Investigating SiC MOSFET body diode's light emission as temperature-sensitive electrical parameter

Ceccarelli, Lorenzo; Luo, Haoze; Iannuzzo, Francesco

Published in:
Microelectronics Reliability

DOI (link to publication from Publisher):
10.1016/j.microrel.2018.07.027

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Investigating SiC MOSFET body diode's light emission as Temperature-Sensitive Electrical Parameter

L. Ceccarelli, H. Luo, F. Iannuzzo

Department of Energy Technology, Aalborg University,
Pontoppidanstraede 111, 9220, Aalborg East, Denmark

Abstract

In this paper, the light emission of SiC MOSFETs during reverse conduction, caused by the Light Emission Diode (LED)-like behaviour of the body diode, is studied and investigated. The photoemission from a 1.2 kV / 20 A commercial device has been measured experimentally using a silicon photodiode. A behavioural characterization of the light output under different junction temperatures and current values has been performed. This allows the implementation of a fast, inexpensive and non-invasive temperature sensing strategy for high-voltage SiC MOSFET chips based on the measurement of light emission during reverse conduction.

1. Introduction

Silicon carbide (SiC) devices are becoming increasingly popular in the design of power electronic converters due to improved electrical and thermal performances and high efficiency [1], [2]. In particular, SiC MOSFETs feature fast switching speed and low on-state resistance, reducing both conduction and switching losses by almost an order of magnitude in comparison to equivalent traditional Si IGBTs under typical operating conditions [3].

The evolution of this technology is moving faster than the development of new packages, able to endure a high amount of thermal stress without failing or deteriorating during the power application's lifetime [4]. Nowadays' commercial SiC MOSFET power devices and modules are still embedded in packages meant for Si applications, which largely limit their full potential and reliability [5]. Thus, monitoring the device's junction temperature is crucial in order to limit the thermal stress on the package.

On the one hand, several techniques have been proposed so far for measuring the junction temperature in power semiconductor devices during operation, making use of direct sensors, such as thermistors, thermocouples and other sensing elements. An overview of the most common methods is given in [6] for Si IGBTs. On the other hand, temperature sensitive electrical parameters (TSEPs) have recently been extensively studied and employed, like in [7–11]. Among others, on-state voltage, gate threshold voltage, short-circuit current and switching delay time are good indicators of the junction temperature [12]. Each of these methods presents, though, advantages and drawbacks. TSEPs are generally relatively easy and cheap to implement, as well as mostly non-invasive for the device, although they require an adequate calibration and decoupling procedure (see e.g. [13]).

Usually, indirect bandgap semiconductors such as SiC do not emit light. However, photoemission (chip glowing in visible light) has been repeatedly observed in the laboratory while testing a 1.2 kV / 20 A rated commercial device from CREE [14]. A simple experimental setup has been built to measure the generated light intensity and identify its dependency on current and temperature. As proven later, the emitted light intensity is clearly influenced by current and junction temperature, and can therefore be used as a temperature indicator. The aim of this paper is to provide a first proof of concept.

Section 2 provides basic theoretical information about the SiC photoemission. The experimental setup is presented in section 3, while the experimental results and analysis are reported in section 4. Section 5 concludes the paper.

2. Light emission in 4H-SiC diodes

The electroluminescence of semiconductor materials was first discovered in 1907 using SiC [15] and the first commercial blue-light Light Emission Diodes (LEDs) with wavelength between 450 and 500 nm, in 1989, were based on SiC substrates [16]. However, these devices were soon abandoned in favour of higher brightness ones.

The emitted light characteristics of an LED basically depend on two variables: the forward current I_F, which affects intensity, and the junction temperature T_j , which affects the wavelength [17]. The emitted light intensity increases when the current increases, at constant temperature. On the contrary, for a given current value, if the temperature increases, the light output decreases, due to emission efficiency reduction. As one can observe in Fig. 1 for a commercial red LED [18], the spectral power distribution shifts to a slightly higher wavelength range and its peak drops consistently. This means that, a correlation with junction temperature can be obtained by mapping the light output at different current and temperature values.

