Recent Advancements in SiC power devices & the impact of normally-off SiC JFETs on PV inverter platforms

Jeffrey B. Casady, CTO & VP Bus Dev

SemiSouth Laboratories Inc.

www.semisouth.com

High MW Electronics – Industry Roadmap Meeting
December 11th 2009

SemiSouth

SemiSouth

Introduction

SemiSouth Laboratories is a clean energy enabler

specializing in the design & manufacture of silicon carbide (SiC) power devices used to harvest and transfer power in renewable energy systems, telecom server farms & hybrid electric vehicles.

SemiSouth silicon carbide based devices offer higher efficiency, greater power density and higher reliability than comparable silicon-based devices

Solar

Servers

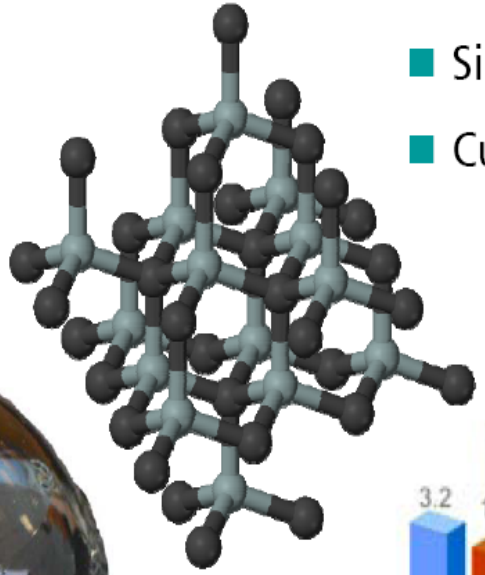
HEV

Wind

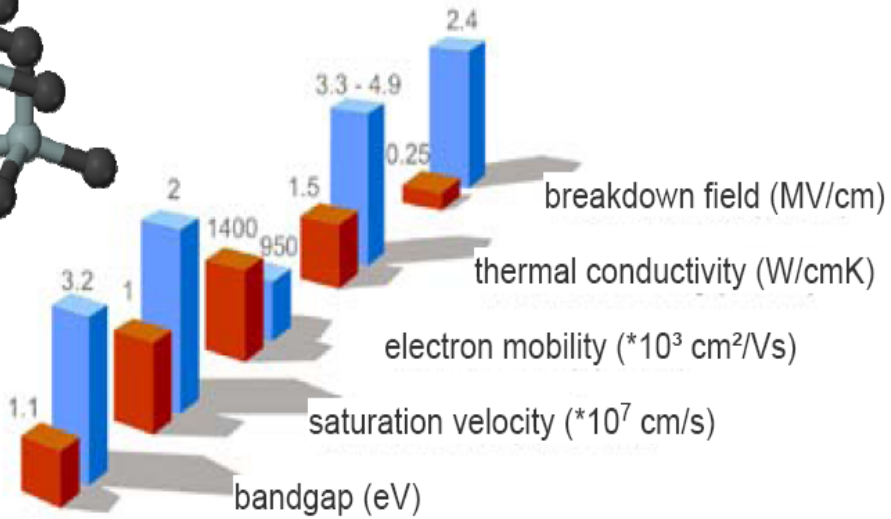
SiC Wafer

World record PV inverter efficiency

SiC Properties



- Silicon and Carbon
- Cubic and hexagonal structure (4H)



Source: www.wikipedia.de

Source: www.siced.de

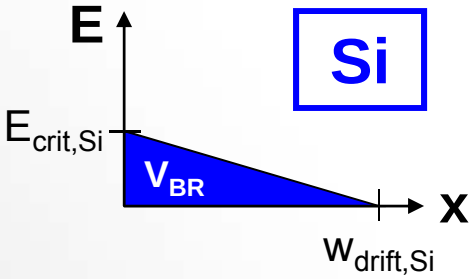
SemiSouth

SiC Advantages

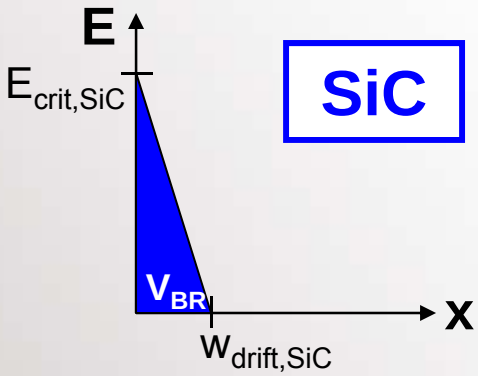
Material property	Si	4H-SiC	GaN
Bandgap	1.12 eV	3.25 eV	3.4 eV
Breakdown field	0.25 MV/cm	~3 MV/cm	~3 MV/cm
Thermal conductivity	1.5 W/cm•K	4.9 W/cm•K	1.3 W/cm•K
Electron mobility	1200 $cm^2/V•s$	800 $cm^2/V•s$	900 $cm^2/V•s$
Dielectric constant	11.7	9.7	9

- Silicon carbide is the 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*

Thinner Devices, Lower Losses



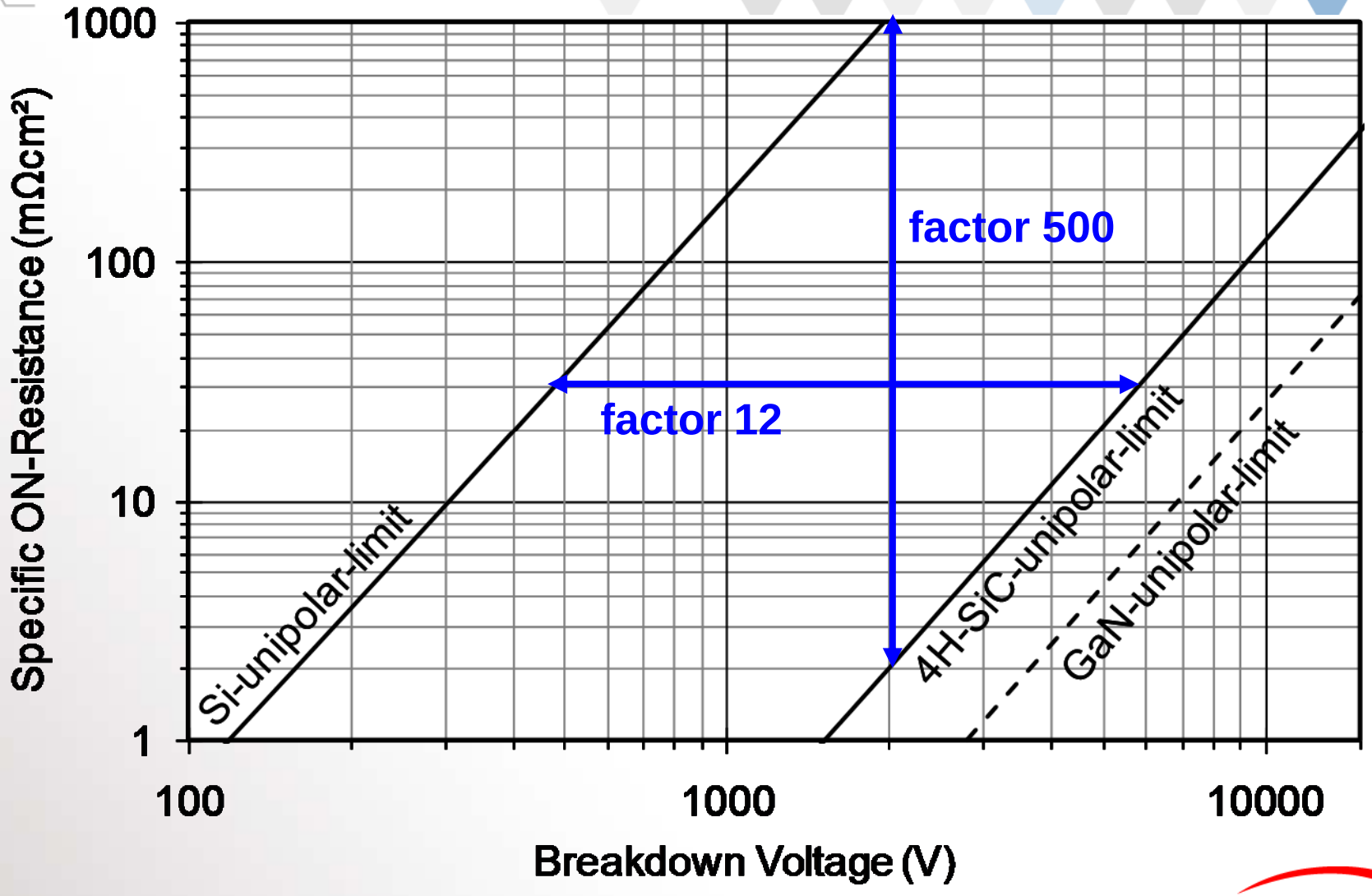
	unipolar devices	bipolar (plasma) devices
	$r_{on} \sim w_{drift} / N_D$	$q_{st} \sim w_{drift}^2$
$E_{crit,SiC} \approx 10 \cdot E_{crit,Si}$	$w_{drift,SiC} \approx w_{drift,Si} / 10$ $N_{D,SiC} \approx 100 \cdot N_{D,Si}$	$w_{drift,SiC} \approx w_{drift,Si} / 10$
	$r_{on,SiC} \approx r_{on,Si} / 1000$	$q_{st,SiC} \approx q_{st,Si} / 100$



