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Review

Capacitance–voltage behaviour of Schottky diodes fabricated on p-type silicon for radiation-hard detectors

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ABSTRACT

Capacitance–voltage measurements were carried out on Schottky diodes fabricated on undoped and on metal-doped p-type silicon. The metals used are gold, platinum, erbium and niobium. The obtained results were used to investigate the effects of the metals on the silicon material by inference from the electrical properties of the diodes. The data were used to extract the doping density of the material and the Schottky barrier height of the device. The results show that gold, platinum and niobium all reduce the doping density while erbium increases it. A reduction of the doping density shows that the resistivity has increased. This increase of the resistivity is caused by defects that are created by the metals in the energy gap of silicon. The defects compensate charge carriers to turn the silicon into a relaxation material. Devices fabricated from relaxation material have been found to perform better as radiation-hard detectors. The Schottky barrier height is independent of the doping density to show that it is not a bulk material property.

1. Introduction

There has been much interest in improving the electrical properties of semiconductor diodes to be used under harsh radiation environments (Wysocki et al., 1966; Martini and McMath, 1970; Lindström et al., 1999). The improvement is required because the diodes fail to operate efficiently as radiation detectors. This failure of the diodes is caused by defects that are created in the energy gap of the semiconductor by the irradiation (Sze, 1981; Lugakov et al., 1982). The effects of these defects on the material thus need to be thoroughly investigated in order to determine methods to improve diode properties by manipulating the material bulk.

In trying to improve diode properties, much work has been carried out on silicon doped with gold and with platinum (Kwon et al., 1987; Watanabe and Munakata, 1993; Deng and Kuwano, 1995; Valdinoci et al., 1996; Moloi and McPherson, 2009; Dixon and Ekstrand, 1986). It has been found that gold and platinum create defects that act to suppress the effects of any exposure of the material to radiation by 15 MeV electrons (Kwon et al., 1987; Dixon and Ekstrand, 1986). The suppression of the defects created by gold was also reported by McPherson et al. (1997) for diodes that were irradiated by 1 MeV neutrons. These two metals induce nearly similar effects as radiation by 1 MeV neutrons because they both create generation–recombination (g–r) centres, defects that are situated very close to the centre of the energy gap (Jones et al., 1998). At this position the g–r centres interact equally with both bands to maintain the Fermi energy at the intrinsic level (McPherson, 2004) and thus to alter the silicon from a lifetime to a relaxation material. A relaxation material differs from a lifetime material in terms of the dielectric relaxation time (τ_D) and the minority carrier lifetime (τ_0). In relaxation material $\tau_D \gg \tau_0$ while in lifetime material $\tau_D \ll \tau_0$ (van Roosbroeck, 1961; Ilegems and Queisser, 1975; Haegel, 1991; Jones et al., 1999b). It has been found that the Fermi energy of a relaxation material is not affected by further irradiation (Brudnyi et al., 1995) and that devices fabricated from such material are radiation-hard (Jones and McPherson, 1999). Thus, the silicon should be made to be relaxation-like so that the devices made on it are radiation-hard. The silicon is also often referred as semi-insulating (Jones et al., 1999a).

The capacitance–voltage (C–V) characteristics of devices fabricated on relaxation material show a low voltage peak in reverse bias and a negative capacitance in forward bias. These characteristics were observed on irradiated silicon p-i-n photodiodes (McPherson, 2002) and on diodes fabricated on gold-doped n-type silicon (Msimanga et al., 2004). The capacitance of silicon p-i-n photodiodes irradiated by 1 MeV neutrons has been found to increase (Moloi and McPherson, 2009a). An increase in capacitance has also been observed in diodes fabricated on n-type silicon (Biggeri et al., 1998). This increase in capacitance indicates

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that the doping density has increased and this is due to the generation of charge carriers by defects that are induced by irradiation or by gold-doping. The results presented earlier (Msimanga and McPherson, 2006) showed that gold in n-type silicon creates defects that are responsible for an increase in capacitance of the diodes fabricated on the material. Thus, gold-doping in silicon induces similar effects as irradiation by 1 MeV neutrons does.

The capacitance of diodes fabricated on p-type silicon has been found to decrease after irradiation by 60 keV gammas (Karataş and Türüt, 2006; Myungsim et al., 2007; Dökme et al., 2008; Güllü et al., 2008). Thus, defects created by irradiation increase the capacitance of diodes fabricated on n-type silicon but decrease that of diodes fabricated on p-type silicon. A decrease in capacitance indicates that the doping density has decreased and this is due to the recombination of charge carriers by the defects that are induced by irradiation with 60 keV gammas. Since irradiation in silicon induces similar effects as gold-doping, it is expected that defects created by gold in p-type silicon will lead to a decrease in the capacitance of the diodes. This decrease of the capacitance due to gold-doping in silicon is shown later.

The results presented in the reviewed literature are based only on gold-doped and irradiated n-type silicon (McPherson et al., 1997; Jones et al., 1998, 1999b; McPherson, 2004, 2002; Jones and McPherson, 1999; Msimanga et al., 2004; Moloi and McPherson, 2009; Msimanga and McPherson, 2006) as well as irradiated p-type silicon (Karataş and Türüt, 2006; Myungsim et al., 2007). There is not much literature available on gold-doping in p-type silicon that could be used to compare the results obtained on n-type silicon. It is thus essential that the effects of gold in p-type silicon are investigated. It is also essential that other metals are investigated in order to compare their effects with those of gold and irradiation.

In this work, Schottky barrier diodes were fabricated on undoped and on metal-doped p-type silicon. The diodes were characterized by the *C–V* technique, a technique that is used mainly to determine the doping density and the Schottky barrier height. The results are compared with those presented by Msimanga et al. (2004) and Msimanga and McPherson (2006) for diodes fabricated on gold-doped n-type silicon. This work also investigates the effects of platinum, erbium and niobium on the *C–V* behaviour of diodes fabricated on p-type silicon. Further, the results obtained are used to explain the low-voltage peak obtained in irradiated silicon *p-i-n* photodiodes (McPherson, 2002) and in gold-doped silicon diodes (Msimanga et al., 2004).

