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Improving efficiency of InGaN/GaN multiple quantum well solar cells using CdS quantum dots and distributed Bragg reflectors

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ABSTRACT

This work demonstrates hybrid InGaN/GaN multiple quantum well (MQW) solar cells with enhanced power conversion efficiency using colloidal CdS quantum dots (QDs) and back-side distributed Bragg reflectors (DBRs). CdS QDs can absorb ultraviolet (UV) photons, which are strongly absorbed by indium tin oxide (ITO), and they emit photons with a longer wavelength. This process improves the collection of photon-generated carriers and is known as the luminescence down-shifting (LDS). Accordingly, CdS QDs can compensate for the poor utilization of UV photons in an ITO layer, enhancing the external quantum efficiency (EQE) in the UV range. The DBRs on the back of the solar cells can reflect photons of longer wavelengths back into the absorber layer, increasing the EQE (380–440 nm). The combination of CdS QDs and DBRs results in broadband EQE enhancement, and yields an overall power conversion efficiency that is 20.7% better than that of a reference device without CdS QDs and DBRs.

1. Introduction

InGaN-based alloys are extensively utilized in light-emitting diodes (LEDs) and laser diodes (LDs). In recent years, InGaN-based alloys have also been considered for use in solar cells because of their favorable photovoltaic properties, including a direct bandgap, a high absorption coefficient at the band edge (of the order of $10^5\ cm^{-1}$), high carrier mobility, superior radiation resistance, thermal stability [1,2], and, most importantly, the wide bandgap of the InN/GaN alloy materials from 0.7 eV to 3.4 eV, which covers almost all of the solar spectrum [3,4]. Additionally, four-junction solar cells with a theoretical conversion efficiency of over 60% have been designed, but these designs require junctions that have bandgaps of greater than 2.4 eV [5]. Very few materials have a bandgap of over 2.4 eV [6], but InN/GaN alloy does. Therefore, InN/GaN alloy is a candidate for use in highly efficient tandem solar cells.

Many challenges must be overcome before InGaN-based photovoltaic devices can be used widely. A large lattice mismatch between GaN and InN limits InGaN-based photovoltaic devices to incorporate a thick absorber with a high indium content for absorbing light. Generally, the critical thickness of $In_{0.1}Ga_{0.9}N$ is approximately 100 nm, and this thickness falls rapidly as the indium content increases [7]. When the thickness of InGaN layer exceeds a critical value, defects are formed as recombination centers [8]. These recombination centers increase the rate of consumption of photo-generated electron–hole pairs, degrading photovoltaic performance. Owing to the need for high crystalline quality, the thickness of absorbers in InGaN-based photovoltaic devices is limited by challenges related to epitaxial deposition such that a compromise of multiple quantum well (MQW) structure is used for the absorbers in InGaN-based photovoltaic devices, which results in insufficient light absorption [9]. However, indium tin oxide (ITO) is typically deposited as a conducting and transparent layer, but it has a high absorption coefficient in the ultraviolet (UV) region without generating a photocurrent. Therefore, a new approach for overcoming the insufficient light absorption and reducing the high absorption of the ITO layer is needed.

Previous studies have utilized several methods for improving the harvesting of light in InGaN/GaN MQW solar cells, such as the use of a ZnO or SiO_2 sub-wavelength structure to realize a graded refractive index interface to reduce Fresnel reflection and simultaneously to increase the light scattering effect [10,11]. Silver nanoparticles have also been used to exploit the surface plasmonic effect to promote the scattering of light [12]. However, neither the

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problem of high absorption in the ultraviolet region by ITO layer nor that of the low external quantum efficiency (EQE) owing to the insufficient light absorption has been solved. A back reflector that reflects the unused light back to the absorber layer provides a solution and has an important role in thin-film solar cells [13]. For this purpose, distributed Bragg reflectors (DBRs) are good candidates for InGaN/GaN MQW solar cells. The advantages of DBRs include high reflectance, a controllable stop band, and a controllable central wavelength [14]. Appropriately chosen DBRs can solve the problem of a low EQE in thin-film solar cell.

In the past, quantum dots (QDs) have been extensively used in optoelectronic devices, such as LEDs and solar cells. CdS QDs on the top of solar cells with luminescent down shifting (LDS) and anti-reflective characteristic have recently been demonstrated [15–17]. The QDs with LDS effect can absorb UV light and emit light of longer wavelength, solving the problem of high absorption of UV light by the ITO layer.

This work demonstrates hybrid InGaN/GaN MQW solar cells in which colloidal CdS QDs and back-side DBRs are used to promote their harvesting of light. The characteristics of InGaN/GaN MQW solar cells with colloidal CdS QDs and back-side DBRs were determined by obtaining reflectance spectra, EQE, and a current density–voltage (*J*–*V*) profile.

2. Process and structure

The InGaN/GaN MQW solar cells were grown by metal–organic chemical vapor deposition (MOCVD) on a *c*-plane sapphire substrate. The devices comprised a 30 nm-thick, low-temperature GaN nucleation layer and a 2 μm-thick undoped GaN layer on sapphire substrate, 14-period $In_{0.15}Ga_{0.85}N$/GaN (3 nm/5 nm) undoped MQW sandwiched by a 2 um-thick Si-doped n-GaN layer (n-doping $=2\times10^{18}$ cm^{-3}) and a 200 nm-thick Mg-doped p-GaN layer (p-doping $=2\times10^{17}$ cm^{-3}). A 110 nm-thick indium-tin-oxide (ITO) p-GaN conducting layer was deposited by a sputtering system. The device was then defined using a 2×2 mm^2 mesa and an inductively coupled plasma reactive ion etching (ICP-RIE) system. Finally, Cr/Pt/Au (50/50/1900 nm) was deposited by electron-beam evaporation, which serves as the p-GaN and the n-GaN contact metal.

