Si PAD DETECTORS[†]

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ABSTRACT

Si pad detectors with 256 separate cells with routing of each pad to external bonding pads for connection with strip detector front-end chips have been developed. The principles of the detector layout and technology are described. These detectors are connected to low noise VA2 chips. The spatial and energy resolution are determined. Some possible applications are discussed.

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 - †) This paper is dedicated to the memory of our friend and colleague Klaus Ratz, who worked for 30 years at CERN and died on the 25th of November

1. INTRODUCTION

In cases where a Si pixel or pad device with only a limited number of cells is needed to measure x,y-coordinates and the energy of radiation, it can be convenient to use multicell readout electronics at the circumference or out of the plane of the device. The pads are simply routed to an area where available 128-channel strip detector front-end chips are mounted. The practical limit when using 4" wafers would be a pad detector with about 6000 pads, each with an area in the range of roughly $100 \times 100 \mu\text{m}^2$ to $1 \times 1 \text{ mm}^2$. In the case of $100 \times 100 \mu\text{m}^2$, the overall sensor size would be maximally $7.5 \times 7.5 \text{ mm}^2$. The main advantages in this approach are that there are fewer constraints on the layout and implementation of FE electronics compared with genuine pixel device readout electronics with bump bond connection. It will be easier to implement low noise performance, implement complex functions and have a simple connection technology with wire bonding.

2. THE PAD SENSORS

The 256-cell sensors have been produced using standard planar technology, which has been developed for the manufacturing of Si strip sensors [1,2]. Two different designs are available, one with $150 \times 150 \mu\text{m}$ cells (device A), and one with $300 \times 300 \mu\text{m}$ cells (device B), with $2.4 \times 2.4 \text{ mm}^2$ and $4.8 \times 4.8 \text{ mm}^2$ surface, respectively (Fig. 1).

The technology involves relatively simple single-sided processing. The p^+ -implantation, to create pn junction pads and guard rings, is performed through $1000 \text{ \AA}$ field oxide. The lateral distance between implants is $20 \mu\text{m}$. After n^+ -implantation on the backside, a $1 \mu\text{m}$ thick oxide (LTO) is deposited on both surfaces of the detector. Small $10 \mu\text{m} \times 10 \mu\text{m}$ contacts are opened in the middle of each pad and the oxide on the backside is removed. Both sides are metallised with Al about $1 \mu\text{m}$ thick and the metal pattern is etched. The size of the metal contact pads is $50 \mu\text{m} \times 50 \mu\text{m}$ and the lines have a width of $5 \mu\text{m}$. The 128-bond pads arranged in double rows at the edge of the detector have dimensions of $60 \mu\text{m} \times 120 \mu\text{m}$. The guard ring surrounding the pad area and two guard rings around the outer periphery of the detector can be contacted separately.

About 45 devices of each type have been produced on $345 \mu\text{m}$ thick high resistivity wafers. Measurement of the reverse bias current yields 25 - 30 pA for a single pad at $V_B = 70 \text{ V}$. The CV curve shows full depletion at $V_B = 70 \text{ V}$.

3. READOUT ELECTRONICS

3.1 *The Si Pad Detector Readout*

In order to fully exploit the low capacitance of the sensor cells, which is estimated to be below 1 pF on average per pad, a readout chip with low input capacitance has been connected to these devices. This CMOS chip is the VA2 [3] chip, a further development of the VIKING chip [4,5]. It consists of 128 channels of preamplifier, shaper, sample/hold, and an input and output multiplexer (Fig. 2). At the output of the shaper, one obtains a true CR-RC pulse form. The noise of this chip was measured by loading one of the 128 inputs with several calibrated capacitances up to 40 pF. In this way a noise of $ENC(rms) = 68 e^- + 11.3 e^-/pF$ was measured (Fig. 3). The value of $68 e^-$ was measured on unbonded channels. The chip was tuned to a peaking time of $\tau_p = 2 \mu s$. The dynamic range was measured to cover $\pm 17 fC$ with full linearity. The output buffer of the chip saturates at about $\pm 25 fC$ (Fig. 4). For these measurements, the chip was powered at about 1.5 mW/channel.

