X-RAY RADIATION DAMAGE IN SILICON STRIP DETECTORS

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The radiation damage effects in silicon strip and silicon pixel detectors caused by X-rays have become recently an important research topic driven mainly by development of new detectors for applications at the European X-ray Free Electron Laser (E-XFEL), where they will be exposed to extreme ionisation doses up to 1 GGy. Our investigation of radiation damage effects in a custom developed silicon strip detector to be used in laboratory diffractometers equipped with X-ray tubes shows that significant degradation of the detector performance occurs at low doses well below 100 Gy, which can be easily reached during normal operation of laboratory instruments. In the paper, basic mechanisms of radiation damage effects in silicon strip detectors are discussed and experimental results for a custom designed silicon strip detector for powder diffraction are presented.

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1. Introduction

Segmented silicon detectors, pixels and microstrips, have become a standard technology for precise tracking detectors in most of recently built collider experiments, in particular in the experiments at the LHC at CERN. The radiation environment in the inner regions of the LHC experiments is so harsh that the lifetime of the detectors is basically limited by the radiation damage to the silicon sensors. Over last two decades, the radiation damage effects in silicon detectors have been studied extensively and significant improvements of the radiation hardness of these devices have been achieved [1].

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In general, one distinguishes radiation damage effects in semiconductor devices due to ionisation effects and due to displacement effects. The ionisation does not create any permanent damage in the silicon bulk. However, in the silicon dioxide layers, the holes get trapped, while the electrons are removed by the electric field, if present. A net result of ionisation processes is building-up a positive charge in the silicon dioxide layers. It is important to note that the radiation damage caused by ionisation effects is dependent only on the total ionising dose (TID) and not dependent on the kind or energy of radiation. The final effects may depend on the dose rate and the post-irradiation annealing procedure, if applied.

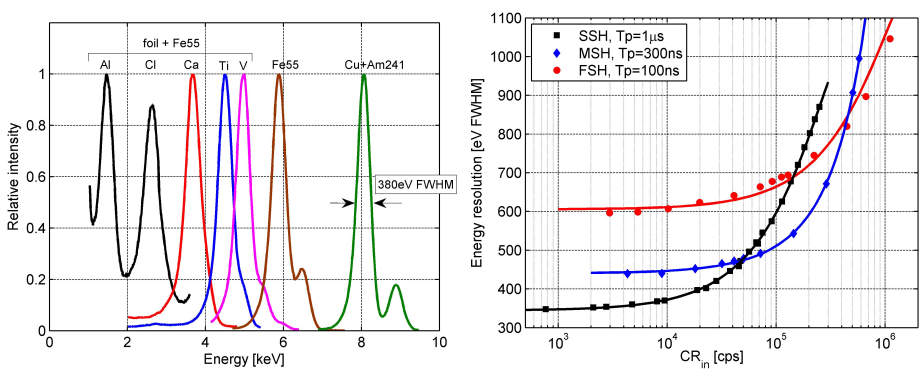
Collisions of charged particles and neutrons with silicon atoms can result in creation of vacancies and interstitials, which finally form some stable defects in the crystal. These defects act as deep energy levels, which contribute to the effective doping of the semiconductor. In silicon detectors, creation of deep level impurities results in two major effects: increase of the space-charge generated leakage current and change of the effective doping which, in turn, results in change of the full depletion voltage. In silicon strip and pixel detectors developed and used in the LHC experiments, the ionisation effects have been mostly ignored as they are predominated by the displacement damage. However, radiation damage in silicon and pixel detectors caused by X-rays has become recently a hot research topic driven mainly by development of new detectors for new synchrotron sources, like the E-XFEL, for example [2]. The radiation hardness requirements for these detectors are extremely high, as TIDs up to 1 GGy (SiO_2) from X-rays are expected [3]. Note that the dose is defined for SiO_2 since the charge produced in the silicon dioxide layers is relevant for the radiation damage.

In this paper, we report on our investigation performed for a silicon strip detector developed for applications in X-ray powder diffractometers. The radiation doses expected in normal operation are in the range of tens of Gy, while the requirements for the detector are pushed to the technological limits so there is a very little margin left for degradation of its performance. Thus, an important question arises whether radiation damage may occur for such low doses. From the tests targeting TID in the range of GGy, we cannot say almost anything about expected effects in the range of a few tens of Gy as those tests, for practical reasons, are usually performed at high dose rate, by many orders of magnitude higher compared to dose rates expected for laboratory instruments.

