GaN-based Micro Pressure and Temperature Sensors for Extreme Planetary Environments

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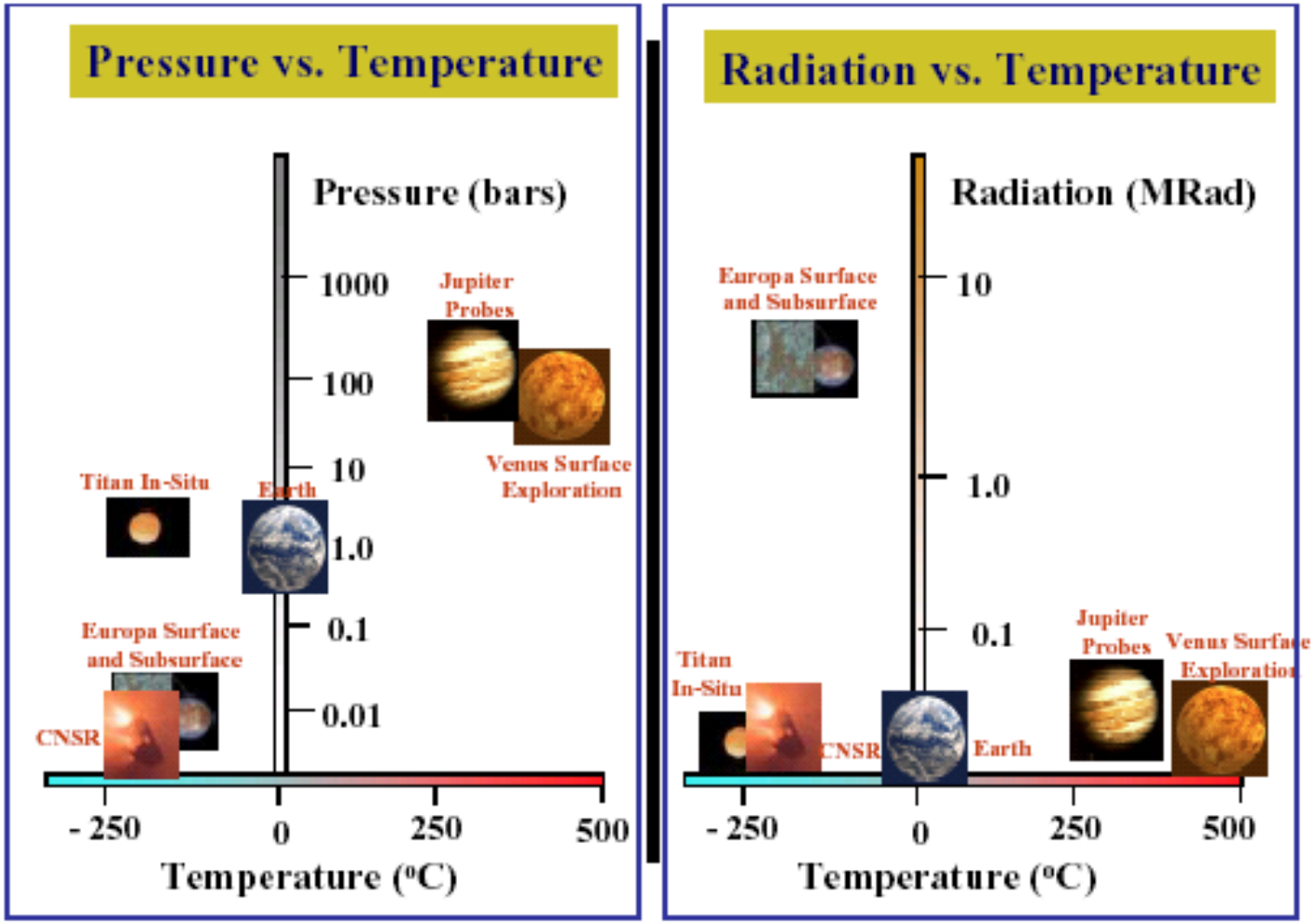
Temperature, Pressure, and Radiation in Reference Missions



Chris Moore, "Technology Development for Extreme Environments Systems" Workshop on Extreme Environments Technologies for Space Explorations, Pasadena, May 14, 2003.

AlGaN/GaN Hetero Structure-based Micro Sensors

Merits:

- Superior materials properties;
  Mechanically strong, chemically & thermally inert, radiation hard
  Minimal in unwanted optical or thermal generation of charge carriers
  → Ideal for operations at extreme environments

- Small volume, low mass, and low power requirement

- Novel device concept and simple and reproducible fabrication

- Monolithic integration of sensors and GaN-based RF transceiver
  with on-chip amplification; wireless remote sensing (X, Q, and K_a bands)

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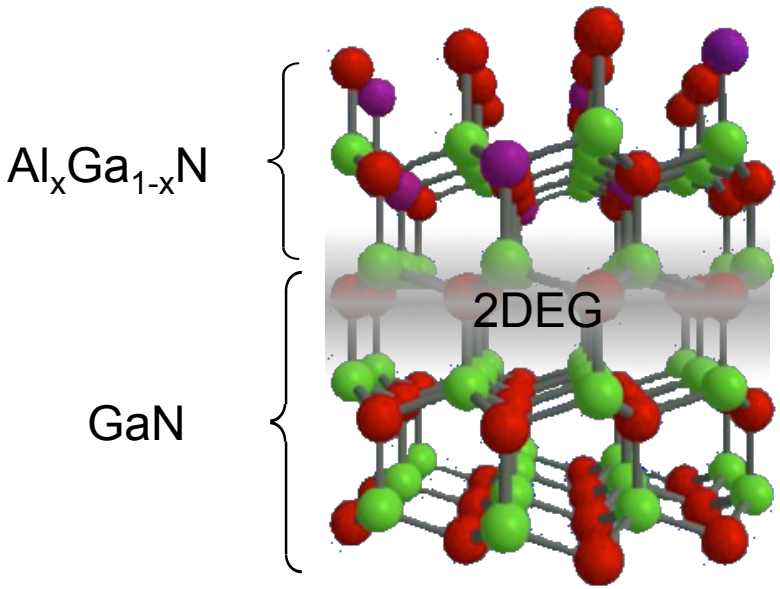
AlGaN/GaN Hetero Structure Devices for Pressure Sensing



(Figure from N. Prokopuk)

- Sheet charge layer (i.e. 2-Dimensional Electron Gas) at the interface of the GaN and AlGaN layers;

  Sheet charge density ~$1x10^{13}$ /cm^2

  High electron mobility ~ 1500 cm^2/Vs

- Modulation of the interfacial polarization charge by applied stress /pressure is the basis of pressure sensing.

