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# Characterization of pulsed laser deposited bismuth oxide ultrathin-film enhanced photovoltaic properties of InGaN solar cells

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## 1. Introduction

GaN of III-V materials have attracted interesting in the development of optoelectronic devices, such as light-emitting diodes (LEDs) and solar cells [1]. InGaN-based solar cells with the multijunction structures exhibited the photovoltaic characteristic. Unfortunately, most of the reported InGaN solar cells show very low power conversion efficiency of less than 2% [2]. This large discrepancy in efficiency originates from the difficulty in obtaining high-In-content InGaN alloy with good crystalline quality. In order to obtain more high efficiency, we believe better utilization of solar spectrum is necessary. Recently, the science of organic/inorganic nanocomposites is extremely promising for applications in LEDs, photodiodes, and solar cells [3]. Bismuth oxide ($Bi_2O_3$) of inorganic metal oxide material is an interesting material, due to its strong absorption to visible light and intrinsic polarizability, $Bi_2O_3$ could be enhancement the photovoltaic properties [4]. The concept of $Bi_2O_3$ ultrathin-film has, to our knowledge, not yet been applied to InGaN solar cells. Therefore, InGaN solar cells configuration combined $Bi_2O_3$ effects improvement the power conversion efficiency of photovoltaic have not been studied so far.

In this study, we investigate the photovoltaic properties of $Bi_2O_3$ ultrathin-films on InGaN solar cells. InGaN-based solar cell structures with $Bi_2O_3$ ultrathin-film were prepared through a pulsed laser deposition (PLD) method. The wavelength of the photovoltaic efficiency has enhanced by increasing the light absorption at $Bi_2O_3$ ultrathin-film.

## 2. Experiment

InGaN-based solar cell structures were grown on the sapphire substrate by using a metalorganic chemical vapor deposition (MOCVD) system. These solar cell structures consisted of a 30 nm-thick GaN buffer layer, a 12 µm-thick n-type GaN layer, 10 pairs of the InGaN/GaN MQW active layers, and a 0.4 µm-thick p-type GaN layer. The mesa region of 45 x 45 mil$^2$ was defined by the inductively coupled plasma (ICP) etch. A 200 nm-thick indium-tin-oxide layer (ITO) was deposited on the mesa region as a transparent contact layer (TCL). The Ni/Au metal layers were deposited as n-type and p-type contact pads. After fabrication, the nanocrystalline ultrathin-film $Bi_2O_3$ was deposited on InGaN solar cells by PLD method.

$Bi_2O_3$ ultrathin-films under study were prepared by PLD method. The high purity (99.99%) $Bi_2O_3$ were compressed into pellets with 25 mm diameter and 5 mm height and sintered at 600℃ for 12 hours under air atmosphere. $Bi_2O_3$ films were deposited on a substrate in a chamber (depositing pressure ~ 27 Pa of oxygen partial pressure) using a KrF ($\lambda$ = 248 nm) excimer laser (Lambda Physik LPX Pro) to bombard a sample target. The power density of the focused laser on the target is 5–6 J/cm$^2$, and the repetition rate is 1 Hz. To make targets, the starting materials of $Bi_2O_3$ (99.99%) powders were ground and pressed into disk. Then, the disk was sintered at 600 ℃ for 12 hours under air atmosphere. The final sizes of targets are roughly 1 inch in size. The target- substrate distance is approximately 50 mm. The substrate temperature during deposition is 150 ℃. The deposition rate of $Bi_2O_3$ film is about 0.5 Å/shot. In addition, the surfaces of the targets were polished before each deposition to improve reproducibility. InGaN solar cell devices that were fabricated through this process flow without deposited $Bi_2O_3$ were defined as the standard devices.

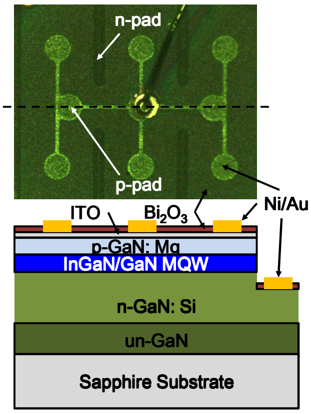


Figure 1. InGaN solar cell device structures with the $Bi_2O_3$ films.

After sample preparation, the $Bi_2O_3$ nanocrystalline structure and growth mechanism were investigated by means of X-ray diffraction (XRD). Fig. 2 shows the XRD patterns of the $Bi_2O_3$ sample. The pattern feature can be well indexed by the diffraction peaks of $Bi_2O_3$. This $Bi_2O_3$ has a monoclinic symmetry with a space group. The $Bi_2O_3$ is a stable low temperature polymorph, which is reported to be monoclinic. In our sample, the diffraction peaks at angles $2\theta = 28^\circ$ and $58.3^\circ$ which are corresponding to (201) and (402) planes, respectively, for tetragonal $\beta$-$Bi_2O_3$ structure (JCPDS: 27-0050).

