High Responsivity in GaN Ultraviolet Photodetector Achieved by Growing on a Periodic Trapezoid Column-Shape Patterned Sapphire Substrate

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Abstract: GaN ultraviolet photodetector with metal-semiconductor-metal structure is achieved by growing on a periodic trapezoid column-shape patterned sapphire substrate using metalorganic chemical vapor deposition. Under 5-V reverse bias, the photodetector fabricated on such patterned sapphire substrate exhibits a lower dark current, a higher photocurrent, and a 476 % enhancement in the maximum responsivity as compare with those of the photodetector fabricated on conventional flat sapphire substrate. It is also found that the much larger UV-to-visible rejection ratio and the fact that responsivity drops in a smaller cut-off region are observed from photodetector fabricated by using a periodic trapezoid column-shape patterned sapphire substrate. These phenomena may all be attributed to the reduction of threading dislocation density and the improved quality of GaN film, as well as the internal reflection and/or scattering effect on the interface between GaN film and the periodic trapezoid column-shape pattern of the substrate.

Keywords: GaN ultraviolet photodetector; periodic trapezoid column-shape patterned sapphire substrate; responsivity; UV-to-visible rejection ratio

1. Introduction

Nitride-based compounds are generally useful for optical devices such as light-emitting diodes (LEDs), laser diodes, and photodetectors (PDs) in blue and ultraviolet regions because of their wide direct band gap and high electrical conductivity [1-3]. However, the high density of threading dislocations (TDs) are inherent in the epitaxial GaN films on sapphire substrate due to the large difference in the lattice constant between the epitaxial layer and sapphire substrate [4,5]. This can incur a significant degradation in the performance of GaN-based devices [6,7]. For instance, TDs can reduce luminous efficiency and also increase leakage current in GaN-based LEDs as a result of TDs form nonradiative recombination centers and leakage current paths in the structure of LEDs. Therefore, how to further reduce the TD density is an important issue for fabricating high-performance UV LEDs or UV PDs.   Many different growth methods have been applied to the nitrides in order to minimize TDs [8,9]. One technique commonly employed is epitaxial lateral overgrowth (ELOG), where a GaN seed layer with a few microns in thickness is first grown on sapphire substrate. A SiO_2 or SiN_x strip type mask is subsequently produced, followed by further

epitaxial growth [10,11]. Several variations of this technique have been developed, where either different mask is used, or the growth conditions are modified for inducing later growth. These techniques require the interruption of growth that is a disadvantage for commercial applications. This problem can be overcome by growing on a patterned sapphire substrate (PSS), where there is no interruption of the growth process [12,13]. Unlike that nitride LEDs with the conventional sapphire substrate, the nitride LEDs fabricated on lamp-form PSS improved the output power, external quantum efficiency, and reverse leakage current reported by Wuu et al. [14]. They attributed the improved results to the elimination of TDs and enhancement of the extraction efficiency by using the PSS.

To explore fully the potential functions and development of III-nitrides, a similar concept is theoretically applicable to other GaN-based optoelectronics devices. UV PDs are important devices that can be used in various commercial and military applications, such as space communications, ozone layer monitoring, and flame detection. The various types of GaN-based UV PDs have been reported on sapphire substrates including Schottky diodes [15], heterojunction [16], p-n junction [17], p-i-n [18] and metal-semiconductor-metal (MSM) structures [19]. Among these structures, MSM PDs have attracted much attention because of their simplicity and high responsivity. MSM structures are also useful in optoelectronic-integrated-circuits (OEICs) due to ease of integrate, potential for high-speed, and compatibility with field effect transistor (FET) process technologies [20]. It has been reported that the high quality of GaN Schottky barrier PD is grown on PSS by the use of parallel stripes along the sapphire $\langle 1\bar{1}00 \rangle$ direction when compared to that prepared on the conventional flat sapphire substrate [21]. Besides, there has been some research to study the influences on the properties of dark current, UV-to-visible rejection ratio, and responsivity for GaN-based p-i-n UV PDs with different patterns of sapphire substrate [22,23]. In contrast, only few studies have so far been made at GaN-based MSM UV PDs fabricated by using PSS. Chang et al. have investigated that the GaN-based MSM UV PDs prepared on PSS can contribute to a much smaller dark leakage and the internal gain than those achieved from the PD fabricated on the conventional flat sapphire substrate [24]. However, the used structure on substrate pattern of GaN-based MSM UV PDs for their study is the shape of paralle stripe. It is well known that the improvement effects for the electrical and optical properties of GaN-based UV LEDs fabricated on PSS depend on different pattern shapes [25-27]. Consequently, the GaN-based MSM UV PDs may also induce a similarity of behavior as the GaN-based UV LEDs grown on different pattern shapes.

