CHIN. PHYS. LETT. Vol. 30, No. 1 (2013) 017302

High Deep-Ultraviolet Quantum Efficiency GaN P–I–N Photodetectors with Thin P-GaN Contact Layer *

LIAN Hai-Feng(廉海峰), WANG Guo-Sheng(王国胜), LU Hai(陆海)**, REN Fang-Fang(任芳芳), CHEN Dun-Jun(陈敦军), ZHANG Rong(张荣), ZHENG You-Dou(郑有炓)

Jiangsu Provincial Key Laboratory of Advanced Photonic and Electronic Materials, and School of Electronic Science and Engineering, Nanjing University, Nanjing 210093

(Received 9 August 2012)

GaN ultraviolet (UV) p–i–n photodetectors (PDs) with a 40 nm thin p-GaN contact layer are fabricated on sapphire substrates, which exhibit enhanced quantum efficiency especially in a deep-UV wavelength range. The PDs show good rectification behavior and low dark current in pA level for reverse bias up to −10 V. Under zero bias, the maximum quantum efficiency of the PD at 360 nm is close to 59.4% with a UV/visible rejection ratio more than 4 orders of magnitude. Even at a short wavelength of 280 nm, the quantum efficiency of the PD is still around 47.5%, which is considerably higher than that of a control device with a thicker p-GaN contact layer. The room temperature thermal noise limited detectivity of the PD is calculated to be $\sim 4.96 \times 10^{14}$ *cm·Hz*$^{1/2}$ *W*$^{-1}$.

PACS: 73.40.Kp, 85.60.Gz, 81.05.Ea DOI: 10.1088/0256-307X/30/1/017302

GaN-based semiconductors are very attractive for fabricating highly sensitive ultraviolet (UV) photodetectors (PDs) owing to their wide direct bandgap, excellent physical and chemical stability, and increasingly improved material growth/processing technologies. These PDs have wide applications in the fields of flame detection, environmental monitoring, chemical/biological agent sensing, and UV astronomy.[1] Over the last few years, various types of GaN-based PDs have been demonstrated with promising performance including photoconductors,[2] metal-semiconductor-metal PDs,[3,4] Schottky barrier PDs,[5,6] and p–i–n PDs.[7–9] Among these structures, p–i–n PDs draw particular interest for their advantages of low dark current, relatively high speed, and high stability.

However, due to the strong UV light absorption by the p-GaN contact layer, top illuminated GaN p–i–n PDs commonly suffer from low quantum efficiency in the deep-UV wavelength range. A ∼90% reduced photo responsivity at 250 nm compared to the peak responsivity at ∼360 nm has been reported for GaN p–i–n PDs.[10] To reduce the light absorption effect by the p-GaN contact layer, in this work we design and fabricate a GaN p–i–n PD with a thin p-GaN contact layer. The device exhibits low dark current, improved quantum efficiency especially in a deep-UV wavelength range, and high detectivity.

The GaN p–i–n structure used in this work was grown on a sapphire substrate by low-pressure metal organic chemical vapor deposition. The epi-structure consists of a 2.25 μm undoped GaN buffer layer, a 1.75 μm GaN:Si (n∼5×10^{18} cm^{-3}) n-contact layer, a 400 nm un-doped GaN light absorption layer, and a 40 nm GaN:Mg (p∼5×10^{17} cm^{-3}) p-contact layer. The thickness of the p-GaN layer is the lowest reported for GaN p–i–n diodes, which was carefully chosen so that the p-GaN layer would not be fully depleted by the built-in junction electrical field while the UV light absorption by this layer is minimized. Another p–i–n structure with an 80 nm p-GaN contact layer was also grown as a control sample.

