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Design of a monolithic CMOS sensor for high efficiency neutron counting

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ABSTRACT

The development of CMOS Pixel Sensors (CPS) for charged particles detection had led to promising applications for dosimetry. Based on our previous studies on the detection of fast and thermal neutrons with a CMOS sensor originally designed for particle tracking in high energy physics, a dedicated integrated CMOS sensor for efficient neutron counting is presented. This sensor has been designed and fabricated in a 0.35 μm CMOS process. It is a low noise, low power consumption sensor with a sensitive area of 6.55 mm^2 and a digital output. The test results indicate that it is suitable for neutron detection, thanks to its equivalent input noise charge of less than 400 e^-, and a 20 kHz detection frequency. In this paper the prototype is presented for both its circuit design and test results.

1. Introduction

The accident at the Fukushima-Daichii nuclear plan has precipitated public concern about the safety of nuclear power in general [1]. Nuclear industry comprises different activities, such as power production, fuel processing, reprocessing of the fuel used and transportation. Neutrons can be encountered at any of these nuclear industry place. Reliable measurement of neutrons for radiation protection relies on well-calibrated devices [2]. Moreover, the widespread use of neutrons in the fields of research leads to an increasing demand of neutron personal dosimeters [3]. Different types of passive and active neutron personal dosimeters have been developed, but a portable and cheap electronic device providing efficient detection of neutrons (free of γ-contamination) is still far from being completely established. We propose a solution based on CMOS sensors, which integrate the sensing element and the processing electronics on the same silicon substrate. Because of the thin sensitive volume ($\sim 10-20$ μm), these sensors have low sensitivity to gamma radiation [4], which is a particularly attractive feature for neutron monitoring. Moreover, the thin sensitive layer allows thinning CMOS sensors down to about 50 μm or even less without affecting the signal generation [5]. This is promising for detecting low-energy recoil protons and α-particles. In addition, they offer high flexibility at low price due to the use of standard industrial technologies. In this work, we present a dedicated CMOS sensor for a future neutron dosimeter.

2. System overview

Our group involved exploring the application of CMOS sensor in operational neutron dosimetry since 2003. A serial experiments have been successfully performed with a CMOS pixel sensor, named *MIMOSA5*, originally developed for charged particle tracking. The *MIMOSA5* consists of four independent matrices each of 512×512 pixels, with each pixel of 17×17 μm^2 in area. The sensitive region is a 14 μm deep epitaxial silicon layer. A single sensitive matrix (area of 0.75 cm^2) with an analog output is used. The results have demonstrated that CMOS sensor allows good γ discrimination with a satisfactory measured efficiency of more than 10^{-3} for both of fast neutrons [4] and thermal neutrons [6]. The study with the *MIMOSA5* indicated that CMOS sensor is a promising candidate for neutron dosimetry, on the other hand, the pixellization of the sensing elements results in a stringent constraint on the low activity sources. Furthermore, this pixelated sensor needs a sophisticated acquisition system that restricts the system miniaturization. Therefore, we propose a new compact device based on CMOS sensors working on a counting mode. Fig. 1 shows the proposed architecture for a new compact neutron dosimetry device. Neutrons can generate charged particles through various reactions with matter, and the choice of the converter depends on the energy of incident neutrons. In particularly, we use a polyethylene radiator to benefit from the high (n,p) elastic scattering cross-section for fast neutrons (100 keV to 10 MeV), as well as B/Li converters for thermal neutrons (1 meV to 1 eV) through (n, α) reactions. Charged particles are detected by a dedicated CMOS sensor, named *AlphaRad2*, which consists of the sensing part and the signal processing electronics on the same substrate. It has a binary output connected with a counter to register the hits. For the detection of neutrons in a large energy

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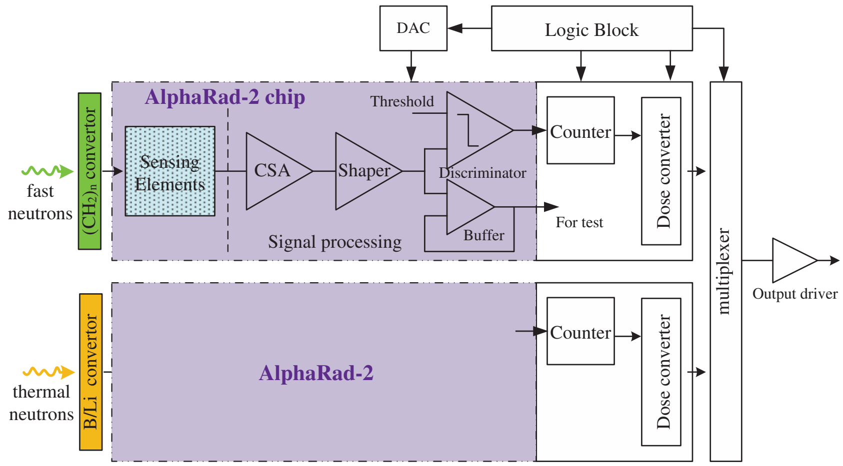

Fig. 1. Architecture of the compact device with CMOS sensors for operational neutron dosimetry.

