Readout ICs for High Spatial Resolution Slot-Scan Imaging with CZT or CdTe Pixel Arrays

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Abstract—We have developed a new version of the MARY (MAMmogRaphY) pixel detector with its custom readout integrated circuit (IC) optimized for electron collection in semiconductor detectors such as CdZnTe (CZT), CdTe, a-Se and GaAs. This new pixel detector and readout IC, the MARY-N50, is essentially comprised of a 192 x 384 array of channels at a 50 µm x 50 µm pitch, which can be flip-chip bump-bonded with a matching detector pixel array. A 100 µm pitch pixel detector, the MARY-N100, was also developed, with a 64 x 192 pixel array. Standard features of both versions of MARY-N include: TDI (Time Delay Integration) or “staring” CCD readout capability; low noise and wide dynamic range; internal clock drivers; fat zero input; overflow control; multiple independent readout stages (24 for MARY-N50, 8 for MARY-N100) to accommodate large charge collection due to direct conversion.

In staring mode, charge from the detector array is accumulated for a period of time into the CCD elements. In TDI mode – used in slot-scan imaging – the packets of charge move from pixel row to pixel row in synchronism with the movement of the detector but in the opposite direction, so that charge that results from x-ray transmission through a given region of the object is accumulated into one packet.

We will present the design of these two MARY-N pixel detectors, performance data for their readout ICs, and preliminary x-ray imaging results obtained from first engineering prototype hybrid CdTe pixel detectors.

I. INTRODUCTION

APPLICATIONS of position-sensitive solid-state radiation detectors have grown rapidly in recent years as a consequence of parallel advances in detector materials science and low-noise microelectronics design [1], [2]. The sensor and signal processing components of a detector module have increasingly assumed monolithic forms, i.e., pixel or strip arrays and multi-channel integrated circuits (ICs), respectively. Whereas the concept for a given detector application often revolves around the characteristics and capabilities of a sensor array, actualizing an instrument design assumes that the matching readout electronics are already available or will be developed as part of the program. As such, it has become generally recognized that readout ICs and their associated support electronics are an essential and integral part of a detector unit. Ideally, a readout IC would be designed to meet the specific performance requirements of a given application. Custom IC development can however be a time-consuming, high-risk and financially onerous undertaking, which most R&D projects cannot afford. Broadening the applicability and accessibility of readout ICs that do get development funding would therefore benefit manifold efforts to prototype emerging detector designs. To this end, one could adopt a “generic IC” approach, premised on the fortune of direct sponsorship that is virtually independent of instrument development. This would proceed by: identifying commonalities within an application category; defining corresponding generic IC classes; and, developing an IC for the requirements of each class. More realistically, since most new IC designs are carried out within an application development program, one could simply expand the features of the application-specific IC (ASIC) in question. This approach would provide ranges and options for key specifications and accommodate additional functions as far as technically and logistically reasonable.

We have taken both approaches in developing solid-state detectors with readout ICs. We present here the development and results for a two-dimensional (2D) pixel detector array (Fig. 1) for high spatial resolution imaging.

NOVA has been developing pixel detectors for digital mammography for several years. This paper discusses the results of the development of a new generation and wider application pixel detectors for digital mammography together with Aguilas Technologies under an NCI STTR Phase II grant. First generation pixel detectors were developed with silicon pixel detectors, which did not produce optimum DQE due to low Atomic Number Z (14). Therefore, we have targeted high Z solid-state detectors such as CZT, CdTe, Se, GaAs and PbI2 for the new generation pixel detectors.

This next generation of the original MARY (MAMmogRaphY) detector [3], which we call MARY-N, is an electron-collecting and -integrating pixel detector optimized for high Z solid-state materials. The MARY-N readout IC is a CCD channel array that offers both TDI (Time Delayed Integration) and staring mode readout. In the following sections we describe the new MARY-N hybrid pixel detector and how it is fabricated. We also discuss the latest results obtained from these pixel detectors.

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II. HYBRID PIXEL DETECTORS

Fig. 1 shows a hybrid CdZnTe (CZT) solid state pixel detector design where the detector with matching pixel array is bump bonded on top of an application specific integrated circuit (ASIC) for reading out the pixel detector. Fig. 2 illustrates the inside of a CdZnTe pixel detector bump bonded on a 2D readout ASIC as an incident gamma ray interacts, creating electron-hole pairs in the process. Although indium bump bonds are used in these figures, other bump bond technologies such as gold stud or solder bump bonding can also be used.