N. Kaminski, EPE2009

IALB

ON-Resistances: Theoretically



N. Kaminski, EPE2009

IALB

A Note on Device Size

- SiC devices can not be 500 times smaller
  - 500 times higher current densities are tough
  - 500 times higher loss densities are deadly (same losses on 500 times smaller area)

- Rather: Design on the same loss density
  - Area and losses reduced by the same factor
  - Benefit would be $\sqrt{BFoM}$, i.e. still factor 22

- Note: Threshold voltages do not scale!

Material Properties

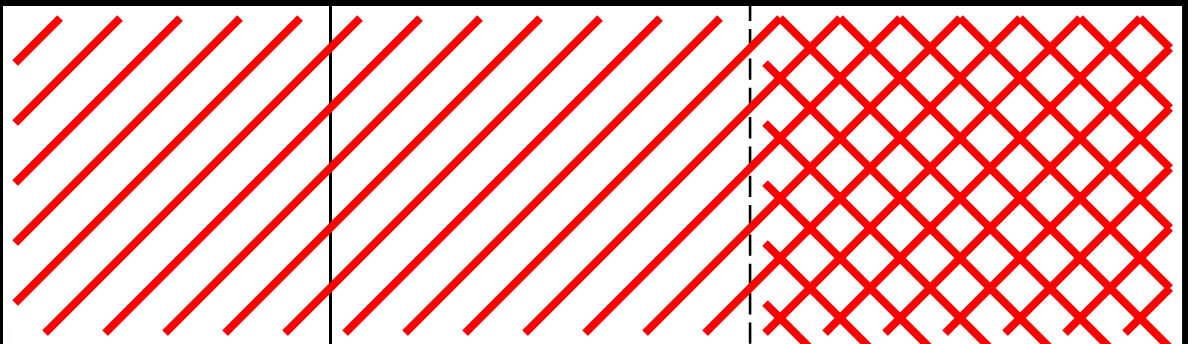
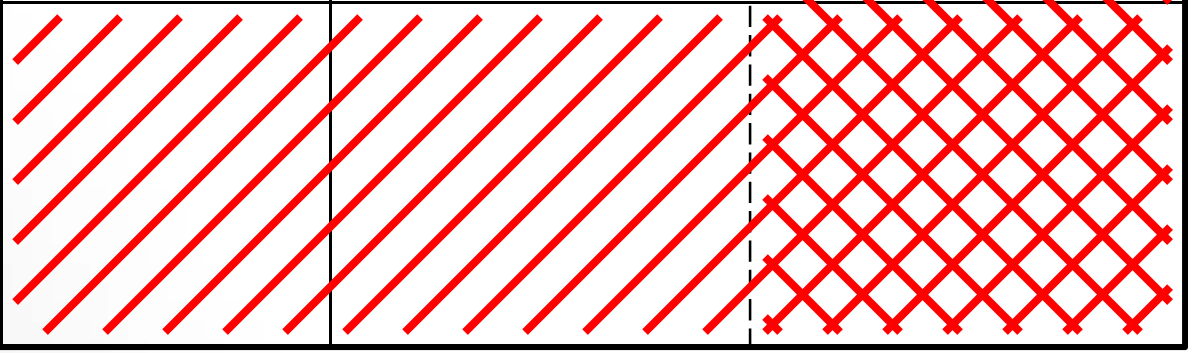
Parameter		Silicon	4H-SiC	GaN	Diamond
Band-gap E_g	eV	1.12	3.26	3.39	5.47
Critical Field E_{crit}	MV/cm	0.23	2.2	3.3	5.6
Permitivity ε_r	–	11.8	9.7	9.0	5.7
Electron Mobility μ_n	$cm^2/V{\cdot}s$	1400	950	1500	1800
BFoM: $\varepsilon_r{\cdot}\mu_n{\cdot}E_{krit}^3$	rel. to Si	1	500	2400	9000
Intrinsic Conc. n_i	cm^{-3}	$1.4{\cdot}10^{10}$	$8.2{\cdot}10^{-9}$	$1.9{\cdot}10^{-10}$	$1{\cdot}10^{-22}$
Thermal Cond. λ	W/cm·K	1.5	3.8	1.3	20

- Low leakage currents (at least theoretically)
- High temperature operation possible (packaging!)
- Better cooling and temperature homogeneity

