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High-speed solar-blind AlGaN-based metal–semiconductor–metal photodetectors

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Solar-blind AlGaN metal–semiconductor–metal (MSM) photodetectors with fast pulse response have been demonstrated. The devices were fabricated on MOCVD-grown epitaxial $Al_{0.38}Ga_{0.62}N$ layers, using a microwave compatible fabrication process. The photodiode samples exhibited low leakage with dark current densities below 1×10^{-6} A/cm^2 at 40 V reverse bias. Photoconductive gain-assisted photoresponse was observed with a peak responsivity of 1.26 A/W at 264 nm. A visible rejection of ~3 orders of magnitude at 350 nm was demonstrated. Temporal high-speed measurements at 267 nm resulted in fast pulse responses with 3-dB bandwidths as high as 5.4 GHz. This corresponds to a record high-speed performance for solar-blind detectors.

1 Introduction Solar-blind photodetectors are important components for applications including missile warning and tracking, engine/flame monitoring, chemical/biological agent detection, and covert space-to-space communication [1, 2]. AlGaN-based solar-blind photodetectors have been extensively studied recently and high-performance solar-blind detection is demonstrated using numerous detector structures [3–9]. Compared with Schottky and p–i–n structures, MSM type of photodiodes (PDs) have the advantage of easier growth and fabrication process. MSM PDs have no p+ or n+ ohmic layers/contacts and high-quality Schottky contacts are easily formed on wide bandgap AlGaN layers. Solar-blind AlGaN MSM PDs with low dark current, low noise and high responsivity have been reported previously [10–12]. The fastest solar-blind MSM PD reported to date had a 3-dB bandwidth of 100 MHz [13]. This was an order of magnitude lower than the bandwidth demonstrated with solar-blind Schottky PDs [14]. In this letter we report on high-speed solar-blind AlGaN MSM PDs with multi-GHz bandwidth.

2 Experimental results and discussion The device structures were grown by MOCVD on sapphire substrates. The active detector layer was a 1 µm thick unintentionally doped $Al_{0.38}Ga_{0.62}N$ layer which was grown on top of a ~2 µm thick GaN buffer layer. The thick buffer layer was grown to reduce the defect density in the subsequent AlGaN layer. As the cut-off wavelength of $Al_xGa_{1-x}N$ ternary material decreases for higher Al content, $x \geq 38\%$ was needed to achieve a true solar-blind absorption spectrum [15]. MSM PD samples were fabricated using a four-step microwave compatible fabrication process in class-100 clean-room environment. Standard lithography and semiconductor process techniques were utilized. First, inter-digitated back-to-back Schottky contacts were formed by thermal evaporation of 100 Å Ti and 1000 Å Au metal layers. After lifting the metal off in acetone solution, device mesas (100×100 µm^2) were defined using reactive ion etching (RIE) process where CCl_2F_2 was used as the

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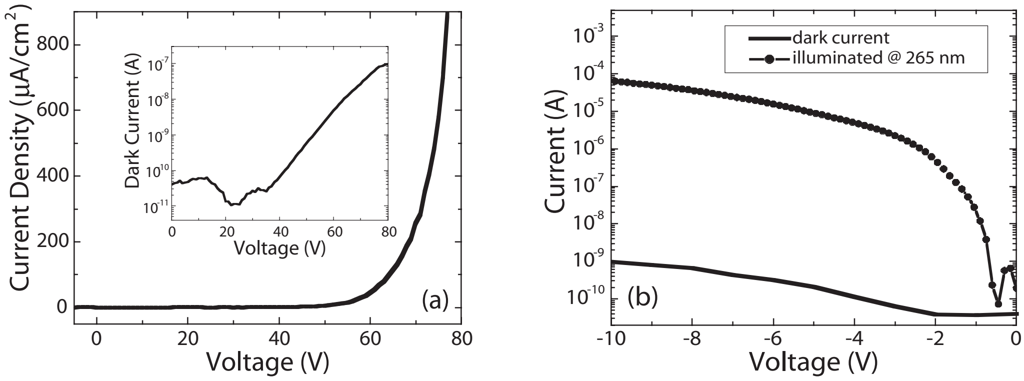

Fig. 1 a) Dark current density of an MSM-PD with 10 μm finger spacing. Inset shows the leakage current in logarithmic scale. b) I–V curves of a device with 5 μm finger spacing under different illumination conditions.

etching gas. To passivate the sample surface and protect the metal fingers, a Si_3N_4 passivation layer was deposited in a plasma-enhanced-chemical-vapour-deposition (PECVD) system. The nitride layer was patterned and etched afterwards in a dilute HF:H_2O (1:100) solution. The process was completed with a metalization and lift-off process of Ti/Au (100 Å/4000 Å) contact pads. MSM-PDs with equal finger spacings and widths varying between 3 and 10 μm were fabricated.

