First measurements with DUO/ROSITA pnCCDs

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ABSTRACT

A new generation of pnCCDs has been developed for the proposed X-ray astronomy missions, DUO and ROSITA. The DUO/ROSITA CCD is a frame store pnCCD based on the concept of the XMM-Newton pnCCD and has both, improved performance and new features. This detector permits accurate spectroscopy of X-rays as well as imaging and high time resolution with high quantum efficiency in the energy band from 0.3 keV to 10 keV. Interfering electron-hole pair generation due to optical and UV light is prevented by a deposition of an on-chip filter. We describe the frame store pnCCDs developed and fabricated for the DUO and ROSITA missions in the semiconductor laboratory of the Max-Planck-Institut für extraterrestrische Physik. An overview about the CCD concept and design is given along with some details about the fabrication of the devices. In addition, we introduce a new analog signal processor which has been developed specifically for the readout of the frame store pnCCD signals. The main focus of this paper is to present the very first measurements with this CCD type and its analog signal processor. Towards this aim we report the operation of this new sensor and its key performance parameters. Finally we discuss ongoing and future tests with the DUO/ROSITA CCDs.

Keywords: CAMEX, CCD, DUO, frame store, pnCCD, ROSITA, XMM-Newton, X-ray detector.

1. INTRODUCTION

DUO[1], the Dark Universe Observatory, and ROSITA[2], the Roentgen Survey with an Imaging Telescope Array, are proposed X-ray astronomy missions with similar instrumentation requirements. Each of their focal plane cameras consist of seven X-ray CCD detectors which are dedicated to seven X-ray telescopes with different fields of view (see Figure 1). These projects require a tailor-made focal plane X-ray detector which we have designed.[3] The concept of this charge coupled device is based on that of the pnCCD developed for XMM-Newton.[4] The XMM-Newton satellite of the European Space Agency (ESA) was launched in 1999 and after more than 5 years in orbit, all 12 pnCCDs of the EPIC-PN focal plane camera are operating nominally. There was no need to optimize any operating parameter of the camera. In particular it was not necessary to change the operating temperature of -90°C. The charge transfer inefficiency (CTI) degradation which is caused by protons is quite low, corresponding to earlier predictions.[5, 6] Therefore the degradation of energy resolution (expressed as FWHM of the spectral line) changes less than 1% per year. For example, the FWHM of the Mn-K_α line (5.9 keV) of the on-board calibration source degraded from 155 eV to 161 eV during 5 years in orbit. For the Al-K line (1.5 keV) the FWHM broadened from 110 eV to 111 eV (see Figure 2).

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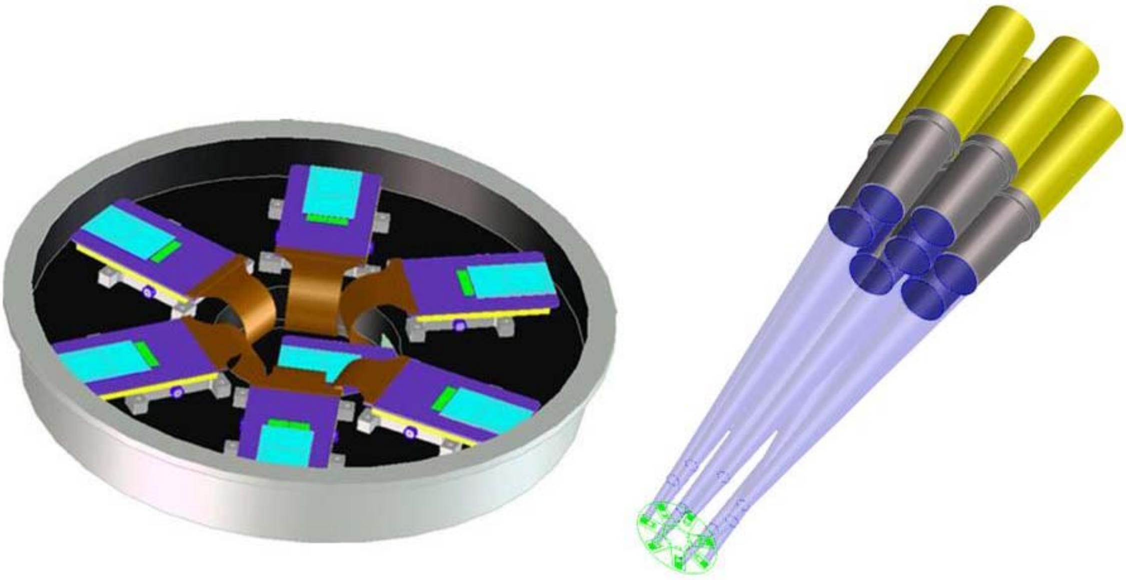

