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Transient Photocurrent from High-Voltage Vertical GaN Diodes Irradiated with Electrons: Experiments and Simulations

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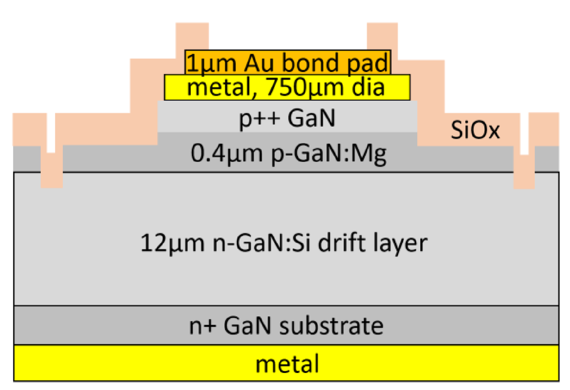
Abstract

High-voltage vertical GaN diodes are being developed for power electronics used in ionizing radiation environments. We present simulations of the transient photocurrent response of diodes exposed to ionizing irradiation with 70 keV and 20 MeV electrons at dose rates in the range of 1.4x10^{7}- 5.0x10^{8} Rad(GaN)/s and uncover the physical processes involved that cannot be otherwise experimentally observed due to orders of magnitude larger RC time constant of the test circuit. The simulations correctly predict the trend in measured steady-state photocurrent. The simulations were performed using an Exploratory Physics Development (XPD) code developed at Sandia National Laboratories (SNL). The code offers the capability to include carrier-defect reactions under more general conditions, not included in commercially available software packages, which enhances the versatility of the simulations.

Experiments

Growth & Device Processing

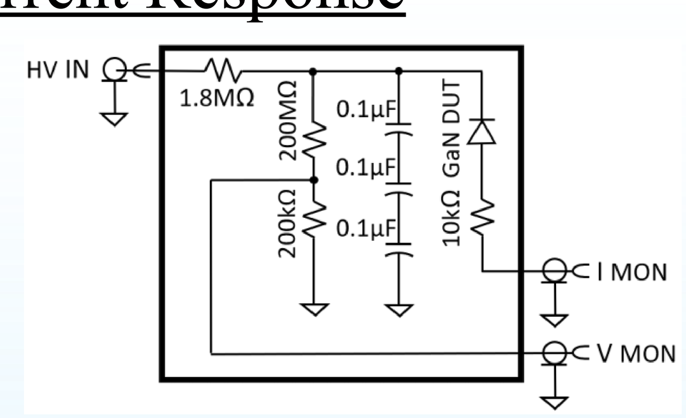


Schematic cross sections of the etched JTE diode structures exposed to electron beam irradiation.

- MOCVD growth (SNL Microsystems Engineering Sciences Applications complex)
- Etched junction termination extension (JTE) to manage electric field distribution and achieve higher breakdown voltages
- Effective junction diameter of 810 µm determined from COMSOL simulations of the electric field distribution
- n-GaN drift regions with thickness 12 µm and doping 1-2x10^{16}/cm^{3} to obtain breakdown voltages up to 1-1.7 kV

Measuring Photocurrent Response

circuit bias voltage, Vb = 1000 V
diode bias voltage, Vd = Vb - IR
(diode debiasing with a 10 kΩ resistor)
radiation pulse ~ 500 ns



Test circuit for measuring photocurrent.

