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High temperature processed ZnO nanorods using flexible and transparent mica substrates for dye-sensitized solar cells and piezoelectric nanogenerators

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Abstract
The authors report the synthesis of ZnO nanorods on flexible and transparent mica substrates. The coupled use of polyethylenimine and ammonium hydroxide provided a direct method for growing vertically well-aligned ZnO nanorods with a high aspect ratio. Using mica as a substrate material enabled thermal annealing processes, which improved the structural and optical properties of ZnO nanorods with uniform surface coverage and excellent adhesion, increased transmittance of indium tin oxide (ITO)/mica (52%), and decreased sheet resistance of ITO/mica (80%). We have fabricated ZnO nanorod-based dye-sensitized solar cells (DSSCs) and piezoelectric nanogenerators (NGs) and investigated their annealing effects on the device performances. Specifically, the thermal treatment at 500°C for 30 min increased the energy conversion efficiencies of DSSCs by 53%. Furthermore, we observed a three-fold increase in the NG's output voltage and output current density through this thermal annealing process. As
Introduction

The development of optically transparent electronic devices fabricated on mechanically flexible substrates has been the subject of much recent research, in that it represents the next generation electronics technology because of its great potential and functionality to significantly enhance many industries from a commercial perspective. Substantial research has been conducted on developing and analyzing transparent and/or flexible devices, such as thin-film transistors, light emitting diodes, solar cells, supercapacitors, and batteries [1-5]. Metal foil, polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and cellulose nanopaper have commonly been used as flexible and transparent substrate materials [6-10]. However, these substrate materials have some limitations. For example, dye-sensitized solar cells (DSSCs) using opaque metal foil as a substrate material must be illuminated from the back-side of the cell and there are large losses of incident light through the counter electrode and electrolyte before the light reaches the dye attached onto the photoanode. This reverse illumination decreases the energy conversion efficiency by 20% compared to the front-side illumination [11, 12]. Another consideration is the typical use of thermal annealing processes, which are essential for improving the overall device performance in a variety of applications. Indium tin oxide (ITO) is widely used as transparent conductive oxide, and the transparency and conductivity of ITO can be improved by a thermal annealing process in excess of 300 °C [13-15]. A post-growth annealing process has also been useful for improving the crystal quality of active layers in devices [16-19]. PET, PEN, and cellulose nanopaper are highly flexible and transparent materials but their processing temperatures, 78 °C for PET, 120 °C for PEN, and 200 °C for cellulose nanopaper, prevent their use above these temperatures. The transference of active layers to PET, PEN, or cellulose nanopaper substrates after the annealing process at high temperature is another viable alternative for improving the crystal quality of active layers, though this process is somewhat more complex to undertake [20, 21]. Consequently, determining novel substrate materials with high flexibility, transparency, and thermal stability is a critical necessity for developing flexible and transparent applications.

Muscovite mica sheets are chemically inert, highly transparent, flexible, light-weight, perfectly insulating, and are also stable when exposed to moisture, light, and high temperatures. In addition, they cleave perfectly into very thin pliable sheets whose two principal axes are almost parallel to the cleavage plane, thus providing a sufficiently large sheet of uniform thickness [22]. These outstanding characteristics of mica satisfy the requirements of the substrate material for flexible and transparent applications.

In this work, we will first elucidate the development of our high temperature processed ZnO nanorods on flexible and transparent mica substrates using a hydrothermal method depending on the several growth conditions, including growth temperatures and concentrations of polyethylenimine (PEI) and ammonium hydroxide. Under elaborately managed growth conditions, vertically well-aligned ZnO nanorods with a high aspect ratio were successfully grown on mica substrates. We have fabricated flexible and transparent ZnO nanorod-based DSSCs and piezoelectric nanogenerators (NGs), and investigated the effects of both the growth time and the annealing process on DSSCs and NGs.

The use of mica substrates enabled annealing processes at higher temperatures, which consequently improved the structural and optical properties of ZnO nanorods as well as the transmittance and sheet resistance of ITO/mica substrates. We expect that this approach will provide a breakthrough for overcoming the limited process temperature on plastic substrates for flexible and transparent electronics.