Silicon Carbide can be manufactured in a number of different epitaxy poly-types: 4H-SiC, 6H-SiC, and 3C-SiC, among others. The 4H-SiC manufacturing is nowadays the most used for power device substrates. In [19] a measurement of the photoemission bandgap shows that a 4H-SiC junction can emit photons with ~3.26 eV energy, which corresponds to a wavelength of ~387 nm, meaning that the emission occurs in the ultraviolet spectrum - though very inefficiently, being an indirect bandgap semiconductor [20]. However, due

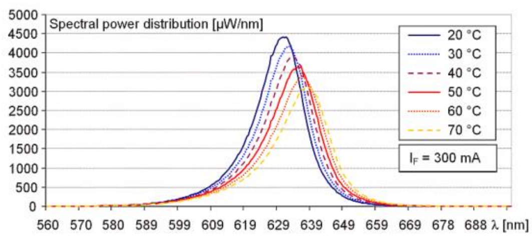

Fig. 1. Temperature dependence of the spectral distribution of the light output of a red LED [18].

to the deep energy levels caused by doping elements and lattice impurities, a 4H-SiC p-n junction can emit in the visible spectrum with a wavelength range of ~400-500 nm (blue-green light) [21]. This mechanism occurs in SiC MOSFETs during reverse conduction of current through the body diode, which, in some extent, behaves like an LED.

Understanding whether this phenomenon can be used as an indicator of current and temperature in SiC MOSFET in a practical and repeatable way is the main scope of this experimental investigation.

Fig. 2 depicts the experimental setup schematic used to sense the light output of the SiC body-diode.

3. Setup description

Silicon PiN photodiodes can be used as light detectors in many applications. They feature a good sensitivity over a broad light spectrum – roughly 400 to 1000 nm - even without external bias. A device from Vishay was selected for this task [22]. The photodiode current is proportional to the sensed light, and was measured through a RC low-pass filter to reduce the

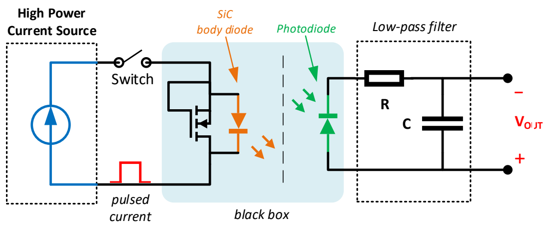

Fig. 2. Experimental setup schematic.

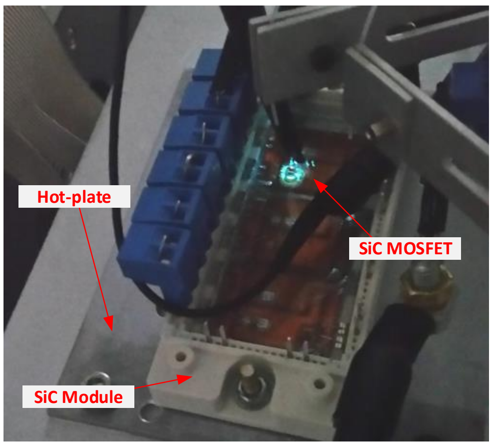

Fig. 3. Picture of the experimental setup (the photodiode has been removed to show the LED glow).

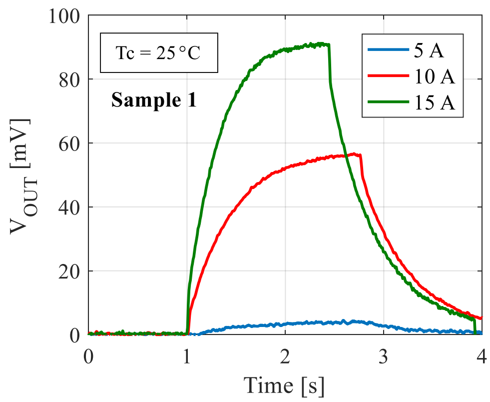

Fig. 4. Photodiode voltage output at T_c=25°C and different diode forward current values. (Sample 1)

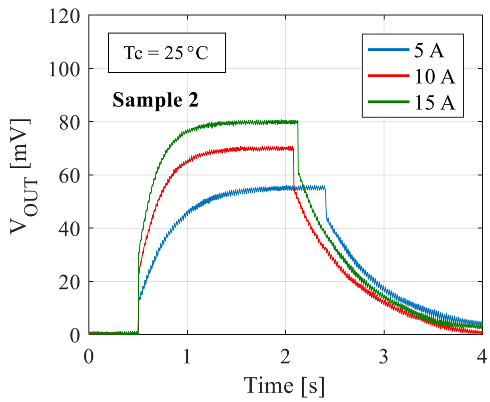

Fig. 6. Photodiode voltage output at T_c=25°C and different diode forward current values. (Sample 2)

