Remote Power Transmission Using High Power GaN HEMTs and Diodes for Regenerative Fuel Cells

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Planned Completion = March 31, 2007

Research Goals and Objectives

- To develop enabling technologies to build a novel wireless power transmission (WPT) system for NASA Space Missions
- applications of such systems would include:

  remote transmission of energy to charge regenerative fuel cells for NASA space missions

  Additional potential applications include unmanned aerial vehicles and unmanned drones with capability for very long duration surveillance, microwave powered aircraft and reusable aeronautical vehicles designed to provide cellular communication services
- Investigate high power density GaN devices and circuits that are the most promising candidates for the necessary high power microwave system at frequencies of a few GHz to mm-wave.
- demonstrate high voltage, high temperature capability of GaN diodes and transistors (this project) and design of RF transmitter architectures for high DC-to-RF conversion efficiency (the other project led by Lin)

Relevance to Current State-of-the-Art

- Existing microwave technology based on GaAs devices and circuits does not achieve the necessary power densities.
- GaN devices can be operated ~ 400 °C and have higher breakdown field (5MV/cm) than Si, GaAs, and 6H-SiC
- Output power of GaN devices > 5x best Pmax of GaAs devices ,> 2x best Pmax SiC devices
- Extremely radiation hard(~50x harder than GaAs for 40MeV protons and 2MeV gamma rays)
- Tested to proton fluxes equivalent to 100 years in low earth orbit

Relevance to NASA

Remote transmission of energy to charge regenerative fuel cells (RFC) for NASA space missions.
Wireless power distribution grid in space and on new planets.
Remote powering of unmanned aircrafts and vehicles for NASA and DOD missions.

Budget, Schedule and Deliverables

- $64K for FY04
- **Milestones**
- 1st Quarter: complete design of edge termination
- 2nd Quarter: fabricate first batch of rectifiers
- 3rd Quarter: test devices up to 1kV reverse breakdown
- 4th Quarter: test devices up to 5kV
- 5th Quarter: assembly of initial power amplifier
- 6th Quarter: complete testing of power amplifiers
- **Products and Deliverables**
- 1st Quarter: optimized surface passivation of rectifiers
- 2nd Quarter: individual AlGaN power rectifier with >1A conduction current
- 3rd Quarter: optimized array design and initial array fabrication
- 4th Quarter: large area (> 1 cm diameter) AlGaN power rectifier arrays with breakdown voltage VB > 5 kV, on-state resistance < 0.05 Ω cm2 and forward conduction current > 10A
- 5th Quarter: assembled power amplifier
- 6th Quarter: assembled power rectifier

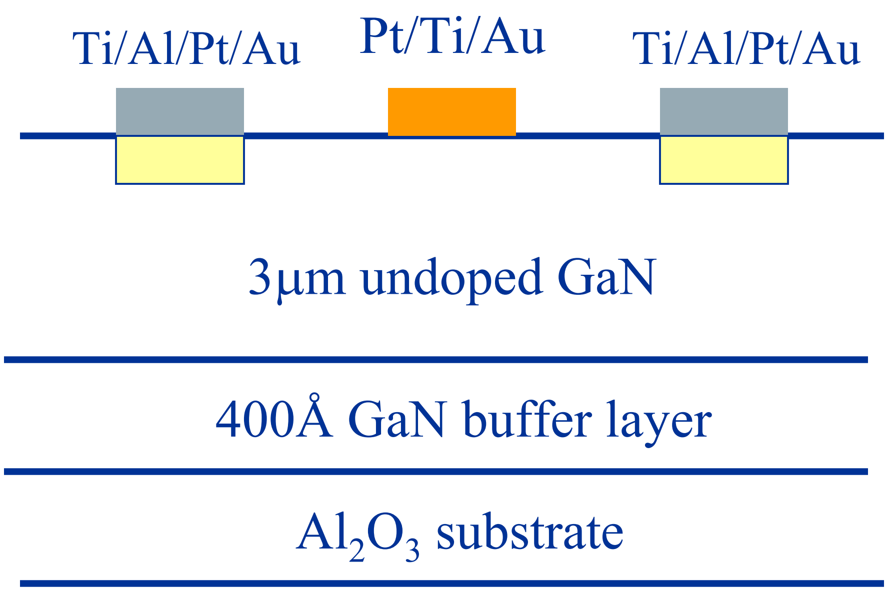
Anticipated Technology End Use

- Lightweight wireless power transmission circuits that are radiation hard, can operate in uncooled mode and used to deliver a focused microwave beam over a very long distance at light speed.
- Compatible with next generation microwave communication base station technology using GaN HEMT circuits and with high power inverter modules for hybrid electric vehicles using GaN Schottky diodes

