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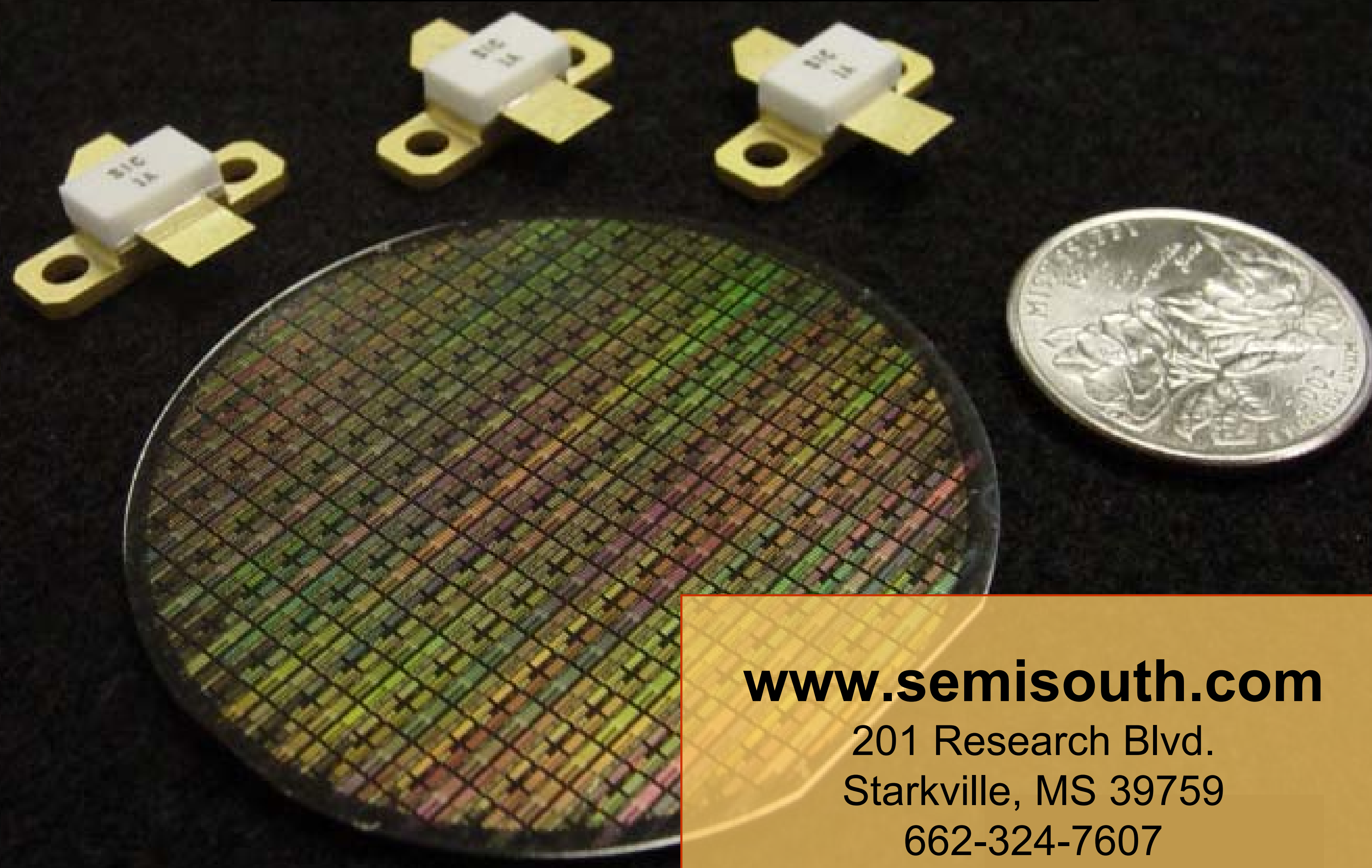

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Power Electronics for High Tech Inverters

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and
Center for Advanced Vehicular Systems,
Mississippi State University

Outline

- Introduction
  - Components in inverters
  - Power component R&D
- Silicon Carbide Power Electronics
  - System Benefits
  - Capabilities
  - Trends

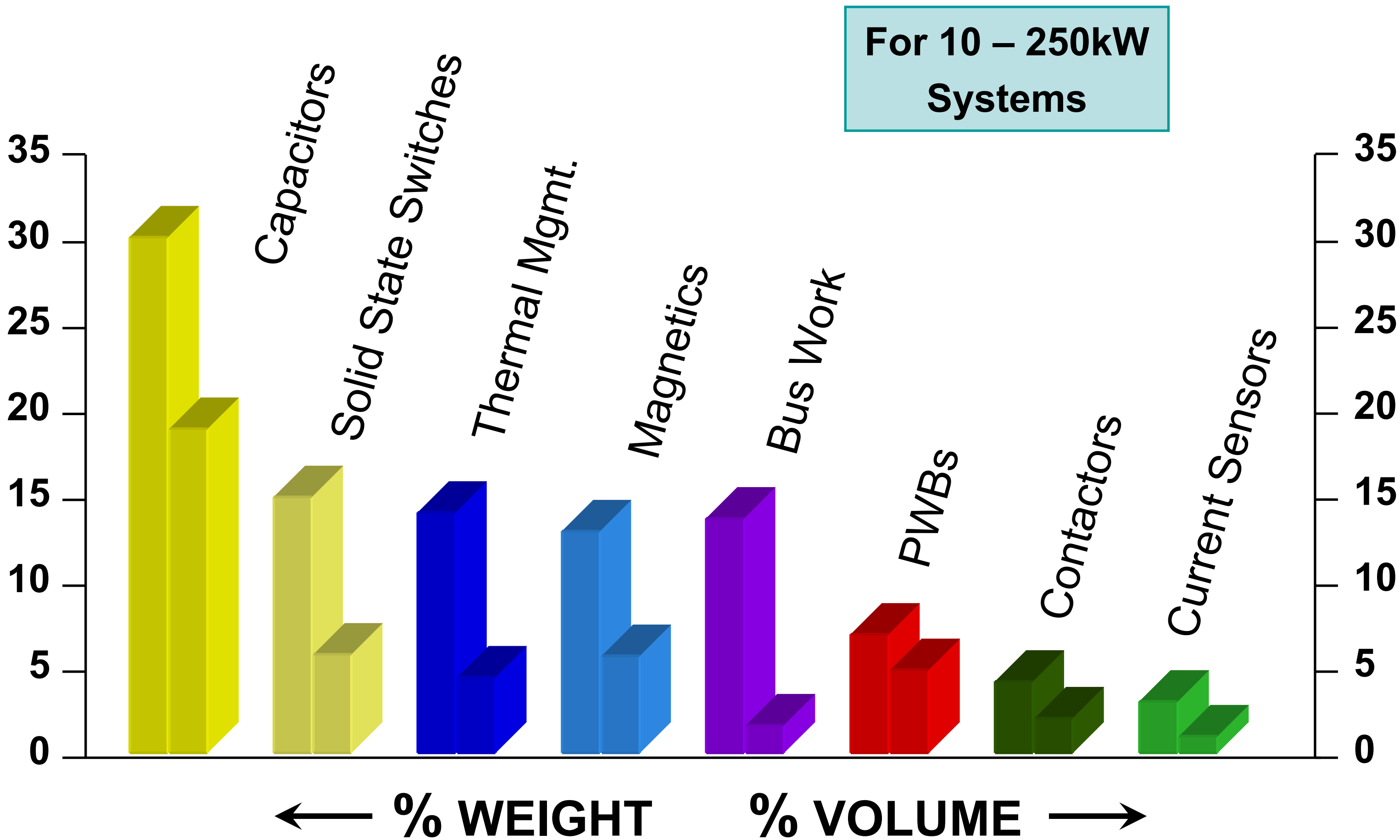
Introduction

Components in Inverters

SEMISOUTH LABORATORIES

Mississippi State UNIVERSITY

ALL INVERTERS, CONVERTERS AND MOTOR CONTROLLERS CONSIST OF . . . .



