Silicon Carbide Device Update

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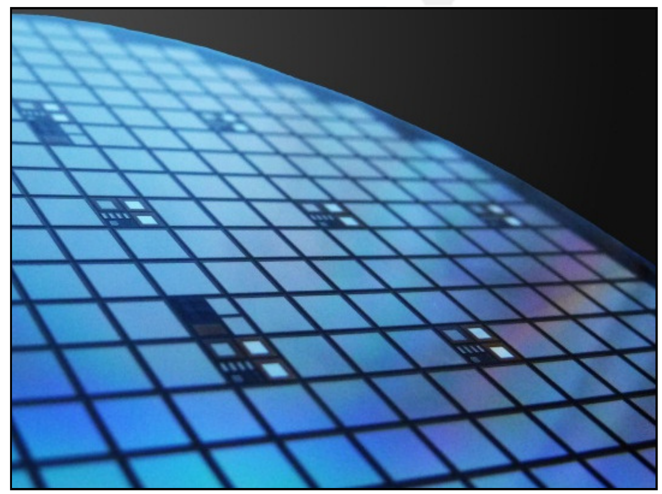

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SiC Advantages

Material property	Si	4H-SiC	GaN
Bandgap	1.12 eV	3.25 eV	3.4 eV
Breakdown field	0.25 MV/cm	~3 MV/cm	~3 MV/cm
Thermal conductivity	1.5 W/cm•K	4.9 W/cm•K	1.3 W/cm•K
Electron mobility	1200 $cm^2/V \cdot s$	800 $cm^2/V \cdot s$	900 $cm^2/V \cdot s$
Dielectric constant	11.7	9.7	9

- Silicon carbide is an ideal power semiconductor material
- Most mature “wide bandgap” power semiconductor material
- Electrical breakdown strength ~ 10X higher than Si
- Commercial substrates available since 1991 –
  - ✓ **now at 100 mm dia; 150 mm dia soon**
- *Defects up to 1,000 times less than GaN*
- *Thermal conductivity ~ 3X greater than Si or GaN*

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SemiSouth Introduction

SemiSouth → SiC Power Semi Technology Leader

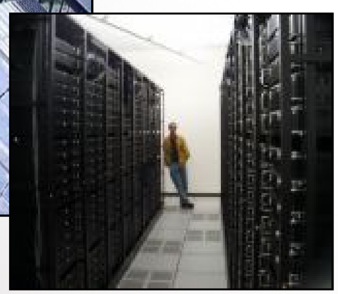
→ **1200 V – 1700 V Trench "normally – off" JFETs**

→ **650 V, 1200V – 1700 V Trench "normally – on" JFETs**

→ **1200 V Schottky Diodes**

SemiSouth silicon carbide trench technology offers higher efficiency, greater power density & higher reliability than comparable silicon-based devices

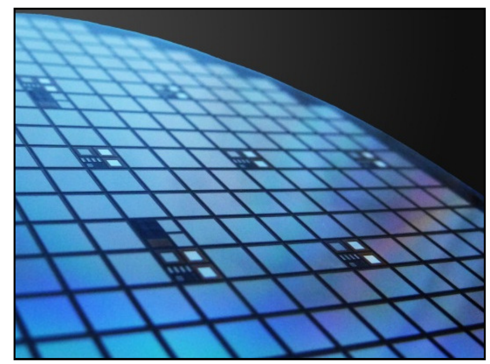
Solar



Servers

HEV

Wind



SiC Wafer

SemiSouth SemiSouth VJFET Technology

- **Why the SiC Trench JFET?**
  - **Cost**
  - **3-10 X smaller** die size
  - Up to **50% fewer manufacturing steps**

Performance
  - **5-10X lower** switching energies
  - **Normally-on or off** (industry first and only)
  - Enables high-frequency ***and*** high-efficiency
  - Industry best on-resistance per unit area

Reliability
  - Rugged structure for SiC JFET switch
  - Over 1,000 hour HTRB
  - No known degradation issues
  - Robust operating range