Recent advances in our knowledge, it is found that the GaN MSM UV PD grown on periodically geometrical PSS have not yet been reported. In this study, we investigate for the first time, the characteristics of GaN UV PD with MSM structure fabricated on periodic trapezoid column-shape patterned sapphire substrate (PTCPSS) using metalorganic chemical vapor deposition (MOCVD). We also report the fabrication and characterization of GaN MSM UV PD with PTCPSS. A more detailed study on structural, electrical, optical, and responsive properties of the fabricated PD prepared by such patterned substrate will be discussed.

2. Experimental Procedure

The PTCPSS used in this study is fabricated by standard photolithography and subsequent inductive couple plasma (ICP) etching in which Cl_2/BCl_3 gases are used. For fabricating PTCPSS, a photoresist layer is deposited by spin coater on top of the sapphire substrate as the mask. The

photoresist layer is prepared to be a periodic column pattern, where the depth and diameter of column pattern are 2 and 2.8 µm, respectively. The column array with a spacing of 3.5 µm is formed by using a standard photolithography process. Next, the sapphire substrate is etched using Cl_2/BCl_3 gases in an ICP etcher at 100 V dc bias. Finally, the photoresist mask is removed using a lift-off solution to complete the PTCPSS structures. The micrograph of the PTCPSS is examined by scanning electron microscopy (SEM), as shown in Fig. 1. Figure 1(a) shows the perspective view of PTCPSS. In the micrograph, we can observe that the PTCPSS containing a periodic trapezoid column-shape structure has a depth of 1.6 µm with a sidewall angle of 70°. The top and bottom diameters of pattern are 2.8 and 4.6 µm, respectively, which are separated from each other in an interval of 1.4 µm. The top view of PTCPSS is shown in Fig. 1(b), we can also confirm that the trapezoid column-shape pattern is uniformly arranged and all the geometrical patterns are of equal size.

Afterward, GaN film is grown on the fabricated PTCPSS by MOCVD. Ttrimethylgallium (TMGa) and ammonia (NH_3) are used as the sources of gallium and nitrogen, respectively. The substrate is initially heated to 1100 °C in hydrogen (H_2) ambient to remove surface contamination, and then lowering to 550 °C to grow a 30-nm-thick low-temperature GaN buffer layer. The temperature is subsequently raised to 1100 °C to grow a 2-µm-thick undoped GaN film.

Prior to the fabrication of MSM PD, the GaN film is dipped a diluted hydrochloric acid water solution for 3 min to remove the native oxide. Ni (5 nm)/Au (5 nm) are subsequently deposited onto the GaN film by electron-beam evaporator as the Schottky contact electrodes for the fabrication of MSM PD. The MSM PD consists of two interdigitated contact electrodes, which is fabricated through standard photolithography and etching. The fingers of the contact electrodes are 10 µm-width and 150 µm-length with a spacing of 10 µm, and the detective area is 150 × 510 µm². After contact electrodes deposition, Au layer is deposited to serve as bonding pads. For comparison, the GaN film and MSM PD fabricated on a conventional flat sapphire substrate (CFSS) under the same conditions are also prepared respectively. The TDs of GaN samples are examined by etch pit

| (a) | (b) |
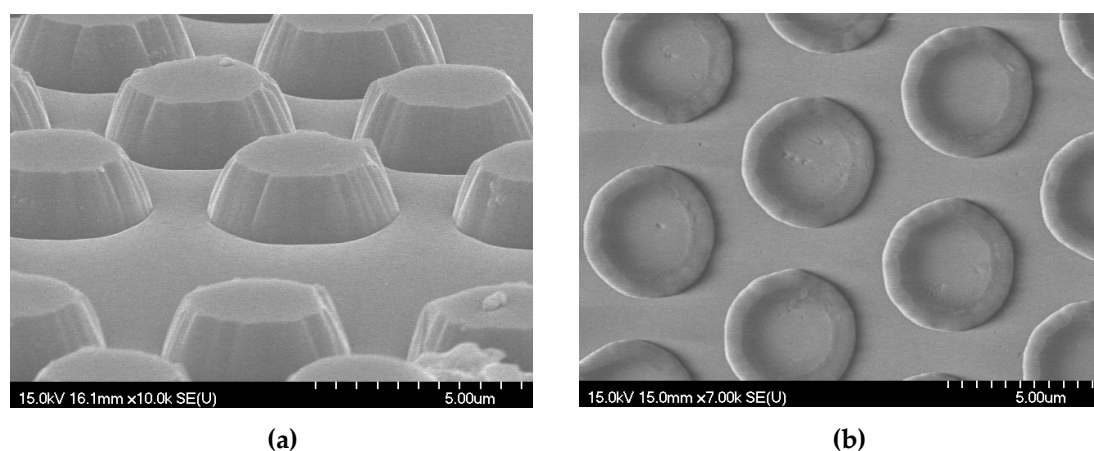
Figure 1. SEM micrographs of (a) perspective view and (b) top view on PTCPSS.