Figure 1: Focal plane camera and telescope array as planned for the DUO and ROSITA missions. Each of the seven Wolter telescopes has a dedicated X-ray pnCCD detector. Six detectors are accommodated on a circle and the seventh is in the centre of the camera.

2. CONCEPT, DESIGN AND FABRICATION OF THE PNCCDS

The name of the pnCCD is derived from the fact that all active structures of the charge coupled device are made up of pn-junctions. This crucial feature holds for the transfer registers as well as for the photon entrance window of the back illuminated CCD. The 450 µm thick chip is fully depleted and thus sensitive to X-rays. The advanced pnCCD design for DUO and ROSITA is equipped with a frame store, unlike the XMM-Newton pnCCD which is operated in full frame mode. In addition our concept includes transfer channels that are each terminated with an anode and an on-chip transistor like the XMM-Newton pnCCD (see Figure 3).

The image area of the DUO and ROSITA CCD is comprised of 256 rows and 256 channels. The pixel size specified by the X-ray optics is 75 µm x 75 µm. The 256 on-chip JFETs of the CCD channels have designated signal processor channels. This parallel architecture of the detector allows for a very fast readout of images and thus a high frame rate. After an X-ray photon integration time of 50 ms, the whole image is transferred within less than 100 µs to the frame store area. In this shielded part of the device, the pixels are read out row by row, while the photons of the next frame accumulate in the image area. Since low-loss transfer of signal charges can be carried out much faster than low-noise signal processing, the implementation of the frame store allows for high frame rates in conjunction with small out-of-time event probability. Out-of-time (OOT) events are caused by X-rays hitting the CCD during transfer of the image. Resulting from the transfer and readout times given above, we obtain an OOT event probability of less than 0.2% for the X-ray astronomy missions which will result in practically no image smearing.

(Please note that the specified time resolution of 50 ms for the 4 cm^2 image area is not limited by the readout speed of the signals but by the thermal budget for the focal plane detector on the satellite. The parallel architecture of the pnCCD and the CAMEX signal processor allows a frame rate of a factor of 10 higher without loss of performance if the operating temperature is maintained. Of course the OOT event occurrence would then be more frequent.)

