Measurement of Radiation Damage to 130nm Hybrid Pixel Detector Readout Chips

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Abstract

We present the first measurements of the performance of the Medipix3 hybrid pixel readout chip after exposure to significant x-ray flux. Specifically the changes in performance of the mixed mode pixel architecture, the digital periphery, digital to analogue converters and the e-fuse technology were characterised. A high intensity, calibrated x-ray source was used to incrementally irradiate the separate regions of the detector whilst it was powered. This is the first total ionizing dose study of a large area pixel detector fabricated using the 130nm CMOS technology.

I. INTRODUCTION

This paper presents recent measurements of the performance of the Medipix3[1] pixel readout chip after exposure to large doses of x-rays. Medipix3 is the first full pixel readout chip to be fabricated in the IBM 130nm CMOS technology, thus its ability to survive irradiation is a strong indicator of the technologies expected intrinsic hardness of the technology[2], and its suitability for use in high readiation environments such as proposed sLHC[3] detector systems.

II. MEDIPIX3

Medipix3 is the most recent addition to the Medipix family of single photon counting pixel readout chips. It is designed as part of a hybrid pixel detector assembly. As with its predecessor, Medipix2[4], it provides individual readout channels for a 256 by 256 array of 55um square pixels. Each pixel channel is electrically connected to its corresponding structure in the sensor chip by means of a solder bump bond. Each channel provides analogue amplification, shaping and two discriminators driving two programmable binary counters. The chip as a whole is then read out with a 'shutter' signal. The primary design goal of both Medipix2 and Medipix3 is to provide single photon counting x-ray detection with high resolution, high dynamic range and high signal to noise ratio.

Medipix3 builds on the concept of Medipix2 but adds several new features and modes that extend its functionality, especially in the area of single photon spectrometry. A limiting factor in Medipix2's ability to reconstruct a spectrum was the charge sharing phenomena. A photon falling between two or four pixels will share its energy amongst them, with each of the two or four signals produced having a significantly lower chance of passing the discriminator threshold. Medipix3 contains charge summing circuitry in its analogue front end, allowing four neighbouring pixels to communicate and allocate the full charge to the pixel with the largest initial signal, before the signal is passed to the discriminator. This effectively removes the distortion of the spectrum caused by charge sharing. In addition to this Medipix3 can operate in a spectroscopic mode, whereby spatial resolution is sacrificed for a greater ability to determine photons' energies. Groups of four pixels are ganged together to form 110um square pixels, sharing each pixel's discriminators and counters between them. This gives each super pixel eight separate threshold levels and counters, which is sufficient to capture a detailed spectroscopic image. Additionally Medipix3 can be read with less dead time than its predecessor and with multiple overlapping shutter signals. It is anticipated that the 130nm fabrication technology will be significantly more radiation hard than the 250nm technology used for Medipix2.

The first Medipix3 wafers were delivered at the beginning of 2009 and have been undergoing extensive testing in the intervening period. The charge summing and spectroscopic modes described above operate as expected and the pixel front end has been shown to operate with a very low noise. The measured equivalent noise charge of a pixel being just ~60e^- rms. This noise level was measured when running the chip in standard single pixel mode.

III. IRRADIATION STUDIES

The radiation tolerance of the Medipix3 readout chip is of interest to physicists working in HEP, high intensity synchrotron x-ray sources and with the Medipix3 chip in commercial products. The studies that are reported in this section were carried out with a Seifert RP149[5] calibrated x-ray source. Whilst it is acknowledged that the effect of single point defects caused by photons is significantly less than that of defect clusters caused by hadrons, the very large flux of x-rays used means that some useful conclusions can be drawn even in comparison with hadronic irradiation. In these tests an unbonded Medipix3 chip was used to allow us to decouple the effects of sensor and readout chip irradiation.

Initially a single Medipix3 chip was exposed to 60Mrad of irradiation with the x-ray beam spot covering a majority of the pixel matrix. It was intended that the matrix would be read out continuously whilst the irradiation was in progress. This measurement demonstrated that one of the analogue voltage levels supplied to the pixels front end by a Digital Analogue Converter (DAC) was unexpectedly sensitive to irradiation at levels below 1Mrad. It was discovered that the design of several switches in the analogue section of the pixel left a leakage current path to ground through pairs of minimum sized NMOS transistors that were susceptible to radiation damage. At dose levels of 1Mrad the cumulative leakage current on this DAC across the pixel matrix was too large to sustain the required operating voltage. This voltage drop leads to the chip ceasing to function across the whole matrix, regardless of the level of irradiation the individual pixels have suffered. In addition, it was found that the electrostatic protection diode structure on each pixel was being damaged and degrading the performance of pixels on an individual basis, specifically increasing the noise in the pixel.

