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$Al_xGa_{1-x}N$-based avalanche photodiodes with high reproducible avalanche gain

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The authors report high performance solar-blind photodetectors with reproducible avalanche gain as high as 1560 under ultraviolet illumination. The solar-blind photodetectors have a sharp cutoff around 276 nm. The dark currents of the 40 μm diameter devices are measured to be lower than 8 fA for bias voltages up to 20 V. The responsivity of the photodetectors is 0.13 A/W at 272 nm under 20 V reverse bias. The thermally limited detectivity is calculated as $D^* = 1.4 \times 10^{14}$ cm Hz$^{1/2}$ W^{-1} for a 40 μm diameter device. © *2007 American Institute of Physics*.
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The recent developments in high Al-content $Al_xGa_{1-x}N$ material growth technology made it possible to fabricate high performance solar-blind photodetectors operating in the ultraviolet (UV) spectral region with improved receiver sensitivity, low noise, low dark current density, and high speed.[1–3] AlGaN-based Schottky, *p-i-n*, and metal-semiconductor-metal photodetectors with very high performances have already been demonstrated.[4,5] The UV-filtering nature of the atmospheric ozone molecules blocks the solar radiation to reach the earth's surface for wavelengths shorter than 280 nm. In this case, UV photodetectors with cutoff wavelengths around 280 nm, which are also called solar-blind detectors, can detect 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, ozone-layer monitoring, and gas detection. Due to their high responsivity (>600 A/W), high speed, high cathode gain (on the order of a million), and low dark current properties, photomultiplier tubes (PMTs) are frequently used in such applications. However, PMTs are very expensive and bulky. Besides, they require a cooling system, and they have high operation voltages in excess of 1000 V. To achieve solar-blind detection, PMTs should also be integrated with complex and expensive filters. In order to avoid these disadvantages, high performance solid-state UV photodetectors with high internal gain are needed.[6] Wide band-gap semiconductor photodetectors, such as $Al_xGa_{1-x}N$ with $x=0.4$, are ideal candidates for this purpose. These devices are intrinsically solar blind, in which no additional filters are needed, they have low noise,[7] and fast response times.[8] The lack of high internal gain has been the major limitation for the usage of AlGaN photodetectors for applications that require high sensitivity detectors. There have been several theoretical research work that examined the avalanche effect in GaN and AlGaN-based structures.[9–11] Experimental work on both GaN (Refs. 12–18) and AlGaN-based (Refs. 4, 19, and 20) avalanche photodiodes (APDs) were also reported. However, reproducible high gain in AlGaN-based APDs is still a major limitation. In this letter, we report the realization of solar-blind AlGaN-based avalanche photodetectors with reproducible high avalanche gain.

The epitaxial structure of the avalanche photodetector is designed for solar-blind operation with high avalanche gain. The $Al_{0.4}Ga_{0.6}N$ absorption layer was used as a multiplication layer with $\lambda_c = 276$ nm. The $Al_xGa_{1-x}N$ epitaxial layers of our Schottky photodiode wafer were grown on a 2 in. double side polished (0001) sapphire substrate using a metal-organic chemical vapor deposition (MOCVD) system, which is located at the Bilkent University Nanotechnology Research Center. First, a thin AlN nucleation layer was deposited, and then a 0.3 μm thick AlN buffer layer was deposited. Subsequently, a highly doped ($n^+ = 1.08 \times 10^{18}$ cm^{-3}) 0.3 μm thick $Al_{0.4}Ga_{0.6}N$ layer was deposited for Ohmic contact, followed by a 0.2 μm thick $Al_{0.4}Ga_{0.6}N$ layer with relatively low doping ($n^- = 1.45 \times 10^{17}$ cm^{-3}) for Schottky contact.

The samples were fabricated by using a five-step microwave-compatible fabrication process in a class-100 clean room environment. The dry etching was accomplished via reactive ion etching (RIE) under CCl_2F_2 plasma, a 20 SCCM (SCCM denotes standard cubic centimeter per minute at STP) gas flow rate, and 200 W rf power. The mesa structures of the devices were formed via the RIE process, by etching all of the layers (>0.8 μm) down to the sapphire layer for better mesa isolation. After an Ohmic etch of ~0.3 μm, Ti/Al (100 Å/1000 Å) contacts were deposited via thermal evaporation and left in acetone solution for the lift-off process. The contacts were annealed at 700 °C for 60 s in a rapid thermal annealing system. An ~100 Å thick Au metal was evaporated in order to form Au/AlGaN Schottky contacts. Thereafter, a 200 nm thick Si_3N_4 was deposited via plasma enhanced chemical vapor deposition for passivation. Finally, an ~0.25 μm thick Ti/Au interconnect metal was deposited and lifted-off to connect the Schottky layers to the coplanar waveguide transmission line pads.