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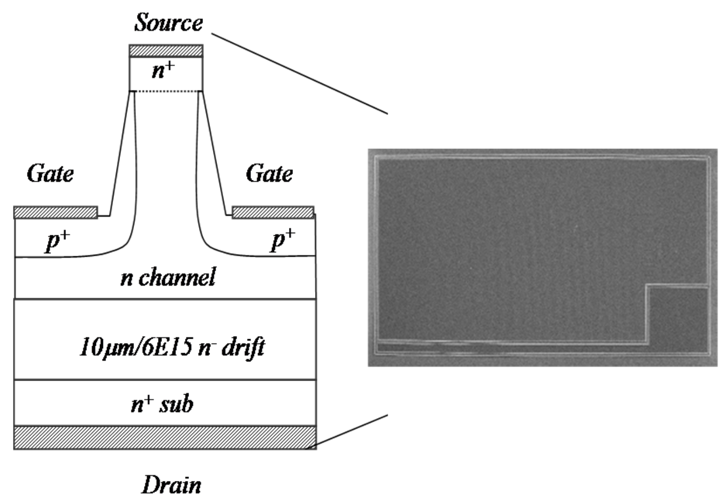
Vertical-Channel JFET*



- (+) **Few mask layers**
- (+) **Low RPT**
- (+) **$R_{(on)sp} \approx$ 2-3 mΩ*cm²**

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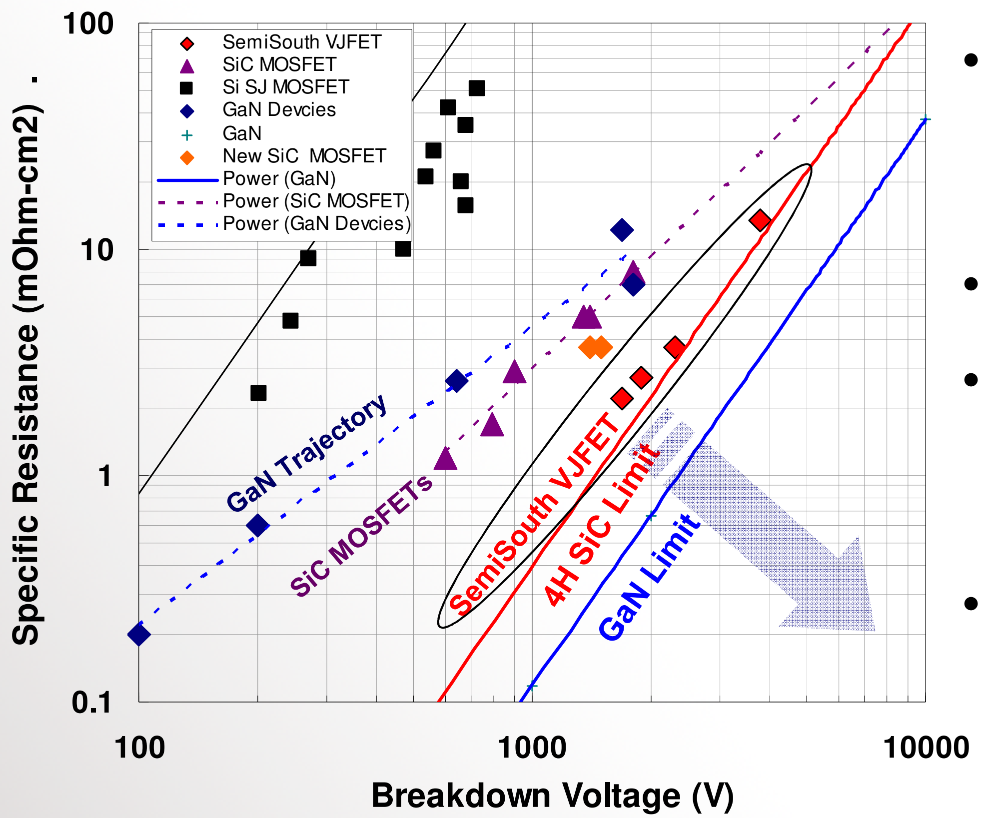
Industry Leading Performance