Courtesy of Dr. James Scofield, Propulsion Directorate,
Air Force Research Laboratory, Wright-Patterson Air
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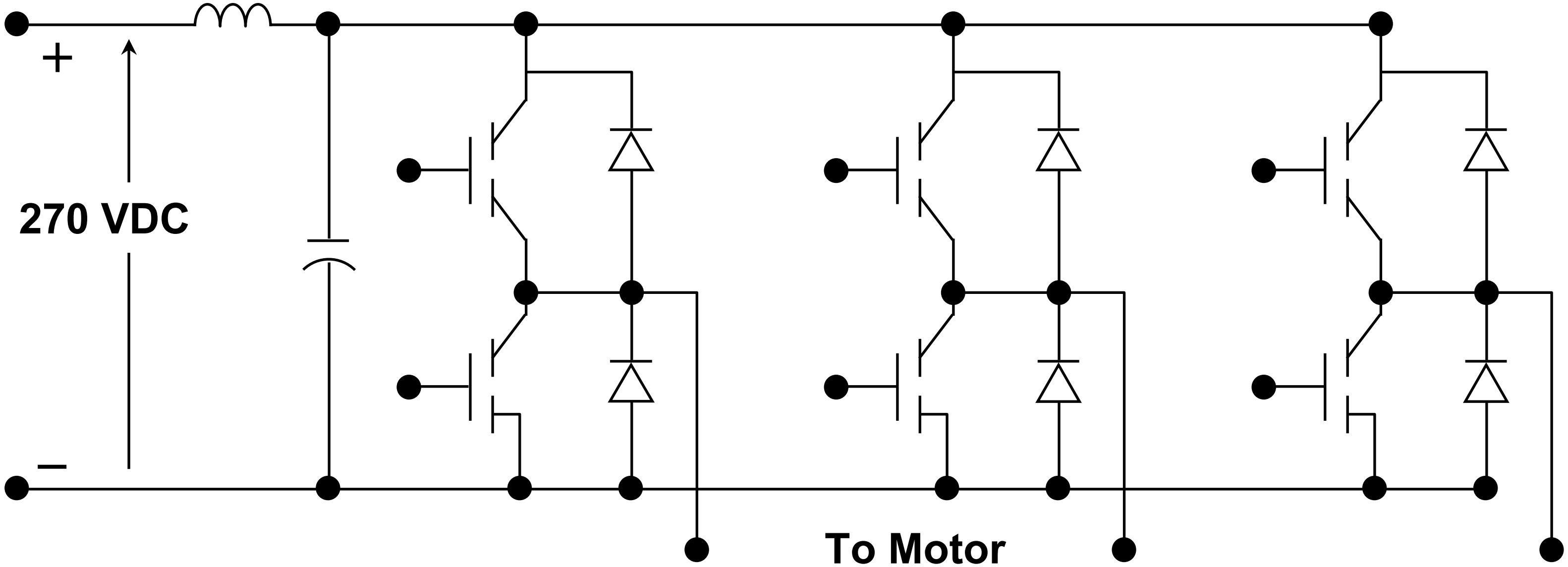
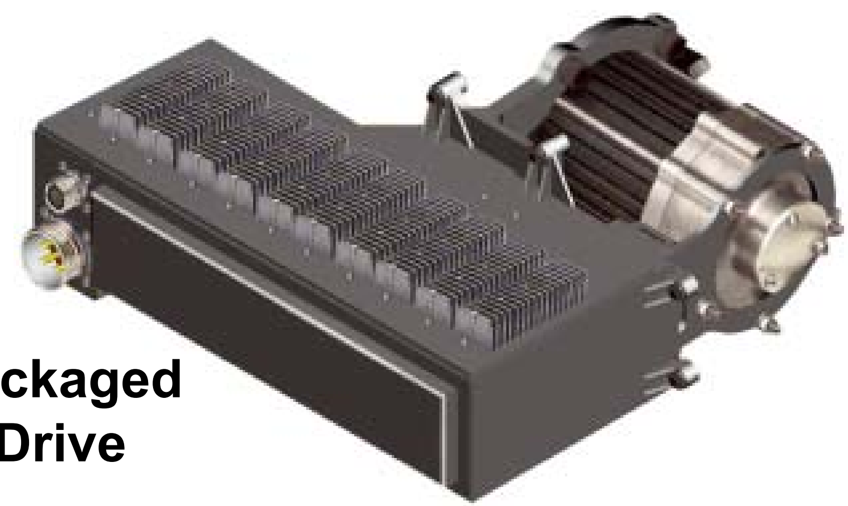
Typical Inverter Topology



- Six-pulse topology.
- Switches are typically IGBT's or MOSFET's
- Each switch has an integral anti-parallel rectifier.

Courtesy of Dr. James Scofield, Propulsion Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base



Flight Packaged Motor Drive

Applications Driver – *Power Density*

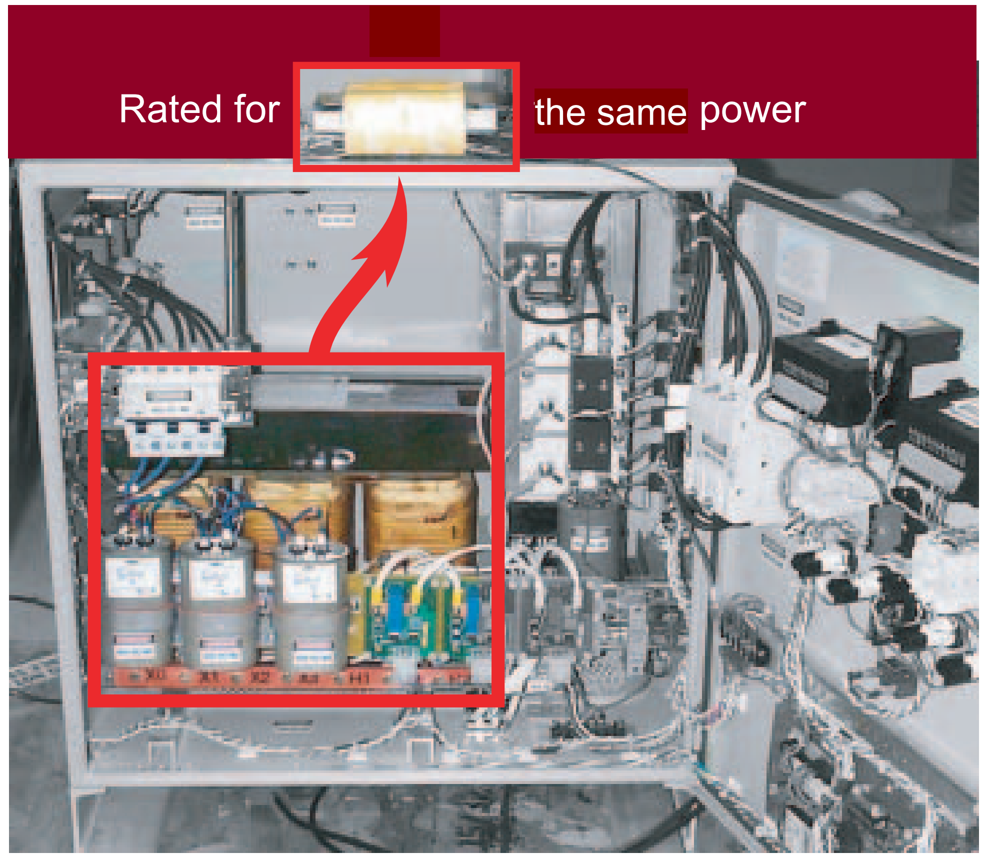
- Much of the cumulative improvement in power density is still in the future (Moore's law for power?).
- Civilian transportation and communication applications will drive much of the technology development (affordable).
- The ultimate is goal is monolithically manufactured power supplies.

