Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Power Electronic Systems Laboratory

Novel Gate Driver for Normally-off SiC JFET and General High Temperature SiC Converter Technology

Benjamin Wrzecionko, Dominik Bortis and Johann W. Kolar
Power Electronic Systems Laboratory, ETH Zurich, Switzerland
www.pes.ee.ethz.ch

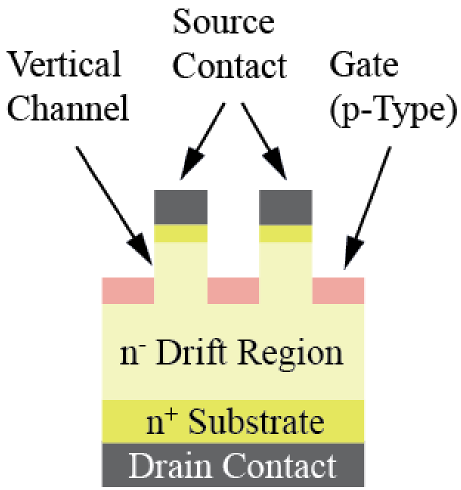
Outline

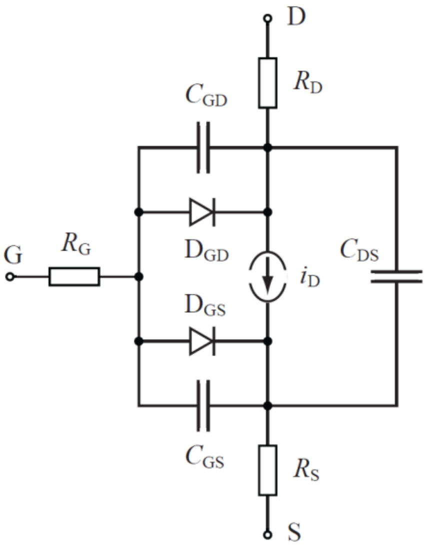
- **Novel Gate Driver for Normally-off SiC JFET**
  - SiC normally-off 1200 V JFET
  - Existing Gate Driver Concepts
  - Novel Gate Driver
  - Experimental Results

- **General High Temperature SiC Converter Technology**
  - High Ambient Temperature Inverter System
  - High Temperature Current Measurement
  - High Temperature Fan

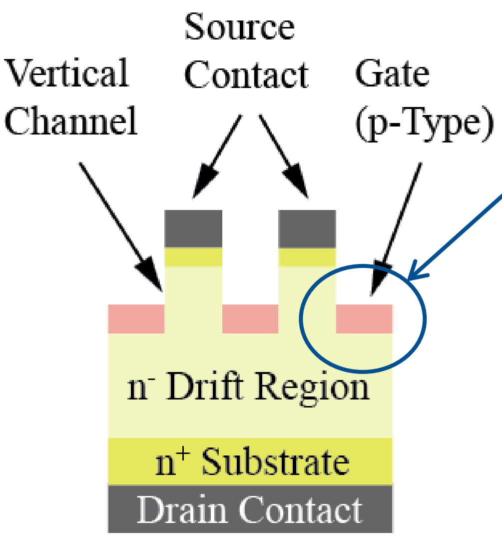
SiC Normally-off JFET

SiC Normally-off JFET (SemiSouth)	
$V_{DS,BD}$	1200 V
$I_{D,cont}$	30 A
$R_{DS,on}$	50 mΩ
A_{chip}	9 mm²





