High-Performance Solar-Blind AlGaN Photodetectors

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Photodetectors which respond only to λ<280 nm radiation are defined as solar-blind photodetectors. Within the atmosphere, such a detector would not detect any solar radiation. Hence, if a solar-blind (SB) photodetector detects a signal this is a sign of an external UV emitter (flame, missile plume, etc.) [1].

The immunity from solar interference makes solar-blind detectors unique for a wide range of commercial and military applications: environmental (ozone layer) monitoring, flame detection/fire alarms, sterilization/detection of biological and chemical agents, engine monitoring, missile plume detection, secure intersatellite communications, and underwater/sub-marine communication systems. These applications require high-performance SB photodetectors with low dark current, high responsivity, high detectivity, and high bandwidth.

Solar-blind detection was traditionally accomplished by photomultiplier tubes (PMTs) and silicon photodiodes. With the advent in material growth of high-quality $Al_xGa_{1-x}N$ ternary alloys AlGaN-based wide bandgap SB photodetectors emerged as a potential alternative for the PMT and Si-based detector technology. The long-wavelength cut-off of $Al_xGa_{1-x}N$ can be tuned from 360 to 200 nm by increasing the Al content and for x>0.38, AlGaN becomes intrinsically solar-blind. Therefore, unlike PMT and Si technology, AlGaN-based SB detectors do not need complex and costly filters. In addition, they can operate under harsh conditions (high temperature and power levels) due to their wide band gap and robust material properties [2]. These features made the $Al_xGa_{1-x}N$ material system the choice for the realization of high-performance SB detectors. High-performance AlGaN-based SB photodetectors were demonstrated using different device structures [3, 4]. In this paper, we report our research efforts and achievements on high-performance AlGaN-based SB photodiodes (PDs). Schottky, p-i-n, and MSM structures were designed, fabricated and characterized. SB detectors with record low dark current density, solar-blind detectivity, and 3-dB bandwidth performance are demonstrated.

The $Al_xGa_{1-x}N$ layer structures were grown by MOCVD on sapphire substrates. High-Al content active layers were designed for true SB response. 0.8 μm-thick $Al_{0.38}Ga_{0.62}N$, 100 nm-thick $Al_{0.45}Ga_{0.55}N$, and ~2.0 μm-thick $Al_{0.6}Ga_{0.4}N$ absorption layers were used in Schottky, p-i-n, and MSM PD structures, respectively. n+/p+ ohmic layers consisted of highly n/p-type doped GaN. The devices were fabricated using a microwave-compatible fabrication process. n+ and p+ ohmic contacts on GaN were formed with annealed Ti/Al and Ni/Au alloys. Schottky contacts were formed with non-annealed Au and Ti/Au films for Schottky and MSM structures respectively. Ohmic contact and mesa isolation etch processes were done via CCl_2F_2-based RIE. Figure 1 shows several drawings and pictures of the completed AlGaN PDs.

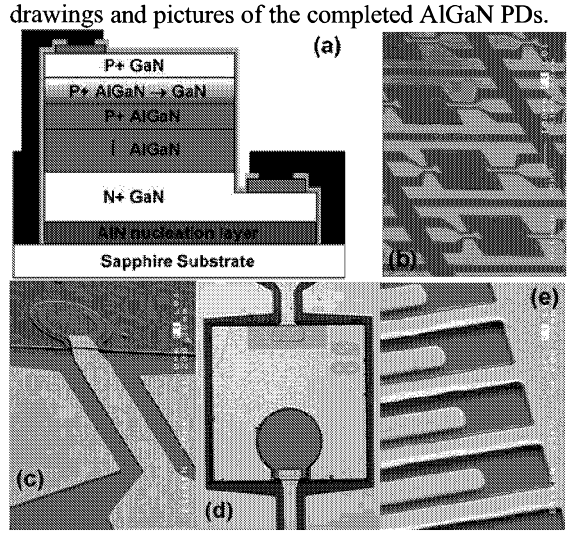

Fig. 1: (a) Cross-sectional schematic of a completed pin PD. (b)-(c) SEM pictures of SB AlGaN p-i-n PD sample. (d) Microphotograph of an AlGaN Schottky PD. (e) SEM photo of interdigitated Schottky fingers of an AlGaN MSM PD.

The fabricated devices were characterized in terms of current-voltage (I-V), spectral photoresponse, and high-speed pulse response. Detectivity analysis was carried out using the results of dark-current and responsivity measurements. The measurements were done on-wafer using a low-noise probe-station. A Kethley 6517A high-resistance electrometer with low-noise triax DC probes were used for fA-resolution I-V measurements. To measure the temporal response of the PD samples, sub-ps UV pulses were generated using a femto-second Ti:Sapphire pulsed laser and a non-linear frequency tripling setup. The UV pulse response of SB AlGaN PDs was recorded by a 20 GHz oscilloscope using 40 GHz microwave probes.

