Semiconductor Materials and Structures for Power Electronics

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New: ARPA-E
(Feb 2010)
Overview

I. Background on Emerging Systems for Power Electronic Devices
II. Materials for Power Electronics
III. Epitaxial Dielectrics on GaN for FETs
IV. Summary
Motivating System Needs For Power Electronics

- Greater Efficiency with reduced Size, Cost and Weight
- Applications Segmented By Voltage and Current Ratings
- Small Scale Power Supplies (man) to Vehicle Traction (air, sea or land) to Power Distribution Systems (grid)
- At Core: Systems Need Switches (transistors) and flyback Diodes (fast)

SI ? SiC ? GaN ?
System Efficiency Losses

60W inverter losses on a 1200W solar array is equivalent to 19% vs 20% efficiency

Inverter Resistive and Switching Losses:
Normally-off Transistor
Fast Recovery Diode

Energy for Cooling:
High Temperature Operation

Storage:
Round-trip Losses
Today’s Power Grid

Problems:

- Not user friendly
  - No plug-and-play interface
- Large-scale integration of Distributed Renewable Energy Resource (DRER) would cause system collapse due to:
  - Lack of management system
  - Lack of energy storage
Notional Distribution System

**Legacy grid**

- 69kV
- 1 MVA

**FREEDM Substation**

- Distributed Grid Intelligence (DGI)
- ESD
- User Interface

**Market & Economics**

**Distributed Renewable Energy Resource (DRER)**

**Distributed Energy Storage Device (DESD)**

**IEM**: Intelligent Energy Management

**IFM**: Intelligent Fault Management

**LOAD**

- 120 V
- 3Φ 480V

**DRER**

- 10 kVA
- 100 kVA

**DESD**

**Legacy grid**

**Notional Distribution System**

**NC STATE UNIVERSITY**

**FREEDM Systems Center**

**NSF**
Technology Path

Conventional Transformer

[ 60Hz ]

Solid State Transformer (SST)

[ 10-15 kHz ]

5 X size reduction
10 X weight reduction

Leverage SiC MOSFET Technology

- John Palmour in Breakout -
Technical Development Program Linkages

Toward Green Energy Society

Today's non-green legacy grid

12 kV Communication

1 MW FREEDM Green Energy Hub Testbed

System Demonstration

Four Generation Development

Enabling Technology

Fundamental Science

IFM Intelligent Fault Management

IEM Intelligent Energy Management

PHEV/PEV Plug-In Hybrid Electric Vehicle

Plug-In Electric Vehicle

Current system lacks:
- Distributed control
- Communication
- Controllable transformer
- Storage
- Fast fault protection

Requires:
- New power devices
- Better storage
- New systems theory

Basic Deliverables

Theory & Models

Devices

Storage Cell

Post-silicon Devices

Advanced Storage

System Theory Modeling & Control

Distributed Grid Intelligence

Fault Isolation Device

Solid-State Transformer

Distributed Energy Storage Device

Reliable & Secured Communication

Integration

Integration

Integration

Integration

Integration

Four Generation Development
Comparison of Power Densities

Hybrid Vehicle Inverter

20kW – 120 kW
< 0.1 m³
Silicon IGBT Based
Currently Water Cooled

Power Distribution

20kVA – 120 kVA
~ 1 m³
All Passive – No Communication, Control or Dispatch
Highly Efficient
Why Anything but Silicon?

