UNIFORMITY AND PERFORMANCE CHARACTERIZATION OF GaN P-I-N PHOTODETECTORS FABRICATED FROM 3-INCH EPITAXY

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ABSTRACT

Gallium nitride wafer epitaxy on large diameter substrates is critical for the future fabrication of large area UV linear or 2D imaging arrays, as well as for the economical production of other GaN-based devices. Typical group III-nitride deposition is now performed on 2-inch diameter or smaller sapphire substrates. Reported here are visible blind, UV GaN *p-i-n* photodetectors which have been fabricated on 3-inch diameter (0001) sapphire substrates by RF atomic nitrogen plasma MBE. The uniformity across the wafer of spectral responsivity and shunt resistance (R_0) for the *p-i-n* photodetectors has been characterized. Spectral responsivity and 1/*f* noise as a function of temperature exceeding 250°C will be presented for the GaN *p-i-n* photodetectors. Spectral response with >0.17 A/W at peak wavelength and having 4-6 orders of magnitude visible rejection has been achieved. 1/*f* noise typically less than 10^{-14} A/Hz$^{1/2}$ at room temperature also has been achieved with GaN *p-i-n* photodiodes. The results have been correlated with proposed models for dark current and 1/*f* noise in GaN diodes.

INTRODUCTION

Gallium nitride (GaN) and its alloys with aluminum are the most promising semiconductors for development of ultraviolet (UV) photodetectors for applications such as combustion monitoring, space-based UV spectroscopy and missile plume detection. With a direct bandgap energy of approximately 3.39 eV (366 nm), GaN is an ideal material for the fabrication of photodetectors capable of rejecting near infrared and visible regions of the solar spectrum while retaining near unity quantum efficiency in the UV. GaN is also an extremely robust semiconductor suitable for high temperature (>200°C) applications.

GaN devices are normally fabricated on sapphire substrates with diameters of two inches or less. The growth and fabrication of GaN UV photodetectors on larger diameter substrates is important for the realization of cost effective discrete detectors, linear detector arrays and 2-dimensional imaging arrays. Other reports on GaN *p-n* UV photodetectors have included 0.05 mm^2 junction area devices with 0.07 A/W peak responsivity [1], 0.04 mm^2 junction area devices [2], and 0.25 mm^2 junction area devices with 0.1 A/W peak responsivity [3]. Presented here is the first reported performance data for GaN *p-i-n* UV photodetectors with 0.59 mm^2 junction areas fabricated on 3-inch diameter substrates.

EXPERIMENT

The GaN *p-i-n* ultraviolet (UV) photodiodes were grown on (0001) basal-plane 3-inch sapphire substrates by molecular beam epitaxy (MBE) using an RF atomic nitrogen plasma source [4]. Details of the growth process have been previously reported [5-6]. The detector epitaxial layers consisted of a $5 \cdot 10^{18}$ cm^{-3} *n*-GaN layer followed by a 5000 Å intrinsic region with unintentional *n*-type doping in the 10^{15} cm^{-3} decade. The topmost epitaxial layer consisted of 2000 Å $1 \cdot 10^{18}$ cm^{-3} *p*-GaN. Mesas reaching the *n*-GaN cathode contact layer were formed by inductively coupled plasma (ICP) plasma etching with chlorine-based chemistry. Ohmic contacts to the *n*-type and *p*-type GaN were made by Ti-based and Ni-based metallizations, respectively. All of the GaN *p-i-n* UV detectors were fabricated with an optical detection area of 0.5 mm^2 and a *p-i-n* junction area of 0.59 mm^2, which is considerably larger (>12.5 times) than other GaN *p-n* detectors reported with noise measurements [1-3].

Shunt resistance and spectral responsivity data were collected using on-wafer probing. The shunt resistance was determined by the linear trace of the current-voltage (IV) characteristic from -10 mV to +10 mV. The spectral responsivities of the UV photodiodes were measured in photovoltaic mode (zero bias) using a 75 W xenon arc lamp chopped at 700 Hz and filtered by a 1/8 meter monochromator set to a 5 nm bandpass. The power of the monochromatic light was measured with a calibrated, NIST traceable, silicon photodiode and then focused onto the 3" GaN wafers resting on a micropositioner stage. The GaN *p-i-n* diode photocurrent was amplified, and the power spectral density in a 1 Hz bandwidth at the modulation frequency was monitored with a FFT spectrum analyzer. Measurements of incident power and photodiode current were made in 10 nm intervals.

