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**IMAGING OF VISIBLE PHOTONS USING HYBRID
SILICON PIXEL DETECTORS***RD19 Collaboration*C. Da Vià, M. Campbell, E.H.M. Heijne and G. Stefanini
CERN, Geneva, Switzerland**Abstract**

A novel type of visible-photon pixel detector, which combines the usually conflicting features of fine spatial resolution and high readout rate, is being investigated. For this purpose, a modified, high-resistivity silicon detector has been bump-bonded to a CMOS readout chip and the device has been illuminated with various pulsed monochromatic light sources. The device has 1006 active elements with a short dimension of 75 μm , and can be read out at a clock frequency of 5 MHz. Although the structure was not optimized for photon detection, it was possible to measure almost the same quantum efficiency as a commercial silicon photodiode for short wavelengths and a better one in the near infrared. These photopixels could be used for high-speed, two-dimensional photon imaging and could replace, after image intensification, CCDs or multi-anode PMTs.

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1 INTRODUCTION

Hybrid silicon pixel detectors are of great interest in applications where very high spatial precision and a high readout rate are required. Several groups have been developing pixel detectors for tracking applications in high-energy-physics experiments [1], [2]. Other possible applications for such devices exist in the detection of X-rays and gamma rays in medicine and biology [3]. There are also cases in which it is impossible to use silicon devices as primary detectors because of the inefficiency of silicon as a detection medium. In these cases, the pixel detector might be used as a secondary detector where the primary detector converts an arriving particle into something which interacts with silicon. We decided to investigate a possible modification to the existing silicon pixel detectors developed by the CERN RD19 Collaboration, in order to obtain a two-dimensional photosensitive matrix with a high spatial resolution combined with a high readout rate. This paper reports on the optical characteristics which were measured using one of the modified pixel structures.

2 THE HYBRID PIXEL DETECTOR

The mechanical structure of the hybrid silicon pixel detector is shown in Fig. 1. A high-resistivity silicon detector is solder bump-bonded to a CMOS readout chip. The detector is segmented on the bump side into 1024 diodes which can be fully depleted by applying a voltage to the back side. The CMOS readout chip is also segmented into 1024 identical readout channels whose physical dimensions match those of the diodes. Each pixel measures $75\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$ and the matrix is arranged in 16 columns of 64 pixels. Thus the total sensitive area of the detector is $\sim 4.8\text{ mm} \times 8\text{ mm}$.

The block diagram of each electronic readout channel is shown in Fig. 2. A full discussion of the behaviour of the Omega-Ion pixel readout chip can be found in Ref. [4]. Briefly, charge detected on the diode is integrated on the feedback capacitor of the preamplifier and compared with an externally defined threshold. If the charge is greater than the threshold and its delayed arrival time coincides with the experimental trigger (strobe), a '1' is put in the D flip-flop. The flip-flops of one column form a shift register and all columns are read out as 16-bit words in 64 clock cycles. A typical threshold level is $8\,000\text{ e}^-$ and the readout clock frequency can be up to 5 MHz. Thus one complete frame can be read out in $12.5\text{ }\mu\text{s}$.

In the photosensitive version of the pixel detector, the aluminium layer on the back side of the silicon detector has been removed. The ohmic contact to the back side is assured by an n^+ implantation.

3 NOISE AND NON-UNIFORMITIES

In previous publications [5] we have been able to assess the behaviour of the readout chip using a row of test pixels at the top of the matrix, electrically injecting a signal across a test capacitance. In the case of the photosensitive pixel detector we have the possibility to address every pixel in the matrix.

A schematic diagram of the experimental set-up used for this purpose is shown in Fig. 3. In this case we focus the light of an infrared (IR) Light-Emitting Diode (LED) ($\lambda = 1060\text{ nm}$) into a $250\text{ }\mu\text{m}$ diameter fibre to produce a spot of the same diameter on the detector back side. The LED was then pulsed with the same frequency as the detector strobe and the strobe was adjusted to correspond with the 500 ns internal delay of the readout circuit.

From our previous electrical measurements we expected a large threshold variation from pixel to pixel. The threshold is measured by varying the input signal such that the output of a particular pixel responds positively to 50% of given strobes. We were able to vary the input signal amplitude by adjusting the LED bias voltage. The output in photons of the LED varies linearly with the applied voltage in the region of interest. Figure 4(a) shows the threshold variation across one row (row 37) and Fig. 4(b) shows the same data for one column (column 9). As we are unable to know in absolute terms how many electrons we are collecting in one pixel, we can make a first estimate of the threshold variation by dividing the standard deviation of the LED bias voltage by the mean. We find,

$$\sigma_{th}/Q_{th} \sim 16\% ,$$

where σ_{th} is the standard deviation of the threshold and Q_{th} is the mean. This number corresponds very closely to our electrical measurements [5]. In the column the variation was somewhat lower,

$$\sigma_{th}/Q_{th} \sim 12\% .$$

We expected this lower value because the electrical biasing for the pixel readout chip was done on a column-by-column basis.

We can make an estimate of the noise by plotting the number of positive responses over a given number of strobes versus the input signal amplitude. The curve obtained using this technique is shown in Fig. 5. The difference in input signal between 2% and 98% is equivalent to $4 \sigma_n$, where σ_n is the noise referred to the input. Calculating the ratio of noise over mean threshold,

$$\sigma_n/Q_{th} \sim 2\% ,$$

which corresponds to around $200 e^-$ if we assume a threshold of $10\,000 e^-$. This figure agrees with our radioactive source measurements [5].

