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Improved performance of GaN-based Schottky barrier photodetectors by annealing Ir/Pt Schottky contact in O_2

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ABSTRACT

Nitride-based UV Schottky barrier photodetectors (PDs) with Ir/Pt after annealing in O_2 at 600 °C were fabricated successfully. With −5 V applied bias, the reverse leakage current of the annealed PD was 3.65×10^{-12} A. It was found that we could achieve the larger Schottky barrier height, the smaller dark current and the larger photocurrent to dark current contrast ratio by annealing Ir/Pt. After annealing, the Schottky barrier height increased from 0.91 eV to 1.03 eV and the ideality factor decreased from 1.58 to 1.16. Such a result indicated that the dominant current transport mechanism may be thermionic emission and the Schottky contact is near-ideal after annealing. These results could be attributed to the formation of IrO_x phase. It was also found that responsivity and the UV-to-visible rejection ratio were 0.19 A/W and 1.05×10^3 after annealing with −6 V applied bias.

1. Introduction

III-nitride semiconductor materials have recently attracted much interest owing to their excellent electrical and optical properties. In recent years, these materials have been extensively investigated and can be used for various optoelectronic devices, such as light emitting diodes (LEDs) [1,2], laser diodes (LDs) [3,4] and ultraviolet (UV) photodetectors (PDs) [5]. Owing to their wide direct band-gap, superior radiation hardness and high temperature resistance, nitride-based UV PDs are potentially useful in many commercial and military applications. In the last few years, various types of nitride-based UV PDs have been reported [6–9]. Compared with bipolar PDs, the response speed of Schottky barrier PDs is faster. However, it is known that dislocation density in GaN epitaxial layers was high due to the large differences in lattice constant and thermal expansion coefficient between GaN and sapphire. The large dislocation density will result in large leakage current for nitride-based Schottky barrier PDs. Therefore, reducing the leakage current is an important issue for GaN-based Schottky barrier PDs.

One possible way to reduce leakage current is to employ a metal with high work function, such as Pt, Ni, or Pd. However, the high work function metals may be unstable at high temperatures owing to severe inter-diffusion [10]. Previously, it has been reported that iridium (Ir, 5.46 eV) could form thermally stable Schottky contact on AlGaN/GaN hetero-structure [11]. However, to our knowledge, it was reported that Ir/Pt alloy is more stable, more corrosion-resistant and more durable [12,13]. Therefore, we use Ir/Pt alloy as the Schottky contact on GaN. In some cases, the as-deposited Ir/Pt contacts were annealed in O_2 to improve the performance of the devices. In this study, the properties of the fabricated Schottky barrier PDs with and without annealing in O_2 will both be characterized.

2. Experiments

Samples used in this study were all grown by metallorganic chemical vapor deposition (MOCVD) on 2-in c-face (0 0 0 1) sapphire substrates. Prior to the growth of GaN films, sapphire substrates were heated to 1100 °C to remove any surface contamination. The samples consisted of a 30-nm-thick low-temperature GaN nucleation layer, a 2-μm-thick Si-doped GaN layer ($n \sim 10^{18}$ cm^{-3}), and a 0.3-μm-thick unintentionally doped GaN layer ($n \sim 10^{17}$ cm^{-3}). PDs were then fabricated based on this structure. First, Ti (13 nm)/Al (150 nm) was used as the ohmic contact material. After Ti/Al deposition, the alloy was thermally annealed at 600 °C for 8 min so as to achieve an ohmic contact. Ir (4 nm)/Pt (2 nm) was used as the Schottky contact material. The diameter of the fabricated circular diodes was kept at 400 μm. To improve the device performance, the Ir/Pt contact was subsequently annealed by furnace at 600 °C in O_2 for 20 min. Finally, we deposited Ni (40 nm)/Au (100 nm) as the contact pad. Here, we call the PD with as-deposited Ir/Pt and 600 °C-annealed Ir/Pt PD_A and PD_B, respectively.

The electrical properties of the PDs were then characterized by a HP 4155 semiconductor parameter analyzer both in the dark and under illumination. For

