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Electrically active defects in p-type silicon after alpha-particle irradiation

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A B S T R A C T

In this work, we investigated the defects introduced when boron (B) doped silicon (Si) was irradiated by making use of a 5.4 MeV americium (Am) 241 foil radioactive source with a fluence rate of 7×10^{6} cm^{-2} s^{-1} at room temperature. Deep level transient spectroscopy (DLTS) and Laplace-DLTS measurements were used to investigate the electronic properties of the introduced defects. After exposure at a fluence of 5.1×10^{10} cm^{-2}, the energy levels of the hole traps measured were: H(0.10), H(0.16), H(0.33) and H(0.52) The defect level H(0.10) was tri-vacancy related. H(0.33) was identified as the interstitial carbon (C_i) related defect which was a result of radiation induced damage. H(0.52) was a B-related defect. Explicit deductions about the origin of H(0.16) have not yet been achieved.

1. Introduction

Silicon (Si) is arguably the most important semiconductor material. It has been studied extensively and widely used in commercial products [1]. This is mainly due to its low cost, thermal stability, good durability [2] and reliability of its oxide for use in complementary metal-oxide semiconductor (CMOS) technology [3]. These properties have enabled researchers to make major advances towards reliable and cost-effective silicon-based photonic–electronic integration [4].

The study of radiation-induced defects in semiconductors comprises a significant area of research on materials from the point of view of device applications [5]. For Si, studies using high energy electron irradiation, have been primarily motivated by the strong degradation effects on Si solar cells caused by radiation during space use. Gamma-rays and neutrons have also been used to study defects in Si which are generally produced in electronic devices in nuclear radiation environments such as those provided by nuclear reactors [5]. α-radiation from packaging was well-known as the major source of failure in Si memory devices causing both soft [6] and hard [7] errors. Thus, α-particle-induced defects are a cause of principal concern for the in-use failure of these electronic applications of Si devices. Not many studies on alpha-particle radiation induced defects exist in literature [5] these have primarily focused on n-type material. Takeuchi *et al.* [7] reported on deep level defects produced by α-particle irradiation in the upper half of the band gap of the p-type Si. A detailed and comprehensive characterisation of defects in p-type material in both halves of the band gap is generally lacking in the literature [5]. Furthermore, reports on hole traps are not many due to the struggle in fabricating quality Schottky contacts on p-type Si for consistent electrical characterisation [8].

In this paper we report on defects introduced in B doped p-type Si after irradiation by α-particles at room temperature. The defects were investigated using deep level transient spectroscopy (DLTS) and Laplace-DLTS which are quantitative electrical characterisation techniques highly suitable for point defect studies.

2. Experimental details

Aluminium (Al) Schottky contacts were fabricated on the p-Si samples with indium-gallium eutectic as the ohmic contact. Current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements were conducted to ascertain the quality of the contacts produced. Thereafter, DLTS measurements were carried out on the samples. The samples were then irradiated with α-particles at room temperature. This was achieved by making use of a 5.4 MeV Am-241 radioactive source with a fluence rate of 7×10^{6} $cm^{-2}s^{-1}$. The Al samples were first irradiated for 30 min at a fluence of 1.3×10^{10} cm^{-2} then the samples were exposed for 120 min at a cumulative fluence of 5.1×10^{10} cm^{-2}. *I-V* measurements, *C-V* measurements and DLTS were done in the 40 – 300 K temperature range at a scan rate of 2 K/min, after each irradiation. High resolution Laplace-DLTS was used to resolve the defects observed. In this study, the Al diodes were made using resistive evaporation which is known not to introduce defects in concentrations that can be measured by DLTS [9].

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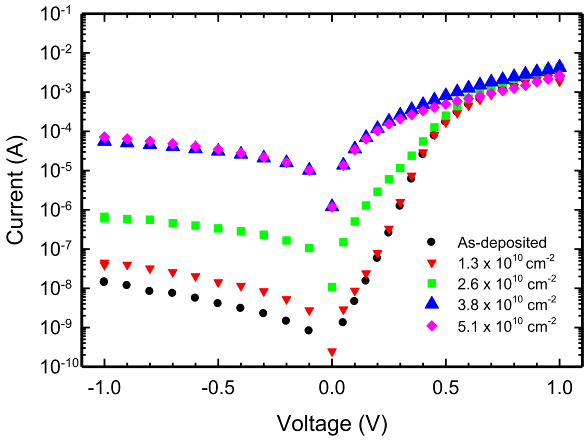

Fig. 1. Semi-logarithmic plot for forward and reverse *I-V* characteristics for the Al/p-Si contacts before and after α-particle irradiation up to a fluence of 5.1×10^{10} cm^{-2}.