Proprietary Compact design leads to ultra-low specific on-resistance in power JFET (normally-on or normally-off versions available)



- SemiSouth first and only to offer TRENCH SiC JFET beginning in 2008
- Near theoretical specific R_{DSON}
- Normally-OFF *OR* Normally-ON use same device structure & manufacturing steps
- High reliability

Advanced JFET Concepts

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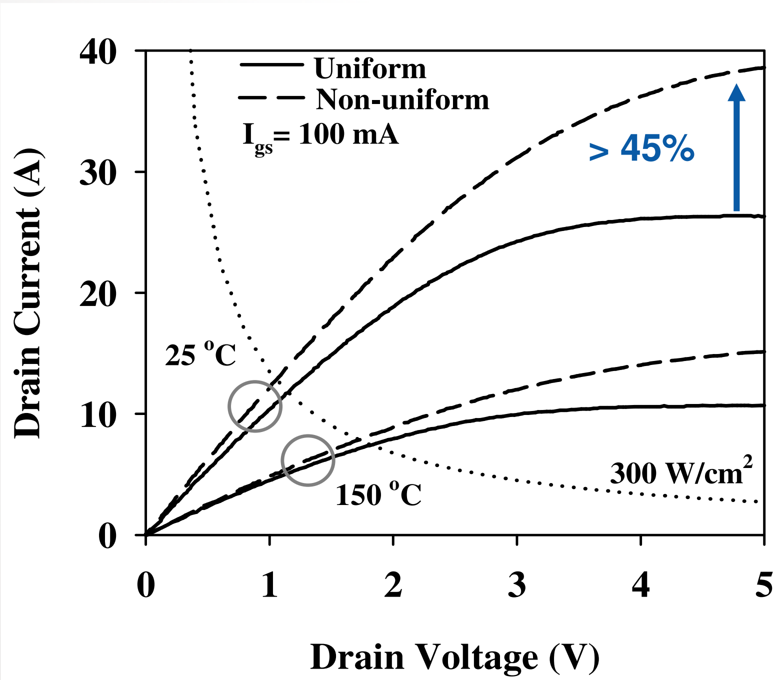
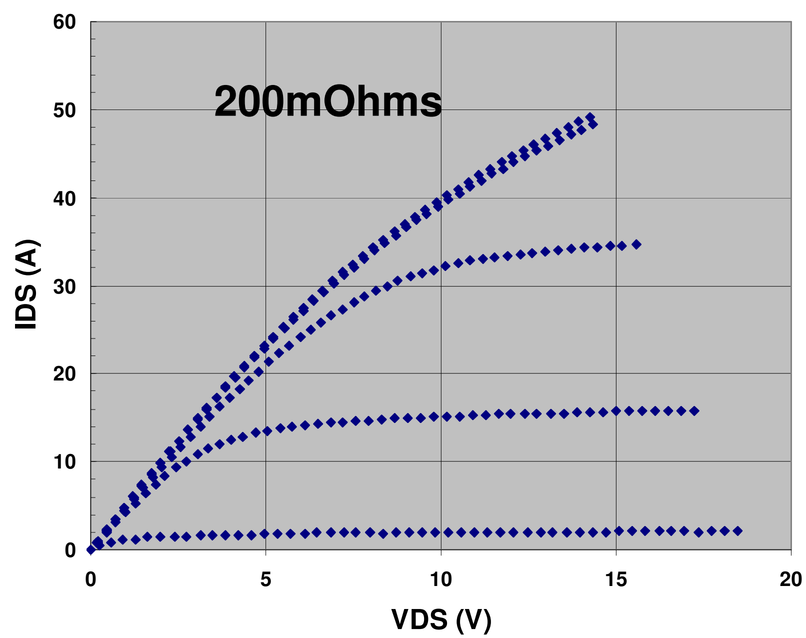
High Current Normally-Off

- Demonstrated novel channel design for improved saturation current
- Significant increase in current and increased threshold range

3.3kV Design Normally-Off

- Normally-off SiC JFET – 3.8kV Design (edge termination limited)
- Exceptionally low Rds(on) = 200mOhms - > 50A saturation current





