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Radiation damage effects on the EPIC PN-CCD Detector aboard XMM-Newton

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Abstract. The PN-CCD focal plane detector of the EPIC instrument operates meanwhile for more than 3.5 years on the *XMM-Newton* X-ray observatory. Due to the highly eccentric orbit of the spacecraft the instrument is exposed to a harsh radiation environment. We investigate here the occurrence of radiation damage effects in the novel PN-CCD during its first-time application in space. Two types of damage effects have been observed, an expected one and an unanticipated damage.

Key words. EPIC – micrometeoroid – PN-CCD – radiation damage – XMM-Newton

1. Introduction

The *XMM-Newton* X-ray observatory of the European Space Agency was launched in December 1999. One of the three focal plance cameras of the EPIC instrument is equipped with the novel PN-CCD detector developed at the Max-Planck-Institut für extraterrestrische Physik (Strüder et al. 2001). Twelve CCD systems are monolithically integrated on a four inch silicon wafer and provide an image area of 6 cm x 6 cm. The CCDs are organized for redundancy reasons into four quadrants with dedicated electronics.

The PN-CCD differs from all other X-ray CCD types in the concept to build up the device with pn-diodes. They are in particular implemented for the transfer gate structure and the photon entrance window (see Fig. 1). The backside illuminated CCD is fully depleted, i.e. the full device thickness of about 300 μm is sensitive to X-rays. Each transfer channel is terminated with an anode and a JFET for on-chip amplification of the signals. The transistor is connected by wedge bonds with a dedicated preamplifier channel for further signal processing. The parallel architecture of the CCD and its readout chip allows for a fast readout of the images. In the case of the EPIC PN-CCD, the 3 cm^2 large image area of a CCD system is read out within a time of 4.6 ms. Another special feature of this detector is the transfer of the signal electrons relatively far away from the surface, deep in the silicon bulk where the dopant and impurity concentrations are small.

Since the first light observation of the PN-CCD detector in January 2000 we have the opportunity to study the performance stability of this new CCD type. In particular we can check during the first-time space application of the device whether the radiation hardness of the PN-CCD meets the requirements. The highly eccentric orbit of the satellite with an

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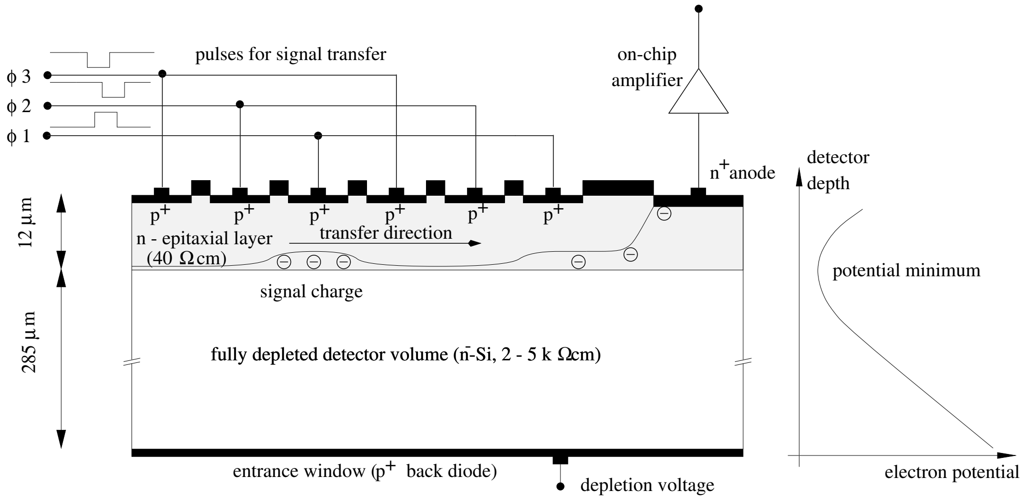

Fig. 1. A schematic cross section through the fully depleted PN-CCD along a transfer channel. The X-ray photons enter from the homogeneous back diode. The generated signal electrons are stored in the potential minimum about 11 μm below the shift register surface. An appropriate voltage pulse sequence applied at the three registers $\Phi1$, $\Phi2$ and $\Phi3$, transfers the signal electrons to the anode. The signal is amplified by a JFET-transistor which is monolithically integrated on the silicon device (on-chip electronics).

