The Franz-Keldysh (F-K) effect is observed in Gallium Nitride (GaN) p-n junction diodes via spectral variation in the photocurrent; the absorption onset redshifts with increasing reverse bias. This band-bending-induced sub-bandgap absorption is used to determine the local electric field inside the depletion region. The local field in a p-n junction is parametrized by the total local bias ($V_l$) across the depletion region that can be significantly different than expected due to electrostatic non-uniformities. The measured photocurrent spectra are fit to the Franz-Keldysh-Aspnes (FKA) model using $V_l$ as a fit parameter that determines the local electric field maximum and depletion widths. As $V_l$ varies linearly with the applied bias ($V$), the built-in bias ($V_{bi}$) is determined by extrapolating $V_l$ at $V = 0$, which roughly agrees with independent C-V measurements. These measurements demonstrate F-K photocurrent spectroscopy as a local probe of electric field in wide bandgap diodes that can be used to map out regions of device breakdown (hot spots) for improving electrostatic design of high voltage devices.

GaN is a III-V compound semiconductor with a wide bandgap (~3.4 eV) and a high breakdown electric field ($> 3.3$ MV/cm), making it useful for power devices and optoelectronics. Heterostructures based on GaN result in high responsivity Metal-Heterojunction-Metal (MHM) ultraviolet photodetectors. However, the stability and lifetime at high voltages for GaN based power electronics still remains a challenge to the device industry. Vertical devices such as p-n junctions have electric field peaks near the device edge, which are managed using junction termination structures such as field plates and guard rings. Lateral devices such as AlGaN/GaN HEMTs also show field variation across the gate-drain region. It is a challenge to measure the actual field distribution in such devices, and device engineers usually rely on device simulations to estimate the electric field profiles. Furthermore models used to estimate electric field profiles may ignore inhomogeneity, and thus may not provide accurate estimates of hot spots in such structures. Thus, a local probe of electric field would
be a useful tool for mapping out the field distribution, identifying hot spots, and validating or refining complex electrostatic models and device designs.

Semiconductors exhibit the F-K effect due to which photons with energy \( E_{ph} \) below the bandgap \( E_g \) are absorbed due to electric-field induced band bending. Electron and hole wave functions exhibit finite overlap at energies below the bandgap due to band bending, which results in a sub-bandgap absorption tail.\(^{21}\) The band bending can be characterized by photocurrent spectroscopy through the redshift of the absorption spectrum with reverse bias.\(^{22-24}\) Recently, the electric field maximum, depletion width, and surface charge in AlGaN/GaN heterostructures were determined based on fitting photocurrent and photovoltage spectra to an FK-model that was derived for the special case of linear and parabolic band bending.\(^{25}\) Similarly the F-K effect in a GaN p-n junction and schottky diode was modeled to determine the electric field in the device active region.\(^{26-28}\) In analyzing their results, Maeda et al. used the weak-field-approximation to calculate the \( V \) dependence of photocurrent measured at constant excitation wavelength. Building on these previous works, here we develop a spectrally-resolved measurement and model of the F-K effect in GaN p-n diodes. Bias dependent photocurrent responsivity spectra are well-fit to the Franz-Keldysh-Aspnes (FKA) model\(^ {29}\) using \( V_l \) as an adjustable parameter from which the local electric field maximum and depletion widths are sensitively determined. Since the electric field mainly results in a spectral red-shift of the absorption edge, its measurement is insensitive to position-dependent variation in light intensity and optoelectronic efficiency.

