A V_2O_5/4H-SiC Schottky diode-based PTAT sensor operating in a wide range of bias currents

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Abstract

A proportional to absolute temperature sensor (PTAT) based on V_2O_5/4H-SiC (vanadium pentoxide/4H polytype of silicon carbide) Schottky diodes is presented. The linear dependence on temperature of the voltage difference appearing at the terminals of two constant-current forward-biased diodes has been used for thermal sensing in the wide temperature range from T=147 K to 400 K. The proposed sensor shows a sensitivity of 307 µV/K, a good reproducibility and a stable linear output also in case of deviation of the two bias currents from the best operating condition.

Keywords: Schottky diodes, Sensor system and applications, Silicon carbide, Silicon compounds, Temperature sensors.

1. Introduction

In the last few years 4H-SiC (4H polytype of silicon carbide) diodes have been widely explored for high-temperature thermal sensing [1-5]. The main advantage of these devices is the high linearity of the voltage-temperature characteristic and the long-term stability.

In a previous work, we presented a proportional to absolute temperature (PTAT) sensor consisting of two Schottky diodes with Ti/Al metal contacts [6]. The maximum sensitivity was achieved by biasing the diodes at well precise currents in their linear (resistive) region. However, in this bias range the non-linear contribution of the series resistance, R_s, can affects the diode sensor performances and, to minimize its impact, the diodes have to be biased in the exponential region of the *I-V* characteristics where R_s can be considered negligible [7-9].

To date, many works reported in literature on temperature sensors are based on SiC Schottky diodes with Ni [2-4] or Ti/Al contacts [6, 7]. Although different materials have been used to fabricate 4H-SiC-based Schottky diodes [10-12], a thin layer of vanadium pentoxide (V_2O_5), 5 nm-thick, was recently proposed as an alternative contact [13-14]. It has been shown that V_2O_5/4H-SiC Schottky diodes have a rectifying behavior with a quasi-ideal characteristic, being the ideality factor close to 1, and a wide temperature range (T=100-425 K) stability [13].

Its technological advantage is the limited thermal budget involved in the annealing process, which is about 150 K lower than that typically used for conventional 4H-SiC metals, e.g. Ni [15]. This allows to fabricate Schottky-diode sensors at the end of an integrated circuit realization process flow.

In this letter, the performance of a PTAT sensor based on integrated V_2O_5/4H-SiC Schottky diodes is investigated. In particular, sensitivity, linearity, root mean square error (*rmse*) and repeatability are accurately analyzed in a wide range of temperatures ($147 \leq T \leq 400$ K) and currents.

2. Device Structure and experimental set-up

The fabricated Schottky diodes consist of a 5 µm−thick $(8.8 \pm 2.2) \times 10^{15}$cm^{-3} n-doped epilayer, grown on a <0001> 4° off-axis Si-face, 350 µm-thick and ρ~21 mΩ×cm n^+ 4H-SiC substrate, as schematically shown in Fig. 1. The technological process steps are well reported in Ref. [13]. A shadow mask was explored to form circular V_2O_5/Al dots of 500 µm in diameter, the distance between the two devices is 1 mm, which allows to neglect

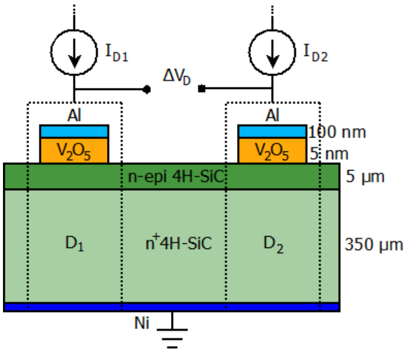

Fig. 1. Electrical circuit of the PTAT sensor. Drawing not to scale.

crosstalk effects among them.