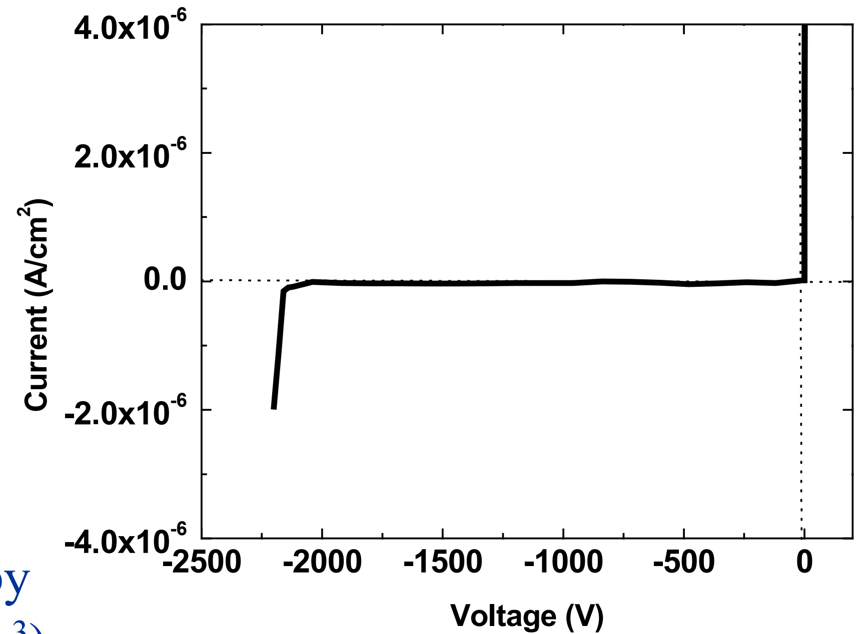
Accomplishments and Results

- Designed the optimal edge termination procedures for the power Schottky diodes and also the optimized surface passivation. Both are necessary to prevent surface-related breakdown.
- Several batches of rectifiers fabricated-achieved the highest reported breakdown voltages for any GaN device, i.e. a reverse breakdown voltage of ~3kV for GaN diodes. The figure-of-merit $(V_B)^2/R_{ON}$ was 1125 $MW \cdot cm^{-2}$, the highest yet achieved for GaN power devices
- Designed and fabricated an initial diode array of ~100 devices on free-standing GaN substrates with total forward conduction current of 160A.Individual diodes were operable up to a maximum pulsed currents of 1.72A, a record for GaN devices

Device Structure and Experimental Results

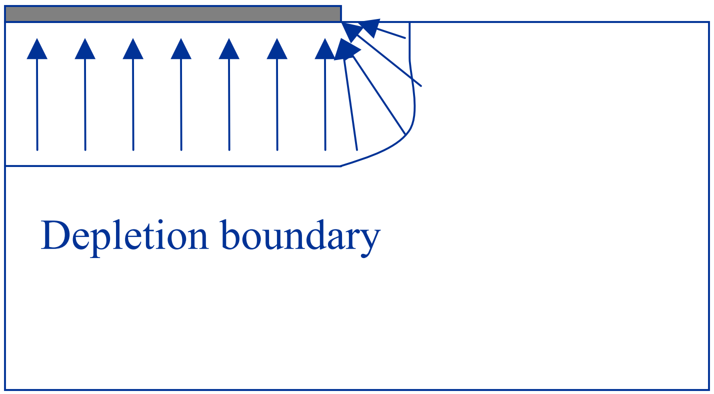


- Breakdown voltage below the theoretical value (>4000V)



