A high-speed pnCCD detector system for optical applications

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Abstract

Measurements of a frame-store pnCCD detector system, optimized for high-speed applications in the optical and near infrared (NIR) region, will be presented. The device with an image area of 13.5 mm by 13.5 mm and a pixel size of 51 \(\mu\)m by 51 \(\mu\)m exhibits a readout time faster than 1100 frames per second with an overall electronic noise contribution of less than three electrons. Variable operation modes of the detector system allow for even higher readout speeds by a pixel binning in transfer direction or, at slightly slower readout speeds, a further improvement in noise performance. We will also present the concept of a data acquisition system being able to handle pixel rates of more than 75 megapixel per second.

The application of an anti-reflective coating on the ultra-thin entrance window of the back illuminated detector together with the large sensitive volume ensures a high and uniform detection efficiency from the ultra violet to the NIR.

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1. Introduction

Adaptive optics (AO) has found widespread use in astronomical settings during the past years. Almost all current generation ground-based optical and near infrared (NIR) telescopes like VLT in Paranal in Chile or KECK on Hawaii are using this technique to improve the telescopes’ resolution. Due to advances in AO, these telescopes are often performing at the diffraction limit of the main optics [1]. A new generation of ground-based optical and NIR 30–100 m telescopes may open a completely new window on the universe and produce unprecedented results, with a resolution and sensitivity hundreds or even thousands of times beyond what is available today. AO systems for future telescopes will require wavefront sensors comprising very large pixel arrays (256 \(\times\) 256 up to 1024 \(\times\) 1024 pixels) due to the fact that these telescopes are going to have deformable mirrors with several thousand actuators [2]. A frame rate of more than thousand frames per second will be required as well as detector systems with an extremely low readout noise and a high quantum efficiency in the optical and NIR region.

In this paper, we will give a description of the responsitivity of a pnCCD detector to optical light in the visible and near-infrared region. We will further present the concept and measurements of a high-speed CCD detector system, which enables a detector with 256 \(\times\) 256 pixels to be operated at more than 1100 frames per second with an overall electronic noise contribution of much less than three electrons equivalent noise charge (ENC).

2. Design and concept of the pnCCD

The principle concept of a pnCCD differs in many ways from that of most other detector concepts. Its basic concept
is based on the principle of sidwards depletion of a pnp-structure [3]. The devices are fabricated in a double-sided wafer process on high-purity n-type silicon. The transfer registers of the three-phase CCD are formed on the front side of the device by p$^+$-implantations in high-purity n-type silicon. On the back side of the device, a homogeneous and unstructured p$^+$-implantation serves as the radiation entrance window. The application of voltages in an appropriate way to both sides of the detector results in a full depletion of the device [4]. A schematic cross-section along one transfer channel is shown in Fig. 1. The advantages of this concept are reflected in a variety of remarkable detector properties:

- the full wafer depletion with a thickness of 450 $\mu$m results in a high detection efficiency for incident radiation over a wide spectral region;
- the unstructured and homogeneous radiation entrance window can easily be tailored for the needs of detector applications, by the ways of both the profile of the implanted junction and the implementation of additional dielectric layers on top of the silicon device, working as an anti-reflective coating (ARC);
- the rectifying pn-junction at the radiation entrance window leads to a maximum electric field strength close to the radiation entrance window and thus reduces a spatial widening of generated charge clouds.

To allow high-speed operations while maintaining the two-dimensional imaging capabilities, the detector is designed to operate in a split-frame-transfer mode. The image with an area of 13.5 $\times$ 13.5 mm$^2$, comprising 264 $\times$ 264 pixel with a size of 51 $\mu$m in square, is split into two halves for readout. Each half image is transferred to its storage region for readout on opposite sides of the detector within 50 $\mu$s. Fig. 2 shows a schematic layout of the CCD and its readout ASICs [5].

3. Detector readout

The pnCCD is a channel-parallel type of CCD, which means that all channels are readout in parallel and omitting any serial registers on the detector itself. Each channel of the CCD is wire bonded to a multi-channel readout ASIC. This CAMEX (CMOS Amplifier and MultiplEX) chip facilitates an amplification of all of its 132 channels in parallel. The CAMEX-chip uses the multi-correlated double sampling (MCDS) signal shaping concept. Fig. 3 shows a schematic layout of one of the 132 amplifier channels. A description of the commonly used sequence of this method is shown in Fig. 4. After an initial reset of the amplifier (A), the baseline samples are taken (B). By freely programmable internal registers of the CAMEX chip, any value between one-fold up to eight-fold sampling is selectable, allowing a tradeoff for either an optimized noise behaviour, since the noise contribution is proportional to the square root of samples taken, or a gain in speed by reducing the sampling number. A corresponding number of sampling capacitors is preloaded according to the output voltage of the first amplifier. Thereafter the signal content of the last line of the CCD is transferred to the readout anode, giving a voltage rise at the amplifier output (C). Again, the output level of the amplifier is sampled and the sampling capacitors are loaded (D). The
parallel weighting functions of consecutive cycles are separated in time. An amplifier reset between the measurements prevents information of one cycle to be used in the following cycle. For the second described method, the parallel weighting functions are not separated anymore. Information of the signal of one cycle is used as the baseline information in the successive cycle. However the shape of the weighting function, and therefore the noise properties of the shaping process, persists.