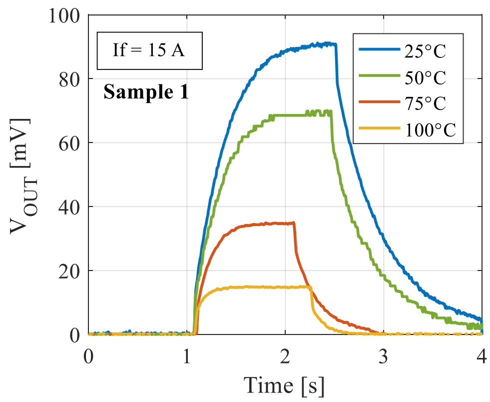

Fig. 5. Photodiode voltage output with 15 A forward current and different temperatures. (Sample 1)

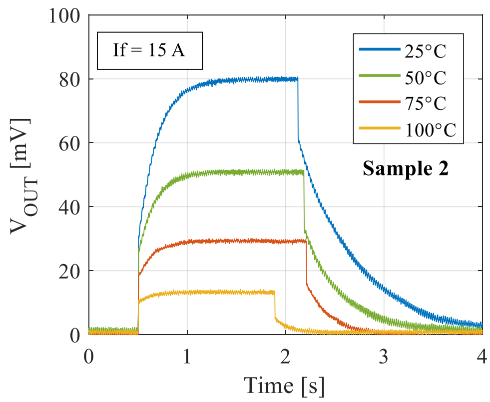

Fig. 7. Photodiode voltage output with 15 A forward current and different temperatures. (Sample 2)

ambient noise. A current pulse was supplied to the body-diode by a current source. The values of pulsed current were 5, 10 and 15 A, and the pulse duration was 1÷2 s.

The module's top lid was removed and the photodiode was placed approximately 2 mm over the SiC MOSFET chip under test (Sample 1), on top of the silicone gel layer. Fig. 3 shows the setup during the test without the photodiode in place, in order to show the observed light emission. It is worth to note that the isolating gel is transparent to visible wavelengths, therefore light can be detected correctly. A dark box has been placed on top of the setup to shield off the ambient light.

Being not relevant to the purpose, the bond-wire connections of the external SiC Schottky diode have been cut.

The module has been placed on a temperature-controlled hot plate and heated up to 100°C in 4 temperature steps. It is assumed here that the case temperature of the device is equal to the hotplate one. Furthermore, it is assumed that the initial junction temperature is equal to the case/hotplate temperature.

During the experiment, the current pulse duration has been controlled manually. The adopted duration of up to 2 s, which is indeed very long for practical applications, has been chosen here in order to be able to give a proof of concept at static conditions. However, the effect of self-heating cannot be neglected for pulses this long, so the junction temperature error had to be calculated in order to obtain an accurate characterization.

The procedure was repeated for another SiC MOSFET chip (Sample 2) of the same module sample, in order to verify its repeatability.

4. Experimental results and characterization

Fig. 4 shows the measured voltage output V_{OUT} transient at a constant case temperature T_c of 25°C for three different current pulses in Sample 1. The voltage output, as well as the light output, are heavily influenced by the current magnitude.

In Fig. 5 one can clearly observe as the light output decreases for increasing temperature.

Fig. 6 and 7 show the results for the same tests applied to Sample 2. It can be noted that the voltage output differs in the two cases, being in the same order of magnitude, though. In particular, the photoemission dependency on forward current is very strong in Sample 1 (~5 mV/A) and weaker in Sample 2 (~1 mV/A). This means that the light emission intensity is not the same for different chips and actually depends on the specific levels of impurities and doping. Therefore, an individual calibration has to be carried out on each of the samples to calculate the correct junction temperature.

The influence of the device's self-heating on junction temperature during the measurements can be estimated by means of the following steady-state thermal conduction equation:

$$T_j = T_c + P_j \,/\, R_{\theta,jc} \qquad (1)$$

Where P_j is the power injected into the junction and $R_{\theta,jc}$ is the steady-state junction-to-case thermal resistance of the chip. The injected power can be calculated, knowing the forward voltage drop of the body-diode V_F, as $P_j = I_F V_F$. Both V_F and the thermal resistance $R_{\theta,jc}$ are available from the device datasheet [14]. Therefore, the test temperature values can be compensated. The compensation factors in this case are respectively 16.4°C (5 A), 47.2°C (10 A) and 79.2°C (15 A).