Specific Gate Driver Requirements – On-State



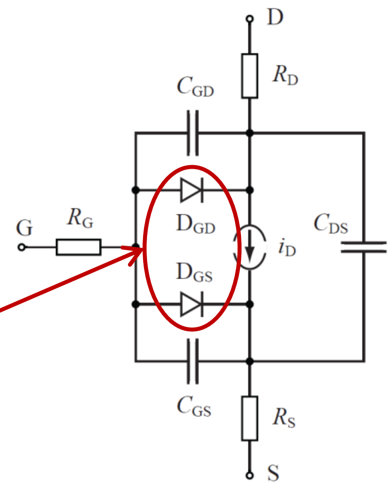
pn-junction

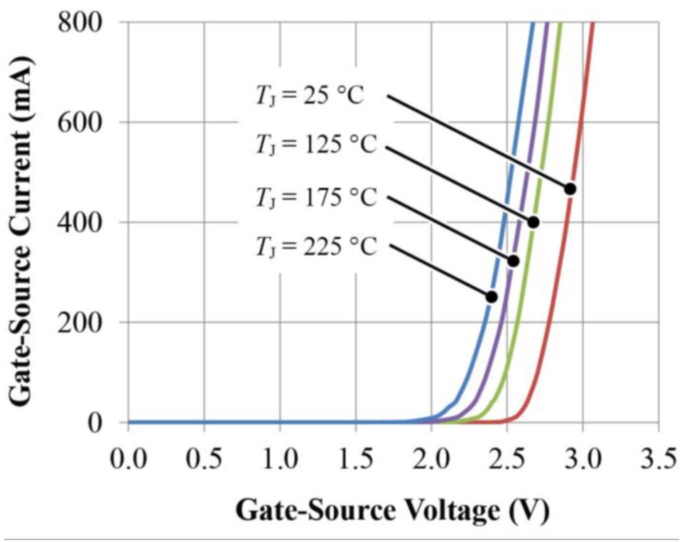
⇩

SiC diodes
at the gate

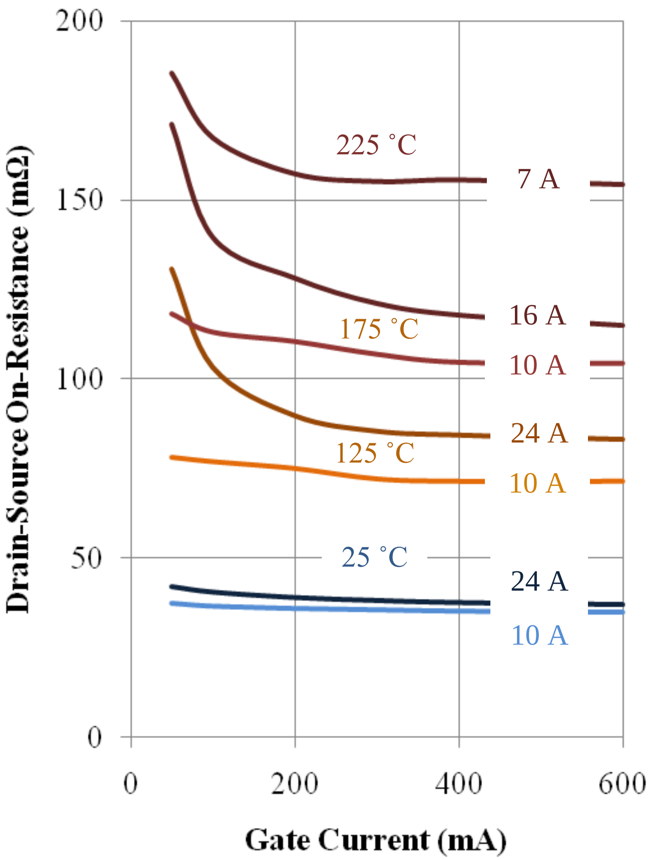
⇩

Operated in
forward direction
during on-state



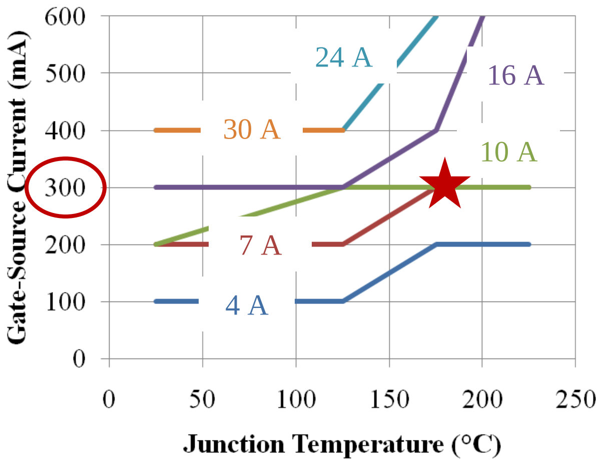


Specific Gate Driver Requirements – On-State

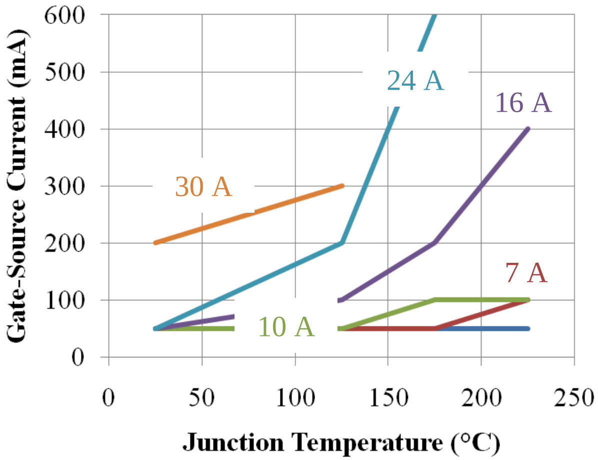


Actual Choice:
I_G = 300 mA
V_{GS} = 2.5 V

$I_{G,min}$ for $R_{on,min}$

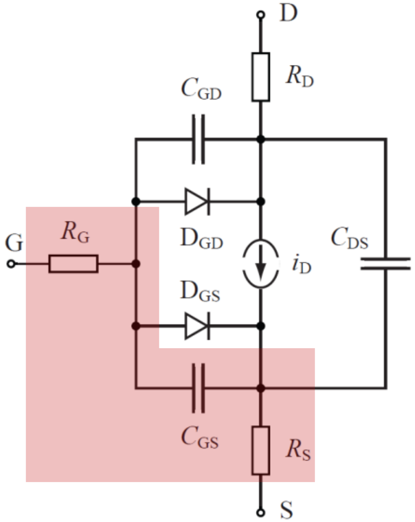


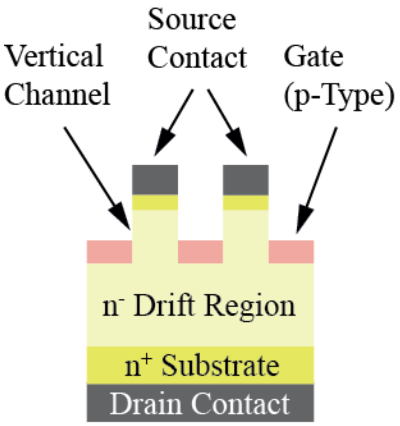
$I_{G,min}$ for $1.1 \cdot R_{on,min}$



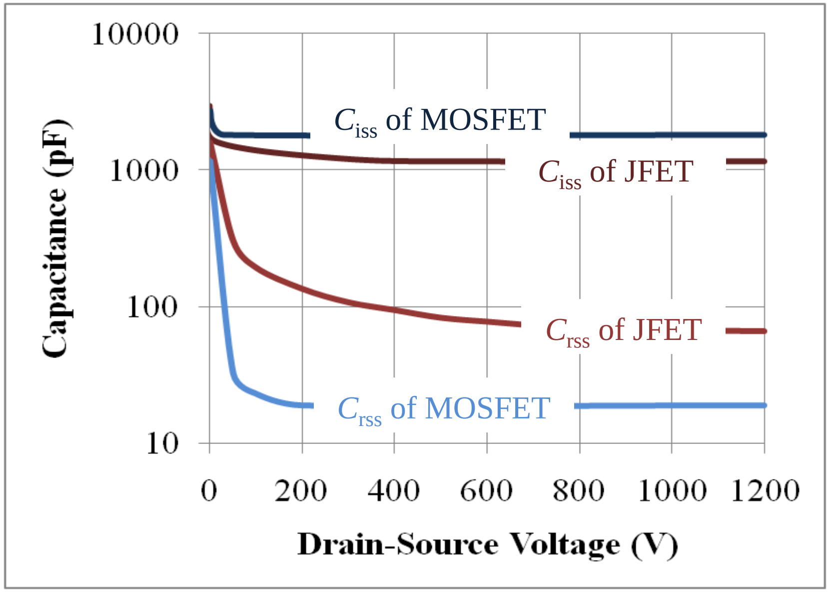
Specific Gate Driver Requirements – Switching

- Turn-on and -off: ±15 V for fast charging of $R_{GS}C_{GS}$-circuit
- C_{GD} is up to a factor of 10 higher for the JFET





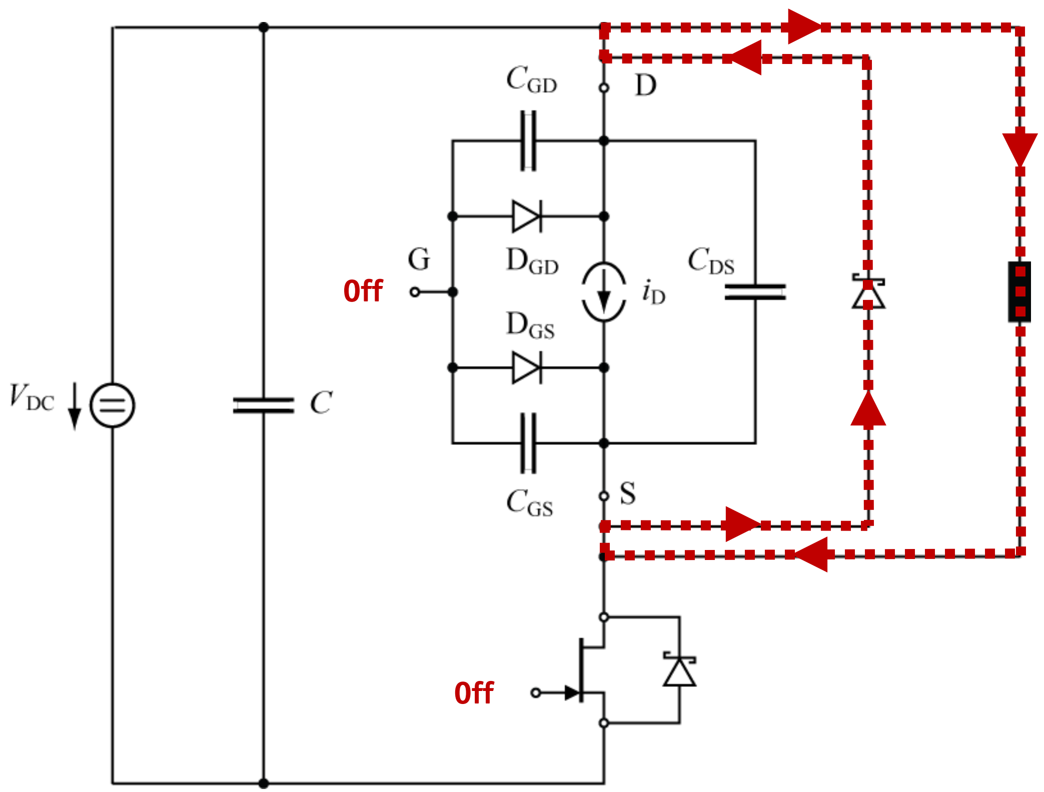
SiC JFET vs. SiC MOSFET (1200V, 20 A @ 175 ˚C)



