Toward the Development of an Efficient Bulk Semi-Insulating GaN Photoconductive Switch

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Abstract

Photoconductive semiconductor switches (PCSS) made from bulk, semi-insulating GaN have been fabricated and tested under pulse-charged conditions. Switching response and photocurrent efficiency of GaN PCSSs triggered by sub-10 ns, 355 nm laser pulses is reported. It is shown that fast rise time (<300 ns) voltage pulses can be used to charge a GaN PCSS to fields well beyond the DC breakdown field strength of GaN and improve switching performance. GaN's wide band gap, breakdown field strength, and electron mobility make it a material superior to SiC and far superior to GaAs for PCSS applications, though historically these materials have dominated PCSS research due to their relative ease of fabrication. Recent improvements to crystal quality and wafer size have allowed GaN and more recently semi-insulating GaN to play an increasing role in high-power and high-voltage solid state devices.

I. INTRODUCTION

Direct band gap photoconductive semiconductor switches (PCSS) are in principle, capable of two modes of operation: low-gain (<1) linear mode, and a high gain (>>1) nonlinear mode known as lock-on. Observed in GaAs in 1987 (ref) and in other direct band gap materials since then (ref), lock-on enables reduced requirements for optical trigger energy by over two orders of magnitude, and as such greatly improves the trigger and portability requirements of PCSSs. High gain or lock-on mode has never been observed in GaN, and the material's wide band gap (3.39 eV), nominal breakdown field (4-5 MV/cm), and thermal conductivity (3.7 W cm^{-1} K^{-1}) make it a substrate superior to any other commonly available direct-band gap material for PCSS construction. Since 2006 (ref), semi-insulating (SI) GaN has been commercially available and crystal quality has improved significantly. The high breakdown field and minimal leakage current of such SI GaN material may enable an appropriately packaged PCSS to sustain the fields necessary to observe the predicted phenomenon of lock-on in a wide-bandgap material.

II. EXPERIMENTAL DESIGN

A. Pulse Generator

To maximize the field applicable to each device, a pulse generator was constructed (fig. 1) to provide up to 58 kV pulses with <300 ns rise time. A 30 ns transmission line is pulse charged, and the pulse is held high by a stack and discharged after microseconds by a dry air-pressurized spark gap.

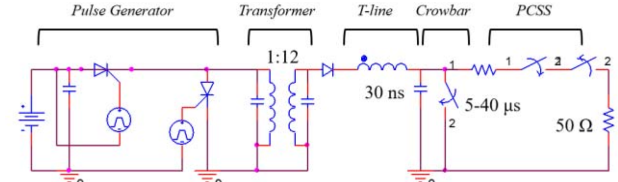

Figure 1. Pulse generator design schematic

B. Switch Design

Vertical and lateral switch geometries were implemented, and lateral geometry switches were fabricated with and without a field-shaping electrode. The breakdown field

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and current-handling capabilities of vertical geometry switches are superior to those of lateral switches. Initially lateral geometry switches were fabricated with only a metal contact (Au, 1 μm) to form ohmic contact with the underlying SI GaN. These contacts were 2 x 2 mm with 3 mm gap between them arranged in a 2 x 2 pattern on the substrate, allowing 4 total current paths per lateral device. Poor switch lifetime (~5 shots at >100 kV cm^{-1}) and microscopic analysis of failure mode suggested field enhancements at the contact edge were largely responsible. To mitigate this, a rounded electrode of 700 μm radius was fabricated and bonded to the contact top of successive switches. While peak electric field reduced moderately, switch lifetime was improved fourfold. The metal stack was also improved, with a stack of Ti(20 nm)/Ni(50 nm)/Au(1000 nm) deposited for each successive switch; ohmic contact is formed with a rapid thermal anneal in N_2 atmosphere at 600 ℃ for 100 s.