Power Density – How to increase it?

- Increase the conversion frequency.
  - Size and weight of passive components $\propto$ 1/f.
  - Typically, 75% of size and weight of power converters is in the passive components.
- Increase the voltage.
  - Insulation is always lighter than copper.
  - Skin depth further leverages voltage at higher frequency.
  - Mobile platforms have common bus voltages:
    - 270 V $\rightarrow$ 600 V device family (JSF, HE-HMMWV, AUV's, etc.)
    - $\pm$300 V $\rightarrow$ 1200 V device family (insulation the same, ½ the Cu)
- Improve the packaging (get the heat out).

Example: Transformer Size & Weight

- Two transformers rated for 10 kVA.
- Increasing the frequency from 400 Hz to 100 kHz decreases the transformer weight from 150 lbs. to 5 lbs.



Why is an anti-parallel diode needed?

1

- Bidirectional power flow for dc-ac inverters.
  - Supplying reactive power.
  - Conducting harmonic currents.
- Energy recovery in motor drives.
  - Recover energy stored in parasitic inductances.
  - PWM in Brushless DC (BLDC) motor drives.

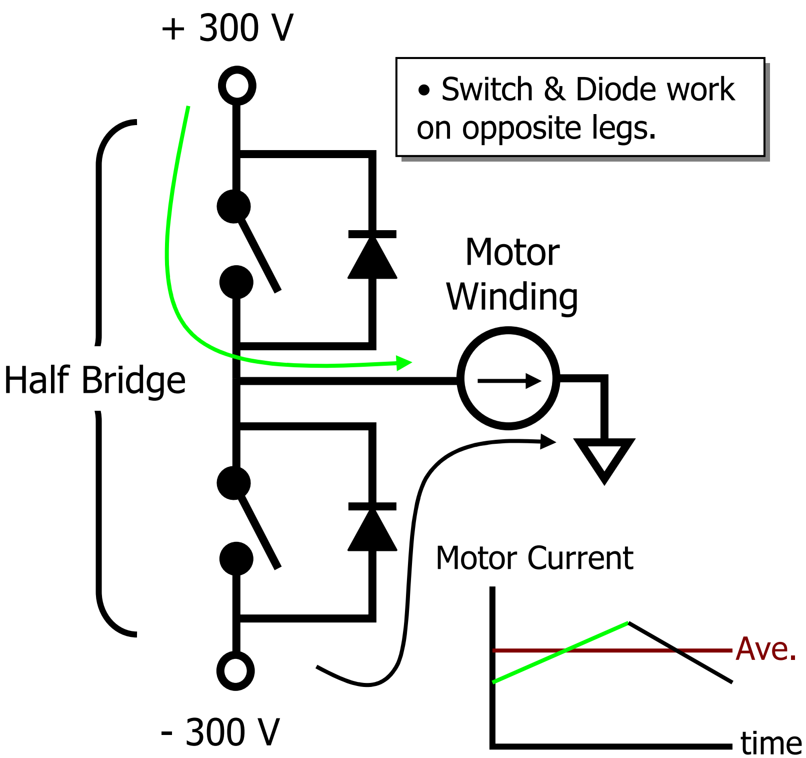
2

- Conducting resonant currents in soft-switched power supplies and drives.
  - To continue increasing conversion frequency, minimizing inductance between switch and anti-parallel diode is essential.
  - <u>Lowest possible inductance is achieved monolithically.</u>

Anti-parallel current paths: Two possibilities

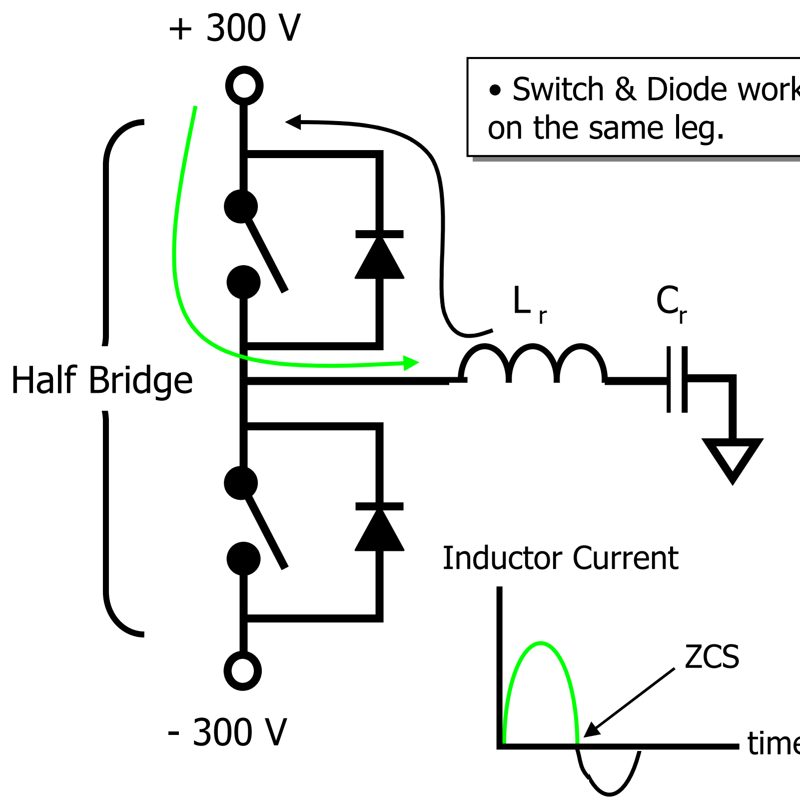
Hard-Switched BLDC Motor Drive

- Switch & Diode work on opposite legs.



