Solar-Blind AlGaN-Based p-i-n Photodiodes With Low Dark Current and High Detectivity

N. Biyikli, I. Kimukin, O. Aytur, and E. Ozbay

***Abstract*—We report solar-blind $Al_xGa_{1-x}N$-based heterojunction p-i-n photodiodes with low dark current and high detectivity. After the p+ GaN cap layer was recess etched, measured dark current was below 3 fA for reverse bias values up to 6 V. The device responsivity increased with reverse bias and reached 0.11 A/W at 261 nm under 10-V reverse bias. The detectors exhibited a cutoff around 283 nm, and a visible rejection of four orders of magnitude at zero bias. Low dark current values led to a high differential resistance of 9.52 $\times 10^{15}$ Ω. The thermally limited detectivity of the devices was calculated as 4.9 $\times 10^{14}$ cm $\cdot$ $Hz^{1/2}W^{-1}$.**

***Index Terms*—AlGaN, dark current, detectivity, heterostructure, high-performance, p-i-n photodiode.**

SOLAR-BLIND detectors with long-wavelength cutoff around 280 nm have important applications including missile plume sensing, flame detection, chemical–biological agent sensing, and covert space-to-space communications [1]. With the advent in material growth of high-quality $Al_xGa_{1-x}N$ ternary alloys, AlGaN-based solar-blind photodetectors emerged as a potential alternative for the photomultiplier tube (PMT) and silicon-based solar-blind detector technology. They have the advantage of intrinsic solar-blindness, and therefore, do not need complex and costly filters. In addition, AlGaN-based solar-blind detectors can operate under harsh conditions due to their wide bandgap and robust material properties [2]. Several research groups have demonstrated high-performance solar-blind photodetectors using $Al_xGa_{1-x}N$ material system [3]–[12].

Detectivity is an important detector performance parameter which gives the signal-to-noise performance of the device. For low noise detection, detectivity should be as high as possible. The typical detectivity of a cooled PMT is about $D^* = 4 \times 10^{14}$ cm $\cdot$ $Hz^{1/2}W^{-1}$ around 300 nm [13]. A comparable detectivity performance ($D^* \sim 3 \times 10^{14}$ cm $\cdot$ $Hz^{1/2}W^{-1}$ at 275 nm) was reported recently with a solar-blind AlGaN-based back-illuminated p-i-n photodiode [14]. In this letter, we report the design, fabrication, and characterization of solar-blind AlGaN p-i-n photodiodes with record dark current and detectivity performance. The measured dark current was below 3 fA at 6-V reverse bias and a PMT-exceeding solar-blind detectivity of $D^* = 4.9 \times 10^{14}$ cm $\cdot$ $Hz^{1/2}W^{-1}$ at 267 nm was achieved.

The p-i-n photodiode wafer was grown by metal–organic chemical vapor deposition on sapphire substrate. The detector structure was designed for front (p-side) illumination. The active absorption region of the photodiode was formed with a 100-nm-thick unintentionally doped $Al_{0.45}Ga_{0.55}N$ layer which was sandwiched between a 250-nm-thick n+ GaN layer and a 10-nm-thick p-type-doped $Al_{0.45}Ga_{0.55}N$ layer. To improve the p-ohmic contact quality, a 30-nm-thick p-type GaN cap layer was grown on top of p-$Al_{0.45}Ga_{0.55}N$ layer. A five-step microwave compatible semiconductor fabrication process was utilized to complete the device fabrication [15]. In the first two steps, ohmic contacts were formed. A 250-nm deep dry-etch for n+ ohmic contact was done via CCl_2F_2-based reactive ion etching (RIE). This was followed by a Ti–Al (100/1000 Å) metallization. Then, Ni–Au (100/200 Å) was deposited for p-type contact. Both contact metals were annealed at 700 °C for 1 min. After the device mesas were defined and electrically isolated with RIE, the sample surface was passivated with a ~200-nm-thick Si_3N_4 layer deposited using plasma-enhanced chemical vapor deposition at 350 °C. The fabrication process ended with the formation of ~0.6-μm-thick Ti–Au interconnect metal pads.