- Low doped GaN and $Al_XGa_{1-X}N$ grown by MOCVD (Hall measurement: ~$1\times10^{15}cm^{-3}$)
- 30μm spacing between Schottky and Ohmic metals
- n^+ implant Si^+/Si^{++}
- Anneal under N_2 using AlN cap (1150ºC anneal)

Edge Electric Field Crowding

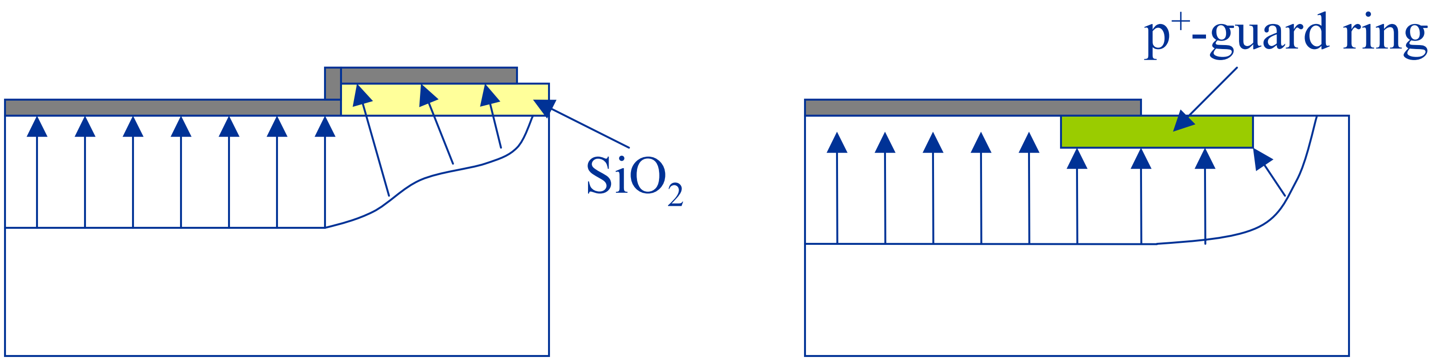


$$\alpha_n = \alpha_0 \exp\left(\frac{-b_0}{E}\right)$$

Where:
α_n : impact ionization coefficient
a_0, b_0 : constants
E: electric field

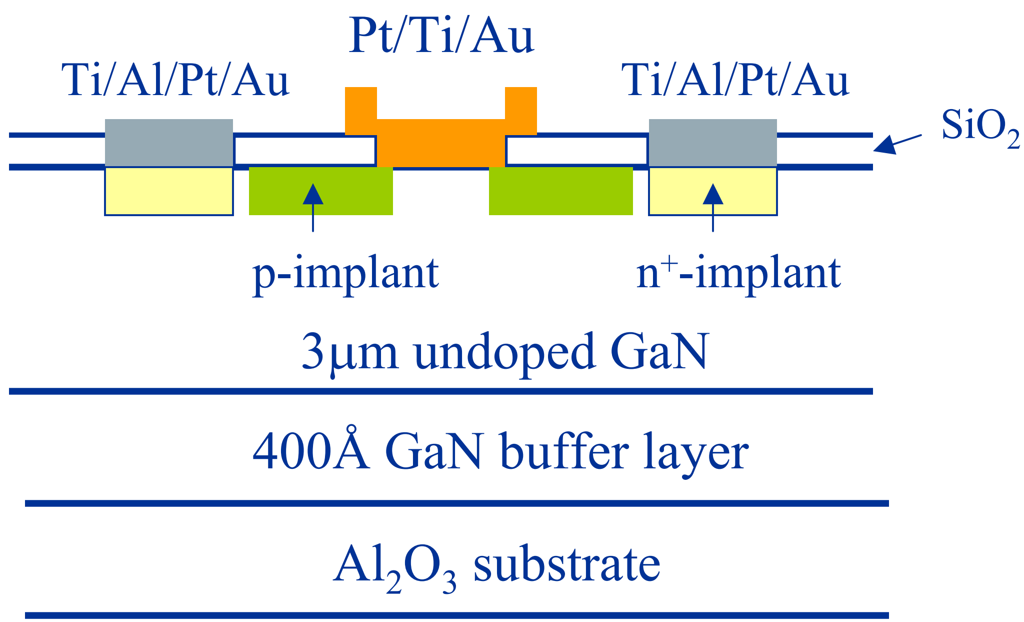
- Severe electric field crowding occurs at the edge of the metal
- Very high leakage current and soft breakdown well below the calculated value

