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

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JPL
UMN
VCU
ARC
Temperature, Pressure, and Radiation in Reference Missions


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Extreme Environments in Five Space Science Reference Missions

All five missions have to survive in extreme environments.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Venus Surface Exploration &amp; sample return</td>
<td></td>
<td>460 C</td>
<td></td>
<td>90 bar</td>
</tr>
<tr>
<td>Giant Planets Deep Probes</td>
<td>-140 C</td>
<td>380 C</td>
<td></td>
<td>100 bar</td>
</tr>
<tr>
<td>Comets Nucleus Sample Return</td>
<td>-140 C</td>
<td></td>
<td></td>
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<tr>
<td>Titan <em>In Situ</em></td>
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<tr>
<td>Europa Surface &amp; Subsurface</td>
<td>-160 C</td>
<td></td>
<td>5 MRad</td>
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</table>

Chris Moore, "Technology Development for Extreme Environments Systems"

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AlGaN/GaN Hetero Structure-based Micro Sensors

Merits:

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

- Small volume, low mass, and low power requirement

- Novel device concept and simple & reproducible fabrication

- Monolithic integration to GaN-based RF transceiver

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AlGaN/GaN Heterostructure Devices for Pressure Sensing

- Sheet charge layer (2-Dimensional Electron Gas) at the interface of GaN and AlGaN
- Applied stress/pressure

Modulation of the electron concentration & the conduction in the 2DEG.

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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

Expected operational range:
0-10 kbar with 1 mbar accuracy
30 K - 870 K with 0.1 K accuracy

Expected volume: \( \sim 1 \, \text{cm}^3 \)
mass: < 5 g
power requirement: < 10 mW

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Conduction Band Diagram of GaN/Al$_{x}$Ga$_{1-x}$N/GaN sensor

Conduction band diagram of n-GaN/Al$_{0.13}$Ga$_{0.87}$N/n-GaN
- for 10 nm thick undoped Al$_{0.13}$Ga$_{0.87}$N and 2x10$^{17}$ cm$^{-3}$ doping in both n-GaN regions
- estimated polarization charge at the Al$_{0.13}$Ga$_{0.87}$N/n-GaN: 7.24 x10$^{12}$ ecm$^{-2}$
- calculated barrier height: 1.33 eV
- 12 meV decrease of barrier height expected from 1% reduction of polarization charge; 60% increase in thermionic emission current over the barrier.

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Theoretical Modeling of Pressure Effect on n-l-n Sensor

Normalized change of current densities, \( \frac{(J_0-J)}{J_0} \), calculated for GaN/Al\(_x\)Ga\(_{1-x}\)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.
GaN/Al\textsubscript{x}Ga\textsubscript{1-x}N/GaN (n-I-n) Sensor Structure

<table>
<thead>
<tr>
<th>Al\textsubscript{x}Ga\textsubscript{1-x}N thickness: ( t )</th>
<th>10nm</th>
<th>20nm</th>
<th>30nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al\textsubscript{x}Ga\textsubscript{1-x}N %</td>
<td>12%</td>
<td>CVD1210</td>
<td></td>
</tr>
<tr>
<td>15%</td>
<td>CVD1209</td>
<td>CVD1208</td>
<td>CVD1211</td>
</tr>
<tr>
<td>30%</td>
<td></td>
<td>CVD1205</td>
<td></td>
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</table>
I-V Characteristics of n-l-n Sensors

Different Al compositions in $\text{Al}_x\text{Ga}_{1-x}\text{N}$

Different thicknesses of $\text{Al}_x\text{Ga}_{1-x}\text{N}$

Higher turn-on voltage with higher Al content and thicker $\text{Al}_x\text{Ga}_{1-x}\text{N}$

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Electrical Responses of n-l-n Sensor to Hydrostatic pressure

Pressure response measured for the n-GaN/Al$_{0.15}$Ga$_{0.85}$N /n-GaN

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 current with increasing pressure
- Reversible response

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Theoretical Modeling of Temperature Responses of 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 $3 \times 10^{18} \text{ cm}^{-3}$ for top GaN layer and $3 \times 10^{17} \text{ cm}^{-3}$ for bottom GaN layer. 10 nm thick undoped AlGaN layer is assumed.

Current decreases strongly with decreasing temperature.

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Temperature response of n-l-n sensor

Temperature response of GaN/Al$_{0.15}$Ga$_{0.85}$N/GaN sensor

20 nm-thick Al$_{0.15}$Ga$_{0.85}$N layer. The current was measured with a forward bias of 1.5 V.

- Good linearity between current and temperature

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Modeling of Temperature Responses of n-l-n under High Pressure

Normalized change of current density under 10kbar for GaN/Al$_{0.15}$Ga$_{0.85}$N/GaN

Calculated with doping density of $3 \times 10^{18}$ cm$^{-3}$ for top GaN layer and $3 \times 10^{17}$ 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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Pressure Responses of n-I-n Sensors

<table>
<thead>
<tr>
<th>Sample Parameters</th>
<th>Maximum PGF [GPa⁻¹]</th>
<th>Maximum SGF</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>(t_{AlGaN} [\text{nm}])</td>
<td></td>
</tr>
<tr>
<td>0.12</td>
<td>20</td>
<td>-0.492</td>
</tr>
<tr>
<td>0.15</td>
<td>20</td>
<td>-0.541</td>
</tr>
<tr>
<td>0.30</td>
<td>20</td>
<td>-1.02</td>
</tr>
<tr>
<td>0.15</td>
<td>10</td>
<td>-0.626</td>
</tr>
<tr>
<td>0.15</td>
<td>30</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

*pressure gauge factor (PGF): normalized current change per unit pressure*

Higher gauge factor measured for nIn sensors with higher Al content in Al\(_x\)Ga\(_{1-x}\)N

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Pressure Responses of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{GaN}$ HEMT Sensor

Relative change of saturation current with pressure

- Linear decrease of current with increasing pressure
- Reversible response
Pressure and Temperature Responses of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}/\text{GaN}$ HEMT Sensor

$I_d$ measured during pumping (from 1 bar to 0 bar)
GaN HEMT Ni L12W25

$I_d$ measured during heating from 25C to ~270C
GaN HEMT Ni L12W25

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Summary

- Investigated n-GaN/Al\textsubscript{x}Ga\textsubscript{1-x}N/n-GaN (n-l-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\textsubscript{x}Ga\textsubscript{1-x}N layer and for the thicker Al\textsubscript{x}Ga\textsubscript{1-x}N layer.

- The vertical transport current measured with n-GaN/Al\textsubscript{x}Ga\textsubscript{1-x}N/n-GaN (X=0.12, 0.15 & 0.2) sensors is consistent with the modeling studies.

- Linearity and reversibility in pressure response; n-GaN/Al\textsubscript{x}Ga\textsubscript{1-x}N/n-GaN is promising for high-pressure sensing in extreme environments.

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