EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–EP/98–162
21 September 1998

PERFORMANCE OF A 4096 PIXEL PHOTON COUNTING CHIP

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Abstract

A 4096 pixel Photon Counting Chip (PCC) has been developed and tested. It is aimed primarily at medical imaging although it can be used for other applications involving particle counting. The readout chip consists of a matrix of 64 x 64 identical square pixels, whose side measures 170 μm and is bump-bonded to a similar matrix of GaAs or Si pixel diodes covering a sensitive area of 1.18cm^2. The electronics in each cell comprises a preamplifier, a discriminator with variable threshold and a 3-bit threshold tune as well as a 15-bit counter. Each pixel can be individually addressed for electrical test or masked during acquisition. A shutter allows for switching between the counting and the readout modes and the use of a static logic in the counter enables long data taking periods. Electrical tests of the chip have shown a maximum counting rate of up to 2 MHz in each pixel. The minimum reachable threshold is 1400 e$^-$ with a variation of 350 e$^-$ rms that can be reduced to 80 e$^-$ rms after tuning with the 3-bit adjustment. Electrical noise at the input is 170 e$^-$ rms. Several read-out chips have been bump-bonded to 200 μm thick GaAs detectors. Tests with γ-rays and β$^-$ sources have been carried out. A number of objects have been imaged and 260 μm thick aluminium foil which represents a contrast to the surrounding air of only 1.9 % has been correctly imaged.

(Presented at the 43rd SPIE International Symposium on Optical Science, Engineering, and Instrumentation, July 19-24, 1998, San Diego, California, USA; SPIE Proceedings 3445-31)

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ABSTRACT

A 4096 pixel Photon Counting Chip (PCC) has been developed and tested. It is aimed primarily at medical imaging although it can be used for other applications involving particle counting. The readout chip consists of a matrix of 64 x 64 identical square pixels, whose side measures 170 μm and is bump-bonded to a similar matrix of GaAs or Si pixel diodes covering a sensitive area of 1.18 cm^2. The electronics in each cell comprises a preamplifier, a discriminator with variable threshold and a 3-bit threshold tune as well as a 15-bit counter. Each pixel can be individually addressed for electrical test or masked during acquisition. A shutter allows for switching between the counting and readout modes and the use of static logic in the counter enables long data taking periods. Electrical tests of the chip have shown a maximum counting rate of up to 2 MHz in each pixel. The minimum reachable threshold is 1 400 e^- with a variation of 350 e^- rms that can be reduced to 80 e^- rms after tuning with the 3-bit adjustment. Electrical noise at the input is 170 e^- rms. Several read-out chips have been bump bonded to 200 μm thick GaAs pixel detectors. Tests with γ-ray and β^- sources have been carried out. A number of objects have been imaged and a 260 μm thick aluminium foil which represents a contrast to the surrounding air of only 1.9 % has been correctly imaged.

Keywords: MEDIPIX, medical imaging, GaAs, pixel detector, x-rays, mammography, photon counting chip, low contrast, ASIC, VLSI.

1. INTRODUCTION

In medical x-ray imaging it is desirable to produce precise 2-dimensional information while limiting the dose to the patient. Another requirement is the possibility to image objects which are very similar in density to the surrounding tissue thus presenting a low contrast. One way to address these issues is to couple a highly segmented semiconductor detector to a matrix of readout electronics. Each small detection element is connected to electronics which counts the number of single x-ray photons seen by the detector[1]. It is necessary that the detector material chosen presents a high cross section to the impinging photons and that the electronics be sufficiently sensitive to detect the small signals generated. Also the problem of interconnect between the 2-dimensional detector array and the associated electronics has to be addressed. Hybrid pixel detector technology presents an interesting solution to this problem.

Hybrid pixel detectors were first used successfully in the WA97 experiment at CERN[2] following the developments in the RD19 collaboration[3]. Since that time many particle physics experiments are developing sub-detectors based on this new technology. Hybrid pixel detectors consist of one or several ASICs, each containing a 2-dimensional matrix of readout electronics, which are bump-bonded to an equally segmented semiconductor detector. Normally the readout requirements for

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HEP are rather different from imaging and, as a consequence of this, a new chip, the single Photon Counting Chip (PCC)[4], has been realised. In this chip a modified version of the front-end electronics of the LHC1/Omega3 chip[5] has been used and each pixel has been equipped with a 15-bit counter. The new chip has been bump-bonded to a detector made of GaAs as this material has a high detection efficiency for x-rays in the diagnostic energy range (10-100 keV)[6].

