藉由降低平台高度增進藍光波段氮化銦鎵光伏元件之電流收集效率

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摘 要

本文探討在藍寶石基板上成長具有超晶格結構作為吸收層之光伏元件，其於照光情況下，光載子的傳輸特性與材料品質相關且載子生命期也主導光伏元件的電流收集效率。本研究之元件磊晶層成長在藍寶石基板後，於製程時設計不同的元件平台高度，來探討具有高缺陷密度 n^+-GaN 層的等效厚度對元件特性之影響。初步結果顯示，當平台高度為 300 奈米時，其元件光電轉換效率與平台高度為 1000 奈米的元件比較起來約可提升 35%。

關鍵詞：光伏、氮化銦鎵、電流收集

Enhancing Current Collection for Blue Band InGaN-Based Photovoltaic Devices with Shallow Mesa

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Abstract

InGaN-based photovoltaic devices that incorporate a p-i-n design with GaN/InGaN superlattice absorption layers epitaxially grown on sapphire substrates by metal-organic vapor phase epitaxy techniques are produced. The stacked superlattice structure with thin barrier and well layers is applied and used as the absorption layer. Since the carrier lifetime can dramatically dominate the current collection’s efficiency of a photovoltaic device, the devices are designed in this study to have different mesa heights for evaluating the effect of effective thickness of n^+-GaN layer with high-density defects (i.e., short diffusion length of carriers) on device performance. The conversion efficiency of the devices with a mesa height as low as 300 nm can be improved by around 35% as compared to that of devices with a mesa height of 1000 nm.

Keywords: Photovoltaic, InGaN, Current Collection.

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I. Introduction

Group III-nitride compound semiconductors of $In_XGa_{1-X}N$ alloys providing a full-solar-spectrum photovoltaic (PV) perspective have been predicted since 2002 through the bandgap confirmation of InN [1-2]. Applying the direct bandgap $In_XGa_{1-X}N$ semiconductors, the photon energy within the solar spectrum, especially in the visible and infrared regions yielding the most solar energy conversion, is continuously available for the PV fabrication between 0.7 eV (InN) of infrared and 3.4 eV (GaN) of ultraviolet regions. Recently, because of the potential multi-junction solar cells for ultra-high conversion efficiency over 50% by selective bandgaps, aiming at terrestrial power plants (highly concentrated PV) and extraterrestrial satellites, several groups have reported their results regarding their respective research works on InGaN-based PV devices. However, the present InGaN-based materials exhibit more difficulties in terms of epitaxy growth than conventional Si or GaAs semiconductors. The native structure defects mainly originate from lattice mismatch between epitaxial layers and substrates [3-5]. Previous studies have discussed InGaN/sapphire-based PV devices with low indium contents (less than 12%) [4-6]. In these studies, the PV response under irradiance have often been performed by UV-enhanced or concentrated light sources to magnify PV parameters in absorbing more ultra-violet parts. In fact, the absorption of solar power by GaN converts just a small part of the solar spectrum, thus yielding a theoretical conversion efficiency of only about 1% [7]. Based on the theoretical calculations and experimental results, studies have reported that the conversion efficiency depends on the critical thickness of InGaN-based semiconductors grown on sapphire or even on GaN substrates [8-11]. Therefore, some fundamental studies for InGaN-based PV devices must be conducted before the full-solar-spectrum PV device could be realized. Although InGaN/sapphire-based materials with a large number of threading dislocations (1×10^{8} to 1×10^{12} cm^{-2}) show high efficiency in light emitting devices (i.e., defect insensitivity) [3], the InGaN-based materials in absorption applications encounter much greater problems, such as different optima growth temperature of InN (<600℃) and GaN (~1000℃), phase separation, and other native defects. Such factors may seriously influence the performance of InGaN-based PV devices that use such materials. At present, it is still a great challenge to grow InGaN alloys with bandgap energy lower than 2 eV because the material quality will degrade rapidly while increasing either the indium content or thickness of the InGaN epilayers. When InGaN-based materials are applied to PV devices, the dense defects, most likely the dislocations, might become the carrier killers and thereby result in a reduction of conversion efficiency. The high-density defects will lead to a short diffusion length of the carriers and thereby result in a poor collection efficiency of photo-generated carriers by electrodes. For example, when the defect density of GaN is in the range of $3\sim5\times10^{9}$ cm^{-2}, the diffusion length (L_d) of about 250 nm is expected, based on the rough assumption that there is a homogeneous dislocation distribution [12]. For GaN/sapphire-based bipolar devices, the anode and the cathode electrodes are placed laterally on the same surface of the sapphire substrate. This lowers efficiency even further when the distance between the electrodes is larger than the L_d of the carriers. In this study, the devices are designed to have different mesa heights in order to evaluate the effect of the vertical distance between the electrodes on the device efficiency.