Experimental section

Growth of ZnO nanorods on mica substrates

The mica used as substrates in this research was high quality muscovite mica (Ted Pella Inc.) and the mica sheets were cleaved to ensure high transparency. The cleaved mica substrates were cleaned ultrasonically in acetone for 10 min and then rinsed with deionized (DI) water. ZnO seed layers were deposited on mica substrates using a sol-gel spin-coating method. Specifically, the sol-gel solution was prepared by dissolving 0.005 M zinc acetate dehydrate (Zn(CH3COO)2·2H2O, 99%, Sigma-Aldrich) in ethanol. After spin-coating, the ZnO seed layers were heated at 350 °C for 20 min in order to evaporate the solvent and remove the organic residue. The spin-coating and pre-heating processes were repeated four times. In order to crystallize, the ZnO seed layers were over-heated in an air atmosphere at 500 °C for 30 min.

ZnO nanorods were grown on the ZnO seed layers via a hydrothermal process. The samples were transferred into a Teflon jar that contained an aqueous solution of 0.05 M zinc nitrate hexahydrate (Zn(NO3)2·6H2O, 99%, Sigma-Aldrich), 0.05 M hexamethylenetetramine (C6H12N4, 99.5%, Sigma-Aldrich), 0.005 – 0.015 M PEI (end-capped, molecular weight 800 g/mol LS, Sigma-Aldrich), and 0.1 – 0.4 M ammonium hydroxide (NH4OH, 28 – 30%, Sigma-Aldrich). To investigate the effect of temperature on the nanorod growth, the growth temperature was varied from 75 to 95 °C. After a
reaction for 9 h, the sample was rinsed thoroughly with DI water and air dried naturally.

**Fabrication of DSSCs and NGs**

ITO thin films were deposited as a transparent electrode on mica substrate by sputtering at our laboratory for DSSCs and NGs because the ITO electrode on a mica substrate is currently unavailable commercially. The ZnO nanorod samples grown on ITO were sensitized in a solution of 0.3 mM di-tetrabutylammonium cis-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)ruthenium(II) (N719 dye, Sigma-Aldrich) in ethanol for 24 h. The photoanode was then removed and rinsed with ethanol to remove excess dye adsorbed. A platinum-coated ITO/mica was used as the counter electrode, and the two electrodes were assembled using a 60-μm thick hot-melt sealing foil (Meltonix 1170-60, Solaronix). Silver paste was applied to the external electrodes to reduce contact resistance. The space between the two electrodes was filled with the iodide based electrolyte (Iodolyte AN-50, Solaronix) immediately prior to characterization of the cell performance.

For NGs, a 2-μm thick poly(methyl methacrylate) (PMMA) layer was spin-coated on the ZnO nanorods at the speed of 3000 rpm; the PMMA effectively transmits the bending force equally throughout the ZnO nanorods. An ITO-coated mica substrate was then attached on the PMMA-coated surface via a curing process at 180 °C that was used as the counter electrode. The size of the effective working area of the NG was 1 cm × 1 cm. Schematic diagrams of the fabricated ZnO nanorod-based DSSCs and NGs are shown in Figure 1.

**Characterization**

Field-emission scanning electron microscopy (FE-SEM; Hitachi, S-4800) and transmission electron microscopy (TEM; Hitachi, H-9500) were used to characterize the morphology and crystal size of the ZnO nanorods. The crystallinity and crystal phase of the ZnO nanorods were analyzed by X-ray diffraction (XRD; Rigaku, Ultima IV Diffractometer) using Cu Kα radiation (λ = 1.54 Å). The optical properties of the ZnO nanorods were investigated using Raman spectroscopy (Thermo Scientific, Almega XR) in a backscattering geometry using the 488 nm emission line as an excitation source. The transmittance and sheet resistance of ITO/PET and ITO/mica substrates were compared using an ultraviolet-visible-infrared spectrophotometer (Perkin Elmer, Lambda 900) and a four-point probe, respectively. The photovoltaic performance of DSSCs was obtained by measuring the photocurrent-voltage curves. The cell was irradiated using a solar simulator (Newport, 91160 300 W) with an AM 1.5 spectrum distribution calibrated against a NREL reference cell to accurately simulate a full-sun intensity (100 mW/cm²). The output signal of NGs was recorded via a low-noise voltage preamplifier (Stanford Research Systems, SR560) and a low-noise current preamplifier (Stanford Research Systems, SR570). For comparison, all tests were carried out under the same experimental conditions, in which the applied strain was 0.13% at a strain rate of 2.2% s⁻¹.