The GaN p-n junction is grown by plasma-assisted molecular beam epitaxy (PAMBE) in a Veeco Gen 930 system. A schematic of the GaN p-n diode is shown in Fig 1. The layers are grown under Ga-rich conditions at a substrate temperature (T\(_{\text{sub}}\)) of 675°C (pyrometer), at a growth rate of 4 nm/min, RF power of 300 W, and N\(_2\) flow rate of 2.5 sccm. The epitaxial structure for the diode consists of 1 \( \mu \)m n- GaN drift layer (Si = 1\( \times \)10\(^ {17} \) cm\(^ {-3} \)) grown on an n+ GaN/sapphire template. Next a 200 nm thick layer of p- GaN (Mg = 1\( \times \)10\(^ {18} \) cm\(^ {-3} \)) is grown at T\(_{\text{sub}}\) = 650°C. Finally, the 30 nm p+ GaN cap layer (Mg = 1\( \times \)10\(^ {20} \) cm\(^ {-3} \)) is grown at T\(_{\text{sub}}\) = 600°C. The Si and Mg concentration are estimated based on secondary ion mass spectroscopy (SIMS) doping calibration. The top ohmic contact to p+ GaN is formed by depositing a Pd/Ni/Au (30 nm/30 nm/30 nm) metal stack using an e-beam evaporator followed by annealing in N\(_2\) for 1 min at 400°C. The p-GaN layer is etched for mesa isolation in ICP RIE using BCl\(_3\)/Cl\(_2\). Following a deeper etch, the n+ GaN layer is contacted using an Al/Ni/Au (30
nm/30 nm/150 nm) metal stack deposited by e-beam evaporation. The average net doping concentration 
\( (N_d - N_a) \) determined by C-V measurement was \( 4 (\pm 0.4) \times 10^{16} \text{ cm}^{-3} \). Figure 1(a) shows the band edge diagram, obtained using a one-dimensional self-consistent Poisson solver.\(^{30,31}\) The carrier concentration in the two regions is shown in Fig. 1(b), where the zero-bias depletion region width is 0.12 \( \mu \text{m} \). The vertical (x-axis) electric field component is,\(^{32}\)

\[
F(x) = \begin{cases} 
-\frac{eN_a}{\varepsilon_s} (W_n + x), & -W_p \leq x < 0 \\
-\frac{eN_d}{\varepsilon_s} (W_n - x), & 0 < x \leq W_n 
\end{cases},
\] (1)

where, \( e \) is the electron charge, \( N_a \) (\( N_d \)) is the acceptor (donor) density, \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon_s = 10.4\varepsilon_0 \) is the static dielectric constant of GaN, \( W_n \) (\( W_p \)) is the depletion width of the n (p) region given by,

\[
W_n = \sqrt{\frac{2\varepsilon_s(V_{bi} - V)N_a}{q(N_d + N_a)N_d}},
\] (2a)

\[
W_p = \sqrt{\frac{2\varepsilon_s(V_{bi} - V)N_d}{q(N_d + N_a)N_a}},
\] (2b)

where \( V_{bi} = \frac{k_BT}{e} \ln \left( \frac{N_a N_d}{n_i^2} \right) \) is the built-in bias defined as a positive quantity such that the total bias is \( (V - V_{bi}) \), \( k_B \) is Boltzmann’s constant, \( T \) is the temperature, and \( n_i \) as the intrinsic carrier concentration. The zero bias field profile calculated using Eq. 1 is plotted in Fig. 1(c), yielding \( W_n + W_p = 0.12 \mu \text{m} \), matching the band diagram simulation.

