The development and use of the pnCCDs for science and industry

(Recollections of Lothar Strüder about the development of pnCCDs for the XMM – Newton mission)

1. Start of the pnCCD development in 1984
   It all started in 1983/1984 when Emilio Gatti and Pavel Rehak presented the Sideward Depletion principle and the Silicon Drift detector. The theoretical possibility to use the principle of lateral depletion for a new type of CCD was already mentioned in the first paper of Gatti and Rehak in a few lines. On this basis Gerhard Lutz from the MPI für Physik (MPI) (my PhD supervisor) offered me a PhD position to develop a pnCCD as a tracking detector for experiments in high energy physics experiments. But it soon became clear that charge transfer devices where too slow to keep track with the steadily increasing repetition rates of the future HEP colliders. In 1986 Joachim Trümper, director at the Max-Planck-Institut für extraterrestrische Physik in Garching heard about the work of Lothar Strüder (LS) and decided to propose the pnCCDs for the European XMM-Newton X-ray mission which just became a cornerstone mission in ESA´s space science program. Heinrich Bräuninger and Claus Reppin – both group leaders at the Max-Planck-Institut für extraterrestrische Physik (MPE) in Joachim Trümpers division visited Gerard Lutz and me at the MPI für Physik (MPI) and outlined a possible collaboration. In 1987 I moved from the MPI for physics to the MPE to start the development of the pnCCDs for X-ray astronomy.

2. Building up a semiconductor laboratory
   a. Start at TUM
      In 1984 was the moment when Josef Kemmer who developed the pn-junction process technology started to move from the TU Munich to the MBB company – now integrated in the AIRBUS cooperation. The very first pnCCD devices were still fabricated in the old clean room facilities at the TUM where Josef was affiliated to and the Physics department allowed him to continue to use the old clean room. In 1988 the first operational pnCCD devices were in our hands: The number of pixels was small; the noise was high and the signal charge transfer was moderate. But those first devices showed me the way how to proceed in future designs and fabrications. We needed to persuade the company WACKER, the supplier of the high resistivity silicon wafers to modify their production process and to fabricate on top of the high resistivity wafers another lower resistivity epitaxial layer where the charge transfer of the signal charges was supposed to occur. This needed top level discussions - including MPE director J. Trümper – because WACKER was not willing to develop that very special silicon growth process. Finally, WACKER decided as a compromise to deliver the epitaxial silicon from their research team on the basis of best effort. The second generation of pnCCDs was still

fabricated at the TUM – never at MBB. By the end of 1988/1989 Josef decided to leave MBB and to found his own company KETEK.

b. Move to Munich-Pasing and the fabrication of the XMM pnCCDs
   In 1990, after a long struggle with the Max-Planck Society Joachim Trümper got the approval to start negotiations with the Fraunhofer Society who owned a clean room in Munich Pasing. The Fraunhofer-Institut für Festkörpertechnologie wanted to move to their new facilities in the Hansastrasse in Munich. The vision of an MPI owned and operated cleanroom facility to develop their own scientific instruments was a joint effort of the MPI for Physics and the MPE. As MPE had the stronger scientific case and resources Joachim Trümper was leading this process. In 1992 operation started in Munich-Pasing. A contract between MPI and MPE was established to define the modes of operations. The facility was called: MPI-HLL, the semiconductor laboratory of the Max-Planck-Institutes for Physics and extraterrestrial Physics. All devices for the XMM mission were fabricated in Munich-Pasing. The core people associated with the development and qualification of the pnCCD camera were: Dr. Heike Soltau (technology development and control, scientific data analysis, qualification and sensor selection), Peter Holl (design, layout, simulation, SAQ and online software), Robert Hartmann (operation, qualification, calibration, thin windows), Christoph von Zanthier (test), Norbert Meidinger (test of radiation damage, camera testing) and many others including the author LS, Gerhard Lutz and J. Kemmer.
   From my personal point of view this was a very challenging time for all of us as we promised to Joachim Trümper to deliver for XMM the world’s largest and most sensitive X-ray CCD camera ever built. We have to admit that at this time we were newcomers in the field of CCD sensor fabrication with non-standard designs, non-standard process technologies and non-standard operations. As a lot of effort and resources were spent to establish a new semiconductor laboratory – we were not allowed to fail. We needed over all 5 fabrication process iterations in 7 years’ time to come to the final design and to the final device. The results were extraordinarily convincing. The world´s largest X-ray CCD, with unprecedented sensitivity, extreme radiation hardness and very high readout speed at low noise was leaving the semiconductor laboratory in 1997 for further integration in the XMM pn-camera and satellite environment.

c. Move to the SIEMENS campus
   In 2000/2001 the MPI semiconductor laboratory moved to the research campus of SIEMENS in Munich – Neuperlach. This happened one year after the successful launch of XMM-Newton. The sensors for eROSITA, SVOM and the prototypes for ATHENA were all fabricated here.

