Low noise p-π-n GaN ultraviolet photodetectors

A. Osinsky, S. Gangopadhyay, R. Gaska, B. Williams, M. A. Khan, D. Kuksenkov, and H. Temkin

Citation: Applied Physics Letters **71**, 2334 (1997); doi: 10.1063/1.120023
View online: http://dx.doi.org/10.1063/1.120023
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/71/16?ver=pdfcov
Published by the AIP Publishing

Low noise p-π-n GaN ultraviolet photodetectors

A. Osinsky,[a] S. Gangopadhyay, R. Gaska, B. Williams, and M. A. Khan[b]
APA Optics, Inc., Blaine Minnesota 55449

D. Kuksenkov and H. Temkin
Electrical Engineering Department, Texas Tech University, Lubbock, Texas 79409

(Received 18 June 1997; accepted for publication 21 August 1997)

We report on the fabrication and characterization of p-π-n GaN ultraviolet detectors. The peak responsivity at $\sim$363 nm is measured to be 0.1 A/W in the photovoltaic mode, and 0.14 A/W with a bias of -15 V. Speed measurements have shown the photoresponse to be RC-limited with the response time decreasing from 17.4 ns at zero bias to 10.3 ns at -6 V bias. For a 200×200 μm^2 device, we measure the dark current to be 2.7 pA at -3 V bias, and a noise density of less than 10^{-25} A^2/Hz, the noise floor of the measurement. Extrapolating the noise data taken at higher reverse biases, we estimate the noise equivalent power to be 6.6×10^{-15} $W/Hz^{1/2}$. © *1997 American Institute of Physics.* [S0003-6951(97)00542-1]

Significant progress has been achieved in the development of visible-blind GaN-AlGaN photodetectors, yielding responsivities as high as those of UV-enhanced silicon and SiC detectors. However, leakage current, noise, and speed performance have so far been inferior to those of silicon and SiC. Our recent work on vertical geometry Schottky barrier n^-/n^+ GaN detectors grown by metalorganic chemical vapor deposition (MOCVD) showed responsivities as high as 0.18 A/W and RC-limited response time of 118 ns. The first noise measurements performed on these detectors identified $1/f$-like behavior with the noise equivalent power (NEP) of $\approx7\times10^{-12}$ $W/Hz^{1/2}$.[1] This relatively high value of the NEP was attributed to large leakage currents.

In general, the reverse bias leakage current across a p-n junction is expected to be lower than that across a Schottky barrier due to larger barrier height. The first p-n junction photodetectors grown by MOCVD have shown responsivities of 0.09 A/W, leakage current of $\sim$10 nA/mm^2, and response time of 0.3 ms.[2] More recently, molecular beam epitaxy grown p-i-n GaN detectors have shown responsivity of 0.11 A/W, leakage currents of 54–171 $\mu A/mm^2$, and response time of 8.2 μs.[3] With the exception of very small MSM structures with low dark currents[4] most of the reported GaN devices are slow with large leakages that could restrict them from many applications. This letter reports fabrication of single element p-π-n GaN photodetectors with extremely low noise and dark current characteristics, even lower than those of Si detectors. In addition, our photodiodes exhibit responsivities comparable to other GaN detectors, but with much higher speed.

High quality p and n epilayers of GaN can be deposited over sapphire substrates using MOCVD.[5] In our growth sequence we first deposit a thin AlN nucleation layer at 600 °C. The n- and the p-type GaN layers are deposited at 76 and 500 Torr, respectively, and at 1000 °C. The photodiode structure consists of $\sim$0.8 μm thick n-GaN ($n=10^{18}$ cm^{-3}), followed by $\sim$2.2 μm thick p GaN (Mg-doped). The Mg dopant is activated by thermal annealing at 800 °C. The p-doping profile along the growth direction varies from $\sim10^{16}$ cm^{-3} at the p-n interface to $\sim7\times10^{17}$ cm^{-3} at the surface, as determined from capacitance–voltage ($C-V$) and resistivity data, and confirmed by Hall measurements. The graded doping profile of the p-GaN layer is due to a gradual substitution of the doping reagents at elevated growth pressure (500 Torr) and a consequent variation in the degree of compensation near the physical p-n junction. The variation of the junction capacitance with the reverse-bias voltage follows a power law $V\propto C^{-\beta}$, where β is less than 1/3, suggesting a gradual p-n junction.[6] The resulting structure, therefore, is p-π-n, where π stands for a lightly p-doped compensated layer sandwiched between more heavily doped p and n layers. The surface morphology of the total structure is featureless without cracks, indicating that our p-GaN growth, although carried out at a higher pressure, does not introduce excessive strain between the p and the n layer.

