

High Temperature, Smart Power Module for Aircraft Actuators

Khalil EL FALAHI, Stanislas HASCOËT, Cyril BUTTAY,
Pascal BEVILACQUA, Luong-Viet PHUNG,
Dominique TOURNIER, Bruno ALLARD, Dominique PLANSON

Laboratoire Ampère, Lyon, France

8/7/13

Introduction

Selection of Power Devices

Custom Gate Drive

Prototype and Test Setup

Results

Conclusion

Introduction

Selection of Power Devices

Custom Gate Drive

Prototype and Test Setup

Results

Conclusion

The More Electric Aircraft



- ▶ Increase in on-board electric power:
 - ▶ More than 1 MW for the B787
 - ▶ Need for higher voltage network: 540 V DC
- ▶ Electric actuators in harsh environment:
 - ▶ Jet engine controls (e.g. thrust reverser controls)
 - ▶ Electric brakes

Requirements:

- ▶ Strong thermal cycling (-55/+200 °C)
- ▶ Long operating life (target 30 years)
- ▶ Excellent reliability



High Temperature Inverter building blocks

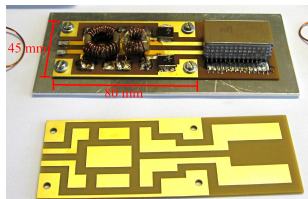
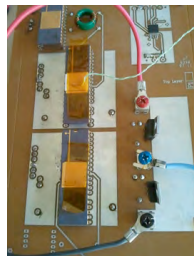


Power module:

- ▶ 6 JFETs in an hermetic package
- ▶ $T_A = 200^\circ\text{C}$, $I_{out} = 6\text{ A}$ per phase, $20\text{ kHz} < F_{SW} < 300\text{ kHz}$

Gate drivers

- ▶ Integrated technology (SOI)
- ▶ Development of many functions
 - ▶ Output buffer, signal conditioning
 - ▶ Safety functions
 - ▶ Temperature compensation



EMI filter

- ▶ Characterization of passives for wide temperature operation ($25/250^\circ\text{C}$)
- ▶ Evaluation of long-term ageing ($>1000\text{ h}$ at 200°C)

Introduction

Selection of Power Devices

Custom Gate Drive

Prototype and Test Setup

Results

Conclusion

MOSFET

- ▶ Easy to drive, much like a silicon MOSFET
- ▶ “Normally-off” device
- ▶ Gate oxide reliability issues at high temperature

Overview of SiC Power Devices

MOSFET

- ▶ Easy to drive, much like a silicon MOSFET
- ▶ “Normally-off” device
- ▶ Gate oxide reliability issues at high temperature

JFET

- ▶ “Mature” device
- ▶ No gate oxide, making it very reliable at high temperature
- ▶ The chosen device is a “Normally-on” device

Overview of SiC Power Devices

MOSFET

- ▶ Easy to drive, much like a silicon MOSFET
- ▶ “Normally-off” device
- ▶ Gate oxide reliability issues at high temperature

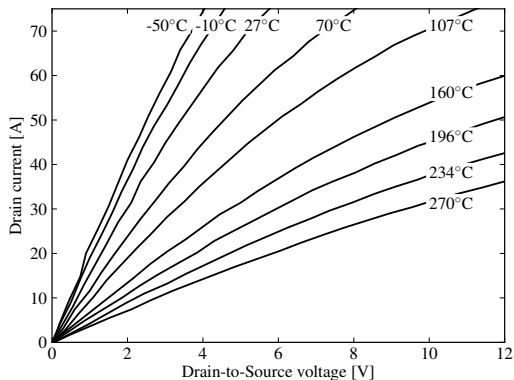
JFET

- ▶ “Mature” device
- ▶ No gate oxide, making it very reliable at high temperature
- ▶ The chosen device is a “Normally-on” device

BJT

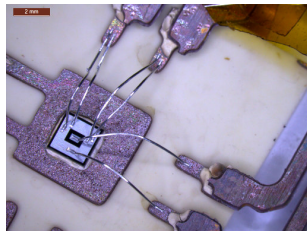
- ▶ Reliability affected by substrate material quality
- ▶ “Normally-off”
- ▶ Driving not as simple as with FET devices

Forward characteristic of the SiCED JFET



$I_D(V_{DS})$ characteristic for $V_{GS} = 0\text{ V}$

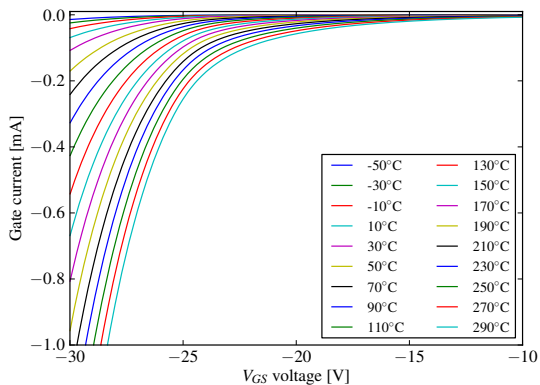
- ▶ $4.08 \times 4.08\text{ mm}^2$ SiC die
- ▶ Purchased in 2009
- ▶ Manufactured by SiCED
- ▶ Normally-on
(off for $V_{GS} < -21\text{ V}$)
- ▶ Tested up to 300°C



