First images with a Medipix2-Silicon detector assembly

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Abstract-- **The Medipix2 photon counting chip is composed of a matrix of 256 x 256 identical pixels each of which is connected by bump bonding to a pixel detector diode. Each pixel is square and measures 55 µm on the side. There are about 500 transistors per pixel combining analogue and digital functions. The bump bonding pad is connected to a charge sensitive preamplifier with local feedback which compensates for detector leakage current and whose output is connected to a window comparator. The upper and lower thresholds of the comparator are globally and independently adjustable and each has 3-bits of local fine tuning to reduce threshold variations. The comparator output is connected via a pulse shaping circuit to a 13-bit counter. An externally applied shutter signal determines whether the chip is in counting mode or readout mode. The input referred noise and the tuned threshold variation have been measured to be around 100 e- rms each. The chip has been bump-bonded to a high resistivity silicon sensor matrix and images have been taken using radioactive sources and an x-ray tube. The chip measures 14 mm x 16 mm.**

I. Introduction

PIXEL DETECTORS for High Energy Physics (HEP) are required to provide event by event images of interactions at rates of 10's of MHz with spatial precision in the order of 10 µm [1]. High resistivity silicon is the detector material of choice as it is extremely uniform and can be obtained in large areas at relatively low cost. A Minimum Ionizing Particle (MIP) deposits around 80 e- per micron of detector thickness. A typical detector is around 300 µm thick with rectangular shaped elements of 50 µm by 500 µm. Due to the high readout bandwidth and the sparse nature of the data front-ends usually comprise a pre-amplifier/shaper circuit followed by a comparator. Several events may be stored before a "trigger" from another detector selects the event of interest. All of this must be achieved using minimal material which implies low power consumption.

During the development of such detectors it became obvious that similar techniques could be applied to x-ray imaging. The advantage is that photons could be counted one by one and it would be possible to select photons of a given energy. At the same time image distortion due to dark current is eliminated. A good review of the field can be found at [2]. A first generation chip [3] was developed and reported interesting results but was limited in its applications by the rather large pixel pitch of 170 µm. This paper reports on first images obtained with a second generation single photon counting pixel device, Medipix2. A full description of the chip is given in [4] and electrical measurements are reported in [5].

Firstly, the architecture of the chip is reviewed. Then there is a summary of the electrical characteristics of the chip. A number of images were taken using the chip bump-bonded to a high resistivity silicon detector. These are reported in the fourth section. Finally, we draw some conclusions and make suggestions for future research.

II. Chip description

The Medipix2 chip is composed mainly of an active area of 256 x 256 pixels. Each pixel measures 55 x 55 μm^2 resulting in a total sensitive detection area of 1.98 cm^2 representing 87 % of the entire chip area. The periphery includes the IO control logic, 13 8-bit DACs and 127 IO wire-bonding pads. The periphery is placed at one side of the chip allowing for three-side buttability. In a multi-chip configuration there would be no dead area between neighbouring chips but there is a slight loss in spatial resolution as two 165 µm wide pixel rows and columns are used on the detector side to cover the unavoidable gaps between the readout chips.

Both the analog and digital circuitry have been designed to operate with independent 2.2 V power supplies with a total analog power consumption of ~ 500 mW. The digital power consumption varies as a function of the readout frequency and peaks during the readout phase. Using an 80MHz clock the peak digital consumption is ~ 100 mW. The chip contains around 33 million transistors.

A. Pixel Cell

The pixel cell works in photon counting mode. A polarity select line defines whether it is sensitive to electrons or holes. When a charged particle interacts in the detector material it deposits a charge which drifts towards the collection electrode. This charge is then amplified and compared with two different thresholds that form an energy window. If the detected charge falls inside this energy window a 13-bit digital counter is incremented. If the high threshold is set below the level of the low threshold all hits above the low threshold are counted. Figure 1 shows the schematic and layout of the Medipix2 pixel cell.

The pixel has two working modes depending on the CMOS input *Shutter* state. When the *Shutter* signal is low the pixel is in acquisition mode. In this case, the output of the double discrimination logic is used as the clock of the counter as described above. When the *Shutter* is high an external clock is used to shift the data from pixel to pixel.

Each pixel has eight independent configuration bits. Six of them are used for the fine threshold adjustment (three bits for each discriminator), one for pixel masking, and one to enable the input charge test through the 8 fF on-pixel capacitance. Each pixel has 504 transistors and a static power consumption of ~ 8 µW. Particular care has been taken in the design in order to minimize any systematic deviations in the behaviour of the cells as a consequence of effects such as top-down power supply voltage drops.

