English
Research Express@NCKU Volume 8 Issue 1 - March 20, 2009
[ http://research.ncku.edu.tw/re/articles/e/20090320/4.html ]

# High Responsivity of GaN p-i-n Photodiode by Using Low-Temperature Interlayer

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Applied Physics Letters 91, 173502 (2007)

## Abstract

Gallium nitride p-i-n ultraviolet photodiodes with low-temperature GaN interlayer have been fabricated. It was found that the dark current of photodiode with LT-GaN interlayer is as small as 143pA at 5-V reverse bias. It was also found that the responsivity of the photodiode with LT-GaN interlayer can be enhanced at a small electric field (~0.4 MV/cm) due to the carrier multiplication effect. The UV photocurrent gain of 13 and large ionization coefficient ($\alpha=3.1\times10^5$ cm$^{-1}$) were also observed in the detector with LT-GaN interlayer. Furthermore, we can achieve a large peak responsivity of 2.27 A/W from the photodiode with LT-GaN interlayer.

Nitride-based semiconductors have been commercialized on light-emitting diodes[1] (LEDs) and laser diodes[2] (LDs) due to their excellent optical and electrical properties. On the other hand, the devices based on nitride semiconductors are also suitable as detectors for ultraviolet (UV) radiation detection because of their wide direct band gap, high breakdown fields and high temperature operation. GaN-based photodiodes have potential applications in chemical sensing, flame and heat detection, and missile detection.[3,4] In the past few years, GaN p-i-n photodiodes have been fabricated in different types of structures.[5-12] In this work, we present the properties of a p-i-n structure which inserts a low temperature GaN (LT-GaN) thin layer in intrinsic absorption layer. It is known that the LT-GaN layer as nucleation layer is necessary to grow high quality GaN epitaxial films.[13] It is also known that LT-GaN interlayer can suppress threading dislocations extending to the subsequently grown high-temperature GaN (HT-GaN) epitaxial layers.[14,15] The LT-GaN cap layer also can be used to serve as the passivation layer of GaN Schottky diodes.[16,17] We applied thin LT-GaN layer as interlayer in the absorption layer of the GaN p-i-n structures. The electrical and optical properties of the fabricated photodiodes with and without LT-GaN interlayer will also be discussed.

The device structures of this work were all grown on c-plane (0 0 0 1) sapphire substrates by a low-pressure metalorganic chemical vapor deposition system. Trimethylgallium (TMGa), trimethylaluminum (TMAl) and ammonia ($NH_3$) were used as the source materials of Ga, Al and N, respectively. Silane (SiH4) and biscyclopentadienyl-magnesium ($Cp_2Mg$) were used as the n-type and p-type dopant sources. The carrier gases were hydrogen and nitrogen. A two-step growth procedure was employed with a low-temperature GaN nucleation layer grown at 520°C and the high-temperature epitaxial layers grown at 1120°C. The p-i-n photodiode structure consists of a 25-nm-thick GaN nucleation layer, a 4-μm-thick Si-doped n-GaN layer, a 1-μm-thick undoped GaN absorption layer, a 20-nm-thick Mg-doped p-GaN layer, an Mg-doped $Al_{0.15}Ga_{0.85}N$/GaN strain layer superlattice (SLS) structure, and a 12-nm-thick delta-doped p-GaN contact layer (sample A). The Mg-doped $Al_{0.15}Ga_{0.85}N$/GaN SLS structure consists three pairs of 8-nm-thick $Al_{0.15}Ga_{0.85}N$ layers and 8-nm-thick GaN layers. The purpose of using p-AlGaN/GaN SLS structure is to achieve a higher hole concentration and more photon incident at GaN absorption range.[18] The other p-i-n structure is the same as sample A, but inserts a 30-nm-thick LT-GaN layer in the middle of 1-μm-thick undoped GaN absorption layer (sample B). GaN p-i-n photodiodes were then fabricated by conventional photolithography and inductively coupled plasma etching. Ni-Au contact was subsequently evaporated onto the p-type GaN surface to serve as the p-electrode. On the other hand, Cr-Pt-Au contact was deposited onto the exposed n-type GaN layer to serve as the n-electrode. The wafers were then lapped down to 100 μm and fabricated to the size of 325×325 $\mu m^2$ chips. After these procedures, we used an HP-4156B semiconductor parameter analyzer to measure current-voltage (I-V) characteristics of the fabricated photodiodes. Spectral responsivity measurement was also performed by JOBIN-YVON SPEX 1000M System with a xenon arc lamp light source. All the optical systems are calibrated by using a UV-enhanced silicon photodiode.

