Research Article

Characteristics of GaN/InGaN Double-Heterostructure Photovoltaic Cells

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Received 29 March 2012; Revised 18 June 2012; Accepted 26 June 2012

Academic Editor: Wayne A. Anderson

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The p-GaN/i-In_xGa_{1-x}N/n-GaN double-heterostructure photovoltaic (PV) cells have been fabricated and the theoretical photovoltaic properties were also calculated in this work. From theoretical simulation, higher efficiency can be obtained in GaN/InGaN double-heterostructure photovoltaic cells with higher In composition in i-InGaN intrinsic layer. GaN/InGaN double-heterostructure photovoltaic cells with In compositions of 10%, 12%, and 14% were fabricated and characterized for demonstrating with the simulated results. The corresponding photoelectrical conversion efficiency of fabricated GaN/InGaN photovoltaic cells with In compositions of 10%, 12%, and 14% is 0.51%, 0.53%, and 0.32% under standard AM 1.5G measurement condition, respectively. GaN/InGaN photovoltaic cells with In composition of 10% showed high open-circuit voltage (V_{oc}) of 2.07 V and fill factor (F.F.) of 80.67%. The decrease of V_{oc} and FF was observed as In composition increasing from 10% to 14%. For comparing with the fabricated GaN/InGaN photovoltaic cells, theoretical conversion efficiency of GaN/InGaN photovoltaic cells with In compositions of 10%, 12%, and 14%, is 1.80%, 2.04%, and 2.27%, respectively. The difference of GaN/InGaN photovoltaic properties between theoretical simulation and experimental measurement could be attributed to the inferior quality of InGaN epilayer and GaN/InGaN interface generated as the increase of In composition.

1. Introduction

GaN-based material system has been extensively investigated in light-emitting diodes (LEDs) [1], laser diodes (LDs) [2], and solar-blind photodetectors (PDs) [3] applications. With the revised band gap of InN [4], InGaN material can be varied continuously from the infrared (0.7 eV) to the ultraviolet (3.4 eV) region. InGaN-based ternary alloys showed an optical match to most of the solar spectrum and were suitable for photovoltaic (PV) applications [5, 6]. However, several critical issues in In-rich InGaN would limit the photovoltaic characteristics, such as conductivity in p-type InGaN alloy, high In incorporation in InGaN material, and epitaxial growth of thick InGaN film. The p-GaN/i-InGaN/n-GaN double-heterostructure photovoltaic cells

have been experimentally demonstrated with open-circuit voltage (V_{oc}) of approximately 2.4 V and internal quantum efficiency (IQE) of approximately 60% [5]. In this study, the photovoltaic properties of double-heterostructure p-GaN/i-InGaN/n-GaN photovoltaic cells with In composition of 10%, 12%, and 14% were fabricated and characterized under standard AM 1.5G measurement condition. Theoretical photovoltaic properties of the fabricated GaN/InGaN photovoltaic cells were also calculated for comparison with the measured photovoltaic properties.

2. Theoretical Efficiency Calculation Model

Figure 1 shows the light absorption route inside the GaN/InGaN photovoltaic cells, including surface transparent

FIGURE 1: Light absorption route inside the GaN/InGaN photovoltaic cell. Inset graph: absorption rate of incident light within the GaN-based material.

conduction layer (ITO film), p-GaN top layer, i-InGaN active layer, and n-GaN layer. High absorption coefficient of GaN-based material ($>10^5 \text{ cm}^{-1}$ at the band edge) has been indicated in the literature [7]. The inset graph in Figure 1 shows that about 99% of the incident light was absorbed in the GaN/InGaN photovoltaic cells within the first 500 nm. The thickness of p-GaN layer was designed of 150 nm to maximize the light absorbed by i-InGaN active layer and offer good p-ohmic property. To obtain good epitaxial quality of GaN/InGaN double heterostructure, the thickness of i-InGaN active layer with In composition of 10%, 12%, and 14% were all defined of 150 nm.

Theoretical photovoltaic properties were calculated for comparison with the measured photovoltaic properties of the p-i-n GaN/InGaN photovoltaic cells fabricated in this work. In our simulation model, photovoltaic efficiencies were calculated based on some assumptions listing below. (1) Perfect quantum response of the GaN/InGaN materials; (2) photocurrent induced from the electron and hole pairs were generated from incident photons of energy $h\nu > E_g$; (3) no transmission loss during the collection of photo-induced carriers; (4) AM 1.5G solar spectrum illumination was performed based on American Society for Testing and Materials (ASTM).

Short-circuit current density (J_{SC}) is given by the photocurrent density (J_{ph}) of the GaN/InGaN photovoltaic cells. The photocurrent density is produced from the incident

photons with $h\nu > E_g$ [8]. Then, photocurrent density of the GaN/InGaN photovoltaic cells can be defined as

$$J_{ph} = q \int Q_s(\lambda) [1 - e^{-\alpha(\lambda)d}] d\lambda, \quad (1)$$

where q is the electron charge, Q_s is the number of photons with $h\nu > E_g$ per unit area and unit time, α is the absorption coefficient of the materials, and d is the thickness of the absorption layer.

