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Research Article

GaN Schottky Diode with TiW Electrodes on Silicon Substrate Based on AlN/AlGaN Buffer Layer

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We report the fabrication of GaN Schottky photodiodes (PDs) on Si(111) substrates coated with an AlN/AlGaN buffer multilayer. It was found that their dark current was much smaller than that of identical devices prepared on sapphire substrates. With an incident wavelength of 359 nm, the maximum responsivity of the n^--GaN Schottky photodetectors with TiW contact electrodes was 0.1544 A/W, corresponding to a quantum efficiency of 53.4%. For a given bandwidth of 1 kHz and bias of 5 V, the resultant noise equivalent power (NEP) of n^--GaN Schottky photodetectors with TiW electrodes was 1.033×10^{-12} W, corresponding to a detectivity (D^*) of 1.079×10^{12} cm-Hz$^{0.5}$ W^{-1}.

1. Introduction

There are numerous applications demanding the usage of ultraviolet (UV) photodetectors (PDs). Both civil and military disciplines require high-performance UV PDs for solar UV monitoring, source calibration, UV astronomy, flame sensors, detection of missile plumes, space-to-space communications, and many other applications. GaN has a wide direct band gap ($E_g = 3.4$ eV) and a high saturation velocity ($vs = 2.7 \times 10^7$ cm/s) and is therefore widely considered to be one of the most promising materials for realizing UV PDs [1–13]. Moreover, this material is also remarkably tolerant of aggressive environments because of its thermal stability and radiation hardness.

Traditionally, GaN-based epitaxial layers are grown on sapphire or SiC substrates. Sapphire substrates are electrically insulating and poor thermal conductors. On the other hand, although SiC substrates are comparably good thermal and electrical conductors, their high cost precludes wide use. Compared with sapphire and SiC substrates, GaN epitaxial layers on Si appear to be a reasonably good substitute, not to mention the fact that the use of Si substrates also has the unique advantage of allowing monolithic integration of GaN-based devices with Si-based microelectronics.

Even though it is rather difficult to grow high-quality GaN epitaxial layers on Si, GaN-based light-emitting diodes (LEDs) and heterostructure field-effect transistors have nevertheless already been realized on Si substrates [14–19]. Our earlier report successfully documented the growth of high-quality InGaN/GaN LED epilayers on a Si(111) substrate [20]. Growth of high-quality InGaN/GaN films on a silicon substrate was possible owing to prior deposition of an AlGaN buffer and two high-temperature (HT) AlN interlayers before attempting GaN growth. This particular growth scheme effectively confined the threading dislocation to the vicinity of the interfacial layer in the AlGaN/HT-AlN buffer layers. In fact, our transmission electron microscopy (TEM) and scanning electron microscopy (SEM) studies carried out earlier had clearly demonstrated a smooth and crack-free GaN surface with a noticeable reduction in threading dislocation density [20].

In this paper, the deposition of titanium tungsten (TiW) metal contacts on GaN surfaces via RF magnetron sputtering is described. The growth of n^--GaN epitaxial layers on Si substrates and the subsequent fabrication of GaN

Schottky photodiodes are discussed thereafter, along with their resultant optical and electrical properties.

2. Experimental

Epitaxial samples investigated in our study were all grown on Si(111) substrates using metalorganic chemical vapor deposition (MOCVD) [21–24]. Trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) were used as source materials for gallium (Ga), aluminum (Al), and nitrogen (N), respectively. To obtain a lightly Si-doped n-type GaN (n^--GaN) structure, a 25-nm-thick AlN buffer layer was deposited on a Si(111) substrate at 1090°C. Then, two stacks of buffer multilayers were inserted between the 25-nm-thick AlN buffer layer and the topmost 500-nm-thick 1090°C-grown n^--GaN epitaxial layer. Each stack of buffer multilayers consisted of a 30-nm-thick 540°C-grown AlN layer, a 50-nm-thick 1090°C-grown AlN layer, a 60-nm-thick 1090°C-grown $Al_{0.3}Ga_{0.7}N$ layer, a 40-nm-thick 1090°C-grown $Al_{0.2}Ga_{0.8}N$ layer, and a 100-nm-thick 1090°C-grown undoped-GaN layer.

