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Efficiency analysis and promising applications of silicon drift detectors

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ABSTRACT

Silicon drift detectors (SDDs) stand as a groundbreaking technology with a diverse range of applications, particularly in the fields of physics and medical imaging. This paper provides an analysis of the performance of SDDs as detectors for X-ray radiation measurement, shedding light on their exceptional capabilities and potential in medical imaging. Compared to conventional detectors, SDDs have several notable advantages. Their high efficiency in capturing X-rays allows them to provide outstanding sensitivity and accuracy in detecting even low-energy X-rays. In addition, SDDs exhibit significantly low electronic-noise levels, contributing to better signal-to--noise ratio and better data quality. Furthermore, their high resolution enables exact spatial localization of radiation sources, which is essential for accurate diagnosis. This research is devoted to the evaluation of efficiency and potential application of SDDs in X-ray spectroscopy, with particular emphasis on their application in medical imaging. We focus on evaluating the performance characteristics of SDDs, such as their linearity, stability and sensitivity in detecting X-rays. The aim is to highlight the suitability of SDDs for a wide range of applications.

KEYWORDS

SDD, medical imaging, X-ray detection, X-ray spectroscopy

INTRODUCTION

X-ray-based imaging techniques are widely used in a diverse range of applications, both medical and nonmedical [1]. In particular, they find broad usage in nuclear and particle physics [2, 3], non-destructive testing [4], precision measurements [5], materials science research [6, 7], industry [8], geophysics [9], and security screening [10, 11]. In the medical field, X-ray methods are extensively employed [12] for digital radiography [13], fluoroscopy [14], digital tomosynthesis [15], image-guided radiation therapy [16] and cone-beam-computed tomography [17]. The role of X-ray registration is crucial in contemporary imaging techniques such as computed tomography and, consequently, in PET/CT systems [18, 19]. The combination of positron emission tomography (PET) and computed tomography (CT) technologies has significantly changed medical imaging, allowing the simultaneous obtaining of metabolic and anatomical data [20]. This is not only essential for accurate diagnosis but it also increases the efficiency of treatment planning and monitoring. Currently, one of the most crucial issues in the development of a new generation of PET/CT techniques for total body imaging [21, 22] is the improvement of X-ray registration techniques. The aim is to minimise radiation exposure [23] without affecting the quality of the images obtained, and possibly even improve it. Given the growing use of these imaging techniques, reducing radiation dose becomes a high priority. The ongoing evolution and optimisation of these technologies depends on progress in detection systems, in particular in increasing compactness and spatial resolution.

In an attempt to resolve the inherent limitations of conventional detection technologies, which are often based on scintillators combined with photomultiplier tubes (PMTs) and photodiodes (PDs), silicon drift detectors (SDDs) [24, 25] have emerged as a promising alternative. SDDs have shown their exceptional capability to detect ionising radiation while offering several key advantages, including excellent spatial resolution, low power consumption and compactness.

The emergence of SDDs can be attributed to the pioneering work of Gatti and Rehak, who introduced the concept of silicon drift chambers [26]. Initially, SDD prototypes had a simple design in which charge carriers generated by ionising radiation drifted to the anode under the effect of an applied electric field. A significant breakthrough came with the development of monolithic SDDs, in which the detector and readout circuitry were integrated on a single silicon wafer. This innovation not only improved the detection performance but also significantly reduced its size, making it more compact and efficient. Currently, SDDs play a key role in a wide range of applications, from particle physics [27] and astrophysics [28] to medical imaging [29, 30], highlighting the significant progress in semiconductor detector technology.

The primary aim of this study is to comprehensively analyse the efficiency of SDDs and to explore their promising applications in medical imaging. Our objectives include assessing the linearity and stability of SDDs and demonstrating their high sensitivity in detecting X-rays.