The photocurrent spectroscopy setup incorporates reflective optics (Al-coated) enabling measurement across the deep-UV to visible wavelengths without chromatic aberration. The light source is a 75W Xenon Arc lamp (OBB Powerarc) focused through the entrance slit of a 140 mm monochromator (Horiba MicroHR) with a 250 nm blazed holographic grating. The average spectral bandwidth across the measurements reported here is 2.5 nm. An optical chopper operating at 200 Hz (2.5 ms open/close time) modulates the monochromatic light, which is focused on the edge of the top deposited metal, which is a circular device structure with 30 \( \mu \text{m} \) diameter, using a 40× reflective microscope objective. The photocurrent is pre-amplified and then fed into a digital lock-in amplifier (Zurich instruments HFLI), referenced to the chopper frequency. Reverse bias (\( V < 0 \)) is applied to the device using a Keithley 2604B source meter unit. The photocurrent is normalized by the measured
optical power at each wavelength using a wavelength corrected power meter (Thorlabs PM 100D) to obtain the photocurrent responsivity \( I_{PR} \) as a function of \( E_{ph} \). Responsivity data measured from the GaN p-n diode are shown in Fig. 2(a), obtained at a step voltage of 5 V from \( V = 0 \) to \(-40 \) V. The F-K effect is observed as a bias-induced red shift of the absorption spectra, such that photocurrent is obtained for \( E_{ph} < E_g \). Figure 2(b) shows \( I_{PR} \) on a logarithmic scale, where the broadening of the absorption edge is more apparent. The absorption edge energy \( E_{edge} \) is quantified using the Tauc equation\(^{33,34}\) and plotted in Fig. 2(c) as a function of \( V \). The transmission spectrum is acquired simultaneously with \( I_{PR} \) to determine the zero-bias absorption coefficient \( \alpha_0 = 2.303 \times (a/t) \), where, the absorbance \( a = 2 - \log(T) \), and \( t \) is the overall thickness of GaN in the device.\(^{35}\) As shown in Fig. 2(d), \( E_g \) calculated using the Tauc formula using either \( \alpha_0 \) or \( I_{PR} \) spectra give the same value of \( E_g = 3.35 \pm 0.2 \) eV.

The electric field dependence of the absorption coefficient for GaN is determined using the FKA model,\(^{29}\)

\[
\alpha(E_{ph}, F(x)) = \frac{|M_{cv}|^2 \mu_\perp}{\varepsilon_0 m_0^2 n c E_{ph}} \left( \frac{2 \mu_\perp e^7 F(x)}{\hbar^5} \right)^{1/2} \left[ \text{Ai}^2 \left( \frac{E_g - E_{ph}}{\left( \frac{2\hbar^2 F(x)^2}{2\mu_\perp} \right)^{1/3}} \right) - \frac{E_g - E_{ph}}{\left( \frac{2\hbar^2 F(x)^2}{2\mu_\perp} \right)^{1/3}} \text{Ai}^2 \left( \frac{E_g - E_{ph}}{\left( \frac{2\hbar^2 F(x)^2}{2\mu_\perp} \right)^{1/3}} \right) \right],
\]

(3)

where \( \mu = \frac{m_e m_h}{m_e + m_h} \) is the reduced mass, \( \mu_\parallel (\mu_\perp) \) is the reduced mass along (perpendicular to) the optical axis \([0001]\), \( m_e \) (\( m_h \)) is the electron (hole) effective mass, \( m_0 \) is the electron rest mass, \( n = 2.5 \) is the refractive index of GaN assumed constant over the data fitting range of \( E_{ph} = 3 - 3.3 \) eV, \( c \) is the speed of light, \( \hbar \) is the reduced Planck’s constant, and \( |M_{cv}|^2 \) is the momentum matrix element obtained from fitting the \( \alpha_0 \) spectrum to Eq. 3. Assuming a single round-trip path, passing through the depletion region, reflecting at \( x = W_d \) and returning to \( x = -W_d \), the photocurrent density due to the FKA effect, as derived by Maeda et al. is,\(^{26,27}\)

\[
J_{FKA}(E_{ph}) = e \eta^* \varphi_0 \left[ 1 - e^{2 \int_{-W_p}^{W_d} \alpha(E_{ph}, F(x)) dx} \right], \quad (4)
\]

where \( \varphi_0 \) is the photon flux incident on the surface, and we introduce a new term \( \eta^* \) (compared with Refs. 22 and 23), the optoelectronic efficiency, which accounts for reflection, absorption, and recombination losses. First, the photon flux transmitted into GaN is \( \varphi_0 (1 - r) \), where \( r \) is the surface
reflectance. This is a bias independent parameter, but strongly depends on the position on the device because of shadowing or reflection changes. Next, the photons that enter the device are also absorbed in the non-depleted regions of the device and at the electrodes. Since, the signal of interest is below bandgap, then such absorption should be small, but could have a significant impact on the photocurrent spectra. The photon flux arriving at the depletion region is therefore, \( \varphi_0 (1 - r)(1 - a) \), where \( a \) is the absorbance of the p-GaN above the depletion region. Finally, inside the depletion region, the photocarriers recombine with traps arising from defects or even with oppositely charged carriers. The fraction of photocarrier flux that results in photocurrent is therefore,

