English

Research Express@NCKU Volume 4 Issue 7 - May 30, 2008
[http://research.ncku.edu.tw/re/articles/e/20080530/1.html]

InGaN-GaN MQW Metal-Semiconductor-Metal Photodiodes With Semi-Insulting Mg-Doped GaN Cap Layers

Ricky W. Chuang*, C. L. Yu, and S. J. Chang

Institute of Microelectronics and Department of Electrical Engineering, National Cheng Kung University
Email:rwchuang@mail.ncku.edu.tw

IEEE Photonics Technology Letters, Vol. 19, No. 11, pp. 846-848, June 1, 2007

Owing to their direct and wide bandgap, III-nitride compound semiconductors are highly suitable for fabricating ultraviolet (UV) photodiodes (PDs). In particular, the use of InGaN alloys offers the possibility of shifting the detection edge from the UV to visible (VIS), and even to the infrared (IR) range. To date, most of the efforts have concentrated on developing III-nitride PDs based on bulk-like epilayers. In contrast to the bulk-layer design, the use of multiple quantum wells (MQWs) in the active region of standard structures including p-n junction, Schottky barriers, metal-semiconductor-metal (MSM) and others certainly offers considerable advantages, such as an easier integration of emitter and detector functions, an extra flexibility to tune the detection edge by adjusting well width and In-Al composition, and the possibility of realizing multicolor detection pixels.

To date, a variety of GaN-based PDs have been proposed and fabricated. Among them, MSM PDs offers quite a few attractive features including the process compatibility with field-effect transistor for possible device integration. However, one of notorious characteristics commonly associated with these detectors is the high leakage current, which is primarily due to the high dislocation density present in the epilayers. To counter this adverse effect, one of possible solutions is to adopt a metal-insulator-semiconductor structure to significantly reduce the leakage current. Here, we propose an alternative structure by incorporating an *in situ* grown, unactivated, Mg-doped GaN into MSM PD. Without activation, it is known that Mg-doped GaN is considered highly resistive (> 10^6 Ω-cm) due to the compensation of residual donors. Hence, adding this highly resistive layer believable would help to suppress the leakage current. Therefore, our work is primarily dedicated to the performance analysis of the characteristics of MQW MSM PDs incorporated with a semi-insulating Mg-doped GaN cap layer.

