High-resolution imaging X-ray spectrometers

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Abstract

The successful commissioning of the XMM-Newton focal plane detectors, radiation hard X-ray imaging spectroscopic CCDs, has attracted some attention: Reliably operating X-ray CCDs are delivering extraordinary images, recorded in a single-photon counting mode, imaged through the largest X-ray telescope ever built. The experimental boundary conditions from space applications will serve as a setting to confine the scope of this review. Of course, related applications in other fields of basic and applied science will also be treated. State of the art X-ray detectors with energy, position and time resolution at high quantum efficiency from the near-infrared up to 20 keV are described in detail: todays most advanced systems comprise charge coupled devices and active pixel sensors as well as pixellized silicon drift detectors. They have been developed for astrophysics experiments in space, for material analysis and for experiments at synchrotron radiation facilities. The functional principles of the silicon devices are derived from basic solid-state device physics. The spatial resolution, the spectroscopic performance of the systems, the long-term stability and the limitations of the detectors are described in detail. Field applications show the unique usefulness of silicon radiation detectors.

1. Introduction

Since the discovery of X-rays more than hundred years ago [1] a large variety of techniques for their detection was invented. The ability of high energetic photons to penetrate through matter as a function of their energy and the material composition was soon recognized and used mainly in medical applications.

In contrast to visible and infrared radiation, true two-dimensional imaging of X-rays is restricted to rather expensive and/or inefficient techniques from the optics point of view: Mainly total reflection [2] on high-quality surfaces or coded mask schemes are used. But also multilayer crystals are nowadays being developed for diffraction-limited X-ray optics in X-ray astronomy [3] and X-ray microscopes make use of zone plates for X-ray imaging in material analysis [4]. With the improving quality of the X-ray imaging systems, the X-ray detector development is progressing continuously.

The ‘Röntgenstrahlung’ can roughly be subdivided in soft X-rays (from 50 to 1000 eV), in medium energy X-rays (from 1000 to 20000 eV) and hard X-rays (from 20 to 500 keV). Above 500 keV we call them gamma rays. The UV light
spectrum extends from above the visible light from about 4 to roughly 50 eV. Classically, the separation of X-rays in the energy bins as shown above was made through the physical generation mechanisms of the photons: K-shell radiation was called X-rays, nuclear radiation was called gamma-rays and the emitted light from the outer shells of light atoms was called UV or visible light. As all energy bands are overlapping the limits are somewhat arbitrary.

Imaging of photons is best known in the visible domain, ranging from a wavelength of 3500 up to 6000 Å. For those applications optics and detectors are equally well developed. But all those imaging systems do not count the incoming photons individually to measure their position, energy and arrival time. The photon information is either integrated in the grains of a photographic film that is afterwards developed chemically or the photons are collected in individual picture cells (pixels) and after a given time sequentially read out. The photographic or electronic content of each grain or pixel is then “counted” to measure the intensity of the incident photon flux. The energy of the photons is determined by an arrangement of various filters, transparent only for a narrow, well-defined bandwidth of the incoming photons. In this sense, an image is a static, integrated reconstruction of a local photon intensity distribution.

Individual, single ‘optical’ photons cannot be counted up to now in a practical manner, i.e. with arrays larger than 10 × 10 pixels, with more than 10^9 photons per image recorded within a fraction of a second. The energy of the photons is too small to detect them individually: it is a fraction of an eV in the near-infrared and up to 4 eV for the violet part of the visible spectrum. In gas detectors more than 20 eV are needed for the ionization of a detector gas atom, and room temperature semiconductor detectors need at least 1 eV for the generation of an electron–hole pair. For a proper electronic extraction of such a weak signal of one optical photon, read out electronics should operate below 0.1 e− equivalent noise charge (ENC). This is by far not reached today in the state of the art silicon sensor systems. From approximately 11 000 to 3000 Å only one electron–hole pair per photon is generated due to the ionization process and its statistics in silicon. In this sense, direct spectroscopic information in the optical is physically not available from silicon detectors.

The X-ray imaging systems which are described below record simultaneously the energy, position and arrival time of each individual X-ray photon without using selective absorbers. The physical reasons for being able to make truly energy-dispersive X-ray detectors are the low electron–hole pair creation energy (average) of about 3.65 eV in silicon at room temperature and the very thin radiation entrance windows of only a few tens of partially insensitive atomic layers of silicon and native SiO₂, which can be penetrated by the (even soft) X-rays. For a good quantum efficiency at higher X-ray energies only the depleted thickness of silicon (charge collection depth) is relevant. At 500 μm sensitive detector thickness, e.g. 25% of 25 keV X-rays are converted in electron–hole pairs and can be collected and detected. For two-dimensional silicon detectors with high position and energy resolution, the fabrication by a planar process – comparable to the fabrication in state-of-the-art microelectronics – is obligatory. Depletion thicknesses of 1000 μm are technically a limit for the detector fabrication in planar processes [6]. In the energy band between 0.1 and 25 keV state of the art imaging silicon detector systems are ideal for the direct detection with high quantum efficiency, position and energy resolution.

The astrophysical requirements have driven the developments of the high-resolution X-ray detectors from 100 eV to 10 keV in the last 10 years. The X-ray Multi Mirror Mission (XMM) of the European Space Agency (ESA) was successfully launched in a highly eccentric orbit on December 10, 1999 with three large X-ray telescopes and reflecting grating spectrometers all having specially designed X-Ray Charge Coupled Devices (CCDs) in their focal planes [7–9]. In addition an optical monitor is mounted on XMM. The Advanced X-ray Facility of the National Aeronautics Space
The full kinematic reconstruction of the electron and scattered photon in the Compton effect equally allows for the determination of the direction and energy of the incident photon. But this technique is only usable for the hard X-ray band and above.

Wide bandwidth X-ray optics have to use techniques which avoid the absorption of the photons in the optical system. Only upon arrival in the X-ray imaging detector the absorption of the X-ray is required: In the focus of the optical system, the energy, the position and the arrival time of the incident photon have to be measured as precisely as necessary, depending on the application.

2. X-ray telescopes

The nature of X-rays, to penetrate into matter as a function of their energy and to deposit their total energy in a delta-like interaction, affects optics as well as detectors. As the wavelength $\lambda$ varies from 1 Å to hundreds of Å (10 keV–100 eV) the photon screens the atomic structure of the materials used for the optical system and the detector. This feature is equally responsible for the usefulness of X-rays and for the difficulty to develop optics and detectors.

In the classical optical approach, two physical phenomena are used to perform imaging: diffraction and reflection. Both effects can be used for X-ray optics as well.\(^2\) Wide bandwidth X-ray optics have to use techniques which avoid the absorption of the photons in the optical system. Only upon arrival in the X-ray imaging detector the absorption of the X-ray is required: In the focus of the optical system, the energy, the position and the arrival time of the incident photon have to be measured as precisely as necessary, depending on the application.

2.1. X-ray optics

The two actual large observatories Chandra [12] (NASA) and XMM-Newton [13] (ESA) both carry a Wolter-type I X-ray optics. Fig. 1 shows the principle: The gold-coated mirror surfaces are polished with a resulting surface roughness of less than 5 Å. Coaxially incoming X-rays are totally reflected at the smooth mirror surfaces twice if their grazing incidence angle is smaller than e.g. $1^\circ$ for an energy of about 5 keV. If first reflected at the parabolically shaped mirror shell and subsequently at the hyperboloid, the X-ray is focussed on one focal point. This was first introduced by Wolter and later on adapted to the modern X-ray optics by Aschenbach [2]. Off-axis radiation, still fulfilling the total reflection criteria are distorted in a well-defined way. But the angle of incidence can be recovered quite precisely with the help of ray tracing programs. The effective area of this type of X-ray optics is increased by nesting many individual mirror shells; in total 3 times 58 mirror shells are integrated to form the XMM X-ray mirror system. The collecting area of one XMM mirror system is about 1200 cm\(^2\) at 1 keV and about 150 cm\(^2\) at 10 keV. One telescope is equipped with the pn-CCD camera, the two other telescopes have a front illuminated MOS-CCD as a focal plane detector. The field-of-view of each telescope is about 30 arcmin. The angular resolution is approximately 13 arcsec (Half Energy Width, HEW), the FWHM is typically 7 arcsec. With the focal length

\(^2\)The full kinematic reconstruction of the electron and scattered photon in the Compton effect equally allows for the determination of the direction and energy of the incident photon. But this technique is only usable for the hard X-ray band and above.
of 7500 mm the required position resolution translates to about 450 μm (HEW) at the focal surface.

2.2. X-ray detectors

The absorption depth of photons in silicon oxide and silicon varies over five orders of magnitudes in the bandwidth of 1 eV to 20 keV as can be seen in Fig. 2. The average range of the photon in the silicon varies from several mm in the near-infrared to a few tens of Å only for UV light and then increases again for higher energies to 1 mm for approximately 20 keV. The absorption is most efficient at the silicon M-, L- and K-edges at approximately 20, 100–150 and 1830 eV, respectively.

The X-ray detectors should be able to absorb all incident radiation and transfer a variation of five orders of absorption length’s into a quantum efficiency over the whole range of interest with high homogeneity and an efficiency close to 100%. This should be independent of the photon interaction location in the detector body, where the photon–electron/hole conversion occurred.

The primary conversion process of the incident radiation into a detectable quantity can go into light, heat and electrical charges: The incident photons can directly be converted into light, e.g. in scintillators, which will then be analysed with the help of light sensitive detectors, i.e. photomultipliers or photodiodes to finally yield an electronic signal. Another technique makes use of the increase of temperature caused by the absorption of the photon’s energy. The temperature increase is then used to break up Cooper pairs in a superconductor or to make a current or voltage change in
a micro-thermometer, resulting in an electronically detectable quantity. The last possibility is to convert the incident radiation into electrical charges. The generation of electron – hole or electron – ion pairs in semiconductors and gas counters can be directly amplified to yield an electronic pulse, proportional to the energy of the incoming photons. Till now all three types of techniques have been used to realize two-dimensional, X-ray-sensitive detector systems [14].

Scintillators with photodiode or photomultiplier readout can go to the highest energies; cryogenic detectors as bolometers or superconducting tunnel junctions can achieve to date the best energy resolution; avalanche photodiodes can achieve a time resolution for individual events of several ps; with proportional gas counters sensitive areas without insensitive gaps in the order of several hundred cm² have been built; operation at high temperatures have been achieved with HgI detectors, but there is no detector combining all needed properties in one single detector system with highest quality. Up to now, only state of the art X-ray Charge Coupled Devices (CCDs) and active pixel sensors (APS) unify the broad band properties, with some compromises in the above list of desired physical parameters. The most advanced systems are all made on silicon as absorbing detector material and with integrated on-chip electronics.