Figure 1 shows measured photocurrent under xenon light source illumination at room temperature. It can be seen that the photocurrent increased largely after 20 V reverse bias at the sample with LT-GaN interlayer. The increase of photocurrent also shows an internal current gain in sample B. In contrast, the photocurrent of sample A was almost flat in the whole measurement range as shown in Fig. 1. The inset of Fig. 1 shows the dark currents of the two fabricated photodiodes measured at room temperature. The dark currents of sample A at 5 V and 40 V reverse bias are 15.7 pA and 36.6 nA, respectively while the dark currents of sample B at 5 V and 40 V reverse bias are 143 pA and 147 nA, respectively. The slight increase of dark current in sample B may be attributed to the leakage paths formed from LT-GaN interlayer. It also can be seen that the reverse break-down voltage of both samples is more than 40 V. Thus, the current gain in sample B can not be attributed to avalanche multiplication effect.

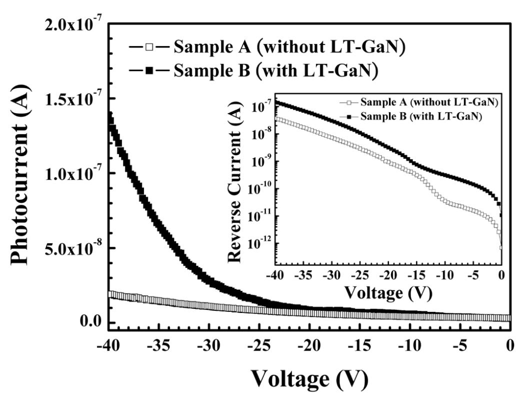



Figure 1. Measured photocurrent of photodiodes with (sample B) and without (sample A) LT-GaN interlayer under xenon light illumination. The inset

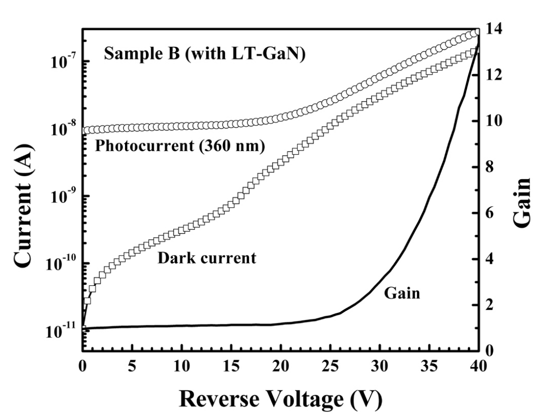



Figure 2. Reverse I-V characteristics of sample B in the dark and 360 nm light illumination. The right-

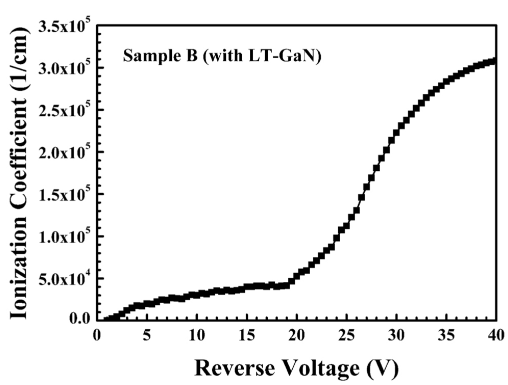
shows the dark I-V characteristics of both samples. hand axis indicates the photocurrent gain.

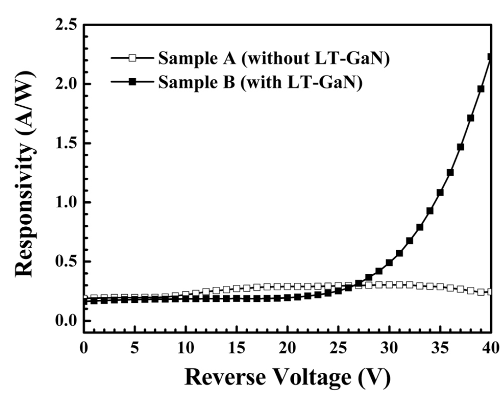
Figure 2 shows the UV photoresponse to excitation with 360 nm light and dark current of sample B. The current gain was also shown in the right axis of Fig. 2 and determined by using the photocurrent at a bias of 1 V as the unity gain reference point. It was found that the current gain occurred at 20 V reverse bias and reached a value of 13 at 40 V reverse bias (limited by measurement equipment). It is known that current gain can be obtained through the avalanche multiplication effect in avalanche photodiodes. The avalanche multiplication not only depends on the high electric field, but also the overall spatial distance. An electric field around 3.5 and 2.8 MV/cm across the transition region with i-layer thickness 100 and 300 nm is necessary for GaN avalanche photodiodes to operate at avalanche mode.[19,20] Comparing to these avalanche photodiodes, the thickness of absorption layer of sample B is larger than that of avalanche photodiode. The carrier multiplication would be achieved with a lower estimated electric field around 0.4 MV/cm (with 40 V reverse bias across the 1000 nm i-layer) by the p-i-n structure proposed in this work (sample B). It was also known that the crystal quality of LT-GaN layer is not as good as the quality of HT-GaN layer. Then some defect related trap levels should exist within the band gap of LT-GaN interlayer. The bonding energy of defect-trapped carriers should be smaller than energy of lattices bonding. Thus, less energy is needed to cause carrier multiplication from these energy levels within the band gap of the LT-GaN interlayer. The electric field we need in sample B is much smaller than that in other reported GaN avalanche photodiodes.[19,20] It is also found that the current gain increased smoothly, which means that no microplasma emissions are observed.[19]

