# Use of Body-Diode for Thermal Monitoring of Power MOSFET

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***Abstract*—The dependence on temperature of the body-drain voltage appearing across a forward-biased body-diode is used to estimate the junction temperature of power Metal-Oxide-Semiconductor Field-Effect Transistors. Moreover, the temperature sensor sensitivity, linearity, resolution, error and output repeatability are accurately discussed. The integrated diodes are characterized in a typical working temperature range, between about 22 °C and 150 °C and for currents between 1 µA and 1 mA. The best trade-off between sensitivity and linearity is found at a low bias current of 21 µA.**

***Keywords-Junction temperature; Power MOSFET; Temperature measurement; Temperature sensors; Linear sensors.***

## I. INTRODUCTION

The monitoring of the junction temperature ($T_J$) of power semiconductor devices is of paramount importance in many applications. In particular, the measurement of the junction temperature is essential to evaluate the performance of a circuit and of semiconductor devices as it has a strong influence on electrical parameters, reliability and operating lifetime of power devices [1][2].

However, the direct measurement of junction temperature is very difficult, and still an open issue among designers, who have generally to rely on external sensors placed in contact with the observed device metal case.

An alternative way for the monitoring of the junction temperature of a power MOSFET consists in using Temperature-Sensitive Electrical Parameters (TSEPs) of the same device [1][2]. Studies have demonstrated the possibility to monitor the MOSFET junction temperature through TSEPs, *e.g.*, the on-state resistance, turn-on delay of pulse signal, turn-off delay time and gate drive current [3]-[6].

In previous works, we have shown that Schottky and p-i-n diodes can be used as linear temperature sensors thanks to the favorable temperature dependence of their forward bias voltage drop [7][8]. As commercial power MOSFETs include an intrinsic diode (body-diode), formed at the body-drain P-N junction connected between drain and source, the body-drain voltage ($V_{BD}$) can be considered itself a TSEP, varying almost linearly with temperature when this body-diode is forward biased with a proper DC current.

The aim of this paper is to demonstrate the possibility of monitoring the power MOSFET junction temperature through $V_{BD}$-T relation. The almost linear dependence between the body-drain voltage and junction temperature has been studied in the MOSFET operative temperature range from room temperature up to 150 °C.

The paper is organized as follows. The Section 2 consists of two parts; first, the linear dependence between voltage and temperature, the electrical circuit and the experimental setup used for measuring the junction temperature are described. The second part reports the experimental results with particular attention to temperature sensor performance, i.e., linearity, sensitivity and temperature error. Finally, conclusions and future works are presented in Section 3.

## II. RESULTS AND DISCUSSION

### A. Use of Body-Diode as Temperature Sensor

As well-known, the $I_D$ current flowing in a diode at a given applied voltage $V_{BD}$ can be analytically described using the following formula:

$$I_D = I_S\left(e^{\frac{q(V_{BD}-R_S I_D)}{\eta kT}} - 1\right), \tag{1}$$

where $\eta$ is the ideality factor, $I_S$ is the saturation current, $R_S$ is the series resistance, $q$ is the electronic charge and $k$ is the Boltzmann constant.

The characterization of the sensor output has been performed under forward bias condition where, at constant DC current, the voltage across the diode is linearly dependent on the temperature. In fact, if $q(V_{BD}-R_SI_D) >> \eta kT$, the voltage drop dependence on temperature can be

 

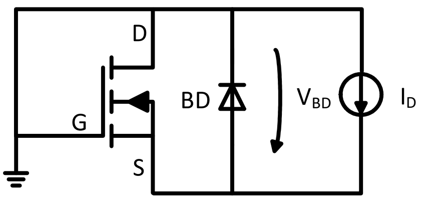


Figure 1. Electrical circuit for the measurement of the body-drain voltage ($V_{BD}$) in the bias current range from 1 µA up to 1 mA.

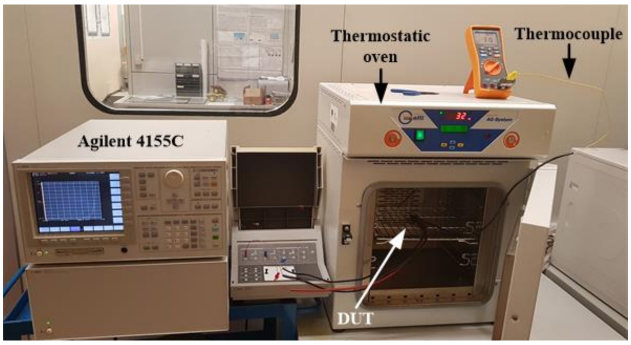


Figure 2. Experimental setup

obtained from (1), yielding:

$$V_{BD} = \frac{kT}{q}\eta\, ln\left(\frac{I_D}{I_S}\right) + R_S I_D . \qquad (2)$$

As demonstrated in [8], equation (2) makes explicit the linear dependence $V_D$-$T$ as long as the contribution of the series resistance can be considered negligible. Keeping the diode operating in its exponential region with a low bias current helps meeting this requirement. Moreover, the use of low bias currents allows to avoid both self-heating effects, which can negatively affect the sensor linearity, and excessive power consumption.

