Mapping the in-plane electric field inside irradiated diodes

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Outline

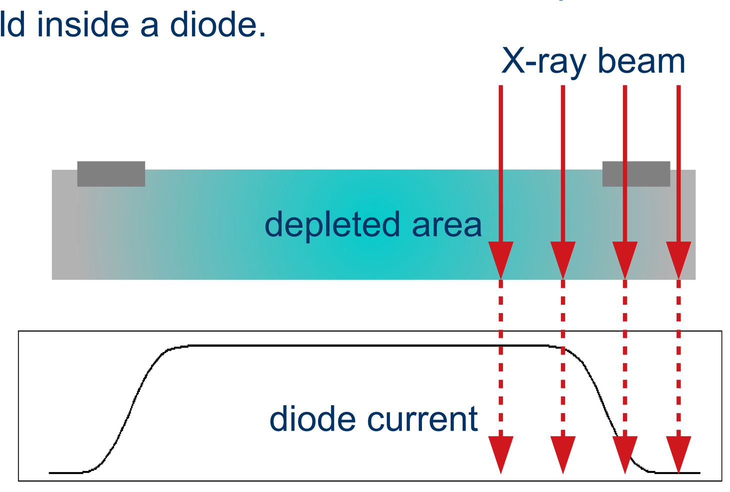
A significant aspect of the Phase-II Upgrade of the ATLAS detector is the replacement of the current Inner Detector with the ATLAS Inner Tracker (ITk). The ATLAS ITk is an all-silicon detector consisting of a pixel tracker and a strip tracker. Sensors for the ITk strip tracker have been developed to withstand the high radiation environment in the ATLAS detector after the High Luminosity Upgrade of the Large Hadron Collider at CERN, which will significantly increase the rate of particle collisions and resulting particle tracks.

During their operation in the ATLAS detector, sensors for the ITk strip tracker are expected to accumulate fluences up to 1.6 $\cdot 10^{15}$ n_{eq}/cm^2 (including a safety factor of 1.5), which will significantly affect their performance. One characteristic of interest for highly irradiated sensors is the shape and homogeneity of the electric field inside its active area.

This measurement explores the possibility of using a micro-focused (2 x 3 μm²), monochromatic (15 keV) X-ray beam to map the depleted area of highly irradiated diodes using the total measured current. Three different versions of diodes were irradiated up to different fluences using reactor neutrons.

Measurement setup

Measurement principle: within the depleted area of a diode, an X-ray beam will increase the measured current more than in an un-depleted diode area, which can be used to map the electric field inside a diode.