p-Guard Ring or metal overlap edge termination

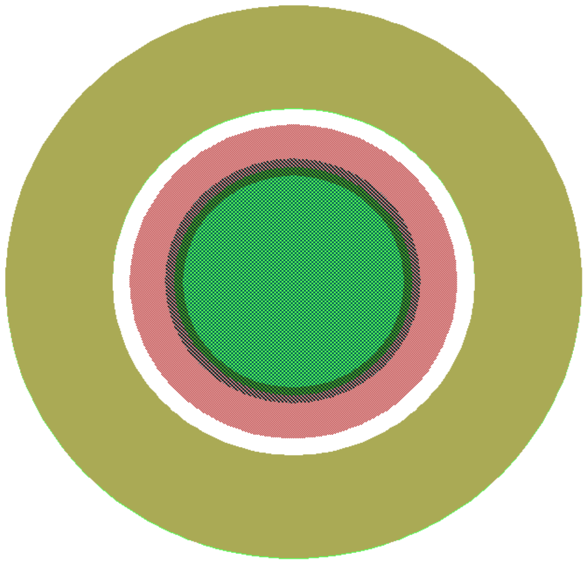


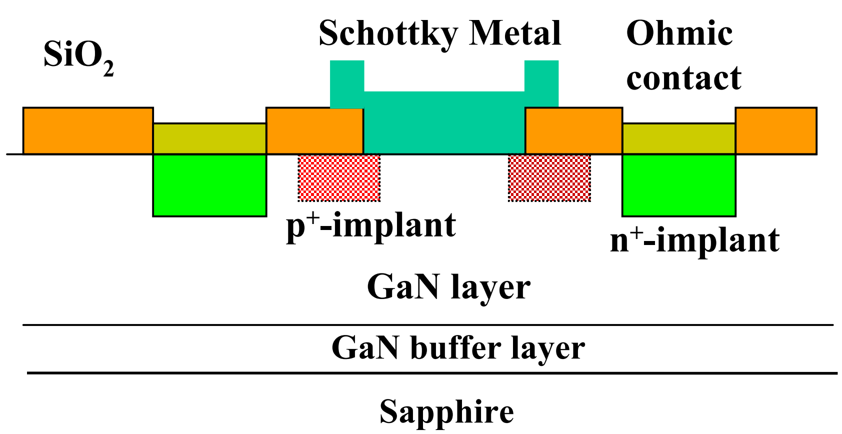
- p^+ Guard Ring: Place a p-type diffused guard ring at the edge of the Schottky barrier metal
- Metal overlap: Extend the Schottky barrier metal over an oxide layer at the edge

