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

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ABSTRACT

Current–voltage (*I–V*) 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 *I–V* data were used to extract the saturation current, the ideality factor and the Schottky barrier height for each of the five diodes. These parameters were correlated to the defect levels generated by the metals in silicon. The results show that in all cases the silicon has become relaxation-like after doping since the device current is Ohmic. This is in agreement with the existence of the midgap defect in all the doped devices as compiled from the literature. Such metal doped (or relaxation) devices have been found to perform better as radiation-hard particle detectors.

1. Introduction

Silicon has been used widely to fabricate radiation detectors that are used in high energy physics experiments to detect charged particles. These detectors are diodes that have a potential for such applications because of their conductivity, which can vary either as a function of temperature or as a function of impurities added into the semiconductor [1]. It has, however, been shown that the detectors fail to operate efficiently under high radiation environments [2]. This failure is attributed to defect levels that are created within the energy gap of the semiconductor by the incident radiation that the devices are intended to detect.

Several studies have been carried out in order to understand better the properties of the defects and their influence on the detectors [3]. These studies show that the defects are responsible for changes in the electrical properties of the diodes. The leakage current and the full depletion voltage of the diodes increase after exposure to radiation [3]. It has also been observed that after irradiation an increase in forward current with voltage changes from an exponential behaviour to a linear behaviour [4]. The conductivity-type of the semiconductor also changes and it has been observed to occur at a radiation fluence of $1.4\times10^{13}\,\mathrm{n\,cm^{-2}}$ for 1 MeV neutrons [5,6].

In order to fabricate radiation-hard detectors, it is necessary that the properties of the material are understood. This is done in order to investigate possibilities to alter the properties to suit our purpose. Several studies have been carried out on silicon material made radiation-hard either by pre-irradiation [7,8] or by doping the material with metals [9]. These studies show that pre-irradiation by 1 MeV neutrons renders the silicon completely damaged such that no further degradation can occur when the detector is under operation.

Doping silicon with metals was initially carried out in order to reduce the switching time of electronic devices [10]. Gold was preferred mainly because in silicon it acts as a lifetime killer. Since the carrier lifetime is reduced in this case, it follows that the material would be in a relaxation state. Thus, gold doping was initially carried out in order to reduce the lifetime but later it was done in order to suppress the effects of device exposure to radiation as well [11,12]. However, metals in silicon also create defect levels [13] some of which can have similar effects as those

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that are created by exposure to radiation. These defects tend to render the material useless while others can make the material useful for the fabrication of particle detectors [9]. As a result, it is important that the amount and the nature of metals introduced into the silicon are controlled so that the desired properties are improved while the undesired ones are minimized. This can be done by studying the effects of various metals introduced into silicon with different atomic concentrations.

Much research has been carried out to investigate the effects of gold and platinum on the electrical properties of silicon diodes [11,12,14]. At this stage, the results obtained from these studies have not been fully analysed nor understood. In addition, there is not much literature available that compares the results obtained from gold and platinum with other metals such as erbium and niobium [15–17]. Thus, we find that this is a main weakness in the current investigation to make silicon radiation-hard. This paper attempts to address this weakness.

In this work, Schottky barrier diodes were fabricated on undoped and on metal-doped p-silicon. The metals used are gold, platinum, erbium and niobium. The diffusion of gold and platinum into silicon occurs by the interstitial and vacancy mechanisms [18,19] whereby these metals create defect levels in the energy gap of silicon. Gold in silicon creates three different defect levels at E_c −0.34 eV, at E_c −0.55 eV and at E_v +0.34 eV [20]. Since gold creates a strong recombination centre in silicon [13], it is expected that after gold-doping the conductivity of the material will be reduced as mobile carriers become recombined.

Platinum in silicon has also been found to create three different defect levels at E_c −0.23 eV, at E_c −0.52 eV and at E_v +0.36 eV [21]. The donor level in the lower half of the energy gap is more active than the acceptor level in the upper half [13]. It is thus expected that after platinum-doping the conductivity of the material will be reduced as the donor level compensates any majority carriers.