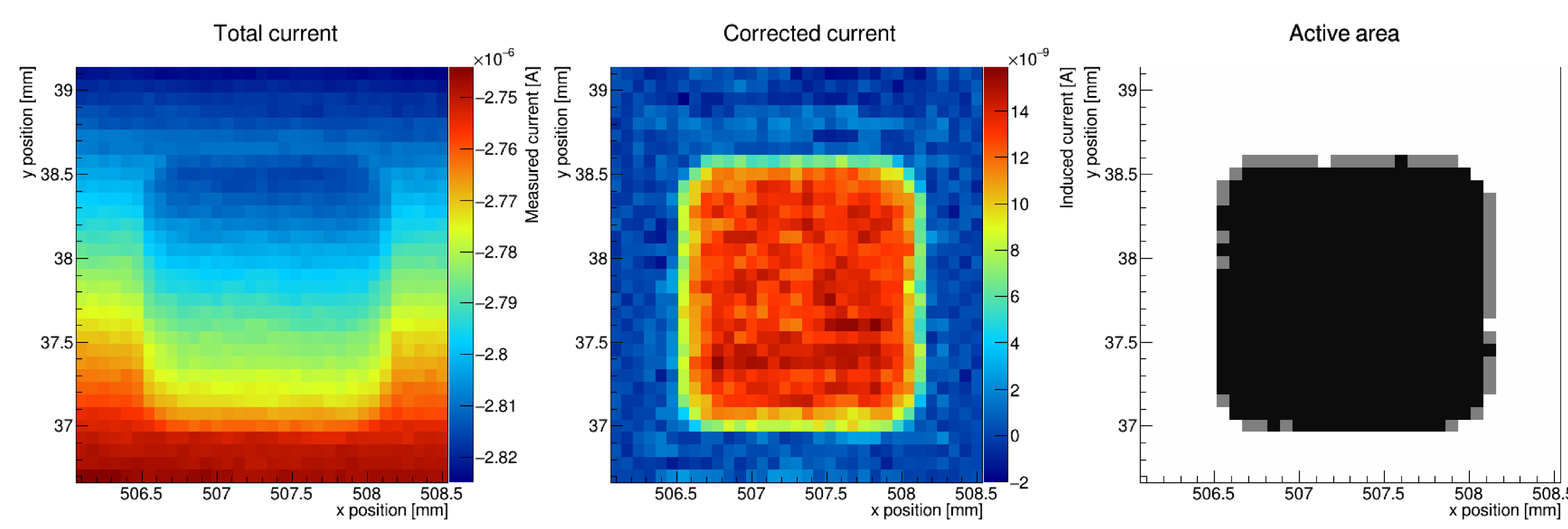


All diode measurements shown here were conducted with an applied bias voltage of -500 V, matching the foreseen bias voltage of sensors in the ITk strip tracker. The measurement volume was flushed with nitrogen to prevent condensation on the diodes.

During measurements, diodes were cooled down to -20°C using a peltier-element cooling jig inside a light-sealed cold box (see picture below). Precision stages allowed to move diodes under investigation with respect to the X-ray beam in order to obtain 2D maps.

A Keithley 2410 high voltage power supply was used to both bias diodes under investigation and measure the corresponding current.

Current correction



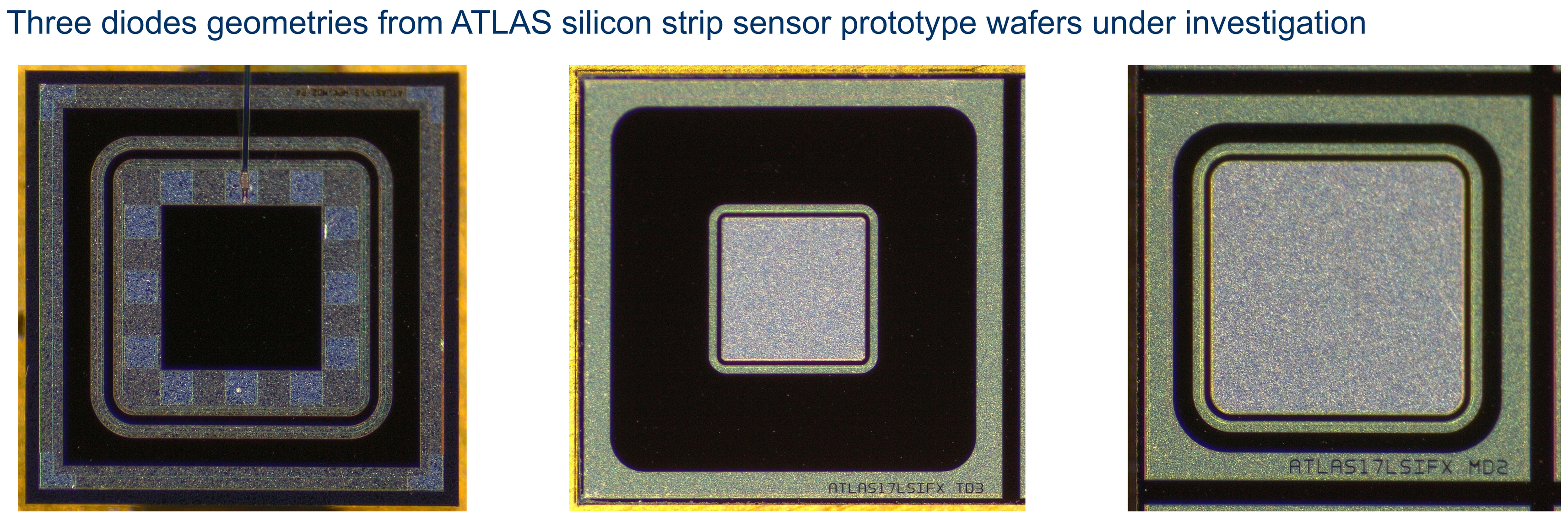
During measurements, the total diode current was read out. For irradiated diodes, the measured current was dominated by the sensor leakage current, which varied with the sensor temperature. In order to map the depleted diode area, the diode leakage current was subtracted from the total measured current.

At a sensor temperature of about -20°C, fluctuations in the sensor leakage current were small compared to the X-ray beam induced current. Subtracting the average leakage current per scan area showed the underlying electric field in the diode (here: IFX MD2, irradiated up to $1{\cdot}10^{15}$ n_{eq}/cm^2).