Specific Gate Driver Requirements – Off-State

- High C_{GD} reinforces the Miller-Effect

Current Freewheeling in high side diode **Turn-on of low side switch**

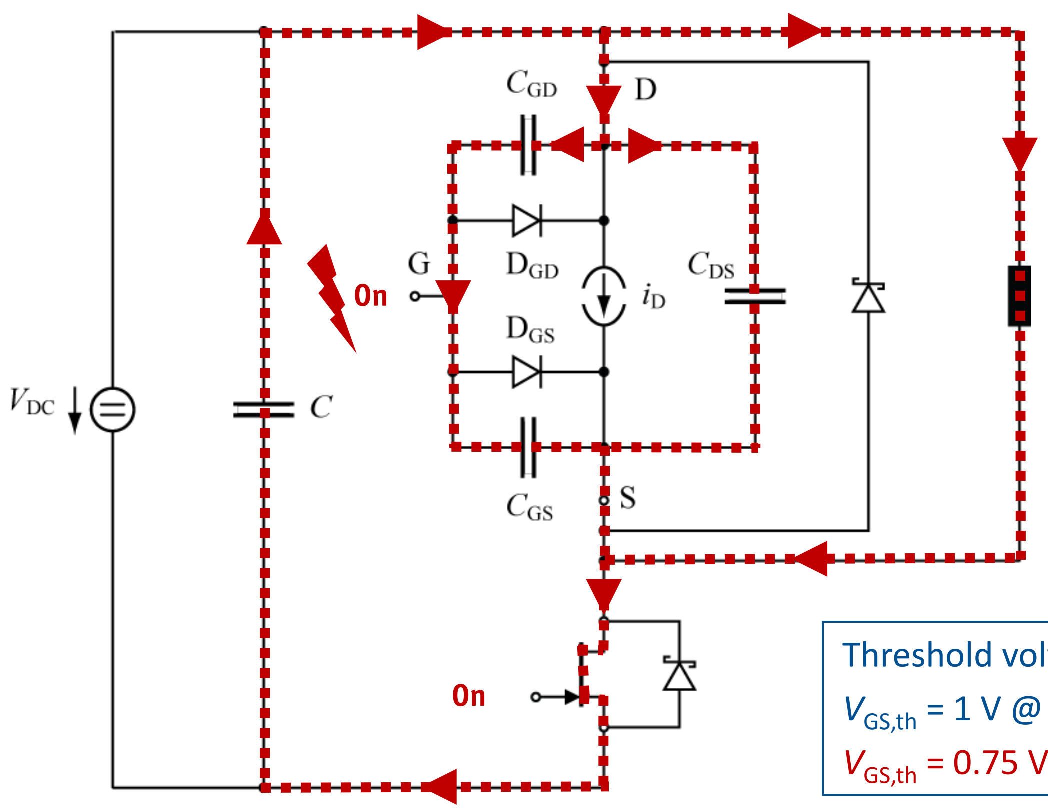


Specific Gate Driver Requirements – Off-State

- High C_{GD} reinforces the Miller-Effect

Current Freewheeling in high side diode

Turn-on off low side switch



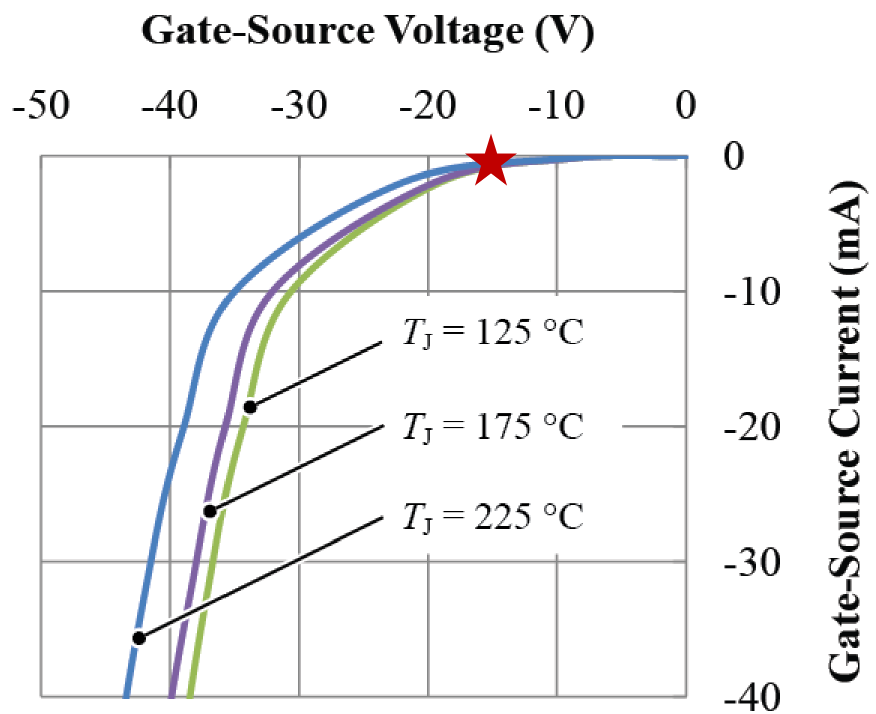
Threshold voltage:

$V_{GS,th}$ = 1 V @ 25 ˚C

$V_{GS,th}$ = 0.75 V @ 175 ˚C

Specific Gate Driver Requirements – Off-State

- Low $V_{GS,th}$ requires negative bias
- Limited to - 15 V due to leakage currents (2 mA)

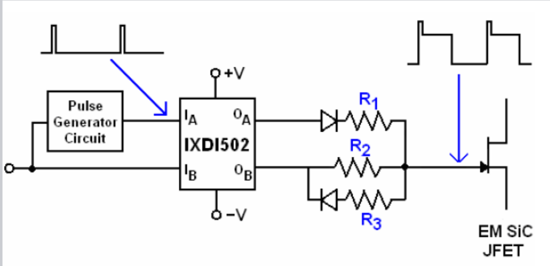


Specific Gate Driver Requirements – Summary

- Voltage and current levels:
  - Turn-on: V_{GS} = +15 V
  - Turn-off: V_{GS} = -15 V
  - Off-state: V_{GS} = -15 V (during converter operation) and fast removal of Miller charge
  - On-state: I_G = 300 mA, V_{GS} = 2.5 V for I_D = 10 A @ 175 ˚C
    - I_G = 100 mA for 10% higher $R_{DS,on}$
- Standard requirements:
  - Wide operating frequency range
  - Arbitrary duty cycles
  - Conventional control with 1 signal per switch
  - Low circuit complexity and cost

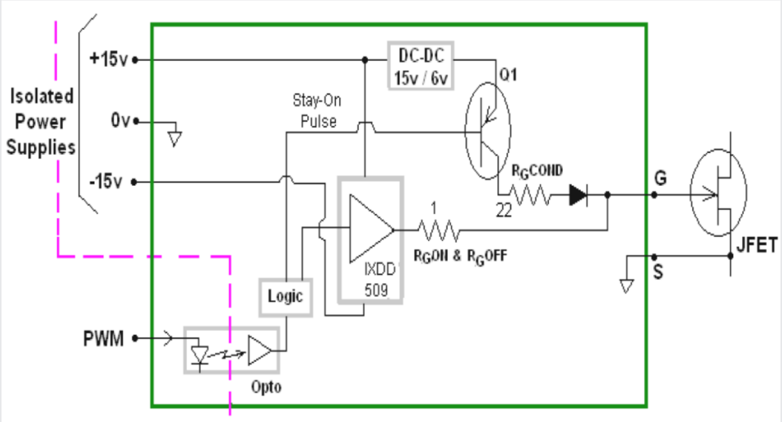
State-of-the-Art Gate Drivers

Two-stage gate drivers



1)

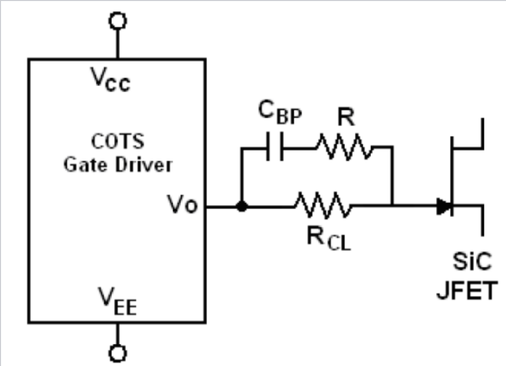
+ Required voltage and current levels
– Significant power loss in R_2 and additional IC required



2)

+ Required voltage and current levels
– Significant power loss in DC-DC conv. & additional ICs required

AC coupled gate driver



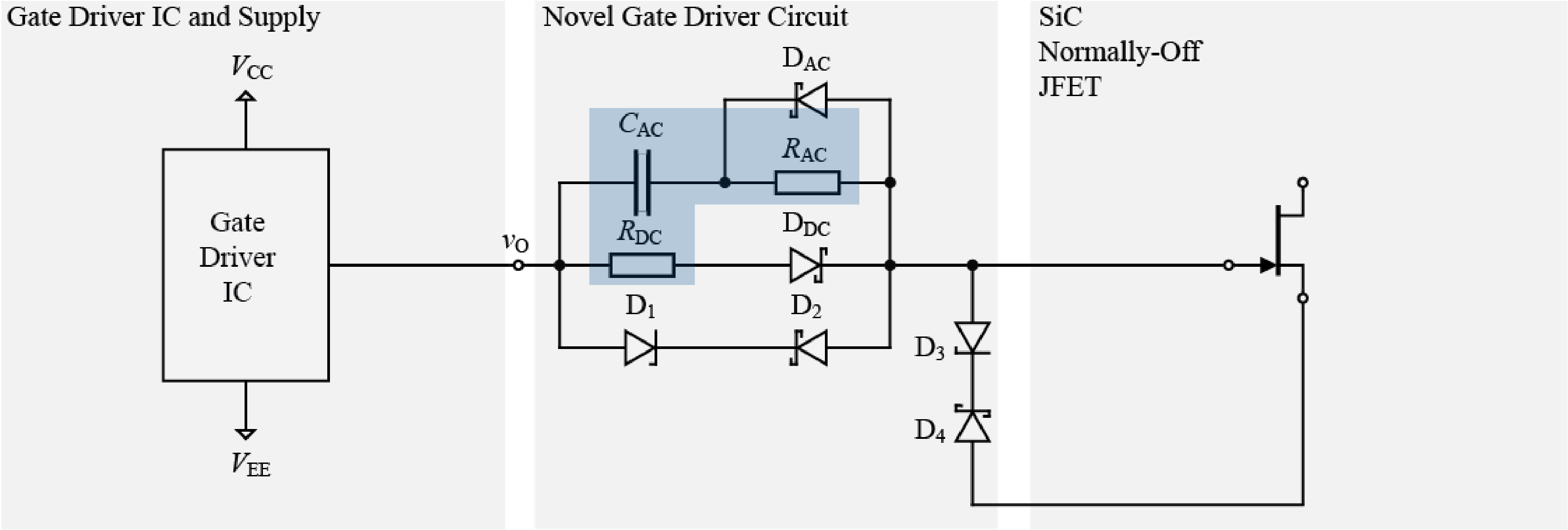
3)

+ Required voltage and current levels
– Significant power loss in R_{CL}
– No fast removal of Miller charge
– Duty cycle limitations due to discharge of C_{BP}

1) SemiSouth Laboratories, Application Note AN-SS1, 2009
2) Kelley, Improved Two-Stage DC-Coupled Gate Driver for Enhancement-Mode SiC JFET, 2010
3) SemiSouth Laboratories, Application Note AN-SS1, 2009

