Overview on Industrial Applications of WBG devices
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SSIE 2017, Bressanone/Brixen, Italy
Outline

• Properties of WBG devices
• General trends and challenges
• Roadmaps, market and possible lead applications
• Overview on Applications
• Conclusion
## Properties of SiC and GaN

<table>
<thead>
<tr>
<th>Name of material</th>
<th>Si</th>
<th>4H-SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap $E_g$ (eV)</td>
<td>1.1</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Mobility $\mu$ (cm$^2$/Vs)</td>
<td>1,400</td>
<td>8,000</td>
<td>1,200</td>
</tr>
<tr>
<td>Dielectric breakdown field $E_c$ (MV/cm)</td>
<td>0.3</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Relative dielectric constant</td>
<td>11.8</td>
<td>9.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Baliga's figure of merit $Si = 1$</td>
<td>1</td>
<td>340</td>
<td>870</td>
</tr>
<tr>
<td>Low frequency $(\mu E_c^3)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High frequency $(\mu E_c^2)$</td>
<td>1</td>
<td>50</td>
<td>104</td>
</tr>
</tbody>
</table>

Source: Flosfia
Why EBG devices and challenges

Trends:
- Higher power density, less losses, less cooling
- Higher operating temperature
- Higher switching frequency
- Higher voltages
- Longer lifetime

But:
- Packaging
- Cost
- Module design
- Insulation
- Reliability?
- 2nd source
Power electronic market evolution

Power electronics market evolution: two possible paths
(Source: Status of the power electronics industry 2016 report, June 2016, Yole Développement)

Source: Yole
History of SiC technology

- 1992: Start of power device development, SiC diodes and transistors for high power industrial applications
- 1998: Start of 2" wafer technology integration in the high voltage silicon power manufacturing line of Infineon
- 2001: Worldwide first release of commercial SiC power devices
- 2006: Release of the first power modules with SiC devices inside for industrial motor drive applications (hybrid modules)
- 2007: Move to 1" wafer production
- 2008: Release of 3rd generation diodes with improved thermal properties
- 2009: Release of first high power module with SiC diodes
- 2010: Move to 100 mm 4" wafer diameter
- 2012: Roll out of SiC portfolio for solar power string inverters
- 2013: Release of 5th generation of diodes, introduction of thin wafer manufacturing for SiC
- 2014: Commercial release of Infineon’s ultra reliable SiC JFET switch
- 2014: Extension of the 5th generation principle toward 1200 V diodes
- 2015: Start of 150 mm conversion in manufacturing
- 2016: Technology launch of CoolSiC™ MOSFET at the PCIM in Nuremberg
- 2017: Commercial release of CoolSiC™ MOSFET lead products in power modules and discrete versions

Source: Infineon
SiC

- Efficiency increase
- Power density improvement
- System cost reduction

Source: Infineon
Expected effects of using SiC in Automotive

**Smaller battery**

Battery

**Higher autonomy**

Source: Infineon
GaN in the hype cycle

(From: Power GaN 2016: Epitaxy and Devices, Applications and Technology Trends report, Yole Développement, September 2016)

Adopted from the Gartner Hype Cycle concept

The commercial availability of a certain device is not equal to the device’s adoption. Although we are excited about the product releases in 600V/650V GaN HEMT, their future is still hazy for many applications.

Source: Yole
GaN Manufacturer

Source: Yole
Power America Roadmap for SiC

SiC Strategic planning

- Diodes for Volume
  - MOSFETs for Potential
  - transfer of existing Processes
- PA enabled 1st products
  - X-fab In House
  - Process complete
- PA Process Used by Academia, Industry
- Initial SiC Foundry
  - Capital Equipment Investment
  - HV Diode, MOSFET Processes
- Develop JFET, JST
- Packaging of improved through teaming
  - and R&D. More focus on 3.3-10 kV
- 1st Devices Delivered to Device Bank
- Reliability
  - WBG
  - Established
- PV (due to Volume)
- Increased Automotive
  - Data Center, UPS, Solid State Fuse
  - HV Grid
  - Increased HF magnetics, Passives
- WAfer costs assumed to reduce over time due to increased volume

Big Road Mapping Questions:
- How low in voltage will SiC Go? (Impact on Automotive, GaN)
- Enough U.S. HV Packaging Expertise?
- How can reliability best be communicated?