initial perigee of 7 000 km and an apogee of 114 000 km results in a severe radiation exposure mainly determined by high-energetic solar protons. They can penetrate the radiation shield of the detector and their non-ionizing energy loss (NIEL) causes a damage in the crystal lattice of the silicon device. The total NIEL damage to the detector which is accumulated during a mission time of 10 years was estimated to be equivalent to a 10 MeV proton fluence of about 5×10^8 cm^{-2}.

2. Radiation damage effects

Concerning the instrument status we notice that all 12 CCDs of the four quadrants are operational and that their performance is practically not degraded. In particular, there was no need to change any of the CCD operating parameters, e.g. a supply voltage or temperature, for a recovery of detector performance.

In agreement with the predictions and test results before launch (described in Meidinger et al. 2000), we observe only a slight increase of charge transfer inefficiency (CTI) at the nominal operating temperature of -90°C. The CTI rises by a value of about 1.3×10^{-5} per year for the Mn-K$_\alpha$-line (5894 eV) from the on-board calibration source. Compared with the initial value of 4.1×10^{-4}, this means a CTI degradation by 3.2% per year as can be seen in Fig. 2. The progression appeared primarily constant, but shows meanwhile some indication for a smaller increase in the future. The radiation damage tests in the laboratory have shown that the CTI increases proportional with the particle fluence. Hence the recently observed smaller rise of the CTI with time can be explained by the solar cycle because the observatory was launched in 1999 during solar maximum.

The origin of the CTI change is the irradiation induced formation of electron traps. These defects are created as a result of the displacement of silicon atoms from their lattice sites which leads primarily to a generation of interstitial silicon atoms and vacancies. A trap can capture a single electron during the transfer of the signal charges to the anode. The analysis of the radiation damage tests revealed the trap types which are responsible for the CTI in-

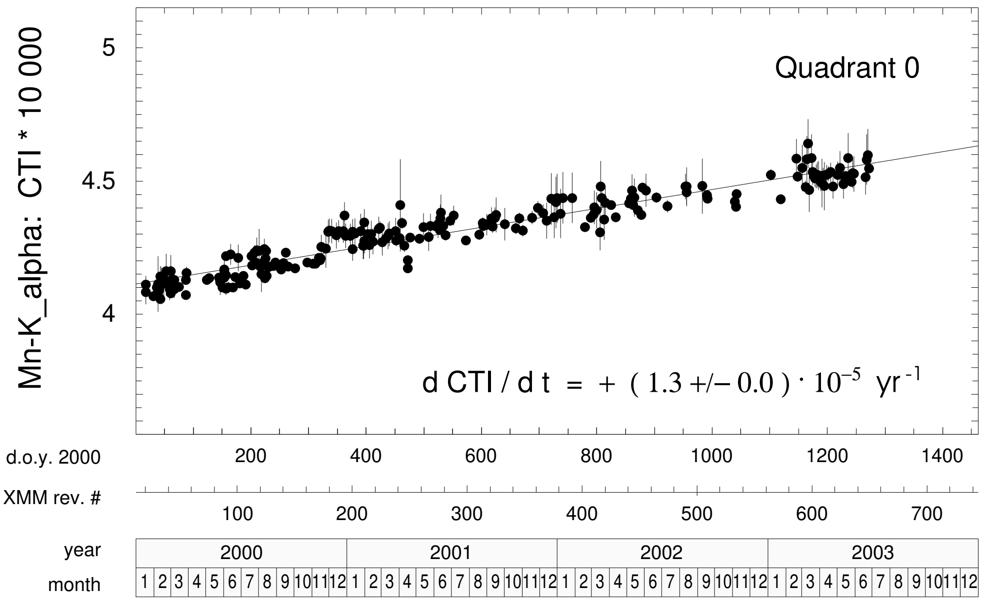

Fig. 2. Progression of the charge transfer inefficiency of the PN-CCD detector on *XMM-Newton* with time. For the Mn-K_α-line of the on-board calibration source we measure an increase of about 1.3×10^{-5} per year. Referring to the pre-launch value this means a change of 3.2% per year.