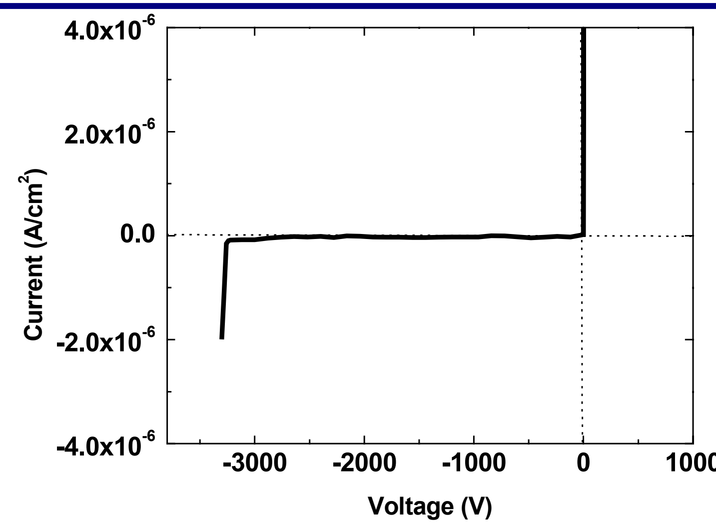
GaN Rectifiers with Edge Termination

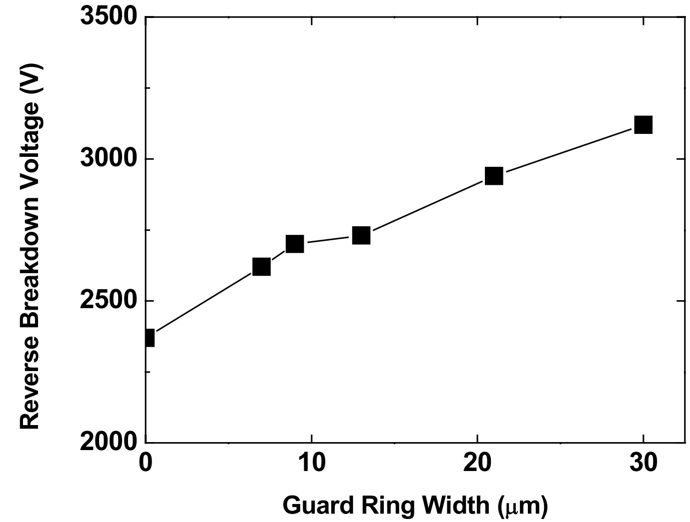


- 30µm spacing between Schottky and Ohmic metals
- n^+ implant Si^+/Si^{++}
- p implant Mg^+
- anneal under N_2 using AlN cap (1150ºC anneal)