Figure 3 shows the ionization coefficient of sample B versus applied reverse bias. The ionization coefficient ($\alpha$) can be extracted from the following equation by the assumption that electron ($\alpha_e$) and hole ($\alpha_h$) ionization are the same in GaN ($\alpha_e=\alpha_h=\alpha$).[21]

$$M = \frac{1}{1-\int_0^L \alpha dx}$$

where $M$ is the multiplication gain, $L$ is the length of multiplication region, and $\alpha$ is the ionization coefficient. Since the carrier multiplication only happened in the photodiode with LT-GaN interlayer. We can assume that the multiplication region is exactly the LT-GaN interlayer, i.e., $L$=30nm. Thus, the ionization coefficient which can be calculated from the above equation is $3.1\times10^5$ cm$^{-1}$. This value of ionization coefficient is larger than that in other reported photodiodes by Carrano et al.[19] ($\alpha=9.6\times10^4$ cm$^{-1}$) and Limb et al.[20] ($\alpha=3.3\times10^4$ cm$^{-1}$). The larger ionization coefficient could be attributed to the large multiplication carrier generated from the defect-trapped levels in the LT-GaN interlayer. In Fig. 3, we also observed the saturation trend at high reverse bias. This saturation trend in ionization coefficient shows multiplication carrier generated from the intermediate energy states, not from the valence band.[22]



Reverse Voltage (V)

Figure 3. Ionization coefficient in sample B versus various reverse biases.

Reverse Voltage (V)

Figure 4. Spectral responsivities (360 nm) of sample A and sample B measured at different reverse biases.

Figure 4 shows the responsivities of sample A and sample B, which are measured at 360 nm wavelength. A typical responsivity of a GaN p-i-n photodiode varied with voltages was observed in sample A. The responsivity increased slightly with increasing applied voltage. The 360 nm wavelength responsivities of the sample A at 0 and 40 V reverse bias are 0.18 and 0.24 A/W, respectively. In contrast, the responsivity of sample B increased largely with increasing applied voltage because of the carrier multiplication effect. The 360 nm wavelength responsivities of sample B at 0 and 40 V reverse bias are 0.16 and 2.27 A/W, respectively. In Fig. 4, it was also found that the peak responsivity (360 nm) of sample B was smaller than that of sample A at a reverse bias of less than 25 V. This may be due to that the photogenerated carriers were compensated by the defect levels of LT-GaN interlayer in sample B. On the other hand, the responsivity of sample B was much larger than that of sample A when the applied bias was higher than 25 V reverse bias. This could be attributed to the carrier multiplication effect caused by the same defect levels of LT-GaN interlayer in the sample B. The peak responsivity of sample B was 9.5 times larger than that of the sample A at 40 V reverse bias.

In summary, nitride-based p-i-n UV photodiodes with LT-GaN interlayer have been fabricated. It was found that the dark current of photodiode with LT-GaN interlayer is as small as 143pA at 5 V reverse bias. It was also found that the responsivity of the photodiode with LT-GaN interlayer can be enhanced at a small electric field (~0.4 MV/cm) due to the carrier multiplication effect. The UV photocurrent gain of 13 and large ionization coefficient ($\alpha=3.1\times10^{5}$ $cm^{-1}$) were also observed in the detector with LT-GaN interlayer. Furthermore, we can achieve a large peak responsivity of 2.27 A/W from the photodiode with LT-GaN interlayer. This value of responsivity is 9.5 times larger than the responsivity of the conventional p-i-n GaN photodiode.

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