Studying signal collection in the punch-through protection area of a silicon micro-strip sensor using a micro-focused X-ray beam

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Abstract

For the Phase-II Upgrade of the ATLAS detector [1], a new, all-silicon tracker will be constructed in order to cope with the increased track density and radiation level of the High-Luminosity Large Hadron Collider. While silicon strip sensors are designed to minimise the fraction of dead material and maximise the active area of a sensor, concessions must be made to the requirements of operating a sensor in a particle physics detector. Sensor geometry features like the punch-through protection deviate from the standard sensor architecture and thereby affect the charge collection in that area. In order to study the signal collection of $n^+p^-p^+$ silicon strip sensors over their punch-through-protection area, ATLAS silicon strip sensors were scanned with a micro-focused X-ray beam at the Diamond Light Source. Due to the highly focused X-ray beam ($2 \times 3 \mu\text{m}^2$) and the short average path length of an electron after interaction with an X-ray photon ($\leq 2 \mu\text{m}$), local signal collection in different sensor areas can be studied with high resolution. This study presents results of high resolution 2D-scans of the punch-through protection region of ATLAS silicon micro-strip sensors, showing how far the strip signal collection area extends toward the bias ring and how the region is affected by radiation damage.

Keywords: ATLAS, silicon strip sensors, radiation damage, punch-through protection

1. Introduction

Silicon sensors for the ATLAS strip tracker are designed to be operated in the high-radiation environment of the High-Luminosity Large Hadron Collider [2].

A structured gap between strip implant and bias ring (punch-through protection) pro-

ducts readout electronics from high currents induced by beam splashes [3]. While this gap is short compared to the length of a sensor strip ($16.2 \mu\text{m}$ compared to about 2.4 cm strip length, i.e. less than 0.1% , for modules with short sensor strips), it will make up a combined area of about 800 cm^2 on the 18,000 detector modules foreseen to be built for the ATLAS strip tracker [4], corresponding to the area of eight modules.

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Figure 1: Structured gap between strip implants (brown) and bias ring (grey) with unknown signal collection (marked orange for individual sensor strip).

For efficient tracking, the strip tracker is designed to minimise gaps between the active sensor areas of adjacent modules. Inefficient charge collection in the punch-through protection region would effectively increase the amount of inactive material surrounding the active sensor area and hence reduce the detector performance.

It was thus important to study how far a sensor strip can collect signals beyond the end of its implant (see figure 1).

2. Experimental setup

Studying this sensor region requires a position resolution $\mathcal{O}(\mu\text{m})$, which was achieved by using a micro-focused X-ray beam ($2 \times 3 \mu\text{m}^2$) and μm precision positioning stages at the Diamond Light Source beamline B16 [5].

Given the dimensions of the implant width ($16 \mu\text{m}$) and the strip pitch ($75.5 \mu\text{m}$), the micro-focused beam was well suited to study the strip responses in different areas.

The Diamond Light Source provides photons every 2 ns. Using only monochromatic 15 keV photons reduces the flux to 1.2 ± 0.2 photons arriving within 10 ns. A 15 keV photon has a 51 % probability to react within $300 \mu\text{m}$ of silicon, so that each recorded event (sampling time 25 ns) contains deposited charge from 1.4 ± 0.3

photons. Data was taken continuously without triggering.

Two $n^+p^-p^+$ type ATLAS R0 mini sensors [6] (1 cm^2 , thickness $300 \mu\text{m}$) were tested in comparison:

- one unirradiated sensor (operated fully depleted at -400 V)
- one irradiated with neutrons at the reactor of the Jožef Stefan Institute (JSI, Ljubljana) to $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (operated under-depleted at -800 V)

Both sensors were tested at -20°C in dry air (humidity $< 0.01 \%$).

The sensors were wire bonded to an analogue readout board (ALiBaVa) [7] used for data acquisition. For each event, the charge registered in each readout channel was compared to the channel's noise and pedestal value. A hit was registered if the read out charge exceeded the channel noise by a pre-set signal-to-noise-ratio (SNR). While standard ALiBaVa analyses require an SNR of 5 to classify an input charge as a hit, the lower input charge caused by a 15 keV photon (4,200 electrons compared to $> 20,000$ electrons for a minimally ionising particle) required a lower SNR of 1.6.

