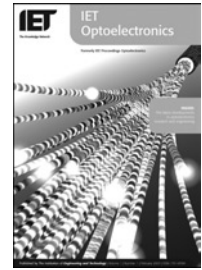


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# GaN p-i-n photodetectors with an LT-GaN interlayer

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**Abstract:** Nitride-based p-i-n ultraviolet (UV) photodetectors with a low-temperature (LT) GaN interlayer were proposed and fabricated. Compared with a conventional GaN p-i-n photodetector, it was found that both the dark current and ideality factor of the p-i-n photodetector with an LT-GaN interlayer became larger whereas the UV-to-visible rejection ratio became smaller because of the poor crystal quality of the LT-GaN interlayer. However, the responsivity of the GaN p-i-n photodetector with an LT-GaN interlayer was larger than that of the conventional GaN p-i-n photodetector under a high reverse bias because of the carrier multiplication effect and/or internal gain that originated from the defect levels.

## 1 Introduction

During the past two decades, tremendous progress has been achieved in GaN-based blue, green and ultraviolet (UV) light emitting diodes (LEDs) [1] and laser diodes [2]. For example, GaN-based blue and green LEDs prepared by metalorganic chemical vapour deposition (MOCVD) have already been extensively used in full-colour displays and high-efficient light sources for traffic light lamps. GaN-based LEDs have also been successfully commercialised. These materials are also the ideal candidates for UV photodetectors. With a large bandgap of 3.4 eV, GaN-based photodetectors are insensitive to visible light. In other words, GaN-based photodetectors should be able to provide us a large UV-to-visible rejection ratio. These visible-blind photodetectors are potentially useful in chemical sensing, flame and heat detection, and missile detection [3, 4]. Other than the rejection ratio, absolute

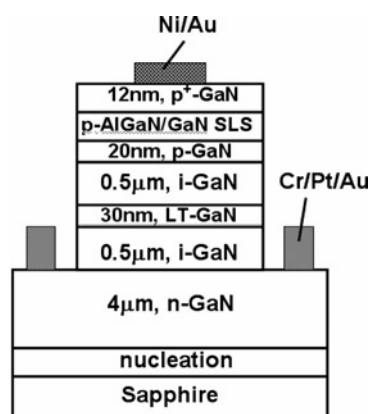
responsivity, response linearity, noise level and response speed are also parameters in evaluating the performance of photodetectors. Depending on the application, it is possible that one of these parameters is more important than the others. For example, absolute responsivity should be more important than other parameters for photodetectors used in digital communication and power meter application. To achieve absolute responsivity of the photodetectors, one could either improve the crystal quality of the epitaxial layer and/or enhance internal gain of the photodetectors.

A low-temperature (LT) GaN layer is commonly used as the nucleation layer for nitride-based devices [5]. Although crystal quality of the LT GaN layer itself is poor, it can significantly reduce threading dislocations in the subsequently grown high-temperature GaN epitaxial layers [6, 7]. Very recently, it has been shown that the LT-GaN can be used to serve as the passivation layer of GaN-based

Schottky diodes and metal-semiconductor-metal photodetectors [8, 9]. In this paper, we fabricated novel p-i-n photodetectors with a thin LT-GaN interlayer in the intrinsic absorption layer. Properties of the fabricated photodetectors with and without the LT-GaN interlayer will also be discussed.