The availability of very good starting silicon, the highly elaborated fabrication techniques and the well matched physical properties of silicon, makes silicon microsystems—detector and electronics, monolithically unified—a good candidate for satisfactory performance figures for many application scenarios.³

3. The silicon drift detector

To obtain the lowest possible noise in radiation measurements, the total capacitance of the signal charge collecting node must be minimized. In conventional structures the sensitive area always correlates with the readout capacitance. Either the sensitive area is made very small or the sensitive thickness very large to reduce capacitance. The silicon drift-type detectors decouple collection area from the readout node, since an electrical field parallel to the wafer surface transports the signal charge to a small output node, whose size is independent of the sensitive area. All three kinds of X-ray detectors presented below (Silicon Drift Detectors (SDD), Charge Coupled Devices (CCD) and Active Pixel Sensors (APS)) make use of the so-called principle of sideward depletion.

3.1. Silicon drift detectors

As the functional principles of silicon drift detectors and charge coupled devices are strictly related, SDDs and pn-CCDs will be treated in more detail: The silicon drift detector could be called a phaseless CCD, because the charge is continuously drifted out, or a CCD could be called a discrete SDD, since a CCD drifts the charge packets in clocked time intervals—discretely—to the readout node.

In 1983 Gatti and Rehak proposed a new detector scheme based on sideward depletion [15]. The idea is that a large semiconductor wafer of e.g. high resistivity n-type silicon can be fully depleted from a small n' ohmic contact positively biased with respect to the p' contacts covering both surfaces of the silicon wafer (see Fig. 3).

In the standard configuration the depletion zones will expand from all rectifying junctions simultaneously as long as the ohmic access from the n⁺ anode to the entire (non-depleted) bulk is not interrupted (see Fig. 3 upper diagram). At a given voltage the depletion zones propagating from the p⁺ areas touch each other (see Fig. 3 middle diagram). Under this condition the former conducting electron channel symmetrically located in the middle of the substrate between the p⁺ implants will abruptly disappear. At this moment the depletion of the whole wafer is completed at a voltage which is four times lower than the voltage needed to deplete a simple diode of the same thickness. Under the above-described condition the electron

³Simple silicon pad and strip detectors, as well as hybrid pixel detectors (detectors and electronics on different chips, then bump bonded to form a hybrid detector) will not be treated, because their use is restricted to count X-rays. They are unable to reach Fano-limited energy resolution, mainly because of their high electronic readout noise.
potential energy in a cut perpendicular to the wafer surface has a parabolic shape, with an electron potential minimum in the middle of the wafer without a potential gradient drifting electrons to the read node.

The silicon drift chamber is derived from the above principle of sideward depletion by adding an electrical field, which forces the electrons to the n⁺ readout anode. This is simply achieved by implantation of a parallel p⁺ strip pattern at both sides of a semiconductor wafer (instead of the homogeneous implant on both surfaces shown in Fig. 4) and superimposing a voltage gradient at both strip systems. The direction of the voltage gradient is such that the n⁺ readout anode has the highest positive potential, therefore collecting all the signal electrons accumulated in the local potential minimum (bottom of the parabola in Fig. 5) and drifting them to the absolute potential minimum for electrons at the n⁺ readout node (Fig. 6). The holes from the ionization process disappear directly in their local potential minimum in the p⁺ strips. From Poisson equation it can be easily derived, that in the case of full depletion with the depletion voltage $U_D$ and in a one-dimensional approximation across the silicon wafer ($y$) and a linear superimposed drift field parallel ($x$) to the wafer surface, the electrical potential $\phi(x, y)$ is

$$
\phi(x, y) = U_D - \frac{\rho}{2\varepsilon_0\varepsilon_S} (y^2 - yd) - \frac{\phi_{\text{out}} - \phi_{\text{in}}}{x_{\text{out}} - x_{\text{in}}} x. \tag{1}
$$
The drift field $E_d$ is usually applied between the outer p' drift structures ($\phi_{\text{out}}$) and the inner p' drift strips or rings ($\phi_{\text{in}}$) in the vicinity of the readout node. Neglecting the potential perturbations close to the n' anode, the x component of the drift field can be written as $E_d = (\phi_{\text{out}} - \phi_{\text{in}})/(x_{\text{out}} - x_{\text{in}})$.

The typical drift times for practical drift fields vary between 0.1 and 1 ns per µm drift path. The maximum drift length realized up to now is about 4 cm [16].

### 3.1.1. Energy resolution

The measurement of the total energy of the incident radiation is achieved by a careful, low-noise "counting" of all electrons arriving at the n' readout node. We assume, that the number of created electron–hole pairs is proportional to the energy of the incident X-ray and that the average energy required to create one electron–hole pair is 3.7 eV at $-90^\circ$C. For the following considerations, we assume to operate the first amplifying stage in an ideal source follower configuration. The detector's anode, collecting all signal charges, represented by the readout capacitance can in principle be made very small, limited only by technological parameters. If this readout node is then directly coupled to the gate of an on-chip preamplifying first transistor, the total read-node capacitance can be kept as low as 50 fF, translating in a high sensitivity of the on-chip amplifier, i.e. the increase of the readout node voltage with the arrival of one electron. With

$$U_{\text{out}} = \frac{Q_{\text{inj}}}{C_{\text{tot}}}$$

where $U_{\text{out}}$ is the increase of the output voltage, $Q_{\text{inj}}$ the injected charge and $C_{\text{tot}}$ total readout node capacitance, an X-ray of 6 keV stimulates a voltage change of 5.2 mV. This corresponds to a sensitivity of 3.2 µV/electron. The noise in such configurations can be kept as low as three electrons rms at temperatures around $-30^\circ$C.

For optimum noise and speed performance the implementation of the first amplifying stage on the detector is essential to the use of SDDs (and later on pn-CCDs). A brief description is given below.

The anode is connected to an amplifying junction field effect transistor (JFET) integrated directly on the detector chip (see Fig. 7). This way the capacitance of the detector–amplifier system is minimized by eliminating bond wires between detector and amplifier, thus avoiding all kinds of stray capacitances between the readout node and ground, making the system again faster and less noisy. Further advantages are evident as the effect of electrical pickup is significantly reduced and problems of microphony, i.e. noise by mechanical vibration, are excluded.

With the help of Fig. 7 the basics of the amplification process of the integrated FET can be easily understood. In the centre of the schematic drawing, a single sided n-channel JFET is shown. Let’s assume that electrons, generated by the ionizing radiation drift towards the readout anode. The voltage change, generated at the readout node is directly coupled to the p+ gate of the n-channel transistor (source and drain are n' implants, the transistor channel is a deep n implant). The negative voltage on the p+ gate reversely biases the junction, thus depleting into the transistor channel, resulting in a current drop through the transistor. This change of current can be precisely measured.

As it collects more and more electrons the FET gate gets increasingly reverse biased relative to the
transistor channel. At a given potential difference the gate is discharged by impact ionization in the transistor channel close to the junction of the p⁺ gate and the drain at the end of the channel [17]. During detector operation the gate adjusts its potential in a way that all signal electrons and leakage current are compensated by the breakdown mechanism. In other words: the integrated FET resets itself automatically, there is no need for an externally clocked reset pulse, and the SDD and integrated electronics are operated with dc voltages only.

Eq. (3) reflects the various electronic noise components which occur in a charge measurement. A detailed derivation is given in [18].

\[
\text{ENC}^2 = \left( \frac{2kT}{g_m} C_{\text{tot}} A_1 \right) \frac{1}{\tau} \quad \text{series noise}
\]
\[
+ \left[ \left( 2\pi a_i C_{\text{tot}}^2 + \frac{b_i}{2\pi} \right) A_2 \right] \quad \text{low-frequency noise}
\]
\[
+ \left( qI_1 + \frac{2kT}{R_f} A_3 \right) \tau \quad \text{parallel noise}. \tag{3}
\]

ENC is the equivalent noise charge, \( g_m \) the transconductance of the FET, \( A_1, A_2 \) and \( A_3 \) are constants depending on the shaper’s filter function, \( a_i \) and \( b_i \) are constants, which parametrize the amount of low-frequency noise, \( I_1 \) is the total leakage current and \( R_f \) is the equivalent resistor of the feedback. As can be seen from Eq. (3) the various noise components have different functional dependences with respect to the signal shaping time constant \( \tau \). For the white series noise ENC scales with \( 1/\sqrt{\tau} \), for the white parallel noise ENC scales with \( \sqrt{\tau} \) and ENC is independent of the shaping time for the low-frequency noise or dielectric noise. The white series noise is the thermal noise through a resistor with \( R = 1/g_m \), represented by the transistor channel. The parallel noise comprises all currents flowing to the electronics input. This is predominantly the detector and gate leakage current and in the cases of a charge-sensitive amplifier the feedback current through the feedback resistor \( R_f \). The leakage current has its physical origin in the thermal generation of electron–hole pairs in the semiconductor through energy levels in the forbidden band gap. Those levels may arise from (mainly) metal contamination in the silicon or imperfections in the silicon lattice. In the case of ‘mid-band-gap’ traps, the leakage current attenuates approximately a factor of two every 7 K in temperature reduction. In the case of the low frequency, or 1/f-noise, electrically active traps capture and release the charge carriers in the transistor channel and therefore give rise to a change of the electrical field in the channel, influencing the current flow. The perturbations of the electrical field are described by the density of traps and their capture and emission time constants.

If the detector leakage current could be made infinitely small (e.g. by cooling the detector and front-end electronics) the time shaping constant should be made as long as possible to obtain the lowest ENC, up to the moment, when the shaping time constant independent 1/f noise sets an upper limit for the noise. Of course, again, this conflicts with the requirement of high count rate capabilities; long shaping times, i.e. long signal processing times lead to signal pile-up and therefore degrade the system performance. To beat pile-up, again, the only possibility is to lower the total input capacitance \( C_{\text{tot}} \) and thus lower \( \tau \) to achieve the same ENC. The 1/f noise contribution is independent of \( \tau \), which cannot easily be overcome by operational means (see also Chapter 6.4).
technologically intrinsic limitation of the noise level has its origins in the non-perfect crystal properties of the starting material and the fabrication process.

The achievable energy resolution of a silicon drift detector can be as good as

\[ \Delta E_{\text{FWHM}} = 2.355 \sqrt{\text{ENC}^2 + \frac{FE}{w}}. \quad (4) \]

\( F \) is the Fano factor [19,20], \( E \) the total X-ray energy, \( w \) the pair creation energy, ENC the rms fluctuation of the readout noise and 2.355 the conversion factor between the standard deviation \( \sigma \) (rms) of a gaussian and the FWHM. With \( F = 0.115, \ w = 3.65, \) for \( E = 6 \) keV and a readout noise of 10 electrons (e.g. close to room temperature), the best achievable energy resolution is 150 eV FWHM. Those values were achieved at \(-10^\circ \text{C}\) with SDDs. By further reduction of the temperature, i.e. reduction of the detector leakage current, i.e. reduction of ENC from 10 to 5 electrons, the energy resolution improves to 125 eV FWHM. State of the art silicon drift detector systems operate very close to the above values \[21,22\]. For ENC = 0, the Fano limit can be derived, which is 119 eV (FWHM) for 6 keV X-rays (see e.g. Fig. 44).