Gate Characteristic

V_{GS} is limited by punch-through

- ▶ Depends on current capability of the driver



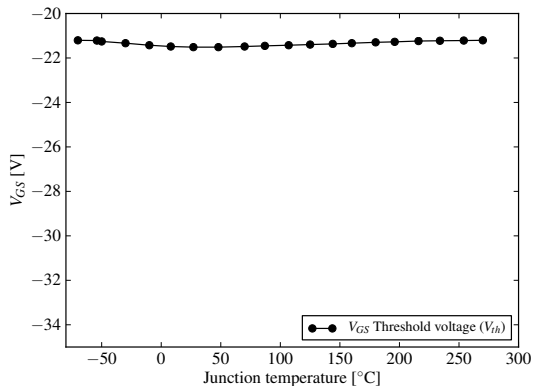
Gate Characteristic

V_{GS} is limited by punch-through

- ▶ Depends on current capability of the driver

To block the JFET we need

- ▶ $V_{GS} < V_{th}$



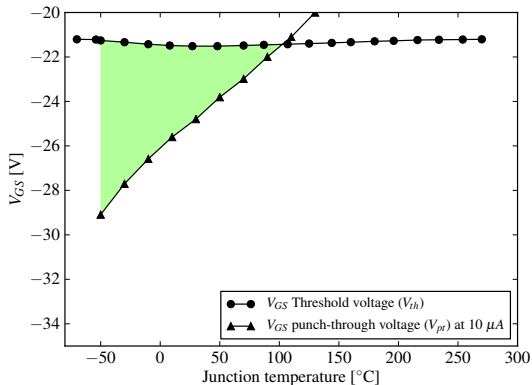
Gate Characteristic

V_{GS} is limited by punch-through

- ▶ Depends on current capability of the driver

To block the JFET we need

- ▶ $V_{GS} < V_{th}$



Gate Characteristic

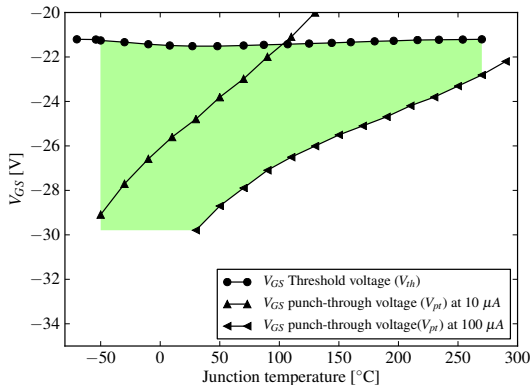
V_{GS} is limited by punch-through

- ▶ Depends on current capability of the driver

To block the JFET we need

- ▶ $V_{GS} < V_{th}$

No damage observed on the JFET, even for $I_G > 10\text{ mA}$



Gate Characteristic

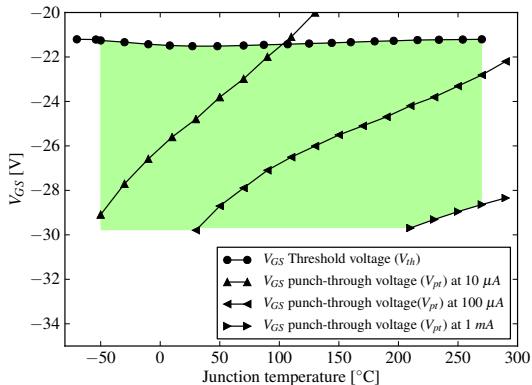
V_{GS} is limited by punch-through

- ▶ Depends on current capability of the driver

To block the JFET we need

- ▶ $V_{GS} < V_{th}$

No damage observed on the JFET, even for $I_G > 10\text{ mA}$



A driver that can source 1 mA continuously ensures safe turning off up to very high temperature, with a wide V_{GS} margin