A review of the design of the single pixel and of the overall chip is given in section 2. In section 3 we summarise the results of electrical tests. Some images have been produced using both β- sources and γ-rays. Measurements of objects with a known contrast have also been performed. These are presented in section 4.

2. DESIGN OF THE READOUT CHIP

PCC is a 64 x 64 matrix of identical square pixels whose side measures 170 μm. The chip is designed in the SACMOS1 technology of FASELEC (Zurich). The total area of the chip is about 1.7 cm^2 with a sensitive area of 1.18 cm^2. Each cell contains a full readout chain and can be bump-bonded to an identically segmented semiconductor detector.

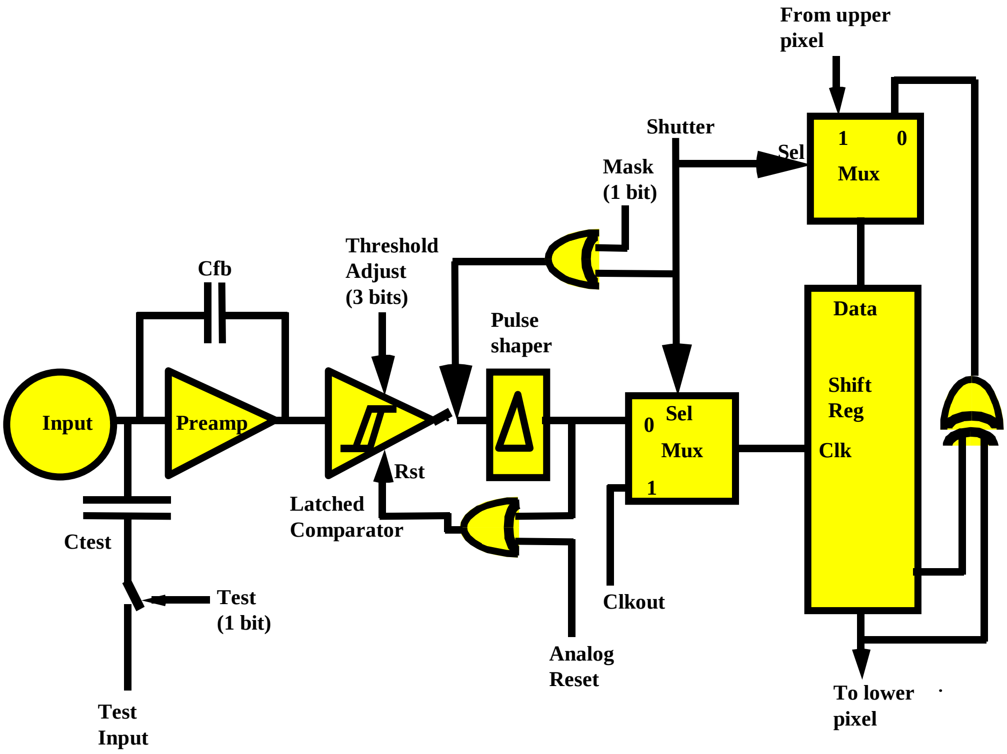

Figure 1: Block diagram of the pixel cell.

The block diagram of the pixel cell is shown in Figure 1. Each pixel consists of a charge sensitive preamplifier with leakage current compensation followed by a latched comparator with an externally controllable threshold which can be locally adjusted via 3 fully static flip-flops. The preamplifier can receive signals from the detector via the bump-bond or test signals from an external pulse generator via a test capacitance for electrical characterisation. There are 2 additional static flip-flops to mask noisy pixels and to enable electrical testing. These flip-flops along with the threshold adjust flip-flops are organised as a shift register. The output of the preamplifier is connected to a short delay line producing a pulse which is used to reset the comparator and to act as a clock for the counter when the shutter is low. This counter is a shift register whose 14^{th} and 15^{th} bits are fed back via an exclusive-or gate to the input. This is in fact a pseudo-random counter[7]. When the shutter is high, the feedback loop of the counter is broken and the 15 bits are connected in series to the upper and lower pixels of the same column in order to form a

15 x 64-bit shift register. The 64 columns of the chip are connected in groups of four and multiplexed onto the 16-bit input/output bus. The same bus is also used to load the 5 x 64-bit configuration register. Both loading and readout operations can be performed at a frequency of 10 MHz. A photograph of the chip is shown in Figure 2.