III. MARY-N IC DESCRIPTION

Like the original MARY [3], MARY-N50 is a solid-state pixel detector with a 192 x 384 array of 50 µm x 50 µm pixels (MARY-N100 is 64 x 192 array of 100 µm x 100 µm pitch) operated in current mode and using a CCD charge transfer technique with TDI. The test results and images produced with the original MARY Si, CdTe and CdZnTe pixel detectors have been published previously [3].

The solid-state detector, which can be silicon, a GaAs PIN photodiode array, CdTe, or CdZnTe (CZT) can be bump bonded onto the MARY-N IC. It is also possible to deposit detector material such as amorphous Se or PbI₂ on top of the ASIC. This technique can reduce cost significantly. The basic element of the array is a TDI group of eight pixels. Charge is integrated in capacitive charge wells underneath each pixel for a preset time period, typically 1 ms, and then transferred to the next pixel row. This shifting occurs synchronously with, and in the opposite direction of, the motion of the detector, so that the charge packets remain stationary with respect to the object being imaged. This accumulate-and-shift operation occurs continuously. To avoid saturating the charge wells, the charges are only transferred through eight shifts of position and then presented to an output buffer through a column multiplexer and eventually to the external system. Reading out the entire IC thus requires 24 output buffers for MARY-N50, eight for MARY-N100; the digitized data from the different buffers are added off-chip with the appropriate delays.

These pixel detectors also have staring imaging mode. In this mode the full ASIC is read out without TDI; it can be used to produce staring images of objects and is also useful in testing, calibrating and monitoring the solid-state pixel detector and its dedicated readout IC.

The standard features of the MARY-N50 and MARY-N100 pixel detectors are listed in Table I. Fig. 3 shows a photograph of a fabricated MARY die and the MARY-N50 layout. MARY-N100 layout is shown in Fig. 4. We present preliminary results from these new pixel detectors below.
Table I

<table>
<thead>
<tr>
<th>Specification</th>
<th>MARY-N50</th>
<th>MARY-N100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readout</td>
<td>Selectable on-chip TDI using CCD technique for charge transfer or staring mode imaging.</td>
<td></td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>50 x 50 μm² and 100 x 100 μm² for MARY-N50 &amp; MARY-N100, respectively.</td>
<td></td>
</tr>
<tr>
<td>Pixel Array Size</td>
<td>192 x 384 and 64 x 192 for MARY-N50 and MARY-N100, respectively.</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>≥16 Bit</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>Designed for low noise. (Not yet measured)</td>
<td></td>
</tr>
<tr>
<td>Clock Drivers</td>
<td>Internal or External</td>
<td></td>
</tr>
<tr>
<td>Test Input</td>
<td>Fat Zero</td>
<td></td>
</tr>
<tr>
<td>Overflow Control</td>
<td>Overflow Controlled</td>
<td></td>
</tr>
<tr>
<td>Signal readout</td>
<td>8 or 24 Independent Readout Taps for MARY-N100 and MARY-N50, respectively.</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5 illustrates the charge collection system for the MARY and MARY-N50/N100 pixel detectors, respectively. The major difference between these two detectors are that MARY collects holes because it was designed for silicon pixel detectors and MARY-N collects electrons because it is designed for solid state detectors which have higher electron than hole mobility, such as CZT, CdTe, PbI₂, HgI₂ and Se detectors.

Fig. 6 illustrates the charge collection system for the MARY and MARY-N50/N100 pixel detectors, respectively. The major difference between these two detectors are that MARY collects holes because it was designed for silicon pixel detectors and MARY-N collects electrons because it is designed for solid state detectors which have higher electron than hole mobility, such as CZT, CdTe, PbI₂, HgI₂ and Se detectors.

MARY Pixel Detector Results

We present below several images taken using the original hole-collecting MARY pixel detector with CZT and CdTe detectors indium bump bonded onto its surface, to show what has been previously achieved with the original MARY pixel detector [3]. The CZT section of these detectors had been thinned to 0.15 mm to reduce the effects of hole trapping.

Excellent high contrast images were obtained with these MARY pixel detectors. Fig. 8 shows two images of a 2 cm long Mosquito fish taken with both of the original MARY pixel detectors. CZT produced the higher contrast image due to its high resistivity and low leakage current.