density (EPD) measurement. The as-grown GaN samples are characterized by X-ray diffraction (XRD). Photoluminescence (PL) characteristics are determined using 325 nm He-Cd laser as excitation power, and the carrier concentration is evaluated by Hall effect measurement. A

HP-4155B semiconductor parameter analyzer is used to measure the current-voltage (*I-V*) characteristics of the fabricated PDs in dark and under illumination. For photocurrent measurements, a deuterium lamp illuminating from the front side of the fabricated PDs is used as the light source. A xenon arc lamp is used as the light source for spectral responsivity measurements, and a standard synchronous detection scheme is employed to measure the front-side illuminated detector signal. A calibrated UV-enhanced Si detector is used for signal detection.

3. Results and Discussion

For EPD measurements, the GaN samples are immersed in H_3PO_4 at 160 °C for 3 min. Figure 2 indicates the SEM cross-sectional micrographs of the etched GaN samples. In Fig. 2(a), it is found that vertical striations are clearly observed from the GaN film grown on CFSS. On the other hand, the vertical striations disappeared for the GaN film grown on PTCPSS, as shown in Fig. 2(b). This observation can be attributed to the enhancement of the lateral overgrowth of GaN film by using appropriate PTCPSS which may be resulting in TDs reduction in GaN film.

(a)   **(b)**
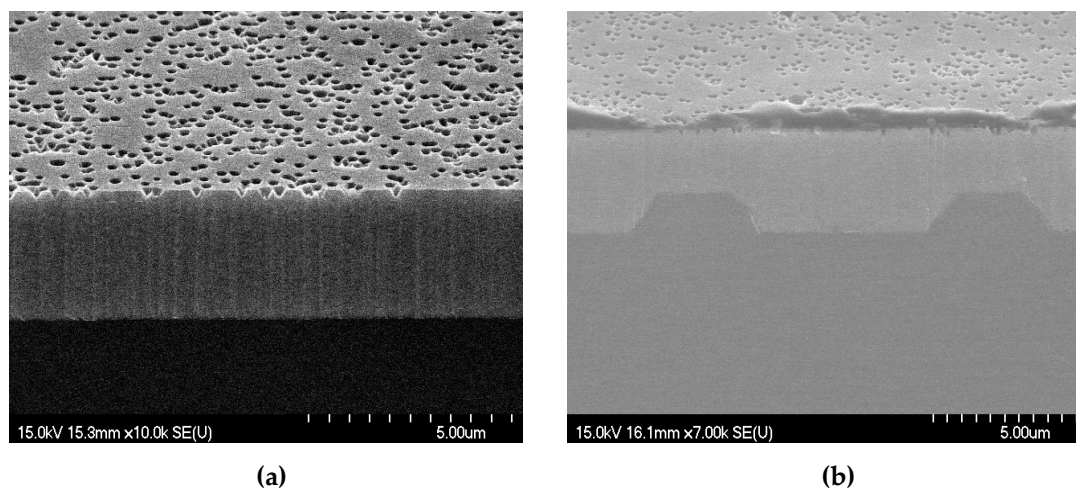
Figure 2. SEM cross-sectional micrographs of the etched GaN films grown on (a) CFSS and (b) PTCPSS.