The current density-voltage (J - V) function of the GaN/InGaN photovoltaic cells under illumination is given by

$$J = J_{SC} - J_0 (e^{qV/kT} - 1), \quad (2)$$

where J_0 is the saturation current density, k is the Boltzman constant, and T is the temperature. The saturation current density J_0 can be calculated from

$$\begin{aligned} J_0 &= qn_i^2 \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right) \\ &= qN_C N_V \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right) \exp\left(-\frac{E_g}{kT}\right), \end{aligned} \quad (3)$$

where n_i is the intrinsic carrier concentration. The electronic properties of the GaN and InGaN system, such as D_n , D_p , L_n , and L_p , were cited from [9].

From (2), the open-circuit voltage ($J = 0$) can be expressed as

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{J_{SC}}{J_0} + 1\right). \quad (4)$$

Then, the maximum power (P_m) can be obtained from the differential of (2), and the photo-electrical conversion efficiencies of the GaN/InGaN photovoltaic cells can be defined as

$$\eta = \frac{P_m}{P_{in}} = \frac{V_{OC} \times J_{SC} \times FF}{P_{in}}, \quad (5)$$

where P_{in} is the incident irradiance per unit area in mW/cm^2 .

3. Experiments

The p-GaN/i-InGaN/n-GaN double-heterostructure photovoltaic cells were grown on 2-inch c-plane sapphire substrates by MOCVD using the conventional two-step growth process. The growth details have been described elsewhere [6]. The p-i-n GaN/InGaN photovoltaic structure consists of $3\mu\text{m}$ n-GaN, $0.15\mu\text{m}$ InGaN, and $0.1\mu\text{m}$ p-GaN top layer. Transmission electron microscopy (TEM), photoluminescence (PL), and high-resolution X-ray diffraction (HRXRD) properties demonstrate the epitaxial quality of GaN and InGaN layers. To investigate PL properties of InGaN layer and GaN/InGaN heterostructures without p-GaN capping layer were intentionally grown. The GaN/InGaN photovoltaic cells with a size of $1 \times 1\text{ mm}^2$ was designed and fabricated and the photovoltaic performance of the fabricated GaN/InGaN photovoltaic cells were measured under standard AM 1.5G measurement condition.

4. Results and Discussions

Figure 2 shows the XRD images and PL images (inset graph) of GaN/InGaN photovoltaic cells with In compositions of 10%, 12%, and 14%. The peak wavelength (λ_{peak}) and fullwidth at half maximum (FWHM) were listed in Table 1. The measured peak wavelength of GaN/InGaN photovoltaic cells with In compositions of 10%, 12%, and 14% were 393.65 nm, 402.34 nm, and 408.30 nm, respectively. The FWHM of GaN/InGaN photovoltaic cells with indium composition of 10%, 12%, and 14% were 198.0 arcsec, 205.2 arcsec, and 237.6 arcsec, respectively. The epitaxial quality of i-InGaN film of GaN/InGaN photovoltaic cells showed degradation as In composition increasing. Figures 3(a), 3(b), and 3(c) showed the cross-sectional TEM images of GaN/InGaN interfaces with In composition of 10%, 12%, and 14%, respectively. The GaN/InGaN photovoltaic cell with 10% In composition gives an abrupt interface and there is no phase-separated In-rich quantum dots (QDs) or dislocations that were not observed in the InGaN active layer. However, as In composition increasing to 14%, rough GaN/InGaN interface and dark spots occurred within the i-InGaN active layer and the GaN/InGaN interface. The dark regions shown in the TEM image could be caused from the phase-separated In-rich QDs and such a result showed a

FIGURE 2: XRD images of GaN/InGaN photovoltaic cells with 10%, 12%, and 14% In compositions. Inset graph: PL images of GaN/InGaN photovoltaic cells.

TABLE 1: Peak wavelength and XRD FWHM of GaN/InGaN photovoltaic cells with In compositions of 10%, 12%, and 14%.

GaN/InGaN PV cells	In = 10%	In = 12%	In = 14%
λ_{peak} (nm)	393.65	402.34	408.30
FWHM of InGaN film (arcsec)	205.2	198.0	237.6

match with the degradation of FWHM measured from XRD analysis and photovoltaic properties.