The MARY pixel detector was developed for digital mammography applications. Fig. 9 compares imaging results for an ACR phantom obtained by the original MARY pixel detector to those from a commercial digital mammography system. Further significant contrast improvement and higher DQE can be expected from the electron collecting MARY-N pixel detectors, because thicker CZT, 0.3 mm to 0.5 mm, can be fabricated.
IV. MARY-N PIXEL DETECTOR TESTING & IMAGING

MARY-N Pixel Detector Readout IC Testing

All functions and modes of the MARY-N50 and MARY-N100 devices were found to work correctly during the tests performed to date.

Performance data from a representative functioning MARY-N50 are summarized in Table II. The output signal swing was found to approach the design value of 2.4 V (1.8 V to 4.2 V); we observed a signal range of about 2.1 V (1.8 V to 3.9 V) in one case but closer to 2.4 V in others, the differences being likely due to process variation. Settling time was observed to be less than 1 µs, consistent with simulation results. The RMS noise level on the analog output line was measured at 1.65 mV to give a dynamic range of over 10 bits for a single stage. Linearity of the output versus input signal was measured to be about 97%. The charge transfer efficiency (CTE) was determined to be 0.9997.

<table>
<thead>
<tr>
<th>Signal Range</th>
<th>≥2.1 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linearity</td>
<td>97%</td>
</tr>
<tr>
<td>Noise</td>
<td>1.65 mV</td>
</tr>
<tr>
<td>Dynamic Range for a Single Stage</td>
<td>&gt;60dB (10 bits)</td>
</tr>
<tr>
<td>Charge Transfer Efficiency (CTE)</td>
<td>0.9997</td>
</tr>
<tr>
<td>Settling Time</td>
<td>&lt;1 µs</td>
</tr>
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</table>

Optical Imaging

Prior to bump-bonding pixel detector arrays to the MARY-N devices, we took advantage of their sensitivity to visible light to perform optical imaging experiments, with the readout system operated in staring as well as full TDI mode. A Tecomet high-resolution collimator disk was used as the test object (Fig. 11). The various images thus acquired are shown in Fig. 12; the background was subtracted to increase contrast in the images displayed. In order to test the scanning capabilities of MARY-N50, for example, the collimator pattern was scanned and a total of 600 frames acquired. Since it takes 192 frames to acquire the first complete image row, this gave us 409 rows. The scanning speed was matched to the charge transfer rate, as discussed above, to provide the sharpest image scanning in TDI mode. The collimator pattern
presents several structures with different shapes and size, the smallest holes being 150 \( \mu m \) in diameter. The collimator pattern image from the 50 \( \mu m \) pixel pitch MARY-N50 is sharper than that from MARY-N100 with 100 \( \mu m \) pitch as expected for both the staring and TDI images. The TDI images are also more uniform and better than the single shot staring images. Note that the light source was not a point source, which shows up as blurring in the images.

**Fig.12:** Optical images of the collimator disk recorded with the MARY-N devices: MARY-N50 in a) staring (384 x 192 pixels) and b) TDI mode (384 x 409 pixels); and MARY-N100 in c) staring (192 x 64 pixels) and d) TDI mode (192 x 200 pixels). Scanning direction in b) and d) is from top to bottom.

The optical imaging results demonstrate that the MARY-N device performs according to specification in all modes. The optical image quality (sharpness, contrast, resolution, etc.) is as expected.

**Hybridization of MARY-N100 with CdTe array**

The original 50 \( \mu m \)-pixel-pitch MARY hybrid detectors were hybridized using Raytheon’s unique indium bump-bonding technique. This is a proven and high performing technique for pixel pitch <100 \( \mu m \). It is a relatively expensive technique and will be used for MARY-N50 pixel detectors with pixel pitch 50 \( \mu m \times 50 \mu m \).

We decided to test first the MARY-N100 pixel detectors because they have 100 \( \mu m \times 100 \mu m \) pixel pitch and they can be bump bonded using more conventional and lower cost techniques for initial testing. We used a 2 mm thick CdTe detector and selected a method that uses silver epoxy on the CdTe and a low temperature wafer plating technique on the IC wafer. The CdTe and the diced die are then aligned and hybridized. Since the CdTe sensor was smaller than the MARY-N pixel array, it was centered along the longer axis of the MARY-N100 device but positioned away from the wire bond I/O pads. The various stages of the CdTe/MARY-N100 assembly process are illustrated in Fig. 13a through Fig. 13c.