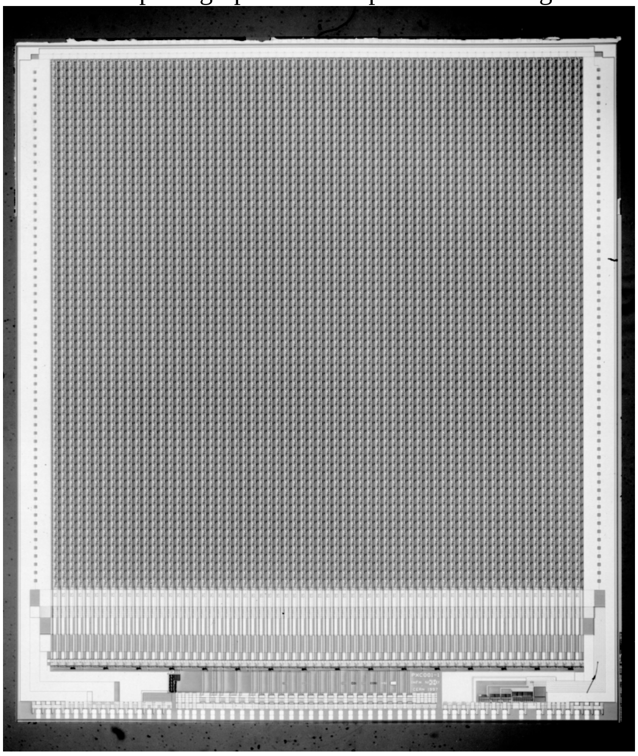

Figure 2: Photograph of the single Photon Counting Chip.

3. ELECTRICAL MEASUREMENTS

A complete characterisation of the electrical performance of the chip has been carried out prior to bump-bonding. As already mentioned, electrical tests are possible thanks to a capacitance which is connected to the input of the readout chain and is enabled by a configuration bit. The input capacitance is identical to the one used for LHC1/Omega3, for which calibration measurements gave a value of 14.9 fF. An accurate calibration of the PCC input capacitance has not been carried out, but preliminary measurements with γ-rays sources are in reasonable agreement with that value. The electrical test results are summarised in Table 1.

Minimum Threshold	1 400 e^-
Threshold linearity	1 400 e^- to 7 000 e^-
Threshold variation (no adjust)	350 e^-
Threshold variation (adjust)	80 e^-
Noise	170 e^-
Maximum input signal	> 80 000 e^-
Maximum counting rate	2 MHz

Table 1: Summary of electrical measurements of the PCC chip.

These measurements have been repeated on several chips and show good reproducibility. Some wafers have been probe tested and Known Good Die have been selected for bump bonding. The criteria followed for selecting chips were based on functionality, minimum threshold and threshold dispersion considerations. Chips with less than 2500 e^- as mean minimum threshold, less than 400 e^- before adjustment and more than 4000 working pixels met these criteria. These chips have been selected for bump-bonding to the detector.

4. RADIOACTIVE SOURCE MEASUREMENTS

Prior to making images with the chip/detector assemblies the operating point of the electronics has been optimised, the threshold locally adjusted and then reduced to the minimum achievable value. The minimum mean threshold obtained with the detector connected is 2 000 e^- with a variation of 125 e^- rms(see Figure 3).

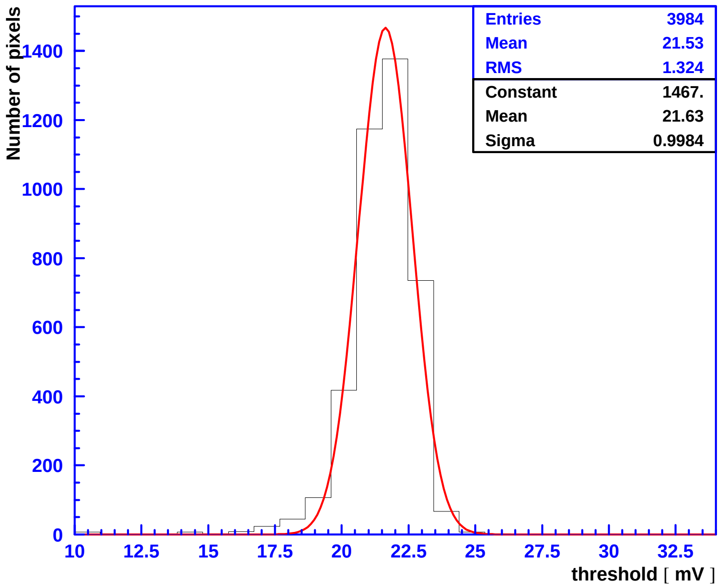

Figure 3: Distribution of thresholds after adjustment.