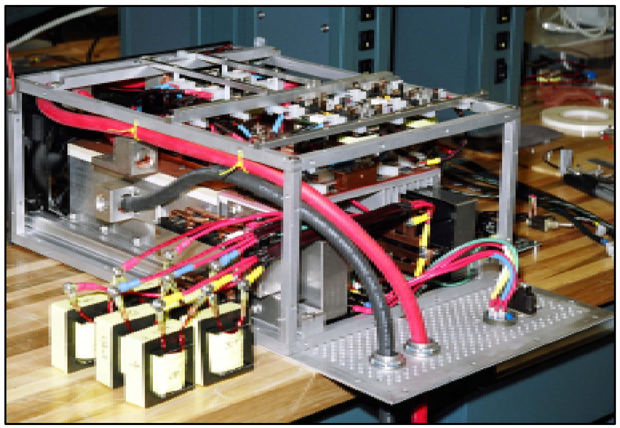
Soft-Switched Resonant Power Supply

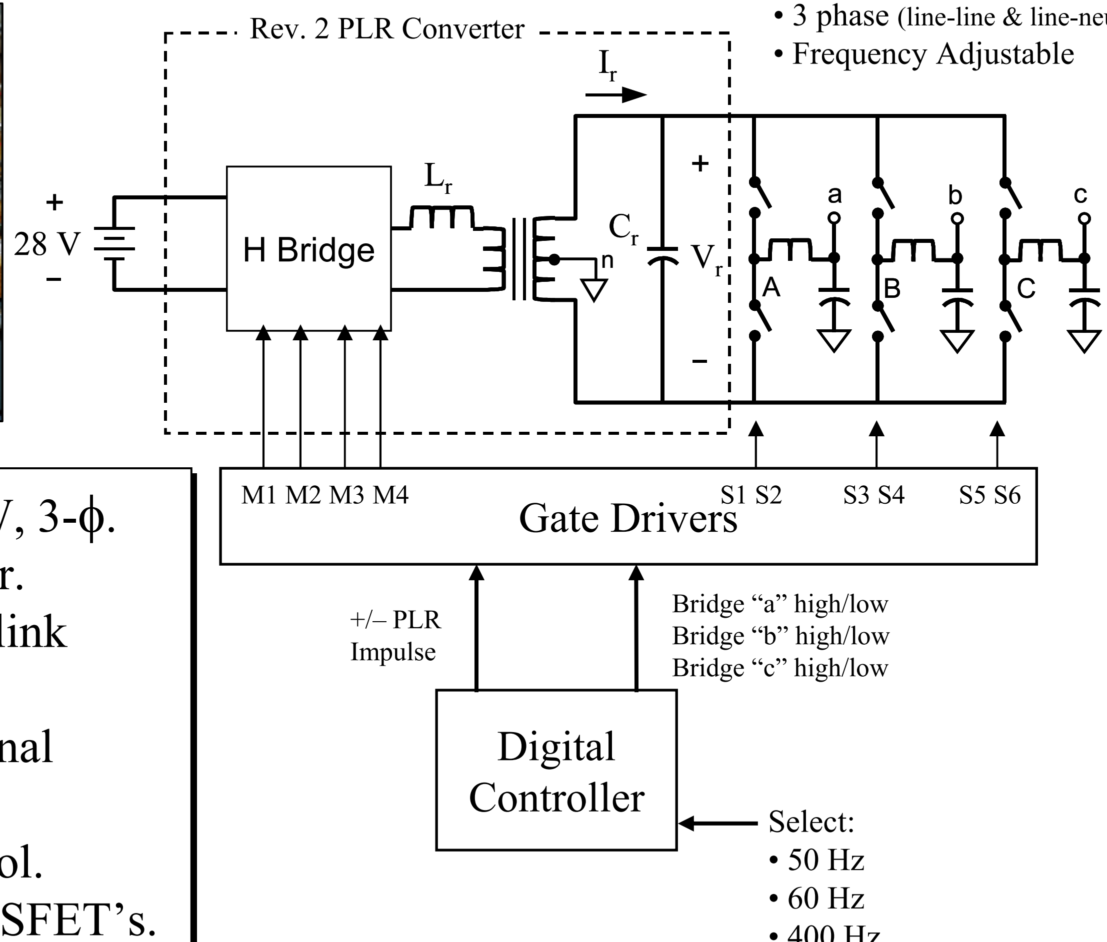
- Switch & Diode work on the same leg.



DC-AC Inverter for On-Vehicle Applications

Output:
- 208 VAC (rms)
- 3 phase (line-line & line-neutral)
- Frequency Adjustable

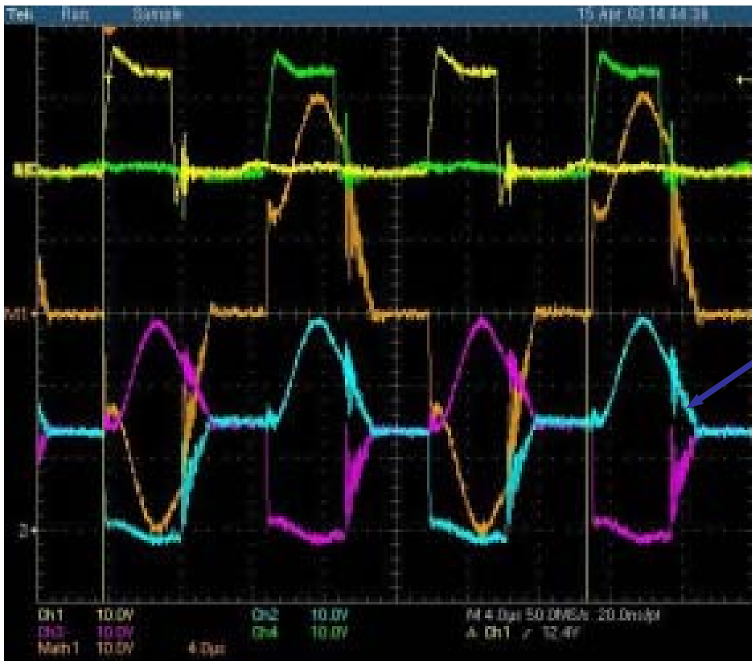




- 28-VDC to 208-VAC, 10-kW, 3-ϕ.
- Voltage boost: PLR Converter.
- Link: high-frequency ac (no link rectifier).
- Inverter: six pulse, bidirectional switches.
- Preprogrammed digital control.
- Limiting Component: Si MOSFET’s.

The PLR Voltage Pulse in an AC-Link Inverter

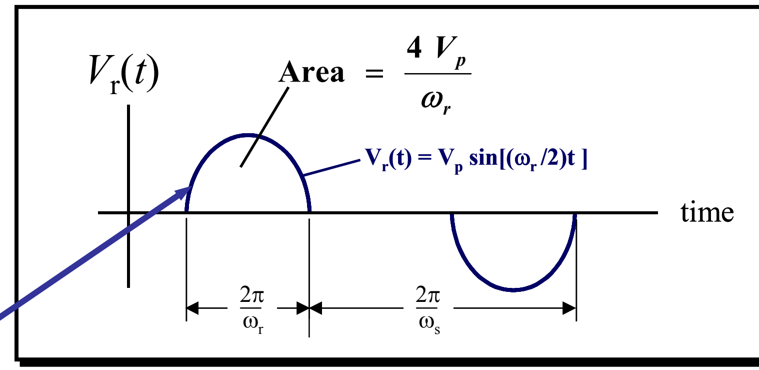
Peak Inverter MOSFET Stress > 800 V.
MOSFET RMS Current = 28 A.