N. Kaminski, EPE2009

IALB

Device Concepts for WBG

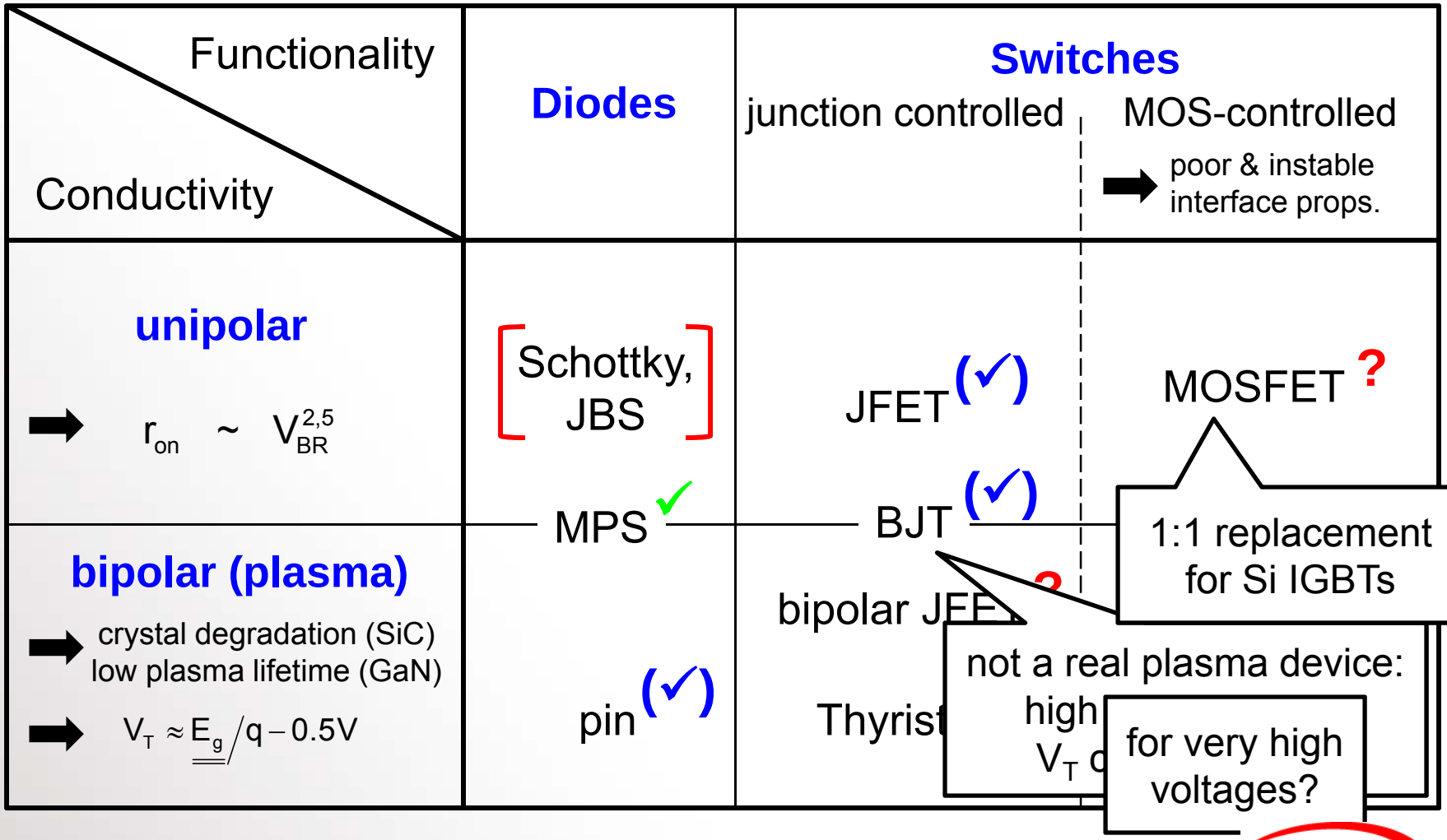
Functionality / Conductivity	Diodes	Switches: junction controlled	Switches: MOS-controlled
unipolar ➡ $r_{on} \sim V_{BR}^{2,5}$			
bipolar (plasma) ➡ crystal degradation (SiC) low plasma lifetime (GaN) ➡ $V_T \approx E_g/q - 0.5V$			

MOS-controlled: ➡ poor & instable interface props.

