pnCCD for photon detection from near-infrared to X-rays

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Abstract

A pnCCD is a special type of charge-coupled device developed for spectroscopy and imaging of X-rays with high time resolution and quantum efficiency. Its most famous application is the operation on the XMM-Newton satellite, an X-ray astronomy mission that was launched by the European space agency in 1999. The excellent performance of the focal plane camera has been maintained for more than 6 years in orbit. The energy resolution in particular has shown hardly any degradation since launch. In order to satisfy the requirements of future X-ray astronomy missions as well as those of ground-based experiments, a new type of pnCCD has been developed. This ‘frame-store pnCCD’ shows an enhanced performance compared to the XMM-Newton type of pnCCD. Now, more options in device design and operation are available to tailor the detector to its respective application. Part of this concept is a programmable analog signal processor, which has been developed for the readout of the CCD signals. The electronic noise of the new detector has a value of only 2 electrons equivalent noise charge (ENC), which is less than half of the figure achieved for the XMM-Newton-type pnCCD. The energy resolution for the Mn-K\textsubscript{a} line at 5.9 keV is approximately 130 eV FWHM. We have close to 100% quantum efficiency for both low- and high-energy photon detection (e.g. the C-K line at 277 eV, and the Ge-K\textsubscript{a} line at 10 keV, respectively). Very high frame rates of 1000 images/s have been achieved due to the ultra-fast readout accomplished by the parallel architecture of the pnCCD and the analog signal processor. Excellent spectroscopic performance is shown even at the relatively high operating temperature of −25°C that can be achieved by a Peltier cooler. The applications of the low-noise and fast pnCCD detector are not limited to the detection of X-rays. With an anti-reflective coating deposited on the photon entrance window, we achieve high quantum efficiency also for near-infrared and optical photons. A novel type of pnCCD is in preparation, which allows single optical photon counting. This feature is accomplished by implementation of an avalanche-type amplifier in the pnCCD concept.

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1. Introduction

The pnCCD was developed in the 1990s for the XMM-Newton mission of the European space agency. The original performance of the XMM-Newton pnCCD has been preserved up to date since its launch in 1999. This detector chip was produced on a 4 in. wafer with an image area of 6 × 6 cm\textsuperscript{2} [1]. It has a time resolution of 0.07 s for full-frame readout. Power consumption is less than 1 W in the focal plane. The quantum efficiency and the electronic noise (5 electrons equivalent noise charge (ENC)) have not changed in the more than five years of instrument operation in orbit. During this time, the energy resolution has only degraded slightly, due to an increase of charge transfer inefficiency caused by protons. The FWHM of the 6 keV onboard calibration source line has changed from 155 to 161 eV in space [2].
Of course, the pnCCD is also applied in other projects. A few examples are the CAST experiment at CERN searching for solar axions [3], multi-photon experiments [4], transition radiation experiments [5], X-ray microscopy [6] and electron-emission-channeling spectroscopy [7].

The further development of the pnCCD detector was again motivated by an X-ray astronomy mission. Roentgen survey with an imaging telescope array (ROSITA) is a space telescope proposed by the Max-Planck-Institut für extraterrestrische Physik [8]. It consists of seven Wolter telescopes and seven assigned focal plane detectors. Scientific goals are the detection of new sources in the X-ray sky, and precise measurements of dark-energy and dark-matter density of the universe. The ROSITA CCD has been tailored according to the requirements of the mission.

After an introduction into the frame-store pnCCD concept, we present the X-ray performance of the new device.

In addition to the application for X-ray experiments, the frame-store pnCCD can be used for the detection of near-infrared and optical photons, e.g. as image sensor for optical telescopes or in the field of adaptive optics. We describe the advantages of the frame-store pnCCD in this wavelength band and what had to be modified in comparison to its use as X-ray detector.

Finally, the concept of a special pnCCD type is introduced which allows us to detect single optical photons.

