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Measurements of the reverse current of highly irradiated silicon sensors to determine the effective energy and current related damage rate

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ABSTRACT

The reverse current of irradiated silicon sensors leads to self heating of the sensor and degrades the signal to noise ratio of a detector. Precise knowledge of the expected reverse current during detector operation is crucial for planning and running experiments in High Energy Physics. The dependence of the reverse current on sensor temperature and irradiation fluence is parametrized by the effective energy and the current related damage rate, respectively. In this study 18 n-in-p mini silicon strip sensors from companies Hamamatsu Photonics and Micron Semiconductor Ltd. were deployed. Measurements of the reverse current for different bias voltages were performed at temperatures of $-32\,^{\circ}$C, $-27\,^{\circ}$C and $-23\,^{\circ}$C. The sensors were irradiated with reactor neutrons in Ljubljana to fluences ranging from $2\times10^{14}\,n_{eq}/cm^2$ to $2\times10^{16}\,n_{eq}/cm^2$. The measurements were performed directly after irradiation and after 10 and 30 days of room temperature annealing. The aim of the study presented in this paper is to investigate the reverse current of silicon sensors for high fluences of up to $2\times10^{16}\,n_{eq}/cm^2$ and compare the measurements to the parametrization models.

1. Introduction

Silicon sensors are widely used in High Energy Physics. In modern experiments like CMS and ATLAS, with high luminosity and particle energy, the sensors as well as electronic readout devices have to withstand a very harsh radiation environment. To study the radiation damage occurring during operation, detector components are irradiated to fluences of up to $2\times10^{16}\,n_{eq}/cm^2$.

For the operation of silicon sensors and the design of related detector components, e.g. the cooling system, one has to be able to predict the reverse current of the sensor. Among other parameters like the sensor volume, the reverse current strongly depends on the sensor temperature and the fluence Φ. For the parametrization of the temperature dependence the effective energy E_{eff} is commonly used as a scaling parameter [1]. Furthermore experimentally a linear relationship between irradiation fluence and reverse current was found, which is described by the current related damage rate α [2–5].

This study is related to previous measurements performed by Sven Wonsak [6]. It was observed, that the effective energy E_{eff} decreases for sensors irradiated with fluences higher than $1\times10^{15}\,n_{eq}/cm^2$. The aim of the study presented in this paper is to investigate the reverse current of silicon sensors, irradiated with reactor neutrons in Ljubljana to fluences of up to $2\times10^{16}\,n_{eq}/cm^2$, and determine if the parametrization models hold at high fluences expected in High Luminosity LHC (HL-LHC) operation (as given in e.g. Ref. [7]).

2. Models

2.1. Effective energy E_{eff}

The ratio of reverse currents $I(T)$ at two different temperatures T_1 and T_2 is described by Eq. (1), where k_B denotes the Boltzmann constant. With this relation it is possible to determine the effective energy E_{eff} by measuring the reverse current at different temperatures. Also for a known effective energy it allows to predict the reverse current at a certain temperature, given the reverse current at some reference temperature.

For silicon sensors the literature states a value of the effective energy of $E_{eff} = (1.214 \pm 0.014)$ eV [1].

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

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2.2. Current related damage rate

Experimentally one observes a linear dependence of the increase of the reverse current due to irradiation on the irradiation fluence, corresponding to Eq. (2). $I(\Phi_0)$ and $I(\Phi_{eq})$ are the reverse currents before and after irradiation with fluence Φ_{eq}. The constant of proportionality α is called current related damage rate.

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

Usually the depleted detector volume (V) has to be known to calculate the current related damage rate. The sensors irradiated to very high fluences, as presented in this study, cannot be fully depleted. Furthermore TCT-measurements have shown that the theoretically neutral area in a not fully depleted sensor is not completely free of an electric field [1,8]. Therefore the *geometric current related damage rate* α^* is used instead, using the full physical volume for calculation. This procedure is described in Ref. [6]. For a fully depleted sensor α and α^* are the same.

3. Experimental method

3.1. Sensors

For the measurements of the reverse current 18 n-in-p mini strip sensors from Hamamatsu Photonics K.K. [9] and Micron Semiconductor Ltd. [10] were used. The Hamamatsu sensors have a thickness of 293 μm and an active area of (0.8348×0.86) cm^2. The sensors from Micron are 143 and 50 μm thick and have an active area of (1.0985×1.0973) cm^2. The sensors were irradiated to fluences from 2×10^{14} to 2×10^{16} n_{eq}/cm^2 with reactor neutrons in Ljubljana.

