InGaN/GaN multiple quantum well solar cells with an enhanced open-circuit voltage*

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In this paper, InGaN/GaN multiple quantum well solar cells (MQWSCs) with an In content of 0.15 are fabricated and studied. The short-circuit density, fill factor and open-circuit voltage (V_{oc}) of the device are 0.7 mA/cm^2, 0.40 and 2.22 V, respectively. The results exhibit a significant enhancement of V_{oc} compared with those of InGaN-based hetero and homojunction cells. This enhancement indicates that the InGaN/GaN MQWSC offers an effective way for increasing V_{oc} of an In-rich $In_xGa_{1-x}N$ solar cell. The device exhibits an external quantum efficiency (EQE) of 36% (7%) at 388 nm (430 nm). The photovoltaic performance of the device can be improved by optimizing the structure of the InGaN/GaN multiple quantum well.

Keywords: InGaN, solar cell, multiple quantum wells

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1. Introduction

Recent studies have revealed that the band gap of an InGaN alloy can be varied continuously from 0.7 eV to 3.4 eV,[1−3] which perfectly matches the solar spectrum. Therefore, InGaN meterials have attracted increasing attention for the fabrication of high-efficiency tandem solar cells.[4,5] Jani *et al.*[5] designed InGaN/GaN p–i–n solar cells in which InGaN is treated as an active layer. We have modeled the performances of InGaN single- and double-junction solar cells[6,7] and studied the photovoltaic (PV) effects in InGaN p–n junctions.[8] Neufeld *et al.*[9] have demonstrated $In_{0.12}Ga_{0.88}N$/GaN p–i–n double heterojunction structures, each with an external quantum efficiency as high as 63% and an open-circuit voltage (V_{oc}) of 1.81 V under a concentrated air mass zero (AM0) spectrum. Zheng *et al.*[10] designed a p–GaN/i–$In_{0.1}Ga_{0.9}N$/n–GaN double heterojunction solar cell with a V_{oc} value of around 2.1 eV and a fill factor of up to 81% under AM 1.5 illumination.[10] Horng *et al* fabricated GaN/InGaN thin film solar cells by removing sapphire using a laser lift-off technique, their conversion efficiency is 0.8% under air mass (AM) 1.5 global conditions.[11]

Most of the reported InGaN-based solar cells have demonstrated poor photovoltaic performance and very low conversion efficiencies. One of the main problems is that high-quality In-rich $In_xGa_{1-x}N$ film has not been obtained due to phase separation caused by the low miscibility of InN in GaN.[5] In order to suppress phase separation in InGaN film and enhance the photovoltaic effect of the InGaN-based solar cell, an InGaN/GaN multiple quantum well (MQW) structure[12] should be used to form an InGaN multiple quantum well solar cell (MQWSC). Furthermore, MQWSCs are able to achieve higher efficiencies than single bandgap cells in an alternative approach to tandem or multi-bandgap cells.[13] The basic principle of MQWSCs is that the output voltage is dominated by the wider bandgap barrier material and the short-circuit current is determined by the width and the depth of the quantum well. Therefore, it is necessary to optimize the design of the MQWSC in order to ex-

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ceed the limiting efficiency of a single bandgap cell. In this paper, we report on the fabrication and characterization of InGaN/GaN MQWSCs with enhanced V_{oc}.

2. Experiment

The materials were prepared by metal-organic chemical vapour deposition (MOCVD) on (0001) sapphire substrates. As shown in Fig. 1, the structure of the InGaN/GaN MQWSC consists of a 1.2-μm-thick undoped GaN layer, a 180-nm p–GaN top layer, an undoped eight period $In_xGa_{1-x}N$(3 nm)/GaN(12 nm) MQW structure and a 2.8-μm n–GaN layer.

