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TECHNICAL REPORT

Active Region Extent Assessment with X-rays (AREA-X)

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Abstract: The development of semiconductor sensors for new particle tracking detectors places increasing limits on sensor characteristics such as uniformity, size and shape of inefficient areas and size of active compared to inactive sensor areas. Accurately assessing these relatively subtle effects requires either measurements in particle beams or the modification of samples to be used in dedicated laser test setups.

Active Region Extent Assessment with X-rays (AREA-X) has been developed as an alternative method for the fast, efficient and precise study of the active area of a semiconductor sensor. It uses a monochromatic, micro-focused X-ray beam with a 10–20 keV energy range as provided by several synchrotron beam lines and uses the photo current induced in the sensor to measure the depth of the responsive sensor volume. It can be used to study local inhomogeneities or inefficiencies, the overall extent of the active sensor volume and its shape and its localised application, which makes the need to gather statistics over a large area unnecessary, allowing for fast readout, which enables studies of the sensor behaviour at a range of external parameters, e.g. temperature or applied bias voltage.

This paper presents the measurement concept and technical setup of the measurement, results from initial measurements as well as capabilities and limitations of the method.

Keywords: Si microstrip and pad detectors; Particle tracking detectors; Performance of High Energy Physics Detectors; Radiation-hard detectors

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1 Introduction

Semi-conductor sensors for future high energy physics tracking detectors are developed to provide high efficiency under challenging new conditions including high track density, high radiation levels, minimal material budget and air cooling concepts. As a result, sensors need to be developed to have high spatial resolution, reduced thickness, good timing resolution and a large fraction of active to inactive material, reducing the size of inactive sensor areas, e.g. between dicing edge and guard rings or bias rings. The requirements placed on these sensors regarding efficiency and performance requires characterisation methods beyond traditional probing tests, which are mainly achieved in particle beam experiments or two-photon-absorption test setups currently under development.

While particle beam tests provide a realistic assessment of the extent and shape of the active area of a sensor under investigation, they are limited by a need to accumulate sufficient statistics to achieve the intended statistical resolution and, thereby, the speed of the readout system and particle tracking setup. High-precision laser setups provide a more convenient alternative to beam tests, but require access to the sensor volume and removal of any metal layers on the outside of the sensor and therefore require significant sample modifications to achieve similar results

Active Region Extent Assessment with X-rays (AREA-X) has been developed as an alternative method to traditional tests in either particle beams: instead of using charged particles, it uses a micro-focused X-ray beam to scan areas of interest in a grid scan to map the extent and shape of a depleted sensor volume or local inefficiencies within a sensor area. Different from particle beams, it does not rely on the accumulation of sufficient statistics for the area covered by the beam, but can be targeted towards any area of interest and used to scan that area exclusively, which makes this method fast and very efficient for localised defect detection. AREA-X is comparable to current laser test setups, but provides more flexibility since the X-ray photons used here can traverse sensor layers intransparent to lasers.

AREA-X relies on the readout of the photo current induced in the depleted volume of a sensor, which is used as an indicator for the thickness of the depleted sensor volume. It therefore allows to

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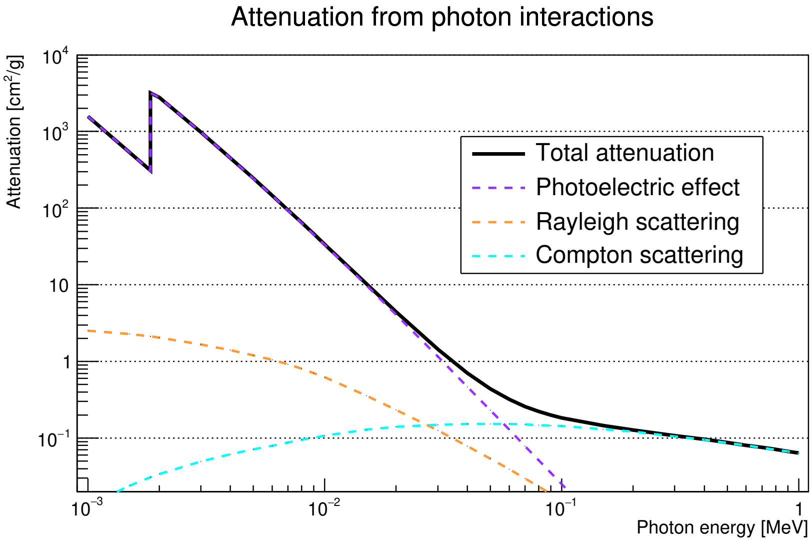

Figure 1. Attenuation of photons in silicon: for an energy range of 10–20 keV, the photoelectric effect contributes 98–99 % to the total attenuation.

not only map the depleted sensor volume, but also to assess its changes under different conditions, such as different bias voltages or changing environmental conditions, which makes it an excellent tool for defect diagnosis.

