CURRENT-VOLTAGE CHARACTERISTICS OF ALUMINIUM AND ZINC IMPLANTED SILICON FOR RADIATION DETECTION APPLICATIONS

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Crystalline p-silicon was implanted with Aluminium and Zinc at the fluence of $\sim 1.0 \times 10^{17}$ ions cm^{-2}. A change in silicon conductivity due to the implantation was investigated by the use of current-voltage (I-V) technique at room temperature. The qualitative analysis of the I-V characteristics showed that the implantation reduces the measured current of the material indicating that the conductivity of the material has decreased after ion implantation. The I-V trends of the metal-implanted silicon show ohmic I-V behaviour. A change in parameters such as saturation current, ideality factor, and Schottky barrier height due the implantation was also investigated in this study. The results, in general, show that in silicon, Aluminium and Zinc are responsible for conversion of silicon from lifetime to relaxation material. A material exhibiting relaxation behaviour has been found promising to be radiation-hard. This conversion of material to relaxation behaviour indicates that both metals are suitable dopants to improve radiation-hardness of silicon.

Keywords: Silicon, Aluminium, Zinc, Schottky diodes, Current-voltage

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1. Introduction

A study on interaction of radiation with silicon has given rise to a wide range of applications such as switches to electronic devices and radiation detectors for high radiation physics. It has been experimentally [1 -4] and theoretically found [5] that metals embedded in silicon play an important role in proving radiation hardness of material for detection applications. The metals in the materials generate defects that are responsible for the suppression of radiation damage hence improve radiation hardness of the material. This formidable effect of metals in production is due to the mid-gap defect introduced by metals in the material. The mid gap defect is a defect level that is situated at the center of silicon energy gap where it interacts equally with both bands to reduce the conductivity of the material [6]. In this case, carriers are generated and recombined at the same rate to maintain the intrinsic behavior of the material [6]. Material rich of this defects exhibits ohmic I-V behavior; a feature that has not been fully understood nor explained. It is therefore, important that more studies on I-V properties of the metal-doped silicon based devices are conducted in order to justify the suitability of the relaxation theory which was established longtime ago [7 -9] but still not welcome in the field of semiconductors. Relaxation theory has been found promising to explain this ohmic behavior and it could be alternative to explain defects in silicon. Additionally, understanding of this ohmic behavior would lead to acceptable recommendations for fabrication of efficient silicon radiation detector to be used in high energy physics experiments.

Studies available on literature are based on metal dopants that are expensive like gold and platinum; hence, there is a need for alternative dopants. Aluminum (Al) and Zinc (Zn)-doped silicon based diodes were fabricated and characterized by I-V technique at room temperature in order to investigate a change in electrical properties of the devices due to doping. The material behavior was then inferred from the devices to establish the suitability of the material for detector fabrication of radiation-hard detector after doping.

2. Experimental details

2.1 Sample preparation

A p-silicon of resistivity 1-20 Ω.cm and the thickness of 275 ± 25.0 μm was used in this work. The wafer was diced into 0.6 cm x 0.6 cm pieces using a laser cutter. The standard procedure of cleaning silicon samples was followed to remove any grease and to reduce the oxide layer [10-11]. After the cleaning process, all pieces were mounted in the chamber for aluminum and zinc implantation. The implantation was carried out using an ion implanter set up at iThemba LABS, Gauteng, South Africa. Aluminum and Zinc were implanted onto the polished side of silicon pieces at the energy of 160 keV and fluence of 1.0×10^{17} ions cm^{-2}.

2.2 Diode fabrication

Schottky diodes were fabricated on unimplanted, aluminium-implanted and zinc- implanted crystalline p-silicon. Prior to diode fabrication, silicon pieces were cleaned again using the standard procedure [10-11]. The pieces were then loaded into an evaporation chamber for formation of Schottky contacts. The contacts were achieved by evaporation and deposition of 100 nm Aluminium through a mask of 0.6 mm diameter holes. The deposition was carried at 10^{-6} mbar at the rate of 1Å/s. The Ohmic contact was then realized by evaporation and deposition of gold onto the back (unpolished) surface of the pieces. The finished devices each consists of 6 diodes on a piece and with one common Ohmic contact.

