Influence of radiation damage on the absorption of near-infrared light in silicon

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ABSTRACT

The absorption length, λ_{abs}, of light with wavelengths between 0.95 and 1.30 μm in silicon irradiated with 24 GeV/c protons to 1 MeV neutron equivalent fluences up to 8.6×10^{15} cm^{-2} has been measured. It is found that λ_{abs} decreases with fluence due to radiation-induced defects. A phenomenological parametrization of the radiation-induced change of λ_{abs} as a function of wavelength and neutron equivalent fluence at room temperature is given. The observation of the decrease of λ_{abs} with irradiation is confirmed by edge-TCT measurements on irradiated silicon strip detectors. Using the measured wavelength dependence of λ_{abs}, the change of the silicon band-gap with fluence is determined.

1. Introduction

A standard way of determining the Charge-Collection-Efficiency, CCE, of radiation-damaged silicon sensors uses red and near-infrared (NIR) light to generate electron–hole pairs. In order to determine the absolute number of produced charge carriers, the light-absorption length, λ_{abs}, has to be known. Radiation produces defect states in the silicon band-gap, which are expected to cause a reduction of λ_{abs}.

In Ref. [1] the photo-conductivity of silicon for wavelengths up to $\lambda = 3$ μm has been measured before and after irradiation. Before irradiation no photo-conductivity has been observed. After irradiation it becomes significant. The results have been described by an irradiation-induced reduction of the silicon band-gap by up to 100 meV. However, the fluences of these studies are significantly higher than the ones investigated in this paper, for which a band-gap narrowing of only a few meV is expected.

In this work the transmittance of high-ohmic n-doped silicon irradiated with 24 GeV/c protons up to 1 MeV neutron equivalent fluences, Φ_{eq}, of 8.6 $\times 10^{15}$ cm^{-2} for light with λ between 0.95 and 1.30 μm has been measured. From the results $\lambda_{abs}(\Phi_{eq}, \lambda)$ is derived and the inverse of the radiation-induced absorption length

$$\alpha_{irr}(T, \Phi_{eq}, \lambda) = 1/\lambda_{abs}(T, \Phi_{eq}, \lambda) - 1/\lambda_{abs}(T, 0, \lambda) \qquad (1)$$

determined. The observed decrease of λ_{abs} with Φ_{eq} is confirmed by edge-TCT measurement using light from a sub-nanosecond laser with $\lambda = 1.052$ μm [2,3]. The measured dependence of λ_{abs} on Φ_{eq} is also used to investigate a possible narrowing of the silicon energy band-gap, E_{gap}, with Φ_{eq}.

2. Samples and light-absorption measurements

Four samples of phosphorus-doped silicon with ≈ 3.5 kΩ cm resistivity and ≈ 300 μm thickness were irradiated with 24 GeV/c protons to $\Phi_{eq} = (2.4, 4.9, 6.4, 8.6) \times 10^{15}$ cm^{-2} at the CERN PS. The uncertainty of the fluence is about $\pm 10\%$. For the calculation of Φ_{eq} a hardness factor $\kappa = 0.62$ is used [4]. After irradiation, the samples were stored in a freezer, being only warmed up to room temperature for the measurements; these were performed at 20 ± 2 °C. A fifth sample, which was not irradiated, provided the results for non-irradiated silicon. The crystals were bare and the thickness of the naturally grown SiO$_2$ layer is much smaller than the wavelength of the light used for the transmission measurements. The mechanical thicknesses of the silicon pieces were measured using a caliper to an accuracy of 2 μm.

The transmittance measurements were performed using an Agilent CARY 5000 UV–VIS–NIR spectro-photometer [5]. Fig. 1 shows the results. The transmittance, Tr, is close to zero at $\lambda = 0.95$ μm and increases to $\approx 50\%$ at $\lambda = 1.30$ μm. Tr decreases smoothly with Φ_{eq}. From repeated transmittance measurements of the non-irradiated samples a reproducibility of the results at the 0.1% level for $\lambda \geq 1.05$ μm is deduced. For $\lambda < 1.05$ μm, Tr has a strong temperature dependence and the reproducibility worsens to $\approx 1\%$.

