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Characterization and calibration of radiation-damaged double-sided silicon strip detectors

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ABSTRACT

Double-sided silicon strip detectors (DSSSD) are commonly used for event-by-event identification of charged particles as well as the reconstruction of particle trajectories in nuclear physics experiments with stable and radioactive beams. Intersecting areas of both p- and n-doped front- and back-side segments form individual virtual pixel segments allowing for a high detector granularity. DSSSDs are employed in demanding experimental environments and have to withstand high count rates of impinging nuclei. The illumination of the detector is often not homogeneous. Consequently, radiation damage of the detector is distributed non-uniformly. Position-dependent incomplete charge collection due to radiation damage limits the performance and lifetime of the detectors, the response of different channels may vary drastically. Position-resolved charge-collection losses between front- and back-side segments are investigated in an in-beam experiment and by performing radioactive source measurements. A novel position-resolved calibration method based on mutual consistency of p-side and n-side charges yields a significant enhancement of the energy resolution and the performance of radiation-damaged parts of the detector.

1. Introduction

Segmented silicon-strip detectors are indispensable detectors for charged particles in nuclear physics experiments to obtain precise information on the position (x,y), energy E, and energy loss ΔE of impinging particles. Typically, particles and energies may vary from electrons or protons with a few hundreds of keV up to heavy ions with energies of some hundreds of MeV/u [1]. When employed as ancillary detectors in in-beam γ-ray spectroscopy experiments for event-by-event particle identification as well as reconstruction of particle trajectories, both energy and precise position information are crucial for an accurate Doppler correction of emitted γ rays [2–5]. In particular, segmented silicon detectors are used to investigate super-heavy elements [6] and exotic radioactive nuclei by detecting the heavy ions that are implanted into the detector and measuring the subsequent light charged decay products like electrons/positrons from β decay [7], protons [8] or α particles [9].

Double-sided segmented silicon strip detectors (DSSSD) are manufactured from large silicon wafers and are segmented with doped p-side and n-side contacts on their front and back side, respectively. Intersecting areas of both N_p p- and N_n n-side segments form $N_n \times N_p$ individual *pixel* segments allowing for a high two-dimensional detector granularity. This is required to obtain an optimum position resolution, to measure high multiplicities, and to reject signal pile-up. DSSSDs are often employed in demanding experimental environments and have to withstand high count rates of impinging nuclei.

Livingston et al. reported on heavy ion radiation damage induced by α particles and fission fragments of a ^{252}Cf source in a 100 µm thick DSSSD in 1995 [10]. The amount of collected charge was observed to increasingly decline, resulting in a gradual downward shift of the measured particle energies and a reduced energy resolution for an integrated incident particle flux of up to $\approx 4 \times 10^6$ particles/mm^2. In addition, higher accumulated radiation doses caused a fatal resistance breakdown of the SiO_2 inter-strip isolation on the detector side facing the impinging ions, effectively destroying the segmentation of the detector. Barlini et al. [11] reported on the impact of radiation damage on the pulse-shape analysis performance of silicon detectors irradiated by heavy ions with $A \sim 120 - 130$. A linear decrease of the total

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collected charge was observed as a function of the increasing fluence.

These effects limit the lifetime of the detector in an experiment and, in an early stage, the quality and the resolution of the recorded energy spectra. The illumination of the detector is often not homogeneous due to the angular dependence of scattering cross sections, beam defocusing, local target inhomogeneities or diverging target thicknesses. Consequently, radiation damage of the detector may also be distributed non-homogeneously. Position-dependent effects of radiation damage in DSSSDs were first described by Iwata et al. [12]. The group measured signal amplitudes as a function of the bias voltage and hit position on irradiated detectors by using a laser test stand. Position-dependent signal amplitudes and charge losses were observed both below and above the full depletion voltage.

A careful energy calibration of the detector system is crucial for e.g. spectroscopic applications in which a precise energy has to be measured. Modern self-consistent or *intrinsic* calibration approaches [13–15] employ the information from the strips on one side of the detector as references to calibrate the strips on the other side and vice versa. However, these calibration methods require that the response and the resolution of the segments are independent of the position of the impinging particle on the detector. Detector parts that are subject to heavier radiation damage yield an incomplete charge collection on the front- and back-side electrodes which needs to be corrected in calibration procedures that are highly position dependent.

This paper discusses the impacts of radiation damage and degradation effects on the detector response of double-sided silicon strip detectors and is organized as follows: The experimental setup and the data acquisition are comprised in Section 2. Data from an in-beam experiment employing a DSSSD, presented in Section 3, show an advancing degradation with increasing irradiation. A refined analysis of another irradiated detector is featured in Section 4. The response of both p and n-side faces is investigated. A position-resolved calibration method is presented in Section 6. It is based on the fact that each event is registered simultaneously on the p- and n-side segments. This enables an optimum performance of the degraded detector. The paper closes with a summary and conclusions.

