X- and Gamma Ray Imaging Systems based on CdTe-CMOS Detector Technology

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Abstract*–Both charge integrating and single photon identifying X- and gamma ray imaging devices constructed of CdTe pixel detectors bump bonded to CMOS ASICs have been developed, tested and utilized in a variety of applications. The charge integrating devices apply either frame mode or time delayed integration (TDI) signal readout schemes on the CMOS pixels depending on the requirements of the application. Frame mode readout is applied in real time and tomographic imaging as well as in low speed scanning, and TDI readout in high speed (up to 50 cm/s) industrial on-line scan imaging. The small pixel size of 100 µm of the charge integrating sensors combined with the high absorption efficiency of CdTe, optimized CMOS readout circuitry and real time calibration result in exquisite performance (high DQE) throughout a wide X-ray energy window (10 – 300 keV) and superb image quality very close to the theoretical ideal. Additionally, these sensor systems exhibit good stability over time and negligible afterglow. System level descriptions of various customized X-ray imagers are presented including up to 30 cm long scanning multiple line TDI cameras and small field of view real time area cameras which can be custom made to desired shapes of active area. Example images acquired in several different applications are shown. The unique photon identifying device (PID) comprises eight CdTe-CMOS hybrids each having 2048 pixels with a pitch of 350 µm. Every pixel accommodates a charge sensitive preamp followed by peak/hold, comparator and user selectable ADC/counter circuitry. The PID hybrids can be operated in several functional modes providing photon counting and energy dispersive imaging and timing measurements. 8 bit pixel amplifier offset and gain tuning yields a full field energy resolution close to the single pixel resolution which is measured to be 7 keV FWHM for the Am-241 main peak (60 keV). The PID system description is presented together with energy selective X- and gamma ray images and energy spectra of Am-241 and Co-57 sources. The PID is to be utilized in gamma imaging, X-ray back scatter imaging, energy selective photon counting X-ray imaging, X-ray diffraction experiments etc.

I. Introduction

THE development of X- and gamma ray imaging devices based on CdTe semiconductor detectors and CMOS electronics is motivated by the high photo electric attenuation coefficient of CdTe and by the advanced level of CMOS technology. CMOS circuitry enables high speed and low noise signal acquisition either in the charge integration or in the photon counting mode in a variety of readout configurations such as frame or time delayed integration (TDI) or sparse readout.

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The method of direct conversion of radiation energy to signal charge has the potential of a very sharp line spread function (LSF) limited only by the pixel size. A sharp LSF together with the high absorption efficiency of CdTe and low noise readout circuitry yields a high detective quantum efficiency (DQE) which ultimately describes the performance of an imaging system. We have demonstrated [1] that quantum limited performance is indeed possible with CdTe-CMOS imaging devices.

In combination with a bump bonded CMOS ASIC a CdTe pixel detector becomes an imaging sensor with separated signal detection and signal readout elements. This makes it possible to read out image frames during signal collection and eliminates any dead time between subsequent image frames. Hence, as long as the radiation intensity does not exceed the single frame signal integration capacity, the dynamic range is in principle unlimited. Since the X-rays are converted to charge in the CdTe crystal no conversion elements are needed on the ASIC pixels resulting in a fill factor of 100 % regardless of the pixel size.

In order to benefit fully from the obvious potential of CdTe-CMOS technology one needs to overcome some rather demanding engineering challenges. These include the growth of uniform low dark current CdTe crystals, the deposition of electrically isolated thin film pixel electrodes, reliable bump bond connections, real time calibration algorithms to compensate for time and temperature dependent signal response variations and tiling techniques to build larger imaging areas. So far we have relied on p-type CdTe crystals produced by Acrorad Co., Ltd. For the charge integrating sensors In-CdTe-Pt detectors operated in the hole collection mode have been found most suitable. In photon counting sensors Pt-CdTe-Pt detectors are used in the electron collection mode. Material from other suppliers has also been tested recently with promising results. High surface resistivity is maintained by AlN passivation between the pixel electrodes. An in-house low temperature Sn-Bi bumping and bump bonding process has been developed for high yield and reliable interconnections between the CdTe detectors and CMOS pixel circuits. Nonlinear real time calibration algorithms have been developed to take into account also the time dependent crystal polarisation.

In this work we introduce highly advanced CdTe-CMOS imaging systems some of which are already routinely produced and used in real world applications.

