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Study of point- and cluster-defects in radiation-damaged silicon

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ABSTRACT

Non-ionising energy loss of radiation produces point defects and defect clusters in silicon, which result in a significant degradation of sensor performance. In this contribution results from TSC (Thermally Stimulated Current) defect spectroscopy for silicon pad diodes irradiated by electrons to fluences of a few 10^{14} cm^{-2} and energies between 3.5 and 27 MeV for isochronal annealing between 80 and 280 °C, are presented. A method based on SRH (Shockley–Read–Hall) statistics is introduced, which assumes that the ionisation energy of the defects in a cluster depends on the fraction of occupied traps. The difference of ionisation energy of an isolated point defect and a fully occupied cluster, ΔE_a, is extracted from the TSC data.

For the VO$_i$ (vacancy-oxygen interstitial) defect $\Delta E_a = 0$ is found, which confirms that it is a point defect, and validates the method for point defects. For clusters made of deep acceptors the ΔE_a values for different defects are determined after annealing at 80 °C as a function of electron energy, and for the irradiation with 15 MeV electrons as a function of annealing temperature. For the irradiation with 3.5 MeV electrons the value $\Delta E_a = 0$ is found, whereas for the electron energies of 6–27 MeV $\Delta E_a > 0$. This agrees with the expected threshold of about 5 MeV for cluster formation by electrons. The ΔE_a values determined as a function of annealing temperature show that the annealing rate is different for different defects. A naive diffusion model is used to estimate the temperature dependencies of the diffusion of the defects in the clusters.

1. Introduction

Bulk-radiation damage in silicon limits the use of silicon detectors in high-radiation environments like at the CERN-LHC or in space. Although both microscopic and macroscopic effects of bulk damage are qualitatively understood, in spite of claims to the contrary, a consistent quantitative description of the data available has not yet been achieved. However, this is required for reliably predicting the sensor performance as a function of particle type and fluence, sensor design and operating parameters. The reason is that the number of radiation-induced states in the silicon band gap is large (see Fig. 1), their properties are frequently only poorly known, and *effective states* [1] have to be used in simulations because of the large number of defects. In addition, a quantitative understanding of defect clusters is lacking and in the TCAD simulations they are approximated by point defects.

In this contribution we propose a simple, physics motivated parametrisation of the properties of cluster defects and apply it to spectroscopic results from TSC (Thermally Stimulated Current) measurements. We present results for silicon irradiated with electrons of 3.5–27 MeV kinetic energy [2,3]. As the threshold for defect cluster production is expected to be around 5 MeV for electrons [4], these data are well suited to check the validity of the method.

In the present work single vacancy related defects are considered to be point-like defects (e. g. the VO$_i$ defect). Such isolated point defects are produced in silicon by low energy recoils, whereas an agglomeration of defects (or a cluster for short) results from high energy recoils that introduce a dense cascade of silicon atoms displaced from their original lattice position.

2. Test structures and measurements

For the studies p$^+$n n$^+$ pad diodes, produced on 283 μm thick float-zone n-type silicon with a phosphorous-doping of approximately 10^{12} cm^{-3} and an oxygen concentration $<10^{16}$ cm^{-3}, were used. The p$^+$ implant of 25 mm^2 area is surrounded by a guard ring. A window in the aluminium on top of the p$^+$ implant with the shape of a decagon and an area of 3.25 mm^2 allows to inject light through the p$^+$ contact. The n$^+$ back contact is covered by an aluminium grid.

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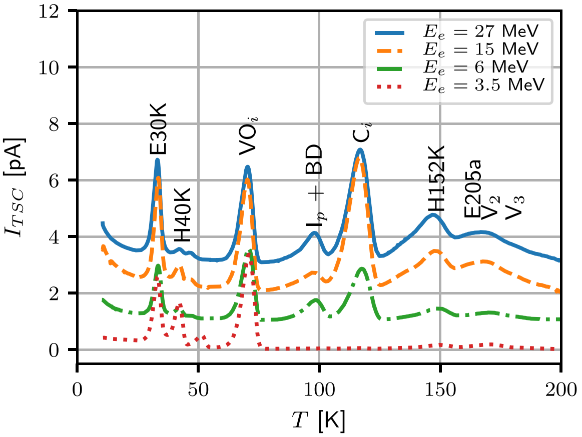

Fig. 1. TSC spectra, $I_{TSC}(T)$, normalised to an electron fluence of $\Phi = 10^{14}$ cm^{-2}, after irradiation by electrons with different energies and annealing for 30 min at 80 °C, measured at a heating rate of 0.183 K/s. The pad diodes were fabricated using standard float-zone silicon. For the trap filling forward-current injection has been applied at $T_0 = 10$ K, so that both electron (E) and hole (H) traps contribute to $I_{TSC}(T)$. For clarity, the individual curves are shifted vertically by 1 pA. For the identification and labelling of the individual defects we refer to [2] and references therein. The dark current, which starts to dominate above 200 K, is subtracted.

The pad diodes have been irradiated with electrons of $E_e = 3.5$, 6, 15, and 27 MeV to fluences between 1 and $10{\times}10^{14}$ cm^{-2}. For the sample irradiated with 15 MeV electrons, TSC measurements were performed before and after isochronal annealing for 30 min at temperatures T_{ann} = 80 – 280 °C, in 20 °C steps. At the other energies, data were only taken before and after annealing of 30 min at T_{ann} = 80 °C. After annealing the pad diodes were stored in the dark at −25 °C. For the TSC measurements the bias was applied to the back n$^+$ contact, and both p$^+$ contact and guard ring were at ground potential.

