Nuclear Instruments and Methods in Physics Research A 377 (1996) 224–227

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

The effect of radiation induced defects on the performance of high resistivity silicon diodes

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Abstract

An overview of defect kinetics in high resistivity silicon is presented. A device model which gives type inversion due to the presence of deep acceptors is described.

1. Introduction

The aim of this work has been to understand radiation induced changes in the macroscopic properties of silicon diodes manufactured on high resistivity silicon in terms of the microscopic defects created by irradiation. To understand the data it is important to have a model for the formation of defects. Our analysis is based on the model of Ref. [1] suitably extended to neutron irradiation. Irradiation gives rise to vacancies (V) and interstitials (I), most of which rapidly recombine. Those escaping this initial recombination diffuse through the crystal, reacting with impurity atoms and other defects. Reaction rates are controlled by the concentration of impurities and defects and their relative capture radii. Important reactions include:

$$\mathrm{V + V \rightarrow VV \text{ or } V_2}\,, \qquad \mathrm{I + C_s \rightarrow C_i\ (transient)}\,,$$
$$\mathrm{V + O \rightarrow VO\ (Si\text{–}A\ centre)}\,, \qquad \mathrm{C_i + C_s \rightarrow C_iC_s}\,,$$
$$\mathrm{V + P \rightarrow VP\ (Si\text{–}E\ centre)}\,, \qquad \mathrm{C_i + O \rightarrow CO}\,,$$

where the subscripts "s" and "i" refer to carbon atoms in substitutional or interstitial sites respectively. Divacancies are mainly produced directly within a PKA (Primary Knock-on Atom) cascade. Neutrons produce terminal clusters containing divacancies and more complex defects. By studying these reactions using Deep Level Transient Spectroscopy (DLTS) after gamma irradiation the carbon and oxygen concentrations have been estimated to be a few $10^{15}\ \mathrm{cm}^{-3}$.

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2. Experimental details

Irradiations with ^{60}Co gammas and ^{252}Cf neutrons were performed on diodes of size 5 mm by 5 mm, manufactured by Sintef. The substrate material was high resistivity (4 kΩ cm), n-type, float-zone silicon supplied by Wacker. The diodes were measured to have a donor concentration of $10^{12}\ \mathrm{cm}^{-3}$ by capacitance–voltage analysis. Photoluminescence measurements on similar material yielded a phosphorus concentration of approximately $10^{12}\ \mathrm{cm}^{-3}$, the concentration of boron being a factor of 10 to 20 less than this. After irradiation, DLTS was used in conjunction with high temperature annealing to investigate the defect kinetics. From such studies the phosphorus removal constant due to neutron irradiation was estimated to be $(1\pm0.1)\times10^{-14}\ \mathrm{cm}^2$ [2]. This is a factor 30 lower than has been inferred from fitting N_{eff} versus neutron fluence data [3].

The hole traps, H(157) – $\mathrm{C_i}$, and H(198) – $\mathrm{C_iC_s}$ and/or $\mathrm{C_iO_i}$, allow one to study the behaviour of the carbon after irradiation. Fig. 1 shows the annealing behaviour of these traps using DLTS measurements at 330, 340 and 360 K. The time constants derived from Fig. 1 give the characteristic energy associated with the decay and growth of these two peaks – (1.0±0.2) eV. The time constant for these reactions at 20°C is 14 days.

3. Device modelling

It is clear that a new explanation is required for the N_{eff} behaviour versus neutron fluence. From Refs. [4–6] it is evident that the silicon in equilibrium becomes intrinsic after heavy neutron irradiation. It only becomes effectively p-type under bias due to the presence of a deep acceptor(s). A one dimensional device model has been developed

