

Fast X-ray/ γ -ray imaging using electron multiplying CCD-based detector

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Abstract

New designs of electron multiplying charge coupled devices (EMCCDs) combine superior spatial resolution and low noise of a conventional CCD with the internal gain of an avalanche photodiode (APD). The presence of internal gain not only enhances the device sensitivity, but virtually eliminates the read noise associated with current CCDs, even when the device is read at very high frame rates of 100 frames per second or higher. Thus, the EMCCDs can simultaneously provide very high sensitivity and a high signal-to-noise ratio (SNR).

At RMD we are exploiting these properties of EMCCD for use in radionuclide and X-ray imaging. Specifically, we have developed a system that makes use of an EMCCD with 512×512 , $16 \times 16 \mu\text{m}$ pixels. Special fiberoptic reducers have been designed to enhance the detector sensitive area. The system gain is software selectable and may be varied from 1 to 1000. This paper describes the detector design along with its γ -ray/X-ray imaging performance.

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1. Introduction

Charge coupled devices (CCDs) are in common use in X-ray imaging applications such as digital dental radiography and macromolecular crystallography [1–6]. They offer very high spatial resolution, low noise, high quantum efficiency over the entire visible range, and wide dynamic range. However, the limited active imaging area and read noise associated with high speed operation limit their use in applications where large active imaging area and/or high frame rates are needed. The first of the two limitations is usually addressed by means of image de-magnification using either a lens-based system or by using a fiberoptic reducer. Although significant light losses are possible due to such couplings, a suitable balance between the active imaging area and the desired signal-to-noise ratio (SNR)

for a given application can be achieved [7]. The second limitation of high frame rate readout is a direct consequence of noise associated with the on-chip output amplifier of the CCD, which increases with increase in clocking frequency. The new generation of electron multiplying CCDs (EMCCDs) is designed specifically to address this second issue [8]. Since our applications require both, large active area of $>10\text{cm} \times 10\text{cm}$ and readout rates ranging from 1 to 500 Hz, our new X-ray/ γ -ray detector is based on an EMCCD (e2V Model CCD887 BI) coupled to a fiberoptic reducer as described in this paper.

2. Background on EMCCDs

The new EMCCDs manufactured by e2v Technologies [9] work like conventional CCDs except that they provide internal gain via an avalanche mechanism. Thus, an imaging system based on the EMCCD does not require

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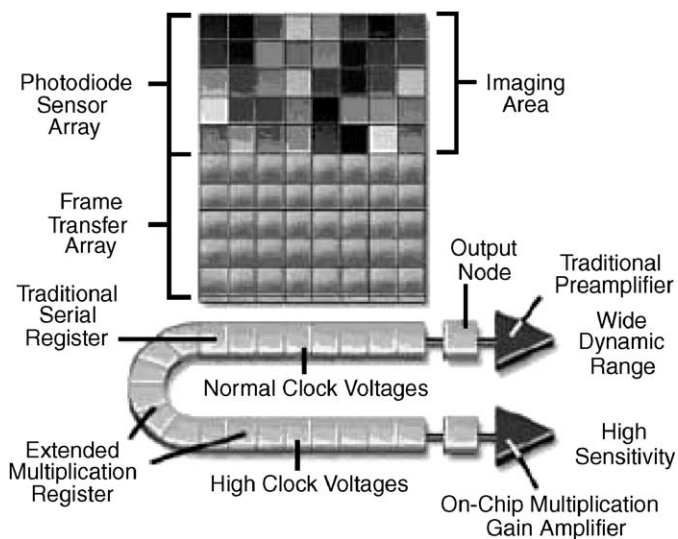


Fig. 1. Schematic of EMCCD sensor developed by e2V [9].

the use of intensification stages even though it allows detection of extremely low light levels at high frame rates. As shown in Fig. 1 [8,9] an EMCCD consists of an imaging area of active pixels and an additional area of optically shielded pixels as a frame transfer array. During conventional operation, the detector integrates the image for a specified time, and is then shifted rapidly out of the image zone and into the optically shielded frame storage zone. For the 512×512 pixel EMCCD system used in our design, the entire pixel data is read out in ~ 31 ms for a maximum speed of ~ 32 fps. Higher frame rates of up to 526 fps can be achieved by sacrificing the pixel resolution by binning or reducing the imaging area.

