High bandwidth-efficiency solar-blind AlGaN Schottky photodiodes with low dark current

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Abstract

Al0.38Ga0.62N/GaN heterojunction solar-blind Schottky photodetectors with low dark current, high responsivity, and fast pulse response were demonstrated. A five-step microwave compatible fabrication process was utilized to fabricate the devices. The solar-blind detectors displayed extremely low dark current values: 30μm diameter devices exhibited leakage current below 3fA under reverse bias up to 12V. True solar-blind operation was ensured with a sharp cut-off around 266nm. Peak responsivity of 147mA/W was measured at 256nm under 20V reverse bias. A visible rejection more than 4 orders of magnitude was achieved. The thermally-limited detectivity of the devices was calculated as 1.8 × 1013cmHz1/2/W. Temporal pulse response measurements of the solar-blind detectors resulted in fast pulses with high 3-dB bandwidths. The best devices had 53ps pulse-width and 4.1GHz bandwidth. A bandwidth-efficiency product of 2.9GHz was achieved with the AlGaN Schottky photodiodes.

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1. Introduction

Solar-blind ultraviolet (UV) detectors with cut-off wavelength around 280nm can sense very weak UV signals under intense background radiation. These devices have important applications including missile plume detection, chemical/biological agent sensing, flame alarms, covert space-to-space and submarine communications, and ozone-layer monitoring [1–3]. Wide bandgap AlxGa1−xN alloy is an intrinsic solar-blind material for x > 0.35. Since the first demonstration of solar-blind AlGaN photoconductors [4,5], research on high Al-content AlxGa1−xN solar-blind detectors resulted in high-performance devices. AlGaN-based solar-blind photodetectors with very low leakage and noise levels [6,7], high responsivity [8,9], high detectivity [10,11], and fast pulse response [12] have been reported.

AlGaN Schottky photodiodes do not suffer from p+ contact problems. High-quality Schottky and n+ ohmic contacts on AlGaN layers can be formed using standard processes. In addition, the temporal pulse response of Schottky detectors is not degraded by minority carrier diffusion which makes them suitable for high-speed operation [13–15]. Using these properties, high-performance solar-blind AlGaN Schottky photodiodes were reported by several research groups [16–18]. Recently, we have demonstrated solar-blind AlGaN Schottky photodiodes with solar-blind AlGaN Schottky photodiodes with low dark current and high detectivity performance [11]. The bandwidth of these detectors was
below the GHz level [19]. In this study, we report low
dark current solar-blind AlGaN Schottky photodiodes
with improved leakage and bandwidth performance.
Leakage current of a few fA and bandwidth-efficiency
product of 2.9GHz was achieved with the fabricated
solar-blind AlGaN Schottky detectors.

2. Experimental

The solar-blind devices were fabricated on MOCVD-
grown Al0.38Ga0.62N/GaN heterostructures. The detector
active region was an unintentionally doped 0.8μm
thick Al0.38Ga0.62N absorption layer. For ohmic con-
tacts, highly doped n+ GaN layer was utilized. The de-
tails of the epitaxial structure can be found elsewhere
[20]. Fabrication process of the AlGaN Schottky photo-
diodes was accomplished using a microwave compatible
five mask-level standard semiconductor process [20,21].
In sequence, ohmic contact formation, mesa isolation,
Schottky contact formation, surface passivation, and
interconnect metallization steps were completed. Etch-
ing process of AlGaN/GaN layers was done using a
reactive ion etching (RIE) system. Ti/Al alloy was used as
ohmic contact metal. Schottky contacts were formed
with thin (~100 Å) semitransparent Au films.

