High Voltage GaN Lateral Photoconductive Semiconductor Switches

Andrew D. Koehler, Travis J. Anderson, Ani Khachatrian, Anindya Nath, Marko J. Tadjer, Stephen P. Buchner, Karl D. Hobart, and Fritz J. Kub

High voltage (>4000 V) GaN lateral photoconductive semiconductor switches (PCSSs) were developed and characterized. The epitaxial structure consisted of 1.4 μm of semi-insulating GaN grown on a SiC substrate. Intrinsic mode operation, where above bandgap light is used to trigger the PCSS, results in the highest amount of photocurrent. These PCSSs can also be triggered in extrinsic mode, where sub-bandgap illumination excites carriers from extrinsic defect levels, but this results in a significantly lower photocurrent. Triggering at near bandgap with 10 V applied, the on-state photocurrent is over eight magnitudes higher than the dark off-state leakage, indicating extremely high responsivity. A 293 nm picosecond pulse width laser was used to determine the rise time of the PCSS to be ~160 ps. Various geometry devices were fabricated, and the low voltage on-state current obeyed a linear trend as a function of perimeter/gap optically while optically gating the PCSS, which is analogous to the width/length of a metal oxide semiconductor field effect transistor. Off-state breakdown voltages >4000 V were achieved and were likely limited by the thickness of the GaN epitaxial layer.

Wide bandgap photoconductive semiconductor switches (PCSSs), such as GaN PCSSs, have gained recent attention due to high critical electric field strength, high electron saturation velocity, and the ability to provide high power ultrafast devices. Previously, extrinsic mode, vertical GaN PCSSs were demonstrated on high resistivity freestanding hydride vapor phase epitaxy (HVPE) GaN substrates. However, operation of extrinsic mode PCSSs is governed by optical absorption at defect and/or impurity states located within the semiconductor’s bandgap, resulting relatively low optical absorption and therefore low efficiency. But this low optical absorption translates into deep optical penetration, on the order of centimeters, which allows for vertical PCSS architectures. Intrinsic mode PCSSs rely on above excitation at or above the bandgap to promote electrons from the valence to conduction band, which can provide fast response time, but limits the penetration depth to only several microns, depending on the optical absorption of the semiconductor and the energy of the photons. This, however, also restricts intrinsic mode PCSSs to lateral architectures. Lateral devices can be easily scaled since the gap dimension is determined by photolithography rather than thick epitaxial growth. GaN PCSSs have previously been demonstrated on semi-insulating GaN achieved by Fe compensation doping in order to reduce leakage currents. However, Fe is known to have strong memory effects, which can redistribute Fe into subsequent films, as well as a narrow window of acceptable doping levels. In addition, Fe creates deep electron traps ($E_C \approx 0.9$ eV), and deep hole traps ($E_V \approx 0.9$ eV), which is beneficial for creating semi-insulating films, but can also result in charge traps with long time constants leading to current collapse in devices. PCSSs with fast response time are required for applications requiring high repetition rates. In this work, we leverage high resistivity, unintentionally doped semi-insulating GaN epitaxial layers grown on SiC to demonstrate high voltage lateral GaN PCSSs with fast response time.

Experimental

Lateral geometry PCSS structures are formed by growing 1.4 μm thick high resistivity, unintentionally doped semi-insulating GaN with resistivity (>10$^{12}$ Ohm-cm) on a SiC substrate by metal organic chemical vapor deposition (MOCVD). As these films are grown by MOCVD, the compensation mechanism is likely due to carbon or oxygen impurities inherent to the growth process. Topside electrodes were formed by patterning and lifting-off electron beam evaporated Ti/Al/Ni/Au (20 nm/120 nm/40 nm/80 nm) followed by rapid thermal annealing at 850°C in N$_2$ for 30 seconds. Unpassivated linear, annular, and a variety of interdigitated finger devices were fabricated, with various spacing between pads. Fig. 1 shows a schematic cross-section of the later GaN PCSSs with plan views of the interdigitated finger, lateral, and annular geometries.

The photocurrent of GaN PCSSs triggered as a function of illumination wavelength were investigated by exciting the entire active area with monochromated light from a 300 W Xe arc lamp, directed by a fiber bundle, onto the device. Photoluminescence (PL) measurements were illuminated by a 325 nm, 50 mW, HeCd laser. Fast transients of the GaN PCSS was characterized by 293 nm optical pulses generated by frequency doubling the 586 nm output of a cavity-dumped mode-locked dye laser with a full width half maximum (FWHM) pulse width of 2 ps.

Schematic Cross-Section Plan View of Pad Configurations

Figure 1. a) Schematic cross-section of GaN PCSSs and plan view of b) linear, c) annular, and d) interdigitated fingered pad configurations.

