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Experimental Demonstration of Ultra-fast SiC MOSFET Overload Protection Using Embedded Current and Temperature Sensors

Dominique Tournier[1,a*], Thomas Vadebout[1,b], Pascal Bevilacqua[1,c], Pierre Brosselard[1,d], and Jean-François de Palma[2,e]

[1]Univ Lyon, INSA Lyon, Univ. Claude Bernard Lyon 1, Ecole Centrale Lyon, CNRS, Ampère, F-69621, France

[2]MERSEN France Angers SAS, 2, rue de Déry. 49480 Verrières en Anjou. France

[a*]dominique.tournier@insa-lyon.fr, [b]thomas.vadebout@insa-lyon.fr, [c]pascal.bevilacqua@insa-lyon.fr,[d]pierre.brosselard@insa-lyon.fr, [e]jean-francois.depalma@mersen.com

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Abstract. Fault protection of AC and DC network using semiconductors requires accurate electro-thermal design of active and passive devices to keep power losses low in nominal condition and to sustain high current overload. Using SiC MOSFET for SSPC arises challenges to keep power losses low and to ensure robustness versus abnormal operating condition. Indeed, unpredictable events can dramatically damage the device integrity such as current overload, short-circuit... To overcome those issues, ones are generally carefully design driving system, implementing sensors and fast digital control circuit computing to sense simultaneously current, voltage and temperature, to analyze and detect abnormal operating condition. To reduce the whole detection transmission and reaction chain, we have designed a 1200V ; 30A ; 65mΩ instrumented SiC MOSFET, including both a current mirror and a temperature sensor in the active area of the die. This paper reports for the first-time real-time SiC instrumented MOSFET temperature and current measurement without the need of external sensors nor estimators.

Introduction

SiC MOSFET power devices are reaching a significant level of maturity. Those devices are addressing mainstream application: eHV, conversion, protection. SiC MOSFET reliability dependance on operating mode is a great challenge [1]. To ensure the best performances, a SiC MOSFET must have the lowest on resistance value, it's threshold voltage must be kept stable within the operating temperature range, its robustness versus abnormal operating condition must be guaranty. Unpredictable events such as current overload, short-circuit, and mis-operation of cooling system can dramatically damage the device integrity. To overcome those issues, sensors and complexe fast digital control circuit are designed to sense current, voltage, and estimate junction temperature. Those monitored or evaluated signals are used to detect abnormal operating condition with respect to the system environment and the mission profile. The MOSFET gate control must then be generated within time ranges between few microseconds in case of short-circuit or several seconds accounting thermal response to moderated current overloads. Those constrains requires a high level of knowledge and modeling of both the MOSFET, its package and the environment of the power device in the converter [2].

Instrumented SiC MOSFET Description

Having sensors embedded into the die area is a great benefit to simplify both the signals sensing, conditioning [3, 4], and digital computation of a control low. To reduce the whole detection transmission and reaction chain like desaturation circuit [5], a range of 1.2kV [65mΩ, 130mΩ and 320mΩ] instrumented devices have been designed by CALY Technologies, manufactured by Clas-SiC WaferFab. A custom

IMS package allowing rapid prototyping has been designed by DEEP Concept. Fig.1-left shows the top side metal view of a 3 mm x 3.8 mm, 1.2kV 65mΩ, packaged instrumented SiC-MOSFET with both current and temperature sensors. The equivalent iMOSFET circuit is presented on Fig.1-right. It is composed of a MAIN MOSFET in parallel with a MIRROR MOSFET (current sensor) and an integrated sensing resistor. The current sensing ratio $ratio = I_{SOURCE}/I_{MIRROR}$ corresponds to the geometrical ratio of the respective channel length $ratio = length(MAIN/MIRROR)$. To measure the main MOSFET current, an external circuit can be used on the mirror electrode such as a virtual ground sensing topology [6] or more specific dedicated driver as [7].

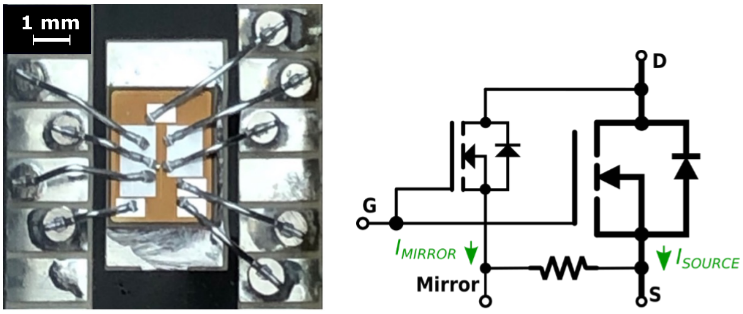


Fig. 1: Top side metal view of the 60mΩ, 1200V instrumented SiC MOSFET with both current and temperature (left) sensors [die size : 3.8 mm x 3mm]. Equivalent circuit (right).