The DBRs comprised 11-period HfO_2/SiO_2, and were deposited on the glass substrate and grown by an electron beam evaporation system at room temperature. To control the central wavelength and the stop band of the DBRs, quartz was used to monitor the deposition rates. Fig. 1(a) plots the obtained reflectance spectra of 11-period HfO_2/SiO_2 DBRs from a wavelength of 385 nm to a wavelength of 460 nm, with a reflectance of over 98%.

Following regular semiconductor processes, the spin-coating method was used to form a CdS QDs thin film on the top of the device and 11-period HfO_2/SiO_2 DBRs were put on the back of device. In this study, a colloidal CdS QDs solution in toluene with a concentration of 1 mg/ml was used. Fig. 1(b) presents the device structure with CdS QDs and DBRs.

Fig. 2(a) presents the absorbance and photoluminescence spectra of CdS QDs in toluene. The absorbance spectrum includes a sharp rising edge around 400 nm and exhibits peak absorption at approximately 380 nm. The photoluminescence spectrum was obtained with 365 nm excitation, and a major emission wavelength of approximately 405 nm was found. The inset in Fig. 2 (a) presents the InGaN/GaN MQW solar cells with CdS QDs not irradiated and irradiated with a UV light. Fig. 2(b) and (c) presents 45-tilted (Fig. 2b), and cross-sectional (Fig. 2c) scanning electron microscopic (SEM) images of CdS QDs on the top of InGaN/GaN MQW solar cells. The approximately nanospherical structures on the surface were the self-assembled CdS QD clusters with diameters of 80–100 nm [18]. In this study, four types of InGaN/GaN MQW solar cell are prepared for analysis—one with CdS QDs, one with DBRs, one with both CdS QDs and DBRs, and one bare cell as a reference.

The system for measuring power conversion efficiency (PEC) comprised a power supply (Newport 69920), a 1000 W Class A solar simulator (Newport 91192A) with a xenon lamp (Newport 6271A) and an Air Mass 1.5 Global (AM1.5 G) filter (Newport 81088A), and a probe stage with a source-meter (Keithley 2400). The use of the PEC measuring system closely followed the procedure in international standard CEI IEC 60904-1. The spectrum of the solar simulator was measured using a calibrated spectroradiometer (Soma S-2440) at wavelengths in the range 300–1100 nm. The devices were operated under a 1000 W Class A solar simulator with AM1.5 G illumination [19] with a power density of 1000 W/m^2. The temperature was maintained at 25 ± 1 °C during the measurements using an automatic temperature control system. According to the calibration report by Newport Corporation, the temporal instability was 0.88%, and the non-uniformity was 0.79%. Before measurements were made, the intensity of the solar simulator was calibrated using a mono-crystalline silicon reference cell with a 2 cm × 2 cm illumination area (VLSI Standards, Inc.).[20].

The system for measuring external quantum efficiency (EQE) comprised a 300 W xenon lamp (Newport 66984) with a monochromator (Newprot 74112), a lock-in amplifier (Standard Research System, SR830), an optical chopper unit (SR540) that was operated at a chopping frequency of 260 Hz, and a 1 Ω resistor in a shunt connection to transform the photocurrent to voltage. Before measurements were made, a calibrated silicon photodetector with a known spectral response (Newport 818-UV) was used to calibrate the EQE measuring system. During the measurement process, the temperature of the probe stage was maintained at 25 ± 1 °C using an automatic temperature control system.

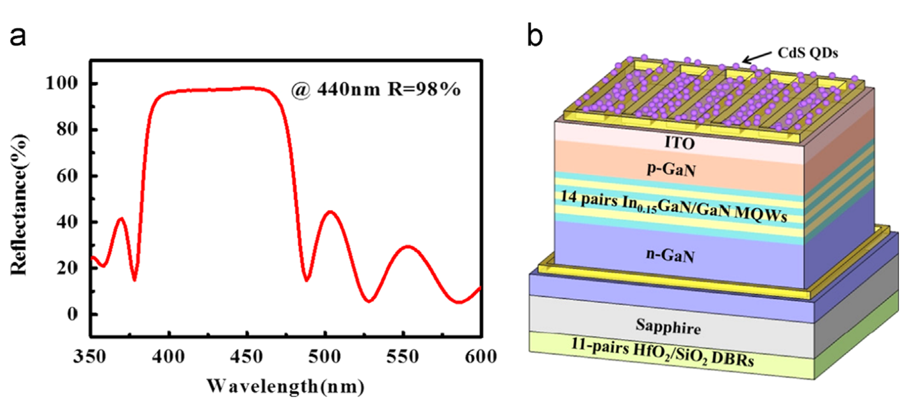

Fig. 1. (a) Measured reflectance spectra of 11-period HfO_2/SiO_2 DBR (b) Schematic illustration of InGaN/GaN MQW solar cell with CdS QDs and DBRs.