Next, the transmittance measurements are compared to the expectations from literature values. Refs. [6,7] give tables of $n(\lambda)$ and $1/\lambda_{abs}(\lambda)$ and their temperature dependencies at 300 K. The transmittance, $Tr(\lambda)$, of an optical material of thickness d, index of refraction $n(\lambda)$ and absorption length $\lambda_{abs}(\lambda)$ is given by

$$Tr(n, \lambda_{abs}, d) = \frac{Tra^2 \cdot e^{-d/\lambda_{abs}}}{1 - \left(Ref \cdot e^{-d/\lambda_{abs}}\right)^2}, \qquad (2)$$

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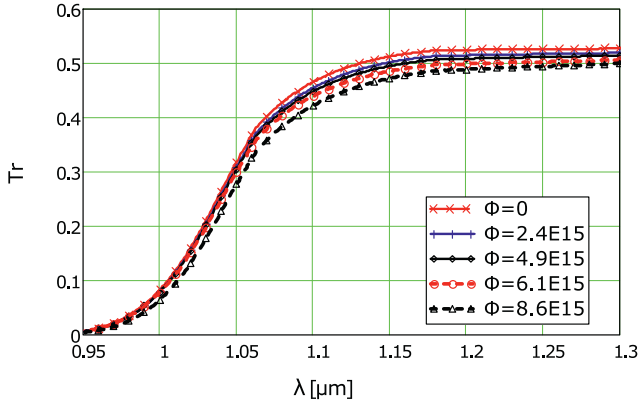   *E-mail address:* Christian.Scharf@desy.de (C. Scharf).

Fig. 1. Measured transmittance as a function of wavelength, λ, for different 1 MeV equivalent neutron fluences, Φ_{eq}, in units of cm^{-2}.
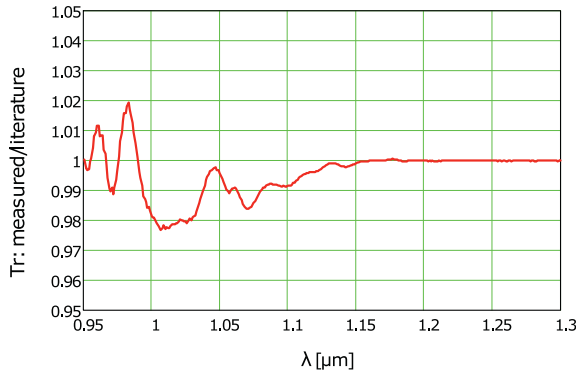

Fig. 2. Ratio of the measured transmittance, $Tr(\lambda)$, to the literature values at +20 °C for the non-irradiated silicon.

Fig. 3. Measured λ_{abs} as a function of λ for the different Φ_{eq}-values, and comparison to the values from Ref. [6] for non-irradiated silicon.

Fig. 4. α_{irr} as a function of Φ_{eq} for selected wavelengths. Within the experimental uncertainties $\alpha_{irr}(\Phi_{eq})$ is proportional to Φ_{eq}.

with the relations for the transmittance, $Tra(\lambda)$, and reflectivity, $Ref(\lambda)$, of a single air-silicon interface

$$Ref(\lambda) = \frac{(n(\lambda)-1)^2}{(n(\lambda)+1)^2} \quad \text{and} \quad Tra(\lambda) = 1 - Ref(\lambda) = \frac{4 \cdot n(\lambda)}{(n(\lambda)+1)^2}. \quad (3)$$

These are the Fresnel formulae for normal light incidence between a medium of refractive index 1 (air) and n (silicon). To derive Eq. (2), multiple transmissions and reflections at both air-silicon interfaces have to be considered. This results in a geometrical series which, in the limit an infinite number of reflections, gives Eq. (2).

Fig. 2 shows for the non-irradiated silicon the ratio of the measured to the expected transmittance at 20 °C, after the following corrections: The λ-scale is shifted by -1.0 nm and the transmittance scaled by 0.4%, which is within the calibration uncertainty of the photospectrometer. With these corrections, the maximum difference is below $\pm3\%$. Without them, the difference is +15% at $\lambda = 0.95$ μm, illustrating the high sensitivity of the results to the λ-scale at short wavelengths.