For device characterization, current–voltage (I–V) and spectral responsivity measurements were carried out. To analyze the effect of p-type GaN cap layer on the dark current and responsivity performance, the measurements were done in two steps: before and after the recess etch of top GaN cap layer. The recess etch was done using the same RIE recipe used for n+ ohmic and mesa etching. A high-resistance Keithley 6517A electrometer with low-noise triax probes was used to measure the I–V characteristics of the fabricated solar-blind photodiodes. All measurements were performed at room temperature. Fig. 1(a) shows the measured dark current of a 100×100 μm^2 device after complete recess etch GaN cap layer. For reverse bias values smaller than 6 V, the measured dark current fluctuated below the 3-fA level, which corresponds to a dark current density smaller than 3.0×10^{-11} A/cm^2. This is the lowest dark current density measured for AlGaN-based detectors. Dark current was below 7 fA for reverse bias values up to 10 V. Low dark current values proved the high growth quality of AlGaN wafer with low defect density. The measured forward turn-on voltages were small (<1 V) and reverse breakdown behavior was observed for reverse bias values over 40 V. Fig. 1(b) shows the dark current density measured before and after recess etch and the ultraviolet (UV) photocurrent generated by the photodiode under 4.3-μW illumination at 267 nm. The strong UV photocurrent shows that

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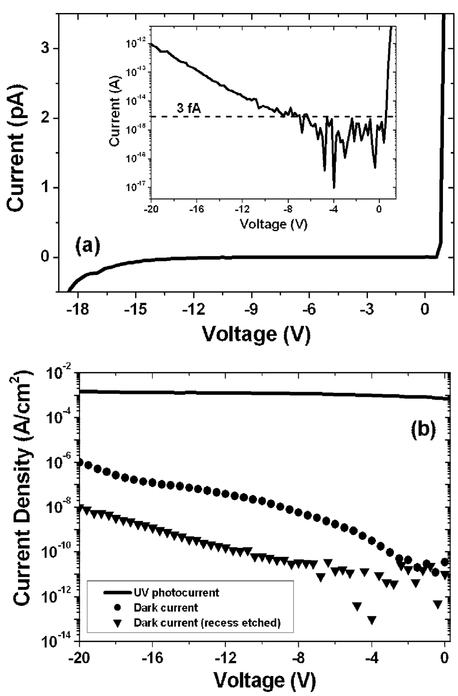

Fig. 1. (a) Dark current of a $100 \times 100\ \mu m^2$ solar-blind AlGaN photodiode. The inset shows the same plot in logarithmic scale. (b) Dark current density before/after recess etch and UV photocurrent obtained from the same device.

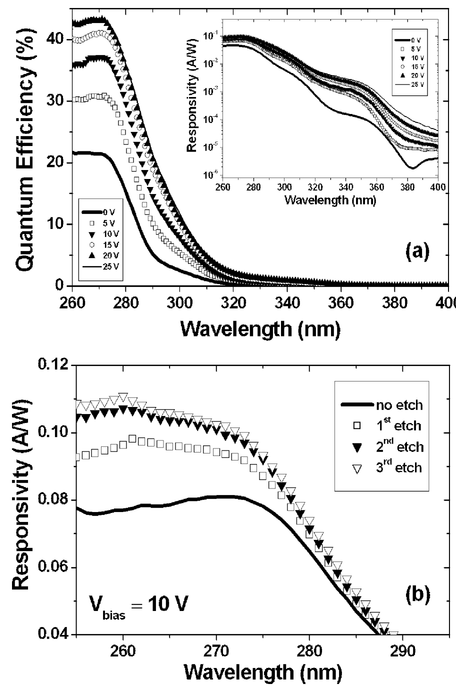

Fig. 2. (a) Spectral quantum efficiency and the corresponding responsivity curve of the nonetched solar-blind detector. (b) Spectral responsivity as a function of recess etch of the p+ GaN cap layer. The peak responsivity under 10-V reverse bias was measured as 0.11 A/W.

the detectors are operating in solar-blind spectrum. The I–V measurements showed that the dark current dropped by over two orders of magnitude after the GaN cap layer was removed. This result was well expected since the lower bandgap GaN layer generates more carriers due to thermal generation. The dark current of nonrecess etched sample was below 10 fA at a reverse bias of 3 V.

