Front. Optoelectron. China 2009, 2(4): 442–445
DOI 10.1007/s12200-009-0059-z

RESEARCH ARTICLE

InGaN/GaN multi-quantum-well-based light-emitting and photodetective dual-functional devices

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Abstract In this study, we fabricated and characterized an InGaN/GaN multi-quantum-well (MQW)-based p-n junction photodetector (PD) for voltage-selective light-emitting and photo-detective applications. The photodetector exhibits a cutoff wavelength at around 460 nm which is close to its electroluminescence (EL) peak position. The rejection ratio was determined to be more than three orders of magnitude. Under zero bias, the responsivity of the device peaks at 371 nm, with a value of 0.068 A/W, corresponding to a 23% quantum efficiency. The overall responsivity gradually rises as a function of reverse bias, which is explained by the enhanced photocarrier collection efficiency.

Keywords GaN, multi-quantum-well (MQW), photodetector (PD), light emitting diode (LED)

1 Introduction

III-nitride semiconductors have direct band gap energy tunable between 0.7 and 6.2 eV depending on compositional ratios, which covers a very wide spectrum wavelength range from near-infrared to ultraviolet. This intrinsic material property makes III-nitrides an ideal material system for development of high-performance opto-electric devices such as light-emitting diodes (LEDs) [1], laser diodes [2,3], and photodetectors (PDs) [4]. For general ultraviolet (UV) and specifically solar-blind detection applications, several groups have reported promising performance for GaN-based PDs with various configurations such as p-n junction, p-i-n, Schottky barrier, and metal-semiconductor-metal (MSM) structures. Most of these devices are fabricated on bulk-like epitaxial materials. Comparatively, multi-quantum-well (MQW) PDs have several advantages over bulk devices. In particular, by designing optimized well width, barrier height as well as composition ratio of the absorbing well-materials, the cutoff wavelength and response window of MQW-PDs can be easily tuned. To date, although MSM PDs fabricated on AlGaN/GaN MQWs [5] or InGaN/GaN MQWs [6] have been reported, p-n junction-based MQW-PDs are less studied while such devices have an important advantage over planar devices for dual-functional applications [7]. That is, if under forward bias, p-n junction-based MQW-PDs can also emit light with considerable efficiency, which will not only enhance device functionality but also facilitate the realization of GaN-based optoelectronic integrated circuits by using a similar epi-structure and fabrication process.

In addition, recent attempts to fabricate InGaN-based solar cells have been attracting growing attention. This is because the band gap energy range of InGaN alloys has a nearly perfect match to full solar spectrum, which makes it possible to realize multi-junction solar cells with ideal band gap energies for maximum conversion efficiency. Meanwhile, InGaN alloys also exhibit superior radiation resistance, thus offering great potential for outer-space solar cell applications [8]. Currently, although several proto-type devices with promising characteristics have been reported [9,10], research in this field is still fairly preliminary. Therefore, while previous studies on III-nitride-based PDs were mostly concerned with their UV detectability, worldwide interest on solar cells has encouraged more investigations on the visible response of InGaN alloys.

Aiming for the above applications, in this study we fabricated and characterized a p-n junction-based light-emitting InGaN/GaN MQW-PD. In spite of having a thin effective absorbing layer of only 15 nm, this device exhibits a distinct response window in the blue-to-UV

Received June 30, 2009; accepted July 24, 2009

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range, with a 23% quantum efficiency at 371 nm under zero bias. We also studied the photo-response of the MSM-PD as a function of reverse bias.

2 Experiment

The epi-structure of the device was grown epitaxially on a 2-inch *c*-plane sapphire substrate by metal-organic chemical vapor deposition. After growing a low-temperature GaN nucleation layer, a 2-μm-thick Si-doped n-GaN layer (~5×10^{18} cm^{-3}) was deposited, followed by the growth of five periods of undoped MQWs consisting of 3-nm-thick $In_{0.2}Ga_{0.8}N$ wells and 7-nm-thick GaN barriers. Finally, a p-contact layer of 0.2-μm-thick Mg-doped GaN with a hole concentration of about 3×10^{17} cm^{-3} was deposited. The MQW-PD, having a mesh size of 1 mm×1 mm, was fabricated using standard photolithography and dry etching processes. Annealed Ti/Al/Ni/Au and Ni/Au (25 Å/25 Å) multi-layers deposited by e-beam evaporation were employed as ohmic n-contact and semitransparent p-contact, respectively. A p-contact Au-pad designed to have a star-like pattern was added to enhance the collection efficiency of photo-generated holes, while no anti-reflection layers were coated. A cross-sectional schematic and a top-view image of a fabricated device are shown in the insets of Fig. 1, respectively. For electrical and optical characterizations, a Keithley 2612 source-meter was used to measure current-voltage (*I-V*) characteristics, while electroluminescence (EL) spectrum was collected by an optical fiber and analyzed by using an Ocean Optics spectrometer. Spectral responsivity of the PD was measured with a system consisting of a xenon lamp, a monochromator, a lock-in amplifier and a mechanic chopper. The light output from the monochromator was calibrated with a UV-enhanced Si photodiode.