### 3.1.2 Position resolution

In standard applications of silicon drift detectors in the high-energy physics experiments the position resolution of SDDs is obtained by a precise measurement of the drift time. The 'start' signal could be delivered by the bunch crossing time mark and the 'stop' time by the SDD. In our short consideration we restrict ourselves to minimum ionizing particles (mip), traversing the SDD perpendicular to the detector’s surface. According to

\[ x_{\text{drift}} = \mu_n \cdot E_d \cdot t_{\text{drift}} \]

the position \( x_{\text{drift}} \) can be obtained easily with the electron mobility \( \mu_n \), the electrical drift field \( E_d \) and the measured drift time \( t_{\text{drift}} \). If the readout anode is segmented in many individual nodes, the position is measured in two dimensions, with the help of the drift time \( (x) \) and the position of the anode \( (y) \) as indicated in Fig. 12.

The position resolution of a silicon drift detector was derived for minimum ionizing radiation by Rehak [23] including the effects of charge spreading during the collection and drift time. For realistic assumptions in the high-energy physics experiments, the limit for the position measurement precision of SDDs is approximately 2 \( \mu \text{m} \) rms.

With the SDD principle in mind, the designer has great flexibility in the choice of anode configurations and drift directions. For instance at the semiconductor laboratory of the Max-Planck Institutes (MPI-HLL) large SDDs have been fabricated with linear drift geometry (see Fig. 12), i.e. parallel strips [24], up to 4.2 \( \times \) 3.6 cm\(^2\) and a 55 cm\(^2\) cylindrical geometry on 4 in wafers, in which electrons drift along the radial direction to one of 360 anodes placed at the wafer edge [25]. Both systems have been used as particle trackers.

For the use in imaging X-ray spectroscopy this straightforward use of silicon drift detectors is not practical. The controlled drift detector in Chapter 4.3 shows alternatives for the simultaneous measurement of position and energy with silicon drift detectors.

### 3.2 Silicon drift detectors for X-ray detection

To make the detectors suitable for X-ray applications, the strip system on both surfaces is replaced by a large area pn-junction on one side, which is used as a very homogeneous thin entrance window for the radiation [21,26] (see Fig. 7). A further improvement is the use of circular drift electrodes, which force the signal electrons to a very small anode in the centre of the device, from where they are transferred to the gate of an integrated JFET. A single-sided JFET is already integrated in the centre of the cylindrical SDD (Figs. 7, 8).

The radiation entrance window, denoted as ‘back’ contact in Fig. 7, plays an important role in X-ray spectroscopy for the detection of light elements, i.e. for X-ray radiation between 100 eV and 1 keV and for the detection of trace elements in the presence of additional (strong) continuous and X-ray line emission [27,28]. X-ray absorbing layers on top of the radiation entrance window as e.g. SiO\(_2\) or Si\(_3\)N\(_4\) and polysilicon in front illuminated MOS-CCDs or SDDs would significantly lower the quantum efficiency for low-energy X-rays. Depending on the photon energy, a fraction of the
Fig. 8. Potential energy distribution in a circular silicon drift chamber with homogeneous radiation entrance window. The simulation includes the whole detector shown in Fig. 7 including the electron collecting readout node.

X-rays would be stopped in the insensitive layers (Fig. 9).

Fig. 10 schematically indicates the different physical processes giving rise to uncomplete charge collection. (1) If the signal charges are generated close to the interface of SiO$_2$ and Si$_3$N$_4$ with silicon, a fraction of the signal charge may go into the detector, the rest is left in the layers of the dielectrics. This causes the so-called partial events, distributed in the spectrum from 0 to the X-ray energy, often labelled as “flat shelf” in a log scale energy spectrum. (2) Towards the low-energy tail of the spectrum of a monochromatic X-ray line a “shoulder” appears, which is due to partial recombination of the signal charges close to the SiO$_2$–Si interface or in the rectifying p$^+$ junction. In the case of the SiO$_2$–Si interface recombination, an improvement is achieved by soothing the interface states at the boundary by technological means, e.g. hydrogen termination of bonds. The shoulder effect of the reverse biased p$^+$ implant is improved by reducing the energy and dose of the implant and to anneal the implantation-caused damage with the appropriate temperature cycles. If the recombination is prevented or suppressed due to proper thermal treatments, the signal charges diffuse in the field free region of the p$^+$ implant until they eventually reach the edge of the space charge region. At that moment, the charge is swept away to the n$^+$ readout node.

Both components of detector background (1) and (2) strongly determine the usefulness of a spectrometer. Beside the energy resolution the peak to background (or peak to valley) ratio is the most important performance figure since it defines the ability of the instrument to separate weak X-ray lines from the dominant lines.

Within the cylindrical area no charge splitting is possible,$^4$ resulting in a single reading of a given charge package. The low-energy response down to 100 eV can be made as good as in any other semiconductor detector, keeping all fast timing

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$^4$In some cases we have observed charge losses to the on-chip JFET if generated close to the JFET. That can be prevented by a redesign of the integration of the JFET and by a different biasing of the SDDs.
Fig. 10. Schematic diagram of the physical processes responsible for the backside originated ‘partial events’ in silicon detectors.

capabilities of the SDD system. In addition to the above-mentioned features an electron sink electrode at the structured surface is implemented as well as an integrated voltage divider. The electron sink takes out all surface generated current components, reducing the leakage current to the pure bulk contribution of less than 1 nA per cm² for a depletion depth of 300 μm. The integrated voltage divider supplies all voltages for the drift rings. Only the innermost and outermost p⁺ ring need to be contacted. The details of these techniques are described in Ref. [29]. For a SDD of 5 mm² active area the maximum drift time from the edge of the detector is about 150 ns, while the time spread of the signal charges of one-photon event is approximately 5 ns. As we have usually no event trigger signal in the field of X-ray detection, the device has no position resolution within the sensitive area.

The electrical potential of the cylindrical silicon drift chamber is shown in Fig. 8 in a two-dimensional cut perpendicular to the surface through the the silicon wafer. It shows the potential energy for electrons of the SDD of Fig. 7, including all field strips and the central electron collecting anode. The equipotential of the homogeneously doped radiation entrance window can be seen on the back, the field strips (rings) with their decreasing (negative) potential on the front side. There is no field free region in the device and all electrons in the sensitive area are guided within less than 150 ns towards the readout node. However the time spread of the charge cloud is only in the order of 5 ns. Overlapping charge clouds limits the single-photon counting capability.

The cylindrical SDD has outstanding properties: At moderate temperatures of about −10°C (achievable by Peltier cooling), the devices have already good spectroscopic properties [30], comparable to the state of the art Si(Li) detectors, but with count rate capabilities up to 10⁶ counts per second (cps) to be compared to the order of 10⁴ of the classical Si(Li) detector concept, without the need of liquid nitrogen cooling (see Fig. 11). The energy resolution at two different shaping times and temperatures are shown in Fig. 18. If the incident photons are correctly collimated within the sensitive area, the peak-to-valley ratio (P/V), i.e. the ⁵⁵Fe peak count rate divided by the average number of counts around 1 keV, can be as large as 15000:1. The P/V ratio determines the sensitivity.

Fig. 11. Silicon drift detector energy resolution as a function of the X-ray (⁵⁵Fe source) count rate. The measurement was done at room temperature. The signal shaping τ was 100 ns.
3.3. The controlled drift detector (CDD)

For X-ray imaging purposes, a detection scheme which needs the time mark of the X-ray to be detected is disadvantageous. A new readout scheme was invented recently [33,34]. In addition to the drift field for the transport of charges parallel to the wafer surface, a potential barrier for electrons is implemented which provides a channel guide for electrons [35], thus the lateral spread of the charges is prevented (see Fig. 13). This technique is very similar to the channel stop configurations discussed in the next chapter for the pn-CCDs. In order to keep the generated electrons at their position for a well-defined time, i.e. in the integration time for the incoming photons, an electron potential barrier is formed perpendicular to the channel stop implants. This additional control of the electrons in the direction of the readout node can be made by means of clocking the drift strips. At a given, externally determined moment, the potential barriers are released, defining the start signal for the drift time measurement. Upon arrival at the readout node, the stop mark is measured, and thus the position of the generated signal-charge cloud according to Eq. (5) calculated. No external trigger is needed, the trigger signal is generated by the detector system itself.

Both concepts use a homogeneous large rectifying $p^+$ implant for the complete depletion of the detector (see Fig. 13). The large $p^+$ (backside) contact is the radiation entrance window for the photons. A structured surface would lead to (a) inhomogeneous response as a function of the incident photon energy and position and (b) incomplete charge collection of the signal-charge package.
Fig. 14. Simulation of the two-dimensional controlled silicon drift detector in the signal accumulation mode. The generated signal charges are confined in their local potential minima.

Fig. 15. Simulation of the two-dimensional controlled silicon drift detector in the signal drift mode. The signal charges in the pixels drift towards the readout nodes.

Fig. 16. Silicon drift detector array with 39 individual readout channels with a radius of 1.2 mm for each individual subunit.

when produced close to the gaps of p⁺ field strips. The simulation of the CDD intuitively shows the functional principle: Fig. 14 shows the electrical potential during the photon integration time, which must be long compared to the signal drift and readout time. Fig. 15 shows the potential distribution once the drift strips have been clocked to remove the electron potential barrier towards the readout nodes.

The time measurement of the arriving electrons with a precision of 10 ns would yield a position measurement precision of 50 μm for standard drift fields, depending on the pixel size. This scheme makes the CDD extremely interesting for X-ray measurements for high photon rates and fast, low noise readout. As the SDD and the pn-CCD, the controlled drift detectors has on-chip amplifiers integrated on the detector, one for each individual readout node. Concerning the readout speed and count rate capability, the controlled drift detector is a real alternative to the charge coupled devices (CCDs) described in the next chapter. The drift towards the readout node happens with a velocity which is only controlled by the externally applied drift field. The transfer is not interrupted by a pixel-wise reading of the charge content, as in the case of CCDs. For 1 cm long drift distance a CDD typically needs 5 μs, while a pn-CCD type detector requires about 500 μs.

The development status of the CDD is progressing towards a detector system, which is showing all performance parameters as designed. To date, the CDD is existing in a prototype version [36].

3.4. Silicon drift detector arrays

Another concept for (coarse) position-resolved X-ray spectroscopy with silicon drift detectors, for ultra high count rates is shown in Fig. 16 [21]. The whole sensitive surface is segmented in relatively small drift detectors, each having its own amplifying chain [37]. Every channel is connected to an individual signal processing chain, producing its own position-resolved X-ray spectrum with count...
rates around 100 000 counts per second (cps) at a temperature of 0°C with a resolution of better than 180 eV for the Mn Kα line of an $^{55}$Fe source. This corresponds to a count rate capability of $2 \times 10^6$ cps/cm², which is just right for the X-ray holography applications planned at HASYLAB. The position resolution is in the order of 1 mm in both directions. A $4\pi$ detector with about 1000 readout channels is actually being prepared [38]. The total count rate of the system is designed to be $10^8$ cps with spectroscopic quality. The SDD arrays compensate the disadvantage of having relatively small areas for the single cell units. By adding the spectra of multi-cell SDDs, operation at room temperature can be maintained with the excellent energy resolution of a single cell, at the expense of increased electronic complexity.