2 Mechanism

For these measurements, X-ray photons in an energy range of 10–20 keV are used to investigate silicon sensors. In that energy range, the majority of photons interacts through photoelectric absorption (see figure 1).

A photoelectric interaction results in a complete energy transfer from the photon to an electron, which then travels up to 10 µm in silicon, producing electron-hole-pairs. If the photon interaction occurs within the charge depleted area of silicon, it results in a photo current that can be measured for a photon beam with sufficient intensity. Outside the depleted sensor volume, electron-hole pairs recombine without causing a photo current. The measured photo current therefore depends on the depth of the depleted volume within the sensor and can be used to map the depleted sensor volume by moving a photon beam over a sensor area of interest.

Different from measurements in particle beams, where readout electronics are used to register particle hits and which are therefore limited by the readout speed and statistics, the photo current induced by a photon beam has been found to stabilise within seconds, allowing grid scans with 5 s per point independent of the sensor area and shape. Each beam position on a sensor under investigation (perpendicular to the sensor surface) combines information from the sensor volume covered by the beam area (2×3 µm for the micro-focused X-ray beam used for these tests [1]) and the approximately 10 µm radius of the electron path after the photoelectric interaction.

By using a micro-focused X-ray beam with a monochromatic energy and choosing an appropriate energy, the measurement can be set up to ensure that a sufficient number of photon interactions

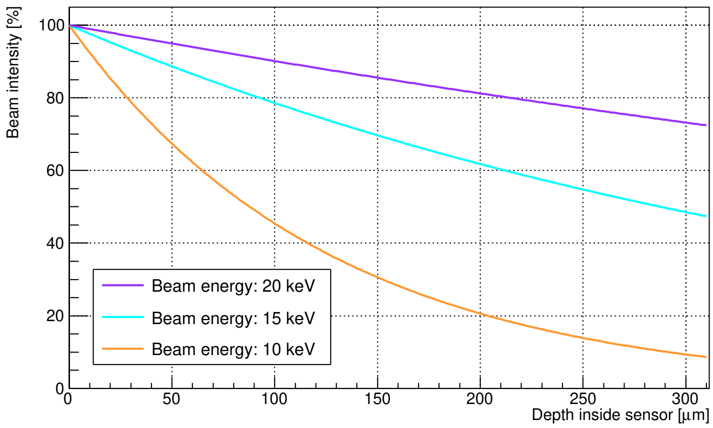

Figure 2. Intensity loss of an X-ray beam at different energies within silicon. Depending on the thickness of the sensor under investigation, a beam energy can be chosen to ensure a sufficient number of photon interactions within the sensor thickness.

occurs within the sensor (see figure 2). Since the measured current (consisting of leakage current and induced photo current) contains contributions from all layers of the sensor, the beam energy can additionally be chosen to lead to a mostly flat absorption profile for similar contributions from all sensor depths. Measurements for silicon sensors with a thickness of 300 µm have been performed with 15 keV photons [2–6].

Using the photo current to map the depleted sensor volume has successfully been used for sensors after proton irradiation up to $2 \cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$ [6] and can also be used for scans along the sensor edge, if the beam energy allows a sufficient number of photons to traverse the sensor edge.

3 Measurement setup

Sensor tests are performed with the sensors inside a box that is both light tight (to prevent photo current from outside light sources) and mostly air tight, so that the ambient humidity inside the box can be reduced by flushing the box with dry air or nitrogen. This is especially important for tests of structures after irradiation, which require cooling and therefore a low humidity to prevent condensation on the samples under test.

Samples under investigation are mounted on PCBs developed for X-ray beam tests: different from tests in electron beams, the setup does not require optimisation to minimise interactions along the beam path, therefore samples can be mounted on solid PCBs (see figure 3):

A negative voltage is applied to the sample backside, wire bonds are used to connect the diode surface to a ground pad for reverse biasing. A high voltage filter is added to the high voltage connection in order to avoid voltage spikes. Since the current is read out from the power supply which also provides high voltage, no additional connections are required for current measurements. An SHT21 sensor on the PCB is used for temperature and humidity readout.