In our set-up, the integrated Body-Diode (BD) was biased at a forward constant current ($I_D$), as schematically reported in Figure 1, while the gate was connected to ground.

It is clear that the use of this technique in a working power circuit, e.g., a static converter, for the real time measure of the internal operating temperature of a switching MOSFET, the so called junction temperature $T_j$, would require the temporary switch-off of the device and the forcing of the probe $I_D$ current through the body diode. This scheme, however, should not have a serious impact on the circuit performance because of the very limited time interval necessary to proceed with the $V_{DB}$ measurement, of the order of a few milliseconds.

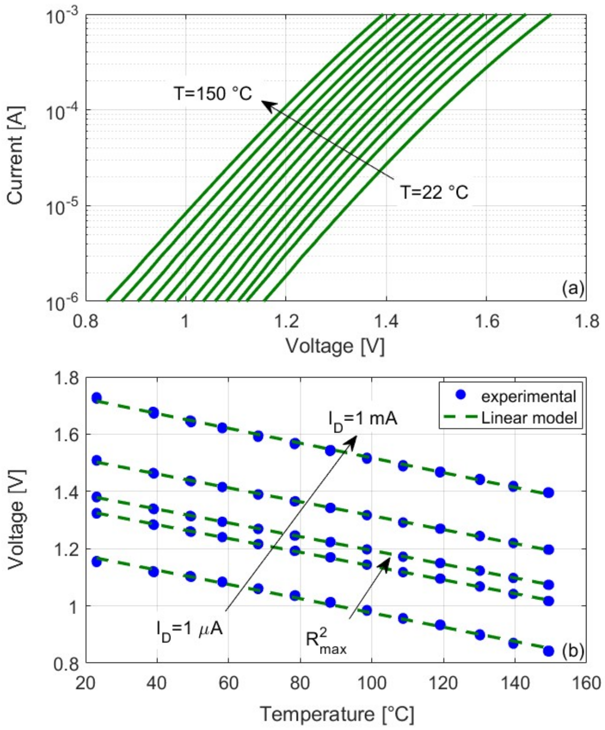


Figure 3. (a) Current-voltage ($I_D$-$V_{BD}$) characteristics in the temperature range T=22-150°C in steps of 10 °C. (b) Measured (points) body-drain voltage versus temperature. Experimental data are fitted with the best-calculated linear model.

## *B. Temperature Sensor Performance*

The experimental measurements are carried out on a commercial SiC MOSFET (C2M0025120D) [9] having a maximum drain-source voltage of 1200 V, a maximum continuous drain current of 90 A and a drain-source on-state resistance of 25 mΩ. Moreover, the operating junction temperature range is claimed from -55 °C up to 150 °C. The device has been tested in a thermostatic oven (Galli G210F030P) setting the reference temperature through its internal Proportional Integral Derivative (PID) digital microcontroller. A thermocouple (K-type) temperature sensor was placed in contact with the Device Under Test (DUT) in order to monitor, during measurements, the exact temperature set points, gradually varied from (down to) ~22 °C up to (from) 150 °C. By using an Agilent 4155C semiconductor parameter analyzer, tests were made for $I_D$ varied in a range from 1 µA to 1 mA ±(0.12%·$I_D$+500 nA+2 nA·$V_{BD}$) accuracy, 100 nA resolution [10], and the corresponding voltage drops $V_{BD}$ across the body-diode were measured. The experimental setup used for temperature measurements is shown in Figure 2.

While the DC bias current, $I_D$, was varied in the given range, the corresponding voltage drop $V_{BD}$ across the body-diode was measured as reported in Figure 3(a). At each

 