3.2 *The Backplane Trigger*

In order to use the detector for measurement of X-rays or beta particles, which stop in the sensor, a backplane trigger circuit was connected to the backside n+ electrode. The circuit consists of a conventional charge amplifier, followed by a semi-Gaussian filter with one differentiation and five integration time constants. The amplifier was designed for a $1.2 \mu s$ peaking time. Low noise was obtained by using the SONY 2SK300 JFET in the input stage with an input capacitance of 8 pF, reasonably well matched to the capacitance of the whole backplane of about 15 pF. The measured noise was $ENC = 63 e^- + 3.3 e^-/pF$. The input JFET was operated at 15 mA drain current (Fig. 5). The trigger pulse, which generates the hold signal for the VA2 chips, occurs when a charge deposited in the Si gives rise to a voltage output of the shaper exceeding a set threshold on a comparator, which is part of the circuit.

3.3 *The Data Acquisition*

The data are sequentially clocked out at a rate of 2.5 MHz into a 10 MHz flash ADC. The flash ADC is part of a VME-controlled readout processor, which stores the result of the digitisation of each pulseheight in memories. The data are then written to hard disk for further off-line analysis.

Alternatively, a specially designed PC-compatible readout system has been used. This system has twelve 80 kHz ADC's, controlled by a DSP 56001, which also generates the necessary control signals and clocks for the VA2 chip. The DSP organises the data transfer into the PC via DMA.

4. FIRST RESULTS

4.1 *Energy Resolution*

Both devices, A and B, have been exposed to γ 's from ^{241}Am and several X-ray sources. In order to measure the energy resolution, events have been selected in 3 classes : events with a signal in one pad only (sample I), events with signals in 2 adjacent pads (sample II) and events with signals in 4 pads with one common corner (sample III). The selection was performed by requesting one pad with a signal larger than 10σ noise and none of the surrounding pads with a signal more than 2σ noise for sample I. Corresponding cuts requesting either one or three adjacent pads to have a signal larger than 3σ for sample II and sample III were applied. Seed signals occurring in any of the edge pads have been excluded for the purpose of this study, since for such events it is impossible to determine if charge has been shared with the surrounding guard ring.

Channel to channel gain corrections have to be applied, since one expects small gain variations across the 128 channels of each chip. The relative gain of each channel was determined with a sample of ^{241}Am events with an energy spectrum plotted for each pad separately. A Gaussian fit was performed to find the peak position for the spectrum of each pad (Fig. 6). The fit was performed identically for each spectrum by always choosing the same number of bins to the left and right of the peak to be included in the fit. The gain variations for the two chips of device B are shown in Fig. 7. A new data set is then taken and all data from all pads are combined in one plot. The noise values measured from the baselines are shown as Lego plot in Fig. 8. The distribution of noise values for all pads of each device is shown in Fig. 9. Gaussian fits give an average of 0.640 keV FWHM with a spread of $\sigma = 56$ eV for device A and 0.840 keV FWHM with the same spread for device B. The resulting ^{241}Am spectrum is shown in Fig. 10 for both devices A and B. For device B, the spectrum is separated in pads belonging to chip 1 and chip 2, the chip mountings on both sides having slightly different noise performance. The results from the Gaussian fits are shown in Table 1.