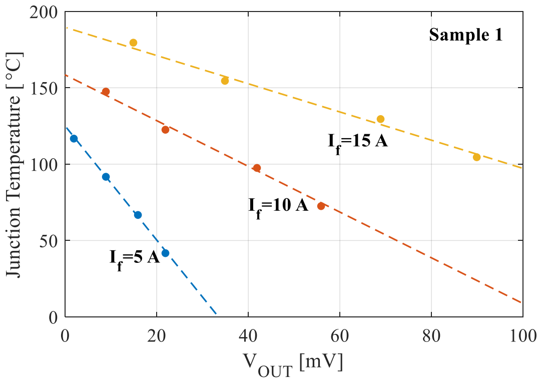

Fig. 8. Junction temperature vs. photodiode voltage output (Sample 1) for different current values.

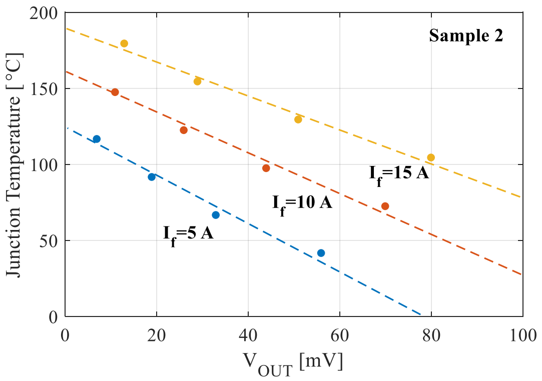

Fig. 9. Junction temperature vs. photodiode voltage output (Sample 2) for different current values.

Fig. 8 and 9 show the estimated junction temperature T_j versus the photodiode output V_{OUT} with fitting trend-lines for each test current value, respectively for Sample 1 and 2. The characteristics show outstanding linearity. The slope of the characteristics shows an inversely-proportional dependency from the body-diode current.

If one knows V_{OUT} and I_F, the junction temperature can be calculated by means of the behavioural functions in Eq. 2 (for Sample 1) and Eq. 3 (for Sample 2).

$$T_{j1}\,(V_{OUT}, I_F) = (0.27\, I_F - 4.8)\, V_{OUT} + 6.7\, I_F + 89.4 \quad (2)$$

$$T_{j2}\,(V_{OUT}, I_F) = (0.04\, I_F - 1.7)\, V_{OUT} + 6.7\, I_F + 91.4 \quad (3)$$

It is worth to point out that the above results are only true at steady-state conditions, i.e. for pulses with long duration. An implementation of this technique during the normal operation of the device should include a more accurate dynamic thermal model and a better EMI shielding for the measurement system.

5. Conclusions

The first attempts of measuring the light output from commercial SiC MOSFET chips during freewheeling operations have shown rather interesting results. The photodiode output voltage could be correlated to the light emission intensity changing current and case temperature and was proven to be a promising temperature-sensitive electrical parameter. A calibration procedure was performed for two samples with the same part number. The impact of device self-heating during the tests has been taken into account in the calibration.

The photoemission is shown to be changing from a device to another, due to the parameter scattering introduced by the semiconductor manufacturing process. However, the calibration process for each of the samples is fast and easy to perform and can easily be automated. The method also shows remarkable sensitivity and linearity.

Moreover, this novel technique is extremely cheap and completely non-invasive for the device and the module, enabling high-voltage monitoring. The sensing element is small enough to be easily embedded in the package, allowing online temperature estimation.

Finally, it cannot be excluded that this method could potentially be employed for power devices based on different semiconductor materials, given the possibility to detect the photoemission in the proper wavelength range with enough sensitivity.

References

[1] J. W. Palmour, "Silicon carbide power device development for industrial markets," in *proc. of 2014 IEEE International Electron Devices Meeting*, 2014, p. 1.1.1-1.1.8.

[2] S. Acharya, X. She, R. Datta, M. H. Todorovic, and G. Mandrusiak, "Comparison of 1.7kV, 450A SiC-MOSFET and Si-IGBT based modular three phase power block," in *proc. of 2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017, pp. 5119–5125.

[3] S. Hazra, A. De, L. Cheng, J. Palmour, M. Schupbach, B. A. Hull, S. Allen, S. Bhattacharya, "High Switching Performance of 1700-V, 50-A SiC Power MOSFET Over Si IGBT/BiMOSFET for Advanced Power Conversion Applications," in *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4742–4754, Jul. 2016.

[4] A. Castellazzi, A. Fayyaz, G. Romano, L. Yang, M. Riccio, and A. Irace, "SiC power MOSFETs performance, robustness and technology maturity," in *Microelectron. Reliab.*, vol. 58, pp. 164–176, Mar. 2016.