2. Experimental procedure

The material used in this work is a p-type silicon wafer polished on one side. The wafer was diced into 0.9×0.9 cm square substrates. The resistivity of the material ranges from 1 to 20 Ω-cm. The thickness ranges from 350 to 400 μm. The substrates were cleaned with an ultrasonic cleaner, using methanol, acetone, trichloroethane and de-ionized water in succession. The oxide layer on the substrates was removed by dipping them into 20% hydrofluoric solution. The substrates were then rinsed in de-ionized water for 5 min. Before they could be loaded into the vacuum chamber for metal doping, the substrates were blow-dried using nitrogen gas. The metal deposition, the metal diffusion and the device fabrication processes have been outlined elsewhere (Moloi, 2009) and will not be repeated here.

The *C–V* measurements were carried out in reverse bias using an HP4192A LF analyzer, at 300 K and at 1 MHz. It is expected that at this frequency the diodes would not show the low-voltage peak that was observed by McPherson (2002), Msimanga et al. (2004), Msimanga and McPherson (2006) and Dökme et al. (2008). This peak is argued to be caused by charges at the interface (Karataş and Türüt, 2006; Dökme et al., 2008) that follow the AC signal and that contribute to the measured capacitance at frequencies lower than 1 MHz. It is also argued to be due to the built-in charge near the contacts (McPherson, 2002). At frequencies of 1 MHz or higher the charge in either case is independent of the signal and the measured capacitance is then only due to the space charge region. Thus, the capacitance measured in the instance of this work will mostly be due to the space charge. Even though gold is often used on n-type silicon for Schottky contacts (Msimanga et al., 2004; Kumar et al., 2006), the results obtained in this work show that gold can be used on p-type silicon as well. This is shown later where the fabricated diodes exhibit typical diode characteristics.

3. Results and discussion

The results presented here are derived from the depletion region capacitance measured in reverse bias. These measurements are used widely to study the behaviour of the diodes since they yield important parameters such as the doping density and the Schottky barrier height. In Schottky diodes, the junction capacitance can be expressed (Schroder, 2006) as

$$C = A\sqrt{\frac{e\varepsilon_s\varepsilon_0 N_D}{2(V_{bi}+V)}} \tag{1}$$

where A is the active area of the diode, e is the electronic charge, ε_s is the dielectric constant of the semiconductor, ε_0 is the dielectric constant of free space, N_D is the doping density, V_{bi} is the built-in voltage of the diode and V is the applied voltage. The above equation can be rearranged as

$$C^{-2} = \frac{2}{A^2}\left(\frac{V_{bi}+V}{e\varepsilon_s\varepsilon_0 N_D}\right) \tag{2}$$

which can be expanded to be

$$C^{-2} = \frac{2}{A^2}\times\frac{V_{bi}}{e\varepsilon_s\varepsilon_0 N_D}+\frac{2}{A^2}\times\frac{V}{e\varepsilon_s\varepsilon_0 N_D} \tag{3}$$

to show that the doping density is determined from the slope of the linear region of a C^{-2} against V graph. From the above equation, it can be noted that the built-in voltage can be determined by using the intercept on the C^{-2} axis. The obtained values of N_D and V_{bi} are then used to determine the Schottky barrier height (Çetin et al., 2005) as

$$\Phi = V_{bi} + \frac{kT}{e}\ln\left(\frac{N_V}{N_D}\right) \tag{4}$$

where k is the Boltzman constant, T (=300 K in the measurements) is the room temperature and N_V is the effective density of states in the valence band and is given (Sze, 1981) as

$$N_V = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{\frac{3}{2}} \tag{5}$$

and evaluated as 1.1×10^{19} cm^{-3} for silicon at 300 K (Schroder, 2006). Here, m_p^* is the effective mass of a hole and h is Plank's constant.

3.1. Undoped p-type diodes

The main analysis in this work is based on the *C–V* plot to determine the depleted state of a device. An example of this type of analysis is shown in Fig. 1 for diodes fabricated on undoped p-type silicon. The *C–V* profile of diode 1 is similar to that of diode 2. Both plots indicate a steep fall in the capacitance at low

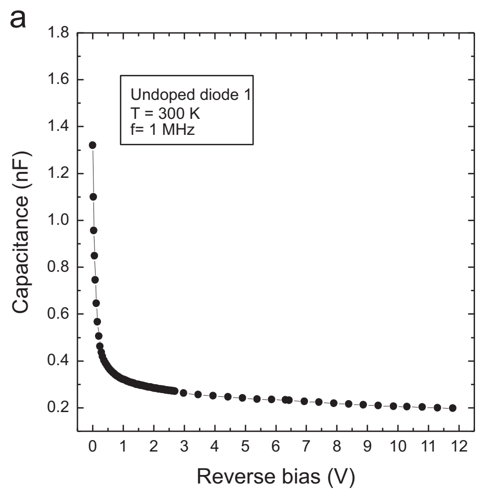

Fig. 1. The *C–V* characteristics of diodes fabricated on undoped p-type silicon measured at 300 K and 1 MHz.