© The Author(s) 2017. Published by ECS. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 License (CC BY, http://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse of the work in any medium, provided the original work is properly cited. [DOI:10.1149/2.0231711jss] All rights reserved.
Results and Discussion

The wavelength dependence of the steady-state photocurrent (measured at 30 seconds after opening the shutter) of the high resistivity, unintentionally doped semi-insulating GaN PCSSs is shown in Fig. 2a. The photocurrent is measured on interdigitated devices with 5 fingers, 50 μm gap, 50 μm finger width, and 500 μm finger length at 10 V bias. The peak photoresponse is near the GaN bandgap at ∼3.4 eV. The photoresponse decreases slightly with increasing energy above the ∼3.4 eV peak. Just below 3.4 eV, the photoresponse drops orders of magnitude until ∼3.2 eV. The C5 shallow acceptor of GaN has previously been identified to be located at EC – 3.2 eV by deep level optical spectroscopy (DLOS). This explains the photocurrent with excitation of energies from 3.2 to 3.4 eV, where electrons are promoted from this shallow acceptor state up to the conduction band. With excitation below 3.2 eV, some photocurrent is still observed until ∼2.6 eV. This is likely a result of the broad blue luminescence band, centered at ∼2.8 eV, also seen in the room temperature PL spectrum (Figure 2b). The PL shows the bandgap located at 3.41 eV with an additional shoulders located around 3.36 eV and 3.30 in the PL spectrum, likely attributed to hydrogen-carbon complexes such as C6O3H6. In addition, the broad yellow and blue luminescence band is observed, however, the intensity of this defect luminescence is an order of magnitude less than the band edge. The periodic modulations within the yellow and blue luminescence band are a result of interference effects due to the 1.4 μm thick GaN film.

The on-state current (under 3.4 eV illumination from the Xe arc lamp) is shown as a function of device geometry in Fig. 3. The on-state current of interdigitated finger devices, linear, and annular designs, were plotted versus the pad perimeter divided by the gap between the pads, giving a linear relationship. This indicates the operation of these lateral GaN PCSSs operate similarly to a transistor, where the perimeter/gap is analogous to the transistor width/length for the on-state current. At low voltages in the on-state, the shape of the device is not relevant, but the on-state current density is proportional to the width and length dimensions. Excitation from above bandgap light turns the PCSS on, optically gating the GaN, allowing current to flow between contact pads across the gap.

The long temporal response of the steady-state photocurrent of the same interdigitated device as previously characterized under 3.4 eV illumination from the Xe arc lamp is shown in Fig. 4. The on/off ratio is over eight orders of magnitude, showing high efficiency of photogeneration of electron-hole pairs and high efficiency of charge collection. The turn-on occurs much faster than the turn-off, indicating some slow transient persistent photoconductivity. After the illumination is turned off, sudden drop (over three orders of magnitude) occurs quickly due to direct recombination. It takes longer (∼10 seconds) for the photocurrent to exponentially decay to the baseline dark current value, likely a result of emission of carriers from deep trap states within the semiconductor bandgap resulting in persistent photoconductivity. This observed persistent photoconductivity could limit the repetition rate of the PCSS. However, it is likely that PCSSs based on GaN with
lower defect densities, such as GaN on native substrates can reduce the persistent photoconductivity transient. To investigate speed of the rise time and fall times, triggering was performed using a 293 nm picosecond laser. A 100 kHz repetition rate with 0.084 pJ/pulse was focused to a 50 μm x 25 μm rectangular spot using a 0.4 cm focal length lens to excite a 25 μm wide area between a linear structure with a gap of 25 μm. As shown in Fig. 5, the rise time (10% to 90%) was characterized to be on the order of \( \sim 160 \text{ ps} \) and the fall time is \( \sim 8 \mu\text{s} \). Since the laser is operated at 100 kHz, the PCSS does not reach the absolute baseline dark current, which takes \( \sim 10 \text{ seconds} \) for the photocurrent to decay, as shown in Fig. 4.

The off-state, dark, I-V breakdown curves are shown in Fig. 6a. The breakdown voltage of the GaN:PCSSs are shown as a function of annular gap spacing (up to 250 μm) in Fig. 6b, with constant inner diameter pads of 250 μm. Due to sample limitations, these are the only devices available for breakdown testing. The differences in off-state leakage current could be a result of non-uniformities in the epitaxial layer or processing variations. All breakdown measurements were performed in a vacuum (1 \( \times 10^{-4} \) mbar) probe station to avoid surface flashover. The breakdown is defined as the voltage when the device fails catastrophically. The breakdown strength of the PCSS is \( \sim 0.27 \text{ MV/cm} \), and the breakdown voltage saturates at \( \sim 4 \text{ kV} \) as a function of gap spacing. Likely, the epitaxial GaN layers limit the breakdown of these PCSSs. The thickness of the GaN epitaxial layers used in this work (1.4 μm) is significantly thinner than previous results where heteroepitaxial GaN-on-Si was grown to 5.5 μm, which resulted in 2.3 MV/cm.\(^{11}\) In addition, the buffer layers were not specifically engineering for high blocking voltage operation, as the design of these buffer layers is known to significantly impact the breakdown voltage.\(^{12}\) Integration of plasma enhanced chemical vapor deposition (PECVD) SiN\(^{13}\) and PECVD SiO\(_2\) surface passivation resulted in reduced blocking voltage, and will be investigated further as effective high voltage passivation layers is essential for optimal performance. Therefore to obtain higher breakdown voltages, thicker GaN layers and optimized buffer layers would be advantageous. However, when compared to previously demonstrated lateral GaAs PCSSs, where the epitaxial layer thickness was 0.6 mm and the gap between pads was 2 mm to achieve a blocking voltage of 6 kV,\(^{14}\) the GaN PCSS in this work could achieve \( >4 \text{ kV} \) blocking voltage with only a 100 μm gap due to the superior critical electric field of GaN opposed to GaAs.

