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GaN-based Metal-Semiconductor-Metal Photodetectors Fabricated on Patterned Sapphire Substrates

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1. Introduction

GaN and related III-nitrides grown on sapphire substrates have been successfully applied in optical and electronic devices [1, 2]. However, the large different in lattice-mismatch and thermal expansion coefficient between GaN film and sapphire substrate often result in a large threading dislocation (TD) density in the GaN film. This could degrade the performance of GaN-based devices significantly [3]. For example, threading dislocations can form nonradiative recombination centers to reduce emission efficiency of GaN-based light-emitting diodes (LEDs). Threading dislocations can also form leakage current paths in GaN-based diodes and at metal–GaN Schottky interface. As a result, leakage currents in GaN-based diodes and Schottky barrier photodetectors (PDs) are high in general. By epitaxial lateral overgrowth (ELOG) with SiN or SiO mask patterned on as-grown GaN seed crystal, threading dislocations can be significantly decreased [4]. Although this overgrowth technique can dramatically improve crystalline quality, the requirement of two-step growth procedure is time-consuming and easily introduced contamination. Recently, the single-step growth using patterned sapphire substrate (PSS) without mask has been proposed to overcome the problems of threading dislocation [5, 6]. Besides, geometrical shape of the sapphire patterns can also effectively enhance light reflection at GaN/PSS interface.

To explore fully the potential functions and development of III-nitrides, a similar concept is theoretically applicable to other GaN-based optoelectronics devices. It is known that ultraviolet (UV) radiation is a hazard to the human body. Thus, detecting UV light has become an important issue [7]. Metal–semiconductor–metal (MSM) PDs have attracted much attention because of their simple structure and having high responsivity. MSM structures are also useful in optoelectronic integrated-circuits (OEICs) since they are easy to integrate, highly potential for high-speed application, and compatible with field effect transistor (FET) process technologies [8].

In this study, GaN-based UV MSM PDs fabricated on PSS using metalorganic chemical vapor deposition (MOCVD) has been investigated. A more detailed study on electrical and optical and responsive properties of the fabricated PDs will be reported.

2. Experiments

The PSS 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. The PSS contains a periodically trapezoid column-shaped pattern with a depth of 1.6 μm and the slanted sidewall angle of 70°. The dimensions of the structure are as follows: the diameter of top and bottom is 2.8 and 4.6 μm, respectively, which are separated from each other in an interval of 1.4 μm. Figure 1 shows cross-sectional scanning-electron-microscopy (SEM) micrograph of PSS structure. Afterward, GaN film is grown on c-face 2-inch PSS by MOCVD. Ttrimethylgallium (TMGa) and ammonia (NH_3) are used as Ga and N sources, respectively. Prior to the growth, the substrate is initially heated to 1100 °C in hydrogen (H_2) ambient for cleaning the surface of substrate. The structure consists of a 30-nm-thick low-temperature GaN buffer layer grown at 550 °C, a 1.5-μm-thick undoped GaN film grown at 1100 °C. For comparison, the GaN film fabricated on a conventional plane sapphire substrate (CSS) is also prepared.

To fabricated GaN MSM PDs, Ni (5 nm)/Au (5 nm) are deposited by electron-beam evaporator as the Schottky contact electrodes, and subsequently thermal annealing at 550 °C for 3 minutes for alloying. Standard photolithography and lift-off are then used to define the two interdigitated contact electrodes. The fingers of the contact electrodes are 10 μm-width and 150 μm-length with a spacing of 10 μm.

3. Results and discussion

Crystal quality of the as-grown GaN films is evaluated by etch pit density (EPD), X-ray diffraction (XRD), and Hall measurements. Prior to EPD measurements, we immerse the samples in H_3PO_4 at 160 °C for 3 min. From SEM images, it is found that EPD of GaN grown on PSS and CSS is estimated to be 3×10^8 and 1×10^9 cm^{-2}, respectively. The much lower EPD observed from GaN grown on PSS implies that we can indeed reduce TD density by using PSS. For XRD rocking curve scan, the full-width at half-maximum (FWHM) of the GaN (0002) peak observed from GaN grown on PSS is 316 sec. Such a value is much smaller than the 414 sec XRD rocking curve observed from GaN grown on CSS. In addition, The residual carrier concentration of undoped GaN film grown on PSS and CSS measured by Hall measurement is 3.22×10^{16} and 1.37×10^{17} cm^{-3}, respectively. The much lower TD, a smaller FWHM of XRD rocking curve and the fact that a lower residual carrier concentration are observed suggest a high quality of GaN film can be achieved by using PSS.

