Power conversion switch technology: the who, when, where and why of using Si, SiC and GaN transistors

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Infineon Technologies AG
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1. What drives next generation power devices?

2. Playground for Wide band gap technologies today and tomorrow

3. Is Silicon for power already at the end?
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Power conversion by switching in a nutshell – avoid losses in switch elements since those just generate heat.

Ideal switch: losses zero (UxI = 0 in each phase)
Power conversion by switching in a nutshell – avoid losses in switch elements since those just generate heat.

Real switch: on-state and switching losses, $U \times I > 0$.
Power conversion by solid state switches – origin of losses

Loss origin – conduction
- resistance (MOSFET, HEMT, IGBT)
- knee voltage (IGBT)

Loss origin – switching
- C- charging (MOSFET, HEMT, IGBT)
- minority carrier dynamics (IGBT)
- minority carrier dynamics (pn-diode)

MOSFET/HEMT normally preferred since losses due to knee voltage or minority carriers not in place, but in case of silicon significant penalty by increasing conduction losses
Wide bandgap characteristics offer advantages for power electronics

- Higher voltage operation
- Improved head dissipation
- Higher frequency switching
- Thinner active layers

Extended power density

### Comparison of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Bandgap [eV]</th>
<th>Breakdown field [MV/cm]</th>
<th>Electron mobility [cm²/V·s]</th>
<th>Thermal conductivity [W/cm·K]</th>
<th>Electron drift velocity [10⁷ cm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.1</td>
<td>0.3</td>
<td>1.5</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>SiC</td>
<td>3.3</td>
<td>2.2</td>
<td>1.1</td>
<td>4.9</td>
<td>2.0</td>
</tr>
<tr>
<td>GaN</td>
<td>3.5</td>
<td>2.0</td>
<td>1.3</td>
<td>1.3</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Bandgap [eV]
Breakdown field [MV/cm]
Electron mobility [cm²/V·s]
Thermal conductivity [W/cm·K]
Electron drift velocity [10⁷ cm/s]

Si, SiC, GaN
WBG based semiconductors can withstand higher internal electric fields – what does it mean? Example: 5kV power device

Very high number of free electrons
\[ R_s = 0.02 \, \Omega \text{cm}^2 \]
\[ d = 0.05 \, \text{mm} \]

Very low number of free electrons
\[ R_s = 10 \, \Omega \text{cm}^2 \]
\[ d = 0.5 \, \text{mm} \]
Infineon will complement each of its leading edge silicon solutions by a wide bandgap technology!

**TRENCHSTOP™ to CoolSiC™**

**CoolMOS™ to CoolGaN™ and CoolSiC™**

**OptiMOS™ to CoolGaN™**
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Si, SiC and GaN – positioning across various applications

Si, SiC, GaN

› Depending on application requirements Si, SiC and GaN all have a specific value proposition in the 600V/650V segment

SiC

› SiC complements Si in many applications and enable new solutions
› Targeting 600V – 3.3 kV
› High power - high switching frequency

GaN

› GaN enable new horizons in power supply applications and audio fidelity
› Targeting 100V - 600V
› Medium power - highest switching frequency

Si, SiC and GaN complement Si in many applications and enable new solutions. Depending on application requirements, Si, SiC, and GaN all have a specific value proposition in the 600V/650V segment. SiC complements Si in many applications and targets 600V – 3.3 kV, offering high power and high switching frequency. GaN enable new horizons in power supply applications and audio fidelity, targeting 100V - 600V and offering medium power with the highest switching frequency.
System integration and energy savings will be a key lever for power electronics – example SiC situation

Chip costs
SiC
Si

System costs
SiC@10kHz
Si
SiC@40kHz

Cool SiC™
best in class switching frequency, conduction losses and radically improved efficiency

Si-IGBT & Si-diode
Si-IGBT & SiC-diode
SiC-switch
Recovery losses
30%
80%
Turn-off losses
Turn-on losses
Where are the major playgrounds for SiC devices today and what are the next big moves – tipping point model

- **Photovoltaic**
  - reduction of system cost
  - reduction of system size

- **EV charging**
  - faster charging cycles

- **IPS**
  - higher efficiency,
  - reduced total cost of ownership

- **eMobility**
  - higher reach per charge
  - more compact main inverter

- **Traction**
  - lower system cost
  - higher seat capacity

- **Drives**
  - reduced system size
  - reduced total cost of ownership
Tipping point passed in solar - Customer value proposition for PV string inverters: power density increase by 2.5