First the current–voltage characteristics of the completed solar-blind MSM-PDs were measured. The dark current measurement of a device with 10 μm finger spacing is shown in Fig. 1a. The MSM-PD exhibited a dark current density less than 1 μA/cm^2 at 40 V bias, along with a breakdown voltage in excess of 80 V. Sub-nA dark current was observed at bias voltages as high as 54 V (see inset figure). The low-leakage results can be attributed to high material quality and good Schottky contacts. Figure 1b shows the current–voltage (I–V) characteristics of an MSM-PD with 5 μm finger spacing in dark and under UV illumination. This plot indicates the existence of UV photocurrent as a function of applied bias voltage.

The spectral responsivity measurements were carried out in the 250–350 nm range, using a xenon lamp, monochromator, multi-mode UV fiber, and a lock-in amplifier. The incident optical power was measured with a calibrated UV-enhanced Si photodetector. Figure 2a shows the measured spectral responsivity curves under different bias conditions. The corresponding spectral quantum efficiency under 2 V bias is plotted in Fig. 2b. At this bias voltage, the PD had a peak quantum efficiency of 40% at 264 nm. The solar-blind MSM-PDs had shown true solar-blind photoresponse with a cut-off wavelength

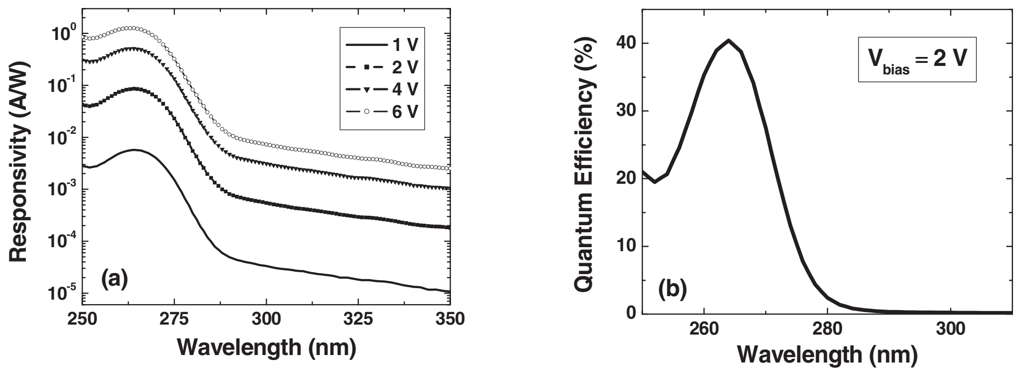

Fig. 2 a) Measured spectral responsivity curves of AlGaN MSM PDs as a function of bias voltage. b) Linear-scaled plot of the corresponding spectral quantum efficiency under 2 V bias.

of 272 nm. Photoconductive gain mechanism dominated the photoresponse for relatively low bias voltages. The peak responsivity under 6 V bias was measured as 1.26 A/W at 264 nm, corresponding to an external quantum efficiency of ~600%. The photoconductive gain in AlGaN MSM PDs can be explained by the presence of hole-trapping sites due to threading dislocations [16]. Holes are accumulated at the trap sites, increasing the electron injection at the cathode. This injection results in photoconductive gain which is proportional to the electric field between the electrodes.

A sharp drop in responsivity around 275 nm was observed. A visible (VIS) rejection of nearly 3 orders of magnitude was obtained at 350 nm. The rejection at longer wavelengths was measured using continuous wave Ar and Ti:sapphire laser lines. Under zero bias, at 458 nm (the shortest line of Ar), the rejection was measured as 2×10^4. The rejection increased to 1×10^6 at 800 nm. The rejection ratios increased even more for biased measurements. Under 6 V bias, a rejection of 3×10^7 was achieved at 514 nm.