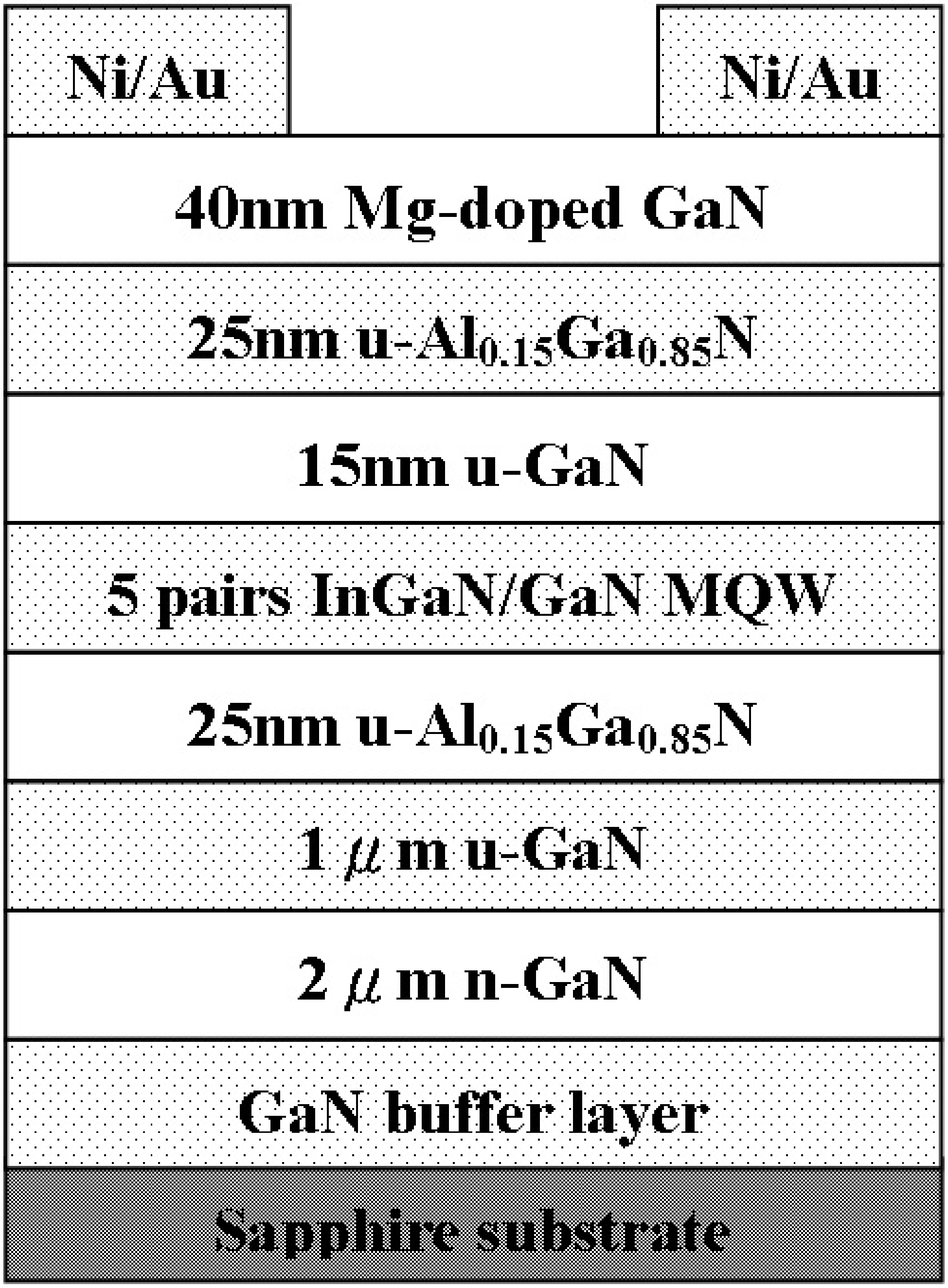

Fig. 1.The schematic diagram of the PD_A.

The samples used in this study were epitaxially grown on c-face sapphire substrates by metal-organic vapor phase epitaxy (MOVPE). Each sample consists of a 25 nm-thick low temperature GaN nucleation layer, a 2 μm-thick Si-doped n-type GaN, 1 μm-thick unintentionally doped GaN, a 25 nm-thick unintentionally doped $Al_{0.15}Ga_{0.85}N$, an unintentionally doped InGaN/GaN MQW active region, a 15 nm-thick unintentionally doped GaN cladding layer, a 25 nm-thick unintentionally doped $Al_{0.15}Ga_{0.85}N$ and a 40 nm-thick un-activated, Mg-doped GaN cap layer (i.e., PD_A). The active region consists of 5-period MQW, with 3 nm-thick $In_{0.05}Ga_{0.95}N$ well layers and 12 nm-thick GaN barrier layers. The un-activated Mg-doped GaN cap layer behaves like an insulator with a sheet resistivity larger than $10^8 \Omega/\square$. For comparison, samples without the Mg-doped cap layer (i.e., PD_B) were also prepared. Ni/Au (40 nm/100 nm) contact electrodes were then deposited onto samples for the fabrication of MQW MSM UV

PDs. Figure 1 shows schematic diagram of the InGaN/GaN MQW MSM UV PDs. The fingers of the contact electrodes were 24 μm wide and 100 μm long with 6 μm spacing. Four pairs of fingers were used to achieve a total photodetector active area of 100×234 μm^2.