Figure 3 shows the SEM surface morphologies of the etched GaN films grown on CFSS and PTCPSS, respectively. The EPD of GaN film grown on CFSS is estimated to be $1 \times 10^9 \, cm^{-2}$. Whereas, the EPD is only $3 \times 10^8 \, cm^{-2}$ for GaN film grown on PTCPSS observed from Fig. 3(b). The much lower EPD observed from the GaN film implies that we can effectively reduce TD density by the use of PTCPSS. Figure 4 compares the XRD rocking curves of the GaN films grown on CFSS and PTCPSS. In XRD spectra, the full-width-half-maximum (FWHM) of the GaN (0002) peak is 414 and 316 sec for GaN films grown CFSS and PTCPSS, respectively. The sharp and narrow XRD rocking curve for GaN grown on PTCPSS reveals that the crystal quality of GaN film is drastically improved by using PTCPSS. Figure 5 shows the PL spectra measured at 20 K from the GaN films

(a) **(b)**
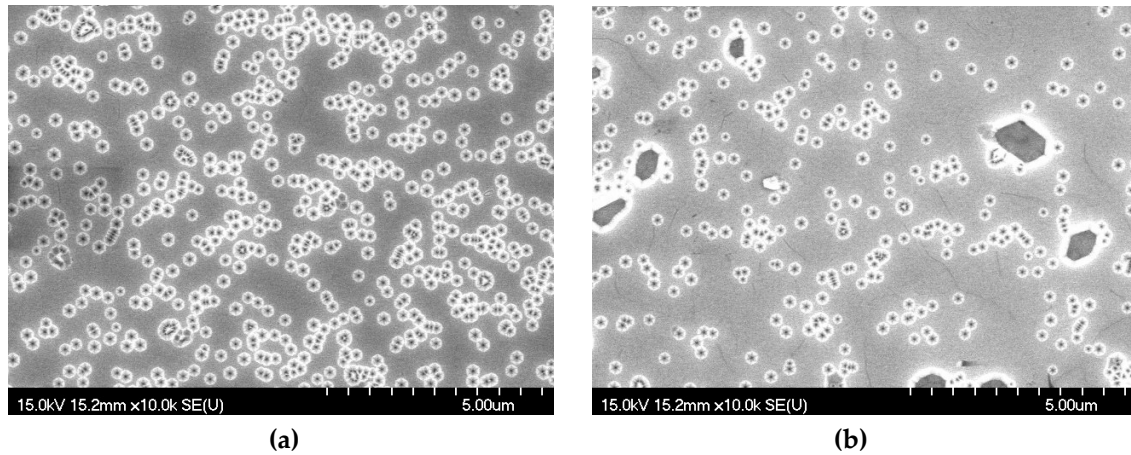
Figure 3. SEM surface morphologies of the etched GaN films grown on (a) CFSS and (b) PTCPSS.
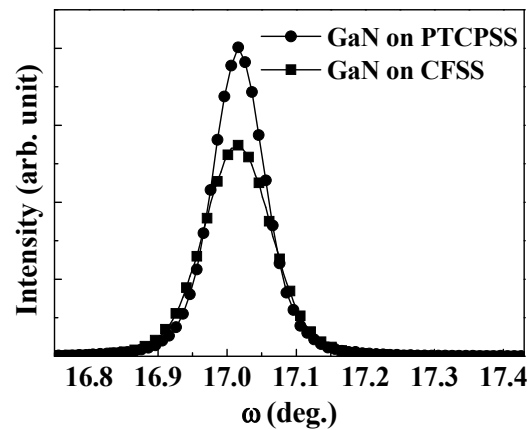
Figure 4. XRD rocking curves of the GaN films grown on CFSS and PTCPSS.

grown on CFSS and PTCPSS, respectively. It can be seen clearly that the PL spectrum of the GaN film grown on CFSS exhibits a relatively weak band-edge emission at 3.468 eV and a notorious yellow band (YB) emission near 2.3 eV [28]. In contrast, a strong band-edge emission PL peak with a sharp 14 meV FWHM is observed from the GaN film grown on PTCPSS. The increase in the PL intensity and absence of YB emission indicate that crystal quality is improved and the TD density is reduced for GaN film grown on PTCPSS. From Hall effect measurement, the residual carrier concentration of GaN film is 1.37×10^{17} and 3.22×10^{16} cm^{-3} for CFSS and PTCPSS, respectively. The reduction in the residual carrier concentration demonstrates again that crystal quality is improved for GaN film grown on PTCPSS. The results of Hall effect measurement are in reasonable agreement with the observed results by XRD and PL measurements.