The number of hits obtained per channel and beam position were used to map the responding sensor region.

3. Performed measurements

The main challenge of this study was locating the position of the gap between implant and bias ring prior to the measurement. In order to obtain sufficient statistics at each sensor position, a data acquisition time of about 2.5 min was required (corresponding to 50,000 events). With the chosen step sizes (see table 1), the allocated beam time allowed to scan a length of $170 \mu\text{m}$ along the sensor strip. In order to scan across a gap with a length of $16 \mu\text{m}$, the scan thus required a positioning precision of about

	Coarse scan	Fine scan
Step size x, [μm]	15	15
Scan length x, [μm]	240	240
Step size y, [μm]	50	5
Scan length y, [mm]	1.6/1.7	0.085/0.12
Number of events	50,000	50,000

Table 1: Parameters for coarse and fine scans of unirradiated/irradiated sensor

$\pm 80 \mu\text{m}$ for this scan. The sensor was positioned with respect to the beam using a positioning laser with a positioning uncertainty of about $\pm 500 \mu\text{m}$, which was insufficient for the required precision.

A method was conceived for the precise location of the end of the strip implant using sensor features: in previous studies, aluminium bond pads on sensors (AC pads) had been found to affect the response of sensor strips [8]. In the vicinity of bond pads on a sensor strip, this strip collects charges over a larger area than sensor strips without bond pads. Bond pads are large ($200 \times 56 \mu\text{m}^2$) compared to the punch-through protection region and thus can be found and mapped in a coarse scan over a large sensor area. Since the position of the punch-through protection region with respect to the position of AC pads is known from the sensor geometry, the location of AC pads allows the subsequent location of the end of the strip implant.

Scans were thus performed in two stages (see table 1): in a first step, a coarse scan was performed over a comparably large sensor area. The data analysis of this scan was used to locate the positions of AC pads on the sensor and extrapolate the positions of bias ring and structured gap. Afterwards, a second scan was set up using the coordinates determined in the first step.

Figures 2a and 2b show the hit maps obtained in the coarse sensor scans. Using the

(a) Unirradiated sensor

(b) Irradiated sensor

Figure 2: Hit maps from coarse scans on an unirradiated sensor (left) and an irradiated sensor (right), showing hits from two adjacent channels each. The hit patterns allow to identify AC pads (violet) and DC pads (red) and to extrapolate the position of the gap between implant and bias ring (marked yellow).

reconstructed positions of AC pads from the coarse scan, the positions of bias ring and end of strip implant were determined with a precision of $\pm 20 \mu\text{m}$.

4. Results

Hit maps obtained at the end of strip implants showed few hits being collected between the end of the strip implant and the bias ring, both for an unirradiated sensor (see figure 3a) and an irradiated sensor (see figure 3b). Figures 4a and 4b illustrate the variation of collected hits along the end of the strip implant: the number of collected hits increases around the end of a sensor strip, where the implant is wider, and decreases towards the bias ring, both for an unirradiated and an irradiated sensor. The gap between strip implant and bias ring thus does not provide reliable charge collection.

5. Conclusion and Outlook

Measurements of charge collection in the punch-through protection region of a sensor showed little charge collection in the gap between strip implant and bias ring. The punch-through-protection region thus needs to be treated as dead sensor material.

After measuring the signal collection in the sensor region between the ends of strip implants and bias ring, future measurements are planned to assess the signal collection between the outermost sensor strips and the sensor bias ring (in the region parallel to the strip direction) as well.

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Figure 3: Hit maps from fine scans on an unirradiated sensor (left) and an irradiated sensor (right), showing hits from two adjacent channels each. Between the circular end of the strip implant (orange) and the bias ring (blue), few hits are collected.

(a) Unirradiated sensor

(b) Irradiated sensor

Figure 4: 1-dimensional projection of hits collected along two sensor strips in the region between end of strip implant (orange) and bias ring (blue)

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