SDD arrays have also been used for the scintillation light readout of CsI(Tl) crystals in γ-ray cameras. The high quantum efficiency at a wavelength around 4500 Å and the low-noise readout have led to an energy resolution in the detection of γ-rays better than the conventional photomultiplier readout of the scintillator [39]. The promising results have initiated the study of an ‘Anger camera’ for the functional analysis of biological tissues. A matrix of six low-noise SDD’s was coupled to a CsI(Tl) scintillator. The 122 keV line of $^{57}$Co was used as an X-ray source, collimated through a pinhole. The measured position resolution was 0.9 mm and the simultaneously measured energy resolution was 15%. For astrophysics applications this is equally interesting: Compton telescopes require the precise tracking (topology of the track and length of the track for energy determination) of the Compton electron (double-sided silicon strip detectors) and the position and energy of the scattered photon (scintillator arrays) [40]. As all kinematic quantities are known, the direction and energy of the incident gamma ray can be reconstructed.

3.5. Works of art investigations with silicon drift detectors

In archeometry different kinds of investigations are used for the characterization of art objects. In particular, the XRF (X-ray fluorescence) spectroscopy is a non-destructive technique widely used for the identification of chemical elements in pigments, metal alloys, and other materials. The classical high-resolution cryogenic detectors, like Si(Li) and HP(Ge) detectors (whose energy resolution is of the order of 140 eV FWHM at the Mn Kα line), are not completely suitable for the realization of portable instrumentation because of the need of liquid nitrogen in the cooling system.

Recently new silicon PIN diodes simply cooled by a Peltier element have been introduced. Their energy resolution (of the order of 200 eV FWHM at the Mn Kα line at $-30^\circ$C) is in some cases unsatisfactory (especially for the analysis of light chemical elements). At low-energy, the main contribution to the FWHM is due to the electronic noise of the detector front-end system, which is associated to the detector-capacitance, directly dependent on the detection area. In addition this performance is only obtained with a PIN-type detector at very low output count rates, typically 1000 cps.

The possibility to operate the SDD at non-cryogenic temperatures and the good energy resolution (in the order of 150 eV FWHM at 6 keV, Fig. 17) makes these detectors suitable for the realization of high-resolution portable instrumentation. Recently a portable high-resolution X-ray spectrometer – based on the Silicon Drift Detector, cooled by a Peltier element – was realized at the research laboratories of Politecnico di Milano [41]. A commercial miniaturized X-ray tube was utilized as an excitation source. The measurements on different kinds of art objects confirmed the ease of use combined with the high class performance, in particular the high-energy resolution. Fig. 18 shows a spectrum of an orange pigment recorded with the above-described system. The almost background-free detection of the individual chemical elements helps to identify the composition of complex materials directly at the location of the work of art. Many measurements were carried out in the Vatican museum and various cathedrals in Italy.

3.6. Element imaging in electron microscopes with silicon drift detectors

Silicon drift detectors have been tailored to use them as energy dispersive spectrometers in scanning
electron microscopes. The RÖNTEC-XFlash™ system was developed to record at temperatures achievable with single-stage Peltier cooler, X-ray fluorescence spectra at about 10 times higher count rates than conventional energy dispersive X-ray spectrometers. This results in spatially resolved element mapping with a high dynamic range, i.e. several hundred gray levels within short measurement times. Fig. 19 shows the analysis of a meteorite with a spatial resolution of 280 × 224 pixels. The measuring time was 10 min and the average X-ray count rate was 250 000 counts per second. The RÖNTEC-MAX™ pulse processor system was used for the data acquisition, the images were processed with a system from Point Electronic. The upper left image of Fig. 19 is the scanning electron image, the others show Fe, Mo, Ni, Ca and Mg, as distributed in the meteorite. Compared to conventional EDX systems, a factor of 6 is gained in the number of gray steps. An additional factor of 4 in count rate capability can be obtained by further improvements of the pulse processing electronics of the SDD system, mainly by reducing the time shaping constant $\tau$ to about 50 ns.

A comparison was made between a conventional EDX system, a high end digital pulse processor-based system and the RÖNTEC-XFlash™ system. A state-of-the-art system with a digital pulse processor achieves with 50 kcps 58 gray steps, while the RÖNTEC MultiMAX™ system reaches 236 gray steps in the same measurement. The XFlash™ detector system was operated at −10°C while the conventional systems were run at liquid nitrogen temperatures. All silicon drift detector configurations

![Image of an orange pigment acquired with the XRF-spectrometer based on a Silicon Drift Detector.](image)

Fig. 18. Spectrum of an orange pigment acquired with the XRF-spectrometer based on a Silicon Drift Detector.

![Figure 17 showing manganese spectra recorded with a SDC at 25°C and -13°C.](image)

Fig. 17. (a) Manganese spectrum recorded with a SDC at 25°C. The shaping time was 0.25 μs, the FWHM is 178 eV. (b) Manganese spectrum recorded with a SDC at −13°C. The shaping time was 1 μs, the FWHM is 144 eV. The peak-to-valley ratio is as good as 15 000.
Fig. 19. Element imaging with a silicon drift detector. The upper left image shows the topological image with the scanning electron microscope. As inserted in the pictures five element images are shown: Fe, Mo, Ni, Ca and Mg. The spatial resolution is $280 \times 224$ pixels, the measuring time was 10 min and the average count rate was 250,000 counts/s. The iron image, e.g., contains 236 gray steps. The images were processed with a system from Point Electronic™.

described above are now commercially available through KETEK GmbH [42].

4. Fully depleted backside illuminated pn-CCDs

Conceptually the pn-CCD is a derivative of the silicon drift detector. The development of the pn-
CCDs started in 1985. In the following years the basic concept was simulated, modified and designed in detail [43,44]. N-channel JFET electronics was integrated in 1992 [45,46,18] and the first reasonably fine working devices were produced in 1993. Up to then, all presented devices were “small” devices, i.e. 3 cm$^2$ in sensitive area [47,48].
The flight-type large-area detectors were produced from 1995 to 1997, with a sufficiently high yield to equip the X-ray satellite missions ABRIXAS and XMM [49–52] with defect free focal plane pn-CCDs. XMM was launched on December 10 in 1999 from Kourou in French-Guyana. Commissioning of the scientific payload was completed in the middle of March this year. In this overview, the basic instrument features as previously planned, will be shown as well as their measured performance in space, with a special emphasis on perturbations caused by heavily ionizing charged particles.

4.1. The concept of fully depleted, backside illuminated, radiation hard pn-CCDs

For ESAs X-ray Multi-Mirror mission, we have developed a $6 \times 6$ cm$^2$ large monolithic X-ray CCD [53] with high detection efficiency up to 15 keV, low noise level (ENC $\approx 5e^{-}$ (rms) at an operating temperature of $-90^\circ$C) and an ultrafast readout time of 4.6 ms per $3 \times 1$ cm$^2$ large subunit (see Figs. 21 and 26). A schematic cross section, already showing some of the advantages of the concept is displayed in Fig. 20.

The pn-CCD concept and the fabrication technology allow for an optimum adaption of the pixel size to the X-ray optics, varying from 30 up to 300 $\mu$m pixel size. The XMM telescope performance of 13 arcsec half-energy width (HEW) translates to 470 $\mu$m position resolution in the focal plane. The FWHM of the point spread function (PSF) is about 7 arcsec. A pixel size of $150 \times 150$ $\mu$m was chosen, with a position resolution of 120 $\mu$m, resulting in an equivalent spatial resolving capability of 3.3 arcsec. The energy response is higher than 90% at 10 keV because of the sensitive thickness of 300 $\mu$m according to the wafer thickness. The low-energy response is given by the very shallow implant of the p$^+$ back contact; the effective “dead” layer is smaller than 200 $\AA$ [27,28]. The good time resolution is given by the parallel readout of 64 channels per subunit, 768 channels for the entire camera. A high radiation hardness is built in by avoiding active MOS structures [54] and by the fast transfer of the charge in a depth of more than 10 $\mu$m. For, e.g. low-energy protons up to 5 MeV, imaged through the X-ray optics [55] or penetrating through the shielding material in front of the pn-CCD, the device is “self-shielding”, because the particles have to propagate through 290 $\mu$m of silicon before damaging the transfer channel, giving rise to charge transfer losses. As there is only a negligible transmission of protons through the X-ray optics above 500 keV, there is no problem for the pn-CCD with low-energy protons. Measurements in a proton accelerator at the university of Tübingen with a proton flux up to $1.4 \times 10^9$ protons...
The low-energy proton irradiation was performed after the XMM launch, when the focal plane CCDs of the Chandra X-ray satellite mission (NASA) observed a severe degradation in energy resolution (from 135 eV FWHM to 500 eV at 6 keV photon energy) after only four revolutions in a comparable highly eccentric orbit. Those protons were imaged up to an energy of 200 keV through the X-ray mirrors.

![Fig. 21. One pn-CCD subunit with 64 on-chip amplifiers and a size of 3 x 1 cm².](image)

The spatially uniform detector quality over the entire field of view is realized by the monolithic fabrication of the pn-CCD on a single wafer. For reasons of redundancy 12 individually operated 3 x 1 cm² large pn-CCDs subunits were defined. Inhomogeneities over the whole sensitive area from 500 eV up to 8 keV were not observed, the measurements were always limited by Poisson statistics. The insensitive gap in the vertical separation of the pn-CCDs is about 40 μm, neighbouring CCDs in horizontal direction have insensitive regions of 190 μm.

The basic concept of the pn-CCD is shown in Fig. 20 and is closely related to the functional principle of the SDDs. A double-sided polished high-resistivity n-type silicon wafer has both surface covered with a rectifying p⁺ boron implant. One the edge of the schematic device structure (see Fig. 20) a n⁺ phosphorus implant (readout anode) still keeps an ohmic connection to the non-depleted bulk of the silicon. A reverse bias is now applied to both p⁺ junctions, i.e. a negative voltage is applied with respect to the n⁺ anode. For simplicity let us assume, that the silicon bulk is homogeneously doped with phosphorus with a concentration of 1 x 10¹² per cm³. The depletion in the high ohmic substrate, with a resistivity of about 4 kΩ cm, develops from both surfaces, until the depletion zones touch in the middle of the wafer in the case of homogeneous doping of the wafer. The potential minimum for electrons is now located in the middle of the wafer. An additional negative voltage on the p⁺ back diode shifts the potential minimum for electrons out from the centre towards the surface having the pixel structure. Typical depletion voltages on the backside [56] are between −150 and −200 V. To make a CCD-type detector, the upper p⁺ implant must be divided in p⁺ strips as shown in Figs. 20 and 25. Adequate voltages should now be applied to the three shift registers, such, that they form local potential minima for e⁻ in a distance of approximately 10 μm from the surface. Three p⁺ strips (shift registers) with the potentials (φ₁, φ₂ and φ₃) comprise one pixel. Charges are collected under φ₃, the potential minimum for electrons. A reasonable change with time of the applied voltages transfers the charges in the local e⁻ potential minimum in a discrete way towards the n⁺ readout node. In reality the side having the p⁺ shift registers has an additional phosphorus-doped epitaxial layer, 12 μm thick, with a concentration of approximately 10¹⁴ donors per cm³. The interface of the epi-layer and the high resistivity bulk silicon fixes the electron potential minimum to a distance of about 10 μm below the surface. As can be seen in Fig. 21, one pn-CCD subunit consists of 64 individual transfer channels each terminated by an on-chip JFET amplifier. Figs. 22–24 show the charge transfer mechanism in a depth of approximately 10 μm below the shift registers. The p⁺ backside contact is not shown: it expands quite uniformly an additional 260 μm towards a negative potential of −160 V. The sequence of changing

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5 The low-energy proton irradiation was performed after the XMM launch, when the focal plane CCDs of the Chandra X-ray satellite mission (NASA) observed a severe degradation in energy resolution (from 135 eV FWHM to 500 eV at 6 keV photon energy) after only four revolutions in a comparable highly eccentric orbit. Those protons were imaged up to an energy of 200 keV through the X-ray mirrors.
Fig. 22. Negative potential of a pn CCD shift register. In this operating condition the signal charges are stored under the register $\phi_3$ only. The $p^+$ backside potential is only shown up to the depth of 40 $\mu$m for clarity.