crease in the PN-CCD. We found the A-centre, an oxygen-vacancy defect, and the divacancy (Meidinger et al. 2000). The statistical nature of charge transfer losses due to traps causes the so-called transfer noise. Thus the charge transfer losses result in a small degradation of the energy resolution although a CTI correction is carried out. Starting with a FWHM value of 155 eV for the Mn-K_α line at the beginning of the mission, the time dependent degradation dFWHM/dt accounts for about 1 eV per year as shown in Fig. 3.

A second, unexpected 'radiation damage' effect occurred during revolution 156 in the first year of the mission. About 35 individual bright pixels lightened suddenly up out of the in total 150.000 pixels. We found evidences that this damage was due to a micrometeoroid impact on the telescope. Fragments which had been produced by the impact were scattered onto the focal plane CCD. Consequently, individual pixels became bright, i.e. a high dark current generation occurred where the fragments impinged on the CCD. Details about this event and its verification are reported in Strüder et al. (2001); Meidinger et al. (2001) and Pfeffermann et al. (this issue).

3. Conclusions

The PN-CCD focal plane detector operates on *XMM-Newton* as stable as expected. Radiation damage due to CTI increase caused a very slight degradation of the energy resolution in the first 3.5 years of the mission. All pixels are similarly affected. Since the annual increment of CTI is only about 3%, we expect no severe degradation of the energy resolution till the end of the mission.

Concerning micrometeoroid events, we have experienced one event since launch. Thus the statistics is too poor for a prediction

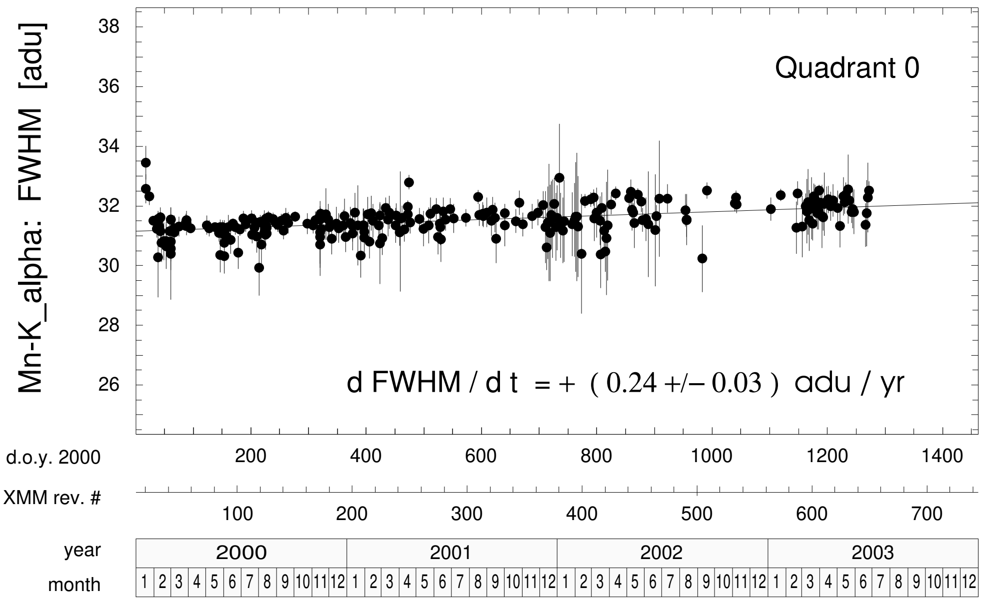

Fig. 3. Degradation of the energy resolution of the PN-CCD detector aboard *XMM-Newton* with time. The initial FWHM of the Mn-K_α-line of 155 eV is degraded by 0.24 adu or 1.2 eV per year. Thus the line is broadened by less than 1% per year as a consequence of radiation damage.

about the probability of another micrometeoroid damage occurrence in the PN-CCD detector aboard the *XMM-Newton* X-ray observatory. The resulting damage appears localized, i.e. a limited number of bright pixels is generated.

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