Silicon Sensors in 3D Technology

Letter of Interest for Snowmass 2021

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4 September 2021

Thematic area: IF3, Solid State Detectors and Tracking
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Silicon sensors of the 3D technology [1] are employed in LHC experiments [2,3] to provide radiation tolerant particle tracking at integrated fluences in the regime of 10^{16} n_{eq}/cm^2. The decoupling of the depletion depth from the sensor thickness allows operation at bias voltages below breakdown despite very high integrated fluence, with significant savings on power dissipation, and the small inter-electrode distance suppresses the effect of radiation-induced charge trapping. The ATLAS IBL sensors, for example, are implemented in p-type with 230 μm thickness and column electrodes of diameter approximately 10 μm, separated by ~62 microns. A slim edge of 200 microns is employed. Designs for application to the HL-LHC, where innermost tracking will be exposed over the course of 10 years to fluence 2.3 x 10^{16} n_{eq}/cm^2, are more aggressive still, in anticipation of conditions in which the carrier lifetime will be reduced to 0.3 ns, corresponding to a mean free path of 30 microns. Up to 200 interactions per 25 ns bunch crossing are expected at the HL-LHC. Small-pitch 3D pixels (25 x 100 μm^2 or 50 x 50 μm^2) have been developed to this purpose, with inter-electrode distances of ~30 microns [4] and a slim edge of 150 microns, and are currently in the pre-production phase for the ATLAS ITk.

Plans [5] for future facilities such as the FCC-hh anticipate a lifetime integrated luminosity of 30 ab^{-1}, predicting integrated fluence at the innermost tracking volume approaching 10^{18} n_{eq}/cm^2. Estimates [6] of the pileup conditions are on the order of 1000 events per crossing. Continued development of silicon sensors of the 3D technology presents prospects both for restoration of signal loss in this environment, and for separation of pileup signals by precision timing.

Measurements [7] carried out on 50 x 50 μm^2 cell 3D sensors have shown signals with a full width of 5 ns, and a rise time of 1.5 ns, with a timing resolution of 30 - 180 ps (depending on the signal amplitude); this is a mode of operation comparable to that achieved by low gain avalanche detectors --- but lacking gain --- with the advantage of higher radiation tolerance and better fill factor. The standard column configuration of 3D has the disadvantages, however, that the electric and weighting fields are non-uniform, leading to a position dependence of the pulse rise time; this is the limiting factor on the timing resolution. New geometries [8,9], involving p-type trench electrodes spanning the entire length of the detector, separated by lines of segmented n-type electrodes for readout, promise improved uniformity and better timing resolution combined with further increased radiation tolerance. Nevertheless, at this time, trenched electrodes cause higher capacitance and introduce larger dead volumes within the substrate. Device optimizations, especially in terms of geometrical efficiency, remain to be carried out. In addition, this problem can be tackled at the system level by tilting the sensor plane with respect to the particle direction, so that a larger fraction of the charge is generated within the depleted volume, and using multiple planes of sensors with an offset between the electrodes, so all tracks would traverse several planes without crossing the electrodes [10].

3D columnar pixels with internal gain [10-12] offer an alternative approach to signal restoration at high fluence. When implemented with very small inter-electrode separation, ~15 microns or less, these devices can achieve controlled charge multiplication at voltages on the order of 100 V, both before and after irradiation. Moderate gain values can be achieved, sufficient to compensate the loss of charge signal due to irradiation of these thin (~ 100 μm) devices. Design optimization continues with a goal of achieving uniform gain throughout the cell active volume, also benefiting from the wider operating range that is possible due to increasing the breakdown voltage.

The goal of this research is to advance one or two 3D technologies for tracking particles, able to operate with adequate signal to noise ratio at fluences approaching 10^{18} n_{eq}/cm^2, and timing resolution on the order of 10 ps. The planned activities include TCAD simulations, process optimization and fabrication of several generations of prototypes, and thorough characterization of the prototypes before and after irradiation to extreme fluences.

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