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Integrated temperature sensor with diamond Schottky diodes using a thermosensitive parameter

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ABSTRACT

Diamond Schottky diodes with high figures of merit have been previously demonstrated. However, self-heating during characterization process has been widely observed and fast and high temperature monitoring is highly desired, moreover temperature management is of high interest for device parallelization. In this article, we investigate the possibility to monolithically integrate a small area Schottky diode which will be used as temperature sensor. The diode voltage drop at a constant forward bias current will be used as a thermosensitive parameter. This voltage drop has a quasi-linear variation over a temperature range (experimentally demonstrated from 300 K to 440 K in this study due to the maximum operating temperature of the experiments) at constant bias current densities between 0.25 A/cm^2 and 2.5 A/cm^2, with a sensor sensitivity of − 1.6 mV/K. It is also demonstrated that this integrated temperature sensor is affected by the biasing conditions of the main Schottky diode. To perform reliable measurements, the temperature measurement must be done while the main Schottky diode is in OFF-state or the fabrication process must be modified. This integrated temperature measurement allows accurate junction temperature monitoring, offering a diamond Schottky diode operation at its best ON-state performance through an active device temperature management.

1. Introduction

Diamond is considered as the ultimate material for semiconductors for power electronics applications, with higher figures of merit than the other wide-bandgap semiconductors [1]. Schottky diodes have been realized worldwide and show promising performance results with high breakdown voltage capability [2,3], low loss and high temperature operation [4–8]. Boron doped CVD diamond is widely used for these Schottky diodes, offering the best performance in specific ON resistance ($R_{on}S$) vs. Breakdown Voltage. The incomplete ionization of Boron dopants at room temperature allows diamond semiconductors to have a lower R_{on} at higher temperature [4,7]. Then, the self-heating effect of diamond power electronic devices can be used to improve the forward performance of the semiconductor by decreasing forward losses [6], due to the improved ionization of Boron dopants and a negligible decrease of the carrier mobility. A particular care is required for diamond Schottky diodes as they exhibit a negative (from 0 K to 400–600 K) and positive (above 400–600 K, doping dependent) temperature coefficient [9,10]. The measured ON-state resistance of a 500 μm × 500 μm diamond diode presented in Fig. 1 shows an optimized operation of the diamond device at 450 K. Active temperature management is then necessary for diamond semiconductor by optimizing the ON-state semiconductor losses. Accurate temperature information is highly required for such a temperature management. Moreover, as the size of the diamond substrate is still limited, it is needed to consider the parallelization of semiconductors or switching cells in order to increase the effective current of a power converter based on diamond devices. However, paralleled devices require extra attention on its current balancing [11]. For a switching cell parallelization, even if the devices are assembled on a common thermal substrate, the temperature of the devices can be different, inducing unbalanced current between each paralleled leg. Detecting a large temperature difference between the devices and modifying the hottest switching cell will avoid the current to be unbalanced. Such an active parallelization will be allowed by accurate temperature measurement at the device level, offering the possibility to react and control the current flow to hottest or coolest leg.

We propose here a solution to accurately estimate the junction temperature using a thermosensitive electrical parameter of a

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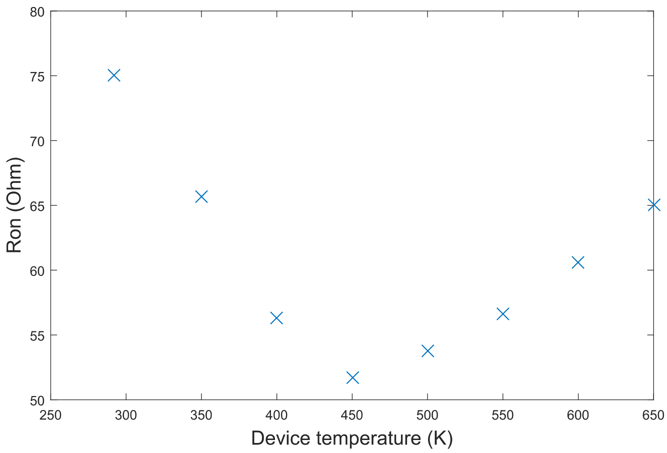

Fig. 1. Measured 500 μm × 500 μm diamond diode ON-state resistance as a function of the device temperature. A 200 nm p^+ Layer is grown on a Ib HPHT diamond substrate, a 1.3 μm p^- layer doped at 5.10^{15} cm^{-3} is then grown on the p^+ layer.

monolithically integrated diamond diode. The fabrication process has already been described [5]. The monolithically integrated Schottky diodes have a common anode (Ohmic contact: Ti(20 nm)/Pt(20 nm)/Au(10 nm)) and isolated cathodes (Schottky contacts: Zr(30 nm)/Pt (20 nm)/Au(10 nm)) although no specific Junction Termination Extension (JTE) is included. Fig. 2 presents the fabricated sample with the used electrical parameters, containing several large area power diodes (highlighted in red) and small area temperature sensor diodes (highlighted in green). 3D simulations have shown that static and transient temperatures are very close between the power diode and the sensor diode.