\[
\eta^* \varphi_0 = \eta_{\text{int}} \varphi_0 (1 - r)(1 - a),
\]

where \( \eta_{\text{int}} \) is the internal quantum efficiency. Finally, we obtain the overall expression for the photocurrent responsivity,

\[
I_{PR}(E_{ph}) = \frac{J_{\text{FKA}}}{E_{ph} \varphi_0} = \frac{\eta^*}{E_{ph}} \left[ 1 - e^{-2 \int_{-W_p}^{W_n} \alpha(E_{ph},F(x)) \, dx} \right].
\]

Accordingly, the \( I_{PR} \) spectra are sensitive to electric field via the FKA-effect. In our measurements, the p-n diode is kept in reverse-bias-mode. The dark current is removed using lock-in detection, and thus, the measured current is due to photons absorbed in the active region (p-n junction) that are converted into electron-hole pairs, collected by the electrodes. Because the diode is not in forward bias mode, stray electric fields cannot energize carriers that might induce different transport mechanisms that would otherwise complicate the analysis. As a result, the \( I_{PR} \) spectral line shape inherently depends on local electrostatics and provides a way to map the local electric field across devices. When there is zero applied voltage, the only band-bending present is due to the built-in potential, i.e. if \( V = 0 \), then \( V_i = -V_{bi} \). When an external voltage (\( V \)) is applied, the average potential across the entire device area is \( (V - V_{bi}) \), but due to variation in the charge distribution at that spot, the total local vertical bias can be larger or smaller than \( (V - V_{bi}) \). Thus, we define the total local bias (\( V_i \)) to parametrize this variation in the electrostatics of the device and determine the local vertical field maximum and depletion widths, i.e. we substitute \( (V - V_{bi}) \) with the newly defined \( V_i \) in Eq. 2. Within a p-n junction, Eq. (1) describes the triangular electric field profile in the depletion region. The field slope is independent of bias as it is a function of doping density, which is determined from the C-V measurements. The local field maximum is affected by changes in the local depletion widths (\( W_n \) and
Using $V_l$ as an adjustable parameter, $I_{PR}$ spectra are fit using Eq. (6) for different values of $V$. We treat $\eta^*$ as a bias-independent fit parameter (held constant for each value of $V$) since it will vary mainly due to differences in reflectance at different positions along the device, but not change as a function of bias at any given position. We further note that Eq. 6 is valid only if there is no significant absorption outside of the depletion region, i.e. $0 < a \ll 1$, thus it is necessary to restrict the data fitting only to $I_{PR}$ taken below the onset of strong absorption in GaN at zero field. As the depletion widths and device dimensions are in the ~1 μm range, we choose $\alpha_0 < 10^3/cm$ as an upper bound for the measurement and therefore fit data for $E_{ph} < 3.3 \text{ eV}$.

In Fig. 3(a), we compare $I_{PR}$ obtained experimentally (points) and calculated (lines) using Eq. 6 by assuming $V_l = V - V_{bi}$. The strong discrepancy clearly demonstrates that the true $V_l$ must be smaller than the average total bias. When $V_l$ is treated as a fit parameter, Fig. 3(b), we obtain good agreement between the measured spectra and model ($R^2 \geq 0.91$). Figure 3(c) plots the optical absorption data and fit to Eq. 3 from which $|M_{cv}|^2 = 2 (\pm 1) \times 10^{-4}$ J·kg and $E_g = 3.37 (\pm 0.05)$ eV are determined.

