Characterization of Optically Modulated Semi-Insulating GaN Photoconductive Semiconductor Switches

Geoffrey M. Foster[1], Andrew Koehler[2], Karl Hobart[2], Sadab Mahmud[3], Samuel Atwimah[3], Raghav Khanna[3], and Travis Anderson[2]

[1]Jacobs Inc., Washington DC 20375, USA geoffrey.foster.ctr@nrl.navy.mil 202-404-6788
[2]U.S. Naval Research Laboratory, Washington DC 20375, USA,
[3]University of Toledo, Toledo, OH 43606

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Abstract

Semi-insulating, carbon-doped gallium nitride is an excellent candidate for a photoconductive switch. This material has a high critical field strength, resulting in a high breakdown voltage. By utilizing a high-powered commercial off-the-shelf (COTS) light emitting diodes (LEDs), the energy levels from the carbon-related defects allow photocurrent generation from near to above band gap light. Modulating the optical power density modulates the on-resistance.

INTRODUCTION

Photoconductive semiconductor switches (PCSSs) have the potential to outperform conventional unipolar semiconductor power devices [1]. A Gallium Nitride Photoconductive Semiconductor Switch (PCSSs) can meet the need for a fast and efficient switch that operates at high power. These devices operate using photoconductivity, wherein the material becomes conductive after the absorption of light [2-4]. Traditionally, silicon switches have been used. However, in recent years, wide bandgap photoconductive semiconductor switches, such as GaN PCSSs, have gained attention due to high critical electric field strength, high electron saturation velocity, and the ability to provide high power ultrafast devices[5,6].

Conventional, unipolar, power semiconductor devices are constrained by the resistance of the drift layer, which is required for voltage blocking, but adds additional resistance in the on-state. While providing a higher breakdown voltage, a thicker or more lightly doped drift layer will increase the on-resistance, which creates a tradeoff for the design of high-voltage devices with low conduction losses. A PCSS can overcome the on-resistance vs. breakdown voltage limits of unipolar power devices by optically modulating the conductivity of the entire drift layer through high-density free-carrier injection. This mechanism of modulating channel-conductivity by optically injecting charge facilitates fast switching speeds while inherently providing optical isolation to the gate driver control circuitry.

EXPERIMENT

Four microns of GaN was grown on a silicon carbide (SiC) substrate by metal organic chemical vapor deposition (MOCVD), with a carbon doping concentration of 5×10^{17} cm^{-3}. Ti/Al/Ni/Au contacts were deposited, using a lift off technique with an 800C rapid anneal, varying the distances between the two contacts, as seen in Figure 1.

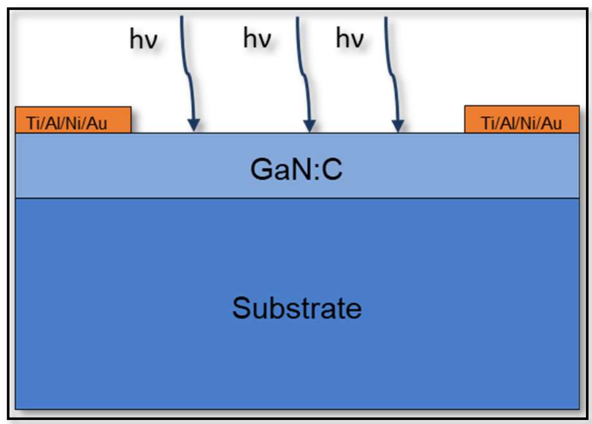

Figure 1. Cross section for a lateral PCSS with incident photons at the surface.

In order to characterize the electric characteristics of PCSS's a Keithley 4200 parameter analyzer was used to measure the current while a voltage is applied, while an external monochromatic light or an external LED is applied across the gap of the PCSS. To measure off state hold off characteristics, a Bertan 225 high voltage supply was used to provide high voltage across the device, measured in a vacuum probe station to avoid surface flashover (when the air breaks down before the material).