**Fig. 13:** Photographs of: a) the CdTe pixel array sensor (top, 2 mm thick with high leakage current) and MARY-N100 before bonding; b) a section of MARY-N100 pad array with Ni-Au bumps; and c) a section of the CdTe pixel array with polymer bumps.
MARY-N100 Pixel detector Images

One of the completed CdTe MARY-N100 detector hybrids is shown in Fig. 14a. The detector is seen at a slight angle to the IC because the actual pixel pattern deposited on CdTe was at an angle. The cathode at the top of the CdTe is deposited with gold, the color appears dark in Fig. 14a due to the angle of reflection. The hybrids were wire-bonded to MARY-N daughter boards (Fig. 7). We then tested the CdTe detectors by irradiating them in staring mode with x-rays from our LORAD M-II mammography x-ray system, operating at 25 kVp. The response of the MARY-N100 CdTe detector to x-ray exposure for 5, 30, 70 and 125 ms (clockwise from top left), in staring mode is shown in Fig. 14b. The dark (striped) margins on the left and right of each image correspond to the areas of the readout IC that were not covered by the detector.

In Fig. 14b the increasing response with increasing exposure duration over most of the detector area indicates that a large majority of the pixels were bonded successfully. The dark regions in the upper left and lower right corners of the CdTe array are likely due to the mismatch between the sensor and IC sizes that caused difficulties in aligning the parts to each other.

We imaged the Tecomet high-resolution collimator disk shown in Fig. 11 in TDI mode. One of the TDI images acquired with the CdTe MARY-N100 detector is shown in Fig. 14c. Even the smallest holes (150 µm diameter) are clearly visible, fanning out like spokes between the larger elongated openings in the top left corner of the image, indicating that the pixels are not shorted together. These results also demonstrate that the bump bonding was successful for the 100 µm pixel pitch.

It is interesting that although the CdTe detector was 2 mm thick we were able to see the 150 µm diameter holes of the collimator. Since the energy of the x-rays was 25 kVp, almost all of the photons were only penetrating a very small depth at the cathode. Therefore, the charge was travelling about 2 mm to reach the anode pixel, making it strongly prone to charge diffusion. This demonstrates that the charge diffusion between 100 µm x 100 µm pixels of the 2 mm thick pixel detector was negligible. This is an interesting result, which shows that it may be possible to use thick solid-state detectors for higher energy medical, industrial and security imaging, if parallax errors can be kept to a minimum by using smaller detector area, curved detectors or larger pixels.

Another interesting result was that we were using a Eurorad CdTe material, which has higher leakage current than CZT. In spite of this, and although MARY-N is a current integrating pixel detector, the images are excellent. This may mean that the results can be even better with a CZT pixel detector.

The MARY-N pixel detectors presently are not abuttable. However, they can be designed into a staggered array configuration. Fig. 15 shows an artist’s impression of how a staggered linear array of MARY-N pixel detectors can be fabricated. We are in the process of designing a staggered array for slot scan applications such as digital mammography.

Fig. 14. (a) Hybridized MARY-N100 pixel detector; (b) Response of the MARY-N100 CdTe detector to x-ray exposure for 5, 30, 70 and 125 ms (clockwise from top left), in staring mode; and (c) Initial, raw TDI x-ray image (192 x 400 pixels) of collimator disk acquired using the CdTe MARYN-100 pixel detector. Scanning direction is from top to bottom. The dark margins on two sides correspond to the areas of the readout IC that were not covered by the undersized detector.

Fig. 15. Artist’s impression of a linear array of MARY-N hybrids. The detectors are mounted on separate PCBs that can be tilted at an angle to each other in the slot direction to allow the x-ray beam to be perpendicular to the center of each detector.
V. SUMMARY

We have shown that the new MARY-N50/N100 readout ASICs are working in both the TDI and staring imaging modes. We have demonstrated that CdTe MARY-N100 pixel detector is producing images in both the staring and TDI imaging modes.

We are now working on Se coated MARY-N50 pixel detector fabrication. We plan to test the Se pixel detectors when they are ready and also measure their MTF and DQE. Work is also progressing on designing a modular staggered linear array system.

VI. ACKNOWLEDGMENT

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VII. REFERENCES