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The effects of high-energy proton irradiation on the electrical characteristics of Au/Ni/4*H*-SiC Schottky barrier diodes

E. Omotoso [a,b,*], W.E. Meyer [a], P.J. Janse van Rensburg [a], E. Igumbor [a], S.M. Tunhuma [a], P.N.M. Ngoepe [a], H.T. Danga [a], F.D. Auret [a]

[a] *Department of Physics, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa*
[b] *Department of Physics, Obafemi Awolowo University, Ile-Ife 220005, Nigeria*

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ABSTRACT

Au/Ni (20:80) Schottky barrier diodes (SBDs) were resistively evaporated on nitrogen-doped *n*–type 4*H*-SiC. Current-voltage (*I-V*) and capacitance-voltage (*C-V*) characteristics of the SDBs were investigated before and after bombardment with 1.8 MeV proton irradiation at a fluence of 2.0×10^{12} cm^{-2}. The measurements were carried out in the temperature range 40–300 K in steps of 20 K. Results obtained at room temperature (300 K) showed highly rectifying devices before and after bombardment. It was observed that the proton irradiation induced an increase of ideality factor from 1.05 to 1.13, a decrease in Schottky barrier height from 1.40 to 1.22 eV, an increase in series resistance from 10 to 66 Ω and a noticeable increase of the saturation current from 3.0×10^{-21} to 6.8×10^{-17} A. The increase in saturation current after proton irradiation was attributed to the presence of interfacial states created by irradiation-induced defects. Thermionic emission dominated the *I-V* characteristics in the temperature range 120–300 K but the *I-V* characteristics deviated from thermionic emission theory at temperatures below 120 K for devices both before and after irradiation. The variation of the SBDs characteristics with temperature was attributed to the presence of lateral inhomogeneities of the SBH. Modified Richardson constants were determined from a Gaussian distribution of barrier heights to be 133 and 165 A cm^{-2} K^{-2} before and after irradiation, respectively.

1. Introduction

A Schottky barrier diode (SBD) is a metal semiconductor device that is widely used where diodes with low forward voltage drop, junction capacitance and very fast switching speeds are required. This makes SBDs ideal for use as rectifiers in photovoltaic systems, high-efficiency power supplies and high frequency oscillators [1]. In addition, SBDs have important use in optoelectronics, high frequency and bipolar integrated circuits applications [2]. The reliability of the diodes depends on the quality of the metal-semiconductor (M-S) junction [3]. The performance of SBDs may be quantified experimentally in terms of ideality factor, Schottky barrier height (SBH), saturation current and series resistance. Among these properties of the M-S interface, SBH plays a major role in the successful operation of many devices in transporting electrons across the M-S junction [4]. To extract the SBH from the *I-V* characteristics, the value of the Richardson constant is needed.

The Richardson constant is one of the most important parameters in the thermionic emission theory of current transport across M-S junctions. Here, it is the proportionality constant in the relationship between the current and the voltage for the flow of electrons across the M-S junction. The theoretical value of the effective Richardson constant of 4*H*-SiC reported in literature is 146 A cm^{-2} K^{-2} [5], which differs significantly from the experimentally observed values due to various factors. The factors responsible for deviation may be small active area of devices and atomic or barrier inhomogeneities at the M-S interface, which are caused by defects, multiple phases and grain boundaries.

The 4*H* polytype of SiC has a wide band gap of 3.26 eV [6], and a promising material for vertical type high-voltage devices due to its higher bulk mobility and smaller anisotropy. Due to its capability to operate at a very high temperature, high power and high frequency, it is a suitable substrate material for producing high power, high frequency electronic devices. Also, due to its radiation hardness, SiC has many applications in radiation harsh environments, such as space, accelerator facilities and nuclear power plants [7]. The effects of radiation and temperature on semiconductor devices are scientifically significant for radiation sensing

* Corresponding author at: Department of Physics, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa.

E-mail address: ezekiel.omotoso@up.ac.za (E. Omotoso).

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applications, as well as technologically important for manufacturing processes and high temperature and high power applications [8].

Experimental and theoretical studies of defects in semiconductors have been reported [8–12], but room temperature *I-V* and *C-V* measurements characteristics alone cannot provide comprehensive information about the mechanisms responsible for the formation of a barrier at the junction of the M-S and electrical properties of SBDs [13]. More information about diodes is revealed by characterising them over a wide temperature range (40 – 300 K).

In the previous studies, the radiation hardness of some wide bandgap semiconductors, such as SiC, ZnO and GaN, that make them suitable for use in radiation environments has been studied [14]. We have reported the influence of alpha-particle and high energy electron irradiation on the electrical characteristics of 4*H*-SiC measured at different temperatures [8,12]. To the best of our knowledge, the effect of 1.8 MeV proton irradiations at fluence of 2.0×10^{12} cm^{-2} on Au/Ni/4*H*-SiC SBDS has not been reported.

In this work, we report the effect of 1.8 MeV proton bombardment on the electrical characteristics of nitrogen-doped, *n*-type 4*H*-SiC SBDs measured over a wide temperature range (40–300 K). The major aim of this work was to determine the extent to which the characteristics of Au/Ni contacts on *n*-type 4*H*-SiC would be affected by proton irradiations with 1.8 MeV measured at different cryogenic temperatures.

