Highly Linear Temperature Sensor Based on 4H-Silicon Carbide p-i-n Diodes

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***Abstract*— The linear dependence on temperature of the voltage drop difference measured on two diodes biased at different constant currents has been characterized in a range from room temperature up to 573 K. The realized proportional to absolute temperature sensor shows a good level of linearity and the corresponding rms error lower than 0.3%. Moreover, a maximum sensitivity of 610 μV/K has been obtained, with an extrapolated output converging to 0 V at $T = 0$ K, in agreement with theory and allowing a single-point temperature calibration.**

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

I. Introduction

Diodes are the most common semiconductor devices used for temperature sensing. These sensors exploit the quasi-linear dependence on temperature of the voltage drop, V_D, across a forward-biased diode. The advantage of such devices, if compared to other sensors, *i.e.* thermistors and thermocouples [1], is the high compatibility with the integrated circuit (IC) technology and, more important, the highly linear output while preserving a high sensitivity.

Silicon carbide (SiC)-based devices generally operate at high power regimes maintaining good performances also at elevated temperatures [2]. To date, all of the high temperature sensors reported in literature exploit the dependence on temperature of the voltage drop across a single diode [3], [4] showing however a limited linearity.

In a recent work we proposed a temperature sensor based on 4H-SiC Schottky diodes [5] where the non-linear effects of the saturation current, I_s, and the diode parasitic series resistance, R_s, on the sensor characteristics were overcome through the use of a proportional-to-absolute-temperature (PTAT) configuration realized using two identical integrated diodes biased with different currents kept constant over the temperature range.

In this letter we present, for the first time to our knowledge, results about a high performance PTAT sensor fabricated integrating twin 4H-SiC p-i-n diodes biased in the exponential region of the *I-V* characteristics where the series resistance can be considered negligible.

II. Sensor Structure

The 4H-SiC p-i-n diodes were fabricated and provided by CNR-Institute for Microelectronics and

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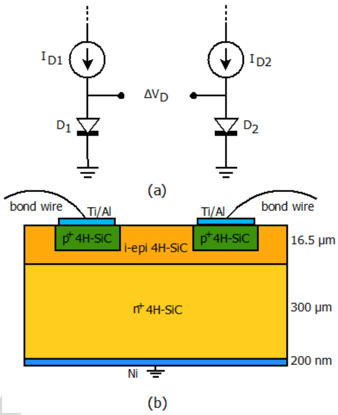

Fig. 1. (a) Electrical circuit of PTAT sensor. (b) Schematic cross section of the 4H-SiC integrated p-i-n diodes.

Microsystems (IMM), unit of Bologna (I). They were fabricated on <0001> 7°62′ off-axis 4H-SiC n^+-type homoepitaxial commercial wafers [6], with a thickness of 300 μm and a conductivity of 0.021 Ω·cm. The epi-layer is 16.5 μm thick and has a net doping density of about 3×10^{15} cm^{-3}. The corresponding fabrication process involves technological steps that are standard for microelectronic industry, ensuring reproducibility of results. In particular the circular p^+-type anode regions were obtained simultaneously by ion implantation of Al through a SiO_2 mask designed to pattern the vertical p-i-n diodes with p-type area of 7.54×10^{-4} cm^2. Photolithography and wet chemical etching were used to define the circular p-i-n Ti/Al top contacts. A 200 nm-thick Ni film was deposited on the back of the wafer to form the ohmic back contact. Finally, the chip was annealed in vacuum at 1000°C for 8 min. Full details about the fabrication are provided in [7] and [8].

In Fig. 1(a) the schematic equivalent circuit of the on-chip integrated PTAT sensor is shown.

The microchip contains several p-i-n diodes with the common cathode consisting of the n^+ 4H-SiC substrate. The 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 (PCB) to allow an electrical connection to the measurement set-up.

A detail of the chip cross section is schematically shown in Fig. 1(b). The distance between the two devices is 190 μm.