2.3 Diode characterization

The I-V measurements were carried at room temperature using Keithley 6487 Picoammeter with a built-in voltage source. The data were taken over the range of -2 to 2V within a voltage step of 0.01V. Throughout the experiments, the current limit was set at 2.5mA while the time between measurements was maintained for 1s to allow the device to stabilize.

3. Results and discussion

The current through the diodes is related to the applied voltage (V) [12] as:

$$I = I_s \left[exp\left(\frac{eV}{\eta kT} - 1\right)\right] \tag{1}$$

where η and I_S is the ideality factor and saturation current, respectively.
The saturation current I_S is derived from the straight linear fitting at zero bias and is expressed as:

$$I_S = AA^*T^2 \left(\frac{-e\Phi_B}{kT}\right) \tag{2}$$

where A is the diode area, Φ_B is barrier height and A^* is the Richardson constant and is 32 A-cm^{-2}-K^{-2} for p-type silicon. The ideality factor was calculated from the linear region of the slope of forward bias ln I versus V plot as

$$\eta = \frac{e}{kT}\frac{dV}{d(lnI)} \tag{3}$$

Where, $\frac{dV}{d(lnI)}$ is the reciprocal of the slope of the linear region of lnI versus V plot.
η is a measure from the deviation of ideal diode behaviour. For the ideal diode, η is equal to 1 but in practice, it is always greater than 1for real Schottky diode.
The evaluated I_S from equation 2 is used to calculate the Schottky barrier height as:

$$\Phi_B = \frac{kT}{e} ln\left(\frac{AA^*T^2}{I_S}\right) \tag{4}$$

3.1 Undoped p-silicon

Figure 1shows current-voltage characteristics of the diodes fabricated on undoped p-silicon both in linear (a) and logarithmic (b) scales. It is observed from figure 1 (a) that the trends exhibit typical characteristics of semiconductor diode, indicating that the diodes were well fabricated. In figure 1(b), it can be seen that the forward current increases slightly with voltage up to 0.05V thereafter, it then increases drastically up to 1.2V. At the higher voltage, there is a tendency of the trend to flatten due to the effect of series resistance that comes into play when the applied voltage is large [11-12]. The reverse current on the other hand, increases gradually indicating that it depends slightly on the applied voltage. These results are expected since the device was fabricated on a relatively 'defect-free' material.

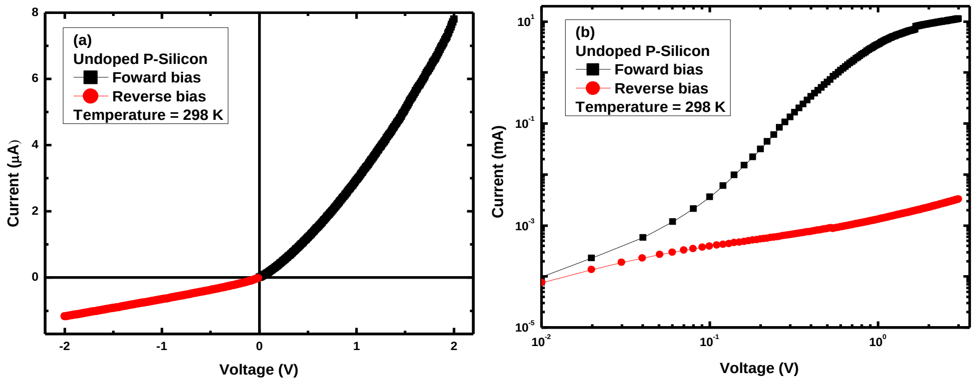

Figure 1. I-V characteristics of diodes fabricated on Undoped p-silicon in a linear (a) and a logarithmic (b) scales

3.2 Aluminium-doped p-silicon

The I-V behavior of diodes fabricated on aluminium-doped p-silicon is shown in figure 2. It can be seen from figure 2 (a) that the forward current is linear at the lower voltage and increases sharply after 0.7V. The trends in figure 2 (a) are similar to those in figure 1 (a) apart from that in this case the current starts to increase exponentially at 0.7V. In figure 2 (b), the I-V plots exhibits a greater difference from that in figure 1 (b). For example, the reverse and forward current trends have come close to each other indicating that they are equal, particularly at lower voltages. Unlike in the case of undoped p-Si, the reverse current of Aluminium-doped silicon diodes increases linearly with voltage for the whole voltage range. It has to be noted that the forward current at 2V is 8.0×10^{-2} mA lower than 10^{1} mA of undoped silicon indicating a decrease in charge carriers generation rate. This decrease in the rate can be noticed by a change in the forward current trend from exponential to linear increase after doping with aluminium. This change in I-V behaviour indicates that properties of the material have been changed due to aluminium doping.

