4H-SiC p-i-n diode as highly linear temperature sensor

4H-SiC p-i-n diode as Highly Linear Temperature Sensor

Sandro Rao, *Member, IEEE*, Giovanni Pangallo, and Francesco G. Della Corte, *Member, IEEE*

***Abstract*— The linear dependence on temperature of the voltage drop V_D across a forward-biased 4H-SiC p-i-n diode is investigated experimentally. The results show that the fabricated temperature sensor has a high degree of linearity in the range from room temperature up to 573 K corresponding to a root-mean-square error lower than 0.5%. A maximum sensitivity of 2.66 mV/K was calculated. The low saturation current of the p-i-n diode, well below the forward biasing current also at high temperatures, reduces the nonlinear effects in the V_D–T characteristic allowing the design and fabrication of highly linear sensors operating in a wider temperature range.**

***Index Terms*— p-i-n diodes, power semiconductor devices, silicon carbide, temperature sensors.**

I. Introduction

THE ADVANTAGES of diode-based temperature sensors, if compared with other integrable sensors, e.g., thermistors, are the compatibility with IC technology, the low manufacturing costs, the quasi-linear ~~voltage temperature,~~ ~~V_D–T,~~ ~~and behavior~~ preserving at the same time a high sensitivity [1].

To date, Schottky diodes are the most common commercially available temperature sensors, although p-n and p-i-n diodes are, in principle, a better alternative due to the lower dependence of the saturation current I_s on temperature. A high value of I_s induces, in fact, a nonlinear behavior of the V_D–T characteristics limiting therefore the maximum operating temperature range [2], [3].

In this context, silicon (Si) is by far the most commonly used semiconductor in electronics thanks to the low cost and well-established fabrication processes brought by the CMOS technology.

However, the physical properties of Si degrade when high thermal budgets are involved, making Si-based devices not suitable for temperatures exceeding about $T = 430$ K [4].

More recently, the use of silicon-on-insulator (SOI) technology allowed to extend the Si sensors operating range up to 523 K [5], [6]. Such an improvement was achieved exploiting lateral p-i-n diodes with a very thin active Si layer ($t_{Si} = 80$ nm) on top of a 390-nm-thick buried oxide.

The linear dependence on temperature of the voltage drop across the diode at a fixed current is ensured by the small volume of the depletion region and therefore by the corresponding low saturation current in the whole extended temperature range.

The SOI diode is an attractive choice for the fabrication of a high-temperature sensor thanks to its compact size and the rather simple technological integration inside an electronic microchip.

The use of diodes based on wide-bandgap materials, e.g., silicon carbide (SiC) and gallium nitride (GaN), allows to further extend the above mentioned temperature measurement limit [7], [8]. SiC and GaN devices generally operate at high-power regimes maintaining good performances also at elevated temperatures [9].

In fact, the favorable physical properties, as the high-energy bandgap ($E_g = 3.23$ eV) [10] and high-breakdown electric field ($E_c = 3$–5 MV $\cdot$ cm^{-1}) [11], enable SiC devices to support high voltages and high currents up to a theoretical temperature limit of 1100 K [7]. With respect to several semiconductors, the lower intrinsic carrier concentration ($\sim 10^{-7}$ cm^{-3} at room temperature), the higher saturated electron velocity (2×10^7 cm/s), and thermal conductivity (3–5 W/cm $\cdot$ K) [12] make SiC one of the most promising materials for harsh condition operations, such as oil and gas exploration or nuclear-rich environments [12]–[16].

SiC is therefore an attractive material also for high-temperature operating gas sensors as well as solid-state transducers, such as pressure sensors and accelerometers for automotive and space industry applications using microelectromechanical systems [17]–[19].

To date, all the 4H-SiC-based high-temperature sensors reported in the literature exploited the dependence of the voltage appearing at the junction of Schottky diodes [13], [20]–[22], while in a recent work we proposed, for the first time, a proportional to absolute temperature sensor based on two identical 4H-SiC Schottky diodes biased with different currents [23].