Cooling blocks with peltier elements can be utilised to cool the sensor on the PCB, if cooling is required. In order to minimise interactions in front of the sample, the testing box was designed with cutouts in the beam path, covered with thin aluminium foil (see figure 4).

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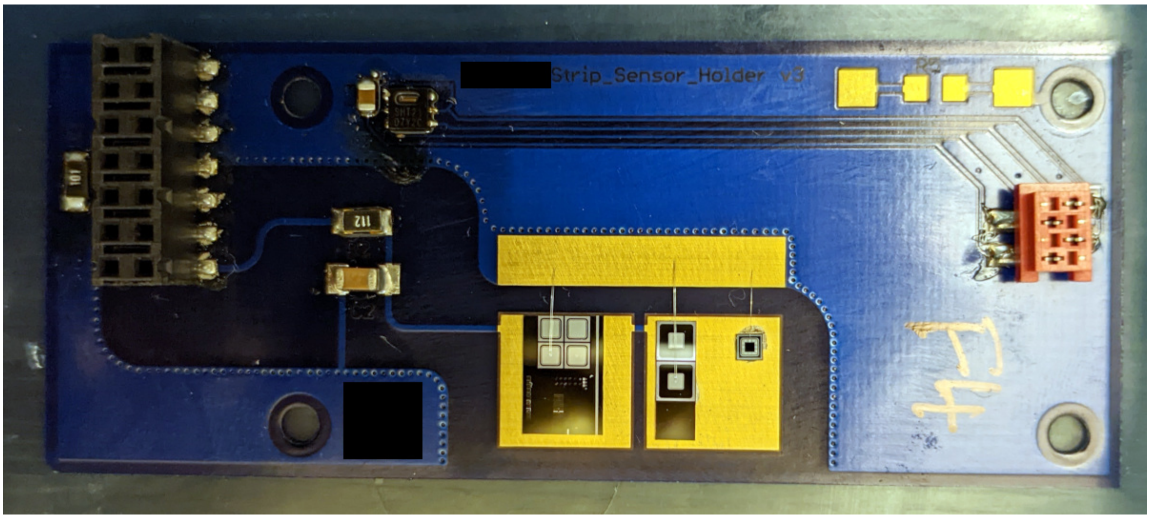

Figure 3. PCB to mount small samples (in the image: two diode arrays and one individual diode) for AREA-X measurements.

An aluminium plate holding the test PCB is positioned on a cooling jig consisting of a cooling plate cooled to 10°C and peltier elements, which reduce the aluminium holder's temperature to −20°C. Nitrogen is fed into the box through a tube to reduce the humidity level and avoid condensation. Cables for high voltage (to bias the sensor under test and read out their current), the temperature sensor readout and to power the peltier elements are fed through air- and light-tight connectors in the testbeam box.

For silicon sensor tests, the sensor was cooled down to 10°C for unirradiated samples and to −20°C for irradiated samples, and flushed with nitrogen to achieve a relative humidity of < 1%. An SHT21 temperature and humidity sensor was used to monitor environmental conditions during measurements. Since this setup only requires

- powering cables for the peltier elements
- a readout connection for temperature and humidity
- a high voltage connection, through which the sensor current is read out using a source measurement unit

the test box can be small enough to comply with size limitations of most X-ray beamlines.

During a measurement, the sample is mounted on an x-y-stage with high positional precision, that can be controlled during the scan. A 2D-scan of the sample surface is programmed through python scripts interfacing with the beam line electronics, generally consisting of

- an outer loop scanning steps through positions in x with a defined step size
- an inner loop scanning steps through positions in y with a defined step size
- the readout performed at each position, consisting of:
  - a check of the beam current (the measurement is only started if beam is present)
  - a timestamp for later correlation of stage positions and measured current values

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Figure 4. Setup for AREA-X measurements: the sensor test PCB is mounted on an aluminium holder plate for easy exchange.

- a 3.3 V TTL trigger signal, sent by the stage control system, to start the current measurement
- a waiting time while the current is being measured

Stage movements are controlled separately from the current measurement: when the readout system registers a trigger, a wait time is added to allow the sensor current to stabilise, before it is read out and written into a file together with a time stamp and environmental conditions for later current correction, if needed. Communication between stage controls and current readout can be one-directional by having stage movements trigger current readout and using wait times to allow sufficient time for current measurements.

