Sensors and Actuators A 269 (2018) 171–174

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

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

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ARTICLE INFO

Article history:
Received 1 February 2017
Received in revised form 4 November 2017
Accepted 10 November 2017
Available online 13 November 2017

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

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 which extends down the state-of-the art of more than 80 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.

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].

In particular, as reported in [13], the rectifying behavior of Al/V_2O_5/4H-SiC stack is due to the presence of a Schottky potential barrier at the V_2O_5/4H-SiC interface induced by the difference between the V_2O_5 work function (in the range between 4.7 and 5.3 eV [15,16]) and the 4H-SiC electron affinity. Such evidences are supported by experimental measurements of *I-V*/*C-V* characteristics under light excitations at different temperatures and justified by physical-based analytical models [14]. Moreover, the ideality factor of *I-V* curves results close to one and, in [13], it has been ascribed to a low density of inhomogeneities at the Schottky contact [17]. Indeed, the interface quality among the materials can induce a spatial variation of the value of potential barrier height along the whole contact and, moreover, a variation of the ideality factor value from the unity.

From a technological point of view, the main advantage is the limited thermal budget involved in the V_2O_5 annealing process, which is about 150 K lower than that typically used for conventional 4H-SiC metals, e.g. Ni [18]. This allows to fabricate Schottky-diode sensors at the end of an integrated circuit realization process flow. However, Al/V_2O_5/4H-SiC Schottky diodes cannot operate at temperatures higher than 425 K [13] due to a lower Schottky Barrier (SB) Height with respect to Ni or Ti 4H-SiC SB devices.

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https://doi.org/10.1016/j.sna.2017.11.026
0924-4247/

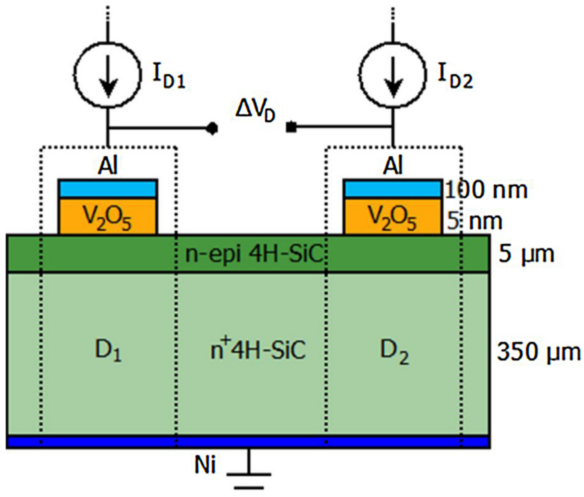

Fig. 1. Electrical circuit of the PTAT sensor. Drawing not to scale.

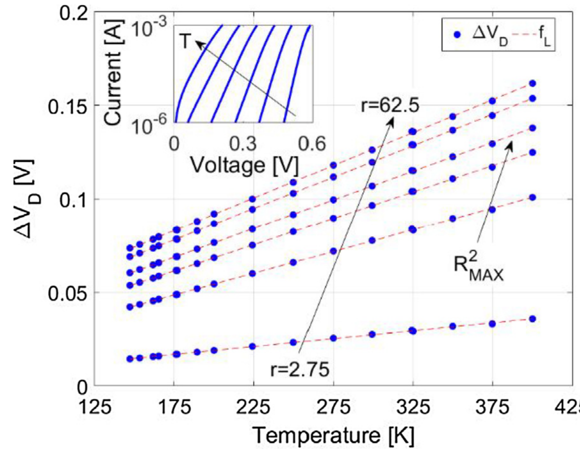

Fig. 2. Measured (points) V_D-T for I_{D1} = 16 μA and different current ratios r (2.75, 15.75, 28.25, 38, 53.25, 62.5). The dashed lines are the best linear fits, $f_L(T)$, of the experimental data. The inset shows the I-V-T characteristics in semi-log scale, in the temperature range 147–400 K.

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.

If compared to Si technologies [19–22], the performance of SiC-based Schottky diodes exceed that of Si-based counterparts in particular for applications requiring high-temperature and high-power. In this work, the realized sensor extends-down the operating temperature range ($\Delta T = 253$ K), with a high sensitivity ($S = 307$ μV/K), therefore it is particularly suitable for applications at very low temperatures, i.e., full military, automotive, extended industrial and avionic applications.

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 $\rho \sim 21$ 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 crosstalk effects among them. Indeed, considering that the lateral contribution of the current is due to the majority carriers diffusion, the electron diffusion length is less than 6 μm for our devices [14] and, therefore, a minimum distance of about 120 μm is enough to avoid the mutual effects on the electrostatic potentials among devices.

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]:

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

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 [23]. 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 [24]), 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 μA < I_D < 1 mA) the instrument provides a resolution of 10 nA and an accuracy of ±12 nA [25].

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 [7], 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 ($\Delta T = 253$ K). 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 [26]. The corresponding sensitivities were calculated from the slope of the