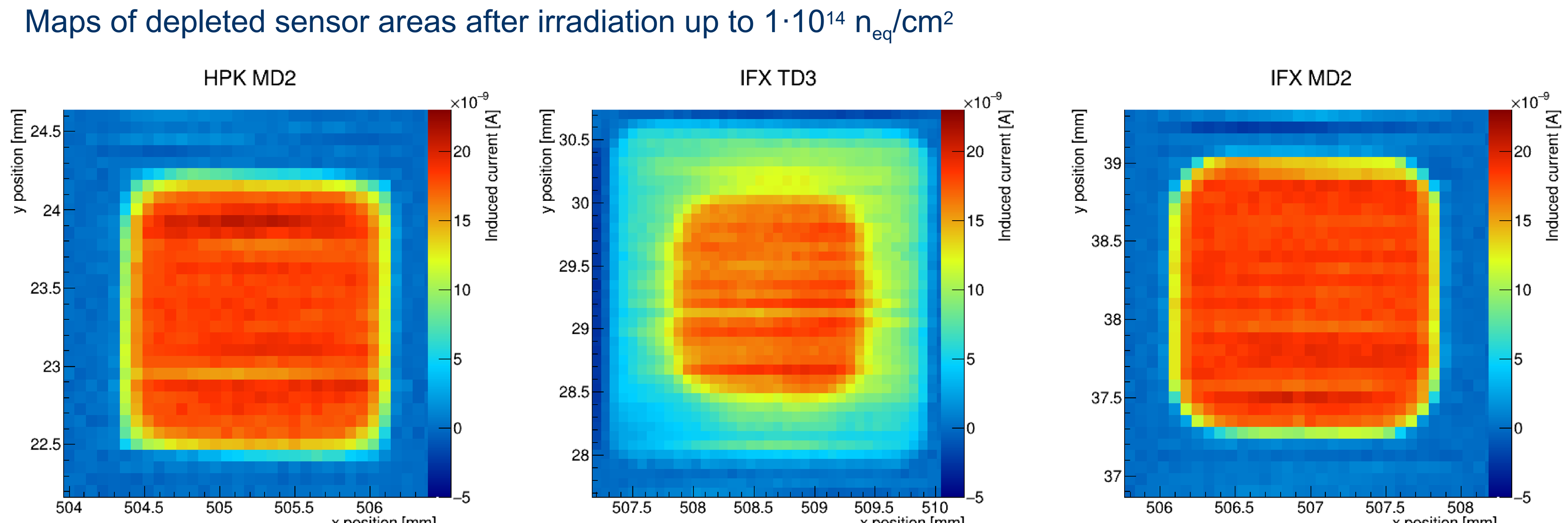
The active sensor area was calculated from the resulting corrected current map: bins in the main pedestal (within fluctuations) were counted towards the active area, bins within a window between background and pedestal were counted towards the uncertainty of the active area.

Diode geometries and field shape

Three diodes geometries from ATLAS silicon strip sensor prototype wafers under investigation

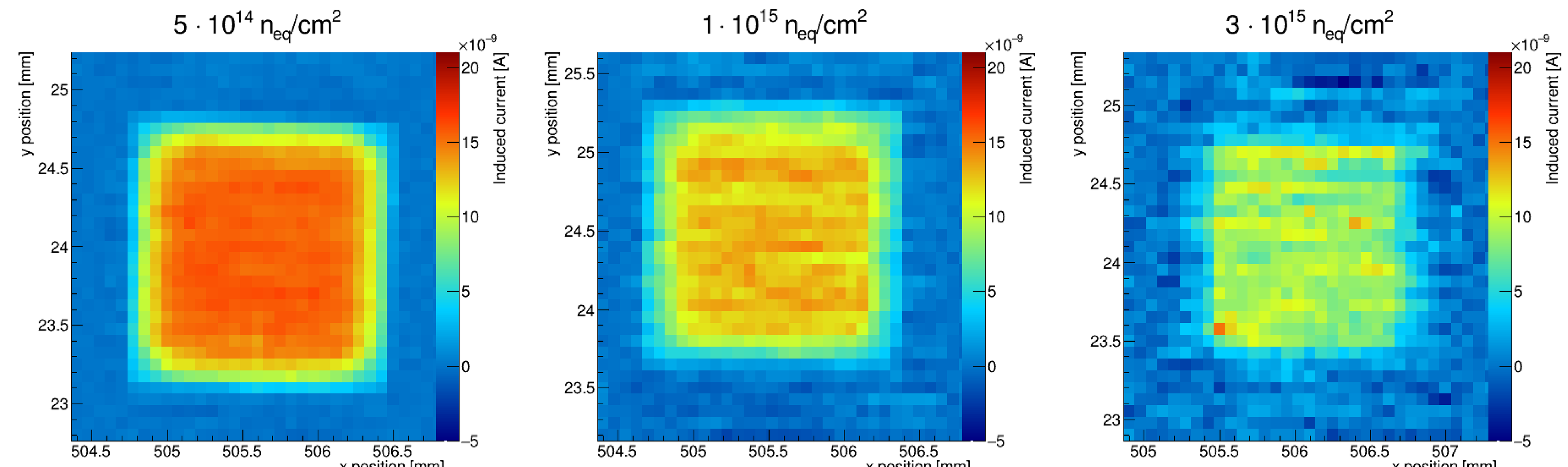


Maps of depleted sensor areas after irradiation up to $1{\cdot}10^{14}$ n_{eq}/cm^2