For high temperature testing, individual GaN *p-i-n* photodiodes chips were diced from the wafers and mounted on a heated stage. All measurements were performed in an oxidizing, open air environment. The temperature dependent spectral responsivities were performed as described above. The 1/*f* noise measurements were performed with both the dice and heated stage mounted in an enclosure designed to suppress electromagnetic interference. For 1/*f* measurement, the signal from a battery powered, transimpedance amplifier-photodiode circuit was input into the FFT. The operational amplifier in the circuit was specified with a 1 kHz input noise current of 0.16 $fA/Hz^{1/2}$, and the minimum noise power density of the measurement setup was approximately $4 \cdot 10^{-24}$ A^2/Hz.

RESULTS

All GaN UV photodector responsivity measurements reported here were obtained with the devices operating in the unbiased, photovoltaic mode. Shown in Figure 1 is a 25°C spectral responsivity curve for a UV photodetector with 0.194 A/W peak responsivity and 4 orders of

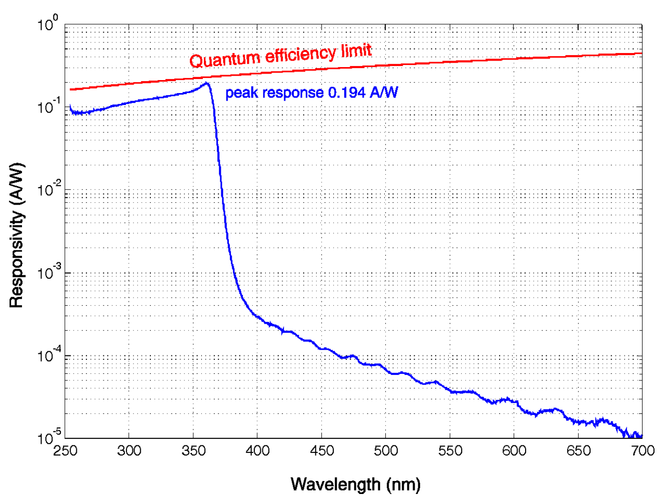

Fig. 1: Typical GaN *p-i-n* UV photodetector unbiased spectral response.

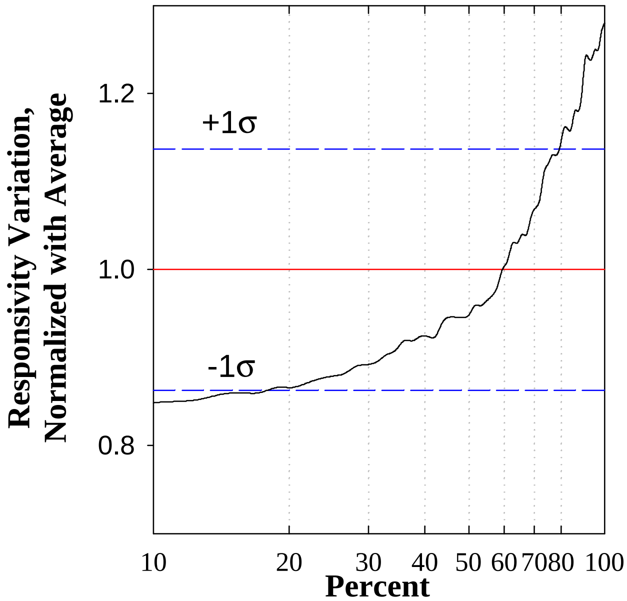

Fig. 2: Variation plot of unbiased peak responsivity normalized with the mean value.