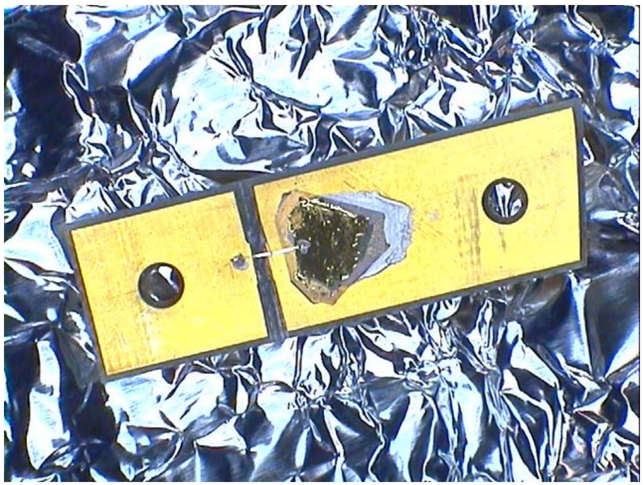


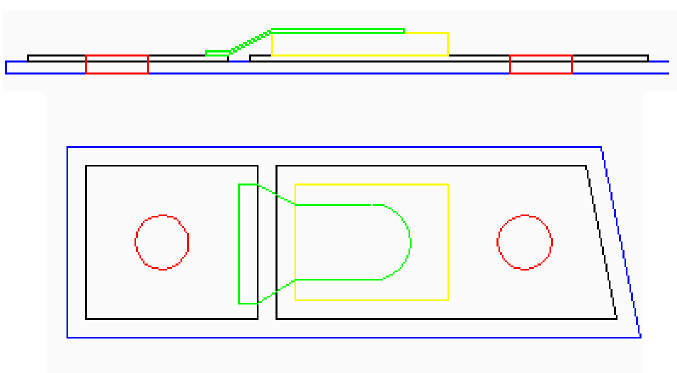


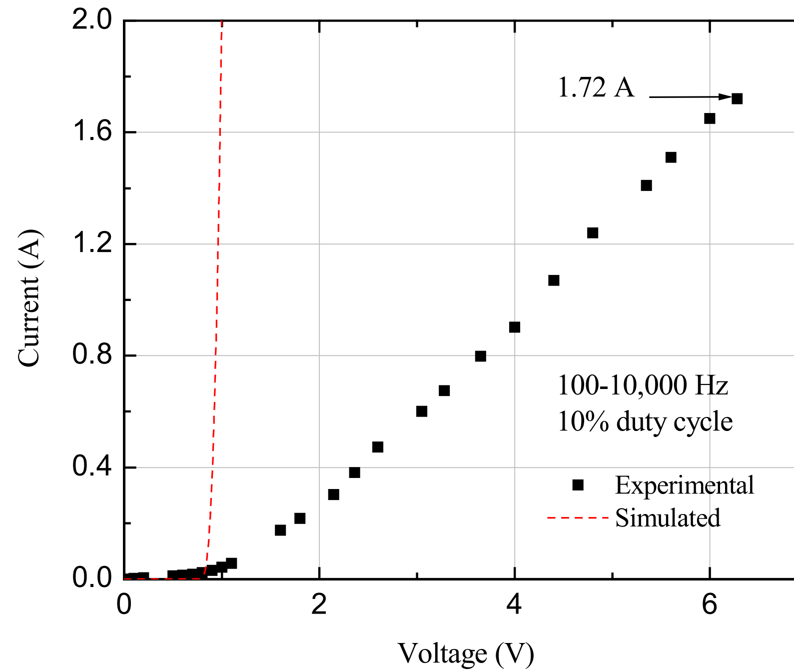


- I-V from devices with 30 μm guard rings

Pulse Measurements of Large-Area Diode

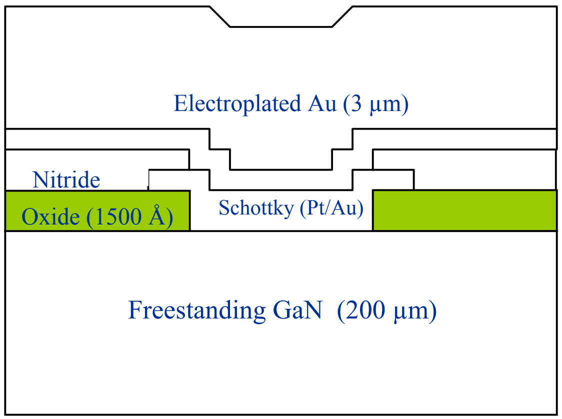




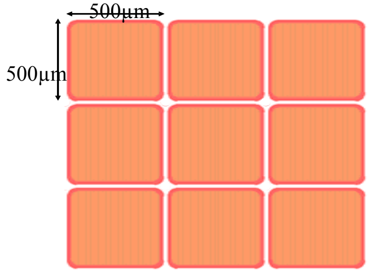


- Independent of measurement frequencies
- R_{ON}=3.4 $\Omega\cdot cm^2 \geq 3.31\ m\Omega\cdot cm^2$
- The total defect density determined by TEM is ~$10^6\ cm^{-2}$.