Comparison IGBT vs SiC

- Comparison of Vincotech Module
  With IGBT vs SIC JFET

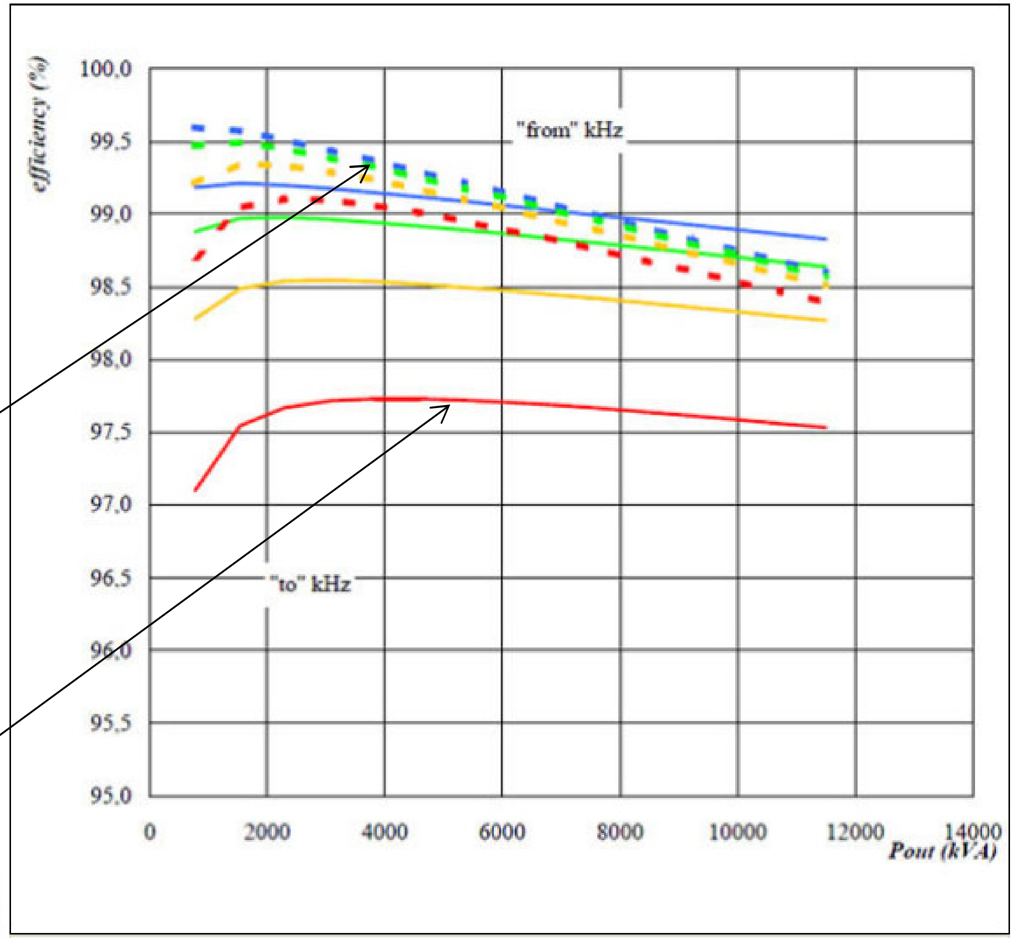
- Dotted Line SiC
  - Blue 8kHz -> Red 64kHz