A second irradiation, with an integrated dose of 400Mrad, targeting the DAC and readout structures at the chips periphery demonstrated that the effect on these structures was relatively small, compared with that on the pixel matrix. It also showed that the effect on the performance was largest at approximately 3Mrad, as demonstrated in tests by F. Faccio, and that the performance of the DACs recovers after further irradiation. There was no measurable effect on the LVDS readout drivers or e-fuse identification logic. The 400Mrad beam spot overlapped the region of irradiation on the pixel matrix giving a smaller region of pixels that received a dose of 460Mrad.

In order to further understand the leakage current problem on the pixel matrix a second chip was irradiated, this time in smaller steps of 100krad, up to the maximum damage level of 3Mrad. To reduce the total leakage current drawn by the chip, the x-ray spot was targeted at a corner, thus irradiating far fewer pixels. The chip operated up to a dose of 1500krad with a significant drift in the threshold value being recorded. The data from these measurements was used to determine the interplay of the voltages supplied to the analogue section of the pixels. By using this data to map the points where the voltage drop was causing switches to turn off, and by compensating by adjusting other balancing voltage levels, not affected by the radiation, it was possible to bring both chips back to an operating state very close to nominal.

By configuring the chip in this manner it was possible to read out the full matrices of both chips and take measurements of the increase in noise, gain and threshold variation with radiation by comparing the irradiated and unirradiated parts of the matrices.

IV. DAC Stability

As described above it was possible to read the values of the DACs continuously during the 400Mrad irradiation. Figure 1 shows their variation with the received radiation dose. These measurements clearly show the recovery effect after the 3Mrad level, with both types of DAC stabilizing as the dose becomes higher. The small step seen at the 400MRad point is the immediate annealing effect as the x-ray tube was turned off. The rate of irradiation here was much faster than is expected in any realistic application and this immediate annealing would be a benefit in all expected applications. As can be seen from these results the NMOS and PMOS DACS have shifts of just 9mV and 33mV respectively, although the effect at 3Mrad is higher and in the case of the PMOS DAC in the opposite direction to the annealing.

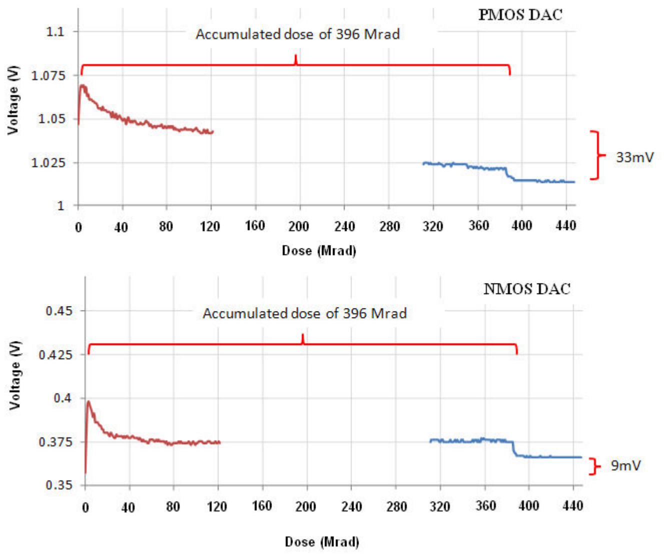

Figure 1: The voltage produced by the NMOS and PMOS DACs between 0Mrad and 400Mrad.

V. Pixel Performance

Once the alternative operating point of the Medipix3 chips had been determined it was possible to operate the chips normally. This made it possible to measure the noise increase, gain variation and threshold stability by comparing irradiated and unirradiated parts of each pixel matrix.

The performance of the chip with the 60Mrad / 400Mrad / 460Mrad regions is shown in Figures 2 to 5.

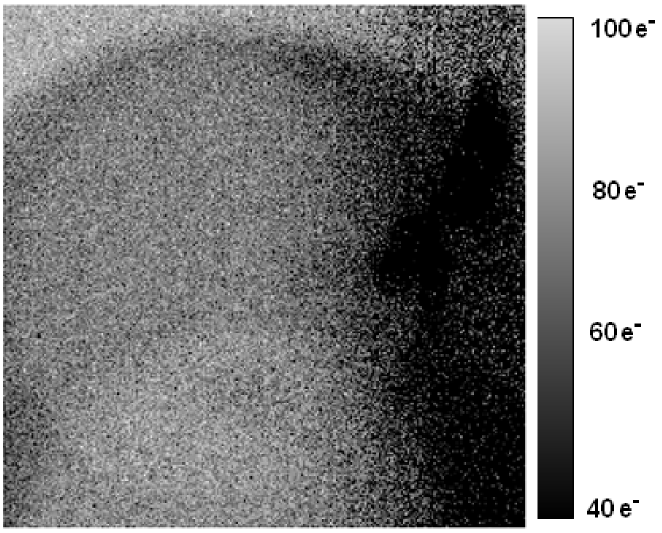

Figure 2: The noise recorded across the pixel matrix. The dark region to the right is a yield artifact present before irradiation. The circular regiion centered on the matrix was irradiated to 60Mrad. The semicircular region centered on the bottom edge of the matrix was irradiated to 400Mrad.