2. Experimental setup and detectors

The two circular DSSSDs described in this article are ~ 310(10) μm thick. They have a geometrical outer diameter of 100 mm and an inner hole of 28 mm diameter. Inner and outer diameter of the active area are 32 and 85 mm, respectively. The silicon wafers were manufactured by RADCON Ltd. (Zelenograd, Russia). The silicon disks were mounted and bonded onto printed circuit boards at the University of Lund, Sweden. The active area is divided into 64 radial segments (sectors) on the p-type junction side and into 32 annular segments (rings) on the ohmic n-side. Therefore, the detectors have a granularity of 2048 virtual pixels by combining the intersecting areas on the front and back side. The pixels cover areas from (innermost) 5.3 to (outermost) 13.7 mm^2. Photographs of both front and back side are presented in Fig. 1. Full depletion in reversed bias is reached at a voltage of 50 V. The SiO_2 surface passivation layer is reported to be 0.48 μm thick on the junction side and 1.9(2) μm on the ohmic side. Adjacent sectors and rings are isolated against each other by an inter-sector or inter-ring area of quoted 110 μm width.

Surface features of a DSSSD of the same type as described above were investigated employing atomic-force microscopy (AFM). The AFM measurements were obtained on an Asylum Research MFP-3D Infinity (Santa Barbara, CA, USA), using the non-contact AC mode under ambient conditions. The used cantilevers were AC200TS-R3 (Olympus, Tokyo, Japan) with a nominal resonance frequency of 115 kHz and a spring constant of 9 N/m. Fig. 1(c) shows an area of 90 × 90 μm^2 from an AFM measurement of the sector side. The image is made at the edge between a sector and an inter-sector area as visible as black lines in Fig. 1(a). The roughness [16] in the measured section is

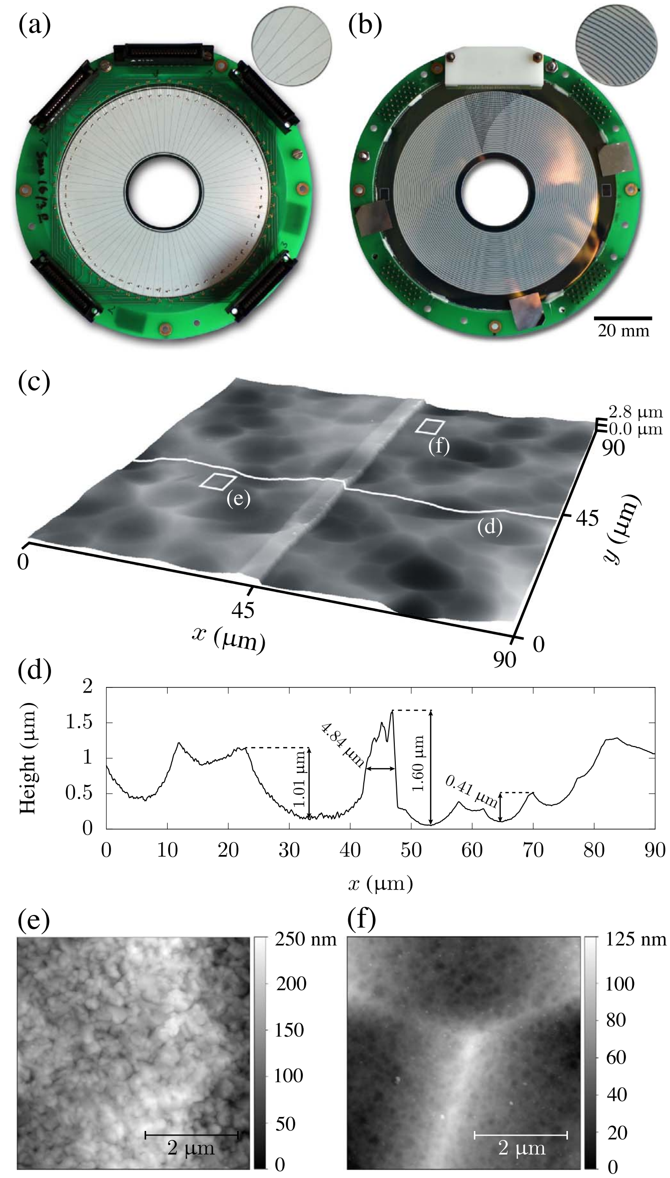

Fig. 1. (a) Photography of the front side of the DSSSD segmented into sectors, (b) back side of the detector with ring segments. Closeups of the ring and sector segmentation are shown in the insets. (c) 90 × 90 μm AFM image of the DSSSD surface of the sector side at the edge between a sector and an inter-sector area. (d) One-dimensional projection along the white line marked in (c). (e) and (f): Closeup AFM measurements of the insets marked in (c).

R_a = 0.322 μm. A one-dimensional projection along the white line in Fig. 1(c) is shown in panel (d). The coating at the ≈5 μm wide sector boundary between the sector and the inter-sector area has a height of Δz = 1.6 μm. The DSSSD's SiO_2 passivation layer surface features irregular piles and valleys with relative heights of up to 1 μm. More detailed images of the depicted insets in Fig. 1(c) are presented in Figs. 1(e) and (f). Here, different substructures exhibit grainy textures with height differences in the order of Δz = 100 to 200 nm.

A first DSSSD was investigated in a dedicated experimental setup at the University of Cologne. The detector was previously used in an in-beam experiment to detect light particles from (d,p) reactions in inverse kinematics using a ^{48}Ti beam at an energy of 100 MeV, impinging on a deuterated titanium target [4,17]. The detector was mounted under forward direction with respect to the target position. The detector was then stored in darkness at room temperature for five years. In the present setup the DSSSD was operated under a vacuum of 2.0 × 10^{-2} mbar at room temperature with an operating voltage of 60 V.