Figure 2 shows room temperature PL spectra of the MQW structures with and without the semi-insulating Mg-doped cap layers. It was found that PL peak wavelength for PD_A and PD_B was 384.9 and 383 nm, respectively. The slight difference in PL peak wavelength is probably due to the growth temperature fluctuation when growing the relevant device structures. It is known that PL peak wavelength of nitride-based MQW shows a strong dependency on the growth temperature; in fact a 1°C difference in nitride-based MQW growth temperature will result in a 1-2 nm shift in PL peak position. Besides, a GaN related peak was also observed from PL spectra of both PD_A and PD_B. The GaN related peak in PL spectra is around 363 nm. On the other hand, PL full-width at half-maximums (FWHMs) of PD_A and PD_B are 69.5 meV and 73.7 meV, respectively, which suggest crystal qualities of these two samples are good and nearly identical.

Figure 3 shows the measured I-V characteristics of two PDs. It was found that the dark current was around 10^{-11} A for PD_A, while the dark current of PD_B was at least six orders of magnitude larger. With same −5 V reverse bias applied, the reverse leakage current of PD_A was 2.25×10^{-11} A, whereas for PD_B the leakage current was elevated to 2.75×10^{-5} A. A comparably lower reverse leakage current could be attributed to a thicker and higher potential barrier as result of including a highly-resistive Mg-doped GaN cap layer. In addition, it is known that a large leakage current along the Schottky interface of metal-semiconductor-metal photodetector is related to the surface defects (possibly threading dislocations). Therefore, a highly resistive Mg-doped GaN cap layer potentially can block most of leakage paths incurred by TD surface terminations.