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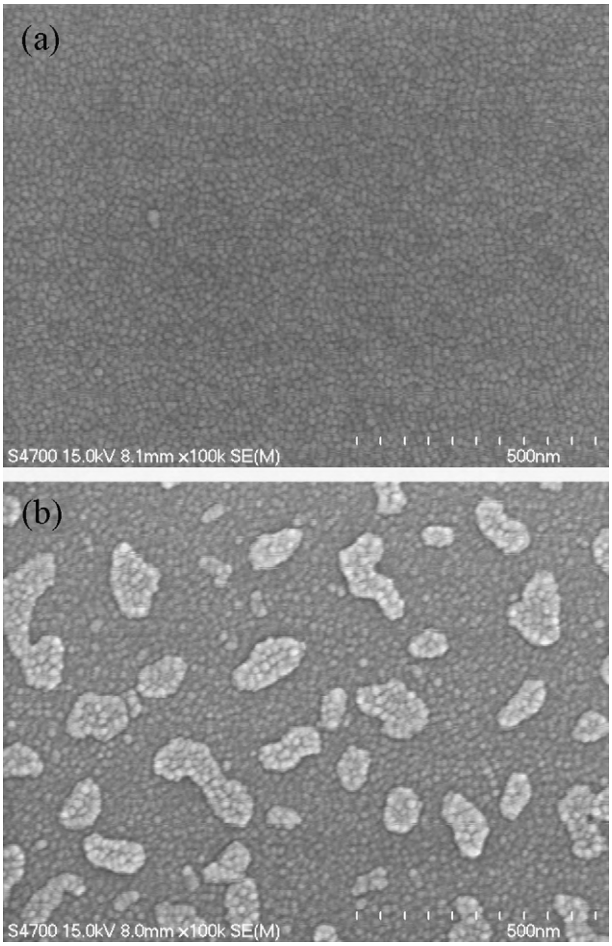

Fig. 1. The SEM images of Ir/Pt (a) before and (b) after annealing at 600 °C in O_2 for 20 min.

photocurrent measurements, a 150 W D_2 lamp was used as the light source. For spectral responsivity measurements, a xenon arc lamp was used as the light source. The monochromatic light, calibrated with UV-enhanced Si photodetectors and an optical power meter, was collimated onto the fabricated PDs using an optical fiber.

3. Results and discussion

Fig. 1(a) and (b) illustrates the scanning electron microscopy (SEM) images of the as-deposited Ir/Pt film and 600 °C-annealed Ir/Pt film, respectively. From these two images, we could find the regular grain sizes were about 40 nm and 180 nm, respectively. But after annealing, the surface became rougher and this was attributed to a "balling-up" effect, which has been widely observed in metallization processes and phase transition. We thought that the bright gray particles should be IrO_x. In other words, the "balling-up" of the IrO_x layer occurred during the thermal process and resulted in the rougher surface.

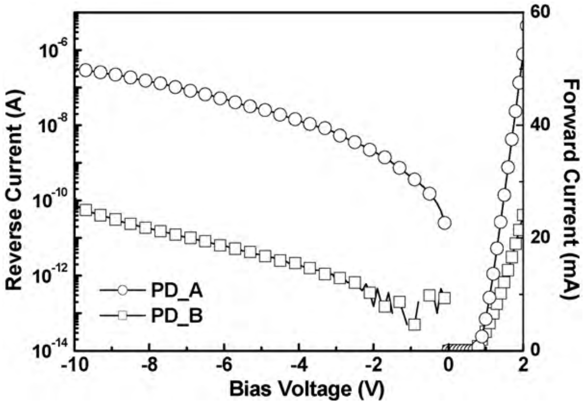

Fig. 2. Dark *I–V* characteristics for PD_A and PD_B.

Fig. 2 shows the measured current-voltage characteristics of PD_A and PD_B. Under forward bias, it was found that the turn-on voltages of PD_A and PD_B were 0.9 V and 1.6 V, respectively. It is well known that the interface states and chemical reactions at metal/semiconductor interface can play an important role in the electrical properties of devices. During the annealing process, Ir might react with oxygen atom and IrO_x with higher work function would form at the interface. Besides, the formation of alloys between Ir/Pt and GaN and the reduction of interface states might also occur during annealing. Hence, we thought the increase of turn-on voltage after annealing might be attributed to the combined effects of interfacial reaction, such as IrO_x. The reverse leakage current for the diode decreased significantly by at least three orders of magnitude after annealing. With −5 V applied bias, the reverse leakage currents of PD_A and PD_B were 2.61×10^{-8} A and 3.65×10^{-12} A, respectively. Note that the higher leakage current occurred for the as-deposited Ir/Pt film. This could be foreseen because of their low Schottky height and higher surface state density.

Many methods have been suggested to calculate the barrier heights and ideality factors for a metal–semiconductor Schottky contact from *I–V* data. Linear curve fitting for the forward characteristic of log(*I*) vs *V* is used widely. The Schottky barrier heights and ideality factors can be deduced from the y intercept and the slope of the fitted curves. Fig. 3 demonstrates the variations of the Schottky barrier height and ideality factor by simple thermionic emission model as a function of annealing temperature. It should be noted that values showed in Fig. 3 were extracted by at least 10 devices for each diode. The diodes after annealing showed the better performance on either Schottky barrier height or ideality factor. The thermal process has been generally reported to take effect on improving the Schottky characteristics due to the reduction in the density of interfacial states [14]. The Schottky barrier height increases from 0.91 eV to 1.03 eV after annealing. The possible reason for the increase in Schottky barrier height is the formation of IrO_x and the reduction in the density of the interface states after annealing owing to the passivation of IrO_x and re-arrangement of atoms. In addition, discussion on the change of ideality factor can be developed to support this consequence. Before annealing, the ideality factor for as-deposited Ir/Pt contact was 1.58. After annealing, the ideality factor decreased to 1.14. It is believed that added tunneling and generation-recombination components [15] besides thermionic emission simultaneously affect the current transport at