After amplification, the signal levels of all 132 channels are serialized to one or, respectively, 66 channels to two readout nodes. The output multiplexing of the amplified signals is done in parallel to the amplification of the successive line of the CCD. This highly parallelized signal processing allows for a very fast readout of the images and thus a high frame rate. For a readout time per line of 7 μs, corresponding to a frame repetition rate of nearly 1100 Hz, the electronic noise contribution of the entire system was below 2.3 electrons ENC at an operating temperature of −55 °C.

Apparently due to the lack of an amplifier reset, the internal voltages at the amplifier outputs increase with each signal amplitude and thus limit the maximum photon rate per column and frame of the CCD. In the highest gain mode of the first amplification stage of the CAMEX chip, an upper limit for optical photons per column and frame is in the order of 6000. This corresponds in mean to more than three million optical photons in total per frame and is in case of applications for AO systems a minor limitation. By reducing the gain of the first internal amplifier, this number can be increased up to approximately 300,000 optical photons per column. Prior to the next frame image to be read out, a reset of the internal amplifiers will be done.

4. Measurement results

To describe the optical properties of a pnCCD, two aspects need to be taken into account: absorption and reflection losses of layers covering the radiation entrance window of the detector, and the detection efficiency for radiation reaching the sensitive volume of the detector, the “internal quantum efficiency”. Fig. 6 shows the internal quantum efficiency from the vacuum UV (VUV) to NIR region, which is the result of two independent measurements. We measured the spectral response of a detector and, using the same device, the specular reflectance in two independent test setups. The internal efficiency remains nearly 100% over the entire spectral region between 300 and 950 nm. Below 300 nm the internal efficiency increases due to the beginning of secondary ionization processes. In the NIR region, an as expected decrease is observed due to radiation transversing the 300 μm thick detector volume [6]. For a nowadays used 450 μm thick detector, the break-off point is even moved towards longer wavelengths.

Losses due to reflection or absorption processes for interfaces with different refractive index at the radiation
The entrance window can easily be calculated by solving the Fresnel equations [7]. In case of a simple vacuum to silicon interface, approximately 30% of the incident radiation is reflected in the visible light region. With an appropriate deposition of dielectric layers, an ARC can be created. By adjusting the kind of materials and thicknesses of the deposited layers, the properties of the ARC can be tailored for the desired application. Measured quantum efficiencies (QE) for two different ARCs are shown in Fig. 7. In both cases the ARC consists of a stack of two layers, namely SiO2 and Si3N4, with different thicknesses. Based on the knowledge of the exact thicknesses of the two layers, as obtained by ellipsometric measurements during the fabrication process, the measured QE for both devices is very well described by calculations. The discrepancies around the break-off point at 1000 nm are not quite understood. They may be caused by a lack of accuracy in the optical data of silicon within this region.

The spectroscopic response including noise behaviour was investigated by using soft X-ray lines. In particular, the detector performance at the carbon K-line at 277 eV, corresponding to the generation of 76 electron–hole pairs per incident photon (±3 electrons due to the statistical process of charge generation), was studied. A measured energy dispersive spectrum is shown in Fig. 8. The energy resolution for all reconstructed events is 48 eV (FWHM). One may very well extrapolate from the obtained carbon spectrum a detection limit in the optical region to be less
than ten optical photons which can be recorded with a QE close to 100%.

5. Summary

A high-speed detector system was set up, which allows to operate a 264 × 264 pixel pnCCD at a frame rate of more than 1000 frames per second at an overall noise contribution of less than 2.3 electrons ENC at highest speeds. The noise contribution further improves to values below two electrons ENC for reduced frame repetition rates up to 400 per second. Accompanying the detector development, we designed and successfully tested a data acquisition system.
which is able to handle data rates higher than 75 million pixel per second, equivalent to more than 150 MByte per second. Parallel working signal processors allow to setup a scaleable readout system even for larger detector formats without exceeding the capabilities of state-of-the art computer bus systems [8].

Optical measurements of the detectors have very well confirmed the calculations of the detector response for different ARC. Due to large sensitive volume of our detectors of 450 μm, a high efficiency in the NIR region was achieved. Commonly observed fringing effects in this wavelength region are effectively suppressed.

The high operating speed of the devices combined with their high detection efficiency for optical and NIR light and their extremely low noise contribution makes them a suitable instrument as a wavefront sensor for future AO systems.

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References