Using the same gain corrections, X-ray spectra were taken with Tb, Ba, Ag, Mo, Rb and Fe X-ray sources. The results are shown in Fig. 11 for device A and in Fig. 12 for device B. In the figures, one can observe for each K_{α} -line a distinct peak about 15% in energy below each line. These peaks are caused by pick-up of signals on routing lines and bond pads from X-rays hitting the detector outside the actual p^+ pad area. This is due to the fact that the guard ring was not extended under the routing lines and bond pads situated outside the sensitive pad area. It has been corrected in new devices which will soon be available. Gaussian fits are performed by separately fitting two lines for the K_{α} peak and two lines for the K_{β} peak of each element. The free parameters in the fits are the peak position of one line, the width of each line (assumed to be the same), and the relative intensities. For Rb the 2 K_{α} lines are separated by only 60 eV. Therefore, in this case, a fit of 3 Gaussians for a single K_{α} line and 2 K_{β} lines with fixed distance of the peaks was performed. The separation of K_{α} lines and K_{β} lines in each fit is entered as a constant ($\Delta E_{\alpha,\beta}$ in Table 1), which is taken from precise spectroscopic measurements [6]. Table 1 shows the results for these fits. It should be noted that the data with the Rb source for device A have been taken after retuning the device. The fit results can therefore not be compared directly with the other measurements.

Correcting the values from ^{241}Am for the natural ionisation width with a Fano factor of $F = 0.14$, the energy resolution due to electronic noise from the detector load capacitance and parallel noise due to leakage

current for device A is 750 eV FWHM. This value is dominated by the series noise of the preamplifiers (see Fig. 9).

Events which share charge between pads are expected to have worse energy resolution. For sample II and sample III events, the ^{241}Am spectra are shown in Fig. 13 and Fig. 14. The Gaussian fit values for the peak energy and width are given in Table 2. A small signal loss with respect to sample I events is observed. For comparison the noise values for 2 and 4 adjacent pedestals summed up are also shown.

4.2 Measurement in a High Energy Particle Beam

Device A was set up in a 100 GeV $^1\text{-beam}$ at the centre of a high resolution Si strip detector beam telescope [7]. Track extrapolation to the pad detector can be done with a precision better than $\sigma_{\text{EXT}} = 2 \mu\text{m}$. Data were taken with the beam impinging at 0° with respect to the direction perpendicular to the surface of the pad detectors and at 30° , 45° and 60° . Some preliminary results are reported here from data sets at 0° , 30° and 60° . These measurements were done to determine the intrinsic spatial resolution of such devices. Studies of this kind can, however, also provide useful information on the design of pixel detectors planned for LHC.

4.2.1 Perpendicular Tracks

A typical signal for a 0° track is shown in Fig. 15. The measured signal over noise distribution is shown in Fig. 16. A signal over noise ratio at the peak of the Landau distribution of about 330:1 is observed. This corresponds to an average noise of all the channels of $78 e^- \text{ ENC}$, in good agreement with what is expected from the noise slope of the VA2 chip and a capacitive load of each pad between 1 to 2 pF.

The coordinate in the pad detector was taken at the centre of the pad for single-hit events and it was calculated by analog interpolation, using the observed η distribution [7] in the case of double-hit events (η is the pulseheight of one pad divided by the sum of pulseheights on two pads). The difference of this coordinate and the extrapolated position of the related track on the pad detector calculated from the reference telescope results in residual distributions shown in Fig. 17. Gaussian fits result in a spatial resolution of $\sigma = 3.7 \mu\text{m}$ for two-pad hits in both co-ordinates and of $\sigma = 34 \mu\text{m}$ for one-pad hits. Roughly 50% of all events show charge sharing between pads either in x or y.

4.2.2 Inclined Tracks

Similar preliminary studies have been done for the data sample with tracks impinging at 30° and 60° . As expected in the case of 30° , at least two pads and in the case of 60° , most of the time five pads have a measurable charge signal.

Here only preliminary results on the spatial resolution are quoted. The coordinate being affected by the track inclination is measured with a precision $\sigma = 16 \mu\text{m}$ and $\sigma = 18 \mu\text{m}$, for 30° and 60° tracks respectively (Fig. 18). In the orthogonal coordinate, the results are similar as for 0° , namely $\sigma = 4.9 \mu\text{m}$ and $\sigma = 36 \mu\text{m}$ in the case of charge sharing or no charge sharing between neighbouring pads for 30° tracks and $\sigma = 8.3 \mu\text{m}$ and $\sigma = 33 \mu\text{m}$ for 60° tracks. The deterioration of the resolution in the case of charge sharing

compared with the 0° track sample is explained by the fact that the signal always appears on more than one pad and therefore the noise of several pads affects the resolution.