In our setup, two Schottky diodes, D_1 and D_2, with almost identical I_D-V_D-T characteristics (maximum *rmse*=1.01×10^{-5} calculated over the full bias range from 1 µA to 1 mA) and same ideality factor ($\eta_1(I_D,T)\sim\eta_2(I_D,T)=\eta$), were driven by two external and independent current sources, providing constant I_{D1} and I_{D2} currents (Fig. 1).

The difference between the voltage drops across the two diodes (ΔV_D) is given by the following equation [6]:

$$\Delta V_D = V_{D2} - V_{D1} = \frac{kT}{q}\eta\, ln(r) + R_S(I_{D2} - I_{D1}) \tag{1}$$

where $V_{D1,2}$ are the diode voltage drops for D_1 and D_2, respectively, R_s is the series resistance, q the electron charge, T the absolute temperature, k the Boltzmann constant and $r=I_{D2}/I_{D1}$ is the bias currents ratio.

The 4H-SiC/V_2O_5 Schottky diodes are biased in the exponential region of their I-V characteristics to reduce the contribution of $R_S\cdot(I_{D2}-I_{D1})$ and, therefore, to increase the sensor linearity in a widest range of bias currents [6]. In such way, ΔV_D is linearly proportional to T for a fixed r and assuming η almost constant. This last assumption will be validated below.

Experimental measurements were performed through a Janis Research Inc. cryo−system [16]. Measurements were conducted in vacuum at a pressure lower than 5×10^{-6} mbar and a Lake Shore Cryotonics Inc. 335 temperature controller was used to automatically control the temperature from 147 to 400 K and vice-versa. A reference sensor (Lake Shore Cryotonics Inc. DT-670B-SD silicon-diode [17]), with an accuracy of ±0.032 K up to 305 K and ±0.33% T (i.e. ±1.4 K at T=440 K) for higher temperatures, was placed in thermal contact with the 4H-SiC microchip in order to monitor the true chip temperature. Another sensor (DT-670B-CU-HT), placed on the sample stage, was used to control the thermal stability of the overall equipment. Each measurement was taken several minutes after the temperature was set in order to be sure about the system thermal stability.

The external current sources used to bias the 4H-SiC Schottky diodes were provided by an Agilent HP4155B Semiconductor Parameter Analyzer. For the considered current range (1 A< I_D<1 mA) the instrument provides a resolution of 10 nA and an accuracy of ±12 nA [18].

3. Results

In the inset of Fig. 2, I_D-V_D characteristics are reported for the temperature range 147-400 K. By using the extraction procedure of [1], in the evaluated temperature range, η remains almost constant with a mean value of around 1.05 and a standard deviation lower than 0.02. As previously mentioned, this result confirms the highly linearity of the output characteristic of the ΔV_D-T sensor.

The best linear fittings, $f_L(T)$, of the ΔV_D *vs.* T experimental points obtained in three cycles of measurements in a range from (down to) T=147 K up to (from) 400 K are reported in Fig. 2. In particular, D_1 was biased with I_{D1}=16 µA, where the 4H-SiC diode, previously characterized as single-diode temperature sensor, showed its best behavior, whilst I_{D2} was varied from 44 µA to 1 mA. The plot of Fig. 2 shows that ΔV_D and T are linearly dependent each other in the considered wide temperature range. To mathematically evaluate the sensor linearity, we calculated the coefficient of determination (R^2) that allows to quantify how much the experimental points deviate from the best-linear regression [19]. The corresponding sensitivities were calculated from the slope of the ΔV_D *vs.* T characteristics. In all cases shown in Fig. 2 (I_{D1}=16 µA; $2.75<r<62.5$) the sensor has a good degree of linearity. The sensitivity reaches its lowest value for I_{D2}=44 µA (S=84 µV/K)

