Published in final edited form as:

Nucl Instrum Methods Phys Res A. 2008 May 1; 589(2): 250–258. doi:10.1016/j.nima.2008.02.010.

A compact 7-cell Si-drift detector module for high-count rate X-ray spectroscopy

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Abstract

A new Si-drift detector module for fast X-ray spectroscopy experiments was developed and realized. The Peltier-cooled module comprises a sensor with $7 \times 7\text{-mm}^2$ active area, an integrated circuit for amplification, shaping and detection, storage, and derandomized readout of signal pulses in parallel, and amplifiers for line driving. The compactness and hexagonal shape of the module with a wrench size of 16mm allow very short distances to the specimen and multi-module arrangements. The power dissipation is 186mW. At a shaper peaking time of 190 ns and an integration time of 450 ns an electronic rms noise of ~ 11 electrons was achieved. When operated at 7°C , FWHM line widths around 260 and 460 eV (Cu-K_α) were obtained at low rates and at sum-count rates of 1.7 MHz, respectively. The peak shift is below 1% for a broad range of count rates. At 1.7-MHz sum-count rate the throughput loss amounts to 30%.

Keywords

Silicon drift detector; X-ray spectroscopy; Spectroscopic performance

1. Introduction

Semiconductor diodes are widely used for the detection of single photons in various X-ray applications for several decades. The drift-diode principle, introduced by Gatti and Rehak in 1984, makes it possible to keep the charge-collecting anode small even for a diode with a large sensitive area, compared with conventional Si(Li)-based or HPGe-based detector systems in which the anode occupies the entire area. Improvements in the manufacturing process technologies permit the monolithic integration of junctionfield effect transistors (JFETs) near to the anode of the Si-drift detector (SDD) [1]. The integrated JFET offers onsensor chip amplification for an improved spectral resolution. It further provides an internal and self-adapting discharging mechanism, so that there is no need of an external reset. Even at highest incoming flux the SDD is able to achieve a spectroscopic information with a resolution that is far beyond the capability of other systems [2-5]. The SDD can be operated in the room temperature range, which can easily be achieved with single-stage Peltier cooling, compared to -190°C of Si(Li) and HPGe detectors that requires cooling with liquid nitrogen. Nevertheless, also the SDD's spectral line width and its statistical spread decreases with decreasing temperature. With cooling at and below 0°C , the typical

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resolution of the Mn-K_α line is already well below 200 eV [1,2,5], which is even more than satisfactory for fast counting applications with energy discrimination like X-ray absorption spectroscopy (XAFS) or X-ray standing waves (XSW) [6]. This energy resolution was also achieved at temperatures at and below −20 °C with a commercial 40-mm² quadelement SDD operated with integrated JFET [2], a 50-mm² single-element SDD operated with external FET [3] as well as with a commercialized 12-element SDD having an active area of 60 mm² [4], all three at rates up to ~2 MHz. Although these systems disclaim liquid-nitrogen cooling, their form factors do not fit to the necessarily mentioned target experiments, e.g. flat and seamless multi-module arrangements. Furthermore, many thousand spectra per sample will be taken during XAFS and XSW beam times requiring highest count-rate capability and therefore a high cell number. For example, diluted samples element concentrations typically below 0.1–1% requires the detection of characteristic X-ray fluorescence to isolate the minor contribution of interest from the dominant matrix. For a statistical noise of 0.1%, a number of counts in the line of 10⁶ is necessary (Poisson limit). Typically, at least 500 spectra will be taken during a single XAFS scan. In order to limit the

measurement time per spectrum and scan below $\frac{1}{10}$ s and 1 min, respectively, sum-count rates well above 10MHz must be achieved. Data-acquisition (DAQ) systems having the potential to process the data of such multi-cell arrangements are available at DESY [7]. Recently, the fabrication and test of 10 7-cell SDDs have been successfully finished [8] as the first step of a houseinternal development and production of modules which fits these claims with a good cost-versus-performance tradeoff.

