Electrical characterization of undoped and niobium-doped n-type silicon diodes

M J Thebe[1], S J Moloi[1 (a)] and M Msimanga[2]
[1] University of South Africa, Department of Physics, P.O. Box 392, Pretoria 0003, South Africa.
[2] Tshwane University of Technology, Department of Physics, Private Bag X 680, Pretoria 0001, South Africa.

Email: mohapit@vut.ac.za

Abstract. This work presents the effects of niobium impurities on electrical characteristics of silicon diodes. The work is carried out with the ultimate aim of improving radiation-hardness of silicon. Schottky diodes were fabricated on niobium- doped *n*-silicon substrates. The diodes were also fabricated on pure *n*-silicon for control purpose. The fabricated diodes were characterised by current-voltage and capacitance-voltage measurements. The diodes fabricated on niobium-doped *n*-silicon show Ohmic behaviour and low-voltage peak. These two features indicate that silicon has become relaxation material after doping with niobium. Relaxation material is radiation-hard since the effects of radiation on device based material are suppressed.

1. Introduction

The dominance of silicon in a wide variety of applications such as in high energy physics detectors, microelectronics, solar cells and photodiodes cannot be argued against [1]. This dominance is ascribed to well established methods that are available for manufacturing silicon into single crystals which make it cost effective when compared to other semiconductor materials. This study focuses on silicon diodes that are used as radiation detectors. When they are used continuously under harsh radiation environments, these detectors fail to operate efficiently [2]. The incident radiation damages the detectors and this result in a change in electrical characteristics of the devices [3]. The detector exhibits degradation in charge collection efficiency and increase in leakage current and in depletion voltage [4] after the damage. These changes are due to the defect levels that are created in the band gap of silicon material by incident particles [5]. It is then required that the characteristics of detectors are stable throughout their operational lifetime.

Defect engineering has been found to be an effective strategy to mitigate the failure experienced by detectors operating in harsh radiation conditions [6]. Defects in silicon, in this case, are intentionally introduced by metal doping or by irradiation before the fabrication of detector. Metals that have been used for doping are gold and platinum [7-10]. Erbium and niobium in silicon have been found to have similar effects as gold and platinum [11]. These metals create 'midgap defects' in the band gap of silicon and have been found to be responsible for making silicon radiation tolerant [7, 10]. Pre-irradiation, on the other hand, involves exposure of silicon material to heavy radiation prior to fabrication or processing of the devices for radiation detector [12]. Doping with metals and pre-irradiation generate defect levels in the energy gap that are responsible for relaxation behaviour of the material [10]. Relaxation material is radiation-hard and differs from lifetime material in terms of the magnitude of carrier lifetime. In relaxation material $\tau_D >> \tau_0$ while in lifetime material $\tau_D << \tau_0$ [13]. In these relations τ_D is dielectric relaxation time and τ_0 is the minority carrier lifetime. The work presented here aims to consolidate and build on studies presented earlier [9-11].

2. Experimental Details

A 7.62 cm diameter *n*-type silicon (111) oriented wafer was acquired from Semiconductor Wafer Inc. The resistivity of the wafer was quoted by the manufacturer as 1 - 20 **Ω**.cm and the thickness as 275± 25.0 µm. The wafer was diced into 0.5 cm x 0.5 cm pieces using a laser cutter. The standard procedure of cleaning silicon samples was followed [14]. After cleaning process the two pieces were mounted in the chamber for niobium implantation. The implantation was carried out using an ion implanter set up at iThemba LABS (Gauteng). Niobium was implanted onto the front (or polished) side of silicon pieces at an energy of 160 keV. The implanted dose was measured by Rutherford Backscattering Spectrometry (*RBS*) technique and found to be 0.93 x 10^{15} cm^{-2}[15]. A detailed material process has been outlined elsewhere [15] and will not be repeated here.

