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Pt/GaN Schottky Type Ultraviolet Photodetector with Mesa Structure

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Abstract

A Schottky type GaN ultraviolet photodetector with a mesa structure was fabricated by depositing an Al ohmic contact on an n^+-GaN layer and a Pt Schottky contact on a GaN layer. The undoped GaN(0.5 um)/n^--GaN(0.1 um)/n^+-GaN(1.5 um) multi-layer structure was grown on a sapphire substrate using MOCVD. The Schottky contact properties were characterized for different passivation conditions. The leakage current of the fabricated Schottky diode was 2 nA at a reverse voltage of 5 V. Plus the photocurrent was 120 uA using a hydrargyrum lamp with an optical power of 1 mW at a wavelength of 365 nm. The diode exhibited an ultraviolet-visible rejection ratio of 10^2.

I. Introduction

Due to the current information age, there has been a growing demand for optical photodetectors for systems such as electronic appliances, mechatronics, telecommunication and military systems.

In particular, UV (ultraviolet) photodetectors have a great potential for application in the areas of nuclear reactor monitors, ozone monitors, flame detectors, and space communications. With the advent of reliable Ⅲ-nitride semiconductor growth technology, many electronic and optical devices have been developed using III-nitride materials. In the case of nitride semiconductors, the cutoff wavelength of UV photodetectors can be optimized from 200 nm to 365 nm by changing the Al mole fraction of the $Al_xGa_{1-x}N$ alloy in the epitaxy.

The first time research on nitride UV photodetectors was conducted Khan in the early 1990s[1]. Recently, a Pd-Schottky photodetector was developed by Chen from the same research group[2]. Plus, Ruden et.al. produced p-i-n structure UV photodetectors with a responsivity of 0.2 A/W with a low dark current of 5 pA[3]. Furthermore, Walker et. al. created MSM type UV photodetectors with a high responsivity of 0.4 A/W and fast response time of 10 ns[4]. GaN Schottky photodiodes were first commercialized by APA optics in January 1998. These devices consisted of vertical Pd Schottky barriers on GaN grown on c-sapphire, with a diameter of 250 um. The typical dark current was 2 nA at a 1 V bias and the responsivity was 130 mA/W with a UV-visible contrast of 10^3[5]. In spite of these commercial products,

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the heteroepitaxy of a nitride semiconducting crystal results in a high dislocation density (~10^8 cm^{-2}), thereby limiting the UV-visible rejection ratio in GaN UV detectors. In this study, for high responsivity photodetector, a GaN Schottky diode was fabricated and investigated mainly for the leakage current reduction by etching and passivation conditions.

II. Design and Fabrication of Device

To create a high quality ultraviolet photodetector, the optical layer materials, their structure, and dimensions were all optimized. In a structure where the input light comes through the bottom of the sapphire substrate, there is a significant decrease in the intensity until arriving at the depletion region. In addition, the two dimensional defects (dislocation density) of about 10^8~10^{10} cm^{-2}, generated at the interface between the sapphire and the GaN film, affect the inactive photo-generated carriers[1]. Consequently, top incident light structure was chosen where the ultraviolet signal can arrive at the depletion region through the transparent metal electrode layer. Pt is known to have flat transmission characteristics over a wide spectral region and high potential barriers to GaN[6]. Therefore, semi-transparent Pt film of 7~10 nm was deposited for the Schottky contact on undoped GaN thin film. Figure 1 shows a structural cross-sectional of the proposed device.

The Schottky electrodes were in a circular pattern with a 350 um radius. Plus, the resistive electrode, which surrounded the Schottky electrode, was ring shaped with a 100 um diameter. The interval between the two electrodes was determined as 50 um[7].

