Gallium nitride metal-semiconductor-metal photodetectors prepared on silicon substrates

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Gallium nitride (GaN) ultraviolet metal-semiconductor-metal photodetectors (PDs) grown on Si substrates were demonstrated. The dark current of PDs fabricated on Si substrates was substantially smaller in magnitude compared to identical devices prepared on sapphire substrates. With an incident wavelength of 359 nm, the maximum responsivities of the $n$-GaN MSM photodetectors with TiW and Ni/Au contact electrodes were 0.187 and 0.0792 A/W, corresponding to quantum efficiencies of 64.7% and 27.4%, respectively. For a given bandwidth of 1 kHz and a given bias of 5 V, the corresponding noise equivalent powers of our $n$-GaN MSM photodetectors with TiW and Ni/Au electrodes were $1.525 \times 10^{-12}$ and $5.119 \times 10^{-12}$ W, respectively. Consequently, the values of detectivity ($D^*$) determined for devices with TiW and Ni/Au electrodes were then calculated to be $1.313 \times 10^{12}$ and $3.914 \times 10^{11}$ cm Hz$^{0.5}$ W$^{-1}$, respectively. © 2007 American Institute of Physics.
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I. INTRODUCTION

Ultraviolet (UV) photodetectors (PDs) have become an active area of research in recent years. Both civil and military applications demand high performance UV PDs for applications including solar UV monitoring, source calibration, UV astronomy, flame sensors, detection of missile plumes, and securing space-to-space communications. Gallium nitride, a well-known semiconductor with direct wide band gap ($E_g=3.4$ eV) and high saturation velocity ($v_s=2.7 \times 10^7$ cm/s), is undoubtedly well suited for fabricating UV PDs.\textsuperscript{1-13} In addition, the other beneficial properties associated with this material also include the thermal stability, radiation hardness, and remarkable tolerability of aggressive environments. Conventional GaN-based epitaxial layers were grown either on sapphire or on SiC substrates. However, sapphire substrate is an insulator with poor thermal conductivity. On the other hand, SiC substrate is considered more favorable based on thermal and electrical considerations, but the chance for its widespread use is being hampered by its relatively high cost. Compared with sapphire and SiC substrates, GaN epitaxy on Si appears to be a compromising and cost-effective solution. The other potential advantages associated with the use of Si substrate also include the possibility of monolithically integrating GaN-based devices with Si-based microelectronics. Although several growth-related difficulties remain, reports on the fabrication of GaN light-emitting diodes and heterostructure field effect transistors on Si substrates have been documented in internationally renowned scientific journals.\textsuperscript{14-19} We have previously reported the growth of high quality InGaN/GaN light-emitting diode (LED) epilayers on Si (111) substrate.\textsuperscript{20} We were able to grow high quality InGaN/GaN films on silicon substrate by incorporating an initial AlGaN buffer along with two high-temperature (HT) AlN interlayers to effectively confine threading dislocation near the interfaces of AlGaN/HT-AlN buffer layers. In fact, our previous transmission electron microscopy (TEM) and scanning electron microscopy (SEM) images revealed a smooth and crack-free GaN surface, along with a noticeable reduction in threading dislocation density in region away from the interfacial site bordering the silicon substrate.\textsuperscript{20} In this study, the growth of $n$-GaN epitaxial layers on Si substrates and the fabrication of GaN metal-semiconductor-metal (MSM) PDs are discussed, and the resultant optical and electrical properties of fabricated PDs are also reported.

II. EXPERIMENTS

The samples used in this study were all grown on Si (111) substrates by metal organic chemical vapor deposition (MOCVD).\textsuperscript{21-24} Trimethylgallium (TMGa), trimethylaluminum (TMAI), and ammonia ($\text{NH}_3$) were used to supply the source materials for gallium (Ga), aluminum (Al) and nitrogen (N), respectively. For the lightly Si-doped $n$-type GaN ($n$--GaN) structure, a 25-nm-thick AlN buffer layer was deposited onto the Si (111) substrate at 1090 °C. Then, two stacks of buffer multilayer were inserted between a 25-nm-thick AlN buffer layer and a topmost 500-nm-thick...
1090 °C-grown \( n^- \)-GaN epitaxial layer. Each stack of buffer multilayer consists 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. The schematic structure is depicted in Fig. 1.