Novel AC Coupled Gate Driver

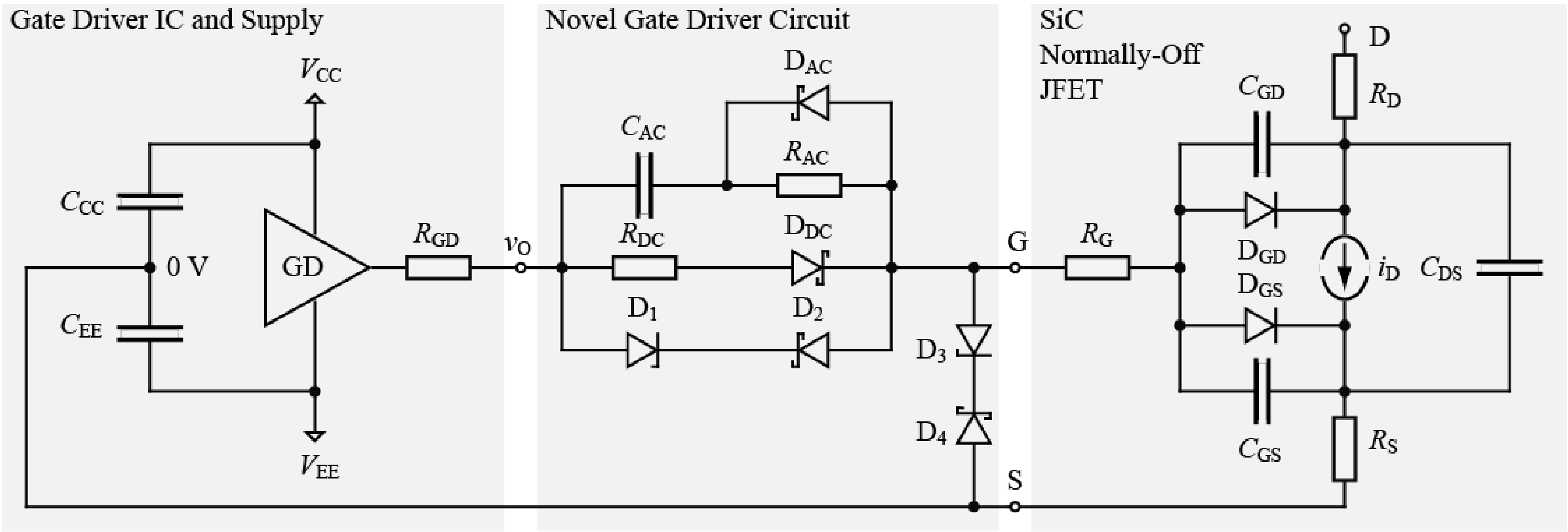
Eliminating week points of conventional AC coupled driver by:



- 2 Zener diodes and 4 Schottky diodes
- Adjustment of supply voltage levels:
  - $V_{CC} \approx 4$ V
  - $V_{EE} \approx -25$ V

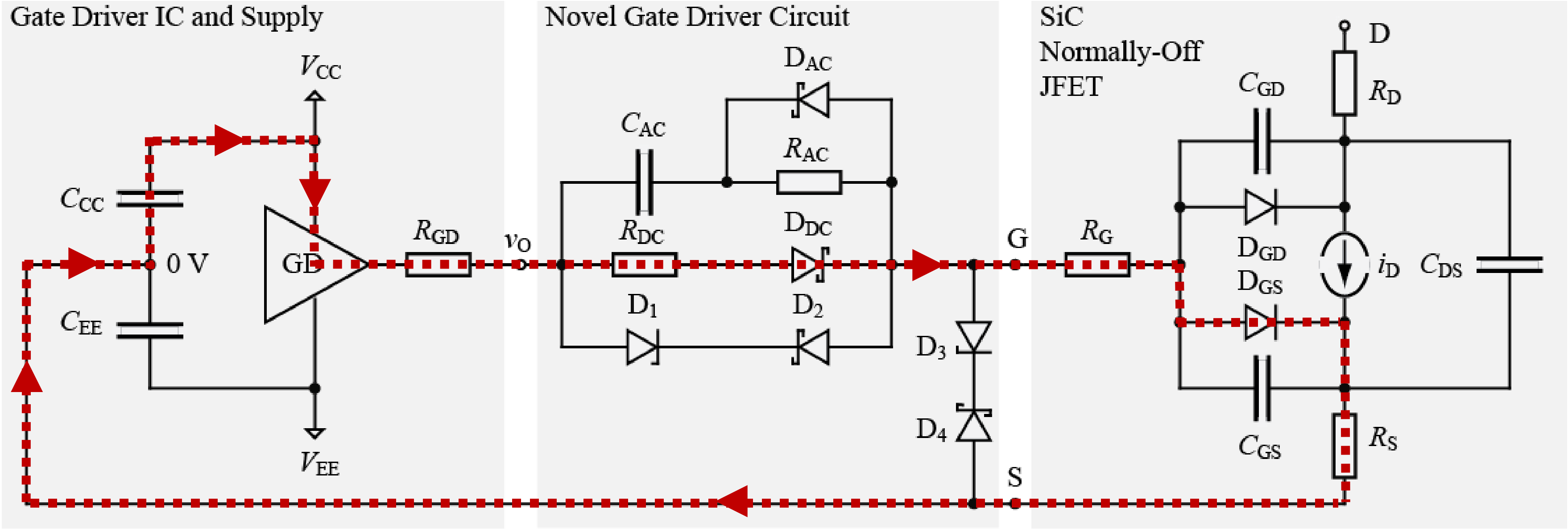
Novel AC Coupled Gate Driver – Principles of Operation

On-State Turn-off Off-State Turn-on



Novel AC Coupled Gate Driver – Principles of Operation

On-State Turn-off Off-State Turn-on

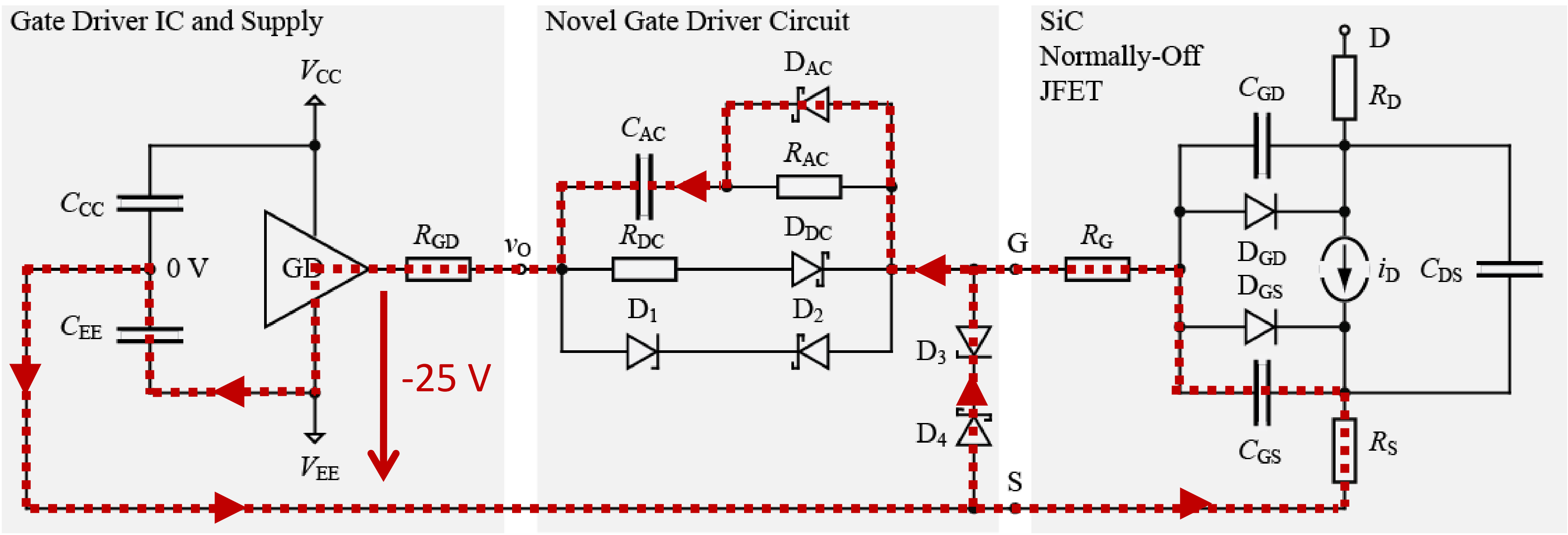


- $V_{CC} \approx 4$ V $\Rightarrow$ very small power loss in R_{DC}

$R_{GD} + R_{DC} \approx 1\ \Omega$ $V_{D,DC} \approx 0.3$ V $I_{RD,DC} \approx 3$ mA

