal of Physical Chemistry B*, vol. 110, no. 15, pp. 7635–7639, 2006.
- [6] C. Y. Chou, J. S. Huang, C. H. Wu, C. Y. Lee, and C. F. Lin, "Lengthening the polymer solidification time to improve the performance of polymer/ZnO nanorod hybrid solar cells," *Solar Energy Materials and Solar Cells*, vol. 93, no. 9, pp. 1608–1612, 2009.
- [7] D. C. Olson, J. Piris, R. T. Collins, S. E. Shaheen, and D. S. Ginley, "Hybrid photovoltaic devices of polymer and ZnO nanofiber composites," *Thin Solid Films*, vol. 496, no. 1, pp. 26–29, 2006.
- [8] B. D. Yao, Y. F. Chan, and N. Wang, "Formation of ZnO nanostructures by a simple way of thermal evaporation," *Applied Physics Letters*, vol. 81, no. 4, pp. 757–759, 2002.
- [9] Y. Dai, Y. Zhang, Q. K. Li, and C. W. Nan, "Synthesis and optical properties of tetrapod-like zinc oxide nanorods," *Chemical Physics Letters*, vol. 358, no. 1-2, pp. 83–86, 2002.
- [10] A. J. Cheng, Y. Tzeng, Y. Zhou et al., "Thermal chemical vapor deposition growth of zinc oxide nanostructures for dye-sensitized solar cell fabrication," *Applied Physics Letters*, vol. 92, no. 9, Article ID 092113, 3 pages, 2008.
- [11] W. I. Park, D. H. Kim, S. W. Jung, and G. C. Yi, "Metalorganic vapor-phase epitaxial growth of vertically well-aligned ZnO nanorods," *Applied Physics Letters*, vol. 80, no. 22, pp. 4232–4234, 2002.
- [12] X. Liu, X. Wu, H. Cao, and R. P. H. Chang, "Growth mechanism and properties of ZnO nanorods synthesized by plasma-enhanced chemical vapor deposition," *Journal of Applied Physics*, vol. 95, no. 6, pp. 3141–3147, 2004.
- [13] K. Ogata, K. Maejima, S. Z. Fujita, and S. G. Fujita, "Growth mode control of ZnO toward nanorod structures or high-quality layered structures by metal-organic vapor phase epitaxy," *Journal of Crystal Growth*, vol. 248, pp. 25–30, 2003.
- [14] Y. H. Ni, X. W. Wei, J. M. Hong, and Y. Ye, "Hydrothermal preparation and optical properties of ZnO nanorods," *Materials Science and Engineering B*, vol. 121, no. 1-2, pp. 42–47, 2005.
- [15] L. Fan, H. Song, T. Li et al., "Hydrothermal synthesis and photoluminescent properties of ZnO nanorods," *Journal of Luminescence*, vol. 122-123, no. 1-2, pp. 819–821, 2007.
- [16] D. Polsongkram, P. Chamminok, S. Pukird et al., "Effect of synthesis conditions on the growth of ZnO nanorods via hydrothermal method," *Physica B*, vol. 403, no. 19-20, pp. 3713–3717, 2008.
- [17] H. Ahn, Y. Wang, S. H. Jee, M. Park, Y. S. Yoon, and D. J. Kim, "Enhanced UV activation of electrochemically doped Ni in ZnO nanorods for room temperature acetone sensing," *Chemical Physics Letters*, vol. 511, no. 4–6, pp. 331–335, 2011.
- [18] M. Guo, P. Diao, and S. Cai, "Hydrothermal growth of well-aligned ZnO nanorod arrays: dependence of morphology and alignment ordering upon preparing conditions," *Journal of Solid State Chemistry*, vol. 178, no. 6, pp. 1864–1873, 2005.
- [19] C. J. Brabec, N. S. Sariciftci, and J. C. Hummelen, "Plastic solar cells," *Advanced Functional Materials*, vol. 11, no. 1, pp. 15–26, 2001.
- [20] J. J. Kim, K. S. Kim, and G. Y. Jung, "Fabrication of flexible dye-sensitized solar cells with photoanodes composed of periodically aligned single crystalline vertical ZnO NRs by utilizing a direct metal transfer method," *Journal of Materials Chemistry*, vol. 21, no. 21, pp. 7730–7735, 2011.
- [21] A. Hu, F. Wu, J. Liu et al., "Density- and adhesion-controlled ZnO nanorod arrays on the ITO flexible substrates and their electrochromic performance," *Journal of Alloys and Compounds*, vol. 507, no. 1, pp. 261–266, 2010.
- [22] H. Ahn, J.-H. Park, S.-B. Kim, S. H. Jee, Y. S. Yoon, and D.-J. Kim, "Vertically aligned ZnO nanorod sensor on flexible substrate for ethanol gas monitoring," *Electrochemical and Solid-State Letters*, vol. 13, no. 11, pp. J125–J128, 2010.
- [23] N. Lepot, M. K. Van Bael, H. Van den Rul et al., "Synthesis of ZnO nanorods from aqueous solution," *Materials Letters*, vol. 61, no. 13, pp. 2624–2627, 2007.
- [24] Joint Committee on Powder Diffraction Standards, "Mineral powder diffraction file: databook: sets 1–42," Powder Diffraction File no. 36-1451.
- [25] B. Lo, J. Y. Chang, A. V. Ghule, S. H. Tzing, and Y. C. Ling, "Seed-mediated fabrication of ZnO nanorods with controllable morphology and photoluminescence properties," *Scripta Materialia*, vol. 54, no. 3, pp. 411–415, 2006.
- [26] A. Umar, B. Karunakaran, E.-K. Suh, and Y. B. Hahn, "Structural and optical properties of single-crystalline ZnO

