High-performance temperature sensor based on 4H-SiC Schottky diodes

Sandro Rao, Giovanni Pangallo, Fortunato Pezzimenti, Francesco G. Della Corte

***Abstract*—A high-performance temperature sensor based on coupled 4H-SiC Schottky diodes is presented. The linear dependence on temperature of the difference between the forward voltages appearing on two diodes biased at different constant currents, in a range from 30 °C up to 300 °C, was used for temperature sensing. A high sensitivity of 5.11 mV/°C was measured. This is, to the best of our knowledge, the first experimental result about a proportional-to-absolute-temperature sensor made with SiC diodes, showing both a good degree of linearity and long-term stability performance.**

***Index Terms*—Schottky diodes, Silicon carbide, Temperature sensors, Wide band gap semiconductors.**

I. Introduction

Temperature measurements in hostile environments, in particular at high temperatures, are of great interest to many industries. Among the different types of temperature-sensing devices, semiconductor diode- or transistor-based sensors have the advantages of high sensitivity and compatibility with electronic integrated circuits (ICs).

Temperature sensors made of silicon (Si) are the most common devices thanks to the low cost fabrication processes, fully compatible with the CMOS technology.

However, the physical properties of silicon degrade when high thermal budgets are involved making Si-based devices not suitable for temperatures exceeding about T=130°C [1].

In this context, silicon carbide (SiC), gallium nitride (GaN) and other wide band-gap (E_g) materials seem to be the most promising candidates for applications in hostile or harsh environments with respect to Si and other related materials [2,3].

In particular, SiC (E_g=3.2 eV) has received remarkable attention during the last decade as a useful material for high power applications due to its high thermal conductivity (3-5 W/cm°C) and high critical electric field for breakdown setup (E_c=2-5 MV/cm) [4-6].

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In this letter we present, to our knowledge, the first experimental results about a PTAT (proportional to absolute temperature) sensor obtained by using twin 4H-SiC Schottky diodes (Fig. 1) integrated on the same chip. The temperature sensor was characterized in a temperature range from 30 °C up to 300 °C showing at the same time a very good level of linearity and a high sensitivity (*S*=5.11 mV/°C).

To date, similar high temperature sensors are based on a single 4H-SiC diode [6-8]. This technique requires the accurate knowledge of the non-linear behavior with temperature of the saturation current in order to find an explicit relationship between voltage and temperature. All of these simple devices reported in literature exploit the almost linear dependence of the forward voltage (or reverse current) on temperature, showing sensitivities not higher than *S*=3.5 mV/°C (5 μA/°C) and relatively poor linearity.

II. Device Structure

The 4H-SiC PTAT sensors were fabricated at the Institute for Microelectronics and Microsystems-CNR, Unit of Bologna (Italy). The schematic cross section is shown in Fig. 1(b) together with the geometrical dimensions. The vertical Schottky diodes have been fabricated on a 300 μm-thick <0001> 7°62' off-axis n-type homoepitaxial 4H-SiC commercial wafer with a measured conductivity of 0.021 Ω·cm.

The fabrication process involves standard steps and commercial materials to ensure reproducibility of results.

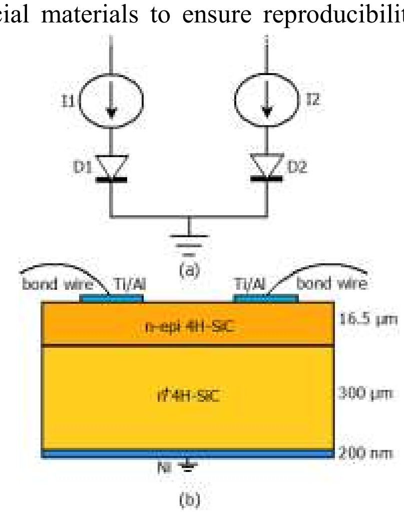

Fig. 1. (a) Electrical circuit of PTAT sensor; (b) Schematic cross section of integrated 4H-SiC Schottky diodes. Plot not in scale.

The 16.5 µm-thick and lightly n-doped (N=3×10^{15} cm^{-3}) epi-layer was grown with an industrial process on a commercial 4H-SiC substrate [9]. Sputter deposition was subsequently used to deposit a 200 nm-thick Ti/Al metal contact. Standard photolithography and wet chemical etching were used to pattern square, 150×150 µm^2, Schottky contacts, spaced each other by about 155 µm. Finally, a 200 nm-thick Ni film was deposited on the back side to form the cathode contact, and an annealing process was performed in vacuum at 1000 °C for 2 min [10,11].

The device surface was unpassivated, and measurements were conducted in air. However, in an optimized design, the formation of a passivation layer and the adoption of round contacts should be considered to improve reliability through control of the detrimental effects of both surface oxidation and uneven current distribution due to edge effects.