II. ACHIEVEMENTS IN CdTe-CMOS IMAGING TECHNOLOGY

A. *Small Field of View Real Time X-ray Cameras*

The structure and performance of the basic Ajat small field of view real time CdTe-CMOS X-ray camera have been presented in [1]. The Ajat real time X-ray camera applies charge integration signal collection and frame mode readout with 100 µm pixel pitch. The maximum readout speed is 50 fps. The active imaging area is constructed of several 2.5 cm x 2.5 cm large CdTe pixel detectors each bump bonded to two CMOS ASICs. Various shapes of the approximately 25 cm^2 imaging area are possible as a combination of the CdTe-CMOS hybrids. An example is shown in Fig. 1. In addition to the nonlinear real time calibration routine a short high voltage cut is applied every 30 s to refresh the polarised crystal.

Fig. 1. A photograph of a small field of view CdTe-CMOS X-ray imager with a hole in the center of the active area.

The camera of Fig.1 is used in nondestructive testing of heat exchanger welds by the German Federal Institute for Materials Research and Testing (BAM) [2]. The hole in the center of the imaging area is required for the X-ray tube which is pushed into the pipe to be inspected. The beam target of the X-ray tube is located as indicated by the white arrow in Fig. 1. X-rays are emitted from the target through the pipe cross sections to the CdTe-CMOS hybrids. An X-ray image acquired with the camera is shown in Fig. 2 in comparison to a film image demonstrating the contrast resolving power of the CdTe-CMOS camera

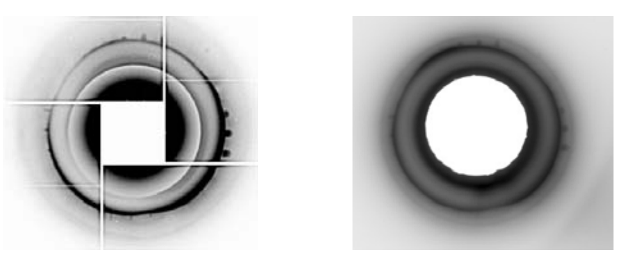

Fig. 2. Cross section X-ray images of a pipe, left: image acquired by the CdTe-CMOS camera and right: the corresponding film image [2].

Fig. 3 shows an X-ray imaging system for pipe inspection also developed by BAM. The so called TOMOCAR system utilizes an Ajat CdTe-CMOS camera and provides X-ray laminography images of welded joints of the pipe under test. Fig. 3 also shows an X-ray image of a pipe weld acquired with the TOMOCAR The image reveals undesired cracks in the joint.

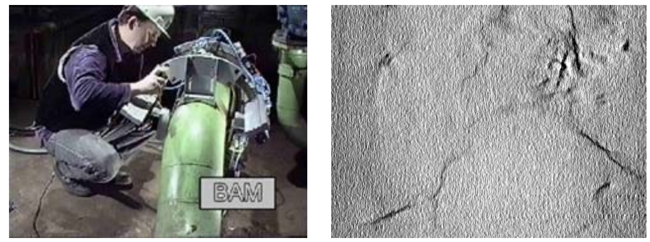

Fig. 3. The TOMOCAR imaging system by BAM (left) and an X-ray image of a welded joint acquired by the system with the Ajat CdTe-CMOS X-ray camera [2].

B. *Frame mode X-ray scanners*

The structure and operational principle of the Ajat frame mode X-ray scanners are similar to those of the small field of view X-ray cameras. The CdTe-CMOS hybrids are arranged in a slot configuration of desired length as shown in Fig. 4.

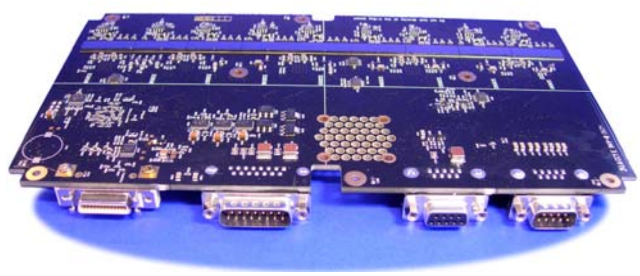

Fig. 4. An Ajat frame mode CdTe-CMOS X-ray scanner. The scanning slot has 9 hybrids giving a total slot length of 22.7 cm.

With one readout channel/hybrid the readout speed of the frame mode scanners is 300 fps. With the 100 µm pixel size the maximum scan speed is then 3 cm/s.

