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3D pixel devices; design, production and characterisation in test beams

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The Large Hadron collider (LHC) will under go a luminosity upgrade to the High-Luminosity-LHC (HL-LHC). This will result in an order of magnitude increase in radiation levels experienced by the silicon sensors of the experiments'tracking and vertex detector systems. The development of ultra-radiation hard silicon sensors, capable of withstanding particle fluences beyond 10E16 1 MeV Neutron-equivalent per cm2, is therefore required for the innermost tracking layers.
Three-Dimensional (3D) silicon sensors offer potential advantages over standard planar sensors for radiation hardness. The 3D sensors have columnar electrodes etched through the silicon bulk which are spaced at a pitch less than the thickness of the substrate this electrode structure greatly reduces the charge collection distance over that of a planar device which results in significantly less charge trapping, the major concern for heavily irradiated silicon sensors. The reduced electrode spacing also significantly reduces the operational voltage required over that of planar sensors and therefore reduces the power dissipation of the sensor. The detector structure, however, may introduce inefficiencies due to the columnar electrodes and low field regions which are present throughout the device if it is not fully depleted. The fabrication process is also more complex and therefore yields maybe an issue. 3D sensors are being fabricated at a number of manufactures; here we concentrate on devices from CNM, Barcelona.
A large number of 3D sensors have been fabricated and characterised electrically and as pixel detectors in the lab and at test-beams, both before and after irradiation to a range of fluences up to the maximum expected for tracking detectors of the experiments at the HL-LHC.
We report on the significant progress in the fabrication of 3D detectors at CNM over the past 5 years. The latest designs of pixel sensors from CNM will be shown; including in-pixel bias structures and slim edge technology incorporating the 3D guard structure. The simulation of the electrical field in the edge structures is discussed along with electrical measurements that demonstrate its functionality. The plans for device structures for future pixel production runs will be discussed.
Simulations of the electric field inside the detector and the charge collection from minimum ionizing particles are shown for different bias conditions and fluence ranges.
The possible inefficiencies in the device are probed y studying variations in the response across a unit pixel cell in a 55um pitch 3D pixel sensor bump bonded to TimePix and MediPix2 readout ASICS in test-beam. Two complementary characterisation techniques are discussed: the first uses a custom built TimePix based telescope and a 120 GeV pion beam from the SPS at CERN; the second employs a novel technique to illuminate the sensor with a micro-focused synchrotron X-ray beam at the Diamond Light Source UK. The response from pixel detectors before irradiation and after an irradiation to 1E16 1 MeV Neutron-Equivalent per cm2 are shown. For a pion beam incident perpendicular to the sensor plane an overall pixel efficiency of 93.0 ± 0.5% is measured before irradiation. After a 10O rotation of the device the effect of the columnar region becomes negligible and the overall efficiency rises to 99.8 ± 0.5%. The double-sided 3D sensor shows significantly reduced charge sharing to neighbouring pixels compared to the planar device. The charge sharing results obtained from the X-ray beam study of the 3D sensor are shown to agree with a simple simulation in which charge diffusion is neglected, therefore confirming that the charger diffusion inside the device dose not widen the collected charge cloud as expected for the 3D geometry. The devices tested are found to be

compatible with having a region in which no charge is collected centred on the electrode columns of a radius 7.6±0.6μm. Charge collection above and below the columnar electrodes in the 3D sensor is observed.
The paper shows the significant progress made in the 3D technology with the fabrication of pixel detectors suitable for HL-LHC experiments being demonstrated. The electrical characteristics of the device are shown and are well understood. The response of the detector to minimum ionizing particles is understood through electrical simulations and test beam measurements.

Primary author: Dr BATES, Richard (Department of Physics and Astronomy)

Co-authors: Dr PARKES, Chris (Department of Physics and Astronomy); Dr PELLEGRINI, Giulio (CNM, Barcelona); Mr KOEHLER, Michael (Universität Freiburg); Dr PARZEFALL, Ulrich (Universität Freiburg)

Presenter: Dr MAC RAIGHNE, Aaron (Glasgow University)

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