Different from beam tests in charged particle beams, which generally use pixel-sensor based beam telescopes for position information, e.g. EUDET beam telescopes [7], X-ray beams do not provide tracking information. While precision stages generally provide precise relative position

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information with respect to a given starting point, identifying the absolute position of the beam on the usually much larger sample requires an initial positioning scan relating the beam position to known features of the sample under investigation, e.g.

- scans across the full depleted area to find its edges and map out the full area to be scanned [4]
- scans across known features of the sensor to locate areas from where positions of interest can be extrapolated [2]
- scans across areas with different amounts of material over the sample so that its position can be determined based on induced photo current variations due to beam attenuation [3]

Depending on the stage movement speed and allocated time for the photo current to stabilise after position changes, grid scans have been performed requiring only about 6 s per point (5 s for the actual current measurement with an additional 1 s waiting time to allow for stage movements).

Depending on the spacing between points, an area of $2 \times 2\,\mathrm{cm}^2$ has successfully been scanned within 45 min with 100 µm step size [4].

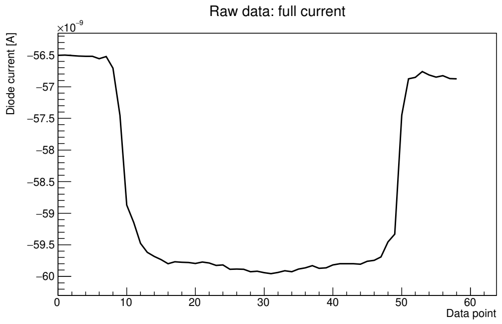
4 Selected results

Initial X-ray beam tests were conducted on ATLAS ITk strip tracker detector module prototypes [8] using the modules' own data acquisition system to compare the sensor maps obtained in particle beams and X-ray beams. These studies tested whether the different interaction mechanisms of electrons with an energy in the GeV range and X-rays with in the keV range obtained comparable results for localised sensor inhomogeneities [2]. It was found that the X-ray beam was not only able to obtain the same results, but its higher position resolution was able to map the effects under investigation much more clearly than the particle beam.

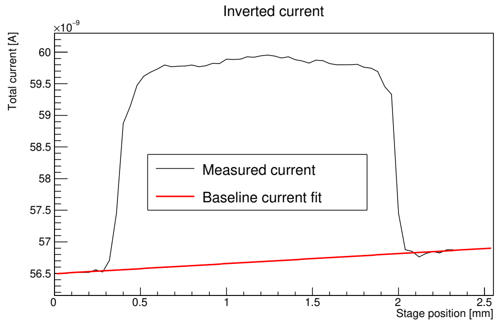
While full detector modules continued to be used for measurements where the interactions between sensor and readout electronics were necessary for the performed study (e.g. for pick-up in sensors with embedded pitch adapters [5] or time-resolved noise measurements correlated with the signal induced in a single strip [3]), AREA-X was developed specifically for the study of individual sensors or sensor structures using only the induced photo current.

Proof of concept measurements for AREA-X were performed using different geometries of test diodes, i.e. test structures with a similar edge structure as full size devices, but without segmentation into pixels or strips (for a full geometry description see [4]). For these diodes, the shape of the depleted volume based on the applied bias voltage was studied. As a follow-up measurement, the same study was performed for the same diodes, irradiated with protons up to different fluence levels to investigate the signal-to-noise-ratio required to map the depleted sensor volume [6].

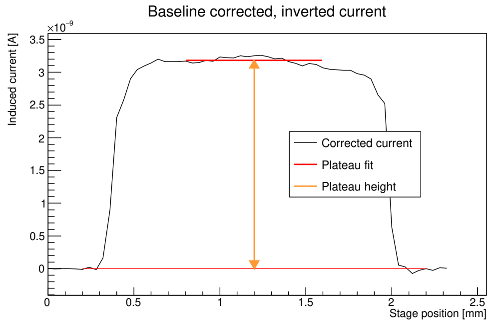
In addition to proof of concept measurements, the method was used to study the extension of the depleted diode volume and its development after irradiation as a function of the applied bias voltage. For this measurement, diodes of two geometries (for a detailed description of the diode geometry, see [4]) were irradiated up to 1 and $5 \cdot 10^{14}\,\mathrm{n_{eq}/cm^2}$ and tested at reverse bias voltages between -1 and -1000 V. The test was performed by first identifying the centre of each diode in a preliminary mapping scan and then moving the sensor with respect to the beam to cover the full diode length in one horizontal and one vertical scan at each bias voltage.