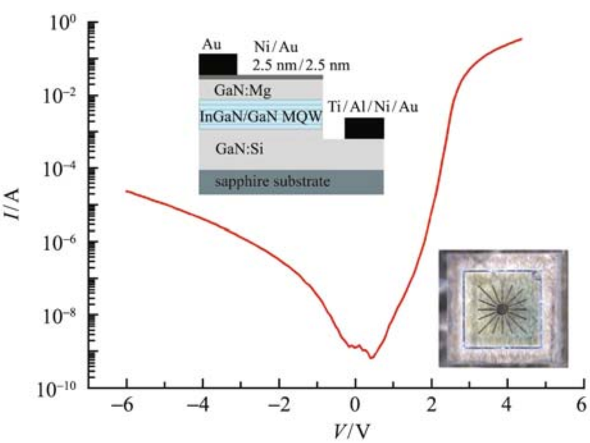

Fig. 1 Typical *I-V* characteristic of a 1 mm×1 mm InGaN/GaN MQW-based p-n junction photodetector (top and bottom-right insets show a cross-sectional schematic and a top-view image of fabricated device, respectively)

3 Results and discussion

The *I-V* curve of a 1 mm×1 mm PD is shown in Fig. 1, manifesting typical LED-type *I-V* characteristics. The turn-on voltage of the device at I = 350 mA is 4.3 V, and the leakage/dark current under 5 V reverse bias is about 10 μA. By comparing the luminescence intensity of a commercial GaN LED chip of the same size via on-wafer testing, the optical output power of our unpackaged device is estimated to be 5–6 mW under an injection current of 20 mA. The EL spectrum under forward bias (I = 50 mA) is shown as the dashed line in Fig. 2, confirming that the device can also be used as a light emitter. The EL spectrum exhibits a single peak at 462 nm with a full-width-at-half-maximum of 19.3 nm. Thus, both the *I-V* characteristic and the EL spectrum indicate reasonable quality of the epi-structure. Next, the device was tested as a conventional PD. The spectral response of the device under zero bias is shown in Fig. 2 as the solid line. The curve peaks at 371 nm with a value of 0.068 A/W corresponding to a 23% quantum efficiency. The cutoff wavelength of the PD is around 460 nm which is close to its EL peak position, indicating that the blue-to-UV photo-response should be due to the efficient light absorption within InGaN quantum wells. Here we define the rejection ratio as the responsivity measured at 371 nm divided by the responsivity measured at 500 nm (the high energy end of PL peak). The rejection ratio is determined to be more than 3000, which is a relatively high value for III-nitride-based PDs.

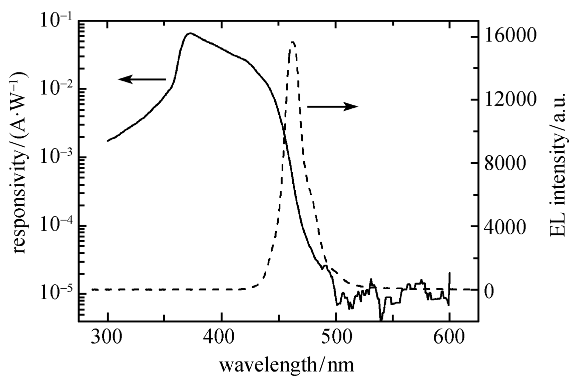

Fig. 2 EL spectrum under forward bias (I = 50 mA, dashed line) and spectral response of PD under zero reverse bias (solid line)

There is an apparent blue-to-UV photo-response window of the MQW-PD, as shown in Fig. 2. With increasing wavelength, the responsivity decreases gradually from peak position at 371 nm until about 440 nm, then decreases at a faster rate, cutting off at around 470 nm. It is clear that the responsivity of our InGaN/GaN MQW-PDs does not cut off as sharply as conventional PDs fabricated on bulk-like materials. We believe that this observation should be due to the effective band gap inhomogeneity which originates from In compositional fluctuations within the

InGaN quantum wells [11]. Meanwhile, the gradual rise of responsivity from 440 to 370 nm can be explained by the increase of the absorption coefficient of InGaN alloys at shorter wavelength. In addition, light absorption by the p-GaN within the space-charge region should also have contribution to the peak responsivity at 371 nm. On the other side of the photo-response window, a sharp decrease of responsivity is observed as the wavelength goes from the peak position (371 nm) towards the shorter-wavelength direction. This observation indicates that most photons with energy larger than the GaN band gap energy are effectively absorbed by the p-GaN capping layer [12] and therefore have no contribution to photo-response.