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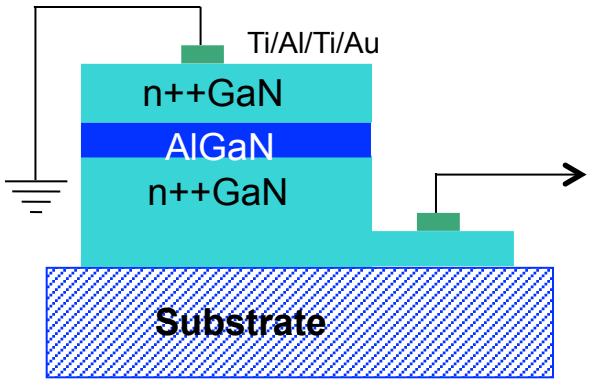
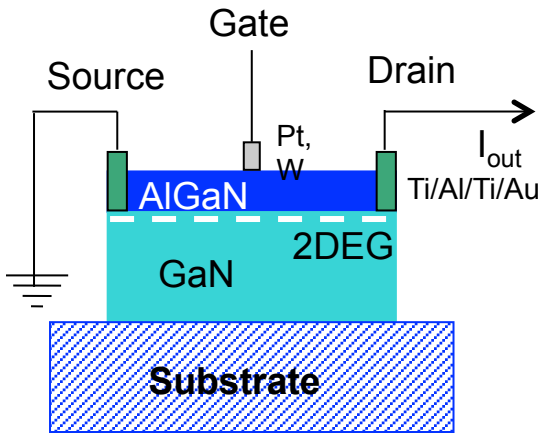
AlGaN/GaN based High Pressure Sensors



Schematic cross section of n-GaN/AlGaN/n-GaN (n-I-n) vertical transport diode sensor



Schematic cross section of AlGaN/GaN HEMT sensor

Expected operational range:
0-10 kbar with 1 bar accuracy
4 K - 870 K

Expected volume: ~ 1 cm^3
mass: < 5 g
power requirement: < 10 mW

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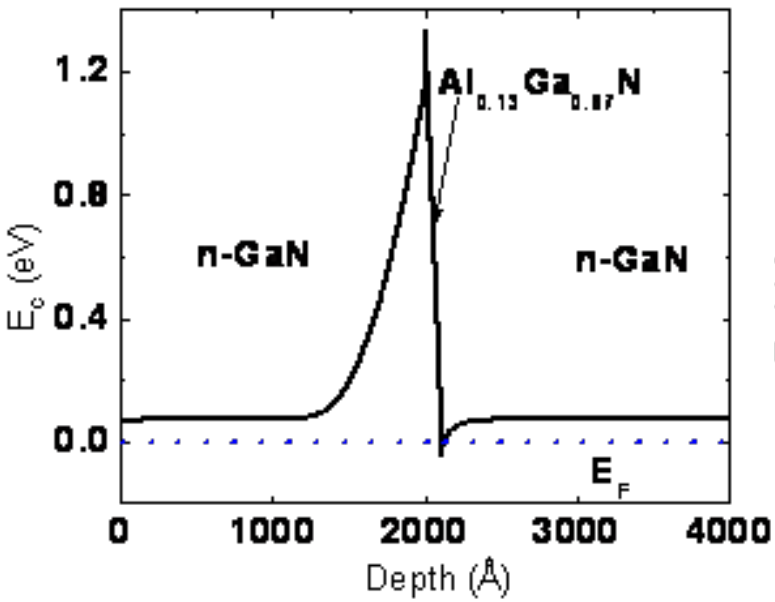
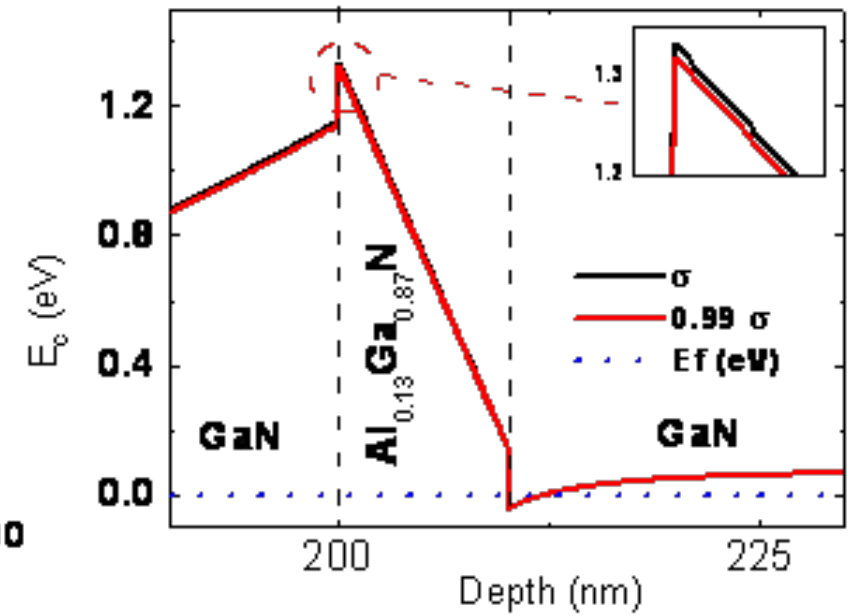
Conduction Band Diagram of $GaN/Al_xGa_{1-x}N/GaN$ Device





Conduction band diagram of an n-GaN/$Al_{0.13}Ga_{0.87}N$/n-GaN

10 nm thick undoped $Al_{0.13}Ga_{0.87}N$ layer and doping concentration of $2x10^{17}$ cm^{-3} in both n-GaN regions are assumed. The estimated polarization charge formed at the $Al_{0.13}Ga_{0.87}N$/n-GaN is 7.24 $x10^{12}$ ecm^{-2} and a barrier height of 1.33 eV is calculated. A decrease of the barrier height by 12 meV is expected from 1% reduction of polarization charge, which corresponds to 60 % increase in thermionic emission current over the barrier.

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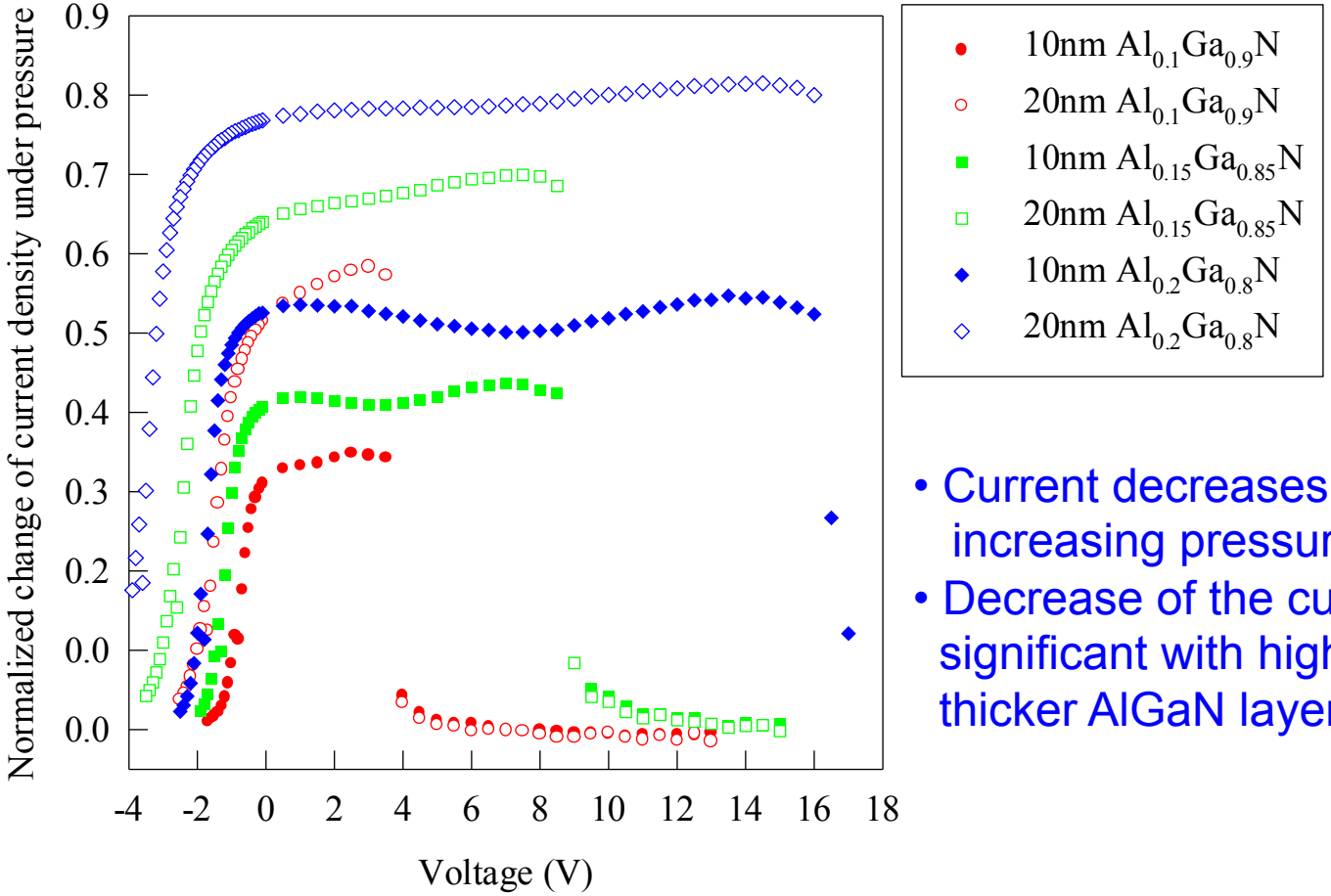
Theoretical Modeling of Pressure Effect on $GaN/Al_xGa_{1-x}N/GaN$ (n-I-n) Sensor