Novel AC Coupled Gate Driver – Principles of Operation

On-State Turn-off Off-State Turn-on

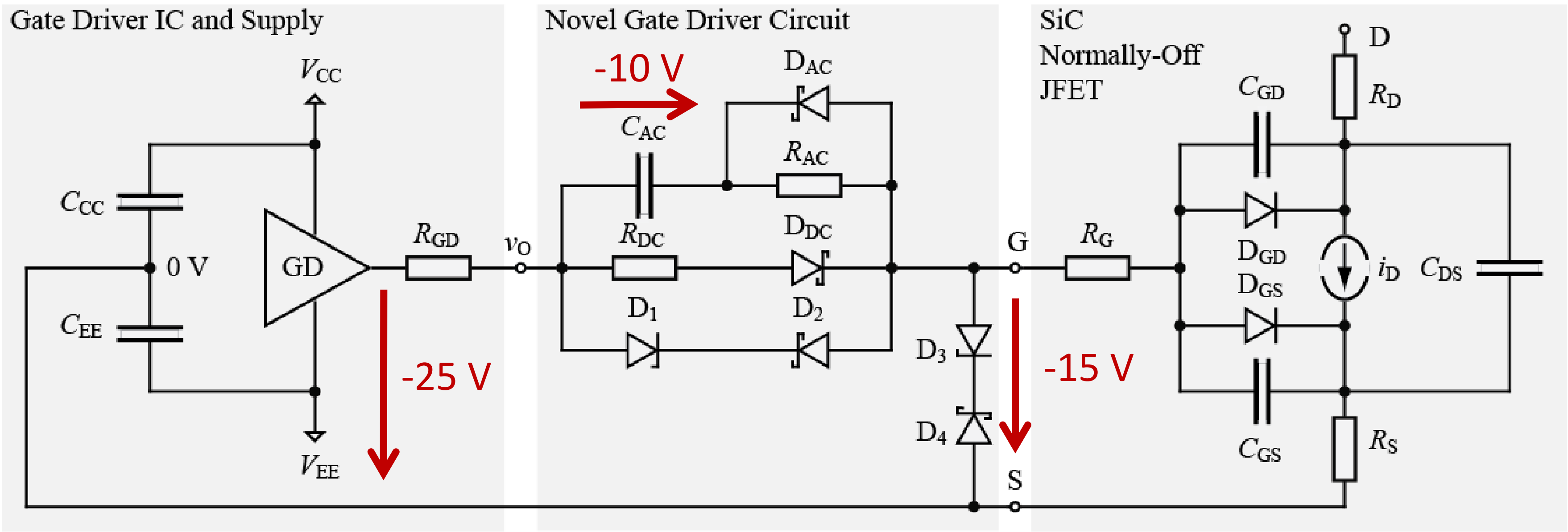


- $V_{EE} \approx$ -25 V and $V_{Z,D3} \approx$ 15 V $\Rightarrow$ C_{AC} is charged to 10 V
- Low-impedance path for charging C_{AC} $\Rightarrow$ no duty cycle limitations

$C_{AC} \approx$ 6 nF $V_{D,AC} \approx$ 0.2 V

Novel AC Coupled Gate Driver – Principles of Operation

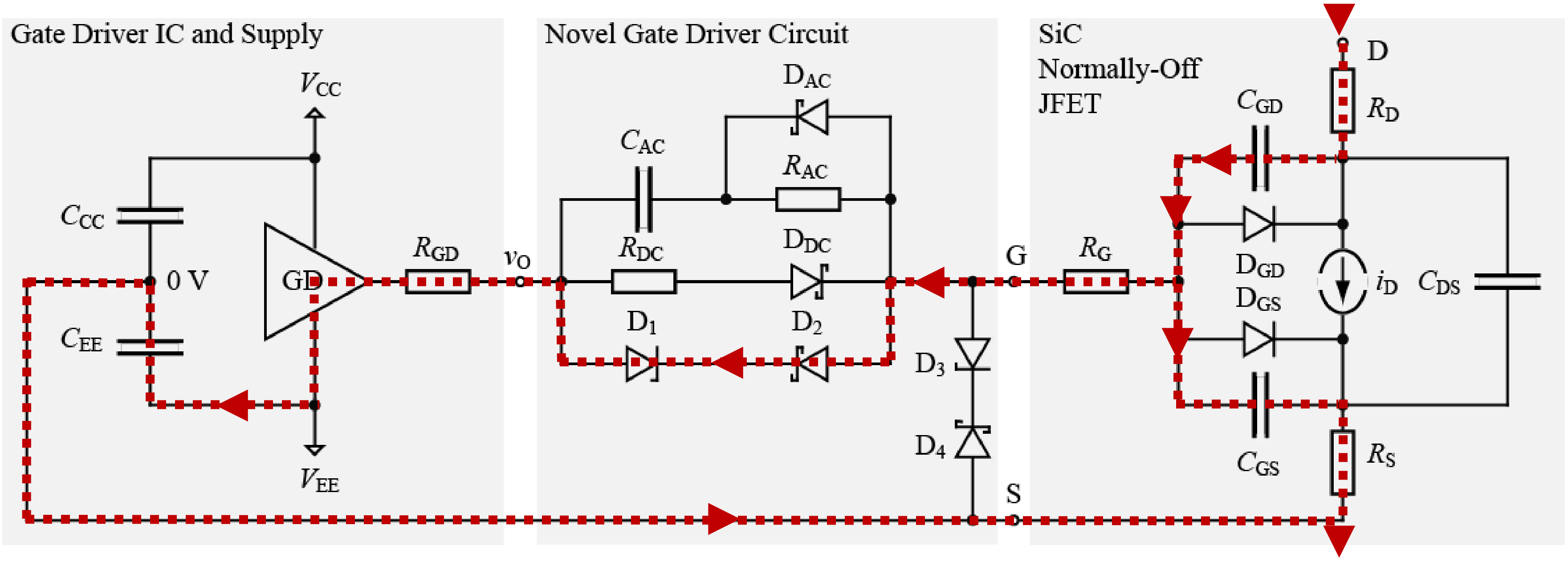
On-State | Turn-off | **Off-State** | Turn-on