The functional behaviour of the assembly as well as the bump-bonding uniformity was verified using a ^{90}Sr source. This source produces β^- particles with a cut-off energy of 2.32 MeV resulting from the decay of the ^{90}Y daughter isotope. Only a few pixels did not respond in this test.

Figure 4 shows the image of a 6 mm long steel screw placed on the back of the detector and irradiated with a ^{109}Cd source which has gamma photon emissions at 22.1 keV (~ 85 %) and 25 keV (~ 17%). The spatial resolution of the device is demonstrated by the possibility to observe the 500 µm thread of the screw. Moreover, this indicates that the mean threshold of the device is below the 22.1 keV line. A second image was taken of a 500 µm thick Tungsten wire bent in the form on an ‘m’ (see Figure 5). Once again the uniformity of response of the matrix can be appreciated.

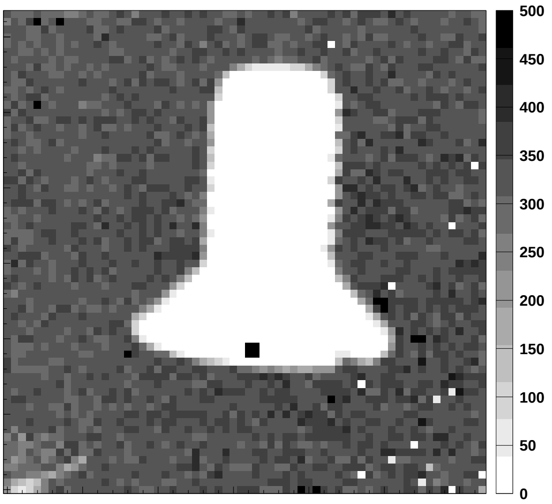

Figure 4: A 6 mm screw placed on the back of the detector and illuminated with ^{109}Cd.

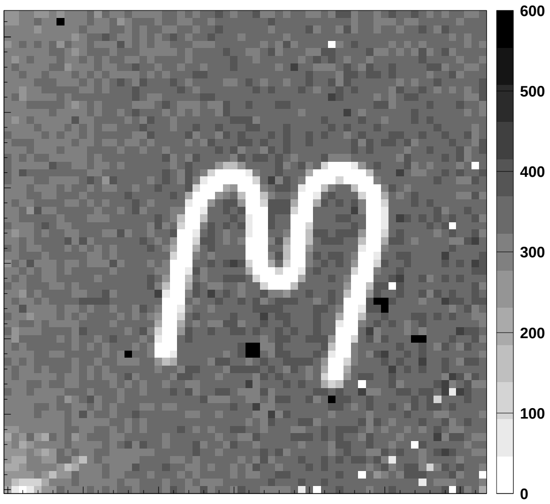

Figure 5: A 500 μm thick Tungsten wire placed on the back of the detector and illuminated with ^{109}Cd.

Another series of images were taken using an ^{241}Am source which has a peak emission at 60 keV. In each case one image was taken with the object in place and this was subtracted form the image taken without the object. This attenuates the effects of detector non-uniformity. Figure 6 shows the image of a steel object shaped like a cog, but with thickness varying between 300 μm and 500 μm and an inside diameter of 3 mm. The device was placed about 0.5 cm above the detector with the source around 1 cm away.

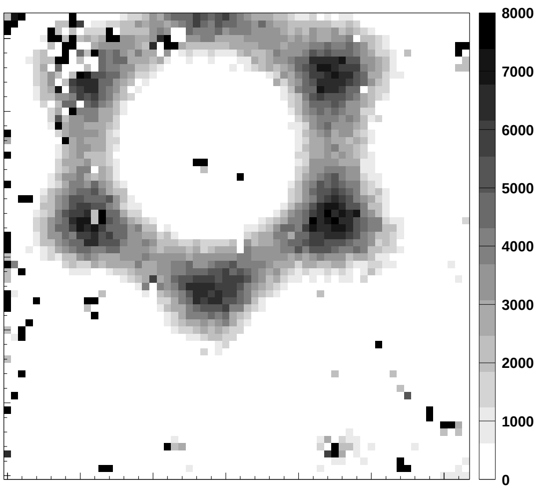

Figure 6: A steel object 0.5 cm from the back of the detector and illuminated with ^{241}Am. Background subtracted.