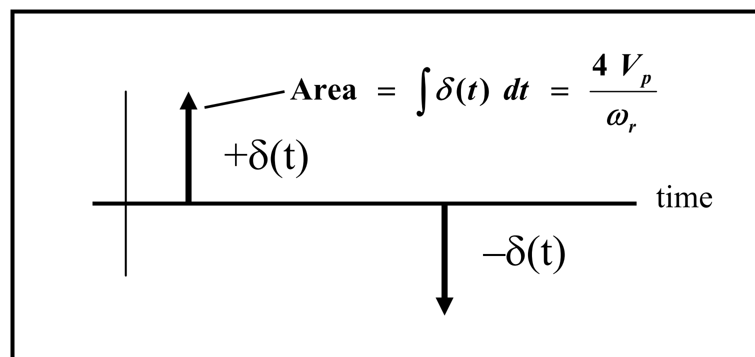


PLR Converter Voltage Waveforms

Components are stressed by resonant voltages and currents well in excess of inverter terminal ratings.

Sine Function Model of Resonant Capacitor Voltage





Impulse Function Model of Resonant Capacitor Voltage

Introduction

Power Component Research & Development

Air Force Investment Strategy in High Temperature Electronics Driven by Study Results

AFRL/PRPE TECHNOLOGIES

STUDY	HIGH TEMP SiC	HIGH TEMP PASSIVES	CRYO POWER COND	PULSE POWER CAPS	HIGH VOLT/PWR SWITCH	HIGH VOLTAGE DIODES	TRANSFORMER/INDUCTOR	HIGH VOLTAGE WIRING	LOW VOLTAGE HIGH ENERGY CAPS	LIGHT CONTROLLED DEVICES	IVHM
MEA Gen II Engine Study	X	X									
SiC Benefits Study	X	X								X	X
Fighter Based Laser Study	X	X								X	X
Airborne Electric Laser			X							X	
UCAV HPM Study	X	X		X	X	X	X	X		X	
HEX	X	X			X	X	X	X			
SBR Study	X	X									
Space Baseload Study	X	X									
Space SBL Study (Schafer)											
Space SBL Study (SAIC)									X		
MEA Adv Motor Drive II Study	X	X								X	
LRSA Study	X	X								X	X
Dielectric Study				X							
UCAV Requirements	X	X								X	X

What is Silicon Carbide?

- Silicon forms a stronger chemical bond to carbon than to silicon!
  - SiC is very hard (third hardest substance known)
  - SiC handles very high temperatures (wafers are made at over 3600°F)
  - SiC handles very high voltages (ten times that of silicon and gallium arsenide)
- Single crystal SiC wafers for electronics use commercially available:
  - 1990 - 1 inch diameter
  - 2003 – 3 inch diameter
  - 2006(?) – 4 inch diameter
- Early versions of SiC power devices perform better than the best performing silicon power devices.
- SiC power products are commercially available and in commercial use.

Motivation to Develop SiC Power Devices

Silicon vs. Silicon Carbide Power Semiconductors

PROPERTY	SILICON	SILICON CARBIDE
BANDGAP (eV@ 300K)	1.1	2.9
MAXIMUM OPERATING TEMPERATURE (K)	425	>900
BREAKDOWN VOLTAGE (10^6 V/cm)	0.3	4
THERMAL CONDUCTIVITY (W/cm - °C)	1.5	5
PROCESS MATURITY	HIGH	LOW
INTRINSICALLY RAD HARD	NO	YES

SiC Power Electronics

System Benefits

Overview of Benefits

- **Lower On-resistance** → **increased system efficiency**
- **Higher Frequency** → **smaller power supplies**
- **Higher Temperature** → **relaxed cooling requirements**

Payoff: Improved System Performance

(size, weight, cost, reliability, efficiency)

Current commercial applications

1. High-end server power supplies: improved efficiency means smaller supply with the same or less heat generation

Potential future SiC power switch applications

1. High-temperature motor drives & inverters.
2. High-power-density resonant inverters with high voltage stress.

Obstacles to increasing Power Density

- Simultaneous increases in voltage and frequency limited by silicon – *Efficiency cannot be compromised!*
  - MOSFET silicon switches are fast but not voltage scalable.
  - IGBT's voltage scalable, but not as fast (~ 20 kHz).
  - Reverse recovery of anti-parallel diode another limitation.
- Parasitic inductances and capacitances require resonant circuits ("soft switching") above 100 kHz and 1-10 kW.
  - Soft switching requires teaming fast switches with ultra fast anti-parallel diodes.
- VJFET is the best available >1 MHz, 600-1800 V SiC switch.
  - "Normally on" and "Normally off" available
  - Has the best possible anti-parallel diode: a SBD

Vehicle-Level SiC Benefits

	Weight Savings (lbs)	Volume Redn.(in^3)
Flight Control EHAs/EMAs	58.5	1,350
Utility Control Actuators	15.4	313
EPS Equipment	45.1	657
Avionics	17.6	245
ECS/Fuel/Misc Motors	10.9	252
TMS Equipment	30+	400+
Total	**177.5+**	**3,217+**

Minimum 177 lb Equipment Weight and 3,210 in^3 Equipment Volume Savings.

SiC Power Electronics

Capabilities

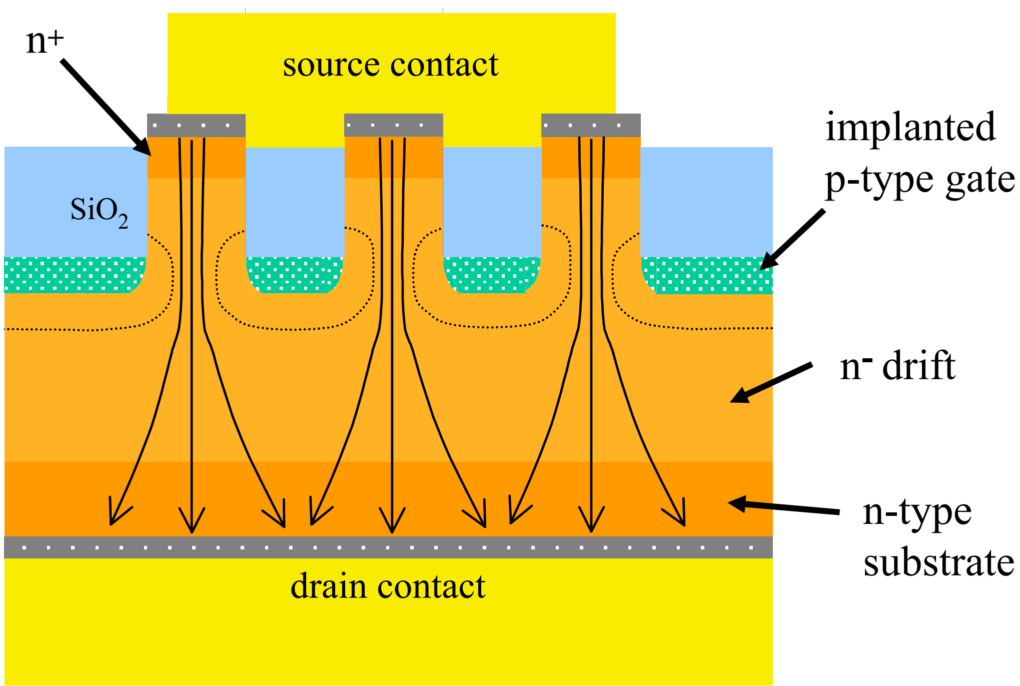
Candidates for SiC Switches

- **<u>SiC MOSFET</u>**
  – Unipolar
  – Normally off
  – *p-n* body diode
    - Always present
  – Low channel mobility
  – Oxide reliability issues