Fig. 23. Negative potential of a pn CCD shift register. In this operating condition the signal charges are stored under the registers $\phi_2$ and $\phi_3$. The electrons now share a larger volume for a short time.

Fig. 24. Negative potential of a pn CCD shift register. In this operating condition the signal charges are stored under the register $\phi_2$ only. The charge was transferred by one-third of the pixel length in approximately 150 ns.

potentials shows nicely the controlled transfer from register $\phi_3$ to register $\phi_2$, one-third of a pixel. This concept is seen from a different point of view in Fig. 25, seen from the inside of a pn-CCD: X-rays hit the detector from the rear side (back contact). The positively charged holes move to the negatively biased back side, electrons to their local potential minimum in the transfer channel, located about 10 $\mu$m below the surface having the pixel structure. As can be seen in Fig. 25, each CCD line is terminated by a readout amplifier. The on-chip single-sided JFET was already described in Section 3 as the first amplifying element in the SDD.

The focal plane layout of XMM is depicted in Fig. 26. Four individual quadrants each having 3 pn-CCD subunits are operated in parallel. The camera housing and its mechanical, thermal and electrical properties are described in the Refs. [57–61].

4.2. Detector performance (on ground)

The best values for the readout noise of the on-chip electronics is $3e^-$ rms at 150 K, typical values scatter around $4-5e^-$ rms. This includes all noise contributions described in Eq. (3). The charge transfer properties of the pn-CCDs are good, in the order of a few % signal loss from the last to the first pixel over a distance of 3 cm charge transfer. As the charge transfer losses describe the position dependent energy resolution, it is one of the key parameters for the spectroscopic performance, especially after radiation damage may have occurred. Fig. 30 shows a $^{55}$Fe spectrum of a pn-CCD in a flat-field measurement resulting in a typical energy resolution of 130 eV at an operating temperature of $-120^\circ$C [7]. The XMM flight camera was operated at $-90^\circ$C on ground during calibration with a resolution of about 145 eV (FWHM) over
Fig. 25. Inside the pn-CCD. The X-rays hit the device from the backside (bottom). The charges are collected in the pixel well close to the surface having the pixel structure. After integration, they are transferred to the on-chip amplifier.

Fig. 26. The focal plane of the pn-CCD camera on XMM and ABRIXAS consist of 12 independent, monolithically integrated pn-CCDs with a total area of $6 \times 6 \text{ cm}^2$. In total 768 on-chip amplifiers process the signals and transfer them to a VLSI JFET-CMOS amplifier array. 12 output nodes of the CAMEX arrays are fed into four ADCs, i.e. one ADC per quadrant.

the entire area of 36 $\text{ cm}^2$. The main effect on the degradation of energy resolution was the reduction of the charge transfer efficiency (CTE) at warmer temperatures. Leakage currents and on-chip JFET properties only played a minor role. The impact of the material properties of silicon and related impurities and their consequences for the operation of scientific grade X-ray pn-CCDs including the effects of radiation damage, is treated in detail in Refs. [62–64]. The equivalent dose of 10 MeV protons over the expected life time of XMM is $4 \times 10^8 \text{ p/cm}^2$. Figs. 27 and 28 show the results of the irradiation tests with 10 MeV protons: the expected decrease of energy resolution over the 10 year dose is from 145 to 158 eV at an operating temperature of $-100^\circ\text{C}$. At the actual operating temperature of $-90^\circ\text{C}$ the expected effect of trapping and detrapping at A-centres, generated by the radiation, is even reduced.

In a single-photon counting mode the quantum efficiency was measured with respect to a calibrated solid state detector. Fig. 29 shows measurements from the synchrotron radiation facilities in Berlin and Orsay. At 525 eV a 5% dip can be seen from the absorption at the oxygen edge in SiO$_2$ layers. The same happens at the Si$_K$ edge at 1840 eV showing the fine structure of a typical XAFS spectrum (see inset of Fig. 29). For all energies the quantum efficiency is nicely represented by a model using the photo absorption coefficients from the atomic data tables. The quantum efficiency on the low-energy side can be further improved with respect to the measurements shown in Fig. 29, by increasing the drift field at the p$^+$ junction entrance window [28] and by using ⟨100⟩ silicon instead of
Fig. 27. Fe$^{55}$ energy spectrum after different proton fluences of 0 p/cm$^2$ (dotted line), $4.1 \times 10^8$ p/cm$^2$ (solid line), $6.1 \times 10^8$ p/cm$^2$ (dashed line), measured at the low (and after irradiation unfavourable) temperature of 142 K. The expected dose over a life time of 10 years is $4 \times 10^{10}$ MeV p/cm$^2$.

Fig. 28. FWHM of the Mn-K$_\alpha$-spectrum (5894 eV) in dependence on proton fluence and temperature. Before proton exposure the lower operating temperature of 140 K gains better results. After a 10-MeV proton fluence of more than $2 \times 10^8$ cm$^{-2}$ the higher temperature of 174 K results in a better energy resolution. The FWHM is degraded from 135 eV (140 K) to 160 and 175 eV (174 K) after $4.1 \times 10^8$ and $1.9 \times 10^9$ p/cm$^2$, respectively. A FWHM of 160 eV is expected after the 10 year XMM mission.

$\langle 111 \rangle$ silicon. The useful dynamic range of the pn-CCD camera on XMM was adjusted from 95 eV to 15 keV.

Split events, i.e. events with electrons in more than one pixel, originating from one single photon, were reconstructed and summed to one-photon event. In total, about 70% of all events are single-pixel events, 28% are two pixel events and 2% are events with three and four pixels involved. In the case of the XMM pn-CCDs one single X-ray photon spreads the generated signal charge never over more than four pixels.

The readout electronics of the pn-CCD system is described in Refs. [53,65]. A charge sensing amplifier followed by a multicorrelated sampling stage, multiplexer and output amplifier (CAMEX64B JFET/CMOS chip) guide the pn-CCD pixel content as a voltage signal to a 10 MHz 12 bit flash ADC system. The whole system, i.e. CCD and CAMEX64B amplifier array dissipate a power of 0.7 W for the entire camera (768 readout channels), a value which is tolerable for the XMM satellite mission. A further increase of the readout speed can be made only at the expense of further increase of power, or a degradation of the noise performance (Fig. 30).

The charge handling capacity of the individual pixels was tested with the 5.486 MeV alpha particles from a radioactive $^{241}$Am-source. Around $10^6$ electrons can be properly transferred in every pixel. The spatial resolution was intensively tested in the PANTER [66] facility with the flight mirror module in front of the focal plane. The first light image of the Large Magellanic Cloud in Fig. 31 in the next section, as well as the quantitative analysis of the point spread function have shown a perfect alignment of the telescope system on ground: The spatial resolution of the entire telescope system measured on ground corresponds exactly to the performance in orbit.

4.3. Operation in orbit

Three weeks after the successful launch of the Ariane 5 from French-Guyana the camera door
Fig. 29. Quantum efficiency of the pn-CCD as a function of the incident photon energy. The energy scale ranges from 150 eV to 30 keV. The solid line represents a 300 \( \mu \text{m} \) thick sensitive volume, the dotted line 500 \( \mu \text{m} \).

Fig. 30. Mn-K\(_a\)-spectrum of an \(^{55}\text{Fe}\) source. The measured FWHM is 130 eV at \(-120^\circ\text{C}\).

was opened to evacuate the pn-CCD camera system. Two more weeks later commissioning started in mid-January 2000. After stabilizing the temperature to \(-90^\circ\text{C}\) – the nominal operating temperature during the entire mission – the power was sequentially switched on in all four quadrants without any deviation from the nominal values. The major reasons for the increased CCD temperature compared to previous planning were protection against contamination and reduction of thermal stress on electronic printed circuit boards. After the switch-on of the pn-CCD camera, the calibration source was immediately seen, holding all properties studied during ground calibration.

Up to now, six months after launch, no instrumentational surprise occurred: The energy resolution is equal to the ground measurements as is the case for the charge transfer efficiency. To date, the electrical stability of the instrument is perfect. The first light images in Figs. 31 and 32 qualitatively summarize the above enthusiastic statements. The paper now summarizes the up-to-date analysis of the instrument background, mainly arising from charged particles and X-ray fluorescence stimulated by charged particles.

4.4. Performance in orbit – background analysis

XMM is placed in a 48-h elliptical orbit around Earth. Inclined at 40° with a southern apogee at 114 000 km, the perigee altitude is 7000 km. After the satellite has passed through the Earth’s radiation belts, astronomers have the observatory at their disposal for about 40 h. Operation of the instruments is foreseen down to 40 000 km close to perigee. In most cases up to now, operation was discontinued at 60 000 km before perigee, to first study the charged particle background in the vicinity of the radiation belts.

In order to properly understand the X-ray spectra of the pn-CCD camera, we have to better understand the background of the instruments. At least four components contribute to the measured instrument background:

1. The tracks of minimum ionizing particles, typically leaving 80 electron–hole pairs per \( \mu \text{m} \) track length in silicon. Those tracks can easily be discarded, by not accepting pixel event e.g. above 15 keV and rejecting all pixel neighbors of those events.
2. Low energetic electrons, protons and heavy ions. Their energy is spread from 0 eV to several MeV, having the event topology of a short track or medium long tracks (tens of microns), with a high ionization density. In many cases (low-energy, single-pixel event) they can be mixed with X-rays from astrophysical sources.
3. X-ray fluorescent radiation stimulated by the charged particles traversing the entire
Fig. 31. The Large Magellanic Cloud in X-ray colours. First Light Image of the pn-CCD camera. The field of view of 30 arcmin corresponds approximately to our perception of the size of the moon. The image shows the area of 30 Doradus a supernova remnant as an extended source of X-rays. The “north-east” of 30 Dor shows an emission of X-rays up to 5 keV (blue), while the ‘south-west’ rim appears much softer in X-rays (yellow and red). The supernova 1987A is the bright source ‘south west’ of 30 Doradus. About 40 new X-ray objects have been found in this exposure. The exposure time was about 10 h.