N. Kaminski, EPE2009

IALB

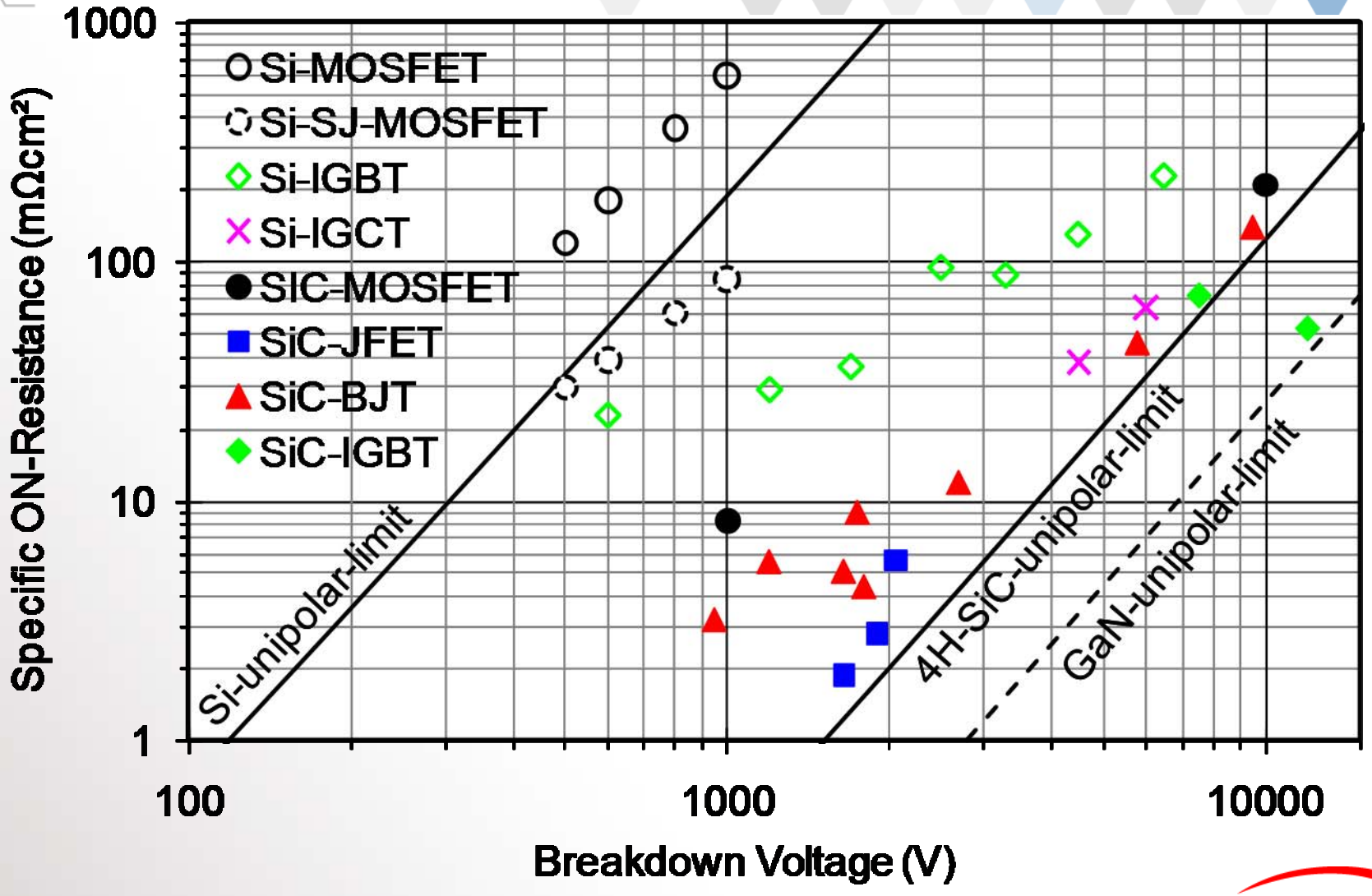
Device Concepts for WBG



N. Kaminski, EPE2009

IALB

ON-Resistances: State of the Art



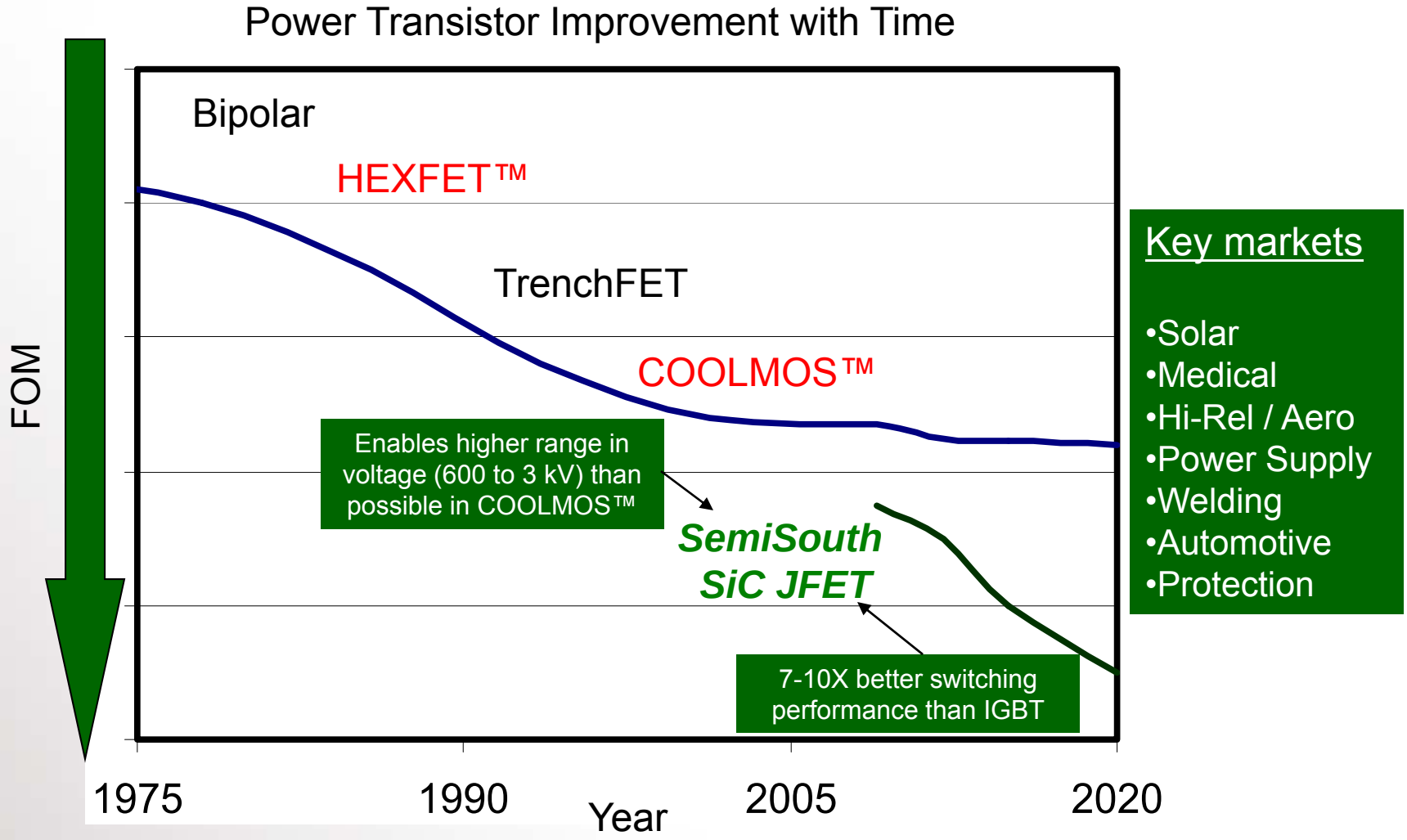
N. Kaminski, EPE2009

IALB

SemiSouth

SiC is the Ideal Power Device Technology

SemiSouth JFETs can Replace IGBTs and MOSFETs for Higher Efficiency and Higher Frequency Switching
….Power Dissipation can be reduced by over 50%

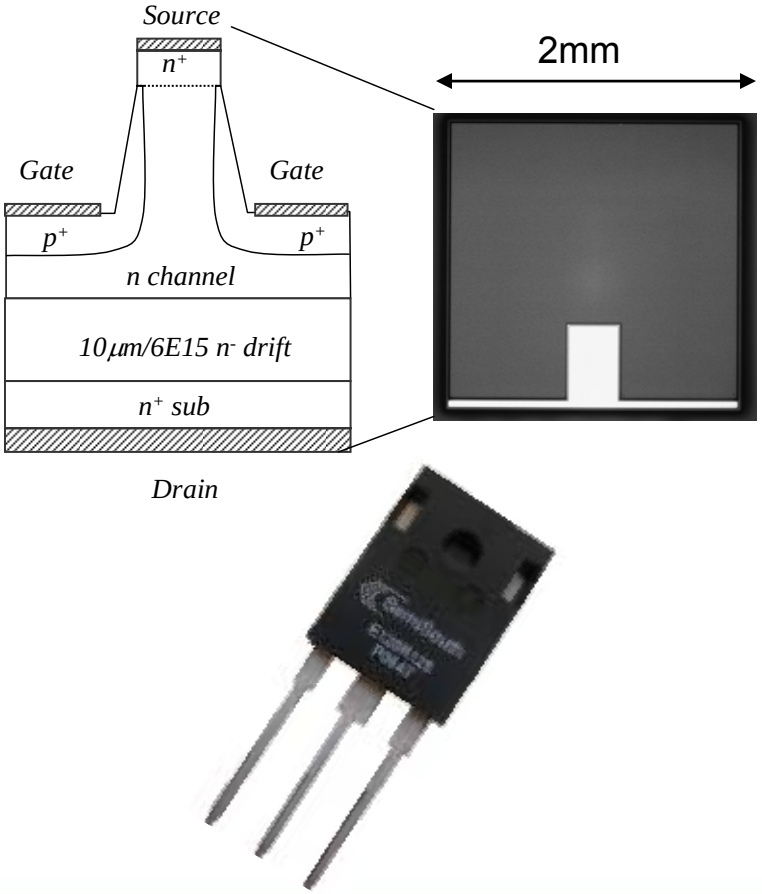

Power Transistor Improvement with Time
FOM
Bipolar
HEXFET™
TrenchFET
COOLMOS™
Enables higher range in voltage (600 to 3 kV) than possible in COOLMOS™
SemiSouth SiC JFET
7-10X better switching performance than IGBT
1975
1990
2005
2020
Year
Key markets
•Solar
•Medical
•Hi-Rel / Aero
•Power Supply
•Welding
•Automotive
•Protection

JFET Technology

SemiSouth JFET advantages

- All benefits of SiC
- Normally-off
- Low process complexity
- No degradation issues (bipolar, MOS, etc.)
- No body diode
- Easily paralleled for high power modules
- Demonstrated stable operation at 350C+
- Lowest Rds(on),sp of EM SiC devices
- fast switching / low switching energy