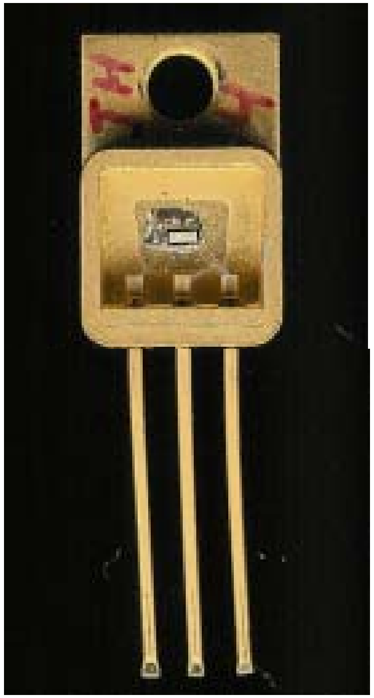
- **<u>SiC JFET</u>**
  – Unipolar
  – Normally on
    - Normally off and "quasi-on" options
  – No body diode
  – Not as sensitive to oxide interface and reliability issues

4H-SiC Vertical JFET

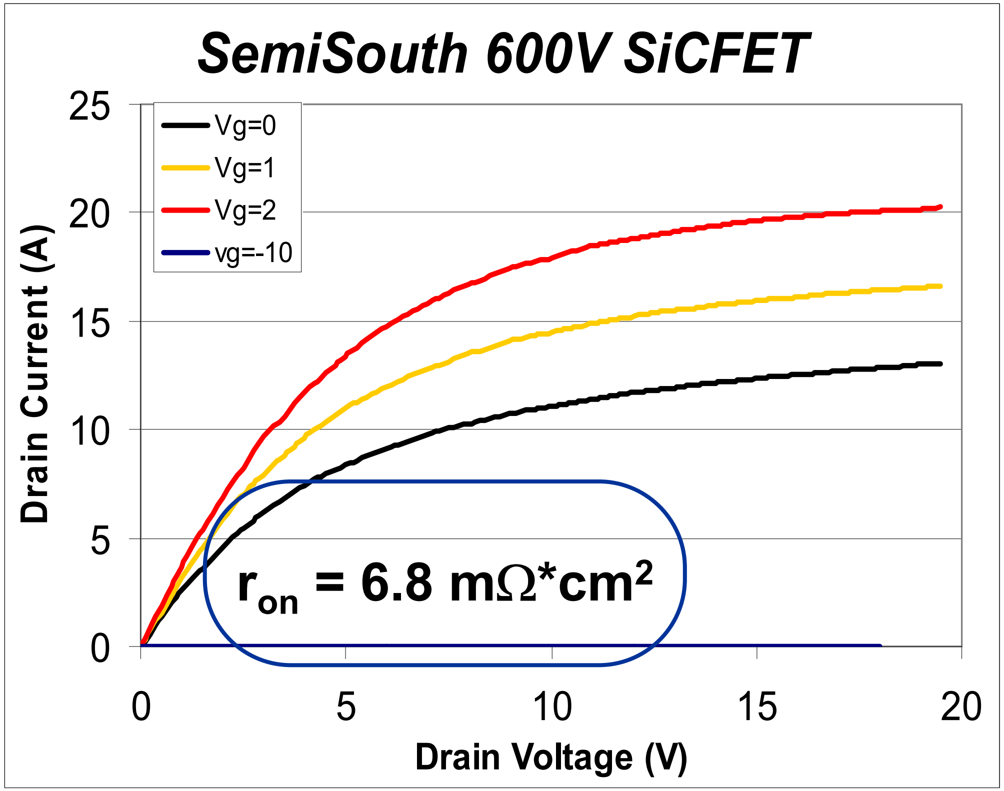
Basic device cross-section



Finished JFET in a TO-257



VJFET Technology



- Hard Switch @ 20MHz
- T_{jmax} ≥ 300 °C
- Parallel multiple die for high total current

600V, 20A

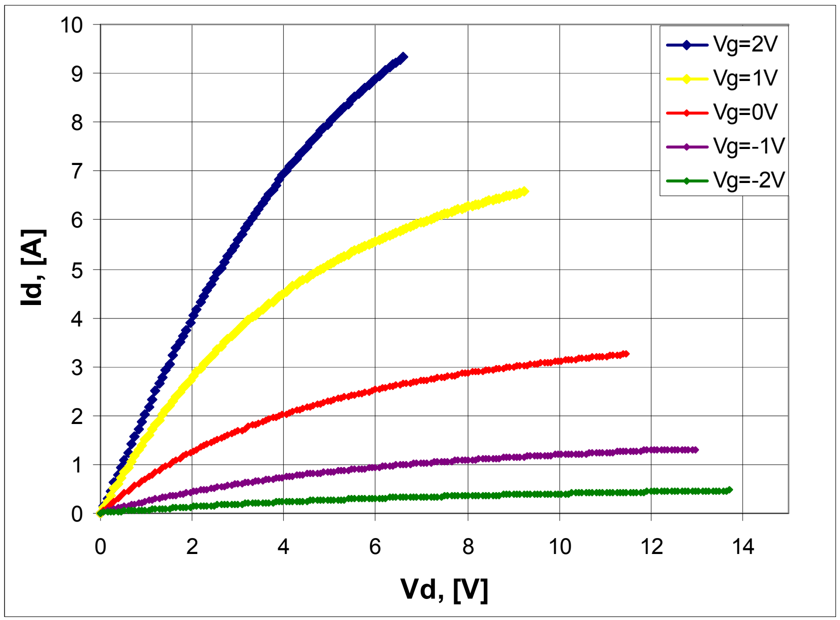
Multi-die package

Sept 2003

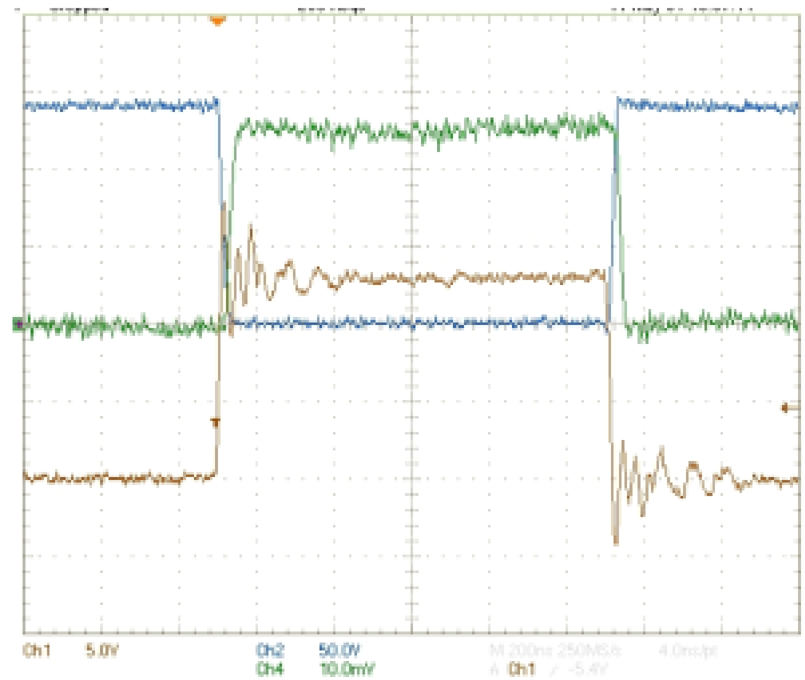
Parts currently being sampled to customers

