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ScienceDirect

Procedia Engineering 168 (2016) 1003 – 1006

Procedia Engineering

www.elsevier.com/locate/procedia

30thEurosensors Conference, EUROSENSORS 2016

Divanadium pentoxide/4H-silicon carbide: a Schottky contact for highly linear temperature sensors

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Abstract

A new temperature sensor based on a divanadium pentoxide/4H-silicon carbide (V_2O_5/4H-SiC) Schottky diode is presented. The realized device shows a good linear dependence vs. temperature of the voltage drop measured across the forward-biased junction. The diode performance, i.e. linearity and sensitivity, were analyzed in the temperature range from 147 K up to 400 K. Moreover, fundamental diode parameters were extracted from current-voltage characteristics.

*Keywords:*Silicon carbide, Schottky diode, temperature sensor.

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1. Introduction

The favorable physical properties of 4H-Silicon Carbide (SiC), if compared to silicon (Si) and other semiconductors enable SiC devices to support high current and voltage, also at high temperature [1-5]. In fact, during the last years, 4H-SiC based diodes have received remarkable attention as promising temperature sensing devices for harsh environment applications [6-12]. The advantage of diode-based temperature sensors, if compared with other sensors that can be on-chip integrated, e.g., thermistors, are the compatibility with IC technology, the low manufacturing costs, the quasi-linear output characteristic, preserving at the same time a high sensitivity [13-14].

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doi:10.1016/j.proeng.2016.11.326

In this work we present a high performance single diode integrated temperature sensor based on V_2O_5/4H-SiC Schottky diode [15-16]. Compared to other metallic Schottky contacts, the thin layer of V_2O_5 can be deposited at relatively low temperatures, i.e. 723 K, with respect to those typically used for Ni, i.e., around 870 K [17]. The sensor sensitivity, together with the linearity of the V_D-T output characteristics, were analyzed in a wide range of bias currents, and temperatures from 147 K to 400 K. Moreover, the main physical diode parameters, such as ideality factor (η) and Schottky barrier height (Φ_B), were calculated from *I-V-T* measurements.

2. Temperature sensor

2.1. Device structure

The schematic Schottky diode structure is reported in Fig. 1. It consists of a lightly n-doped ($N=8.8\times10^{15}\pm2.2\times10^{15}cm^{-3}$), 5 µm-thick, epi-layer grown with an industrial process on a 350 µm-thick commercial 4H-SiC substrate. The thermal evaporation of 5 nm-thick V_2O_5 (99.99% powered) layer was followed by the deposition of an Aluminum metal contact, 100 nm-thick, patterned through a shadow mask in circles of 500 µm in diameter, to form the anode contacts. Subsequently, the wafer was annealed at 723 K in Nitrogen environment for 10 min. Finally, a thin film of Ni was deposited on the n^+ cathode to form the back contact.

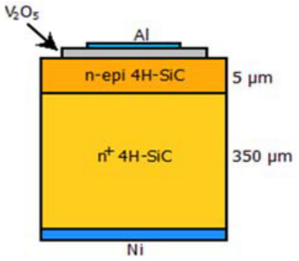

Fig. 1. Schematic cross section of integrated V_2O_5/4H-SiC Schottky diode.

2.2. Theory

As well known, according to the Boltzmann statistic, the I_D diode current 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 Schottky diode was biased with a current I_D kept constant in the temperature range from 147 K up to 400 K. I_s can be expressed as:

$$I_S = AR^{**}T^2e^{\frac{-q\Phi_b}{kT}} \tag{2}$$

where R^{**}(R^{**}=146 A·cm^{-2}·K^{-2} for 4H-SiC [18]) is the Richardson constant and $q\Phi_B$ is the Schottky barrier height.
For $qV_D >> \eta kT$ and for a diode current range in which ohmic effect is negligible, the voltage dependence on temperature can be obtained from (1), as follows:

$$V_D = \eta\Phi_B + \frac{kT}{q}\eta\ln\left(\frac{I_D}{AR^{**}T^2}\right) \tag{3}$$

The equation (3) allows an indirect temperature measurement after the diode parameters extraction.

2.3. Diode parameters extraction

The devices were tested in a Janis Research Inc. cryo-system and several temperature ramps were performed from 147 K to 400 K and vice-versa. The SiC microchip temperature was accurately monitored by using two Lake Shore Cryotonics Inc. silicon-diodes. In our setup, the dc bias current I_D was varied in a range from 1 µA to 1 mA and the corresponding voltage drop V_D across the V_2O_5/4H-SiC Schottky diode was measured as reported in Fig. 2(a).