Normalized change of current densities, $(J_0-J)/J_0$, calculated for $GaN/Al_xGa_{1-x}N/GaN$ heterojunction under 10kbar hydrostatic pressure



- Current decreases with increasing pressure.
- Decrease of the current is more significant with higher x and the thicker AlGaN layer.

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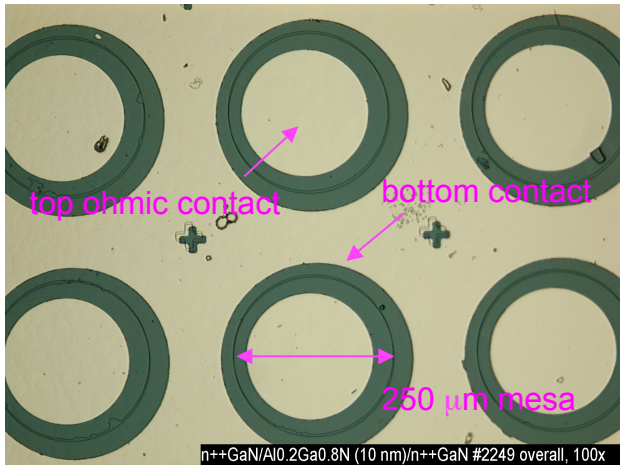
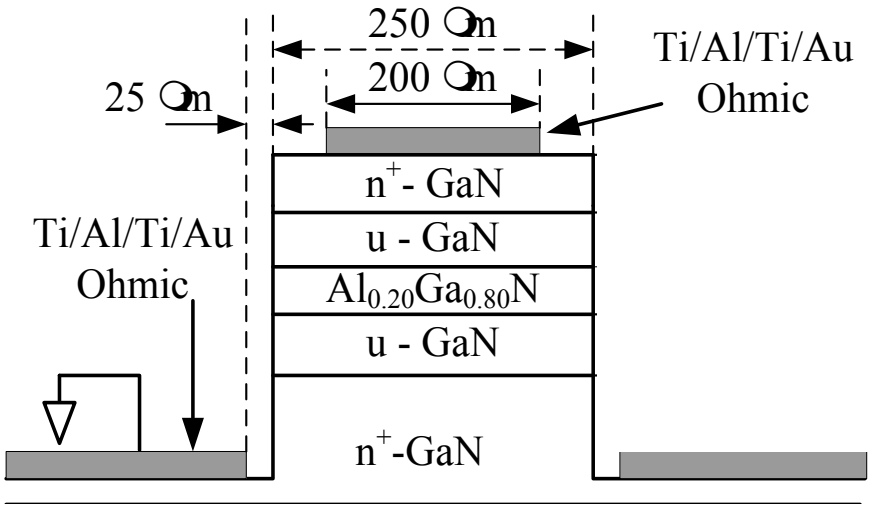
n-GaN/$Al_{0.2}Ga_{0.8}N$/n-GaN Heterojunction Device



Optical microscope image of n-GaN/$Al_{0.20}Ga_{0.80}N$/n-GaN heterojunction device.
Epi layers are grown with MBE.



The AlGaN layer is 10 nm thick , and the doping density is 3×10^{18} cm^{-3} for the GaN layer above AlGaN layer, and 7×10^{17} cm^{-3} for the GaN layer below AlGaN layer.

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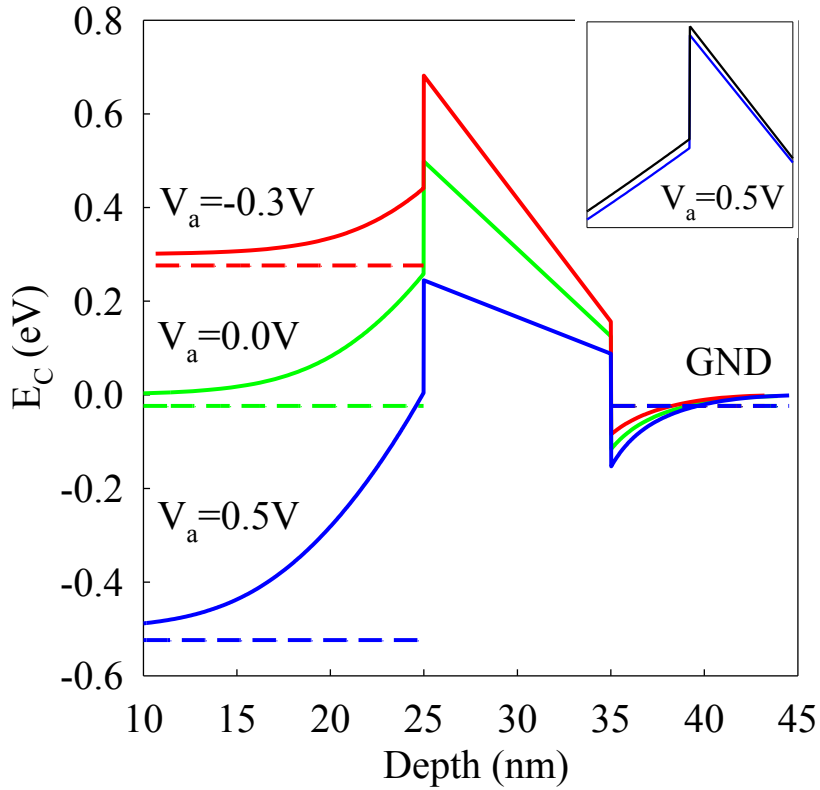
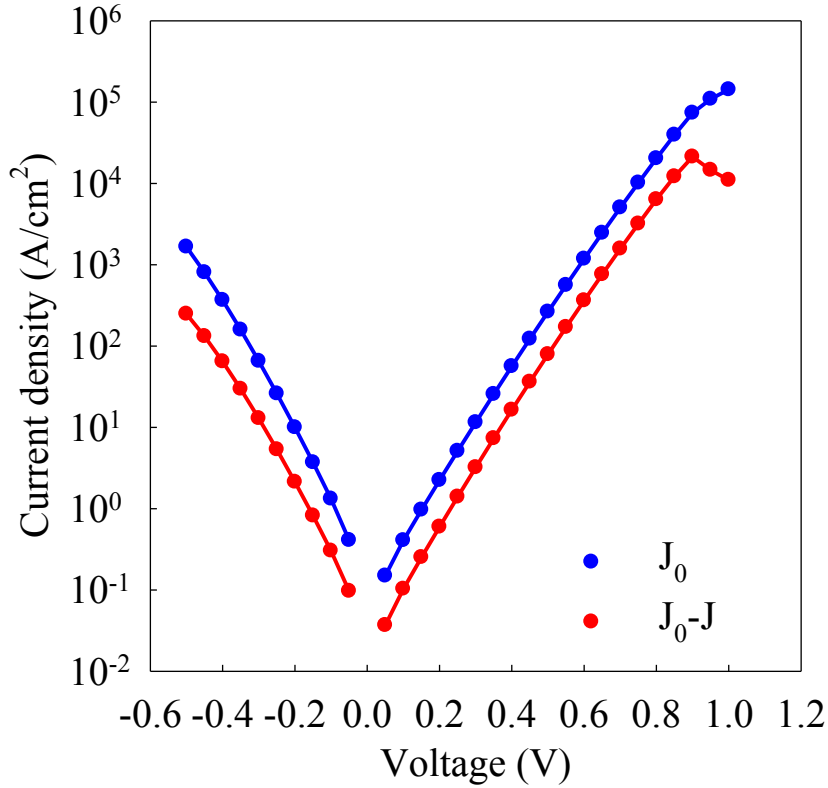
I-V Simulations of n-GaN/$Al_{0.2}Ga_{0.8}N$/n-GaN Sensor