3. Results

From Eq. (2) the dependence of λ_{abs} on Tr can be derived:

$$\lambda_{abs}(\lambda) = \frac{d}{\ln\left(\frac{Tra(\lambda)^2 + \sqrt{Tra(\lambda)^4 + 4 \cdot Ref(\lambda)^2 \cdot Tra(\lambda)^2}}{2 \cdot Tr(\lambda)}\right)}. \quad (4)$$

Fig. 3 shows the experimental results for $\lambda_{abs}(\lambda)$ for the different Φ_{eq}-values, using $n(\lambda)$ at 20 °C from Ref. [6] for both irradiated and non-irradiated silicon. In addition, the values for λ_{abs} at 20 °C from Ref. [6] are shown. The results for the non-irradiated sensor agree with
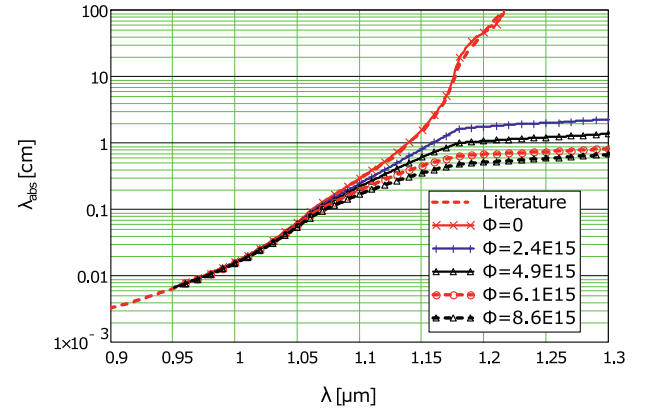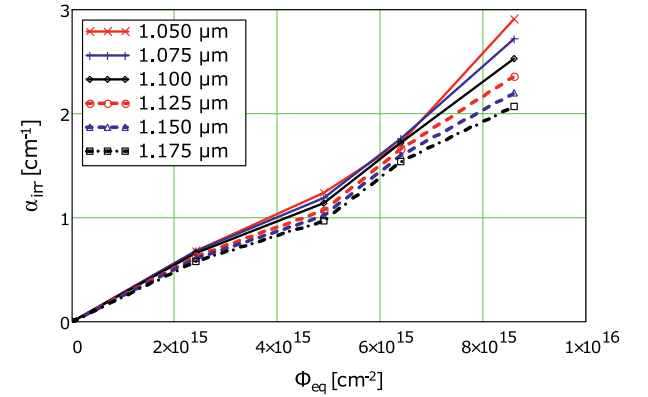
the literature values up to $\lambda = 1.25$ μm. For higher values they deviate. Note that at $\lambda = 1.2$ μm, $\lambda_{abs} \approx 50$ cm, which is much larger than the sample thickness of 0.03 cm, and the determination of λ_{abs} becomes unreliable. For the irradiated silicon λ_{abs} decreases with Φ_{eq}.

The inverse of the radiation-induced absorption length, α_{irr}, has been introduced in Eq. (1). Fig. 4 shows the experimental results for $\alpha_{irr}(\Phi)$ for selected values of λ. It is observed that $\alpha_{irr}(\Phi_{eq})$ is approximately proportional to Φ_{eq}. Fig. 3 shows that λ_{abs} rapidly decreases with decreasing λ, and that for small λ values, α_{irr} is the difference of two large numbers. As a result, the determination of α_{irr} is very sensitive to the λ calibration of the spectrophotometer for $\lambda \lesssim 1.05$ μm. Given these uncertainties, only results for $\lambda \geq 1.05$ μm are shown in the following.