5. **POSSIBLE APPLICATIONS**

At present there are a number of pad devices developed to be installed in collider experiments (e.g. the backward Si tracker in the H1 experiment, a Si multiplicity detector in the WA80 heavy ion experiment, the DELPHI experiment, etc...). There could however be a large number of applications in imaging, both in biomedical, medical and material science. Here follows a brief discussion of two developments aimed at an application of Si pad detectors in a Compton camera for nuclear medicine [8] and in a hybrid multicell photon detector for detecting photons from Cerenkov radiation [9].

5.1 *A Compton Camera for Nuclear Medical Imaging*

At present, conventional γ - cameras, using detection techniques based on thick Pb filters, have efficiencies at the best between 10^{-4} to 10^{-5} [10].

Using the Compton effect, a method has been worked out [11] to reconstruct the direction of the primary photon, coming from the object to be imaged, by iterative back projection methods (Fig. 19).

With the Compton Camera principle, which does not need a Pb collimator, one can expect a conversion probability of several percent (e.g. 5 slabs of Si 1 mm [2 mm] thick will give a Compton interaction probability of about 10% [20%]).

The pad detector, which measures the recoil electron from the Compton process, has to measure the γ impact position with 1 - 2 mm accuracy. The error of the determination of the original photon's direction will be dominated by the energy resolution. At 140 keV incident energy and 45° scattering angle, an error of 1keV in the energy-measurement results in an error of 2.5° in the determination of that angle.

A prototype detector of $3\text{cm} \times 3\text{cm}$ with $1.2 \times 1.2 \text{ mm}^2$ pads has been designed and is under production (Fig. 20).

The detector to measure the position and energy of the Compton scattered γ is assumed to have an efficiency of nearly 100%. Again this detector could be an array of Si pads measuring scintillation photons emitted when the scattered γ is absorbed in a layer of CsI(Tl).

5.2 *A Hybrid Photon Detector*

This project aims at a development of a hybrid photon detector (HPD) [12] to be the main detection element in a RICH counter. The Cerenkov photons create photoelectrons in the photo cathode of a relatively large tube with a diameter of about 10 cm. A high voltage ($\sim 10 - 15$ kV) accelerates the electrons to 10 to 15 keV. On the bottom a 256-element Si pad detector with $4 \times 4 \text{ mm}^2$ pads measures the electron position and

energy. Considering the low energy of the electrons, the entrance window into the pad detector has to be thin. A prototype sensor is under development. Optimally-adapted low-noise electronics is required to measure signals in the range of 2000 - 4000 electron-hole pairs.

6. CONCLUSIONS

Multicell Si pad detectors with readout on the periphery of the sensor have been tested using low noise Si strip detector readout electronics. Excellent energy resolution has been demonstrated with an ^{241}Am source and several X-ray sources. For two 256 cell devices, an energy resolution between 750 eV and 1000 eV has been measured. These devices have also been exposed to a 100 GeV l^- beam. A signal to noise ratio for minimum ionising particles of 330:1 has been measured. For a device with $150\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$ pads, a spatial resolution of $\sigma = 35\text{ }\mu\text{m}$ for events with a single hit and $\sigma = 4\text{ }\mu\text{m}$ for events with charge deposited on 2 pads has been measured. For inclined tracks at 30° and 60° , the spatial resolution measured was $\sigma = 16 - 18\text{ }\mu\text{m}$.

Several possible applications for such pad devices are discussed.

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Table 1
Results from Gaussian fits to ^{241}Am and X-ray spectra. See text.