The basic idea of our module concept is to integrate a hexagonal array of seven 7-mm² SDD cells with integrated JFETs into a single sensor chip and to give also the module a hexagonal shape with a diameter as small as possible. In this way, several modules can be combined to larger honeycomblike arrangements in accordance with the experimental requirements and with the space available in a specific experiment. This module array can easily be modified in its dimensions and layout. For example, using the 10 modules a 77-cell sensor system can be build-up in a flat arrangement with outer dimensions of 64 mm × 46.2 mm. The small form factor of the module requires the integration of a suitable low-power and low-noise VLSI spectroscopy amplifier chip for the parallel readout of all sensor cells, the implementation of a radiation shield between sensor and electronics in order to avoid damage by transmitted X-rays, the insertion of a Peltier cooler for moderate cooling, and a compact cable for the electrical interconnection to the subsequent DAQ electronics and power supplies.

This paper describes the design and construction of the sensor module and presents results obtained in test experiments at a synchrotron beam line. Section 2 gives an overview of the module's key components. In particular, the sensor, readout electronics, cooling unit, and cable connection are described. A detailed description of the module construction and possible multi-module arrangements is given in Section 3. Finally, its spectroscopic behaviour was investigated. Spectra obtained for different input count rates are analyzed. The influence of the count rate on resolution and peak position as well as the throughput behaviour is presented.

2. Overview

Fig. 1 shows a photograph of the module. It consists of the sensor head, tube, and cable with connector. The length of the head with tube amounts to 21.2 cm. The wrench size is 16 mm. The 7-cell sensor with on-chip diode for temperature measurements and 7-channel readout integrated circuit (ROIC) are the main components of the sensor head. The power dissipated in the head can be removed by a single-stage thermoelectrical cooler (TEC) into the tube mounted on top of it. The tube also encloses further parts of the readout electronics and cable connection and acts therewith as an electrical shielding. The tube can be mechanically fixed by using clamp jaws. A round cable of 12-mm diameter and ~32-cm length is assembled with a multi-delta-ribbon (MDR) connector and realizes the electrical connection to a subsequent DAQ, temperature regulator, and power system (not shown).

Fig. 2 depicts a simplified block diagram of the module electronics. The ROIC (grey block) processes the analog signals of seven sensor cells in parallel, and sends two time-multiplexed analog signal streams to the subsequent line drivers. Their step-like output pulse streams (analog Out) are synchronized to external clock signals (Clocks). In this way, the random appearance of photons absorbed in the individual SDD cells and detected by a ROIC-internal trigger circuit (self-trigger) is derandomized, where the step level is directly proportional to the photon energy. The on-sensor diode (Temp) and Peltier cooler (TEC) are components of a temperature regulator. Its circuitry is located outside the module. Internal power-filter blocks serve for ripple and noise reduction of supply voltages (Power).

2.1. Sensor part

The high-resistivity n-type silicon of the SDD cell is fully depleted by p^+ -contacts on the substrate's top and bottom side negatively biased with respect to an ohmic n^+ -contact (anode) located in the cell center on top side. The p^+ -contacts on top side are segmented into concentric hexagonally shaped electrodes, so that a nearly radial symmetrical field gradient can be superimposed to the transversal field, forcing signal electrons radially inwards to the n^+ -contact. In this way, the small charge-collecting anode is defined, whose capacitance is independent of the cell area. The anode is directly connected to the gate of the on-sensor integrated JFET, keeping the total node capacitance C_{det} as low as ~110 fF [8]. A photon-absorbing mask located in front of the sensor's entrance window (see Fig. 1) covers cell boundaries and JFET areas. Therefore, incomplete charge collection is avoided for zero-divergent radiation, which improves the spectral peak-to-background ratio [8,9]. Taking a substrate thickness of 450 μm into account, the quantum efficiency drops to 97%, 50%, 10%, and 3% at 10, 17, 34, and 64 keV, respectively. To comply with a larger energy range, two different mask materials were chosen. Zr is used for photon absorption between 2.5 keV (its highest L emission line) and 18 keV (its K-edge). For higher photon energies E_{ph} , a 1.3-mm thick Al_2O_3 mask is available, where its efficiency depends on E_{ph} . The transmission coefficient raises to 1%, 10%, 50%, and 75% at 12, 15, 23, and 34 keV, respectively. Based on these results, the main spectral operation range of the sensor is 2.5 keV E_{ph} 18 keV. Nevertheless, the sensor can be used for higher energies depending on the spectral resolution, peak-to-background and count-rate requirements of the underlying experiments. Typical spectral resolution is about 300 eV between 4.5 and 18 keV at room temperature

and low count rates [8]. Smaller values around 230 eV (Fe-K_α) have been achieved by “moderate” cooling down to 7 °C. The sensor’s radiation tolerance has been verified by 17-keV irradiation. After irradiation with a total dose of ~2 Mrad the spectral resolution decreases by ~40% [8].