Spectral responsivity of the solar-blind AlGaN p-i-n photodiode samples was measured using a xenon lamp light source, a single-pass monochromator, a lock-in amplifier, a chopper, a dc bias source, a multimode UV fiber, and a calibrated UV-enhanced silicon photodetector [16]. The measured spectral quantum efficiency and corresponding responsivity curves before recess etch are shown in Fig. 2(a). The device responsivity increased with applied reverse bias. Zero-bias peak responsivity of 47 mA/W at 271 nm improved to 95 mA/W for 20-V reverse bias. Responsivity did not increase for higher reverse bias values, which indicates that the undoped $Al_{0.45}Ga_{0.55}N$ active layer was totally depleted at 20 V. The corresponding peak external quantum efficiency under full depletion was 43% at 271 nm. The cutoff wavelength of the detectors was around 283 nm. As can be seen from the semilog plot, a visible rejection of $\sim$4 orders of magnitude was achieved at zero bias. To observe the effect of GaN cap layer removal, this layer was recess etched in three equal ($\sim$10 nm) steps. The corresponding responsivity curves at 10-V reverse bias for each etch step are shown in Fig. 2(b). As the GaN cap layer was recess etched, the optical loss due to absorption within this layer was reduced, resulting in higher device responsivity. GaN cap layer was completely etched in three etch steps. The peak responsivity improved from 81 to 111 mA/W, while the peak wavelength changed from 271 to 261 nm. The peak quantum efficiency performance achieved after three etch steps was 53% at 261 nm. The zero bias peak responsivity after the third etch step was measured as 65 mA/W at 267 nm, which will be used for detectivity calculations.

Based on the fact that the background radiation is very small with respect to the thermal noise within the solar-blind spectrum, we can safely assume that the detectivity of solar-blind detectors is thermally limited. Therefore, neglecting the background radiation component, the thermally limited specific detectivity can be calculated by $D^* = R_\lambda (R_0 A/4kT)^{1/2}$, where R_λ is the photovoltaic (zero bias) device reponsivity, R_0 is the dark impedance at zero bias which is also known as differential resistance, and A is the detector area [17]. To calculate the thermally limited specific detectivity of our devices, we have determined R_0 by fitting the dark current data with a curve fitting method [18]. Fig. 3 shows the dark current measurement data of a $100 \times 100\ \mu m^2$ device and the exponential fitting curve in both logarithmic and linear scale. By taking the derivative (dV/dI) of the resulting curve equation at zero bias, we obtained a differential resistance of $R_0 = 9.52 \times 10^{15}\ \Omega$. Combining with $R_\lambda =$ 65 mA/W, $A = 10^{-4}$ cm^2, and $T = 293$ K, we achieved a detectivity performance of $D^* = 4.9 \times 10^{14}$ cm $\cdot$ Hz$^{1/2}$/W^{-1} at 267 nm. This result shows that the room-temperature solar-blind detectivity performance of these AlGaN p-i-n photodiodes exceed the typical detectivity performance of a cooled PMT detector.

In summary, we have reported high-performance solar-blind AlGaN p-i-n photodiodes with low dark current and high solar-blind detectivity performance. Improvement in dark current and responsivity performance was observed with the removal of GaN cap layer. The recess etched p-i-n detectors exhibited extremely low dark current density

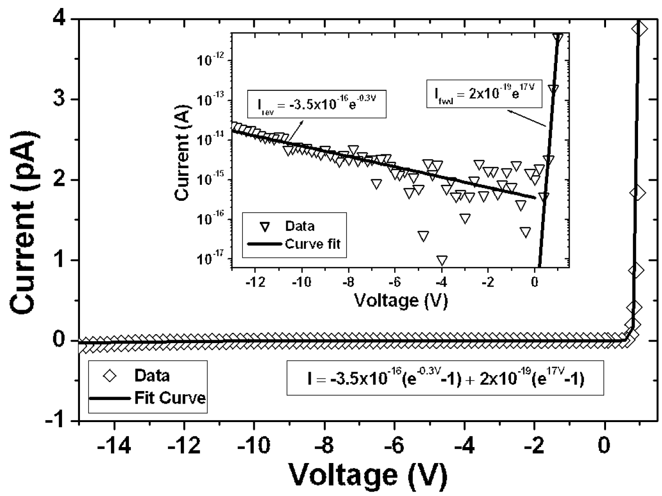

Fig. 3. Exponential curve fitting to the measured dark current of a 100×100 μm^2 device. Inset figure shows the reverse and forward bias part fitting curves separately in a semilog plot. From the fitting curve equation, differential resistance (dark impedance) of the solar-blind detector was calculated as $R_0 = 9.52 \times 10^{15}$ Ω.

($< 3 \times 10^{-11}$ A/cm^2 at 6 V) and a peak quantum efficiency of 53% at 261 nm under 10-V reverse bias. Low dark current values resulted in a very high differential resistance of $R_0 = 9.52 \times 10^{15}$ Ω. The solar-blind detectivity was calculated as $D^* = 4.9 \times 10^{14}$ cm $\cdot$ Hz$^{1/2}$/W^{-1} at 267 nm, which corresponds to the highest detectivity performance reported for AlGaN-based solar-blind detectors.

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