Calculated band profiles of n-GaN/$Al_{0.2}Ga_{0.8}N$/n-GaN at three applied voltages. The inset shows the effect of 10kbar pressure on band structures.

Calculated current density at zero pressure, and the change of current density with 10 kbar pressure. The AlGaN layer is 10 nm thick , and the doping density is 3×10^{18} cm^{-3} for the GaN layer above AlGaN layer, and 7×10^{17} cm^{-3} for the GaN layer below AlGaN layer.

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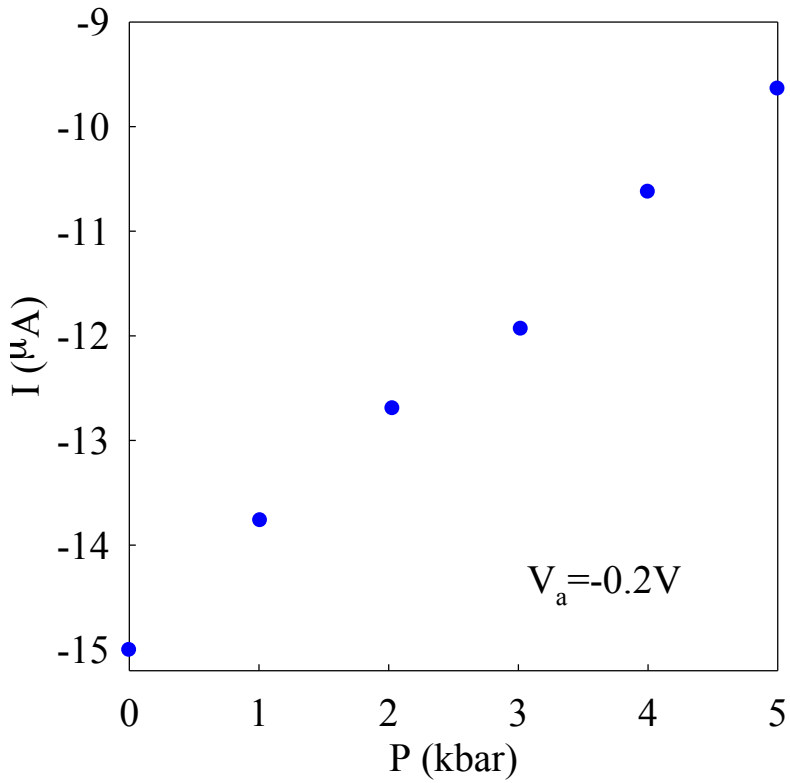
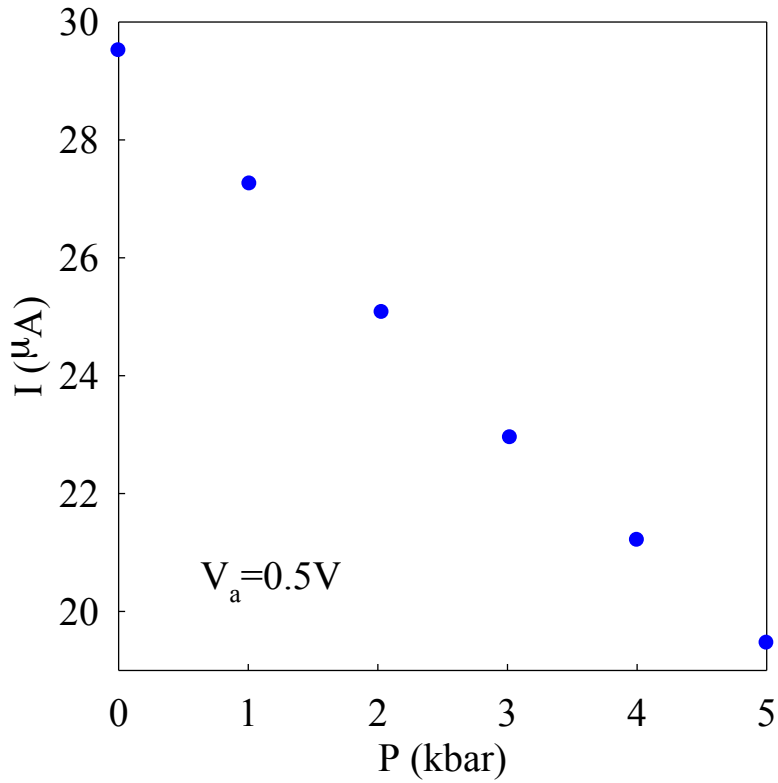
Electrical Responses of n-GaN/$Al_{0.2}Ga_{0.8}N$/n-GaN Sensor to Hydrostatic pressure





Pressure response measured for the n-GaN/$Al_{0.2}Ga_{0.8}N$ /n-GaN single barrier vertical transport device. Current was measured under hydrostatic pressure at a fixed forward bias (-0.2 V and +0.5 V).