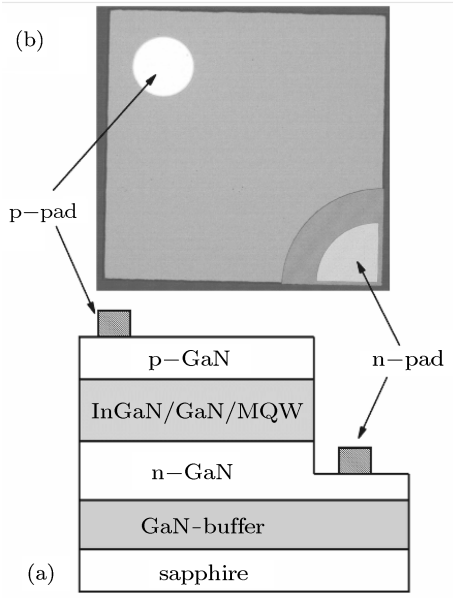


Fig. 1. Structure (a) and optical microscopic image (b) of the InGaN/GaN MQW solar cell device.

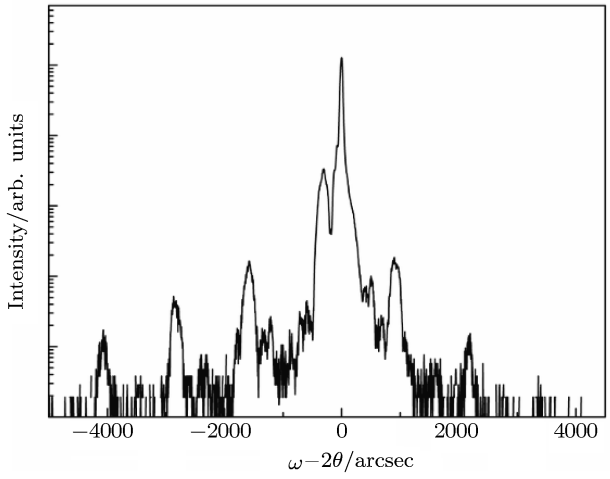


Fig. 2. High resolution x-ray diffraction spectrum of the InGaN/GaN MQWSC.

The carrier concentrations of the n–GaN and p–GaN layers are around 3×10^{18} cm^{-3} and 5×10^{17} cm^{-3}, respectively. The content of the MQW, determined by high-resolution x-ray diffraction and shown in Fig. 2, is 15%, which corresponds to a 2.82-eV bandgap with a bandgap bowing parameter of 1.43 eV.[14] The 2.82-eV bandgap is also accordant with the measured peak photoluminescence (PL) emission at 439 nm (shown in Fig. 6).

Mesas to isolate each cell and to expose the n–GaN layer for n-contact were fabricated using an inductively coupled plasma (ICP) etching system. For n-type Ohmic contact, Ti/Al/Ni/Au (30/100/50/30 nm) layers were deposited on n–GaN and then annealed at 800 °C for 30 s in an N_2 atmosphere. A p-Ohmic contact was formed by evaporating an Ni/Au (20/20 nm) layer on p–GaN and then annealing it at 800 °C for 5 min in air atmosphere. The current–voltage (I–V) characteristics of the n- and p-contacts were studied using the transmission line model (TLM) and the results, shown in Fig. 3, exhibited good Ohmic behaviour. Finally, the InGaN/GaN MQW photovoltaic device was shaped into a size of 1.5×1.5 mm^2 without an antireflection coating or a surface passivation layer. The I–V characteristics were measured using a Keithley 2610 source meter. The device was illuminated with a Xe lamp (100 mW/cm^2) calibrated by a silicon detector. Monochromatic illumination for quantum efficiency measurement was provided by coupling the Xe lamp to a Digikrom DK240 monochromator.

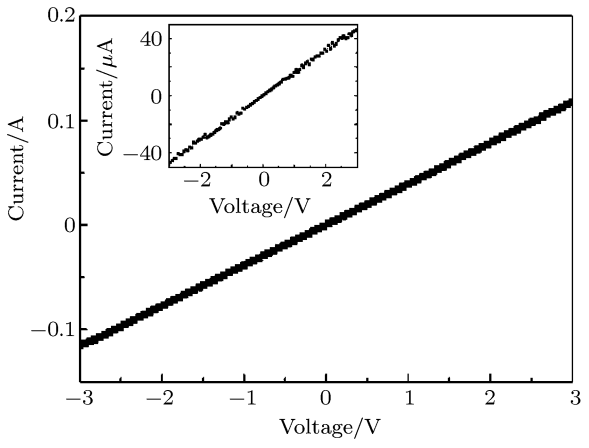


Fig. 3. The I–V curves of n-contact and inset for p-contact measured using the TLM method.