FA2: Device Fabrication
- US Maintains Competitive WBG
  - Fabrication of Devices and Modules

FA4: Accelerate Commercialization
- PA enabled devices in John Deere
  - Toshiba, ABB, and other U.S. Products

Power America Roadmap for GaN

**GaN Strategic Planning**

- Triquint/RFMD Merger. Transphorm Fab. Japan Navitas @ TSMC
- GaN Foundry in US could be important. Second source, allow GaN innovation.
- Will Vertical GaN be ready? When 8 inch GaN/Si?
- Improved packaging, improved P.E. manufacturing methods (Fred Lee)
- 1st devices delivered to device bank
- Reliability WBG established
- PV (due to volume)
- Increased automotive?
- Data centers, consumer elect., adapters, wireless power
- Increased HF magnetics, passives
- WA costs assumed to reduce over time due to increased volume

**FA2: Device Fabrication GaN**
- US maintains competitiveness in design, I.P., and GaN innovation

**Big Road Mapping Questions:**
- Timing of GaN market growth?
- What voltage will power GaN excel?
- Importance of gate drive integration?
- How to leverage RF foundries?

**FA4: Accelerate Commercialization**
- PA enabled GaN applications
- Manufactured in US.

Source:
PowerAmerica Draft Public Roadmap, May 2016
Application fields of SiC/GaN

**WBG MARKET SEGMENTATION AS A FUNCTION OF VOLTAGE RANGE**

*Current status and Yole's vision for 2020*

While SiC is used for high voltage applications, GaN is mainly used for low voltage. The 600-900V range will be the battlefield.

Source: Yole/ECPE
Relevant applications for SiC/GaN

Relevant applications
Where does GaN play a role?

Application
- HVDC
- High-voltage DC
- Large drives
- Ships
- Locomotives
- Large solar plants
- Trams, buses
- Electric cars
- On-roof PV
- Small drives
- Air conditioner
- Robotics
- Washing machine
- SMPS
- Chargers/Adapters

Future Scenario Power Electronics

- Power by application (W)
- ULTRA HIGH POWER
- HIGH POWER
- MID POWER
- LOW POWER

Thyristor
IGBT
SiC Module
SiC
MOSFET
GaN

Source: U. Kirchner, Infineon Technologies, ECPE/CLINT
Roadmap Workshop, 04.10.2016 in Ismaning
Overview Si, SiC and GaN applications

- SiC
  - Reaching tipping point
  - Targeting 600 V – 1.7 kV
  - High power
  - High switching frequency

- Si
  - Remains mainstream technology

- GaN
  - Lower cost than SiC
  - Targeting 100 V – 600 V
  - Medium power
  - Highest switching frequency

Source: Infineon
Yoles view on GaN based Power Electronics

GaN-based Power Electronics

Estimated accessible markets, growth rate, and time to market

Source: Yole

Written in the bubbles is the main device voltage target for GaN

Bubble size is related to Si device market as of 2013, most likely accessible to GaN

Source: Yole
GaN market

2010-2020 GaN device market size, split by voltage in %

Source: Yole
The SiC power semiconductor market

Source: IHS
The GaN power semiconductor market

![Graph showing the growth of GaN power semiconductor market from 2014 to 2025. The x-axis represents the years from 2014 to 2025, while the y-axis represents revenue in $m. Different colored lines indicate the growth of various sectors such as Other Applications, Downhole Drilling, Military & Aerospace, PV Inverters, Industrial Motor Drives, HEV Charging Infrastructure, Hybrids & Electric Vehicles, UPS, Wireless Charging, and Power Supplies.](image)

Source: IHS

Lead Applications

Possible Lead Applications ...