The temperature sensor is a lateral device implemented within the PWELL of the MOSFET. The sensor integrated at the top surface of the MOSFET gives the real time image of the hottest temperature point of the die. The manufacturing process is compatible with the implementation of either a resistance sensor (N-type or P-Type) or a lateral PiN diode. The structure is not detailed for confidentiality issue. The three sensors flavor have been characterized. The lateral PiN diode sensor characteristics is reported in Fig. 2 from 25°C up to 125°C for polarization current varying between 5 µA and 400 µA. The sensor sensitivity is depending on the polarization current and varies between 3.4mV/°C up to 4.5mV/°C for a polarization current between 400 µA to 5 µA. The linearity of the sensor is quite stable and independent of the polarization current. The polarization current value can be selected to adjust the sensitivity and to minimize self-heating effect.

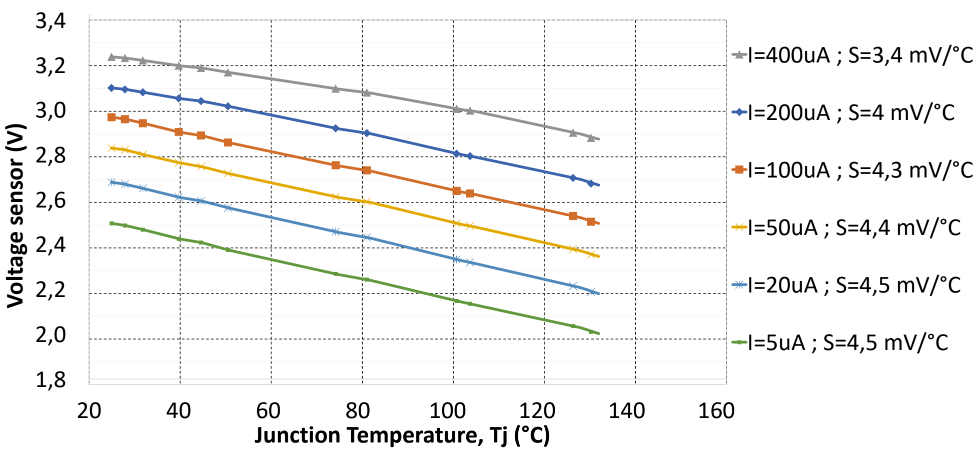


Fig. 2: PiN Diode sensor characteristics versus temperature for various polarization current.

Evaluating die temperature based on Rdson and current measurement is quite challenging. Indeed the MOSFET on-resistance variation versus temperature is in the range of $\Delta R_{DS-ON} = 20\%$ for $\Delta T = 75°C$ (Fig.3-left). Using PiN Diode as temperature sensor is straight forward with an analog circuit. In the same manner, the current mirror electrode provides MOSFET current information. The current sensor ratio variation, Fig.3-right, is lower than $\Delta Ratio < 2\%$ over the operating temperature range. It is accurate enough for large over-current detection and faster than classical Hall effect current sensing devices with limited bandwidth.

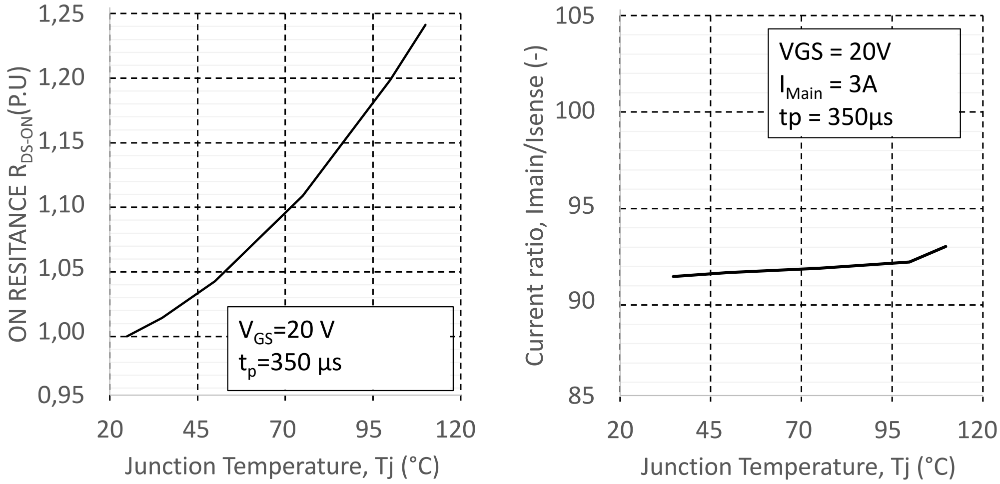


Fig. 3: Embedded current sensor ratio dependance versus temperature (right).