2. Silicon strip detector for X-ray powder diffractometers

The developed detector is an example of a fully customized design based on available semiconductor technologies: silicon strip detector technology and Application Specific Integrated Circuits (ASICs). The detector module comprises a silicon strip sensor with an active area of 2.5 cm^2 divided into 384 strips, which are read out by four 96-channel ASICs. The detector works as a 1-D position sensitive X-ray counting detector with the spatial resolution determined by the strip pitch of 75 μm. A unique feature of this design is the energy resolution, which is sufficiently high to enable electronic discrimination between the K_α and K_β emission lines in diffractometers using X-ray tubes. More details on the design and performance of the detector developed in collaboration between the Faculty of Physics and Applied Computer Science of the AGH UST and Bruker AXS can be found in [4].

In the basic operation mode, the detector works with a window discriminator set in the readout ASICs. For diagnostic purposes, the full energy range can be scanned with a narrow discriminator window allowing measurement of the energy spectra. Examples of such measurements, which illustrate the energy resolution of the detector, are shown in figure 1. Figure 1 (a) shows the energy spectra measured for low energy X-ray fluorescence lines at room temperature. The energy resolution is at a level of 380 eV FWHM for the 8 keV line and X-ray energies down to 1.5 keV can be measured. Figure 1 (b) shows dependence of the energy resolution as a function of single strip count rate for the three peaking times available in the readout ASICs. Since all 384 strips (readout channels) work independently, the whole detector can handle intensities up to 4×10^8 cps per detector area.



(a) (b)

Fig. 1. Spectroscopic performance of the detector. (a) Energy spectra of characteristics fluorescence radiation at room temperature. (b) Energy resolution as a function of the count rate for the three peaking times.

3. Irradiation test results

The detector has been irradiated from the strip side with X-rays from Fe-55 source with a dose rate of 0.42 Gy/hour up to a total dose of 66 Gy (SiO_2). During irradiation, the detector was biased with nominal voltage of 300 V and the readout ASICs were operating in the normal data taking mode. The total detector leakage current was monitored continuously and the energy spectrum was measured every 10 minutes.

3.1. Detector leakage current and interstrip capacitance

The two electrical parameters of the detector which affect the Equivalent Noise Charge (ENC) are the interstrip capacitance and the detector leakage current. Both these parameters are expected to be affected by the charge trapped in the surface oxide layer. In order to measure separately the leakage current of the active strip area and of the guard detector bias, connections had to be rearranged. In order to measure the interstrip capacitance readout, channels had to be disconnected from some number of strips. Therefore, these measurements were performed only before and after irradiation session. The I–V characteristics of the active strip area and of the guard ring, normalised to temperature of 20°C, are shown in figure 2 (a) and figure 2 (b) respectively. The plots show the characteristics measured before irradiation, immediately after irradiation, and then in two 5-day steps to observe possible annealing. During annealing, the sensor was kept under nominal bias conditions of 300 V at temperature of 30°C.

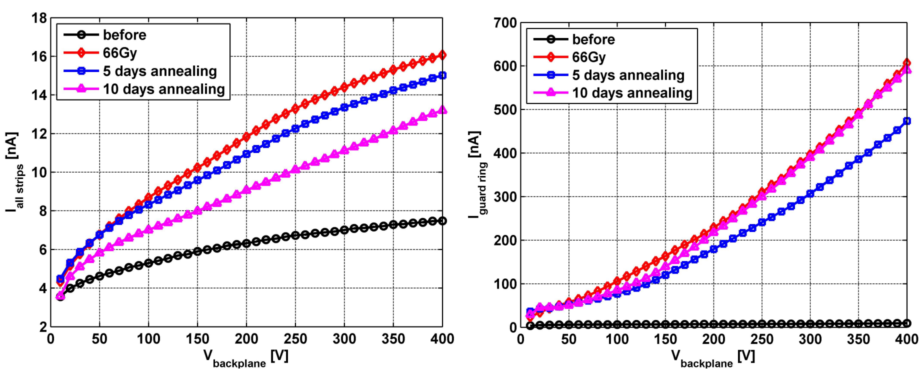


Fig. 2. Radiation damage effects on the detector leakage current. (a) I–V characteristics of the active area before irradiation and after a dose of 66 Gy. (b) I–V characteristics of the guard ring before irradiation and after a dose of 66 Gy.

After a total dose of 66 Gy, the leakage current of the active strip area increases by a factor of about 3 which certainly will affect the noise performance. Increase of the guard ring current is very large, however, this current should not affect the noise performance of the detector. After irradiation, we observe some slow annealing of the active area leakage current.

The interstrip capacitance depends on the charge density in the surface oxide layer. Because various hole and electron traps in the oxide have different relaxation time constants, the interstrip capacitance is frequency dependent. The interstrip capacitance was measured for test signal frequencies of 1 kHz, 100 kHz, and 2 MHz. After irradiation, we observed a small, about 5%, increase of the capacitance for 1 kHz, almost no change for 100 kHz, and large increase, about 30%, for 2 MHz.