The chip surface was unpassivated. In an optimized design, the formation of a passivation layer should be considered to improve reliability by avoiding undesired effects such as surface oxidation and/or current cross-talk between the two diodes, however not observed in this experimental work.

In our setup, two p-i-n diodes, D_1 and D_2, with almost identical $I_D - V_D$ characteristics (root mean square error, rmse $= 1.01 \times 10^{-5}$ calculated over the full bias range), were driven by two external and independent current sources, providing constant I_{D1} and I_{D2} currents [Fig. 1(a)] over the whole temperature range. For ease of use, it is suggested that the same scheme is replicated in practical applications, with an off-chip driving circuit, unless a current mirror-based circuit is implemented on the same substrate. The two currents are described by the analytical expression:

$$I_{D1,2} = I_{S1,2}\left[\exp(qV_{D1,2}/\eta_{1,2}kT) - 1\right] \quad (1)$$

where $I_{S1,2}$, $V_{D1,2}$ and $\eta_{1,2}$ are the saturation current, the diode voltage drop and the ideality factor for D_1 and D_2, respectively.

If the two diodes show the same ideality factor ($\eta_1 = \eta_2 = \eta$), the difference between the voltage drops across the two diodes ($V_{D2} - V_{D1}$) can be written from (1) as:

$$\Delta V_D = V_{D2} - V_{D1} = (kT/q)\eta \ln(I_{D2}/I_{D1}) \quad (2)$$

Eq. (2) indicates that, for a fixed I_{D2}/I_{D1} ratio, the sensor output, ΔV_D, is ideally proportional to T if η is a constant. In order to have a high linearity it is therefore necessary to ensure an ideality factor that is highly stable with T. This result can be obtained by ensuring in turn that, at all temperatures, the diode operation is constantly dominated by a specific physical phenomenon. In fact, as shown in [9], four main current components are present in a SiC p-i-n diode, namely electron (hole) injection in the anode (cathode) region, electro-hole recombination in the space charge region, and recombination in the neutral part of the i-region. Each of them is characterized by a particular value of η. For specific current regimes, one of them can be dominant, for example the minority carrier injection, thus fixing the η, which therefore remains constant with T as long as the relevant physical phenomenon prevails.

The sensitivity S is the temperature derivative of the previous equation:

$$S = d\Delta V_D/dT = (k/q)\eta \ln(r) \quad (3)$$

where $r = I_{D2}/I_{D1}$ is the current ratio. In order to enhance the sensitivity, the ratio r can be increased. Eq. (3) also predicts that S benefits from high values of the ideality factor. However η in excess of 3 are generally only observed in poor quality, highly resistive, diodes, for which (1) is no more valid.

III. Experimental Results and Discussion

The device has been tested in a thermostatic oven (Galli G210F030P) setting the reference temperature through its internal PID digital microcontroller. Two calibrated and certified resistance temperature detectors (RTDs) based on platinum wire (PT100), with an accuracy of ± 0.3 K, were placed in contact with the PCB, through a thermal conductive paint, very close to the device under test in order to monitor, during measurements, the temperature set points. Once each operating temperature was set, and the system temperature was stable for tens of minutes,

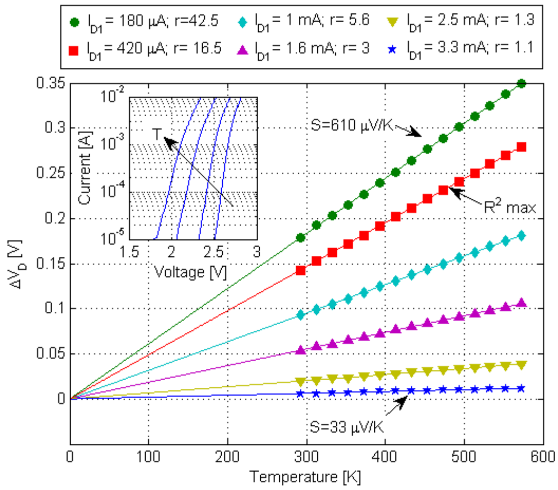

Fig. 2. Forward voltage drop difference, ΔV_D, *vs.* temperature for different bias currents, I_{D1} and I_{D2}, and current ratio $r = (I_{D2}/I_{D1})$. The extrapolated liner fittings (straight lines) show a convergence to the origin ($T = 0$ K and $\Delta V_D = 0$ V) with a maximum error of $\Delta T = \pm 0.2$ K. The inset shows the *I-V* characteristics in semi-log scale at four temperatures (293 K, 373 K, 473 K, 573 K).

