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A single photon resolution integrating chip for microstrip detectors

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ABSTRACT

A charge integrating readout chip for silicon strip sensors is currently under development at Paul Sherrer Institut. The goal of the project is to provide a readout system that can sustain, through charge integration and automatic gain switching, the instantaneous many-photon deposition typical of the forthcoming XFEL machines. Nevertheless, a charge integrating readout with single photon sensitivity presents several features that can be exploited in many Synchrotron source applications: the possibility of a higher position resolution, the high photon rate capabilities and the possibility to detect low energy photon. A prototype of the readout chip (ROC) has been integrated with a strip detector and with a dedicated DAQ electronic, and it has been tested at the SYRMEP beam line (ELETTRA, Trieste). This work presents the readout chip and shows the results of the beam line tests in terms of spatial resolution and rate capabilities.

1. Introduction

Paul Scherrer Institut is part of the AGIPD collaboration whose goal is to provide a pixel detector for the forthcoming European XFEL [1]. Since in the case of XFEL machines up to several 1000 photons impinge on one detector channel at a time, a photon counting approach cannot be used and a charge integrating system with single photon sensitivity has to be developed.

However, a charge integrating readout offers several advantages compared to photon counting electronics also in synchrotron source applications. Unlike a photon counting detector, that ceases to work if the charge is always shared on two or more strips [2], smaller strip pitches are possible. Moreover, it is feasible to use the analog information to further improve the spatial resolution through charge interpolation methods.

A second feature is that very high photon rates can be handled, since pile-up is not an issue. Finally, trading off the single photon resolution, very low energies are accessible, the only limit being the absorption in the entrance window and in the dead Si layer of the sensor.

A prototype of the charge integrating readout chip for silicon strip sensors (GOTTHARD, Gain Optimizing microsTrip sysTem witH Analog ReaDout) has been designed and integrated with a sensor and with a dedicated DAQ electronic. The noise, dynamic range and gain switching performances of GOTTHARD have been reported in Ref. [3]. The present work will focus on the spatial resolution and rate capabilities of the system, tested at the SYRMEP [4] beam line at Elettra.

2. The chip and the detector module

The prototype of the GOTTHARD readout chip, designed in UMC 0.25 μm technology, consists of 100 identical parallel channels. The sketch of a channel is shown in Fig. 1. The switching gain logic, not discussed in the present work, is described in Ref. [3]. The circuit is basically a low noise preamplifier in charge integrating configuration where the small feedback capacitor provides the high gain needed for single photon resolution. As soon as the reset switch is released, the charge starts to be integrated on the feedback capacitor, so that the output voltage follows the $V_{out}=Q_{in}/C_f$ relation.

Two sample and hold capacitors are present; it is thus possible to perform the first sampling of the output voltage just after the reset and a second sampling at the end of the integration time. The difference of the two readouts gives the integrated charge free from any reset noise contribution; this procedure is called Correlated Double Sampling (CDS). The voltage on the sampling capacitor is sent out, one channel after the other, to an external ADC at the end of the integration time. In order to perform the high resolution measurement a four chip module has been assembled with a 320 μm thick, multi-pitch silicon strip sensor designed by PSI and manufactured by Hamamatsu. A closeup of the sensor is shown in Fig. 2. It has nine groups of strips with

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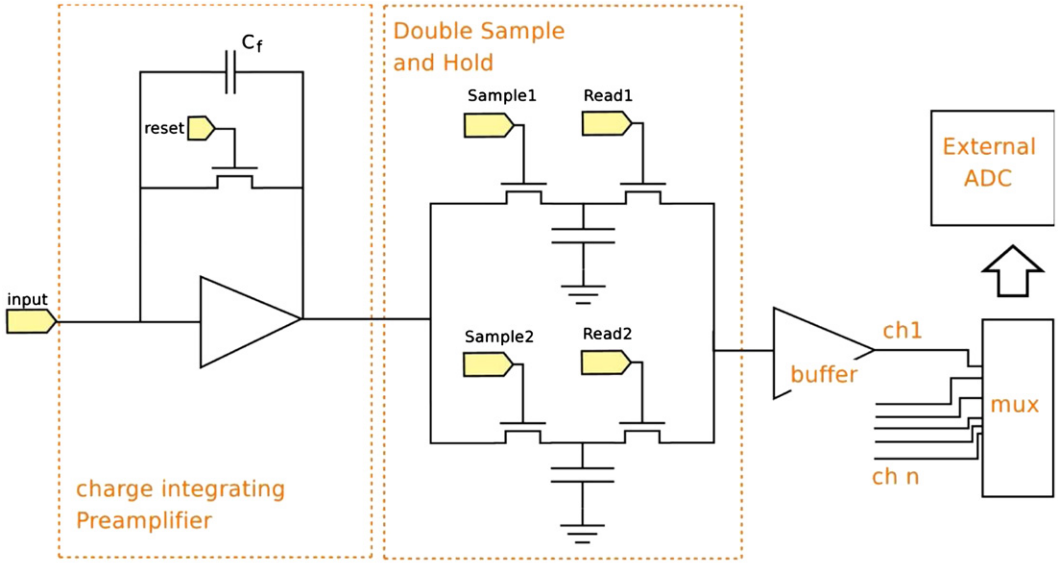