Development of Kaco String Inverters

Value Proposition

- Power density increase by factor 2.5 (50 kW → 125 kW)
- Reduction of number of switches (5-level to 3-level) leads to reduced risk of field failures
- SiC provides less reduction in efficiency at high operating temperatures → better efficiency (99,1% vs 98,9%)

The next big opportunity for SiC transistors
High Power UPS Topologies

<table>
<thead>
<tr>
<th>Si 2-Level</th>
<th>Si 3-Level NPCT</th>
<th>SiC 2-Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Years ago</td>
<td>5 Years ago</td>
<td>In 2019</td>
</tr>
<tr>
<td>3.2% losses* at 6kHz</td>
<td>2.9% losses* at 8kHz</td>
<td>1.7% losses* at 32kHz</td>
</tr>
</tbody>
</table>

*% Losses of Power Semi Devices at 300kW and 400Vac
Tipping point reached by significant cost of ownership reduction

500kWhrs x 24 hours x 365 days x 5 years = 22 million kWhrs processed power through UPS

- **Si 2-Level at 3.2% loss** = 700,000 kWhrs x 1.2 factor* = 840,000 kWhrs
  - In EU at €.10 per kWhr = €84,000

- **Si 3-Level at 2.9% loss** = 640,000 kWhrs x 1.2 factor* = 760,000 kWhrs
  - In EU at €.10 per kWhr = €76,000

- **SiC 2-Level at 1.7% loss** = 374,000 kWhrs x 1.2 factor* = 450,000 kWhrs
  - In EU at €.10 per kWhr = €45,000

*1.2 factor reflects the energy used for air conditioning to extract heat from a building with UPS installed*
CoolGaN™ initial target applications

- Servers
- Telecom
- Wireless charging
- Audio
- Adapters

Exploring...
Benefit of GaN versus Superjunction MOSFETs - $Q_{\text{oss}}$

- **70 mΩ, 600 V GaN HEMT**
  - $Q_{\text{oss}}$ (nC) vs. $V_{DS}$ (V)
  - $E_{\text{oss}}$
  - $Q_{\text{oss}}$-related turn-on loss

- **70 mΩ, 650 V Superjunction**
  - $Q_{\text{oss}}$ (nC) vs. $V_{DS}$ (V)
  - $E_{\text{oss}}$
  - $Q_{\text{oss}}$-related turn-on loss

PSMA
Feature comparison between GaN, SiC and Si SJ for power supply applications

<table>
<thead>
<tr>
<th>Feature</th>
<th>CoolGaN™ advantage</th>
<th>SJ</th>
<th>GaN</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FOM ( R_{DS,ON\times} )</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q_{RR} )</td>
<td>High, snappy</td>
<td>zero</td>
<td>Very small</td>
<td></td>
</tr>
<tr>
<td>( E_{OSS} )</td>
<td>low</td>
<td>lower</td>
<td>lower</td>
<td></td>
</tr>
<tr>
<td>( C_{OSS} ) shape</td>
<td>Non-linear</td>
<td>linear</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>( Q_G )</td>
<td>high</td>
<td>Very low</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>( Q_{OSS} )</td>
<td>Very high</td>
<td>low</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Device concept</td>
<td>vertical</td>
<td>lateral</td>
<td>vertical</td>
<td></td>
</tr>
</tbody>
</table>

In the 600V segment 600 V CoolGaN™ and CoolSiC™ are ideal components for Totem Pole PFC and LLC/ZVS PSFB

- **Simpler, HB topology**
- **Highest efficiency with reduced component count**
- **System cost reduction**
- **For single switch topologies Eoss is key**
  - CoolMOS™ is still the best choice
- **Higher fsw, no penalties**
- **Higher power density**
- **Next generation will target multi-chip integration**
PFC – WGB enables simpler and more efficient half bridge topologies such as Totem Pole

Nowadays, several high efficient topologies for CCM PFC are available. BOM costs and part count depend on efficiency targets.

### Interleaved Stages

Body diode (Qrr) prevents half bridge topologies.