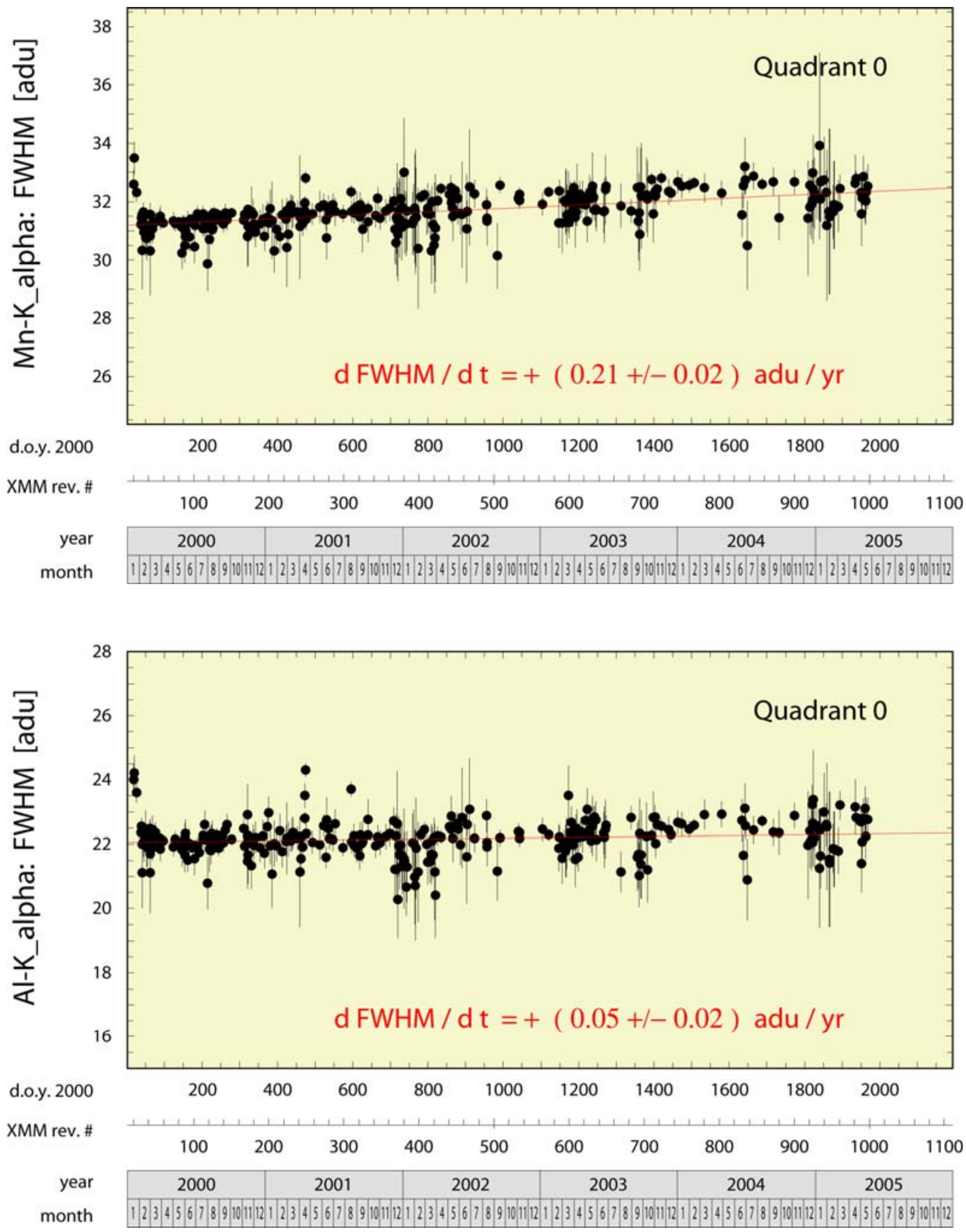

Figure 2: Energy resolution of the X-ray pnCCD detector on the XMM-Newton satellite against time. The upper figure shows the slight degradation of the energy resolution for the Mn-K_{α} line (5.9 keV) and the lower chart for the Al-K_{α} spectral line (1.5 keV). Both spectral lines are emitted by the on-board calibration source. One adu corresponds to 5 eV. The change in energy resolution is less than 1% per year. The single measurements show large fluctuations but the trend is clearly visible for the time period of about 1000 revolutions (> 5 years) and beyond.

The intended operating temperature of the CCDs in space is ≥ -80°C; this is a temperature increase compared to the XMM-Newton pnCCD which is operated at -90°C. The higher temperature is possible for the new devices due to their smaller and more uniformly distributed thermal generation current. A temperature increase far above -80°C is possible in the laboratory but will be more limited in space due to radiation damage from the proton environment.