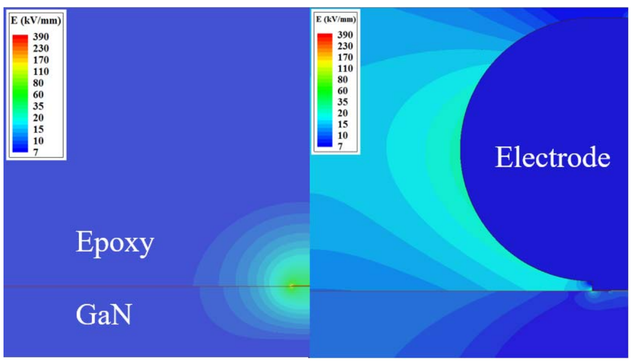

Figure 2: Electrostatic simulations of lateral switch charged to 30 kV (100 kV/cm) without (left) and with (right) a contact-top field shaping electrode

To reduce the peak field (mitigate field enhancements) further, a vertical geometry utilizing a transparent cathode (fig. 3) was designed. In electrostatic simulations this reduced the peak field in the device and concentrates field enhancements outside the region of illumination/current conduction, thereby increasing the switch hold-off capability. As is observed in lateral GaAs PCSS designs, at high field illumination of only the cathode contact can trigger a (linear mode) switching event. This illumination condition is one of several possible in the lateral geometry, but is the only one possible (with intrinsic triggering) in the vertical geometry, since absorption depth at above-band gap optical energies is < 1 μm, while the substrate thickness is 350-450 μm.

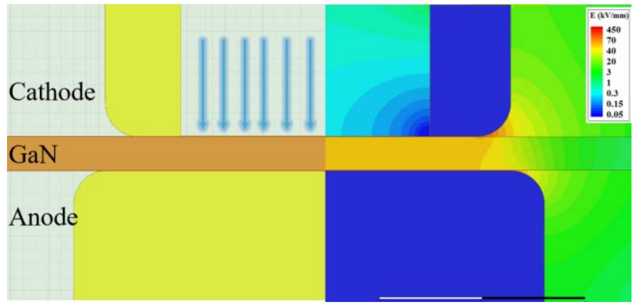

Figure 3. Cross-sectional view of vertical switch geometry as a schematic (left) and electrostatic simulation (right)

C. Experimental Setup

A frequency-tripled Nd:YAG fast-pulse laser serves as the trigger source, emitting an 8 ns-wide, 355 nm wavelength pulse at variable energy (4 mJ cm^{-2} on target was used for the results reported here). The pulse generator is triggered 600 ns before the laser pulse arrives, allowing the transmission line to charge and the voltage to stabilize before the PCSS is triggered. Current through the load resistor (fig. 1) is measured with a CVR and the transmission line voltage (voltage across the PCSS) is monitored with a high voltage probe.

III. EXPERIMENTAL DESIGN

A. Substrate Characterization

Semi-insulating substrates were procured from Kyma Technologies Inc. and Ammono S.A. of Poland. Three 10 x 10 x ~0.45 mm c-plane bulk substrates were acquired from Kyma. A single 1.5-inch c-plane wafer of thickness 350 μm was acquired from Ammono S.A; this was diced into ~10 x 10 mm samples. The samples are identified in table 1.

Table 1. GaN samples used

ID	Manufacturer	Grade	Geometry
A2	Ammono	n/a	Lateral
A3	Ammono	n/a	Lateral
A5	Ammono	n/a	Vertical
1578.2	Kyma	Production	Lateral
1578.5	Kyma	Production	Lateral
2158.2	Kyma	Production	Vertical
2241.8	Kyma	Research	Lateral

The materials were characterized by high-voltage IV measurements, optical spectroscopy, and SEM. On samples A2, A3, 1278.2, and 1578.5, gold contacts were deposited on the epi-ready face by e-beam deposition and sputtering. Four contacts were deposited on each face with a 3.2 mm gap separating each contact (figures 4, 5) and IV traces were taken for each current path. At high voltages, resistivity varies strongly with respect to voltage. Resistivity values in Table 2 are taken assuming current conduction throughout the entire sample depth.