After fabrication, the devices were characterized in terms of current-voltage and spectral responsivity. The fabricated devices had breakdown voltages higher than 60 V. In order to have better mesa isolation, we etched down to the sapphire substrate,[21] which enabled us to attain low leakage current. *I-V* measurements of the larger area devices resulted

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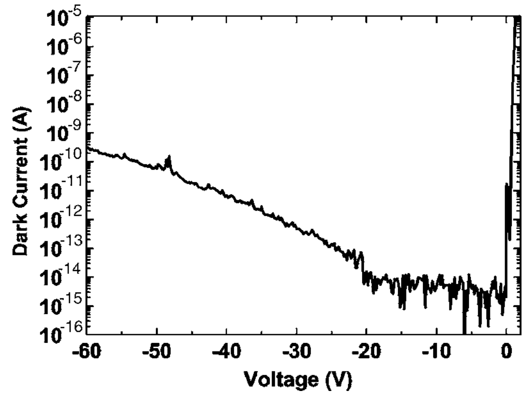

FIG. 1. Dark current measurement data from a 40 μm diameter photodetector device.

in higher leakage currents. Therefore, we chose to use the smaller area devices with 20, 40, and 60 μm diameters. Current-voltage characterization of the fabricated Schottky photodetectors was carried out by using a Keithley 6517A high resistance electrometer with low noise triax cables. Figure 1 shows the dark current measurements of a 40 μm diameter device. The dark current for a 40 μm diameter device at 60 V reverse bias was approximately 0.3 nA. For reverse bias values below 20 V, the measured dark current was limited by the experimental setup and was less than 8 fA. The Hall measurements of the MOCVD grown samples showed that the active AlGaN layer had a Si doping concentration $N_d = 1.45 \times 10^{17}$ cm^{-3} and the Ohmic AlGaN layer had a Si doping concentration $N_d = 1.08 \times 10^{18}$ cm^{-3}.

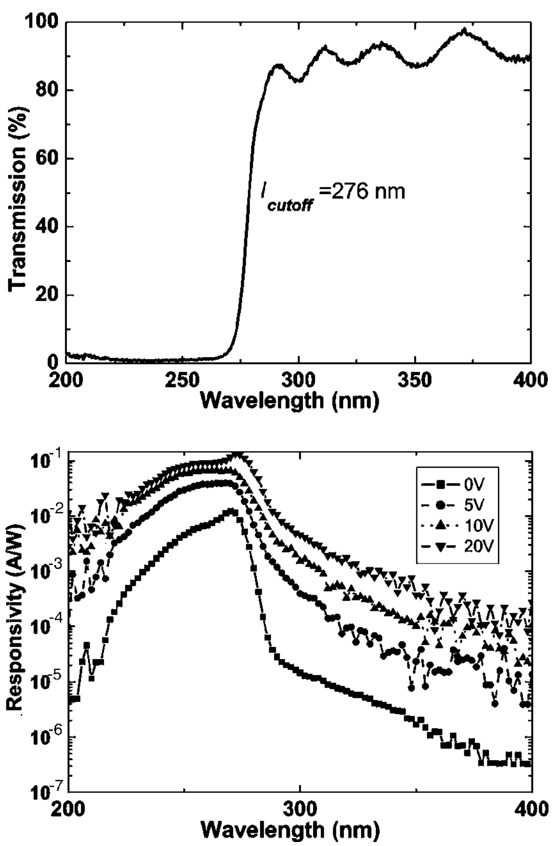

FIG. 2. (a) Transmission data from a double side polished wafer which is used in the fabrication. (b) Responsivity measurements result from a 150 μm diameter device.