3.2. Energy resolution and charge loss

For a strip detector, one of the factors which determine the energy resolution is charge sharing between adjacent strips. The charge built-up at the surface between the strips affects the electric field distribution around the strips which, in turn, modifies charge sharing. In addition, an increase of the leakage current and interstrip capacitance leads to an increase of the ENC. Taking all these effects together, we expect some degradation of the energy resolution after irradiation. In order to evaluate this effect, the spectrum of X-rays from Fe-55 source was measured every 10 minutes during the irradiation session. Examples of measured spectra at four steps during irradiation session are shown in figure 3 (a). Extracted FWHM for the K_α *vs.* accumulated dose is shown in figure 3 (b) (upper plot). After initial small drop, we observe continuous increase of the FWHM up to 22% after 66 Gy.

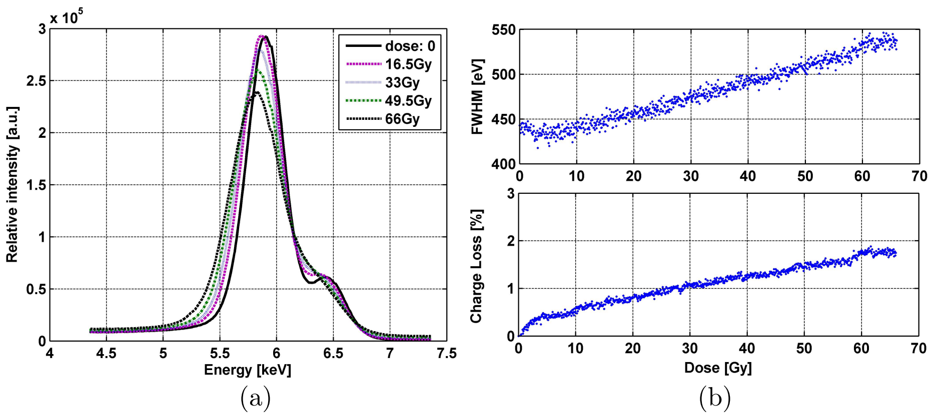


Fig. 3. Spectroscopic performance of the detector *vs.* accumulated dose. (a) Evolution of the Fe-55 spectrum *vs.* accumulated dose. (b) Energy resolution (upper) and charge lose (lower) *vs.* accumulated dose.

Additional interface states induced in the interstrip regions not only modify the electric field and affect charge sharing, but also trap charge carriers transported from the detector volume resulting in losses of the total collected charge. This results in a shift of the peak position in the energy spectrum. The charge loss *vs.* accumulated dose is shown in figure 3 (b) (lower plot). After total dose of 66 Gy, we observe charge loss of about 2%.

4. Conclusions

The test results presented in the paper show clearly that silicon strip detectors are susceptible to low energy X-rays at low total ionisation doses as expected in typical laboratory instruments using X-ray tubes, like diffractometers and X-ray spectrometers. The basic mechanism of radiation damage is trapping of charge in the surface oxide layer, which affects electrical parameters of the detector: leakage current and interstrip capacitance, and modifies electric field around the strips. An increase of the leakage current and interstrip capacitance results in an increase of the ENC. Modification of the electric field around the strips affects charge sharing between adjacent strips and causes direct trapping of the signal charge. Both these effects result in further degradation of the signal-to-noise ratio.

It is important to note that all the reported effects are dependent on the total ionising dose absorbed in the surface oxide layer. In order to limit this dose, one can consider illuminating the detectors from the ohmic contact side (back side) instead of the strip side. For back-side illuminated detectors, the flux of X-rays reaching the oxide layers on the strip side is greatly reduced by absorption in the detector bulk. For example, for a typical detector thickness of 500 μm and X-ray energy of 8.04 keV, as used in the diffractometers, the dose absorbed in the surface oxide layer is by a factor of 10^{-3} smaller when detector is irradiated from the back side compared to the strip-side irradiation. However, the absorption length increases strongly with increasing the X-ray energy and for higher energies, such as 17.4 keV and 22 keV also often used in diffractometers, a very significant fraction of the photon flux will reach the strip-side surface, 49% and 68% respectively. Thus, the radiation effects in the surface oxide layer have to be taken into account for such application. Even if for the back-side illuminated detectors the energy and spatial resolution is slightly worse compared to the strip-side illumination the back-side illumination may be a preferable solution to reduce the radiation effects and avoid significant degradation of the detector performance during the operation.

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