RESULTS AND DISCUSSION

As shown in Figure 2, PCSS devices were characterized using photoionization spectroscopy with a monochromatic light source. Light is shone across the gap of the PCSS with a varying wavelength to induce current by photoionizing trap states or by direct band-to-band transitions. At illumination with energy at bandgap (3.4 eV), a strong photoresponse, with eight orders of magnitude on/off current, is observed. Below bandgap, at 3.1eV an increase of photocurrent is seen, indicating a response from carbon-related defects. This is indicative of a deep trap state in the bandgap that is contributing to the overall photoconductivity.

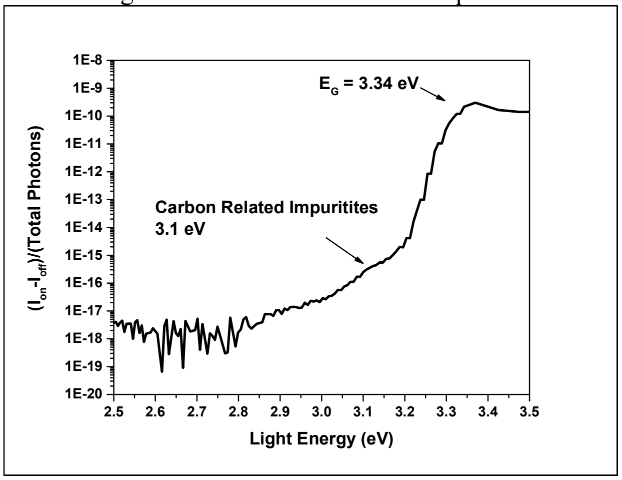

Figure 2. Photoionization spectroscopy showing a band gap photoresponse at 3.34 eV and an impurity related response at 3.1 eV. At bandgap, there is 8x on/off current

A COTS 365 nm LED is used to produce a photoresponse several orders of magnitude greater than the monochromatic light. The increase in optical power density results in an increase in generated free carriers, corresponding to a proportional reduction of R_{ON}. A 1mm wide device with a gap of 20 microns was characterized using a COTS 365 nm LED source while modulating the intensity of the LED. The resulting family of curves in Figure 3, illustrates decreasing resistance with increasing power density of photons. The on-resistance is 334.1Ω at LED intensity of 33.33 mW/cm^2, and is 193.2Ω at LED intensity of 191.67 mW/cm^2. With a higher-powered LED, this resistance would continue to decrease.

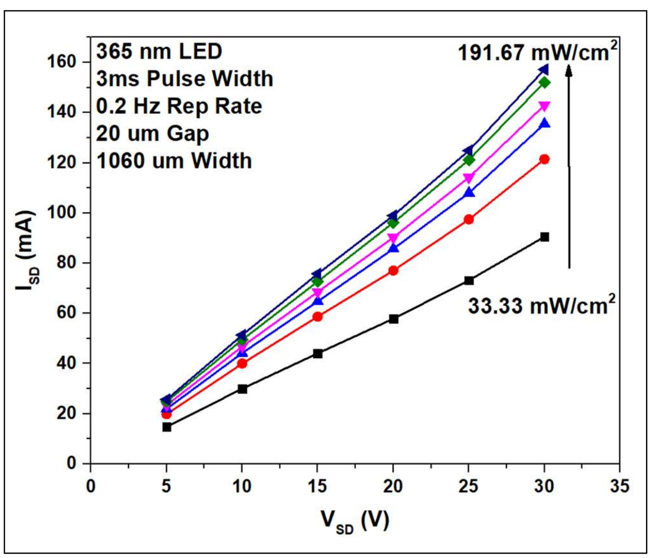

Figure 3. I-V curves on a 1mm device that show a decreasing resistance with increasing LED intensity

Table 1. Extracted values from CTLM measurement show decreasing sheet and contact resistance with increasing LED intensity.

CTLM	R_S (Ω/□)	L_T (µm)	ρ_C (Ωcm^2)	R_C (Ωmm)
Low Illum.	3.80E3	4.24E1	6.84E-2	1.61E2
High Illum.	3.16E3	3.68E1	4.28E-2	1.16E2

CTLM structures were measured to extract values for sheet resistance, transfer length, contact resistivity, and contact resistance using high illumination (191.67 mW/cm^2) and low illumination (91.67 mW/cm^2) and are shown in Table 1. All of these values decrease with increasing optical power density from the LED. Figure 4 shows off-state breakdown values, measured from CTLM structures, ranging from 2760V at a gap of 50 microns to 8444V at a gap of 250 microns.