Several measurements have been carried out in order to get information about the minimum detectable contrast, where the contrast, *c*, is defined as:

$$c = \frac{n - n'}{n}$$

where *n* is the number of photons in the background and *n'* is the number of photon inside the target image. Aluminium strips of variable thickness and a width of around 1 mm have been imaged. The strips were placed ~ 1cm above the detector and the source was ~ 8 cm away inside a Plexiglas collimator . Table 2 shows the aluminium strip thickness, the theoretical contrasts and the measured contrasts with errors. From 3000 μm to 1000 μm there is a systematic underestimate of the contrast of the objects. This was associated with the photon scattering from the sides of the collimator. For the 540 μm and the 260 μm objects (see Figure 7) the collimator was removed and the measured results are in agreement with the theoretical values.

Al thickness (μm)	Theoretical contrast	Measured contrast
3000	20.29 %	17.12 % ± 1.67 %
2000	14.03 %	11.92 % ± 0.98 %
1000	7.28 %	6.45 % ± 0.56 %
540	4.00 %	3.87 % ± 0.48 %
260	1.94 %	1.85 % ± 0.24 %

Table 2: Theoretical and measured contrasts for Aluminium strips of varying thickness

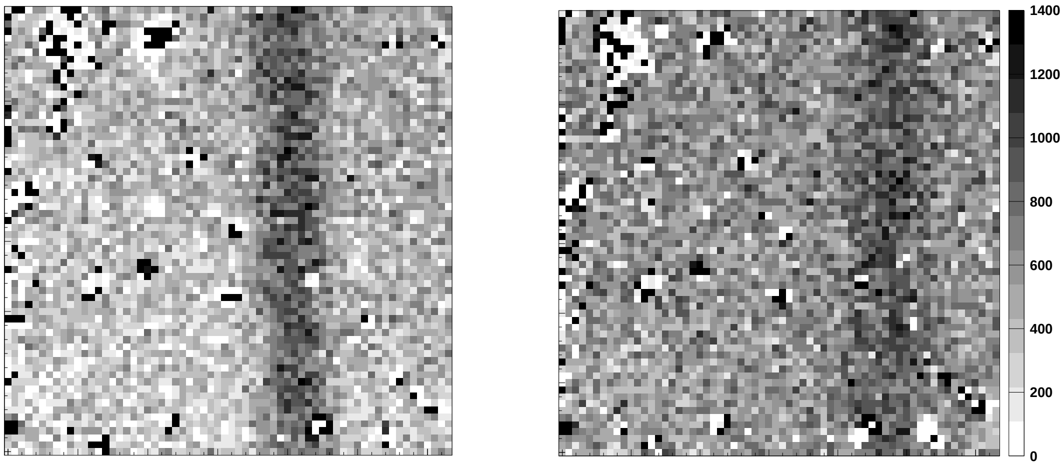

Figure 7: Images of 2 strips of Aluminium. On the left the strip is 540 μm thick representing a contrast of 4 % and on the right the strip is 260 μm thick representing a contrast of 1.9 %. Background subtracted.

5. CONCLUSIONS

A single Photon Counting Chip comprising 64 x 64 identical elements has been developed, characterised and bump-bonded to a GaAs detector. A minimum threshold of 2 000 e^- with a variation of 125 e^- rms after adjustment has been measured electrically subsequent to bump-bonding. Objects have been imaged using radioactive sources including ^{109}Cd with emissions at 22.1 keV and 25 keV. An object presenting a contrast of only 1.9 % has been successfully imaged.

5. ACKNOWLEDGEMENTS

The readout chip was developed as part of the Medipix project, a common development between CERN, University of Freiburg, University of Glasgow and INFN-Pisa. We gratefully acknowledge the contribution of G. Humpston of GEC-Marconi Materials Technology Limited, Caswell, Towcester, Northants., England for the bump-bonding.

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