3. Results and discussion

3.1. I-V characterisation

The *I-V* characteristics of the Al Schottky contacts prior to and after α-particle irradiation are shown in Fig. 1. The as-deposited samples produced a linear forward *I-V* curve. At this point the thermionic emission model can be used to explain the transport mechanism at the metal-semiconductor interface and can be expressed as

$$I = I_s exp\left(\frac{qV}{nkT}\right)\left[1 - exp\left(\frac{-qV}{kT}\right)\right]$$

Where I is the measured current, I_s is the saturation current, V is the applied voltage, q is the electronic charge, n the ideality factor, k_B is the Boltzmann constant and T is the absolute temperature. The forward-semi-logarithmic *I-V* curves obtained after irradiation deviated from linearity as the time of exposure to irradiation increased. This is ascribed to defects introduced by irradiation which lead to generation recombination current therefore the non-linear curves at low voltages.

Table 1 summarises the diode characteristics obtained from *I-V* and *C-V* measurements. The Schottky barrier height (SBH) was modified as the irradiation fluence increased. The ideality factor increased tremendously from 1.36 to 5.68. which was very large and indicated that the thermionic emission model doses not hold and other mechanisms, e.g. generation recombination dominate [10].

The *I-V* SBH decreased with increasing radiation fluence while the *C-V* SBH increased with increasing radiation fluence. These changes in both *I-V* and *C-V* characteristics were attributed to radiation damage [7]. The reverse leakage current, measured at −1V, increased from 1.44×10^{-8}A before irradiation to 7.15×10^{-5} A after irradiation with a fluence of 5.1×10^{-10} cm^{-2}. This could have been a consequence of interface states present at the metal-semiconductor interface or a non-uniform thin oxide layer at the interface [11].

The free carrier density was obtained from the slope of the $1/C^2$ versus V curve. The free-carrier density was 2.4×10^{15} cm^{-3} before irradiation. The initial radiation exposure decreased the free carrier density to 2.3×10^{1} ^{5}cm^{-2}. It remained at this value for the subsequent two doses then it decreased to 2.2×10^{1} ^{5}cm^{-3} at a fluence of 5.1×10^{10} cm^{-2}. We deduce from this that the concentration of deep levels is much less than the carrier density and the sample is therefore suitable for Laplace-DLTS investigations.

Table 1
Parameters obtained from *I-V* and *C-V* measurements as the irradiation fluence increased.

Fluence (cm^{-2})	n	I-V SBH (eV)	C-V SBH (eV)	I_R at -1V (A)	Free carrier density (cm^{-3})
0	1.36	0.81	1.25	1.4×10^{-8}	2.4×10^{15}
1. 3×10^{10}	1.43	0.79	1.20	3.9×10^{-8}	2.3×10^{15}
2. 6×10^{10}	2.55	0.64	1.24	6.7×10^{-7}	2.3×10^{15}
3. 8×10^{10}	4.30	0.52	1.32	5.6×10^{-5}	2.3×10^{15}
5. 1×10^{10}	5.68	0.51	1.30	7.2×10^{-5}	2.2×10^{15}

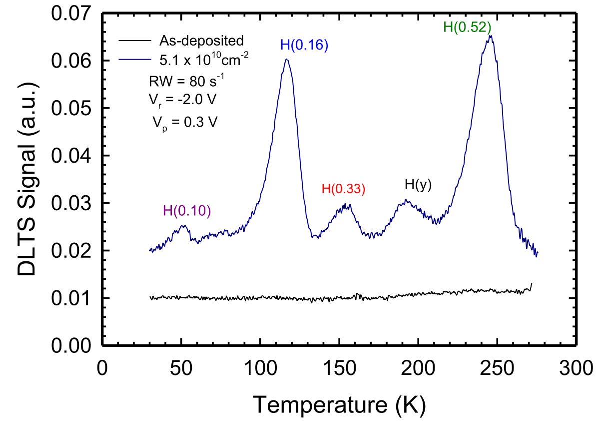

Fig. 2. DLTS spectra illustrating the as deposited sample and defects obtained after α-particle irradiation at a fluence of 5.1×10^{10} cm^{-2}.