The noise map shown in Figure 2 contains a yield artefact, as it was expected the chip would not survive this x-ray dose a perfect chip was not used. Once this has been accounted for the mean noise across the matrix is 71.6e- with an uncertainty of 12.9e-. This is very close to the unirradiated value of 60e- and is will within operational parameters. The noise values for pixels in different irradiated regions along several columns are shown in Figure 3.

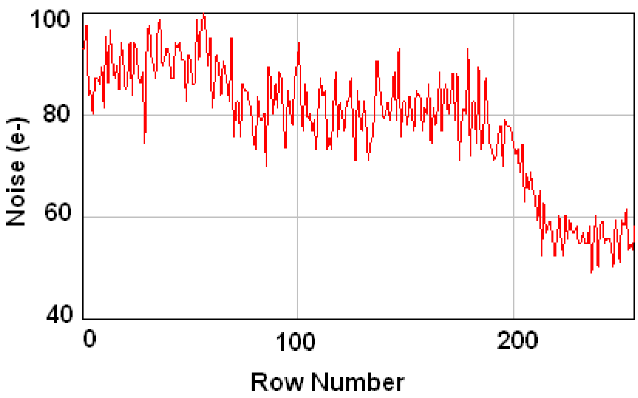

Figure 3: The noise as a function of row, showing 460Mrad (0 to 100), 60Mrad (100 to 200) and unirradiated (200 and above) regions of the chip.

By using the internal charge injection test circuitry to stimulate the analogue front end of the chips it is possible to measure the gain performance. It can be seen in Figure 4 that there is essentially no gain variation measureable with a 2ke- signal between irradiated and unirradiated pixels on the same matrix.

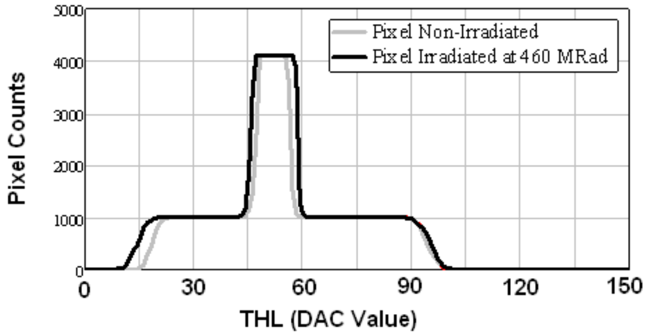

Figure 4: The noise peak and test pulse plateau shown for irradiated and non irradiated pixels. It can be seen that the two lines completely overlap for the positive test pulse case, which replicates the nominal operating situation.

Very little increase in threshold variation can be seen in the threshold values achieved across the pixel matrix. The spread of threshold values is shown in Figure 5. The variations between the 0/60/400/460Mrad regions can be completely compensated for by the chip's five bit threshold equalisation circuitry that is designed to compensate for natural threshold variations between pixels.

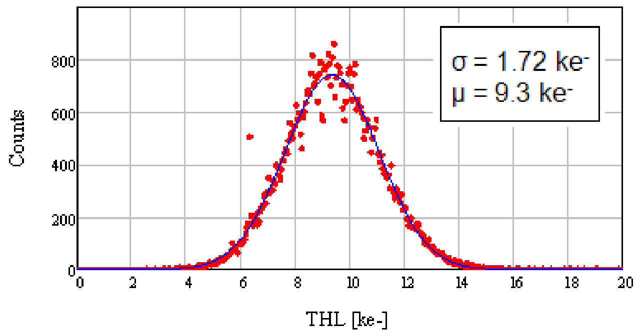

Figure 5: The threshold variation across the pixel matrix.

The effects of irradiation to 3Mrad are slightly more pronounced than the effects of the higher irradiation levels, however as before the chips show gain, noise and threshold variations well within operational limits. The noise in the irradiated pixels is between 70 and 90e-, the gain variation with a 2ke- test pulse is still minimal and the threshold variation is approximately 60 DAC steps and can be automatically equalised as before. No measureable increase in the analogue or digital currents drawn by the chip was observed.

VI. Conclusions

The results presented above provide confirmation that the Medipix3 chip and the 130nm CMOS technology are intrinsically radiation tolerant to levels that are several orders of magnitude higher than the 250nm fabrication technology. This has implications for the designs of future pixel detectors for sLHC and high intensity x-ray sources, and indicates that 130nm is a strong contender for their fabrication technology. It was intended to find an upper limit to the Medipix3 operation, however the device seems to be operating well at 460Mrad and further measurements will be needed to find a break down point.

It should be noted that these measurements were carried out with an x-ray source and so should not be used to accurately quantitatively estimate the effect of hadronic radiation on devices.

VII. Acknowledgements

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VIII. References

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