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Nuclear Instruments and Methods in Physics Research A 589 (2008) 250–258

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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

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Received 15 October 2007; received in revised form 18 December 2007; accepted 8 February 2008
Available online 19 February 2008

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 16 mm allow very short distances to the specimen and multi-module arrangements. The power dissipation is 186 mW. 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$_\alpha$) 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%.

PACS: 85.25.Oj; 87.64.K−; 85.30.Tv; 85.30.De

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 junction-field effect transistors (JFETs) near to the anode of the Si-drift detector (SDD) [1]. The integrated JFET offers on-sensor 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 resolution of the Mn-K$_\alpha$ 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-mm^2 quad-element SDD operated with integrated JFET [2], a 50-mm^2 single-element SDD operated with external FET [3] as well as with a commercialized 12-element SDD having an active area of $60\,\text{mm}^2$ [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

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2008.02.010

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 10^6 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 10 MHz 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 house-internal 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-mm^2 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 honeycomb-like 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

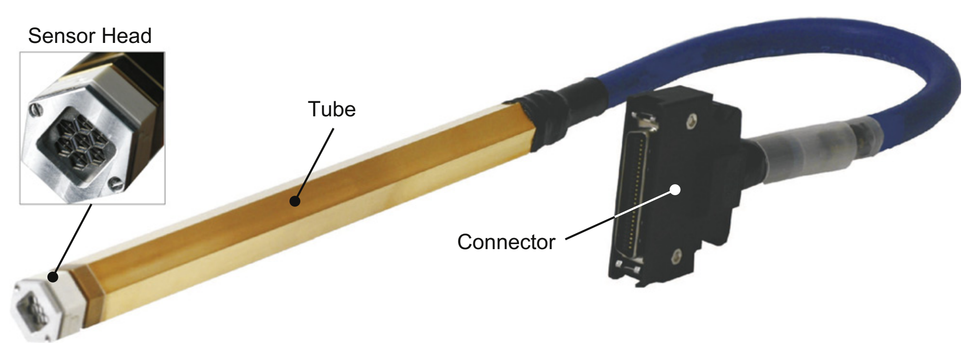

Fig. 1. Photograph of the 7-cell SDD module with cable connection. The length and wrench size of the sensor head and tube is 21.2 cm and 16 mm, respectively.