Solid State RF Power
The Route to 1W per Euro Cent

Oliver Heid
Corporate Technologies
Siemens AG, Munich
Design of Solid State Amplifiers Today

190 kW SOLEIL Solid State Amplifier

POLYFET Si LDMOS (LR301),
682 modules x 1 transistor,
315 W power each

J. Jacob, WEXPA02, Proceedings of EPAC 2006, Edinburgh, Scotland

CRE312 - 72 MHz 150 kW Solid State Cyclotron Amplifier

Si VDMOS transistors,
6x2x10x4 combiner tree
~400 W each

M. Getta et al. TU5PFP081 Proceedings of PAC09,
Vancouver, BC, Canada
Cost position?
Cost position?

Switch from Si to wide bandgap semiconductors
Cost position?

Switch from Si to wide bandgap semiconductors

Complexity
Modular approach
Herd of Elephants vs Army of Ants
Single stage RF power combiner
Cost position?

Switch from Si to wide bandgap semiconductors

Herd of Elephants instead of Army of Ants modular approach

Single stage RF power combiner

Minimal use of specialized passive components: economics of scale
RF Power Devices – State of the Art

The diagram illustrates the performance of different RF power devices based on their power and frequency capabilities. Key technologies include:

- **SiC** and **GaN** for high power and frequency applications.
- **Grided Tubes** and **TW Tubes** for medium power applications.
- **Klystrons** and **Gyrotrons** for high power and frequency applications.

The chart categorizes devices by power levels (1W, 1KW, 1MW) and frequency bands (1GHz, 10GHz, 100GHz). Materials like Silicon, SiGe, GaAs, and InP are used in the design of these devices.
Wide Bandgap RF Semiconductors

- SiC intrinsically 10x faster than silicon
- Significantly enhanced power density
- Radiation hardened
- High heat conductivity

<table>
<thead>
<tr>
<th>Materials Property</th>
<th>Si</th>
<th>SiC-4H</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap [eV]</td>
<td>1.1</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Critical Field [MV/m]</td>
<td>30</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>Electron Mobility [cm²/(Vs)]</td>
<td>1450</td>
<td>900</td>
<td>2000</td>
</tr>
<tr>
<td>Electron Saturation Velocity [km/s]</td>
<td>100</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>Thermal Conductivity [W/cm² K]</td>
<td>1.5</td>
<td>5</td>
<td>1.3</td>
</tr>
</tbody>
</table>
SiC RF Power vJFET

Normally on vertical junction FET (vJFET) with intrinsic body diode
Based on commercial switch mode PSU power transistor design
Optimized for low gate series impedance

2.4x2.4mm² die size
\[ U_{DS} = 1700V, \quad I_{DSS} = 60A \]
\[ U_{pinchoff} \sim -16V \]
SiC RF Power vJFET

High efficiency (>85%)
Class F mode operation

Hyperfast Schottky-like body diode enables four quadrant operation
Reflected RF power does not destruct device
No output circulators, protection measures needed

“Voltage source” low output impedance operation, no need to match RF load

High voltage operation (~700VDC) enables extremely high power at reasonable impedances
SiC 6mm² die
7 kW_{pk} (200\mu s burst)
~ 1 GHz unity gain frequency

GaN 1.5mm² die
250 W_{pk} (200\mu s burst)
~ 2 GHz unity gain frequency
SiC RF Power Modules

Parallel push-pull circuit assists class F operation
Stable under load impedance variations, device parallelization

8 transistors per module
On 60x80mm$^2$ Al$_2$O$_3$ carrier
SiPLiT package: no bond wires
Commodity 700V DC supply

50 kW RF pulse power into 5$\Omega$:
700V$_{pk}$, 140A$_{pk}$
200 $\mu$s pulse duration, 1% dc
15dB large signal power gain
RF Power Combiner Teststand

32 x 2,5kW = 80kW
RF Power Combiner: Solid State Direct Drive™

- Much higher power levels possible by single stage combiner
- Low output impedance gives very low combined power reduction under point failures: reliability
Cost Position

Minimal complexity
- High power density, power per device: low device count, low circuit complexity
- Straightforward single stage power combining, no power circulators, protection circuits
- RF power gating within amplifier stage: Simple DC power supply

Economics of scale
- Bulk SiC, epitaxial GaN and Si have similar material and production cost per Watt RF
- Voltages, currents within range of standard consumer/industrial component specs
- Modular design covers diverse customer requirements with few module designs

“green”, dependable
- High efficiency class F operation: low thermal load, energy costs
- Gracefully degrading RF power generator under point failures: preventive maintenance
Conclusions

1 Watt / Euro Cent

?
Conclusions

1 Watt per Euro Cent seems to be within reach

SiC and GaN are about cost competitive with Si
Conclusions

1 Watt per Euro Cent seems to be within reach

SiC and GaN are about cost competitive with Si

BUT

The big win is its secondary effects on the system complexity and cost
Thank you for your attention!

Dr. Oliver Heid
Siemens AG
Corporate Technology
Mozartstrasse 57
91052 Erlangen
Germany