Radiation Physics and Chemistry 85 (2013) 73–82

Contents lists available at SciVerse ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Review

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

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ARTICLE INFO

Article history:
Received 5 April 2012
Accepted 1 December 2012
Available online 8 December 2012

Keywords:
Semiconductor
Silicon
Diode
Schottky
Capacitance
Detector

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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0969-806X/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.radphyschem.2012.12.002

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

$$C=A\sqrt{\frac{e\varepsilon_s\varepsilon_0N_D}{2(V_{bi}+V)}} \quad (1)$$

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

$$C^{-2}=\frac{2}{A^2}\left(\frac{V_{bi}+V}{e\varepsilon_s\varepsilon_0N_D}\right) \quad (2)$$

which can be expanded to be

$$C^{-2}=\frac{2}{A^2}\times\frac{V_{bi}}{e\varepsilon_s\varepsilon_0N_D}+\frac{2}{A^2}\times\frac{V}{e\varepsilon_s\varepsilon_0N_D} \quad (3)$$

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

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

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

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

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