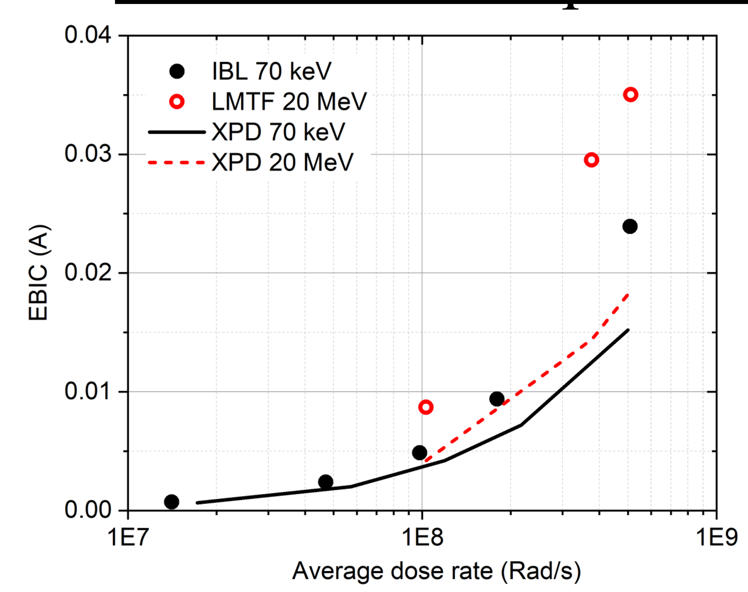
- 70 keV electron irradiation at current densities of 34 - 1118 µA/cm^{2} with corresponding dose rates of 1.4x10^{7}- 5.0x10^{8} Rad(GaN)/s (SNL Ion Beam Lab in Albuquerque, NM)
- 20 MeV electron irradiation at current densities of 8.6x10^{2} - 4.26x10^{3} µA/cm^{2} with corresponding dose rates of 1.0x10^{8} - 5.0x10^{8} Rad(GaN)/s (Little Mountain Test Facility Medusa Linear Accelerator in Ogden, UT)

XPD Simulations

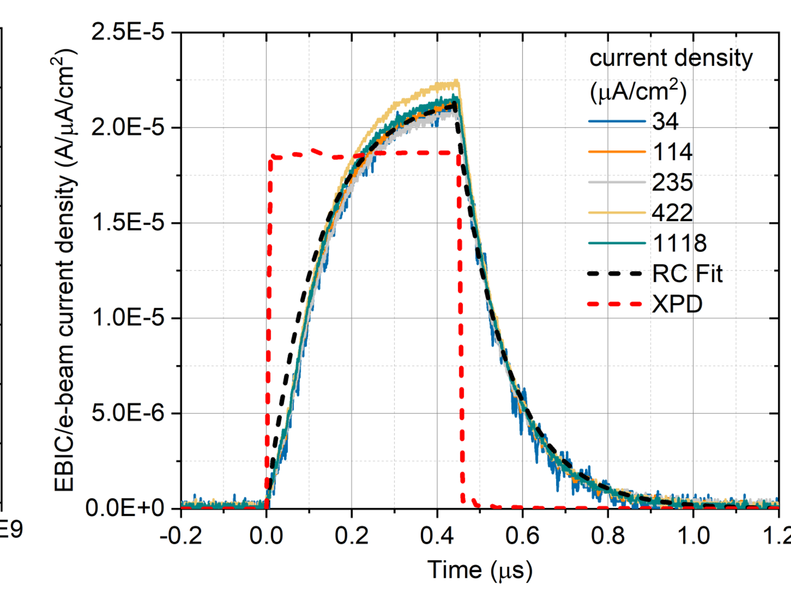
Treatment Approach

- 1D drift-diffusion model and Poisson's equation
- carrier generation by ionizing radiation (includes depth dependence)
- carrier generation by impact ionization leading to breakdown
- carrier recombination (direct, Auger, and rate equations for carrier capture and emission by defects with (+,0,-) charge states)
- debiasing and RC time constant from10kΩ resistor and 12 pF diode capacitance