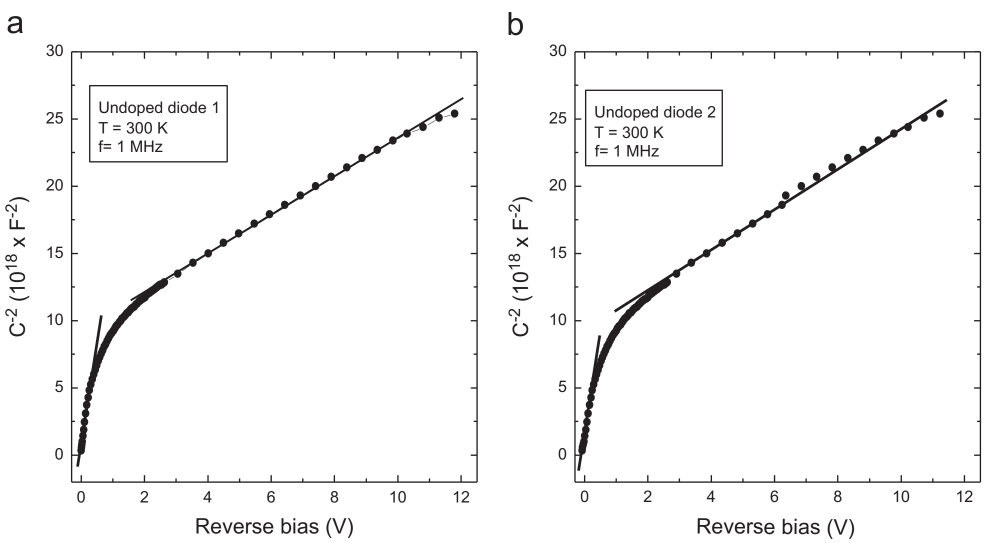

Fig. 2. The C^{-2}–V characteristics of diodes fabricated on undoped p-type silicon generated from the data of Fig. 1.

voltages which changes to a gradual fall. At high voltages the fall in capacitance is almost negligible. The initial fall of the capacitance is due to an increase of the depletion width as the voltage increases.

At high reverse voltages the fall in capacitance is negligible as the capacitance saturates to show that the diodes become fully depleted. These well known trends of the capacitance have been observed before Msimanga et al. (2004) on diodes fabricated on n-type silicon. They have also been observed on commercial silicon *p-i-n* photodiodes (McPherson, 2004; Bourenane et al., 2007; Cho, 2006). This typical behaviour of the diodes, thus, indicates that the use of gold for Schottky contacts on p-type silicon does not have any more effects and that the diodes are properly fabricated. The results presented by Yeganeh and Rahmatollahpur (2010) also show that gold can indeed be used for Schottky contacts on p-type silicon.

A second method of analysis is based on a C^{-2}–V plot used to ascertain the doping profile and to determine the doping density in the material. An example of this type of analysis is shown in Fig. 2 for diodes fabricated on undoped p-type silicon. Two different linear regions are observed in both plots to show that the doping profile in the material is not the same. The linear region at voltages lower than 1 V is smaller than that at voltages between 2 and 12 V. This shows uniformity over two different regions, one at low voltages and the other at high voltages. The second voltage range is large and means that the doping profile is uniform over a large depletion width. It is therefore assumed that the material has a uniform doping profile in the range 2–12 V.

Values of the calculated doping density, built-in voltage and Schottky barrier height for the undoped p-type diodes are given in Table 1. The parameters were evaluated as outlined in Eq. (3). The calculated parameters for the two diodes are different even though the diodes were fabricated on the same substrate. This could be due to inhomogeneous deposition of gold during the fabrication of the Schottky contact, a surface effect. It could also be due to inhomogeneous introduction of the p-type dopant at ingot growth. However, the parameters are not much different and we shall consider them as equal and so assume uniform doping. It can be seen from the table that a low doping density (2.19×10^{15} cm^{-3}) in diode 1 corresponds to a high Schottky barrier height (0.59 V). This type of variation of the doping density and the Schottky barrier height has been reported by other authors before Karataş and Türüt (2006), Güllü et al. (2008), Çetin et al. (2005), Karataş et al. (2005), Tataroglu and Altindal (2006).

The three parameters were also evaluated at low-voltage linear regions but these are not presented in the table and since we assumed the uniform doping we shall not concentrate on these results.

3.2. Gold-doped p-type diodes

Fig. 3 shows C–V characteristics for the diodes fabricated on gold-doped p-type silicon. The profiles for both diodes are similar apart from the fact that the initial capacitance differs, being ~0.6 nF for diode 1 at 0 V and is ~1.7 nF for diode 2. This difference in capacitance might be due to the diffusion properties of gold into silicon. Deposition is at room temperature and low pressure while diffusion is at high temperature and at normal pressure. However, at voltages higher than 0.5 V, the capacitance for both diodes shows a tendency to slowly saturate. Unlike in the case of the undoped diodes, the capacitance profile for gold-doped diodes tends to slope slightly at low voltages indicating a change in the doping profile within the material.

Fig. 4 shows C^{-2}–V characteristics of diodes fabricated on gold-doped p-type silicon. A linear region is observed in plot (a) to show that the doping profile in this diode is uniform over the whole depletion region. For diode 2, however, linearity is from 0.25 to 2.8 V showing that the doping profile is uniform over a larger depletion region for our work. A uniform doping density is assumed over the whole sample.

Table 2 shows parameters evaluated from the C^{-2}–V plot of the gold-doped diodes. The parameters are different even though the diodes were fabricated on the same substrate. This shows the possibility of inhomogeneous deposition of gold during the fabrication of the Schottky contacts. It could also be due to inhomogeneous diffusion of gold into the bulk of the wafer prior to contact fabrication, a bulk effect. Both processes are highly temperature dependent.

The parameters are, however, not related to each other in the same manner as the parameters obtained for the diode fabricated on undoped p-type silicon. The high doping density (0.40×10^{15} cm^{-3}) in diode 1 corresponds to a high Schottky barrier height (0.70 V) while the low doping density (0.36×10^{15} cm^{-3}) in diode 2 corresponds to a low Schottky barrier height (0.47 V). From the reviewed

Table 1
Diode parameters evaluated from C^{-2}-V plots for diodes fabricated on undoped p-type silicon.