**Results and discussion**

We investigated the growth characteristics of ZnO nanorods on mica substrates because there is as yet no data on these...
characteristics. However, it is known that the addition of low-molecular-weight PEI to the solution when using a hydrothermal method results in the creation of ZnO nanorods with a high aspect ratio. The polymer chain of the PEI molecules is effectively adsorbed onto the nonpolar lateral planes of the ZnO nanorod, i.e. (11\overline{2}0) (a-plane) and (10\overline{1}0) (m-plane); as a result, the steric hindrance of the PEI chain inhibits the crystal growth along the faces [23-26]. Consequently, the ZnO nanorods preferentially grow along the c-axis [0001] direction resulting in a high aspect ratio. Figure 2 shows ZnO nanorods grown at 90 °C with the different concentrations of PEI (0 - 0.01 M). At low PEI concentrations (0 and 0.005 M), large ZnO nanorods are sparsely formed by the direct agglomeration among adjacent nanorods, which results in the creation of ZnO nanorods of a non-uniform length and diameter. As the PEI concentration increases, the fluctuation in diameter of the ZnO nanorods decreases, resulting in the acquisition of a relatively uniform group of ZnO nanorods with the PEI concentration of 0.01 M. No ZnO nanorods were found growing on a mica substrate with 0.015 M PEI (Figure S1), which was due to the excessive PEI chain inhibiting the formation of nucleation sites on the ZnO seed layers. 

Figure S2 shows ZnO nanorods grown under temperatures varying from 75 to 95 °C with a constant PEI concentration (0.005 M). The uniformity of the length and diameter of nanorods exhibited an opposite dependence upon growth temperature. Specifically, at the growth temperature of 75 °C, the length of nanorods was non-uniform while the diameter of nanorods was uniform. Conversely, however, the growth at 95 °C exhibited the opposite tendency of a uniform length and a non-uniform diameter. The average length and diameter of nanorods was found to increase with a corresponding increase in growth temperature. At high temperature, the decomposition rate of hexamethylenetetramine was so rapid that the produced OH⁻ was large enough to generate a sufficient and thorough growth of ZnO. Consequently, both the lateral and vertical growth rates largely increased compared to those of the low temperature process [27,28]. In our experiment, the moderate uniformity in length and diameter of nanorods was obtained at the growth temperature of 85 °C.

In a hydrothermal method, a ZnO crystal is also formed into white precipitates in the bulk solution through a homogeneous nucleation because of a high degree of supersaturation with respect to ZnO or Zn(OH)₂ in the reaction system. The homogeneous nucleation can be suppressed effectively with the introduction of ammonium hydroxide into the reaction solution. The coordination of ammonia to zinc ion results in complexes based on the following reaction: \( \text{Zn}^{2+} + n\text{NH}_3 \rightarrow \text{Zn}((\text{NH}_3)_n)^{2+} \), where \( n = 1, 2, 3, \) or 4. These complexes also serve as a buffer for \( \text{Zn}^{2+} \) and continuously supply \( \text{Zn}^{2+} \) while lowering the degree of supersaturation in the reaction mixture [24,27]. Moreover, the degree of supersaturation has less effect on the crystal growth rate of nanorods on the seeded substrate compared to the homogeneous nucleation [29]. Therefore, introducing ammonium hydroxide into the reaction mixture can suppress the homogeneous nucleation and thus reduce ZnO precipitates in the bulk solution while maintaining moderate growth rate of ZnO nanorods on the seeded substrate.