Reactive ion etching with $SiCl_4$ plasma is used to define 200×200 μm^2 and 500×500 μm^2 mesas. The ohmic contacts are made of Ti/Al/Ti/Au[7] and Ni/Au[8] multilayers to the bottom n-GaN and to the top p-GaN, respectively. Rapid thermal annealing at 900 °C, 30 s for the n type and at 550 °C, 2 min for the p-type contacts is used. The fabricated devices are protected with a polyimide layer and packaged into a TO-5 module.

Figure 1 shows a typical reverse bias current–voltage characteristic for a 200×200 μm^2 area p-π-n GaN detector taken in the temperature range 300–550 K. At room temperature (Fig. 1, trace 1), the leakage current exhibits exponential dependence on the bias voltage with two different exponents, above and below -7 V. Leakage current densities measured at -3 V reverse bias vary from 22 pA/mm^2 to 120 pA/mm^2. An increase in the leakage current with the device temperature is also approximately exponential in the measured range of reverse bias voltages. Although the room temperature leakage at small reverse bias is less than a picoampere, it is still $\sim10^4$ times higher than the saturation current of 2.1×10^{-16} A expected from the measured forward

[a]Electronic mail: andrei@apaoptics.com
[b]Current address: Department of Electrical and Computer Engineering, University of South Carolina, Columbia, SC 29208.

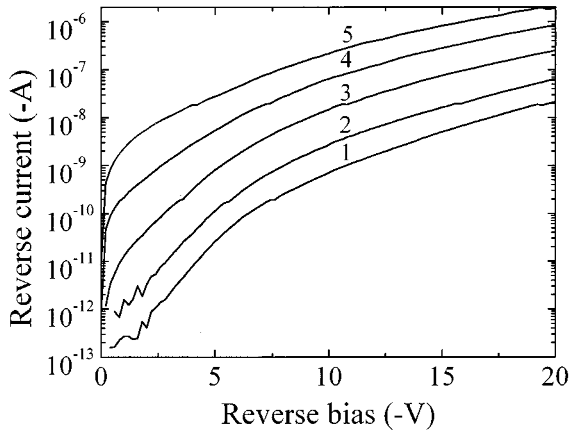

FIG. 1. Reverse current-voltage characteristics of a 200×200 μm^2 p-π-n GaN photodiode at temperatures: (1) 300 K, (2) 355 K, (3) 420 K, (4) 490 K, (5) 550 K.

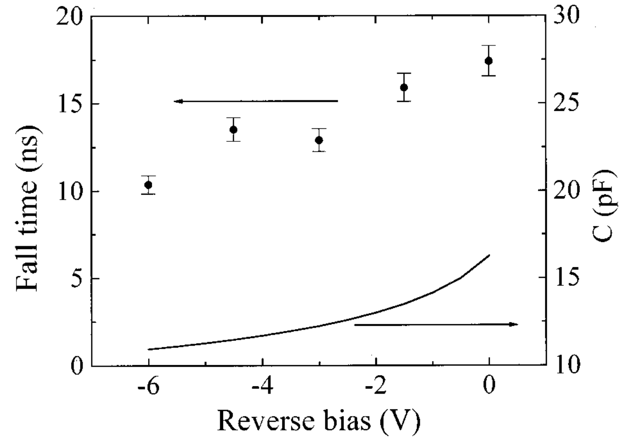

FIG. 3. Variation of decay time with the reverse bias voltage (closed circles); $C-V$ measurement at 1 MHz (line).

bias characteristics. The series resistance across the photodiode is estimated to be 1.5 kΩ.

The spectral response of the photodiodes is measured in photovoltaic mode as well as with a reverse bias of 15 V, as shown in Fig. 2. A calibrated 150 W Xe light source and a monochromator are used. Trace (a) shows the response of the device illuminated from the top (zero bias), traces (b) and (c) correspond to back-illumination through the transparent sapphire substrate and the bottom n layer. The peak responsivities corresponding to curves (b) and (c) at ~363 nm are 0.1 and 0.14 A/W, respectively. These values are not far from the maximum responsivities calculated for the GaN p-n-junction from an analytical model.[3] The peak response drops by more than three orders of magnitude above the cut-off wavelength. The photocurrent is almost independent of the reverse bias, from −2 V to −20 V.

The strong peaking of the spectral response with front illumination [trace (a)] can be explained by the reduced diffusion length of electrons in the top p-GaN layer. Preliminary data from electron beam induced current (EBIC) measurements indicate that for acceptor concentration of 1×10^{17} cm^{-3}, the diffusion length of minority carriers (electrons) is shorter than 2 μm, and comparable with the diffusion length of holes in n-type GaN.[9] Since the photocurrent is found to be diffusion-limited, reducing the thickness of the p layer is expected to increase the responsivity of the device illuminated from the top.