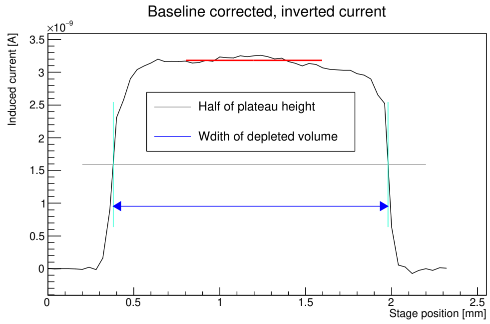
(a) Total diode current measured per position.



(b) Inverted diode current, scaled with step size.



(c) Inverted diode current after subtracting leakage current and fit of diode plateau.



(d) Determining the width of the depleted diode volume using 50 % point of plateau.

Figure 5. Current measurement and data analysis for a measurement across an individual diode at one bias voltage.

Afterwards, the resulting current profile (see figure 5(a)) was plotted in absolute terms (see figure 5(b)) and the baseline leakage current was subtracted (see figure 5(c)). Since the diode leakage current after irradiations was several orders of magnitude higher than the induced photo current, this step also served to correct for changes in the leakage current caused by minor temperature changes during the scan (see tilted baseline fit in figure 5(b)).

The resulting profile was then used to measure the plateau height, indicating the depth of the depleted volume, and the width of the depleted diode volume, determined at 50 % of the diode plateau height (see figure 5(d)).

Similar to a charge collection efficiency measurement, the plateau height of the obtained current profile indicates the full depletion voltage of the diode under investigation (see figure 6(a)). For both diodes, the horizontal and vertical scans show good agreement. Additionally, both diodes show similar depletion levels for corresponding bias voltages, which matches the expectation of diodes with similar characteristics and thickness. As expected, full depletion is reached at higher voltages for higher levels of hadronic irradiation.

Comparing the widths of the depleted volumes for both diodes and fluences (see figure 6(b)), the data shows that in all cases (for both diodes and both fluences), the width of the depleted volume increases beyond the diodes' full depletion voltages. This observation agrees with simulations predicting that the depleted sensor volume bulges out beyond the nominal diode area for both unirradiated and irradiated sensors [4]. This effect is shown for both diode geometries and fluences.

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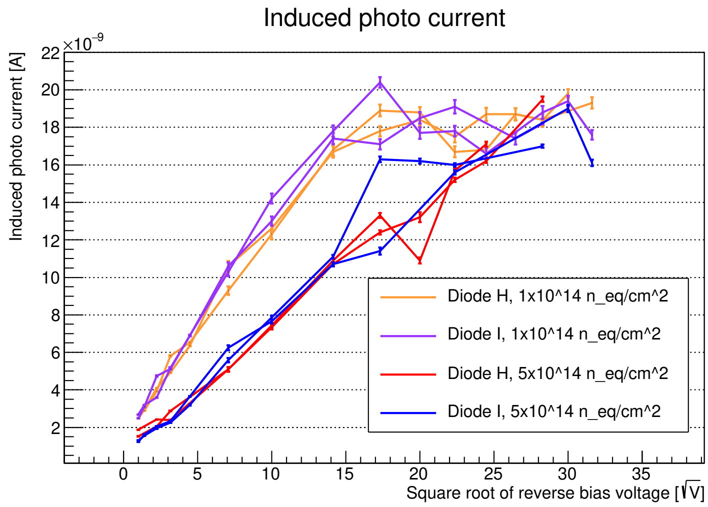
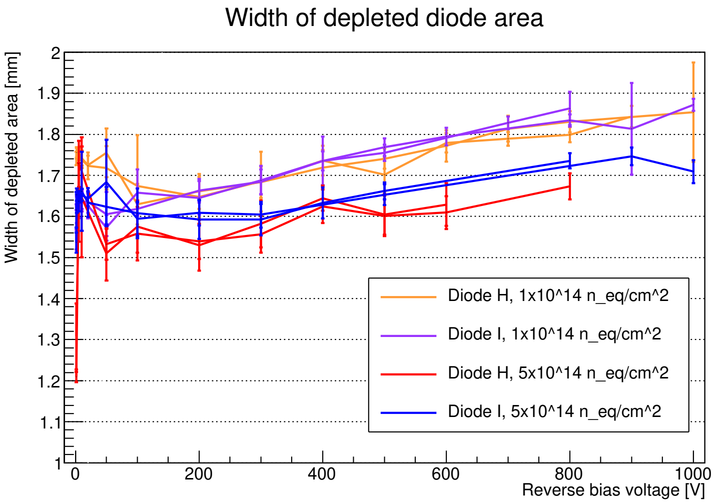