Photocurrent Dependence on Dose Rate and Time



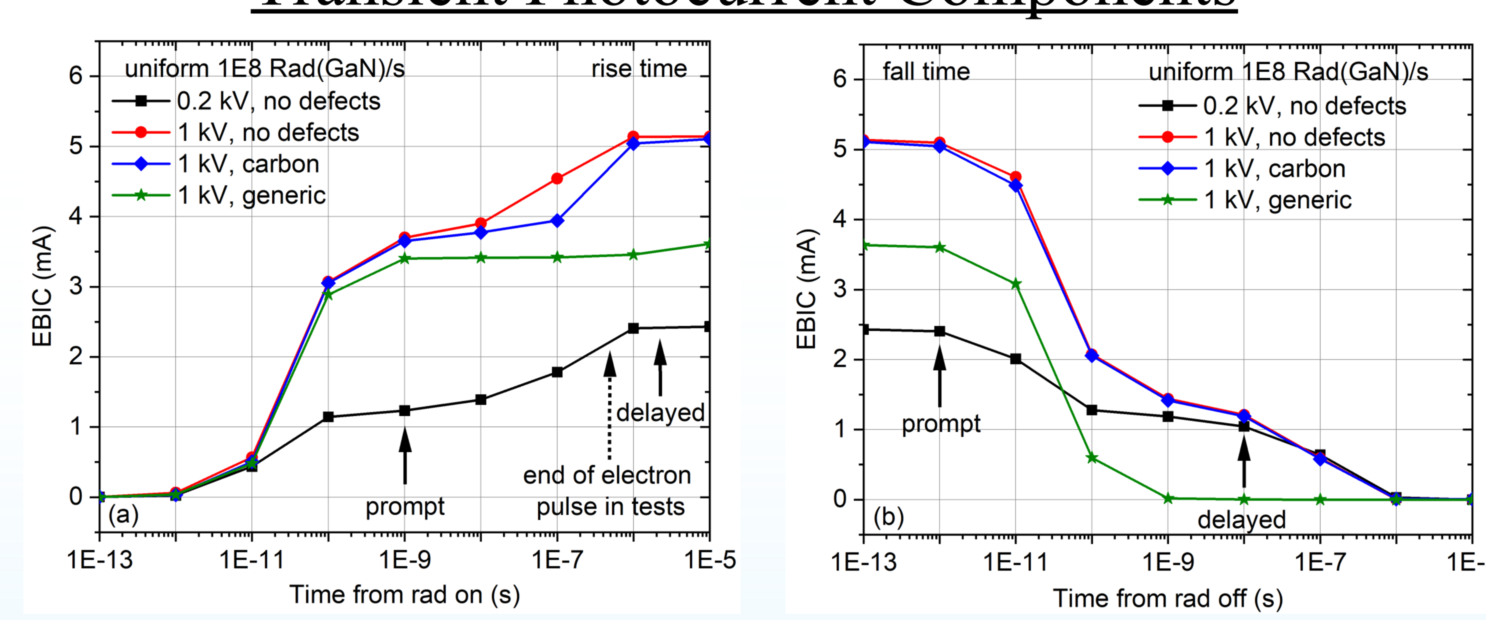
Measured EBIC vs average dose rate for 70 keV and 20 MeV electron irradiations with corresponding simulations.



Normalized EBIC vs time for a diode irradiated with 70 keV electrons using current densities of 34-1118 µA/cm^{2} at a circuit bias voltage of 1 kV.

- Simulations predict EBIC within a factor of 2 from the measured values
- Simulations predict the transient photocurrent response of a diode with rise and fall times of 0.1 ns concealed by the circuit RC time constant of 120 ns