II. Experiments

The samples used in this study were grown on c-face sapphire (Al_2O_3) substrates using a commercial metal-organic vapor phase epitaxy (MOVPE) reactor system (EMCORE D-180). The epilayer structures for PV device fabrication were designed into a p-i-n scheme grown after buffering a 1-μm undoped GaN layer, followed by a 2.3-μm Si-doped n^+-GaN, an unintentionally doped InGaN-based active layer, and a 60-nm Mg-doped p-InGaN. The carrier concentrations of n^+-GaN was around 1×10^{19} cm^{-3} confirmed by Hall measurement. The active layer used was the GaN/$In_{0.25}Ga_{0.75}N$ superlattice structure with a total thickness of 200-nm, stacking 28 pairs of GaN/ $In_{0.25}Ga_{0.75}N$ superlattice. The thickness of the GaN barrier and $In_{0.25}Ga_{0.75}N$ well were set at 4 nm and 3 nm, respectively. The fabrication process of the PV devices is similar to conventional GaN/sapphire-based light emitting diodes (LEDs) with lateral electrodes. Inductively-coupled plasma (ICP) dry etching was applied to expose the underlying n^+-GaN for the formation of Ohmic contacts. In addition, we used indium tin oxide (ITO) as the Ohmic contact on the p-InGaN top layer. Finally, Cr/Au (50/1000 nm) bi-layer metal was deposited onto the exposed n^+-GaN surface[13] and the ITO layer at the same time to serve as the cathode and the anode electrode pads, respectively. Figure 1 shows the schematic of our fabricated devices with electrodes in digitated arrangement; in this scheme, the lateral spacing between electrodes is about 160 μm. The total area is 1000μm×1000μm. No antireflection coatings are applied to these devices.

III. Results and discussion

To evaluate the effect of mesa height on the device performance, the lateral spacing between the anode and cathode electrodes was fixed at 160 μm but the vertical distance between the anode and cathode electrodes (i.e., the height of mesa, as shown in Fig.1) was designed with two difference values. The first kind of devices with mesa height of 300 nm were labeled as PV-I. This means the distance from the exposed n^+-GaN surface to the active layer is around 40 nm because the total thickness of the p-InGaN layer and the active i-layer ($In_{0.25}Ga_{0.75}N$/GaN superlattice) is around 260 nm. The other devices have mesa height of around 1000 nm, corresponding to a distance from the exposed n^+-GaN surface to the active layer of around 740 nm, and they were labeled as PV-II. In other words, the effective thickness of n^+-GaN layer (t_{effn}) in the PV-I and PV-II are 40 and 740 nm, respectively. Figure 2 shows the typical external quantum efficiency (EQE) as a function of the incident light wavelengths. It should be noted that the measurement of the EQE is not calibrated by a standard sample. However, it should be harmless to the qualitative comparison between the PV-I and the PV-II. It is clear

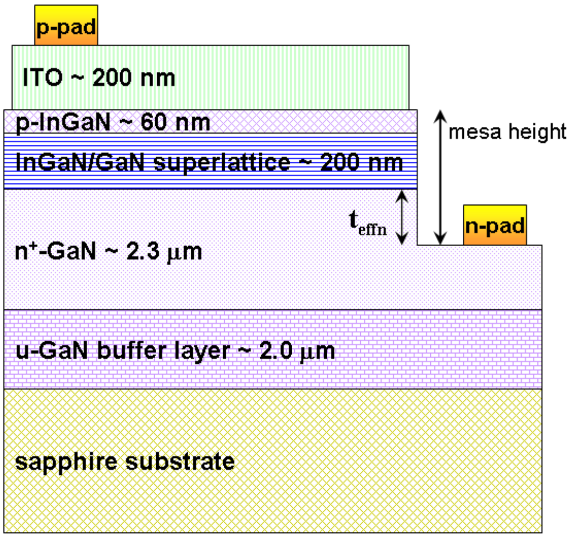

Fig.1 The schematic layer structure of the fabricated InGaN/GaN PV devices.

