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On-Chip Temperature Monitoring of a SiC Current Limiter

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Abstract. High voltage and high current potentiality of SiC based devices has been proved, and various devices able to work at high temperature have been reported as well. Nevertheless, packaging is one of the main constrains for high temperature operation of these devices. Up to date, no specific power package has been reported for high temperature operation. Moreover, it is desirable to predict the SiC die temperature to avoid any related failure in order to improve the efficiency of the packaged SiC device.

This paper deals with an integrated temperature sensor for SiC current limiting devices. The current limiter is based on a VJFET structure, which capability for dissipating high power density (140 kW/cm²), in the limiting state, has been previously demonstrated [2]. Carrier mobility dependence with temperature was extracted from cryogenic measurements. The temperature estimation is based on the measurement of the variation of the electrical resistance (caused by mobility variation) of the sensing device integrated with the current limiter.

In this paper we will first describe the temperature estimation methodology using various technological solution (from metallic resistor solution to the SiC integrated sensor). Then experimental temperature measurements using an integrated SiC sensor within a packaged current limiting devices will be presented. Electro-thermal measurements on the fabricated devices show that the current limiter is able to work at 205°C under steady state conditions (320 V), without degrading their electrical performances. Finally, perspectives in terms of integration and reliability will be proposed.

Introduction

In order to get the full benefit of silicon carbide material properties; i. e. high voltage and high temperature working operation [1], the development of specific package is a great challenge on the roadmap to silicon carbide technology. Therefore a great effort has to be put on packaging development and reliability study. In this field and in order to monitor devices temperature, we have implemented a very simple integrated temperature sensor.

It is critical to reduce thermal interfaces between heating and sensing elements in order to reach a certain precision on temperature rising during transient operation. Conventional metallic sensor can be used (Pt, or Al made). Nevertheless, the drawback of such devices lies on their thermal response time. Moreover their thermal sensibility and the different thermal expansion coefficients in comparison to SiC leads to mechanical stress and finally makes the sensor subject to failure or de-rating.

In the case of a metal layer, the variation of the resistivity of the metal can be assumed to vary lineally with temperature, that makes simple the temperature rising estimation. However, we have preferred the integrated SiC sensor option to get a more reliable temperature monitoring.

Sensor and methodology description

Temperature sensor description

Unlike metallic sensor, an integrated sensor has the advantage to reduce interface layers effect and mechanical stress since the sensor is integrated with the device (figure 2). The sensor consists in a resistor that can be vertically or laterally integrated within the current limiting device. The lateral sensor has the advantage of being fully insulated by the P-buried layer.

In addition, the response time of the sensing element will be almost the same to that of the heating element.

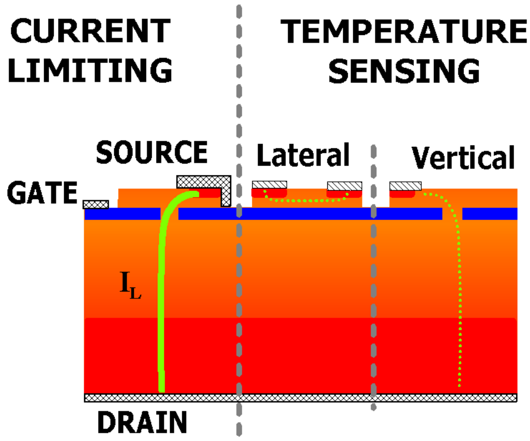

Fig. 2.- Cross-section of the integrated temperature sensor with the current limiter.

We have used a LVJFET current limiter with a high power density (140 kW/cm²), which has been previously checked [2], to demonstrate the possibility to measure the temperature evolution. The mobility variation with temperature is assumed to vary as describe in (1).

$$\mu(\theta) = f\left(\left(\frac{\theta}{\theta_0}\right)^{\alpha}\right). \text{ Equation 1.}$$

The dependence coefficient "α" was extracted through cryogenic measurements ($\alpha = 2.2$ was found, close to literature reported results [3]).The temperature estimation technique, based on this law, will be analysed below and then illustrated by experimental measurements on a packaged current limiting device.