Devices in this study are silicon diodes that were fabricated on undoped and niobium-doped *n*-type crystalline silicon. Prior to diode fabrication, silicon pieces were cleaned using the standard procedure [14]. The pieces were then loaded into an evaporation system for formation of Schottky contacts. The contacts were achieved by evaporation and deposition of 100 nm palladium through a mask with 0.6 mm diameter holes. The deposition was carried at 10^{-6} mbar at the rate 1Å/s. The Ohmic contact was realised by rubbing Indium Galinide (InGa) onto the back (unpolished) surface of the pieces. The finished devices each consists of 16 diodes on a piece and with one common Ohmic contact.

3. Results and discussion

The fabricated diodes have been characterized by current-voltage (*I-V*) and capacitance (*C-V*) techniques in the dark and at room temperature. The current through the diode of series resistance, *R* is given [16] as

$$I = I_s\left[\exp\left(\frac{q(V-IR)}{\eta k_B T}\right) - 1\right] \qquad (1)$$

where I_S is the saturation current, q is the electronic charge, V is the applied voltage, η is the ideality factor, k_B is the Boltzmann constant, and T is the absolute temperature. The term IR in equation 1 is the voltage drop across R. The above equation indicates that the current varies exponentially with applied voltage. It can also be noticed from the equation that the magnitude of the current obtained in reverse bias is lower than the one obtained in forward bias at the same voltage.

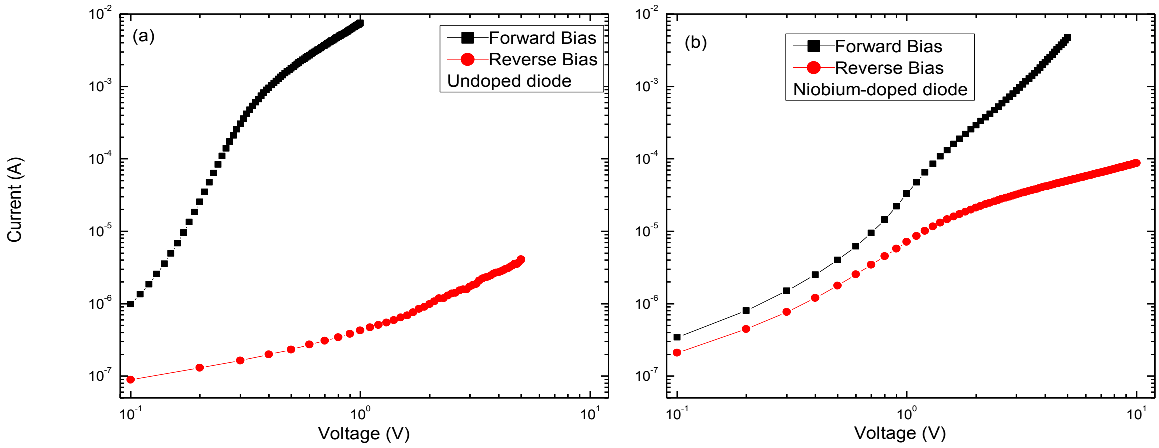

Figure 1: *The I-V characteristics of diodes fabricated on undoped (a) and niobium-doped (b) n-type silicon at 300 K.*

Figure 1 shows the *I-V* characteristics of the diodes fabricated on undoped and niobium-doped *n*-type silicon in a logarithmic scale. Figure 1(a) shows typical characteristics of silicon diodes with a big gap between reverse and forward bias trends. This gap indicates that the current measured in reverse bias is much lower than that measured in forward bias. These results indicate that the diode is well fabricated since they exhibit typical behaviour of silicon diodes [16-17]. This typical behaviour is justified by the evaluated ideality factor (of 1.19 ± 0.04) close to the unity. Thus, the diodes are fabricated on lifetime material [16-17].

Figure 1(b) shows *I-V* characteristics of the diodes fabricated on niobium-doped *n*-type silicon in logarithmic scale. The plots show a notable difference from those presented in figure 1(a) for undoped *n*-type silicon. The trends in figure 1(b) are close to each other especially, at lower voltages, ranging from 0.1 to 0.6 V. This shows that the diodes have changed from typical exponential to Ohmic behaviour after doping with niobium. This Ohmic behaviour has been explained in terms of "midgap defect" [9-11]. This defect is found at the centre of the energy gap (0.56 eV) and is responsible for change in silicon material from lifetime to relaxation behaviour [9-11]. Similar results were obtained on the diodes that were fabricated on *p*-type silicon material [11]. Thus, niobium doping induces similar effects in both types of the material.