Currently the main application of the Ajat frame mode scanners is dental panoramic X-ray imaging. Several hundreds of installations of the Ajat dental X-ray cameras are in daily use in many countries at dental clinics. In dental panoramic imaging the readout speed of the sensor (corresponding to the movement of the X-ray film in conventional analog systems) is synchronized with the rotational scan movement to acquire one projection in focus. With fast frame readout, however, it is possible to acquire enough data for reconstruction of several projections of different depths of the teeth profile. This feature is unique and is not possible with CCD imagers which have to rely on TDI readout. The image quality of properly calibrated CdTe-CMOS dental scanners is superior to technologies applying indirect conversion of X-rays. A panoramic projection image of human teeth acquired with the Ajat frame mode scanner is shown in Fig. 5.

Fig. 5. A panoramic projection of human teeth acquired at 70 kV X-ray tube power with an Ajat frame mode X-ray scanner.

C. TDI mode X-ray scanners

In many scanning applications the scan speed of the frame mode scanners is not enough. Fast scanning is possible with TDI signal readout. TDI readout is widely used in CCD scanners in which the signal charge integrated in the pixel rows is moved backwards and summed to the following row step by step with a speed equal to the scan speed. The last row eventually contains one line of image data and is read out with high speed.

Ajat CMOS TDI scanners apply the same principle of signal adding row by row as a CCD TDI sensor but use a somewhat different logic in transferring and summing the signals of the pixel rows. Each pixel of the Ajat CMOS TDI readout circuit has a signal charge integrator element and a voltage adder element. The signal integrated in one pixel can be transferred and added to any one of the voltage adders of the pixels in the same column, i.e., to a pixel of the same column belonging to a row either preceding or following it anywhere in the column. The transfer is done via an interim voltage storage element. Each column has its own interim voltage storage. An example of one readout cycle is illustrated in Fig. 6.

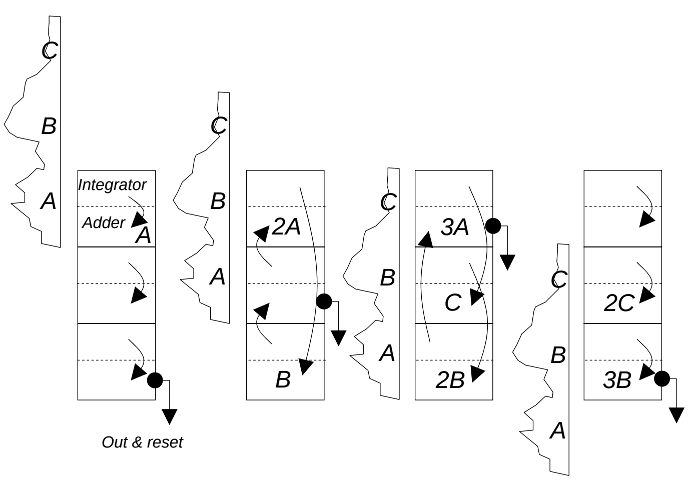

Fig. 6. Illustration of the Ajat CMOS TDI readout logic.

To understand the logic of the CMOS TDI let us consider an object scanned over one pixel column with three pixels of subsequent rows and study one readout cycle. When data from object part A has been accumulated in the integrator of the first pixel the data is transferred to the adder of the same pixel as indicated by the arrows in Fig. 6. The adder of the last pixel (which is still empty) is read out and all integrators and the adder read out are reset. The adder of the first pixel now contains data A. When the object has moved to the next position and image signals have been acquired to the pixel integrators the data is transferred from the second pixel integrator to the first adder so as to sum additional data from object part A to the first adder. Similarly data from object part B is built up in the last pixel and data from part C is stored in the second pixel. The adders are connected to the output bus and read out in sequence (unlike a CCD TDI sensor) resulting in the output data chain of 3A, 3B, 3C.

The maximum scan speed of the Ajat TDI mode scanner is 50 cm/s.

A special feature of the Ajat CMOS TDI ASIC is that each pixel integrator can also be connected to the column output bus enabling frame mode readout with the same ASIC. This feature is essential in identifying and masking faulty pixels.

Some signal loss occurs during the transfer process of data from the integrators to the adders due to the stray capacitance of the switches between the interim storage and the pixels. The imaging performance of the Ajat CdTe-CMOS TDI scanners has not yet been quantitatively analysed but it is evident that the performance is not as close to the quantum limit as that of the frame mode scanner. Nevertheless, the visual image quality is quite impressive as can be seen in Fig. 7 which shows an X-ray scan of a printed circuit board. The image was acquired with an Ajat TDI scanner (also shown in Fig. 7) at a speed of 10 cm/s. The height of the image is 30 cm.