2.2. Readout electronics

The ROIC [10] consists of seven parallel analog signal-processing channels. Each channel comprises an input stage, a filter stage with comparator, and a track-and-hold (T&H) stage for amplification, shaping and detection (self-trigger), and storage of signal pulses, respectively. If the switch of the T&H-stage (see Fig. 2) is closed (write cycle) its voltage response $V_{T\&H}$ from a single-photon energy in the frequency domain is given by

$$V_{T\&H} \simeq \underbrace{\frac{qE_{ph}}{wC_{det}}}_{\text{anode}} \cdot \underbrace{\frac{A_{sf}}{1+j\frac{f}{f_{sf}}}}_{\text{source follower}} \cdot \underbrace{j2\pi fC_C}_{\text{ac coupling}} \cdot \underbrace{\frac{A_{csa}}{\left(1+j\frac{f}{f_1}\right)\left(1+j\frac{f}{f_2}\right)}}_{\text{chargesensitive amplifier}} \times \underbrace{\frac{A_{bf}}{\left(1+j\frac{f}{f_{bf1}}+\left(\frac{jf}{f_{bf2}}\right)^2\right)\left(1+j\frac{f}{f_{bf3}}+\left(\frac{jf}{f_{bf4}}\right)^2\right)}}_{\text{Bessel filter}} \times \underbrace{\frac{1}{j2\pi fC_{T\&H}}}_{\text{memory cell}} \quad (1)$$

where q is the electron charge, $w = 3.65$ eV the energy needed to create an electron–hole pair in Si, j the complex operator, and f the frequency. The single photon-induced charge collected on C_{det} causes a voltage step given by the first term on the right-hand side of Eq. (1). The on-sensor JFET and a ROIC-internal current source operate in a source-follower configuration. Its transfer function is given by the second term having a single pole located at $f_{sf} \approx 1.2$ MHz. The source follower’s output is ac coupled ($C_C = 15$ pF) to the input of a charge-sensitive amplifier with pole-zero cancellation. The amplifier introduces two poles at $f_1 = 2.1$ MHz and $f_2 = 9.5$ MHz (cf. term 4 in Eq. (1)). The subsequent filter stage is of fourth-order Bessel type and shows two complex conjugate pole pairs (cf. term 5), described by $f_{bf1} = 2.6$ MHz, $f_{bf2} = 5.1$ MHz, $f_{bf3} = 4.6$ MHz, and $f_{bf4} = 5.7$ MHz. $A_{sf} = 0.97$, $A_{csa} = 18$, and $A_{bf} = 2$ is the ac-voltage gain for small frequencies of the source follower, charge-sensitive amplifier and Bessel filter, respectively. The last term on the right-hand side of Eq. (1) with $C_{T\&H} = 1.8$ pF represents the impedance of the memory cell. Afterwards, the stored events are 6-to-1 time multiplexed and buffered by two parallel stages. The voltage gains of these on-chip stages are 1.33 and 1. A digital controller block (cf. Fig. 2: Cntr) generates the control signals for the write and read switches of the memory cells from external 6-MHz (sampling clock of the DAQ’s digitizer) and 1-MHz (first-channel marker) clock signals to avoid conflicts between the random event-driven write accesses and the clock-synchronous read accesses on $C_{T\&H}$. An on-chip register (Reg) can be loaded with further control data (cf. Fig. 2: Data) for e.g. gain (A_{bf} , $C_{T\&H}$), bandwidth ($f_{bf1} \dots f_{bf4}$) and timing control purposes (trigger threshold, T&H integration time t_{int}). The peaking time of the shaper is ~190 ns. The FWHM-pulse width of the T&H current is ~210 ns, its fall time is dominated by the parasitic pole at f_{sf} . Considering the time delay between gate-voltage step and start of

the integration phase of ~ 90 ns, about 96% of the T&H current pulse charge will be integrated during $t_{\text{int}} = 450$ ns. The achieved electronic rms-noise level is ~ 43 eV representing an equivalent-noise charge of ~ 11 electrons. All circuit blocks of the ROIC, including the inputs and outputs are designed fully differential. Further circuit details can be taken from Ref. [10]. The differential ROIC outputs are connected to four unity-gain voltage-feedback CMOS operational amplifiers (Burr Brown OPA354) for cable line-driving purposes. The ROIC with sensor has already shown its mega-count rate capability at room temperature [11].