- Only small leakage currents flowing

Novel AC Coupled Gate Driver – Principles of Operation

On-State | Turn-off | **Off-State** | Turn-on

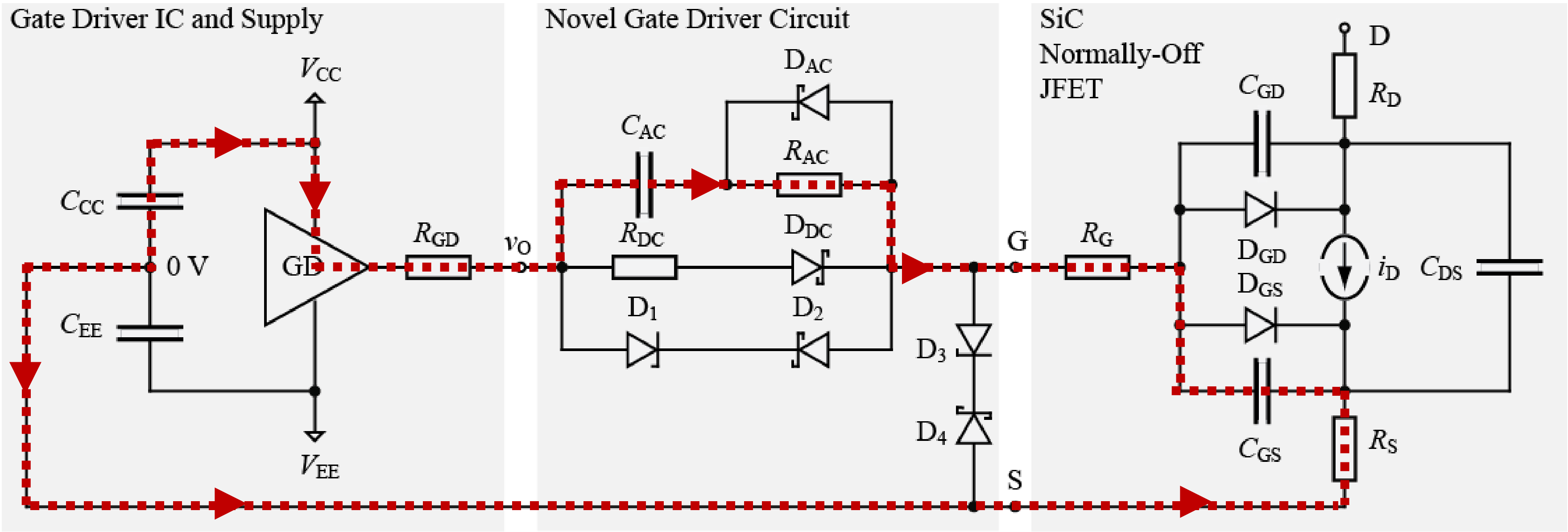


- Miller charge can flow into C_{GS} (negative bias) *and* gate driver

$V_{Z,D1} \approx 10$ V

Novel AC Coupled Gate Driver – Principles of Operation

On-State | Turn-off | Off-State | **Turn-on**

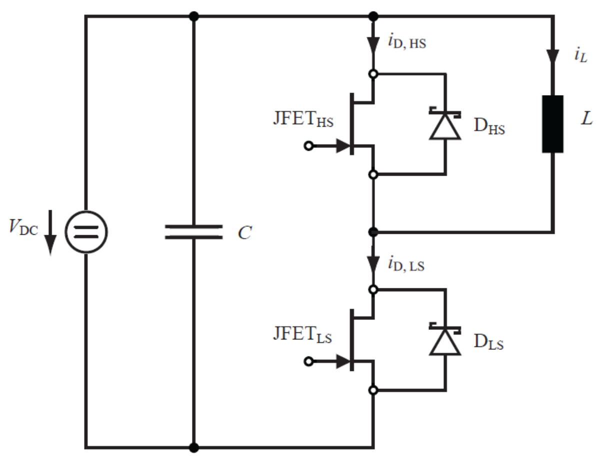


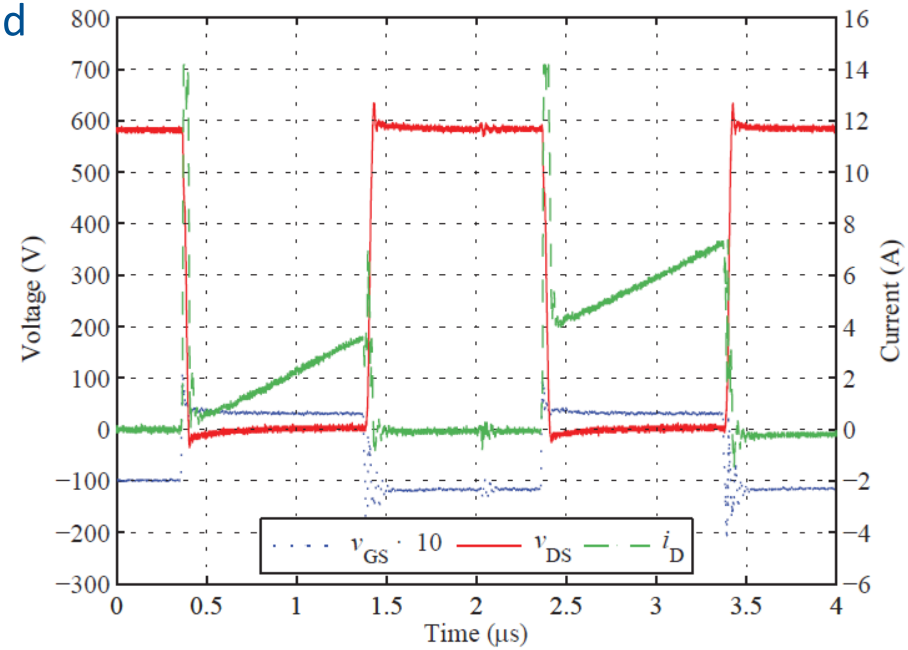
- Voltage across C_{AC} adds to V_{CC} ⇒ $V_{GS} \approx 14$ V

$C_{AC} \approx 6$ nF	$R_{AC} \approx 0\ \Omega$

Novel Gate Driver – Experimental Results

- Test setup: Half-bridge with inductive load



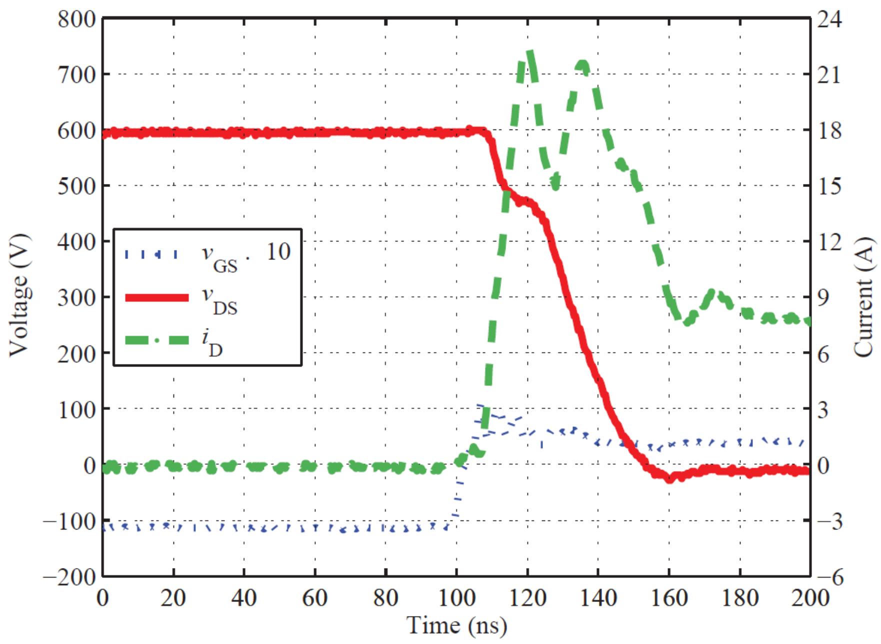


- Testing scenarios:
  - 4 chips in parallel (symmetrical setup important for balanced currents)
  - Various drain currents, faster turn-off with higher I_D
  - T_J up to 225 ˚C (30% slower turn-on at 225 ˚C)
  - Switching frequencies up to 50 kHz

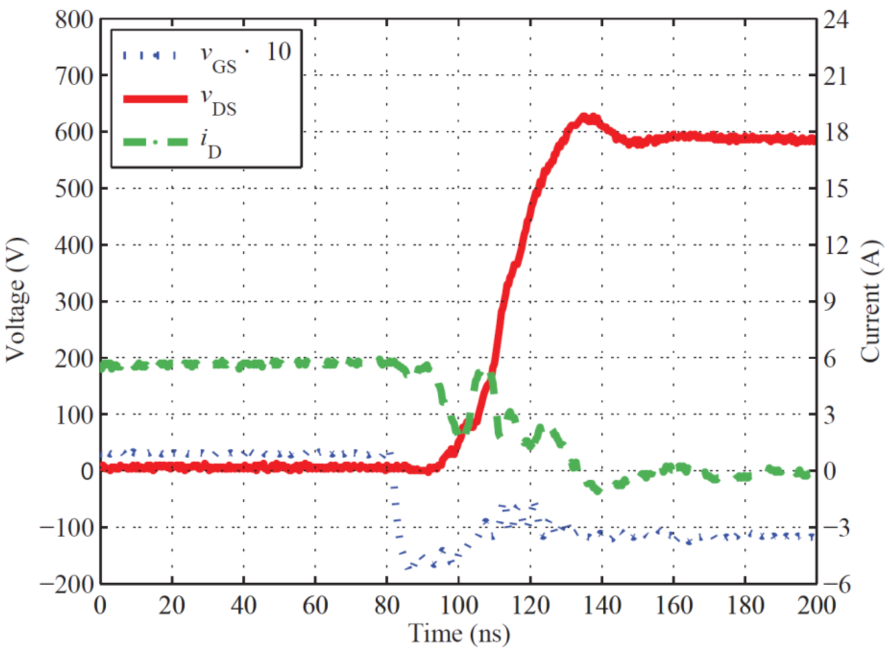
Novel Gate Driver – Switching waveforms

- Switching times for 600 V and 8 A:

Turn-on: 30 ns (20 kV/µs)