Fig. 32. The Hickson Group 16. The second exposure of the pn-CCD camera was shooting at a group of spiral galaxies about 260 million light years away. Several hard sources with energies up to 10 keV have been detected in the lower part of the image. In this picture the blue colour shows X-rays between 8 and 10 keV, red means X-rays from 100 eV to 1 keV. Of course, all scientific information about the X-ray data, such as energy spectra, light curves, etc. are stored but not included in the colored images.

instrument. They cannot be separated from the photons imaged through the telescope.

4. Compton electrons, generated by X- and gamma-rays. The spectrum of the electron energy deposition shows a flat compton plateau up to the maximum energy transferred, which occurs for a photon scattered through 180° (backscatter) and is seen as a Compton edge. The Compton edge is outside the dynamic range of our instrument, but the plateau is clearly identified (see Fig. 38.)

Those four major components are now analyzed on the basis of data which have been taken up to eight weeks after the beginning of the commissioning of the camera.

4.4.1. Minimum ionizing particles

In a standard operating mode (full-frame mode, extended full-frame mode, large window mode) the charged particle tracks are already taken out of the data stream on board of the satellite. If we disable the minimum ionizing particle (mip) rejection we are able to count the background and to measure the energy profile of the recorded events. In a Low Gain Mode (reduction of a factor 22 in gain), the charged particle background can be studied quite well, since the camera extends the energy range for the deposited particle tracks of up to 320 keV per pixel. The energy deposition above 320 keV is collected in an overflow channel, allowing for simply counting the number of occurrences above this threshold.

Out of radiation belts we typically get, under normal observing conditions (no solar flare, no source in the field of view) in total 100 background counts per second and per quadrant (≈ 9 cm²).

As typically eight pixels are affected per event, we get about 50 background events from minimum ionizing particles per second and per 36 cm². This
corresponds roughly to the pre-launch estimated numbers of 1–2 charged particles per cm$^2$ and s. In the absence of solar flares the event patterns (e.g. in Fig. 35) are completely dominated by mips, the contribution of low energy (heavily ionizing) particles is below 0.1 counts per cm$^2$ and s.

Minimum ionizing particles have (a) an average energy loss in silicon of 39 keV per 100 μm, the most probable energy loss (b) however is 26 keV in 100 μm. This translates to a total energy loss in 298 μm silicon of 116 keV (a) and 75 keV for 0(b). But this assumes, that the most probable track is perpendicular to the plane of the detector. But this is of course not true, because the mips traverse the detectors under all angles, as can be seen from the different track lengths in Fig. 35. A Monte-Carlo simulation in Figs. 33 and 34 shows the expected results for a $4\pi$ irradiation of isotropically distributed
mips on the pn-CCD. With the help of Monte-Carlo techniques the position of the mip hit is calculated on a 64 × 200 pixel array and the incident angle of the incoming particle. This serves to determine the track length in all affected pixels. The energy loss per micron track length is then convoluted with a Landau distribution to get the profile of the deposited energy per pixel. The most probable track length segment is 150 μm with a most probable energy deposition of 38 keV. The increased number of counts at lower energies, e.g. below 15 keV, corresponding to a track length of less than 50 μm, arise from the fact, that pixels were only “softly hit”, i.e. the track lengths in those specific pixels were less than 50 μm. This is always associated with a neighboring pixel having a longer track length. Thus the separation from the energies of interest between 100 and 15 000 eV is still remarkable and allows for a perfect separation of X-rays and mips.

The measurement of the mip background in Fig. 36 shows exactly the features simulated in the Figs. 33 and 34: for ‘all events’ the peak of the mip spectrum is found at 40 keV, the single-event peak at about 80 keV. The steeper increase towards lower amplitudes is dominated by the X-ray fluorescence background from the camera components: a Cu Kα line is clearly seen in the single-event...
spectrum at 8 keV, corresponding to about 70 arbitrary digital units 3(adu). The high gain mode measurement with mip rejection and with the internal calibration source is shown in Fig. 38. The mip-induced fluorescent lines Cu Kα and Kβ lines are clearly seen around 1600 ADU’s.

4.4.2. Low-energy charged particles

We have observed that the background figures significantly vary with time, partially independent from the “warning” from the radiation monitor on XMM, which reacts only for protons above 3.5 MeV and electrons above 50 keV. During the background measurements shown in Fig. 35 the camera was operated in the “Low-Gain” mode. A comparison shows the effect of low energy protons with (upper part of Fig. 35) and without (lower part) a soft proton flare. The number of single pixel events suddenly goes up and the energy spectrum shows a steep exponential drop (see Fig. 37) with maximum energies around 100 keV during a 20 min. observation. The spectrum in Fig. 37 was generated by subtracting the deposited energy of two equal time slices, with and without the flare. From this measurement we can conclude, that the incident particle energies are below a few hundred keV. The energy cut-off in the proton spectrum is most probably due to the proton transmission properties of the X-ray mirrors [55].

4.4.3. X-ray fluorescence background

Additional background, which cannot be separated from useful photons arises from the X-ray fluorescence, generated by the mips, passing through the camera. Besides Al Kα, Mn Kα and Mn Kβ, emitted from the internal calibration source another nine fluorescent lines were measured all arising from the material surrounding the pn-CCD. The strongest lines are Cu Kα and Cu Kβ, Zn Kα, Ni Kα. The Cr Kα line hidden under the low energetic shoulder of the Mn Kα peak. In addition, V Kα, Ti Kα, the Silicon escape peak and the K Kα peaks are clearly resolved. Because of the low intensities, the Kβ lines can not always be seen. All lines can be used for instrument calibration purposes. The most prominent line, the Mn Kα in Fig. 39 shows a FWHM of about 150 eV, measured with an event threshold of 115 eV. The actual threshold is now at 100 eV, which allows a more accurate discrimination of the so-called “single events”. Fig. 38 also shows a steep increase of the intensity of the low-energy background from 6 keV at a level of 30 counts to 200 eV with a level of almost 1000 counts. This contributions is due to photoelectrons, generated in the calibration source on the Al fluorescent target. Once the calibration source is turned out of the field of view of the CCD, this background component vanishes almost completely.
4.4.4. Compton background

Scattering of gamma-ray photons at an electron transfers momentum and energy to the electron. Not all the initial energy can be transferred and so this partial energy loss process results in an energetic electron and photon under the boundary condition of momentum and energy conservation. The analytical expression for the electron energy in a Compton process can be derived from the Klein–Nishina formula. The higher the energy of the initial photon, the flatter the energy spectrum of the electron extends towards higher energies. This flat electron background component can nicely be seen in Fig. 38 up to the end of the dynamic range of our signal processing system.

The contribution of Compton processes is relatively small in the measurement of Fig. 38. About 14 h of data are compiled in this measurement. The flat distribution from ADC channel 1700-2500 is the level of Compton background in the pn-CCD detector, which extends down to the lowest energies. About 20 000 counts have been recorded over 14 h in the 36 cm² large detector. This leads to 0.01 Compton events per cm² and second integrated over the whole energy bandwidth from 100 eV to 15 keV.

5. Active pixel sensors (APS) for X-ray spectroscopy

Large format arrays covering a wide energy bandwidth from 1 eV to 25 keV will be used in the focal plane of X-ray telescopes of the next generation [67]. As the readout speed requirements increase drastically with the collecting area, but noise figures have to be on the lowest possible level, CCD-type detectors do not seem to be able to fulfill the experiment needs. Future active pixel sensors (APS) have the capability to arbitrarily select areas of interest and to operate at readout noise levels below 1 electron (rms).

One prominent candidate for the use of an APS is XEUS: The X-ray Evolving Universe Spectroscopy mission [68]. The launch is supposed to be around 2010. It represents a potential follow-on mission to the ESA cornerstone XMM currently in orbit. The XEUS mission is considered as part of ESA’s Horizon 2000⁰ program within the context of the International Space Station (ISS).

5.1. The wide field imager for XEUS – an introduction

The wide field imager (WFI) on XEUS is one out of three scientific instruments in the focal plane of
Note that the pile-up limit in a simplified approach is given by the product of pixel area and readout time per pixel. This is correct as long as the signal charge cloud is significantly smaller than the pixel size.

5.2. The device and system concept

In all CCD-type concepts, charges are transferred slowly over large distances, they are intrinsically sensitive to radiation damage or to metallic contamination of the base material, because of the presence of traps in the bulk silicon. In addition, because of the relatively slow charge transfer, X-rays may hit the CCD during the readout time. This gives rise to events whose position is erroneously assigned in transfer direction – the so-called out-of-time events.

The XMM-EPIC pn-CCD system is limited with pile-up at count rates in the order of 10 counts per HEW and second. But with the anticipated collecting area up to 30 m$^2$ several hundreds of counts per HEW and second are expected for comparable observations. That means that a factor of 20 or more in the XEUS phase A and a factor of about 100 in phase B in frame speed is needed as compared to the pn-CCD camera on EPIC-XMM, to exploit the capabilities of the XEUS mirror system and therefore its astrophysical significance.

The challenge of the wide-field imager system is that $10^6$ pixels can be read out 1000 times/s, delivering several Gigabyte of data. This is the unavoidable drawback of detection systems with high position resolution and simultaneous fast readout. This makes an efficient data reduction mandatory immediately after the analog-to-digital conversion.

5.2.1. Perspectives of the DEPFET system

The DEPFET detector system belongs to the family of “active pixel sensors”. That means, that every pixel has its own amplifier and can be
adressed individually by external means. This results in a high degree of operational freedom and performance advantages.

The major advantages of DEPFET type devices are:

1. Operation with high spectroscopic resolution at temperatures as high as $-50^\circ C$, keeping the total readout noise below five electrons (rms) for a single reading of the signal charges.

2. The charge does not need to be transferred parallel to the wafer surface over long distances. That makes the devices very radiation hard, because trapping (radiation induced defects), the major reason for degrading the charge transfer efficiency, is avoided.

3. The ratio between photon integration time and readout time can be made as large as 1000 : 1 for a full frame mode, that means that the so-called out-of-time events are suppressed to a large extent.

4. As the integration time per event will be in the order of 1 ms and the readout time per line about 1 $\mu$s, more than 1000 counts/s per HEW (2 arcsec, i.e. $7 \times 7$ pixel) can be detected with a pile-up below 6%.

5. No additional frame store area is needed; the device is as large as the processed area.

6. Any kind of windowing and sparse readout can be applied easily, different operation modes can be realized simultaneously.

7. The DEPFET transistor amplifier structure offers the possibility for a repetitive non-destructive readout (RNDR). Under those conditions the readout noise can be reduced to below 1 electron (rms) by a repetitive reading of the physically same signal charge. This readout mode can be applied in selected areas, while the rest of the device is operated in the standard readout mode.

From the conceptional point of view this is currently the most advanced semiconductor X-ray pixel detector as it offers a lot of additional features like the analog storage of 2D X-ray images. Some more recent experimental results are given in Refs. [71] and [72]. More conceptual system aspects and operating conditions are given in Ref. [67].