Parameter	Diode1	Diode 2	Average
N_D ($\times 10^{15}$ cm^{-3})	2.19	2.25	2.22 ± 0.04
V_{bi} (V)	0.37	0.35	0.36 ± 0.01
Φ (V)	0.59	0.57	0.58 ± 0.01

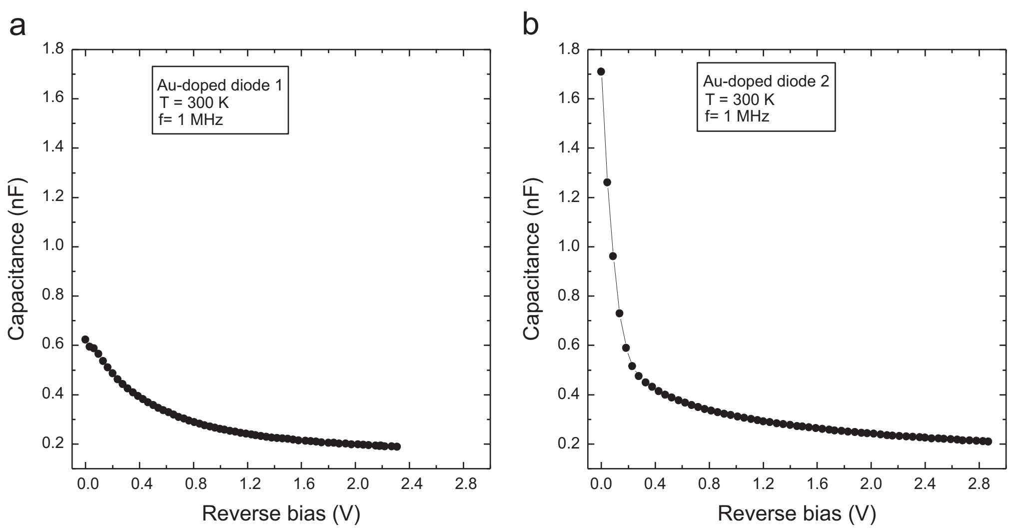

Fig. 3. The C–V characteristics of diodes fabricated on gold-doped p-type silicon measured at 300 K and 1 MHz.

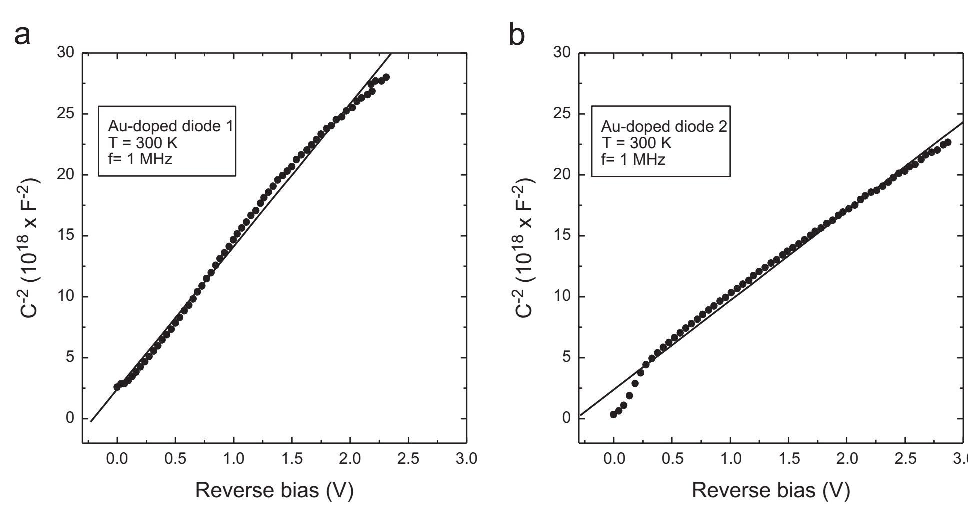

Fig. 4. The C^{-2}–V characteristics of diodes fabricated on gold-doped p-type silicon generated from the data of Fig. 3.

literature, this type of variation has not been reported before and is contrary to normal diode behaviour. It may be a sign of the onset of relaxation behaviour in p-type silicon. If so then this is a new phenomenon.

3.3. Platinum-doped p-type diodes

Fig. 5 shows C–V characteristics of diodes fabricated on platinum-doped p-type silicon and it can be seen that the trends for both diodes are similar. Even though titanium was used to fabricate the Schottky contacts on the platinum-doped substrate, the results presented in Fig. 5 show similar characteristics as those where gold was used to fabricate the contacts. As has been found for other semiconductors such as *p*-SiC (Lee et al., 2001) and *p*-InGaP (Gombia et al., 2003), it is found in this work that gold can be used to form Schottky contacts on p-type silicon in a similar manner as titanium is used.

Fig. 6 shows C^{-2}–V graphs for platinum-doped p-type silicon. It can be seen in plot (a) that the doping profile is uniform over the whole depletion region. In plot (b) two linear regions are observed to show that the doping profile in this diode is not uniform over the whole depletion region. The plot, however, shows that the profile is uniform over a larger depletion region in the voltage range of 0 to 8 V.

The parameters evaluated for platinum-doped diodes are presented in Table 3 where a lower doping density in diode 1 ($0.45\times10^{15}\,cm^{-3}$) corresponds to a high Schottky barrier height (0.83). In diode 2 a higher doping density ($0.46\times10^{15}\,cm^{-3}$) and it corresponds to a low Schottky barrier height (0.40 V). The variation of parameters is similar to that of diodes fabricated on undoped p-type silicon even though the Schottky contacts were fabricated using a different metal (titanium) for this set of diodes. This result shows that the parameters do not depend on the type of metal used to fabricate the Schottky contacts. Therefore, a change in diode properties is due to the metals deposited into the material bulk and not the metals deposited onto the material surface to fabricate the contacts. This independence of diode properties from the metal used to fabricate the Schottky contact was also explained based on the results that were obtained on diodes fabricated on n-type silicon (Msimanga et al., 2004).

Table 2
Diode parameters evaluated from C^{-2}-V plots for diodes fabricated on gold-doped p-type silicon.