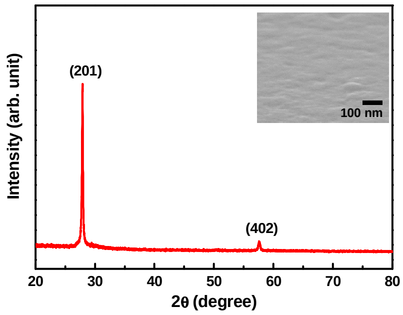


Figure 2. XRD of $Bi_2O_3$ ultrathin-film was produced by PLD.

## 3. Results and Discussion

Fig. 3 indicates the UV-vis absorbance spectra of the InGaN solar cell devices. It can be seen that the maximum light absorption peaks at 375 nm and 466 nm. This could be explained by the size quantization effect the first excited electronic state (the fundamental absorption edge) of a quantum dot is expected to show a shift to lower wavelengths (higher energies) with respect to the band gap absorption edge of the corresponding bulk material [5].

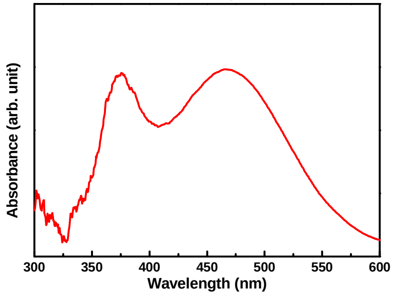
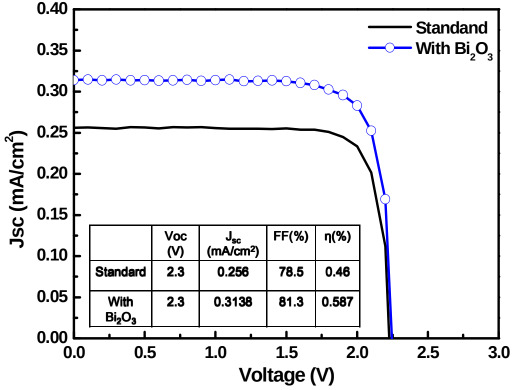


Figure 3. UV-vis absorbance spectra of the $Bi_2O_3$ ultrathin-films.

The photovoltaic efficiency of the InGaN solar cell with and without $Bi_2O_3$ ultrathin-film were also analyzed using a Keithley 236 source meter, and a monochromatic illumination that was obtained by using 500 W Xe lamp with a monochromator. Fig. 4 shows the photovoltaic current density-voltage ($J_{sc}$-$V$) characteristics of the InGaN solar cells with and without $Bi_2O_3$ ultrathin-film. In Fig. 4, the open-circuit voltage ($V_{oc}$) and short-circuit current density ($J_{sc}$) of all the device structures were also measured under the illumination of AM 1.5G condition. All the device structures had the same $V_{oc}$ values of 2.3 V. A strong enhancement of the short-circuit current density ($J_{sc}$) from 0.256 to 0.3138 mA/cm$^2$ and the power conversion efficiency $\eta$ form 0.46% to 0.587% was observed between the standard and the $Bi_2O_3$ ultrathin-film, and this corresponds to a 21.6% increase in overall efficiency as indicated in Fig. 4. Furthermore, the external quantum efficiency (EQE) of the photovoltaic characteristics as a function of the illuminated wavelength was also measured. The peak EQE values of InGaN solar cells were measured at 0.65 and 0.8 for the without and with $Bi_2O_3$ ultrathin-film, at wavelength 375 nm, respectively.

The power conversion efficiency enhancement 21.6% reason for such case is that, one can conclude that after photon absorption by $Bi_2O_3$ of inorganic semiconductor, it is likely that the created electron-hole pair of free carrier. The $Bi_2O_3$ is an electron acceptor that can transfer the electron to metal oxide of the electron acceptor material. As a result, the $Bi_2O_3$ is with the electron-hole carrier that can drift through the film to the anode of $p$-GaN while the electron carrier is in the acceptor material and can be transported to the cathode of $n$-GaN.



| | Voc (V) | $J_{sc}$ (mA/cm$^2$) | FF(%) | η(%) |
|---|---|---|---|---|
| Standard | 2.3 | 0.256 | 78.5 | 0.46 |
| With $Bi_2O_3$ | 2.3 | 0.3138 | 81.3 | 0.587 |

Figure 4. Typical $J_{sc}$-$V$ characteristics of devices taken from the photovoltaic solar cells illuminated under the AM1.5G spectrum. Inset of measured photovoltaic parameters.

## 4. Conclusion

In this study, the InGaN solar cell structures with the $Bi_2O_3$ ultrathin-film were formed through a PLD process. The enhanced power conversion efficiency of the InGaN solar cell with the $Bi_2O_3$ ultrathin-film was investigated. The $Bi_2O_3$ ultrathin-film offered more photon down conversion capability through a higher light absorbance process increased the power conversion efficiency. As compared to the standard InGaN solar cells, an increase of 21.6% in power conversion efficiency was achieved. We believe that this $Bi_2O_3$ ultrathin-film design could provide an efficient improvement in InGaN solar cells and other related photovoltaic applications in the future.

## Acknowledgement

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