## 2 Experiments

Samples used in this study were all grown by a low-pressure MOCVD system on c-plane (0 0 0 1) sapphire substrates. Details of the growth can be found elsewhere [10–12]. Prior to the growth, the sapphire substrates were first cleaned in situ with pure hydrogen at 1120°C. Trimethylgallium, trimethylaluminum and ammonia were used as the source materials of Ga, Al and N, respectively. Silane and biscyclopentadienyl-magnesium were used as the n- and p-type dopant sources, respectively. The structure of the fabricated p-i-n photodetector consists of a 25-nm-thick GaN nucleation layer grown at 520°C, a 4- $\mu\text{m}$ -thick Si-doped n-GaN layer grown at 1120°C, a 0.5- $\mu\text{m}$ -thick undoped GaN layer, a 30-nm-thick LT-GaN interlayer, a 0.5- $\mu\text{m}$ -thick undoped GaN layer, a 20-nm-thick Mg-doped p-GaN layer, an Mg-doped  $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$  strain layer superlattice (SLS) structure and a 12-nm-thick delta-doped p-GaN contact layer. The Mg-doped  $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$  SLS structure consists of three pairs of 8-nm-thick  $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$  layers and 8-nm-thick GaN layers. The purpose of using p-AlGaIn/GaN SLS structure is to achieve a higher hole concentration and more photons incident at the GaN absorption range [13]. For comparison, samples without the 30-nm-thick LT-GaN interlayer were also prepared. After the growth, the samples were in situ annealed at 750°C in  $\text{N}_2$  ambient for 20 min to active Mg in the p-type layers. GaN p-i-n photodetectors 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. Fig. 1 shows a schematic diagram of the

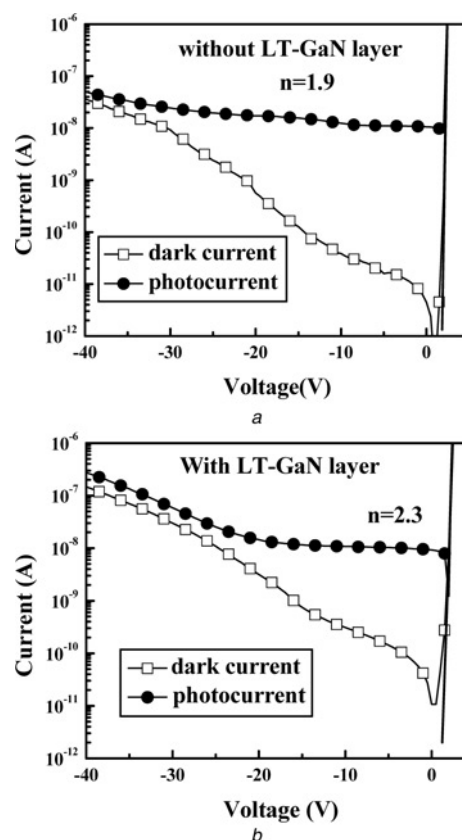


**Figure 1** Schematic structure of the GaN p-i-n photodetector with LT-GaN interlayer

p-i-n photodetector proposed in this study. The wafers were then lapped down to 100  $\mu\text{m}$ . We then used a scribe and breaker to fabricate the  $325 \times 325 \mu\text{m}^2$  chips. After these procedures, we used an HP-4156 semiconductor parameter analyser to measure current-voltage (I-V) characteristics of the fabricated photodetectors. Spectral responsivity measurements were also performed by a JOBIN-YVON SPEX 1000M System with a xenon arc lamp light source. All the optical systems were calibrated using a UV-enhanced silicon photodiode.

## 3 Results and discussion

Figs. 2a and 2b show dark I-V characteristics of the fabricated p-i-n photodetectors without and with the LT-GaN interlayer, respectively. I-V characteristics measured under 360 nm light illuminations were also plotted in these figures. For the conventional p-i-n photodetector without the LT-GaN interlayer, it was found that measured dark currents were 15.7 and 36.6 nA when biased at  $-5$  and  $-40$  V, respectively. On the other hand, dark currents of the p-i-n photodetector with the LT-GaN interlayer were 143 and 147 nA when biased at  $-5$  and  $-40$  V, respectively. The larger dark currents observed from the photodetector with the LT-GaN interlayer should be attributed to the leakage paths formed in the LT-GaN. It was also found that the