Figure 3 shows responsivity curves of the device measured under different reverse bias voltages. It is found that the overall photo-responsivity of the MQW-PD rises with increasing reverse bias. The fact can be easily explained by the enhanced photocarrier collection efficiency due to the higher electrical field at the junction to pull photocarriers towards the electrodes. Meanwhile, there should be a simultaneous extension of the depletion region at higher bias, which also helps to collect photocarriers. In addition, in Fig. 3 the photo-response curve under zero bias shows a responsivity of 0.039 A/W at 400 nm, which corresponds to a quantum efficiency of 12%. Considering that the total thickness of the $In_{0.2}Ga_{0.8}N$ alloy is only 15 nm for 5 periods of MQWs, and neglecting surface reflection as well as internal multi-reflections, a rough estimate will generate an optical absorption coefficient of at least $1\times10^{5}\,cm^{-1}$ for $In_{0.2}Ga_{0.8}N$ at 400 nm to meet the measured quantum efficiency. Since recombination and transport losses are unavoidable during the photo-carrier collection process, the actual absorption coefficient of $In_{0.2}Ga_{0.8}N$ should be even larger than the above value. Therefore, this result confirms that the InGaN alloy is suitable for visible-light detection and solar cell applications.

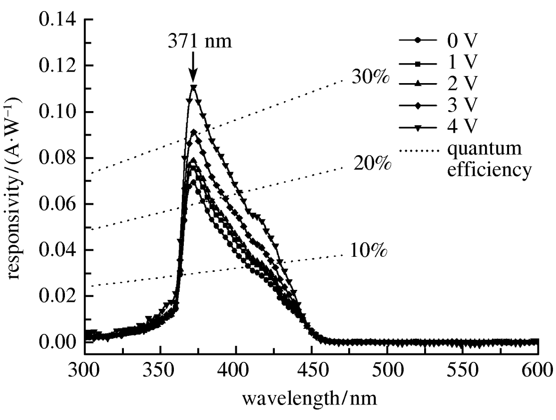

Fig. 3 Responsivity curves of PD under different reverse bias voltages

It is also interesting to observe that the photo-responsivity of the MQW-PD increases with different rates as a function of reverse bias (as shown in Fig. 3). For example, when the reverse bias is larger than 2 V, the photo-response curves clearly rise faster than in the low-bias range. Currently, the exact mechanism underlying this phenomenon is still under investigation. However, we speculate that this observation might be related to the complex interactions between the internal polarization field and external reverse electrical field across the *c*-plane MQWs. It has been well accepted that polarization discontinuities at hetero-interfaces would lead to the formation of an electrostatic field on the order of MV/cm in *c*-plane InGaN/GaN quantum wells. This large polarization field could pull photo-excited electron-hole pairs apart and increase carrier-lifetime in quantum wells. Since recombination is an important carrier-loss process, photo-excited carriers with longer lifetimes will have a greater chance to be collected by electrodes. For our devices, since the InGaN/GaN MQWs are grown along the (0001) direction with p-contact on the top, the external electron field induced by the reverse bias should be in the opposite direction to the polarization field within InGaN quantum wells, while being in the same direction to the polarization field within GaN quantum barriers. As a result, the reverse bias will not only strengthen the average electrical field across the junction, but also affect the recombination efficiency of photocarriers by compensating the built-in polarization field or even reverting the direction of the net electrical field within InGaN quantum wells.

4 Conclusion

In summary, we demonstrated an InGaN/GaN MQW-based light-emitting PD with applied-voltage-selective dual-functionality which could be useful for integrated opto-electronics applications. The device with a thin absorbing layer exhibits high quantum efficiency for blue-to-UV photo-response indicating large optical absorption coefficients of InGaN alloys. This study also suggests that the polarization field within the InGaN/GaN MQWs might play a role in the photocarrier transport process, which will require further investigation in future studies.

Acknowledgements This work was supported by the State Key Program for Basic Research of China (No. 2006CB921803), the National Natural Science Foundation of China (Grant Nos. 60825401, 60806026, and 60721063), and the Program for New Century Excellent Talents in University (No. 07-0417).

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