The fabricated devices were characterized in terms of
current–voltage (I–V), spectral responsivity, and tempo-
ral pulse response. All measurements were made on-
wafer at room temperature using a low-noise microwave
probe station. I–V measurements were performed with a
high-resistance Keithley 6517A electrometer which fea-
tured a sub-fA current measurement resolution. How-
ever, mainly due to the pick-up noise from the
environment and cables, the dark current measurements
were limited by the ~2fA background current floor of
the setup. Spectral responsivity measurements were
done using a 175W xenon light-source, a monochroma-
tor, multi-mode UV fiber, lock-in amplifier and a
calibrated Si-based optical power-meter. The UV-illumi-
nated solar-blind detectors were biased with a DC
voltage source, and the resulting photocurrent was
measured using the lock-in amplifier. Temporal high-
frequency measurements were done at 267 nm. Ultrafast
UV pulses were generated using a laser set-up with two
nonlinear crystals. A Coherent Mira 900F model femto-
second mode-locked Ti:sapphire laser was used to gener-
ate the pump beam at 800 nm. The pump pulses were
produced with 76 MHz repetition rate and 140 fs pulse
duration. These pulses were frequency doubled to gen-
erate a second harmonic beam at 400 nm using a 0.5 mm
thick type-I β-BaB2O4 (BBO) crystal. The second har-
monic beam and the remaining part of the pump beam
were frequency summed to generate a third harmonic
output beam at 267 nm using another type-I BBO crystal
with thickness of 0.3 mm. The resulting 267 nm pulses
had ~1 ps pulse-width and were focused onto the devices
using UV-enhanced mirrors and lenses. The detectors
were biased using a DC voltage source and a 26 GHz
bias-tee. The resulting temporal pulse response was ob-
served with a 20 GHz sampling oscilloscope.

3. Results and discussion

Extremely low leakage currents were observed in the
fabricated AlGaN Schottky photodiode samples. Fig. 1
shows the measured I–V curve of a small area (30 μm
diameter) device. The solar-blind device exhibited leak-
age current less than 3fA and 10 fA for reverse bias up
to 12V and 17 V respectively. Under <12 V reverse bias,
the measured dark current fluctuated below the 3fA
level due to the background noise of the setup. Sub-fA
leakage currents were observed in this range. Using an
exponential fit, we estimate the zero bias dark current
less than 0.1 fA. The corresponding dark current density
for this device at 12 V was 4.2 × 10−10 A/cm2. Typical re-
verse breakdown voltages were measured to be higher
than 50 V. In the forward bias regime, turn-on charac-
teristic was observed at ~4 V. Current in this region in-
creases with a much slower rate than in an ideal photodiode.
At 10 V bias, forward current was only
35 nA. We attribute this result to the high series resis-
tance of the devices.

I–V measurements of larger area devices resulted in
higher leakage currents. Fig. 2(a) and (b) show the dark
I–V curves of 30 μm, 100 μm, and 200 μm diameter
devices in linear and logarithmic scale respectively.
200 μm device displayed the largest dark current. We
measured the reverse bias values where the devices dis-
played 1 pA leakage current. For 30, 100, and 200 μm
diameter detectors, 1 pA dark current was reached at
−32 V, −18 V, and −12 V respectively. To make a fair
leakage comparison between the devices, the current
density values at 5 V reverse bias were calculated.

Fig. 1. Dark current of a 30 μm diameter solar-blind AlGaN photo-
diode. The inset shows the same plot in logarithmic scale.
100 µm and 200 µm devices exhibited 7 fA and 67 fA dark current at −5 V, which led to $8.9 \times 10^{-11}$ A/cm$^2$ and $2.1 \times 10^{-10}$ A/cm$^2$ dark current density values respectively. Due to the experimental setup limit, the actual dark current density of 30 µm device at 5 V reverse bias could only be estimated by exponential fitting curve as $3.3 \times 10^{-11}$ A/cm$^2$. These results correspond to the lowest leakage performance reported for AlGaN-based Schottky photodiodes. As expected, lower breakdown voltages were observed with increasing detector size. Turn-on voltages of ~2.5 V and 5 V were measured for 100 µm and 200 µm devices respectively.