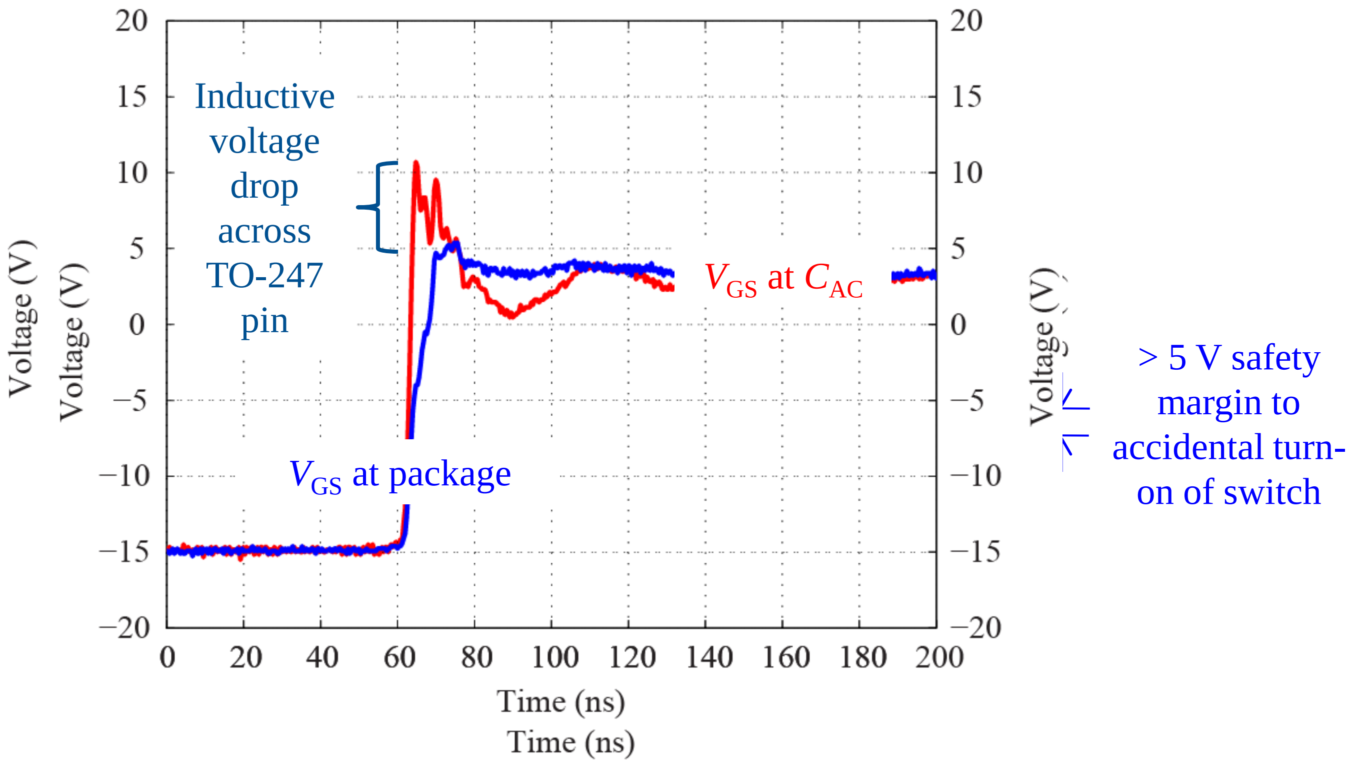


Turn-off: 20 ns (30 kV/µs)



Novel Gate Driver – Experimental Verifications

Function of C_{AC}



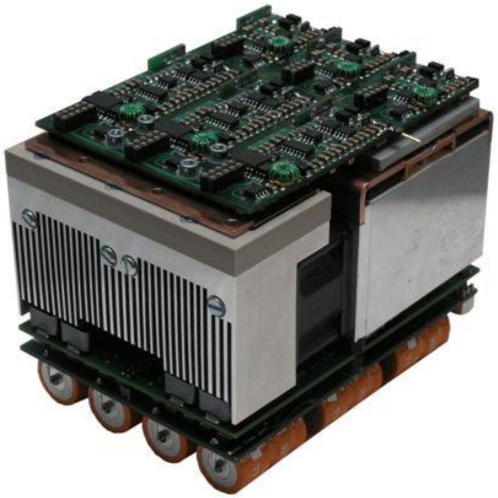
Outline

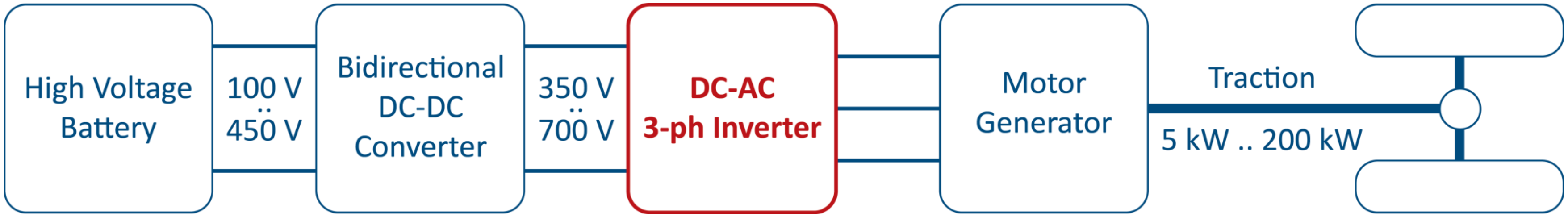
- **Novel Gate Driver for Normally-off SiC JFET**
  - **SiC normally-off 1200 V JFET**
  - **Existing Gate Driver Concepts**
  - **Novel Gate Driver**
  - **Experimental Results**
- **General High Temperature SiC Converter Technology**
  - **High Ambient Temperature Inverter System**
  - **High Temperature Current Measurement**
  - **High Temperature Fan**

High Ambient Temperature Inverter System (1/2)

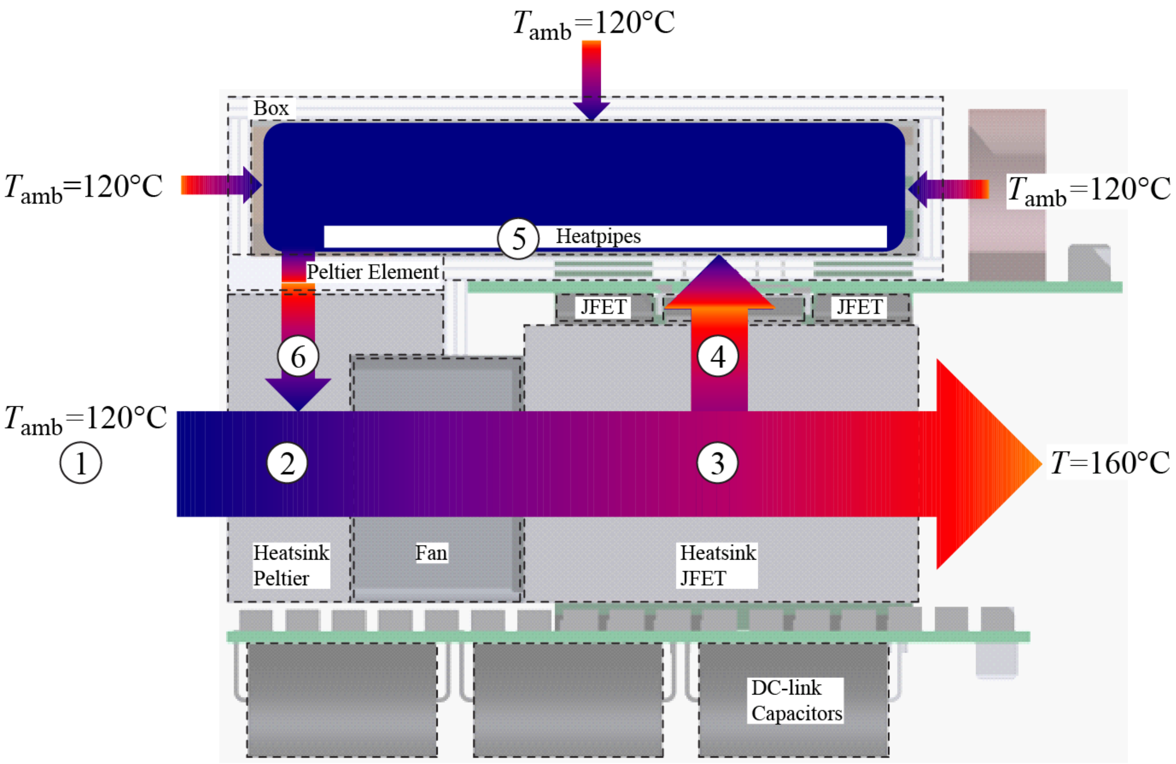
DC-AC 3-ph Inverter System Specifications:

- Ambient Temperature: T_A = 120 ˚C
- Switching frequency: f_{SW} = 50 kHz
- Output frequency: f = 1000 Hz
- Output power: P = 10 kW
- DC link voltage: V_{DC} = 700 V



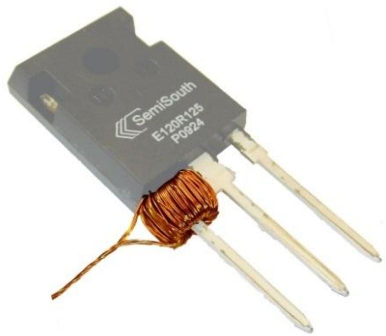


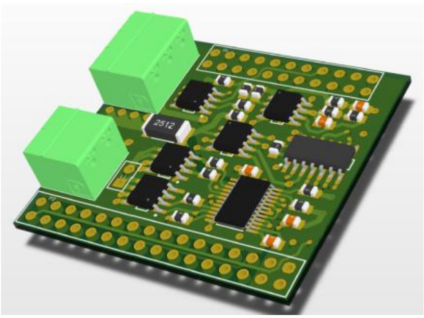
High Ambient Temperature Inverter System (2/2)

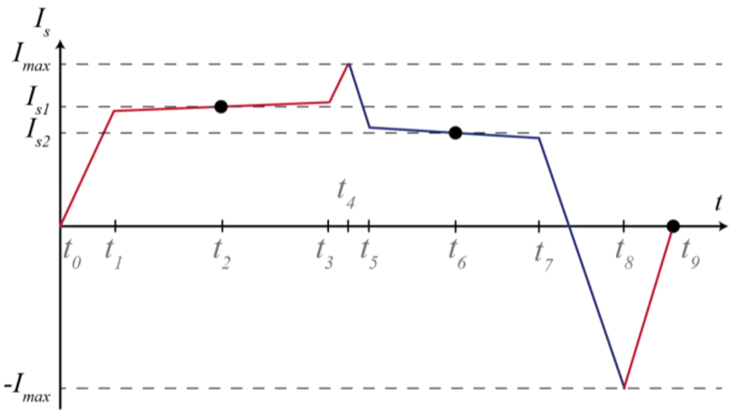


① Ambient air intake
② Peltier heat sink
③ Switches heat sink
④ Heat input to signal PCB
⑤ Horizontal heat transfer
⑥ Heat output of box by Peltier Cooler