PRINCIPLE OF OPERATION

The SDD is a sophisticated semiconductor device operating on the principle of a p-n junction. It involves the creation of a large depleted region within the silicon bulk, where a reverse polarisation field separates electron-hole pairs generated by incident radiation. An additional drift field is applied to transport the charge carriers to the collection anode. The SDD typically is composed of a fully depleted n^- silicon cylindrical bulk, enclosed by p^+ concentric ring strips on one side, while the opposite side features a p^+ nonstructured layer serving as the radiation entrance window [24] (Fig. 1.). This configuration ensures uniform sensitivity over the whole detector surface. The collection n^+ anode is positioned at the centre of the ring strips. To achieve full depletion of the n-type bulk, a negative voltage is applied to the p^+ entrance window and the p^+ ring strips [32]. The voltage on the p^+ rings gradually increases from the ring next to the n^+ anode towards the outermost one, with the voltage of the outermost ring being twice that of the back contact. This unique voltage adjustment creates a drift field that effectively guides electrons towards the collection anode, while the holes are collected by the reversely biased p^+ regions. The efficiency of charge drift, combined with the creation of a large depleted region and uniform sensitivity, results in the excellent performance of the SDDs in detecting incident radiation.

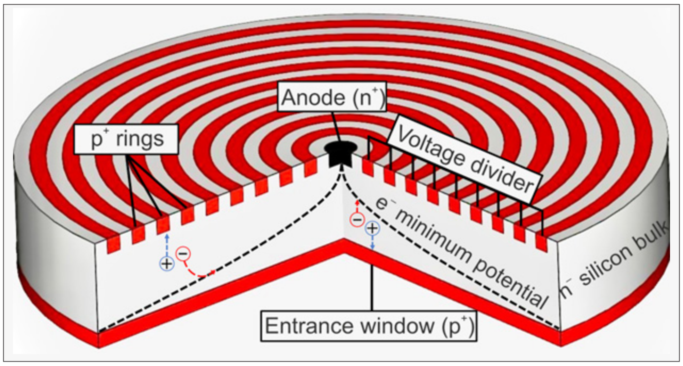

Fig. 1. Schematic cross-section of a cylindrical silicon drift detector (SDD). Electrons are guided by an electric field (dashed lines) to the collecting anode in the centre. Figure adapted from [31].

LARGE-AREA SDDs

The development of SDD technology has led to the creation of monolithic arrays, an innovation driven by breakthroughs in semiconductor processing and microelectronic integration. These arrays merge several SDD units on a single silicon wafer, which optimises the detector geometry and increases the detection area while keeping the individual characteristics of SDDs, such as high resolution and minimal capacitance [29].

The evolution to monolithic arrays of SDDs is a significant step forward in detection technology, in particular due to their ability to process signals in parallel. This attribute is crucial in high--flow applications such as large-scale physics experiments and astrophysical observations, where simultaneous detection of multiple events is essential. Furthermore, the functionality of these arrays extends to medical imaging, where their high resolution and sensitivity are vital for advanced diagnostic techniques. The ability to process multiple signals simultaneously is particularly useful in medical applications, providing clearer, more detailed images that are required for accurate diagnosis. In addition, the integrated structure of these arrays simplifies system architecture and improves reliability by reducing the number of required connections and components.

The seamless integration of CMOS transistors on each individual SDD chip has been a significant advancement in the creation of monolithic SDD arrays. This placement of field-effect transistors (JFETs) directly on each chip provides several important advantages. Firstly, this integration significantly reduces the parasitic capacitances caused by the connections between the detector and the readout electronics [24]. As a result, the level of electronic noise is significantly reduced [33]. This noise reduction improves overall signal quality and the sensitivity of the SDD array, especially in applications where measurement precision is crucial. Additionally, it simplifies the process of reading signals from multielement detectors [30], especially in the context of large arrays.

SDD monolithic arrays offer exceptional design flexibility, allowing for a wide variety of configurations. SDD cells are available in a variety of shapes [34], with square, round and hexagonal geometries being the most frequently used. The choice of cell shape is determined by the specific requirements of the application and the desired packing density. Square SDD cells are easy to manufacture and assemble, making them a common choice for a variety of applications. In comparison, hexagonal cells provide a more efficient packaging layout by minimising the inactive area between cells and maximising the active detection area. This configuration is often favoured in applications where a higher detection efficiency and uniformity are crucial [29].