The fitted values of $V_l$ are plotted as a function of $V$ in Fig. 3d, revealing a linear relation. We therefore obtain the empirical relation characterizing the total local bias,

$$V_l = c_l V - V_{bi} \ , \quad (7)$$

where $c_l$ is a unitless coefficient of proportionality. The local effective applied bias ($V_l + V_{bi}$) is reduced by a factor of $c_l$ compared with the average applied bias. Thus, $c_l$ characterizes the local electric field inhomogeneity. As discussed previously, if $V = 0$, then $V_l = -V_{bi}$. Accordingly, we find a y-axis intercept of -1.9 V in Fig. 3(d), such that $V_{bi} = 1.9 \pm 0.5 V$, which roughly agrees with the independently determined value of $V_{bi} = 2.8 \pm 0.2 V$ obtained via C-V measurements (inset). The difference between these two estimates of $V_{bi}$ is $0.9 \pm 0.7 V$, which could indicate that the local $V_{bi}$ is actually 0.9 V lower than the average value obtained by C-V. However, this would require an unphysically small doping, i.e. below the unintentional doping background. Therefore, we instead make
the assumption that the C-V value of $V_{bi}$ is accurate and uniform across the device, in which case the discrepancy of $V_{bi}$ indicates the systematic error of $V_t$ ($\pm 1$ V). This suggests that these FKA spectroscopy based $V_t$ measurements are only sensitive at high voltages. This limitation is reasonable considering that FKA sub-bandgap absorption requires relatively large electric fields.

Finally, in Fig. 4 the average x-axis electric field profiles are plotted and compared with the local electric field profiles determined by $I_{PR}$ spectral fits. At the particular location of $I_{PR}$ measurements, the field maximum and depletion width are far smaller than the average, indicating that this location is an electrostatic cold spot. Thus, this method of determining local $F$ by fitting the spectral variation of $I_{PR}$ can prove useful in designing GaN based p-n devices within breakdown constraints by mapping out the local electric field and identifying cold and hot spots. Our results highlight the importance of accurately determining local field variation particularly in high-voltage devices where the difference between the local and average vertical field magnitudes can be greatly magnified.

**Acknowledgments** Funding for this research was provided by the Center for Emergent Materials: an NSF MRSEC under award number DMR-1420451 and by the AFOSR GAME MURI (Grant FA9550-18-1-0479, Program Manager Dr. Ali Sayir).
References

1. M. Meneghini, G. Meneghesso, and E. Znoni, *Power GaN Devices: Materials, Applications and Reliability* (Springer International Publishing Switzerland, 2016).

2. J.C. Zolper, Solid. State. Electron. **42**, 2153 (1998).

3. Y. Yoshizumi, S. Hashimoto, T. Tanabe, and M. Kiyama, J. Cryst. Growth **298**, 875 (2007).

4. S. Rajan, P. Waltereit, C. Poblenz, S.J. Heikman, D.S. Green, J.S. Speck, and U.K. Mishra, IEEE Electron Device Lett. **25**, 247 (2004).

5. H.. Amano, Y.; Baines, E. Beam, M. Borgia, T.. Bouchet, P.R.. Chalker, M.. Charles, K.J.. Chen, N.. Chowdhury, R.. Chu, C.. De Santi, M.M. De Souza, S.. Decoutere, L.. Di Cioccio, B.; Eckardt, T.. Egawa, P., Fay, J.J.. Freedsmann, L.. Guido, G.. Haynes, T.. Heckel, D.. Hemakumara, P.. Houston, J.. Hu, M.. Hua, Q.. Huang, A.. Huang, S.. Jiang, H.. Kawai, D.. Kinzer, M.. Kuball, A.. Kumar, K.B.. Lee, X.. Li, D.. Marcon, M.. Marz, R.. McCarthy, G.. Meneghesso, M.. Meneghini, E.. Morvan, A.. Nakajima, E.M.S.. Narayanan, S.. Oliver, T.. Palacios, P.. Daniel, M.. Plissonnier, R.. Reddy, M.. Sun, I.. Thayne, A.. Torres, N.. Trivellin, V.. Unni, M.J.. Uren, M.V.. Hove, D.J.. Wallis, J.. Wang, J.. Xie, S.. Yagi, S.. Yang, C.. Youtsey, R.. Yu, E.. Zanoni, S.. Zeltner, and Y.. Zhang, J. Phys. D. Appl. Phys. **51**, 163001 (2018).