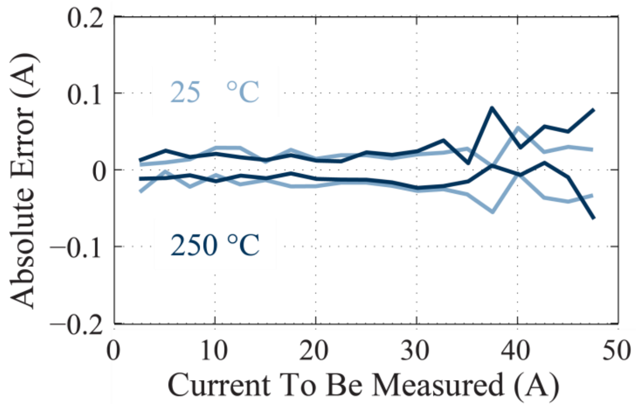
Fast High Temperature Isolated DC and AC Current Measurement





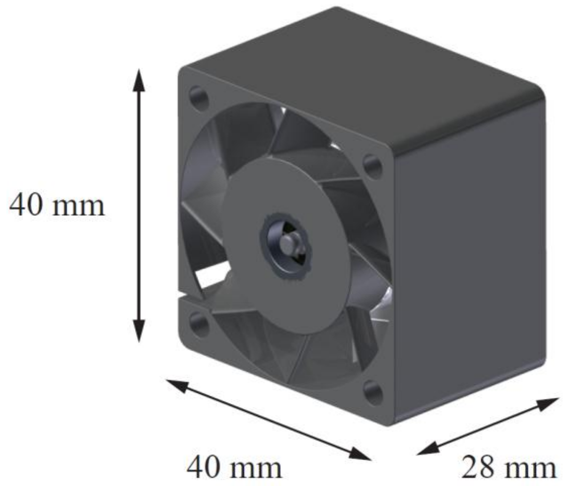


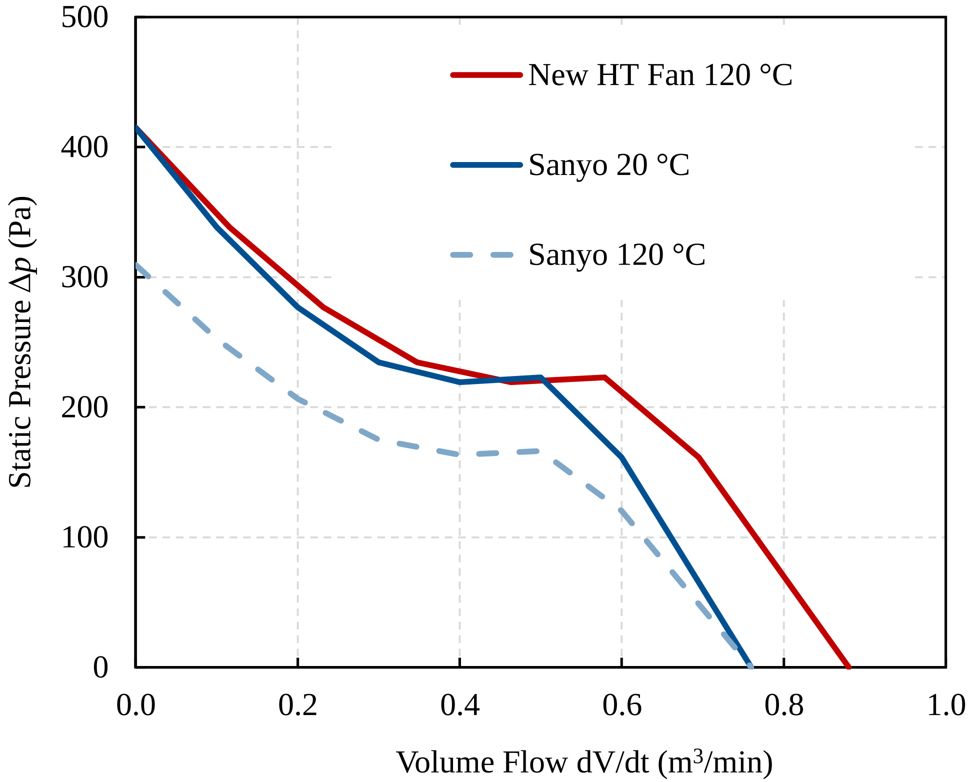
Parameter	Value	Unit
Max. T_A for Sensor	250	˚C
Max. T_A for Signal Electronics	120	˚C
Measurement Range	-50 … +50	A
Measurement Frequency	50	kHz
Max. Error	< 1	%



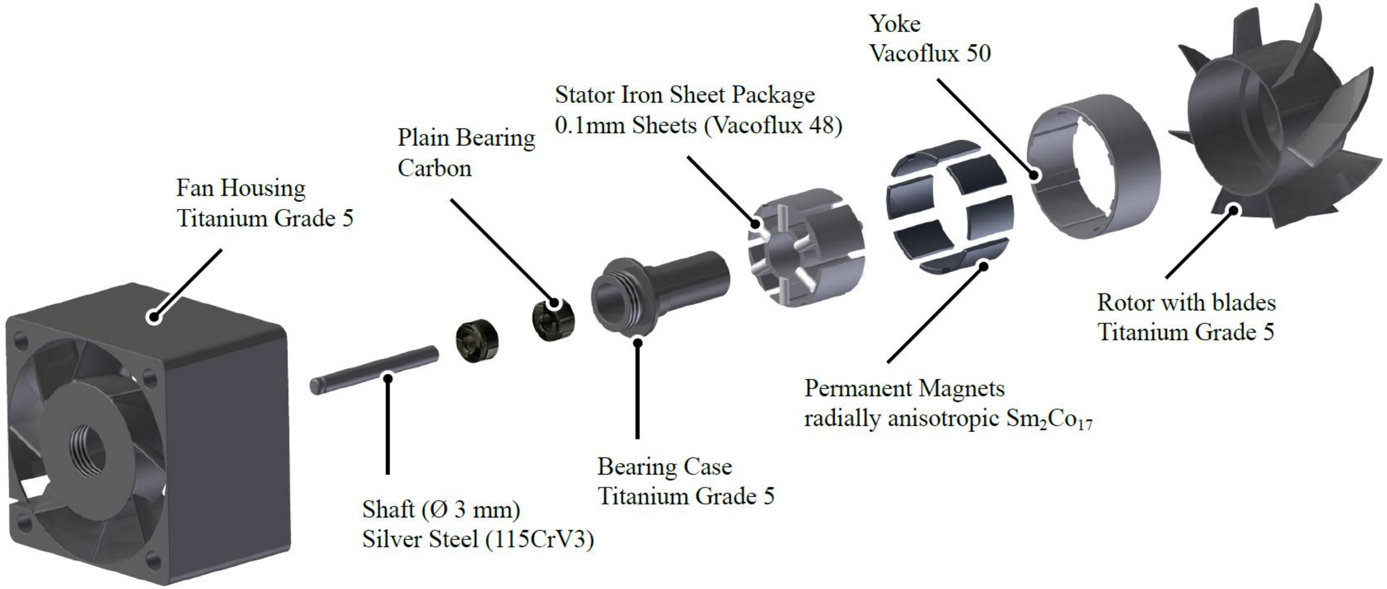
High Temperature Fan for Power Electronics Cooling (1/2)

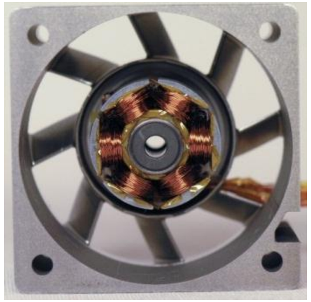
- T_{max} = 250 ˚C
- n = 19’000 rpm
- P_{in} = 15 W
- DC supply voltage: 12 V





High Temperature Fan for Power Electronics Cooling (2/2)





Summary

- **Novel Gate Driver for Normally-off SiC JFET**
  - Detailed analysis of gate driver requirements of normally-of SiC JFET
  - Evaluative comparison of gate driver concepts
  - Presentation of novel AC coupled gate driver
    - Fast switching
    - Wide operating frequency range
    - Arbitrary duty cycles
    - Low circuit complexity and cost

- **General High Temperature SiC Converter Technology**
  - 120 ˚C Ambient Temperature Inverter System
  - 250 ˚C Fast Isolated DC and AC Current Measurement up to ±50 A
  - 250 ˚C High Performance Fan for Power Electronics Cooling

Thank you for your interest.

Please ask your questions!