Introduction

Selection of Power Devices

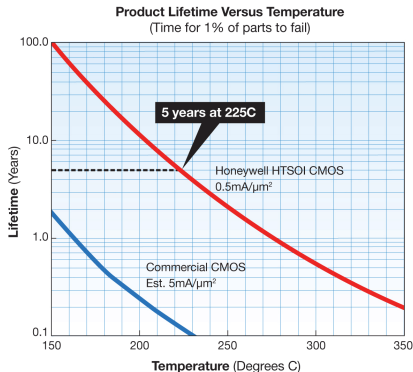
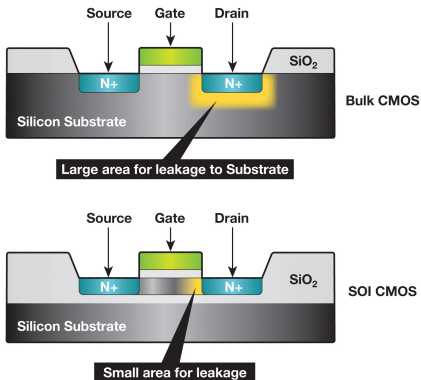
Custom Gate Drive

Prototype and Test Setup

Results

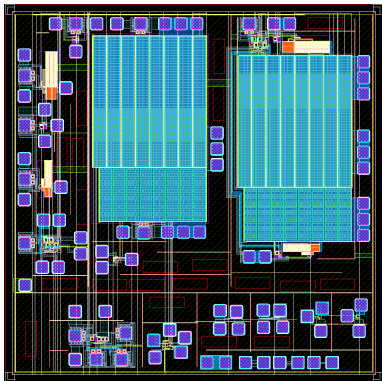
Conclusion

Silicon on Insulator (SOI) is an established technology, which can be used for high temperature electronics:



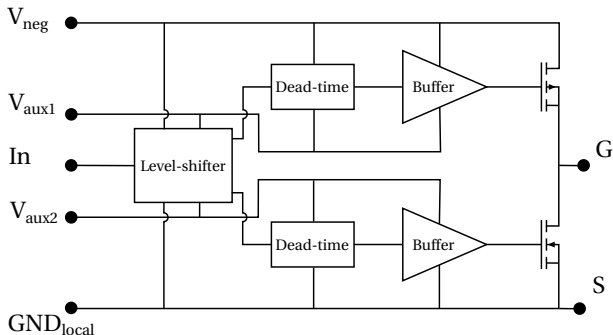
Honeywell ("Extreme Design: Developing integrated circuits for -55 degC to +250 °C", nov 2008)

Design of the Gate Driver



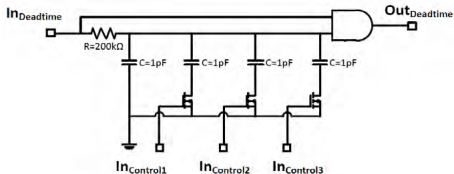
- ▶ Driving requirements for SiCED JFETs:
 - ▶ On: 0 V
 - ▶ Off: ≈ -24 V with 1 mA quiescent and ≈ 1 A peak
- ▶ Commercial IGBT drivers can't be used
- ▶ Chosen technology: Smartis-1 (ATMEL):
 - ▶ 0.8 μm Bipolar-CMOS
 - ▶ Partially-depleted SOI
 - ▶ 3 AlSiCu metal layers
 - ▶ Ti/AlSiCu/TiN interconnects

Driver IC



- ▶ Functions: input signal conditioning, dead time, push-pull output
- ▶ Other blocks (UVLO, short circuit protection. . .) are not used here
- ▶ No external insulation provided for power supply and driving signal

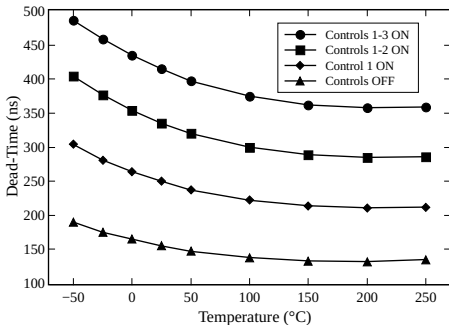
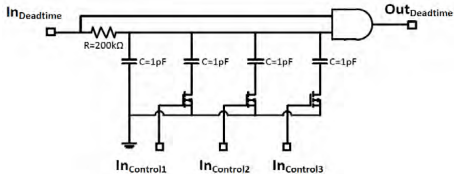
Dead-time generation



- ▶ Delay generation uses RC networks
- ▶ Delay can be adjusted by using 1..4 capacitors
- ▶ Use of a Negative Temperature Coefficient resistor to oppose the increase in resistance with temperature

Example of Function Design for Wide Temp. Range

Dead-time generation



- ▶ Delay generation uses RC networks
- ▶ Delay can be adjusted by using 1..4 capacitors
- ▶ Use of a Negative Temperature Coefficient resistor to oppose the increase in resistance with temperature