- nanorods grown on silicon by thermal evaporation,” *Nanotechnology*, vol. 17, no. 16, pp. 4072–4077, 2006.
- [27] S. S. Hong, T. Joo, W. I. Park, Y. H. Jun, and G. C. Yi, “Time-resolved photoluminescence of the size-controlled ZnO nanorods,” *Applied Physics Letters*, vol. 83, no. 20, pp. 4157–4159, 2003.
- [28] Y. Sun, J. B. Ketterson, and G. K. L. Wong, “Excitonic gain and stimulated ultraviolet emission in nanocrystalline zinc-oxide powder,” *Applied Physics Letters*, vol. 77, no. 15, pp. 2322–2324, 2000.
- [29] Z. L. Wang, “Zinc oxide nanostructures: growth, properties and applications,” *Journal of Physics*, vol. 16, no. 25, pp. R829–R858, 2004.
- [30] H. J. Egelhaaf and D. Oelkrug, “Luminescence and nonradiative deactivation of excited states involving oxygen defect centers in polycrystalline ZnO,” *Journal of Crystal Growth*, vol. 161, no. 1–4, pp. 190–194, 1996.
- [31] J. M. Calleja and M. Cardona, “Resonant Raman scattering in ZnO,” *Physical Review B*, vol. 16, no. 8, pp. 3753–3761, 1977.
- [32] H. C. Hsu, H. M. Cheng, C. Y. Wu, H. S. Huang, Y. C. Lee, and W. F. Hsieh, “Luminescence of selective area growth of epitaxial ZnO nanowires and random-growth-oriented nanobelts,” *Nanotechnology*, vol. 17, no. 5, pp. 1404–1407, 2006.
- [33] R. Cuscó, E. Alarcón-Lladó, J. Ibáñez et al., “Temperature dependence of Raman scattering in ZnO,” *Physical Review B*, vol. 75, no. 16, Article ID 165202, 11 pages, 2007.
- [34] A. J. Cheng, Y. Tzeng, H. Xu et al., “Raman analysis of longitudinal optical phonon-plasmon coupled modes of aligned ZnO nanorods,” *Journal of Applied Physics*, vol. 105, no. 7, Article ID 073104, 7 pages, 2009.
- [35] E. Alarcón-Lladó, J. Ibáñez, R. Cuscó et al., “Ultraviolet Raman scattering in ZnO nanowires: quasimode mixing and temperature effects,” *Journal of Raman Spectroscopy*, vol. 42, no. 2, pp. 153–159, 2011.
- [36] Y. Tong, Y. Liu, C. Shao et al., “Growth and optical properties of faceted hexagonal ZnO nanotubes,” *Journal of Physical Chemistry B*, vol. 110, no. 30, pp. 14714–14718, 2006.



Hindawi

Submit your manuscripts at
<http://www.hindawi.com>