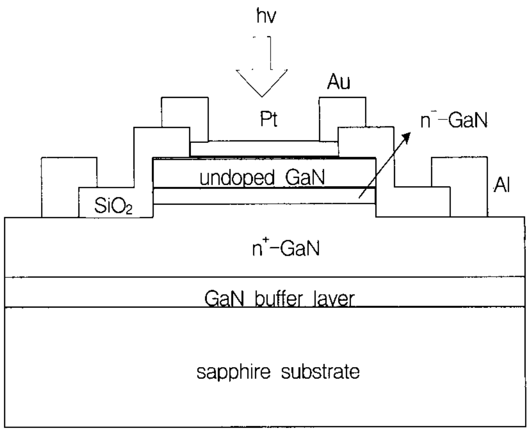

Fig. 1. Cross-sectional view of designed photodetector device

In this experiment, the epitaxial layers were grown on an undoped GaN(0.5 um)/n$^-$-GaN(0.1um)/n^+-GaN(1.5 um) 2-inch (0001) sapphire substrate using MOCVD. The silicon was doped for the n^+ and n^- layers and was intentionally not doped in the undoped layer, which had a carrier concentration of about 3×10^{16} cm^{-3}. Since a lattice mismatch of 16.1 % and thermal expansion coefficient of 23.4 % occurs when GaN is grown directly on a sapphire substrate, a low temperature GaN buffer layer was grown before the main epitaxy[8]. The doping concentration, resistivity, and mobility of the layers were characterized using the Hall method. The GaN layers showed an n-type doping concentration of 1.86×10^{18} cm^{-3} and electron mobility of 288 $cm^2/V\cdot s$.

To fabricate of the Schottky photo-detector, after selectively etching the mesa structure for the ohmic contact area, the Al ohmic metal was deposited and annealed at 600 °C for 10 minutes in N_2 ambient. The Schottky contact was formed using an e-beam evaporation of Pt. Between the metallization processes, SiO_2 passivation was performed using the magnetron sputt-ering method. Figure 2 shows a schematic process flow diagram of the UV detector fabrication.

The electrical properties of the fabricated devices were measured using an HP4145 system. The spectral photo-response studies were performed using a hydrargyrum lamp and the monochromator of a commercial spectro-photometer.

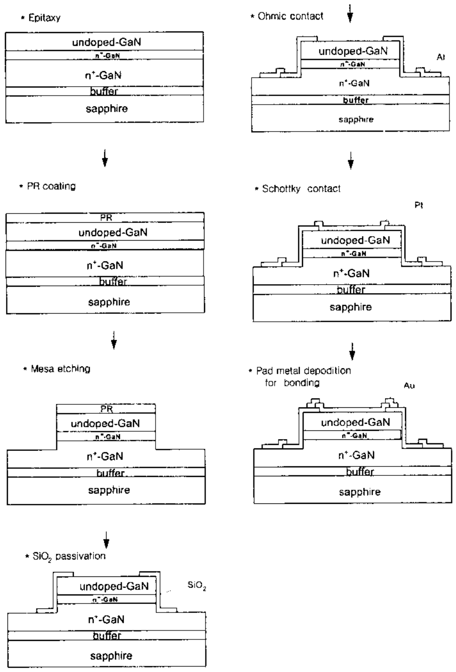

Fig. 2. Schematic process diagram for the etching type UV detector fabrication

III. Results and Discussions

III-1. Leakage current variation with etching

Because of non-ideal interface states and massive defects in the epitaxial layer, there are various leakage mechanisms in GaN-related Schottky devices. However, for highly sensitive photo-detection, the leakage currents of a device must be reduced as much as possible.

To investigate the variation of the leakage current according to the etching depth, transformer coupled plasma(TCP) with CH_4/H_2/Ar was applied to fabricate three Schottky diodes on the same sample with etching depths of 0.8, 1.2 and 1.5 um, then the respective leakage currents were measured. The leakage current increased from 11 to 100 uA under a reverse bias of 1 V as the etching depth increased, as shown in figure 3. As expected, the etching damage increased near the etching surface, whereas in the more intrinsic defects, generated during growth on the lattice mismatched substrate, were denuded near the etching surface.