2.3. Cooling unit

The temperature measurement is restricted to a boundary region of the SDD outside its active region. The position of the diode is on top side and close to the area where the sensor chip is glued onto its carrier. The ROIC leads to a power dissipation of ~ 105 mW for full operation, whereas the power consumption of the SDD with onsensor integrated JFETs amounts to ~ 15 mW. Therefore, it can be expected that the diode is located near to the coolest part of the sensor head housing. The total power of ~ 120 mW is removed by a single-stage TEC (PE-017-7-10 from Supercool AB, Sweden) into a Cu-heat spreader, connected to the hot side of the TEC (see also Fig. 3(a)). The external operational amplifiers are located outside the sensor head and consumes an additional power of ~ 66 mW. When the tube is mechanically fixed by clamp jaws with a contact area of ~ 9 cm² at the cable end of the tube, and the TEC is operated at ~ 0.7 W cooling power, cool down times are typically less than 3 min from ~ 34 to ~ 7 °C. The typical time constant of the exponential decay is less than 80 s. In free-convection mode the sensor temperature remains below ~ 34 °C.

The design of the cooling unit must also take into account the possibility of water condensation on device surfaces, in our case of a non-hermetically sealed module as this can be a potential root cause for electrical failures and reliability problems. Whether water condensation on a device will occur or not, depends on its surface temperature, T_{air} , and the air humidity H_{air} . The critical temperature T_{cr} can be estimated by [12]

$$T_{\text{cr}} = \frac{1}{\frac{1}{T_{\text{air}}} + \frac{R}{\Delta H_{\text{vap}}} \cdot \ln \left(\frac{1}{H_{\text{air}}} \right)} \quad (2)$$

where R is the gas constant and $H_{\text{vap}} = 42.9$ kJ/mol the mean enthalpy of vaporization between 0 and 100 °C. Eq. (2) indicates that a device can be cooled down to $T_{\text{Ref}} = 11.7$ °C without causing condensation at an ambient temperature of 23 °C and humidity of 50%. The hotter and the more humid the ambient environment is, the higher is T_{cr} and the more condensation occurs if the reference temperature would be fixed to 11.7 °C. If operated under non-vacuum condition, the cooling is limited by a device temperature above T_{cr} . Vacuum tests have been performed down to $\sim 7 \times 10^{-7}$ mbar.

2.4. Interface

A shielded 36-wire cable (Leoni Kabel GmbH, Germany) is assembled with a 50-pin solder plug MDR connector (3M, Germany) and realizes the electrical connection to a subsequent DAQ, regulator and power system. The hybrid cable comprises six shielded 100-Ω twisted

pairs ($2 \times 0.09\text{mm}^2$) for analog outputs, clocks and test input, eight 0.15-mm^2 wires for control data, temperature diode output, as well as power ground, and 16 0.25-mm^2 wires for power supply and Peltier cooler. The sensor cells with JFETs and temperature diode are supplied by seven voltages [8], the ROIC is connected to an analog and digital $\pm 1.65\text{-V}$ supply voltage and to a control voltage for the JFET's current source. The line drivers are also supplied by the analog $\pm 1.65\text{ V}$.