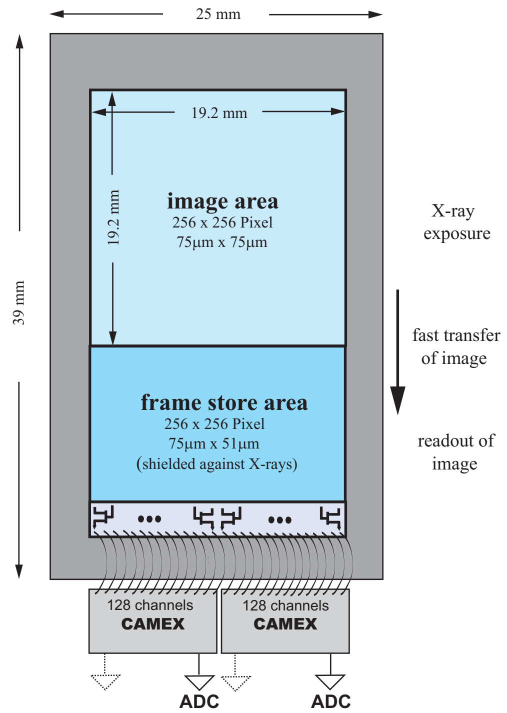

Figure 3: Schematic drawing of the frame store pnCCD for DUO and ROSITA. The chip has a total size of 39 mm x 25 mm. The image area comprises 256 x 256 pixels spanning an area of about 2 cm x 2 cm. Each CCD channel is equipped with an anode which is connected with the gate of a JFET for on-chip signal amplification. The source of the JFET is connected by a wire bond to a dedicated signal processor channel. The 256 analog signal processor channels for the 256 CCD channels are provided by two CAMEX ASICs. Each CAMEX multiplexes the signals finally to the output which is assigned to a 14 bit ADC.

The pnCCDs have been fabricated on ultra-pure, n-type, 6 inch silicon wafers that are polished on both sides. Both wafer surfaces were processed according to the pnCCD concept. The front side carries the transfer registers of the 3-phase CCD, while the photon entrance window is arranged on the back side. The device thickness of 450 µm is fully depleted and thus sensitive to X-rays by reversely biased voltages applied to the transfer registers and the back contact. A high energy implant with 20 MeV phosphorus defines a relatively high doped layer for signal electron storage and transfer in a depth of about 7 µm below the front side. Fifteen of these wafers have been fabricated, each of which has five frame store pnCCDs of DUO/ROSITA type (see Figure 4).

The pnCCD is sensitive to photons of all wavelengths from near-infrared up to X-rays. To avoid any interference of X-ray spectroscopy by photons of other wavelengths in orbit, a filter is used to suppress the intensity of near-infrared, optical and UV light. The process technology used for the pnCCD manufacturing allows us to deposit the filter directly on the photon entrance window of the pnCCD. The on-chip filter is composed of a 30 nm thick SiO_2-layer followed by a 40 nm thick Si_3N_4- layer and then a 100 nm thick Al layer. We have also included a diode monolithically integrated in the border area of the pnCCD chips to allow for precise measurement and control of detector temperature.

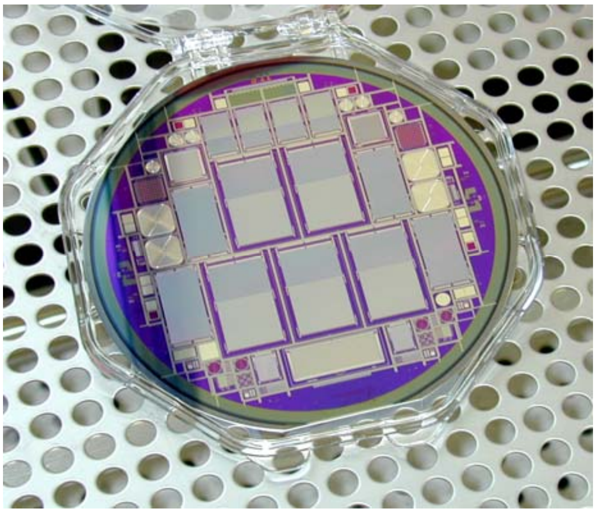

Figure 4: DUO/ROSITA CCD wafer of 6 inch size fabricated in the semiconductor laboratory of the Max-Planck-Institut für extraterrestrische Physik. The five large area DUO/ROSITA frame store pnCCDs are placed in the center of the wafer. Together with the large DUO/ROSITA pnCCDs various other pnCCDs were produced on the wafer, e.g. with smaller chip and pixel sizes, for the purpose of special tests, other applications and further development. Here we look at the front side of the CCDs which contains the transfer registers and the on-chip electronics.