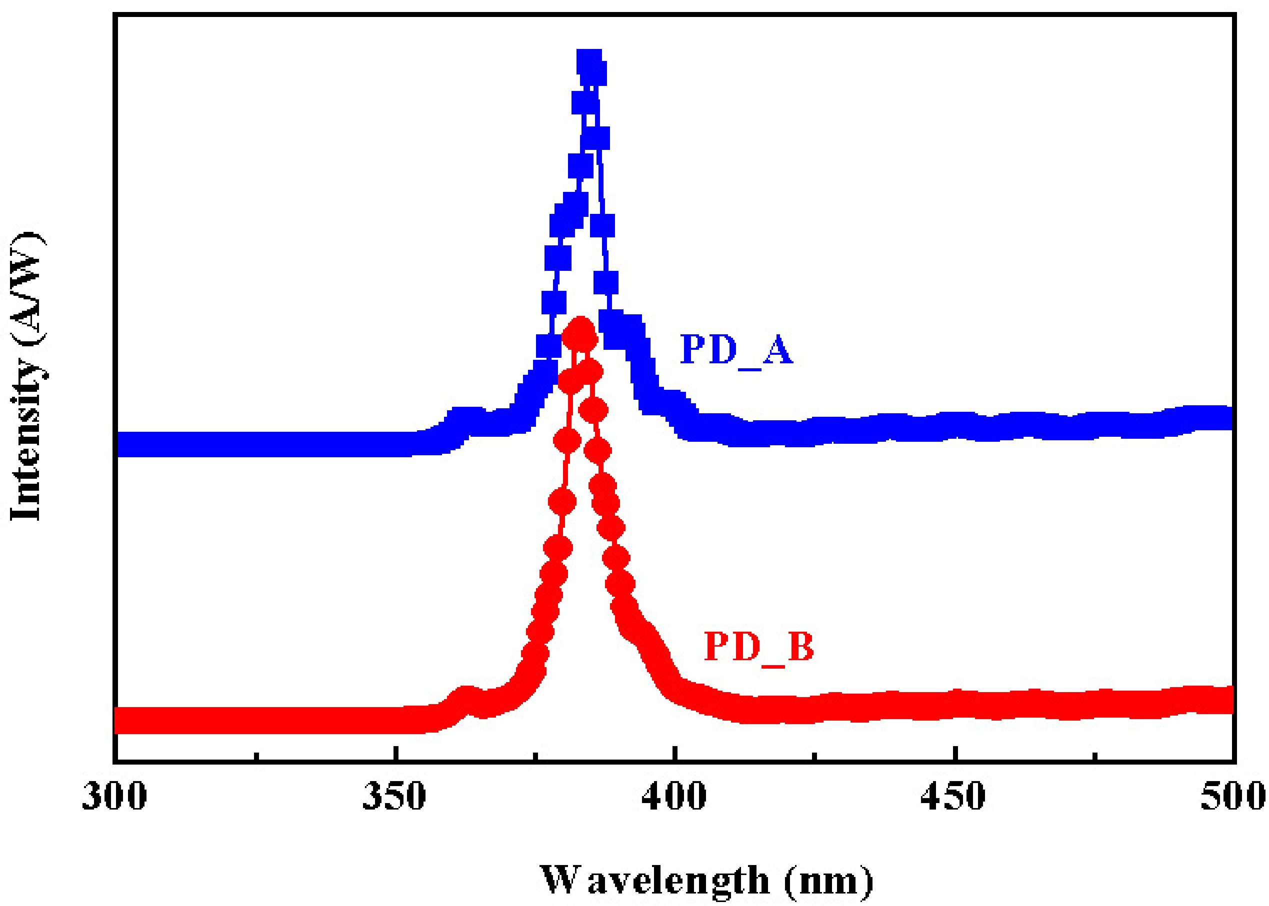

Fig. 2.A typical room temperature photoluminescence spectra of the PD_A and PD_B.