3.2. DLTS characterisation

From the spectrum shown in Fig. 2, the hole traps observed were: H(0.11), H(0.16), H(0.33) and H(0.52). In this nomenclature, "H" means "hole trap" and the number after H is the activation enthalpy, in eV, obtained from an Arrhenius plot of log (T^2/e_n) vs 1000/T. Here e_n is the emission rate at temperature T. The defect H(0.10) was identified as the tri-vacancy (V_3) related defect. The calculated capture cross-section was 2.5×10^{-16} cm^2 from the Arrhenius plot shown in Fig. 3. Markevich *et al.* [12] identified + 0.106 eV as one of the energy levels of V_3. They observed this defect level after irradiating their samples with 6 MeV electrons and subsequent annealing at 100 °C. These authors also employed ab initio modelling for the identification of the same defect.

The defect level H(0.33) was identified as the interstitial carbon (C_i) related defect. It was a result of induced radiation damage [13]. The apparent capture cross-section was calculated to be 1.6×10^{-19} cm^2. Auret *et al.* [14] observed a defect in p-type silicon with the same activation energy in samples that had been fabricated with titanium contacts using resistive deposition. Defects with similar activation energies have been identified in literature [15]. They are all related

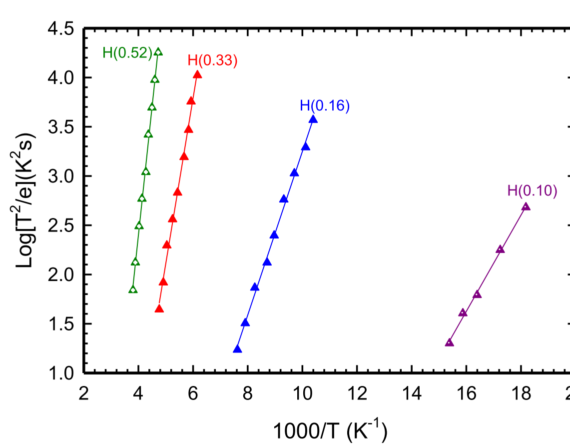

Fig. 3. Arrhenius plots obtained using the L-DLTS technique on Al/p-Si contacts after α-particle irradiation.

to the residual carbon impurity which has been reported to form complexes directly with radiation-induced primary defects or with secondary defects induced by radiation damage. These defects include the interstitial-carbon-interstitial-oxygen (C_i–O_i) complex (C(3) centre) [16], the carbon-oxygen-vacancy complex (K centre) [17,18] and the interstitial-substitutional-carbon complex (C_s–C_i) [5]. In their study, Asghar *et al.* [5] observed that the 0.35 eV defect annealed at approximately 400 °C, in agreement with literature of similar defect levels, E_V+0.38 and E_V+0.33 [17,18]. These reports suggest that the H(0.33) level originates from the carbon-oxygen-vacancy ($C - O - V$) complex. However, studies by Song *et al.* [19] strongly suggest that this defect is associated with C_i–O_i complex. This deep level is probably strongly dependant on the semiconductor and sample since unintentional carbon and oxygen contamination could vary with the material growth technique used as well as device processing [5].

H(0.52) was observed by Volpi *et al.* [20] after wet chemical etching followed by sputter deposition of MBE-grown boron doped silicon. They concluded that the defect was B-related. A similar defect was observed after electron beam deposition (EBD) damage [21]. The apparent capture cross-section of H(0.52) was 1.7×10^{-14} cm^2. H(0.16) was observed by Feklisova *et. al.* [22] it was a radiation induced defect observed in hydrogenated Si after electron irradiation. The capture-cross-section of H(0.16) was 1.8×10^{-17} cm^2. Resolving the peak H(y) using L-DLTS proved to be a challenge. The peak may have been an extension of neighbouring defects or a continuum of defect states.

4. Conclusion

We reported on defects introduced in epitaxially grown B doped p-type Si after irradiation by α-particles at room temperature. The *I-V* characteristics illustrate that the Al contacts rectification properties deteriorated as the irradiation fluence increased. The as deposited sample showed linear forward *I-V* characteristics with the leakage current at 1.4×10^{-8} A. The value of the reverse leakage current increased to 7.2×10^{-5} A while the forward *I-V* graphs lost their linearity as the irradiation fluence increased. The hole traps observed after alpha-particle irradiation of Al contacts were: H(0.16), H(0.33) and H(0.52). H(0.33) was identified as the interstitial carbon (C_i) related defect and H(0.52) was identified as a B-related defect. We have not yet made any explicit deduction about the origin of H(0.16).

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