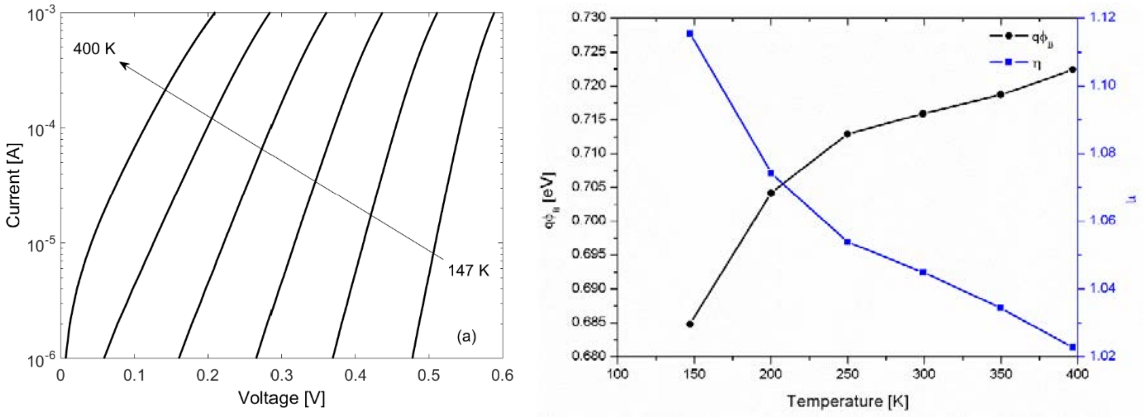

Fig. 2. (a) Current-voltage (I_D-V_D) characteristics in a temperature range T=147 K– 400 K. (b) Temperature dependence of ideality factor (η) and Schottky barrier height ($q\Phi_B$).

The ideality factor, η, and Schottky barrier height, $q\Phi_B$, are important parameters for semiconductor diodes to be taken into account, in particular for their correct characterization as temperature sensors. In particular, $q\Phi_B$ and η are calculated from the intercept with the vertical axis and from the slope of the $ln(I_D)$-V_D characteristics respectively. The obtained value are shown in Fig. 2(b). The ideality factor remains almost constant with temperature (η=1.05) with a standard deviation lower than 0.033, leading to a V_D-T sensor output characteristic highly linear.

2.4. Diode performance and simulation

In Fig. 3(a), experimental V_D-T curves at different bias currents are compared with a linear fitting. Thanks to an almost constant value of the ideality factor, V_D-T characteristics exhibit a very high degree of linearity in the whole considered temperature range. The sensor sensitivity (S) can be calculated from the slope of the experimental data linear fitting, resulting in $1.52<S<1.94$ mV/K. Moreover, in order to evaluate the agreement between the experimental measurements and the corresponding linear best-fit the coefficient of determination (R^2) has been calculated.

In Fig. 3 (b) and (c) are shown the calculated value of S and R^2 for different bias currents. The experimental characteristics show a good degree of linearity (R^2> 0.9995) for I_D≥4 µA. As reported , when I_D is 1 mA the sensitivity is 1.52 mV/K and monotonically increases up to 1.91 mV/K for I_D=5 µA. The maximum of R^2~0.99996 has been calculated for I_D=16 µA corresponding to a sensitivity S=1.86 mV/K.

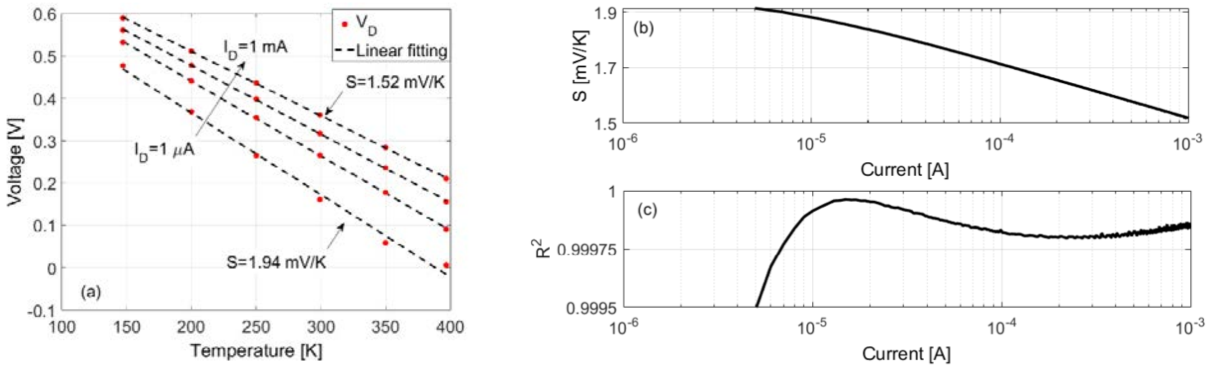

Fig. 3. (a) Measured (points) V_D-T for four I_D values and corresponding sensitivities. The dashed lines are the best linear fittings of the experimental data. (b) Sensitivity and coefficient of determination for bias currents from 5 μA to 1 mA.

3. Conclusions

In conclusion, the characterized sensor showed a good degree of linearity (R^2=0.99996) and a high sensitivity (S=1.86 mV/K) in a wide temperature range, from 147 K up to 400 K, for bias currents I_D~16 μA. The good physical characteristics, i.e. ideality factor η~1 at room temperature remaining almost constant during the thermal variations, allow to obtain a highly linear sensor with respect to those based on conventional Schottky contacts.

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