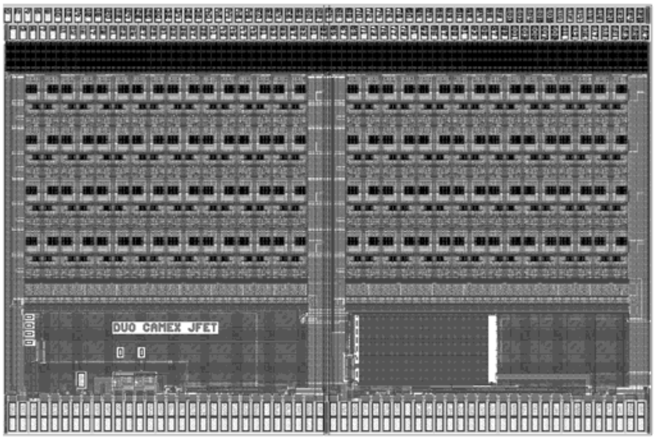

Figure 5: CAMEX analog signal processor developed for the readout of the DUO/ROSITA frame store pnCCD. The ASIC provides 128 channels for simultaneously processing of 128 signals. It has been manufactured according to our design at the Fraunhofer Institut für mikroelektronische Schaltungen und Systeme.

The CCD signals are read out by an analog signal processor fabricated in JFET-CMOS technology like the ASIC developed for the XMM-Newton pnCCDs. The new CAMEX ASIC (CMOS Analog Multiplexing) which has been tailor-made for the DUO/ROSITA pnCCDs, has 128 parallel readout channels and one (or optionally two) output nodes. For low-noise measurements the signals are double sampled with 8-fold correlation. The CAMEX precursor applied for XMM-Newton, offered two gain levels: high gain for X-ray spectroscopy and low gain for the detection of a large amount of signal charge, e.g. caused by a mip (minimum ionizing particle). The new DUO/ROSITA CAMEX permits a choice of several selectable gain levels and as such a variety of possible energy ranges in order to perform the most accurate spectroscopy. Typically soft X-rays will be observed with DUO and ROSITA but spectroscopy of low or high energetic particles, e.g. protons, can also be of scientific interest in space.[4]

These CAMEX ASICS have been fabricated, tested and are already in use for the DUO/ROSITA pnCCD tests (see Figure 5).

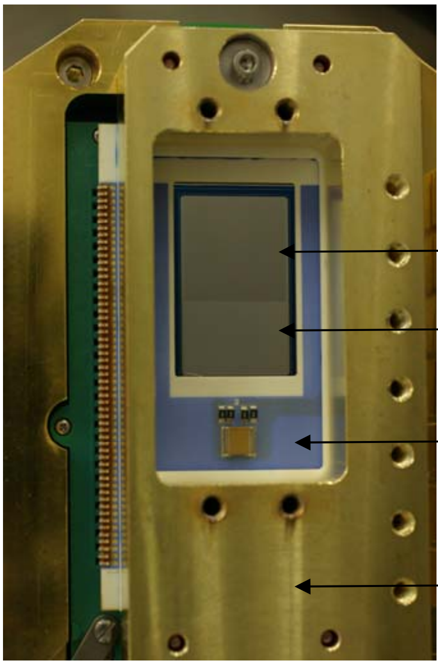

Figure 6: This figure shows the frame store pnCCD of DUO/ROSITA format in the ROESTI test facility. One can see the homogeneous photon entrance window of the image area which is covered on-chip with a 30 nm thick SiO_2, a 40 nm thick Si_3N_4 and a 100 nm thick aluminum layer as UV and light filter. The smaller frame store area is visible here (in the centre of the figure) but for the measurement it is shielded against X-rays. The chip is glued in the cut-out of a PCB on a ceramic carrier. A copper mask surrounds the pnCCD and accomplishes the thermal connection which is required for cooling of the detector. The two CAMEX ASICs are mounted on the other side of the board in order to read out the signals which are transferred row by row to the anodes.