3. Results and discussion

The curves for current- and power-density versus voltage characteristics for $In_{0.15}Ga_{0.85}N$/GaN MQWSCs are plotted in Fig. 4. The short circuit

(J_{sc}), fill factor (FF) and V_{oc} are 0.7 mA/cm^2, 0.40 and 2.22 V, respectively. It is known that the output voltage of the MQWSC is determined primarily by the wider bandgap barrier material, the recombinations in the wells and in the barrier-well interfaces.[15] Nonradiative recombination processes, which are difficult to study, determine the output voltage behaviour, so V_{oc} depends strongly on material quality. Therefore, the voltage dependence of the MQWSC is more difficult to quantify. Barnham *et al.*[16] have investigated the V_{oc} of a GaAs/AlGaAs MQWSC in detail and observed a significant enhancement compared with that of the conventional cell. Our results for InGaN MQWSCs show that there is also an enhancement on V_{oc} compared with those of InGaN-based hetero- or homo-junction solar cells. As shown in Fig. 5, the V_{oc} values decrease with the increase in In content for different types of InGaN solar cells. However, the V_{oc} value of our cell (2.22 V) is much higher than that of the homojunction cell of Cai *et al.*[17] (0.96 V) with the same In content of 15%. Furthermore, this value is equivalent to the open-circuit voltages of the $In_{0.02}Ga_{0.98}N$ homojunction cell in Ref. [17] (2.24 V) and $In_{0.1}Ga_{0.9}N$/GaN heterojunction cells (2.1 V) in Refs. [10] and [11]. This significant enhancement of V_{oc} has also been observed in other $In_xGa_{1-x}N$-based MQWSCs fabricated by Dahal *et al.*[18] and Lai *et al.*[19] It is likely that the barrier layer and the low nonradiative recombination in the MQW caused by using better quality materials in homo and heterojunction cells leads to the increase of V_{oc} in InGaN/GaN MQWSCs. The experimental results therefore indicates an effective way for increasing V_{oc} values of In-rich $In_xGa_{1-x}N$ solar cells and InGaN/GaN MQWSCs and offers a potential application in high-efficiency solar cells.

As shown in Fig. 4, the poor FF of the device is determined mainly by a large series resistance resulting from high contact resistance and undesired defects in the InGaN/GaN MQW structure.[20] The measured series resistance is about 10 kΩ, which is much larger than the 50 Ω reported in Ref. [5]. Therefore, the contact with p–GaN and the crystalline quality of the InGaN/GaN MQW should be further improved to decrease series resistance. The smaller J_{sc} results are mainly caused by two factors: the thin light absorption layer and a high bandgap of the InGaN material due to its low In content. Both of these two factors can limit the total number of photons absorbed by the InGaN/GaN MQWs. Therefore, the InGaN/GaN MQW structure design should be optimized step by step in the following experimental work on improving the PV performances of cells.

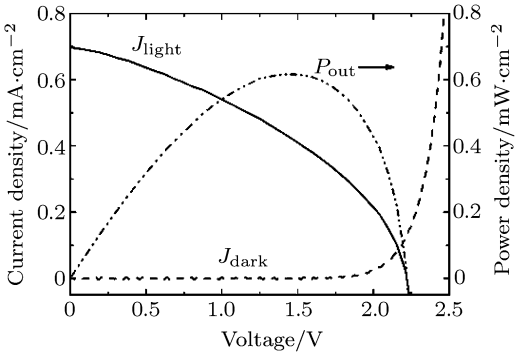


Fig. 4. Current and power density versus voltage characteristics for $In_{0.15}Ga_{0.85}N$/GaN MQWSCs.

