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Measurements of the reverse current of highly irradiated silicon sensors

Sven Wonsak*, A. Affolder, G. Casse, P. Dervan, I. Tsurin, M. Wormald

University of Liverpool, Oliver Lodge Building, Department of Physics, Oxford Street, L68 7ZE Liverpool, United Kingdom

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ABSTRACT

The reverse current of irradiated silicon sensors depends, among other variables, on sensor temperature and irradiation fluence. The temperature dependency is parameterized by the effective energy E_{eff} and the fluence dependency by the current related damage rate α. The literature values for E_{eff} and α were obtained from previous measurements, but α was only measured directly to a fluence up to 1×10^{15} 1 MeV neutron equivalent fluence per cm^2 (n$_{eq}$/cm^2).

Miniature micro-strip sensors ($\approx 1 \times 1$ cm^2) were irradiated with protons to fluences from 1×10^{12} to 1×10^{15} n$_{eq}$/cm^2 and with neutrons from 5×10^{15} to 2×10^{16} n$_{eq}$/cm^2 to investigate the reverse current at higher fluences. Precise temperature and current measurements of sensors from Hamamatsu Photonics K.K. (293 μm thick) and Micron Semiconductor Ltd. (143 μm and 108 μm thick) were carried out. The sensors were measured shortly after irradiation and after room temperature annealing. These measurements allow the determination of the evolution of E_{eff}. Instead of α the geometric current related damage rate α^* is used, which depends on the geometric thickness rather than the depletion depth. For low fluences they are in good agreement while for high fluences α^* is smaller.

1. Introduction

Silicon sensors are widely used in high energy physics experiments like ATLAS and CMS at the LHC. During their usage, they will be irradiated to fluences up to 1×10^{16} 1 MeV n$_{eq}$/cm^2 (n$_{eq}$/cm^2). To design silicon sensors and read-out chips for these high fluences it is necessary to know the reverse current of silicon sensors. Previous measurements, partially within the CERN RD50 collaboration [1], have found a relation between current and temperature which depends on the effective energy E_{eff} (Ref. [2]). A linear relationship between current and irradiation fluence can be found in Refs. [3–6] which depends on the current related damage rate α. These measurements were limited to fluences less than 1×10^{15} n$_{eq}$/cm^2. The aim of the study presented in this paper is to investigate the reverse current of silicon sensors for high fluences up to 2×10^{16} n$_{eq}$/cm^2 and determine if the parameterization models hold in higher fluences expected in HL-LHC operation (Ref. [7]). Because at these high fluences the full depletion voltage is huge and the actual depletion depth unknown the geometric current related damage rate α^* is used, which depends on the geometric sensor volume and not on the depleted volume.

The models for the temperature and fluence dependencies will be presented in Section 2 and the experimental method will be described in Section 3. The results for the effective energy will be shown in Section 4, the results for the geometric current related damage rate in Section 5. Section 6 will include a brief summary.

2. Models

Using the reverse current measured at one temperature ($I(T_1)$) and the standard parameterization of the current-temperature dependency, it is possible to calculate the reverse current at a second temperature ($I(T_2)$), using the following equation from Ref. [8]:

$$\frac{I(T_2)}{I(T_1)} = \left(\frac{T_2}{T_1}\right)^2 \exp\left(\frac{-E_{eff}}{2k_B}\left[\frac{1}{T_2} - \frac{1}{T_1}\right]\right) \quad (1)$$

with the measurement temperature T_1 and the scaling temperature T_2 in Kelvin and the Boltzmann constant k_B. The value of E_{eff} according to Ref. [2] is (1.214 ± 0.014) eV.

After irradiation the reverse current, which is generated in the bulk, increases. From detailed measurements the following relation was derived (Refs. [3–6]):

$$\frac{I(\Phi_{eq}) - I(\Phi_0)}{V} = \frac{\Delta I}{V} = \alpha \Phi_{eq} \quad (2)$$

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* Corresponding author.
E-mail address: sven.wonsak@cern.ch (S. Wonsak).

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with the current before irradiation $I(\Phi_0)$, the current after irradiation $I(\Phi_{eq})$, the depleted sensor volume V and the equivalent fluence Φ_{eq}. In previous measurements up to fluences of approximately 1×10^{15} n_{eq}/cm^2 it was shown that this relation is valid. The current related damage rate depends on the annealing time and the annealing temperature, which is described in detail in Refs. [3,4,9]. The equations in these references were used to calculate α for the different annealing steps of the presented study, which are summarized in Table 1. To compare the values with the measurement results, the short term annealing values of α are used, which agree within the uncertainties with the long term values.

α depends on the depletion depth, which is not well known for high irradiated sensors. The concept of depletion, where the undepleted region has no electric field, is not true for high fluences. In previous edge-TCT measurements (Ref. [10]) it was shown that even in the expected undepleted region a weak electric field can be observed. Instead, the actual thickness is used to calculate the geometric current related damage rate α^*. For a fully depleted sensor α and α^* are the same.

3. Experimental method

The sensors used in this study are n-in-p float zone sensors with an area of approximately 1×1 cm^2 from Hamamatsu Photonics K.K. (ATLAS07 mini, 293 μm thick) and from Micron Semiconductor Ltd. (143 and 108 μm thick). Several Hamamatsu sensors were irradiated with 26 MeV protons at Birmingham from 1×10^{12} to 1×10^{15} n_{eq}/cm^2. Additional sensors from Micron and Hamamatsu were irradiated to fluences from 5×10^{15} to 2×10^{16} n_{eq}/cm^2 with reactor neutrons at Ljubljana. In total 17 devices were irradiated, 7 with protons and 10 with neutrons.