In this paper, a high performance 4H-SiC p-i-n diode temperature sensor, operating up to 573 K, is presented instead. The device was biased in the exponential region of the I–V characteristics where the diode parasitic series resistance R_s can be considered negligible.

The device sensitivity, together with the linearity of the V_D–T characteristics, has been accurately analyzed for a wide

Manuscript received July 29, 2015; revised October 8, 2015; accepted October 29, 2015. The review of this paper was arranged by Editor R. Venkatasubramanian. *(Corresponding author: Sandro Rao.)*

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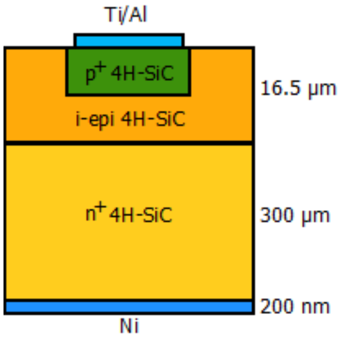
Digital Object Identifier 10.1109/TED.2015.2496913

This is the post-print of the following article: S. Rao, G. Pangallo and F. G. Della Corte, "4H-SiC p-i-n diode as Highly Linear Temperature Sensor," in IEEE Transactions on Electron Devices, vol. 63, no. 1, pp. 414-418, Jan. 2016, doi: 10.1109/TED.2015.2496913. Article has been published in final form at: https://ieeexplore.ieee.org/document/7331278



AQ:6 Fig. 1. Schematic cross section of an integrated 4H-SiC p-i-n single diode (plot not in scale).

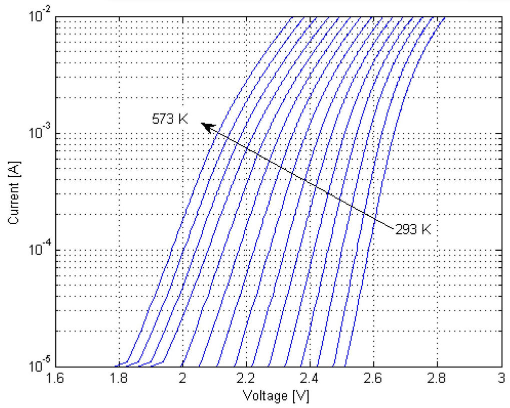


Fig. 2. Forward current–voltage characteristics for temperatures from 293 up to 543 K in step of 20 K.

range of bias currents I_D. This device takes advantage of the lower increase in the saturation current with temperature compared with Schottky diodes, a circumstance that reduces the nonlinear behavior of I_s on the sensor characteristics [3].

II. SiC p-i-n Diode Temperature Sensor

A. Device Structure

The schematic cross section of the fabricated 4H-SiC p-i-n diode is shown in Fig. 1 together with its geometrical dimensions.

AQ:7 The chip, containing several p-i-n diodes, was provided by
AQ:8 the CNR—Institute for Microelectronics and Microsystems, unit of Bologna, Italy. It was fabricated on a ⟨0001⟩ 7°62’ off-axis 4H-SiC n$^+$-type homoepitaxial commercial wafer [24], with a thickness of 300 μm and a conductivity of 0.021 $\Omega\cdot$cm.

The fabrication process involves commercial materials and standard technological steps, ensuring reproducibility of results. The anode region is obtained by ion implantation of Al. Photolithography and wet chemical etching are used to pattern the circular p-i-n top contacts, 310 μm in diameter. Details about the fabrication are provided in [25] and [26].

The unpassivated chip was packaged and the Ti/Al metal contacts were bonded using thin Al wires, 50 μm in diameter, to a custom printed circuit board to allow a stable electrical connection to the measurement setup.