TiW (100 nm) contact layers were then deposited on the samples using an RF magnetron sputter system. Because the Si(111) substrate was heavily doped, the devices were bonded on TO-Can with Ag rubber for ohmic contact. Then, n^--GaN Schottky diodes were fabricated by standard photolithography and a lift-off process. *The active area of photodetectors was* 1.26×10^{-3} cm^2. An HP-4156 semiconductor parameter analyzer was then used to evaluate the dark current-voltage (I-V) characteristics. Spectral responsivity measurements were also performed using a JOBIN-YVON SPEX system equipped with a 450-W xenon arc lamp and a standard synchronous detection scheme. Furthermore, the noise characteristics of the GaN Schottky diodes were measured within a frequency range of 1 Hz–1 kHz using a low-noise current preamplifier and a dynamic signal analyzer.

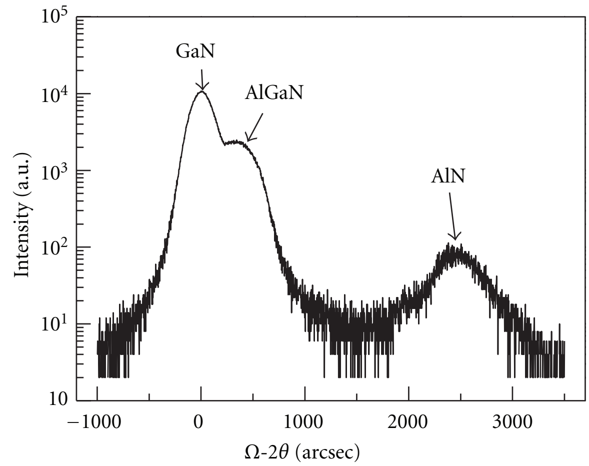

Figure 1: The DC-XRD analysis of n^--GaN epitaxial structure.

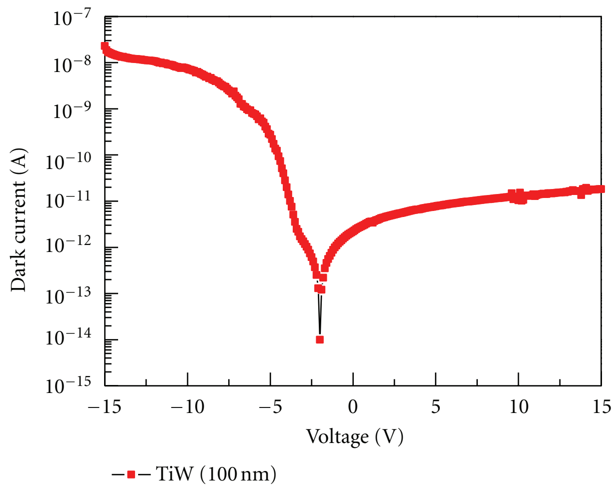

Figure 2: Dark I-V characteristics of the Schottky diode with TiW contact electrodes.

3. Results and Discussion

Figure 1 shows the (002) Bragg reflection double-crystal X-ray diffraction (DCXRD) spectra for a 500 nm n^--GaN epitaxial layer prepared on a Si substrate. The full width at half maximum (FWHM) of the n^--GaN epitaxial layer was measured as 232.11′′. Figure 2 shows the I-V characteristics of a Schottky diode with a TiW contact electrode. Under a 5-V applied bias, the measured dark current of photodetectors with TiW electrodes was 7.72×10^{-12} A. It should be noted that a relatively small dark leakage current could still be observed even though these III-nitrides layers were grown on a lattice-mismatched silicon substrate. The small dark current was in fact a clear benefit derived from the insertion of two additional stacks of buffer multilayers into the overall device structure. Evidently, by further improving the crystalline quality of GaN films, this scheme alleviated the impact of GaN-Si lattice mismatch imposed on the epitaxial growth [25]. Furthermore, the much smaller dark current in the vertical PDs was most likely due to the high resistivity of the HT-AlN layers used. Consequently, a larger Schottky barrier height between the contact electrode and the epitaxial film was realized.