Capacitance for Schottky diodes is represented in terms of the reverse voltage (V_R) [20] as

$$C = A\sqrt{\frac{q\varepsilon_s\varepsilon_o N_D}{2(V_{bi}+V_R)}} \quad (2)$$

where A is the active area of the diode, ε_s (= 11.8) is the dielectric constant of silicon, ε_o is the dielectric constant of free space, N_D is the doping density and V_{bi} is the built in voltage of the diode. Equation (2) shows that $C \propto \sqrt{V_R^{-1}}$ for a constant N_D.

Figure 2 shows *C-V* characteristics of the diodes fabricated on undoped and niobium-doped *n*-type silicon in linear scale. Figure 2(a) shows typical characteristic of silicon diode with rapid decrease of capacitance at low voltages. A tendency of the capacitance towards saturation observed at 1 V indicates a gradual approach of the device towards full depletion. These *C-V* results complement those of *I-V* and indicate that the diode is well fabricated since it exhibits typical behaviour of silicon diode [16-17]

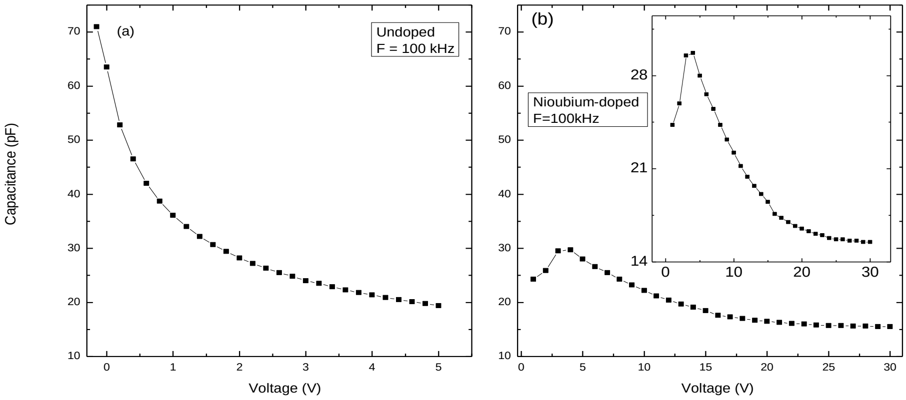

Figure 2: *The C-V characteristics of diodes fabricated on undoped (a) and niobium-doped (b) n-type silicon measured at 300 K and 100 kHz.*

Figure 2(b) shows *C-V* characteristic of the diode fabricated on niobium-doped *n*-type silicon. The figure shows a notable difference from the one presented in figure 2(a) for undoped *n*-type silicon. The trend in figure 2(b) exhibit a capacitance peak at lower voltages and thereafter a gentle decrease in capacitance is observed up to 15 V. At voltages higher than 16 V the capacitance saturates showing the diode has become fully depleted. This gentle decrease in capacitance indicates that the doping density has increased. The existence of the peak, on the other hand, has been a subject of discussion for many years and has not been fully understood. According to Ho *et al*. [21], Sahin *et al*. [22] and Ouennoughi and Sellai [23] the existence of the peak is due to interface states while the work presented by Chattopadhyay and Sanyal [24] explains the peak in terms of series resistance. We argue here that the peak is due to defects that are induced by niobium in the band gap of silicon. If the cause was due to surface effects or interface states, the peak would have also been observed on the diodes that were fabricated on undoped *n*-type silicon. This peak was also observed on the diodes that were fabricated on gold-doped *n*-type silicon and were interpreted in terms of relaxation theory [9]. Similar to gold in silicon, niobium generates defect levels that are responsible for change in material behaviour from lifetime to relaxation behaviour.