- Linear decrease of the current with increasing pressure

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High Pressure Test Setup at UMN

Gas pressure cell
CuBe cell. He gas compressor
Maximum pressure: 15 kbar

Liquid pressure cell
CuBe cell. Hexane/pentane medium
Piston compressor
Maximum pressure: 400 bar

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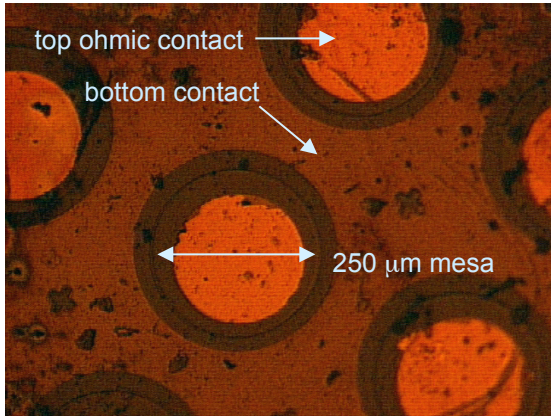
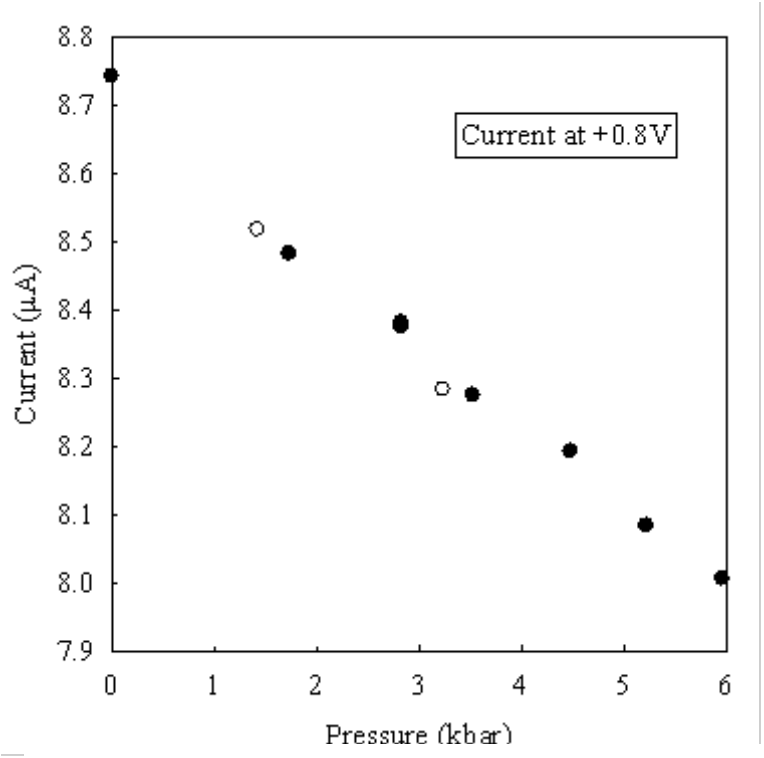
Electrical Responses of n-GaN/$Al_{0.15}Ga_{0.85}N$/n-GaN Sensor to Hydrostatic pressure



Optical image of n-GaN/$Al_{0.15}Ga_{0.85}N$ /n-GaN heterojunction device. Epi layers are grown with MOCVD



Pressure response measured for the n-GaN/$Al_{0.15}Ga_{0.85}N$ /n-GaN single barrier vertical transport device. Current was measured under hydrostatic pressure at a fixed forward bias (+0.8 V) while the pressure was increased (solid dots) and decreased (open dots) as well.

- Linear decrease of the current with increasing pressure
- Reversible response

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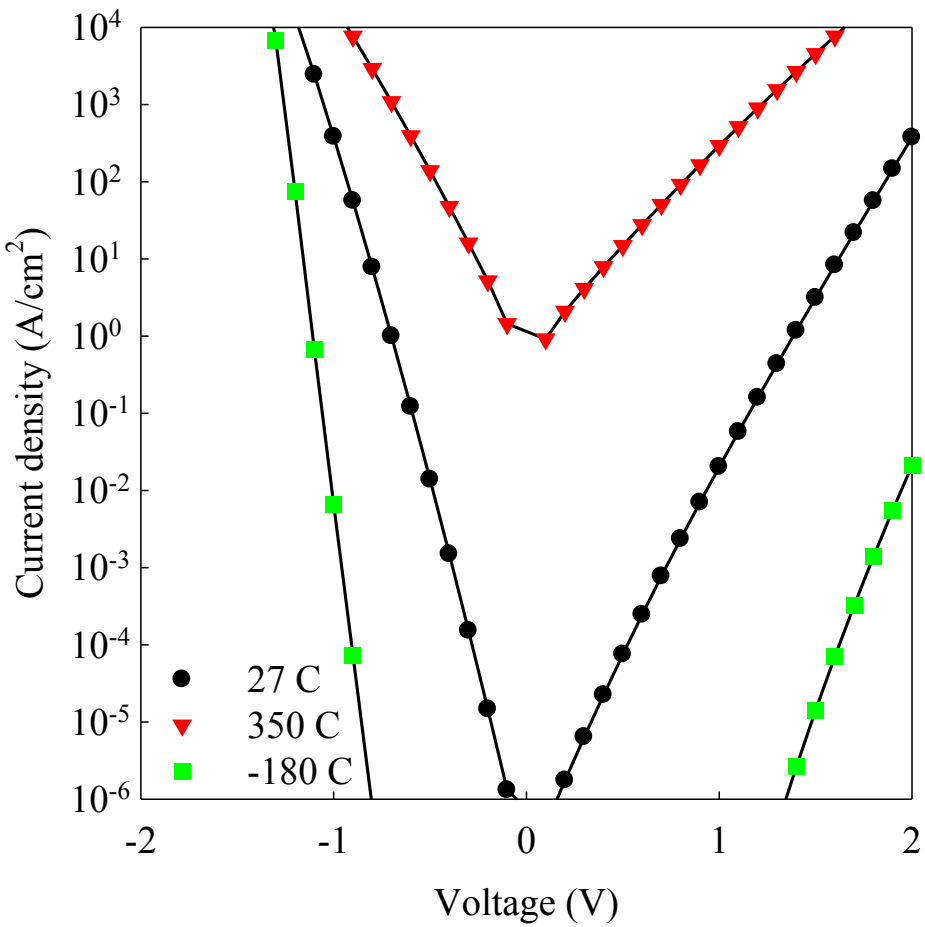
Theoretical Modeling of Temperature Responses of GaN/AlGaN/GaN (n-I-n) Sensor

Current density vs. voltage plots for GaN/$Al_{0.15}Ga_{0.85}N$/GaN sensor at zero pressure



Calculated with doping density of 3×10^{18} cm^{-3} for top GaN layer and 3×10^{17} cm^{-3} for bottom GaN layer.
10 nm thick undoped AlGaN layer is assumed.

Current decreases strongly with decreasing temperature.