Spectral photoresponse of solar-blind AlGaN detectors was measured in the 250–400 nm spectral range. The bias dependent measured spectral responsivity and quantum efficiency curves are plotted in Fig. 3. Fig. 3(a) shows the strong bias dependence of device responsivity. The peak responsivity increased from 61 mA/W at 250 nm to 147 mA/W at 256 nm when applied reverse bias was increased from 5 V to 20 V. The device responsivity saturated for >20 V reverse bias, which indicates the total depletion of undoped Al$_{0.38}$Ga$_{0.62}$N absorption layer. A sharp decrease in responsivity was observed at ~265 nm. The cut-off wavelength of the detectors was found as ~267 nm, which ensured the true solar-blind operation of our detectors. Fig. 3(b) shows the semi-log plot of the corresponding spectral quantum efficiency. The photovoltaic (zero bias) quantum efficiency was very low. When the bias was increased to 5 V, the efficiency was drastically improved by a factor more than 20. The low zero-bias efficiency value and strong bias dependent characteristic of device responsivity indicates photoconductive gain-assisted device operation. The observed photoconductive gain can be explained by the carrier trapping mechanism in Al$_{0.38}$Ga$_{0.62}$N active layer. Pulse response measurements have confirmed our suggestion with carrier trapping limited high-speed results. A maximum efficiency of 71% at 256 nm was measured under 20 V reverse bias. The visible rejection reached a maximum of ~$4 \times 10^4$ at 10 V reverse bias.

The detectivity performance of solar-blind detectors is thermally limited since the background radiation within the solar-blind spectrum is very low compared to thermal noise. Therefore, detectivity of solar-blind detectors can be expressed by

$$D^* \simeq R_A \sqrt{\frac{R_0 d}{4kT}}$$

(1)
where \( R_z \) is the zero bias responsivity, \( R_0 \) is the dark impedance (differential resistance) at zero bias, and \( A \) is the detector area [22]. Curve fitting method was used to determine the differential resistance of the solar-blind devices [23]. Fig. 4(a) shows the measured and exponentially fitted \( I-V \) curves for a 30\( \mu \)m diameter device. A good fit to the experimental data for reverse bias less than 15 V was achieved. The differential resistance was calculated by taking the derivative (\( dV/dI \)) of the resulting curve, which is shown in Fig. 4(b). The extremely low sub-fA dark currents resulted in very high resistance values. A maximum resistance of \( 5.44 \times 10^{17} \Omega \) was obtained at 0.6 V. Zero-bias differential resistance, \( R_0 \) was slightly lower: \( 4.01 \times 10^{17} \Omega \). These resistance values are \( \sim 2 \) orders higher than previously reported solar-blind AlGaN detectors. Combining with \( R_z = 1.4 \text{mA/W}, \ A = 7.07 \times 10^{-6} \text{cm}^2, \) and \( T = 293 \text{K}, \) we achieved a detectivity performance of \( D^* = 1.83 \times 10^{13} \text{cmHz}^{1/2} \text{W}^{-1} \) at 250 nm. The detectivity was mainly limited by the low photovoltaic (zero bias) responsivity of the device.

Time-domain pulse response measurements at 267 nm of the fabricated solar-blind Schottky photodiodes resulted in fast pulse responses with high 3-dB bandwidths. Bias and device area dependence of high-speed performance was analyzed. The corresponding frequency response of the temporal response was calculated using fast Fourier transform (FFT). The detector pulse response was bias dependent. Fig. 5(a) shows the pulse response of a 30\( \mu \)m diameter Schottky photodiode as a function of applied reverse bias. Faster pulses with higher pulse amplitudes were obtained with increasing reverse bias as the n– AlGaN absorption layer was fully depleted under high reverse bias voltages. The pulse-width decreased from 80 ps to 53 ps as bias was changed from 5 V to 25 V. The drop in full-width-at-half-maximum (FWHM) was mainly caused by the decrease in fall time. Short rise times of \( \sim 26 \) ps were measured. Rise time did not change significantly with bias since it was close to the measurement limit of the 20 GHz scope. The corresponding FFT curves are plotted in Fig. 5(b). As expected, 3-dB bandwidth values increased with reverse bias. A maximum 3-dB bandwidth of 4.1 GHz was achieved at 25 V. Table 1 summarizes the bias dependent high-speed measurement results. Fig. 6(a) shows the normalized pulse responses displayed by detectors with different device areas. All measurements were taken under 25 V reverse bias. Larger device area resulted in slower pulse response, which can be explained by the increased RC time constant. The corresponding frequency response curves are shown in Fig.

