Polarization Super-junction

A New Concept for GaN High-Voltage Devices

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-- About POWDEC --

Established: May 2001
Location: Oyama-city, Japan
No. of employees: 20

Powdec core technology:
- GaN growth using the original large scale MOCVD equipment
- Power device development using unique growth techniques such as ELO (Epitaxial lateral overgrowth), PSJ (polarization super-junction)

Powdec is managed independently of its shareholders to pursue its business interests
-- Background --

- Issues for Today’s GaN Power Devices

  - **Reliability**
    - Current Collapse
    - Not high-breakdown voltage
    - Avalanche resistance
    - Life-time degradation

  - **Cost**
    - Substrate
    - Thick buffer growth
    - High cost front-end process

  ✤ Need a new device approach
-- Background --

- Current Collapse

![Diagram showing current collapse](image)

1. **Current Collapse**: Diagram showing the change in drain current ($I_d$) and drain voltage ($V_d$) under different bias conditions. The diagram illustrates the current collapse phenomenon at low and high drain bias.

2. **On-state Off-state Cycle**: The diagram also shows a cycle of on-state and off-state conditions with corresponding drain voltage ($V_d$) and current ($I_d$) changes over time ($Time$). The $V_{stress}$ is highlighted to indicate stress during the on-state.
--- Background ---

◆ Origin of Current Collapse

- Hot electrons captured in Deep traps
- Hot electrons captured in AlGaN
- Gate leakage
  - Electrons captured in the surface

- Trapped electrons act as the negative bias under the channel
- Increase in channel resistance

![Diagram](image)

- High field induces “Hot electrons”
- Electric Field
- Decrease of electron
-- Background --

High field limits GaN’s potential capability.

High field induces;
- Current collapse
- Low breakdown voltage
- Poor life time reliability

How to amend;
- Lower the Field
- Lower the gate leakage
- Decrease the surface trap
- Decrease the deep trap
-- Polarization Super-junction (PSJ) --

- Traditional technology: Field plate (FP)

**Traditional technology**: Field plate (FP)

**Split & decrease the field**

**On-resistance increase**

\[ \frac{(R_{HV} - R_{LV})}{R_{LV}} \times 100\% \]

*Max. Field (MV/cm)*

*V_{DD}=300V*

(Toshiba semiconductor Company, SEMI FORUM JAPAN, power device seminar)
-- Polarization Super-junction (PSJ) --

◆ Super-junction (SJ) concept

Conventional Si-MOS FET

Si Super-Junction-MOS FET

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--- Polarization Super-junction (PSJ) ---

- GaN/AlGaN/GaN Polarization (PJ) structure acts similar to a silicon super-junction

Super-junction Si-MOS FET

GaN/AlGaN/GaN

Polarization Super-junction (PSJ)

GaN/AlGaN/GaN

Band structure

Polarization charge

Super-junction Si-MOS FET

GaN/AlGaN/GaN

Polarization charge

Polarization Super-junction (PSJ)

GaN/AlGaN/GaN

Polarization charge

Ev

Ec
Existence of high density 2-dimensional hole gas (2DHG)

**Layer structure**

- p+GaN
- i-GaN
- i-Al$_{0.23}$Ga$_{0.77}$N
- i-GaN
- buffer
- sapphire

**Temperature dependence of hole concentration**

- Hole Density (1e12/cm$^2$)
- Temperature (K)

- 1.4E13 cm$^{-2}$
- PSJ
- Freeze-out

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**Polarization Super-junction (PSJ)**

- **Existence of high density 2-dimensional hole gas (2DHG)**
Polarization Super-junction (PSJ) --

- Application to lateral devices

Polarization super-junction

Traditional metal field-plate

Field distribution

Without FP

With FP
-- Application to FET (PSJ-FET) --

- No passivation
- No field plate
- Gate-PSJ configuration

**PSJ-FET**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Symbol</th>
<th>Width</th>
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</thead>
<tbody>
<tr>
<td>i-AlGaN</td>
<td>S</td>
<td>3 μm</td>
</tr>
<tr>
<td>i-GaN</td>
<td></td>
<td>5 μm</td>
</tr>
<tr>
<td>i-GaN</td>
<td>B</td>
<td>6 μm</td>
</tr>
<tr>
<td>i-GaN</td>
<td>G</td>
<td>8 μm</td>
</tr>
<tr>
<td>Sapphire sub.</td>
<td>D</td>
<td></td>
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</table>

**Reference HFET**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Symbol</th>
<th>Width</th>
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</thead>
<tbody>
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<tr>
<td>i-GaN</td>
<td></td>
<td>17 μm</td>
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<tr>
<td>i-GaN</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>i-GaN</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Sapphire sub.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
-- PSJ-FET; results --

- $V_{th} = \sim 5\,\text{V}$
- $V_B = \sim 720\,\text{V};\,\text{ref-HFET} < 200\,\text{V}$
- Leak current: $\sim \text{sub mA/mm@700 V}$
--- PSJ-FET; results ---

- Temperature dependence

- Pinch-offed at 250°C
- $I_d$ decreased due to phonon scattering and band modulation

- Did not work at > 150°C
-- PSJ-FET; results --

- Temperature dependence at off-state condition

- ~\(\mu\)A/mm leak current at 250 C

- Exponential increase with temp.