**Summary**

High resistivity, unintentionally doped semi-insulating GaN lateral PCSSs were fabricated on 1.4 μm of semi-insulating GaN grown on a SiC substrate. The highest photoresponse was observed for intrinsic mode triggering. At near bandgap triggering with 10 V applied, the on-state photocurrent is over eight magnitudes higher than the dark leakage current, indicating extremely high responsivity. The PCSS rise time was determined to be \( \sim 160 \text{ ps} \). Various geometry devices were fabricated, and the low voltage on-state current obeyed a linear trend as a function of perimeter/gap optically gating the PCSS, which is analogous to the width/length of a metal oxide semiconductor field effect transistor. Off-state breakdown voltages \( >4000 \text{ V} \) were achieved and were likely limited by the thickness of the GaN epitaxial layer. Demonstration of these lateral GaN PCSSs show promise for future high-speed switches.

**Acknowledgments**

This work was sponsored by the Department of the Navy, Office of Naval Research under Dr. Joong Kim. The authors are sincerely thankful to Dr. Sapharishi Sriram of Wolfspeed, a Cree Company, for providing semi-insulating epitaxial GaN on SiC.

**References**

1. J. S. Sullivan and J. R. Stanley, “Wide bandgap extrinsic photoconductive switches,” *PPPS-2007 - Pulsed Power Plasma Sci.*, 2007, 2(5), 1040 (2007).
2. P. M. Leach, R. Metzger, E. A. Preble, and K. R. Evans, “High voltage, bulk GaN-based photoconductive switches for pulsed power applications,” *Gall. Nitride Mater. Devices IV*, Vol. 8625, 1 (2013).
3. J. S. Sullivan, “Wide Bandgap Extrinsic Photoconductive Switches, Report #LLNL-TH-523591,” 2012.
4. X. Wang, S. K. Mazumder, and W. Shi, “A GaN-based insulated-gate photoconductive semiconductor switch for ultrashort high-power electric pulses,” IEEE Electron Device Lett., 36(5), 493 (2015).

5. Y. Chen, H. Lu, D. Chen, P. Ren, R. Zhang, and Y. Zheng, “High-voltage photoconductive semiconductor switches fabricated on semi-insulating HVPE GaN:Fe template,” Phys. Status Solidi, 13(5–6), 374 (2016).

6. S. Heikman, S. Keller, S. P. Denbaars, and U. K. Mishra, “Growth of Fe doped semi-insulating GaN by molecular beam epitaxy,” Appl. Phys. Lett., 81(3), 439 (2002).

7. A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, and S. J. Pearton, “Electrical and optical properties of Fe-doped semi-insulating GaN templates,” Appl. Phys. Lett., 83(16), 3314 (2003).

8. D.-S. Kim, C.-H. Won, H.-S. Kang, Y.-J. Kim, Y.T. Kim, I.M. Kang, and J.-H. Lee, “Growth and characterization of semi-insulating carbon-doped/undoped GaN multiple-layer buffer,” Semicond. Sci. Technol., 30(3), 35010 (2015).

9. A. Armstrong, A. R. Arehart, B. Moran, S. P. DenBaars, U. K. Mishra, J. S. Speck, and S. A. Ringel, “Impact of carbon on trap states in n-type GaN grown by molecular beam epitaxy,” Appl. Phys. Lett., 84(3), 374 (2004).

10. D. O. Demchenko, I. C. Diallo, and M. A. Reshchikov, “Hydrogen-carbon complexes and the blue luminescence band in GaN,” J. Appl. Phys., 119(3), 1534 (2011).

11. I. B. Rowena, S. L. Selvaraj, and T. Egawa, “Buffer thickness contribution to suppress vertical leakage current with high breakdown field (2.3 MV/cm) for GaN on Si,” IEEE Electron Device Lett., 32(11), 1534 (2011).

12. A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, and S. J. Pearton, “Electrical and optical properties of Fe-doped semi-insulating GaN templates,” Appl. Phys. Lett., 83(16), 3314 (2003).

13. M. J. Tadjer, T. J. Anderson, A. D. Koehler, C. R. Eddy, D. I. Shahin, K. D. Hobart, and F. J. Kub, “A Tri-Layer PECVD SiN Passivation Process for Improved AlGaN/GaN HEMT Performance,” ECS J. Solid State Sci. Technol., 6(1), P58 (2017).

14. W. Shi, C. Ma, and M. Li, “Research on the failure mechanism of high-power GaAs PCSS,” IEEE Trans. Power Electron., 30(5), 2427 (2015).