Double-heterostructure GaN/InGaN photovoltaic cells with In compositions of 10%, 12%, and 14% were also theoretically calculated for comparison. Figure 4 showed the theoretical photovoltaic characteristics of the GaN/InGaN photovoltaic cells with In composition of 10%, 12%, and 14%, and all the related photovoltaic characteristics were listed in Table 2. For comparison, the photovoltaic characteristics of fabricated GaN/InGaN photovoltaic cells measured under standard AM 1.5G solar illumination were also shown in Figure 4. With the increase in In composition from 10% to 14%, the open-circuit voltage decreases and short-circuit current density increases as the energy gap getting small with higher In doped. It is worth to notice, however, the open-circuit voltage of the fabricated photovoltaic cells shows dramatically decay as the In composition increases from 10% to 14%. Such a phenomenon can be attributed to the degradation of epitaxial quality of GaN/InGaN double heterostructure as the increase of In composition. Besides the increase of lattice mismatch between GaN and InGaN, phase separation induced from the low miscibility of InN in GaN also limited the performances of the photovoltaic cell with high In composition [10]. Phase separation caused from high In doping in active InGaN layer may dominate the properties of light absorption and cause the decrease in open-circuit voltage.

FIGURE 3: Cross-sectional TEM images of GaN/InGaN interface of (a) 10%, (b) 12%, and (c) 14% In composition.

FIGURE 4: J - V characteristics of GaN/InGaN double-heterostructure photovoltaic cells under experimental measurement and theoretical simulation.

However, double-heterostructure GaN/InGaN photovoltaic cell with In composition of 10% showed high open-circuit voltage of 2.07 V and fill factor over 80% under the standard AM 1.5G solar illumination. Such a good photovoltaic effect can be contributed to the negligible leakage current obtained from dark current-voltage characteristics, which has been shown in Figure 5 [6]. Figure 6 showed the ideality factor derived from the dark I - V curve of the GaN/InGaN photovoltaic cells. As the In compositions increasing, the GaN/InGaN photovoltaic cells showed higher ideality factor value at low voltages which could be attributed to the decrease of shunt resistance due to the degradation of epitaxial quality. The series and shunt resistance of GaN/InGaN photovoltaic cells with In composition of 10%, 12%, and 14% were listed in Table 3. The GaN/InGaN photovoltaic cell with In composition of 14% shows a relative low fill factor caused from the increase of series resistance

FIGURE 5: The dark I - V curve of the GaN/InGaN photovoltaic cells with 10%, 12%, and 14% In composition.

and decrease of shunt resistance shown in Figure 4. The results could be referred to the difference of conversion efficiency between the theoretical calculation and measured photovoltaic properties of GaN/InGaN photovoltaic cells.

5. Conclusions

GaN/InGaN double-heterostructure photovoltaic cells have been fabricated and their photovoltaic characteristics were also been theoretically calculated in this work. The theoretical conversion efficiency for GaN/InGaN photovoltaic cells with In composition of 10%, 12%, and 14% were 1.80%, 2.04%, and 2.27%, respectively. GaN/InGaN photovoltaic cell with In composition of 10% shows reasonably high V_{oc} and high fill factor of over 80% measured under standard AM 1.5G solar illumination. Such a good photovoltaic performance can be contributed to the good epitaxial quality

TABLE 2: Photovoltaic properties of GaN/InGaN double-heterostructure photovoltaic cells with In compositions of 10%, 12%, and 14% under experimental measurement and theoretical simulation.

GaN/InGaN PV cells	In = 10%		In = 12%		In = 14%	
	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment
V_{OC} (V)	2.66	2.07	2.59	1.83	2.55	1.57
J_{SC} (mA/cm ²)	0.72	0.31	0.83	0.42	0.94	0.46
FF (%)	94.54	80.16	94.43	69.09	94.35	41
η (%)	1.80	0.51	2.04	0.53	2.27	0.3

FIGURE 6: The ideal factors of GaN/InGaN photovoltaic cells with 10%, 12%, and 14% In composition.

TABLE 3: The series and shunt resistance of fabricated GaN/InGaN photovoltaic cells with In composition of 10%, 12%, and 14%.

GaN/InGaN PV cells	In = 10%	In = 12%	In = 14%
R_s (Ω -cm ²)	234.84	416.81	725.45
R_{sh} (Ω -cm ²)	121.66E3	103.08E3	17.38E3

while comparing to GaN/InGaN photovoltaic cells with higher In composition. The results agree with the TEM image of the GaN/InGaN interface of 10% In composition and the negligible leakage current from the dark I - V performance. Theoretical conversion efficiency of GaN/InGaN photovoltaic cells with In compositions of 10%, 12%, and 14% is 1.80%, 2.04%, and 2.27%, respectively. The difference of GaN/InGaN photovoltaic properties between theoretical simulation and experimental measurement could be attributed to the inferior quality of InGaN epilayer and GaN/InGaN interface generated as the increase of In composition.

Acknowledgments

The authors would like to thank the National Science Council and Bureau of Energy, Ministry of Economic Affairs of

Taiwan, for the financial support under Contract no. 100-2221-E-006-168 and 101-D0204-6 and the LED Lighting Research Center of NCKU for the assistance of device characterization. This work was also supported in part by the Center for Frontier Materials and Micro/Nano Science and Technology, the National Cheng Kung University, Taiwan. This work was also supported in part by the Advanced Optoelectronic Technology Center, the National Cheng Kung University, under projects from the Ministry of Education.

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