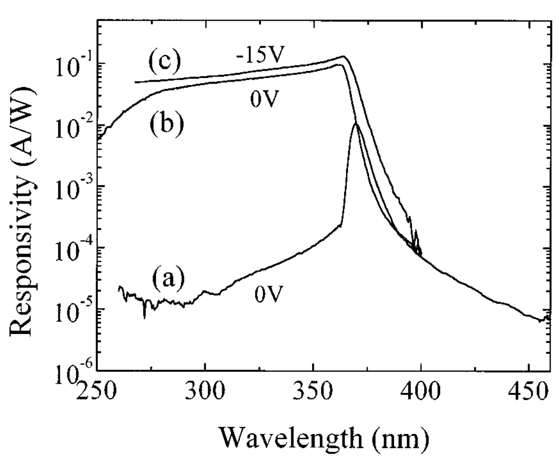

FIG. 2. Spectral response of a 500×500 μm^2 p-π-n GaN photodiode: (a) at zero bias, light incident from the top p side. (b), (c) light incident from the bottom n side at zero and −15 V bias, respectively. A peak responsivity of 0.14 A/W is obtained.

The speed measurements are performed by studying the detector response to ≤1 ns long laser pulses from a N_2 laser operating at 337 nm. The peak power density is decreased to ~10 W/cm^2 to avoid any artificial decrease of response times due to saturation effects. The pulse response is acquired across a variable load with a 400 MHz bandwidth digital oscilloscope at a sampling rate of 2 GS/s. The response curves are fitted to exponential wave forms to obtain the decay time τ (the time it takes to fall to $1/e$ of the maximum value). Variation of the decay time with the load resistance shows no significant deviation from a linear behavior down to 11 ns for a 25 Ω load (for the 200×200 μm^2 detector), suggesting the device is RC limited.[1] This corresponds to a bandwidth of 32 MHz. Correcting for the capacitance of the oscilloscope input and the bias network, we estimate the intrinsic response time of the device to be about 4 ns.

Since the effective time constant is found to be limited by RC considerations rather than by the inherent speed of the detection mechanism (the estimated transit time for electrons in n-GaN is more than 10^3 times shorter[10] than the measured detector time response), the detector should be faster with a reverse bias due to a reduced depletion layer capacitance. To study this we measure the decay time of the detectors as a function of the reverse-bias voltage [trace (a) in Fig. 3]. The detector speed increases by a factor of ~1.5 when the bias voltage is changed from 0 to −6 V. We see a corresponding reduction in the device capacitance, shown in trace (b) of Fig. 3.

The noise characteristics of the p-π-n photodiodes are measured in the frequency range of 1 Hz–100 kHz using a low noise current preamplifier and a fast fourier transform (FFT) spectrum analyzer. The noise floor of the measurement setup, limited by the noise parameters of the preamp-

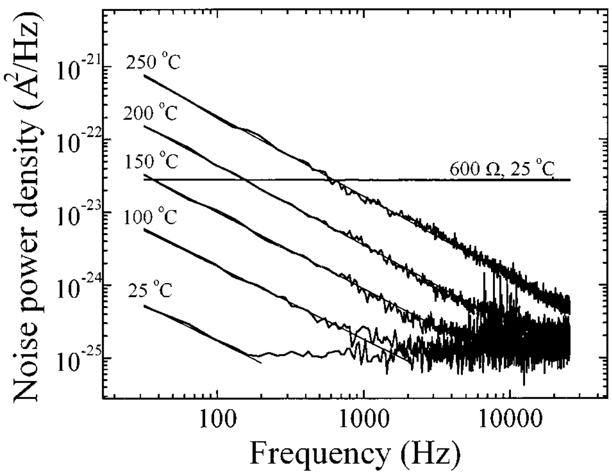

FIG. 4. Frequency dependence of the measured noise power density for a $200\times200\ \mu m^2$ device at a reverse bias of 10 V, and at different temperatures. The straight line fits through the noise spectra are represented by Eq. (1). The horizontal line is the thermal noise of a 600 Ω resistor at 25 °C.

lifier, is $\sim 10^{-25}$ A^2/Hz. The reverse bias is varied from -5 to -30 V, and the sample temperature from 293 to 543 K. At elevated temperatures and/or high values of the reverse bias, where the dark current of the photodiode increases above ~ 1 nA, we observe the appearance of $1/f$-like noise (Fig. 4). We find that all the measured noise spectra can be described by the following relation:

$$S_n = \alpha \frac{I_d^2}{f^\gamma}, \tag{1}$$

where S_n is the spectral density of the noise power, I_d is the dark power, and α, γ are the fit parameters. The value of γ is found to vary from 1.0 to 1.1. The value of α shows no significant dependence on the bias voltage, but it decreases rapidly with increasing temperature. At room temperature it is found to vary within 0.9×10^{-5} and 1.1×10^{-5}.

