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Lessons learned from the EPIC pn-CCD camera for future missions

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Abstract. A special kind of damage occurred only once up to now to the pn-CCD on *XMM-Newton*, with the effect that the spectroscopic performance of more than 30 pixels spread over the 6 cm × 6 cm CCD area was severely deteriorated. Our analysis showed that the only possible explanation for this kind of damage is an impact of a micrometeoroid on the telescope. The experimental verification is presented as well as the analysis of the impact on the mirror and the detector. The background in the X-ray images of the pn-CCD camera is composed of various components. One component consists of fluorescent X-rays generated by cosmic rays in the material surrounding the CCD detector. The possibility of a graded Z-shielding and the characteristics of different shielding materials are discussed.

Key words. X-ray astronomy – CCD detector – micrometeoroid damage – fluorescent X-ray background

1. Introduction

The pn-CCD detector is one of the three imaging focal plane detectors of the European Photon Imaging Camera (EPIC) aboard the *XMM-Newton* X-ray observatory (Strüder et al. 2001). The pn-CCD has been developed in our semiconductor laboratory especially for this application. This effort resulted in the high quality performance of the detector concerning quantum efficiency, spectral resolution, time resolution and radiation hardness. The instrument operates in orbit as calibrated on ground. The performance is stable despite the harsh radiation environment. There is only an expected slight charge transfer inefficiency increase for all pixels of 1.3×10^{-5} per year (Meidinger et al. 2004).

During orbit #156 the pn-CCD detector showed a sudden and unusual strong increase of the count rate. The reason for this event was the simultaneous appearance of 35 bright pixels within one readout cycle of the CCD array. The loss of effective area was only 2×10^{-4}. Detailed investigations were carried out to search for the reason of this event, which are described in the following chapter.

The background events in an X-ray detector in space environment are composed of various components. Events generated by minimum ionizing particles can easily be identified due to their high energy deposit in the pn-CCD. Charged particles within the correct energy band entering the detector cannot be dis-

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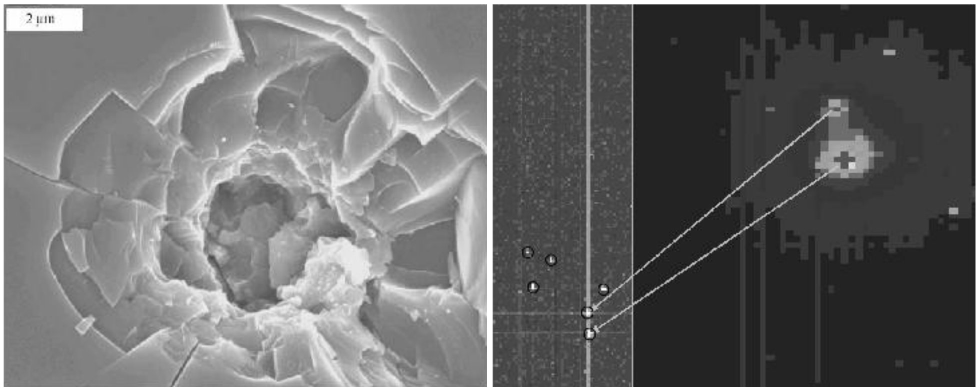

Fig. 1. Left panel shows the electron microscope image of the impact area of a scatter iron particle on a silicon wafer. The left side of the right panel shows the change of the dark CCD image after impact, the right side is the zoom image of the CCD at the scatter particle impact time.

tinguished from real X-ray events as well as fluorescent X-rays generated by charged particles in the material surrounding the CCD detector. Possible materials for shielding of fluorescent X-rays are discussed in the third chapter.

2. Analysis of the bright pixel event

Pixels are characterized as "bright", when its charge content exceeds the lower event threshold in at least every tenth readout-frame. Lattice defects in the original semiconductor material are usually the reason for bright pixels, but these bright pixels are present from the beginning. The generation of lattice defects in orbit can only be explained by strongly ionizing events or by a mechanical damage of the CCD surface. The properties of the bright pixels appearing during revolution #156 in the pn-CCD were following (Meidinger et al. 2002).