Table 2. Sample HV resistivity values for Kyma and Ammono materials

Sample	Field (kV/cm) [Voltage (kV)]	Resistivity (Ω cm)
A3	12.5 [4]	$1.5 \cdot 10^{10}$
A3	31 [10]	$3.2 \cdot 10^{9}$
A3	94 [30]	$1.6 \cdot 10^{9}$
1578.2	12.5 [4]	$5.6 \cdot 10^{9}$
1578.2	31 [10]	$3.7 \cdot 10^{9}$
1578.2	94 [30]	$2.2 \cdot 10^{9}$

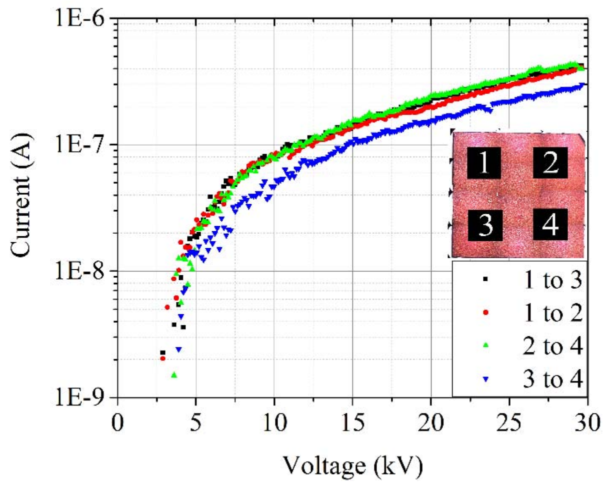

Figure 4. I/V measurements for sample A3

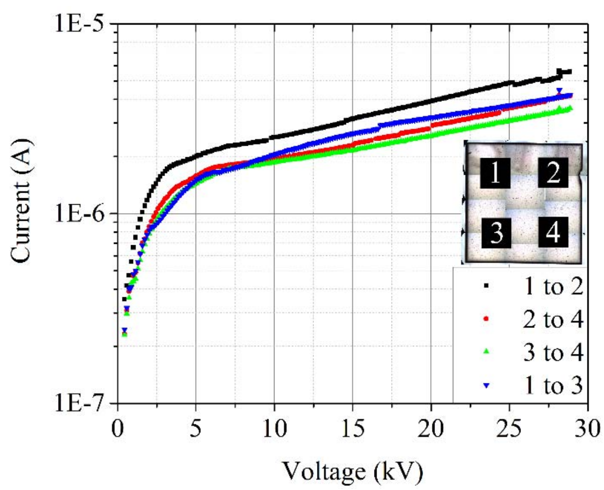

Figure 5. C/V measurements for sample A3

B. Epitaxial n-GaN Growth

To minimize current crowding in both lateral and vertical geometry switches, epitaxial growth of low-resistivity (in this case 0.02 Ω cm) is necessary. Epitaxial growth of GaN via MOCVD is typically (ref) performed in an atmosphere of silane (SiH_4), however this atmosphere at the high temperatures of MOCVD growth can contaminate both the substrate and the susceptor, lowering the quality of the resulting epi layer. A novel (ref) technique of growth in nitrogen addresses this contamination issue. Optimal growth conditions (minimum resistivity, highest mobility, and lowest pit density) occurs under a TMGa flow rate of 12 sccm, NH_3 flow rate of 2000 sccm, and at a temperature of 980 ℃. Under these conditions a 60 nm layer of n-GaN with, $\rho_0 = 4.5 \cdot 10^{-2}$ Ω cm, density, $n = 2 \cdot 10^{17}$ cm^{-3}, and mobility 30 cm^{2} V^{-1} s^{-1} was grown under where the contact metal stack would be deposited.