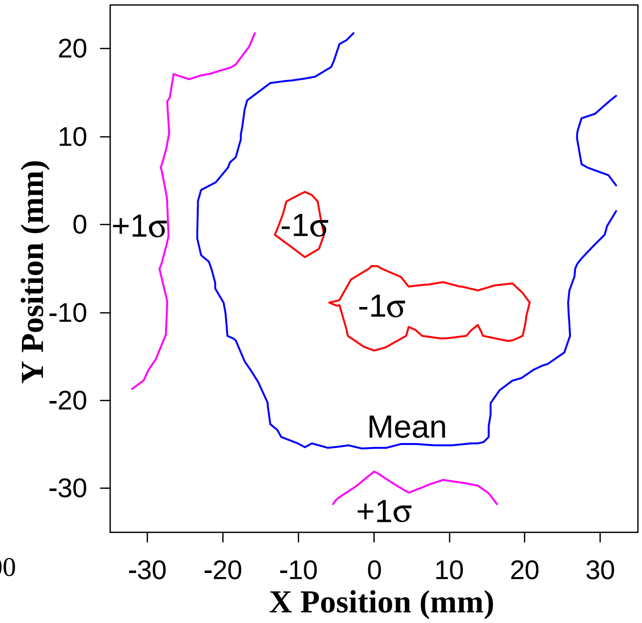

Fig. 3: Mean normalized unbiased peak responsivity contour plot for UV photodetectors verses position on a 3-inch GaN *p-i-n* wafer.

magnitude visible rejection. The statistical distribution of the photodetector devices on a 3" wafer is illustrated with the variation plot in Figure 2. The peak responsivity variation was normalized by the average of all functioning devices, and as a result of a very high yield, the single wafer data set numbered in the thousands. The standard deviation, ±1σ, of the peak spectral responsivity was calculated to be ±13% of the average peak responsivity. Therefore, a 3-inch GaN epitaxial wafer of UV photodetectors with 0.17 A/W peak responsivity would yield devices within the ±1σ deviation range with 0.15-0.19 A/W peak responsivity. 60% of the UV photodetectors on the 3-inch GaN epitaxial wafer functioned within the ±1σ range. Further, nearly all of the UV photodetectors, with the exception of electrically shorted failed devices, functioned within the ±2σ range.

The 2-dimensional (2D) data for the normalized peak responsivity is presented in the contour plot of Figure 3. A diameter of more than 60 mm, or greater than 2 inches, enclosed a circle representing a large number of photodectors with peak responsivities that were near the average of the wafer set. Small patches of devices with peak responsivities between the mean and -1σ were present without any identifiable or expected pattern. An unexpected result was the increasing peak responsivity of the devices near the wafer edge. The 2D distribution of the shunt resistance, which has a strong influence on noise and sensitivity but not on responsivity, was more varied. The contour plot of Figure 4 illustrates the shunt resistance pattern, normalized by the mean, of the GaN *p-i-n* photodetectors on the 3-inch wafer. Higher shunt resistance (up to 3 times the mean) detectors were positioned in the wafer center, and photodetectors with lower shunt resistance (as little as 0.2 times the mean) were distributed around the wafer edge. The majority of the GaN photodetectors exhibited a shunt resistance that was within the same decade of one another.

The high temperature spectral responsivity of a randomly selected GaN UV photodetector chip, previously fabricated and diced from a different wafer lot, is presented in Figure 5. No significant increase in visible responsivity was detectable above the noise level of the test setup as

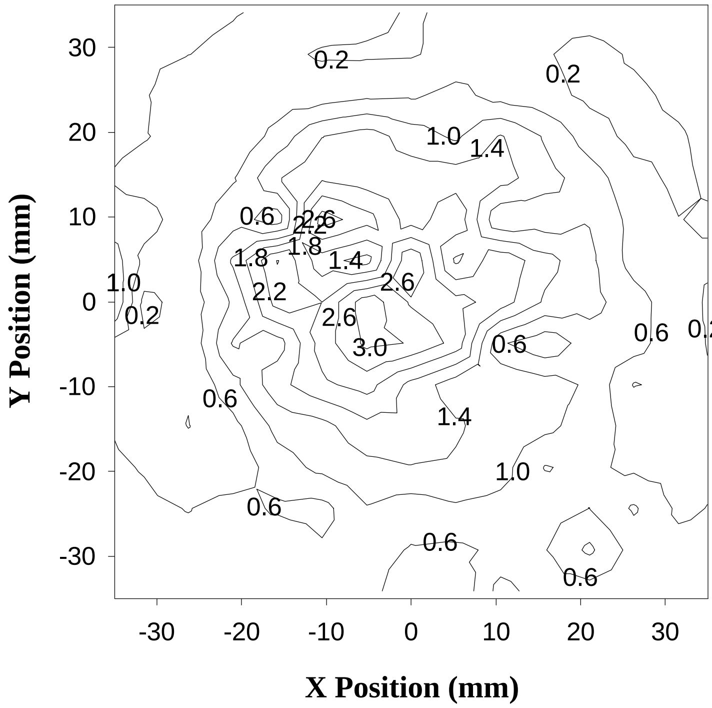

Fig. 4: Contour plot of mean normalized UV photodetector shunt resistance on a 3-inch GaN *p-i-n* wafer.