The device fabrication process started with mesa formation, which was defined by standard photolithography and patterned by Cl_2/BCl_3-based inductively coupled plasma dry etching. The etch depth is ∼700 nm and down to the n-GaN contact layer. Following the mesa etch, the processed wafers were dipped in hot KOH solution (0.1 M, 100℃) for 5 min to reduce the plasma-etching-induced side-wall damage.[11] A Ti/Al/Ni/Au (100/800/100/600 Å) n-ohmic contact layer surrounding the mesa area was then deposited by electron-beam evaporation and defined by lift-off technique. The n-ohmic contact was annealed at 750℃ for 1 min by using a rapid thermal annealing system under nitrogen atmosphere. Next, an Ni/Au (25/25 Å) semi-transparent p-ohmic contact layer was deposited on top of the mesa and annealed at 500℃ for 5 min in air. After the metal contact formation, the whole device was covered by a 200 nm SiO_2 passivation layer grown by plasma-enhanced chemical vapor deposition. Finally, after selectively etching the SiO_2 layer to expose contact regions, a thick Ti/Au (400/800 Å) metal layer was evaporated to form the contact pads for easy electrical probing. Figures 1(a) and 1(b) show a cross-sectional schematic and a top view image of one finished GaN p–i–n PD. The typical active area of the PDs is 230 μm in diameter.

*Supported by the National Basic Research Program of China under Grant Nos 2010CB327504, 2011CB922100 and 2011CB301900, the National Natural Science Foundation of China under Grant Nos 60825401, 60936004, 11104130 and 60990311.

**Corresponding author. Email: hailu@nju.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

Current–voltage (I–V) characteristics of the PDs are measured by using a Keithley 2636 sourcemeter. For photo response measurement, the light output from a 500 W Xe lamp is directed into a monochromator for single wavelength selection. The PD under test is illuminated from its front-side by monochromic light transmitting through an optical fiber, which is coupled onto the output port of the monochromator. The incident optical power is calibrated by using a UV-enhanced Si photodiode.

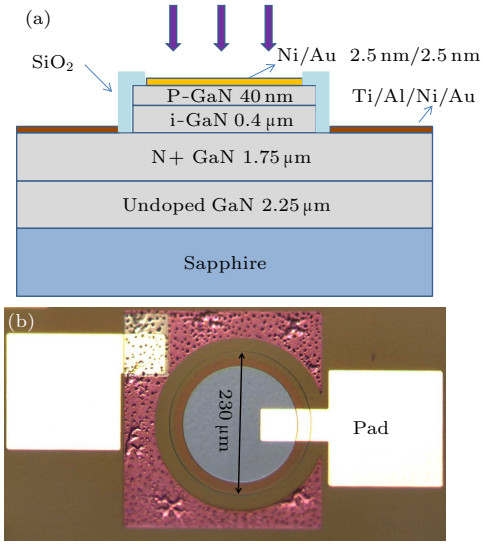

Fig. 1. Schematic cross-sectional view (a) and top view image (b) of one finished GaN p–i–n PD.

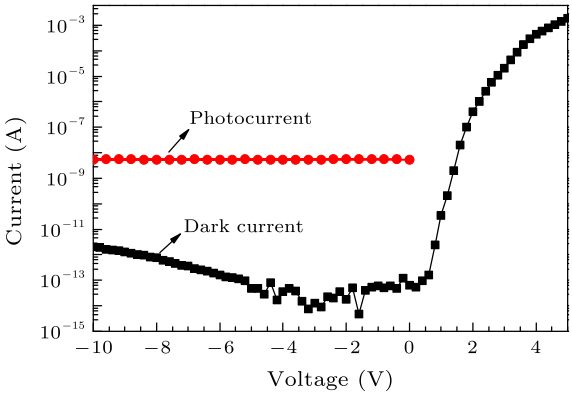

Fig. 2. Dark and photo I–V characteristics of the GaN p–i–n PD with a thin p-GaN contact layer.

Figure 2 shows the room-temperature dark I–V curve of a fabricated PD, which exhibits typical rectifying characteristics of p–i–n junctions. The dark current is less than 3 pA when the reverse bias is up to −10 V. Such a low dark current means that the thin p-GaN contact layer is not fully depleted by the junction electrical field under zero or low reverse bias. The photocurrent curve is measured when the device is front-illuminated by 360 nm UV light with a power density of ∼0.69 μW/mm^2. As shown in Fig. 2, the photocurrent curve is rather flat as a function of reverse bias, indicating comparable quantum efficiency of the PD in the studied bias range. The spectral response characteristics of the GaN p–i–n PD with a thin p-GaN contact layer as a function of reverse bias are shown in Fig. 3. A sharp spectral cutoff is observed at around 365 nm, which corresponds to the optical bandgap of GaN. Meanwhile, the photo response curves exhibit a high UV/visible rejection ratio of $\sim 2.16 \times 10^4$ at zero bias and $\sim 2.87 \times 10^3$ at −8 V. Here the UV/visible rejection ratio is defined as the responsivity measured at 360 nm divided by the value measured at 450 nm. The peak responsivity of the photo response curves occurs at ∼360 nm, which increases from ∼0.17 A/W to ∼0.18 A/W as the reverse bias increases from 0 V to −8 V. The corresponding maximum quantum efficiency increases from ∼59.4% to ∼61.6%. The slightly enhanced quantum efficiency as a function of reverse bias can be explained by further extension of the light-absorption depletion region as well as the improved photo-carrier collection efficiency under a higher junction electrical field.