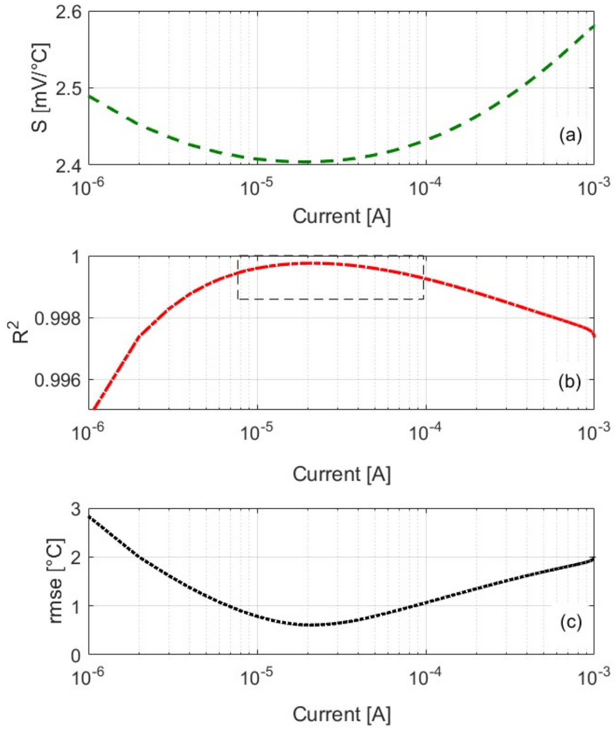


Figure 4. (a) Sensitivity, $S$; (b) coefficient of determination, $R^2$; and (c) root mean square error, *rmse*, within the whole temperature range of 22-150 °C and for bias currents in the range $I_D$=1 µA-1 mA.

temperature, measurements started after waiting for the settling of stable temperatures for several minutes. Moreover, the experimental data are reported at five currents $I_D$ (1 µA, 10 µA, 21 µA, 100 µA and 1 mA).

From $I_D$–$V_{BD}$–$T$ measurements, the $V_{BD}$–$T$ characteristics have been extracted as shown in Figure 3(b), which also reports the linear fitting of data obtained through a proper computer routine.

In our analysis, the coefficient of determination ($R^2$) [11] has been calculated to evaluate the agreement between the experimental measurements and their linear best fit, $f_L(T)$. In particular, $R^2$ allows to quantify the sensor linearity goodness by fitting the experimental data with a linear model.

In Figure 3(b), the measured data are fitted with the best-calculated linear model showing a good degree of linearity ($R^2$ > 0.995) for the considered range of $I_D$. The sensor sensitivity $S$ can be obtained from the slope of the $V_{BD}$–$T$ characteristics. When $I_D$ is 1 µA the sensitivity is 2.49 mV/°C and increases to 2.58 mV/°C for $I_D$=1 mA.

Figures 4(a) and (b) report a detailed analysis of the sensitivity and coefficient of determination for different value of biasing currents $I_D$. The maximum of $R^2$~0.9997 has been calculated for $I_D$=21 µA, corresponding to a sensitivity $S$=2.41 mV/°C.

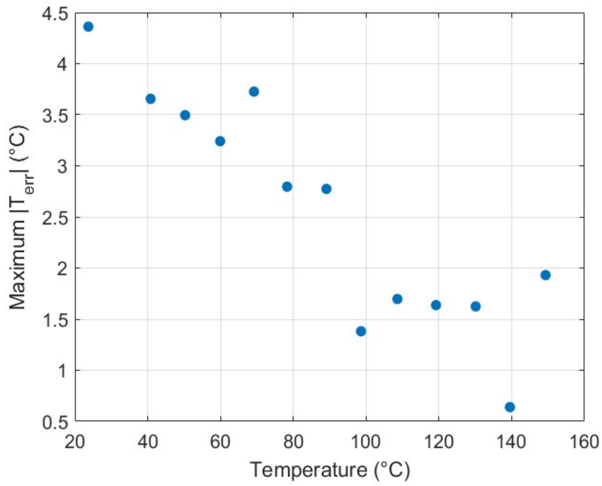


Figure 5. Maximum absolute temperature error between the linear fitting and body-drain voltage ($V_{BD}$) at bias current of $I_D$=21 µA

Another important parameter for the characterization of a linear temperature sensor is the root mean square error (rmse) between the calculated linear best-fit and the experimental measurements. The rmse was first calculated and subsequently converted into a temperature error by dividing by the sensitivity.

The obtained plot, rmse versus $I_D$, for the considered temperature range is reported in Figure 4(c). The root mean square error is always lower than 2.83 °C while a minimum rmse of 0.61 °C is obtained for $I_D$=21 µA, which also provides the maximum linearity.

As shown in the three graphs of Figure 4, the best bias current range for the sensor is from 8 to 100 µA. In fact, in this range the sensor shows a coefficient of determination higher than 0.9993 (see rectangle of Figure 4(b)). It is worth noting that in this current range the $R^2$ varies by only 0.016% from the average of $R_a^2$=0.99953 over the considered temperature range, leading to an integrated temperature sensor with a highly linear behavior also for unwanted variation of the bias current during the short-time sensing phase. The corresponding average values of sensitivity and rmse are $S_a$=2.42 mV/°C and $rmse_a$=0.83 °C with standard deviations of 0.01 mV/°C and 0.15 °C respectively.

