Device engineering for $\beta$-Ga$_2$O$_3$-based high power electronics

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Outline

- $\beta$-$\text{Ga}_2\text{O}_3$: Background and motivation
- Device fabrication/characterization
  - Modulation doped FETs
  - Delta doped MESFETs
  - Enhancement-mode MOS Capacitors
- Conclusions
Power devices: application space

GaAs, GaP, GaN, SiC

Technology opportunities:
- power switching applications
- mm-wave power

β-Ga₂O₃

Si, SiC

Breakdown Field (MV/cm)

Power (W)

Frequency

1 KHz, 1 MHz, 1 GHz, 1 THz

TFT, 2D

SiC, GaN, SiC

Ga₂O₃

InP HBTs, InGaAs HEMTs, SiGe

Yole development 2019

GaN power device industry

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**β-Ga$_2$O$_3$: Introduction**

**β-phase:** Monoclinic crystal structure

Other polymorphs: α, γ, δ and ε

<table>
<thead>
<tr>
<th>Lattice constants</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>12.214 Å</td>
</tr>
<tr>
<td>b</td>
<td>3.0371 Å</td>
</tr>
<tr>
<td>c</td>
<td>5.7981 Å</td>
</tr>
<tr>
<td>α</td>
<td>90°</td>
</tr>
<tr>
<td>β</td>
<td>103.83°</td>
</tr>
<tr>
<td>γ</td>
<td>90°</td>
</tr>
</tbody>
</table>

**Melt-based growth techniques**
- First wide-band gap material
- High quality low cost native substrates
- Homo-epitaxy
- Low defect density
- Controlled n-type doping (Si, Sn, Ge)/insulating (Fe, Mg) films
- $\rho = 10^{-3} - 10^{12}$ Ω.cm, $n = 10^{14} - 10^{20}$ cm$^{-3}$
- p-type Ga$_2$O$_3$
Power switching parameters

- **$R_{ON}$ (on-state resistance)**
  - Conduction loss
  - Dominance at low frequencies

- **$Q_g$ (gate-charge)**
  - Charges to drive the ON-OFF transition
  - Switching loss

- **$V_{BR}$ (Breakdown voltage)**
  - Max voltage the device can block in off-state

$R_{on} = \frac{W_{dep}}{q\mu_n N_D} = \frac{4V_{BR}^2}{\varepsilon_s \mu_n E_C^3}$

$R_{on}Q_g = \frac{4V_{BR}^2}{\mu_n E_C^2}$

Baliga’s FoM

Baliga’s high frequency FoM

FoM’s calculated for $E_C = 8$ MV/cm, $\mu_n = 250$ cm$^2$/Vs

<table>
<thead>
<tr>
<th>Properties</th>
<th>Si</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>$\text{Ga}_2\text{O}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baliga’s FoM ($\varepsilon\mu E_C^3$)</td>
<td>1</td>
<td>16</td>
<td>250</td>
<td>870</td>
<td>2916</td>
</tr>
<tr>
<td>Baliga’s high freq. FoM ($\mu E_C^2$)</td>
<td>1</td>
<td>11</td>
<td>46</td>
<td>100.8</td>
<td>118.5</td>
</tr>
</tbody>
</table>

$P_{loss} \sim I_{out}^2 R_{ON} + I_{out} V_{in} \frac{Q_g}{I_g} f_{sw}$
Critical electric field

- **Device metrics**
  - Low $R_{ON}$ for a given $V_{BR}$
  - Predicted $E_C = 8$ MV/cm
    - $p$-$n$ band-to-band tunneling
- **Real picture**
  - $E_C \sim 3$-$4$ MV/cm: Schottky leakage
- **Breakdown field calculation (unipolar device)**
  - Avalanche breakdown
    - Upper limit on device performance

Credit: Zhanbo Xia
Importance of carrier mobility

- **AlGaN/GaN HEMTs**
  - Lateral power devices
- Ga$_2$O$_3$ heterojunction capability
- Design of (AlGa)$_2$O$_3$/Ga$_2$O$_3$ FETs.
- Lateral power devices
  - Degradation in $R_{ON} \Rightarrow$ dynamic $R_{ON}$
  - Peak field at gate edge
- Field-plate (FP): additional electrode for E lines termination
- Power switching: Enhancement-mode operation

![Graph and Diagram](Image)
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  - Delta doped MESFETs
  - Charge trap layer: e-mode devices
- High-k/bilayer dielectric field management
- Conclusions
MBE growth of $\beta$- Ga$_2$O$_3$ (OSU)

- Substrate: Bulk (010) $\beta$- Ga$_2$O$_3$
- Substrate Temperature: 700° C
- O$_2$ plasma power : 300 W
- Ga flux: 8x10^{-8} Torr (O-rich conditions)
- Chamber pressure: 1.5x10^{-5} Torr
- Growth Rate: 240 nm/hour