Figure 3 shows the room temperature spectral responses of PDs under various applied bias voltages. In order to quantify the peak responsivity, the xenon lamp intensity was first measured by a calibrated GaP UV detector. The difference in sensor-detecting areas between the GaP UV detector and our PDs was then determined in order to reliably estimate the PD responsivity.

As shown in Figure 4, the peak responsivity occurred at 359 nm. The maximum responsivity of photodetectors with TiW contact electrodes was 0.1544 A/W, corresponding to a quantum efficiency of 53.4%. Compared with III-nitride PDs grown on a sapphire substrate [25, 26], the smaller peak responsivity observed from samples grown on Si substrates can be directly attributed to a highly defective epitaxial layer. Similar results were also reported by Osinsky et al. [27]. In our case, the responsivity is highly dependent on

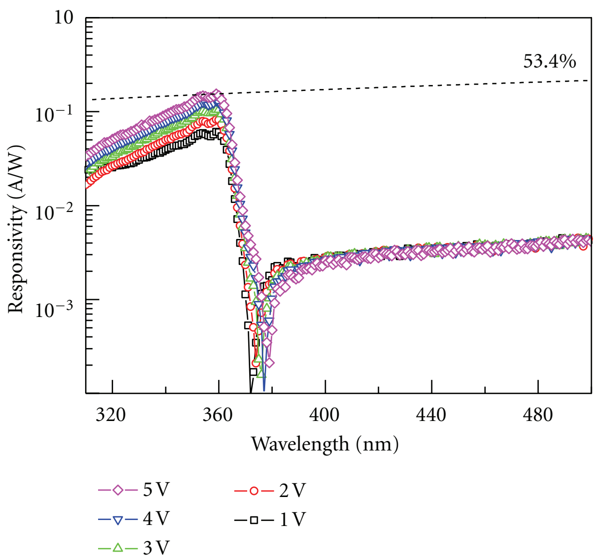

FIGURE 3: Spectral responses of the fabricated detectors with various applied bias.

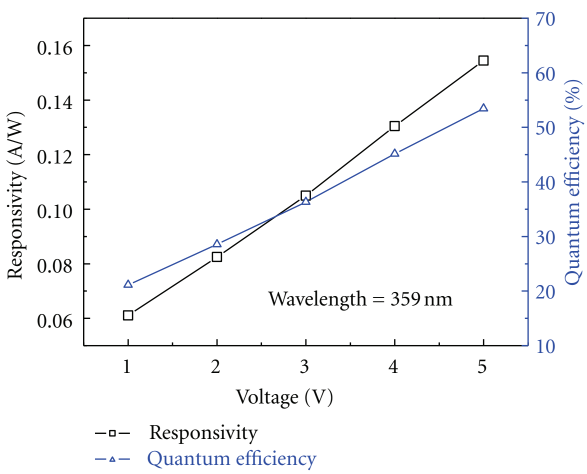

FIGURE 4: Spectral responses and quantum efficiency of photodetectors as functions of applied bias.

the transmittance of the contact electrode, so the higher transmittance of TiW contributes in part to the larger responsivity obtained [25]. In addition, the rejection ratio was determined as the ratio between the spectral responsivity measured at 359 nm and at 385 nm. With an applied voltage of 5 V, the rejection ratio was 114.4 for photodetectors with TiW contact electrodes. The large rejection ratio can be attributed in part to a high light transparency of TiW electrodes. Figure 4 depicts the peak responsivity (359 nm) and quantum efficiency of PDs on Si as a function of bias.