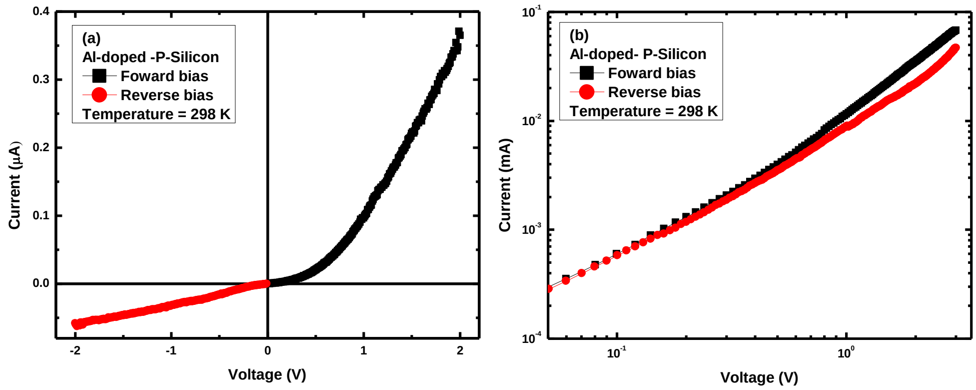

Figure 2. I-V characteristics of diodes fabricated on aluminium-doped p-silicon in a linear (a) and a logarithmic (b) scales

3.3 Zinc-doped p-silicon

To study the effects of zinc on properties of p-type silicon, I-V characteristics of diodes fabricated on Zn-doped p-silicon were investigated. The trend is different from those of figure 1 (a) and figure 2 (a). It can be seen from figure 3 (a) that the forward current increases linearly with voltages. Two different regions are observed, with the one at voltages higher than 1.5V being higher. The reverse current is found to have increased by a factor of two after doping with zinc. In logarithmic scale both trends, forward and reverse currents, shows are linear with a considerable gap between them, unlike in the case of Al-doped p-silicon-based diodes

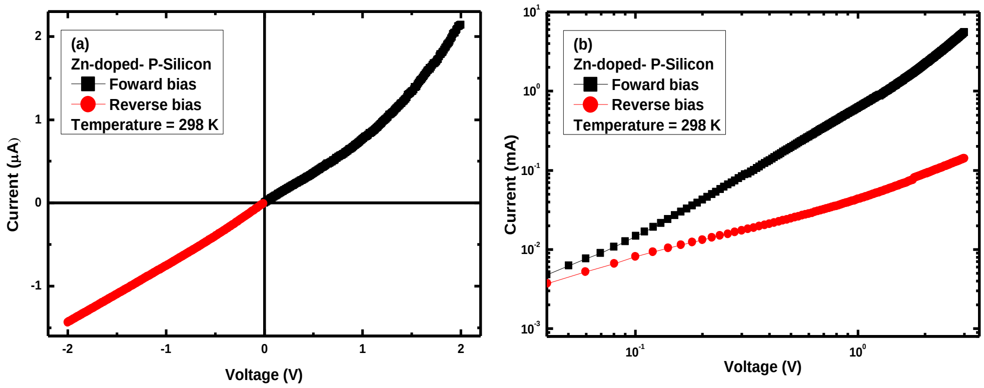

Figure 3. I-V characteristics of diodes fabricated on zinc-doped p-silicon in a linear (a) and logarithmic (b) scales

From the linear part of the I-V plots, diode parameters were calculated and represented in table 1.