The sensor chip contains four diodes, showing almost identical I-V characteristics, as they share the same substrate and epi-layer. The chip was packaged and the contacts were bonded with aluminum wires, 50 µm in diameter, to a custom printed circuit board (PCB) on which the back contact of the PTAT sensor was connected with a silver conductive paint.

III. Experimental Results and Discussions

As is well known, the voltage drop V_D across a forward-biased diode at a given applied current I_D is obtained through the following formula:

$$V_D = \frac{kT}{q}\eta \ln\left(\frac{I_D}{I_S}\right) + R_s I_D \tag{1}$$

where η is the ideality factor, R_s is the parasitic series resistance, I_s is the saturation current, q is the electric charge and k is the Boltzmann constant.

In our setup, the Schottky diodes D$_1$ and D$_2$, with identical I-V characteristics, were biased with two known currents I_{D1} and I_{D2} (Fig. 1(a)), kept constant over the entire temperature working range. The difference between the diode voltages $(V_{D2}$-$V_{D1})$ is related to temperature T according to the following equation:

$$V_{D2} - V_{D1} = \frac{kT}{q}\eta \ln\left(\frac{I_{D2}}{I_{D1}}\right) + R_s(I_{D2} - I_{D1}) \tag{2}$$

Here, if the product $R_s(I_{D2} - I_{D1})$ is negligible and η is constant, the voltage difference $(V_{D2}$-$V_{D1})$ is proportional to T.

In principle, the sensor sensitivity S, namely the temperature derivative of (2), can be made very high by controlling the ratio r=I_{D2}/I_{D1}. However, with real Schottky diodes it is difficult to obtain, at the same time, a high sensitivity and a linear output in a wide temperature range.

The fabricated sensors were tested in a thermostatic oven (Galli G210F030P) setting the reference temperature through the internal digital PID microcontroller. The forward I_D-V_D characteristics in a range from 30 °C up to 300 °C, measured using a Semiconductor Parameter Analyzer (Agilent 4155C), are shown in Fig. 2. Although the specific setup and packaging adopted do not allow a reliable characterization above 300 °C, it is expected that the sensor can be operated at much higher temperatures [6,7]. It is worth noting thatthe curves cross the same I-V point, a typical behaviour for Schottky diodes [12].

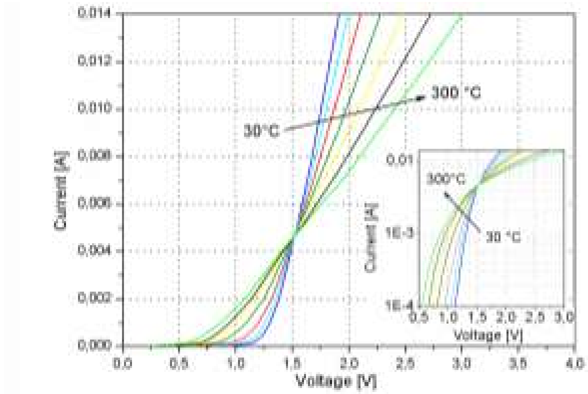

Fig. 2. Forward current-voltage *(I-V)* characteristics for temperatures ranging from 30 °C up to 300 °C. The inset shows a detail of the *I-V* characteristics in semi-log scale.

In our analysis, the coefficient of determination (R^2) [13] was evaluated to assess the agreement between the experimental measurements and their linear best fit. In particular, R^2 quantifies the correlation of the sensor output to a straight linear line.

The voltage difference $(V_{D2}$-$V_{D1})$ between two diodes (Fig. 1(b)), simultaneously measured in a range from (up to) 30 °C up to (from) 300 °C, for three consecutive scans, are shown in Fig. 3 together with their linear fitting model. In particular, the data is shown for five values of r= I_{D2}/I_{D1}.

The plot shows that the voltage difference increases with temperature. All of the characteristics show a good degree of linearity (R^2 > 0.998) for I_{D1} ranging from 0.5 mA up to 1.3 mA and for different current ratios, r.

As reported in Fig. 3, for I_{D1}=1.3 mA and r=4.9, the calculated sensitivity is S=2.85 mV/°C, increasing for higher r and lower bias currents I_{D1}. For r=18.4 and

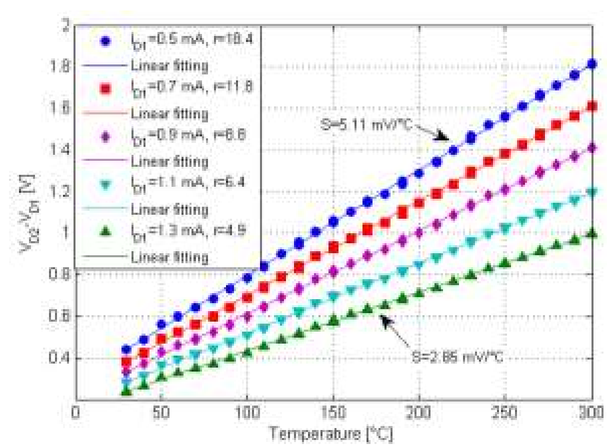

Fig. 3. Measured (symbols) and modelled (lines) voltage difference *vs.* temperature at different bias currents I_{D1} and current ratio r=I$_{D2}$/I$_{D1}$.

