Commercialization of SiC and GaN Power Devices

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Power Semiconductor Devices

Driving forces for power electronics technology and applications

DEVICE
- Thyristor
- Bipolar Transistor
- IGBT
- MCT
- SIC
- III-N

IPEM
- Computer Wireless
- HVAC Custom Power
- Hybrid & electric Cars

THE POWER ELECTRONICS EVOLUTION


*EPRI

Rensselaer
Outline

• Introduction
• Why SiC and GaN?
• Commercialization Efforts
  – Global Players
  – Processes and Foundries
  – Wafer Yield
• Future Trends
## Semiconductor Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ (eV)</th>
<th>Direct/Indirect</th>
<th>$n_i$ (cm$^{-3}$)</th>
<th>$\varepsilon_r$</th>
<th>$\mu_n$ (cm$^2$/V-s)</th>
<th>$E_c$ (MV/cm)</th>
<th>$v_{sat}$ ($10^7$ cm/s)</th>
<th>$\lambda$ (W/cm-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>I</td>
<td>1.5x10$^{10}$</td>
<td>11.8</td>
<td>1350</td>
<td>0.2</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.42</td>
<td>D</td>
<td>1.8x10$^6$</td>
<td>13.1</td>
<td>8500</td>
<td>0.4</td>
<td>1.2</td>
<td>0.55</td>
</tr>
<tr>
<td>2H-GaN</td>
<td>3.39</td>
<td>D</td>
<td>1.9x10$^{-10}$</td>
<td>9.9</td>
<td>1000$^a$</td>
<td>3.3$^*$</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>2H-AlN</td>
<td>6.2</td>
<td>D</td>
<td>$\sim$10$^{-34}$</td>
<td>8.5</td>
<td>300</td>
<td>12$^*$</td>
<td>1.7</td>
<td>2.85</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.26</td>
<td>I</td>
<td>8.2x10$^{-9}$</td>
<td>10</td>
<td>720$^a$</td>
<td>2.0$^a$</td>
<td>2.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Diamond</td>
<td>5.45</td>
<td>I</td>
<td>1.6x10$^{-27}$</td>
<td>5.5</td>
<td>3800</td>
<td>10</td>
<td>2.7</td>
<td>22</td>
</tr>
</tbody>
</table>

**Conventional Semiconductors**

**Wide Bandgap Semiconductors**

**Extreme Bandgap Semiconductors**

Note: a – mobility along a-axis, c-mobility along c-axis, *Estimated value, **2DEG

- GaN grown on SiC can have a similar thermal conductivity as that of SiC
- GaN grown on Si can reduce the wafer cost, have larger wafer size and use Si foundries for processing
Applications of Power Devices

Modified from an Application Note of Powerex, Inc. Youngwood, PA.

• Some devices are pushing Si boundary
• SiC and GaN offers promise for improvement

Operation Frequency (Hz)

SiC or GaN

Silicon

Power (VA)

10 1K 10K 100K 1M

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0.6-3.3kV SiC MOSFETs

Cree/Wolfspeed

V_{DS} = 1200 \text{ V}

R_{DS(on)} = 80 \text{ m} \Omega

I_{D(MAX)} \text{ @} T_c=25^\circ \text{C} = 33 \text{ A}

Mitsubishi Electric
SiC and GaN Power Devices Market

SiC device market size split by application
(Source: Power SiC: Materials, Devices, Modules, and Applications report, Yole Développement, August 2017)

GaN power device market size split by application ($M)

Yole
SiC Device Companies

Companies with commercial products in *Italics*

- Cree/Wolfspeed
- GE
- GeneSiC
- Microsemi
- Monolithic Semi.
- United Silicon Carbide
- Cissoid
- Infineon
- ST Micro(F/IT)
- Hestia
- Episil
- Denso
- Fuji Electric
- Hitachi
- Honda
- Mitsubishi
- Nissan
- Rohm
- Toyota
GaN Device Companies

- EPC
- GaN Systems
- TI
- Transphorm
- MicroGaN
- Infineon
- Panasonic
- Sharp

Companies with commercial products in *italics*
SiC and GaN

• Much tougher and brighter than Silicon

SiC ingot and wafers  GaN powder and crystal  GaN on Si

4H-SiC atomic stacking  GaN on Si
Substrate Sizes

Different crystal diameter expansion
(Source: SiC, GaN, and other Wide Band Gap (WBG) materials for power electronics applications, October 2015)
Present SiC vs. GaN Power Devices

- Vertical
- Homoepi
- Schottky, pn junction, MOS, implantation
- Unipolar and Bipolar devices
- Oxide or Polyimide passivation
- Avalanche capable in commercial devices

- Lateral
- Heteroepi
- Heterojunction
- Schottky, pn junction, MOS, n implantation
- Unipolar devices
- SiN, SiO$_2$, Al$_2$O$_3$, or AlN passivation
- Avalanche not seen in commercial devices
Augmented vs. Dedicated Foundry

- Existing Si CMOS foundry running commercial IC or power MOS processes
  - High wafer volumes
  - Lower per wafer/die cost (<1¢/A needed)
  - Lower manufacturing priority

- Specially designed foundry tailored for SiC or GaN processes
  - Low wafer volumes
  - Optimized facilities
  - Higher per wafer/die cost
Y = 1/(1 + AD)^n, Y – Yield, A – Critical Area, D – Defect Density, n – Number of Critical Levels

Types of Defects

- **Materials**
  - Substrate
  - Epi layer

- **In Process**
  - Photolithography
  - Thin Film Dep./Etching
  - Implant/Anneal
  - Oxidation
  - Metallization
1200V SiC MOSFETs

SiC MOSFET: Cree

\[ V_{DS} = 1200 \text{ V} \]
\[ R_{DS(on)} = 80 \text{ m}\Omega \]
\[ I_{D(MAX)} @ T_c = 25^\circ C = 33 \text{ A} \]

SiC MOSFET: GE

\[ V_{DS,\text{max}} = 1200 \text{ V} \]
\[ R_{DS(\text{ON})} = 55 \text{ m}\Omega \]
\[ T_{j,\text{max}} = 175^\circ C \]
SiC MOSFET Ratings

Cree: 1200V, 33A

GE: 1200V, 53A

Figure 5. Output characteristics

\[ I_D = f(V_{DS}, V_{GS}); T_J=25 \, ^\circ\text{C} \]

Fig 1. Typical Output Characteristics \( T_J = 25 \, ^\circ\text{C} \)
Future Trends

• SiC and GaN power devices and ICs are finding increasing applications in energy efficient systems but enhancing their cost-effectiveness demands high-yield foundry device manufacturing

• New packaging solutions need to be developed to minimize interconnecting parasitics and maximize heat spreading and sinking

• Integrated technology teams are needed to realize and implement WBG technology solutions to sustainable green energy solutions
Thank You!