### Dual Boost

WBG technologies (GaN HEMT or SiC MOSFET) enable to use simpler and cost effective HalfBridge/Hard switching topologies and at the same time to achieve higher efficiency.

### HB TOTEM POLE

GaN has zero Qrr.

### FB TOTEM POLE

The investment in WBG has a compelling payback which allows to absorb very rapidly the initial higher costs of WBG switches.
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IGBT’s have already enabled an impressive Power density race

was enabled by progress in
- IGBT cell technology
- vertical design
- interconnect technology
- increased maximum junction temperature

and will proceed also in the future

Figure out of:
Next IGBT generation – driven by advanced cell concepts

Trend to investigate IGBTs with mesas in the (deep) sub-micron range:
on state voltage < 1 V for a 1200 V IGBT seems achievable; but, reasonable switching losses, switching speed and short circuit robustness “not that easy“.

Fig. out of: A. Nakagawa, “Theoretical Investigation of Silicon Limit Characteristics of IGBTs,” in Proceedings of Int. Symp. Power Semiconductors and ICs, pp. 5-8, 2006.


Advanced gate-driving aspects, example 1: “Scaled” IGBT

- Trend to investigate IGBTs with lower threshold voltage and lower $V_{GE\_use}$ (e.g. 5 V instead of 15 V), very similar to GaN HEMT e.g.
  - Potential “Pro’s“: lower $V_{GE\_sat}$, lower gate charge, lower driving power
  - Potential “Con“: bigger influence of parasitics (e.g. parasitic turn on).

Fig. out of: T. Saraya et al., “Demonstration of 1200V Scaled IGBTs Driven by 5V Gate Voltage with Superiorly Low Switching Loss,” IEDM, pp.189-192, 2018.
Advanced gate-driving aspects, example II: “Dual Gate” IGBT

- Trend to investigate IGBTs with 2 external gates
  - Potential “Pro”: Enabling low on state voltage $V_{CE_{Sat}}$ and low turn off losses $E_{off}$ by decreasing the carrier plasma before turning off using the second gate
  - Potential “Con”: bigger gate-driving effort

Advanced gate-driving aspects, example III: “RC-(DC)” IGBT “Reverse-conducting (diode-controlled)” IGBT

› Trend to investigate IGBTs with integrated freewheeling diode
  › Potential “Pro”: Enabling higher power density by using a large chip area for both IGBT and diode function.
  › Potential “Con”: enhanced process complexity and gate-driving complexity

Fig. out of: D. Werber et al., “A 1000A 6.5kV Module Enabled by Reverse-Conducting Trench-IGBT-Technology,” in Proc. PCIM, 2015, pp. 351 – 358.
It remains attractive to use even thinner chips, as both on-state AND switching losses can thus be reduced.

- for a 1200 V IGBT, a chip thickness of about 85µm seems feasible,
- however, the thinner the IGBT chip, the more critical the switching softness, cosmic ray robustness and short-circuit robustness will become,
- but countermeasures are available.
Not necessarily the decision between WBG and silicon is leading to the best solution – a combination might win – example ANPC

Components used

<table>
<thead>
<tr>
<th>Components</th>
<th>Specifications</th>
</tr>
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<tbody>
<tr>
<td>T1/T4/T5/T6</td>
<td>200A 950V IGBT 7 MPT</td>
</tr>
<tr>
<td>D1/D4/D5/D6</td>
<td>200A 950V Diode</td>
</tr>
<tr>
<td>M2/M3</td>
<td>1200V SiC MOSFETs: 6mOhm</td>
</tr>
</tbody>
</table>
Merging the strength of silicon and wide band gap delivers cost performance optimized solutions

- ANPC is a topology ideally suited for high voltage, fast switching inverters enabling highest efficiencies
- IGBT/FWD are operated with 50/60Hz → optimized for lowest $V_{CEsat}, V_f$
- Switching loss only generated in SiC MOSFET
- SiC MOSFET operated in reverse conducting mode → no external SiC FWD needed
- Losses in MOSFET independent of power factor
- Capability of bi-directional power flow – suitable for storage connection as well
Summary

• WBG technologies offer powerful alternatives in selected applications already today
  – Higher cost in several cases compensated by system savings of cost of ownership savings
• Pure focus on WBG might not always give the cost-performance optimized solution
  – Silicon components still with outstanding performance
  – Combination between various technologies might lead to optimum solution