Introduction

Selection of Power Devices

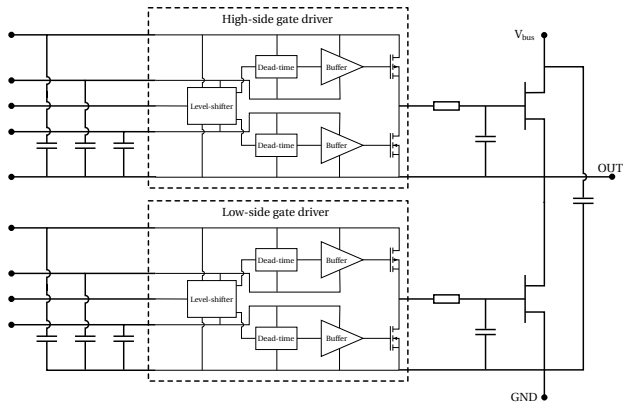
Custom Gate Drive

Prototype and Test Setup

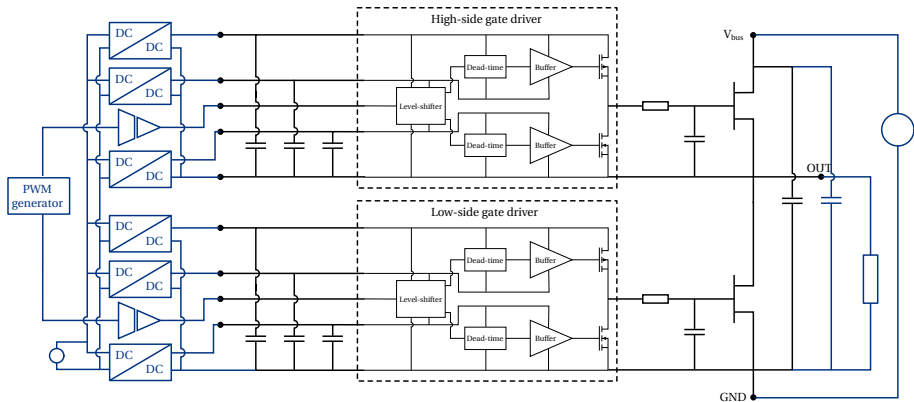
Results

Conclusion

What's Inside and What's Not?

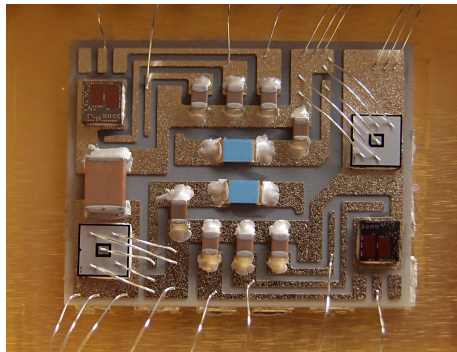
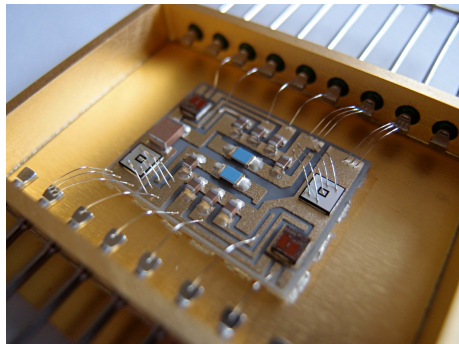


What's Inside and What's Not?



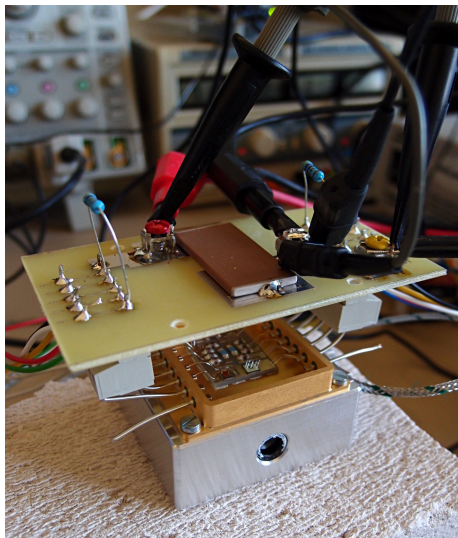
- ▶ Isolation functions (signal and power)
- ▶ PWM signal generation
- ▶ Large value decoupling capacitor (1 μF)

Pictures of the power module



- ▶ CuMo leadframe / NiFe frame case
- ▶ ceramic substrate (AlN) $\approx 20 \times 30 \text{ mm}^2$
- ▶ high temperature passives (Vishay, Presidio)
- ▶ Al wedge Wirebonds, except Au ball for driver
- ▶ Bonding: silver sintering

The Test Setup



No encapsulation used

→ V_{DC} limited to 200 V

Power module attached to a hotplate

→ test from ambient to 315°C

External components at room temp.