**Figure 2** I-V characteristics of the fabricated p-i-n photodetectors

a Without the LT-GaN interlayer  
b With the LT-GaN interlayer

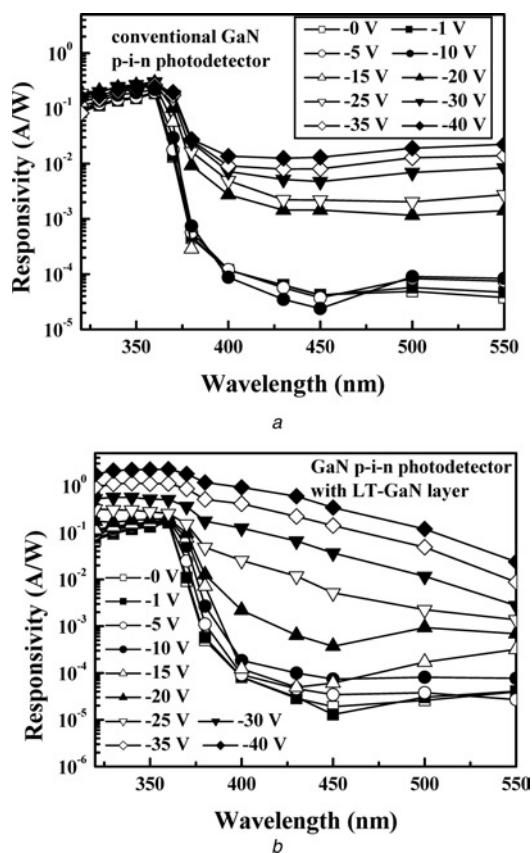
ideality factor of the conventional p-i-n photodetector was 1.9, which suggests that the dominant carrier transport mechanism was the recombination current [14]. In contrast, the ideality factor of the p-i-n photodetector with the LT-GaN interlayer was 2.3. The larger ideality factor indicates that other processes contributed to the dark leakage current. It is possible that additional recombination/generation processes occurred in the LT-GaN interlayer (in the middle of the absorption region) because of its poor crystal quality. It should be noted that the reverse photocurrent of the p-i-n photodetector with the LT-GaN interlayer increased significantly at a high-applied bias. In contrast, the reverse photocurrent of the conventional p-i-n photodetector only depends slightly on the applied bias. The increase of the reverse photocurrent shown in Fig. 2b indicates that the current gain exists in the p-i-n photodetector with the LT-GaN interlayer.

Figs. 3a and 3b show responsivities measured under various applied reverse biases for the fabricated GaN p-i-n photodetectors without and with the LT-GaN interlayer, respectively. It was found that the maximum responsivity occurred at 360 nm for both detectors, which corresponds to the GaN absorption bandgap. Here, we define UV-to-visible rejection ratio as the responsivity measured at

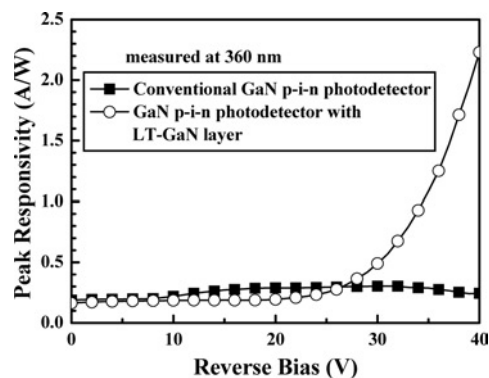
360 nm divided by the responsivity measured at 450 nm. With such a definition, it was found that zero-biased UV-to-visible rejection ratios were both larger than 5000 for these two photodetectors. As we increased the applied reverse bias from 0 to 15 V, no visible change could be found in the spectral responses shown in Fig. 3a for the conventional GaN p-i-n photodetector. However, as we further increased the applied reverse bias, it was found that the responsivity in the long wavelength region (i.e.  $\lambda > 400$  nm) increased significantly whereas that in the short wavelength region (i.e.  $\lambda < 360$  nm) remained almost unchanged. As a result, the UV-to-visible rejection ratio decreased to 65 and 20 when the conventional GaN p-i-n photodetector was biased at -30 and -40 V, respectively. It should be noted that the peak responsivity (i.e. 360 nm) of the conventional GaN p-i-n photodetector only increased slightly from 0.18 to 0.24 A/W as we increased the applied reverse bias from 0 to 40 V. Under a high reverse bias, we believe the increased responsivity in the long wavelength region should be attributed to the tunnelling current that originated from dislocation related defect levels. These defect levels could absorb photons with energy smaller than the bandgap energy,  $E_g$ , of GaN and, thus, enhance long wavelength detector response.