6. H.Z. Xu, Z.G. Wang, M. Kawabe, I. Harrison, B.J. Ansell, and C.T. Foxon, J. Cryst. Growth **218**, 1 (2000).

7. Y. Tian, S.J. Chua, and H. Wang, Solid. State. Electron. **47**, 1863 (2003).

8. J. Wuerfl, E. Bahat-Treidel, F. Brunner, E. Cho, O. Hilt, P. Ivo, A. Knauer, P. Kurpas, R. Lossy, M. Schulz, S. Singwald, M. Weyers, and R. Zhytnytska, Microelectron. Reliab. **51**, 1710 (2011).

9. P.J. Martinez, E. Maset, E. Sanchis-Kilders, V. Esteve, J. Jordán, J.B. Ejea, and A. Ferreres, Semicond. Sci. Technol. **33**, 45006 (2018).

10. J.A. Del Alamo and E.S. Lee, IEEE Trans. Electron Devices **66**, 4578 (2019).

11. G. Meneghesso, G. Verzellesi, F. Danesin, F. Rampazzo, F. Zanon, A. Tazzoli, M. Meneghini, and E. Zanoni, IEEE Trans. Device Mater. Reliab. **8**, 332 (2008).

12. H. Ishida, D. Shibata, H. Matsuo, M. Yanagihara, Y. Uemoto, T. Ueda, T. Tanaka, and D. Ueda, in *2008 IEEE Int. Electron Devices Meet.* (2008).
13. H. Fu, K. Fu, S.R. Alugubelli, C. Cheng, X. Huang, H. Chen, H. Yang, C. Yang, J. Zhou, S.M. Goodnick, and F.A. Ponce, IEEE Electron Device Lett. **41**, 1 (2020).

14. C.B. Goud and K.N. Bhat, IEEE Trans. Electron Devices **38**, 1497 (1991).

15. H. Ohta, K. Hayashi, F. Horikiri, T. Nakamura, and T. Mishima, Jpn. J. Appl. Phys. **57**, 1 (2018).

16. J.R. Laroche, F. Ren, K.W. Baik, S.J. Pearton, B.S. Shelton, and B. Peres, J. Electron. Mater. **34**, 370 (2005).

17. D. Nagulapally, R.P. Joshi, and A. Pradhan, AIP Adv. **5**, 17103 (2015).

18. S. Verma, S.A. Loan, and A.M. Alamoud, J. Comput. Electron. **17**, 256 (2018).

19. J. Möreke, C. Hodges, L.L.E. Mears, M.J. Uren, R.M. Richardson, and M. Kuball, Microelectron. Reliab. **54**, 921 (2014).

20. J. Luo, S.L. Zhao, M.H. Mi, W.W. Chen, B. Hou, J.C. Zhang, X.H. Ma, and Y. Hao, Chinese Phys. B **25**, 2 (2015).

21. A. Cavallini, L. Polenta, M. Rossi, T. Stoica, R. Calarco, R.J. Meijers, T. Richter, and H. Lüth, Nano Lett. **7**, 2166 (2007).

22. J. Ruo-Lian, W. Jun-Zhu, C. Peng, A. -, A. MultilayerStructure on Si Jiang Ruo-Lian, Z. Zuo-Ming, and C. Pen, Chinese Phys. B **12**, 785 (2003).

23. S. Wang, T. Li, J.M. Reifsnider, B. Yang, C. Collins, A.L. Holmes, and J.C. Campbell, IEEE J. Quantum Electron. **36**, 1262 (2000).

24. S.C. Shen, Y. Zhang, D. Yoo, J.B. Limb, J.H. Ryou, P.D. Yoder, and R.D. Dupuis, IEEE Photonics Technol. Lett. **19**, 1744 (2007).