3. PERFORMANCE

The first measurements with the recently fabricated frame store pnCCDs for DUO and ROSITA were conducted in the "ROESTI" test facility of the semiconductor laboratory of the Max-Planck-Institut für extraterrestrische Physik (see Figure 6). The CCDs were mounted together with two CAMEX chips on a 5-layer circuit board printed on a ceramic carrier (Al_2O_3). These chips were then connected with each other and the board by wedge bonds. This detector set-up uses flight-type chips and a board that is similar to the one which is projected for use in space.

We measured an electronic noise figure of 2.3 electrons equivalent noise charge (ENC) for the detector conditions in space, i.e. an operating temperature of -75°C and a photon integration time of 50 ms. The low noise is mainly due to the minimization of the read capacitance of the CCD, the small dark current of the pixels over the entire CCD area, and the 8-fold correlated double sampling of the signals in the CAMEX ASIC. Figure 7 shows the distribution of the noise values of all pixels. A narrow distribution is obtained around the peak with no substantially excessive values.

Another key parameter of an X-ray CCD detector is the quantum efficiency. Without an optical filter (which is solely implemented for light suppression) we obtain at least 90% in the energy band from 0.3 keV to 11 keV. The quantum efficiency curve of the pnCCD and the resulting quantum efficiency after implementation of the filter can be found in reference 3.

For the charge transfer inefficiency (CTI) we obtained a value of $1\text{-}2 \times 10^{-5}$ for Mn-K_α X-rays (5.9 keV). Consequently, the maximum signal charge transfer loss (from the last to the first row of the image area) is limited to 0.5%. Although the signal loss is quite small, it is nonetheless determined and corrected by the data analysis software which was developed for the pnCCDs of XMM-Newton. At that time these devices showed a CTI that was a factor of 30 times worse. For example, the calibration measurements of the XMM-Newton flight pnCCD on ground determined a CTI of 5×10^{-4} for Mn-K_α.

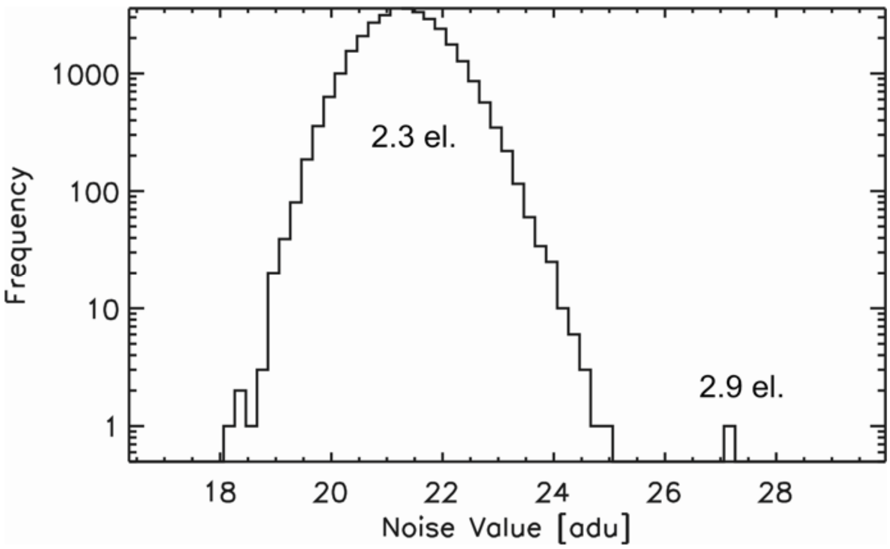

Figure 7: Noise spectrum of a frame store pnCCD measured at an operating temperature of -75°C and with a frame rate of 20 Hz. The mean noise of all pixels has a value of 2.3 electrons ENC. One single pixel shows up with a slightly higher noise value of 2.9 electrons.