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SSDI 0168-9002(95)01413-6

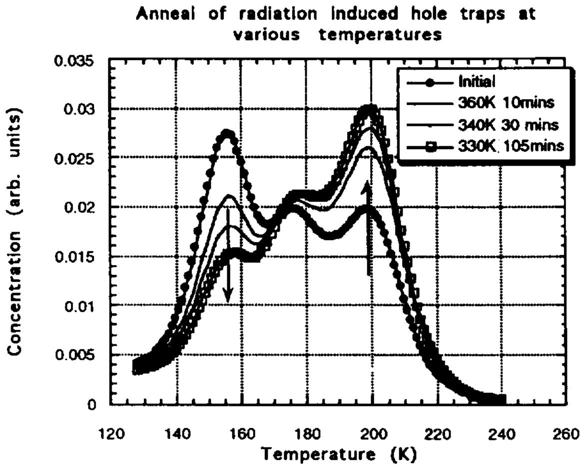

Fig. 1. DLTS hole spectrum showing carbon interstitials, H(157), created by gamma irradiation converting to CC and/or CO centers, H(198), at various temperatures in a high resistivity n-type diode. H(157) and H(198) correspond to energy levels of $(E_v + 0.29)$ and $(E_v + 0.35)$ eV respectively. The hole trap at 175 K existed before the irradiation.

which includes a single energy level acceptor in the Poisson equation. Quasi-fermi levels are used to determine the fraction of acceptors that are filled. Thermal generation of carriers is input using the carrier lifetime. The program is called KURATA and is described in more detail in Ref. [2]. The damage constant for the minority carrier lifetime is related to the neutron fluence, Φ_n by [7],

$$1/\tau = 1/\tau_0 + \Phi_n/K_\tau \approx \Phi_n/K_\tau \quad \text{for large fluences}. \qquad (1)$$

This is for the minority carrier lifetime in the silicon under equilibrium conditions. We make the assumption that the effective lifetime in the depletion region can also be described by such a relation. Hence it is easy to show that the bulk leakage current degradation parameter, α, is given by,

$$\alpha = en_i 2K_\tau , \qquad (2)$$

where K_τ is the damage constant for the carrier lifetime, n_i is the intrinsic carrier concentration and e is the charge on the electron. Messengers 2-level model [7] gives a K_τ around 10^7 neutron s cm^{-2} for high resistivity silicon. Carrier concentrations in the depletion region are low, hence one would expect that the K_τ for high resistivity silicon can be used for the damage constant for the effective carrier lifetime. This gives an α of about 7×10^{-17} A cm^{-1} at 20°C, in agreement with the measured value. In the device modelling, K_τ is set to 10^7 n s cm^{-2} for the n-type diode. On the basis of measurements in Ref. [3], it is set to be 1.3 times smaller for a p-type diode. KURATA simulations resulted in a empirical relationship between the density of acceptors and the effective carrier lifetime. From this came a simple analytical solution. This provides an insight into the effect that filled acceptors have on the effective doping density once the material is intrinsic. Assume that the material is intrinsic. Within the depletion region the electron and hole concentrations are much less than the intrinsic carrier concentration, n_i. The rate of generation of electron–hole pairs is, $G = n_i/2\tau$, where τ is the effective generation lifetime in the depletion region. The electron concentration in the depletion region is small but still finite. If one assumes that it is uniform, as confirmed by the numerical simulation, then the electron current density will be dominated by the drift component, $J_n = e\mu_n En$.

The continuity equation gives, $\mathrm{d}J_n/\mathrm{d}x = -eG$, which implies that $\mu_n n\,\mathrm{d}E/\mathrm{d}x = -n_i/2\tau$. Now making use of the Poisson equation we have, $\mathrm{d}E/\mathrm{d}x = e(p - n - N_A^*)/\varepsilon_{Si} = -eN_A^*/\varepsilon_{Si}$ in the depletion region. N_A^* is the density of filled acceptors which is also the effective doping density N_{eff}. Thus one can see that, $n = \varepsilon_{Si} n_i/(2\tau e\mu_n N_{eff})$.

$$N_{eff} = N_A^* = N_A f(E_T) , \qquad (3)$$

where N_A is the acceptor density and $f(E_T)$ is the occupancy function. For simplicity we will use the Fermi function,

$$f(E_T) = 1/(1 + \exp((E_T - E_{fn})/kT)) ,$$

where E_{fn} is the quasi-Fermi level for electrons. This is equivalent of assuming zero hole capture cross sections. For simplicity, the degeneracy factor is set to one.