2. Concept of the frame-store pnCCD

The 3-phase frame-store pnCCD is a chip with a thickness of about 450 µm, which is fully depleted by reverse-biased pn-junctions on front and back sides (see Fig. 1). Back illumination is necessary to obtain a thin and homogeneous photon entrance window. The relatively deep transfer of the signal electrons in a depth of about 7 µm allows large pixel sizes of 75 x 75 µm², which were specified for the ROSITA project. We minimized the read capacitance to about 25 fF, and thus achieved a high signal-to-noise ratio. For each CCD channel, an n-channel JFET is integrated for on-chip signal amplification. It is connected by wire bond with a dedicated channel of the analog signal processor. This parallel architecture enables fast readout of the image, yielding a time resolution in the millisecond range. CCDs for X-ray spectrosocopy generally have to be cooled to temperatures of about −100 °C in order to keep the dark-current noise contribution small. Otherwise, dark-current electrons, thermally generated in the pixel, join the signal electrons resulting in a deterioration of the energy resolution. Our recently produced frame-store pnCCDs, however, can be operated at relatively high temperatures of about −25 °C due to the following three reasons:

(a) an optimization of the fabrication technology resulted in a substantially smaller dark current of the devices,
very high frame rates of up to 1000 images/s minimize
the number of thermally generated electrons in the
pixels of a frame, and
(c) the number of noisy or bright pixels is negligible even at
such high temperatures.

A high radiation hardness of the pnCCD is ensured (and
in-orbit verified) by the following features. By the use of pn-
diodes, no charging of oxide occurs as in the MOS structures
of the transfer gates of MOS CCDs. Back illumination has
the advantage that the sensitive charge transfer channel is
shielded by the device thickness; accordingly, low-energy
particles cannot generate traps there. Fast transfer and
readout minimizes trapping of signal electrons. Finally, the
number of dark-current electrons generated as a result of
bulk damage, is suppressed by the short exposure time (of
course, the maximum possible operating temperature should
not be chosen in a severe radiation environment where
radiation damage is expected.)

The ROSITA frame-store pnCCD contains 256 channels
and 256 rows in the image area. With a pixel size of
75×75 μm², we obtain a 2×2 cm² large image. In the frame
store, the pixel size is downsized to 51×75 μm². The 256
CCD channels are terminated by 256 anodes and n-channel
JFETs. Each JFET is then assigned to an analog signal
processor channel. For this purpose, the DUO CAMEX
ASIC has been developed (see Fig. 2). It provides 128
parallel-readout channels, which are finally serialized to one
or optionally two output nodes. Low noise is achieved by 8-
fold correlated double sampling of the signals. It is equipped
with various selectable gain levels in order to achieve most
accurate spectroscopy in the respective field of application,
e.g. detection of X-rays, optical photon intensities or
particles. The time sequence, the desired gain level and the
number of used output nodes are programmable. The DUO
CAMEX was produced in 2004 and applied for the
measurements presented in this paper.

For X-ray astronomy missions, the focal plane CCDs
have to be shielded against optical light that would
interfere with X-ray spectroscopy and imaging. However,
the filter has to be very thin to preserve the quantum
efficiency for soft X-rays. The developed foils are thus very
fragile, but have to survive the vibration load of a satellite
launch. Our technology allows the deposition of an
effective UV and light filter directly on the photon entrance
window of the CCD. It is a stack of thin silicon oxide,
silicon nitride and aluminum layers. The ROSITA CCDs
are equipped with this filter.

Fig. 2. Schematic diagram of a DUO CAMEX channel. The anode of a CCD channel is connected with the gate of the on-chip JFET, which is biased by
the current source of the CAMEX. Each CAMEX channel consists of the input stage with current source, a charge-sensitive JFET preamplifier, a passive
low-pass filter, an 8-fold correlated double-sampling filter, and a sample and hold stage. Finally, the processed signals of the 128 channels are serialized to
the cable driver.
3. X-ray performance