Figure 6 shows the *I-V* characteristics of the two fabricated MSM PDs measured in dark and under illumination. With 5-V reverse bias, the dark leakage currents of 5.3×10^{-14} A and 1.2×10^{-11} A are observed for the PDs fabricated on PTCPSS and CFSS, respectively, corresponding to a reduction of three orders of magnitude. It is also found that the dark leakage current of our PD with PTCPSS is 5.3×10^{-14} A and while that of ref. [24] is around 7×10^{-12} A. This phenomenon of the
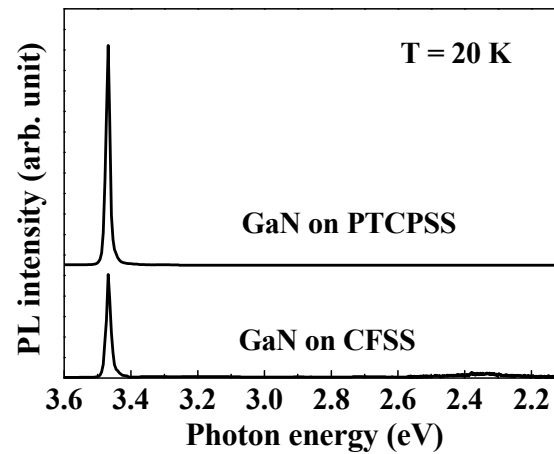
Figure 5. PL spectra measured at 20 K from the GaN films grown on CFSS and PTCPSS.
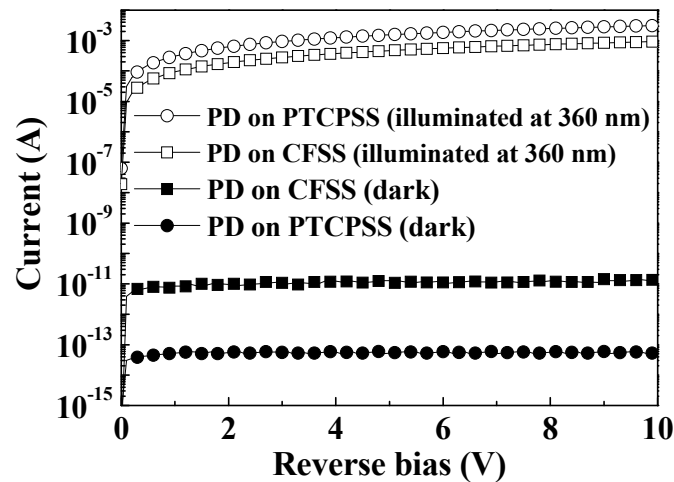
Figure 6. *I-V* characteristics of the PDs fabricated on CFSS and PTCPSS measured in dark and under illumination.

much smaller dark leakage current for our PD may be attributed to the effective suppression of TD density because of the difference of substrate pattern [29]. The reduced TD density of the PD with PTCPSS leads to a smaller probability for the occurrence of leakage current paths. On the other hand, it is found that the photocurrent from the PD with PTCPSS is larger than that from the PD with CFSS about one order of magnitude. Under 5-V reverse bias and 360-nm wavelength light illumination, the photocurrent of PD is 1.6×10^{-3} and 4.6×10^{-4} A for PTCPSS and CFSS, respectively. In order to clarify the influence of substrate in PD photocurrent, the transmittance spectra of the GaN films grown on CFSS and PTCPSS are performed by UV-Visible (UV-VIS) spectrophotometer, as shown in Fig. 7. The oscillations of transmittance spectra from both GaN samples are due to interference behavior. The observation of a steeper transition edge at about 360 nm (i.e., 3.4 eV) from the GaN film grown on PTCPSS reflects the bandgap of the GaN and indicates the crystal
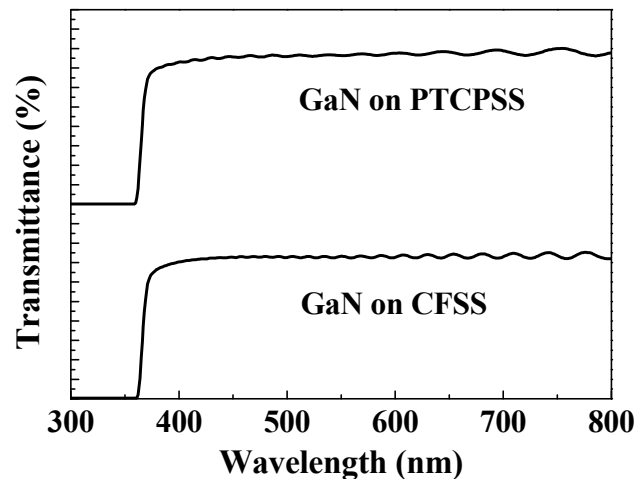
Figure 7. Transmittance spectra of the GaN films grown on CFSS and PTCPSS.