You can switch high Frequency

- Non dotted Line: IGBT
  - Blue 8kHz -> Red 64kHz

You can not switch high Frequency

JFETs gegen IGBTs



© Vincotech

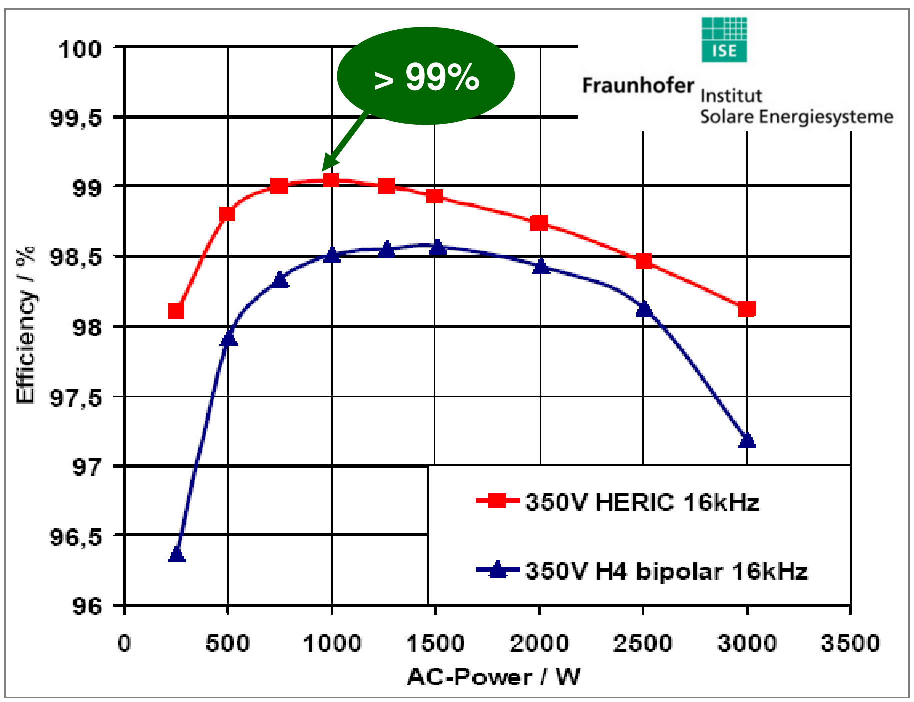
Bild 4: Effizienzvergleich von MNPC-Modulen mit Silizium-IGBTs (durchgezogene Linien) und SiC-JFETs (gestrichelte Linien) bei Schaltfrequenzen von 8 kHz (blau) bis 64 kHz (rot)

Performance Validation

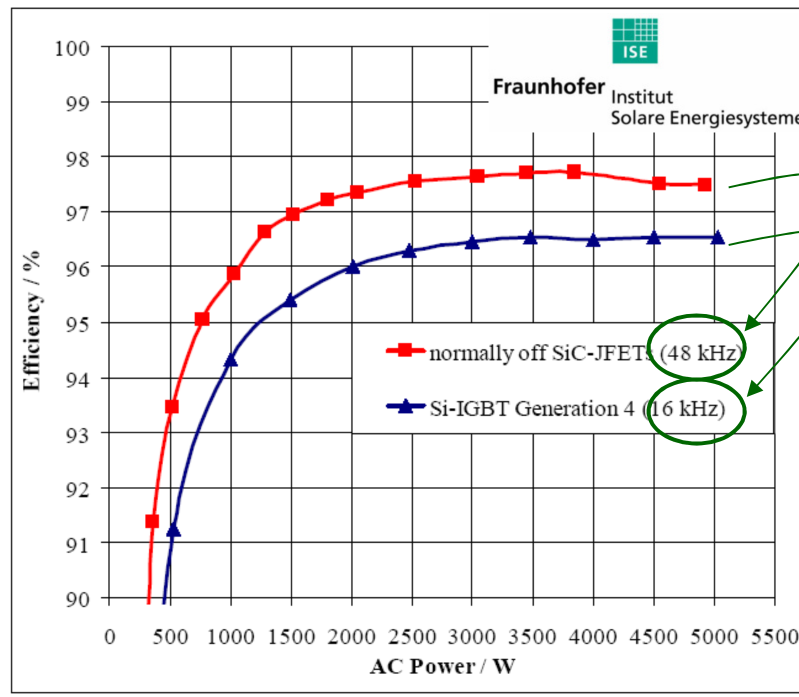
WORLD RECORD Power Conversion Efficiency*

"We now use junction field-effect transistors (JFETs) made of silicon carbide (SiC) manufactured by SemiSouth Laboratories Inc.. This is the main reason for the improvement", - Prof. Bruno Burger, leader of the Power Electronics Group at Fraunhofer ISE, July 2009 press release.