A new generation of monolithic large-area SDD arrays has recently been developed by Fondazione Bruno Kessler (Italy), Politecnico di Milano (Italy), LNF-INFN (Italy) and the Stefan Meyer Institute (Austria) [35]. These innovative arrays consist of eight individual cells, each measuring 8 × 8 mm². These cells are arranged in a 2 × 4 configuration on a 450-μm thick silicon wafer. There is a 1-mm dead region along the border, resulting in an active/total area ratio exceeding 80%. The silicon wafer is bonded to a ceramic carrier. The ceramic carrier provides polarisation to the SDD units and holds eight dedicated CMOS low-noise, pulsed reset, charge--sensitive cryogenic preamplifiers, known as CUBE [36], which are connected to the SDD anodes using 2-mm wire, ensuring seamless integration and optimal performance.

These advanced monolithic SDD arrays have confirmed their worth in the context of the SIDDHARTA-2 experiment at the DAΦNE collider at the LNF-INFN (Italy). This research project is focused on studying kaonic atoms, particles in which a kaon replaces an electron in the atomic orbital [3, 27, 31, 35, 37–39]. In the SIDDHARTA-2 experiment, SDD detectors play a key role by capturing the X-rays emitted during the decay of kaon atoms. This process provides a crucial step towards investigating the isospin-dependent antikaon-nucleon strong interaction. This task requires a detector with exceptional accuracy, sensitivity and reliability. SDD monolithic arrays meet these requirements [31, 38, 39] by providing the experiment with high-resolution data that helps solve the puzzles of these unique atomic structures. The successful application of these monolithic SDD arrays in the challenging conditions of the SIDDHARTA-2 experiment underscores their suitability for cutting-edge research as well as medical imaging, where their excellent resolution can provide clear and informative images.

X-RAY SPECTROSCOPY CHARACTERISATION

One of the most critical aspects of SDDs performance is its linearity, which ensures that its response to incoming X-ray photons remains proportional across a wide range of energies. To evaluate this characteristic, a specific methodology can be applied involving the excitation of known fluorescent lines and the subsequent analysis of their spectral responses.

For example, the linearity of the SDD arrays described above was estimated using an experimental setup with two X-ray tubes, generating a broad spectrum of X-ray energies. Alongside this, a multielement target, when irradiated, emitted characteristic X-ray spectra, producing distinct energy peaks, such as the Ti, Cu and Fe Kα lines [31, 39]. These peaks facilitated the precise calibration of the SDDs' response, enhancing the reliability of the spectral analysis. The SDDs captured the emitted X-rays, and their spectral responses were registered. The main emphasis of the analysis was on the peak positions of the fluorescent lines (see Fig. 2A.).

The energy response function of each SDD was calibrated using a Gaussian curve fit to account for peak shapes and tail function to adjust for factors, such as incomplete charge collection and electron-hole recombination [31]. A crucial step is a detailed comparison of the positions of these peaks with the known energy values of the Ti, Cu and Fe K_α lines, which serves as a fundamental reference for estimating the linearity of SDDs (see Fig. 2B.). These peaks were identified as the centroids of Gaussian curves derived from the overall fit. These points were then plotted against known energy values, as referenced in the literature. To establish the relationship between these values a linear interpolation was employed. The gain parameter of the spectrum, indicating the energy response per channel, was deduced from the slope of this linear fit function and used to transform the arbitrary units of the ADC into energy and obtain energy spectra (see Fig. 2C). The