quality is good. When the incident photons are absorbed by GaN film that generates carriers and then contribute to the photocurrent. The partial unabsorbed photons reach substrate that are reflected and/or scattered back to GaN film via suitably geometrical substrate which probably generates again carriers and subsequently offer the photocurrent. Therefore, the fabricated periodic trapezoid column-shape pattern may improve the photon-recycling efficiency due to the interface between GaN film and PTCPSS resulting in reflecting and/or scattering effect. The larger photocurrent generated from the PD with PTCPSS may be resulting from the more photo-generated carriers by the improved quality of GaN film and the internal reflection and/or scattering effect on the periodic trapezoid column-shape pattern of the substrate. As a result, the photocurrent to dark current contrast is higher than ten orders of magnitude for the PD fabricated on PTCPSS with a 5 V bias voltage, whose value is larger than that of the PD fabricated on CFSS.

Figure 8 shows the spectral responses of both MSM PDs biased at 5 V. It is found that the cutoff
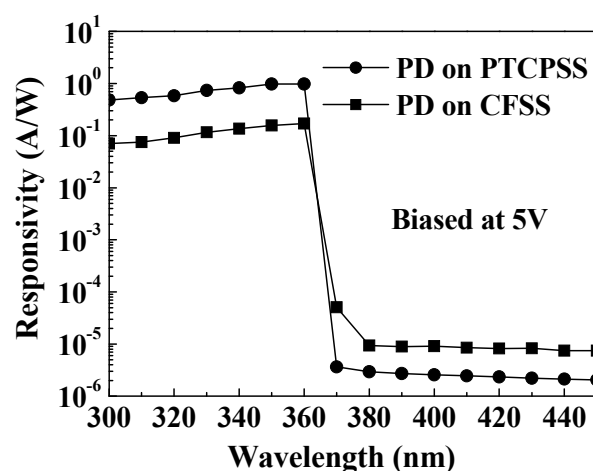
Figure 8. Spectral responses of the PDs fabricated on CFSS and PTCPSS bias at 5 V.

wavelength occur at 360 nm for both PDs. The maximum responsivities at 360 nm are 0.98 and 0.17 A/W for the PDs fabricated on PTCPSS and CFSS, respectively. The maximum responsivity of 0.98 A/W for our PD is also found to be larger than that of around 0.38 A/W reported by ref. [24]. In addition, we can also observe the responsivity drops in a sharp cut-off region of 100 nm for the PD with PTCPSS. In contrast, the cut-off region of responsivity for PD with CFSS is 200 nm. The rejection ratio from UV to visible can be defined as the responsivity measured at 360 nm divided by the responsivity measured at 450 nm. With such a definition, the UV-to-visible rejection ratios are evaluated to be 4.8×10^5 and 2.3×10^4 for PDs fabricated on PTCPSS and CFSS, respectively. The much higher of the maximum responsivity, a larger UV-to-visible rejection ratio and the fact that PD response drops in a smaller cut-off region are observed from PD with PTCPSS may all be attributed to the reduction of TD density and the improved quality of GaN film, as well as the internal reflection and/or back scattering effect on the periodic trapezoid column-shape pattern of the substrate. In other word, the experimental results demonstrate the high-performance of GaN MSM UV PD can be achieved by using PTCPSS with suitably geometrical substrate.

4. Conclusions

GaN UV PD with MSM structure fabricated on PTCPSS using MOCVD has been systematically investigated. Compared with the PD with CFSS, we can achieve a lower dark current of 5.3×10^{-14} A, a higher photocurrent of 1.6×10^{-3} A, and a 476 % enhancement in the maximum responsivity from the PD with PTCPSS at 5-V reverse bias. It is also found that the PD response drops in a smaller cut-off region of 100 nm for the PD with PTCPSS under 5-V applied bias. Furthermore, we also observe the UV-to-visible rejection ratio of the PD with PTCPSS is 4.8×10^5, while that of the PD with CFSS is only about 2.3×10^4 under 5-V applied bias. These improved results observed from the PD fabricated on PTCPSS may all be attributed to the reduction of TD density and the improved quality of GaN film, as well as the internal reflection and/or scattering effect by the use of PTCPSS with suitably geometrical substrate.

In addition, the experimental results also exhibit that the properties in the dark leakage current and the maximum responsivity for our GaN MSM UV PD with suitably geometrical pattern of substrate are better than those of reported by ref. [24].

Author Contributions: Shoou-Jinn Chang provided the equipment for the experiments. Sean Wu assisted in discussion about the research.

Conflicts of Interest: The authors declare no conflict of interest.

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