→ signal and power isolation

→ large DC capacitor

Continuous operation on resistor

Introduction

Selection of Power Devices

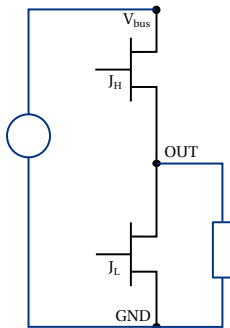
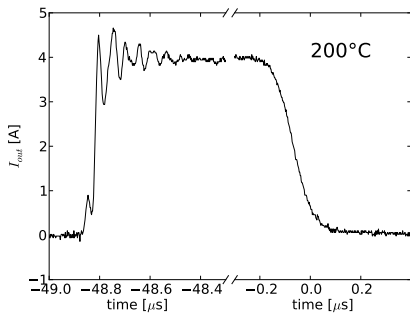
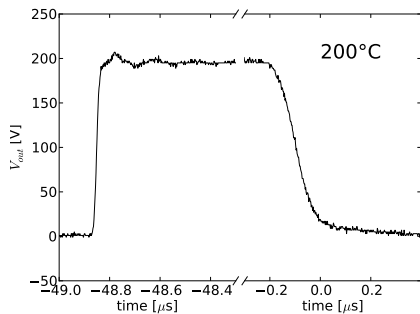
Custom Gate Drive

Prototype and Test Setup

Results

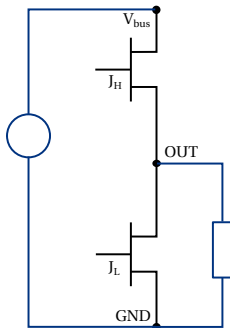
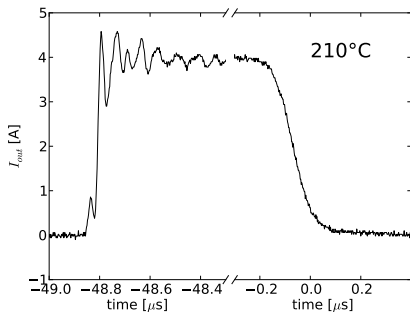
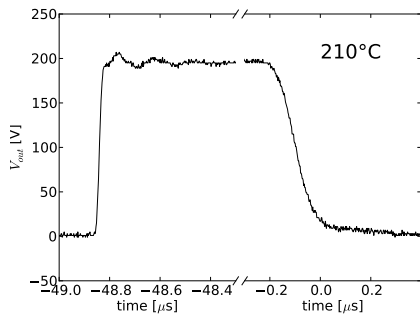
Conclusion

Measurements



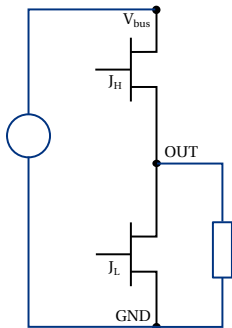
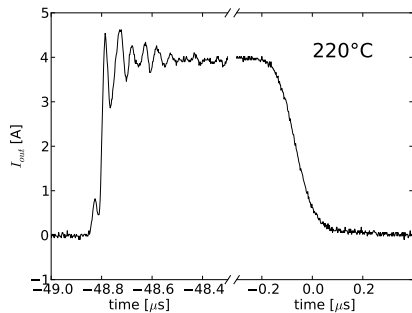
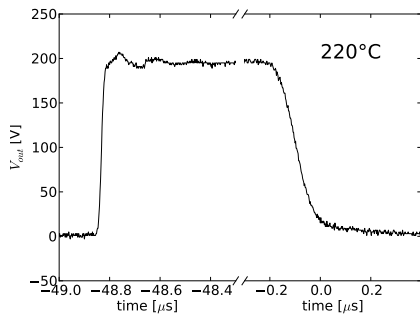
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



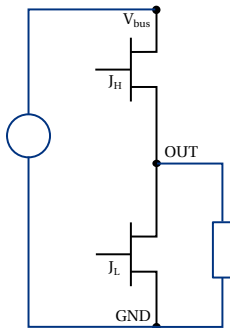
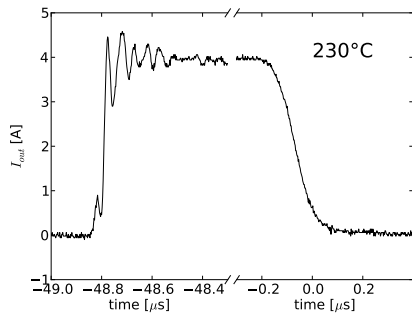
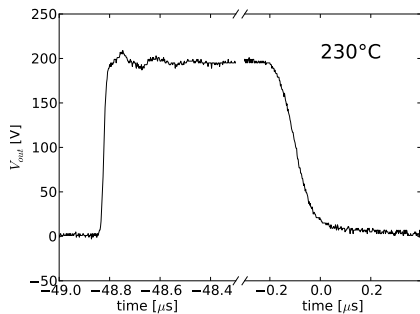
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