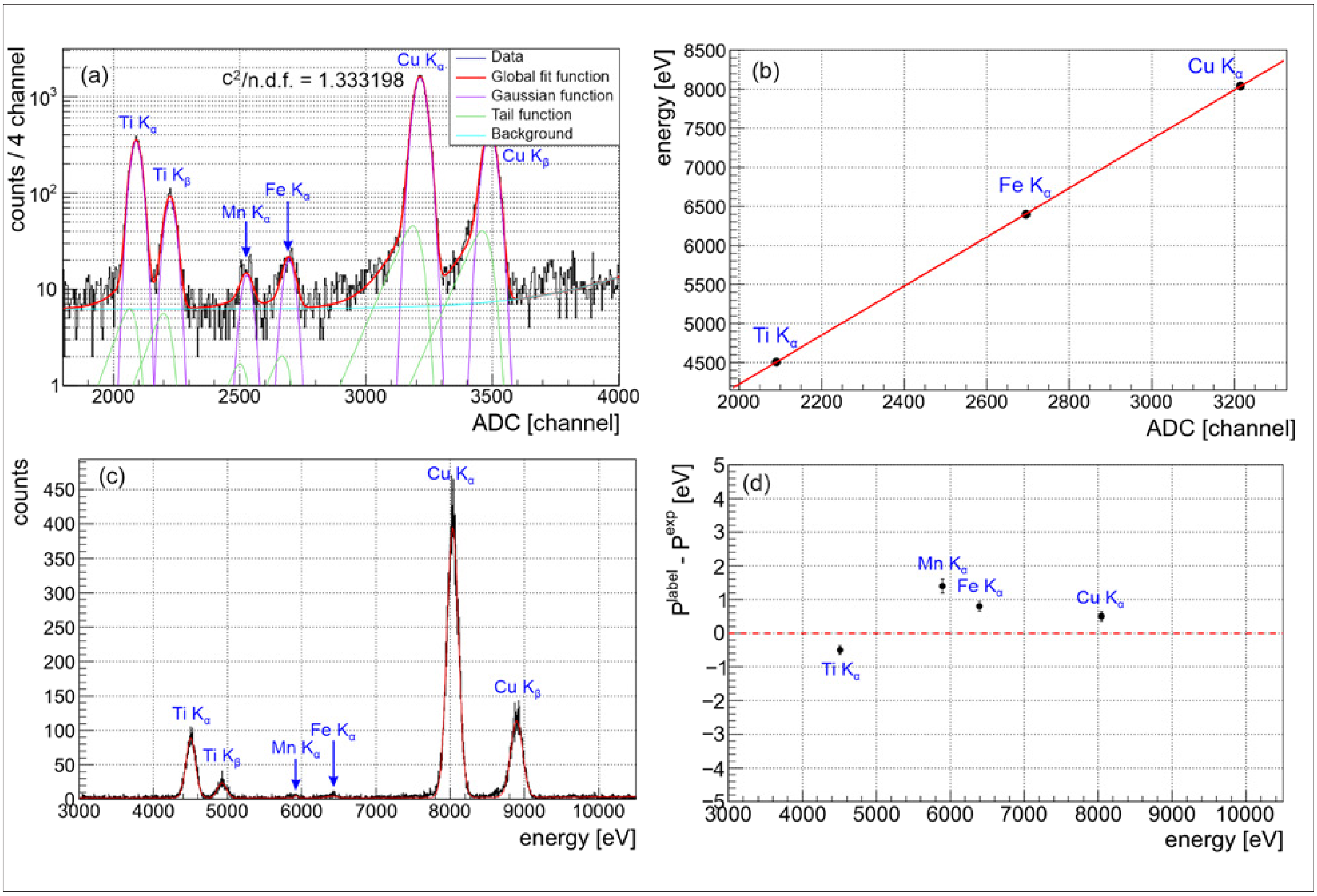

Fig. 2. (A) A fitted fluorescent spectrum for a single SDD in arbitrary ADC units. The red line represents the overall fit function, consisting of Gaussian (violet line) and tail functions (green line) for each peak, in addition to a constant and an exponential function for background modelling (cyan line); (B) linear fit, showing the experimental Kα peak positions relative to the known energy transitions; (C) the calibrated energy spectrum for the SDD and (D) deviation of each experimental Kα calibrated point from its corresponding theoretical value. Figures adapted from [39].