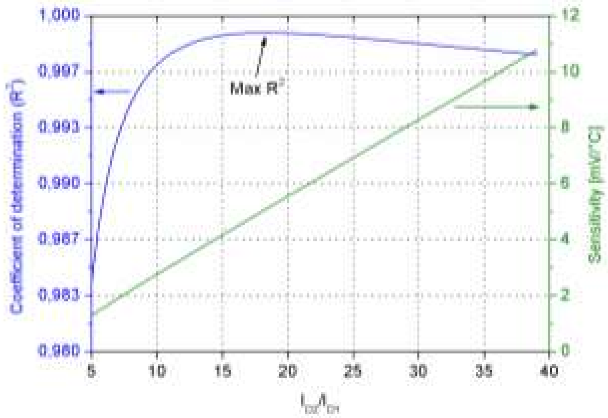

Fig. 4. Coefficient of determination and sensitivity vs. current ratio for I_{D1}=0.5mA, calculated in the temperature range from 30°C to 300°C .

I_{D1}=0.5 mA we get S=5.11 mV/°C. Here the sensor shows its maximum linearity with $R^2\approx0.999$, corresponding to a r.m.s. error of ±0.6°C.

An extended analysis is reported in Fig. 4, showing both R^2 and S for different values of the current ratio (I_{D2}/I_{D1}) and for a bias current I_{D1} of 0.5 mA. It can be noted that, after reaching its maximum for I_{D2}= 9.2 mA, the coefficient of determination R^2 decreases. At these high current levels, well above the crossing point of Fig. 2, the series resistance drop term of (2) is not negligible. In fact, R_s values varying from 38 to 139 Ω were estimated (1) from high current measurements in the temperature range of interest. The worsening of R^2 at high currents, shown in Fig. 4, demonstrates that R_s is itself nonlinear with T.

At lower currents, and in particular below the crossing point, where $R_s(I_{D2}-I_{D1})$ is negligible, the sensor output shows a low R^2 due in turn to the nonlinear behavior of $\eta(T)$.

Compensation between the nonlinear behaviors of R_s and η with temperature is exploited in order to maximize the sensor linearity while preserving a high sensitivity. The best tradeoff is obtained for r between ~13 and ~25, resulting in $R^2\geq0.999$ and $S\geq3.7$ mV/°C. It is worth noting that I_{D1} and I_{D2} lay respectively below and above the crossing point, a circumstance that increases sensitivity because V_{D2} increases while V_{D1} respectively decreases with T, as is evident from Fig. 2.

Four different couples of diodes were characterized and their long-term stability tested, in order to evaluate their reproducibility and how consistently they maintain a stable output over time, by iteratively repeating the same cycles of measurements, from (up to) 30 °C up to (from) 300 °C, in different days.

The results are summarized in Fig. 5, and leaded to a calculated maximum r.m.s. error of less than ±1.5%. Moreover, the coefficients of determination is $R^2 = 0.9993 \pm 2 \times 10^{-4}$ and the corresponding sensitivity is S = 5.02 mV/°C with a standard deviation of 0.18 mV/°C.

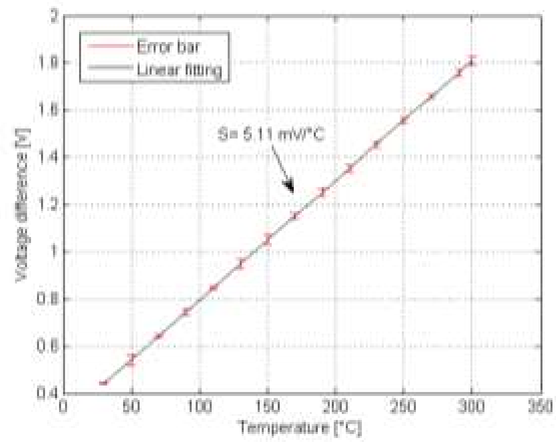

Fig. 5. Linear fit and r.m.s. errors of *(V_{D2}-V_{D1}) vs. temperature* for four sensor pairs. The measurement cycles, from (up to) 30 °C up to (from) 300°C, were done in different days. The bias currents are the same for all the PTAT sensors, I_{D1}=0.5 mA and I_{D1}=9.2 mA.

IV. Conclusion

A high temperature sensor based on two integrated 4H-SiC Schottky diodes was fabricated and characterized. Measurements, performed in a temperature range from 30°C up to 300°C, showed both a very good degree of linearity ($R^2\approx0.999$) and a high sensitivity (S=5.11 mV/°C). The achieved results are, to our knowledge, the best values ever reported for integrated sensors operating in similar wide range of temperatures. Moreover, the proposed PTAT sensor showed a good repeatability, maintaining a stable output over different cycles of measurements taken in different days.

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