![Fig. 4](image-url)  
**Fig. 4.** (a) Linear plot of \( I-V \) data and exponential fit for a 30\( \mu \)m diameter AlGaN detector, (b) calculated differential resistance for the same device.

![Fig. 5](image-url)  
**Fig. 5.** (a) High-speed pulse response of a 30\( \mu \)m diameter device as a function of applied reverse bias, (b) corresponding FFT curves of the temporal data.
6(b). 3-dB bandwidth dropped to 0.95 GHz for 100 μm diameter device. The device area dependent high-speed measurement results are given in Table 2.

Mainly three speed limitations exist for photodiodes fabricated on defect-free materials: transit time across the depletion region, RC time constant, and diffusion of photogenerated carriers in low-field regions. The fabricated AlGaN Schottky detectors do not suffer from carrier diffusion. Moreover, the carrier transit times in AlGaN are much shorter than the measured response times due to the high carrier drift velocity [24–26]. The only limitation comes from RC time constant. This makes sense since the series resistance of these devices was high. If RC time constant was the only limitation for our devices, we should be able to fit the fall time components with a simple exponential decay function. However, a reasonable exponential fit with a single time constant could not be achieved. Instead, responses were fitted well with second order exponential decay functions, i.e. with a sum of two exponential decay functions with two different time constants. This shows that another limitation factor exists in our devices. We believe that the additional and slower decay tail was originated by the carrier trapping effect [12]. Photogenerated carriers can be trapped at the defects/trapping-sites in the AlGaN active layer, which are formed during the crystal growth process. The slower portion of the decay tail is possibly formed by the late arrival of the released carriers which were trapped in these sites. Fig. 7 shows the curve fittings of decay parts for 30 μm and 60 μm diameter detectors.

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<th>Fall time (ps)</th>
<th>FWHM (ps)</th>
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Table 1

Bias dependent high-speed characteristics of AlGaN Schottky photodiodes

<table>
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<th>Fall time (ps)</th>
<th>FWHM (ps)</th>
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Table 2

Device area dependent high-speed characteristics of AlGaN Schottky photodiodes

Fig. 6. (a) Normalized pulse response data for detectors with different areas, (b) corresponding frequency response.

Fig. 7. Second-order exponential fitting to the decay part of pulse response obtained with (a) 30 μm diameter device, (b) 60 μm diameter device.
4. Conclusion

In summary, high-performance solar-blind AlGaN Schottky photodiodes with low dark current, high responsivity, high detectivity, and high bandwidth were fabricated and tested. Setup limited 3fA dark current at 12V reverse bias was measured. Sub-fA leakage and $3.3 \times 10^{-11}$ A/cm² dark current density was estimated at $-5V$. A maximum responsivity of 147mA/W at 256nm was measured at 20V reverse bias. Sub-fA dark current values resulted in record high differential resistance of $R_0 = 4.01 \times 10^{17} \Omega$. The solar-blind detectivity was calculated as $D^* = 1.8 \times 10^{13} \text{cmHz}^{1/2}\text{W}^{-1}$ at 250nm. Pulse response measurements resulted in GHz bandwidths. Combining the 3-dB bandwidth of 4.1GHz with 71% quantum efficiency, a bandwidth-efficiency performance of $\sim 2.9$GHz was achieved. This value corresponds to the highest bandwidth-efficiency performance reported for AlGaN-based solar-blind photodetectors.

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References