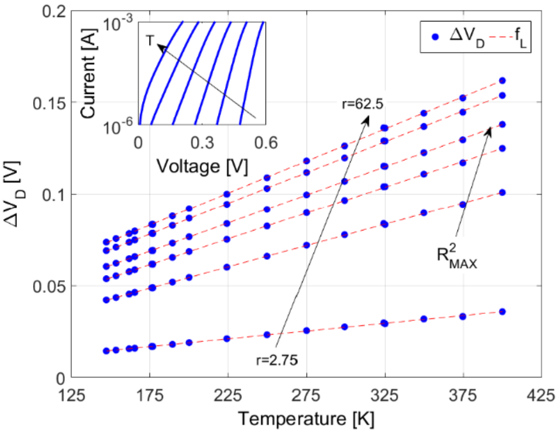

Fig. 2. Measured (points) V_D-T for I_{D1}=16 µA and different current ratios r (2.75, 15.75, 28.25, 38, 53.25, 62.5). The dashed lines are the best linear fits, $f_L(T)$, of the experimental data. The inset shows the *I-V-T* characteristics in semi-log scale, in the temperature range 147 to 400 K.

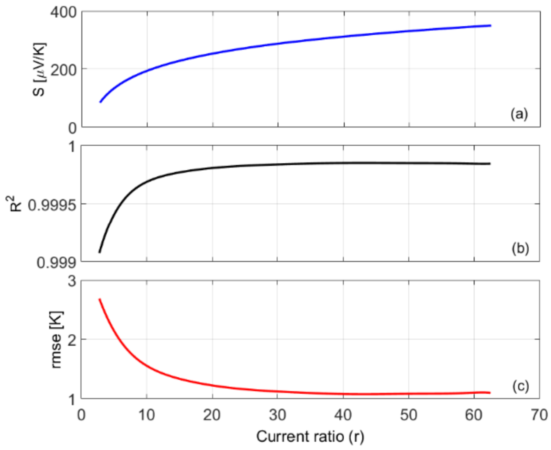

Fig. 3. (a) Sensitivity, (b) coefficient of determination and (c) rmse, vs. current ratio for I_{D1}=16 µA, calculated in the temperature range from 147 K to 400 K

and increases for higher r. For I_{D2}=1 mA we get the highest sensitivity, S=350 µV/K.

The calculated values of S and R^2 are reported in Fig. 3(a) and (b) for the considered bias currents. It is worth noting that our sensor shows a very good linearity, always above R^2=0.99900, with an average value of 0.99979 and a standard deviation of 1.22×10^{-4}. The maximum of R^2=0.99987 occurs for I_{D1}=16 µA and I_{D2}=608 µA (r=38), corresponding to a sensitivity S=307 µV/K. Moreover, the proposed PTAT device presents a linearity almost constant for 34.5<r<59 (Fig. 3(b)) leading, therefore, to a highly linear output also for large unwanted bias currents variations as better detailed in the following.

To evaluate the mismatch between the calculated linear best-fit, $f_L(T)$, and the experimental data, the corresponding root mean square error (*rmse*) was first calculated and subsequently converted into a temperature error value as reported in Ref. [1]. The plot, *rmse vs. r*, for the considered temperature range is reported in Fig. 3(c). The temperature error is always lower than 1%, while a minimum *rmse* of 1.08 K is obtained for r=38.

In our experimental setup, the measured voltage resolution is 2 µV [18] leading to a theoretical device resolution of 6.5 mK, calculated as the ratio between the instrument voltage resolution and the sensitivity of the sensor.

To assess the sensor output stability with respect to the external bias currents variability, R^2 was calculated for all the possible pairs of I_{D1} and I_{D2}, as reported in Fig. 4. As shown, R^2 is ~1 over a wide currents range, in particular for 13 µA<I_{D1}<300 µA and 40 µA<I_{D2}<1 mA. In other words, this allows the sensor to maintain its linearity also in case of variation of both the two bias currents from the best operating condition (I_{D1}=16 µA and I_{D2}= 608 µA). In example, if we consider a large variation of I_{D1} (16±1 µA, *i.e.* ±6.25%), maintaining the same current ratio, r=38, the absolute percentage error between the best case and the experimental points