Fig. 1. Simplified block diagram of the GOTTHARD chip. The switching gain logic is not shown.

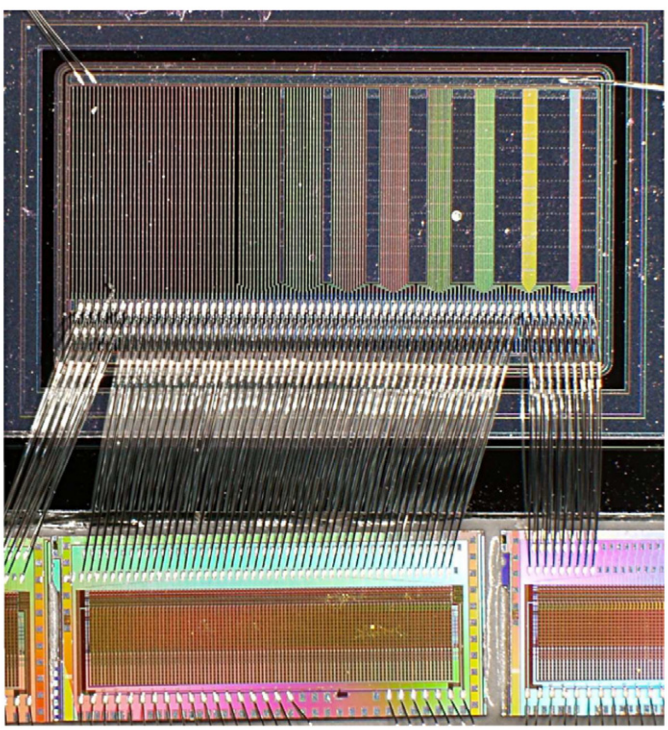

Fig. 2. Picture of the 128 ch. multi-pitch strip sensor bonded to the GOTTHARD readout chips. From right to left structures of 10−15−20−25−30−35−40−45−50 μm pitch are visible.

different pitches, each one made of 11 strips plus the fan out to connect the implants to the 50 μm pitch readout chips. Charge integration systems are very sensitive to the sensor leakage current; for this reason the board hosts a Peltier cooling system that can lower the temperature down to $\sim 10\,^\circ$C reducing the current by roughly a factor 10. The DAQ system is based on an AXIS[1] embedded processor connected to an Altera CycloneII FPGA. The digital control of the ROC is handled by the FPGA, while the analog readout is performed by two 14 bit 80 MHz ADCs[2] whose digital outputs are buffered in the FPGA memory and transferred to the embedded processor. The latter is controlled from the user PC via a tcp-ip socket interface over 100 MBit/s Ethernet, allowing a system readout at frame rates up to ~ 300 Hz.

3. Spatial resolution measurements

The noise figure of the GOTTHARD system in high gain mode is 1.2 keV r.m.s. [3]. That means a signal to noise ratio (SNR) greater than 10 for photon energies of 12 keV or bigger. Tracking applications of strip detector in high energy physics have shown that with center of mass methods it is possible to improve the spatial resolution σ_x down to $\sigma_x \simeq p/SNR$ where p is the strip pitch [5]. With a low noise charge integration system like GOTTHARD it is possible to apply the same principle to an X-ray detector.

Several methods for position interpolation in silicon strip detectors are reported in literature [6,7]: for the early test here reported we have chosen to use a simple analytical approach. If we assume that the charge release of a photon has a Gaussian distribution with width σ, a photon hitting the sensor at a position x from the boundary between strip L and strip R will release a charge $Q_R = Q_{tot}(erf(x/\sigma)+1)/2$ on the right strip, where Q_{tot} is the total charge release.