3. Building a pnCCD camera
   When the pnCCD sensor chips were successfully fabricated and tested in a newly developed

cold chuck probe station we thought: we finally succeeded, now we reached our goal. That was by far not the case. The assembly of the camera head, the integration into the space craft environment and the numerous qualification steps and end-to-end tests were revealing a lot of unpleasant discoveries as you will see later.

The camera head was subdivided in 3 building blocks: (1) the pnCCD chip, (2) the CAMEX ASIC (Application Specific Integrated Circuit) and the PC board housing the pnCCD the ASIC and the filter components of the supply voltages.

a. pnCCD chip development (see above)
   Nobody from outside believed that we would be able to fabricate a high speed, low noise, highly efficient, homogeneously sensitive X-ray sensor covering the full surface of a 100 mm high purity Silicon wafer – except us ! The team spirit of the pnCCD sensor team was outstanding. Most of the main players during that period are still working together today.
   During this period Horst Hippmann and his team built and tested the camera electronics supported by Norbert Meidinger and Elmar Pfeffermann for testing.

b. ASIC development
   For the very first time a CCD with a fully parallel readout of all pixel columns was invented and realized right away in 1989. The ASIC development in the 80' ies was carried out in collaboration with the engineering office of Werner Buttler. The coupling of every individual CCD column with one readout node was conceptually and technologically a breakthrough. LS laid out the concept for the pnCCD analog signal processor system, Gerhard Lutz invented the analog signal shaping scheme of multi-correlated double sampling and Werner Buttler translated it in a CMOS chip. This was an essential and crucial component for the pnCCD camera concept. The ASICs were radiation hard, low power, fast and low noise devices especially adapted to the on-chip JFET amplifier of the pnCCD. The ASIC was fabricated at the Fraunhofer IMS in Duisburg.

c. Radiation hardness
   The radiation damage tests were mainly performed by Norbert Meidinger. That topic became the core theme in his thesis. It is astonishing how precisely he predicted the degradation of the charge transfer efficiency and hence the degradation of energy resolution due to the generation of defects in the silicon lattice by ionizing radiation. In contrast, after the first 5 revolutions of CHANDRA in orbit the energy resolution of the front-illuminated MOSCCDs degraded to that of gas proportional counters. Radiation damage moved into the center of the discussions in the months before the XMM launch.

   d. PANTER, BESSY-PTB testing
      Extensive testing of the pnCCD flight camera was performed to study the homogeneity of response to X-ray radiation. This was mainly done at the PANTER Test facility under the leadership of Heinrich Bräuninger and his collaborators Wolfgang Burkert and Gisela Hartner. Many nights – even in the Christmas period – were spend for these long-standing measurements where all aspects of the X-ray mirror and camera system were analyzed.
      The absolute calibration was done at Bessy I – the very last operation of BESSY I in Berlin Wilmersdorf before it was shut down. The XMM calibration team was grateful to the last BESSY I director Wolfgang Gudat who gave us the permission in a very non-bureaucratic way to operate BESSY I two days longer than originally planned. The data were analyzed under the leadership of Ulrich Briel and put together in a detector response matrix by Konrad Dennerl.