Transient Photocurrent Components

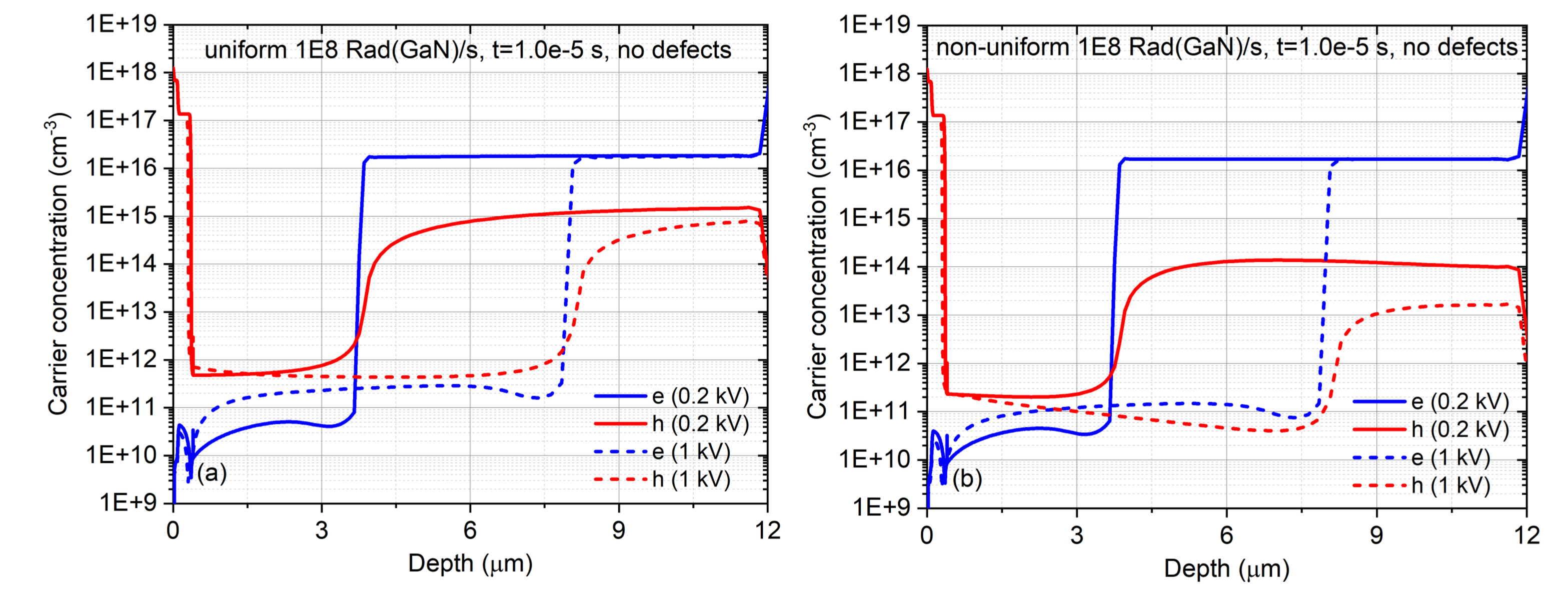


Simulated EBIC vs time after the start (a) and after the end (b) of an electron pulse with uniform dose rate of 10^{8} Rad(GaN)/sec at the surface for a diode with n-GaN net carrier concentration of 1.7x10^{16} cm^{-3} biased at 0.2 kV and 1 kV.

- Prompt component due to carriers generated in the depletion region with time response of 0.1 ns
- Delayed component due to minority carriers generated in the neutral region diffusing to the depletion region with time response of 1 µs
- At Vd = 1 kV, the depletion width is ~7.6 µm and the diffusion length is ~0.18 µm with carrier lifetime 1 ns and low-field mobility of 12 cm^{2}/Vs at 300 K