(a) Total photo currents depending on applied bias voltage, measured for two diodes, irradiated up to two different fluences. Since the photo current increases with increased depth of depletion, this measurement can be used to estimate their individual full depletion voltages.



(b) Width of depleted sensor volume depending on applied bias voltage for two types of diodes, irradiated up to two different fluences. Comparing the diode's widths with the depth of the depletion volume shows the extent to which the depleted sensor volume continues to increase with applied bias voltage even once full depletion is reached.

Figure 6. Width and depth of depleted diode volume measured as a function of applied bias voltage for two types of diode geometries and two levels of hadronic irradiation.

Due to the derivative process of calculating the width of the depleted volume, the two scans performed on each diode (horizontal and vertical) were found to be in slightly worse agreement. However, general trends such as a systematic shift between different fluence levels and an increasing width of the depleted volume beyond full depletion are observed in all cases despite minor fluctuations and are considered systematic effects.

It should be noted that each voltage scan required a measurement time of twelve minutes per diode per voltage, with a total measurement time of four hours for the full test performed on both diodes, due to the known beam size and position with respect to the diode.

This study was chosen to illustrate the opportunities which the AREA-X method presents for the standalone characterisation of devices and detailed studies as well as the investigation of broader trends, e.g. in comparison with simulated behaviour.

5 Comparison with available alternatives

The AREA-X method described here is currently available to obtain 2D-projections of the depleted sensor volume and can be used to map the extension of the in-plane depleted zone as well as a project on the sensor edge. It is therefore comparable to measurements performed with a laser setup or an edge TCT setup and provides less information than e.g. a two-photon-absorption setup. Operating based on a similar mechanism as laser test setups, AREA-X requires less modification of a device under test than a laser mechanism and is therefore applicable to a larger range of devices: laser tests require the removal of any material reflective for the laser in use prior to a measurement, which can be either an aluminised sensor backplane or metal contacts on the sensor surface, such as bond pads. In addition to modifying the sensor characteristics (aluminium bond pads on sensor implants have been found to affect the shape of the electric field underneath), these changes also complicate the process of testing irradiated sensors, as they leave the sensor more vulnerable to damage during the irradiation process or require etching irradiated sensor material. Especially edge TCT measurements, which require a dedicated preparation of the sensor edge, can limit the options for continued tests (e.g. secondary irradiations after a performed measurement) due to the existing modification.

AREA-X does not require any modifications to a sensor under investigation and therefore allow tests on devices where a preparation for laser tests is either not desirable or not possible, such as tests on assembled detector modules. It therefore provides a powerful method for the analysis and diagnosis of devices which can not be tested using laser setups.

6 Conclusion and outlook

AREA-X was developed as a method for semiconductor characterisation that maps the active area of a sensor with high spatial resolution without requiring permanent modifications to the sensor under investigation, especially for structures not suitable for methods relying on lasers, e.g. due to an intransparent aluminium layer covering the sensor volume.

Initial measurements were conducted using simple diodes from test structures to show the feasibility of the method to map the depleted sensor volume depending on applied bias voltage and exposure to high fluences. While these measurements were successful, further optimisation is planned to speed up the data acquisition process and improve the data taking efficiency.

Future measurements are foreseen to be conducted to study the extent and shape of inefficiencies between sensor implants, study the shape of the depleted sensor volume at the edge of a sensor breakdown and to map the shape of the active sensor volume for different sensor technologies, e.g. 3D pixel sensors.

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While the established AREA-X method provides a 2D-projection of a depleted sensor volume, future measurements are planned to extend the method to a full 3D method. Tests are planned to be conducted using a range of beam energies so that the different absorption profiles can be utilised to obtain information about the shape of the depleted sensor volume.

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