Parameter	Diode 1	Diode 2	Average
N_D ($\times10^{15}\,cm^{-3}$)	0.40	0.36	0.38 ± 0.03
V_{bi} (V)	0.44	0.20	0.32 ± 0.12
Φ (V)	0.70	0.47	0.59 ± 0.16

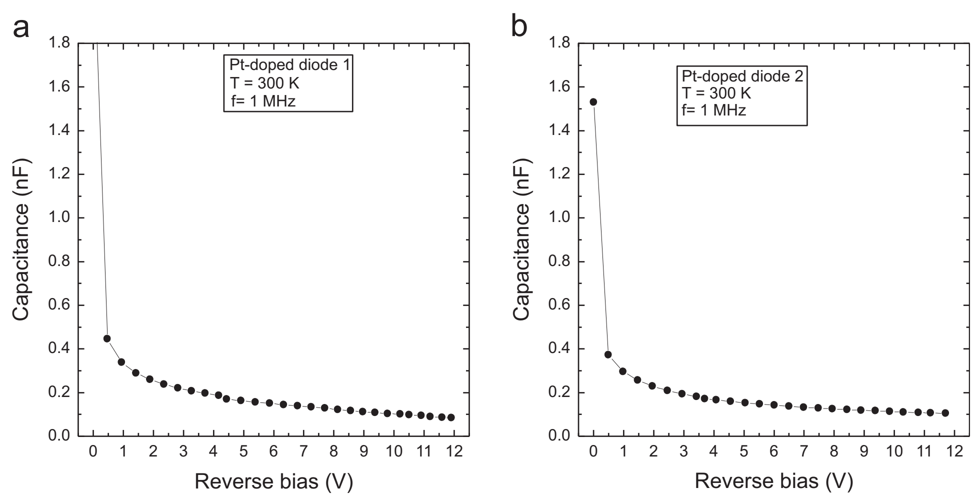

Fig. 5. The C–V characteristics of diodes fabricated on platinum-doped p-type silicon measured at 300 K and 1 MHz.

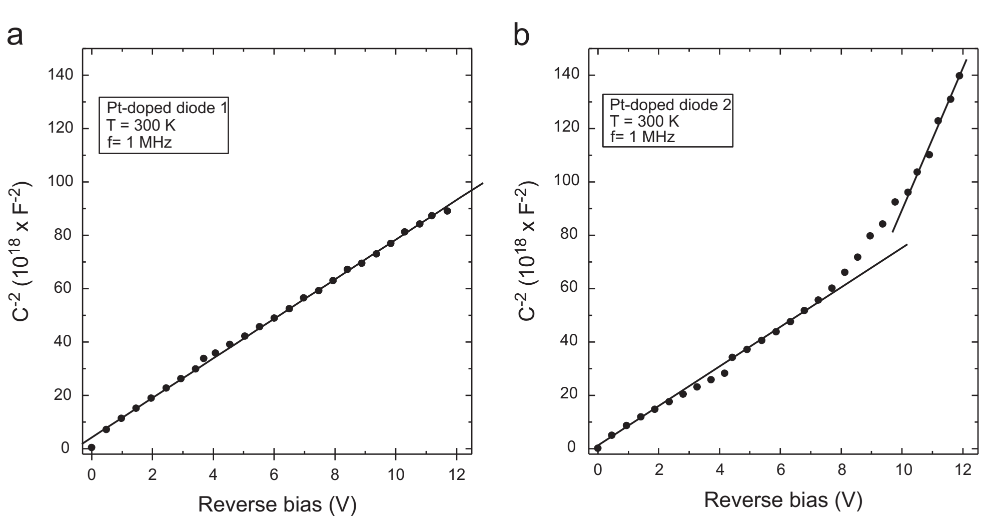

Fig. 6. The C^{-2}–V characteristics of diodes fabricated on platinum-doped p-type silicon generated from the data of Fig. 5.

The large difference in the barrier heights can be explained by the *C–V* trends presented in Fig. 5. The capacitance at 0 V for diode 2 is much lower than that for diode 1. This difference could be due to the surface states that are found at the metal-semiconductor interface or to the built-in voltage at the contacts in the bulk of the semiconductor.

3.4. Erbium-doped p-type diodes

Fig. 7 shows *C–V* characteristics for diodes fabricated on erbium-doped p-type silicon. A point to note immediately is that unlike in the case of the undoped, gold-doped and platinum-doped diodes, where the capacitance decreases sharply at low voltages, in the case of erbium-doped diodes the capacitance decreases gently with voltage and there is no indication of saturation within the voltage range. We must state here that the biasing voltage is kept low because the change in capacitance was very minimal after 1 V. The voltage was not increased as a result and the measurements were stopped.

The results in Fig. 7 can be interpreted in terms of the defect levels that are created by erbium in the energy gap of p-type silicon. The defects generate a very large number of charge carriers. Since at low voltages the electric field is not high enough to draw the carriers out of the depletion region to the respective electrodes, the capacitance appears to be slightly independent of the applied voltage. Thus, the rate at which the carriers are drawn out of the depletion region is low and this shows that a very high voltage is required to fully deplete the diodes. The generation of carriers by the induced defect levels was also observed by *I–V* results obtained from these diodes (Moloi and McPherson, 2009). In contrast to the other diodes of this work, the current measured for diodes fabricated on erbium-doped p-type silicon was found to increase (Moloi and McPherson, 2009).

Similar results as above have also been presented (Moloi and McPherson, 2009a) for a *p-i-n* diode that was irradiated by 1 MeV neutrons to a fluence of 10^{17} n cm^{-2}. The results in that case were interpreted in terms of radiation-induced defect levels that turn silicon into a relaxation material. Thus, some of the defects created by erbium in silicon have similar effects as those created

Table 3
Diode parameters evaluated from C^{-2}-*V* plots for diodes fabricated on platinum-doped p-type silicon.