The proportionality constants, α_{irr}/Φ_{eq}, are obtained by calculating the mean $\alpha_{irr}(\lambda, \Phi_{eq})/\Phi_{eq}$ for every λ-value. Fig. 5 shows the results for $\lambda = 1.05$ to 1.30 μm. The error bars reflect the uncertainty obtained from the straight-line fits to $\alpha_{irr}(\Phi_{eq})$. Other sources of uncertainties considered are: 1% for n, 2% for Tr, 2 μm for the sensor thickness, and 10% for the uncertainty of Φ_{eq}. The latter one, which is the same for all wavelengths, dominates. The results of a fit by a second order polynomial to the data are given in Table 1. The parameters can be used to calculate $\alpha_{irr}(\Phi_{eq}, \lambda)$, and together with Eq. (1) and the values of $\lambda_{abs}(0, \lambda)$ from Ref. [7], the values of $\lambda_{abs}(\Phi_{eq}, \lambda)$. With the assumption that the number of electron–hole pairs is proportional to the light absorption, the number of charge carriers generated by light in radiation-damaged silicon at 20 °C can be obtained.
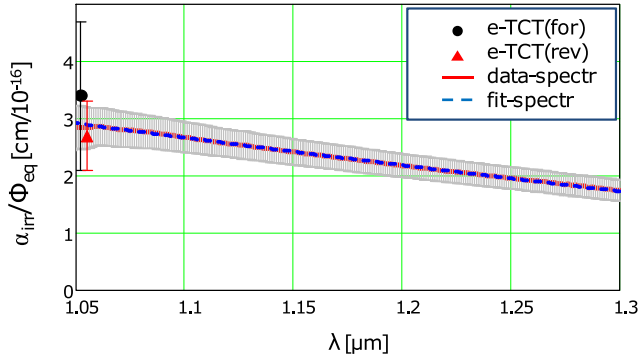
Fig. 5. Results for α_{irr}/Φ_{eq}: The edge-TCT results for $\lambda = 1.052$ μm and -30 °C are denoted *e-TCT (for)* and *e-TCT (rev)* for forward and reverse voltages, respectively. The photospectrometer data at $+20$ °C are labeled *data-spectr*, and the second-order polynomial fit *fit-spectr*. For clarity the *e-TCT* results are drawn at different λ values.

Table 1
Results of the second-order polynomial fit $\alpha_{irr}/\Phi_{eq} = a + b \cdot (\lambda - \lambda_0) + c \cdot (\lambda - \lambda_0)^2$ to the data shown in Fig. 5, with the value $\lambda_0 = 1.15$ μm. The first error of a is the statistical uncertainty, the second an estimate of the systematic uncertainty of the analysis method, and the third the result of other systematic effects, which are discussed in the text.

a [cm]	b [cm/μm]	c [cm/μm^2]
$(2.427 \pm 0.001 \pm 0.4 \pm 0.2) \times 10^{-16}$	$(4.805 \pm 0.005) \times 10^{-16}$	$(1.29 \pm 0.02) \times 10^{-16}$

4. Comparison to edge-TCT results

In Ref. [2,3] the edge-TCT (Transient-Current-Technique) is used to measure $\lambda_{abs}(\Phi_{eq})$ for proton fluences, Φ_{eq}, between 0 and 13×10^{15} cm^{-2}. For edge-TCT [8], focused light from a sub-nanosecond laser is injected through a polished edge into a strip sensor parallel to the surface and perpendicular to the strips, and the current transients are recorded. By moving the beam normal to the sensor surface, the charge-collection efficiency and the electric field as a function of depth, x, can be determined [9]. AC-coupled strip detectors with an active thickness of 285 μm and a strip pitch of 80 μm built on ≈ 5 kΩ cm n-doped silicon were investigated. The fourth strip, located 1350 μm from the sensor edge, and the ninth strip, located $L = 400$ μm from the first strip, were read out. The absorption length is obtained from the integral of the current of the first strip, Q_1, and of the second readout strip, Q_2, using the relation $\lambda_{abs} = L/\ln(Q_1/Q_2)$.

The wavelength of the laser light was $\lambda = 1.052$ μm. Because of high leakage currents, the measurements were performed at -30 °C. The irradiated sensors were biased with forward voltages, V_{forw}, as well as with reverse voltages, V_{rev}, between 0 and 1000 V. A constant charge ratio, $Q_1(x)/Q_2(x)$, as a function of x was expected. However, because of a number of experimental problems, this was not the case [2,3]. The analysis is performed in the x-region, where Q_1/Q_2 is approximately constant.

