Low dark current metal-semiconductor-metal photodiodes based on semi-insulating GaN

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Metal-semiconductor-metal photodetectors on semi-insulating GaN templates were demonstrated and compared with photodetectors fabricated on regular GaN templates. Samples were grown on a metal organic chemical vapor deposition system. Devices on semi-insulating template exhibited a dark current density of 1.96×10^{-10} A/cm^2 at 50 V bias, which is four orders of magnitude lower compared with devices on regular template. Device responsivities were 101.80 and 88.63 A/W at 50 V bias for 360 nm ultraviolet illumination for semi-insulating and regular templates, respectively. Incident power as low as 3 pW was detectable using the devices that were fabricated on the semi-insulating template. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2234741]

Solid state photodetectors based on $Al_xGa_{1-x}N$ based ($0 \leqslant x \leqslant 1$) heterostructures are promising candidates for photodetection in the ultraviolet (UV) spectrum from the near UV to deep UV. A variety of UV photodetectors, such as Schottky barrier,[1,2] *p-i-n*,[3–5] and metal-semiconductor-metal[6–8] (MSM) photodetectors, based on this material system have been reported in the literature. Although structures with high Al content exhibited low dark current values, there have only been a few reports regarding relatively low dark current devices fabricated on GaN. The best result was around 10 pA at 100 V bias.[9] In this letter, we report the fabrication and characterization of MSM photodetectors that are based on semi-insulating (SI) GaN. Identical devices fabricated on regular unintentionally doped (UD) GaN epilayers were used to make a comparison and evaluate the improvement by using the SI-GaN template.

The samples in this study were all grown on *c*-face (0001) sapphire substrates by low-pressure metal organic chemical vapor deposition (MOCVD). Hydrogen was used as the carrier gas, and trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) were used as the Ga, Al, and N sources, respectively. SI-GaN layer was grown on high temperature AlN buffer. Prior to the epitaxial growth, sapphire substrates were annealed at 1100 °C for 10 min to remove surface contamination, and subsequently a 15 nm thick AlN nucleation layer was deposited at 840 °C. Thereafter, the reactor temperature was ramped to 1150 °C and an AlN buffer layer was grown, followed by a 2 min growth interruption in order to reach optimum growth conditions for GaN. The growth conditions of GaN were as follows: reactor pressure of 200 mbars, growth temperature of 1070 °C, H_2 carrier gas, and growth rate about 2 μm/h. A typical UD-GaN control sample was grown on sapphire substrate using the two-step method with a low temperature GaN nucleation layer deposited at 500 °C. For a fair comparison, the thickness and growth parameters of the high temperature GaN (HT-GaN) layers in the two samples were kept constant.

We used a four-step microwave compatible process in a class-100 clean room environment to fabricate the MSM photodiodes. We started with the deposition of 100 Å/1000 Å thick interdigitated Ni/Au fingers on the surface of the UD-GaN and SI-GaN layers of the two samples. Finger width and spacing of fabricated devices varied between 3 and 20 μm, while active detector areas were 100×100 and 200×200 μm^2. Following finger deposition, the device mesas were defined by reactive ion etching. Next, a 120 nm thick Si_3N_4 layer was deposited by a plasma enhanced chemical vapor deposition (PECVD) system for the surface passivation of the samples. The Si_3N_4 layer was also used as an antireflection layer as well as for protecting the metal fingers. Finally, fabrication was finalized by the deposition of 10 nm/400 nm thick Ti/Au interconnect pads. In addition, the transmission line method (TLM) patterns were prepared by the deposition of 100 Å/400 Å/100 Å/400 Å Ti/Al/Ni/Au contact pads on separate samples. The TLM patterns used for sheet resistivity calculations consisted of 200×100 μm^2 pads with separations in the 5–50 μm range. The contacts were annealed at 750 °C for 1 min in a rapid thermal processor oven.

We calculated the sheet resistivities of the two samples using standard TLM measurements. Current-voltage (*I-V*) characterization of the contact pads was carried out with an HP4142B semiconductor parameter analyzer. The sheet resistances of the SI-GaN and UD-GaN samples were calculated as 3.16×10^{11} and 5.8×10^7 Ω/sq, respectively.