Another important feature of the system is the non-uniformity of the internal delay from pixel to pixel. As in the previous measurement, we took advantage of the possibility of addressing a single pixel in the matrix, but for more precise injection of the optical power we used a pigtailed LED (ABB HAFO-1A184A, $\lambda = 850$ nm) with a $50 \mu m$ fibre core diameter. The LED was then pulsed with the same frequency as the detector strobe and the strobe signal rising edge was adjusted to coincide with the falling edge of the internally delayed signal (see Ref. [4]). This corresponds to the minimum delay of the collected charge arrival before the start of the readout.

Figure 6(a) shows the variation of the delay from pixel to pixel for one column (column 8) and Fig. 6(b) shows the same data for one row (row 12). Again the estimation of the delay variation is made by dividing the standard deviation of the measured delays σ_t by the mean delay D_t . For column 8 we found

$$\sigma_t/D_t \sim 3.4\% ,$$

and for row 12

$$\sigma_t/D_t \sim 8\% .$$

The row measurements correspond well to our previous electrical measurements [6] and the column measurements indicate once again a better uniformity than the rows.

4 PIXEL DETECTOR BEHAVIOUR AT DIFFERENT WAVELENGTHS

We then studied the behaviour of the pixel detector using visible light. The test set-up used is shown in Fig. 7. LEDs of three different wavelengths were used: red ($\lambda = 635$ nm), green ($\lambda = 565$ nm) and blue ($\lambda = 470$ nm). In order to check the responsivity of the detector to the various wavelengths, we monitored the current flowing into the back of the detector. This current is the sum of the detector leakage (dark) current and the photocurrent. We injected a constant DC current into the LED and noted the difference in the current from the detector with and without illumination. The results are shown in Table 1. In all cases the detector is sensitive to light. We can see, however, that the quantity of light injected per unit of drive current by the blue LED is less than for the others. We then compared the measured photocurrent of the detector with the photocurrent obtained from a commercial photodiode, UDT-FIL 100V. The results are also given in Table 1. It appears that the high-resistivity silicon detector is more sensitive than the commercial diode especially for longer wavelengths. This can be explained by the greater depletion depth of the silicon detector.

Table 1
Measured response of the silicon pixels and of the commercial photodiode (UDT-FIL 100V) at different wavelengths

LED type	λ (nm)	LED DC current (mA)	Pixel photocurrent (μ A)	Photodiode photocurrent (μ A)
Blue	470	50	0.70	0.64
Green	565	20	0.25	0.27
Red	635	20	3.6	3.9
IR	1060	20	4.2	0.9

The complete pixel detector, including the readout electronics, was then activated using the different LEDs. The LEDs were pulsed with a pulse of variable amplitude and a width of < 5 ns, and the strobe of the pixel electronics was synchronized to the LED drive circuit. As our pixel electronics is optimized for detecting pulsed charge, it is most sensitive when the photoelectric conversion takes place inside the depletion region of the silicon detector. To see this effect, we measured the LED bias voltage necessary to obtain 50% response from the pixel readout electronics at various detector bias voltages. Figure 8 shows the measurements we obtained with red and green light. In the case of the blue light we were never able to detect the converted photons, probably owing to the low intensity of illumination. In the case of the red light-source around 70 V detector bias was necessary before the required LED bias voltage flattened out, whereas with the green light around 110 V was necessary. This can be explained by realizing that most of the green light is deposited in the first 2 μ m of the silicon and this must be depleted for the photoelectrons to be fully detected. As the back side of the detector is implanted with n^+ to provide the ohmic contact, a large voltage is required for full depletion.

We therefore chose to work at 110 V when using the red LED and at 120 V when using the green one.

As a further verification of the good sensitivity of the pixel electronics to visible light, we repeated the noise measurements described above for the IR LED. Figure 9 shows the results we obtained. Again using a correction factor for the LED voltages and calculating σ_n/Q_{th} we obtain 2% for the red LED and 2% for the green LED.

Finally, we calculated the quantum efficiencies of the pixels relative to the UDT-FIL 100V [7] silicon photodiode. The results are shown in Fig. 10. The dots represent the ratio of the measured photocurrents, while the squares represent the ratio between the number of photons estimated at the threshold for a single pixel and the number of photons measured with the UDT photodiode at the same condition. The error on this second approach is essentially due to the incertitude of the dimension of the focused spot and, consequently, to the incertitude of the number of pixels illuminated during the measurement.

5 CONCLUSIONS

A modified version of the hybrid, micropattern detectors sensitive to visible photons has been tested. Using IR light we were able to confirm previous electrical measurements of noise, threshold, and timing for a row. We were also able to examine these parameters for a column. Furthermore, the pixel detector performed equally well for green and red light. The quantum efficiency of a matrix of 1024 elements has been measured showing good agreement with that of a commercial silicon photodiode. The possibility of using without any modification the already existing smart readout electronics and its further optimization makes the photopixels particularly attractive for applications of light detection requiring concurrently very high spatial precision and very high readout speed.

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Fig. 3 The optical set-up used for injecting light from the infrared LED

Fig. 4 Threshold levels expressed in terms of the LED bias voltage (normalized) (a) for row 37, (b) for column 9.

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Fig. 1 Sketch of a hybrid pixel detector

Fig. 2 Circuit block diagram of the readout electronics for one pixel channel. This circuit contains about 80 transistors.

Fig. 5 Number of positive pixel responses divided by the number of strobe pulses given for various input signals. This curve can be used to estimate the noise of the system.

Fig. 6 Internal delay distribution through the pixel matrix (a) for column 8, (b) for row 12.

Fig. 7 The optical set-up used for injecting visible light into the pixel detector

Fig. 8 The LED input voltage required to have pixel responses in 50% of strobes

Fig. 9 Noise measurement results obtained for red and green LEDs

Fig. 10 Comparison of the quantum efficiency of the silicon detector with the commercial photodiode