To facilitate internal gain serial register of the EMCCD is extended as shown in Fig. 1. Charge transfer into the gain section of the CCD structure results in avalanche multiplication and the amplitude of the applied clocking voltage determines the resulting gain, which can be varied from 1 to over 1000. Although the gain boosts the signal, for a given readout frequency, the read noise remains constant. Thus, increasing the gain effectively increases the SNR. This may be viewed as though the internal gain effectively reduces the read noise. Experimentally we have verified that for the readout rate of 10 MHz the amplifier noise is effectively eliminated if the gain is set at ~ 40 . Setting the gain beyond this point increases the SNR, but at the cost of reducing the dynamic range.

3. Choice of scintillator

Due to its excellent properties, low cost, and easy availability [10], microcolumnar CsI(Tl) has been the scintillator screen of choice for digital radiology imaging applications [11,12]. It is also attractive for nuclear medicine applications such as intra-operative surgical probes and SPECT. CsI(Tl) has one of the highest conversion efficiencies of any known scintillator

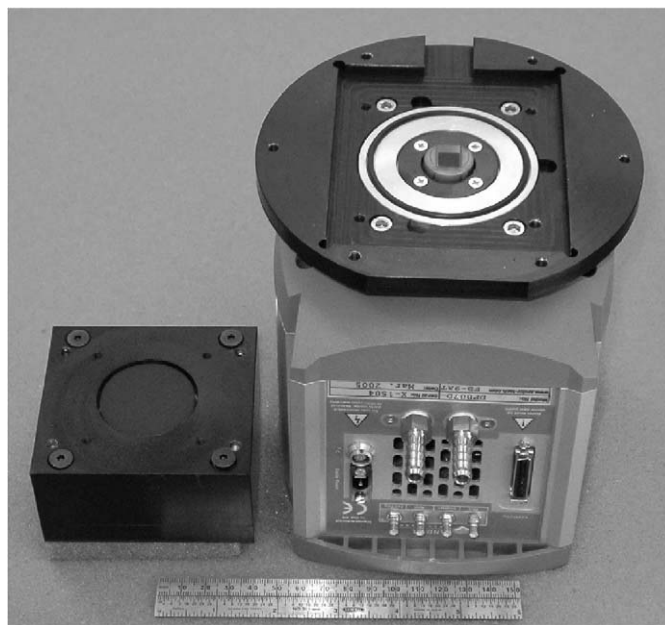


Fig. 2. A photograph of the prototype EMCCD detector showing the permanently attached 1:1 fiberoptic window. The detachable 3:1 fiberoptic taper is shown on the left.

(64,000 photons/MeV), a rapid initial decay (680 ns), an emission in the visible range (540 nm), and a cubic structure that allows fabrication into microcolumnar films required to achieve high spatial resolution of 10 lp/mm or greater [13]. It has a relatively high density (4.53 g/cm^3), high atomic number ($Z = 54$), and is transparent to its own light.

For imaging, 8 to 140 keV X-rays/ γ -rays, microcolumnar CsI(Tl) films ranging from $30 \mu\text{m}$ to 2.6 mm in thickness have been fabricated at RMD using indigenously developed vapor deposition process [14]. Depending on the application, films of various thicknesses may be coupled to the front end of the detector. For example, for X-ray imaging using 40 kVp X-rays only $150 \mu\text{m}$ thick films may be used to achieve over 80% absorption, whereas for 140 KeV^{99m}Tc γ -ray imaging (radioisotope typically used in SPECT imaging) $\sim 500 \mu\text{m}$ to 3 mm thick films may be used to achieve high absorption efficiency up to 70%.