TiW (100 nm) and Ni (10 nm)/Au (90 nm) contact layers were then separately deposited onto the samples using thermal evaporation and rf magnetron sputter systems. Then, \( n^- \)-GaN MSM photodetectors were fabricated by standard photolithography and lift-off process. The dimensions of the electrode fingers of the interdigitated metal contact patterned on MSM photodetectors were 10 \( \mu \)m wide and 200 \( \mu \)m long, and with a gap of 10 \( \mu \)m in between. An HP-4156 semiconductor parameter analyzer was then used to measure the dark current-voltage \( I-V \) characteristics of these PDs. Spectral responsivity measurements were also performed using a Jobin-Yvon SPEX system equipped with a 450 W xenon arc lamp light source and a standard synchronous detection scheme. Furthermore, the noise characteristics of GaN MSM UV PDs in the frequency range of 1 Hz to 1 KHz were measured using a lownoise current preamplifier and a dynamic signal analyzer.

### III. RESULTS AND DISCUSSION

Figure 2 presents the symmetric \( I-V \) characteristics of MSM photodetectors with TiW and Ni/Au contact electrodes. In a dark environment when 5 V applied bias was administered, the measured dark currents of photodetectors with TiW and Ni/Au electrodes were 1.36 \( \times \)10\(^{-10} \) and 1.21 \( \times \)10\(^{-10} \) A, respectively. Notice that relatively small dark leakage currents were detected for our detectors covered with TiW or Ni/Au finger electrodes, considering the fact that these III-nitride-based device layers were grown on the lattice-mismatched silicon substrate. The small dark current obtained in our experiment clearly resulted from insertion of two extra stacks of buffer multilayer into the overall device structure. This scheme helps to alleviate the detrimental impact of lattice mismatch between GaN and silicon during the epitaxial growth by further improving the crystalline quality of GaN films as the numbers of dislocations and defects are effectively minimized.\(^{26}\) As a result, a larger Schottky barrier height was obtained for contact electrode deposited on the epitaxial film. Figure 3 shows room temperature spectral responses of MSM PDs measured with 5 V applied bias. In order to reliably quantify the peak responsivity, the xenon lamp intensity was first measured using a calibrated GaP UV detector. The difference in sensor-detecting areas between GaP UV detector and our PDs was then taken into account before using this information to assess the true PD responsivity. As shown in Fig. 3, the peak responsivity occurred at 359 nm for both MSM PDs with different metal Schottky contacts. The maximum responsivities of MSM photodetectors with TiW and Ni/Au contact electrodes were 0.187 and 0.0792 A/W, corresponding to quantum efficiencies of 64.7% and 27.4%, respectively. When compared with III-nitride PD grown on sapphire substrate,\(^{25,26}\) a smaller peak responsivity observed for the device sample grown on Si substrate was directly attributed to a highly defective epitaxial layer. Similar results were also reported by Osinsky \textit{et al.}\(^{27}\) In our case, the responsivity is highly dependent on the transmittance of contact electrode, so a higher transmittance of TiW renders a device with larger responsivity.\(^{26}\) Beyond the cut-off wavelength, the responsivities of both PDs were almost the same, indicating the nearly identical
Schottky barrier heights for TiW and Ni/Au contacts. To clarify the significance of device responsivity measured, the rejection ratio was thereby defined as the ratio between the spectral responsivity measured at 359 nm and also at 385 nm. With such definition, we found that the resultant rejection ratios were 111 and 43 for MSM photodetectors with TiW and Ni/Au contact electrodes, respectively. A larger rejection ratio observed from a detector with TiW electrode was undoubtedly attributed to the higher transmittance of TiW electrode.