All samples exhibited extremely low dark currents at the fA-level. At low reverse bias voltages, the measurement was limited by the noise floor of the setup. The measured I-V curves of AlGaN Schottky PD sample is shown in Fig. 2. The solar-blind device exhibited leakage current less than 3 fA for reverse

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bias up to 12 V. Sub-fA leakage currents were observed for <10 V bias. 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/cm^2. p-i-n sample displayed similar dark I-V characteristics with even lower dark current density of 3.0×10^{-11} A/cm^2 at 6 V reverse bias. AlGaN MSM sample showed extremely large breakdown voltage (>300 V) with <10 fA dark current at reverse bias as high as 100 V.

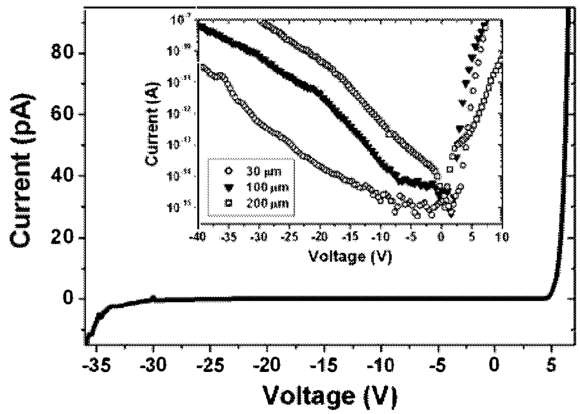

Fig. 2: I-V measurement of a 30 μm diameter AlGaN Schottky PD. Inset shows the device area dependence of the measured dark current.

Spectral UV photoresponse measurements confirmed the true solar-blind response of the devices. Cut-off wavelength below 280 nm was achieved. The measured spectral quantum efficiency of MSM and p-i-n samples are shown in Fig. 3. Due to its high Al content, $Al_{0.6}Ga_{0.4}N$ MSM samples showed the lowest cut-off with $\lambda_c \approx 255$ nm. Schottky sample also showed true solar-blind response with $\lambda_c < 274$ nm. 89 mA/W and 0.11 A/W peak responsivity values were measured for Schottky and p-i-n samples respectively.

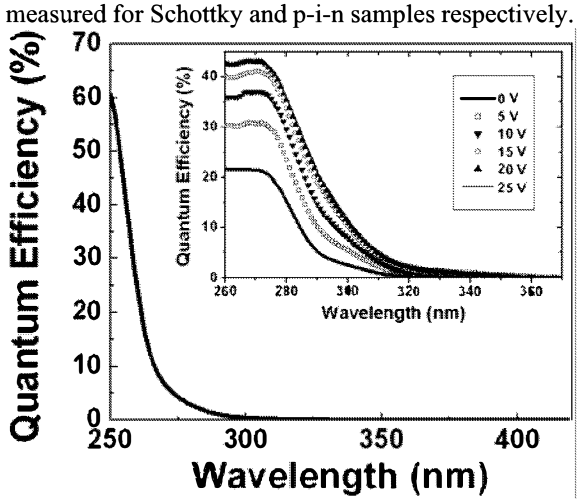

Fig. 3: Spectral quantum efficiency of AlGaN MSM PD. Inset shows the bias-dependent efficiency curves for SB AlGaN p-i-n PD sample.

Since the background radiation is very small with respect to the thermal noise within the SB 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 $D^*=R_\lambda(R_0A/4kT)^{1/2}$, where R_λ is the photovoltaic device reponsivity, R_0 is the dark impedance at zero bias which is also known as differential resistance, and A is the detector area. We obtained $R_0 = 9.52\times10^{15}$ Ω and a detectivity performance of $D^*= 4.9\times10^{14}$ cmHz$^{1/2}$W^{-1} at 267 nm for p-i-n sample. Schottky and MSM PD samples exhibited lower detectivity performance due to lower photovoltaic responsivity.

High-speed measurements resulted in GHz-level bandwidth performance for SB Schottky and p-i-n PD samples. MSM sample suffered from the photoconductive gain mechanism. Figure 4 shows the measured pulse response under 267 nm illumination and the corresponding frequency response of a 30 μm diameter AlGaN Schottky sample. The fastest response under 25 V bias had 53 ps FWHM and 4.1 GHz 3-dB bandwidth.

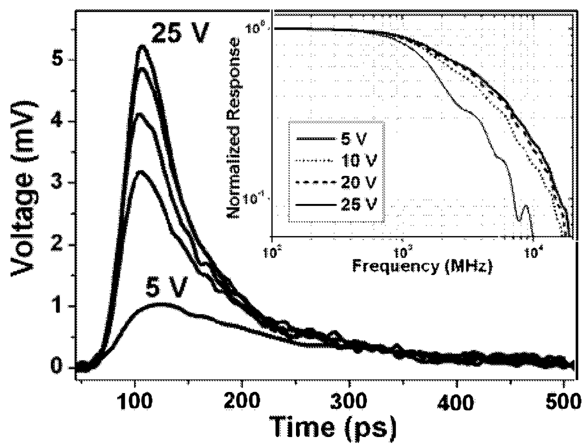

Fig. 4: UV pulse-response of a 30 μm Schottky PD. Inset shows the corresponding frequency response.

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