The fill factor of the pnCCD is 100% and the quantum efficiency amounts to at least 90% in the entire energy band from 0.3 to 11 keV (without optical filter) [9]. We detected a charge-handling capability of more than $1 \times 10^5$ electrons/pixel. Less than 100 μs are needed for the transfer of the image into the frame store. The readout time is 5 ms for the 4 cm² large image area. The maximum frame rate is consequently 200 images/s for a format of 256 × 256 pixels in standard operation mode. We measured with the recently produced frame-store pnCCDs, read out by the DUO CAMEX, an electronic noise of 2 electrons ENC. In highest gain mode and at a temperature of about −70 °C, even 1.8 electrons ENC was achieved. The noise contribution of the CAMEX (without current source) including the subsequent electronics was measured to about 0.7 electrons. The power consumption of the 128-channel CAMEX is 0.6 W. By the analysis of line spectra, we calculated the energy resolution of the pnCCD detector. For the Mn-Kα line at 5.9 keV emitted by a Fe55 source, we found a FWHM of 131 eV (Fig. 3). For the single-event spectrum, i.e. events with the signal charge collected in only one pixel, the FWHM amounts even to only 123 eV. This energy resolution is very close to the theoretical limit of approximately 120 eV given by the Fano noise contribution. The low-energy response was tested with the C-K line at 277 eV generated by an X-ray tube. We measured an excellent FWHM of 47 eV for this line energy. Both results were obtained at low operating temperatures of approximately −80 °C.

Fig. 3. Fe55 spectrum measured at a low operating temperature of −83 °C. A FWHM of 131 eV is analyzed for the Mn-Kα spectrum at 5.9 keV including all event pattern types. The plotted Gauss fit shows that the shape of the spectrum is Gaussian. In addition to the total spectrum, the spectra of the individual event pattern contributions are presented as well. Applying an event threshold of 40 eV (5 × ENC), we obtain for about 50% of the 5.9 keV photons a signal which is spread over two pixels, i.e. double events. The other three event pattern types, i.e. singles, triples and quadruples, have roughly the same frequency of occurrence. Spreading of the signal charge over more than 4 pixels is not observed.

Fig. 4. Fe55 spectrum (all event patterns) measured with the frame-store pnCCD at a “warm” operating temperature of −23 °C. As a result of the higher thermally generated dark current, we obtain an electronic noise of 5 electrons. The FWHM of the Mn-Kα line (5.9 keV) increases to a value of 151 eV, which is still appropriate to perform high-resolution spectroscopy.

Fig. 5. Low-energy response of the frame-store pnCCD at a warm operating temperature of −26 °C. We obtain for the C-K line at 277 eV, generated by an X-ray tube, a FWHM of 64 eV. The nearly Gaussian shape of the line indicates that the occurrence of partial events (i.e. events with incomplete collection of their signal charge) is negligible.

The measurements were repeated at “warm” operating temperatures of about −25 °C. Of course, we got a worse energy resolution because of the higher thermally generated current, but the change was not severe. We obtained a FWHM of 151 eV for the Mn-Kα line (5.9 keV), and a FWHM of 64 eV for the C-K line (277 eV) (see Figs. 4 and 5, respectively).

4. Near-infrared and optical photon detection

Apart from the use of the frame-store pnCCD in the field of X-rays, the device shows multiple advantages to be applied for the detection of near-infrared and optical photons:

Firstly, the unstructured and ultra-thin entrance window of the back-illuminated pnCCD yields a homogeneous
response with high quantum efficiency. This is in particular important for blue and UV wavelengths, where the absorption length of radiation is very short (\( \approx 1 \mu m \) in silicon).

Secondly, the entire detector thickness of 450 \( \mu m \) is radiation sensitive. In the red and near-infrared regions, photons have a long absorption length (\( \gg 10 \mu m \) in silicon), so we obtain a high quantum efficiency too. Fringing effects due to multiple light reflections between detector front and back sides are negligible for such a large distance between the device surfaces.

Thirdly, the small pnCCD detector capacitance and the low-noise readout by the CAMEX analog signal processor result in a high signal-to-noise ratio. One optical photon generates one electron–hole pair in the wavelength region from 300 to 1100 nm and yields a signal contribution of one electron after successful collection and transfer of the charge. Due to the high quantum efficiency and the small charge transfer losses, the associated noise contributions are relatively small and the number of read out signal electrons is nearly equal to the number of photons per pixel. This signal size has to be compared with the noise figure of 2 electrons rms of the dark image.

Lastly, the anti-reflective coating, which is necessary to prevent photon reflection at the entrance window, can be easily deposited with the process technology of our semiconductor laboratory.

The first three items are part of the device concept; only the last one needs special preparation for our frame-store pnCCD.