4. The prototype detector

The prototype X-ray/ γ -ray detector is a custom designed system developed by RMD in collaboration with Andor Technologies and uses back-thinned e2v BI CCD887 EMCCD with 512×512 pixel resolution. A 1:1 fiberoptic window is optically bonded to the CCD, which permits coupling of an additional fiberoptic reducer (3:1 or 6:1 demagnification ratio). Fig. 2 shows the photograph of the camera along with a 3:1 fiberoptic taper. For X-ray/ γ -ray imaging the microcolumnar CsI(Tl) is pressure coupled to the CCD fiberoptic window or to the large end of the fiberoptic taper attached to the CCD window.

5. Gamma ray imaging

To evaluate the spatial resolution of the detector, a 500 μm thick CsI(Tl) screen was coupled to the front end of the camera and a 30 μm Pb slit was placed directly in front of the screen with a 10 mCi 122 keV ^{57}Co source at 100 cm from the slit. The camera was operated at 30 fps, and 10,000 frames were acquired. Fig. 3 shows data frames where individual γ -ray events are evident as clusters of

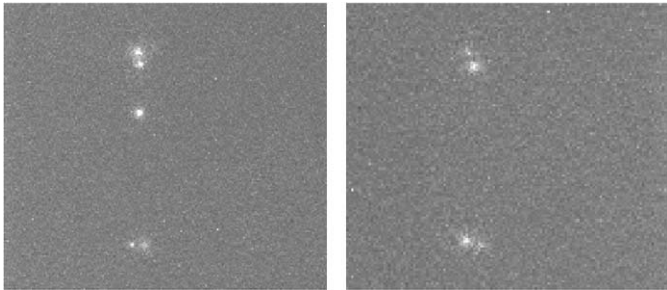


Fig. 3. Two data frames showing detection of 122 keV ^{57}Co γ -rays. The frame size is $\sim 8\text{ mm} \times 8\text{ mm}$.

signal in the images. Typically, 91% of the 122 keV interactions in CsI(Tl) are due to the photoelectric effect; of these 79% produce K X-rays. The mean interaction length of Cs and I K X-rays ranges from 124 to 350 μm in CsI(Tl), but is typically $\sim 300\text{ }\mu\text{m}$. Consequently, signal clusters are often paired due to the separately resolved primary interaction and the secondary K X-ray interaction. Single clusters are usually photoelectric interactions in which all the energy is deposited near the interaction site, or in the case of thin detectors, a primary interaction site with subsequent K-escape. The spatial resolution can be improved by rejecting the K X-ray interactions and finding the centroid of the primary interaction cluster in such image frames.

Fig. 4 shows an image of the 30 μm slit obtained with the EMCCD and CsI(Tl) film operated in a conventional ‘integrating’ mode as well as in ‘photon counting mode’. The frame images were smoothed and a threshold was used to identify clusters. Then the centroid and total signal were determined for each cluster from the original un-smoothed frames. A threshold on the total signal was used to reject K X-ray interactions [15]. The measured FWHM resolution was 206 μm for the integrating mode and 87 μm for the