XPD Simulations

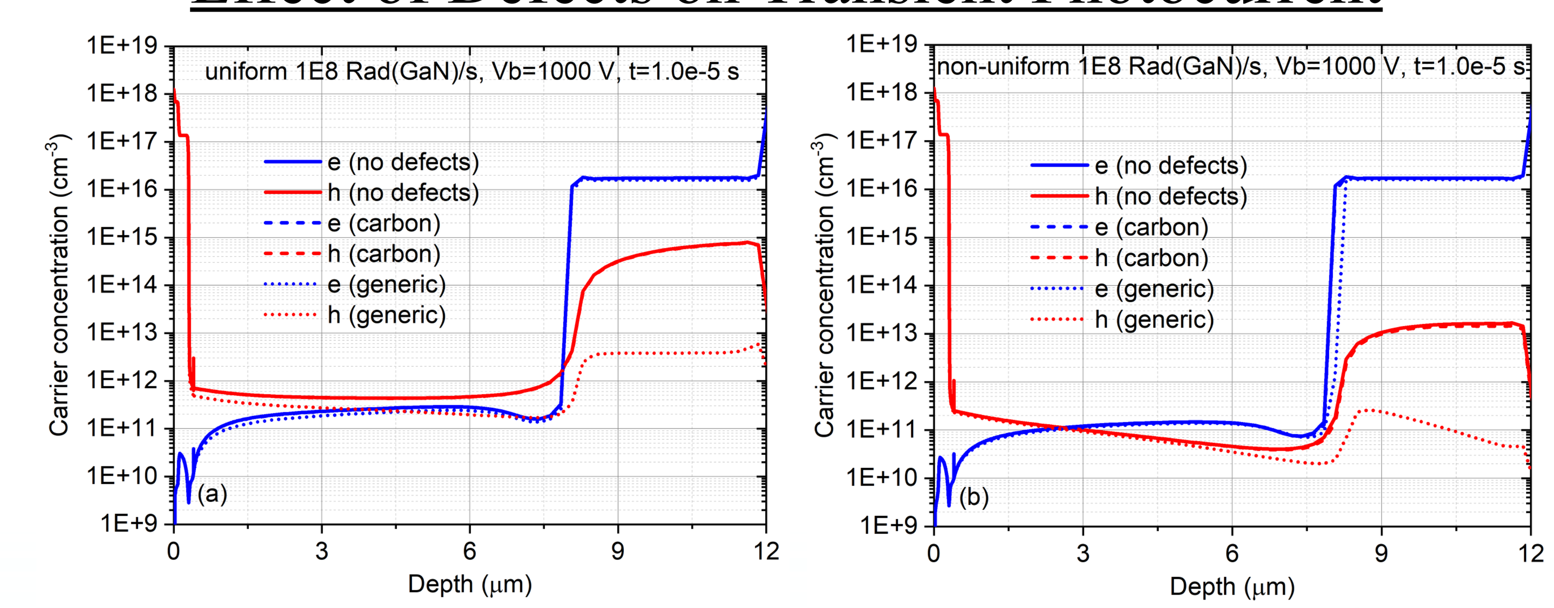
Effect of Voltage Bias on Transient Photocurrent



Simulated carrier concentration vs depth for a GaN diode during irradiation at time 10^{-5} s at diode bias voltage of 0.2 kV and 1 kV.

- The prompt component increases with bias due to more carriers being collected from a larger depletion width
- The delayed component remains unchanged with uniform irradiation but decreases with bias with non-uniform irradiation due to smaller minority carrier concentration within a diffusion length in the neutral region

Effect of Defects on Transient Photocurrent



Simulated carrier concentration vs depth for a GaN diode biased at 1 kV during irradiation at time 10^{-5} s without and with defects (carbon, generic) with defect concentration 10^{15} cm^{-3} . The carbon parameters used here are from Reshchikov et al., Phys. Rev. B, vol. 98, no. 12, pp. 125207, Sept. 2018. The generic defects have mid-gap levels with capture rate coefficients of 10^{-6} cm^{3}/s and represent other defects that may be introduced during device growth.

- Carrier recombination at defects has a small effect on the carrier concentration in the depletion region while it strongly reduces the hole concentration in the neutral region and, therefore, the delayed photocurrent component.
- With non-uniform irradiation, the delayed component is further reduced due to lower carrier generation rate with depth compared to that of uniform irradiation

Conclusions

The XPD simulations capture the real device physics and predict the rise and fall times of the photocurrent response during and post irradiation otherwise not observed in the measured response due to circuit effects. The transient photocurrent consists of a prompt drift component and a delayed diffusion component which depend on the carrier generation rate with depth, bias voltage, and carrier-defect interactions.

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