Current-voltage characterization of the fabricated MSM photodiodes was carried out using a Keithley 6517A high resistance electrometer with low noise triaxialcables. The de-

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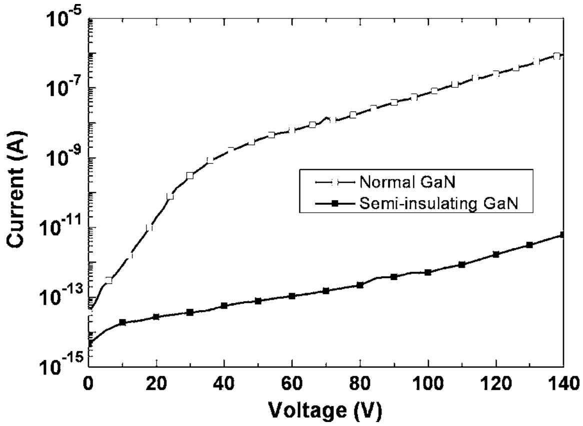

FIG. 1. Current-voltage characteristics of $200\times200\ \mu\mathrm{m}^2$ MSM photodiodes with 10 μm/10 μm finger width/spacing on two different chips.

vices fabricated on the SI-GaN sample exhibited extremely low dark currents, while those fabricated on the UD-GaN sample exhibited higher dark currents, which is typical for such devices. No breakdown was observed for bias voltages as high as 200 V for $200\times200\ \mu\mathrm{m}^2$ active area detectors fabricated on the SI-GaN and UD-GaN samples. Figure 1 compares the dark *I-V* curves of 10 μm finger width/spacing devices from the two chips. The dark current measured from devices fabricated on the SI-GaN chip remains below 1 pA and up to 100 V bias voltage. The dark current density (at 50 V bias) of a device fabricated on the SI-GaN chip is calculated as $1.96\times10^{-10}\ \mathrm{A/cm^2}$. In comparison, the 50 V dark current density calculated for a similar device fabricated on the UD-GaN chip is $8.1\times10^{-6}\ \mathrm{A/cm^2}$, which corresponds to four orders of magnitude improvement.

Spectral responsivity measurements of both samples were performed in the range of 250–450 nm using a Xe arc lamp, a monochromator, and a calibrated Si photodetector which is calibrated through the range of 190–1100 nm. Photocurrent was measured in two different ways: The dc (unmodulated) photocurrent was measured using a high resistance electrometer, whereas the ac (modulated) photocurrent was recorded by a lock-in amplifier using an optical chopper to modulate the monochromator output. Figure 2 illustrates unmodulated responsivity curves as a function of applied bias voltage for $200\times200\ \mu\mathrm{m}^2$ devices with 3 μm/3 μm finger width/spacing on the two different chips.

Devices on both chips exhibited a sharp cutoff at 365 nm, while the peak of the photoresponse was observed at 360 nm. Device responsivity increased with applied voltage and reached 101.80 A/W for SI GaN and 88.63 A/W for UD GaN at 50 V bias and 365 nm UV illumination. These very high responsivity values indicate that devices have a gain of about 700 that can be attributed to the photoconductive gain mechanism in MSM detectors. Using thermally limited detectivity (D^*) formula,[10] $D^*=R_\lambda\sqrt{R_0A/4kT}$, where R_λ is device responsivity at 0 V bias, R_0 is differential resistance, and A is the device area, we find detectivity values of 1.3×10^{14} and $1.2\times10^{13}\ \mathrm{cm\,Hz^{1/2}/W}$ at 360 nm at 0 V bias for SI-GaN and UD-GaN chips, respectively. Detectivity of the SI-GaN sample reached $3.12\times10^{17}\ \mathrm{cm\,Hz^{1/2}/W}$ at 50 V bias. These detectivity values are the best results reported in the literature for a GaN based MSM photodiode. These high detectivity values are even comparable with those of photomultiplier tubes and AlGaN based photodetectors.[11,12] We also performed a modulated photoresponse measurement in order to investigate the dependence of the gain on modulation frequency. Figure 3 shows the photoresponse of a device on the SI-GaN sample. Although device responsivity decreases with the chopper frequency as expected,[13] a significant gain is observed even at the setup high frequency limit of 400 Hz.