3. Setup and mechanics

3.1. Module construction

Fig. 3(a) shows a photograph of the sensor head with TEC and heat spreader as well as the flexlead of the hybrid circuitry. To operate the sensor at low temperature, the thermal conductivity of the housing parts should be as high as possible. Electrothermal simulations of a similar sensorhead construction have shown that a housing material with a thermal conductivity around $100\text{W}/(\text{mK})$ would lead to a sufficient low temperature level [12]. Furthermore, a material with a K-level emission line below the lower limit of the energy range of sensor operation is needed. We have chosen machinable aluminium nitride (AlN) ceramic Shapal M (Goodfellow GmbH, Germany) as base material and the dual-component adhesive H70E-175 (Polytec GmbH, Germany) for gluing procedures. Two holes in the corners of all sensor-head parts and of the heat spreader allows a screw connection to the tube. In this way, the TEC is clamped between the frame plate capping the sensor head (cf. Fig. 3(c)) and the heat spreader. Ti screws were chosen in order to realize an electrical connection to an Al-end cap (cf. Fig. 1) and limit the thermal bypass between the TEC's cold and hot side. The TEC owns two dedicated lines from its regulator. Both wires are fed through holes in the heat spreader. A rigid-flexible 5-layer printed-circuit board (PCB) using high-density interconnection/microvia technology (Cicorel S.A., Switzerland) carries all passive and active electrical devices. Its flexlead is 19.5 cm long and $370\text{ }\mu\text{m}$ thick, and consists of a narrow and wide part. The last-named one has 40 pads for solder connections of cable wires and shields. As it can be seen from Fig. 3(a), the narrow part comprises 61 passive components and the four line drivers.

The rigid part of the hybrid has an area of 1.1 cm^2 and is placed on top of a frame plate. The minimum trace width and gap is $100\text{ }\mu\text{m}$. Fig. 3(b) gives a bird's eye view of the baseline substrate as part of the open sensor head. The ROIC and 12 passive components of case size 0402 occupy about 32% of the area. The SDD is placed with the downward oriented entrance window on a base frame in thin-film technique. To connect the output and biasing pads of the sensor and accordingly the pads on the base frame to the hybrid circuitry, conventional wire-bonding technique is used.

In order to avoid damage of the ROIC by transmitted X-rays and to minimize undesired back fluorescence contributions from upper module parts a multilayer radiation shield is placed between the sensor and the electronics [6]. It is mounted in a recess of the frame plate which covers the base frame. Thermal decoupling of the SDD from the ROIC is obtained by implementing polyimide foils between the metal parts of the radiation shield and frame parts (not shown). The task of the abovementioned Al-end cap is to enclose the screw heads and prevent therewith the SDD from Ti fluorescence.

The electrical connection of the head-internal devices to the subsequent passive components and line drivers is realized by the flexlead, which leaves the housing through a slot in the frame plate as shown in Fig. 3(c). The sensor head has a volume of $\sim 2.3 \text{ cm}^3$, its height amounts to 10 mm. The bending radius of the flexlead is about 1 mm. In Fig. 3(d) the wide part of the flexible interconnection foil can be seen. All wires and shields are soldered on their pads and the flexlead is round bended to fit the inner diameter of the tube. After final positioning of the tube and fixing the sensor head with the screws, the outer cable shield is soldered to the tube in order to obtain a pull relief and low impedance connection between all metallic module parts.

3.2. Module arrangements

As illustrated in Fig. 4 10 modules can be combined to larger flat 1-D and 2-D arrangements. Considering the above stated wrench size of 16 mm the active SDD region covers about 23% of the total hexagonal area. This value also remains unchanged in all configurations. The DAQ system provides 20 analog input channels [7]. Each module has two time-multiplexed analog outputs (cf. Section 2). Thus the DAQ system has the potential to process the data of all 77 detector cells. The supply voltage of the innermost ring contact must be SDD-chipwise adopted to achieve the maximum spectral resolution [8]. Therefore, only 10 individual voltages are necessary to operate all 10 modules in parallel. The fabrication cost during the development phase amounts to $\sim 3 \text{ k Euro}$ per cell, thereof 50% are for the readout electronics (10% ROIC, 40% hybrid) allowing us to realize such large instruments at a reasonable cost level.