In order to investigate the effects of ammonium hydroxide on the size of ZnO nanorods grown on mica substrates, ZnO nanorods were grown at ammonium hydroxide concentrations ranging from 0.1 M to 0.25 M with a constant PEI concentration (0.005 M) and growth temperature (85 °C). The average length and diameter of nanorods increased with a corresponding increase in the concentrations of ammonium hydroxide (Figures 3 and S3). However, at an ammonium hydroxide concentration over 0.25 M, the growth of ZnO nanorods did not entirely cover the surface of the mica substrate because of a very low degree of supersaturation and of a deviation of the suitable pH range for the growth of ZnO nanorods [30]. Specifically, the direct agglomeration among the adjacent nanorods became severe with an excess of ammonium hydroxide beyond 0.2 M. As previously stated, a higher ammonium hydroxide concentration within the moderate pH ranges provides more zinc ions for the growth of ZnO nanorods on the seeded substrates while suppressing the homogeneous nucleation. Consequently, a larger PEI polymer chain is necessary to ensure the inhibition of crystal growth along the lateral planes and a preferential growth of ZnO in the direction of the c-axis [0001]. In this experiment, an insufficiency of PEI over the 0.2 M ammonium hydroxide is expected. Therefore, to grow ZnO nanorods with a high aspect ratio, the lateral growth must be effectively inhibited, which requires controlling the growth conditions of temperature and the concentrations of both PEI and ammonium hydroxide.

The coupled use of PEI and ammonium hydroxide was most successful in growing vertically well-aligned ZnO nanorods on mica substrates under 0.01 M PEI and 0.4 M ammonium hydroxide at 85 °C for 9 h (Figure 4a and b). The average length and diameter of nanorods were about 5 μm and 170 nm, respectively. TEM analysis was carried out for further structural characterization. Prior to the TEM measurement, ZnO nanorods were dispersed ultrasonically from the mica substrate in acetonitrile for 30 min, and then a few drops of this mixture (ZnO in acetonitrile) were placed on the copper TEM grids and dried for subsequent observation. A low-magnification TEM image of the ZnO nanorod is shown in Figure 4c. The inconsistency in the length (1.25 μm) of the nanorod compared to FE-SEM result is because the ZnO nanorods were mechanically broken when peeled away from the substrate by sonication. A high-resolution TEM (HRTEM) image of the ZnO nanorod is shown in Figure 4d. The measurement of the lattice spacing is 0.26 nm, which is a close approximation of the literature value for the distance between (0001) planes in the ZnO crystal, indicating that the ZnO nanorods preferentially grow along direction of the c-axis [0001] [31-33]. Fast Fourier transform (FFT) pattern (Figure 4d, inset), performed on individual nanorod, showed the single crystalline of the ZnO nanorods with the hexagonal wurzite phase growing in the [0001] direction.

To investigate annealing effects on the structural and optical properties of ZnO nanorods grown on mica substrates, a post-growth annealing process was conducted at 500 °C for 30 min. Figure 5a shows the XRD patterns of the as-grown and annealed ZnO nanorods. Two ZnO diffraction peaks were observed, at 34.48° and 72.54°, respectively, which correspond to the subsequent respective ZnO crystallographic reflections: (002) and (004). Except for the peaks from the mica substrate which are marked with an asterisk in Figure 5a, all of the peaks in the obtained spectrum were well-indexed to the hexagonal ZnO phase, indicating the
single-phase structure of all ZnO nanorods [34]. The intensity of the ZnO(002) diffraction peak was higher compared to that of the standard ZnO diffraction pattern, which indicates a preferential growth direction along the c-axis.

The optical properties of the ZnO nanorods were investigated using spontaneous Raman scattering. ZnO has a wurtzite crystal structure and belongs to the $C_{6v}$ space group with two formula units per primitive cell, where all the atoms occupy the $C_{3v}$ symmetry. Near the center of the Brillouin zone, group theory predicts the existence of the following phonon modes: $\Gamma = A_1 + 2B_1 + E_1 + 2E_2$. $B_1$ modes are forbidden while $A_1$, $E_1$, and $E_2$ modes are (Raman)