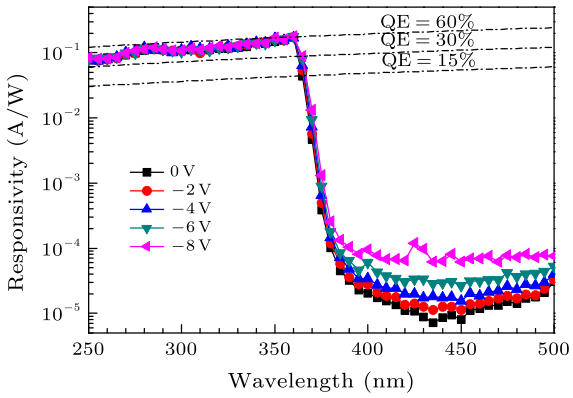

Fig. 3. Spectral response characteristics of the PD measured at various reverse bias.

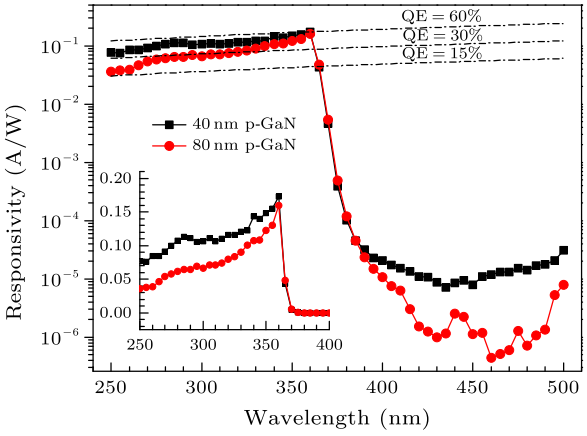

Fig. 4. Zero-bias spectral response characteristics of the GaN p–i–n PD with the 40 nm p-GaN contact layer and the control device with the 80 nm p-GaN contact layer. The inset shows the same plot in linear scale.

The focus of this study is to improve the quantum efficiency of GaN p–i–n PDs in a deep-UV wavelength range. To illuminate the design advantage of the thin

p-GaN contact layer, the photo response curve of a control GaN p–i–n PD with a thicker p-GaN contact layer (80 nm) along with that of the specially-designed sample is shown in Fig. 4 for comparison. The zero-bias peak responsivity of the control device is ∼0.16 A/W at 360 nm, which is lower but still comparable to that of the device with 40 nm p-GaN contact layer (∼0.17 A/W), indicating that the thin p-GaN design does not have a big impact on photo response around the band edge absorption wavelength. However, as the wavelength becomes shorter, the photo responsivity of the GaN p–i–n PD with a 40 nm p-GaN contact layer is clearly less reduced and is significantly higher than that of the control device. For example, as shown in the inset of Fig. 4, at 280 nm their photo responsivities are ∼0.11 A/W and ∼0.06 A/W, respectively, suggesting an improvement of 75% in quantum efficiency. The high deep-UV quantum efficiency (∼47.5% at 280 nm) of the specially-designed GaN p–i–n PD can be explained by the remarkably reduced UV-light absorption by the thin p-GaN contact layer. Such effect is stronger in the shorter wavelength range, as the optical inter-band absorption coefficient of GaN increases rapidly as wavelength decreases. The additional amount of deep-UV light reaching the i-GaN active layer by employing the thin p-GaN cap layer should be proportional to $e^{\alpha(d_1-d_2)}$, where α is the absorption coefficient of GaN ($\sim 1.5\times10^5\,\mathrm{cm}^{-1}$ at 280 nm[12]) and d is the thickness of the p-GaN cap layer ($d_1 = 40$ nm and $d_2 = 80$ nm in our case). Assuming that all enhanced UV light absorption is converted into photo-current, the theoretical maximum improvement of quantum efficiency should be ∼82% at 280 nm, which is comparable to the improvement of 75% obtained experimentally. Here it should also be noted that the deep-UV quantum efficiency of our PD is considerably higher than those of some past reports. For example, the maximum quantum efficiency of the GaN-based p–i–n PDs fabricated by Lin *et al.* barely exceeds 18% at 280 nm.[13] Despite having very low noise, the PD reported by Zhang *et al.* has a maximum quantum efficiency of 35% at 280 nm under a high bias of 70 V.[8]