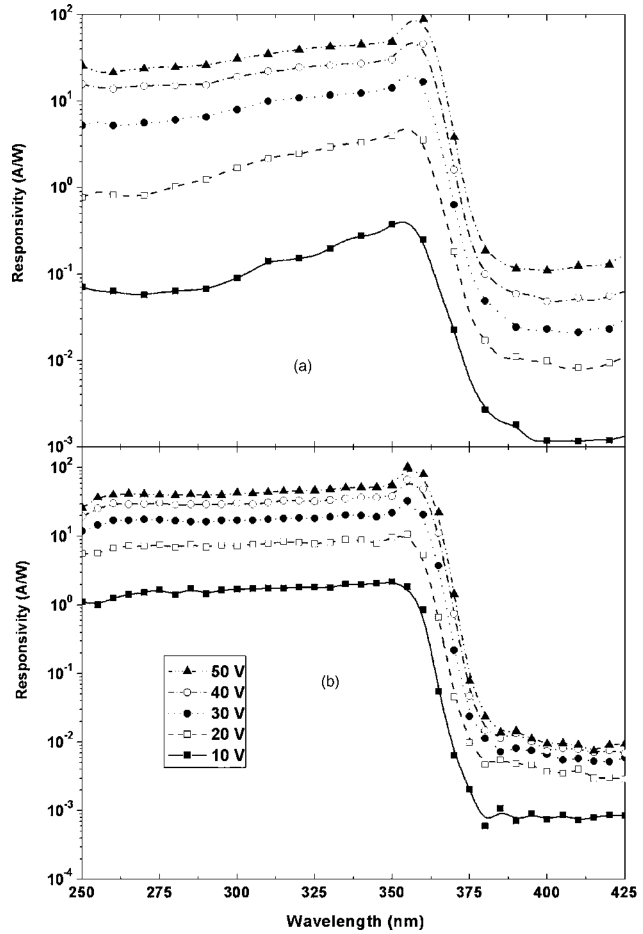

FIG. 2. Measured spectral responsivity curves of $200\times200\ \mu\mathrm{m}^2$ devices with 3 μm/3 μm finger width/spacing on the (a) UD-GaN chip and (b) SI-GaN chip as a function of applied bias voltage.

Finally, a low optical power responsivity measurement was performed in order to determine the minimum detectable

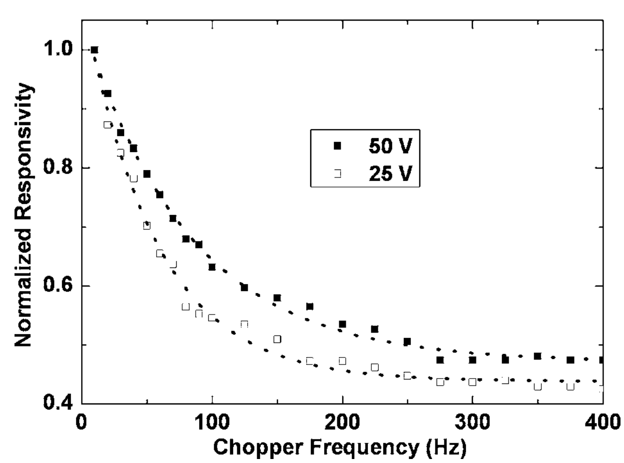

FIG. 3. Normalized modulated photoresponse of a $200\times200\ \mu\mathrm{m}^2$ device with 3 μm/3 μm finger width/spacing on the SI-GaN chip as a function of chopper frequency.

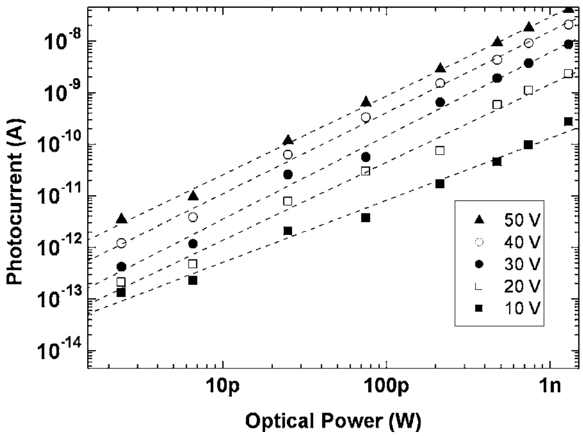

FIG. 4. Measured photocurrent of a $200 \times 200\ \mu\text{m}^2$ device with $3\ \mu\text{m}/3\ \mu\text{m}$ finger width/spacing on the SI-GaN chip as a function of optical power and bias voltage. The dashed lines represent linear fits to the plotted data.

optical power. A series of neutral density filters were used to vary the incident optical power in the range of a few picowatts to 1 nW. As expected, very low level signals are detectable because of the large gain and low dark current values. As shown in Fig. 4, the measured dc photocurrent is well above the dark current at the corresponding bias voltage even for incident optical powers as low as 3 pW.

In conclusion, we have fabricated and tested MSM photodiodes on SI-GaN templates. We also compared these devices with identical ones fabricated on a regular UD-GaN control sample. Devices on the SI-GaN chip exhibited a dark current density of $1.96 \times 10^{-10}\ \text{A/cm}^2$ at 50 V bias voltage, which is four orders of magnitude lower compared with that of the devices on the UD-GaN chip. No sign of device breakdown was observed at bias voltages as high as 200 V for both samples. For 360 nm UV illumination and at 50 V bias, responsivity values as high as 101.8 and 88.63 A/W were obtained from the SI- and UD-GaN samples, respectively. Photoresponse of both samples was comparable with no significant difference. All of the devices exhibited relatively flat response in the 250–360 nm range with a sharp cutoff at 365 nm. Because of high internal gain and low dark current, MSM photodetectors fabricated on SI-GaN templates can detect low level optical signals on the order of a few picowatts.

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