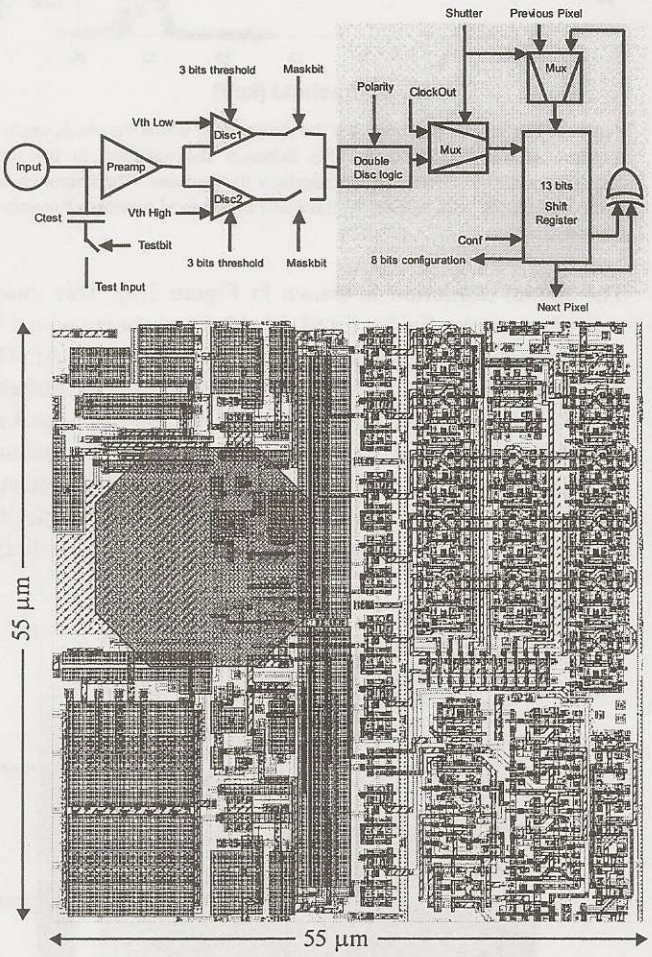

Figure 1: Medipix2 pixel cell schematics and layout.

B. *The Periphery*

When the matrix is accessed to perform any IO operation the data is organized in 256 columns of 256 x 13 bits as shown in Figure 2. Therefore each chip has 851968 bits to be read or written for any matrix IO operation. The Medipix2 uses a high-speed LVDS logic for configuration and serial readout. Readout may also be carried out using a parallel 32-bit single-ended CMOS bus for applications requiring even higher frame rates. The setting of the configuration register in the matrix and of the 13 8-bit DACs is always done serially through the LVDS receivers. Using a clock of 100 MHz the matrix is readout in less than 9 ms through the serial port, while using the parallel option the readout is done in 266 µs.

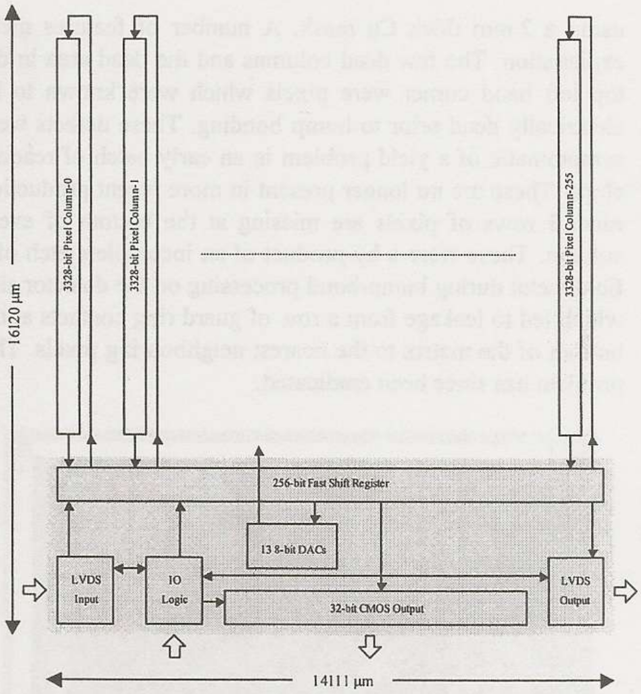

Figure 2: Schematic floorplan of the Medipix2 chip.

III. ELECTRICAL MEASUREMENTS

The chip can be tested electrically using the test injection capacitor in each pixel. Although the value of this capacitor is not known precisely such measurements provide useful information about the overall functionality of the chip and any systematic effects which may appear. These measurements are also carried out on the probe station to produce wafer maps of chips suitable for bump-bonding.