Similar results were also found for AlGaN metal-semiconductor-metal PDs prepared on an Si substrate [28]. The higher voltage enhances the penetration of electron-hole pairs through the grain boundary so as to effectively facilitate the collection by electrodes of these charge carriers.

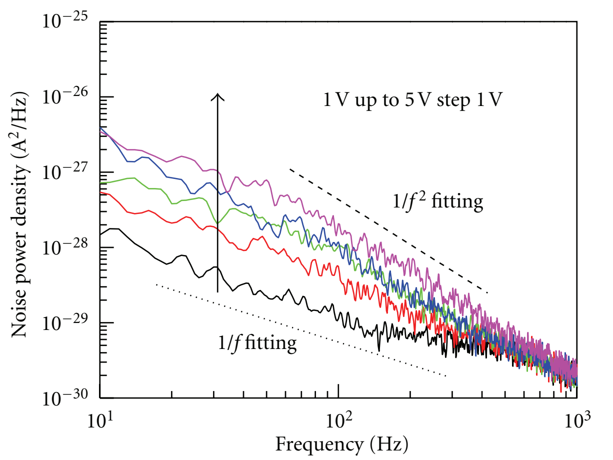

FIGURE 5: Measured noise power densities of the GaN Schottky diode with TiW contact electrodes.

The observation of bias-dependent responsivity of PDs-on-Si was also reported by Osinsky et al. [27].

Figure 5 shows the measured noise power density of the GaN Schottky photodetectors with TiW contact electrodes. Noise curves reveal that $1/f$ (flicker) is a dominant noise mechanism, which is expected for Schottky photodetectors operating at low frequency. Moreover, the noise curves obey the relation of Hooge-type equation with a fitting parameter α. It should be noted that the measured low-frequency noise was classified as a $1/f$-type ($\alpha = 1$) noise for low bias and a $1/f^2$-type ($\alpha = 2$) noise for high bias. For a specified bandwidth (B), the total square of noise current, $\langle i_n \rangle^2$, can be determined by integrating the noise power density $S_n(f)$ such that

$$\langle i_n \rangle^2 = \int S_n(f)\,df. \quad (1)$$

On the other hand, the noise equivalent power (NEP) can be calculated by

$$\mathrm{NEP} = \sqrt{\frac{\langle i_n \rangle^2}{R}}, \quad (2)$$

where R is the responsivity of the PDs. Furthermore, the normalized detectivity (D^*) can be determined by

$$D^* = \frac{\sqrt{A}\sqrt{B}}{\mathrm{NEP}}, \quad (3)$$

where A is the area of the photodetector and B is the bandwidth. For a given bandwidth of 1 kHz and a given bias of 5 V, the corresponding noise equivalent power of Schottky photodetectors with TiW electrodes was 1.033×10^{-12} W. These values in turn led to the calculated detectivity (D^*) of 1.079×10^{12} cm-Hz$^{0.5}$W^{-1}. A smaller current density was responsible for the smaller NEP observed for Schottky photodetectors on Si. It should be noted that on an average, higher D^* was obtained compared with that of devices with similar interdigitated electrode dimensions fabricated on sapphire substrates [25, 29]. These results were again attributed to the smaller noise power density of the PDs prepared on Si(111) substrates. The benchmark values realized for the noise and detectivity of our devices fabricated on silicon show that these Schottky photodetectors are well suited for low-noise applications.

4. Summary

In summary, GaN Schottky photodiodes were prepared on Si(111) substrates with an AlN/AlGaN buffer multilayer. It was found that the dark current of PDs fabricated on Si substrates was substantially smaller than that of identical devices prepared on sapphire substrates. With an incident wavelength of 359 nm, the maximum responsivity of the n^--GaN Schottky photodetectors with TiW contact electrodes was 0.1544 A/W, corresponding to a quantum efficiency of 53.4%. For a given bandwidth of 1 kHz and a given bias of 5 V, the corresponding noise equivalent power (NEP) of n^--GaN Schottky photodetectors with TiW electrodes was 1.033×10^{-12} W. Finally, the detectivity (D^*) was determined, therefore, to be 1.079×10^{12} cm-Hz$^{0.5}$W^{-1}.

