Radiation Hardness of Charge Coupled Devices for X-Ray Astromomy ◇

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A new type of charge coupled device, the fully depleted pn-CCD (fig. 1), was developed as focal plane detector for the European Photon Imaging Camera (EPIC) on the X-ray Multi Mirror (XMM) Mission [1]. This second cornerstone mission of ESA's Horizon 2000 program performs soft X-ray imaging and spectroscopy in the 0.1 keV to 15 keV photon range [2]. Besides a high quantum efficiency, energy and time resolution, another important requirement for the detector concerns the radiation hardness. The satellite is exposed to solar flares and crosses the geomagnetic radiation belts once per orbit (48 hours) during its mission time of ten years.

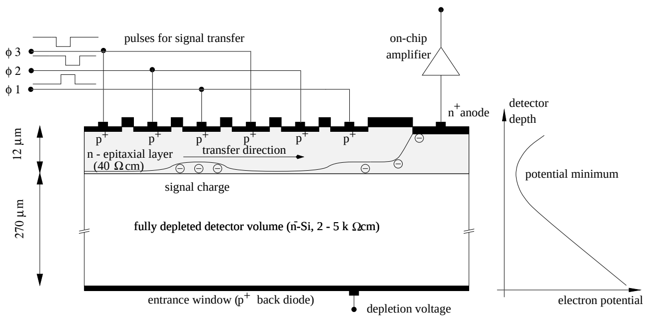

Fig. 1: A schematic cross section through the fully depleted pn-CCD along a transfer channel. The X-ray photons are entering from the homogeneous backside. The potential minimum for signal electrons is about 10μm below the register surface. An appropriate voltage pulse sequence at the three registers $\Phi1$, $\Phi2$ and $\Phi3$ causes the signal electrons to move to the anode.

The radiation damage to the detector will be primarily caused by protons due to the combination of a high flux and a high non-ionizing energy loss.

For this reason we studied the effects of radiation damage by protons and developed techniques to minimize them.

We have mounted several devices in a vacuum chamber of the TANDEM accelerator to irradiate them with 10 MeV protons. This energy is high enough to penetrate the 280 μm thick detector and to deposit more than a quarter of the proton energy. The proton beam was dispersed by Rutherford scattering at a thin gold foil for a simultaneous damaging of the devices at different doses.

After a first radiation hardness test, a few years ago [3], with pn-CCD proto-types, we have irradiated in this experiment flight type detectors.

None of the devices failed after the proton irradiation. A performance test with X-ray photons confirmed the former results. A degradation of the energy resolution of the detector is caused by signal charge losses during the transfer through the device to the anodes. The relative signal loss per pixel (CTI) turned out to be dependent on the irradiation fluence as well as on several detector and environmental parameters, especially on the operating temperature [4] (fig. 2).

The observed radiation damage is generated by the non ionizing energy loss of the particles in the silicon. The resulting crystal lattice defects (traps) can be analyzed with the pn-CCD because of their temperature and time characteristics. The main radiation induced defect type could be identified as an oxygen-vacancy complex with the maximum effect to CTI at a very low temperature of 115 K.

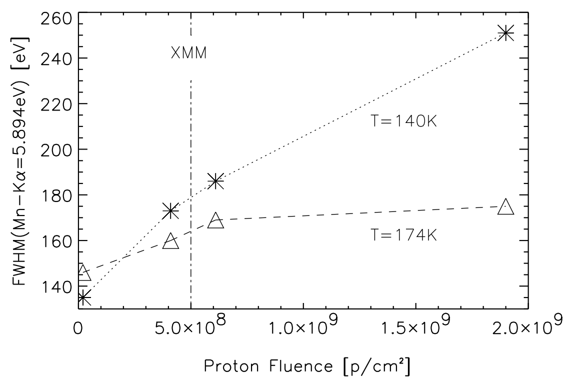

Fig. 2: Dependence of the energy resolution (FWHM) on the proton fluence for two operating temperatures of the detector on XMM. The proton fluence during the 10 years of mission time is estimated to $5 \cdot 10^8$ protons per cm^2. While before irradiation a low operating temperature of 140 K results in a better energy resolution than 170 K, this temperature dependence is reversed after less than half of the expected total damage dose.

A thermal annealing of the lattice defects needs a temperature of 350 °C which is not feasible on the satellite. However the CTI could be minimized for the pn-CCDs by the usage of several techniques: an optimum operating temperature of about 170 K, a fast readout (4 ms per 3 cm^2 detector area), an operating voltage optimization, a reduction of the transfer channel width (notch) and optionally the usage of periodical charge injection for trap saturation.

An accurate calibration of the detector charge transfer losses in dependence on all relevant parameters is necessary for their optimal correction. The pn-CCD shows then after proton exposure still an excellent energy resolution with a significantly lower degradation compared to other types of X-ray CCDs.

References

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