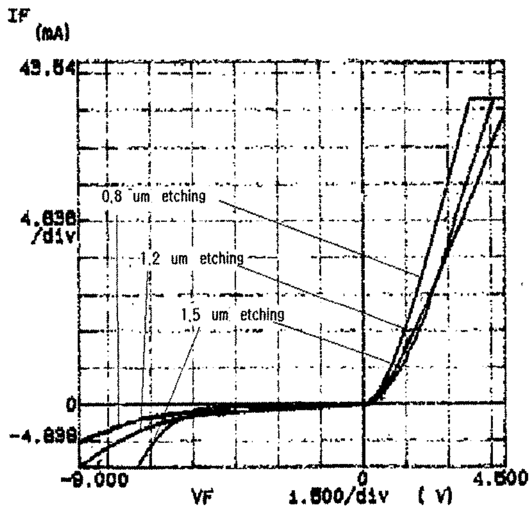

Fig. 3. I-V Characteristics of Schottky diodes with different etching depths. (a) 0.8 um (b) 1.2 um and (c) 1.5 um etching.

Figure 4 shows the PL spectrum of the GaN layers grown on sapphire as figure 2 (a) using He/Cd laser. As shown in the figure, a near band emission peak was observed at 362 nm and a yellow band emission peak at 560 nm. The yellow emission was caused by the intrinsic defects as well as the impurity defects. The dis-location density, which reduces the photo-generated carriers in the photodetector, may be minimized for optical sensing applications through the use of proper growth tech-nologies such as nucleation buffer layer optimization and selectively overgrown layers.

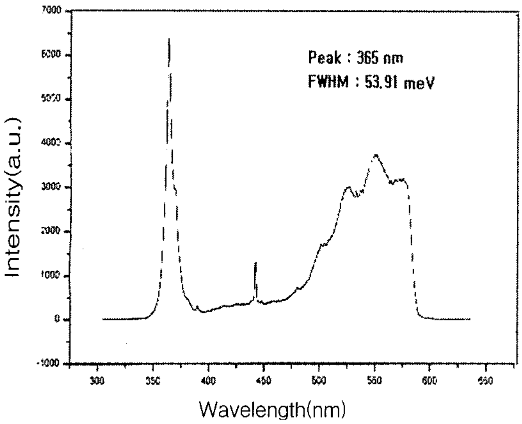

Fig. 4. Photoluminescence spectrum of photodetector layers.

III-2. Effects of SiO_2 passivation layers

A low leakage current is a prerequisite for obtaining high responsivity in a junction type photodetector. In this work, a ring-shaped SiO_2 passivation layer was created between the electrodes to reduce the leakage currents flowing through the etched surfaces.

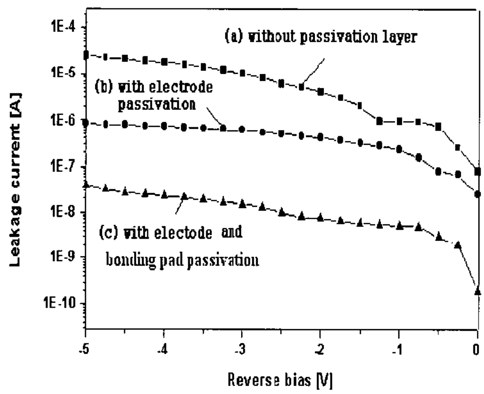

Fig. 5. Leakage currents of Schottky diode relative to passivation.
(a) without passivation
(b) SiO_2 passivation between contacts
(c) SiO_2 passivation between contacts and contact pad

As shown in figure 5, the result of the experiment showed that, when the reverse bias voltage was 5 V, the leakage current of the Schottky diode with a passivation layer decreased from tens of uA to only a few nA. The saturation current, ideality factor, and Schottky barrier height, calculated based on the measured forward current characteristics, were 3.17×10^{-5} A, 1.97, and 0.65 eV respectively, without any passivation layer (as shown in figure 5(a)) and 3.95×10^{-9} A, 1.42 and 0.76 eV respectively, with full passivation (as shown in figure 5(c)). We could think that if the passivation layer was formed properly between the two electrodes and over the bonding pads, the reverse characteristics of the device would be significantly improved. In this case, the device had quite wide gap between the ohmic and Schottky electrode, and it made the large surface states, which might increase the leakage current. The contact resistivity of the Al electrodes, formed on the etched n^+- GaN thin film, was about $2\times10^{-4}\ \Omega\cdot cm^2$, which was quite high because of the poor metallization condition.