- **Size**: Limit to Current Rating Leads to Large Area Devices, Lower Frequency and Overall Weight

- **Efficiency**: Resistive and Switching Losses Potentially Less with SiC or GaN Devices

- **Temperature**: Larger Bandgap Energy Allows Higher-Temperature Operation Leading to System Efficiency

- **Why Now?**: Emergence of SiC and GaN Materials for Optoelectronic Applications Provides Unique Opportunity for Advancement in Power Electronics

- **Gallium Nitride**: Direct Wide Bandgap; Wurtzite (polar) Crystal Structure, AlGaN/GaN Heterostructures, good Electronic Transport Properties, ...
Periodic Table and Wide Bandgap Semiconductors

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GaN & SiC
LEDs
Blue Lasers
Power Electronics

GaAs
Mobile Phones
Wireless

Silicon
Microprocessors
Moore's Law
Power Controllers
Silicon Carbide and Gallium Nitride
Wide Bandgap Semiconductors

Most Wide Bandgap Semiconductors have a Hexagonal Structure
Most III-V Semiconductors have Zincblende Structure
## Comparison of Semiconductor Materials

<table>
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<th>Silicon</th>
<th>4H-SiC</th>
<th>GaN (Epitaxial)</th>
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<td>Breakdown Field (MV/cm)</td>
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<td>2.3</td>
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<td>Electron Mobility (cm²/Vs)</td>
<td>1500</td>
<td>1000</td>
<td>1250</td>
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<td>Thermal Conductivity (W/mK)</td>
<td>150</td>
<td>490</td>
<td>130</td>
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<tr>
<td>Saturated Electron Velocity (cm/s)</td>
<td>1.0x10⁷</td>
<td>2.0x10⁷</td>
<td>2.2x10⁷</td>
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Combined Figure of Merit

\[ K_{th} \varepsilon \mu_e v_s E_c^2 \]

### Problems:

1) What is Device Meaning of the Combined Figure of Merit?
2) Evolution of Measured Material Properties with Advancement in Materials Technology \((E_c, K_{th}, \mu_e, \ldots)\)

Figures of Merit

- **Combined Figure of Merit (General Assessment)**
  \[ k_{th} \varepsilon \mu_e v_s E_c^2 \]

- **Keyes Figure of Merit (Power Density & Speed)**
  \[ k_{th} \sqrt{c v_s / (4\pi \varepsilon_s)} \]

- **Baliga Figure of Merit (Resistive Losses)**
  \[ \varepsilon \mu_e E_c^3 \]

- **Baliga High Frequency Figure of Merit (Switching Losses)**
  \[ \mu_e E_c^2 \]

R. W. Keyes, "Figure of Merit for Semiconductors for High Speed Switches,“ *Proc. IEEE*, vol. 60, pp. 225-232, 1972


Resistive Loss in Power Rectifiers

- Minimize Series Resistance Loss at Voltage Rating
- Assume Series Resistance Dominated by n- Drift Region (Low Contact Resistance)
- From Device Model
  
  \[ R_{on} = \frac{4 \cdot BV^2}{\varepsilon \cdot \mu e \cdot E_c^3} \]

Mobility at Drift Region Doping Levels NOT Values for Undoped Material
GaN Laser Diodes: Lateral Growth Reduces Crystal Defects

UnMasked  Masked

Fig. 1. Schematic of: (a) PE growth from GaN seed laterally off the sidewalls then vertically and laterally over the silicon nitride mask; (b) PE growth from GaN seed laterally off the sidewalls and vertically off the stripe.

Davis, et.al.

Laser Diode Lifetimes > 1000 hrs with Low Defect GaN
Micro-morphology and dislocation density

\[ N_{\text{dis}} = 2 \times 10^7 \, \text{cm}^{-2} \]

250-\mu\text{m-thick}
free-standing
HVPE GaN

\[ N_{\text{dis}} = 2 \times 10^8 \, \text{cm}^{-2} \]

10-\mu\text{m-thick}
HVPE GaN

\[ N_{\text{dis}} = 3 \times 10^8 \, \text{cm}^{-2} \]

3-\mu\text{m-thick}
buffer
6H SiC

\[ N_{\text{dis}} = 4 \times 10^8 \, \text{cm}^{-2} \]