As mentioned earlier the chip is sensitive to either electrons or holes depending on a polarity select line. In both cases the measured noise is ~ 100 e- rms and the threshold variation after fine tuning is also ~ 100 e- rms. The minimum threshold (which is limited by the digital to analog cross-coupling via supplies and substrate) is ~ 1000 e-. The threshold is linear up to ~ 12 ke- using the on-chip DAC which can be over-ruled by an externally applied voltage taking the linearity up to ~ 80 ke-.

IV. MEASUREMENTS WITH SOURCES AND AN X-RAY TUBE

A number of readout chips have been bump-bonded to high resistivity silicon detectors using a fine pitch bump-bonding service provided by VTT, Finland [6]. After some fine tuning of the bump deposition process the detector leakage current was measured to be ~ 200 nA at 100 V. The total sensitive area is ~ 2 cm^2.

An important parameter of such pixel systems is the minimum operating energy threshold. This has been determined experimentally to be ~ 4 keV and the threshold variation appears to be consistent with electrical measurements. The first image taken with an ^{55}Fe source (5.9 keV) is shown in Figure 3. This was taken in 10 mins using a 2 mm thick Cu mask. A number of features merit explanation. The few dead columns and the dead area in the top left hand corner were pixels which were known to be electrically dead prior to bump bonding. These defects were symptomatic of a yield problem in an early batch of readout chips. These are no longer present in more recent production runs. 3 rows of pixels are missing at the bottom of every column. These were a by-product of an incomplete etch of a field metal during bump-bond processing on the detector side which led to leakage from a row of guard ring contacts at the bottom of the matrix to the nearest neighbouring pixels. This problem has since been eradicated.

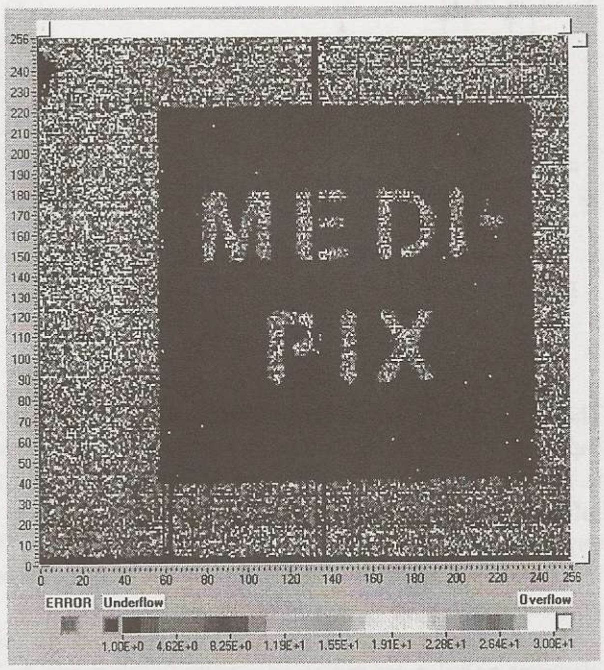

Figure 3: A first image taken using the Medipix2 chip bump-bonded to a high resistivity silicon detector. A 2 mm thick Cu mask is used and illuminated by a ^{55}Fe source.

A further measurement was carried out using a ^{109}Cd source (lines at 22 keV and 25 keV) and varying the global threshold voltage to determine the threshold variation across the matrix. Figure 4 shows a spectrum which was produced by summing over 11 000 pixels. The broken curve indicates the number of pixels which start counting at a given threshold. This gives an estimate of threshold variation. A Gaussian fit to that curve has a sigma of 0.8 keV, roughly in line with a quadratic sum of the threshold variation and the noise. The unbroken curve shows the differential of the total number of counts on all 11 000 pixels. There is clear separation between the 22 and 25 keV lines. The tail to the left of the peaks is due to charge sharing effects which mean that some photons share the deposited charge between neighbouring pixels. These charge sharing effects distort somewhat this measurement. Further measurements are underway with a monochromatic pencil beam to quantify better the values given here.

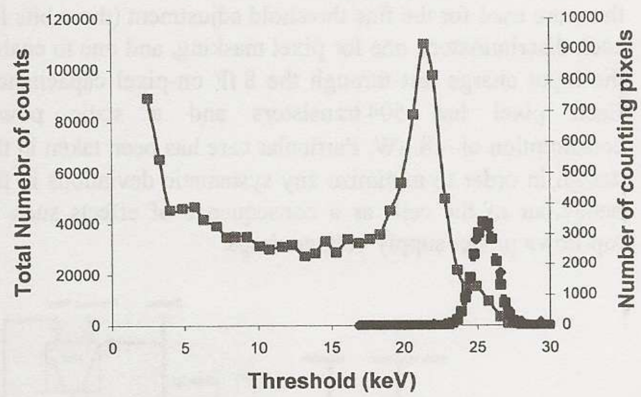

Figure 4: The broken line indicates the threshold at which the pixels begin to response to the ^{109}Cd source. This indicates the variation in the pixel thresholds which is summed quadratically with the noise. The unbroken line is the differential with respect to threshold in the total number of counts in the matrix.