2. Experimental details

A nitrogen-doped, *n*-type 4*H*-SiC wafer supplied by Cree Research Inc. was used for this study. The epilayer was grown by chemical vapour deposition. It was polished on both sides with the Si-face epi ready with resistivity of 0.02 Ω-cm and doping density of 1.6×10^{16} cm^{-3}. Samples were cut into smaller sizes from the wafer. Before metallization of the ohmic contact on the highly doped side (1.0×10^{18} cm^{-3}) of the sample, degreasing and etching were carried out as described in Refs. [8,12,15,16]. Nickel ohmic contacts of 300 nm in thickness were thermally evaporated at a deposition rate of ~0.09 nm s^{-1} and vacuum pressure of ~2×10^{-5} mbar. The ohmic contacts were annealed in a quartz tube heated by a Linderberg Hevi-Duty furnace in flowing Ar at 950 °C for 10 min to reduce the contact (metal-semiconductor) resistance by the forming of nickel silicide. Prior to Schottky contact evaporation on the front (epi-layer) side of the samples, the samples were degreased as reported in Refs. [8,12,15,16]. Au/Ni Schottky contacts, 0.6 mm in diameter with a thickness of 200/800 nm, were thermally evaporated through a metal contact mask at very low deposition rate of ~0.02 nm s^{-1} and vacuum pressure of ~1×10^{-5} mbar.

The suitability of the contacts was tested immediately after evaporation by characterizing them using an *I-V* and *C-V* system comprising an HP 4140 B pA Meter/DC Voltage Source and an HP 4192A LF Impedance Analyzer, respectively. The characterization of the samples was done at room temperature and in the dark.

Thereafter, the sample was placed under vacuum in a closed cycle helium cryostat and the *I-V* and *C-V* measurements were carried out on a particular SBD in the temperature range of 40–300 K in intervals of 20 K under control of a program written in Labview™.

After *I-V* and *C-V* measurements, the same SBD was bombarded at room temperature under a high vacuum with 1.8 MeV protons from a Van de Graaff accelerator. The diode received a fluence of 2.0×10^{12} cm^{-2}. Immediately after proton irradiation, the contact quality was evaluated using current-voltage-temperature and capacitance-voltage-temperature measurements. The experiment was repeated on other diodes for confirmation of the results observed.

3. Results and discussion

3.1. Current-voltage characteristics

The suitability of the Au/Ni/4*H*-SiC contacts for temperature dependent *I-V* studies before and after proton irradiation was confirmed from the results obtained at room temperature as shown in Figs. 1. Some of the important electrical parameters such as ideality factor (n), Schottky barrier height ($\phi_{I\text{-}V}$), series resistance (R_s) and saturation current (I_s) obtained from the measurements are summarized in Table 1. The ideality factor determined from the slope of the linear region of the semi-log *I–V* characteristics was close to unity and the SBH evaluated from the intercept was relatively high, which shows that thermionic emission (TE) model sufficiently described the current flow from Au/Ni to 4*H*-SiC. We concluded that the Au/Ni/4*H*-SiC SBDs were highly rectifying and thus suitable for temperature dependent measurements. A significant deviation was observed after proton irradiation at fluence of 2.0×10^{12} cm^{-2}. The deviation was as a result of the increase of deep level defect density at the interface with irradiation [8,12,15,17].

Fig. 1 shows the semi-logarithmic forward bias *I-V* characteristics of the SBDs before and after proton irradiation measured over the temperature range 40–300 K. The plots before and after proton irradiation were linear up to a current of ~10^{-4} A, but deviated below 80 K. The deviation of the plots from linearity at high forward voltages may be due to series resistance caused by the interfacial layer between Au/Ni and 4*H*-SiC, and the bulk of the material. From Fig. 1, the *I-V* plots show lower current at lower temperature, which is in accordance with thermionic emission-diffusion theory [18]. It was also observed that the decrease of the forward bias current with decrease in temperature was less pronounced after irradiation, which was attributed to the presence of interfacial states created by irradiation-induced defects [15,19].

The linear part of the plots was fitted over the forward voltage range, where thermionic emission was the dominant transport mechanism. From the fits, the important electrical parameters that give better understanding of the devices performance at different temperatures were determined according to Eqs. (1) and (2) as reported in Refs. [3,8,12,20–22].

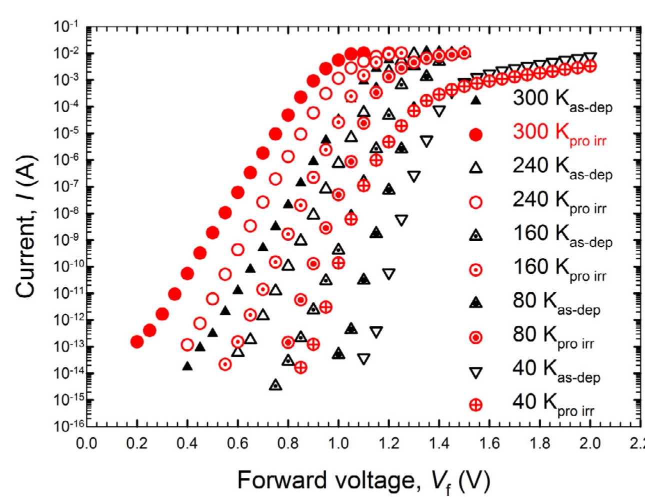

Fig. 1. Semi-logarithmic forward *I-V* characteristics of Au/Ni/4*H*-SiC Schottky diodes before and after proton irradiation at a fluence of 2.0×10^{12} cm^2, measured at different temperatures between 40 K and 300 K.