Temperature estimation methodology

The temperature estimation is based on the measurement of the resistance variation (caused by mobility variation) of the sensing device. Fig. 2 shows the integrated temperature sensor with the current limiter. The measured sensor resistance is inversely proportional to mobility. Measurements of the resistance variation, ΔR, with temperature Δθ allow to simply compute the temperature, θ, if one knows a reference resistance value at room temperature (R_0, θ_{amb}):

$$\Delta R(\theta) = \beta \times \frac{\rho \times L}{S} = \beta \times \frac{L}{S} \times \frac{1}{N \times q \times \mu(\theta)} = K \times \left(\frac{1}{\mu(\theta)}\right) = R_0 \times \left[\left(\frac{\theta}{\theta_0}\right)^{\alpha}\right]. \text{ Equation 2.}$$

(K includes sensor parameters: channel section and width). From (2), we can deduce the relation between θ and R_θ:

$$\theta = \theta_0 \times \left(\frac{R_0 - R_\theta}{R_0}\right)^{1/\alpha}. \text{ Equation 3.}$$

Experimental results

Method validation: IR measurements

According to Mc Cluskey [4], plastics packaged devices are able to work at temperature around 125°C with the same reliability as ceramic or metallic package. Thermal ageing study shows that a stable behaviour is achieved at temperatures as high as 175°C. Thus, we have assumed a maximal case temperature of 150°C to perform our study. Back case temperature was measured with a K-type thermocouple. Measurements were done using a cellular current limiter as heater and a vertical VJFET as sensor. The die (4 mm × 4 mm) was soldered in a TO220 metallic package (figure 3).

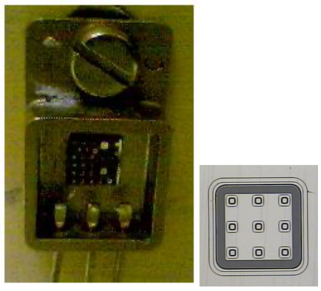

Fig. 3.- Packaged current limiter (metallic TO-220 package).
(die de 4mm × 4 mm)
(limiter 460µm × 460 µm)

IR-measurements were performed to check the temperature distribution between the heating device (H) and the sensing device (S). The figure 5 shows two cross sections along line L01 of figure 4 for two different V_{DS} bias applied to the current limiter (V_{DS} = 21V and V_{DS} = 42 V). We can see from figure 5 that the contact metal temperature is similar in both the heating element (H, at 0.4 mm) and sensing element (S, at 1.2 mm) for both V_{DS} applied bias.

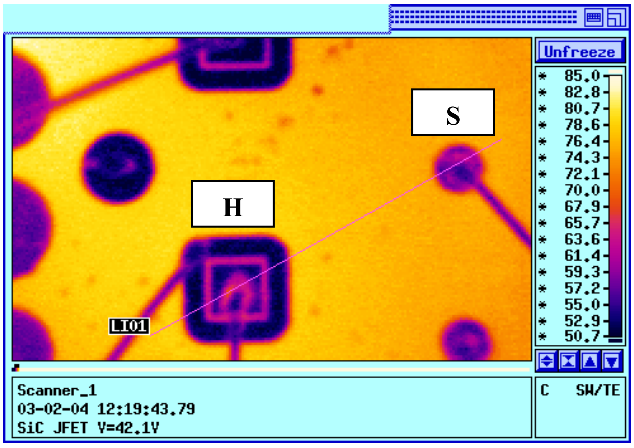

Fig. 4.- IR measurement at low drain bias (V_{DS} = 42 V) on heating (H) and sensing (S) chips

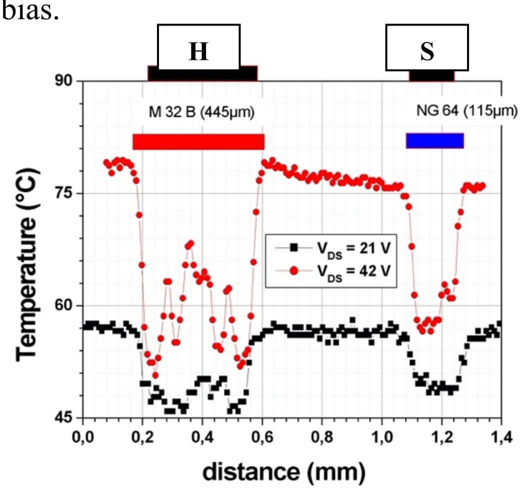

Fig. 5.- Temperature cross-section along LI01 of the left IR-picture (fig. 4).