Fig. 1 shows typical TSC spectra of pad diodes irradiated by electrons of different energies after 30 min annealing at 80 °C. Trap filling has been applied at $T_0 = 10$ K with a forward-current of approximately 1 mA, so that both electron- and hole-traps are filled and contribute to the TSC spectra. The heating rate was $\beta = 0.183$ K/s. For more details we refer to [2,5,6]. In the following we will limit the discussion to the point defect VO$_i$ (vacancy-oxygen interstitial) at 70 K and to the states in the 120–200 K region, which are known to be cluster defects and have a significant impact on the sensor performance [7].

For the TSC measurements analysed in this paper, the diodes were cooled to $T_0 = 10$ K at 200 V reverse bias to assure empty traps. At the temperature T_0 the traps were filled with electrons by injecting light of 520 nm through the 3.25 mm^2 window of the p$^+$ contact, and the current, I_{TSC}, released by the traps was recorded as a function of T for a constant heating rate $\beta = 0.183$ K/s. As a result of the light injection, only electron traps are filled and only the charges released from electron traps contribute to I_{TSC} (see Fig. 2).

3. Analysis method

According to SRH statistics [8,9] the temperature dependence of the TSC current, $I_{TSC}(T)$, from acceptor states at an energy E_a from the conduction band, which are filled with electrons at the temperature T_0 to the concentration N_t, is given by:

$$I_{TSC}(T) = \frac{A \cdot d \cdot q_0}{2} \cdot e(T) \cdot f_t(T) \cdot N_t, \tag{1}$$

$$e(T) = \sigma \cdot v_{th}(T) \cdot N_C(T) \cdot \exp\left(-\frac{E_a}{k_B T}\right), \tag{2}$$

$$f_t(T) = \exp\left(-\frac{1}{\beta}\int_{T_0}^{T} e(T')\,\mathrm{d}T'\right), \tag{3}$$

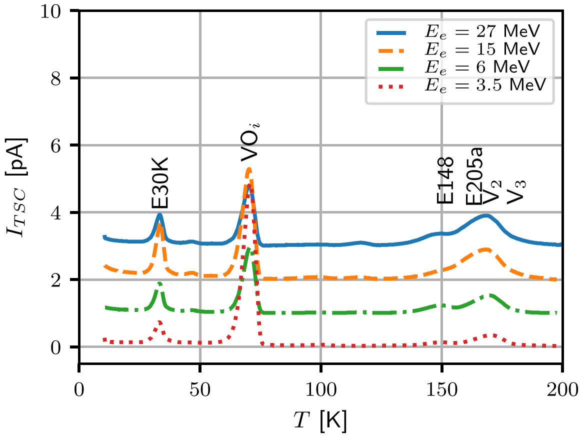

Fig. 2. TSC spectra, $I_{TSC}(T)$, obtained after trap filling with light injection (with $\lambda = 520$ nm) through the 3.25 mm^2 window of the p$^+$ contact at $T_0 = 10$ K, for the same irradiation conditions and samples as the data shown in Fig. 1. As a result of the trap filling by light injection, only electron traps contribute to the TSC current. For clarity, the individual curves are shifted vertically by 1 pA.

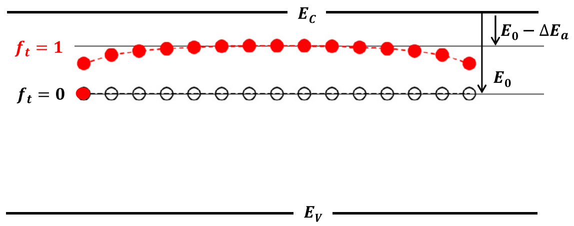

Fig. 3. Schematic presentation of the potential energy of the electrons in a cluster consisting of 15 point defects equally spaced on a straight line. E_V denotes the edge of the valence band and E_C of the conduction band. The filled dots show the ionisation energies for the individual defects, when all traps are filled. The electron occupying the central defect has the lowest ionisation energy, $E_0 - \Delta E_a$. It will discharge first, when the sample is heated in the TSC measurement. The open circles correspond to the ionisation energy when only one state is filled with an electron. Its value is E_0, the ionisation energy of the point defects, which build the cluster.

with the elementary charge q_0, the diode volume where the traps have been filled $A \cdot d$, the emission rate $e(T)$, the ratio of filled states at the temperature T relative to T_0, $f_t(T)$, the thermal velocity of electrons $v_{th}(T)$, the electron capture cross-section σ, and the density of states at the conduction band $N_C(T)$. For these quantities the default values of Synopsys TCAD [10], in particular the relation $v_{th}(T) = \sqrt{8 \cdot k_B T / \left(\pi \cdot m_{th}(300\ \mathrm{K})\right)}$ of [11], are used. The effective thermal electron mass $m_{th}(300\ \mathrm{K}) = 0.278 \cdot m_e$, with the Boltzmann constant k_B and the free electron mass m_e.

For point defects a constant value for E_a is expected. As proposed in [12], cluster defects can be characterised by an occupation-dependent value of $E_a(f_t)$. For the dependence $E_a(f_t)$, i. e. the change of the ionisation energy with the fraction f_t of defects filled in a cluster, a linear dependence is assumed:

$$E_a(f_t) = E_0 - \Delta E_a \cdot f_t. \tag{4}$$

The schematic drawing of Fig. 3 shows the potential energies of electrons in a cluster of 15 equally spaced electron traps on a straight line. The full dots correspond to $f_t = 1$, when all 15 traps are filled with electrons. The empty circles is the situation $f_t \to 0$, when only a single trap is filled and the energy is equal to the energy of the single isolated trap. The ionisation energy $E_a = E_0 - \Delta E_a$ is minimal for $f_t = 1$, and reaches its maximum $E_a = E_0$, the value for point defects, for $f_t \to 0$.