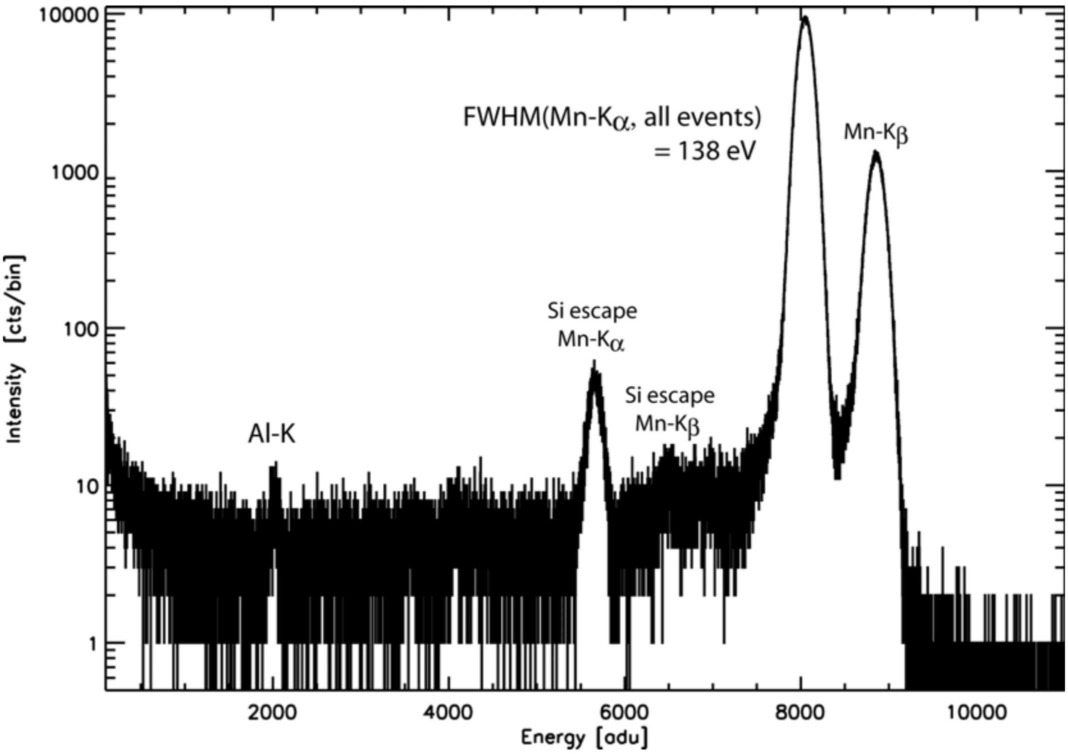

Figure 8: Spectrum of an Fe55 radioactive source measured with the frame store pnCCD of DUO/ROSITA type. A FWHM of 138 eV is obtained for the Mn-K_α line at 5.9 keV. We observe a small Al-K peak (1.5 keV) in the spectrum in addition to the escape peaks of the Mn-K_α and Mn-K_β lines. It is caused by fluorescence radiation (excited by the Mn-$K_{\alpha,\beta}$ X-rays) of the radioactive source housing and of the aluminum layer on the photon entrance window.

The signal charge generated by an X-ray photon is distributed over up to four pixels depending on the distance of the photon hit position to the pixel borders. The resulting events are referred to as single, double, triple or quadruple events according to the number of involved pixels. For a 75 µm x 75 µm pixel size and a chip thickness of 450 µm, about 50% of 6 keV X-ray photons appear as double events, while the other three event types emerge with roughly equal frequencies of occurrence if an event threshold of 42 eV (= 5 x ENC) is applied. A spreading of the signal charge over two neighboring pixels is then, in this case the most probable event. However for low energy X-rays a relatively high probability for the occurrence of single events is obtained. For C-K X-rays with an energy of 277 eV we find about 60% single, 37% double, 2% triple and 0.7% quadruple events (again for an event threshold of 42 eV).

The energy resolution of a spectral line is typically expressed as full width at half maximum (FWHM) of the line. For the Mn-K_α line with energy of 5.9 keV, a FWHM of 138 eV was measured taking into account all events, i.e. singles to quadruples (see Figure 8). The frame store pnCCD shows an excellent low energy response even when equipped with a light filter. This is shown by a C-K spectrum with line energy of 277 eV (see Figure 9). The shape of the spectrum is almost Gaussian; the probability for partial event generation (caused by incomplete signal electron collection close to the detector surface) is thus practically negligible. The FWHM of C-K line was determined to 47 eV if all events are considered; and if only single events are taken into account, a FWHM of 45 eV is measured.

