How SiC revolutionizes Sustainable Power Electronics

Carl-Mikael Zetterling
John Palmour, 1960 - 2022

FROM N.C. STATE:
The Department of Materials Science and Engineering shares with great sorrow the passing of alum Dr. John Palmour on Sunday, November 13, 2022.

John was one of the founders of Cree, Inc./Wolfspeed and served as its Chief of Technology. John earned his B.S. in 1982 and his Ph.D. in 1988, and was inducted into the MSE Hall of Fame in 2015. John was also a recipient of the College of Engineering Distinguished Alumni Award.
Short history of Silicon?

Si and SiC

Jöns Jacob Berzelius
1779 - 1848
Celebrate December 23, 1947
And/or June 1948

Bardeen Shockley Brattain 1948

https://eds.ieee.org/about-eds/75th-anniversary-of-the-transistor
Evolution of the transistor and integrated circuit

- Point contact transistor
- Bipolar junction
- Lithography
- Planar process
- MOSFET
- Self-alignment
- FinFET
- and more

⇒ MOORE’s Law
Why is Power electronics of interest?

Power Electronics is everywhere and its efficiency is most relevant.

How many power converters does your electricity go through?

Even if the efficiency is 90-95% per stage, after 5 conversions the loss is still noticeable!
Wide Band Gap materials for Power Semiconductors

**WBG materials**

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Si</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap energy, $E_g$ (eV)</td>
<td>1.12</td>
<td>3.25</td>
<td>3.4</td>
<td>5.5</td>
</tr>
<tr>
<td>Critical field strength, $E_{Bc}$ (MV/cm)</td>
<td>0.25</td>
<td>2.5</td>
<td>2.0</td>
<td>10</td>
</tr>
<tr>
<td>Electron mobility, $\mu_n$ (cm$^2$/Vs)</td>
<td>1500</td>
<td>800</td>
<td>900</td>
<td>2000</td>
</tr>
<tr>
<td>Thermal conductivity, $\lambda_e$ (W/cm K)</td>
<td>1.5</td>
<td>4.9</td>
<td>1.3</td>
<td>20</td>
</tr>
<tr>
<td>Dielectric constant, $\varepsilon$</td>
<td>12</td>
<td>9.7</td>
<td>10</td>
<td>5.7</td>
</tr>
<tr>
<td>Figure of merit vs Si</td>
<td>1</td>
<td>1400</td>
<td>220</td>
<td>540 000</td>
</tr>
<tr>
<td>FOM = $\varepsilon \cdot \mu_n \cdot E_g^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Unipolar devices

**Expected impact from WBG power devices:**
- Reduced conduction losses
- Reduced switching losses
- Higher temperature rating
- Higher component cost
- Reduced system cost

Efficiency improves from 96 to 98 %, i.e. half the losses
System cost may still be higher, but offset by energy savings

$$R_{on} = \frac{(4 \ V_B^2)}{\left(\mu_n \ \varepsilon_r \ \varepsilon_0 \ E_c^3\right)}$$
Higher Switching Frequency

Potential impact from WBG power components

- **Improved energy efficiency**
  - Improved power density
  - Cooling system
  - Reduced operational cost
  - Higher efficiency

- **Reduced switching losses**
  - Higher switching frequency
  - Improved power density
    - Reduced size (cost) of reactive elements

- **Higher junction temperature operation**
  - Allows higher ambient temp
  - Cooling system

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Can we afford SiC/WBG devices?

YES, reduced BOM (purchase) cost for whole system, without taking energy savings into account
Higher Operating Temperature

HT Integrated Circuits in SiC

<table>
<thead>
<tr>
<th>Technology</th>
<th>Temp (°C)</th>
<th>Who</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>400</td>
<td>Several</td>
</tr>
<tr>
<td>Bipolar</td>
<td>600</td>
<td>KTH</td>
</tr>
<tr>
<td>JFET</td>
<td>800</td>
<td>NASA</td>
</tr>
</tbody>
</table>

www.WorkingonVenus.se
IEEE Spectrum, p 20-24, May 2021

Radio signal to satellite

Intrinsic concentration $n_i = (N_C N_V)^{0.5} \exp\left(-E_g / 2 k T\right)$

Not really a selling point for most SiC power systems
The TESLA Effect – If TESLA uses SiC it must OK!

Model 3 Main Inverter – Featuring 24 SiC MOSFET modules from ST Microelectronics (Source: Munro Assoc.)
PECTA in Sweden

Swedish link: https://www.kth.se/pecta

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