Figures 4(a) and 4(b) depict the measured noise power densities of the GaN MSM photodetectors with Ni/Au and TiW contact electrodes, respectively. According to the noise curves obtained, 1/f (flicker) indicatively appears as a dominant noise mechanism, which is expected for MSM $n^-$-GaN detectors operating at low frequency. Moreover, the noise curves obey the Hooge-type equation with a fitting parameter $\alpha$. Notice that the measured low frequency noise could further be classified as $1/f$-type ($\alpha=1$) and $1/f^2$-type ($\alpha=2$) noises in low and high bias conditions, respectively. Figures 5(a) and 5(b) respectively show the noise power density as a function of dark current measured at 100 Hz for the GaN MSM photodetectors with Ni/Au and TiW contact electrodes. We can derive the noise power density $S_n$ using the Hooge-type equation

$$S_n(f) \sim \frac{P^\beta}{f^\alpha}. \quad (1)$$

From the curves shown in Figs. 4(a) and 4(b), the value of $\beta$ extracted was around 1.16 at low bias and then became 2.49 at high bias for the photodetector with Ni/Au contact electrode. On the other hand, the $\beta$ was around 1.07 at low bias and was elevated to 4.3 at high bias for the photodetector with TiW contact electrode. The variation in the fitting parameter $\beta$ extracted from PDs grown on Si substrate was directed attributed to the highly defective epitaxial layers. A large $\beta$ again suggests that some defect-related states existed in the depletion region or in the forbidden gap of our photodetectors. These extra states contribute to a stronger trapping process, which is responsible for the larger noise observed. For a specified bandwidth $B$, the overall sum of the square of noise current, $(i_n)^2$, can be determined by integrating the noise power density $S_n(f)$,

$$\int (i_n)^2 df.$$  \quad (2)

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

$$\text{NEP} = \sqrt{\frac{(i_n)^2}{R}}. \quad (3)$$

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

$$D^* = \frac{\sqrt{A/B}}{\text{NEP}}. \quad (4)$$

where $A$ is the area of the photodetector and $B$ is the bandwidth. With a given bandwidth of 1 kHz and a given bias of 5 V, the measured noise equivalent powers of $n^-$-GaN MSM photodetectors with TiW and Ni/Au electrodes were $1.525 \times 10^{-12}$ and $5.119 \times 10^{-12}$ W, respectively. These values in
turn led to the final $D^*$'s of $1.313 \times 10^{12}$ and $3.914 \times 10^{11}$ cm Hz$^{0.5}$ W$^{-1}$, respectively, which were larger than the detectivities measured earlier for GaN MSM photodetectors with similar interdigitated electrode dimensions fabricated on sapphire substrates.$^{26,28}$ Specifically, the NEPs and maximum $D^*$s of MSM photodetectors with TiW and Ni/Au electrodes were $1.987 \times 10^{-10}$ W and $6.365 \times 10^9$ cm Hz$^{0.5}$ W$^{-1},$ $^{26}$ and $2.14 \times 10^{-9}$ W and $2.62 \times 10^9$ cm Hz$^{0.5}$ W$^{-1},$ $^{28}$ respectively. The relatively higher detectivities obtained were evidently attributed to smaller noise power densities of the PDs prepared on Si (111) substrates. The benchmark values realized for the noise and detectivity of devices fabricated on silicon show that our MSM photodetectors are well suited for low-noise applications.

IV. SUMMARY

In summary, GaN ultraviolet MSM photodetectors grown and fabricated on Si substrate were prepared. The dark currents of PDs prepared on Si substrates were much smaller than those measured for similar devices prepared on sapphire substrate. With an incident wavelength of 359 nm, the maximum responsivities of $n$-GaN MSM photodetectors with TiW and Ni/Au contact electrodes were 0.187 and 0.0792 A/W, corresponding to the quantum efficiencies of $1.525 \times 10^{-4}$ and $1.313 \times 10^{12}$ and $3.914 \times 10^{11}$ cm Hz$^{0.5}$ W$^{-1}$, respectively, which led to the detectivities ($D^*$s) of $1.313 \times 10^{12}$ and $3.914 \times 10^{11}$ cm Hz$^{0.5}$ W$^{-1}$, respectively.

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