		Device A		Device B		
		Peak [keV]	σ [keV]	Peak [keV]	σ [keV]	ΔE Double-fit [keV]
^{55}Fe (Mn)	$K_{\alpha,\beta}$	5.7	0.32	5.8	0.39	0.6
Rb	$K_{\alpha 1}$	13.1	0.40	13.3	0.39	0.06
	$K_{\beta 1}$	14.6	0.40	14.8	0.39	0.23
Mo	$K_{\alpha 1}$	17.0	0.36	16.7	0.37	0.11
	$K_{\beta 1}$	19.1	0.34	18.8	0.34	0.36
Ag	$K_{\alpha 1}$	21.7	0.38	21.9	0.42	0.17
	$K_{\beta 1}$	24.3	0.31	24.9	0.46	0.54
Ba	$K_{\alpha 1}$	31.5	0.43	31.6	0.41	0.47
	$K_{\beta 1}$	36.1	0.48	36.2	0.47	0.96
Tb	$K_{\alpha 1}$	43.6	0.42	43.8	0.44	0.74
	$K_{\beta 1}$	50.3	0.41	50.4	0.49	1.47
^{241}Am (60)		59.58	0.36	59.59	0.46	
^{241}Am (26)		25.84	0.42	25.99	0.51	
First chip				59.60	0.42	
Second chip				59.60	0.48	

Table 2
Peak position and energy resolution for events that share charge between pads.

	Device A				Device B			
	Peak [keV]	σ [keV]	quantity [%]	noise [keV]	Peak [keV]	σ [keV]	quantity [%]	noise [keV]
Sample I	59.6	0.44	53	0.36	59.6	0.48	78	0.37
Sample II	58.7	0.70	42	0.52	58.7	0.66	21	0.55
Sample III	57.4	0.95	5	0.76	57.5	0.94	1	0.80

Figure Captions

- Fig.1 The geometrical layout of a pad device. Device B.
- Fig. 2 Schematics of the VA2 chip.
- Fig. 3 Noise slope of VA2 chip.
- Fig. 4 The dynamic range of VA2.
- Fig. 5 Measured noise of the backplane trigger.
- Fig. 6 ^{241}Am energy spectrum of hits in a particular pad. The line represents a Gaussian fit.
- Fig. 7 Gain variations over the 256 channels of both chips of device B.
- Fig. 8 Lego plot of noise values measured for all channels. The vertical scale is calibrated in eV using the Am peak as reference.
- Fig. 9 Average electronic noise. Projection of noise distribution for all channels for device A and B. The channels with noise greater than 350/450 eV are not used in the energy spectra.
- Fig. 10 Gain-corrected Am spectrum for devices A and B. All Pads added. For device B the spectrum is shown for each chip separately. The fits are Gaussians.
- Fig. 11 X-ray spectra with Gaussian fits (as described in text) for device A.
(a) Lines measured with Fe, Rb, Mo, Ag and Am sources;
(b) Lines measured with Ba, Tb and Am sources.
- Fig. 12 The same as in Fig. 11 for device B.
- Fig. 13 Am spectra separately for sample I, II and III events for device A. The fit values are slightly different for sample I events compared with values given in Table 1, since the device has been returned for this measurement.
- Fig. 14 Same as Fig. 13 for device B.
- Fig. 15 Typical event. Pulseheights on pads which receive charge from a traversing 100 GeV pion. The total measured pulseheight for this event gave $S/N = 310$.
- Fig. 16 Signal over noise distribution for 100 GeV π^- traversing pads perpendicular to surface (0° tracks).
- Fig. 17 Residual distributions for 0° tracks; (a) no charge sharing between strips, (b) with charge sharing in x-direction, (c) with charge sharing in y-direction.

Fig. 18 Residual distributions for 30° (a) and 60° (b) tracks for the co-ordinate in which the tracks are inclined.

Fig. 19 Principle of a Compton camera.

Fig. 20 Prototype pad detector layout for Compton camera.

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Compton Imaging System

Fig. 19

Fig. 20