the *I-V* characteristics (inset of Fig. 2) have been measured by using an Agilent 4155C Semiconductor Parameter Analyzer, in steps of $T = 20$ K.

The forward voltage difference ($\Delta V_D = V_{D2} - V_{D1}$) across the two diodes, simultaneously measured in a range from (up to) $T = 293$ K up to (from) 573 K, is reported in Fig. 2 together with the best linear fitting. In particular, data are shown for several values of I_{D1} and r. The plot shows that ΔV_D and T are linearly dependent each other for the whole considered temperature range. The reported corresponding sensitivities were calculated from the slope of the ΔV_D *vs.* T characteristics.

In our analysis, the coefficient of determination (R^2) [10] has been calculated to evaluate the agreement between the experimental measurements and their linear best-fit. In particular, R^2 allowed us to quantify the sensor linearity goodness by fitting the experimental data with a linear model.

The experimental characteristics show a good degree of linearity ($R^2 > 0.999$) for I_{D1} ranging from 180 μA up to 3.3 mA, with $1.1 < r < 42.5$.

On the other hand, the sensitivity is lowest for $I_{D1} = 3.3$ mA and $r = 1.1$, ($S = 33.1 \pm 0.9$ μV/K) and increases for higher r in agreement with (3). For $I_{D1} = 180$ μA and $r = 42.5$ we get the highest sensitivity ($S = 610.2 \pm 0.5$ μV/K).

Moreover, all the ΔV_D *vs.* T characteristics converge, with a very high degree of precision, to $T = 0$ K for $\Delta V_D = 0$ V (2). The extrapolated value of the voltage difference across the forward biased diodes, D_1 and D_2, at $T = 0$ K is in fact ± 20 μV corresponding to a temperature error of $\Delta T = \pm 0.2$ K.

The proposed PTAT sensor can be therefore calibrated in a single temperature point thanks to the linear behavior of ΔV_D *vs.* T characteristics crossing the origin of the axes.

TABLE I
DIODE IDEALITY FACTOR

I_{D1}	I_{D2}	$\eta+\Delta\eta(T)$
180 μA	7.7 mA	2.01±0.03
420 μA	6.9 mA	2.08±0.01
1 mA	5.6 mA	2.22±0.01
1.6 mA	4.7 mA	2.27±0.01
2.5 mA	3.2 mA	2.28±0.02
3.3 mA	3.6 mA	2.49±0.02

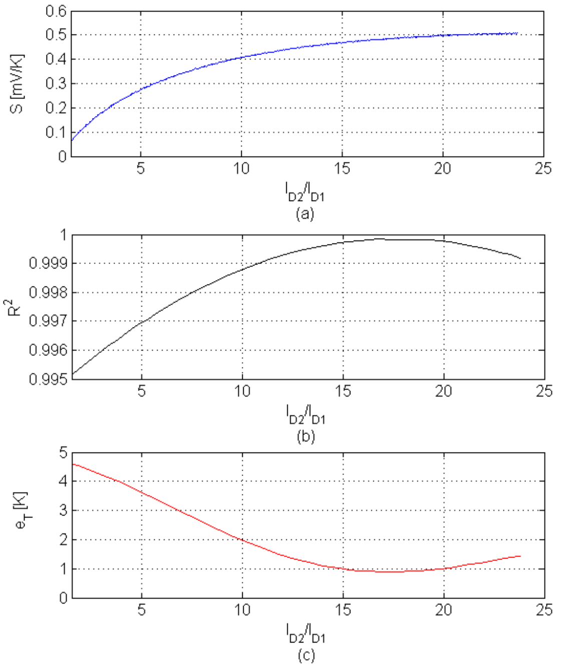

Fig. 3. Sensitivity (a), coefficient of determination (b), and rmse for the whole temperature range of 293-573 K (c) *vs.* current ratio for $I_{D1} = 420\ \mu$A.