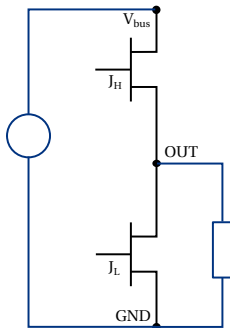
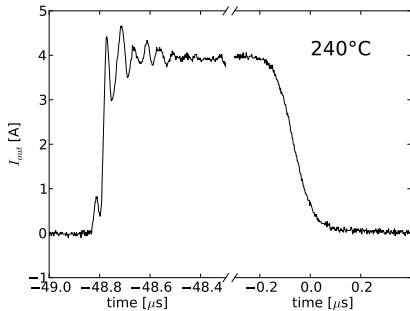
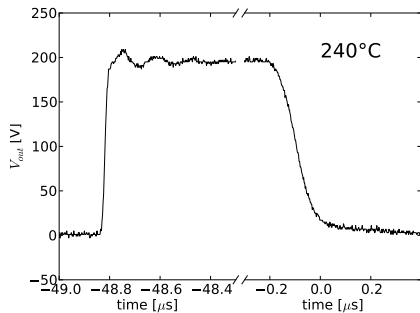
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



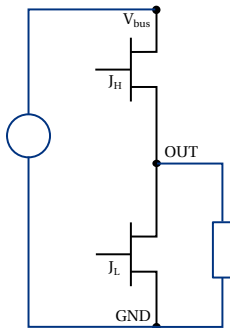
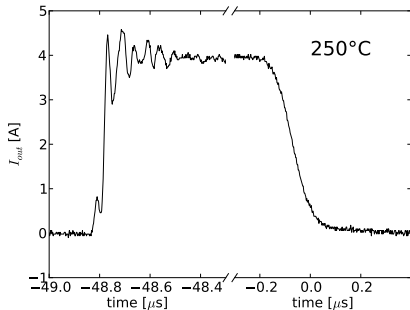
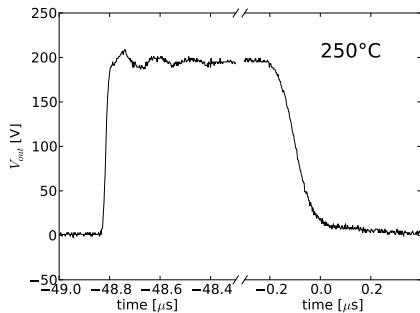
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



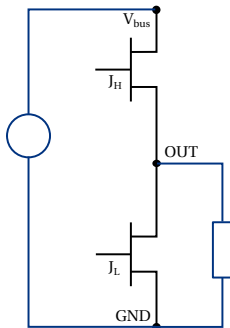
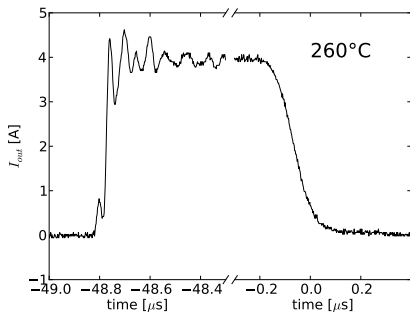
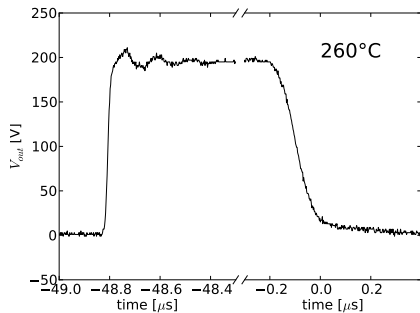
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



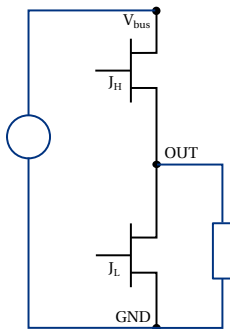
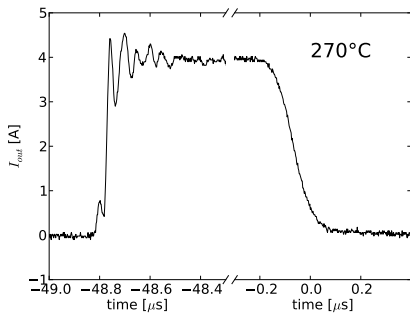
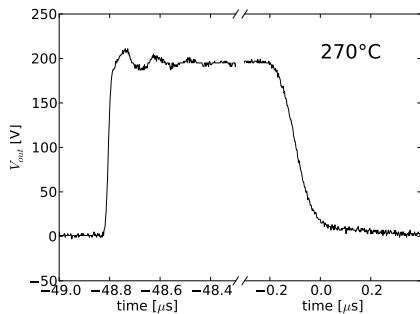
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