SemiSouth
Vertical-Channel JFET



Competitiveness against IGBTs

Critical Parameter		Fairchild NPT IGBT FGL40N	SemiSouth VJFET SJEP120R063	Performance Improvement
Technology		Silicon – IGBT	Silicon Carbide	
Breakdown Voltage	V_{DS}	1200V	1400V	Higher breakdown margin
On Voltage (conduction)	Von	2.5V	Unipolar	Reduced losses at low I …higher light load Efficiency
Input Capacitance	Ciss	1700 pF.	1220pF	Reduced Gate Power Loss
Effective Output Cap Energy Related	$C_{O(ER)}$	260 pF	100 pF	2.5X Lower Switching Losses
Operating Temperature	Tj	-55°C to 150°C	-55°C to 175°C	Safe Operation at higher Temp
Thermal Impedance	Rthj-c	0.25K/W	0.6K/W	X2 worse but offset by overall lower dissipation losses
Turn-On Losses Turn-Off Losses Total Losses	Joules	550uJ 1000uJ 1550uJ	110uJ 70uJ 180uJ	X10 Lower Switching Energy

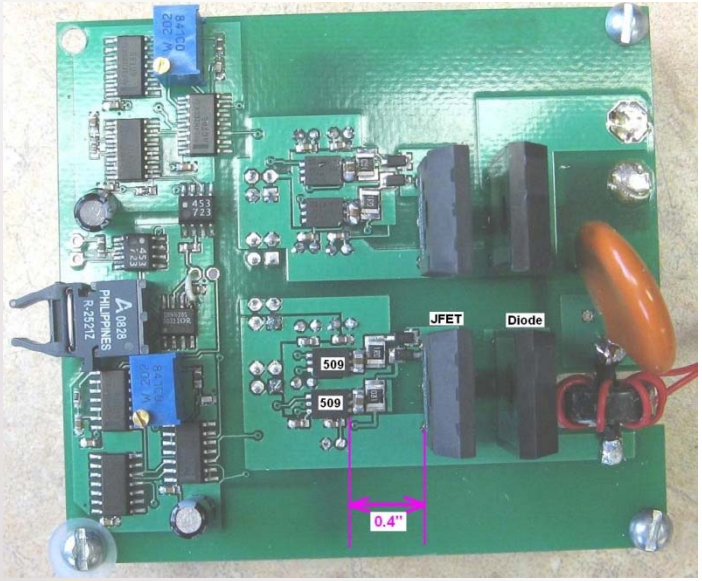
SS JFETs HAVE 50% LOWER LOSSES

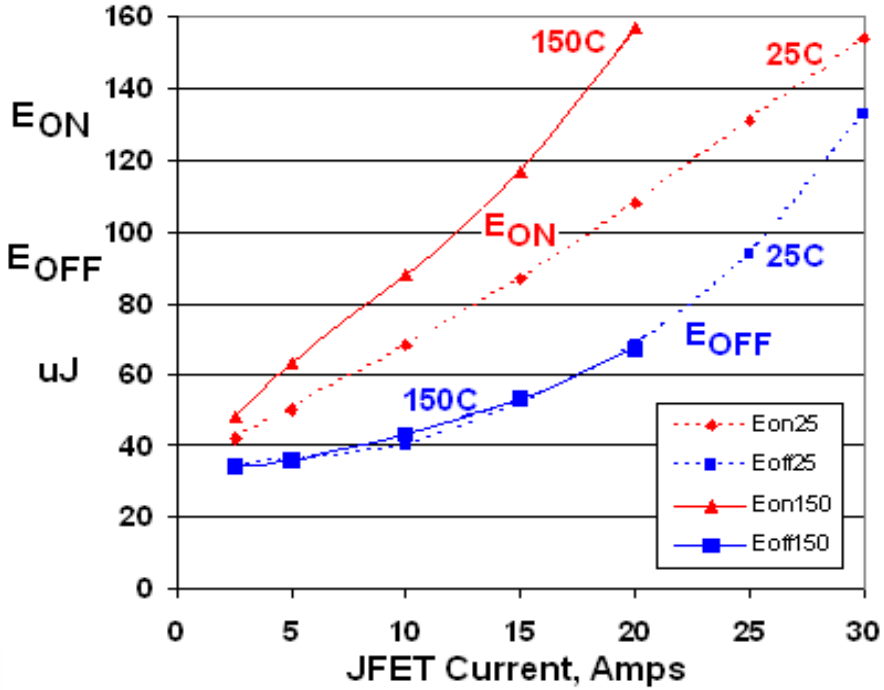
Smallest Switching Energy

- Allows high-frequency, high-efficiency, higher power density solutions!

Half-Bridge Configuration:

- **SJEP120R063: 1200V / 63mΩ VJFET**
- **SDP20S120: 1200V / 20A SBD**





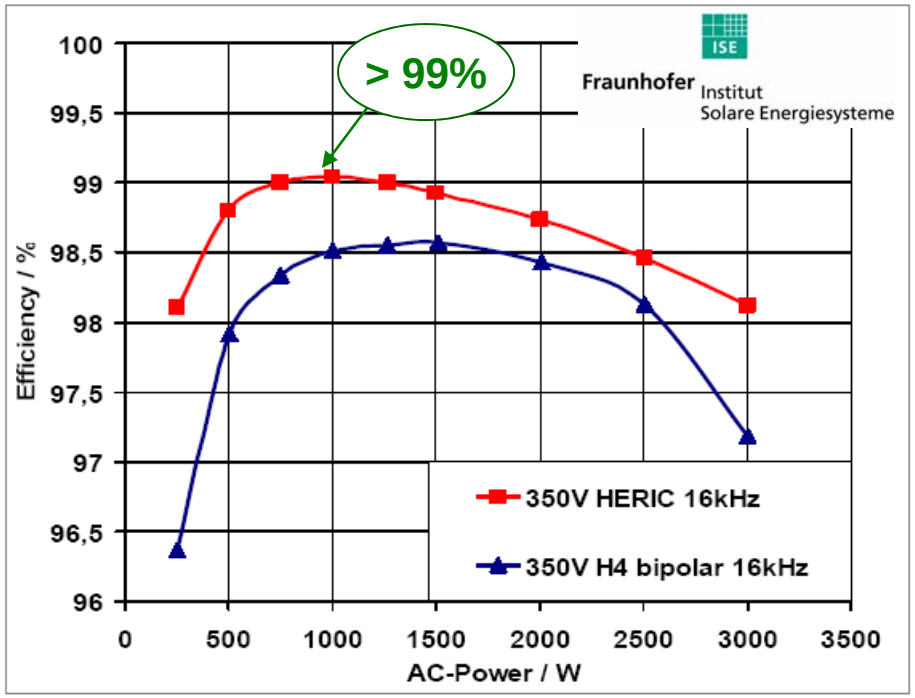
SemiSouth

Performance Validation

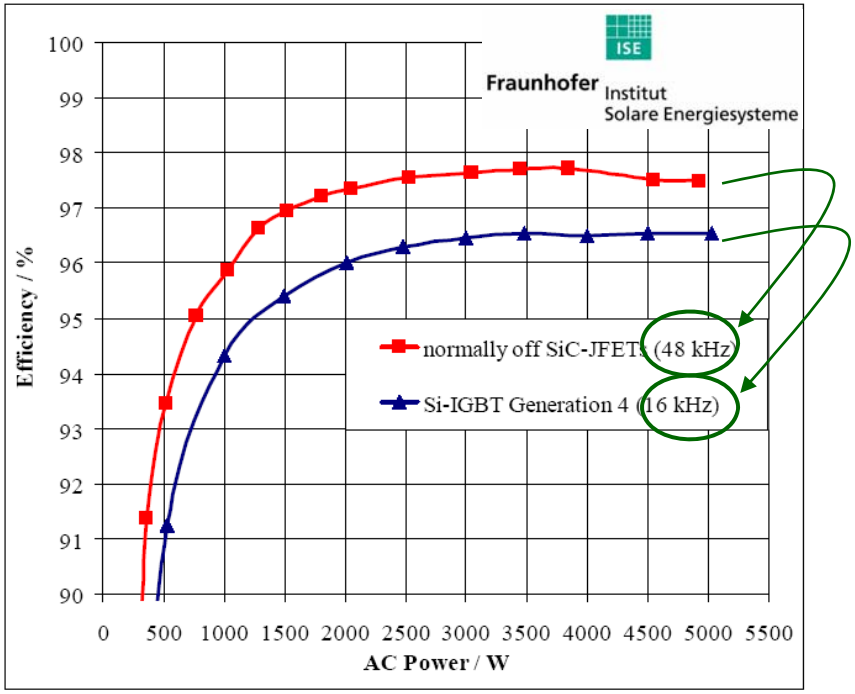
WORLD RECORD Power Conversion Efficiency*

"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.*

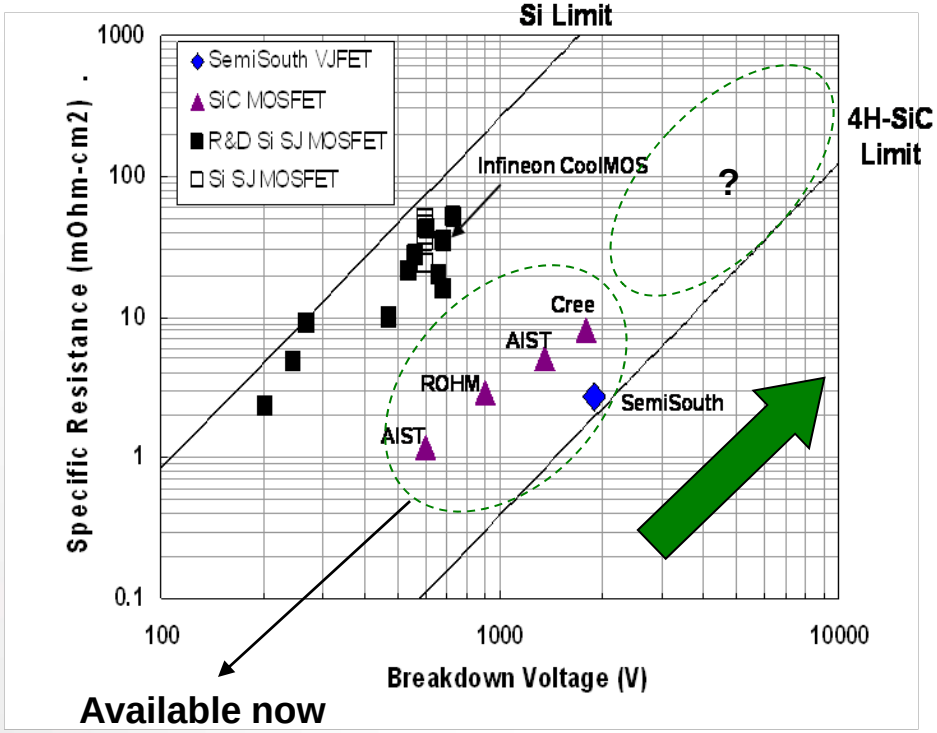


* Bruno Burger, Dirk Kranzer, "Extreme High Efficiency PV-Power Converters," EPE, Barcelona, Spain, 8-10 September 2009

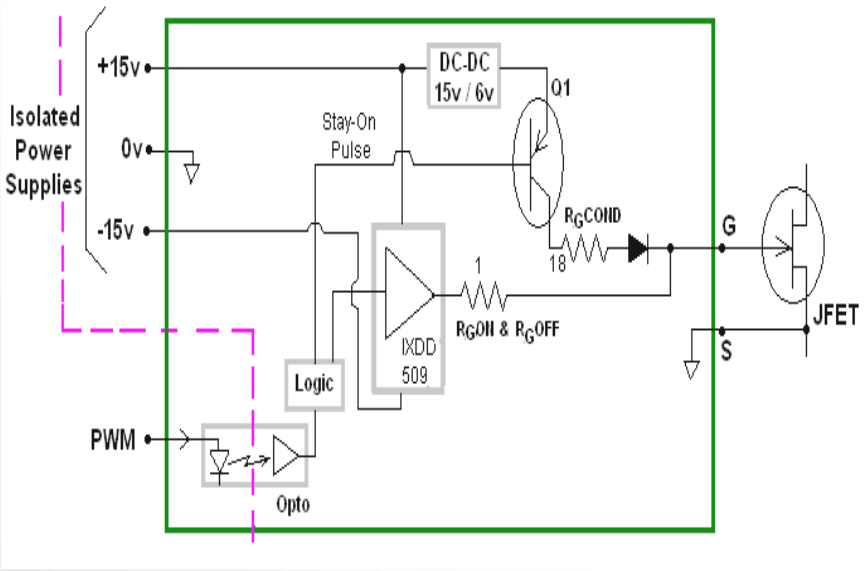
Normally-off JFET Performance

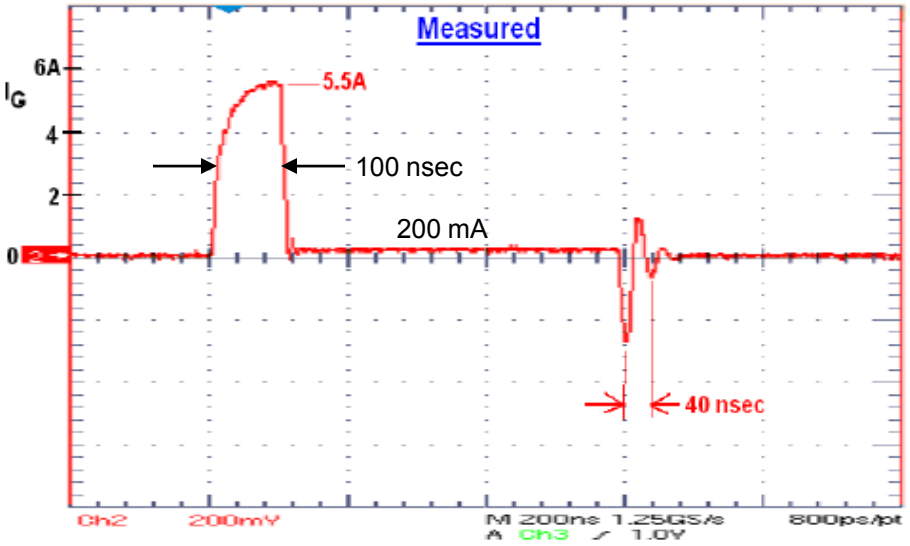
Trench JFET Technology Evolution:

- **Initial demonstration in 2007**
- **Compact design leads to ultra-low specific on-resistance**
- **Initial product release in 2008**



SJEP120R063 JFET Driver Scheme





Opto Coupler: This reference design uses the HP "wide body" HCHW4503 high speed opto coupler enabling fast switching speeds while allowing layout spacing to meet safety isolation requirements.