As shown in Fig. 3b, the peak responsivity of the GaN p-i-n photodetector with the LT-GaN interlayer increased from 0.16 to 2.27 A/W as we increased the applied reverse bias from 0 to 40 V. On the other hand, it was found that the responsivity increased even more significantly in the long wavelength region. As a result, the UV-to-visible rejection ratio decreased to 15 and 7 when the GaN p-i-n photodetector with the LT-GaN layer was biased at -30 and -40 V, respectively. This can again be attributed to the tunnelling current that originated from dislocation related defect levels. Under these biases, it was found that UV-to-visible rejection ratios observed from the GaN p-i-n photodetector with the LT-GaN layer were smaller than those observed from the conventional GaN p-i-n photodetector. It is known that crystal quality of the LT-GaN layer is poor. Thus, dislocation density in the GaN p-i-n photodetector with the LT-GaN interlayer should be much higher than that in the conventional GaN p-i-n photodetector. The large dislocation density should result in a significant amount of defect levels within the GaN bandgap. As a result, absorption and, thus, detector responsivity in the long wavelength region became significantly larger under a high reverse bias.

Fig. 4 shows measured peak responsivities of the two fabricated photodetectors. Under low reverse bias (i.e.  $|V| < 25$  V), it was found that measured responsivity of the GaN p-i-n photodetector with the LT-GaN interlayer was smaller than that of the conventional GaN p-i-n photodetector. This should be attributed to the poor crystal quality of the LT-GaN interlayer. On the other hand, measured responsivity of the GaN p-i-n photodetector with the LT-GaN interlayer was larger than that of the



**Figure 3** Responsivities measured under various applied reverse biases for the fabricated GaN p-i-n photodetectors  
 a Without the LT-GaN interlayer  
 b With the LT-GaN interlayer



**Figure 4** Measured peak responsivities of the two fabricated photodetectors

conventional GaN p-i-n photodetector under a high reverse bias (i.e.  $|V| > 25$  V). This should be attributed to the carrier multiplication effect and/or internal gain that originated from the defect levels [15]. Under 40 V reverse bias, it was found that we could achieve a 9.5 times larger detector responsivity by simply inserting an LT-GaN layer in the intrinsic region of the GaN p-i-n photodetector. Such a large detector response suggests that the GaN p-i-n photodetector with an LT-GaN layer proposed in this study is useful for digital communication and power meter application.

## 4 Summary

In summary, nitride-based p-i-n UV photodetectors with an LT-GaN interlayer were proposed and fabricated. Compared with a conventional GaN p-i-n photodetector, it was found that both the dark current and ideality factor of the p-i-n photodetector with an LT-GaN interlayer became larger whereas the UV-to-visible rejection ratio became smaller because of the poor crystal quality of the LT-GaN interlayer. However, the responsivity of the GaN p-i-n photodetector with an LT-GaN interlayer was larger than that of the conventional GaN p-i-n photodetector under a high reverse bias because of the carrier multiplication effect and/or internal gain that originated from the defect levels.