Table 1. A summary of device parameters evaluated from I-V plots for diodes fabricated on p-silicon

Parameter	**Undoped**	**Aluminum- doped**	**Zinc-doped**
I_S (μA)	2.718	1.452	2.565
η	1.245	1.539	2.650
Φ(V)	0.1814	0.1962	0.1892

The parameters calculated from the diodes fabricated from undoped, aluminium and zinc-doped p-silicon diodes are presented in table 1. The saturation currents of the diodes fabricated on metal doped silicon are found to be lower than that of undoped p-Si based diode. This decrease in saturation current indicates that the resistivity of the material has increased due to compensation resulting in a low density of charge carriers contributing to the measured current. A high resistivity is the most important parameter for the metal to be used for fabrication of a radiation –hard detector [13]. Based on the saturation currents evaluated from these devices, it can be concluded that aluminium is the most suitable dopant to improve radiation- hardness of the material.

The ideality factor of zinc-doped diode (2.65) and zaluminium-doped diode (1.539) is large than the undoped diode (1.245). This high value of ideality factor in metal-doped p-silicon is attributed to other effects, such as the organic layer effect, inhomogeneity of the film thickness and the existence of series resistance [6, 10].

It can be seen from table 1 that aluminium-doped silicon diode has high value of Schottky barrier height (0.1962) compared to diode fabricated from undoped silicon (0.1814). From literature [9] it has been established that the high value of Schottky barrier height is due to donor levels present in the energy gap of p-type silicon. The donor levels are responsible for compensation of majority carriers that causes increase in resistivity.

3.4 Overview and discussion

The effect of metals dopants on the electrical properties of the diodes can be compared in terms of the data presented in figure (4). It can be seen that in silicon both metals are responsible for a change in device behavior from lifetime, exponential, behavior to ohmic behavior. This ohmic behavior indicates that the diodes have been fabricated on relaxation material [14]. The relaxation behavior is due to a defect level that is situated at the center of energy gap (~0.56 eV) in the case of silicon [2]. At this position, this defect interacts with conduction and valence bands where it generates and /or recombine charge carriers at the same rate. Since the density of charge carriers generated would be equal to the one of charge carriers recombined, the magnitudes of both currents, forward and reverse, would be the same. In this case, the material has attained its intrinsic likeness since the charge carrier distribution is due to a defect at intrinsic fermi-level position. Thus, the fermi-level is pinned at the intrinsic level making the device behaviour ohmic. The position of fermi energy pinned at the intrinsic level is independent of incident radiation [15]. Since the electrical properties of the material depend on the position of the fermi energy, it can therefore be concluded that electrical properties of the metal-doped p-Si based diodes would be independent of the incident radiation.

In comparing the effects of metals on the properties of the material, it can be seen that a diode fabricated on aluminium-doped p-silicon shows ohmic behaviour for almost the whole voltage region. A high region of ohmic behaviour is due to the high density of 'midgap' defects, defect centres that are responsible for relaxation behaviour of silicon [14]. Based on these results the diodes fabricated on aluminium-doped silicon could be more resistant to radiation-damage than the one fabricated on zinc-doped p-silicon.

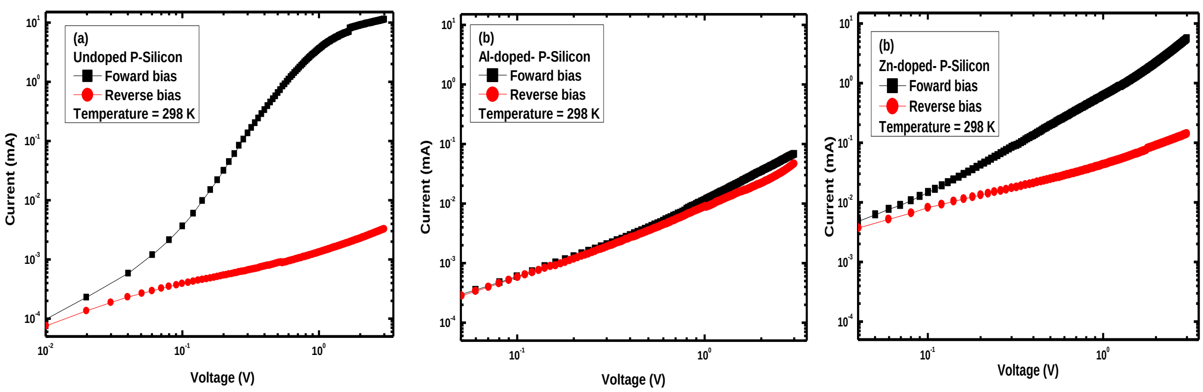

Figure 4. I-V characteristics of diodes fabricated on undoped, Al and Zn-doped p-silicon in a linear (a) and a logarithmic (b) scales