Field shape dependence on sensor fluence

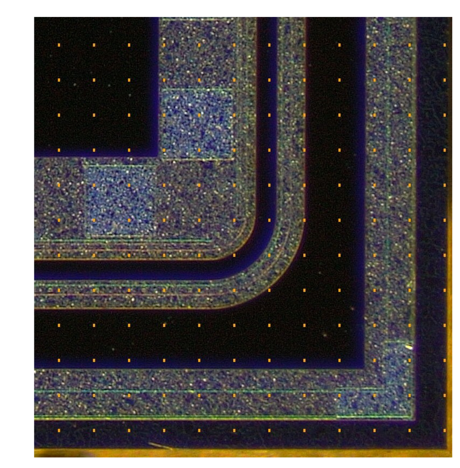
Samples of each diode type were irradiated up to four fluences: $1{\cdot}10^{14}$ n_{eq}/cm^2, $5{\cdot}10^{14}$ n_{eq}/cm^2, $1{\cdot}10^{15}$ n_{eq}/cm^2 and $3{\cdot}10^{15}$ n_{eq}/cm^2 (here: HPK MD2). One diode per fluence was mapped in the beam, except for the highest fluence level, where the signal-to-noise-ratio was found to be too low to map the active area reliably.



Resolution

Measurements were conducted using an X-ray beam focused to a beam size of 2 x 3 μm² with a monochromatic beam energy of 15 keV.

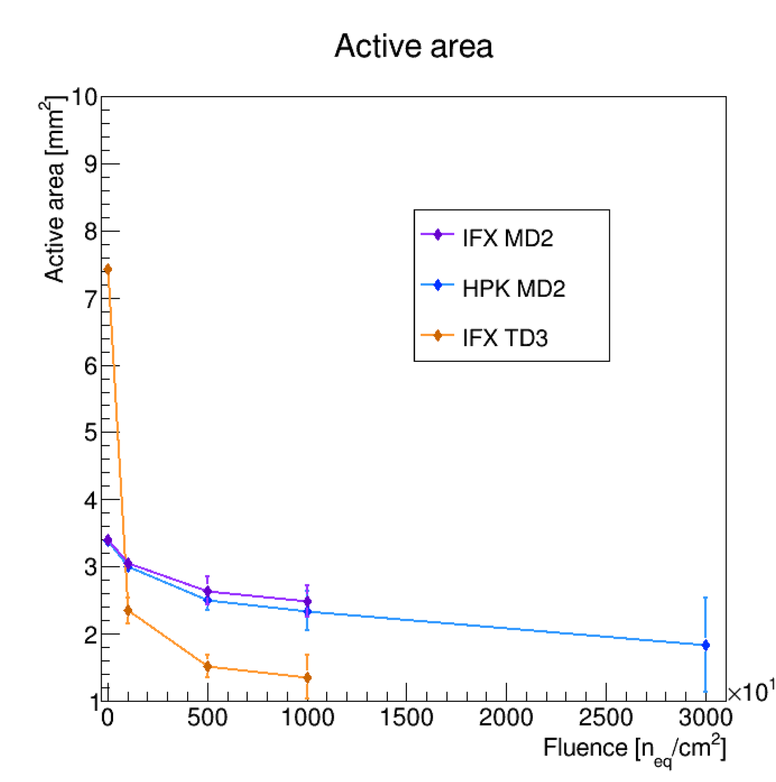
Within a diode of 300 μm thickness, each 15 keV photon has a 51% chance to interact with a silicon atom. The interaction produces one 15 keV electron, which travels up to 20 μm within silicon, which determines the maximum achievable position resolution.



Diodes were scanned in a grid with a step size of 75 x 75 μm to provide good spatial resolution while minimising the beam time required per diode measurement.

Conclusion

The active area of diodes irradiated to different fluence levels was successfully mapped using a micro-focused X-ray beam by reading out the overall diode current.



The signal-to-noise ratio (induced current to fluctuations of leakage current) at a sensor temperature of -20°C was sufficient for fluences up to $1 \cdot 10^{15}$ n_{eq}/cm^2.

Acknowledgements

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