Okumura et. al. (Speck Group - UCSB)

Vertical MBE system (Riber M7) - O Plasma PAMBE

Sources:
- O plasma (unibulb), Ga, Si, Al, Fe
(AlGa)$_2$O$_3$/ Ga$_2$O$_3$ MODFETs

- Dopants spatially separated from channel
  - Eliminate ionized impurity scattering
  - Enhanced mobility
- Thickness confirmed from STEM
- Al composition (22%) from HRXRD

Sriram et al., APL 2017, Joishi et al., IEEE EDL, 2019

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(AlGa)$_2$O$_3$/ Ga$_2$O$_3$ MODFET: Field plate engineering

- To engineer peak field at the gate-drain edge
- SiN$_x$ as the passivation dielectric (140 nm)
- Hall mobility
  - Room T: 101 cm$^2$/Vs @ 3.4X10$^{12}$ cm$^{-2}$
- Device parameters ($L_{SD} = 2$ μm)
  - $I_{D,\text{max}} = 42$ mA/mm
  - $V_P = -1.2$ V
  - $I_{ON}/I_{OFF} = 10^7$

Joishi et al., IEEE EDL, 2019

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(AlGa)$_2$O$_3$/ Ga$_2$O$_3$ MODFET: device characteristics

- **Pulsed IV**
  - **SiN$_x$ passivation: improved knee-walkout**

**Breakdown measurements**
- Device in off-state
- For $L_{GD} = 250$ nm, $F_{AVG} = 3.9$ MV/cm
- For $L_{GD} = 16$ µm, $V_{BR} = 1370$ V
- Schottky gate limited breakdown

**$R_{ON}$-$V_{BR}$ benchmarking**
- Data far-off from intrinsic limit.
Increasing channel charge density

- Designs to increase charge density
  - Modulation doped FETs
    - Increase the conduction band offset
      - Increasing the Al percentage
        - Bottleneck: epilayer growth
  - Quantum well MODFETs
    - Multiple channels:
      - Secluded 2-DEG: growth challenge?
  - Delta doped MESFETs

![Diagram of Fe-doped (010) \(\beta\)-Ga\(_2\)O\(_3\) substrate]

![Diagram of Delta doped MESFETs]

![Diagram of Multiple channel MODFETs]
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**β- Ga$_2$O$_3$ delta doped MESFET**

- High concentration of 2-DEG
- Enables scaling of gate-channel distance
- High gate breakdown voltage
- For similar doping density
  - Higher mobility than uniformly doped films
- Flat C-V characteristics
  - 2-DEG profile: (1.2x10$^{13}$ cm$^{-2}$ charge density)

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Zhanbo et al., EDL 2018
β- Ga$_2$O$_3$ delta doped MESFET

- Breakdown characteristics
- $V_{BR} = 175$ V, $L_{GD} = 1.3$ μm, $F_{AVG} = 1.3$ MV/cm
  - $R_{ON}$ better than single channel MODFETs
- Field management design
- Dispersion characteristics
  - Significant knee-walkout
  - Source ?

From literature
This work
Source of dispersion: Fe doped substrate

- Dispersion characteristics
  - Thicker buffer FET
    - Reduced dispersion
    - Lower $R_{ON}$ degradation
  - Fe a source of dispersion

Buffer thickness

100 nm

300 nm

600 nm

$V_{GS} = 2 \text{V}, \Delta V_{GS} = -2 \text{V}$

$I_{DS}$ (A/mm)

$V_{DS}$ (V)

Lines: DC, Symbols: Pulsed

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Epitaxial passivation: $\beta$-$\text{Ga}_2\text{O}_3$ delta doped MESFET

**Ex situ passivation**
- Non-ideal dielectric/$\beta$-$\text{Ga}_2\text{O}_3$ interface

**Epitaxial passivation**
- Semiconductor-dielectric interface absent
  - No interface exposure to high fields
  - Ex situ surface far off from the 2-DEG
- Better dispersion properties
- High dielectric constant of $\beta$-$\text{Ga}_2\text{O}_3$
  - Better breakdown characteristics
Transistor characteristics

Pulsed IV
- Better dispersion characteristics

Breakdown characteristics
- $V_{BR} = 315$ V, $F_{AVG} = 2.3$ MV/cm
- $R_{ON}$ vs $V_{BR}$ benchmarking

Further device engineering needed!