509 Gate Driver: The IXYS IXDD509 high speed Driver is used to provide a high current Turn-on and Turn-off gate pulse through Rg(on/off) for very fast switching and low switching losses.

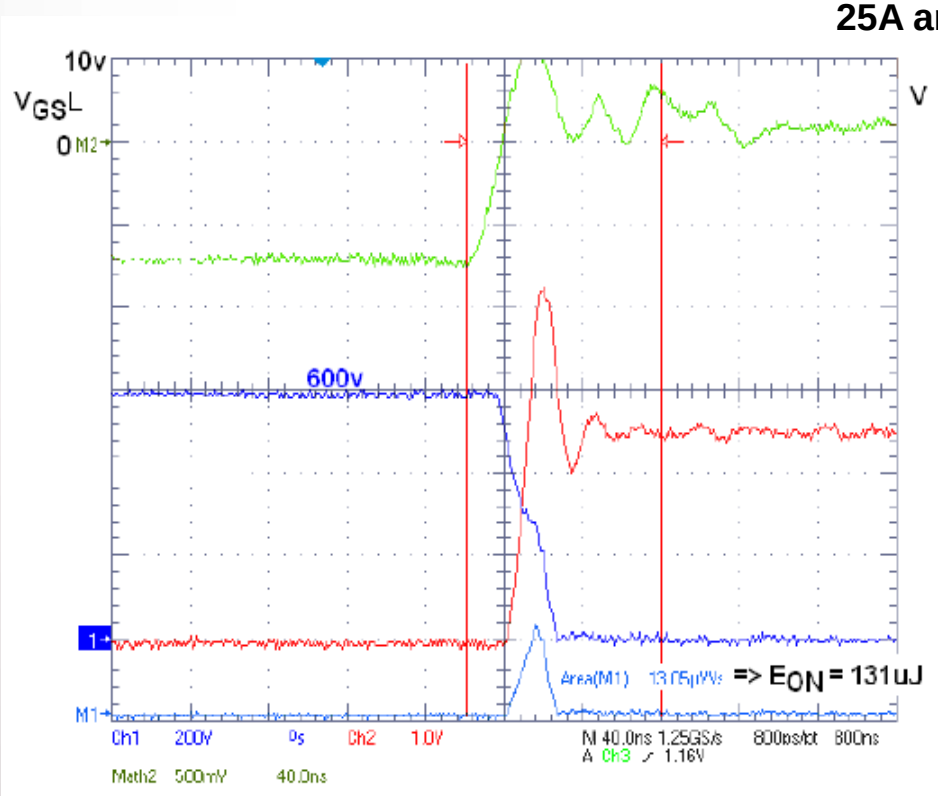
Q1 Conduction Driver: Q1 is a small PNP transistor used to provide the ON-state gate current of 200mA to maintain a low Rds(on) in the SJEP120R063 or 050 JFET during the conduction period.

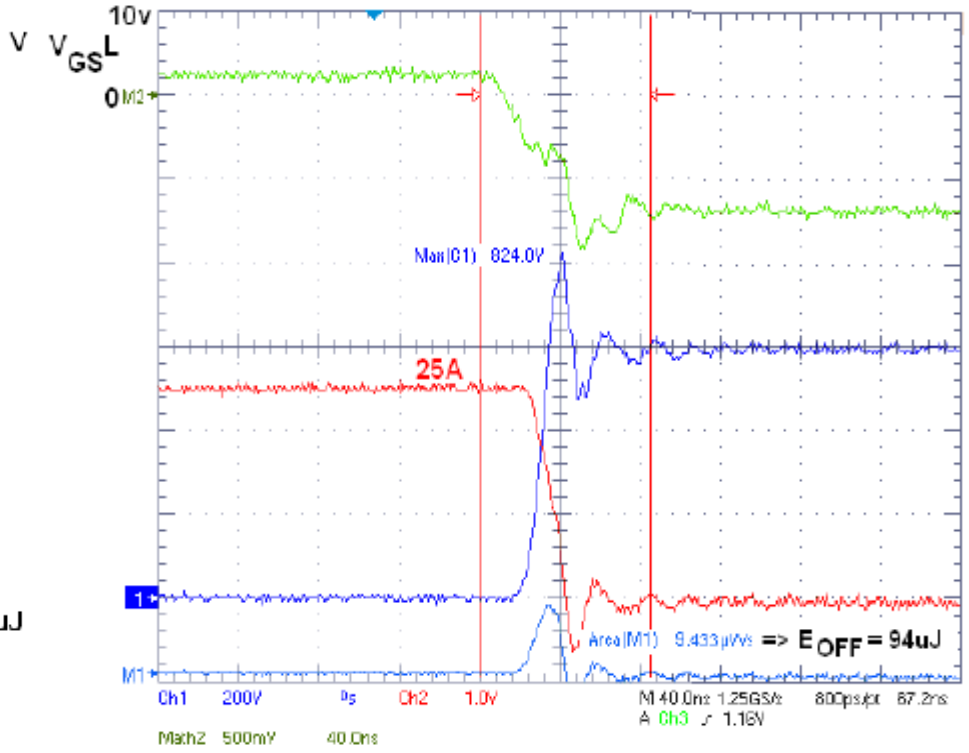
15V to 6V DCDC: This step down (85% eff) DCDC converter IC is used as the power source for Q1 and enables a reduction in gate power loss during the conduction period. (optional).

Timing Logic: The logic / timing circuit generates the required timing signal for the IXDD509 gate Driver and Q1. The timing is set to achieve a 100nsec turn on high I pulse and then maintain the 200mA conduction pulse.