Measuring both current and temperature give a better accuracy than the extrapolation of the temperature from the indirect measurements, as less depending on gate bias voltage and drain voltage.

Experimental validation of dynamic temperature and current sensing

Experimental setup description. To validate the benefits integrated sensor for overload detection (both thermal or over-current), a specific experimental setup has been developed. Fig. 4 presents the test circuit used to generate test patterns. It is composed of a power supply (being either a voltage or a current source), a variable load resistance (R1,R2 and IGBT2), a custom analog discrete gate driver circuit (U1) and the SiC iMOSFET device. The test setup allows to connect several iMOSFET and their driver in parallel and to monitor each branch independently.

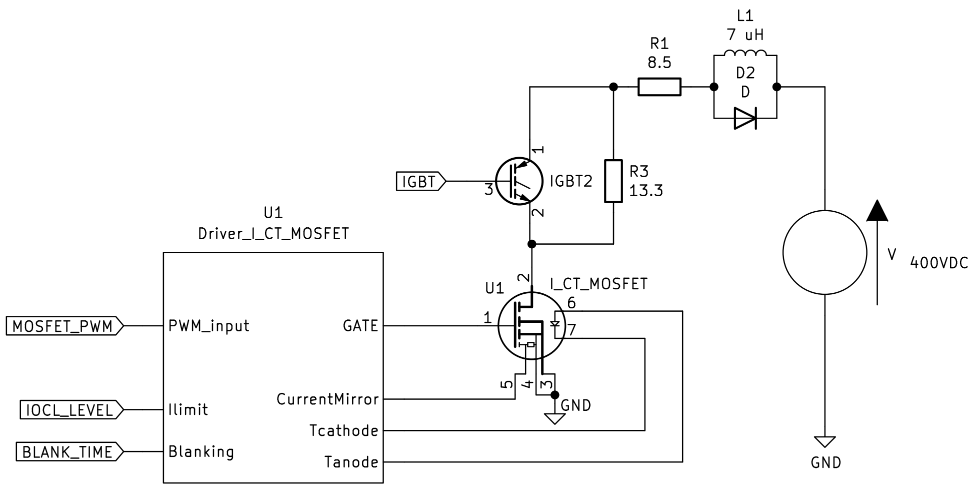


Fig. 4: Test circuit allowing nominal current conduction and overload generation, including protection circuit (detection and gate clamping features).

Sensor real time monitoring demonstration. In a first step, the setup has been used to generate current steps from 10A up to 20A (the power supply being used as a current source). Two iMOSFETs and their drivers have been connected in parallel. Unpaired devices in terms of R_{DSON} have been intentionally selected ($R_{BottomLeft} = 34m\Omega < R_{BottomRight} = 35.2m\Omega$). The current sharing between dies (individual current [5A;7.5A and 10A]) and the dynamic temperature evolution have been recorded.

As inferred from Fig. 5, the device with the higher resistance (Bottom Leftt) has a higher temperature increase over time. The measurement show that the left device is flowing $I_{Left} = 10.35A$ with a maximal temperature of $T_{Left} = 46.4°C$ whereas the right one is flowing $I_{Right} = 10.15A$ with a maximal temperature of $T_{Right} = 45.5°C$. Even if this current unbalanced ($\Delta I = 0.98\%$) induces a small temperature difference $\Delta_{TMAX} < 1\%$, embedded sensors are sensitive enough to measure it.