Figure 2  FE-SEM images of the ZnO nanorods grown at different PEI concentrations: (a and b) 0 M, (c and d) 0.005 M, (e and f) 0.0075 M, and (g and h) 0.01 M. The growth temperature and time are 90 °C and 9 h, respectively. The scale bar in the images is 1 μm.
allowed. Additionally, $A_1$ and $E_1$ are also infrared active and split into two components, i.e., transverse optical (TO) and longitudinal optical (LO) components [35]. The frequencies of Raman active phonon modes in ZnO are as follows: $E_2$ (low) = 102 cm$^{-1}$, $E_2$ (high) = 437 cm$^{-1}$, $E_1$ (TO) = 410 cm$^{-1}$, $E_1$ (LO) = 591 cm$^{-1}$, $A_1$ (TO) = 379 cm$^{-1}$, and $A_1$ (LO) = 577 cm$^{-1}$ [36]. Figure 5b shows the Raman scattering spectra of the as-grown and annealed ZnO nanorods. A sharp and strong peak at 438.5 cm$^{-1}$ is assigned to the $E_2$ (high frequency) optical phonon mode of the ZnO, which is a characteristic of the hexagonal wurtzite phase of ZnO [37]. Two weak peaks located at 380.7 cm$^{-1}$ and 577.4 cm$^{-1}$ are

![Figure 3](image-url) FE-SEM images of the ZnO nanorods grown at different ammonium hydroxide concentrations: (a) 0.1 M, (b) 0.15 M, (c) 0.2 M, and (d) 0.25 M. The growth temperature and concentration of PEI are 85 °C and 0.005 M, respectively. The scale bar in the images is 1 μm. (e) Average length of the nanorods as a function of ammonium hydroxide concentration.

![Figure 4](image-url) FE-SEM images of the ZnO nanorods grown in the solution containing 0.01 M PEI and 0.4 M ammonium hydroxide at 85 °C: (a) cross-sectional view and (b) tilted view. The scale bar in the images is 1 μm. (c) Low-magnification TEM image of the ZnO nanorod. (d) HRTEM image of the ZnO nanorod with its corresponding FFT pattern (inset).
assigned to $A_1$ (TO) and $A_1$ (LO) modes, respectively. The very low intensity of the $E_1$ (LO) mode at 591 cm$^{-1}$ indicates that the ZnO nanorods are of good crystal quality as the $E_1$ (LO) mode is associated with structural defects (zinc interstitials or oxygen vacancies) and impurities in the ZnO crystal.

In addition, the annealing effects on transmittance and sheet resistance of ITO/PET and ITO/mica substrates were investigated to compare the characteristics of the ITO electrode on the two different substrates treated by the different process temperature, which also greatly affected device performances. Figure 5c shows the optical transmittance spectra and top-view photographs of PET (black), mica (orange), ITO/PET (red), ITO/mica (green), and annealed ITO/mica (blue). The transmittance spectrum of mica is similar to that of the PET with the sharp
oscillatory features of mica falling in the range of 700 – 1100 nm; these Fabry–Perot interference effects were identified from internal reflections in the atomically layered structures of the mica [38]. The growth of ITO thin films resulted in a subsequent and significant decrease in transmittance in both PET and mica substrates. However, the transmittance of ITO/mica substrates did realign with its original values after an annealing process that peaked at 500°C for 30 min, while the thermal annealing process could not be conducted on the ITO/PET configuration. The sheet resistance of the ITO/mica substrates also decreased by 80% after the annealing process (Figure 5d) due to the increased grain size and carrier concentration [13,14]. The transmittance at 550 nm and sheet resistance of the ITO/PET and ITO/mica substrates are summarized in Table 1.

Furthermore, we also achieved a much greater coverage and much improved adhesion properties of ZnO nanorods on the mica substrate (Figure 5e and f). In our observations of the non-growth regions of the ZnO nanorods on PET we noted that most ZnO nanorods peeled off from the PET substrate after a bending of 1000 cycles with a bending radius of 5 mm. However, under these conditions ZnO nanorods on the mica neither peeled off nor became brittle. This discrepancy is because the temperature of the spin-coating process for the ZnO seed layers on the mica was high enough to evaporate organic residues and crystallize the ZnO seed layers, while the process temperature for the ZnO seed layers on the PET was limited to 100°C to prevent heat damage and distortion from the process. The comparison of the thermal treatment processes for PET and mica substrates is summarized in Table S1.