The standard DEPFET and DEPMOS devices are p-channel devices on n-type material. The use of p-type base material is very interesting for the DEPFET devices. The reasons for that is, that the use of n-channel JFETs and MOSFETs becomes possible by using holes as the signal charges. This offers an increased transconductance $g_m$ of the transistors by a factor of three improving the equivalent noise charge at least by a factor of 1.5.

5.2.2. Device concept and functional principle

Our DEPFET concepts are based on a detector–amplifier structure, which consists of a field effect transistor working on a depleted high resistivity substrate. The cross section of such a device is shown in Fig. 40. The device, which was proposed by Kemmer and Lutz in 1986 [73], makes use of the sideward depletion principle [15]. Assuming that n-type semiconductor material is used, one can deplete a detector chip in such a way, that there remains a potential minimum for electrons under the channel of a field effect transistor [74] being capable of storing the signal charges for a long time – if needed, up to several seconds according to the operating temperature. It is straightforward to use such a device as detector, where signal charges (electrons) are collected in the potential minimum, from where they can steer the transistor current, acting as a so-called “internal gate”. The signal charges change the transistor current by inducing charges inside the p-type channel of the DEPFET. The result is a simultaneous integration of the first amplifier stage on the detector chip with a detection fill factor of 1.

The potential distribution in the device, calculated by the 2D TOSCA [75] code, is shown in Fig. 41. The potential maximum of the internal gate (minimum for electrons) is clearly visible and is separated from the external gate by the p-channel. The potential difference in the pixel area to its direct surroundings is about 1 V, sufficient to collect more than 100,000 electrons in one pixel.

Since the electrons are collected in a potential maximum (signal charges as well as leakage current) the device has to be reset from time to time by emptying the corresponding internal gate. One straightforward way of doing it, is applying a positive voltage to an adjacent n$^+$ contact, which acts as a drain for electrons.
In a first approach devices were built, where periodically (hundreds of µs) all charges are removed from the potential minimum beneath the transistor. This is done by applying for a short time (hundreds of ns) a positive voltage at the substrate contact. The result of a two-dimensional simulation shows the continuous rise of the bulk potential between the region under the transistor and the substrate contact for this particular case (see Fig. 42). After the clear procedure, signal electrons can be collected and stored again in the electron potential minimum under the transistor channel. As the signal charges have to be removed explicitly and as the internal gate is continuously filled up with thermally generated electrons, the clear procedure can be applied upon request or in a repetitive manner. The clear mechanism acts locally where the clear pulses have been applied. The time required for a complete clear of the internal gate is estimated to be below 100 ns.

The information about the amount of signal charges stored can be recorded by measuring the rise of the transistor current. This measurement does not disturb the stored charges, therefore the
Fig. 42. Result of a two-dimensional simulation of the clear procedure; one can see the potential inside the detector chip while there is a positive voltage pulse (+15 V) applied to the substrate contact; the simulation was done with the program TOSCA for a DEPFET with cylindrical symmetry where the source is in the centre of the structure; the reader is looking from the top of the device into the bulk.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Expected performance figures of the DEPFET focal plane detector system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Integration + readout</strong></td>
<td></td>
</tr>
<tr>
<td>Readout time per row</td>
<td>2.5 µs</td>
</tr>
<tr>
<td>(128 channels)</td>
<td></td>
</tr>
<tr>
<td>Total readout time</td>
<td>1.25 ms</td>
</tr>
<tr>
<td>Integration: readout time</td>
<td>500:1</td>
</tr>
<tr>
<td>Window mode</td>
<td>150 µs for 64 x 64 pixels</td>
</tr>
<tr>
<td><strong>Response to radiation</strong></td>
<td></td>
</tr>
<tr>
<td>QE @ 50 eV</td>
<td>70 %</td>
</tr>
<tr>
<td>QE @ 100 eV</td>
<td>85 %</td>
</tr>
<tr>
<td>QE @ 110 eV</td>
<td>80 %</td>
</tr>
<tr>
<td>QE @ 272 eV (C K\alpha)</td>
<td>90 %</td>
</tr>
<tr>
<td>QE @ 1.740 eV (Si K\alpha)</td>
<td>100 %</td>
</tr>
<tr>
<td>QE @ 8050 eV (Cu K\alpha)</td>
<td>100 %</td>
</tr>
<tr>
<td>QE @ 10000 eV</td>
<td>96 %</td>
</tr>
<tr>
<td>QE @ 20000 eV</td>
<td>45 %</td>
</tr>
<tr>
<td>Depletion depth</td>
<td>500 µm</td>
</tr>
<tr>
<td>Rejection efficiency of MIPs</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>Spectroscopy</strong></td>
<td></td>
</tr>
<tr>
<td>Fano noise at 5.9 keV</td>
<td>118 eV FWHM</td>
</tr>
<tr>
<td>System noise</td>
<td>3 – 5 e⁻ (rms)</td>
</tr>
<tr>
<td>System noise with RNDR $^{55}$Fe resolution</td>
<td>$\approx 1$ e⁻ (rms) for $n = 16$</td>
</tr>
<tr>
<td>C K\alpha resolution</td>
<td>125 eV</td>
</tr>
<tr>
<td><strong>Radiation hardness</strong></td>
<td></td>
</tr>
<tr>
<td>No change up to (@220 K)</td>
<td>$1 \times 10^{10}$ p with 10 MeV per cm²</td>
</tr>
<tr>
<td><strong>Focal plane geometries</strong></td>
<td></td>
</tr>
<tr>
<td>Device size</td>
<td>7.5 x 7.5 cm²</td>
</tr>
<tr>
<td>Device format</td>
<td>1000 x 1000</td>
</tr>
<tr>
<td>Pixel size</td>
<td>475 x 75 µm²</td>
</tr>
<tr>
<td>Position resolution</td>
<td>30 µm</td>
</tr>
<tr>
<td>Fill factor of focal plane</td>
<td>1</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>200 K</td>
</tr>
</tbody>
</table>

5.2.3. System performance

The key parameters of the DEPFET system are listed in Table 1. Their values have been derived from prototype measurements or, if transferable, from measurements with the XMM pn-CCDs. The main properties are summarized in the following sections “Energy Resolution and Noise”, “Position Resolution”, “Count Rate Capabilities” and “Quantum Efficiency”.

readout process can be repeated several times and opens the option of a multiple non-destructive readout. Hence, if a row of DEPFETs is activated by the selective application of the external gate voltages, the charge content can be measured, a clear pulse could be applied and the charge measurement repeated without having signal electrons in the potential minimum. The difference between both measurements is the net signal of electrons in the internal gate.

5.2.4. Energy resolution and noise

Besides the statistical fluctuations of the ionization process (Fano fluctuations) the electronic noise is the dominant limitation of the energy resolution. Therefore the physical models of the devices to understand its basic noise sources are of great importance.

Considering the noise behaviour of the DEPFET, the so-called “total detector capacitance” present in conventional detector–amplifier combinations can be neglected. Only the capacitance of the internal gate is relevant. This leads to very low equivalent noise charge figures for the series noise
5.2.5. Position resolution

Due to the diffusion of the signal charges during their drift from the conversion point inside the silicon into the potential minimum of the pixel, the spatial measurement precision can be improved substantially, for relatively large pixel sizes. The improvement is significant, if the signal charge cloud diameter is in the order of the pixel size. Taking into account a thickness of the silicon wafer of and the according charge collection times, i.e. collection times for the generated electrons, the charge cloud, containing 96% (4σ) of all signal charges will have a diameter of about 30 μm. This would improve the spatial resolution with a pixel size of 50 μm to less than 15 μm for the events which are all contained in one single pixel (less than 20% of all events) and to a spatial resolution substantially below that (≤ 5 μm) for all other events (80%) (see also Fig. 45). This would lead to a useless oversampling in the XEUS case, where the angular resolution of 2 arcsec corresponds to 500 μm in the focal plane.

In the case of a pixel size of 75 μm about 70% of all events will be split events and 30% are contained within one pixel. Under those conditions, the measurement precision will be always better than 40 μm, but for most of the cases better than
Fig. 45. Improvement of the position precision as a function of the gaussian spreading of the electron charge cloud. The typical sigma of the gaussian (“sg”) electron distribution is 7 µm. The assumed pixel size is 50 µm.

20 µm (see also Fig. 46). Those values may be changed by (a) the temperature, (b) by the pixel layout and (c) by the operating voltages. The relatively weak photon energy dependance of the position precision is neglected for this estimation.

A theoretical and experimental study on the position resolution using the charge spreading technique and their impact on energy resolution must be considered. But it seems reasonable that a pixel size of 75–100 µm is adequate for the anticipated angular resolution and focal length. This pixel size can even handle the expected FWHM of the point spread function below 1 arcsec. Tests with the beam trajectory monitor for the TTF-FEL at DESY confirmed the feasibility of submicron position accuracy by centroiding the charge cloud of the incident photons [77].

Figs. 45 and 46 demonstrate the effect of charge spreading and position reconstruction of the incident photon. The X-axis indicates the position of the photon hit: At x = 0, the photon hits the pixel exactly at the boundary to the neighbouring pixel. Here the position resolution is at its optimum. As the physical situation is symmetrical with respect to the centre of the pixel, the X-axis ends at half the pixel size. On the ordinate we plotted the position resolution (rms). The parameter “sg” (sigma of the gaussian) scales the lateral signal spread before arriving in the pixel well. The upper curve indicates a sg = 3 µm and increases to sg = 13 µm at the bottom. For a 500 µm thick detector the typical “sg” is between 7 and 9 µm.

The improvement of the position resolution because of the extension of the electron charge cloud is equally true for the pn-CCD detector.
5.2.6. Count rate capabilities

As the count rate capabilities of the WFI are of major importance to the overall performance of the XEUS mission, the flux losses and pile-up behaviour are treated in more detail. The calculations shown below are based on the models of Ballet [78] and Popp, taking into account a point spread function similar to XMM with an angular resolution of 3 arcsec.

With preliminary parameters describing the envisaged telescope performance, it is possible to simulate the effect of pile-up for the CCD as focal plane instrument. Pile-up is the effect of changing either a pattern type and/or the energy information of an photon event due to the occasional hitting of adjacent (or the same) pixel by more than one photon in a readout cycle.

Two parameters should be considered in this context (for single events): First, the flux loss describes the portion of photons that are absorbed in the detector as single events, but, due to a second hit in an adjacent pixel, are either discarded or recognized as another pattern type. Secondly, the pileup fraction is the portion of photons, that are recognized as singles but carry wrong spectral information, because two (or more) singles hit the same pixel in the same readout cycle.

For the case of the DEPFET detector together with the XEUS – telescope (see Fig. 47), one finds that for a rate of one photon per readout cycle (1000 photons per frame and half-energy width (HEW)), only 6% of the incident flux is lost, and the contamination of the spectrum is about 0.1 % (1000 photons per second correspond roughly to a source of 5 mCrab for the phase 1 telescope configuration). A telescope with 1 arcsec HEW, together with a focal length of 50 m is assumed, corresponding to $3 \times 3$ pixels on the CCD with a pixel size of $75 \times 75 \mu m^2$.