## 5 References

- [1] NAKAMURA S., SENOH M., IWASA N., NAGAHAMA S.C.: 'High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes', *Appl. Phys. Lett.*, 1995, **67**, pp. 1868–1870
- [2] NAKAMURA S., SENOH M., NAGAHAMA S., ET AL.: 'High-power, long-lifetime InGaN multi-quantum-well-structure laser diodes', *Jpn. J. Appl. Phys.*, 1997, **36**, L1059–L1061
- [3] HIRANO A., PERNOT C., IWAYA M., DETCHPROHM T., AMANO H., AKASAKI I.: 'Demonstration of flame detection in room light background by solar-blind AlGaIn PIN photodiode', *Phys. Status Solidi A*, 2001, **188**, pp. 293–296
- [4] COLLINS C.J., LI T., LAMBERT D.J.H., WONG M.M., DUPUIS R.D., CAMPBELL J.C.: 'Selective regrowth of  $\text{Al}_{0.30}\text{Ga}_{0.70}\text{N}$  p-i-n photodiodes', *Appl. Phys. Lett.*, 2000, **77**, pp. 2810–2812
- [5] NAKAMURA S.: 'GaIn growth using GaN buffer layer', *Jpn. J. Appl. Phys.*, 1991, **30**, L1705–L1707
- [6] IWAYA M., TAKEUCHI T., YAMAGUCHI S., WETZEL C., AMANO H., AKASAKI I.: 'Reduction of etch pit density in organometallic vapor phase epitaxy-grown GaN on sapphire by insertion of a low-temperature-deposited buffer layer between high-temperature-grown GaN', *Jpn. J. Appl. Phys.*, 1998, **37**, L316–L318
- [7] BOURRET-COURCHESNE E.D., KELLERMANN S., YU K.M., ET AL.: 'Reduction of threading dislocation density in GaN using an intermediate temperature interlayer', *Appl. Phys. Lett.*, 2000, **77**, pp. 3562–3564
- [8] CHANG S.J., YU C.L., CHEN C.H., CHANG P.C., HUANG K.C.: 'Nitride-based ultraviolet metal-semiconductor-metal photodetectors with low-temperature GaN cap layers and Ir/Pt contact electrodes', *J. Vac. Sci. Technol. A*, 2006, **24**, pp. 637–640
- [9] LEE M.L., SHEU J.K., LAI W.C., ET AL.: 'GaN Schottky barrier photodetectors with a low-temperature GaN cap layer', *Appl. Phys. Lett.*, 2003, **82**, pp. 2913–2915
- [10] CHANG S.J., LAI W.C., SU Y.K., CHEN J.F., LIU C.H., LIAW U.H.: 'InGaIn–GaIn multiquantum well blue and green light emitting diodes', *IEEE J. Sel. Top. Quantum Electron.*, 2002, **8**, pp. 278–283
- [11] CHANG S.J., CHANG C.S., SU Y.K., ET AL.: 'Highly reliable nitride-based LEDs with SPS + ITO upper contacts', *IEEE J. Quan. Electron.*, 2003, **39**, pp. 1439–1443
- [12] CHANG S.J., KUO C.H., SU Y.K., ET AL.: '400 nm InGaIn–GaIn and InGaIn–AlGaIn multiquantum well light-emitting diodes', *IEEE J. Sel. Top. Quantum Electron.*, 2002, **8**, pp. 744–748
- [13] YEH L.S., LEE M.L., SHEU J.K., ET AL.: 'Visible-blind GaIn p-i-n photodiodes with an  $\text{Al}_{0.12}\text{Ga}_{0.88}\text{N}/\text{GaIn}$  superlattice structure', *Solid-State Electron.*, 2003, **47**, pp. 873–878
- [14] CHITNIS A., KUMAR A., SHATALOV M., ET AL.: 'High-quality p–n junctions with quaternary AlInGaIn/InGaIn quantum wells', *Appl. Phys. Lett.*, 2000, **77**, pp. 3800–3802
- [15] CARRANO J.C., LI T., GRUDOWSKI P.A., EITING C.J., DUPUIS R.D., CAMPBELL J.C.: 'Comprehensive characterization of metal-semiconductor-metal ultraviolet photodetectors fabricated on single-crystal GaIn', *J. Appl. Phys.*, 1998, **83**, pp. 6148–6160