B. Theory and Experimental Setup

As well known, according to Boltzmann statistics, the I_D current of a p-i-n diode at a given applied voltage V_D can be described using the following formula:

$$I_D = I_S\left(e^{\frac{qV_D}{\eta kT}} - 1\right) \tag{1}$$

where η is the ideality factor, I_s is the saturation current, q is the electric charge, and k is the Boltzmann constant. In our setup, the p-i-n diode was biased with a current I_D kept constant in the whole temperature range. For $qV_D \gg \eta kT$, the voltage dependence on temperature can be obtained from (1), yielding

$$V_D = \frac{kT}{q}\eta \ln\left(\frac{I_D}{I_S}\right) = \frac{kT}{q}\eta[\ln I_D - \ln I_S]. \tag{2}$$

As already mentioned, (2) makes explicit the linear dependence V_D–T as long as the nonlinear contribution of I_s can be considered negligible with respect to I_D.

The device was tested in a thermostatic oven (Galli G210F030P) setting the reference temperature through its internal PID digital microcontroller. A calibrated and certified PT100 sensor, with an accuracy of ±0.3 K, was placed in contact with the device under test in order to monitor, during the measurements, the temperature set points gradually varied from (to) 293 to (from) 573 K.

The voltage drop V_D as a function of the applied bias current I_D was measured by using an Agilent 4155C Semiconductor Parameter Analyzer.

C. Experimental Results

The dc bias current I_D was varied in a range from 10 μA to 10 mA and the corresponding voltage drop V_D across the 4H-SiC p-i-n diode was measured. In Fig. 2, we report the I_D–V_D characteristics, for different temperatures in a range from 293 up to 573 K in steps of 20 K.

In our analysis, the coefficient of determination (R^2) [27] has been calculated to evaluate the agreement between the experimental measurements and their linear best fit, $f_L(T)$. In particular, R^2 allowed to quantify the sensor linearity goodness by fitting the experimental data with a linear model.

From I_D–V_D–T measurements, the V_D–T characteristics have been extracted as shown in Fig. 3 for different bias currents in the considered temperature range 293–573 K.

In Fig. 3, the measured data are fitted with the best-calculated linear model showing a good degree of linearity ($R^2 > 0.9998$) for the whole considered range of I_D, from 10 μA to 10 mA.

The sensor sensitivity S is defined as the temperature derivative of (2) and, therefore, it can be obtained from the slope of the V_D–T characteristics.

As reported in Fig. 3, when I_D is 10 mA, the sensitivity is 1.63 mV/K and monotonically increases up to 2.66 mV/K for $I_D = 10$ μA.

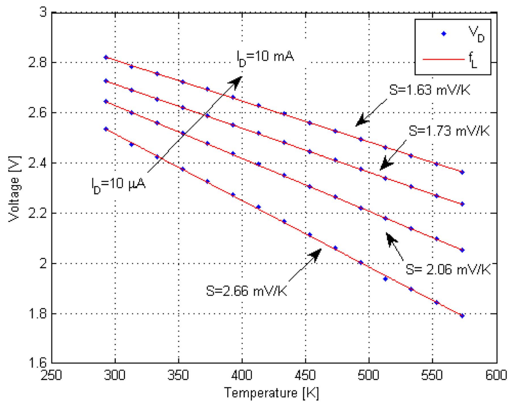
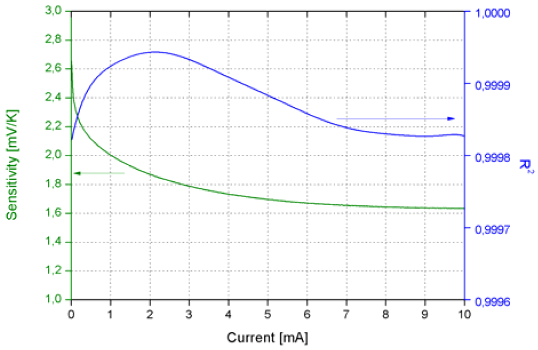
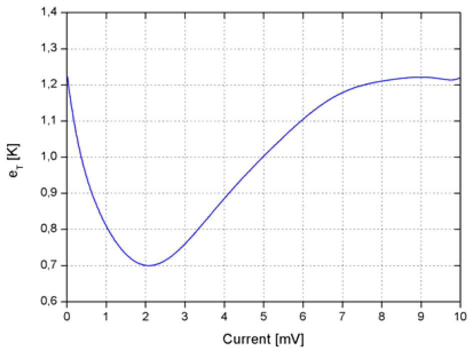