Current-voltage (*I*-*V*) characteristics of the two GaN MSM PDs are measured by a HP4155B semiconductor parameter analyzer in the dark and under illumination as shown in Fig. 2. For photocurrent measurements, the light generated from a xenon (Xe) arc lamp through a calibrated monochromator is used as the light source. Under reverse bias voltage, the dark current is nearly a constant of around 5×10^{-14} A for PD fabricated on PSS. Besides, the dark current of PD fabricated on PSS is at about three orders of magnitude smaller than PD fabricated on CSS. This phenomenon could be attributed to the reduction of TD density which results in a lower leakage current [9]. On the other hand, the photocurrent of PD fabricated on PSS is larger than that of PD fabricated on CSS. The photocurrent is 1.6×10^{-4} A for PD fabricated on PSS with a 5-V bias voltage. The larger photocurrent generated from PD fabricated on PSS could be due to that the carriers are generated efficiently by incident photons reaching the high quality of GaN film. In addition, photon recycling in GaN film can also be enhanced by GaN/PSS interface since geometrical shape of PSS will result in light scattering.

Spectral responsivity of both GaN MSM PDs is also measured using a Xe arc lamp as shown in Fig. 3. It can be seen that the cutoff wavelength occur at 360 nm when the both PDs are biased at 5 V. Furthermore, we found that the maximum responsivitiy at 360 nm is 0.98 and 0.17 A/W for PDs fabricated on PSS and CSS, respectively. Such a high responsivitiy observed from PD fabricated on PSS should be attribuate to its low TD density and photon recycling effect so that we can achieve a higher photocurrent.

4. Conclusions

GaN-based UV MSM PDs prepared on PSS and CSS were fabricated. Experimental results indicate that the GaN grown on PSS could effectively suppress the generation of TD, improve crystal quality, and enhance photon recycling by GaN/PSS interface. The outcome result in a superior performance of PD fabricated on PSS compared with the conventional GaN MSM PD fabricated on CSS.

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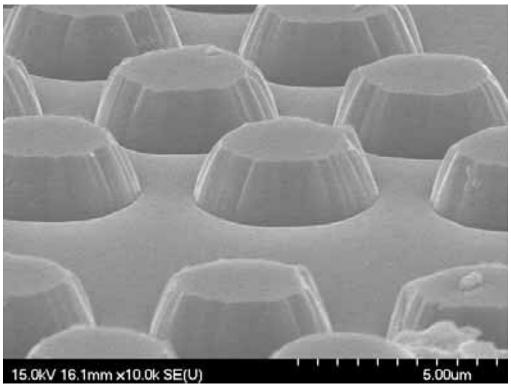

Fig. 1 SEM micrograph of PSS structure.

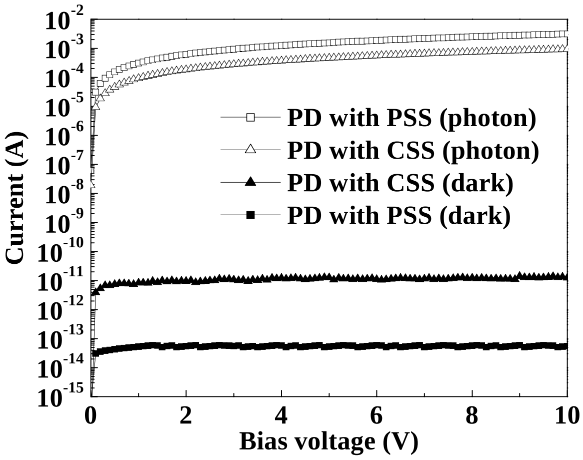

Fig. 2 *I*–*V* characteristics of the two fabricated PDs measured in the dark and under illumination.

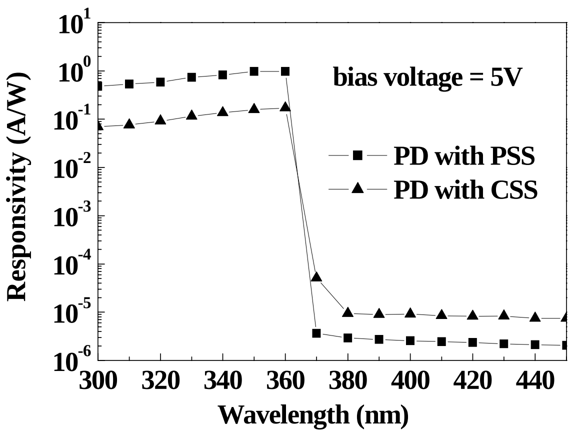

Fig. 3 Spectral responsivity of the two fabricated PDs.