Inverting the relation it is possible to extract the hit position $x = erf^{-1}((Q_R/Q_L+Q_R)2-1)\sigma$ where erf^{-1} is the inverse error function. The width σ is not know a priory, since it is related to many sensor characteristic, like bias voltage and implant size, and to the photon energy; for this reason the parameter is iteratively tuned (starting from a guess value of 10 μm) in order to obtain a flat profile on the position distribution; a value of 9.2 μm is for example used for the 20 μm pitch sensor at 120 V bias and 20 keV photon energy. To test the procedure we performed a knife edge scan [2] at the SYRMEP beam line. The sensor has been placed in the 20 keV X-ray beam, with strips running vertical. The beam was shaped with slits, so that it was hitting the full width of the sensor in the horizontal direction and only ~ 10 μm in the vertical one; in this way the contribution of the sensor alignment to the

[1] http://www.axis.com

[2] AD9640, http://www.analog.com

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spatial resolution is made negligible. Several vertical tungsten slits have been placed in front of the sensor, mounted on a high precision translation stage with a 0.05 μm resolution. A picture of the setup is shown in Fig. 3.

The integration time has been selected in order to have, on any channel, a photon every few frames (20 μs with the available flux). In this condition the photons are most frequently isolated in the frame, i.e. they have at least an unoccupied strip on the left and on the right, so that is possible to apply the position interpolation procedure.

The *W* slits have been horizontally moved in 0.2 μm steps in front of the detector, over a range of a few silicon strips; 9000 frames have been collected at every motor step and the position of the motor has been recorded in the data files. For each frame the positions of all the isolated photons have been interpolated. These positions have been used to fill the X-ray profile corresponding to the given step of the motor. The different profiles, one per step, have been shifted by the motor position and superimposed, obtaining, in the 20 μm pitch case, the edge spread function shown in Fig. 4. The data are fitted with an error function; the width of the latter, corresponding to the width of the Point Spread Function (PSF), is $\sim 3.3\,\mu m$.

The procedure has been repeated for strip pitches in the 15−30 μm range. The 20 μm strip pitch data provided the best result; with bigger pitches the probability of the charge sharing effect to occur is reduced, so that the position interpolation is applied less frequently, while in case of smaller pitches the higher inter-strip capacitance increases the noise and the charge is shared on more than two strips, so the *S*/*N* is degraded. Since the balance of these two opposite effects depends on the detector parameters (e.g. sensor bias voltage, 120 V during our measurement), the optimum for 20 μm pitch has to be considered system specific.

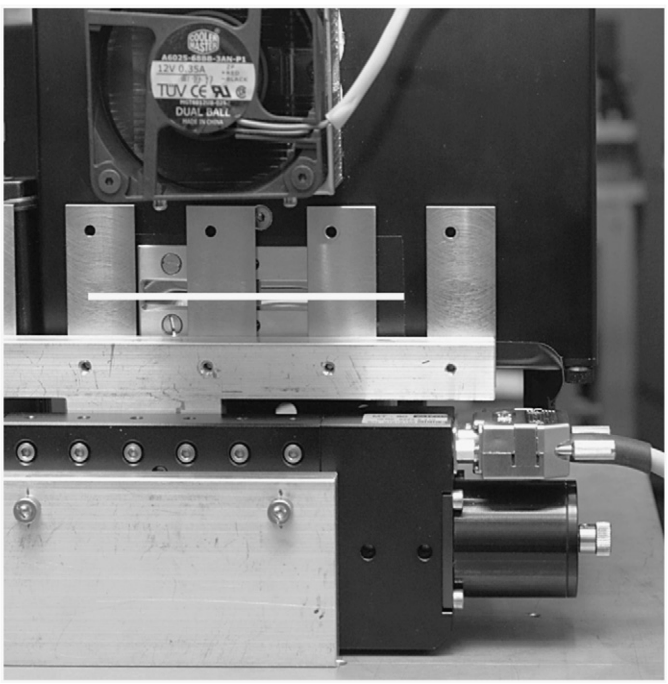

Fig. 3. Setup for knife edge scan measurement as seen from the X-ray beam. The entrance window of the GOTTHARD detector is visible behind the tungsten slits. The slits are 5 mm thick and have a 5° knife angle. The horizontal white bar is an over-sized representation of the 10 μm high photon beam.