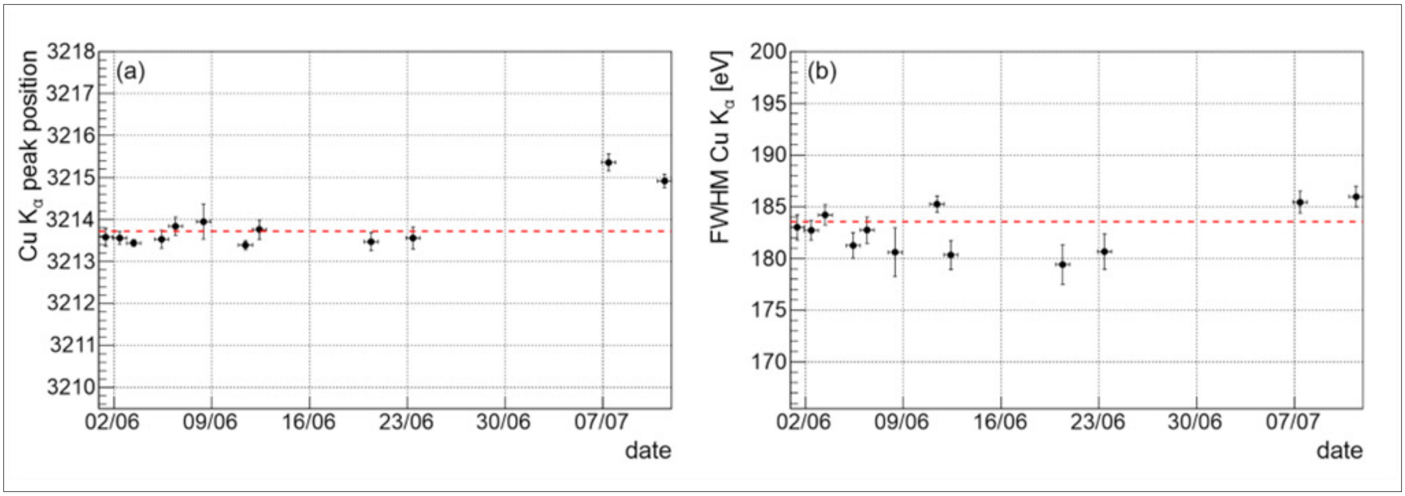

Fig. 3. (A) The position of the Cu Kα peak (in arbitrary ADC units) as a function of time for a typical SDD; (B) width stability of the Cu Kα line. Figures adapted from [39].

observed correspondence between the peak positions and known energy values confirms the linearity of the SDD with an impressive accuracy below 10^{-3} (see Fig. 2D.). Such a high level of precision underscores the suitability of SDDs for various applications.

Monitoring the long-term stability of the SDD system is essential. To evaluate this, the fluctuations in the position of the Cu K_α peak, serving as an indicator of system stability, were monitored for each SDD. The minimal observed fluctuations show the excellent stability of these detectors, which gives confidence in their reliability for accurate measurements (see Fig. 3.). It should be pointed out that the energy resolution of the SIDDHARTA-2 SDDs is 157.8 ± 0.3 (stat) ± 0.2 (syst) eV at 6.4 keV [37]. This highlights their potential to provide reliable and precise results over long periods of time.

CONCLUSIONS

In this communication, we have explored the efficiency and potential applications of silicon drift detectors (SDDs) in X-ray spectroscopy and medical imaging. The findings of this study emphasise the remarkable efficiency and potential of SDDs in medical imaging and X-ray spectroscopy. The investigation highlights the distinct advantages of SDDs, such as their exceptional linearity, stability and high sensitivity in detecting X-rays. These attributes significantly enhance their applicability in various fields, including physics and medical imaging. Particularly in medical contexts, SDDs' ability to provide precise and reliable imaging supports their potential role in advancing diagnostic technologies. However, it's important to note that while SDDs show great promise, their adaptation to certain applications, such as CT scanners, requires further modifications. The study's exploration of SDDs' capabilities and limitations offers valuable insights for future research and development in detector technology.

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