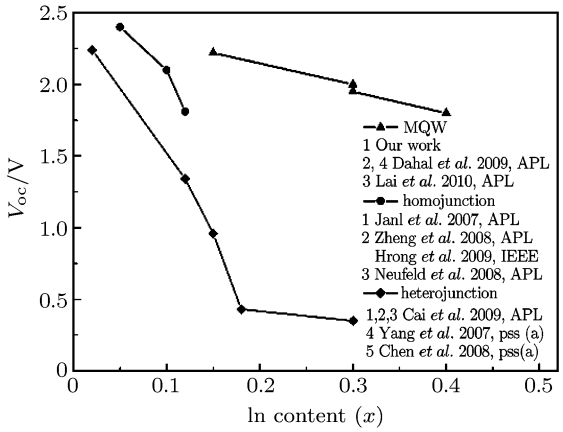


Fig. 5. V_{oc} values of InGaN-based solar cells with different amounts of In content plotted together with other reported results.

Figure 6 shows the curves for the PL spectrum and the external quantum efficiency (EQE) versus wavelength of the InGaN/GaN MQWSC. It is obvious that the peak wavelength of PL (439 nm) is longer than that of EQE (388 nm). The reason is that the relaxing of hot carriers happens before the radiative recombination in the emission process and during the absorption process electrons can be exited to higher states by absorbing higher energy photons.[19] The EQE plot of the device demonstrates a peak value of 36% at 388 nm and a value of 7% at 430 nm. When compared with the $In_{0.15}Ga_{0.85}N$ homojunction solar cell in Ref. [22] (∼7% at 410 nm), the response wavelength is longer in the $In_{0.15}Ga_{0.85}N$ MQWSC. However, the response to the shorter wavelength region (< 360 nm) is limited due to the use of a p-GaN window layer.[9,18] The longer operating wavelengths may result from the high crystalline quality of the InGaN alloy and the limiting response to shorter wavelengths can be improved by using a p-AlGaN window layer.

In addition, the low peak EQE is limited primarily by the thin absorption layer[18] and a large series resistance. Accordingly, the EQE can be enhanced by optimizing the design of the InGaN/GaN MQW absorption region and reducing the series resistance of the device.

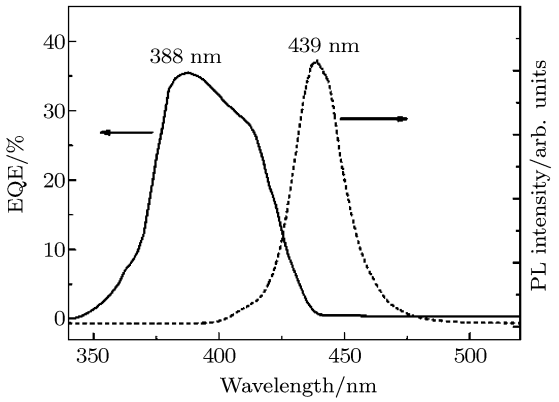


Fig. 6. EQE and PL spectra of $In_{0.15}Ga_{0.85}N$/GaN MQWSCs.

4. Conclusion

We report on the fabrication and characterization of an InGaN/GaN MQWSC with a significant enhancement of V_{oc} compared with those of other reported InGaN-based hetero and homojunction solar cells. The values of J_{sc}, FF and V_{oc} of the device under the illumination of a Xe lamp are 0.7 mA/cm^2, 0.40 and 2.22 V, respectively. A significant enhancement of V_{oc} indicates that InGaN/GaN MQWSCs have offered an effective way for increasing the V_{oc} of In-rich $In_xGa_{1-x}N$ solar cells. The large series resistance leads to poor FF and the small J_{sc} is associated with the thin light absorption layer and low In content in the InGaN material. The device exhibits an EQE of 36% at 388 nm and 7% at 430 nm. The low EQE is limited mainly by a thin active layer and a large series resistance. Therefore, the PV performances of InGaN/GaN MQWSCs can be improved further by optimizing the structure of the InGaN/GaN MQW absorption region.

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