Monitored by Dr. J. Scofield, WPAFB

VJFET Technology



300-V, 5-A, 20-MHz VJFET



Vd=150V **t=51ns**

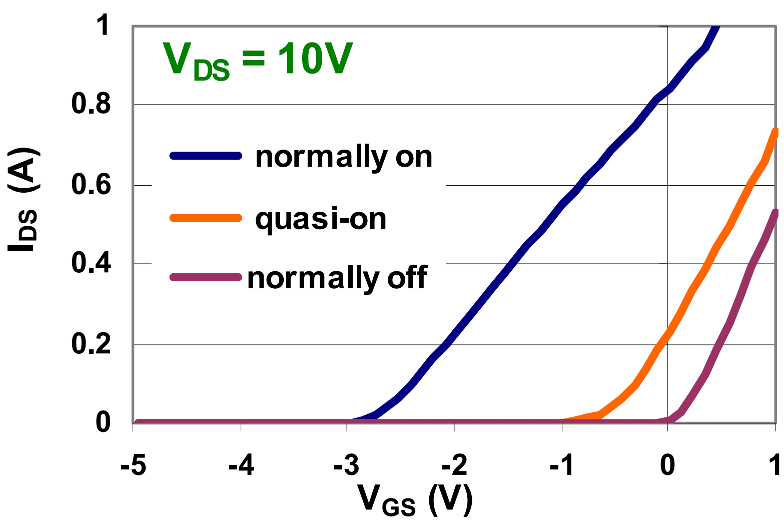
Id=5A **f=19.6MHz**

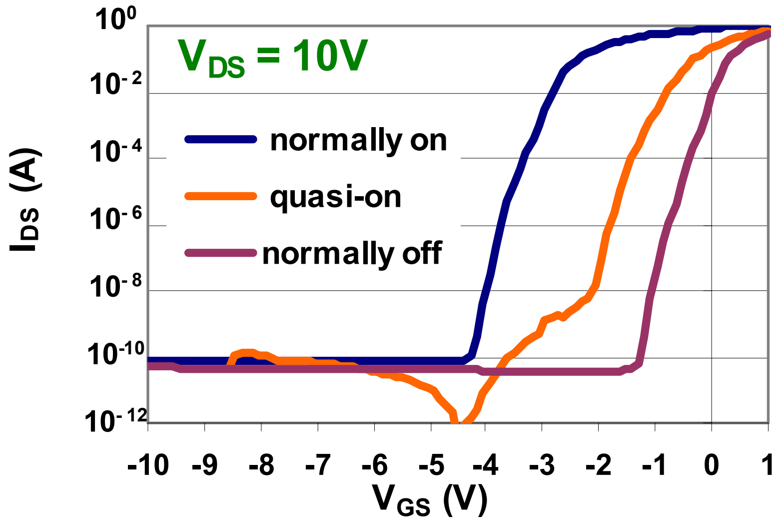
Parts currently being sampled to customers

Monitored by Dr. J. Scofield, WPAFB

The "Quasi-on" Option

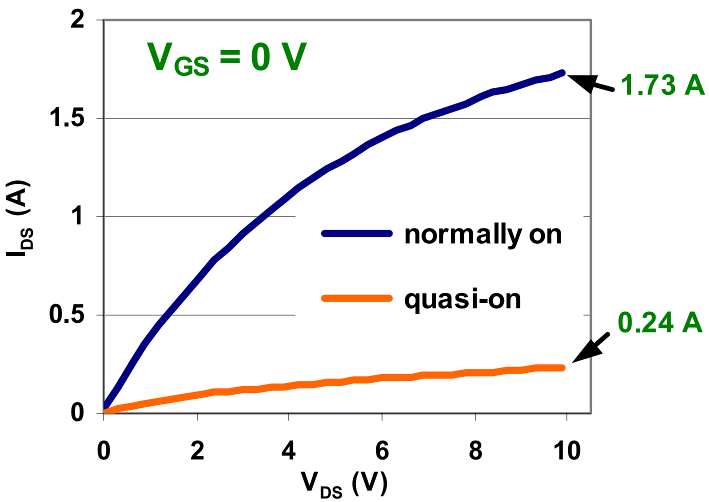
Normally on: V_T is negative.
Normally off: V_T is positive.
Quasi-on: V_T is slightly negative