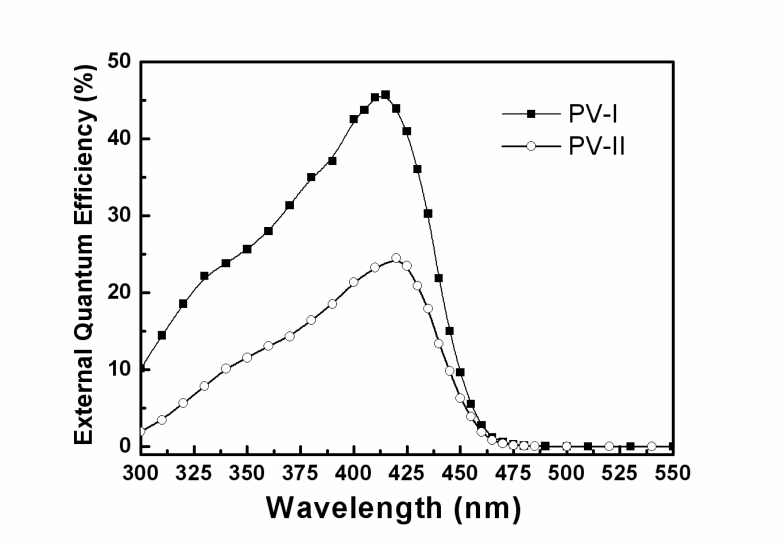

Fig.2 Typical external quantum efficiency as a function of incidental light wavelength

that these spectra show the gradient decline in the ultraviolet region, which could be attributed to the surface absorption of the ITO film and the p-InGaN layer. In addition, one can see that the peak value of EQE taken form the PV-I is markedly higher than that of PV-II. In other words, the EQE of PV-I can be improved by 35% as compared to that of PV-II. This result could be attributed to the fact that the transit time of photogenerated holes in the n^+-GaN layer of PV-II is longer than that of PV-I due to the larger t_{effn} of n^+-GaN layer in the PV-II compared with the PV-I. In principle, the diffusion length of the minority carrier is inversely proportional to the defect density and/or majority carrier density. In the present devices, the dislocation density and electron concentration of n^+-GaN layer are around 2×10^{10} cm^{-2} and 1×10^{19} cm^{-3}, respectively. We thus expect that the diffusion length of the holes in the n^+-GaN layer should be far less than 250 nm [12]. However, the t_{effn} in the PV-II is around 740 nm which is far longer than the reported values of around 250 nm. On the other hand, the t_{effn} in the PV-I is around 40 nm which is far less than the reported values. As a result, the lower collection efficiency of the carriers observed in the PV-II is reasonable.

Figure 3 shows the current density-voltage (J-V) characteristics taken from the PV devices under the illumination of the Oriel solar simulator (model: M-91190A), which was calibrated by the calibration cell of NREL. Under one-sun AM1.5G condition, the short-circuit current densities (J_{SC}) of PV-I and PV-II were 1.05 and 0.78 mA/cm^2, respectively. This result is consistent with the trend of EQE. In other words, the current collection in PV-I is more efficient than in PV-II. Although the measured J_{SC} is still lower than the theoretical maximum value (~5mA/cm^2), it was evidenced again that the effective thickness of n^+-GaN layer (t_{effn}) could affect the collection of the photogenerated carriers and hence the conversion efficiency. One would like to suggest that the effect of t_{effn} on conversion efficiency would be more significant when the material defect density is high. On the other hand, the open-circuit voltage (V_{OC}) of both PV-I and PV-II is around 1.4 V which is much lower than the theoretical value. The low V_{OC} was attributed to the fact that the dislocation density (TD) of 200 nm-thick InGaN/GaN superlattice absorption layer was as high as 10^9~10^{10} cm^{-2}. This high TD could induce considerable current leakage paths and hence the lower shunt resistance in the PV devices. As a result, the measured V_{OC} was far less than the predicted value which is approximately of 2 V. In theory, there may be only two dominant points to cause the low conversion efficiency of InGaN-based PV. First, the conversion efficiency of PV devices made of materials with an absorption band edge of around 445 nm is less than 5% which is theoretically estimated by thermodynamic limit. Second, the large lattice mismatch between GaN and $In_xGa_{1-x}N$