Figure 6 shows photocurrent density–voltage characteristics of the DSSCs using different growth and annealing schemes: sample A (9 h-growth), sample B (18 h-growth), sample C (9 h-growth and post-growth annealing), and sample D (18 h-growth and post-growth annealing). No increase in the length of nanorods over the 18 h-growth (Figure S4) was observed because of a complete depletion of Zn(NO₃)₂·6H₂O in solution. Longer growth time and an annealing process induced an increase in both the open circuit voltage (V_{oc}) and short circuit current density (J_{sc}). As a result, the efficiency was increased by 42% with an increase in growth time from 9 to 18 h, while the efficiency increased by 53% after a post-growth annealing process for the 9 h-growth samples. Finally, the DSSCs based on the

### Table 1 Comparison of transmittance and sheet resistance of the ITO/PET and ITO/mica substrates.

<table>
<thead>
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<th>Transmittance at 550 nm (%)</th>
<th>Sheet resistance (Ω/sq)</th>
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<tbody>
<tr>
<td>PET</td>
<td>87.9</td>
<td>N/A</td>
</tr>
<tr>
<td>Mica</td>
<td>86.0</td>
<td>N/A</td>
</tr>
<tr>
<td>ITO/PET</td>
<td>60.3</td>
<td>731.6 ± 44.5</td>
</tr>
<tr>
<td>ITO/mica</td>
<td>55.3</td>
<td>732.4 ± 37.0</td>
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<tr>
<td>Annealed ITO/mica</td>
<td>84.3</td>
<td>147.1 ± 4.4</td>
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ZnO nanorods (18 h-growth and post-growth annealing) exhibited an efficiency of 0.69% with J_{sc} (3.95 mA/cm²) and V_{oc} (0.65 V).
We then investigated the annealing effects on the NG’s performance by preparing two types of NG devices: one fabricated by using as-grown ZnO nanorods and the other by using post-growth annealed ZnO nanorods. As shown in Figure 7a and b, the output voltage and output current density for the as-grown ZnO nanorod-based NG were approximately 0.5 V and 25 nA/cm², respectively. However, when we used the post-growth annealed ZnO nanorods, the output voltage was approximately 1.5 V, with an output current density approaching 80 nA/cm². Both the output voltage and output current density when the post-growth annealed ZnO nanorods were used were approximately three times higher than the output voltage and output current density obtained from the as-grown ZnO nanorods. In other words, this post-growth annealing process of the ZnO nanorods improves the crystal quality by reducing oxygen-vacancy-related defects, which consequently leads to an increase of piezoelectric potential in the ZnO nanorods under the same external conditions. Since the output of the piezoelectric NG is proportional to the piezoelectric potential created in piezoelectric nanorods, the output performance of the post-growth annealed ZnO nanorod-based NG is increased.

In this work, ITO thin films were deposited on mica substrates in our laboratory because ITO/mica is currently unavailable commercially. To compare the performance of our devices under study, ITO thin films were also deposited on PET substrates. Results indicated that the DSSCs using ITO/PET showed a markedly inferior performance. This deficiency was perhaps due to the lower transmittance and higher sheet resistance of the ITO on PET as well from poor coverage of the ZnO nanorods on PET compared to those on mica as shown in Figure 5c–f. It was also observed that a use of mica substrates narrowed the full width at half maximum (FWHM) of the ZnO(002) diffraction peak compared to PET substrates, which indicated that the ZnO nanorods grown on a mica substrate exhibited a better crystal quality (Figure S5).

Results of both the DSSCs and NGs confirmed that an adoption of the mica substrates permitted a thermal annealing process, which induced the favorable characteristics of improved crystal quality of the active layer and an increased transmittance (by 52% at 550 nm) and decreased sheet resistance (by 80%) of ITO, thus largely improving the overall device performances.

Figures 7a and 7b illustrate the measured output performance of the NG based on as-grown ZnO nanorods (black) and post-growth annealed ZnO nanorods (red): (a) output voltage and (b) output current density.