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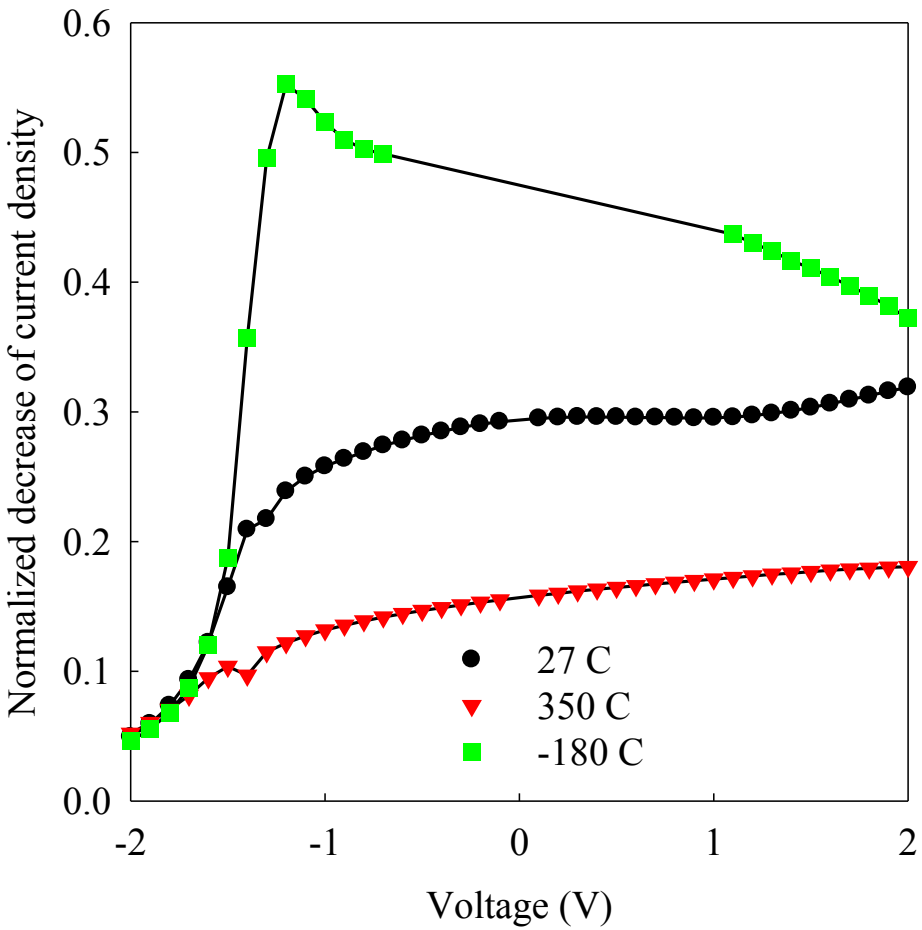
Theoretical Modeling of Temperature Responses of n-I-n Sensor under High Hydrostatic Pressure

Normalized change of current density under 10kbar for $GaN/Al_{0.15}Ga_{0.85}N/GaN$



Calculated with doping density of 3×10^{18} cm^{-3} for top GaN layer and 3×10^{17} cm^{-3} for bottom GaN layer.
10 nm thick undoped AlGaN layer is assumed.

- Current decreases with the applied pressure.
- The decrease gets more significant at lower temperatures.

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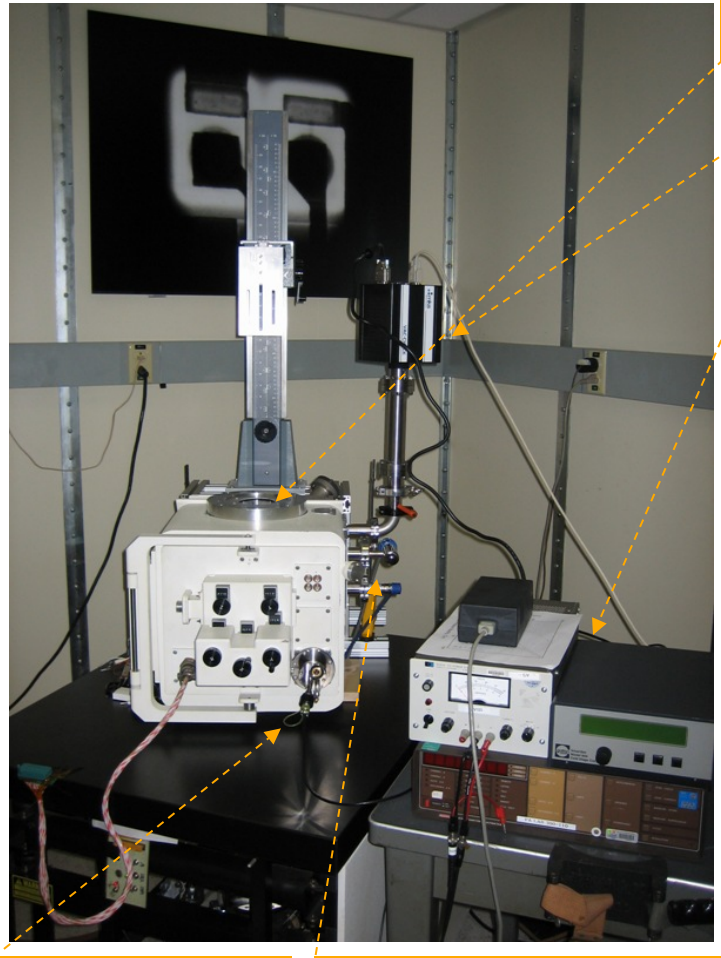
Test Setup for Measuring Sensor Responses in Wide Temperature Range (JPL)



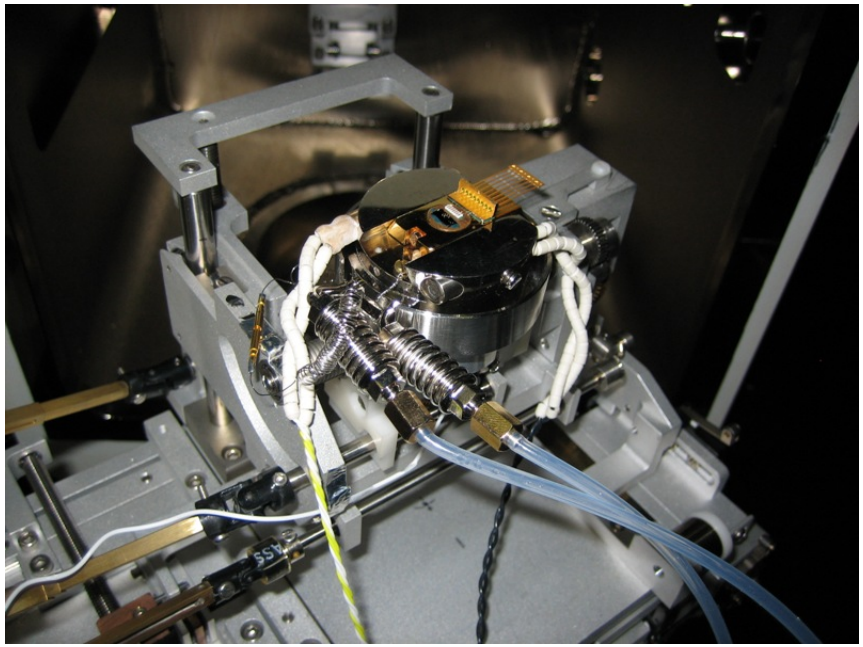
Viewport for IR camera

Mass spectrometer

Temp control system

Sample stage

Gas delivery system



Temperature controllable sample stage; ~100-670K

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Summary

- Investigated n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) devices for pressure sensors in extreme environments.
- Theoretical modeling indicates decrease of electrical currents with increasing pressure due to the increase of polarization charge.
- The modeling predicts more significant decrease of current with higher AlN compositions in the $Al_xGa_{1-x}N$ layer and for the thicker $Al_xGa_{1-x}N$ layer.
- The vertical transport current measured with n-GaN/$Al_xGa_{1-x}N$/n-GaN (X=0.15 & 0.2) sensors is consistent with the modeling studies.
- Linearity and reversibility in pressure response; n-GaN/$Al_xGa_{1-x}N$/n-GaN is promising for high-pressure sensing in extreme environments.