From the definition of the quasi-Fermi level, $n = n\exp((E_{fn} - E_i)/kT)$ one can then write,

$$f(E_T) = 1/(1 + (n_i/n)\exp((E_T - E_i)/kT))) . \qquad (4)$$

The acceptor density, N_A, is related to the neutron fluence by its introduction rate K_A,

$$N_A = K_A \Phi_n . \qquad (5)$$

From Eqs. (1)–(5), one can show that,

$$N_{eff} = \Phi_n(\sqrt{((1/K_\tau\lambda)(K_A + 1/(4K_\tau\lambda)))} - 1/(2K_\tau\lambda)) , \qquad (6)$$

where $\lambda = (2e\mu_n/\varepsilon_{Si})\exp((E_T - E_i)/kT)$. The acceptor energy, E_T, is referenced relative to the intrinsic energy level, E_i. Using the fact that for fluences after inversion, $N_{eff} = \beta\Phi_n$ where $\beta = 0.016\ \mathrm{cm}^{-1}$, [3], Fig. 2 shows the required introduction rate, K_A as a function of the acceptor position in the band-gap. This figure also shows what would happen if the ratio of the hole to electron capture cross-section for the acceptor level were equal to one and ten using a more sophisticated function for estimating the fraction of filled acceptors based on Shockley, Read, Hall statistics [8]. The quasi-Fermi level function corresponds to the ratio of the hole to electron capture cross-section being equal to zero. Eq. (6) can be simplified. If $E_T - E_i$ is less than 0.1 eV below the intrinsic Fermi level then, $N_{eff} = K_A \Phi_n$ i.e. an acceptor below E_i is always filled. If

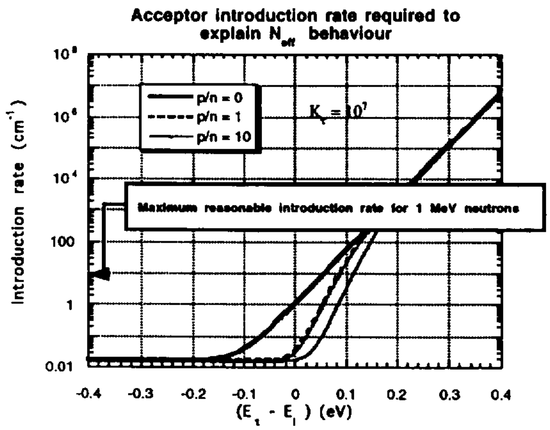

Fig. 2. Introduction rate required for an acceptor at a certain energy level in the silicon band-gap to explain the effective doping density changes caused by 1 MeV neutron irradiation. p/n is the ratio of hole to electron capture cross-section.

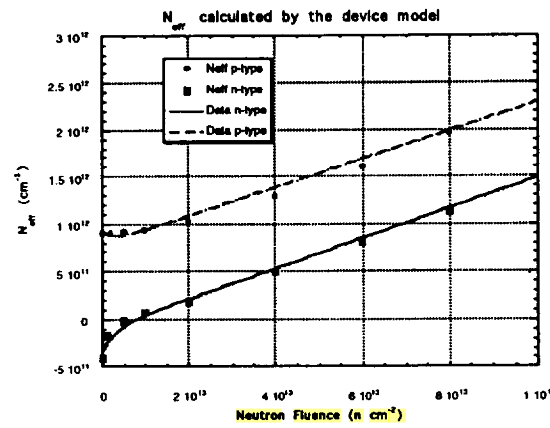

Fig. 4. The effective doping concentration calculated by the device model assuming an introduction rate of $1\ \mathrm{cm}^{-1}$ deep acceptors placed at mid-gap. The lines are fits to data given in Ref. [3].