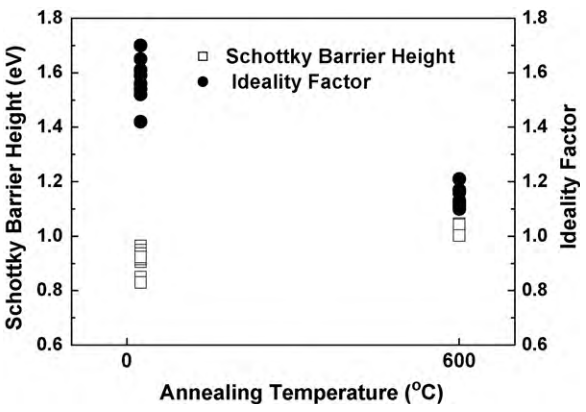

Fig. 3. The electrical properties of PD_A and PD_B from the 10 Schottky diodes.

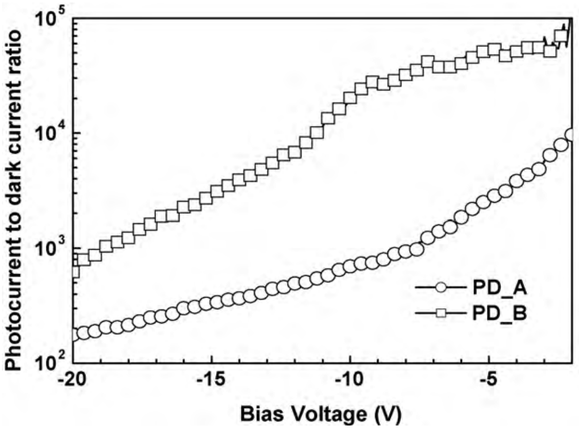

Fig. 4. The measured photocurrent to dark current contrast ratios for PD_A and PD_B.

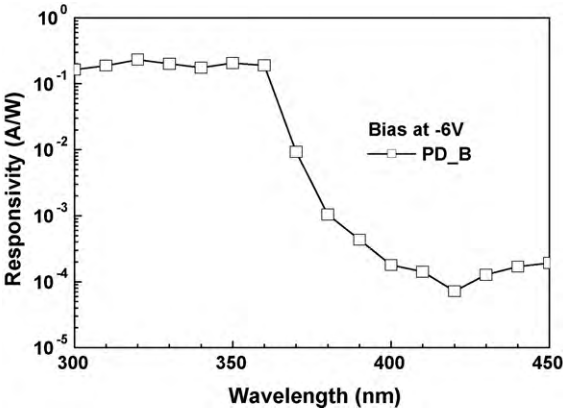

Fig. 5. Spectral responsivity of PD_B.

the metal/GaN barrier before annealing. However, the ideality factor after annealing is close to unity, indicating that the dominant current transport mechanism is thermionic emission. This result can be attributed to the fewer surface state density.

Fig. 4 shows the measured photocurrent to dark current contrast ratios for PD_A and PD_B. It was found that the photocurrent to dark current contrast ratio for PD_B was larger than that for PD_A. With −6 V applied bias, it was found that we could achieve a high 4.03×10^4 photocurrent to dark current contrast ratio from PD_B. Fig. 5 shows the spectral response of PD_B biased at −6 V at room temperature. It was found that photo responses were relatively flat on the short wavelength side while cut-off occurred at 360 nm for PD_B. With an incident wavelength of 360 nm, it was found that the responsivity for PD_B was 0.19 A/W. However, it decreased to 1.79×10^{-4} A/W when the light wavelength was increased to 400 nm. Such a spectral response is typical for visible-blind nitride-based UV PDs. Here, we define UV-to-visible rejection ratio as the responsivity measured at 360 nm divided by the responsivity measured at 400 nm. With this definition, the UV-to-visible rejection ratio is estimated to be 1.05×10^3 for PD_B. This result indicates that we can improve the characteristics of nitride-based PDs by annealing Ir/Pt in O_2.

4. Conclusion

In summary, nitride-based UV Schottky barrier PDs with Ir/Pt after annealing in O_2 at 600 °C were fabricated and characterized. It was found that we could achieve the larger Schottky barrier height, the smaller dark current and the larger photocurrent to dark current contrast ratio by annealing Ir/Pt. It was also found that responsivity and the UV-to-visible rejection ratio were 0.19A/W and 1.05×10^3 after annealing with −6 V applied bias.

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