25. Y. Turkulets and I. Shalish, J. Appl. Phys. **124**, 75102 (2018).

26. T. Maeda, T. Narita, M. Kanechika, T. Uesugi, T. Kachi, T. Kimoto, M. Horita, and J. Suda, Appl. Phys. Lett. **112**, 252104 (2018).

27. T. Maeda, M. Okada, M. Ueno, Y. Yamamoto, M. Horita, and J. Suda, Appl. Phys. Express **9**, 91002 (2016).

28. T. Maeda, T. Narita, H. Ueda, M. Kanechika, T. Uesugi, T. Kachi, T. Kimoto, M. Horita, and J. Suda, Appl. Phys. Lett. **115**, (2019).
29 D.E. Aspnes, Phys. Rev. 147, 554 (1966).

30 M. Grundmann. BandEng: Poisson-Schrodinger Solver Software (2004).

31 B. Jogai, J. Appl. Phys. 91, 3721 (2002).

32 S.M. Sze and K.K. Ng, Physics of Semiconductor Devices Third Edition (Wiley-Interscience, 2007).

33 J. Tauc, Mat. Res. Bull. 3, 37 (1968).

34 D. Verma, A.K. Kole, and P. Kumbhakar, J. Alloys Compd. 625, 122 (2015).

35 J.F. Muth, J.H. Lee, I.K. Shmagin, R.M. Kolbas, H.C. Casey, B.P. Keller, U.K. Mishra, and S.P. DenBaars, Appl. Phys. Lett. 71, 2572 (1997).

36 B. Van Zeghbroeck, Principles of Semiconductor Devices (2007).

37 R. Dingle, D.D. Sell, S.E. Stokowski, and M. Illegems, Phys. Rev. B 4, 1211 (1971).
**Figures Captions**

**Fig. 1.** Schematic of PAMBE grown GaN p-n junction diode with its corresponding (a) band edge diagram along the x-axis, where $E_c$, $E_v$ and $E_f$ are the conduction band edge, valence band edge and fermi energy, respectively. (b) Acceptor ($N_a$) and donor ($N_d$) doping density profile, and (c) x-component of the electric field ($F$) calculated using Eq. 1.

**Fig. 2.** Photocurrent responsivity ($I_{PR}$) as a function of incident photon energy ($E_{ph}$) for various values of applied bias ($V$) plotted on (a) linear, and (b) logarithmic scales. (c) Absorption edge ($E_{edge}$) calculated by applying Tauc’s relation to $I_{PR}$ and plotted as a function of $V$ (points). Line is a guide to the eye. (d) Tauc’s plot ($\alpha_0$) and $I_{PR}$ spectra, indicating $E_g = 3.35 \pm 0.2$ eV.

**Fig. 3.** Sub-bandgap photocurrent responsivity, $I_{PR} (E_{ph} < E_g)$, spectra (points) measured at several applied biases ($V$), and compared with calculations using the FKA model (lines) based on Eq. 6: (a) assuming the total local bias ($V_l$) equals the average total bias ($V - V_{bl}$), and (b) adjusting $V_l$ for the best fit to the data. (c) Zero bias optical absorption coefficient, $\alpha_0(E_{ph})$, measurements (points) fit to Eq. 3 (line) to determine $|M_{cv}|^2$ and $E_g$ used in the FKA calculations. (d) $V_l$ as a function of $V$ (points) obtained from the data fits of $I_{PR}$ (part (b) above). The line is a fit to Eq. 7, such that the y-axis intercept indicates $-V_{bl}$, in rough agreement with C-V measurements (inset, plotted with S.I. units). Color indicates $V$ matching the color of $I_{PR}(E_{ph})$ spectra from panel (b) and Fig. 2.

**Fig. 4.** The local electric field ($F$) profile along the x-axis at the location of the $I_{PR}(E_{ph})$ measurement (solid lines) compared with the average $F$ (dashed lines) of the GaN p-n junction diode. $F$ is plotted at various values of applied bias ($V$) color coded as in Figs. 2 and 3.
FIG. 2
FIG. 3
FIG. 4