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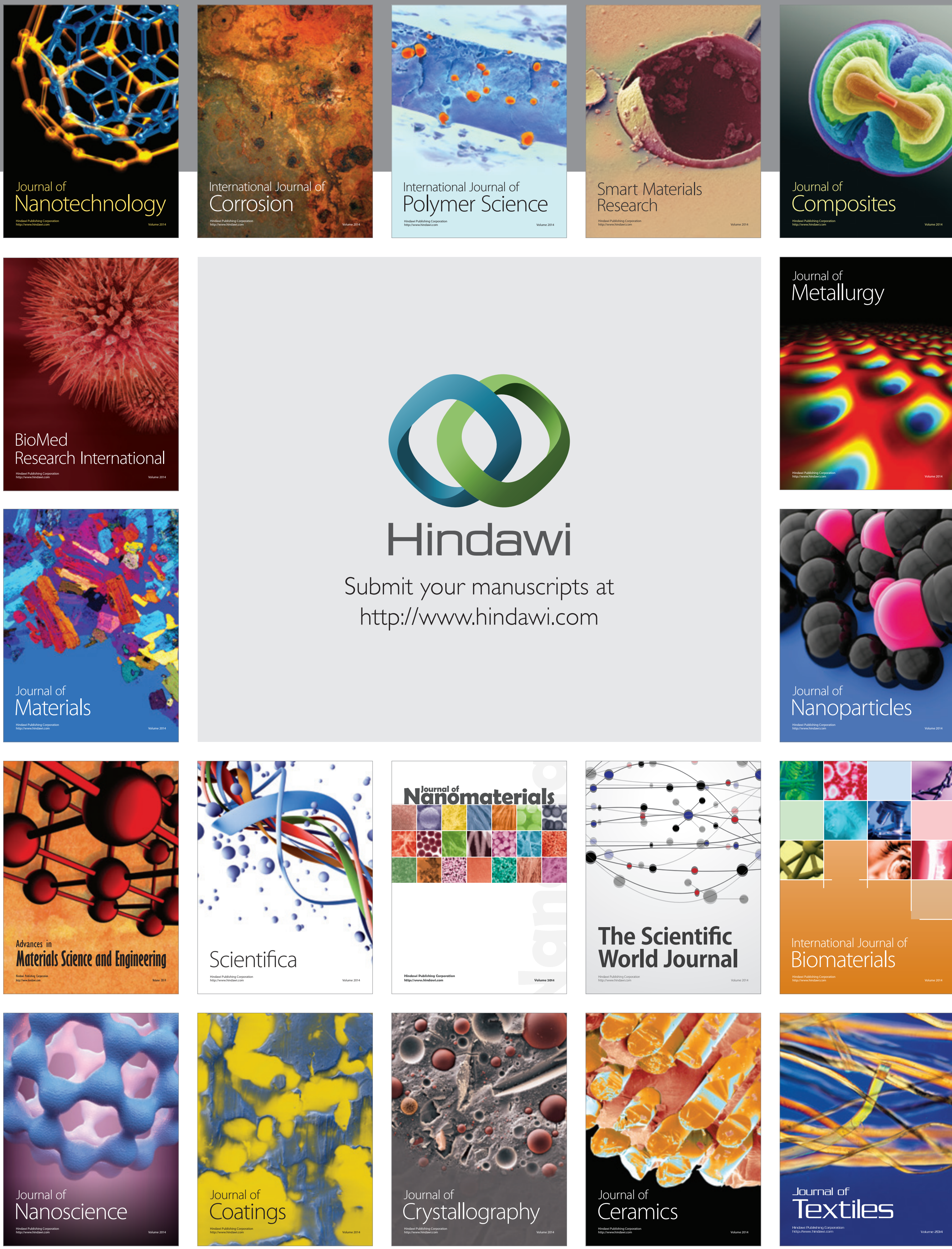
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