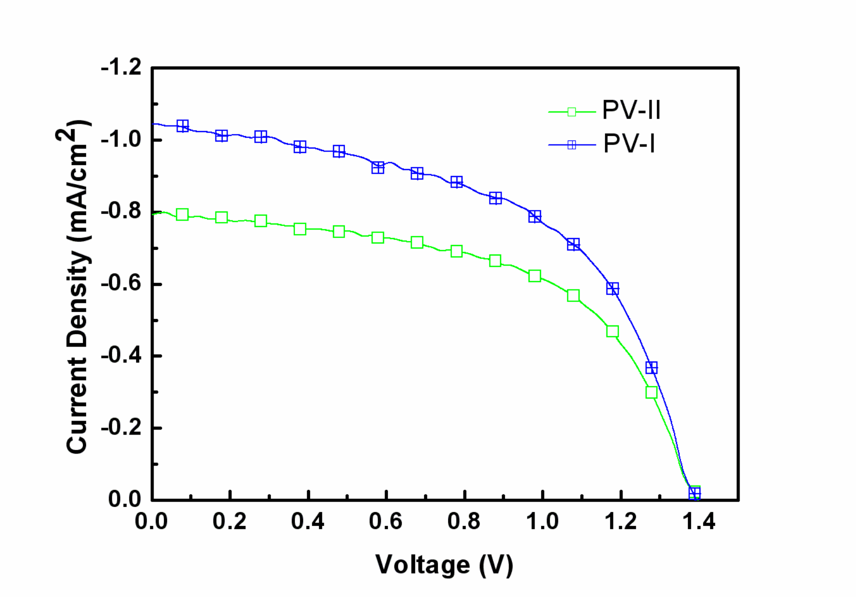

Fig.3 Typical current density-voltage characteristics illuminated under a one-sun AM1.5G conditions.

will cause dense structure defects, such as threading dislocations (TDs), and limit the critical thickness, especially for the high indium content alloys. In fact, Bensaoula et al. have revealed that the internal quantum efficiency (IQE) of PV devices with an $In_{0.3}Ga_{0.7}N$ absorption layer dropped 55% and 88% when the dislocation density increased from 10^5 cm^{-2} to 10^8 cm^{-2} and 10^{10} cm^{-2}, respectively [11]. According to the aforesaid results, in addition to the reduction of defect density in materials, one can alleviate the negative effect of high defect density on carrier collection by reducing the t_{effn}. The latter case is much simpler than the former case because the reduction of material defect density is, in general, costly if the $In_xGa_{1-x}N$ alloys are grown on insulating and lattice-mismatched substrates such as the sapphire [14]. In addition, one would like to note that the carrier diffusion length through each $In_xGa_{1-x}N$-based layer will be much shorter (only a few hundred nanometers) than the spacing between the electrodes (usually tens of micrometers). Therefore, the device area of InGaN-based PV is limited to the distance that light-induced carriers can transport.

IV. Conclusion

In this study, the GaN-based PV devices with a shallow mesa (300 nm) showed a 35% improvement in conversion efficiency compared to that of devices with a mesa height of 1000 nm. Although the conversion efficiency of GaN-based PV devices grown on sapphire substrate are still low compared to the theoretical value, the preliminary results indicated that the GaN-based PV devices grown on sapphire substrates with suitable device structure may be able to provide further improvement in conversion efficiency for future full-solar-spectrum solar cells through the use of InGaN alloys.

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