It is found that $\alpha_{irr} \propto \Phi_{eq}$, as was already observed for the spectrophotometer measurements. The results for the sensor irradiated to $\Phi_{eq} = 9.4 \times 10^{15}$ cm^{-2} are: For V_{forw} between 500 and 1000 V the value found for α_{irr}/Φ_{eq} is $(2.7 \pm 0.6) \times 10^{-16}$ cm, and for V_{rev} between 500 and 1000 V, $(3.4 \pm 1.3) \times 10^{-16}$ cm. The large uncertainties reflect the observed increase of α_{irr} with voltage. As shown in Fig. 5, the results are compatible with the value $(2.9 \pm 0.4) \times 10^{-16}$ cm determined from the spectrophotometer measurements at $+20$ °C. These results confirm the reduction of λ_{abs} due to radiation damage.

5. Discussion of the results

The attenuation of radiation in matter as a function of the path-length x follows an exponential law $e^{-\alpha \cdot x}$, with $\alpha = \sum_i (N_i \cdot \sigma_i)$,
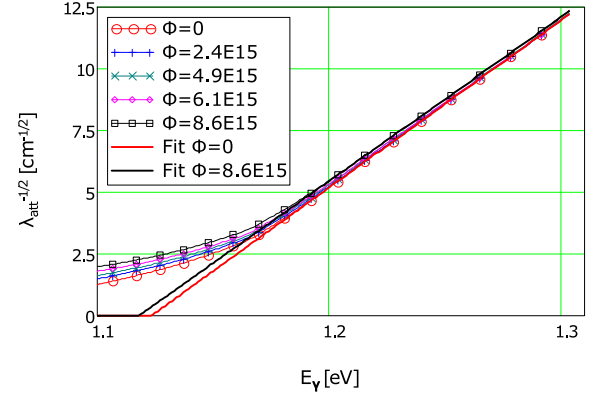

Fig. 6. Plot of $\sqrt{1/\lambda_{abs}}$ as a function of E_γ for the different Φ_{eq}-values. Straight-line fits in the range $E_\gamma = 1.2$–1.3 eV are shown, which allow to determine E_g as a function of Φ_{eq}.

where N_i is the density of scattering centers and σ_i the corresponding cross-sections. Analogously one can define

$$\alpha_{irr}(\Phi_{eq}) = \sum_i \left(N_i(\Phi_{eq}) \cdot \sigma_i(\lambda) \right) = \Phi_{eq} \cdot \sum_i \left(\beta_i \cdot \sigma_i(\lambda) \right). \qquad (5)$$

The right-hand side of the equation uses the experimental observation of Section 3 that $\alpha_{irr} \propto \Phi_{eq}$, which allows introducing the introduction rates $\beta_i = N_i/\Phi_{eq}$ for the individual radiation-produced states.

Typical total radiation-induced introduction rates from microscopic measurements are $(1-10)$ cm^{-1} (Ref. [4,10]). Using the value $\alpha_{irr}/\Phi_{eq} = 3 \times 10^{-16}$ cm from Fig. 5 gives a range for the average σ of $(3 - 0.3) \times 10^{-16}$ cm^2, which is similar to the electron/hole cross-sections obtained from the microscopic measurements. It is also noted that the measured $\sum_i (\beta_i \cdot \sigma_i(\lambda))$ decreases with increasing λ. The interpretation is, that due to energy conservation, the fraction of the band-gap which can be reached by electrons from the valence band increases with photon energy. A similar argument holds for holes.

The light absorption for photons with energies close to the band-gap energy, E_{gap}, is sensitive to the value of E_{gap}. Whereas the dependence of E_{gap} on the dopant density, N_d, in silicon has been studied in detail [11–13], there are hardly any results on its dependence after irradiation. E_{gap} is observed to decrease with N_d, however the change is less than ≈ 5 meV for $N_d < 10^{17}$ cm^{-3}. According to Refs. [14–16] the dependence of the absorption coefficient for a semiconductor with an indirect band gap can be approximated by $\alpha \propto (E_\gamma - E_{gap} + E_{ex} \pm \hbar\omega_p)^2$ for photon energies $E_\gamma > E_{gap} + \hbar\omega_p$. The phonon energy required for energy and momentum conservation is $\hbar\omega_p$. The $+$ sign refers to phonon absorption and the $-$ sign to phonon emission. E_{ex} is the exciton binding energy which describes the interaction of the generated electron–hole pair. Assuming E_{ex} and $\hbar\omega_p$ do not change with irradiation the intercept of a straight-line fit to the linear part of $\sqrt{1/\lambda_{abs}}(E_\gamma)$ with $\sqrt{1/\lambda_{abs}}(E_\gamma = E_g) = 0$ should give $E_g - E_{gap} = const$ similar to Ref. [11]. Methods to determine E_{gap} directly are described in Refs. [15,17] but were not applicable to our data due to the rather large step size of $\Delta\lambda = 1$ nm.