Parameter	Diode1	Diode 2	Average
N_D ($\times 10^{15}$ cm^{-3})	0.45	0.46	0.46 $\pm$ 0.01
V_{bi} (V)	0.57	0.22	0.34 $\pm$ 0.25
Φ (V)	0.83	0.48	0.66 $\pm$ 0.25

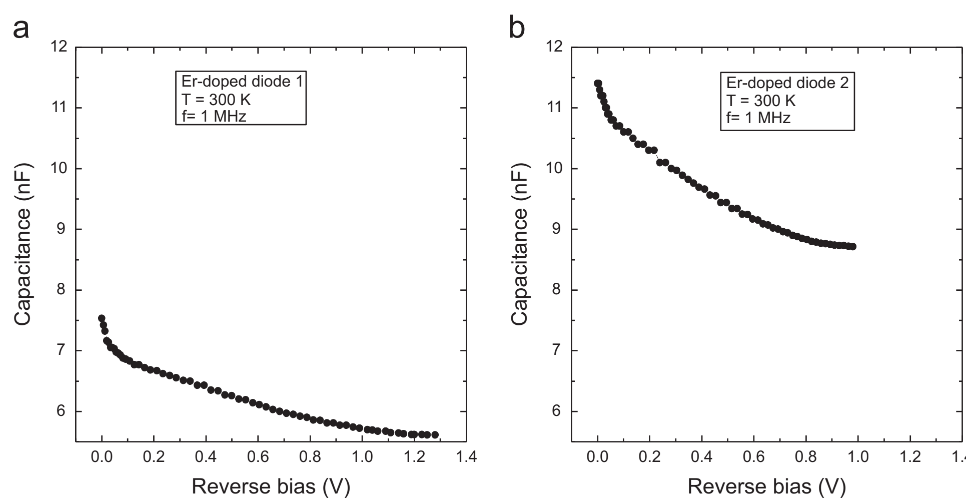

Fig. 7. The *C–V* characteristics of diodes fabricated on erbium-doped p-type silicon measured at 300 K and 1 MHz.

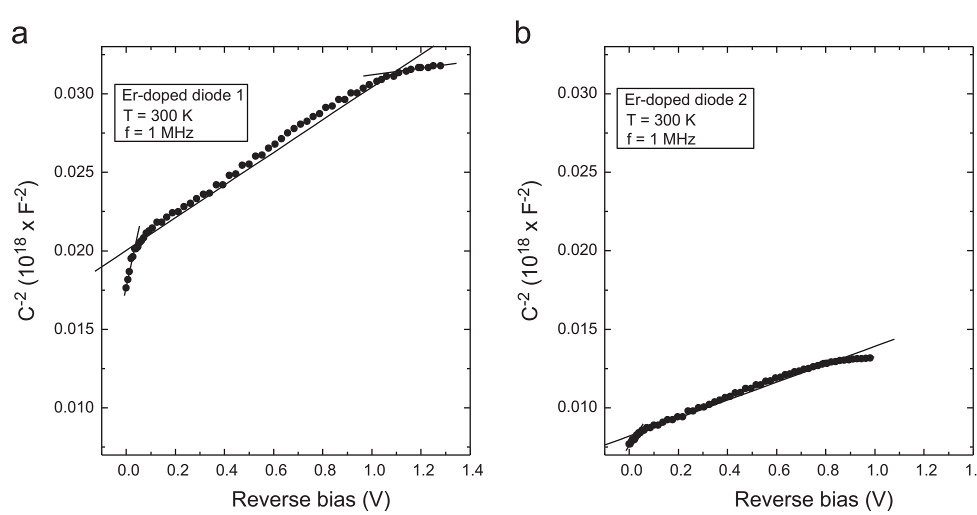

Fig. 8. The C^{-2}–*V* characteristics of diodes fabricated on erbium-doped p-type silicon generated from the data of Fig. 7.

by neutron irradiation. It can be noted from Fig. 7 that the capacitance trends are similar apart from the fact that the zero bias capacitance of diode 1 is much lower (at 7.5 nF) than that of diode 2 (at 11.5 nF). At this stage the difference in capacitance of these diodes is not understood. Since the capacitance was measured at 1 MHz, any differences should be due to bulk effects and not due to surface effects. This is why we contend that the capacitance in damaged silicon might be affected by the built-in charge near the contacts. This, in turn, might be influenced by the diffusion mechanism of erbium into silicon.

Fig. 8 shows C^{-2}–V graphs for erbium-doped p-type silicon generated from the measurements shown in Fig. 7. Even though the profile of diode 1 in plot (a) gives a higher C^{-2} value than that of diode 2 in plot (b), it can be seen that the trends for both diodes are very similar. The doping profile in both diodes is not uniform but the C^{-2}–V variation is linear over a wide voltage range of 0.1–1 V and of 0.1–0.9 V for diode 1 and diode 2, respectively. This diode indicates a larger range of uniformity in doping.

Table 4
Diode parameters evaluated from C^{-2}-V plots for diodes fabricated on erbium-doped p-type silicon.

Parameter	Diode 1	Diode 2	Average
N_D ($\times 10^{15}$ cm^{-3})	624	337	481 $\pm$ 203
V_{bi} (V)	1.56	2.04	1.80 $\pm$ 0.34
Φ (V)	1.63	2.13	1.88 $\pm$ 0.35

The parameters evaluated from the C^{-2}–V plots of erbium-doped diodes are shown in Table 4. The data show that a high doping density in diode 1 (624×10^{15} cm^{-3}) corresponds to a low Schottky barrier height (1.63) and a low doping density in diode 2 (337×10^{15} cm^{-3}) corresponds to a high Schottky barrier height (2.13). This variation of the parameters resembles the variation observed in diodes fabricated on undoped and on platinum-doped p-type silicon.

The average doping density evaluated for these diodes is much higher (at 481×10^{15} cm^{-3}) than that evaluated for the undoped diodes (at 2.22×10^{15} cm^{-3}). This high doping density is due to the fact that erbium creates acceptors in the upper half of the energy gap that increase the value of N_D so that the total doping density is higher. The defect levels that are created by erbium in p-type silicon have been studied sometime ago (Coffa et al., 1995) and have been summarised in Ref. Moloi and McPherson (2009).