As far as we know, the diffusion mechanisms of erbium into silicon have not been published before. This lack of information could be due to the fact that erbium has a very low solubility in silicon [22] such that it is difficult to use for doping. Additionally, the metal reacts vigorously with oxygen. This makes it difficult to study the effects of erbium in the material without studying those of oxygen. It is then required that in introducing the metal into the material, very high vacuum conditions are required so that the amount of unwanted impurities like oxygen is minimized. The results presented by Coffa et al. [17], however, show that the metal in silicon creates defect levels at E_c −0.20 eV, at E_c −0.26 eV, at E_c −0.34 eV and at E_c −0.51 eV. It is clear that all the defect levels are found in the upper half of the energy gap. It is required that the properties of these levels are fully analysed or understood so that they can be compared with those created by gold and platinum. Since there are no defect levels situated in the lower half of the energy gap, it is expected that after erbium-doping the conductivity of the silicon will increase as carriers are generated from the upper half of the energy gap.

At this stage, and as far as we know, the diffusion mechanisms of niobium into silicon are not known. The solubility and diffusivity of the metal are also currently not known. However, the metal in silicon has been found to create defect levels at E_c −0.29 eV, at E_c −0.58 eV and at E_v +0.16 eV [16]. The very shallow level at E_v +0.16 eV is expected to compensate any majority carriers. It is thus expected that after niobium-doping the conductivity of the material will be reduced as majority carriers are compensated.

Irradiation with 1 MeV neutrons also creates defect levels in silicon. These are situated at E_c −0.42 eV, at E_c −0.55 eV and at E_v +0.36 eV [16]. It is expected that the radiation will have similar effects on the properties of the silicon as the metals, mainly because all create the defect situated near midgap (0.56 eV). We term this defect the midgap defect.

In this work, the diodes were characterized using the *I*–*V* technique. This technique in reverse bias is used to determine the leakage current and the breakdown voltage [23,24]. In forward bias the technique is used to determine the saturation current, the ideality factor and the Schottky barrier height [1]. The results were used to investigate the effects of the metals on the silicon by inference from the electrical properties of the diodes. The diodes made on metal-doped silicon all show an Ohmic current. This behaviour indicates that the diodes are fabricated on relaxation-like material [4]. This relaxation material has a very high resistivity due to the low carrier density produced by compensation by midgap defects. These midgap defects tend to interact equally with electrons and with holes to act as generation-recombination (*g*-*r*) centres. We contend here that doping silicon with erbium or niobium induces relaxation-like properties in the material in a similar manner as doping with gold or platinum does. This is because all the metals, like irradiation by 1 MeV neutrons, generate the midgap defect, which has been established at an energy level of 0.545 eV [25] and of ~0.536 eV [26] to be the cause of the relaxation behaviour in such material. Relaxation materials have $\tau_D \gg \tau_0$ while lifetime materials have $\tau_D \ll \tau_0$, where τ_D is the dielectric relaxation time and τ_0 is the minority carrier recombination lifetime [4].

2. Experimental procedure

2.1. Material preparation

The material used in this work is a p-type silicon wafer polished on one side. The wafer was diced into 0.9 cm × 0.9 cm square substrates. The resistivity of the material ranges from 1 to 20 Ω cm and the thickness from 350 to 400 μm. The substrates were cleaned with an ultrasonic cleaner, successively using methanol, acetone, trichloroethane and de-ionized water to remove any dirt and handling grease. Afterwards, they were dipped into 20% hydrofluoric (HF) solution to remove the oxide layer. The substrates were then blow-dried using nitrogen gas after which they were loaded into a high-vacuum evaporation chamber for metal deposition. The deposition and diffusion processes have been outlined elsewhere [27] and will not be repeated here. After diffusion of the metals into the bulk, Schottky diodes were fabricated on the substrates.

2.2. Device fabrication

Prior to device fabrication, it was realised that there still were metal residues on the surface of the metal-difused substrates. It was thus necessary to follow-up the diffusion process with a chemical process. The chemical process involves dipping the substrates into a solution which is intended to only dissolve away or etch the metal residue without reacting with the silicon. In this way, it is expected that any possible surface conduction after device fabrication is minimized as much as possible. We did test this conjecture by repeatedly measuring the surface resistance by a simple probe multimeter and this, read very low for these samples compared to p-silicon samples.

The gold- and platinum-doped substrates were dipped in warm aqua regia solution ($HCl:HNO_3$ in the ratio 3:1) for 50 min. Since platinum residues were found not to be completely etched away from the surface after this time, the substrates were dipped again in aqua regia solution but with an $HCl:HNO_3$ ratio of 3:2 and for 60 min. The erbium- and niobium-doped substrates, on the