The spatial resolution is shown in Figure 5(a). This image was taken using a Seifert FK61-04x12 X-ray source with a W target and a filter which is equivalent to 2.5 mm of Al. The tube was operated at 45 kV and the source-detector distance was 52 cm. The mask used goes up tp 10 line pairs per mm. The MTF has been calculated using the edge function technique under the same conditions. Figure 5(b) indicates the excellent performance of the system. On the same plot are show the Nyquist frequencies of the Medipix2 and Medipix1 systems.

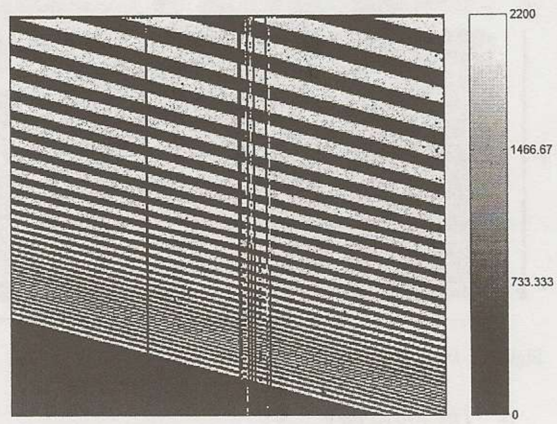

Figure 5(a): Response to a line pair mask illuminated by an x-ray machine.

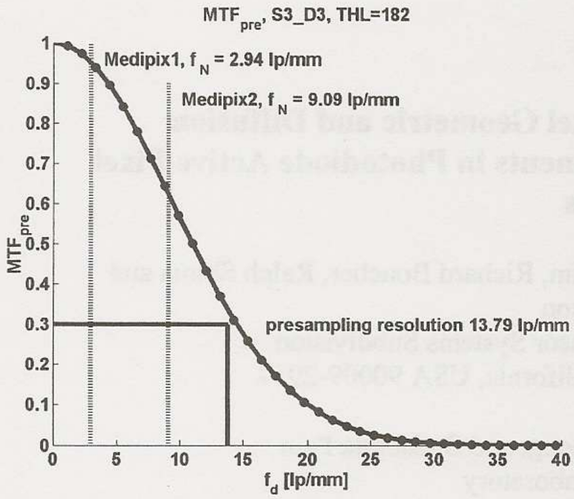

Figure 5(b): MTF calculated by the edge function technique.

Finally, in order to demonstrate the imaging performance of the system an image of a (dead!) house fly was generated using the same x-ray set-up. This time the tube votage was reduced to 13 kV. Figure 6 was generated from 10 sequential exposures of 5 s each amounting to a total of 50 000 counts in the white areas. The image has been corrected using 50 flat field images recorded under identical conditions. There are still a number of electrically inactive cells but the sensitivity and spatial resolution of the device are evident

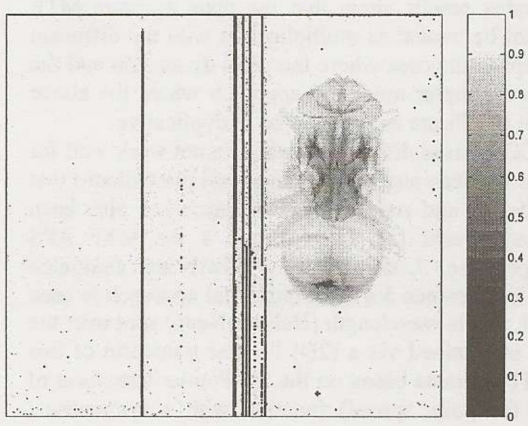

Figure 6: X-ray image of a (dead!) house fly.

V. Conclusions and Further Work

Single photon counting pixel detectors are radically different from other digital imaging techniques which are based on charge integration. The Medipix2 chip is an excellent vehicle allowing the study of such devices. The readout chip features several hardware mechanisms at the pixel level that provide compensation for various non-uniformities by using both analogue feedback (dark current compensation) and programmable digital tuning (upper and lower threshold). First images have been presented which demonstrate the sensitivity and spatial resolution which are achievable. The chip is sensitive to both positive and negative input charges and can therefore be used with other popular x-ray detector materials such as CdTe and GaAs. In order to fully exploit the energy resolution new front-ends are needed to deal with charge sharing [4]. The device, however, probably represents the first of a series of possible devices which will ultimately permit colour x-ray imaging to become a reality.

VI. Acknowledgment

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VII. References

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[6] VTT Information Technology, Tietotie 3, Espoo, Finland.

[7] See http://medipix.web.cern.ch/MEDIPIX/