the device temperature increased from 25°C to 300°C. The peak responsivity shifted with the bandgap edge from 359 nm at 25°C, to 365 nm at 150°C, to 372 nm at 300°C. The GaN UV photodetector chip fully recovered the 25°C spectral responsivity characteristic after being tested at 300°C in the oxidizing environment of open air. The slight differences in spectral responsivity magnitudes are within the error of the high temperature test setup which experienced focusing and position perturbations during measurement as a result of thermal expansion.

The temperature dependent 1/*f* noise characteristics for the GaN *p-i-n* photodetectors are presented in Figures 6 and 7. In Figure 6, the noise power density in photovoltaic mode is plotted over the frequencies including 100 Hz to 1 kHz at temperatures ranging from 25°C to 300°C. A measurable 1/*f* noise signal was not present until the photodetector reached 150°C, and an room temperature extrapolation of the GaN *p-i-n* photodetector noise power density at 100 Hz is presented in Figure 7. Based on the fit shown, the room temperature noise power density for the GaN *p-i-n* photodetectors, with a 0.59 mm^2 junction area, was approximately $3.0 \cdot 10^{-30}$ A^2/Hz ($1.7 \cdot 10^{-15}$ $A/Hz^{1/2}$ noise current density) at zero bias.

Johnson noise, equal to the formula $4kT/R_0$, cannot fully explain the zero bias presence of the 1/*f* noise in the GaN UV photodetectors at higher temperatures. The 1/*f* noise power density, which is normally modeled by a relation including the dark current, suggests the presence of a thermally generated dark current in the photodetectors at zero bias. At temperatures as high as 300°C, thermocouple voltages and/or thermally ionized electron-hole pairs may yield diffusion and recombination in the *p-i-n* junction under equilibrium. Additional characterization and comparison with theory are required to fully explain the high temperature noise characteristics of the GaN devices.

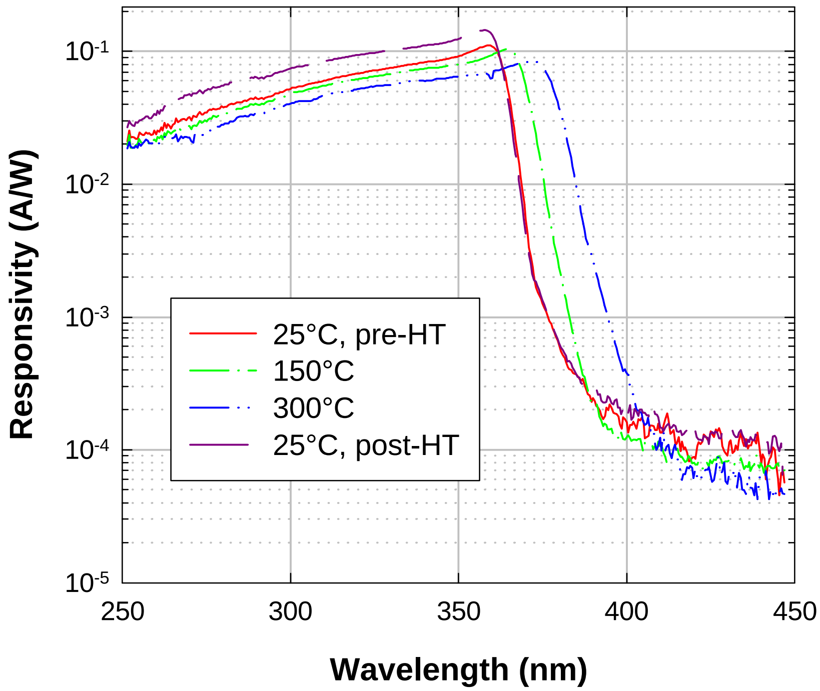

Fig. 5: Temperature dependent, unbiased spectral responsivity for GaN UV photodetector chips up to 300°C.