4. Conclusion

In this work the diode were well fabricated on undoped, Aluminium and Zinc-doped p-Silicon. A change in electrical properties of the diodes due to metal dopants was investigated by the current-voltage technique. The diodes fabricated on metal doped silicon show ohmic I-V behavior indicating that they were fabricated on relaxation material. An aluminium-doped p-Si based diode shows an ohmic region higher than that of Zinc-doped p-Si based diode. The diode fabricated on relaxation material has high resistivity and is resistant to radiation damage. This high resistivity of the diodes was confirmed by low leakage current evaluated from the metal-doped p-Silicon based diodes.

In general, both metals are promising dopants for radiation hardness of silicon with aluminium being the most promising one. In addition, further investigations are needed to confirm the diode property independency of radiation. It is also important to carry out charge collection efficiency measurements on the diodes.

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References

[1] Chrobak and M. Maliński, "Properties of silicon implanted with Fe+, Ge+, Mn+ ions investigated using a frequency contactless modulated free-carrier absorption technique," *Opt. Mater. (Amst).*, vol. 86, no. October, pp. 484–491, 2018.

[2] B. K. Jones, J. Santana, and M. McPherson, "OHMIC I-V characteristics in semi-insulating semiconductor diodes," *Solid State Commun.*, 1998.

[3] E. Vittone *et al.*, "Determination of radiation hardness of silicon diodes," *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 449, no. September 2018, pp. 6–10, 2019.

[4] P. N. K. Deenapanray, M. C. Ridgway, F. D. Auret, and E. Friedland, "A DLTS and RBS analysis of the angular dependence of defects introduced in Si during ion beam channelling using 435 keV alpha-particles," *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 136–138, pp. 1322–1326, 1998.

[5] T. E. Derry, L. I. Lisema, A. T. Magabe, E. Aradi, R. Machaka, and M. Madhuku, "Allotrope conversion and surface hardness increase in ion implanted boron nitride," *Surf. Coatings Technol.*, vol. 355, no. October 2017, pp. 61–64, 2018.

[6] Ö. Güllü, Ş. Aydoğan, and A. Türüt, "Fabrication and electrical characteristics of Schottky diode based on organic material," *Microelectron. Eng.*, vol. 85, no. 7, pp. 1647–1651, 2008.

[7] W. Van Roosbroeck, "Current-carrier transport with space charge semiconductors," *Phys. Rev.*, vol. 12, no. 2, pp. 44-490, 1961.

[8] H.J. Queisser, "Solid State Devices," *Proc. ESSDERC (IOP Conf. Proc 15)*, 1972.

[9] M. Ilegems and H.J. Queisser "Current transport in relaxation-case GaAs." *Phys. Rev.*, vol. 12, no. 4, pp. 1443-1452, 1975.

[10] "Extraction of Schottky diode parameters from forward current-voltage characteristics," *Appl. Phys. Lett.*, vol. 49, no. 2, pp. 85–87, 1986.

[11] B. K. Singh and S. Tripathi, "Fabrication and characterization of Au/p-ZnO Schottky contacts," *Superlattices Microstruct.*, vol. 85, pp. 697–706, 2015.

[12] B. K. Jones, N. Sengouga, and L. Dehimi, "Relaxation semiconductor diodes: a practical review," in *2000 International Semiconductor Conference. 23rd Edition. CAS 2000 Proceedings (Cat. No.00TH8486)*, 2000.

[13] S. J. Moloi and M. McPherson, "RBS measurements of metal-doped p-type silicon used for radiation-hard detectors," *Vacuum*, vol. 104, no. June, pp. 51–56, 2014.

[14] S. J. Moloi and M. McPherson, "Current-voltage behaviour of Schottky diodes fabricated on type silicon for radiation hard detectors," *Phyica B: Condesed Mtter*, vol. 404, no. 16, pp. 2251–2258, 2009.

[15] V.N. Brudnyi, S. N. Grinyaev, and V. E. Stepanov. "Local neutrality conception: Fermi level pinning in defective semiconductors." *Physica B: Condensed Matter*, vol. 212, no. 4, pp. 429-435, 1995