Fig. 6 shows $\sqrt{1/\lambda_{abs}}$ as a function of the photon energy, E_γ, for the different Φ_{eq} values. For $E_\gamma \gtrsim 1.18$ eV the dependence is linear. The intercept of straight-line fits in the range $E_\gamma = 1.2$–1.3 eV with $\sqrt{1/\lambda_{abs}} = 0$ is $E_g(\Phi_{eq})$. For $\Phi_{eq} = 0$ the value $E_g(0) = (1.1230 \times 10^3 \, ^{+1.0}_{-0.4} \pm 2.0 \pm 0.5)$ meV is found. The first uncertainty is obtained by changing the fit range by ± 20 meV, the second by changing the λ scale of the spectrophotometer by ± 2 nm, and the third by calculating the change of E_{gap} for a temperature change by ± 2 °C, using the temperature dependence of E_{gap} of -0.25 meV/°C at $+20$ °C from Ref. [18]. The systematic effect of a possible local variation of the λ scale is not taken into account. The statistical uncertainty of the extrapolation is
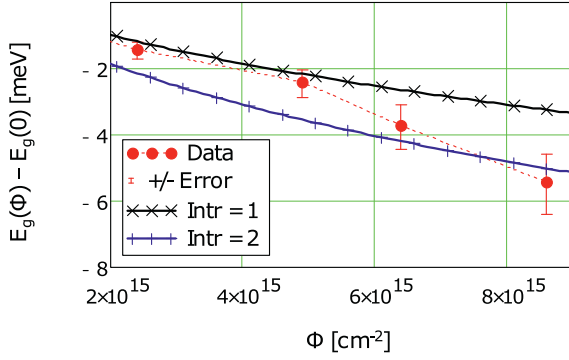
Fig. 7. Difference $E_g(\Phi) - E_g(0)$ obtained from the extrapolation of the straight-line fits shown in Fig. 6. As discussed in the text the difference is to a good approximation equal to $\Delta E_{gap}(\Phi_{eq})$, the change of the silicon band-gap with irradiation. The two curves are obtained by using Eq. (6) assuming $N_d = Intr \cdot \Phi_{eq}$ for the two values $Intr = 1$ and 2 cm^{-1}.

negligible. The value of E_{gap} from Ref. [18] is $E_{gap} = 1.126$ eV with an estimated uncertainty of 1 meV. The observed difference is $E_g - E_{gap}$ is -3^{+4}_{-5} meV.

Fig. 7 shows the difference $E_g(\Phi_{eq}) - E_g(0)$ as a function of Φ_{eq}. The error bars take into account that most of the uncertainties of the E_g determination for the different Φ_{eq} values are correlated and cancel in the difference. Also most of the model uncertainties are expected to cancel in the difference. Assuming that E_{ex} and $\hbar\omega_p$ do not change with irradiation, the change of the silicon band-gap with fluence is $\Delta E_{gap}(\Phi_{eq}) = E_g(\Phi_{eq}) - E_g(0)$. The data shown in Fig. 7 suggest that $\Delta E_{gap}(\Phi_{eq}) \propto \Phi_{eq}$.

In Ref. [13] the following parametrization for ΔE_{gap} as a function of doping N_d is given:

$$\Delta E_{gap}(N_d) = A \cdot \left(\ln(N_d/N_{ref}) \right)^b. \qquad (6)$$

The value of A for *n*-type silicon is $(3.67 \pm 0.20) \times 10^{-5}$ eV if Boltzmann statistics is assumed, and $(4.20 \pm 0.30) \times 10^{-5}$ eV for Fermi–Dirac statistics. The parameter $N_{ref} = 10^{14}$ cm^{-3}, and the exponent $b = 3$. To relate the fluence Φ_{eq} to the number of states, an introduction rate has to be assumed. The curves in Fig. 7 correspond to introduction rates of 1 cm^{-1} and 2 cm^{-1}, respectively, assuming the parameters for Boltzmann statistics. The values of ΔE_{gap} for data and model are similar, however the assumption of an introduction rate of 1 to 2 cm^{-1} for damage states which introduce a band gap shift, is completely ad hoc. It is also not clear, if Eq. (6) can be extrapolated to such low concentrations of charged defects. In Ref. [19] a linear dependence of ΔE_{gap} on neutron irradiation fluence with a value $\Delta E_{gap}/\Phi = -2 \times 10^{-18}$ eV·cm^2 is reported. For the maximal fluence of the absorption measurement of this paper, $\Phi_{eq} = 8.6 \times 10^{15}$ cm^{-2}, the expected value for the band-gap shift would be $\Delta E_{gap} = -17$ meV, significantly larger than what is observed, assuming a hardness factor of 1 for the irradiations of Ref. [19]. Additional work is required to clarify the situation.

It should also be noted that most of the damage by 24 GeV/c protons results in defect clusters, whereas the dopants are atoms located at the lattice points. Ref. [20] proposes that cluster defects can change the potential locally, which results in a local change of the band gap. In Ref. [21] it is shown that the activation energy of states in clusters can be several meV lower than for point defects. Such effects can possibly explain the Φ_{eq}-dependence and the magnitude of ΔE_{gap}.

6. Conclusions and outlook

The change of the light-absorption length in silicon, $\lambda_{abs}(\Phi_{eq}, \lambda)$, due to radiation damage by 24 GeV/c protons for 1 MeV neutron-equivalent fluences, Φ_{eq}, up to 8.6×10^{15} cm^{-2} has been measured using

a spectrophotometer. The measurements were performed at +20 °C for wavelengths, λ, between 0.95 and 1.30 μm. In the Φ_{eq}-range investigated it is found that $\alpha_{irr}(\Phi_{eq}, \lambda) = 1/\lambda_{abs}(\Phi_{eq}, \lambda) - 1/\lambda_{abs}(0, \lambda)$ is proportional to Φ_{eq}. A phenomenological parametrization of $\alpha_{irr}(\lambda)/\Phi_{eq}$ is presented, which, together with the $\lambda_{abs}(0)$ data for non-irradiated silicon of Ref. [6,7], allows to calculate $\lambda_{abs}(\Phi_{eq}, \lambda)$. Edge-TCT measurements of strip sensors irradiated to $\Phi_{eq} = 9.4 \times 10^{15}$ cm^{-2} performed at -30 °C with light of $\lambda = 1.052$ μm confirm the observed decrease of λ_{abs} with Φ_{eq}. The quantity α_{irr}/Φ_{eq} is interpreted as $\sum_i (\beta_i \cdot \sigma_i(E_\gamma))$, the sum over the products of the introduction rates of the radiation-induced damage states β_i times the corresponding photon cross-sections $\sigma_i(E_\gamma)$.

From the measured $\lambda_{abs}(\Phi_{eq}, \lambda)$ the change of the band-gap energy, $\Delta E_{gap}(\Phi_{eq})$, as a function of Φ_{eq} is extracted. $\Delta E_{gap}(\Phi_{eq})$ is approximately proportional to Φ_{eq} and reaches a value of ≈ -5 meV at the highest fluence of $\Phi_{eq} = 8.6 \times 10^{15}$ cm^{-2}.

The measurements and results presented are a step towards a systematic study of the radiation-induced change of light absorption in silicon. A next step could be to determine α_{irr} as a function of temperature using spectrophotometer measurements. With edge-TCT α_{irr} can be studied as a function of temperature, electric field and current. These parameters influence the occupancy of the radiation-induced states and therefore the photon cross-sections σ_i.

As the $\sigma_i(E_\gamma)$ times the densities of damage centers, N_i, enter into the calculation of the specific energy loss of charged particles, dE/dx [22,23], the generation of charge carriers per unit length may be different for non-irradiated and irradiated sensors. However, the expected effect is estimated to be negligibly small. For the band-gap narrowing due to radiation damage further studies are required to verify the results presented in this paper and refine the analysis methods.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

C. Scharf: Conceptualization, Investigation, Methodology, Writing - review & editing. **F. Feindt:** Investigation, Methodology. **R. Klanner:** Validation, Methodology, Writing - review & editing.

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