- Single phase Heric®
- Commercial inverters @ 98%
- SemiSouth's JFET lowers losses ~ 50%



- Three phase full bridge inverter
- SemiSouth JFET ***boosts efficiency*** 1.2%
- SemiSouth JFET operates ***3X higher freq.***



* Bruno Burger, Dirk Kranzer, "Extreme High Efficiency PV-Power Converters," EPE, Barcelona, Spain, 8-10 September 2009

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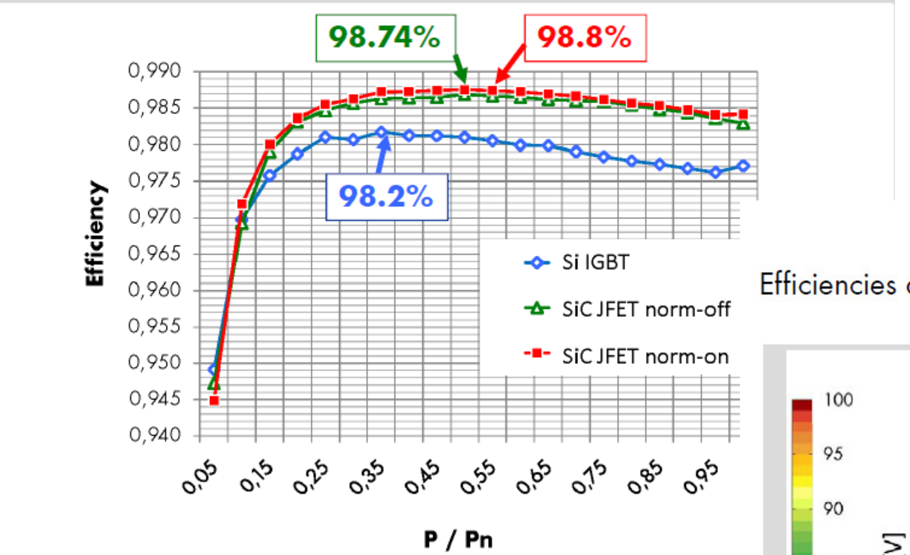
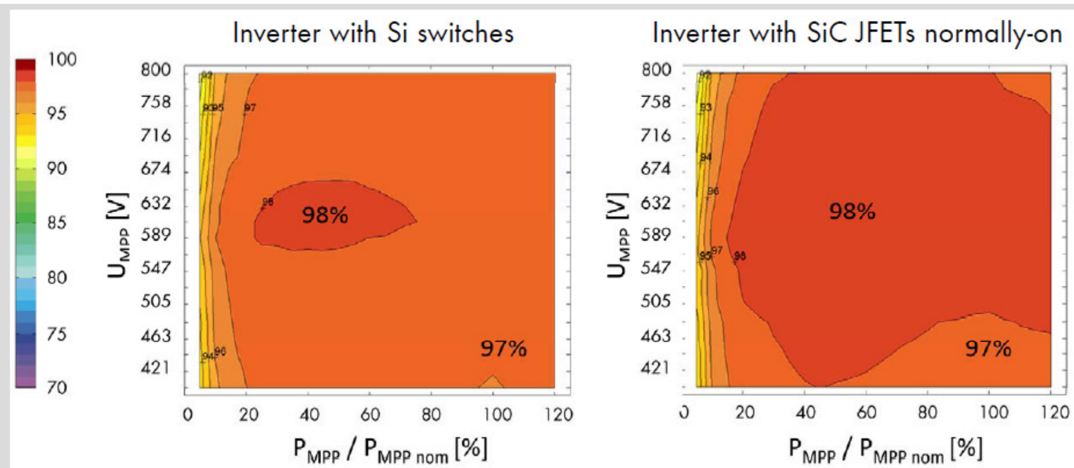
SMA SiC JFET Inverter



Efficiencies at several DC link voltages (400V up to 800V) - „Photon test"