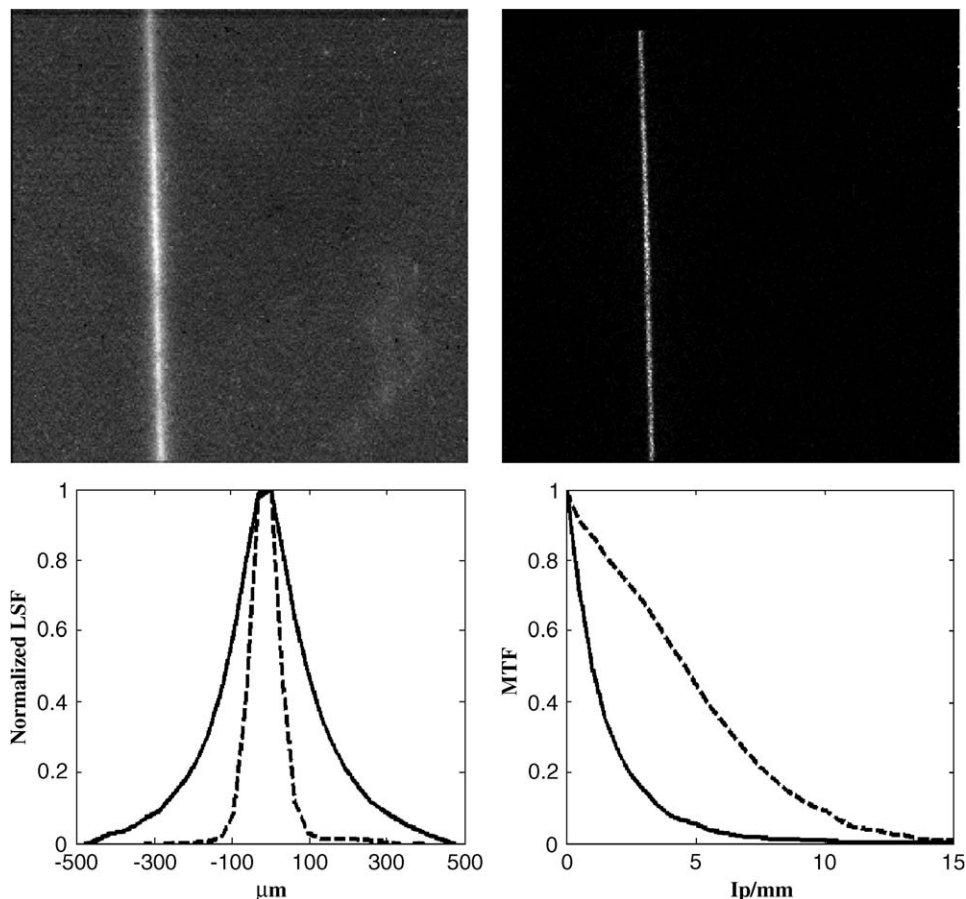


Fig. 4. Images taken of a 30 μm slit and a ^{57}Co point source. An integrated image is at top left; at top right, the centroid of the individual event clusters have been plotted, and a threshold on total cluster signal has been used to suppress K X-rays. Below are plotted the LSFs and MTFs for integrated (solid-line) and centroid corrected (dashed-line) cases. Centroid correction substantially improves spatial resolution.

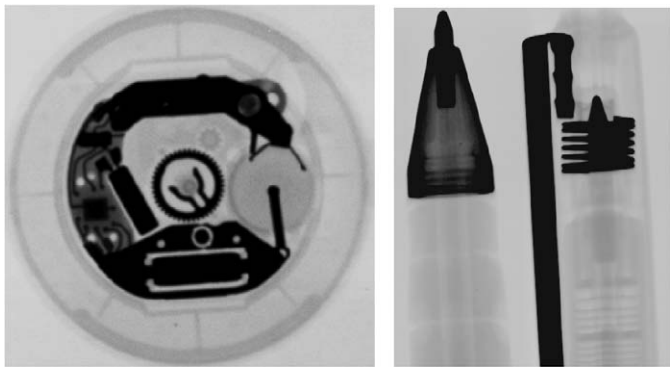


Fig. 5. Images of a wristwatch and ballpoint pens acquired using the EMCCD camera. The objects have several metal as well as plastic parts of varying thickness and densities. Note the excellent contrast and dynamic range seen in the images.

photon counting mode of operation, similar to results reported in literature [16].

6. X-ray imaging

For X-ray imaging, the detector dynamic range is an important issue. While the presence of an internal gain reduces the read noise enhancing the output SNR, it also reduces the CCD dynamic range. This loss is partly compensated by increasing the full well capacity of the gain register from 250 to 850 ke⁻. By operating the EMCCD with an internal gain of ~40, a true dynamic range of 14 bits with the read noise of <1e⁻ can be achieved. This dynamic range is adequate for most of the X-ray imaging applications.

To illustrate the X-ray imaging capability, a 6:1 fiberoptic taper with 200 μm thick CsI(Tl) screen was coupled to the EMCCD. A GE Senographe 600T-FD, Senix H.F mammography source set at 30 kV, 100 mA, 63 mAs was used. The source to detector distance was 60 cm and the imaging objects were placed in close contact with the CsI(Tl) film. Fig. 5 shows an image of a

wristwatch and a set of ballpoint pens obtained at 30 fps speed. These data illustrate the dynamic range and contrast that can be achieved for short exposure times.

Acknowledgments

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