Fig. 3. Measured (points) forward voltages versus temperature at four currents I_D(10 μA, 0.7 mA, 4 mA, and 10 mA). Experimental data are fitted with the best-calculated linear model.



(a)



(b)

Fig. 4. (a) Coefficient of determination and sensitivity calculated for 1001 values of the bias currents between I_D = 10 μA and 10 mA. (b) Corresponding rmse in the temperature range T = 293–573 K.

A more detailed analysis of both R^2 and S is shown in Fig. 4(a) for all values of I_D in steps of 10 μA.

It is worth noting that the coefficient of determination varies by only 0.005% from an average of R_a^2 = 0.9999 over the considered temperature range, leading to a temperature sensor with a highly linear behavior in a wide range of biasing currents.

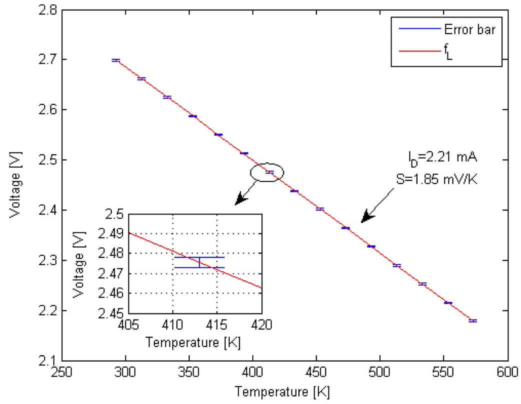


Fig. 5. Linear fit and rmse of VD versus temperature for four different diodes fabricated with the same technological process and measured in a long period of time. Inset: the calculated maximum rmse lower than ±0.5%. The bias current is I_D = 2.21 mA for all four sensors.

Linearity is a key parameter for a temperature sensor since it enables a simplified two-point calibration. The maximum of $R^2 \sim 0.99994$ has been calculated for I_D = 2.21 mA corresponding to a sensitivity S = 1.85 mV/K.

To evaluate the mismatch between the calculated linear best-fit $f_L(T)$ and the experimental measurements, the corresponding root mean square error (rmse) was first calculated and subsequently converted into a temperature error value using the following formula:

$$e_T = \frac{\sqrt{\frac{\sum_{i=1}^{n}(V_D(T_i)-f_L(T_i))^2}{n}}}{S} \tag{3}$$

where n is the number of temperature set points.

The calculated plot, e_T versus I_D, for the considered temperature range is reported in Fig. 4(b). e_T is always lower than 1.3 K while the minimum e_T = 0.7 K is obtained for I_D = 2.21 mA.

The long-term stability and repeatability of the temperature sensor were accurately tested in order to evaluate how consistently it maintains a stable output over time by iteratively repeating the same cycles of measurements from (up to) 293 up to (from) 573 K, in a long period of time and for four different diodes fabricated with the same process.

The results are summarized in Fig. 5, for I_D = 2.21 mA, and leaded to a calculated maximum rmse lower than ±0.5%. Moreover, the coefficient of determination is R^2 = 0.9998 ± 1 × 10^{-4} and the corresponding sensitivity is S = 1.85 mV/K with a standard deviation of 0.08 mV/K.

D. Saturation Current and Ideality Factor Extraction

The ideality factor η and the saturation current I_S are two important parameters for semiconductor diodes to be taken into account, in particular for their correct characterization as temperature sensors. In general, the methods used for the extraction of these parameters are based on the I_D–V_D exponential curve fitting [28].