Typical Switching Waveforms – with SJEP120R063 JFET

25A and 600V



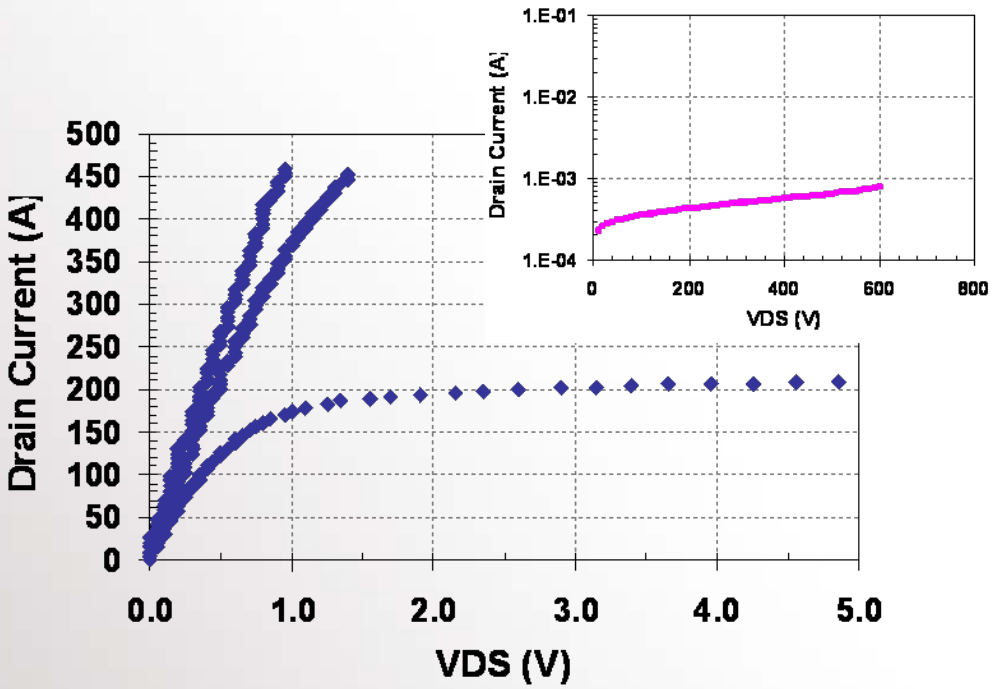


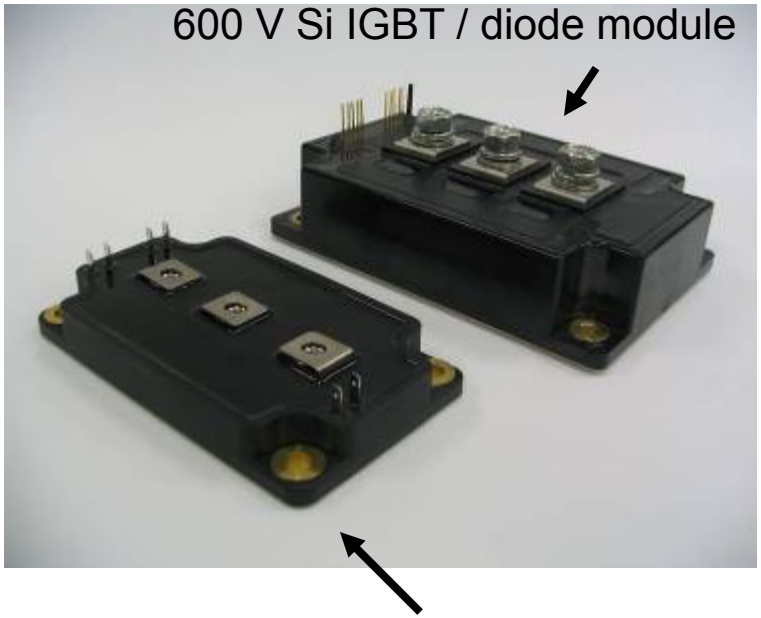
Comments:

1. These switching losses are in line with the data sheet and the higher temperature (150C) switching loses would be similar to the data sheet as well and only 10% higher.

Demo Module Example

- 600 V / 450 A SiC Normally-off JFET module
- Up to 57% reduction in conduction losses possible at 1200 V level (~2.2mΩ @ 1V)





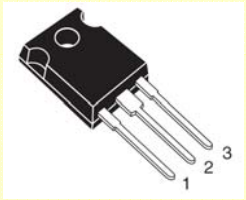
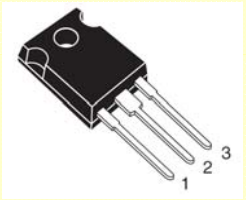
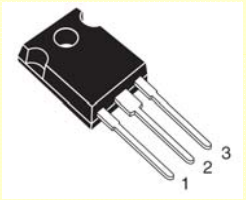
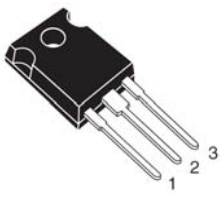
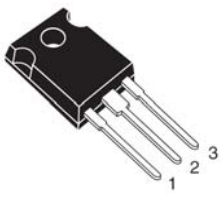
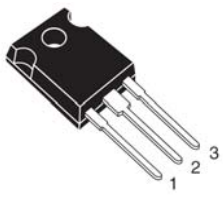
1200 V SiC JFET / diode module
(SemiSouth enhancement-mode JFET)

Vertical Trench JFET Roadmap

Improved "125" to "100"

Dual Die

Products Released in Sept 2008

Part	SJEP120R125	SJEP120R100	SJEP120R063	SJEP120R050	SJEP120R025	SJEP170R550
Package	 3L TO-247	 3L TO-247	 3L TO-247	 3L TO-247	 3L TO-247	 3L TO-247
Voltage (V)	1200	1200	1200	1200	1200	1700
Rds(on)	125 mΩ	100 mΩ	63 mΩ	50 mΩ	25 mΩ	550 mΩ
Ciss Tr*/Tf* (ns) Die size	576 pF 50 /50 4 mm²	TBD TBD 4.5 mm²	2 x 576 pF 50 /50 2 x 4 mm²	1168 pF 50 /50 9 mm²	2320 pF 50 /50 15 mm²	167 pF 50 /50 2 mm²
Co-Pak Options	5A SBD Q2 09	5A SBD TBD	-	10A SBD Q3 09	-	-
Samples	Now	Now	Now	Q3 09	Q1 10	Q2 09
Production	Now	Now	Now	Q4 09	Q2 10	Q4 09

Latest Datasheets at http://www.semisouth.com/products/powersemi.html

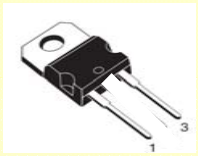
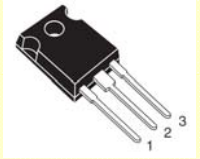
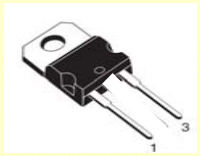
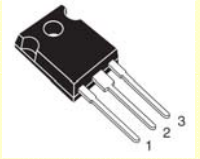
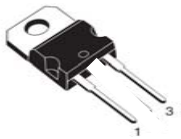
Accepting Sample and Production orders

* 30-50 ns typical

UPDATED 11 Aug 2009

SemiSouth

SiC Schottky Diode Roadmap

Part	SDA05S120	SDP10S120D	SDA10S120	SDP20S120D	SDA30S120	SDP30S120
Package	 2L TO-220	 3L TO-247	 2L TO-220	 3L TO-247	 2L TO-220	 2L TO-247
BV (V)	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**
I_F (A)	**5A**	**10A (2 x 5A)**	**10A**	**20A (2 x 10A)**	**30A**	**30A**
V_{Fmin} (V) V_{Fmax} (V)	**1.6** **1.8**	**1.6** **1.8**	**1.6** **1.8**	**1.6** **1.8**	**1.6** **1.8**	**1.6** **1.8**
Samples	**Now**	**Q1 09**	**Now**	**Now**	**Q3 09**	**Now**
Production	**Q2 09**	**Q2 09**	**Now**	**Now**	**Q4 09**	**Q2 09**

Accepting Sample and Production orders

Summary of SemiSouth JFET

- *SiC is maturing, cost declining*
  - *100 mm dia wafers now; 150 mm dia wafers soon*
  - *SiC FET devices suitable up to 3-4 kV, and being released now*
  - *SiC bipolar (BJT, IGBT, …) for > 3 kV still being developed*
  - *MOS controlled devices still challenging*

- **Released first normally-off SiC JFET in 2008**
  - **High reliability, easily paralleled for high power modules**
  - **Small die + High Performance + Low process complexity**
  - ***Low $ for SiC level performance expectations***

- ***World record (> 99%) PV inverter efficiency***
- ***Enables higher power density inverters***