- Simultaneous formation of more than 30 bright pixels
- The bright pixels were distributed over one half of the active area of the detector with a maximum distance between the bright pixels of about 20 arcmin
- The generation of leakage current within the brightest pixels increased during several days and settled at 10^{-14} - 10^{-13} A at the normal operating temperature of -90 °C
- During revolution #156 MOS1 and MOS2 showed no effect, but similar events with generation of bright pixels were seen in orbit #108 in MOS2 and in orbit #325 in MOS1. The events in the MOS cameras were accompanied by a light flash in the surrounding of bright pixels.

The almost worst case ionizing event would be caused by an 1 GeV Fe nucleus, which is just stopped by 250 μm of silicon. But the number of lattice vacancies generated by such an event in the silicon crystal cannot account for the leakage current observed in the bright pixels at the operating temperature. The leakage current generated by such an event would be several orders of magnitude lower.

The only possible explanation for these bright pixels would be a damage of the CCD surface by a micrometeoroid. Due to the fact that such a particle has no straight trajectory through the Wolter optics of the X-ray mirror system, the micrometeoroid must undergo a scattering process with the mirror surface. During such an interaction the original particle can disintegrate into smaller pieces or it can get stuck in the gold layer of the mirror surface ejecting gold particles. Another possibility is the ejection of filter material during the passage of the particle through the filters of the detector.

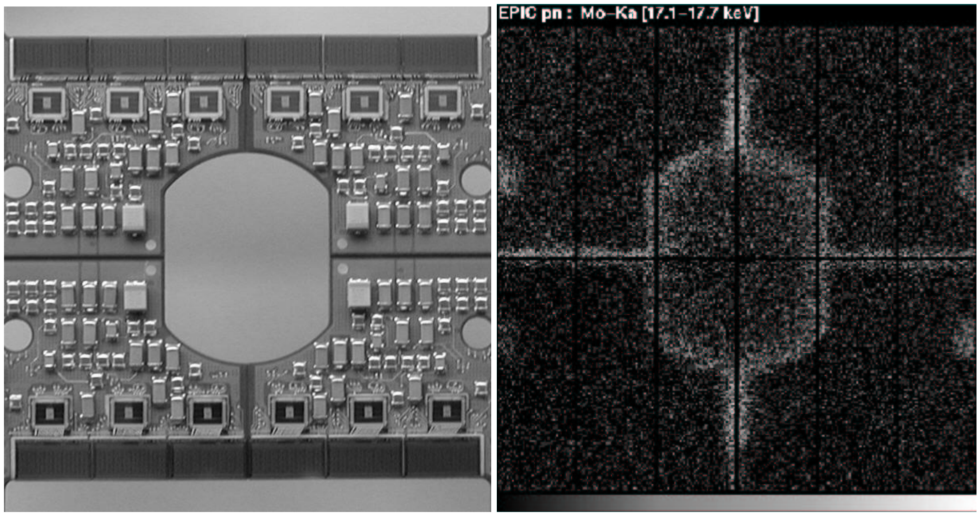

Fig. 2. Left panel: Printed circuit board (PCB), for readout of the CCD array. Right panel: The background image generated by fluorescent X-rays from the molybdenum core of the PCB (Freyberg et al. 2002).

The interaction of dust particles with a mirror surface under grazing incidence conditions were investigated experimentally at the dust accelerator of the MPI für Kernphysik in Heidelberg. In this facility charged iron particles with a size of 0.2 - 2 μm are accelerated in the electrostatic field of a Van-de-Graaff generator to velocities of 1 - 10 km/s. The dust accelerator can be operated in single shot mode (one particle per trigger only) or a continuous mode. A collimator system installed in front and behind the scattering mirror allows the analysis of the dust particles before and after the scattering interaction. The dust particles scattered from the mirror were detected by three different methods. The intensity of the scattered particles was registered with a copper target read out by a charge sensitive amplifier. The traces of impact of scattered particles were registered on a polished silicon wafer, later inspected with a scanning electron microscope. The effect of the scattered particles on an operative CCD was measured directly. The scattering efficiency of the mirror for the dust particles with grazing incidence angles between 0.5 - 4 deg is above 80%. The forward scattering angle is rather small in the order of 0.1 deg. The scattering of the particles on the mirror does not reduce the particle speed. Fig. 1 shows the electron microscope image of the impact of a scatter particle on a silicon wafer surface. The impact of scatter particles on an operative CCD produced a bright pixel event with nearly identical properties compared to the bright pixel event of the pn-CCD detector aboard *XMM-Newton* during revolution #156. Even the light halo around the impact area can be seen in Fig. 1 right side. EDX analysis of the impact area showed an iron contamination but no gold or aluminium particles could be detected. This means that only fragments of the original iron particle were scattered from the mirror on the CCD but neither gold particles from the mirror surface nor aluminium from the filters.