In our study, I_S was obtained through the linear fitting of the $\ln(I_D)$–V_D curves, in semilog scale, at low currents

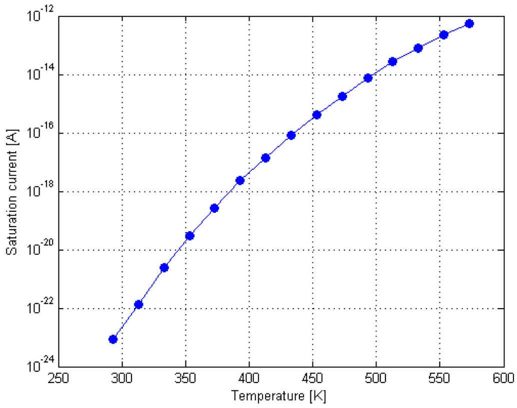


Fig. 6. Saturation current versus temperature calculated at 0 V.

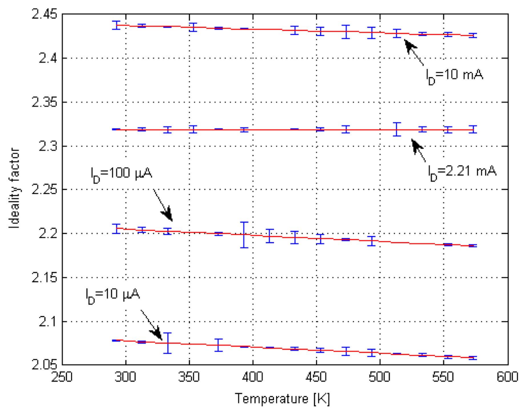


Fig. 7. Ideality factor versus temperature calculated for bias currents of $I_D = 10$ μA, 100 μA, 2.21 mA, and 10 mA. The solid lines are guide to the eye while the error bars represent the standard deviation relative to four characterized sensors.

($I_D < 0.5$ mA) where the corresponding characteristic is approximately a straight line. The y-intercept of the linear fitting, at $V_D = 0$ V, gives the saturation current I_S. The calculated values, reported in Fig. 6, increase with temperature from 8.6×10^{-24} up to 5.3×10^{-13} A.

For the considered temperature range, the calculated saturation currents are well below the driving current flowing through the 4H-SiC diode, hence with no effect on the sensor linearity (2). Although the specific used setup does not allow precise characterization above 573 K, it is expected that our sensor can be therefore used at well higher temperatures with respect to Schottky diodes available to date.

On the other hand, the ideality factor for four bias currents between 10 μA and 10 mA was calculated from the slope of the $\ln(I_D)$–V_D linear fitting. In fact, η is given by the following formula:

$$\eta = \frac{q}{kT}\frac{dV_D}{d\ln(I_D)}. \tag{4}$$

As shown in Fig. 7, once the bias current is chosen, the ideality factor remains almost constant with temperature and the corresponding standard deviation, calculated on a set of four sensors, is always lower than 0.035.

III. Conclusion

A high-temperature sensor based on integrated 4H-SiC p-i-n diode has been designed and characterized.

Measurements showed both a high degree of linearity (average value of $R^2 = 0.9999$) and a high sensitivity ($S = 2.66$ mV/K) in the temperature range $T = 293$–573 K.

The proposed p-i-n diode allows the fabrication of high working temperature sensors thanks to the lower saturation current increase with temperature, limiting the V_D–T characteristic linearity, with respect to commercial diodes available to date.

Different cycles of measurements were iterated on four 4H-SiC p-i-n diodes showing a long-term stability and good output repeatability.

Acknowledgment AQ:9

The authors would like to thank Dr. ~~N. Roberta~~ of CNR-IMM-Unit of Bologna (UOS) (Italy) for providing the AQ:10 p-i-n diodes and for helpful discussions. The authors would also like to thank Dr. S. Lugarà of Mediterranea University of Reggio Calabria for his help with the experimental measurements.

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