4. Performance tests

The experiments were carried out with synchrotron radiation at DESY/HASYLAB beam line C. Using a double-crystal monochromator a Cu foil was irradiated with monochromatic radiation at 9.05 keV. The detector surface was placed in parallel to the beam axis in order to detect the fluorescence photons only. The distance to the sample was $\sim 13 \text{ cm}$. The angle between the sample and beam axis was set to 45° . The incident photon flux was measured using an ionization chamber mounted between the monochromator and sample. The values of the input count rate were derived from the quotient of the total number of counts in the spectrum and the measurement time. This calibration procedure was performed at count rates for which pile up does not affect the spectrum, taking the dead time caused by the 6-to-1 multiplexing scheme (see below) into account. The monochromator crystal was detuned via its stabilizer to provide a range of input-count rates per cell from ~ 2 to $\sim 240 \text{ kHz}$. A digital oscilloscope (Tektronix TDS684A) was dc-coupled to the line-driver outputs in order to record the analog output-pulse streams. The spectra of each cell are collected in parallel through the DAQ system. The operation temperature of the SDD was restricted to $\sim 7^\circ \text{C}$ in order to use its known optimum voltage set [8]. A further temperature decrease requires an operation of the JFETs at lower drain voltages.

Fig. 5 shows the timing diagrams of the ROIC's differential output voltage (left). The pulse streams were recorded in $600 \mu\text{s}$. The upper and lower diagram show events detected by

cells 1–6 (Out1) and cell 7 (Out2), respectively. The voltage pulses have widths of $\frac{1}{6}$ of the

cell-related 1- μ s sampling clock period. As indicated by the pulse-height spectra (y-axis: digitizer bin) on the right-hand side, most of the smaller and larger pulses were excited by K_{α} - and K_{β} -emission lines of Cu at an input-count rate of 45 kHz per cell. Smaller pulse amplitudes and therewith entries at their low-energy side are mainly caused by unintended background radiation (stainless steel), higher values represent pile-up events. Note, that the peak-to-background behaviour of the modules was already presented in Refs. [8, 9]. The larger line width of the sum spectrum (Out1) is caused by channel-to-channel variations of gain and offset.

As a general illustration of the quality of the energy-dispersive spectra produced with the 7-cell SDD, Fig. 6 shows all spectra with logarithmic display of the entries over five orders of magnitudes versus the digitizer's full dynamic range (class 0–4095), as measured at input-count rates of 1.5, 19, 120, and 240 kHz (from bottom to top). All cells of this detector were working properly and were showing good spectra with clear separation of the lines. Coincidence peaks, including first order (e.g. 2 Cu- $K_{\alpha,\beta}$) and higher-order coincidence, are observed at higher count rates at and above 19 kHz. Another measure of spectrum quality is the constancy of the peak position as a function of input-count rate. Fig. 7(a) depicts the relative peak positions of the Cu- K_{α} line related to its peak position at 120 kHz. The peak-shift behaviour of the ROIC has been characterized by stimulating its test inputs by a high-resolution arbitrary waveform generator (Tektronix AWG 420). The shifts caused by the ROIC and by the module stay well below 1% in a rate range between 80 and 300 kHz. With decreasing count rates the peak shift of the module and ROIC reaches some percent and ~1%, respectively. At lower rates the shift behaviour is caused by the non-linearity of the gain, dominated by the capacitive-voltage characteristic of C_{det} [13]. In Fig. 7(b), the Cu- K_{α} energy resolution (FWHM) of the individual cell spectra as a function of input-count rate is plotted. At low count rates the resolution varies between 255 and 330 eV. With increasing count rate the spectral resolution decreases. The FWHM-line width stays below 460 eV at a count rate of 240 kHz/cell in each cell except no. 6, or 1.7 MHz for all seven cells. The ROIC-noise contribution is below 100 eV and independent of the rate, indicating that the achieved energy resolution was limited by the sensor in the present experiment at 7 °C.

Fig. 8 shows the measured throughput rate for the 7-cell SDD module as a function of input-count rate per cell. Triangular symbols represent the measured values for count rates contributing to the whole spectra from ROIC threshold around classes 300–4095 (cf. Figs. 5 and 6). Square symbols mark measured values for pile-up counts above the Cu- K_{β} line (class 2000). The dashed line in Fig. 8 shows the response for a perfect dead time-less sensor system, where the output-count rate R_o equals the input-count rate R_i . Due to the fact that a consecutive readout of the T&H stages are executed without interruption, the time-

multiplexed readout procedure causes a dead time of $\frac{1}{6}$ of the period. The influence on the throughput behaviour is illustrated by the solid straight line representing a loss of 16.7%