**Graphs:**
- **PSJ-FET**
  - Drain Current vs. Drain Voltage
  - Vg = -15 V
  - 250°C, 175°C, 25°C

- **Reference HFET**
  - Drain Current vs. Drain Voltage
  - Vg = -15 V
  - 150°C, 100°C, 25°C
-- PSJ-FET; results --

- Current collapse

- Essentially no current collapse
-- PSJ-FET; results --

◆ Source-PSJ configuration

- \( I_d \) saturate at \( V_g > -2 \) V
- \( V_B > 830 \) V
-- PSJ Applied to a Diode--

◆ Schottky barrier diode

Forward I-V

Reverse I-V

- Vth: 1.2 V
- RonA: 1.3 mΩcm²
- Breakdown voltage > 1.1 kV
- Reverse current: ~1 μA/mm
-- Discussion --

- Scalability of $V_B$ with PSJ length

- Super-junction predicts the linear increase of $V_B$ with the junction length

Scalable with PSJ-length

Scalable with PSJ-length; $L_p$

$**$ MV/cm
-- Discussion --

- Scalability of $V_B$ with PSJ length

**Drain-current at off-state vs. Drain-voltages**

![Graph showing drain current vs. PSJ length](image)

**Acknowledgement:**
High-voltage measurement was supported by "Agilent Technologies International Japan Ltd."
-- Discussion --

◆ Scalability of $V_B$ with PSJ length

- $V_B$ increased linearly with PSJ length.
- Breakdown field was about 1.4 MV/cm, being smaller than 3.3 MV/cm.
-- Discussion --

\[ R_{\text{onA}} \ (\text{m}\Omega \ \text{cm}^2) = \frac{L_{SD}}{|\text{slope}|_{V_g=0}} \]

\( L_p = 10 \mu\text{m} \)

\( L_p = 40 \mu\text{m} \)

\[ R_{\text{onA}} = 22 \text{ m}\Omega\text{cm}^2 \]

\[ R_{\text{onA}} = 110 \text{ m}\Omega\text{cm}^2 \]
-- Discussion --

◆ Comparison of on-resistance

Diagram showing a comparison of on-resistance ($R_{on}$) versus breakdown voltage ($V_B$) for various semiconductor devices. The x-axis represents the breakdown voltage ($V_B$) in kilovolts (kV), while the y-axis represents the on-resistance ($R_{on}$) in milliohms per square centimeter ($\mathrm{m\Omega \ cm^2}$). The diagram includes data points for different manufacturers and devices, such as Panasonic, Toshiba, Infineon, Philips, Denso, Sanken, UCSB, USCC, Rutgers University (SIT), Si-SJ MOSFET, SiC transistors, GaN-HFET, and PSJ-Diode. The graph also highlights the limits for Si, 6H-SiC, 4H-SiC, and GaN.

- **Panasonic ('07)**: Si-SJ MOSFET
- **Toshiba ('07)**: Si-SJ MOSFET, SiC transistors
- **Fuji-Ele.**: SiC transistors
- **Infineon**: SiC transistors
- **Philips**: GaN-HFET
- **Denso**: GaN-HFET
- **Sanken ('07)**: Si-SJ MOSFET, SiC transistors
- **USCC ('06)**: GaN-HFET
- **UCSB ('06)**: GaN-HFET
- **Rutgers Univ. (SIT)**: GaN-HFET
- **PSJ-Diode**: GaN-HFET

Other companies and limits are also indicated, including Cree (DMOS), SiCED, and 6H-SiC-limit, 4H-SiC-limit, GaN-limit.
-- Summary --

We proposed a new method to realize GaN transistors and diodes enabling high-$V_B$ and negligible current collapse.

**Polarization super-junction (PSJ)**

- Which consists of basically GaN/AlGaN/GaN double heterojunction in which 2DHG and 2DEG co-exist.
- The PSJ system acts similar to a silicon super-junction
-- Summary --

As a consequence, the PSJ system can eliminate the barriers encountered in the present metal field-plate based device system.

- Breakdown voltage
- Current collapse
- Process cost
- Epi-cost
- etc.
Thank you very much for your careful attention!!

GaN for Green Future