Fig. 7. An Ajat CdTe-CMOS TDI scanner (left) and an X-ray scan of printed circuit board (right) acquired at 10 cm/s with the TDI scanner.

Another interesting example of the Ajat X-ray scanners demonstrating the excellent performance also at low X-ray energy is the quality inspection of mink furs. Fig. 8 shows an X-ray image of the head part of a mink fur acquired at 20 kV X-ray tube voltage [3] with an Ajat TDI mode scanner.

Fig. 8. An X-ray image of a mink fur acquired at 20 kV X-ray tube power with an Ajat TDI mode X-ray scanner (courtesy of Innospexion ApS, Denmark [3]).

D. *The Photon Identifying Device (PID)*

The latest achievement of the ongoing Ajat development in CdTe-CMOS imaging technology is the Photon Identifying Device (PID). It is a significant step forward from the Ajat mini gamma camera (MGC) presented in [4].

The Ajat PID ASIC comprises 32 x 64 = 2048 pixels of 350 µm pitch with a preamp followed by peak/hold, comparator and counter circuitry in each pixel. The ASIC can be operated in several different functional modes. The pixel preamps can be trimmed with 8 bit offset and gain tuning to align recorded pixel spectra for energy selective photon counting imaging (calibration mode). The peak/hold analog signals can be read out in sequence to provide full energy spectrum recording of each pixel (analog amplitude mode). Alternatively the peak/hold outputs can be connected to the comparator with either a constant user selective threshold or a linear voltage ramp threshold. The constant threshold is used in fast photon counting to discriminate noise hits (counting mode). The ramp is used for on-pixel AD conversion in which the counter is triggered simultaneously with the ramp start (digital amplitude mode). When the ramp has reached the peak/hold value the counter is stopped and the count value which is now proportional to the hit amplitude is read out. The counter can also be used as a time counter fired by a hit and stopped by an external signal (timing mode). The PID logic supports also sparse addressing for readout of single pixels or user specified areas of pixels triggered by individual events (sparse mode). The different modes can be combined in sequence to provide multiple information for detected and counted photons (timing, energy and address).

All the ASIC functionalities have been verified to be operational with probe station tests. However, in connection with a CdTe pixel detector some unexpected noise coupling was observed to deteriorate the performance of the digital amplitude mode.

The Ajat prototype PID camera shown in Fig. 9 can house 8 CdTe-CMOS hybrids forming an imaging area of 4.4 x 4.4 cm^2 with 16,384 pixels. Results of the prototype PID camera operated in the analog amplitude mode are presented below.

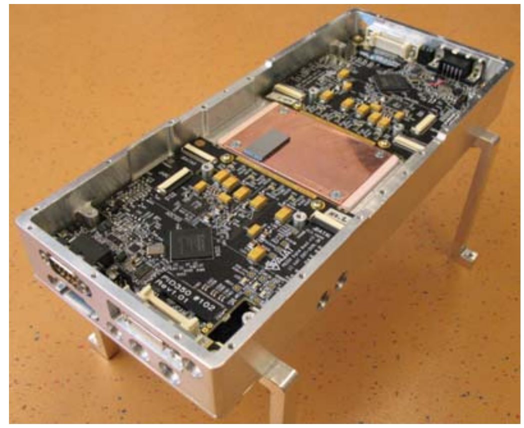

Fig. 9. The Ajat prototype PID camera. The photograph shows the camera with one CdTe-CMOS hybrid.

Fig. 10 shows energy spectra of single pixels and combined spectra of 8,192 pixels (4 hybrids). The data was acquired with a maximum frame rate of 125 fps. The average Am-241 60 keV peak FWHM is approximately 7 keV and the average Co-57 122 keV peak FWHM is 6 keV for single pixels. The peak widths of the combined spectra are only slightly worse proving that the amplifier tuning works well. The final alignment of the pixel spectra is done with software correction. The pixel amplifiers are sensitive and reasonably