Inverter \ Efficieny	η max	η Euro*
with Si semiconductor switches	98,2 %	97,3 %
with SiC semiconductor switches	98,8 %	97,9 %

* European Efficiency – specific weighted average value

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- **Dr. Regine Mallwitz, SMA: SiC & GaN User Forum, Birmingham 2011**

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SMA Quote about SiC

SMA

1. Technical benefit of SiC semiconductors

SiC devices promise

- low switching losses
- high rated voltages
- high operating temperature
- high radiation hardness

For PV inverters this properties offer possibilities toward

- **improved effiency** above 99% (at same switching frequency like today) → reduction of cooling effort → system size
- **higher switching frequencies** (at same level of losses like today) → reduction of system size → system costs
- **higher level of output power** (at same switching frequency and losses) → reduction of specific cost (per W)
- **higher DC input voltages**

- **Dr. Regine Mallwitz, SMA: SiC & GaN User Forum, Birmingham 2011**

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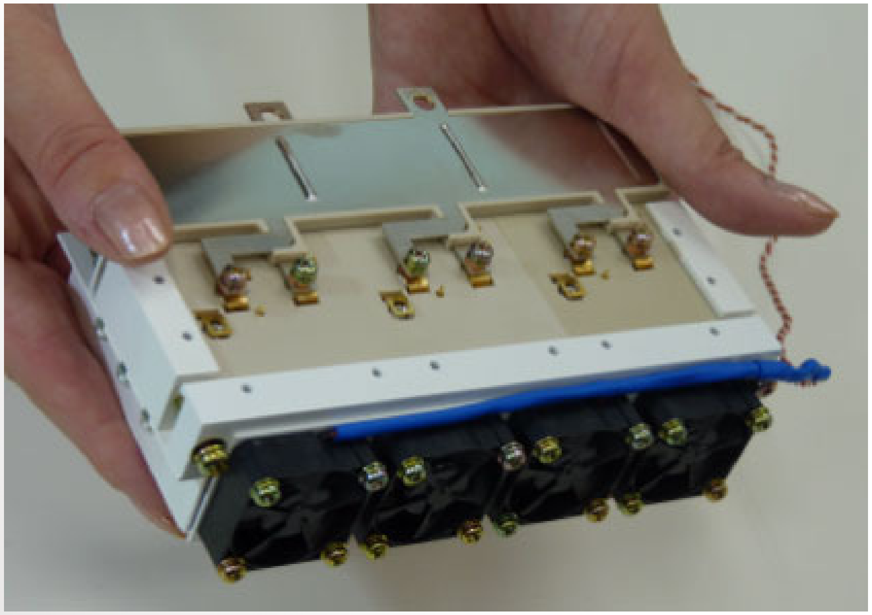
Automotive prototype inverter



FUPET

Sato, *et al*, International Conf. on SiC and Related Materials, Sept 2011

- Future Power Electronics Technology (FUPET) has developed an all-SiC-device-based three-phase inverter with a 0.5-liter volume, verified to achieve an output power density of ***30kWh/l***. "We believe this is the world's highest output power density for a small-volume inverter," commented FUPET officials.
- Using SiC junction field-effect transistor (JFET) devices procured from SemiSouth Laboratories, the power modules operate up to 200 ℃.
- 500cc inverter connected to a three-phase motor achieved ***15kW output***, which is 30kW/l or 30W/cc. At 15kW output, conversion efficiency was ***99%***.