CONCLUSIONS

UV photodetectors with an optically active surface area of 0.5 mm^2 and a junction area of 0.59 mm^2 have been fabricated on 3-inch diameter GaN *p-i-n* epitaxial wafers and characterized for the first time. Wafer maps of photodetector peak responsivity indicated that more than 60% of all the GaN UV photodetectors performed within the $\pm 1\sigma$ statistical range, which corresponded to a ±13% deviation from the average peak responsivity. The remaining UV photodetectors on the 3-inch GaN epitaxial wafer were distributed within the $\pm 2\sigma$ range. Further, the vast majority of GaN UV photodetectors were characterized with shunt resistances that were within one decade of each other.

High temperature testing of the GaN *p-i-n* photodetectors up to 300°C indicated no significant increase in visible spectral responsivity or short term degradation. The room temperature spectral responsivity of the GaN photodetectors was fully recovered after 300°C testing. The 300°C GaN photodetector 1/*f* noise power densities were measured to be $6.6 \cdot 10^{-19}$ and $2.1 \cdot 10^{-21}$ A^2/Hz at 100 Hz and 1 kHz, respectively. The room temperature, 100 Hz noise power density of the GaN photodetectors was extrapolated to be $3.0 \cdot 10^{-30}$ A^2/Hz ($1.7 \cdot 10^{-15}$ A/$Hz^{1/2}$ noise current density).

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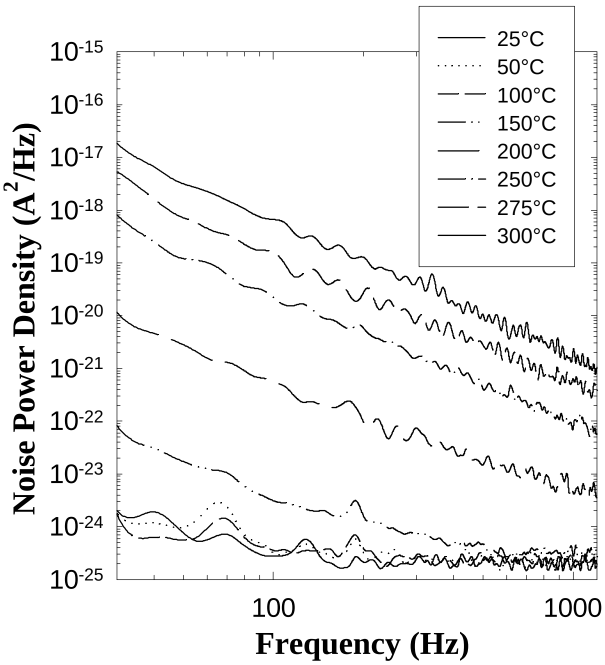

Fig. 6: Typical 1/*f* noise power density for a 0.59 mm^2 GaN *p-i-n* UV photodetector plotted at temperatures up to 300°C. The data were collected at zero bias.

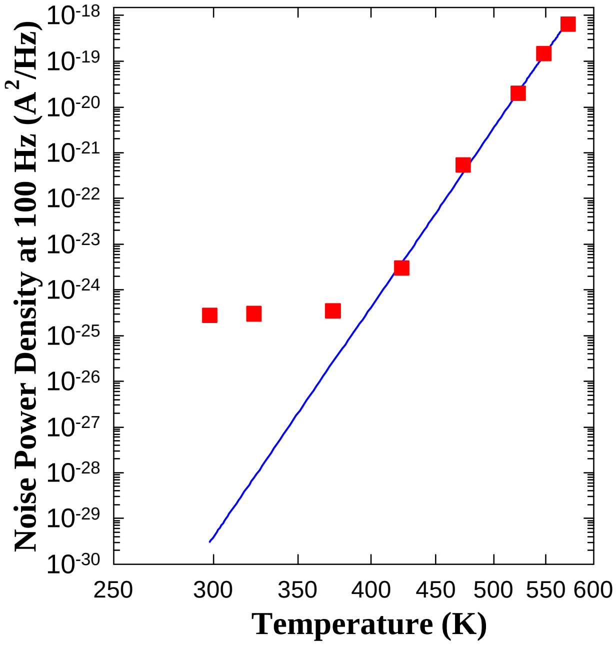

Fig. 7: The GaN *p-i-n* UV photodetector noise power density at 100 Hz. The measurements below 400 K were limited by the test setup noise.

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