The IR measurements confirm the fact that the temperature is similar in both devices and corroborates the temperature measurement feasibility.

Temperature measurements

Once experimentally confirmed the homogenous distribution of temperature, electro-thermal measurements were carried out. Resistance measurements were done using two Keithley controlled sources. Different set-ups C1, C2 and C3 were used to get various dissipated power values. No heat sink was used for set-ups C1 and C2, while a cooling element was used in set-up C3. Another difference consists in the gate electrode polarization that was either leaved floating or connected to the source electrode to achieve different output current levels. For each set-up, a maximum case temperature T_{max}=150°C was fixed. The measurement was stopped when T_{max} was reached. $I_{DS}(V_{DS})$ curves where measured in steady state and the SiC temperature computed form the sensor. Current and temperature measurements are presented in figure 6.

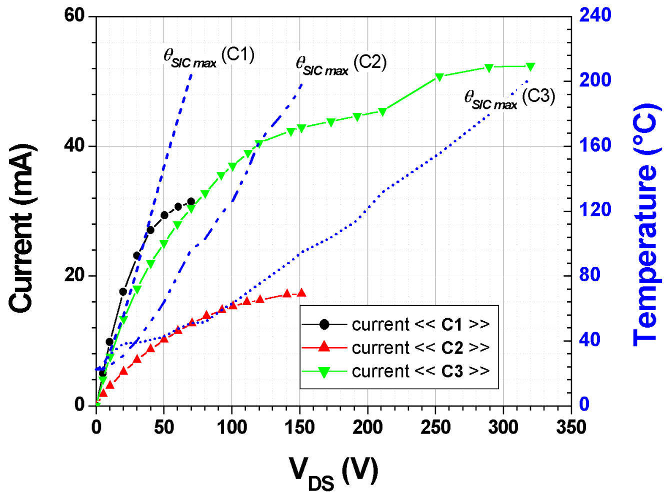

Fig. 6.- Experimental I(V) curves and temperature estimation for the set-ups indicated in table 2.

For set-up C3, a maximum SiC temperature of 201°C is reached at a very high source power density (825 kW/cm²). These results show that the current limiter is able to work at 201°C under steady state conditions (320 V), without degrading neither the electrical performances nor the current limiting function. Results summarized in table 2 shows that high current density can be achieved as well as the temperature monitoring.

Table. 2. Measurements and estimated temperature for the various experiments (C1,C2, C3)

Experiment		C1 (V_{GS} floating)	C2 (V_{GS} = 0V)	C3 (V_{GS} floating)
COOLING		NO	NO	YES
V_{DS} max (V)		70 V	151 V	320 V
I_{DS} max (mA)		31.4 mA	17.3 mA	52.4 mA
J MAX (A/cm²)	Total Area	38 A/cm²	21 A/cm²	63 A/cm²
	Source Area	1558 A/cm²	858 A/cm²	2580 A/cm²
P max (W)		2.2 W	2.6 W	16.8 W
$T_{SiC\ MAX}$ (°C)		204 °C	215 °C	201 °C
$T_{Package\ MAX}$		156 °C	156 °C	151 °C

Thus, we have been able to measure the temperature in limiting operation, which is an important issue when dealing with current limiting devices since temperature is a feed-back parameter for power losses control. Furthermore, the use of an appropriate gate drive will permit to reduce power losses and temperature rising and, consequently to reduce the cooling system size.

Conclusion

We have proposed and illustrate a very simple way to perform on chip temperature monitoring of SiC current limiter with an integrated sensor. Electro-thermal measurements on the fabricated devices have shown that the current limiter is able to work at 205°C, under steady state conditions (320 V), without degrading their electrical characteristics. Different cooling set-ups have been used to illustrate both the temperature measurement and the high current density working operation of SiC devices. Next challenge will consist in the design of a fully integrated current limiter including temperature sensor to be able to prevent any thermal runaway of the packaged device. Such a device will be based on a combination of LVJFET, MESFET and a SiC thermal sensor.

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