3.2. Experimental setup

The goal was to measure the reverse current and sensor temperature while varying the bias voltage (IV-measurement). The measurements had to be performed at different sensor temperatures well below the freezing point while it was important to keep the sensor temperature as constant as possible during each measurement. Similar setups were developed in Liverpool and Freiburg. The sensors were glued on a Printed Circuit Board (PCB) for connection of the bias voltage. A PT1000 temperature sensor was glued directly onto the silicon sensor to measure the temperature as precise as possible. A photo of the test setup and one sensor is shown in Fig. 1. The PCB is mounted onto an aluminum-jig, which is cooled primarily with a Peltier-element. The cooling-rate is controlled with a PID-controller, for which the sensor temperature measured by the PT1000 is used as input. To remove the heat from the warm side of the Peltier-element the whole structure is connected to a metal block. A chiller allows to cool the block down. For the prevention of ice at temperatures below the freezing point a Perspex cover (not shown in picture) is placed on top of the Peltier system to create a box which is flushed with nitrogen.

In Liverpool, Nylon screws and heat conducting paste are used to connect the different parts of the active cooling system (aluminum-jig, Peltier-element and cold block) whereas in Freiburg these parts are glued together directly and in addition the whole setup is placed inside a commercial freezer to sustain a stable environment temperature. For voltage supply and current measurement a Keithley 237 voltage source is used.

3.3. Measurements

Measurements of the reverse current were performed at temperatures of −32 ° C, −27 ° C and −23 ° C directly after irradiation and after 10 and 30 days of room temperature annealing.

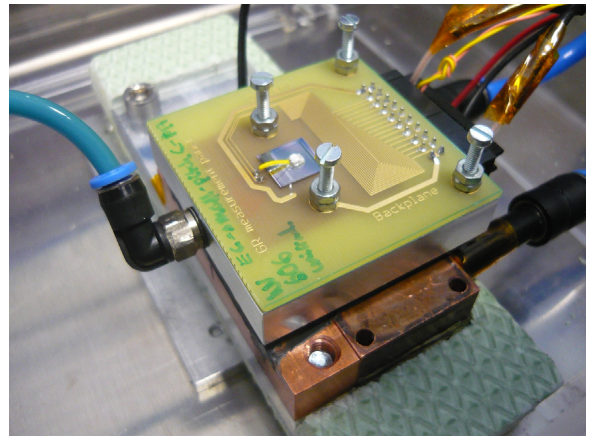

Fig. 1. Photo of the test setup: silicon sensor glued on PCB; temperature read-out with a PT1000, glued on top of the sensor.

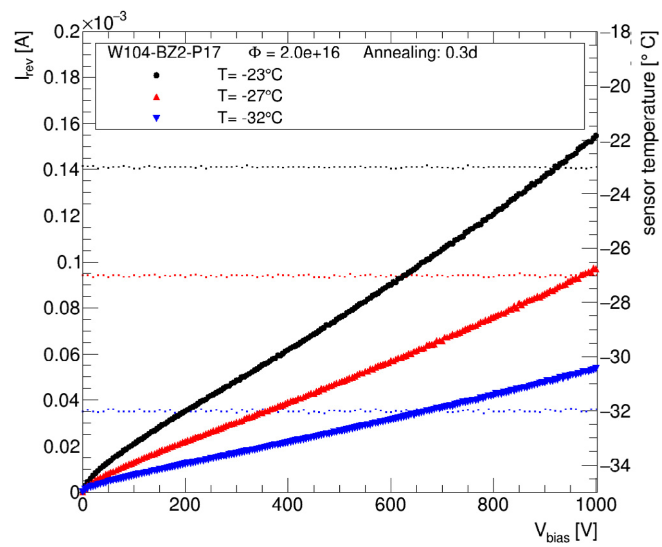

Fig. 2. Reverse current of sensor HPK W104-BZ2-P17 at three different temperatures. The horizontal, dotted lines show every second temperature measurement.

In the preceding study [6] during measurements at higher voltages a severe self-heating of the sensors was observed. The measured temperature varied by several Kelvin during a voltage scan from 0 to 1000 V. To minimize this effect for measurements presented here, special care was taken to stabilize the temperature of the sensor. During the measurements presented here, no self-heating of the sensor was observed. In Fig. 2 IV-measurements of an irradiated ($\Phi = 2 \times 10^{16}$ n_{eq}/cm^2) Hamamatsu sensor are shown as an example. Even for the highest fluence the temperature was kept constant during a complete voltage scan. Also it can be noted that from the IV-curve at this fluence it is not possible to tell when, if at all, the full depletion voltage is reached. Measurements of the reverse current at a temperature of −32 ° C and a bias voltage of 500 V are shown in Fig. 3 for all sensors. The values were scaled to ambient temperature.

4. Analysis method

4.1. Effective energy

To determine the effective energy for each sensor IV-measurements at three different temperatures (−32 ° C, −27 ° C, −23 ° C) were used.