4. Conclusion

Schottky diodes were well fabricated on undoped and niobium *n*-type silicon using palladium as Schottky contacts. Current and capacitance measurements have been used to show that in silicon niobium is responsible for change in electrical properties of the diodes from exponential to Ohmic *I-V* behaviour. The diodes fabricated on niobium-doped *n*-type silicon also show a low voltage capacitance peak. These two features have also been observed in the work presented previously involving gold-doping [9, 11] and were explained in terms of midgap defect that is generated by gold in the energy gap of silicon. This defect level is situated very close to the centre of the energy gap (~ 0.56 eV) and is responsible for relaxation behaviour of the material [18]. Relaxation material is radiation-hard, since properties of the material based diode are not affected by incident radiation [7, 10, 19]. The results presented here show that doping with niobium has similar effects as doping silicon with gold. It is, therefore, expected that the material based diodes would be resistant to radiation environment.

It is intended to perform deep level transient spectroscopy (DLTS) on the diodes to investigate the exact properties of defect levels generated by niobium in silicon. The fabricated diodes will also be irradiated to determine any suppression of radiation effects as it has been done before with gold-doped silicon diodes [10]. This work would then assist in the fabrication of the ultimate radiation detectors.

Acknowledgments
This work has been made possible by financial assistance from Unisa Postgraduate Bursary Department. We would also like to thank iThemba LABS (Gauteng) for assistance with sample preparations.

References
[1] Martini M and McMath T A 1970 *Nucl. Instr. Meth.* **79** 259.
[2] Van Lint V A J 1987 *Nucl. Instr. Meth. A* **253** 453.
[3] Edmonds T 1990 *Appl. Phys. Lett.* **57** 487.
[4] Li Z, Chen W and Kraner H W 1991 *Nucl. Instr. Meth. A* **308** 585.
[5] Moll M *et al*. 1997 *Nucl. Instr. Meth. A* **388** 335.
[6] Moll M, Fretwurst E and Lindstrom G 1999 *Nucl. Instr. Meth. A* **426** 87.
[7] Dixon R L and Ekstrand K E 1986 *Radiation Protection Dosimetry* **17** 527.
[8] Kwon Y K, Ishikawa T and Kuwano H 1987 *J. Appl. Phys.* **61** 1055.
[9] Msimanga M, McPherson M and Theron C 2004 *Radiation Physics and Chemistry* **71** 733.
[10] McPherson M, Sloan T and Jones B K 1997 *J. Phys. D: Appl. Phys*. **30** 3028.
[11] Moloi S J and McPherson M 2009 *Physica B* **404** 3922.
[12] Litovchenko P G *et al.* 2006 *Nucl. Instr. Meth. A* **568** 78.
[13] Haegel N M 1991 *Appl. Phys. A* **53** 1.
[14] Cimilli F E, Saglam M and Turut A 2007 *Semicond. Sci. Technol.* **22** 851.
[15] Thebe M J, Moloi S J and Msimanga M 2015 *Depth profiling of niobium into n- silicon for radiation-hard detectors*, in preparation.
[16] Sze S M 1981 *Physics of Semiconductor Devices*, 2nd ed. (Wiley: New York).
[17] Streetman B G 1990 *Solid State Electronic Devices*, 3rd ed. (Prentice Hall: London).
[18] Jones B K, Santana J and McPherson M 1997 *Nucl. Instr. Meth. A* **395** 81.
[19] Brudnyi V N, Grinyaev S N and Stepanov V E 1995 *Physica B* **212** 429.
[20] Grove A S, 1967 *Physics and Technology of Semiconductor Devices,* Wiley New York.
[21] Ho P S, Yang E S, Evans H L, and Wu Xu 1986 *Phys. Rev. Lett.* **56** 177.
[22] Sahin B, Cetin H and Ayyildiz E 2005 *Solid-State Commun.* **139** 490.
[23] Ouennoughi Z and Sellai A 2010 *Inter. Journ. Electr.* 5 **83** 571.
[24] Chattopadhyay P and Sanyal S 1995 *Appl. Surf. Sci*. **89** 205.