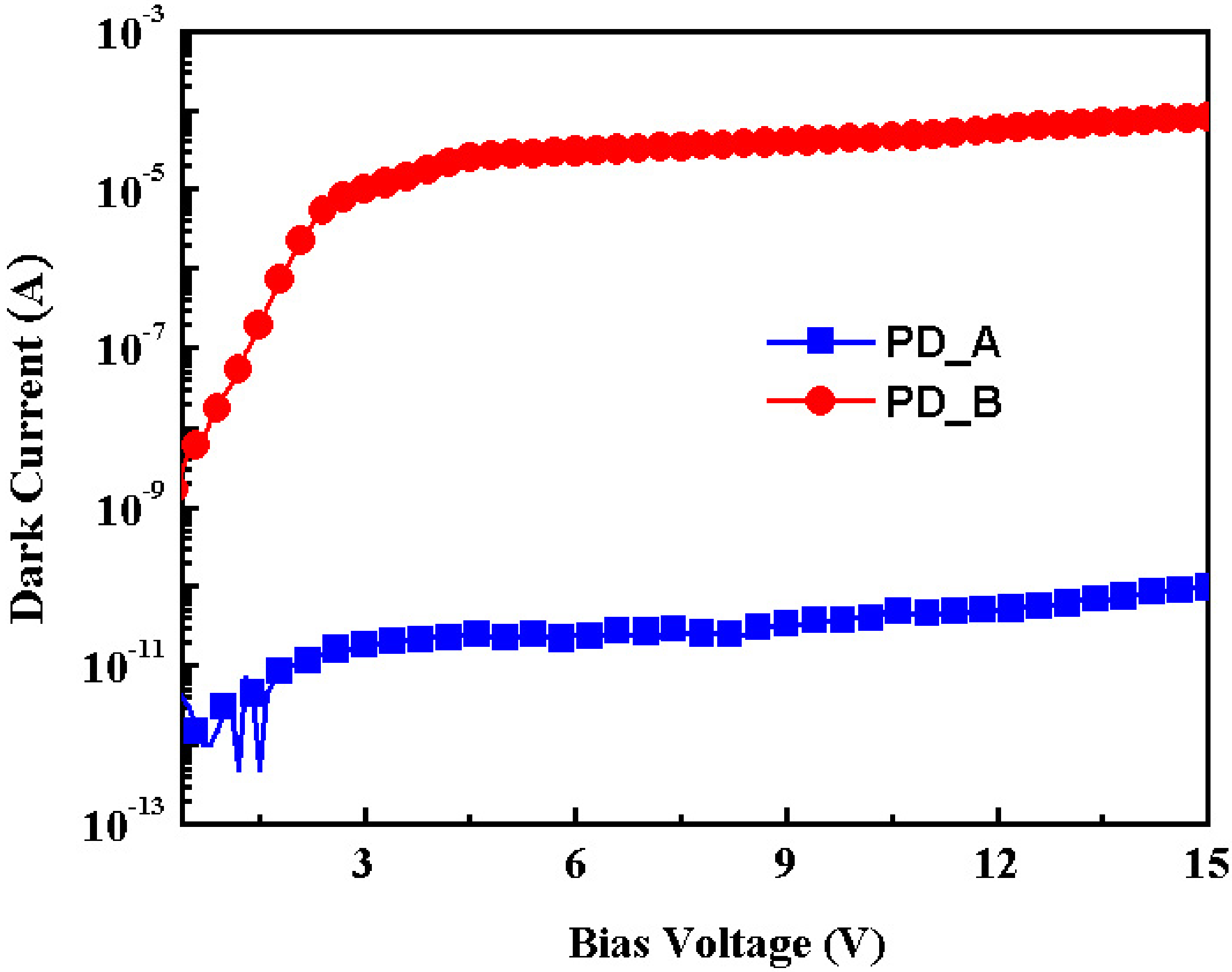

Fig. 3.The current-voltage characteristics of PD_A and PD_B under dark condition.

Figure 4 shows room temperature spectral responses of two PDs biased at 5 V. Both photo responses were observed to be relatively flat in the short wavelength regime, while the cut-off occurring at 380 nm was related to the absorption of InGaN/GaN MQW for both PDs, as shown earlier in Fig. 2. This observation suggested that the quality of our epitaxial layer was reasonably good. The inset of Fig. 4 depicts measured responsivity at 380 nm as a function of applied bias for PD_A and PD_B. It was found that responsivity of PD_A was virtually independent of bias. In contrast, the responsivity of PD_B increased with applied bias. In addition, as also shown in Fig. 4, responsivities at 380nm were 0.372 and 12.21 A/W for PD_A and PD_B, respectively. These results suggested the existence of high internal gain in PD_B. One possible origin of this internal gain is an increased electron injection at the cathode contact due to the lowering of the barrier height when holes are trapped at the surface sites. If this is the case, our result implied the effective passivation of surface states and inhibition of internal gain could be achieved by capping the semiconductor surface with a thin Mg-doped GaN cap layer. In other words, PD_A with a small internal gain might be attributed to the effective passivation of notorious surface states as result of inserting a Mg-doped GaN cap layer. Here, the UV to visible rejection ratio was defined as the responsivity measured at 380 nm divided by the responsivity measured at 400 nm. Therefore, the UV to visible rejection ratio was estimated to be around 1.96×10^{3} and 3.13 for PD_A and PD_B, respectively. Notice that the measured responsivity under various wavelengths obtained from PD_B was much larger than the theoretical limit, i.e., the quantum efficiency was beyond 100%. This result could only be due to the large dark current and surface-states-related internal gain. An enhancement in the UV to visible rejection ratio was indeed realized by incorporating a semi-insulating Mg-doped GaN cap layer into the photodiode structure.