Another important parameter for the characterization of a temperature sensor is the temperature error. In this case, the maximum absolute error $|T_{err}|$ of experimental data was extracted with respect to their linear best fit for different measurement cycles. The obtained values, for the best bias current of $I_D$=21 µA, are reported in Figure 5. As shown in the graph, the maximum absolute error decreases as the temperature rises. Moreover, for temperatures above 100 °C, which might be considered as a safety threshold to avoid MOSFET malfunctions, the maximum error is less than 2 °C. This appears to be a small maximum error if the target is the monitoring of the operating temperature of a power device, at least compared to other techniques that involve the use of an external sensor, placed in contact with the device case.

## III. CONCLUSION AND FUTURE WORK

A highly-linear temperature sensor based on body-drain diode integrated within a power MOSFET has been characterized.

The proposed type of sensor allows to monitor the junction temperature of power MOSFETs during their operation. Different cycles of measurements were iterated showing a good output repeatability. Measurements showed a maximum linearity coefficient $R^2$~0.9997 for $I_D$=21 µA, corresponding to a sensitivity $S$=2.41 mV/°C in the temperature range T = 22–150 °C.

Future work will mainly cover the design and realization of a circuit for monitoring the MOSFETs junction temperature in power converter systems. Moreover, the analysis reported in this work will be extended to MOSFETs of various suppliers.

## REFERENCES

[1] D. Blackburn and D. Berning, “Power MOSFET temperature measurements,” in 1982 IEEE Power Electronics Specialists conference, June 1982, pp. 400–407. DOI: 10.1109/PESC.1982.7072436

[2] Y. Avenas, L. Dupont, and Z. Khatir, “Temperature Measurement of Power Semiconductor Devices by Thermo-Sensitive Electrical Parameters—A Review,” IEEE Trans. Power Electron., vol. 27, no. 6, pp. 3081–3092, dec. 2011. DOI: 10.1109/TPEL.2011.2178433

[3] M. L. Walters and R. D. Lorenz, “Circuit modeling methodology for isolated, high bandwidth junction temperature estimation,” in The 2010 International Power Electronics Conference - ECCE ASIA -, June 2010, pp. 970–974. DOI: 10.1109/IPEC.2010.5542176

[4] B. Shi et al., “Junction Temperature Measurement Method for Power MOSFETs Using Turn-On Delay of Impulse Signal,” IEEE Trans. Power Electron., vol 33, no 6, pp. 5274–5282, June 2018. DOI: 10.1109/TPEL.2017.2736523

[5] H. Niu and R. Lorenz, “Real-time Junction Temperature Sensing for Silicon Carbide MOSFET with Different Gate Drive Topologies and Different Operating Conditions,” IEEE Trans. Power Electron., vol. 33, no. 4, pp. 3424 – 3440, Apr. 2018. DOI: 10.1109/TPEL.2017.2704441

[6] Z. Wang et al., “A High Temperature Silicon Carbide mosfet Power Module With Integrated Silicon-On-Insulator-Based Gate Drive,” IEEE Trans. Power Electron., vol. 30, no. 3, pp. 1432–1445, Mar. 2015. DOI: 10.1109/TPEL.2014.2321174

[7] S. Rao, G. Pangallo, and F. G. Della Corte, “4H-SiC p-i-n diode as Highly Linear Temperature Sensor,” IEEE Trans. Electron Devices, vol. 63, no. 1, pp. 414–418, Jan. 2016. DOI: 10.1109/TED.2015.2496913

[8] S. Rao, L. Di Benedetto, G. Pangallo, A. Rubino, S. Bellone, and F. G. Della Corte, “85 K to 440 K Temperature Sensor Based on a 4H-SiC Schottky Diode,” IEEE Sens. J., vol. 16, no. 17, pp. 6537 - 6542, Sept. 2016. DOI: 10.1109/JSEN. 2016.2591067

[9] CREE, C2M0025120D Datasheet, 2015, [Online] Available: https://www.wolfspeed.com/media/downloads/161/C2M0025120D.pdf.

[10] A. Tecnologies, Agilent 4155B/4156B User’s Guide, 2000, [Online]. Available:http://eecs.oregonstate.edu/matdev /man /Agilent4155C_4156C_Users_Guide_Vol1.pdf.

[11] N. J. D. Nagelkerke, “A note on a general definition of the coefficient of determination,” Biometrika, vol. 78, no. 3, pp. 691–692, Sep. 1991. DOI:10.1093/biomet/78.3.691

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