... for SiC:
- Automotive: on-board charger, DC/DC converter, drive inverter
- Railway traction
- MV grid applications: wind power, PV, SST, circuit breaker
- MV application in medical technology
- New applications (not replacing Si in existing fields)
- ?

... for GaN:
- PFC/Power supplies with very high frequency
- Automotive: on-board charger, DC/DC converter
- Industrial automation and robotics
- PV home systems
- ?

Source: ECPE
Overview of WBG Applications

- Insulated resonant DC/DC converter
- Drive inverter
- Automotive (HEV, DC/DC converter, on-board charger)
- Aerospace (drive inverter, DC/DC converter, propulsion)
- PV systems
- UPS
- Solid state transformers
- HVDC
- Wind power
- DC breaker
What defines the Application?

Requirements
Mission Profile – Drive cycle...(speed..
Translation to electrical values (voltage, current)
Losses (Device specific) – Temperature model (e.g. Cauer, Foster)
Temperatures (temperature level, temperature swing) => cooling
Lifetime curve from tests PC, TC resulta
Lifetime calculation => according to requirements
**Lifetime calculation**

- **Mission profile**
- **Operation profile**
- **Motor Characteristics**
- **Electric parameters**
- **Lifetime curve**
- **Temperature profile**
- **Thermal Characteristics**
- **Power Electronics Devices and Packaging**
Inverter topology

Grid connected inverter

Advantages:
• Less losses = reduced size
• Higher switching frequency = reduced filter size (dV/dt; sinus filter)
• No tail current = shorter dead time
• Today's limit for natural convection is 3kW with WBG maybe up to 7kW (estimation of HS OWL)
• Easier Motor integration
• ~ 2x power density
• Simples topology

Drawbacks:
• Motor winding stress
• EMC
• Robustness
• Cost

Source: HS OWL
Source: Fuji electric
dV/dt issue for drive applications

Limiting factor: Insulation of the motor winding

Rise time $t_r$ of a voltage pulse $U_p$ at the motor terminals acc. to IEC 60034-25

Maximum terminal voltages for partial-discharge-free insulation systems at 600V DC link voltage.
Typical classes: Curve C ($dv/dt = 12$ kV/$\mu$s) or B ($dv/dt = 3$ kV/$\mu$s); ($U_p = U$ peak to neutral)

- Typical asynchronous motors for inverter usage are of class C
- Because of reflection the du/dt at the inverter terminals must not exceed 6 kV/$\mu$s

Source: HS OWL
dV/dt issue for drive applications

Investigations on dV/dt for different devices

- 6 kV/μs is the limit for motors
- All-SiC inverters with maximum possible dV/dt would damage the motor windings
- The rise time of SiC-MOSFETS can be set widely over the gate resistor
- Even slow switching of SiC reduces the inverter losses (50% lower losses seems to be possible)

dv/dt when the gate resistor is varied [1]


Source: HS OWL
Inverter types

Source: HS OWL
Loss reduction in inverters by SiC diodes

Loss reduction by use of Hybrid Modules (SI-IGBT, SiC-Diode)

- Inverter losses of an 40 kVA servo inverter (multi-axis, DC/AC, VDC = 550 V, fs= 8 kHz)

Measured loss reduction (60 Hz): ~ 1%

Source: HS OWL
EMC for drive applications

EMC aspects of high dv/dt

- Shielded motor cable of industrial drive systems: The higher dv/dt of WBG should be no problem for conducted and radiated emission
- The inner EMC is much more difficult

Spectrum of the inverter voltage [1]

Source: HS OWL
Reliability of SiC devices

- SiC has different material properties
  - Thermal conductivity (W/m*K): Si 20°C 160, SiC-4H 20°C 380
  - Specific heat capacity (J/kg*K): 700, 690
  - CTE (ppm/K): 3, 4.3
  - Young's Modulus (GPa): 162 (anisotropic), 501