The sensors were glued on a Printed Circuit Board (PCB) for the bias voltage connection and a PT1000 temperature sensor was glued directly onto the silicon to get the detector temperature as precise as possible, shown in Fig. 1. The sensors were biased up to 1000 V with a Keithley 2410 high voltage power supply and the resistance of the PT1000 was read with a Keithley 2000 multimeter. The PCB was placed in a commercial freezer to perform measurements at temperatures below 0 °C.

Two effects were observed which are related to the set-up: the freezer temperature was only stable if it was running permanently, which was used to make the measurements at the lowest possible temperature (≈ -23 °C). Performing measurements at higher temperatures oscillation of the silicon temperature was observed, which was caused by the temperature controller operating the freezer. These oscillations (≈ 1.5 °C peak-to-peak) also affect the current, but using the scaling Eq. (1) this effect can be compensated. For high fluences ($> 1\times10^{15}$ n_{eq}/cm^2) self-heating of the sensor was monitored: with increasing bias voltage the sensor temperature increased. This was caused by the high current for high irradiation fluences and results in a temperature difference of several degrees Celsius between 0 and 1000 V. This effect can be compensated using the current scaling equation, too. In Fig. 2 both effects are shown. The temperature curve (red squares) shows the freezer related oscillation, distinctly visible at lower bias voltages, as well as the increasing temperature due to self-heating at higher voltages. Both effects have a clear influence on the measured current (blue dots). After scaling the current to a fixed temperature (-18 °C in this graph) the curve is smooth (green triangles).

The sensors were measured after irradiation and gluing with a total annealing time of 0.3 days at room temperature (20 °C). Further measurements were performed after room temperature annealing in a nitrogen cabinet for total annealing times of 10 days and 30 days.

Table 1
Literature values for α at 21 °C for the different annealing steps at room temperature, calculated for short term annealing and long term annealing.

Annealing time (d)	α (10^{-17} A/cm)	
	Short term	Long term
0.3	6.40 ± 0.43	6.24
10	4.32 ± 0.29	4.36
30	3.50 ± 0.23	3.61

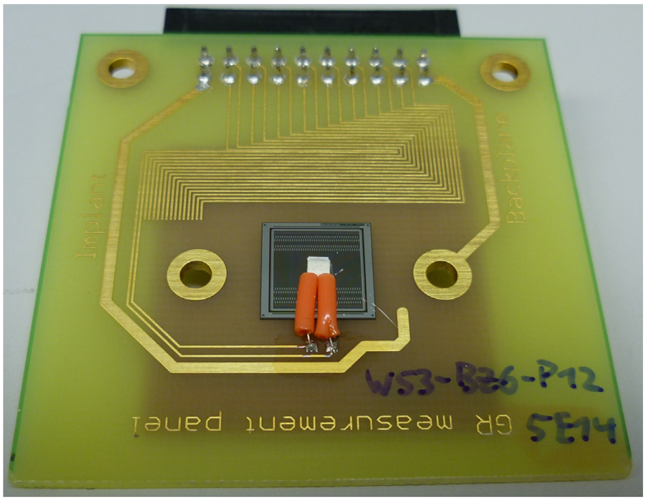

Fig. 1. Silicon sensor glued on PCB; temperature read-out with a PT1000, glued onto the sensor.

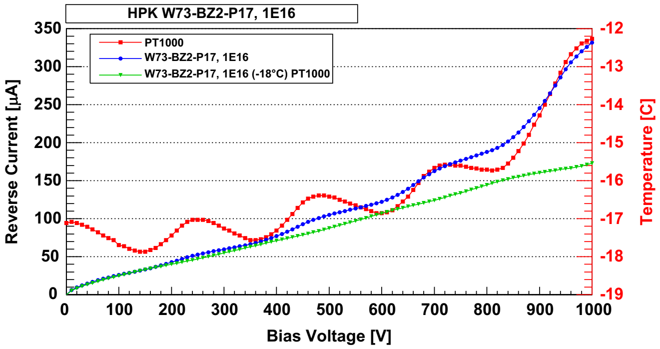

Fig. 2. Reverse current vs voltage characteristics of a Hamamatsu sensor irradiated to 1×10^{16} n_{eq}/cm^2. The temperature measurement (red triangle) shows the freezer related oscillation (low voltage) as well as the self-heating of the sensor (high voltage). Both effects could be seen in the current measurement (blue dots). Using Eq. (1) the current was scaled to a fixed temperature (-18 °C) where both effects are corrected. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

4. Effective energy

To determine the effective energy E_{eff} current measurements from 0 to 1000 V in 10 V steps at two different temperatures (approximately -23 °C and -19 °C) were performed. Fig. 3 shows an example IV curve of one Hamamtsu sensor after irradiation with 1×10^{15} n_{eq}/cm^2. For the analysis the measured temperature (PT1000) at each voltage was used. In Fig. 4 histograms of all measurement results after irradiation and gluing are shown, separated by fluences $\leq 1\times10^{15}$ n_{eq}/cm^2 (hereafter referred to as low fluence) and fluences $\geq 5\times10^{15}$ n_{eq}/cm^2 (high fluence). The peaks were fitted with a Gauss function. For low fluences the measurements show an E_{eff} value of (1.18 ± 0.03) eV, which is in good agreement with the literature value of (1.214 ± 0.014) eV. For

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