Note that the flux loss is a scalar correction factor that can be rather easily handled, while the more complicated case of spectral contamination is more than an order of magnitude smaller.

In Fig. 47, a comparison of cuts through the centre of simulated point spread functions is shown for different rates of incident photons. For 0.01 photons per frame, the point spread function is not disturbed. At a rate of 1 photon per frame, the difference is clearly visible. For 20 photons per frame and more, the maximum at the centre of the psf vanishes. Fig. 48 shows how the pile-up and the flux loss develops as a function of the incident photon flux.

5.2.7. Quantum efficiency

As the XEUS mission intends to achieve high sensitivity from the very low energies (around 50 eV) up to 30 keV the detector entrance window as well as the sensitive thickness must be optimized.
The practical thickness of such a detector is limited to 500 μm because the Compton background of the spacecraft increases with detector thickness. On the low-energy side the studies on ⟨100⟩ oriented silicon will continue, in order to improve the spectroscopic response down to 50 eV. The limiting quantity for the low energy response is clearly the optical blocking filters. As a baseline we propose a 100 Å thick monolithically integrated Al filter on the radiation entrance side.

For X-rays in the range of 0.1 up to 30 keV the response is shown in Fig. 29. As the silicon has the same thickness and a similar radiation entrance window, the quantum efficiency should not differ.

5.3. Pixel matrix system

According to the present experience a monolithic focal plane up to 8 arcmin seem to be possible. But all estimations for the XEUS design are based on a 5 arcmin field of view (FOV).

5.3.1. Focal plane layout and mechanics

Fig. 49 shows the schematic layout of the focal plane. The central part is the pixel matrix chip. It is logically divided into 16 sections according to the control and readout scheme (see below). However, its internal design remains completely uniform. Around the sensitive area the readout (upper and lower sides) and control (left and right sides) chips are placed.

The pixel size is 75 × 75 μm². The matrix consists of 1024 × 1024 pixels resulting in a sensitive area of 76.8 × 76.8 mm. The exposed area assuming a FOV of 5 arcmin and a resulting diameter of 72.7 mm is totally covered by the detector's geometry.

5.3.2. Electronic control and analog readout

The pixel matrix system is divided into two identical subunits (upper and lower), each having their independent control and analog readout electronics. The following description refers to one such
unit. All actions mentioned may happen in both subunits simultaneously.

The pixel matrix needs a control scheme to selectively activate a row of pixels for readout or reset. These units are placed along the left and right sides of the matrix in Fig. 49. From the left side one (horizontal) row of pixels is selected for readout. This is achieved by applying an appropriate gate voltage to all pixels of this row, which switches on the transistor currents. From the other side a clear pulse can be sent to a selected row. The control chips are identical, however a dedicated voltage supply and timing scheme has to account for either clearing or selection for readout.

Each column (512 pixels) of a subunit is fed into one channel of a multiplexing pre-amplifier chip. This ASIC has 128 inputs and one output. A subunit is such subdivided in 8 readout units of 128 × 512 pixels each.

The analog readout is done in four steps:
1. current to voltage conversion and amplification,
2. multi-correlated sampling/filtering with offset subtraction,
3. storage of the amplified analog signals in sample&hold stages,
4. output of these signals.

The first three steps are done for \( n \times 128 \) pixels (channels) in parallel, \( n \) being the number of amplifiers readout (1–8). In step four the signals are sequentially fed output into ADCs (1 ADC per readout unit).

5.3.3. Readout modes

The readout has a high flexibility originating from:

- its non-destructive character,
- a random access to single rows and columns (channels),
- independent and parallel readout of subunits and readout units.

Depending on the scientific goal of an observation different readout modes can be selected, e.g.:

1. **full frame readout**: search for regions of interest (regions of interest (ROI), can have an arbitrary shape),
2. **masked full frame readout**: after ROIs have been defined, all other pixels are either suppressed or readout at much lower frequency,
3. **timing mode**: a selected image region is read out at highest possible frequency,
4. **mixed mode**: different readout modes can be applied to dedicated image regions.

5.3.4. Power consumption

An active pixel (i.e. a pixel selected for readout) delivers a current of typically 200 µA into 5 V. At maximum, \( 2 \times 1024 \) pixels can be simultaneously active resulting in a power consumption of about 2 W for the pixel matrix. Amplifier/multiplexer chips consume about \( 18 \times 1 \) W, clear and readout selectors about \( 2 \times 1 \) W. Total power dissipation in the focal plane adds up to about 20 W.

5.4. The repetitive non-destructive readout (RNDR)

In cases the count rates do not exceed the pile-up limit and/or the area of interest is restricted to a smaller window, e.g. \( 2 \times 2 \) cm\(^2\) the same signal charge can be read out several times. The field of interest for RNDR in the focal plane can be chosen relatively free, leaving the rest of the detector in its conventional readout mode.

Because the electrons are confined in the electric field below the sensing gate of the DEPFET amplifier (floating gate amplifier) and are not mixed with other charges, the measurement of the amount of signal charges can be repeated as often as required. The noise as shown in Eq. (3) can be reduced by

\[
ENC(n) = ENC \times \sqrt{n} \tag{6}
\]

where \( n \) is the number of readings of the signal charges and ENC, the noise of a single reading. We expect a single read noise of the DEPFET structure of \( 4e^- \) at \(-50^\circ\)C with a shaping time of 1 µs. After the single reading, the signal charge is transferred to the neighbouring DEPMOS or DEPFET cell. The charge is read out again and compared to the previous reading. Repeating that procedure 16 times, spending 16 µs for the reading of two pixels (see Fig. 50), we could achieve a single-electron noise floor, corresponding to an energy resolution of less than 10 eV (FWHM). This would allow to
Fig. 50. Two adjacent DEPFET devices are able to transfer the signal charges from one floating gate amplifier to the neighbouring one, reading the same signal charges several times. The read noise is reduced by the square root of $n$, where $n$ is the number of readings.

expand the usable X-ray bandwidth down to 50 eV. Simulations and a design for a DEPMOS non-destructive readout device was recently proposed [79] and is being fabricated. Due to the strong three-dimensional character of the RNDR DEPMOS pixels, we started to make 3D device simulation in collaboration with the Weierstrass Institute for Applied Analysis [80].

As the areas which make use of the non-destructive readout can be selected during operation, we can imagine to run the detector slowly in areas where sources have been detected and fast (without RNDR) where it is not required.

5.5. Status of development

The DEPFET detector is in an early development stage. Prototypes have been fabricated and proven all functional principles. While for the DEPFET arrays basic device physics research is still needed, the pn-CCD frame store concept mainly requires technological research.

The main issues on the device physics level are:

1. Design optimization, e.g. complete clearing of charges, noise filtering in multiple reading mode.
2. Reduction of power dissipation.
3. Data reduction techniques after the ADC.

In a first step matrices of $64 \times 64$ pixels with a pixel size of $50 \mu m$ will be studied. On the device level all further areas of development can be outlined on the basis of the experimental results.

The problems of interconnections and cooling must be solved in a sound way: As the spacing between the readout channels shrinks by a factor of two, wedge bonding does not seem to be fully adequate. Some preliminary tests on bump bonding techniques have already been carried out in collaboration with other institutes. Cooling may require thermoelectric systems and passive radiators. About 2 W of power must be taken out from the focal plane and about 20 W from the front-end electronics closely coupled to the focal plane.

5.6. Frame store pn-CCDs for XEUS

As in conventional CCDs, pn-CCDs equally can be designed in a frame store format. The area to be processed in a quasidefect free manner increases by the size of the store area. A $7 \times 7$ cm$^2$ large image area can be realized monolithically on a 6 in wafer (see Fig. 51). If pn-CCDs should be used also for the $14 \times 14$ cm$^2$ focal plane a possible extension of the focal plane camera is shown in Fig. 52. By that technique the whole field of view could be covered with a minimum of insensitive gaps in between the buttened devices. The central part, the inner diameter of 7 cm, would be homogeneously sensitive.

The major change in concept besides the smaller pixel size is the dramatic increase in frame rate because of the modified readout philosophy: By doubling the processed area and dividing it in an image and store section we will get towards the required readout speed for the large collecting area...
Fig. 51. Example for a pn-CCD operated in a frame store mode. The imaging area may have a pixel size of 50 × 50 µm² or as shown 75 × 75 µm² and the store area of 75 × 50 µm².

of the XEUS mirrors. As will be shown later, we expect to get a frame rate of the whole camera of 200/s. That will lead us to a count rate capability of more than 200 counts/s and half energy width.

As the pixel size shrinks, the number of read nodes and transfers increases. At the same time, the system will be requiring more readout time and being more sensitive to radiation damage due to the higher number of transfers. If spreading of signal charges over more than one pixel is needed for the improvement of position resolution (see Figs. 45 and 46), the effective read noise per event will be higher by a factor \( \sqrt{n} \) (\( n \) is the number of pixels involved). The readout noise of every pixel involved must be quadratically added to get the total noise for one photon event. To maintain the high readout speed of the pn-CCD EPIC-XMM system, the signal processing must be speeded up by a factor of two. The solution of the above “constraints” seems to be realistic, but must be proven experimentally.

To date, the signals of one row (64 pixels) are processed in parallel in 23 µs. The extension to 128 channels on the CAMEX amplifiers, to match the new pixel pitch, was already realized for applications in high-energy physics, but it would involve a redesign of the CAMEX64B for the low noise operation. In addition the signal process time must be shortened by a factor of two. The increased readout speed will certainly have an impact on the power consumption which is actually below 1 W for the 36 cm² array.

If 128 channels are read out with 12.8 MHz, 10 µs would be required for the parallel readout of one pixel line. For the parallel transfer from the image to the storage area 100 ns are needed for one transfer. A device of 1000 × 1000 pixels would be divided (as in the XMM-EPIC case) in two identical halves of the image area, i.e. 500 × 1000 pixels each. For the parallel 500 shifts 50 µs would be needed for the transfer from the image to the insensitive storage area. The readout time for the storage area while integrating X-rays in the image part, would then be 500 × 10 µs = 5 ms. That means, within 5 ms the whole focal plane would be read out. The out-of-time probability for the X-ray events will then be 1 : 100. In this operation mode 200 image frames can be taken in one second with a full frame time resolution of 5 ms.

According to the progress of the development for both detector systems – pn-CCDs and APS – a
decision about the final choice has to be taken at a later stage.

6. Conclusion

Since the invention of the silicon drift detector a large variety of new detector structures basing on the principle of sideward depletion were developed. Those detectors have left their initial fields of applications in high-energy physics, astrophysics and synchrotron radiation research. They are now a mature technology and open many new industrial applications. Experiments in basic research have driven the performance parameters towards the optimum for the specic applications: High quantum efficiency, excellent energy resolution, high radiation tolerance, good position resolution, high speed, large and almost defect free devices, homogeneous response of the full bandwidth of radiation and high background rejection efficiency. It will be the aim of future developments to approach the physical limits in radiation detection and to breathe in additional intelligence into the local detector systems to face the steadily increasing amount of data and power dissipation.

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References