IV.EXPERIMENTAL RESULTS

Each switch configuration was tested at constant optical energy and load resistance, varying laser trigger illumination profile and bias field. Switch performance with respect to illumination profile, bias field, and geometry is outlined in tables 3 and 4. Linear mode switching events are defined experimentally by the rise and fall of measured current conduction through the PCSS with the rising and falling edge of each trigger laser pulse; current is conducted for ~8 ns for an 8 ns-wide pulse (fig. 6).

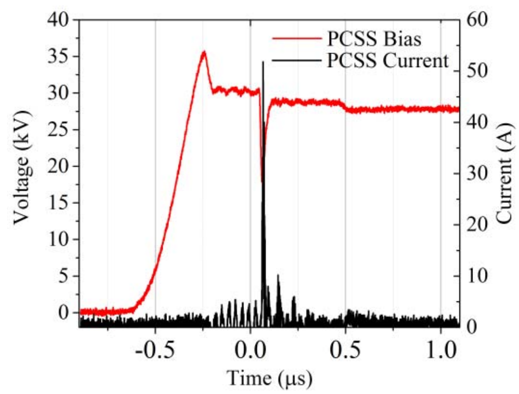

Figure 6. PCSS voltage and current during a linear mode switching event.

Switch failure under partial gap illumination is a consistently two-stage event. At the field at which the device fails when triggered, a linear-mode switching event occurs, with catastrophic failure following <10 ns after the switch opens. After the laser pulse ends, the conducting region rapidly changes its ‘state’ from conductive to insulating, inducing high transient electric fields concentrated at the contacts and inducing failure.

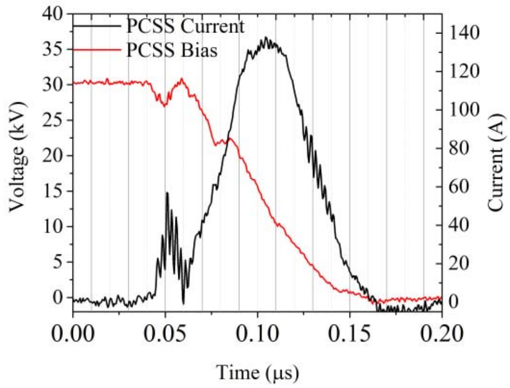

Figure 7. Dual-stage catastrophic failure of a switch at 100 kV cm^{-1}

While no PCSS of GaN or any other material has successfully been switched at these fields (ref), lock-on has not been observed.

Table 3. Switch geometry influence on maximum switching field

Geometry (Material)	Epi Layer	Field (kV/cm)	Mode
Vertical (Ammono)	Yes	200	Linear
Lateral w/ electrode (Kyma)	Yes	100	Linear
Lateral w/out electrode (Ammono)	No	126	Linear
Lateral w/out electrode (Kyma)	No	110	Linear

Table 4. Illumination profile and bias field influence on maximum switching field.

Illumination Profile	Location	Field (kV/cm)	Mode
Sliver	Full gap	53-126	Linear
Spot	Cathode	<100	None
Spot	Cathode	>120	Linear
None	n/a	<130	None
Dual Spot	Contact edges	>120	Linear

V.FUTURE WORK

As work continues to find the threshold field for lock-on in GaN, preliminary modelling work will be undertaken based on the work of Kang and Kambour which describes lock-on in terms of impact ionization by carrier-carrier scattering (ref); and the multiple charge domain theory of Tian and Shi (ref). Both of these have had some measure of success describing lock-on in GaAs, and may provide insight into the field required to observe it in GaN. Experimentally, alternate electrode geometry (Rogowski or Bruce profile) and substrate geometry (mesa etched bulk GaN) will further mitigate field enhancements, enabling switching at greater bulk fields. The high resistivity and low carrier mobility of the available semi-insulating substrates suggest a less resistive nominally undoped or lightly doped material could enable more efficient switching, and potentially have carrier mobility sufficient to allow carrier drifts of the energies necessary to initiate impact ionization and lock-on (ref).