Temporal high-frequency measurements of AlGaN MSM PDs were done at the solar-blind wavelength of 267 nm. Ultrafast UV pulses were generated using a laser set-up with two nonlinear crystals. A femtosecond mode-locked Ti:sapphire laser was used to generate 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 generate a second harmonic beam at 400 nm using a 0.5 mm thick type-I β-BaB2O4 (BBO) crystal. The second harmonic 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 a thickness of 0.3 mm. The resulting 267 nm pulses had sub-picosecond pulse-widths, and were focused onto the devices using UV-enhanced mirrors and lenses. The detectors were biased by a DC voltage source using a 40 GHz bias-tee. The resulting high-speed electrical pulse response was observed on a 50 GHz sampling oscilloscope.

The measured responses had very short rise times and exponentially decaying fall times. Faster pulses were obtained with smaller finger spacings due to reduced carrier transit times. Therefore, the best high-speed results were achieved with 3 μm devices. Temporal pulse response measurements under different bias conditions for the 3μm PD are plotted in Fig. 3a. As expected, the pulse amplitudes had increased with applied bias voltage, due to larger photoconductive gain. Pulsewidths also increased with bias: 76, 99, 121, and 133 ps were the full-width-at-half-maximum (FWHM) values measured at 5, 10, 15, and 17 V bias respectively. Hence, slower responses were obtained under larger bias and gain values. This result was confirmed with the fast Fourier transform (FFT) analysis of the temporal data. Figure 3b shows the corresponding FFT curves of the measured pulse responses. A maximum 3-dB bandwidth of 5.4 GHz was achieved at 5 V bias. Bandwidth decreased with increasing bias: 3-dB bandwidths of 2.1, 1.7, and 1.5 GHz were obtained at 10, 15, and 17 V bias respectively.

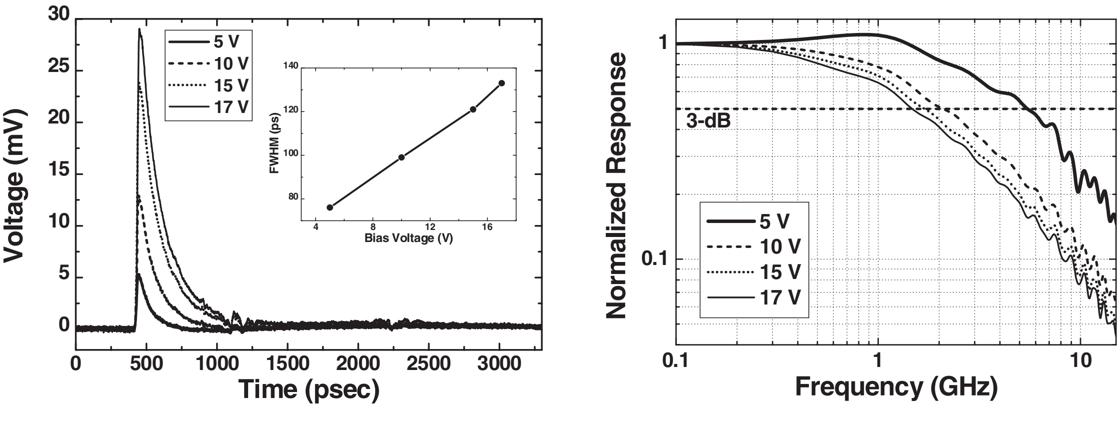

Fig. 3 a) Bias-dependent temporal pulse responses of an AlGaN MSM PD with 3 μm finger spacing. Inset shows the measured FWHM values with respect to bias voltage. b) Corresponding FFT curves with 3-dB bandwidths of 5.4, 2.1, 1.7, and 1.5 GHz at 5, 10, 15, and 17 V bias respectively.

3 Conclusion In summary, high-speed solar-blind AlGaN-based MSM PDs have been designed, fabricated, and characterized. The fabricated devices exhibited low leakage with dark current density less than 1 $\mu A/cm^2$ at 40 V bias. Spectral responsivity measurements showed that photoconductive gain mechanism was dominant for bias voltages higher than 2 V. A peak responsivity of 1.26 A/W at 264 nm was measured at 6 V reverse bias. True solar-blind operation was ensured with a cut-off wavelength of 272 nm. UV/VIS rejections of 3 and 7 orders of magnitude were obtained at 350 and 514 nm. Temporal high-speed characterization at 267 nm resulted in very fast pulse responses. A maximum 3-dB bandwidth of 5.4 GHz was achieved with a 3 μm finger spacing/width device under 5 V bias. The detector bandwidth decreased with increasing bias. The demonstrated high-speed performance of the fabricated AlGaN MSM PD corresponds to the fastest solar-blind detector reported to date.

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