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Radiation hardness of 3D pixel sensors up to unprecedented fluences of 3e16 neq/cm²

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3D silicon detectors, with cylindrical electrodes that penetrate the sensor bulk perpendicularly to the surface, present a radiation-hard sensor technology. Due to a reduced electrode distance, trapping at radiation-induced defects is less and the operational voltage and power dissipation after heavy irradiation are significantly lower than for planar devices. During the last years, the 3D technology has matured and 3D pixel detectors are already used in high-energy physics particle detectors where superior radiation hardness is key: in the ATLAS Insertable B-Layer (IBL) and the ATLAS Forward Proton (AFP) detector.

For the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC), the radiation-hardness requirements are even more demanding with expected fluences up to $2.5\times10^{16} n_{eq}/\text{cm}^2$ for the innermost pixel layer of the ATLAS and CMS experiments after an integrated luminosity of 4,000 fb^{-1}. The baseline scenario foresees a replacement after half of the life time. Moreover, to face the foreseen large particle multiplicities, smaller pixel sizes of 50$\times$50 or 25$\times$100 μm^2 are planned.

In the context of this work, a new generation of CNM 3D pixel sensors with small pixel sizes of 50x50 and 25x100 μm^2 and reduced electrode distances are developed for the HL-LHC upgrade of the ATLAS pixel detector. For the first time, pixel detectors are irradiated and studied up to the unprecedented fluence of $3\times10^{16} n_{eq}/\text{cm}^2$, i.e. beyond the full expected HL-LHC life time to explore the limits of the 3D technology. Since a readout chip with the desired pixel size is still under development by the RD53 collaboration, first prototype small-pitch pixel sensors were designed to be matched to the existing ATLAS IBL FE-I4 readout chip for testing. Irradiation campaigns with such pixel devices have been carried out at KIT (Karlsruhe) with a uniform irradiation of 23 MeV protons up to a fluence of $1\times10^{16} n_{eq}/\text{cm}^2$, as well as at CERN-PS with a non-uniform irradiation of 23 GeV protons in several steps up to a peak fluence of $3\times10^{16} n_{eq}/\text{cm}^2$. The hit efficiency has been measured in several beam tests at the CERN-SPS. The performance of these devices is significantly better than for the previous generation of 3D detectors or the current generation of planar silicon pixel detectors, demonstrating the excellent radiation hardness of the new 3D technology.

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