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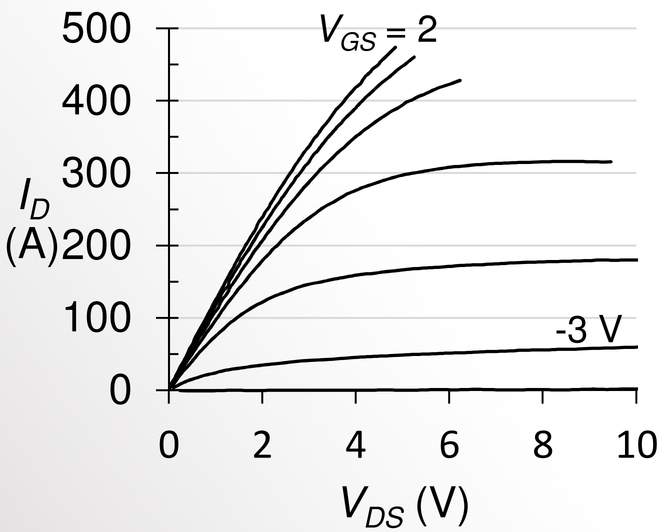
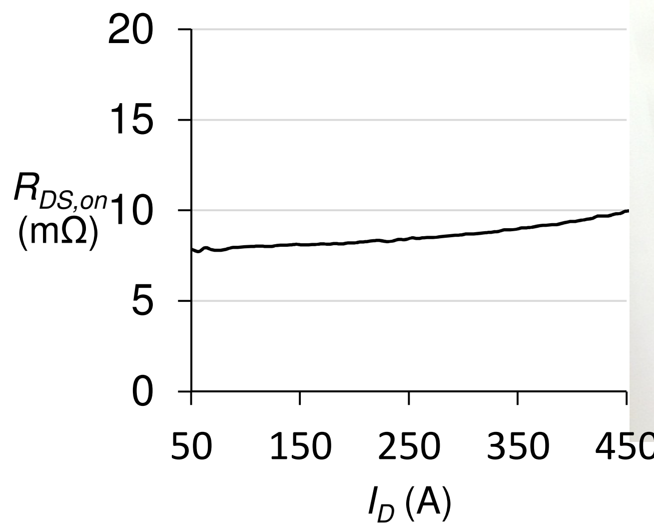
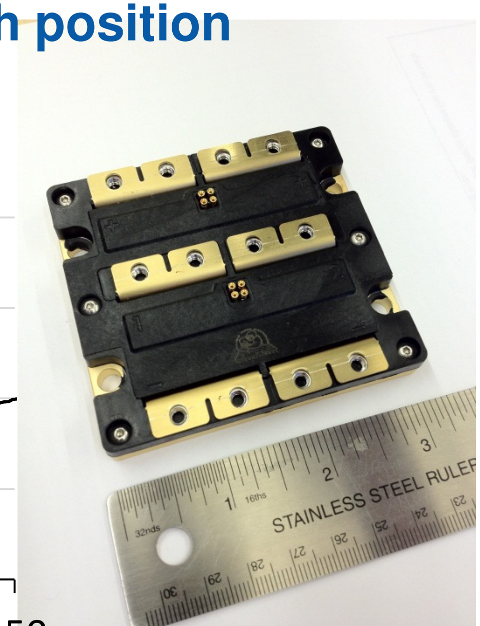
SiC JFET power module

APE INTERNATIONAL – ARKANSAS POWER ELECTRONICS

Only 36 mm² of JFET die area per switch position (4 x SJDC120R045)







Switching energies at 25 ℃ of SiC VJFET modules (I_D = 100 A) and a Si IGBT module (I_C = 150 A)			
	Turn-on energy	Turn-off energy	***Total switching losses***
Enhancement-mode SiC VJFET	0.72 mJ	0.46 mJ	**1.18 mJ**
Depletion-mode SiC VJFET	0.33 mJ	0.90 mJ	**1.23 mJ**
Si IGBT (Infineon)	8.5 mJ	8.5 mJ	**17.0 mJ**

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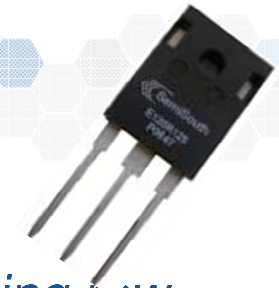
Summary



- SiC trench JFET production since 2008
- *Size and weight reduction are key elements to fight increasing raw material cost*
- *High frequency (power density) with improved efficiency is key to reducing weight and cost*

→ HV SiC devices are possible, and scaling to higher currents

- *What devices are needed for MV – HV applications?*
- *Initial insertion applications?*
- *Device requirements?*
- *Cost targets?*