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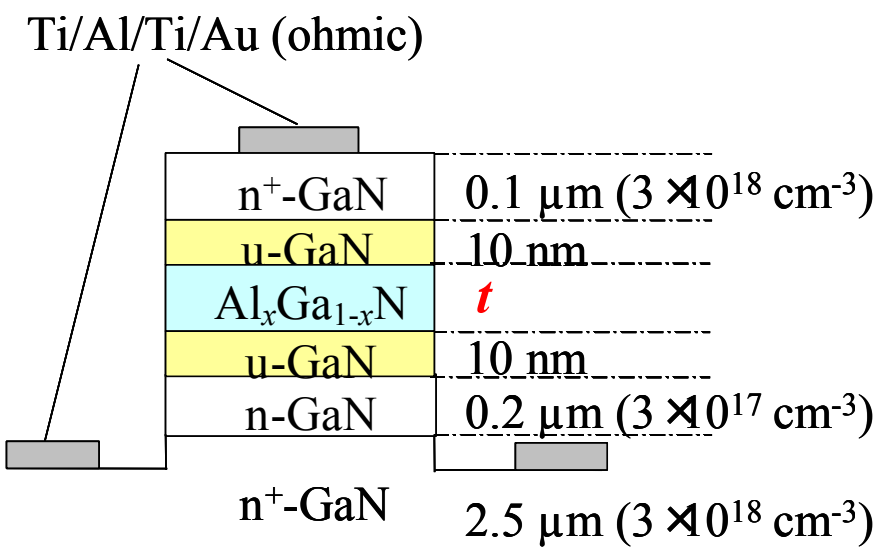
GaN/$Al_xGa_{1-x}N$/GaN (n-I-n) Sensors Fabricated for Characterization of P & T responses



Device structure

Modifying barrier height with AlN mole fraction and thickness

x \ t (nm)	10	20	30
0.10		*	
0.20	*	*	*
0.30		*	

$Al_xGa_{1-x}N$ thickness: t

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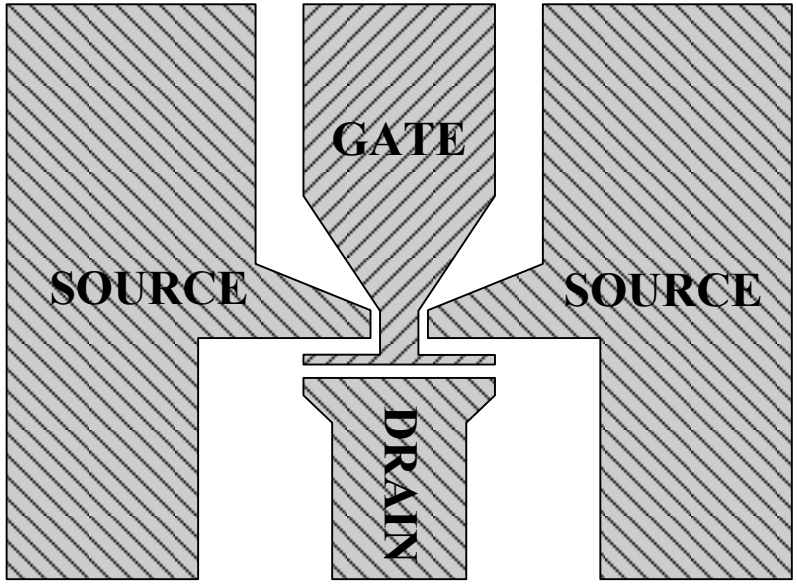
AlGaN/GaN HFET for Characterization of P & T responses



2 nm undoped GaN

18 nm undoped $Al_{0.3}Ga_{0.7}N$

500 nm undoped GaN

2 mm undoped GaN

Sapphire

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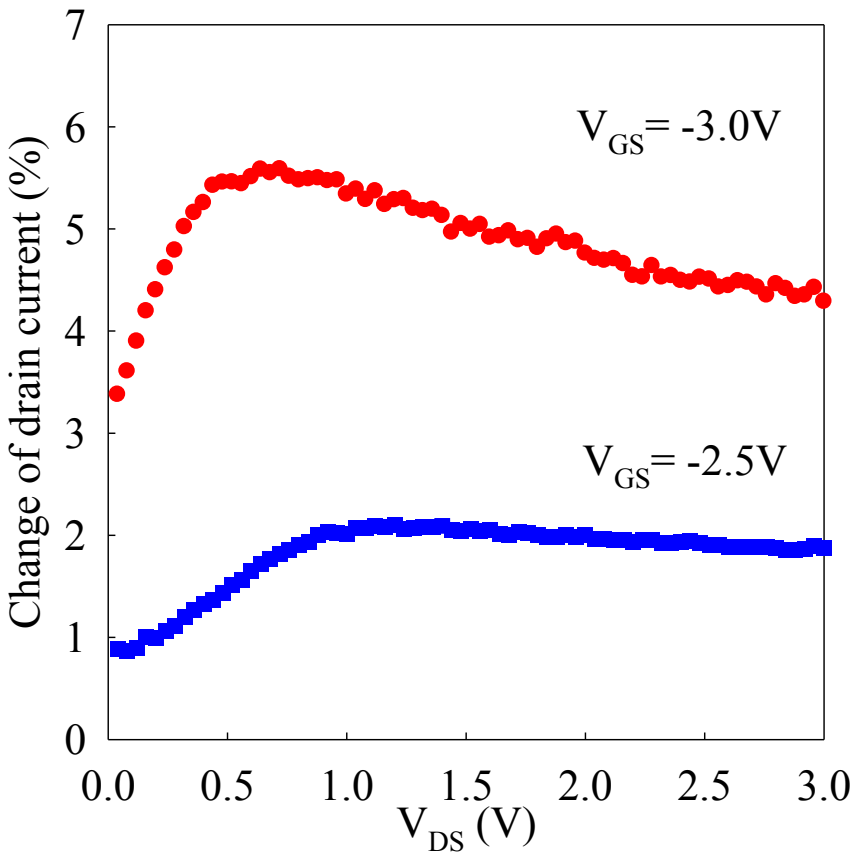
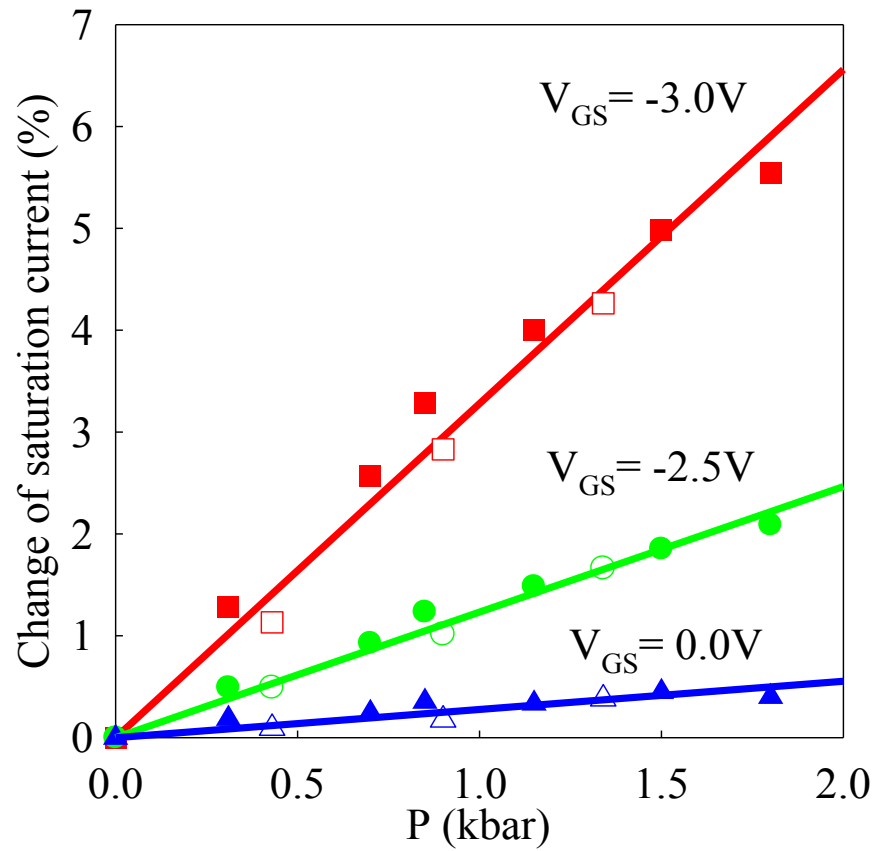
Pressure Dependence of $Al_{0.3}Ga_{0.7}N/GaN$ HFET Sensor