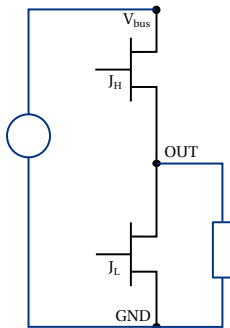
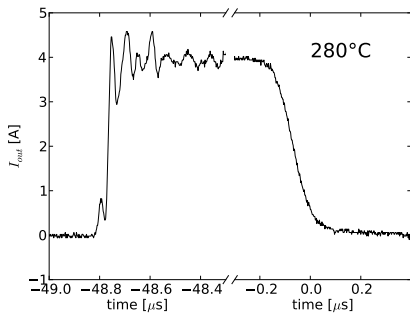
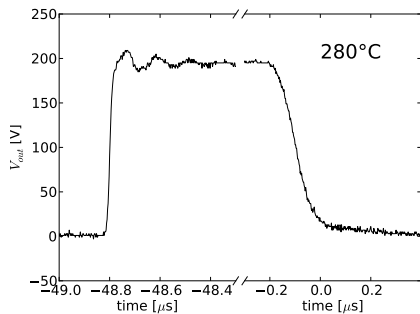
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



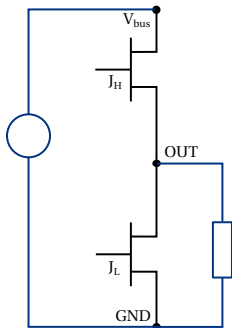
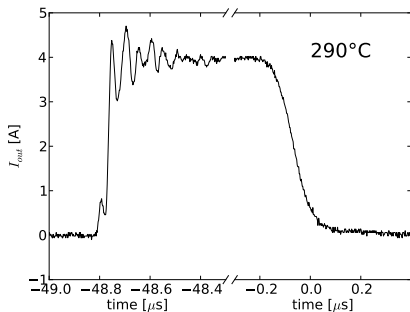
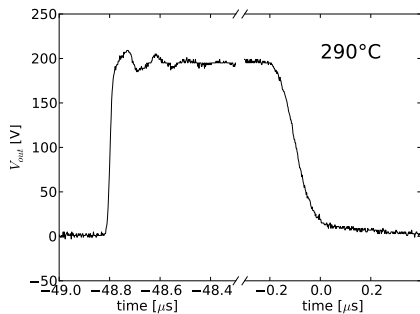
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



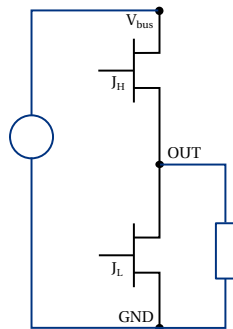
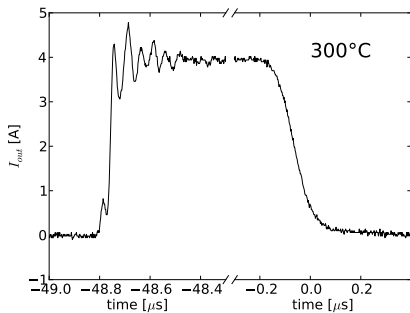
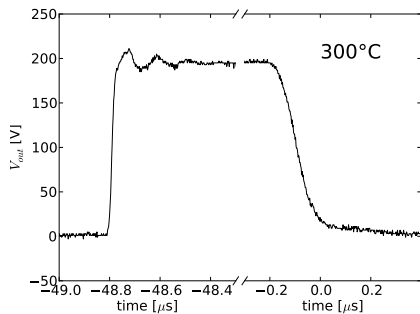
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



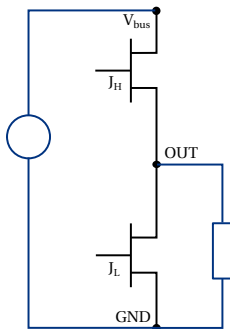
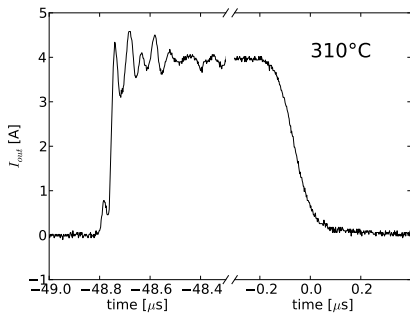
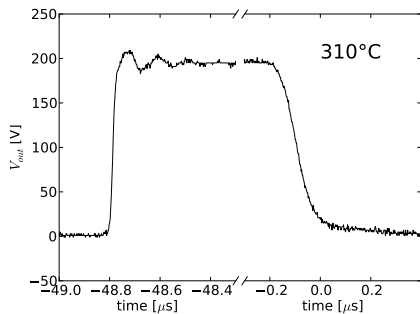
- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Measurements



- ▶ $V_{DC} = 200 \text{ V}$ (no encapsulation)
- ▶ $R_{load} = 50 \Omega$
- ▶ $F_{switch} = 10 \text{ kHz}$
- ▶ $t_{dead-time} = 1.2 \mu\text{s}$