For comparison, we show in Fig. 4 the level of thermal noise current generated in a 600 Ω resistor at room temperature (horizontal line). Even at 100 °C the entire noise spectrum of the photodiode lies below this line. At room temperature and for the reverse bias values lower than 10 V, the detector noise spectra disappear completely under the noise floor of our measurement system.

Since the parameter α is found to be almost independent of the bias voltage, we can estimate the noise magnitude at -3 V using Eq. (1). The dark current at -3 V bias is 2.7 pA, resulting in S_n (at 1 Hz)$=7.3\times10^{-29}$ A^2/Hz. The corresponding NEP for the measured responsivity of 0.14 A/W is 6.1×10^{-14} W/Hz$^{1/2}$. This is three orders of magnitude lower than the value reported on AlGaN Schottky barrier photodetectors.[11] At frequencies higher than 100 Hz, we estimate the magnitude of the noise to be much lower than that of the shot noise $S_{shot}\approx 8.6\times10^{-31}$ A^2/Hz. The corresponding NEP ($f\geqslant 100$ Hz) is 6.6×10^{-15} W/Hz$^{1/2}$.

We find that the dark current scales with the area of the photodiode. Therefore, the leakage path is through the volume of the device rather than through the surface states. Since the most resistive layer is the lightly doped π layer, it comprises most of the depletion layer. Therefore, the properties of the π layer determine most of the leakage behavior.

The $C-V$ measurement results discussed above imply that the depletion layer width varies slowly with the reverse bias. On the other hand, we find that the leakage current changes exponentially with the reverse bias. This cannot be explained using the classic Shockley model for the generation-recombination current in a reverse-biased p-n junction.[12] We suggest that the main physical mechanism responsible for the dark current in the photodiodes investigated here is field-dependent tunneling (hopping) over defects in GaN located at grain boundaries and threading dislocation walls. The observed $1/f$-like noise is then caused by the fluctuating occupancy of these trap states. A more detailed study of the phenomena contributing to reverse bias leakage and noise in GaN p-n junctions will be reported elsewhere.[13]

This work was supported by DARPA Contract No. N00014-95-C-0073 and monitored by Dr. Yoon Soo Park of the Office of Naval Research. Work at Texas Tech University was supported by DARPA and the J. F. Maddox Foundation. We acknowledge R. Torreano and J. Kuznia for material deposition, Dr. Q. Chen for help in p-doping calibration, Dr. J. W. Yang for valuable discussion on growth, and M. Z. Anwar for the mask layout.

[1] Q. Chen, J. W. Yang, A. Osinsky, S. Gangopadhyay, B. Lim, M. Z. Anwar, M. A. Khan, D. Kuksenkov, and H. Temkin, Appl. Phys. Lett. **70**, 2277 (1997).
[2] Q. Chen, M. A. Khan, S. J. Sun, and J. W. Yang, Electron. Lett. **31**, 1781 (1995).
[3] J. M. Van Hove, R. Nickman, J. J. Klaassen, P. P. Chow, and P. P. Ruden, Appl. Phys. Lett. **70**, 2282 (1997).
[4] J. C. Carrano, P. A. Grudowski, C. J. Eiting, R. D. Dupuis, and J. C. Campbell, Appl. Phys. Lett. **70**, 1992 (1997).
[5] M. Asif Khan, J. N. Kuznia, J. M. Van Hove, D. T. Olson, S. Krishnankutty, and R. M. Kolbas, Appl. Phys. Lett. **58**, 526 (1990).
[6] D. Wood, *Optoelectronic Semiconductor Devices* (Prentice Hall, London, 1994).
[7] Z. Fan, N. Mohammad, W. Kim, Ö. Ztkas, A. E. Botchkarev, and H. Morkoç, Appl. Phys. Lett. **68**, 1672 (1996).
[8] M. Asif Khan, Q. Chen, R. A. Skogman, and J. N. Kuznia, Appl. Phys. Lett. **66**, 2046 (1995).
[9] L. Chernyak, A. Osinksy, H. Temkin, J. W. Yang, Q. Chen, and M. Asif Khan, Appl. Phys. Lett. **69**, 2531 (1996).
[10] R. P. Joshi, A. N. Dharamsi, and J. McAdoo, Appl. Phys. Lett. **64**, 3611 (1994).
[11] A. Osinsky, S. Gangopadhyay, B. W. Lim, M. Z. Anwar, and M. A. Khan (unpublished).
[12] T. Sah, R. N. Noyce, and W. Schockley, Proc. IRE **45**, 1228 (1957).
[13] D. Kuksenkov, H. Temkin, A. Osinsky, R. Gaska, and M. A. Khan (unpublished).