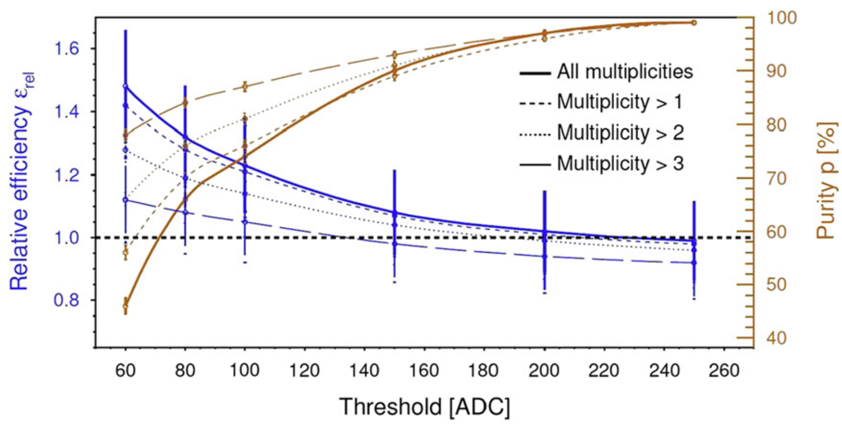

Fig. 2. The relative efficiency and the purity of signal as functions of charge and multiplicity cuts, from [7].

range, the future dosimeter will comprise 2–4 chips, and each one with its own converter and threshold. Then an additional block will be used to convert the counting rates into doses. The first step of the new device development is the implementation of the *AlphaRad2*, which is the key component to achieve the high sensitivity for neutrons.

The *AlphaRad2* chip includes the sensing elements and the signal processing circuit. Although the *MIMOSA5* is unsuitable for a portable dosimeter, its experiments have paved the way for the new version sensor design. The choice can be greatly facilitated if it is based on the results of performances. In order to determine the n/γ response of the *MIMOSA5*, experiments had been performed with a fast neutron source of AmBe [7]. Fig. 2 illustrates the relative efficiency and the purity of signal as functions of charge and multiplicity (defined as the number of hit pixels in a cluster) cuts. The relative efficiency is defined as $\varepsilon_{rel} = n_c/n_p$, where n_c is the total number of counts obtained with the chosen threshold and n_p is the total number of recoil protons. The purity of the proton signal is defined as $p = 1-(n_{e^-}/n_c)$, where n_{e^-} is the number of photoelectrons above the threshold. We observe that the multiplicity cuts cannot give good results with regard to n/γ discrimination. Setting only a charge threshold is sufficient to remove the photon contamination. Eventually, the pixellization is replaced by a small-size-diode array in the *AlphaRad2*. Each diode is an n-well/p-epi (epitaxial layer) diode with an area of $5 \times 5\ \mu m^2$. 32×32 diodes connected in parallel through standard aluminum lines are handled with a single output. With an inter-diode distance of 80 μm, the full sensing part covers an area of $2.56 \times 2.56\ mm^2$. This approach provides a large detecting surface with a relative low capacitance ($\sim$13 pF) and at the same time a very low leakage current ($\sim$pA), which strongly affects the radiation tolerance. The charge collection in the micro-diode array had been studied by the 3D device simulations using the commercially available Sentaurus-TCAD tools [8]. The details of device simulations had been described in [9].

3. Readout circuit design

According to our previous study, a threshold of 28 000 electrons (100 keV) will lead to an efficiency ratio of 0.9 together with a high signal purity of 99% (n/γ ratio) [4]. The device simulations indicated that the charge collection efficiency of the 4×4 diode cluster (with diode size of $5 \times 5\ \mu m^2$, inter-diode distance of 80 μm) is around 60% [9]. Under this threshold, the equivalent noise charge (ENC) at the input of the readout chain should be less than 3000 e^- to guarantee a signal to noise ratio (SNR) larger than 5 (at 100 keV). The main challenge for the readout chain is to achieve the relative low noise performance with a very low power dissipation ($<$1 mW). As shown in Fig. 3, the readout chain of *AlphaRad2* comprises a charge sensitive amplifier (CSA), a pulse shaper and a discriminator.

3.1. Charge sensitive amplifier

A low-noise, low-power single-ended preamplifier fed back by a small capacitance (C_f) is used to convert the input charge to a