In addition, the signal-to-noise performance of a PD is usually described by specific detectivity D^*. When thermal noise is larger than background radiation, the detectivity of a PD can be estimated by[14]

$$D^* \cong R_\lambda \sqrt{\frac{R_0 A}{4k_\mathrm{B}T}}, \qquad (1)$$

where k_B is Boltzmann's constant, T is the device temperature, R_λ is the responsivity at zero bias, R_0 is the differential resistance, and A is the device active area. By fitting the dark I–V curve near zero bias, the differential resistance of the GaN p–i–n PD with a thin p-GaN contact layer is deduced to $R_0 = 4.5\times10^{14}\,\Omega$.[15] Thus, for the 230-μm-diameter device with peak responsivity of $R_\lambda = 0.17$ A/W at zero bias, its detectivity is calculated to be $D^* = 4.96\times10^{14}\,\mathrm{cm\cdot Hz^{1/2}W^{-1}}$, which is of the same order of magnitude than the highest detectivity performance reported for p–i–n UV PDs.[16]

In summary, we have reported the growth, fabrication, and characterization of a GaN p–i–n PD with a 40 nm thin p-GaN contact layer. The PD exhibits high quantum efficiency not only at around band edge absorption wavelength but also in a deep UV wavelength range. The enhanced deep-UV quantum efficiency (∼47.5% at 280 nm under zero bias) is caused by the remarkably reduced UV-light absorption by adopting the thin p-GaN contact layer within the PD. Meanwhile, the PD also exhibits low dark current, high UV/visible rejection ratio and high detectivity.

References

[1] Razeghi M 2002 *Proc. IEEE* **90** 1006
[2] Walker D, Zhang X, Kung P, Saxler A, Javadpour S, Xu J and Razeghi M 1996 *Appl. Phys. Lett.* **68** 2100
[3] Butun S, Gökkavas M, Yu H B and Ozbay E 2006 *Appl. Phys. Lett.* **89** 073503
[4] Xie F, Lu H, Chen D J, Xiu X Q, Zhao H, Zhang R and Zheng Y D 2011 *IEEE Electron Device Lett.* **32** 1260
[5] Zhou Y, Ahyi C, Tin C C, Williams J and Park M 2007 *Appl. Phys. Lett.* **90** 121118
[6] Sheu J K, Lee M L, Tun C J and Lin S W 2006 *Appl. Phys. Lett.* **88** 043506
[7] Butun B, Tut T, Ulker E, Yelboga T and Ozbay E 2008 *Appl. Phys. Lett.* **92** 033507
[8] Zhang Y, Shen S C, Kim H J, Choi S and Ryou J H 2009 *Appl. Phys. Lett.* **94** 221109
[9] Biyikli N, Kimukin I, Aytur O and Ozbay E 2004 *IEEE Photon. Technol. Lett.* **16** 1718
[10] Chiou Y C 2009 *Semicond. Sci. Technol.* **24** 055004
[11] Yang Y and Cao X A 2009 *J. Vac. Sci. Technol.* B **27** 2337
[12] Hovel H J and Cuomo J J 1972 *Appl. Phys. Lett.* **20** 71
[13] Lin J C, Su K Y, Chang S J, Lan W H, Chen W R, Huang K C, Cheng Y C and Lin W J 2008 *IEEE Photon. Technol. Lett.* **20** 1255
[14] Morkoç H, Carlo A D and Cingolani R 2002 *Solid-State Electron.* **46** 157
[15] Collins C J, Li T, Lambert D J H, Wong M M, Dupuis R D and Campell J C 2000 *Appl. Phys. Lett.* **77** 2810
[16] Jiang H and Egawa T 2008 *Jpn. J. Appl. Phys.* **47** 1541