Joishi et al., IEEE TED 2020
Device engineering: towards enhancement mode transistors

- Channel charge density > 1.5x10^{13} cm^{-2}: Significant gate leakage
- Need for dielectrics
- Conventional dielectric for $\beta$-Ga$_2$O$_3$: Al$_2$O$_3$
  - High dielectric constant
  - Positive fixed oxide charge ($N_{OX}$)
  - D-mode operation
    - High channel charge density pinch-off
- SiO$_2$ as a dielectric on Ga$_2$O$_3$
  - Highest known $\Delta E_c$ till date
    - Reduced gate leakage
  - Negative $N_{OX}$
    - E-mode operation
- Bilayer dielectric (Al$_2$O$_3$/SiO$_2$)
  - Leverage the combined benefits of SiO$_2$ and Al$_2$O$_3$
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ALD growth of dielectrics (IITB)

- **SiO₂**
  - Tris(dimethylamino)silane
  - O₂ plasma: 300 W
  - Temperature: 250 °C

- **Al₂O₃**
  - Trimethyl aluminum (TMA)
  - Thermal (DI water)
  - Temperature: 250 °C

- **AlN**
  - Trimethyl aluminum (TMA)
  - NH₃ plasma: 300 W
  - Temperature: 200 °C

- Cambridge Nanotech Fiji 200 ALD system
- Plasma sources: O₂, N₂, NH₃
- Depositions (Plasma/Thermal)
  - SiO₂, Al₂O₃, HfO₂, ZrO₂, AlN, TiN, TiO₂, Nb₂O₅
Device characteristics

- Total charge depleted
  - \( \sim 1.6 \times 10^{13} \, \text{cm}^{-2} \)
- Steep depletion characteristics
  - Better interface, low \( D_{\text{IT}} \)
- Negative \( N_{\text{OX}} \): normally-OFF operation
  - Poor \( V_{\text{FB}} \) retention

\[ \text{Al}_2\text{O}_3 \rightarrow \text{Al}_2\text{O}_3/\text{SiO}_2 \]

Dipankar et al., APL 2019
To engineer negative $N_{ox}$ for e-mode operation
  - Addition of a charge trap (C.T) layer
  - Non-polarized AlN as a CT layer
    - $V_{FB}$ domain
      - [3.5 V, 10 V]
    - Charge depleted
      - $1.5 \times 10^{13}$ cm$^{-2}$
    - Excellent charge retention
      - @ RT and 55 °C

Dipankar et al., APL 2020
Conclusions

- Ga$_2$O$_3$ for power electronics
  - Melt-based growth: cost factor?
- FoM’s for Ga$_2$O$_3$: shows promise but are simple guides
- ON-resistance vs field management in MODFETs and $\delta$-FETs
- AlN as a charge trap layer for tunable $V_T$ transistors

The future

- Delta-doped FETs from OSU + AlN charge trap layer at IITB
  - Enhancement mode delta-doped FETs
- Development of high-K dielectric BZN at IITB
  - Field management designs at OSU and IITB
Thank you
Backup slides
Importance of carrier mobility

- AlGaN/GaN HEMTs
  - Lateral power devices
- Ga$_2$O$_3$ heterojunction capability
- Design Ga$_2$O$_3$ FETs that enable
  - High mobility x charge density.
- Lateral power devices
  - Degradation in $R_{ON}$ => dynamic $R_{ON}$

![Graph showing $R_{ON}$ vs $V_{BR}$](image)

![Diagram of Ga$_2$O$_3$ FET](image)
Motivation: breakdown field management

- Field-plate (FP): additional electrode for E lines termination
- Power switching: Surface passivation, field-plate, e-mode operation
Field engineering: High-K dielectrics

- High-K dielectric to reduce peak field at the gate edge.
  - MIS diodes using Nb$_2$O$_5$ (dielectric constant = 50)

Ref: Zhanbo et al., APL 2019

Credit: Prabhans, Jayeeta
Vertical topology: field management using bilayer dielectrics

- Leveraging the combined benefits of a high-K/low-K dielectric combination

![Diagram showing vertical topology and field management using bilayer dielectrics]

- Schottky Metal (Ni) (φ=1.4eV)
  - p-GaN Guard Ring
  - (30nm) Al₂O₃ (70nm) HfO₂
  - Radius (R)

- 1.25e16 cm⁻³ β-Ga₂O₃
  - Drift Layer (10μm)

- 6.8e18 cm⁻³

![Graph showing FOM (G/W/cm²) vs. N_D (cm⁻³)]

- [100] Ga₂O₃:
  - Al₂O₃
  - HfO₂
  - Bilayer

- E vs Vbr: Al₂O₃
  - Vbr=2412 V
  - Al₂O₃ (8.7MV/cm)
  - Ga₂O₃ (8MV/cm)

- E vs Vbr: HfO₂
  - Vbr=1813 V
  - HfO₂ (5.3MV/cm)

- E vs Vbr: HfO₂
  - Vbr=2681 V
  - HfO₂ (5.3MV/cm)

Credit: Ravikiran