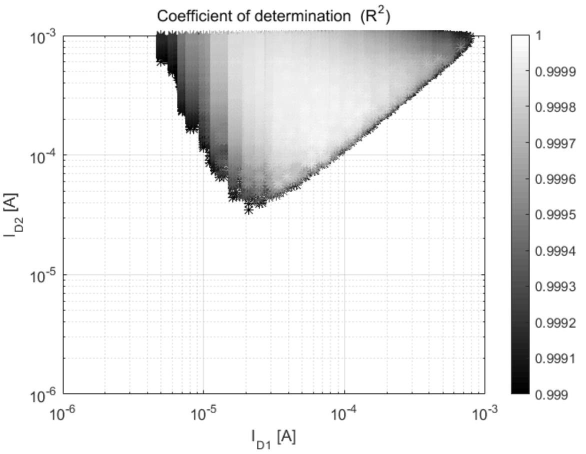

Fig. 4. R^2 for different values of the diode bias currents (I_{D1},I_{D2}).

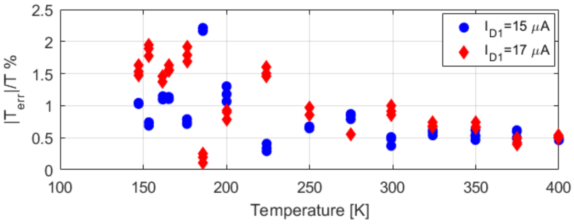

Fig. 5. Absolute percentage error between the linear fitting in the best case (I_{D1}=16 µA) and the voltage difference, ΔV_D, for I_{D1}=15 and 17 µA for r=38

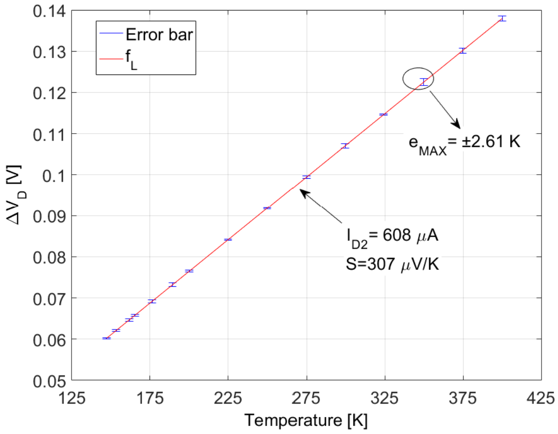

Fig. 6. Linear regression and *rms* error bar of ΔV_D *vs.* T for four diode pairs. Five cycles of measurements, from (down to) 147 K up to (from) 400 K, were done in different days in about one month. The bias currents are the same for all PTAT sensors, I_{D1}=16 μA and I_{D2}=608 μA.

obtained for (I_{D1}=15 μA, I_{D2}=570 μA) and (I_{D1}=17 μA, I_{D2}=646 μA) is always lower than 2.5% of the considered temperature. A plot is reported in Fig. 5 for the three cycles of measurements in a range from (down to) T=147 K up to (from) 400 K. The mean absolute percentage error (MAPE), calculated from all of the values reported in the graph, is about 0.9%.

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 (down to) 147 K up to (from) 400 K, in different days for about one month. All of the results are summarized in Fig. 6, always for I_{D1}=16 μA and I_{D2}=608 μA; the calculated mismatch among different measurements and sensors is always lower than ±1.04%. The coefficient of determination is R^2=0.99928±4×10^{-4} and the corresponding sensitivity is S=307 μV/K with a standard deviation of 11 μV/K.

5. Conclusion

In conclusion, the characterized PTAT sensor based on 4H-SiC/V_2O_5 Schottky diodes showed a high linearity, a good reproducibility and a small sensitivity of the output to bias currents variations. Those performances, in conjunction with a fabrication process allowing a more easy integration in an integrated circuit process flow, make the proposed sensor very competitive for different industrial applications.

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