Summary of the Results

- ▶ The module stopped working at 315°C
 - ▶ Operation resumed once the temperature was reduced
- ▶ “Clean” waveforms
 - ▶ Fast turn-on (≈ 15 ns)
 - ▶ Slow turn-off due to large dead-time and resistive load
- ▶ Test at limited power:
 - ▶ 200 V (target 540 V bus)
 - ▶ 4 A peak (target ≈ 10 A at 200°C ambient)
- ▶ No sign of damage, change in color

Summary of the Results

- ▶ The module stopped working at 315°C
 - ▶ Operation resumed once the temperature was reduced
- ▶ “Clean” waveforms
 - ▶ Fast turn-on (≈ 15 ns)
 - ▶ Slow turn-off due to large dead-time and resistive load
- ▶ Test at limited power:
 - ▶ 200 V (target 540 V bus)
 - ▶ 4 A peak (target ≈ 10 A at 200°C ambient)
- ▶ No sign of damage, change in color

Summary of the Results

- ▶ The module stopped working at 315°C
 - ▶ Operation resumed once the temperature was reduced
- ▶ “Clean” waveforms
 - ▶ Fast turn-on (≈ 15 ns)
 - ▶ Slow turn-off due to large dead-time and resistive load
- ▶ Test at limited power:
 - ▶ 200 V (target 540 V bus)
 - ▶ 4 A peak (target ≈ 10 A at 200°C ambient)
- ▶ No sign of damage, change in color

Summary of the Results

- ▶ The module stopped working at 315°C
 - ▶ Operation resumed once the temperature was reduced
- ▶ “Clean” waveforms
 - ▶ Fast turn-on (≈ 15 ns)
 - ▶ Slow turn-off due to large dead-time and resistive load
- ▶ Test at limited power:
 - ▶ 200 V (target 540 V bus)
 - ▶ 4 A peak (target ≈ 10 A at 200°C ambient)
- ▶ No sign of damage, change in color

Introduction

Selection of Power Devices

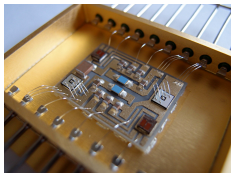
Custom Gate Drive

Prototype and Test Setup

Results

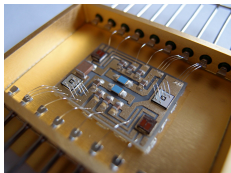
Conclusion

Conclusion



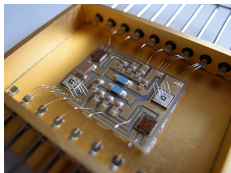
- ▶ Inverter leg with integrated gate drive and passives
 - ▶ Based on SiC JFETs
 - ▶ Using custom-designed driver IC
- ▶ Short term operation demonstrated up to 310 °C
 - ▶ Fast and "clean" waveforms due to proximity with gate drive and decoupling capacitor
 - ▶ Derating to 200 V
- ▶ Nearest temperature limits
 - ▶ Capacitors (260 °C-rated capacitors available)
 - ▶ Silicone Gel (250 °C-rated, but ages very quickly)

Conclusion



- ▶ Inverter leg with integrated gate drive and passives
 - ▶ Based on SiC JFETs
 - ▶ Using custom-designed driver IC
- ▶ Short term operation demonstrated up to 310 °C
 - ▶ Fast and “clean” waveforms due to proximity with gate drive and decoupling capacitor
 - ▶ Derating to 200 V
- ▶ Nearest temperature limits
 - ▶ Capacitors (250 °C-rated capacitors available)
 - ▶ Silicone Gel (250 °C-rated, but ages very quickly)

Conclusion



- ▶ Inverter leg with integrated gate drive and passives
 - ▶ Based on SiC JFETs
 - ▶ Using custom-designed driver IC
- ▶ Short term operation demonstrated up to 310 °C
 - ▶ Fast and “clean” waveforms due to proximity with gate drive and decoupling capacitor
 - ▶ Derating to 200 V
- ▶ Nearest temperature limits
 - ▶ Capacitors (260 °C-rated capacitors available)
 - ▶ Silicone Gel (250 °C-rated, but ages very quickly)

What's Next?

Choice of encapsulation scheme

- ▶ Hermetic sealing
- ▶ Silicone
- ▶ Parylene HT

Integration of signal & power isolation

- ▶ Development of high temperature transformers
- ▶ HT converters and signal conditioning

Actuator Integration

- ▶ Development of a complete 3-phase inverter
- ▶ Direct attachment to a high temperature motor

Thank you for your attention,

cyril.buttay@insa-lyon.fr



- ▶ picture of the Airbus A350: airbus
- ▶ picture of the thrust reverser: Hispano-Suiza
<http://www.hispano-suiza-sa.com/spip.php?rubrique48>