2. Material and methods

Multiple studies have been already conducted to use thermosensitive electrical parameters (TSEP) of diodes in the case of Silicon (Si) and Silicon-Carbide (SiC) devices [12–14]. The diode voltage drop at a low forward bias current is a widely used method due to its easy calibration and the linear variation of the diode voltage drop as a function of the operating temperature [15]. The low bias current density insures a sensor diode operation in the exponential regime of its characteristic, where the ON-state resistance has a negligible impact. Then, the thermosensitive electrical parameter has a negative temperature coefficient in the whole temperature range and is not impacted by the negative and positive temperature coefficient of the ON-state resistance (Fig. 1). In our study, the thermosensitive parameter of a 200 μm × 200 μm diamond diode is first calibrated from room temperature (RT, 300 K) to 440 K at several bias current densities. The temperature of a power diode is then measured with this thermosensitive parameter allowing us to analyze the behavior of this thermosensitive parameter with another diode in operation on the same substrate.

The diamond sample presented in Fig. 2 has been glued with epoxy resin on a metallized alumina (Al_2O_3) substrate, with bonding wires connecting the electrical contacts. This partially packaged sample has been calibrated in a temperature regulated oven with K-type thermocouple placed on the alumina substrate to have reliable device temperature information, as a uniform temperature inside the oven is considered. The oven temperature has been set from RT to 440 K, the highest temperature has been limited by the maximum operating temperature of the measurement connectors and wires inside the oven. An Agilent B1505A Power Device Analyzer/Curve Tracer is used to extract the Current (I_{sense}), Voltage (V_{sense}) characteristics of the diode at different temperatures. These characteristics are shown in Fig. 3. A pulsed source has been used to bias the diamond diode acting as a temperature sensor. The pulsed current source is used to limit the self-heating effect on the sensor diode during the calibration process. A pulse time of 1 ms with an OFF time of 50 ms between two pulses has been used. The device is cooled down during the OFF time between two pulses, decreasing the device self-heating phenomenon and allowing us considering the temperature of the device as the one of the oven temperature.

The variation of the diode voltage drop (V_{sense}) as a function of the operating temperature has been extracted from the Current, Voltage characteristics. In the diode exponential regime (low ON State current), the diode voltage drop variation over the temperature is extracted for a given current density, as shown by the horizontal dash lines in the Fig. 3. Results of the temperature sensitive electrical parameter extraction are presented in the Fig. 4 for bias current densities from 0.25 A/cm^2 to 25 A/cm^2, corresponding to diode power densities from 0.1 W/cm^2 to 22.5 W/cm^2. V_{sense} has a linear variation over the temperature range for current densities up to 5 A/cm^2, with a $R^2 > 0.994$ (R^2 is the sensor sensitivity linear extrapolation coefficient of determination) and a temperature sensitivity from − 1.6 mV/K to − 1.7 mV/K. These low bias current densities allow us to have a negligible device self-heating effect with a maximum power density of 5.4 mW/cm^2 at the scale of the 4.5 mm × 4.5 mm substrate. The linearity of the sensor sensitivity has not been experimentally demonstrated for higher temperature due to the limitation of the experiment temperature. However, to extend a linear sensitivity at high temperature, the sensor bias current can be increased. A 2.5 A/cm^2 sensor diode current density is used at low temperatures while 5 A/cm^2 can be used for high temperature measurement. These sensitivities are lower, but in a same order of magnitude, than those found with 4H-silicon carbide diodes [13]. The higher current densities do not allow for a linear variation of the thermosensitive parameter over the whole temperature range, since higher current densities are governed by a combination of series resistance and the modification of the Schottky barrier height. These bias current densities cannot be used for a linear temperature measurement. Such linear variation of the temperature sensitive electrical parameter can also be obtained for Schottky contacts made of other metals. However as the Schottky barrier height ans the ideality

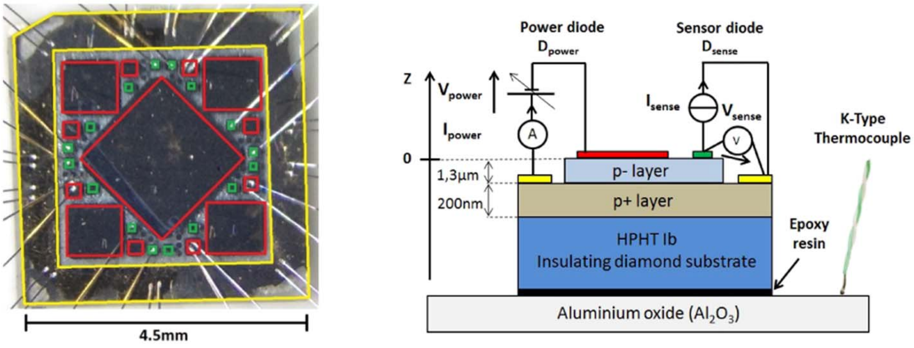

Fig. 2. Picture and schematic cross-section of the diamond diode sample with the Power diodes in red, the sensor diodes in green and the common Ohmic contact in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)