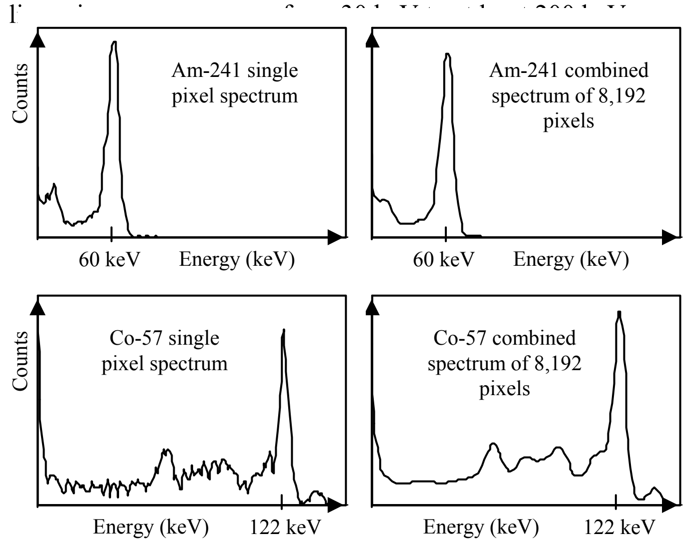

Fig. 10. Energy spectra of the PID.

The amplifier tuning and pixel alignment was also tested by measuring the image signal to noise ratio (SNR) from Am-241 flat images. The images were reconstructed with the energy threshold set at 40 keV. Although the energy resolution of the hardware calibrated camera (8 bit offset and gain tuning) in terms of FWHM of combined spectrum peaks does not improve much when applying the software correction, the final alignment has quite a significant effect on the image SNR. The image SNR of an Am-241 image is plotted in Fig. 11 as a function of image integration time. The SNR of the image reconstructed from the software corrected spectra follow the quantum SNR while the corresponding SNR of the image relying only on hardware calibration levels off at around 10. The reason for this is that even very small shifts of the pixel spectra result in considerable variation in the integrated number of counts/pixel above the threshold.

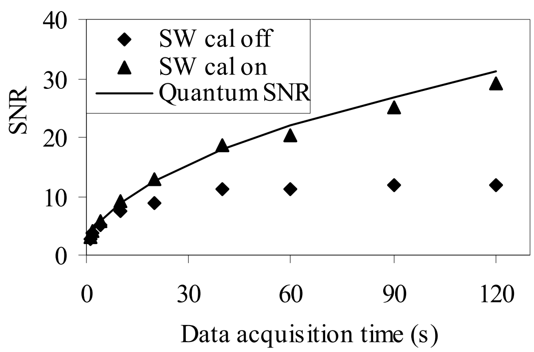

Fig. 11. The SNR of Am-241 images acquired by the PID proto camera.

An image of a standard USB connector acquired with an Am-241 source is shown in Fig. 12. The image was reconstructed with the energy threshold set at 40 keV. The pixel spectra were aligned both with hardware tuning and software correction.

Fig. 13 shows a 90 kVp X-ray image of a workshop tool acquired with the PID camera with 8 CdTe-CMOS hybrids.

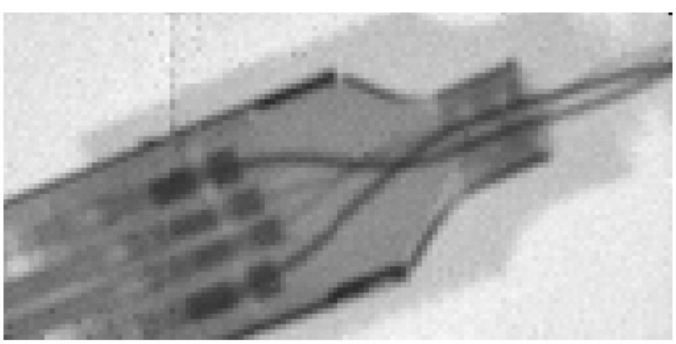

Fig. 12. An Am-241 image of a standard USB connector acquired by the PID proto camera with 4 CdTe-CMOS hybrids.

Further development work will focus on testing the remaining functional modes of the PID CdTe-CMOS hybrids and on analysing the observed noise coupling issue in the digital amplitude mode.

The PID camera will be applied to back scatter X-ray imaging, X-ray diffraction experiments, nuclear medicine etc.

Fig. 13. A 90 kVp X-ray image of a workshop tool acquired with the PID proto camera. The area of the image is 4.4 x 4.4 cm^2.

III. Summary and Conclusions

15 years of development work in CdTe-CMOS imaging technology [5] has resulted in product level small field of view real time X-ray imagers, frame and TDI mode X-ray scanners used in dental panoramic X-ray imaging and in industrial nondestructive testing and in a highly advanced multifunctional energy sensitive photon counting imaging device.

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