On the other hand, when annealing the device for 2 minutes above 550 °C, the Schottky diode was degraded and exhibited a near ohmic property. Since the proposed device had quite substantial distance (50 um) between the contacts, and it did show some degradation during the successive measurements, which was possibly caused from the joule-heated thermal stress of the device. Recently, the current authors presented a new Schottky material, which is far more reliable than other metals previously reported[9].

III-3. Spectral response of fabricated Schottky photodetector

From the experimental results, the Pt

contact had a comparatively low leakage current of a 10^{-9} A with a reverse bias of 5 V and reverse breakdown voltages above 40 V[7]. Figure 6 shows the forward and reverse I-V characteristics of the fabricated Schottky photodetector. The ideality factor and height of the potential barrier of the Pt Schottky diodes were 1.4 and 0.8 eV, respectively. As shown in the figure, the forward bias characteristics of the diode were not as good, because the ohmic contact properties were not optimized and the series resistance was high.

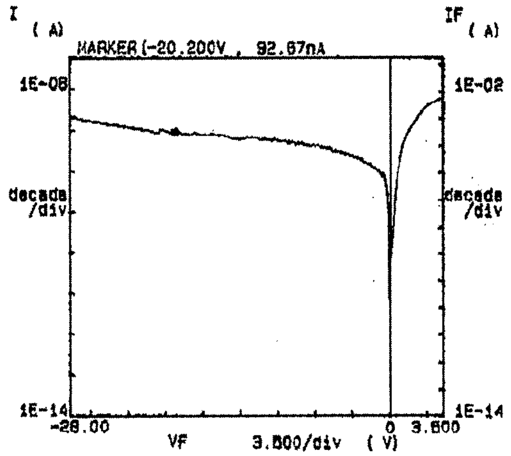

Fig. 6. Log I-V Characteristics of fabricated UV photodetector.

Figure 7 shows the variation of the spectral photo-currents when changing the spectro-photometer wavelength from 380 to 420 nm with reverse biases between 5~23 V. As shown in the figure, the photo-currents were 0.1~2 uA for a UV wave-length of under 360 nm with reverse bias voltages, however, the photo-currents rapidly reduced to the level of only a few nA with a wavelength above 360 nm. The UV-visible rejection ratio at a reverse bias voltage of 15 V was larger than 10^2. In the above case, the noise equivalent power (NEP) was 6×10^{-8} W.

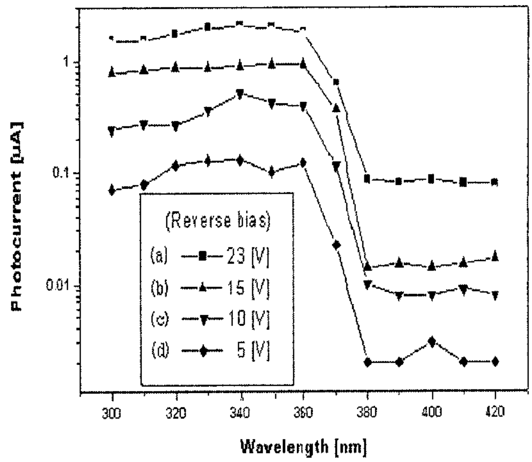

Fig. 7. Spectral photocurrents of fabricated UV photodetector.
(a) 23 V (b) 15 V (c) 10 V (d) 5 V reverse bias.

Ⅳ. Conclusion

In this paper, three layers of undoped GaN(0.5 um)/n^--GaN(0.1 um)/n^+-GaN(1.5 um) were grown on a sapphire substrate using MOCVD. A Pt Schottky diode was fabricated, which had a potential barrier of 0.8 eV, ideality factor of 1.4, and reverse breakdown voltage above 40 V. The SiO_2 passivated device exhibited a significantly low leakage current of 10^{-9} A under a 5 V reverse bias. These results show that the fabricated ultraviolet photodetector had near visible blind characteristics, with a responsivity that decreased rapidly around 365 nm. The UV-visible rejection ratio for the device was about 10^2. When compared to other reports, the fabricated ultraviolet photodetector had a comparatively low leakage current and quite high UV-visible rejection ratio. If the defect density and contact resistivity can be reduced, this would result in a photodetector with a similar performance to commercial one.

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