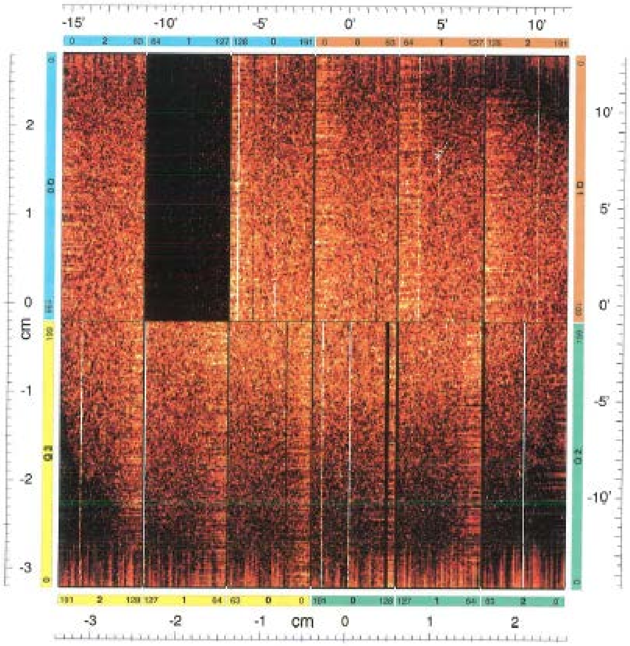
4. pnCCD crises

   a. bond crisis
      When the first vibrational and shaking tests were performed with the full pnCCD focal plane the majority of the 1.000 bond wires connecting the output of the on-chip JFET and the CAMEX input on the PC board were broken. It took a long time until we verified and tested that the coating of the bond feet on the CCD chip with a dedicated epoxy resin was solving the "bond crisis". The focal plane had to undergo various thermal-vacuum tests, pull, vibrational, shaking and electrical tests. At the very end it worked out due to the strong support of Pavel Solc, Mr. Bond, from the MPI for Physics.

   b. delamination crisis
      When the first tests with a fully functional XMM focal plane was subject to the final thermal tests going to the extremes from -140 C to room temperature we found that the electrical behaviour of the camera head was strange and not understood. A part of the camera was working poorly, the rest not at all. When we opened the camera head, we did not trust our eyes: The focal plane printed circuit board with more than ten different electrical layers was delaminating. That means that the different layers were not longer attached to each other but separated. Interconnections were interrupted, bond wires were disconnected and the required absolutely flat surface for the wafer mounting had ripples. We reported this non-conformance behaviour to Robert Lainé, (ESAs XMM project manager). He immediately offered ESAs laboratories to analyze the problem. It was found out that the glue between the PCB layers had a "glass point or glass transition" of approximately – 105 C. That is the temperature were a material makes a transition from a state of elastic deformation to a hard and relatively brittle "glassy" state. The different thermal expansion coefficients of the used materials could

not be "accommodated" at temperatures below the glass point: the PC board destroyed itself while cooling it below the glass point.
The ESA labs found out that the operation at temperatures above – 90 C is safe for the PCB. This exercise and its repair took us several months. Up to now – 20 years later – no misbehavior of the focal plane occurred. We observed stable operation conditions up to now.

c. contamination crisis
During our last tests at the synchrotron LURE next to Paris we noticed that one of the 12 monolithic chips had a problem. A bright spot was appearing in one of the upper CCDs (see figure). The brightness of the spot could be mitigated at the expense of worsening the performance of the 3 other CCDs in one quadrant of the focal plane. After a long series of tests, we identified the origin of this defect: An electrically conductive particle attached between two shift registers of the CCD lead to this short circuit. The area was heated due to the current flowing between the registers (reason for the bright spot) and the nominal voltages of the shift registers to transfer the signal charges to the read node could not be applied any more due to the large current. We tried to remove the particle but we were not successful. This was the camera foreseen for the mission – the flight camera. It has passed all other tests and was very well understood. What a pity to pick up a conductive particle in the sensitive part of the pnCCD sensor – just before delivering the camera to ESA.



The 12 CCDs were arranged in two rows, 6 each, with a size of 3 x 1 cm^2, monolithically integrated on one wafer. In the upper row one unit of 3 x 1 cm^2 was missing. This

camera was called (internally): Missing tooth camera.

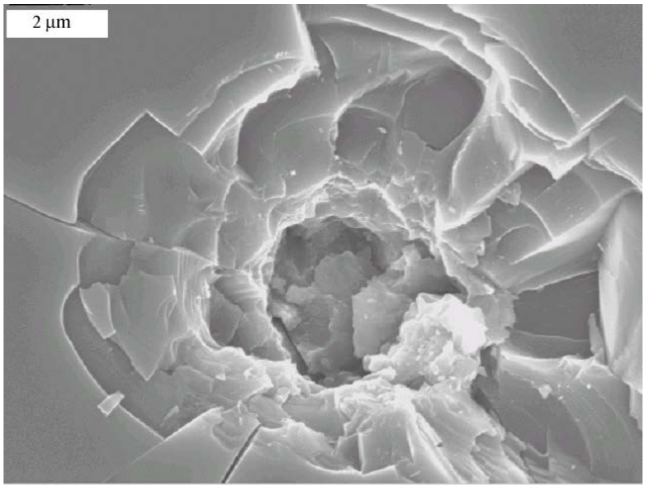
5. Hard decision in Kourou
   When we arrived in Kourou we had two qualified cameras with us: the missing tooth camera and the flight spare camera. The flight spare camera did not have any bright spots, insensitive areas and so forth. Its only disadvantage was that it showed an electrical problem when the detector was not cooled: a bad electrical contact to one of the guard ring structures was causing a feeling of uneasiness. This was something which was not fully understood and therefore the speculations about the reasons of that behaviour was not a sound basis for a decision. Except this strange behaviour at warm temperatures the camera was perfect. But whenever the camera was cooled below -10 C it was working perfectly. Which camera to fly ? But in flight the operating temperature was – 90° C ! So Robert Lainé asked me to come to Kourou to make a final test and a final decision. The test of the flight spare camera went smoothly and reproducible so I decided to fly the flight spare camera. This decision was not supported by all of my colleagues who had preferred to fly a well understood camera with a "missing tooth". At the end as we know now the flight spare camera has performed very well for the first 20 years in orbit. There is no reason why that should change in the future.