3.5. Niobium-doped p-type diodes

Fig. 9 shows the C–V characteristics for diodes fabricated on niobium-doped p-type silicon. These diodes show unusual

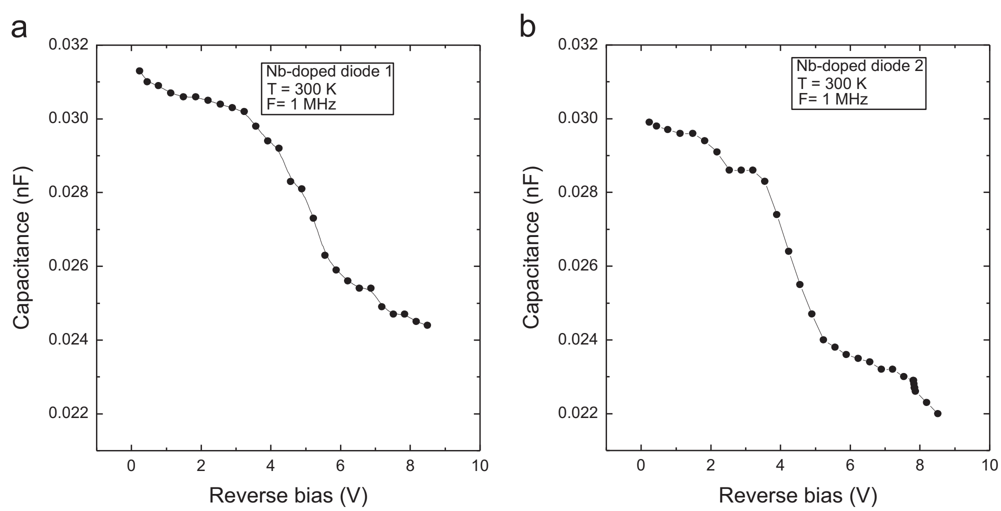

Fig. 9. The C–V characteristics of diodes fabricated on niobium-doped p-type silicon measured at 300 K and 1 MHz.

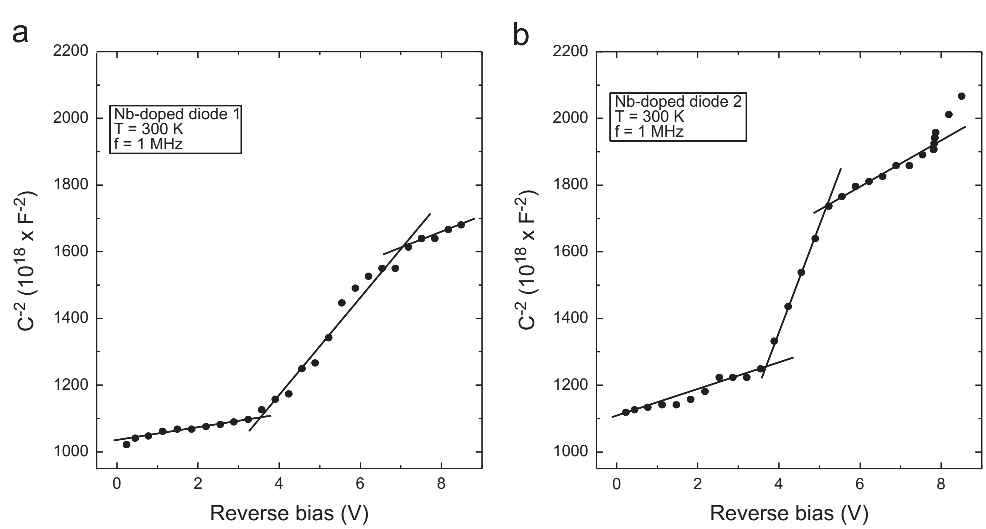

Fig. 10. The C^{-2}–V characteristics of diodes fabricated on niobium-doped p-type silicon generated from the data of Fig. 9.

characteristics, that is, a gentle decrease of the capacitance up to 2 V, after which a steep fall is observed up to 4.5 V. At voltages higher than 4.5 V the capacitance decreases gently. It can be noticed that both diodes do not show any signs of saturation of the capacitance, indicating that a very high voltage might be required to fully deplete these types of diodes.

The behaviour outlined above is uncharacteristic of the diodes and may suggest that the device is not a good diode. However, from the *I–V* data presented in Fig. 5 by Moloi and McPherson (2009) it is clear that the diode current has become Ohmic and so the silicon is a relaxation material. Thus, the diode is a good device for detector technology and all the diodes were fabricated under similar conditions. A probable explanation for the behaviour could be the fact that the doping density has been reduced drastically. This means that niobium in silicon reduces the number of charge carriers, hence, most defects are trapping or recombination centres. Mobile charge is then reduced to reduce the doping density.

Fig. 10 illustrates the doping profiles of the diodes fabricated on niobium-doped p-type silicon in the form C^{-2}–V graphs. Three linear regions are observed in both diodes to show that the doping profile is not uniform. A rapid increase of C^{-2} is observed at about 3 V in both diodes. These trends of C^{-2} have been observed before Siddiqui (1998)) on P^{+}–N diodes. Similar trends were also observed on results obtained from p-type silicon irradiated by 24 GeV protons (Casse et al., 2002). According to Siddiqui (1998), this behaviour of C^{-2} shows that the doping density varies with distance from the junction to the contacts.

The values of the doping density, the built-in voltage and the Schottky barrier height evaluated for the regions where the capacitance variation is linear over a wider voltage range are given in Table 5. It can be seen that the variation of the parameters is similar to the one for the gold-doped diodes shown in Table 2. In niobium-doped diodes a high doping density (0.03×10^{15} cm^{-3}) in diode 1 corresponds to a high Schottky barrier height (4.99 V) while a low doping density (0.01×10^{15} cm^{-3}) in diode 2 corresponds to a low Schottky barrier height (1.38 V).