($R_o = \frac{5}{6} R_i$). Since a read cycle must be finished until the next write cycle is executed, the paralysis time is independent of the T&H-current pulse shape and only determined by the constant integration time $t_{\text{int}} = 450$ ns. Pietraski and Furenlid concluded that the pulsed time

structure of the synchrotron-radiation source has to be carefully taken into consideration when the maximum drift time and the paralysis time are becoming comparable [14]. They derived equations for the lower and upper limit of R_o considered in the following equation:

$$\frac{5}{6} \cdot \frac{R_i e^{-R_i t_{int}}}{R_i t_{int}} \cdot \left(\frac{1 - e^{-2R_i t_{int}}}{2R_i t_{int}} - e^{-2R_i t_{int}} \right) \leq R_o \leq \frac{5}{6} \cdot R_i e^{-R_i t_{int}} \quad (3)$$

where the factor $\frac{5}{6}$ takes the above-mentioned throughput efficiency of the multiplexer into account. The nominator of the second term on the left-hand side as well as the second term of the right-hand side describe the well known throughput rate of paralyzable electronics characterized by the dead time t_{int} [15]. The third term on the left-hand side including the denominator of its preceding term is the correction valid for a circular drift detector operated in a pulsed source environment with a bunch period equal to the maximum drift time. In Fig. 8, the corresponding output-count rate (lower limit of the hatched area) is compared to throughput achievable with a continuous source (upper limit of the hatched area). The measured values lie in between and demonstrate the validity of Eq. (3). The throughput loss reaches ~30% at about 240kHz per cell. The bottom curve in Fig. 8 describes the theoretical increase of pile-up events with increasing inputcount rate. Since the measured throughput remains below the theoretical curve for a continuous source (right-hand side of Eq. (3)), the

measured pile-up rate also remains below its theoretical limit given by $\frac{5}{6} \cdot R_i (1 - e^{-R_i t_{int}})$.

5. Summary

A new 7-cell SDD module with hexagonal outer shape was developed for X-ray spectroscopy applications, where very short distances to the specimen or multi-module arrangements are of great importance. The high degree of module compactness was achieved by the integration of a low-noise, low-power spectroscopy amplifier chip near to the sensor. The spectral properties of the module even in the room-temperature range in conjunction with the high count-rate capability makes it a well suited instrument for X-ray absorption spectroscopy or X-ray standing waves experiments at present and future high-brilliance synchrotron radiation sources.

Acknowledgments

The authors would like to thank P. Lechner from PNSensor GmbH (Munich, Germany) for the availability of the sensor chips, A. Venzmer, E. Wüstenhagen, A. Titze, D. Hammer, and W.O. Lange from DESY-FEC for their active help during design, setup and test of the module, and E. Welter from DESY-HASYLAB for his active support at the beam line.

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Fig. 1. Photograph of the 7-cell SDD module with cable connection. The length and wrench size of the sensor head and tube is 21.2 cm and 16mm, respectively.

Fig. 2. Overview of the module electronics. The output signals of seven SDD cells (left) will be analog processed in parallel and derandomized by the readout electronics.

Fig. 3.

Photograph of the sensor head with TEC, heat spreader, and flexlead of the hybrid (a). The photographs (b), (c), and (d) show the open head, closed head, and bended region of the flexlead with cable connection, respectively.

Fig. 4.

Possible spatial arrangements of 10 7-cell SDD modules. The pictures on the left- and right-hand side represent cases of arrangements without and with center holes (○, beam path), respectively.

Fig. 5.

Differential output-pulse streams (left) and their pulse-height spectra (right) generated by Cu-fluorescence photons at a count rate of 45 kcts/s. Due to the channel-to-channel variations of gain and offset the sum spectrum (top, right) shows a larger line width.

Fig. 6.
Cu-fluorescence spectra of the individual cells recorded at 1.5, 19, 120, and 240 kcts/s (from bottom to top).

Fig. 7.

Channel specific peak shift (a) and resolution (b) versus input count rate. The solid and dotted curves describe the behaviour of the module and ROIC, respectively.

Fig. 8. Measured output-count rate () and pile-up count rate (□) versus input-count rate of the 7-cell SDD module. The bisecting line (dashed) and straight line below give the response for a perfect sensor system without and with multiplexer-related dead time, respectively. The hatched area marks the dead-time range defined by Eq. (3).