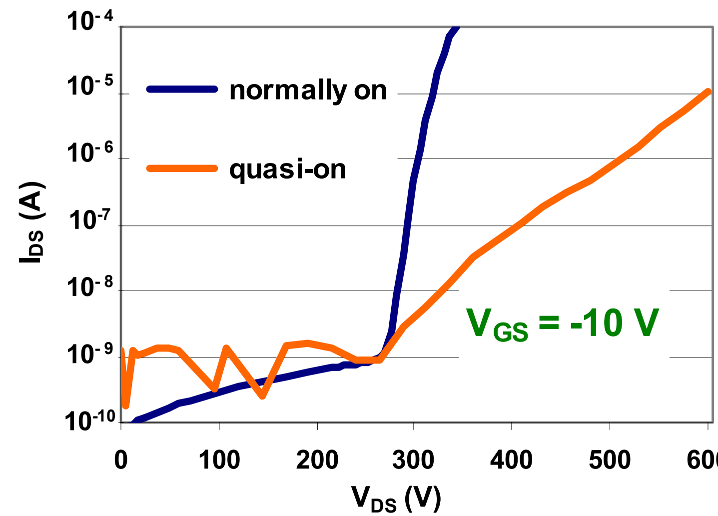


Benefits of a Quasi-on JFET

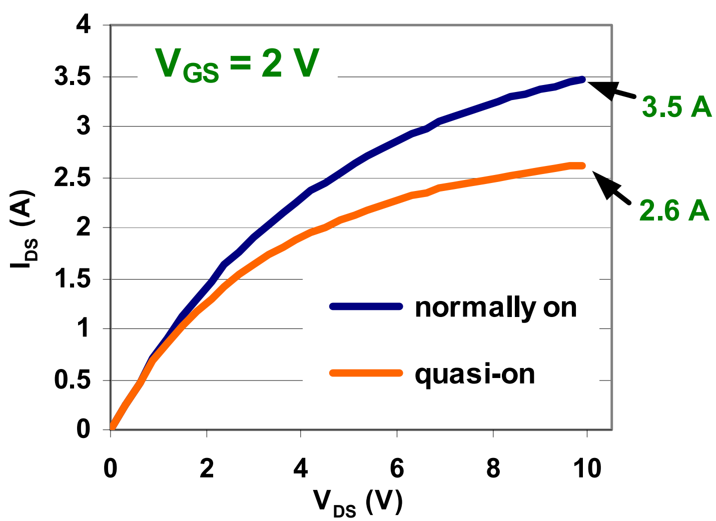
- Circuit protection



- Improved blocking

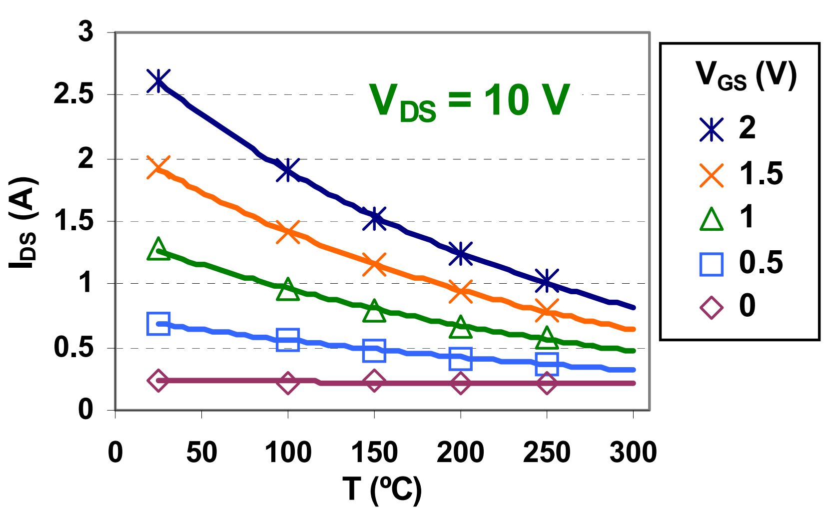


- Acceptable current trade-off

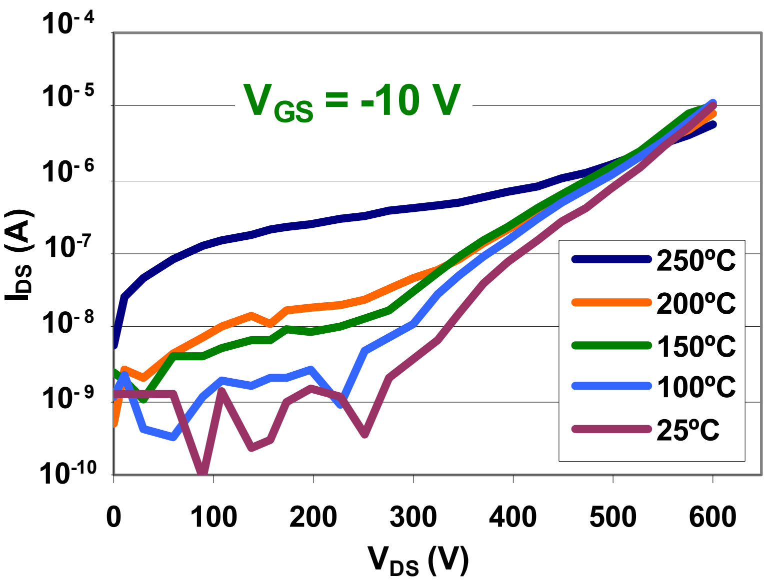


DC Characteristics at Elevated Temperatures

DC I_{DS} at V_{DS} = 10 V as a function of temperature for a 600V 4H-SiC VJFET



DC I_{DS} vs. V_{DS} at V_G = -10 V for temperatures up to 250ºC 4H-SiC VJFET



Summary

- The 600V SiC VJFETs had typical r_{on} values from 6.5 to 10 mΩ*cm^2 at room temperature.
- Devices exhibited an expected decrease in drain current with increasing temperature with I_{DS} at 300ºC = ~ 30% I_{DS} at 25ºC.
- Early generation VJFET had maximum switching frequencies in the MHz range which increased with temperature.
- Next generation VJFET has much reduced gate resistance and RT switching over 20 MHz.

SiC Power Electronics

Trends

Improving SiC Power Switches

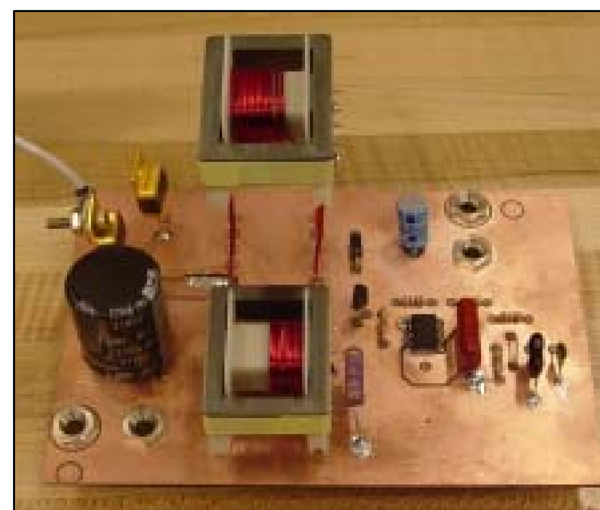
SiC VJFET/Diode in DC-DC Buck Converter (VJFET @ 225°C)

<u>Comparison of SiC switch (specific on-resistance)</u>

Blocking Voltage\	Infineon Si switch	Infineon VJFET-A	Infineon VJFET-B	SemiSouth VJFET
600 V	30 (COOLMOS™)	8	20	<u>6.8</u>
1200 V	400 +	12	22	
1800 V	NA	14	24	

<u>MDA/AFRL Program produced a patented SiC VJFET switch which has:</u>

- ✓Lower on-resistance
- ✓Simpler (inexpensive) fabrication process
- ✓Lower packaging costs



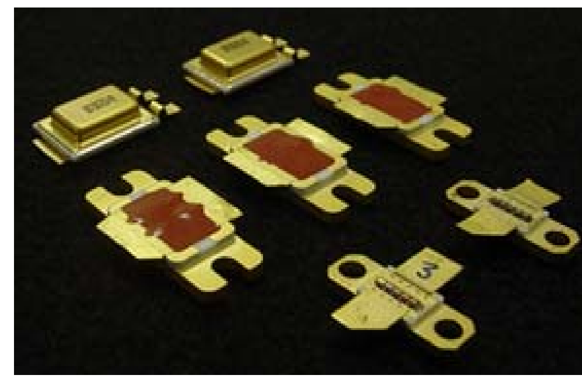
Increased Requirements for High Temperature Electronics

- Near Term (3 - 5 years)
  - 250°C - 300°C (max) junction temperature
  - Reduction in requirements for active cooling
- Far Term (5 - 9 years)
  - 300°C - 350°C (max) junction temperature
  - Supports “high speed” aircraft

SemiSouth and SiC is in the Commercial Market Place

SiC Materials
- Epitaxy
- Quality Control

SiC Devices
- Power Switch
- Power Rectifier
- RF Transistor



SiC OEM
- Device Design
- Device Fabrication

Multiple Sources, Decreasing Prices

Cree	***II-VI***	***SemiSouth***	***Dow Corning***
Substrates ↓ Epi ↓ Devices ↓ End users, VARs	Substrates	Epi ↓ Devices ↓ End users, VARs	Substrates ↓ Epi

- "Virtual" Vertical Integration
  - Provide true direct alternative to Cree
  - But, provides insulation from competing with customers

- Open source of SiC technology – provide industry with true 2nd or alternate source… something many customers want now.

- Provides direct market feedback and drive to emerging 4H epi-wafer market.