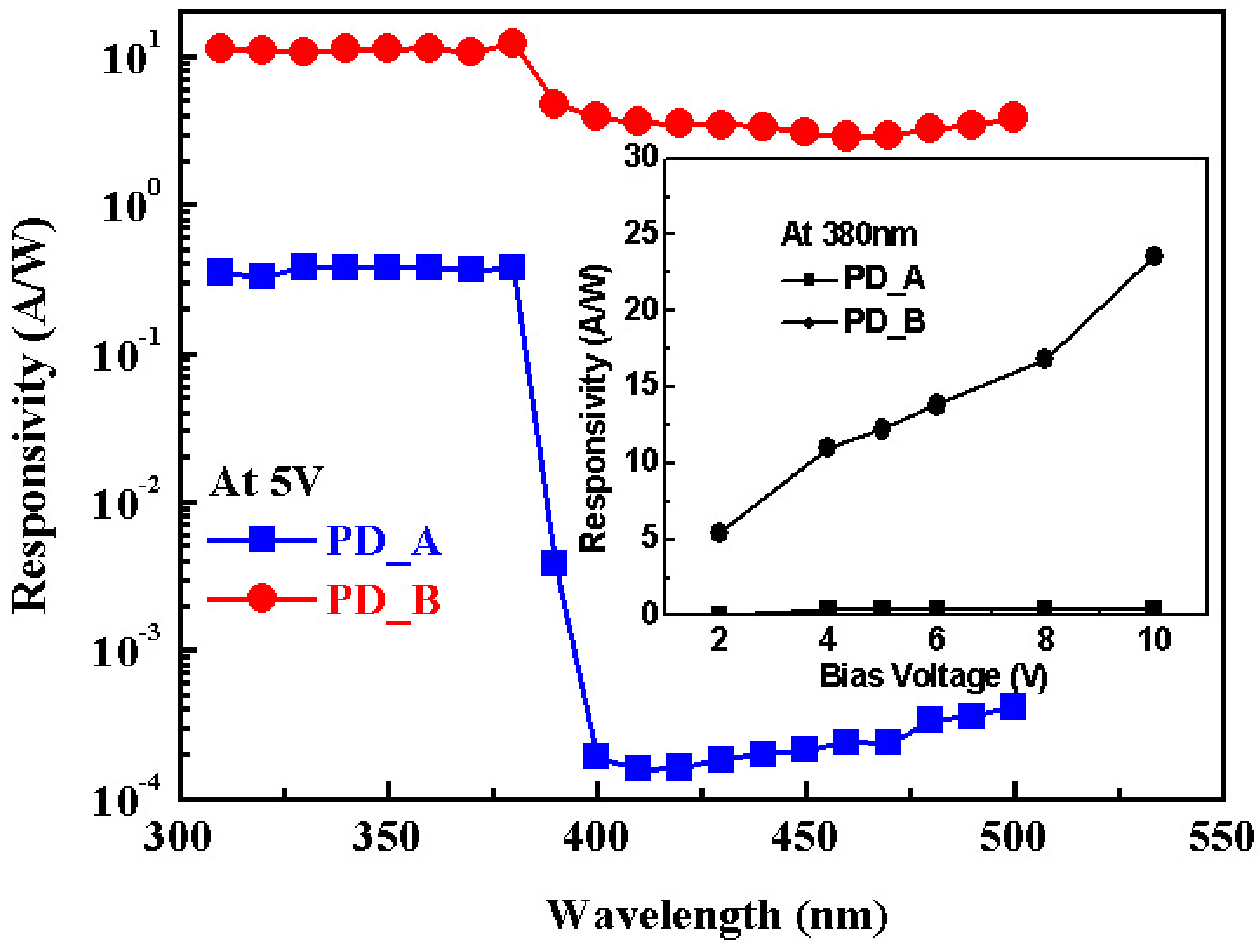

Fig. 4.Measured spectral responsivity of PD_A and PD_B measured at 5V bias voltage.

In summary, nitride-based MQW MSM PDs with semi-insulating Mg-doped GaN cap layers were successfully fabricated. It was found that the dark current of the aforementioned photodiode was comparably much smaller than that of conventional PD without the semi-insulating Mg-doped GaN cap layer. For the PDs with semi-insulating Mg-doped GaN cap layers, the responsivity at 380 nm and UV to visible rejection ratio were 0.372 A/W and 1.96×10^3 when biasing at 5 V, respectively.