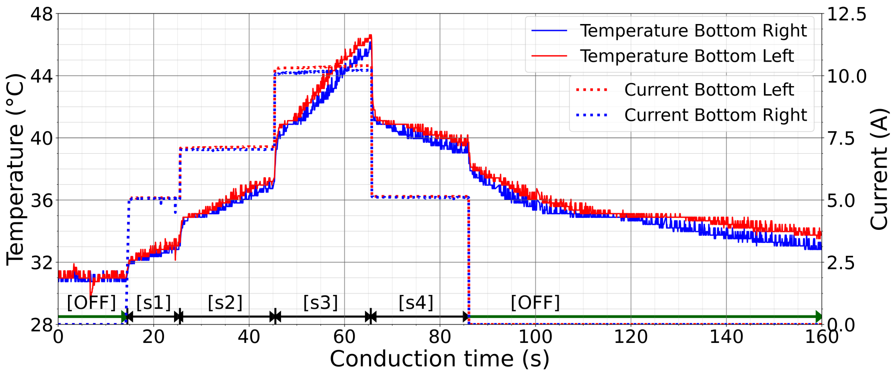


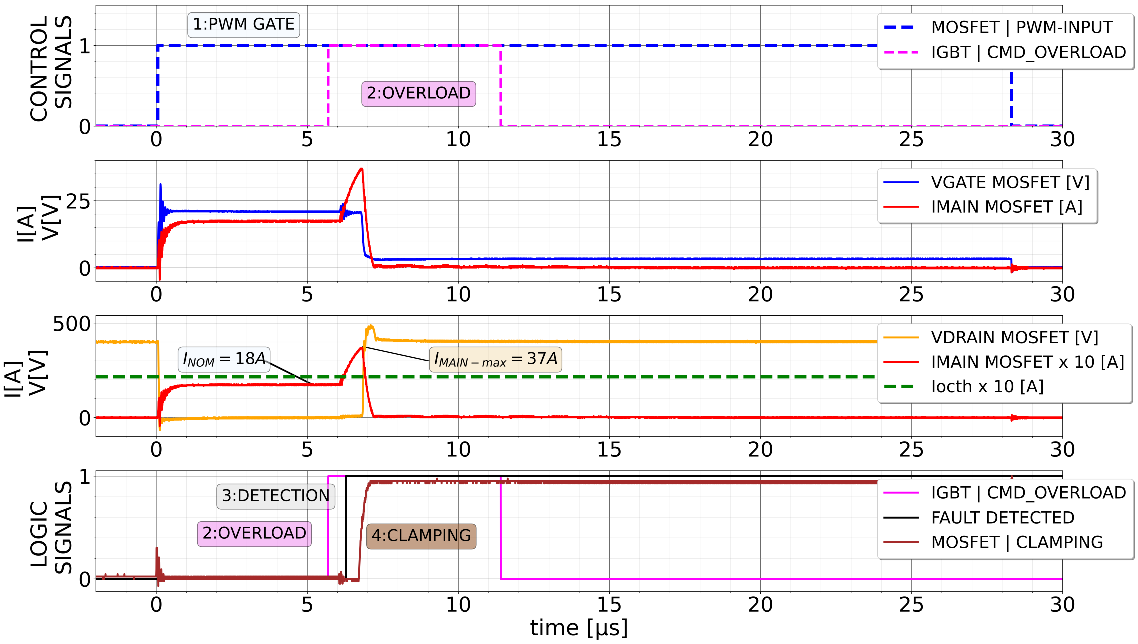
Fig. 5: Recorded temperature sensor output signal (line) and current (dotted) of two iMOSFET connected in parallel for multiple total current steps [s1:10 A; s2:14 A; s3:20 A; s4:10 A].

Embedded sensors allow low temperature unbalance levels measurement without the necessity of measuring both current and voltage of each die. This measurement is furthermore possible during blocking state of the device.

Overload clearance measurement. In this second step the fast overload detection capability has been evaluated. The following operating phases has been generated to monitor the protection circuit in case of an overload: from off state to nominal current conduction, overcurrent generation, fault detection and gate clamping.

- Phase 1: PWM GATE. The gate is turned on, the current is set to nominal value (IMOSFET=18A), Conduction period: 0 < t <5.8µs. [MOSFET-ON ; IGBT-OFF]
- Phase 2: OVERLOAD. The IGBT is turned on, reducing the circuit resistance, and generating a Current Overload Conduction (maximal current value IMOSFET-MAX =47A) Overload period: t > 5.8µs. [MOSFET-ON ; IGBT-ON]
- Phase 3: DETECTION. When an overcurrent (Overcurrent Current Level value IOCL=21A.) is detected, the custom driver generates a clamping signal to turn off the gate. The detection delay is tDETEC = 500ns. Detection period: 6.28µs < t < 6.8us. [MOSFET-ON ; IGBT-ON]
- Phase 4: CLAMPING. The active gate clamping turns off the MOSFET gate in a soft way avoiding over voltage on drain. The gate clamping process duration is tCLAMP=350ns. The driver enters in protection mode for 21.4µs (Latch). Clamping latch period: 6.8us > t > 28.2us. [MOSFET-CLAMPED]