- Plastic strain is ca. 40% higher
- Lifetime power cycling only about 30%

- PC or IOL test is good as it is, but ...
  - WBG devices require better packaging than silicon even to be on par
  - Testing details can have a large impact
  - Avoid discharging of traps by overvoltage

Source: University Bremen
Reliability of GaN devices

- **Transphorm TPH3212PS**
  - Thermal interface material: Thermally conductive foil
  - \( \Delta T = 87 \, ^\circ\text{K} \)
  - \( I_{\text{Load}} = 21.8 \, \text{A} \)
  - \( t_{\text{on}} = 1 \, \text{s} \)
  - \( t_{\text{off}} = 1.5 \, \text{s} \)
  - TSEP: \( R_{\text{on}} \)

- **Cycle until EoL**
  - 214,904
  - First GaN results reasonable
  - Better TSEP to be found

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Source: University Bremen

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Source: J. Lutz, TU Chemnitz

N. Kaminski, A. Brunko, CLINT-WPE Workshop  March 7th 2017, 17
Cost comparison for MV applications

- Si-IGBT with Si-PiN diode → 0% SiC
- Si-IGBT with SiC SBD → 16% SiC
- Si-IGBT with SiC SBD → 33% SiC
- SiC-MOSFET → 33% SiC
- SiC-MOSFET → 50% SiC
- SiC-MOSFET → 100% SiC

Source: University Rostock
Junction temperature calculations for SiC configurations

- Modulation index 1.0 (sine triangle without third harmonic)
- Switching frequency 2.500 Hz
- High performance water cooler, water temperature 40°C

Source: University Rostock
Acceptable cost calculations for SiC for wind power

- Wind power, energy price = 0.07 € / kWh, 20 years

<table>
<thead>
<tr>
<th>Power</th>
<th>kW</th>
<th>40</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours per year</td>
<td>h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1150</td>
<td>1725</td>
<td>1275</td>
<td>1100</td>
<td>625</td>
<td>1975</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Losses per year</th>
<th>Δ [kWh]</th>
<th>Benefit per year [€]</th>
<th>Benefit during lifetime [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-IGBT / Si-PiN - 0% SiC</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Si-IGBT / SiC-SBD - 16% SiC</td>
<td>11278</td>
<td>789</td>
<td>15.789</td>
</tr>
<tr>
<td>Si-IGBT / SiC-SBD - 33% SiC</td>
<td>12021</td>
<td>841</td>
<td>16.830</td>
</tr>
<tr>
<td>SiC-MOSFET - 33% SiC</td>
<td>20266</td>
<td>1.419</td>
<td>28.372</td>
</tr>
<tr>
<td>SiC-MOSFET - 50% SiC</td>
<td>23285</td>
<td>1.630</td>
<td>32.599</td>
</tr>
</tbody>
</table>

Source: University Rostock
Acceptable cost calculations for SiC for wind power

Wind power, energy price = 0.07 € / kWh, 20 years

<table>
<thead>
<tr>
<th>all values for a 600 kW inverter unit with 3 PrimePack modules</th>
<th>SiC SBD 16% SiC</th>
<th>SiC SBD 33% SiC</th>
<th>SiC FET 33% SiC</th>
<th>SiC FET 50% SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefit for the owner of the PV plant</td>
<td>[€] 15.789</td>
<td>16.830</td>
<td>28.372</td>
<td>32.599</td>
</tr>
<tr>
<td>Acceptable cost increase for the PV plant</td>
<td>[€] 7.895</td>
<td>8.415</td>
<td>14.186</td>
<td>16.299</td>
</tr>
<tr>
<td>Acceptable cost increase for the inverter</td>
<td>[€] 3.158</td>
<td>3.366</td>
<td>5.674</td>
<td>6.520</td>
</tr>
<tr>
<td>Acceptable cost increase for the IGBT module</td>
<td>[€] 316</td>
<td>337</td>
<td>567</td>
<td>652</td>
</tr>
</tbody>
</table>