This is a clear advantage of PTAT sensors with respect to those based on a single diode, widely used in particular for high temperature sensing [2], [3].

In our analysis, the diode ideality factor was calculated from the slope of the $ln(I_D) - V_D$ linear fitting over the bias current ranges considered in Fig. 2. In Table I we summarize the calculated $\eta(T)$ valid for the temperature range $T = 293$ K up to 573 K, in good agreement with (3). It is worth noting that the maximum variation of η with T in the considered current range ($I_{D1} = 180\ \mu$A, $I_{D2} = 7.7$ mA) is 1.5% leading therefore to a highly linear temperature sensor.

To evaluate the mismatch between the calculated linear best-fit and the experimental measurements, the rmse was first calculated and subsequently converted into a temperature error.

A detailed analysis of the device performance is shown in Fig. 3, where the sensitivity, S, the coefficient of determination, R^2, and the corresponding average error for the considered temperature range, e_T, is shown for different values of the current ratio, r, and for a bias current I_{D1} of 420 μA.

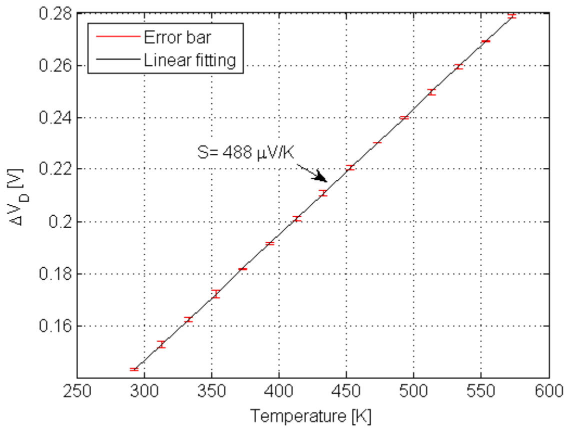

Fig. 4. Linear fit and rms error bar of $(V_{D2} - V_{D1})$ *vs.* T for the four diode pairs. The five measurement cycles, from (up to) 293 K up to (from) 543 K, were done in different days. The bias currents are the same for all PTAT sensors, $I_{D1} = 420\ \mu$A and $I_{D2} = 6.9$ mA.

As r increases the PTAT sensor output exhibits a much higher sensitivity in agreement with (3).

For $r = 16.5$ ($I_{D2} = 6.9$ mA), e_T reaches its minimum, $e_T = 0.9$ K, corresponding to 0.3% over the whole temperature range.

It is worth noting that our sensor shows a very good linearity, always above $R^2 = 0.995$, with an average value of 0.9984 and a standard deviation of 0.0015.

Finally, four different couples of diodes, from two different microchips, were characterized to evaluate the sensor reproducibility by iteratively repeating for five times the same cycles of measurements, from (up to) 293 K up to (from) 543 K, also in different days. Results are summarized in Fig. 4, for $I_{D1} = 420\ \mu$A, and leaded to a calculated mismatch among the different sensors always lower than $\pm 1.1\%$. Moreover, the coefficient of determination is $R^2 = 0.9997 \pm 2 \times 10^{-4}$ and the corresponding sensitivity is $S = 494\ \mu$V/K with a standard deviation of 13 μV/K.

IV. CONCLUSION

In this letter, a PTAT sensor based on integrated 4H-SiC p-i-n diodes was characterized. Measurements showed both a very good degree of linearity and a high sensitivity ($S = 610\ \mu$V/K) in the temperature range 293-573 K.

The proposed PTAT sensor output is independent of the saturation current, has the advantage of being calibratable in just one temperature point and shows a good repeatability maintaining a stable output over different cycles of measurements.

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