GaN Schottky Diode Array

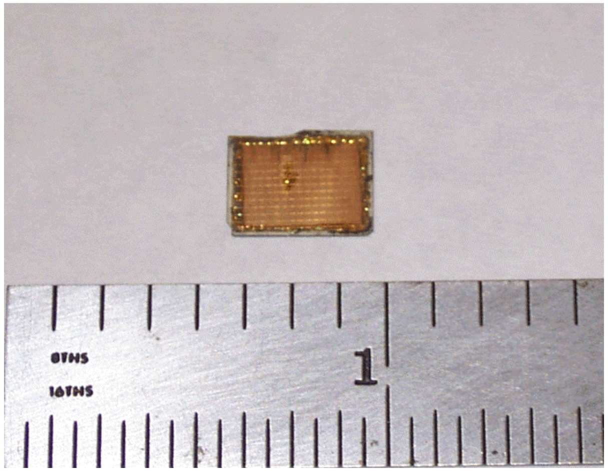


The schematic of high power GaN diode

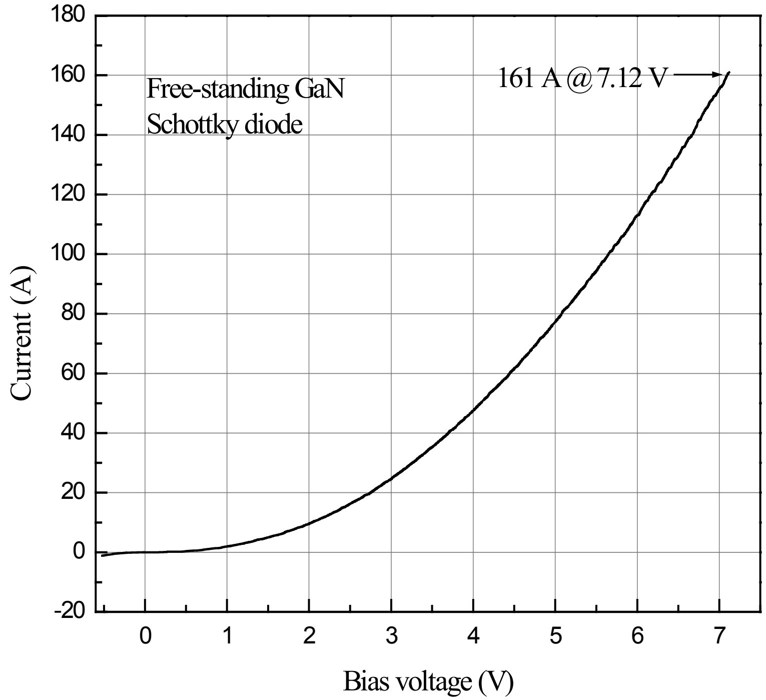


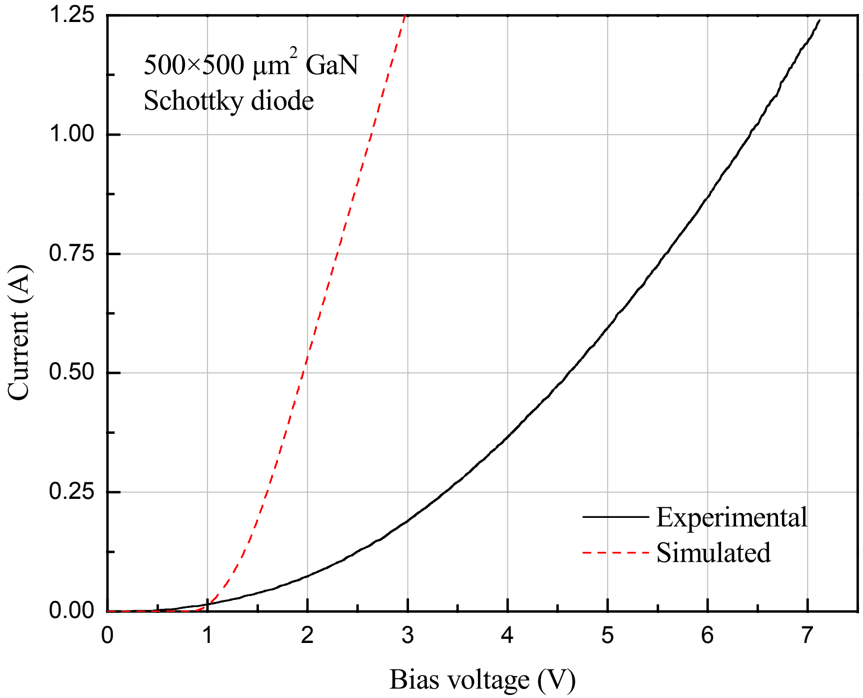
GaN Schottky diode array layout

- Schottky diode array with the size of 500 µm x 500 µm.
- Nitride windows interconnected with electroplated Au (~3µm)



GaN Power Diode Array





- 161 A forward output current @ 7.12 V
- R_{ON} (On-state resistance) = 8 m$\Omega\cdot$cm^2
- 1.1 kW for 6×6 mm^2 (active device area)

- Promising results for practical "on-state current"
- Very close to simulated R_{ON} values (3.3 m$\Omega\cdot$cm^2)

Future Plans

- Fabricate larger area diodes on free-standing GaN and examine the effect of diode size on reverse breakdown voltage.
- Fabricate AlGaN power diodes using epi AlGaN on free-standing GaN substrates -the increase in material bandgap is expected to provide an even higher breakdown voltage than for pure GaN. The free-standing GaN has a thermal conductivity that is higher than that of Si and much better than sapphire, which is the most common substrate for GaN films. This will improve the heat conduction away from the device.
- Examine some high thermal stability Ohmic and Schottky metallization that will improve device reliability under high power operating conditions. Preliminary data shows that boride-based contacts look promising.
- Incorporate these diodes into the high efficiency circuits designed and assembled by Prof. Lin’s group.