Source: University Rostock
Traction application

**CO₂ EMISSIONS**

(Per passenger per kilometre)

- 2.2 gr CO₂
- 30 gr CO₂
- 115 gr CO₂
- 153 gr CO₂

Source: ALSTOM
Device technology for traction applications

<table>
<thead>
<tr>
<th>Performances</th>
<th>Reliability &amp; lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low conduction losses [Pcond]</td>
<td>Low FIT rate during 30 years of service life</td>
</tr>
<tr>
<td>Low switching losses [Pswitch]</td>
<td>Large power cycling capability [Ncyc]</td>
</tr>
<tr>
<td>Large switching robustness</td>
<td>Robustness against environmental conditions</td>
</tr>
<tr>
<td>Operation over a large range of</td>
<td></td>
</tr>
<tr>
<td>• Temperature [ -40 °C / 125 °C ]</td>
<td></td>
</tr>
<tr>
<td>• Voltage [Large variation of network voltage]</td>
<td></td>
</tr>
<tr>
<td>• Current</td>
<td></td>
</tr>
<tr>
<td>Short-circuit capability</td>
<td></td>
</tr>
<tr>
<td>l^2t capability (fault current)</td>
<td></td>
</tr>
</tbody>
</table>

Source: ALSTOM
SiC devices for traction

Source: ALSTOM
SiC devices in a regional train

Source: ALSTOM
Solid state transformer

Line-frequency transformers vs. power electronic transformers

Line frequency transformers (LFT)
- Mature technology
- Cheap, efficient (full load), reliable
- Voltage drop under load
- Sensitivity to harmonics, load unbalances, DC offsets
- No overload protection
- No power flow control
- Low efficiency at light load levels

Power electronic transformers (PET) (solid state transformers, SST)
- Uses high frequency transformers for galvanic isolation
- Power flow control
- Reactive power, harmonics and unbalances compensation
- Can provide LV-DC ports
- Smart protection

Source: SPEED project
Data center (GaN)

- **Total Cost of Ownership (TCO) matters**: hardware/software + operational costs really matters
- **Electricity costs** is ranked in TOP 5 costs
- Efficiency of electricity usage can lead to significant **system cost savings**

### Effect of higher efficiency on electricity costs

<table>
<thead>
<tr>
<th>Stage</th>
<th>Efficiency increase</th>
<th>Savings per server per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFC</td>
<td>0.5%</td>
<td>4.5$</td>
</tr>
<tr>
<td>DCDC (LLC)</td>
<td>0.5%</td>
<td>4.5$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.0%</td>
<td>9.0$</td>
</tr>
</tbody>
</table>

Based on energy cost: 0.06USD/kWh, 1.5kW average power consumption per server, 80% yearly utilization

Source: Infineon
Aeronautic Needs

- Weight reduction
- Reliability and Life time
- Losses reduction
- Cost

Expected Electric systems in future Aircraft

Source: SAFRAN
Harsh Environment applications

Some applications in engine or wheel area to avoid deported electronics and earn filtering, shielded wiring require to withstand high temperature but not with the same mission profile (life time: 30 years)

High lifetime requirements
2500 cycles -50/+250°C
High ambient T° → 200°C
Conclusion I

What is an ideal device for industrial applications

Easy to handle –
  easy to drive
  normally off (cascode is no option)
  robust (overvoltage, cosmic radiation, overcurrent)
  low losses (easy cooling)
  scalable (parallel devices)

Low cost
  device or system cost

Easy to package
Reliable (No change of characteristics, no defects)
Standardized (2nd source)
Conclusion II

• SiC more mature than GaN
• High voltage applications (SiC)
• Very high frequency operation (GaN)
• Market is growing rapidly
• Future applications identified
• Challenges (package, cost)