the acceptor is higher in the band-gap then the level will not be completely filled and the effective doping density is also dependent on the effective lifetime. In this case,

$$N_{\mathrm{eff}} \approx \Phi_{\mathrm{n}} \sqrt{K_{\mathrm{A}} / K_{\tau} \lambda}\,. \tag{7a}$$

For a K_{τ} of $10^{7}\ \mathrm{s\,cm}^{-2}$, the introduction rate required for an acceptor at mid-gap is about $1\ \mathrm{cm}^{-1}$. Eq. (7a) can also be written as,

$$N_{\mathrm{eff}} \approx \sqrt{N_{\mathrm{A}} / \lambda \tau}\,. \tag{7b}$$

This clearly shows the importance of the lifetime and thus

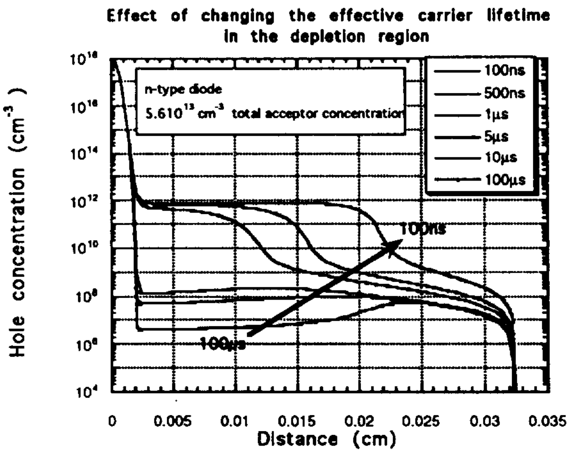

Fig. 3. A device model simulation showing the importance of changing the effective lifetime in the depletion region on the hole concentration in an n-type diode with $5.6 \times 10^{13}\ \mathrm{cm}^{-3}$ deep acceptors at mid-gap.

the dark current on the behaviour of N_{eff}. In the numerical modelling the introduction rate of the acceptor is set to $1.0\ \mathrm{cm}^{-1}$ and it is placed at mid-gap. This is the only free parameter in the model and is used for both p- and n-type diodes. Simulations from the version of KURATA that uses quasi-Fermi levels are given in this paper. The more sophisticated program using SRH statistics gives similar results.

Fig. 3 shows the importance of the carrier lifetime, cf. Eq. (7b). No phosphorus has been removed in these calculations. The model has been used to generate N_{eff} versus neutron fluence for both an n-type and p-type diode, Fig. 4. N_{eff} is calculated using the models' solution for the depletion thickness at a particular bias. The fit to data from Ref. [3] is shown for comparison. There is good agreement between the data and the model.

4. Summary and conclusions

a) Defect kinetics is vital if one is to understand radiation effects in this material. Using gamma irradiation and DLTS measurements the carbon and oxygen concentrations have been found to be of order $10^{15}\ \mathrm{cm}^{-3}$. The phosphorus removal rate under neutron irradiation is a factor 30 smaller than had been thought. This is consistent with our understanding of defect kinetics since the high concentration of oxygen in the starting material acts as a getter for the vacancies suppressing the phosphorus removal.

b) The behaviour of the effective doping density can be explained in terms of the production of a deep level acceptor. N-type diodes only become effectively p-type when biased. In equilibrium they are intrinsic after heavy neutron irradiation. Both n- and p-type detectors can be modelled in terms of one parameter – the introduction rate for the deep acceptor.

c) Carbon is an important sink for interstitials. Moreover, carbon interstitials move around after irradiation with a time constant of about 14 days at room temperature. The role of carbon needs to be better understood. If the carbon concentration was reduced then interstitials would be more likely to recombine with vacancies. The use of epitaxial material which should have low carbon levels needs to be investigated.

Acknowledgements

We acknowledge financial support from the UK Particle Physics and Astronomy research Council. The help of Prof. E. Lightowlers at King's College was invaluable. We are grateful to G. Hall, B. MacEnvoy and R. Wheadon for many useful discussions.

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