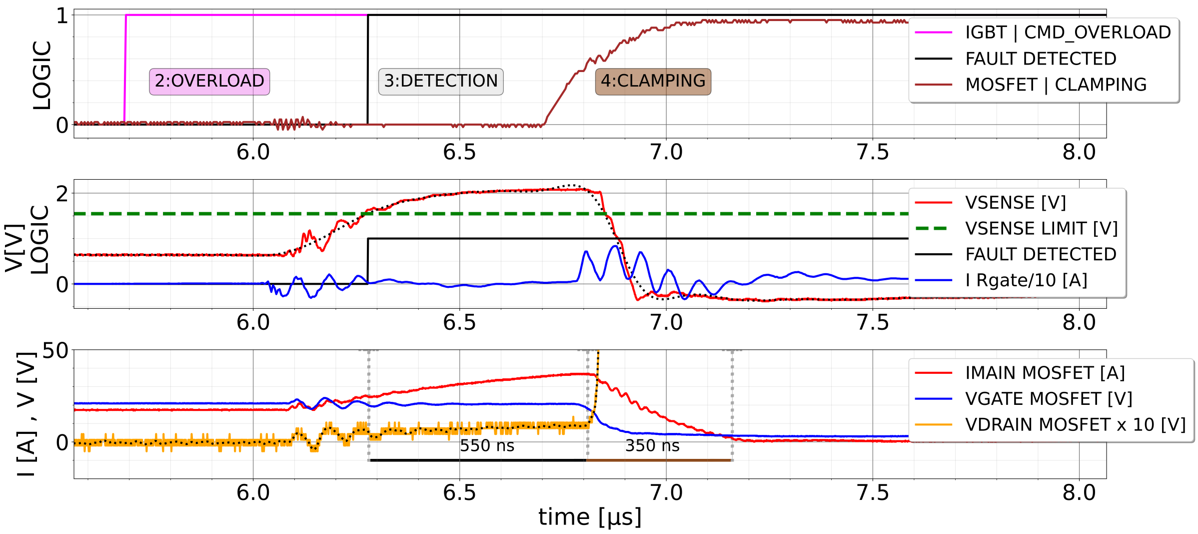
Fig. 6 illustrates the whole experimental sequence whereas Fig. 7 is a focus on the detection and clamping reaction sequence. The test circuit parameters are $[V_{DC} = 400V; L = 7\mu H; R = 8.5\Omega]$. The maximal overload current value (without protection) is $I_{MAX} = 47A$. As inferred from Fig. 6, when a current overload is intentionally generated at $t = 5.8\mu s$, the current start to increase from $I_{NOM} = 18A$ with a reduced time constant $\tau = L/R = 0.82\mu s$.



Full test sequence [1:PWM GATE], [2:OVERLOAD], [3:DETECTION], [4:CLAMPING].

Fig. 6: Experimental demonstration of fast over-current detection and clamping in less than 900ns using a 1200V / 120 mΩ / Current Ratio = 45 instrumented SiC-MOSFET.

The recorded signals $IMAINMOSFET$ shows that over-current is limited to 37A in less than $t_{OFF} = 900ns$. Both the fast detection time and a dynamic soft gate clamp allows to limit the over voltage in the circuit to 440V. Using a simple analog comparator allow an ultra-fast detection (in $t_{detect} = 550ns$) and an efficient Gate clamping in $t_{clamp} = 350ns$ as focused on Fig. 7.



Zoom on over-current detection and active gate clamping sequence

Fig. 7: Experimental demonstration of fast over-current detection and clamping in less than $t_{OFF} = 900ns$ using a 1200V/120 mΩ instrumented SiC-MOSFET (Current Ratio = 45).

Summary

Instrumented 1200V SiC MOSFETs have been and successfully designed manufactured and tested. Ultra-fast over-current detection and clearance have been measured using simple analog detection and protection circuit. The highlighted features demonstrated experimentally are:

- current sensor allowing a fast detection and gate clamping action (in less than 1.2us),
- temperature sensor to detect both short circuits induced over temperature.
- real time monitoring of current and maximal junction temperature allowing advance protection in case of short circuit and overload.

Current sensing allows low cost, low insertion losses and high bandwidth dynamic measurement of current transient phenomenon. This is of a great benefit to implement ultra-fast short-circuit protection and analog dynamic gate control. In addition to current monitoring, being able to measure, and not estimate even if off conduction state, the thermal response of the temperature sensor in case of any overload simplify the driver design, relaxing constrains in terms of packaging and cooling system modeling effort necessary for junction temperature estimation. This new generation of emerging instrumented device pave the way towards advance dynamic SOA implementation for higher reliability converters, unleashing new health monitoring features.

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