3. Internal background

Even though the use of imaging X-ray optics and position sensitive detectors improved considerably the sensitivity of X-ray telescopes, background is still a topic to care about.

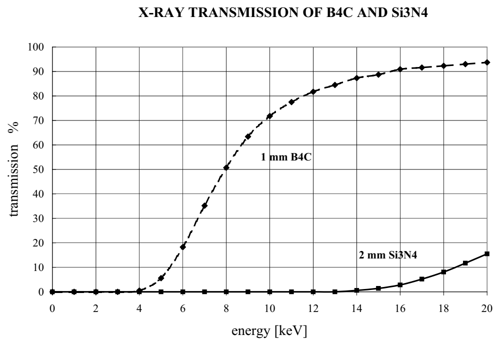

Fig. 3. Shielding characteristics of 1 mm boron-carbide and 2 mm silicon-nitride (Pfeffermann et al. 2002)

Minimum ionizing particles produce enough charge in the pn-CCD to be detected by the upper threshold and by the image-pattern. X-rays in the correct energy band produced by cosmic ray particles in the material surrounding the detector cannot be distinguished from cosmic X-rays collected by the mirror system. Fig. 2 shows an example of the internally generated background of the pn-CCD camera. The right picture shows the background X-ray image at 17.4 keV, the Mo - Kα emission line. The left image is the inner detail of the printed circuit board (PCB) located about 1 mm behind the silicon wafer with the CCD array. The PCB has a molybdenum core to adapt the thermal expansion coefficient of the PCB to the thermal expansion coefficient of the surface mounted devices like ceramic capacitors, resistors and preamplifier chips. In areas, where the PCB has cut-outs like the central hole for outgassing, the edge of the molybdenum core is directly viewed by the rear part of the CCD. The cross shaped part of the X-ray image is a structure, where the PCB has a very thin layer of polyimide and is therefore transparent for the 17.4 keV X-rays.

An active anticoincidence cannot be integrated in a CCD detector, without loosing too much life time even at a fast readout time like in the case of the pn-CCD. The only possibility to protect the CCDs from additional background is a careful material selection for the materials surrounding the CCD and an appropriate shielding. Due to the low operating temperature of the detector the CCD carrier has to have a similar thermal expansion coefficient like silicon to prevent mechanical stress of the CCD. Graded-Z shielding provides an effective tool to shift the energy of locally generated X-rays to low energies where low-Z materials rather produce Auger electrons than fluorescent X-rays. Low energy electrons can be stopped in the passivation layer of the CCD, except in the area of the entrance window. Appropriate combinations of two materials which meet on the one hand thermal requirements and on the other hand the graded-Z shield advantage are Al_2O_3-B_4C, Si_3N_4-B_4C and AlN-B_4C. Fig. 3 shows the X-ray transmission of layers of 2 mm Si_3N_4 and 1 mm of B_4C. A layer of 1mm B_4C is radio-opaque up to 4 keV and therefore absorbs fluorescent X-rays from silicon, aluminium, oxygen and nitrogen. One problem of these ceramics is the purity of the material. Sometimes high-Z adjuvants for sintering are used in the ceramics which should be avoided.

4. Conclusions

The bright pixel event of the pn-CCD camera during orbit #156 was most probably caused by a micrometeoroid impact. Even though the loss of scientific data is negligible in the case of *XMM-Newton*, investigations have to be carried out how future mission are affected by these events.

Due to the fact that a CCD cannot be equipped with an active anticoincidence, an appropriate graded-Z shied should be included in future detectors to reduce the intrinsic fluorescent background.

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