Relative change of the drain current under 1.8kbar pressure



Relative change of saturation current with pressure

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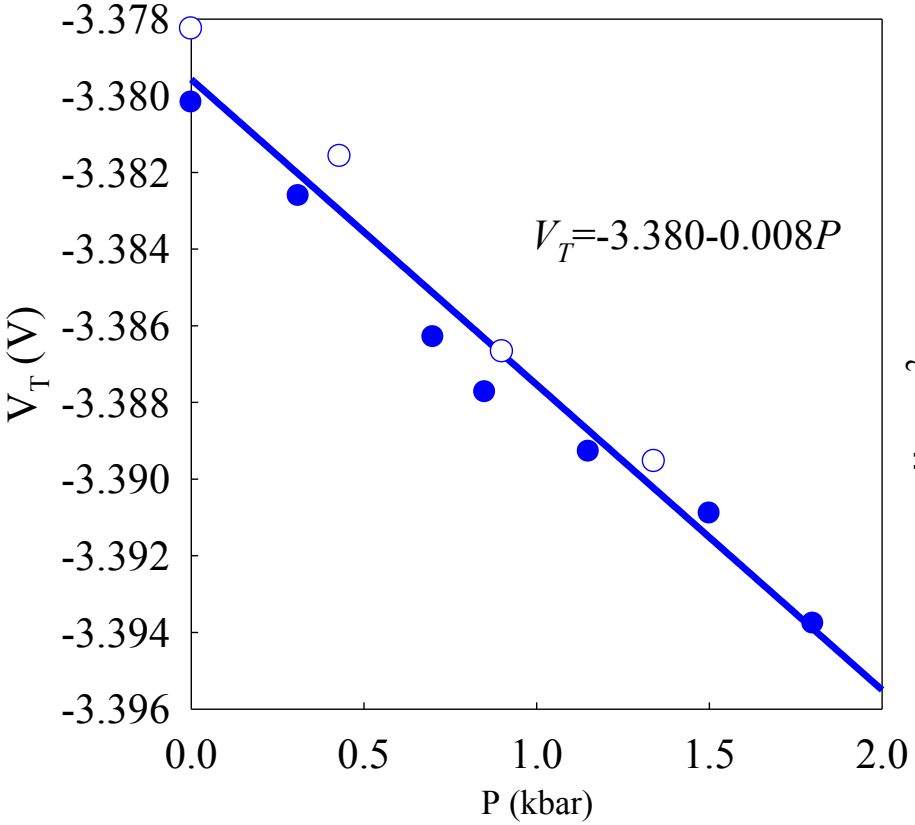
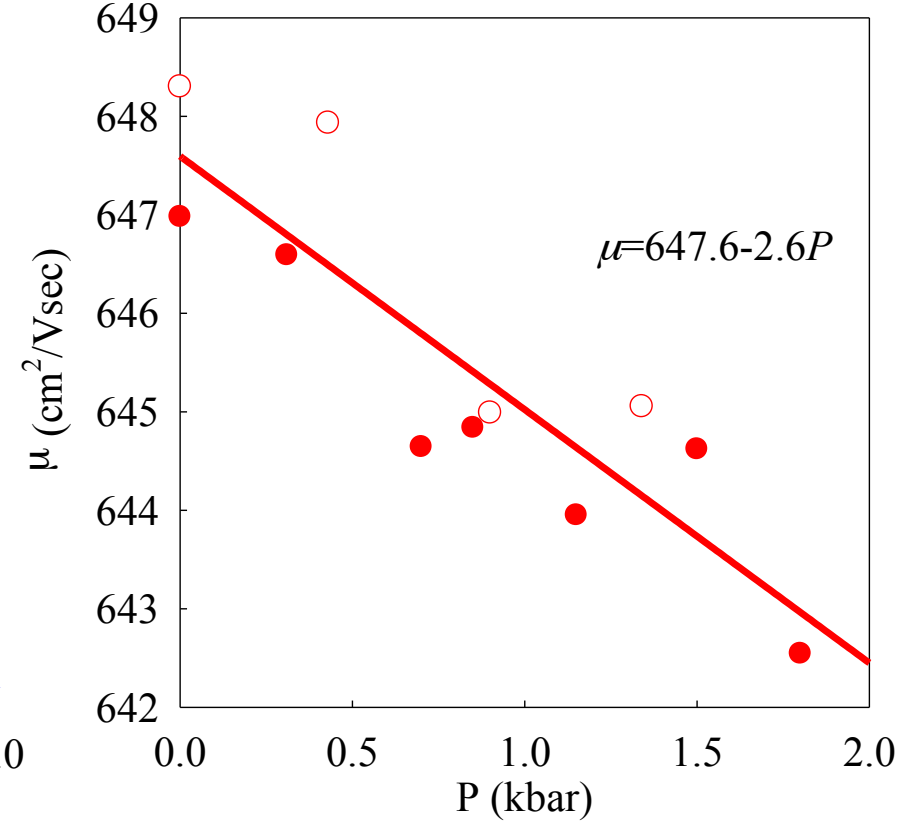
Pressure Dependence of Threshold Voltage & Mobility



Threshold voltage versus pressure extracted from -2.5V gate bias data.



Mobility versus pressure extracted from -2.5V gate bias data.

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Summary of experimental results

Devices	Gauge factors
Ga- GaN Schottky diodes on sapphire	-980
freestanding N- GaN Schottky diodes	-1560
Ga- AlGaN Schottky diodes on sapphire	-1672
AlGaN/GaN HFETs on sapphire	+216
GaN/AlGaN/GaN devices on SiC	-500

- Gauge factors are defined as the relative change of current divided by the strain in the basal plane.

SOA Pressure Sensors for Planetary Applications

Vaisala BAROCAP sensor

- Proposed for current New Frontiers missions
- Si-based capacitive pressure sensor
- operational range: 0.05-1.1 bar
- accuracy: ± 1.5x 10^{-4} bar
- operational temperature range: -40 °C to 60 °C
- packaged sensor with cooling system: several hundred cm^3, ~2Kg
- power ~2 W

Kulite/Glenn SiC pressure sensor

- SiC diaphragm/resonator based pressure sensor
- operational range: 1-70 bar
- operational temperature range: -200 °C to 530 °C
- Sensitivity at 25 °C: 20-80 μV/V/psi
- Sensitivity at 400 °C -500 °C: 50% of sensitivity at 25 °C

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