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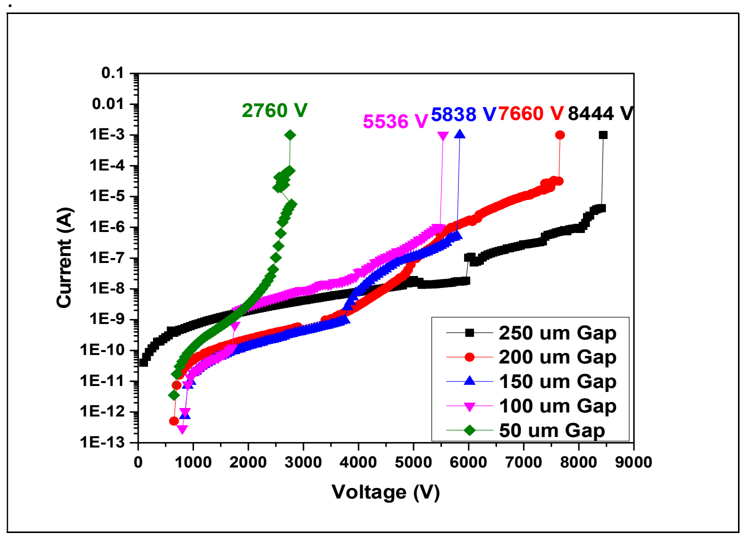

Figure 4. Off-state breakdown of a series of lateral PCSS devices, with breakdown voltages ranging from 2760V at 50 µm gap to 8444V at 250 µm gap.

To further characterize the transient on/off switching times, a custom circuit is being developed. Figure 5 shows a proposed double pulse testing (DPT) [7] circuit that will be used to characterize transient switching behavior for the device under test (DUT) between on- and off-states, while eliminating thermal effects.

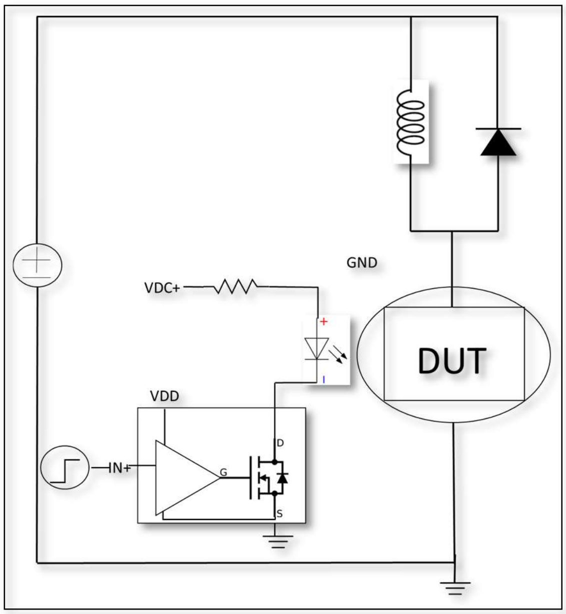

Figure 5. Double pulse testing circuit, allowing for fast transient response measurements while eliminating thermal effects. The LED driving circuit is also present.

SUMMARY

Photoconductive Semiconductor Switches made of carbon doped GaN have been characterized under illumination of both monochromatic light and an LED under variable intensities showing decrease in the on-resistance as the optical power density is increased. As the optical power density is increased from 33.33 mW/cm2 to 191.67 mW/cm2, the on-resistance is decreased from 334.1Ω to 193.2Ω. Similar decreases in sheet resistance and contact resistance are seen from CTLM measurements.

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ACRONYMS

COTS: Commercial Off-the-Shelf
LED: Light Emitting Diode
PCSS: Photoconductive Semiconductor Switch
SIC: Silicon Carbide
MOCVD: Metal Organic Chemical Vapor Deposition
CTLM: Circular Transmission Line Measurements
DPT: Double Pulse Testing
DUT: Device Under Test