4. Overview discussion

A summary of device parameters evaluated from C^{-2} to V plots for all five types of diodes is presented in Table 6. The doping density of the diode fabricated on undoped p-type silicon is 2.22×10^{15} cm^{-3}, a value higher than 1.09×10^{15} cm^{-3} obtained for Sn/*p*–Si (Güllü et al., 2008), very close to 2.20×10^{15} obtained for Ti/*p*–Si [38] but lower than 17.0×10^{15} cm^{-3} obtained sometime ago and reported by Hanselaer et al. (1986) and 13.5×10^{5} cm^{-3} obtained recently and reported by Yeganeh and Rahmatollahpur (2010) on Au/*p*–Si using *C–V* measurements at 1 MHz. This value of the doping density is within a range of those obtained in the reviewed literature to show that the diodes of this work are well fabricated.

It can be noted from Table 6 that the doping density obtained from the gold-doped, the platinum-doped and the niobium-doped diodes is lower than that obtained from the undoped diode. This reduction of the doping density is due to the defects that are induced by the metals in the energy gap of the semiconductor. A summary of these defects is given in Table 7 as compiled from various references cited in the text. In the table E_c and E_v represent the energy at the bottom of the conduction band and the energy at the top of valence band, respectively.

The donor levels created by gold and platinum in the lower half of the energy gap are known to be strong recombination centres (Watanabe and Munakata, 1993). These levels recombine any mobile carriers. As a result, the doping density decreases and so, the conductivity of the material is reduced. The decrease in the doping density of the niobium-doped diode may be due to the shallow levels created at $E_v+0.16$ eV. This level may also recombine majority carriers to reduce the conductivity of the material.

A decrease in the doping density of p-type silicon has been observed (Karataş and Türüt, 2006; Güllü et al., 2008) on gamma irradiated silicon diodes. This decrease was explained in terms of the defects that are induced by irradiation in the energy gap. Thus, irradiation of silicon is similar to doping silicon with metals since both processes create defects that are responsible for the decrease in conductivity of devices made on such material.

The doping density obtained from the erbium-doped diode is, however, quite different from the other diodes. The doping density evaluated from the erbium-doped diodes may be thought to indicate a degenerate semiconductor. The doping density for this diode is higher than that of the undoped diode since the defects induced by erbium are only found in the upper half of the energy gap. The *C–V* profile of the erbium-doped diode is similar to the one observed on the irradiated silicon *p-i-n* diodes (Moloi and McPherson, 2009a). Thus, the effects of erbium on p-type silicon are similar to those of radiation-damage by 1 MeV neutrons.

Based on the discussion above, metal doping in *p*-silicon reduces the doping density to decrease the conductivity. The material exhibits high resistivity and is termed relaxation. The doping density is reduced by a large number of recombination centers created by the doped metals. Such recombination centers can also be created by 1 MeV neutrons. This shows that metal doping has the same effects as radiation damage. Thus, *p*-silicon can be made to be radiation-hard by either method. This radiation-hard silicon is relaxation-like with a damage constant of 6.67 (McPherson, 2004a) and a defect introduction rate of 0.059 (McPherson, 2002).

5. Conclusion

The results obtained here show that gold can be used to make Schottky contacts on p-type silicon and these show good electrical properties. The diodes thus fabricated are characterised and

Table 5
Diode parameters evaluated from C^{-2}-V plots for diodes fabricated on niobium-doped p-type silicon.

Parameter	Diode 1	Diode 2	Average
N_D ($\times10^{15}$ cm^{-3})	0.03	0.01	0.02 ± 0.01
V_{bi} (V)	4.66	1.02	2.84 ± 2.37
Φ (V)	4.99	1.38	3.19 ± 2.55

Table 6
A summary of device parameters evaluated from C^{-2}-V plots for all the diodes.

Parameter	Undoped	Au-doped	Pt-doped	Er-doped	Nb-doped
N_D ($\times10^{15}$ cm^{-3})	2.22 ± 0.04	0.38 ± 0.03	0.46 ± 0.01	481 ± 203	0.02 ± 0.01
V_{bi} (V)	0.36 ± 0.01	0.32 ± 0.12	0.34 ± 0.25	1.80 ± 0.34	2.84 ± 2.37
Φ (V)	0.58 ± 0.01	0.59 ± 0.16	0.66 ± 0.25	1.88 ± 0.35	3.19 ± 2.55

Table 7
A summary of defect levels created by various metals in silicon as compiled from various sources.

	Gold	Platinum	Erbium	Niobium	1 MeV Neutrons
Reference	Watanabe and Munakata (1993)	Kwon et al. (1987)	Coffa et al. (1995)	Pettersson et al. (1993)	McPherson (2004)
	_	_	E_c–0.20 eV	_	
	_	E_c–0.23 eV	E_c–0.26 eV	E_c–0.29 eV	
	E_c–0.34 eV	_	E_c–0.34 eV	_	
	_	_	_	_	E_c–0.42 eV
Midgap defect	E_c–0.55 eV	E_c–0.52 eV	E_c–0.51 eV	E_c–0.58 eV	E_c–0.55 eV
	E_v+0.34 eV	E_v+0.36 eV	__	__	E_v+0.36 eV
	_	_	_	E_v+0.16 eV	

the results are used to infer the effects of metals impurities in silicon material. The doping density evaluated from the gold-, platinum- and niobium- doped diodes decreases to show that the conductivity had decreased. This decrease of the conductivity indicates that the diodes are fabricated on relaxation material. Even though the conductivity of the erbium-doped diodes is found to be high, the *C–V* trends are similar to those of irradiated (or relaxation) diodes (Moloi and McPherson, 2009a). The overall results indicate that doping with metals is similar to radiation-damage. Both methods generate defects that are situated near the midgap and that act as generation-recombination centres with equal empty and fill rates such that the material appears to be of high resistivity. The silicon is actually radiation-hard such that the material has become relaxation.

The results presented in this work show that radiation hardening of silicon can be achieved by doping with metals. This is a cheaper and safer method than irradiating by 1 MeV neutrons.

These results also support previous work that metal-doped silicon behaves like radiation damaged silicon with induced defects acting to reduce the conductivity and to induce relaxation-likeness. Such relaxation material is radiation-hard and appropriate for the fabrication of particle detectors. Such detectors would be useful for colliders like the super LHC.

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