In other words, this post-growth annealing process of the ZnO nanorods improves the crystal quality by reducing oxygen-vacancy-related defects, which consequently leads to an increase of piezoelectric potential in the ZnO nanorods under the same external conditions. Since the output of the piezoelectric NG is proportional to the piezoelectric potential created in piezoelectric nanorods, the output performance of the post-growth annealed ZnO nanorod-based NG is increased.

Conclusions
Mica substrates were first used for the ZnO nanorod-based DSSCs and NGs because of their high flexibility and transparency. Through the coupled use of PEI and ammonium hydroxide, vertically well-aligned ZnO nanorods were successfully grown on mica substrates under 0.01 M PEI and 0.4 M ammonium hydroxide at 85 °C for 9 h. The XRD and Raman scattering measurements indicated that the ZnO nanorods exhibited a good crystal quality with a hexagonal wurtzite structure. The adoption of mica as a substrate material permitted the use of high temperature annealing processes to significantly improve adhesion of ZnO nanorods/ZnO seed layers/ITO/mica as well as transmittance and conductance of ITO/mica. Longer growth times and a post-growth annealing process of ZnO nanorods largely improved the performance of solar cells. Furthermore, the post-growth annealing process of ZnO nanorods led to an increase of the output performance of the NG. In this study, the authors simultaneously presented the potential for flexible and transparent hybrid systems (solar cells/displays/batteries), including medical devices that could serve as the mechanism with which to develop the next generation of mobile technologies.

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Appendix A. Supporting information

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References


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Zong-Hong Lin received his Ph.D. degree from Department of Chemistry, National Taiwan University in 2009. Now he is a postdoctoral researcher working with Professor Zhong Lin Wang in the School of Material Science and Engineering, Georgia Institute of Technology. His research interests include the development of high-output generators with novel design for efficient energy harvesting, self-powered systems for biomolecules detection and environmental sensors, highly efficient and stable catalysts for fuel cell applications, and fabrication of metal/semiconductor nanowires.
Kyoung Hwan Choi received his M.S. and Ph.D. degrees in Chemical Engineering from Yonsei University in 1995 and 1998, respectively. He has joined Samsung Advanced Institute of Technology (SAIT) at Samsung Electronics in 1999 and researched the electrochemical devices for residential and portable applications. He had been a group leader of Fuel Cell Group since 2009. His current research interests are new devices and materials for next-generation energy storage and generation.

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Zhong Lin Wang received his Ph.D. in Physics from Arizona State University. He is the HighTower Chair in Materials Science and Engineering, Regents’ Professor, Engineering Distinguished Professor and Director, Center for Nanostructure Characterization, at Georgia Institute of Technology. Dr. Wang has made original and innovative contributions to the synthesis, discovery, characterization and understanding of fundamental physical properties of oxide nanobelts and nanowires, as well as applications of nanowires in energy sciences, electronics, optoelectronics and biological science. His discovery and breakthroughs in developing nanogenerators established the principle and technological road map for harvesting mechanical energy from environment and biological systems for powering a personal electronics. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices.

Sung-O Kim is currently an assistant professor in the Holcombe Department of Electrical and Computer Engineering and the Center for Optical Materials Science of Engineering Technology (COMSET) at Clemson University. His research interests include plasma medicine, micro-plasma devices, plasma polymerization, flat panel displays, and nanomaterials for flexible electronics. He earned his B.S. degree in Electrical Engineering from Hanyang University in 1996. He also received his M.S. and Ph.D. in Electrical Engineering from Inha University in 1998 and 2000, respectively. Dr. Kim has served in the Department of Photonics and the Display Institute as a faculty at National Chiao Tung University (NCTU) from 2004 to 2008. Prior to joining NCTU, he was a postdoctoral research fellow (2001–2004) in the University of Illinois at Urbana-Champaign (UIUC). Prior to joining the UIUC, he worked for Samsung SDI (2000–2001). He is a member of IEEE, Society of Information Display, American Vacuum Society, American Physical Society, and American Chemical Society.