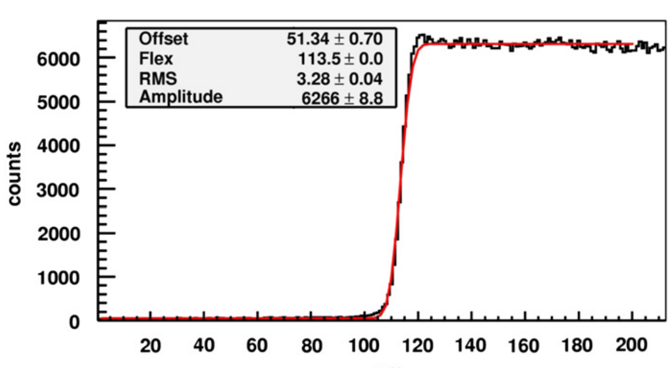

Fig. 4. Edge spread function obtained with the position interpolation method in the 20 μm pitch case. The profile is obtained superimposing the images of the *W* slit recorded at different steps after shifting each one by the corresponding motor position. A fit with an error function is superimposed.

4. High rate capabilities

To verify the capability of the GOTTHARD system to sustain high photon rates, a rate scan has been performed at the SYRMEP beam line. The beam energy was set to 15 keV and the integration time fixed to 5 μs. The intensity has then been varied, by means of an Aluminum filter box, over three orders of magnitude. The beam intensity was monitored with a ionization chamber. At lower rates, when the occupancy is very low, the system behave as a photon counting detector and it is intrinsically linear. On the other hand, when many photons are collected on the same channel during one integration time the number of photons arriving on the sensor is not constant frame by frame but follows Poisson statistics. The fluctuations of the output of the detector at the maximum rate available at the beam line are shown in Fig. 5. The value on the *x*-axis has been obtained by translating the ADC output into number of photons taking into account the single photon average output measured at lower rates. The number of photons has also been cross-checked with the ionization chamber output. As the superimposed Poisson function shows, the

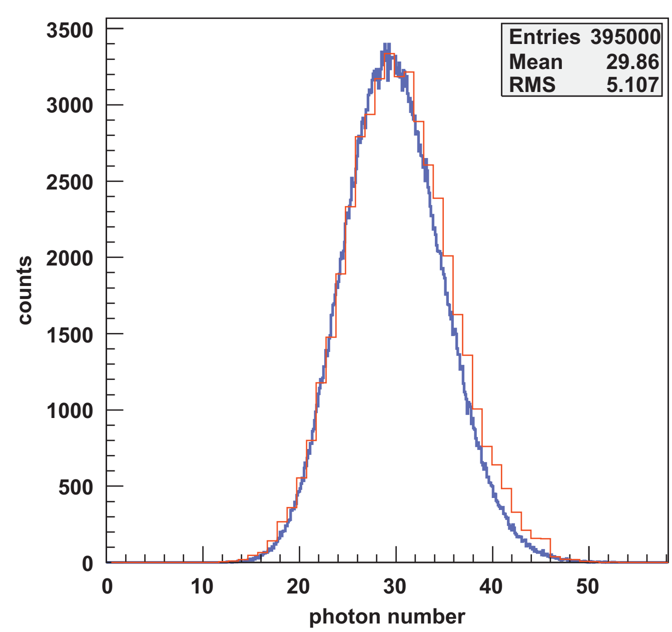

Fig. 5. Distribution of the measured intensities, translated into number of photons, for a number of frames at fixed intensity. A Poisson function with mean ($\lambda = 29$) is superimposed.

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fluctuations are entirely due to Poisson statistics and the electronic noise contribution is negligible. This is a key feature of the system, since it implies the possibility, for a charge integrating detector, to count the number of photon arriving in each integration time with the best possible uncertainty, at least in case of monochromatic beam. It is thus possible to design an integrating detector with the same data quality as a photon counting one but without the limit in maximum photon rate of the latter. In Fig. 5 an average of 30 15 keV photons were counted per integration time, with the output voltage still far from saturation; a range in excess of 100 12 keV photons will be easily obtained with an optimized readout chip.

In such a future system, the effective rate capability will scale with the frame rate. In Fact, even with concurrent acquisition and readout (i.e. the previous frame is readout while the current is being measured), the integration time should not be shorter than the readout one to avoid excessive dead time. Since a realistic frame rate of a ROC for a strip sensor is 1 MHz, the charge integration system will allow an accurate detection of photon fluxes in the order of 100 MHz γ/ch, two orders of magnitude higher than the state of the art photon counting systems [8,9].

5. Conclusions

The measurements with the GOTTHARD prototype presented in this work demonstrate that a charge integrating readout chip can overcome two of the fundamental limitations of photon counting systems for X-ray detection: they can drastically improve the spatial resolution by using smaller pitches and position interpolation algorithms, and they can sustain a much higher incoming photon rate.

The final version of the GOTTHARD chip, which will allow incoming photon rates up to 100 MHz/ch. and a very high spatial resolution for lower rates (few 100 kHz/ch.), is under development.

Acknowledgment

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