   Chandra damage – a few days after launch

   The American CHANDRA mission was launched 5 months ahead of XMM. When they opened the telescope door the first time, they discovered a tremendous radiation damage after the first revolutions in space. It turned out that this was due to low energy proton damage. The very good performance figures measured on ground were degraded by a factor of 2-3. This was raising the question: Would this radiation damage affect the EPIC cameras aboard XMM as well without any precautions? The answer was Yes for the MOSCCDs aboard XMM and No for the pnCCDs.

6. Micrometeorite impact
   During orbit 156 and revolution 157 we observed a sudden increase of leakage current in about 40 pixels out of 160.000 pixels. Simultaneous damage occurred in the MOSCCD cameras. It was concluded from those events that a shower of micrometeorites, i.e. clusters of atoms of a size of a µm were "imaged" through the X-ray mirrors on the EPIC instrument and the reflective grating spectrometers. About 40 pixels became "bright pixel" in the pnCCD camera meaning that they were filled with thermally generated current due to the mechanical damage. We immediately contacted the MPI for Nuclear Physics in Heidelberg to perform damage experiments with the "dust accelerator" of Eberhard Grün. In our experiments we could show that the damage on XMM Newton showed exactly the same characteristics as the submicron sized iron particles in the dust accelerator. After having understood the damage mechanism we

switched off the bright pixels to not overload the telemetry of XMM. Up to now the operation and handling of the bright pixels of the pnCCD camera, caused by the micrometeorite damage is stable.



7. The use of pnCCDs in basic, applied science and industry

   After the successful launch of XMM-Newton a growing interest in the pnCCD sensors and systems emerged: from scientific groups as well as from industry.

   In 2002 Heike Soltau founded the company PNSensor with co-founders from the Max-Planck Society and company employees. In 2007 she founded the company PNDetector altogether today with approximately 80 employees.

   In the following I will list some of the most exciting pnCCD applications. This list is by far not complete.

   a. In science
      i. eROSITA, SVOM, (ABRIXAS, failed after launch)

         In X-ray astronomy a variety of mission proposals included the pnCCD as a spectroscopic X-ray imager. eROSITA and SVOM were finally selected for flight. eROSITA was launched in July 2019 from Baikonur and delivered already the first brilliant X-ray images and spectra. SVOM is supposed to be launched in 2022. pnCCDs have also been installed as wave front sensors at the Large Binocular Telescope (LBT) in the adaptive optics system ARGOS.

      ii. LCLS, FLASH, XFEL, SACLA

         Especially for the new upcoming X-ray Free Electron Lasers the pnCCD system seemed to be the ideal detectors system. First measurements were performed at the UV and soft X-ray facility FLASH on the DESY campus in Hamburg, followed by the first light at the Linac Coherent Light Source (LCLS) at SLAC in Menlo Park at higher X-ray energies, at SACLA in Hyogo, Japan and finally the European X-FEL in Schenefeld in the vicinity of Hamburg. About 30 scientific papers were published in the early years from 2009 to 2013 in top ranked journals like *nature, science* and others.

    iii. BESSY, ESRF, ANKA, DIAMOND, …
    The pnCCDs have been used for experiments at synchrotron radiation facilities all over the world in many different beamlines. New analysis methods have been developed e.g. the energy dispersive Laue diffraction (EDLD), X-ray ptychography ...
    The coupling of the pnCCD to a columnar CsI(Ti) scintillator expanded the usable energy range up to 150 keV – ideal for the analysis of high Z-material science.

    iv. Strong lab sources
    Equally in laboratories with strong X-ray sources pnCCDs are used for solid state analysis and the study of biological samples as for example at the BAM (Bundesanstalt für Materialprüfung), PTB (Physikalisch-Technische Bundesanstalt) and BOKU (Universität für Bodenkultur) and others.

b. In industry
In industry pnCCDs are integrated in larger measurement tools for the direct detection of X-rays and electrons.
One prominent example is the use of the pnCCD as a high-speed electron imager in scanning transmission electron microscopes (STEMs). In this field they have paved the way for new image reconstruction methods like electron ptychography.