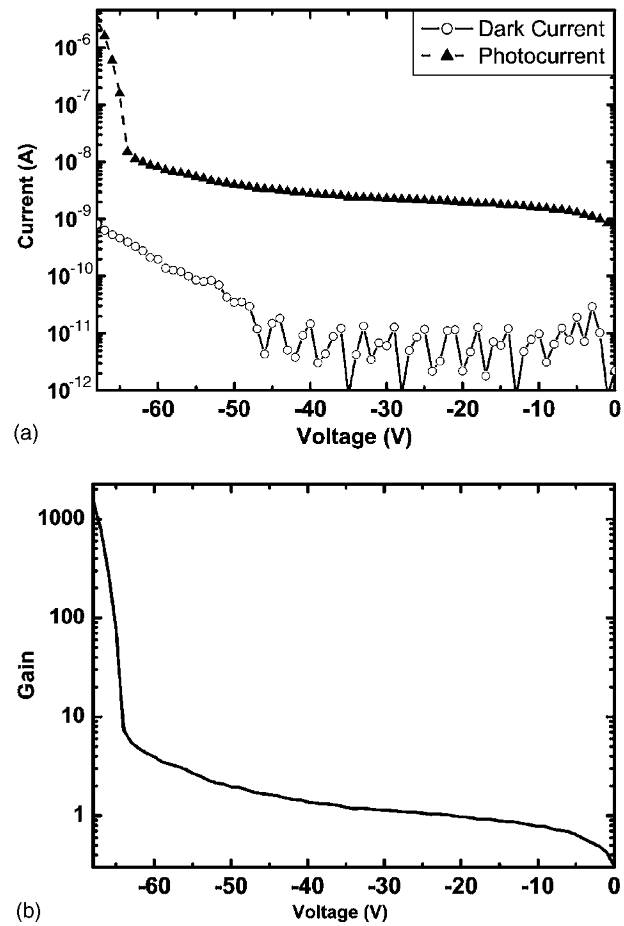

FIG. 3. (a) Gain measurements for a 40 μm diameter device. (b) Avalanche gain extracted from the photocurrent measurements.

Figure 2(a) shows the transmission characteristics of the as-grown epitaxial structure. The AlGaN layer absorbs all photons with energies higher than 4.4 eV. Figure 2(b) shows the responsivity measurements of a 150 μm diameter device. In parallel with the transmission measurement, the responsivity of the fabricated device has a sharp cutoff at 276 nm, which qualifies the AlGaN photodetectors to be solar blind. Under a 20 V reverse bias voltage, the device had a maximum responsivity of 0.13 A/W at 272 nm. Under 0 V bias, the device had a maximum responsivity of 12.2 mA/W at 270 nm under front illumination. The UV/visible rejection ratio for wavelengths larger than 350 nm is on the order of 2×10^4 under zero bias. Thermally limited detectivity is calculated as $D^* = 1.4 \times 10^{14}$ cm Hz$^{1/2}$ W^{-1} which corresponds to the highest value reported for an AlGaN-based Schottky photodiodes. Differential resistance at zero bias is $R_0 = 1.3 \times 10^{16}$ Ω. According to the responsivity measurements, the photocurrent does not significantly increase after 20 V. Therefore, we set the unity gain at 20 V. From the photocurrent and dark current data, we calculated the avalanche gain by first taking the difference between the multiplied photocurrent and dark current data, and then normalizing it with respect to the unmultiplied difference of the photocurrent and dark current. The avalanche gain at a 68 V reverse bias was 1560, which is the highest reproducible avalanche gain reported in the literature for AlGaN-based solar-blind APDs. We proved reproducibility by way of taking the dark current measurement after several photocurrent measurements, in which we saw no significant change in dark

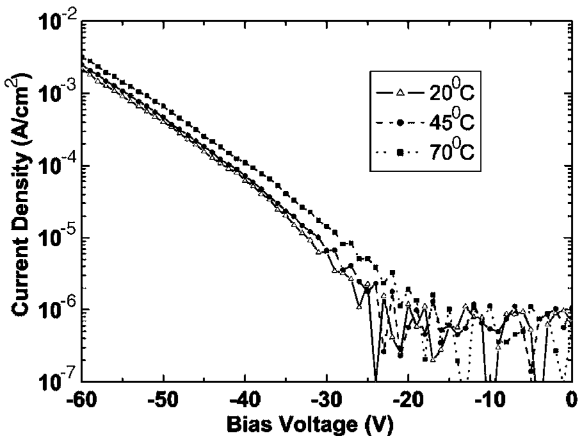

FIG. 4. Dark current measurement data with varying temperatures.

current (ten scans), and consequently, also none in the avalanche gain results (ten scans), which is shown in Fig. 3.

We determined the voltage at which the unity gain occurs via *C-V* and lock-in assisted responsivity measurements. After the 20 V bias, the capacitance does not change which is an indicator of full depletion of the junction. Close to 20 V the lock-in assisted responsivity does not change considerably and after 20 V it does not increase steadily and significantly unlike avalanche gain which starts generally after 60 V.

We also measured the dark currents under different temperatures. In Fig. 4, the dark current of a photodetector shows a strong dependence on temperature. This result proves that Zener tunneling, which is a temperature insensitive process, is not a possible gain mechanism in these devices. The gain measurements showed an exponential dependence on voltage, in which we infer from this result that the photoconductive gain is not a possible gain mechanism in our devices. We know that the photoconductive gain increases linearly with voltage.[19,22] Therefore, we conclude that the gain in these devices result from the avalanche multiplication of the photogenerated carriers in the active region of the devices.

In summary, we present the MOCVD growth, fabrication, and characterization of AlGaN-based solar-blind APDs. The avalanche gain at 68 V was in excess of 1560 with no Geiger mode breakdown. The electric field was on the order of 1.88 MV/cm. The gain in the active region of the devices is attributed to the avalanche multiplication of the photogenerated carriers. This work demonstrates the high potential of AlGaN APDs for replacement of the PMTs for high sensitive solar-blind photodetector applications.

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