The internal quantum efficiency describes the probability to register generated signal charges once incident photons have passed the covering layers of the detector. We measured that the internal quantum efficiency of the pnCCD remains one for the entire spectral region between 300 and 950 nm \[10\]. With a standard entrance window consisting of a thin SiO\(_2\) layer, the total quantum efficiency is limited to \( \leq 70\% \) because of photon reflection. However, by the use of a layer stack, composed of SiO\(_2\) and Si\(_3\)N\(_4\), the quantum efficiency can be optimized close to 100\% for a specific wavelength region (as shown in Fig. 6).

For high-speed operation of the photon-imaging detector, double-sided readout of the pnCCD is used (Fig. 7). The two adjacent image areas consist of 264 columns and 132 rows each. The pixel size is 51 \( \times \) 51 \( \mu m^2 \). Signal readout is accomplished by four CAMEX chips having 132 channels each. By the use of the two output nodes per CAMEX, we have 8 nodes, each connected to its own ADC. For moderate frame rates of up to 400 frames/s, the readout noise amounts to 1.8 electrons ENC. If higher frame rates are requested, the CAMEX is operated in a special mode without amplifier reset after each readout of a pixel of a column. This results in a strict limitation for the detected amount of signal charge, which corresponds to a flux of 1500 photons per CCD channel and frame. However, if a lower gain is chosen, which causes a slightly higher noise level, the limit for the photon flux is increased by a factor of four. By this operating mode, a frame rate of 1000 frames/s was achieved \[11\]. In terms of pixel rate, this means 70 Mpixel/s. The noise increased at this rate to a value of 2.3 electrons.
With this low noise level, even a signal generated by less than 10 photons in a pixel can reliably be detected. For some applications, even higher frame rates are requested. Then, a binning can be carried out on the chip, e.g. 4 pixels/column, and the resulting frame rate is increased by that factor to 4000 frames/s. The noise level of 2.3 electrons remains the same.

5. Avalanche pnCCD

In high time resolution astronomy, faint, rapidly changing astronomical objects are the targets of observations. These projects require a high frame rate of the CCD detector and the capability of single optical photon detection. The present pnCCD allows the detection of a very small number of photons in a pixel. However, the signal generated by a single optical photon, i.e. a single electron, cannot be discriminated from noise fluctuations. To satisfy this demand, the concept of a modified pnCCD has been developed, referred to as avalanche pnCCD. The idea is to integrate an avalanche amplifier in the anode region of each pnCCD channel. The avalanche amplification is carried out between a buried p-layer and the n⁺-anode (see Fig. 8). The avalanche amplifier is biased through a high ohmic resistor, and operated in proportional mode or limited Geiger mode. The signal electron sets off an avalanche current when it is transferred to the anode. As a result, the avalanche current charges the gate of the on-chip transistor (e.g. a p-channel MOSFET). Then, the readout of the on-chip amplified signal is carried out as usual by the CAMEX ASIC, which is connected to the source of this first amplifying transistor by a wire bond.

A single photon causes a signal charge, which is comparable to that of an X-ray photon, and the well-established signal amplification and processing chain of the X-ray pnCCD can be adopted. Finally, with the application of an appropriate threshold, the digital information of whether a photon was in a pixel or not is obtained. Operation of the avalanche amplifier with moderate gain instead of in Geiger mode has the advantage of preventing optical cross-talk. The avalanche pnCCD can also be operated like a normal pnCCD. For this purpose, the amplification is turned off completely by lowering the avalanche reverse-bias voltage.

Simulations have shown the validity of the avalanche pnCCD concept. Presently, the layout of a very first prototype avalanche amplifier is prepared under the constraints of our process technology.

6. Summary and conclusions

The pnCCD is used today in many areas of research. The new version of the pnCCD shows improvements in all key performance parameters, and has become even more attractive for X-ray spectroscopy and imaging. This device allows particle detection and has potential applications in electron spectroscopy. The gain can be adjusted to the energy of the particle. The development of an anti-reflective coating, the low noise and the high frame rate pushes open the door for near-infrared and optical photon detection with our frame-store pnCCD. In near future, the concept of the avalanche pnCCD will even allow single optical photon counting with this device.

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References