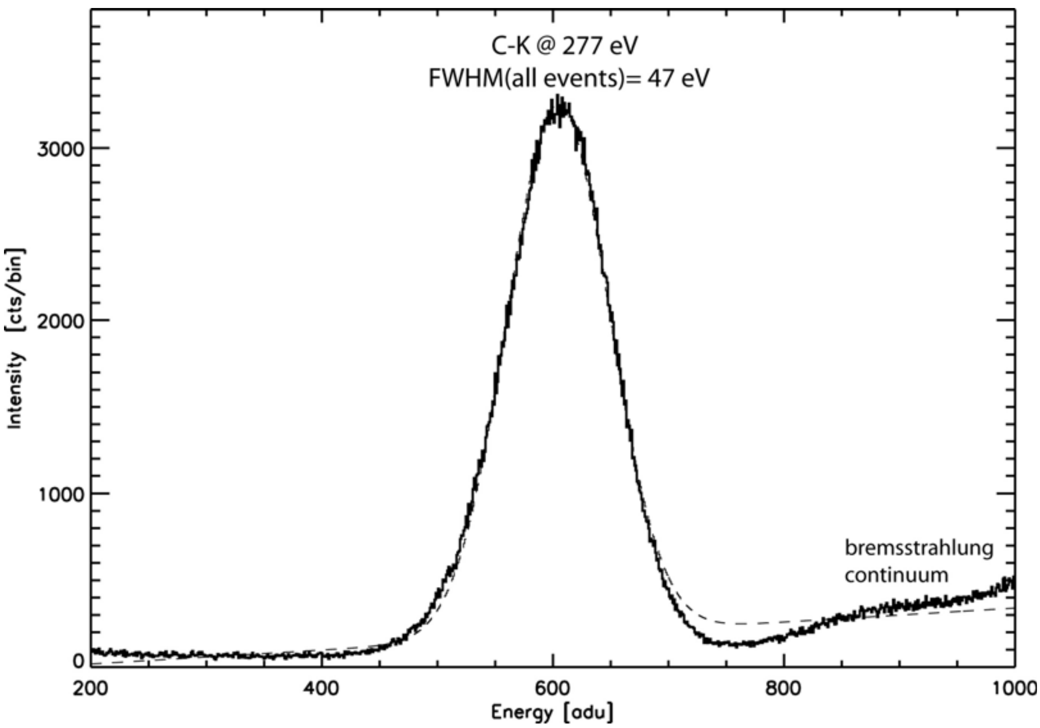

Figure 9: C-K spectrum (277 eV) measured with frame store pnCCD (T = -75°C, frame rate of 20 Hz, photon entrance window equipped with UV and light filter). The C-K line spectrum was generated by an X-ray tube and shows thus in addition a bremsstrahlung continuum component in particular at high energies. Although the line energy is relatively low and only 77 electrons are generated on average by an X-ray photon, we obtain a Gaussian spectrum and a FWHM of 47 eV. The dashed line shows a fit to the measured spectrum with a Gaussian fit for the line and a simple linear fit for the continuum.

4. SUMMARY AND OUTLOOK

These frame store pnCCDs have been developed for the proposed X-ray astronomy missions DUO and ROSITA. In the first tests these CCDs showed a performance clearly superior to that of the XMM-Newton pnCCDs. The new devices have a low electronic noise of only 2 electrons ENC. Practically no noisy pixels were observed at the projected operating temperature of about -80°C. As a result of this and the improved charge transfer efficiency, an excellent energy resolution is obtained from low energies, e.g. a FWHM of 47 eV for C-K (277 eV), up to high energies, e.g. a FWHM of 138 eV for Mn-K_{α} (5.9 keV). These results were achieved with a frame store pnCCD already equipped with the desired light filter deposited on the photon entrance window of the back illuminated CCD.
In addition to extensive tests with more devices we have started to test the frame store pnCCD for use in orbit at operating temperatures considerably higher than -80°C. The first results are quite encouraging. We will also study the radiation hardness and the long term stability of the frame store pnCCD and the CAMEX signal processor experimentally in the near future.

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