[5] L. Ceccarelli, P. D. Reigosa, F. Iannuzzo, and F. Blaabjerg, "A survey of SiC power MOSFETs short-circuit robustness and failure mode analysis," in *Microelectron. Reliab.*, vol. 76-77, pp. 272-276, Sep. 2017.

[6] M. H. M. Sathik, J. Pou, S. Prasanth, V. Muthu, R. Simanjorang, and A. K. Gupta, "Comparison of IGBT junction temperature measurement and estimation methods-a review," in *proc. of 2017 Asian Conference on Energy, Power and Transportation Electrification (ACEPT)*, 2017, pp. 1–8.

[7] U. M. Choi, F. Blaabjerg, F. Iannuzzo, and S. Jørgensen, "Junction temperature estimation method for a 600 V, 30A IGBT module during converter operation," in *Microelectron. Reliab.*, vol. 55, no. 9–10, pp. 2022–2026, Aug. 2015.

[8] N. Baker, L. Dupont, S. Munk-Nielsen, F. Iannuzzo, and M. Liserre, "IR Camera Validation of IGBT Junction Temperature Measurement via Peak Gate Current," in *IEEE Trans. Power Electron.*, vol. 32, no. 4, pp. 3099–3111, Apr. 2017.

[9] N. Baker, H. Luo, and F. Iannuzzo, "Simultaneous On-State Voltage and Bond-Wire Resistance Monitoring of Silicon Carbide MOSFETs," in *Energies*, vol. 10, no. 3, p. 384, Mar. 2017.

[10] H. Luo, W. Li, F. Iannuzzo, X. He, and F. Blaabjerg, "Enabling Junction Temperature Estimation via Collector-Side Thermo-Sensitive Electrical Parameters Through Emitter Stray Inductance in High-Power IGBT Modules," in *IEEE Trans. Ind. Electron.*, vol. 65, no. 6, pp. 4724–4738, Jun. 2018.

[11] Y. Chen, H. Luo, W. Li, X. He, F. Iannuzzo, and F. Blaabjerg, "Analytical and Experimental Investigation on A Dynamic Thermo-Sensitive Electrical Parameter With Maximum dI/dt During Turn-off for High Power Trench Gate/Field-Stop IGBT Modules," *IEEE Trans. Power Electron.*, vol. 32, no. 8, pp. 6394–6404, Aug. 2017.

[12] L. Li, P. Ning, D. Zhang, and X. Wen, "An exploration of thermo-sensitive electrical parameters to estimate the junction temperature of silicon carbide mosfet," in *proc. of 2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, 2017, pp. 1–5.

[13] F. Stella, G. Pellegrino, E. Armando, and D. Daprà, "On-line temperature estimation of SiC power MOSFET modules through on-state resistance mapping," in *proc. of 2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017, pp. 5907–5914.

[14] CREE CCS020M12CM2 SiC power module datasheet: https://www.wolfspeed.com/ccs020m12cm2.

[15] H. J. Round, "A note on carborundum". Electrical World. 19: 309. 1907.

[16] "http://www.cree.com/about/history."

[17] C. J. M. Lasance and A. Poppe, "*Thermal Management for LED Applications"*, vol. 2. New York, NY: Springer New York, 2014.

[18] A. Poppe, G. Farkas, G. Molnár, B. Katona, T. Temesvölgyi, and J.-W. He, "Emerging standard for thermal testing of power LEDs and its possible implementation," 2010, p. 778414.

[19] I. Shalish, I. B. Altfeder, and V. Narayanamurti, "Observations of conduction-band structure of 4 H - and 6 H − SiC," *Phys. Rev. B*, vol. 65, no. 7, Feb. 2002.

[20] X. Cai, D. Zhou, S. Yang, H. Lu, D. Chen, F. Ren, R. Zhang, Y. Zheng, "4H-SiC SACM Avalanche

Photodiode With Low Breakdown Voltage and High UV Detection Efficiency," in *IEEE Photonics J.*, vol. 8, no. 5, pp. 1–7, Oct. 2016.

[21] X. Liu, S.-Y. Zhuo, P. Gao, W. Huang, C.-F. Yan, and E.-W. Shi, "Donor-acceptor-pair emission in fluorescent 4H-SiC grown by PVT method," *AIP Adv.*, vol. 5, no. 4, p. 47133, Apr. 2015.

[22] Vishay VBPW34S Silicon PIN Photodiode datasheet*: "https://www.vishay.com/docs/81128/vbpw34s.pdf."* .