3-\mu\text{m-thick}
buffer
sapphire

G. Brandes, IS on Bulk Nitrides, Sept. 2005, Bremen, Germany
Thermal Conductivity of Low Defect Bulk GaN by 3-ω Method

CL Imaging of Defects

ρ = ~10⁷ cm⁻²

Solution growth GaN

Kyma bulk SI-GaN

Typical heteroepi dislocation densities

NCSU/Kyma bulk measurements

C. Mion, NC State University (2005)
GaN for Power Electronics

GaN as material for high-speed and high-power applications

- BFM – minimized resistive losses $[ \varepsilon \mu E_c^3 ]$
- BHFFM – minimized switching losses $(\mu E_c^2)$
- JFM – minimized switching delay $[ (v_{sat} E_c)^2 ]$

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<th>GaN (epi)</th>
<th>GaN (bulk)</th>
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<td>$K_{th}$ (W/mK)</td>
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<td>490</td>
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<td>$E_c$ (MV/cm)</td>
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<td>2</td>
<td>3.3</td>
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<td>2.7 (exp)</td>
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<td>$v_{sat}$ (x1E7 cm/s)</td>
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<td>2</td>
<td>3</td>
<td>3</td>
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<td>mobility (cm$^2$/Vs)</td>
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<td>850</td>
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Low Resistive Loss
Low Switching Loss
Metamorphic Quasi-Bulk GaN

- HVPE for GaN Boule Synthesis: NH$_3$, Ga, HCl
- Wafering by slicing and polishing
- Defect density reduction with increased thickness: as low as mid-$10^5$/cm$^2$
- Orientation controlled by wafering direction
Substrate Series Conductivity

- **n-ohmic** ~ $10^{-6} \ \Omega \text{cm}^2$
- **Drift** $<10^{-3} \ \Omega \text{cm}^2$ @ 1kV
- **substrate** 100 $\mu$m
  (target) $2 \times 10^{18} \ \text{cm}^{-3}$ n-type
  500 cm$^2$/Vs mobility
  $6 \times 10^{-5} \ \Omega \text{cm}^2$
- **Need**: Thin, highly doped, highly conductive substrates
Nominal GaN MOS Power Transistor and Materials Development Issues

Materials Focus / Problem

III-N MOS Interface Structures

2DEG Fabrication & Epitaxy

Drift Region Power Limit

Low Defect GaN Substrate

ACCUMULATION-MODE Vertical IG-HFET

SOURCE

GATE

Dielectric

N+ SOURCE

AlGaN Strain Dielectric

P+ SHIELDING REGION

N- DRIFT REGION

N+ SUBSTRATE

DRAIN
Lateral GaN MOS Power Transistor and Materials Development Issues

Materials Focus / Problem

- MOS Interface & Structures
- Recess Etching
- 2DEG Fabrication & Epitaxy
- Buffer Layer Defects and Leakage
- Silicon, Silicon Carbide, Sapphire

Enhancement-mode Lateral MOS-HFET

- Source
- Gate
- Drain
- AlGaN 2DEG
- GaN Buffer Layer
- Nucleation Layers
- Substrate
- Gate Dielectric
- Low-k Dielectric

Buffer Layer Defects and Leakage
GaN Dielectric Interface – Fab Process

- Deposition of GaN MOS Dielectric
- Consideration: Structure, Electron Energy and Thermal Stability
- Crystal Growth on III-Nitride Surface: Ga$_2$O$_3$ Interlayer
Summary

- Wide bandgap semiconductors opportunity in Power Systems
  - ‘Last mile’ of Electric Power Systems
  - High Voltage Transmission and Distribution
  - Renewable Energy Generation
  - Smarter Reactive & Resistive Loads

- Properties of WBGS advantageous in efficient power conversion

- Defect Density Key Issue in Wide Bandgap Semiconductors

- Gate Dielectrics for MOS applications

- Focus on GaN and SiC in Breakouts: John Palmour and Keith Evans
Acknowledgements

• Thanks:

• Support
  – NSF-ERC Program: FREEDM Systems Center
  – DARPA: Young Faculty Award
  – MDA, AFRL and ARO SBIR/STTR Programs
Questions?